AD-A168 729 JOINT SERVICES ELECTRONICS PROGRAM - JSEP RESEARCH IN ELECTRONICS(U) UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES ELECTRONIC SCIE.. W H STEIER 30 APR 85 1/2

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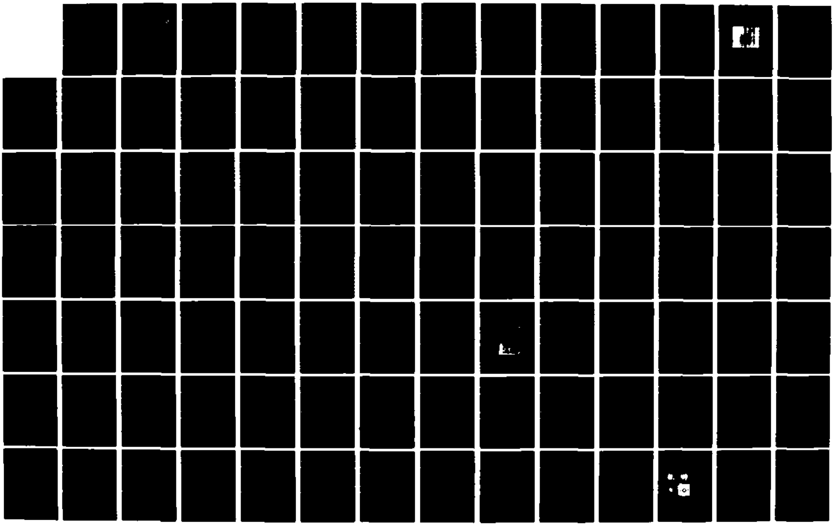

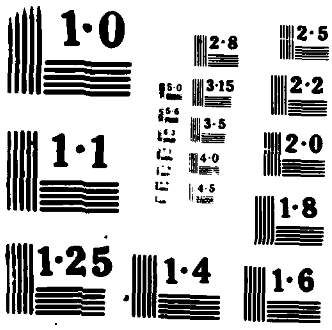
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AD-A168 729

JOINT SERVICES ELECTRONIC PROGRAM - JSEP

UNIVERSITY OF SOUTHERN CALIFORNIA
School of Engineering
Electronics Sciences Laboratory
Final Technical Report

1 April 1981 to 31 March 1985

Contract No. F49620-81-C-0070

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This final technical report summarizes accomplishments and progress of 19 work units (projects) for research performed during the reporting period under the Joint Services Electronics Program by the USC Electronic Sciences Laboratory.

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UNIVERSITY OF SOUTHERN CALIFORNIA

SCHOOL OF ENGINEERING
Electronics Sciences Laboratory

Forward

The Joint Services Electronics Program at the University of Southern California includes topics in three areas: Solid State Electronics, Quantum Electronics, and Information Electronics. The participating faculty are in the Departments of Electrical Engineering, Materials Science, Computer Science, and Physics.

Over the past four-year period, there have been several changes in the program, reflecting the changing areas of importance in electronics. In Quantum Electronics, the research topics under Professors Garmire and Feinberg have been added and the work of Professor Wittig has been dropped from the program. In Solid State Electronics, topics under Professors Madhukar and Dapkus have been included, and the topics under Professors Crowell and Gershenzon have been deleted. This reflects the increased emphasis on MBE and MOCVD growth techniques. In Information Electronics, the work of Professors Li, Moldovan, and Bekey have been added, and the work of Professors Flon, Hayes, and Safonov have been dropped. Seven research topics which were in the program in 1981 have remained through the entire four-year period of this report.

This report presents summaries of the accomplishments and progress for each of the topics funded under JSEP during any part of the period, 1 April 1981 through 31 March 1985, under Contract No. F49620-81-C-0070.

HETEROJUNCTION MATERIALS AND DEVICES EMPLOYING ULTRATHIN LAYERS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD)

Work Unit SS4-1

P. D. Dapkus

1 September, 1982 - 31 March, 1985

RESEARCH OBJECTS

The objective of this program is to optimize the growth of ultrathin layers of semiconductors by metalorganic chemical vapor deposition (MOCVD) and to apply these growth techniques to the fabrication of lattice matched and mismatched heterojunction materials. The characterization of ultrathin heterojunction materials and their application to device structures with new or improved properties will also be pursued.

STATUS OF RESEARCH EFFORT

This project was initiated in September of 1982 with the arrival of P. D. Dapkus at USC. The efforts to date have been focused on the establishment of a state of the art MOCVD facility at USC and to establish a well funded program of materials and device research employing MOCVD This has been accomplished.

The MOCVD system now in operation at USC has a unique design intended to accommodate the growth of heterojunctions in two separate materials systems with minimal cross contamination. This is accomplished by incorporating two growth chambers into a system with one set of sources. The sources (TMGa, TMAl, TMIn, AsH_3, PH_3, etc.) are contained in a common cabinet with the electronic controls (mass flow controllers, pneumatic switches, computer). All reactants are transported in separate lines to a set of switching valves that allows the reactant to be directed to either of the reactor chambers. One of the chambers is a vertical chamber patterned after the work at Rockwell International. It will be used for AlGaAs/GaAs growth. The second chamber will be a horizontal chamber devoted to the growth of Indium containing compounds. A state of the art switching/mixing manifold containing a inject/bypass valve arrangement is located near the entrance of each reactor. This design is patterned after systems used for several years at Rockwell. The manifolds permit rapid exchange of the gases and the formation of abrupt heterojunctions using interrupted or continuous growth.

A schematic diagram of the reactor are shown in Fig 1. This design was developed at USC and the reactor gas handling system was built by CVD equipment of Long Island, N.Y. A different system design was originally ordered from NavTec in 1982 but never delivered owing to that company's bankruptcy. This resulted in a one year delay in setting up our facility

To date only GaAs has been grown with this system. Initial growth studies were plagued by poor morphology indicative of particulate originating from the walls of the reactor.

This problem was found to be caused by disrupted flow patterns in our chamber that occur when a back pressure in the exhaust system is present. It was found that the exhaust treatment facility designed and built at USC was clogging after a few runs and causing back pressure in the reactor. A new exhaust system employing a large area particulate filter and a large capacity charcoal filter to remove unreacted AsH_3 was purchased built and installed. At the same time a new design on the reactor inlet was build to permit the manual valving of the manifold during chamber disassembly. This reduced oxygen contamination in the manifold.

These new design elements eliminated the back pressure in the exhaust but a new morphological defect was observed on the surface reminiscent of oval defects in MBE growth. These defects were traced to stainless steel particles originating from improper cleaning of the new inlet valve assembly. After a more thorough cleaning of this assembly, highly perfect morphology was obtained in subsequent growths. Fig. 2 shown a micrograph of GaAs eptaxial film 5 µm thick grown on a GaAs substrate. The properties of the films appear to be controlled by the starting materials. Room temperature mobilities are carrier concentrations in the range 5000-7000 cm^7/V-sec and $N_D-N_A = 2\text{-}8 \times 10^{14} cm^{-3}$ are being measured. These are indicative of some compensation. Low temperature mobilities are dependent upon film thickness. A study of this is being conducted to determine its origin. Mobilities is high as 55,000 cm^2/V-sec are observed in 15 µm thick films at 77K.

In addition to the growth reactor, other instrumentation to characterize the grown materials have been established. An automated Van der Pauw Hall system has been assembled. At the present time measurements at room temperature and 77K can be accommodated. A room temperature photoluminescence system has been built around an argon laser and Jarrel-Ash spectrometer. We are currently automating this system. F· ·ding for a available temperature dewar is being sought.

A capacitance profiler has been acquired by donation from Rockwell International and is being incorporated into a computer operated measurement system.

During this time period, two DoD/University Equipment grants were received to purchase equipment to analyze the physical and chemical kinetics of the MOCVD growth process. Funds to purchase an excimer- pumped dye laser system, a reactor cabinet, a mass spectrometer and a surface analysis system were awarded in 1983 and 1984. We plan to incorporate these items into an analysis system which will enable us to study the basic chemical reactions in the reactor by laser induced flourescense (LIF), the composition profile of reactants in the reactor by LIF and mass spectroscopy, and the surface kinetics of MOCVD growth by LIF and Auger electron spectroscopy. The laser systems are now in-house and a sampling mass spectroscopy system has been designed. When operational, this system will form the heart of an unique MOCVD study apparatus.

Several characterization and processing tools are being assembled to allow the routine characterization of grown structures and the fabrication of device structures. Photoluminescence and Hall transport apparatus are being assembled to allow routine characterization of materials quality and purity. A SiO_2 deposition system has been built

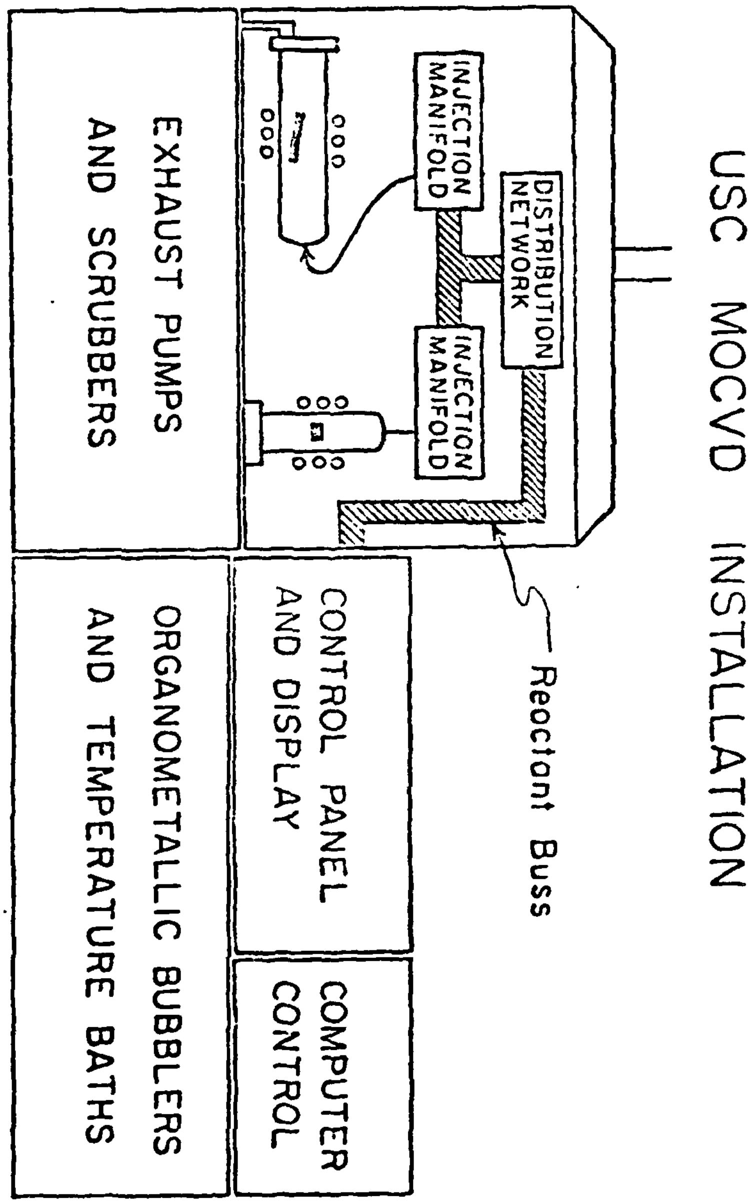


Fig. 1: Schematic Diagram of USC MOCVD installation.

and a sputtering system has been renovated for Si_3N_4 depositions. The latter will be used to define areas of diffusion studies. The remaining portion of this year will be devoted to calibration of the growth system to determine growth rates, composition, and doping at various growth temperatures. A design for the horizontal reactor is being developed. This design will incorporate the various analytical instruments required for studying the MOCVD growth kinetics. Construction of the horizontal chamber will begin in September.

PUBLICATIONS

1. Epitaxial Processes for Multilayer Electronic Device Structures, P. D. Dapkus, Proc. SPIE **387**, 100 (1983).

2. A Critical Comparison of MBE and MOCVD, P. D. Dapkus, J. Crystal Growth, **68**, (1985).

PROFESSIONAL PERSONNEL

1. P. D. Dapkus, Professor of Electrical Engineering and Materials Science

2. Allen Danner, Research Assistant

3. Mark Innocenzi, Research Assistant

4. H. C. Lee, *Research Assistant*

5. W. Jeong, Research Assistant

INTERACTIONS

1. "Heterojunction Electronic Devices by MOCVD," invited talk presented at the 1st International Workshop on Future Electron Devices, Tokyo, February 1984.

2. "A Critical Comparison of MBE and MOCVD," invited talk presented at Second International Conference on MOVPE, Sheffield, UK, April 1984.

3. "Heterojunction Electronic Devices by MOCVD: Progress and Problems," invited talk presented at IEEE Device Research Conference, Santa Barbara, CA, June 1984.

4. "Quantum Well Lasers" invited lecture at School on Semiconductor Lasers, Campinas Brazil, Sept. 1984.

Consultant to:

1. Northrop Technology and Research Center (1983–present)

2. Jet Propulsion Laboratory (1984–present)

3 Honeywell Research Center (1984-present)

4 American Cyanimede

5. Ethyl Corporation (1984)

6. Bendix Aerospace (1985)

7 Wright Patterson Air Force Base Avionics Laboratory (1983)

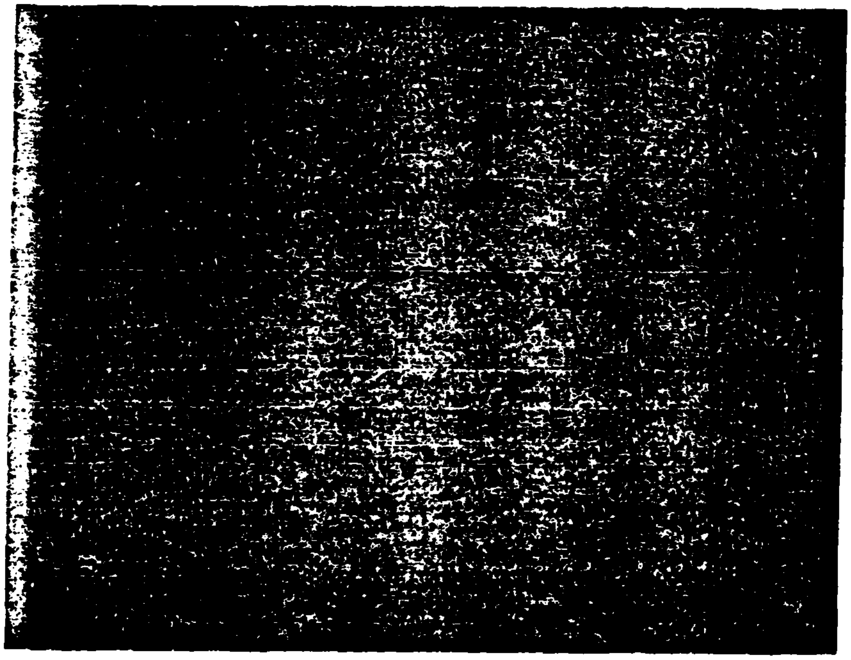
8 ITT Electro Optics Div (1983)

9 United Nations Consultant to Telebras (Brazilian Telephone Company) 1983-1984)

10 Solar Energy Research Institute (1985)

DISCOVERIES/PATENTS

None to report.



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SOME INVESTIGATIONS OF THE KINETICS AND MECHANISM OF MOLECULAR BEAM EPITAXIAL GROWTH

Work Unit SS4-2

A. Madhukar

Report Period: April 1, 1984 -- March 31, 1985

Research Objective

The task proposed under work unit SS4-2 defined its objective to be an examination of the kinetics and growth mechanism(s) of GaAs/AlGaAs MBE growth via the use of reflection high energy electron diffraction (RHEED) intensity dynamics (during growth and recovery) combined with computer simulations of the growth process. In the next section we report on the present status of our progress towards this objective.

Task Status:

This task started on October 1, 1983. By mid-summer of 1984 we completed the redesign and testing of the various critical components of our ϕ-400 MBE machine as was expected according to last year's report. In addition, we designed, acquired appropriate instruments and implemented the RHEED intensity measurement system. An innovative feature of this system is also the capability to video-tape the entire RHEED pattern during the growth and recovery experiments for later analysis and study of the intensity dynamics of various features of interest, thus eliminating the need for repetitous growth sequences.

RHEED intensity dynamics experiments were begun in July 1984 and have revealed a wealth of new and exciting information regarding the kinetics of MBE growth and its exploitation for realization of high quality interfaces and thin films in GaAs/$Al_xGa_{1-x}As$(100) multiple interface structures (e.g. heterojunctions, multiple quantum wells and superlattices). The attached preprints provide information on some of the achievements, with a wealth of data acquired being presently analyzed. In the following we briefly indicate a few of the highlights.

(A) Group V Pressure Dependence of Surface/Interface Morphology:

The configuration-Dependent-Reactive-Incorporation (CDRI) model of III-V MBE growth proposed[1] by us identified the competition between the surface migration kinetics of the group III atoms and the dissociative reaction kinetics and pressure controlled incorporation rate of the group V molecules as the fundamental factor controlling the morphology of the MBE growth front. Computer simulations[2] based upon this model revealed that the surface morphology was consequently very sensitive to the group V pressure employed (see Fig. 1). Consequently, the first RHEED intensity dynamics experiments were carried out to examine the As pressure dependence during GaAs(100) homoepitaxy. Illustrative results of the measurements,[2,3] shown in Fig. 2, are seen to be in conformity with the predictions, thus providing credence for the relative role of the kinetic processes noted above. It is perhaps worth noting that in the past the group V overpressure employed in MBE has never been recognized to be as significant as the RHEED results demonstrate it to be. Its implications for formation of structurally and chemically abrupt interfaces on an atomic scale are of direct practical significance for dense structures, as discussed below.

(B) Notion of Growth Interruption to Optimize Normal and Inverted GaAs/Al$_x$Ga$_{1-x}$As(100) Interfaces:

The CDRI model based computer simulations[1,2] also revealed that the dynamic, steady state growth front profile is structurally rougher than the equilibrium *no-growth surface* due to the competition between the kinetics of group III and group V species as noted above. This is, of course, already substantiated by the damped oscillatory nature of the RHEED specular beam intensity shown in Figs. 1 and 2. The importance of surface migration of the group III atoms in achieving atomically smooth growth front profile thus indicated to us that interrupting growth after deposition of a given layer (say GaAs) and letting the growth front relax towards its smoother no-growth (i.e. static) behaviour would provide a smoother surface for the deposition of the subsequent (say Al$_x$Ga$_{1-x}$As) layer. Consequently, such "static" interfaces are likely to have greater structural and chemical perfection, compared to the customary practice of deposition of a given layer on the dynamic growth front of the previous layer. Motivated by this idea and understanding of the role of kinetics in MBE growth, we undertook RHEED intensity dynamics studies for the GaAs/Al$_x$Ga$_{1-x}$As(100) system with a view towards optimizing the normal (i.e. Al$_x$Ga$_{1-x}$As deposition on GaAs) and inverted (i.e. GaAs desorption on Al$_x$Ga$_{1-x}$As) interfaces. In the following we show some illustrative examples and discuss their significance for device structures.

In Fig. 3 are shown the specular beam intensity behaviour measured for the 2-fold pattern on a (2 X 4) As-stabilized surface during formation of normal and inverted GaAs/Al$_x$Ga$_{1-x}$As(100) interfaces. Curve (a) shows the influence of interruption of Al$_{0.2}$Ga$_{0.8}$As growth to allow the intensity to recover before commencing GaAs growth to form an inverted interface (to be called inverted static). Note that the surface morphology of the fully relaxed (i.e. static) Al$_{0.2}$Ga$_{0.8}$As surface is indicated by the recovered intensity to be as smooth as the starting static GaAs surface. The structural and chemical nature of the inverted static interface is then seen to be comparably good to the normal static interface as manifested by the ratio of the first maximum to the starting intensity. The rate of oscillation damping during GaAs growth, however, is much faster than for GaAs deposition on comparable quality GaAs surface. This faster rate of damping, we propose, is a reflection of the influence of impurity (primarily oxygen and carbon) incorporation on the Al$_{0.2}$Ga$_{0.8}$As surface during the growth interruption -- an undesireable feature. The steady state GaAs intensity being essentially the same as for GaAs/GaAs lend credence to this idea. In Curve (b) is shown an illustrative result for growth interruption at an intensity maximum of Al$_{0.2}$Ga$_{0.8}$As. The essentially recovered intensity is achieved on a much shorter time scale compared to case (a), even though the recovered value is significantly lower than that for GaAs thus indicating a rougher surface. The formation of the subsequent inverted static interface is again seen to be better than the customary practice of no-growth interruption (i.e. formation of dynamic interface) although impurity incorporation is once again reflected by the faster oscillation damping rate during GaAs deposition. Thus, optimization of the growth interruption time is called for to, on one hand, improve the structural nature of the interface and, on the other, keep the background impurity incorporation to a minimum acceptable limit. To this end, Curve (c) provides an illustration of improvement in the inverted interface morphology without serious impurity incorporation achieved via a very short growth interruption time compared to Curve (a). The growth interruption times can be made much shorter while still achieving the same percentage of recovered intensity on a relaxing surface by simply employing a higher substrate temperature. The underlying reason is the faster group III migration kinetics (at higher substrate temperature) which is at the core of the relaxation of the dynamic growth front towards the smoother equilibrium surface. A variety of higher substrate temperatures, varying growth rate and different As pressure data were acquired confirming this essential role of the surface kinetics in controlling the nature of normal and inverted interfaces in multiple interface device structures, but in the interest of brevity, we forego discussing them here.

(C) Role of As pressure relative to Ga and Al pressures:

In Curve (d) of Fig. 3 we illustrate the role of (P_{As}/P_{III} in influencing the reaction and migration kinetics at the dynamic growth front and consequently in controlling the nature of the normal and inverted interfaces. To this end, Curve (d) corresponds to GaAs/AlAs growth to exemplify the role of differing migration rates of Ga and Al (Al is slower). To minimize any complications arising from the high reactivity of Al with background impurities growth interruption is not invoked, and the number of layers grown in the customary dynamic way is kept very low (3 monolayers in Curve (d)). Note first that both the maxima and minima during AlAs deposition decay, the latter in contrast to the rise in the minima during the preceding deposition of 3 monolayers of GaAs. This increased roughness of the AlAs dynamic growth front is a manifestation of (a) the slower migration rate of Al compared to Ga and (b) the increase in the As to Al pressure ratio by a factor of 9 compared to the As to Ga pressure ratio which further reduces the effective migration rate of Al, given its higher reactivity as well. The much higher degree of roughness of the AlAs dynamic growth front due to the above noted role of kinetic processes is remarkably well manifested in the immediate rise in intensity upon switching from AlAs growth to GaAs growth. This is a consequence of the intrinsically faster migration rate of Ga combined with a factor of 9 drop in the As to group III pressure ratio upon commencement of GaAs growth. The faster moving Ga species is able to almost instantaneously smoothen the rougher AlAs dynamic growth front. Finally, note that the rate of decay of the oscillation maxima and the rate of rise of the minima during GaAs growth on AlAs is essentially the same as for GaAs on GaAs indicating that the behaviour discussed above and the inferences drawn are not complicated by impurity incorporation.

A variety of RHEED intensity dynamics data acquired during this reporting period are presently being analyzed to extract some direct information on certain kinetic rates during growth. This would be the first time that such information during growth would become available in the literature and we look forward to making this important contribution. In addition, a variety of multiple interface structures have been grown guided by our RHEED intensity studies and we are in the process of acquiring structural, optical and electrical information on these.

References:

1. S. V. Ghaisas and A. Madhukar, Jour. Vac. Sc. Tech. B3, 540 (1985)

2. A. Madhukar and S. V. Ghaisas, App. Phys. Letts. (In Press)

3. A. Madhukar, S. V. Ghaisas, T. C. Lee, M. Y. Yen, P. Chen, J. Y. Kim and P. G. Newman, To Appear in the Proceedings of the SPIE Conference, January 21-22, 1985, Los Angeles.

Personnel

1. Mr. M. Y. Yen (Graduate Student)
2. Mr. T. C. Lee (Graduate Student; partially supported)
3. Professor A. Madhukar (P.I.)

DoD Interactions

1. AFOSR
2. ONR

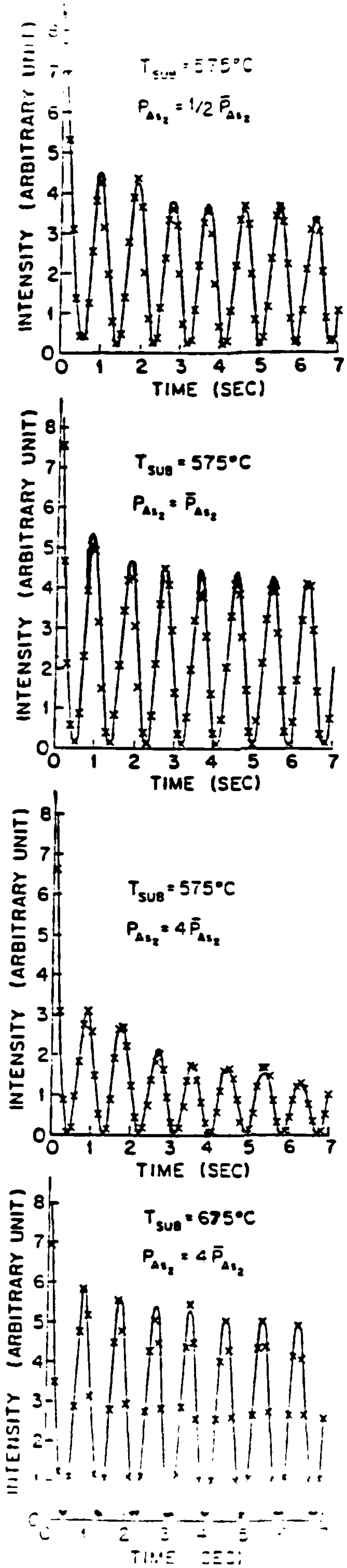
Publications:

1. A. Madhukar, T. C. Lee, M. Y. Yen, P. Chen, J. Y. Kim, S. V. Ghaisas and P. Newman, **"Role of Surface Kinetics and Interrupted Growth During Molecular Beam Epitaxial Growth of Normal and inverted GaAs/AlGaAs(100) Interfaces: A RHEED Intensity Dynamics Study"**, Appl. Phys. Letts. (June 15, 1985 issue; In Press)

Conference Presentations

1. **"The Dynamics of RHEED Intensity Behaviour as a Probe of Crystal Growth: Computer Simulations and Measurements During MBE of GaAs/Al_xGa_{1-x}As(100)"**, SPIE Conference, January 21-22, 1985 Los Angeles, California

2. **"Measurements of the RHEED Diffraction Behaviour During MBE Growth of $GaAs/Al_xGa_{1-x}As(100)$ Interfaces"**, APS Annual Meeting, March 25--29, 1985, Baltimore, Maryland



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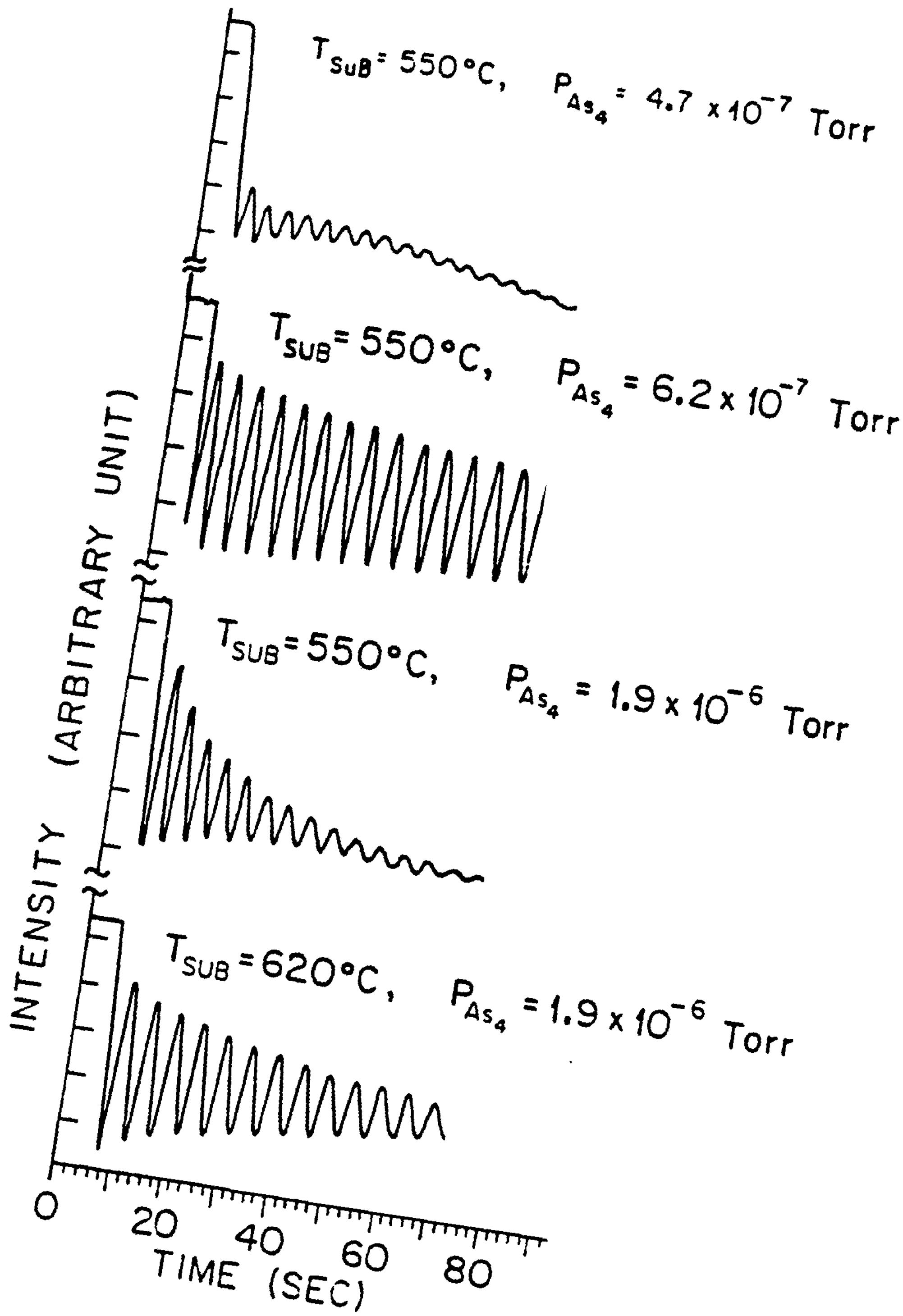

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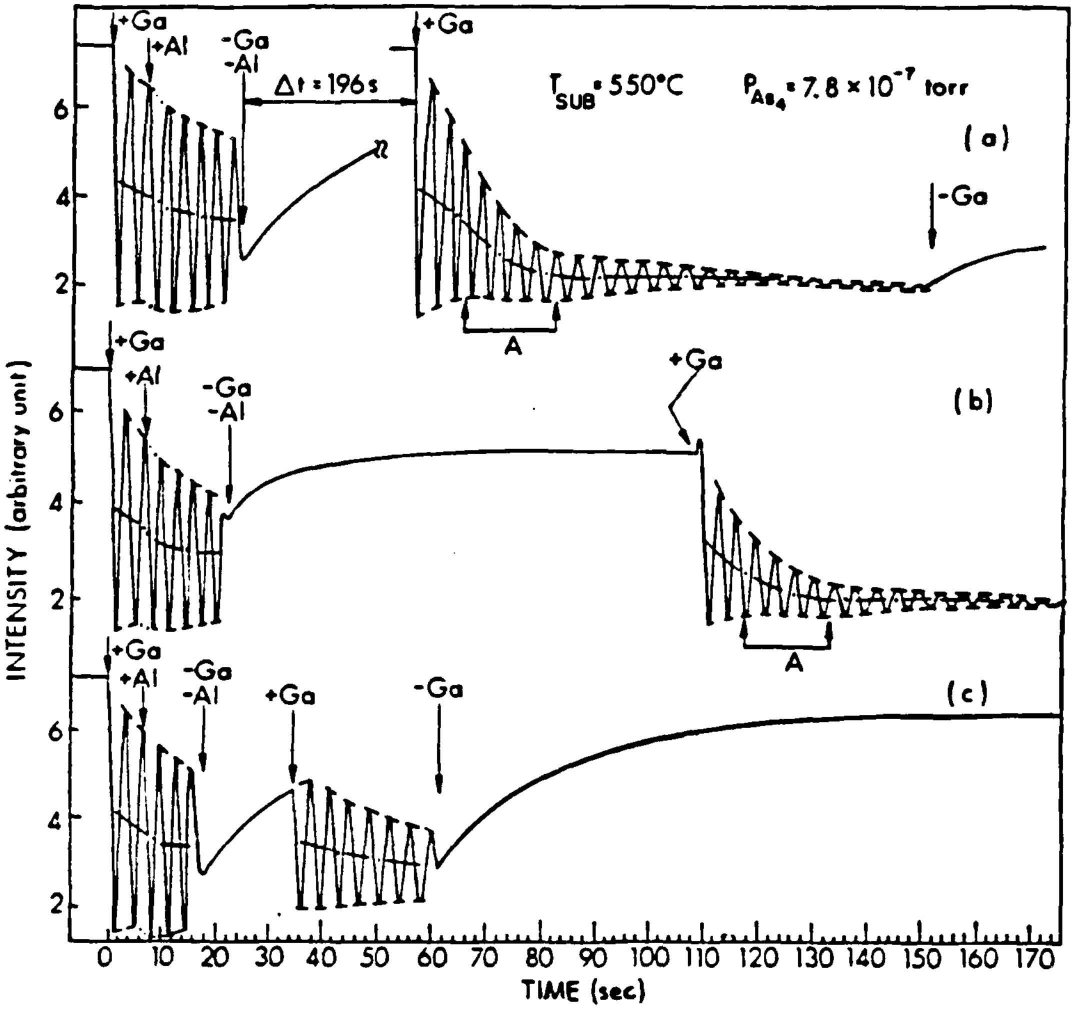
Fig. 2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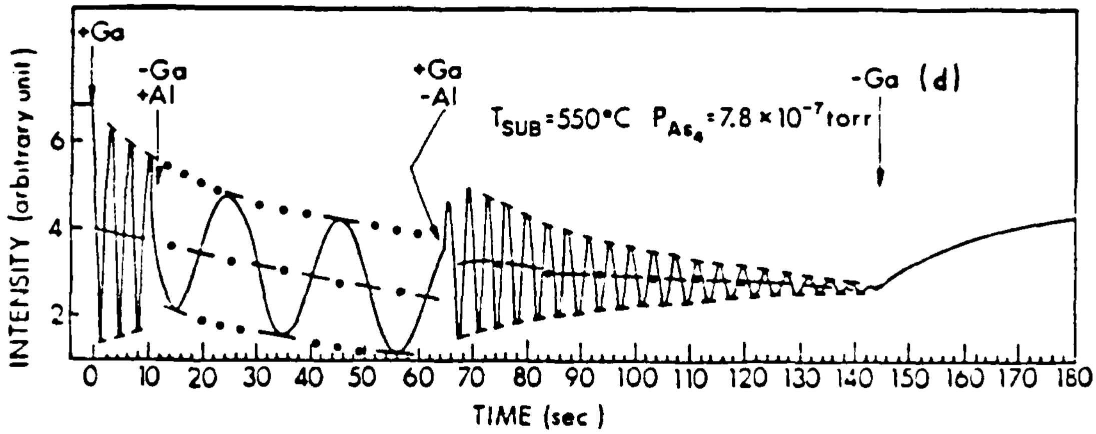
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OPTICAL PROPERTIES AND THERMAL ANNEALING OF ION-IMPLANTED SEMICONDUCTORS

Work Unit SS4-3

WILLIAM G. SPITZER

1 April 1981 to 31 March 1985

RESEARCH OBJECTIVES

To characterize heavily ion-implanted semiconductors and to investigate the annealing behavior of the heavily damaged or amorphous material. Annealing effects include the dependencies of the properties of the implanted layer on a wide variety of implantation and thermodynamically related variables.

STATUS OF RESEARCH EFFORT

(A) Infrared Study of Hydrogen- and Carbon-Implanted Heavily Doped GaAs

A study is given of the effect of ion implantation on the carrier density and the infrared dielectric constant of heavily doped, high carrier density, n-type GaAs. Hydrogen is implanted at 300 keV at room temperature and carbon at 380 keV at near liquid nitrogen temperature. The primary technique employed is to measure the frequency dependence of the infrared reflection which is shown to be sensitive to carrier density changes produced by the implantation process. A computer code is developed to calculate the reflection spectrum for physically realistic models and the calculated curve is fitted to the measured data by using a least-squares method.

For both ions the effect of the implantation and subsequent annealing from 100 to 550°C are examined. The $^{1}H^{+}$ ion implantation and annealing results are compared with available SIMS data and with the carrier density profile obtained from capacitance-voltage measurements of a progressively etched sample. The H and carrier compensation profiles are clearly related and show a deeply diffused layer is present after annealing at $T \geq 200°C$ and grows with anneal temperature for $200 \leq T < 500°C$. After 500°C annealing the carrier compensation in the diffused layer disappears. After annealing at 550°C, some carrier recovery in the implanted layer is observed. The hydrogen results show only small changes in the dielectric constant from effects other than that due to the changing carrier density. The $^{12}C^{+}$ implanted sample shows both carrier compensation and substantial damage-related changes in the dielectric constant. Annealing removes the damage-related changes in a manner similar to that previously reported for undoped, implanted GaAs. No compensated diffused layer such that observed for hydrogen was present in this case. An effective diffusion constant for the hydrogen related defect is tentatively estimated for $300 \leq T \leq 400°C$ by $D_{eff} = D_{o,eff}e^{-E_a/kT}$ with $D_{o,eff} = 3.0\ cm^2/sec$ and $E_a = 1.4$ eV.

(B) Activation of Charge Carriers in Be-Implanted GaAs Annealed at Low Temperatures

Free charge carriers in both room temperature and low temperature Be-implanted GaAs were generated by annealing at 400, 450 and 475°C and were observed by using both infrared reflection and electrical measurements. Annealing at 400°C for two hours removes homogeneously most of the damage-related changes in the refractive index. Longer annealing (~ 50 h) or shorter term annealing at higher temperature produces free carriers. A computer model including plasma effects was used to fit the reflection curves. In general the infrared analysis results and the electrical data were in reasonable agreement. Results for the room temperature implanted samples show the free carrier density profile, approximated by joined half-Gaussians, to be (i) a standard deviation for the deeper half-Gaussian ($\sigma_h \leq 0.1$ µm) which is about the same or smaller than that observed by SIMS measurements (~0.13 µm) for the Be profile, and (ii) a peak position, 1.2 µm, which is deeper than the Be ion peak at 0.95 µm. Both peak positions remain essentially unchanged during the anneals. Activation of carriers at these low temperatures is not seen in either Si- or Zn-implanted GaAs. The Zn-implanted material has a weak plasma effect at 500°C, the Si-implanted material none up to 550°C. The free carrier profile is considered as the combination of the concentration distributions of dopant ions, Ga vacancies and possible compensating damage-related states. The discussion centers on the detailed results for the Be case.

(C) Ion Implantation of Si by ^{12}C, ^{29}Si and ^{120}Sn: Amorphization and Annealing Effects

Several Cr-doped, low carrier density (10-20 Ω-cm), (111)-oriented wafers of Si were ion-implanted at room temperature and ~90K with various doses of ^{12}C, ^{29}Si, and ^{120}Sn. The ion energy was 380 keV except for ^{12}C at 90K where 150 keV was used. Infrared reflection as a function of frequency and cross sectional transmission electron microscopy measurements were made for both as-implanted and thermally annealed (400°C for 2h) samples. The results of these measurements demonstrate the following: (i) The previously reported pair of metastable amorphous states are observed, a-Si-I for high dose as-implanted material and a-Si-II for anneal-stabilized material; (ii) interface positions and microstructural properties show good consistency between the two types of measurements; (iii) the measurements are consistent with the view that the implanted material can be a heterogeneous mixture of undamaged, damaged, and amorphous regions. By using an effective medium approximation and a damage cascade overlap model one concludes that no overlap is required for ^{120}Sn to create amorphous zones, while a large number is necessary for a light ion, 14 for ^{12}C implantations at room temperature; (iv) from several different approximation methods, average values for the critical amorphization energy are obtained, i.e. in units of 10^{21} keV/cm^3 - 1.4 for ^{120}Sn, 2.0 for ^{29}Si; and 13. for ^{12}C (all for room temperature implantations) and 0.5 for all ions for 90K implantations; (v) the measurements show that the annealing-induced recrystallization behavior of incomplete or mixed amorphous layers is very different from that for complete or homogeneous layers which crystallized by planar epitaxial regrowth; (vi) samples were cycled between the a-Si-I and a-Si-II states and it was observed that the energy required for a-Si-II→a-Si-I is about an order-of-magnitude smaller than the critical amorphization energy (c-Si→a-Si-I) for ^{29}Si implantations at room temperature.

(D) Effect of Annealing on the Optical Properties of Ion Implanted Ge

Infrared reflection and transmission measurements are used to study (III)- and (100)-oriented Ge samples which were implanted with sufficient fluences to produce a continuous amorphous layer. Two optical states of amorphous Ge are identified: (i) as-implanted, amorphous state which has an infrared refractive index about 8% larger than that for single crystal Ge, n_c = 0.92 n_l; (ii) thermally stabilized amorphous state with an intermediate refractive index, n_{II} = (0.963 ± 0.002)n_I. A shift of the fundamental absorption edge to higher energy occurs with the transition from the as-implanted to the thermally stabilized, amorphous Ge state, but no change in the density is observed for the transition. Annealing at about 300°c for 2 h produces the thermally stabilized state. Annealing for longer time or at higher temperatures, causes measurable epitaxial regrowth. The regrowth rates and activation energies for both orientations are also determined and compared with values measured previously by another method. With the regrowth rate $\propto e^{-E_a/kT}$, E_a = 2.0 eV for both orientations and the regrowth rates at 350°C are 46 Å/min for (III)-orientation, respectively.

(E) Solid Phase Regrowth of Low Temperature Be-implanted GaAs

Infrared reflection and transmission measurements were used to study the thermally induced regrowth of (100) oriented, Be-implanted GaAs samples. The samples used in this tudy were implanted at low temperature (-100°C) with 250 keV Be ions to a fluence of 6 x 10^{15} cm^{-2}. The samples were postannealed at temperatures ranging from 100 to 550°C. Isochronal and isothermal annealing at a series of temperatures between 180 and 240°C were performed. Infrared reflection spectra were analyzed by using a three or four dielectric model. Analysis of the annealing data suggests that an amorphous layer first anneals to a second metastable amorphous state and then becomes a damaged crystalline layer after annealing at 220°C for 12 h. The observed regrowth is not by a simple epitaxial process. After annealing at 400°C for 1 h, the damage in the layer is reduced sufficiently for the refractive index to recover almost to the preimplantation value. On annealing at 450°C free carriers are observed. From the measured average regrowth rate for the amorphous layer at various anneal temperature, an effective activation energy is estimated to be about 1.45 eV. This compares with activation energies of 2.3 eV for Si and 2.0 eV for Ge.

(F) Thermal Annealing Behavior of Hydrogen-Free Amorphous Silicon and Germanium

Recent work has demonstrated that the infrared properties (refractive index and absorption) of amorphous silicon and germanium prepared by ion implantation depend upon the low temperature thermal annealing history (1500°C<T<600°C). This thermal relaxation phenomenon is the subject of this review. The data suggest the change in refractive index is caused by a structural reorganization of a continuous random network but that changes in absorption and spin density are chiefly caused by the annealing of defects within the amorphous structure.

(G) Amorphous Silicon Produced by Ion Implantation: Effects of Ion Mass and Thermal Annealing

Characterization of the two optical states of amorphous Si produced by ion implantation is extended to include electron paramagnetic resonance, fundamental absorption edge, and density measurements in addition to infrared reflection. It is found that the properties of the two a-Si states are not dependent upon the mass of the incident ion (^{12}C, ^{29}Si, ^{31}P, ^{120}Sn) or upon the anneal temperature for 400°C<T_A<600°C. The dangling-bond density drops about a factor of 2 when the a-Si makes a transition between the two states. The absorption coefficient also drops by more than a factor of 5, but the density of the a-Si does not change when the transition occurs. The transition between states was not completed at T_A = 300°C, so the annealing mechanism may be temperature dependent.

(H) Amorphous Silicon Produced by Ion Implantation, Etching Rate in HF Solution and Effect of Annealing

In previous studies, it was found that amorphous Si produced by ion implantation can exist in two distinct metastable states and that a number of physical properties are different for these two states. Among the interesting properties is the significant decrease of the dangling bond concentration when the a-Si is transformed from the a-I to the a-II state. It is shown in this study that the character of the etching in HF solution also differs for these two states. The etching solution is HF (48% of volume concentration). This solution is selected for the experiment because it will dissolve amorphous Si but will not dissolve crystalline Si. Two techniques are used in measuring the etching rate. One method is a profilometer measurement of the step at the interface between the amorphous and crystalline silicon. The other method is by measurement of the infrared reflection and the use of computer fitting to calculate the layer thickness. The etching rates obtained from these two methods agree with each other within the accuracy of the measurements. For the a-I state the etching is highly non-uniform, rapid (>100Å/hr), and essentially independent in character of the implanted ion (Si^+ or As^+) and the etching method (quiescent, ultrasonic, or stirred). In the a-II state, the material etches uniformly for several hours with a room temperature rate of ~42Å/hr (quiescent), ~70Å (ultrasonic), and ~80Å/hr (stirring). In order to test the influence of possible surface contamination two samples were initially plasma etched to clean the surfaces. There was no significant effect on the HF etching results.

(I) Infrared Properties of Heavily Implanted Silicon, Germanium and Gallium Arsenide

A review of the techniques developed for using infrared reflection spectroscopy to study properties of heavily implanted semiconductors is presented. Several structural models are considered and calculations based on them are applied to measurements of implanted Si, Ge and GaAs. These comparisons of model calculations and measured spectra show how a number of important physical parameters can be obtained as well as new information concerning implantation-induced amorphous material.

(J) Low Temperature Annealing of Be-implanted GaAs

Infrared reflection and transmission measurements of GaAs implanted with large fluences of Be ions have been made as a function of post-implantation annealing temperature. Annealing up to 400°C resulted in decreases in the lattice disorder responsible for changes in the dielectric constant. This decrease appears to take place uniformly throughout the disordered layer rather than by epitaxial process. Annealing at 400°C for 2 h returns the dielectric constant to essentially the preimplantation value with no significant carrier activation being observed. Carrier activation is observed only after prolonged annealing at 400°C, i.e. ≳50 h. Annealing for 1 h at 450°C also produces measurable carrier activation. These results are in general accord with prior electrical data and transmission electron microscope measurements and suggest that the removal of the disorder-induced changes in the dielectric constant and the activation of free carriers might involve different annealing processes.

(K) Properties of Amorphous Silicon Produced by Ion Implantation: Thermal Annealing

The refractive index, electron paramagnetic resonance (EPR) signal strength and density of amorphous silicon were measured as a function of 500°C isothermal annealing time. The EPR signal was found to be correlated with two distinct optical states of amorphous silicon that were previously reported. One state is the as-implanted state which has a refractive index 12% larger than crystalline silicon. The other state is stabilized after thermal annealing and has a refractive index 8% larger than crystalline silicon and an EPR signal strength a factor of three smaller than the first state. This state is stable until epitaxial recrystallization occurs. No correlation is found with the amorphous silicon density.

(L) Infrared Studies of Isothermal Annealing of Ion-implanted Silicon: Refractive Indices, Regrowth Rates, and Carrier Profiles

A model-dependent computer analysis technique developed previously has in this work been applied to the infrared reflection data of a number of <111> and <100> oriented Si samples which were implanted with high fluences of Si or P ions and then taken through an isothermal annealing process. The physical properties deduced from this analysis are: (i) Dielectric properties including the frequency dependent refractive indices of the recrystallized Si and of the a-Si as a function of annealing temperature and time; (ii) structural information including the amorphous layer depth, widths of transition regions, and the epitaxial regrowth rates; and (iii) electrical properties including the depth profile of the carrier density, the carrier mobility near the maximum carrier density, and the carrier activation efficienty. The physical interpretation of the results is discussed and, where possible, comparisons with results of other experiments are made.

(M) Effects of Thermal Annealing on the Refractive Index of Amorphous Silicon Produced by Ion Implantation

Precise infrared reflection measurements of the refractive index of silicon show that there are two well-defined optical states of amorphous silicon produced by ion implantation. One is the as-implanted amorphous state which is the high refractive index state produced by high fluence implantation of Si or P ions into Si samples. The other state, which has a refractive index intermediate between the as-implanted and crystalline values, is induced by thermal annealing and is thermally stable until epitaxial recrystallization occurs.

(N) Electrical and Structural Characterization of Implantation Doped Silicon by Infrared Reflection

A physical model is presented for calculating infrared reflection interference spectra from ion implanted and annealed crystalline materials. The utility of the method is illustrated by presenting best fit spectra for a <111> silicon sample implanted with 2.7 MeV phosphorous to a fluence of 1.74×10^{16} ions/cm^2 and isothermally annealed at 500°C. Non-linear least-squares fitting of reflection data yields structural and electrical information about the implanted region with reasonable precision. The physical quantities determined are (i) the depth of the amorphous layer produced by implantation both before and during isothermal annealing, the thickness of the recrystallized material, and the widths of any transition regions, (ii) the dielectric properties of the amorphous and recrystallized material, and (iii) the characteristics of the free carrier plasma which yield the carrier density profile, the mobility near the carrier density maximum, and the carrier activation efficiency. Up to nine fitting parameters are necessary to describe these physical quantities. A critical discussion of the sensitivity of data fit to variation in the parameters is given to establish the uniqueness of fitted parameters. The infrared method is non-destructive, is applicable to other dopants and semiconductors, and provides information complementary to both ion channeling and resistivity profiling techniques.

PUBLICATIONS

1. "Infrared Study of Hydrogen- and Carbon-Impanted Heavily Doped GaAs," L. L. Liou, W. G. Spitzer, Z. M. Zavada, and H. A. Jenkinson, submitted to J Appl. Phys.

2. "Activation of Charge Carriers in Be-implanted GaAs Annealed at Low Temperatures," L. L. Liou, W. G. Spitzer, J. E. Fredrickson, and S-I. Kwun, submitted to J. Appl. Phys.

3. "Ion Implantation of Si by ^{12}C, ^{29}Si and ^{120}Sn: Amorphization and Annealing Effects," K-W. Wang, W. G. Spitzer, G. K. Hubler, and D. K. Sadana, submitted to J. Appl. Phys.

4. "Effect of Annealing on the Optical Properties of Ion Implanted Ge," K-W. Wang, W. G. Spitzer, G. K. Hubler and E. P. Donovan, J. Appl. Phys. (in press).

5. "Solid Phase Regrowth of Low Temperature Be-implanted GaAs," S-I. Kwun, M-H. Lee, L. L. Liou, W. G. Spitzer, H. L. Dunlap, and K. V. Vaidyanathan, J. Appl. Phys. 57, 1022 (1985).

6. "Thermal Annealing Beahvior of Hydrogen-Free Amorphous Silicon and Germanium," G. K. Hubler, E. D. Donovan, K-W. Wang, and W. G. Spitzer, Proc. of SPIE, 530 (in press).

7. "Amorphous Silicon Produced by Ion Implantation: Effects of Ion Mass and Thermal Annealing," C. N. Waddell, W. G. Spitzer, J. E. Fredrickson, G. K. Hubler and T. A. Kennedy, J. Appl. Phys. 55, 4361 (1984).

8. "Amorphous Silicon Produced by Ion Implantation: Etching Rate in Hf Solution and Effect of Annealing," L. Liou, W. G. Spitzer and S. Prussin, J. Electrochem. Soc. 131, 672 (1984).

9. "Infrared Properties of Heavily Implanted Silicon, Germanium and Gallium Arsenide," W. G. Spitzer, L. Liou, K-W. Wang, C. N. Waddell, G. K. Hubler and S-I. Kwun, Proc. of SPIE 463 (Advanced Semiconductor Processing and Characterization of Electronic and Optical Materials), 46 (1984).

10. "Low Temperature Annealing of Be-Implanted GaAs," S-I. Kwun, C-H. Hong and W. G. Spitzer, J. Appl. Phys. 54, 3125 (1983).

11. "Properties of Amorphous Silicon Produced by Ion Implantation: Thermal Annealing," W. G. Spitzer, G. K. Hubler and T. A. Kennedy, Nucl. Instrum. Methods, 209/210, 309 (1983).

12. "Infrared Studies of Isothermal Annealing of Ion-Implanted Silicon: Refractive, Indices, Regrowth Rates, and Carrier Profiles," C. N. Waddell, W. G. Spitzer, G. K. Hubler and J. E. Fredrickson, J. Appl. Phys. 53, 5851 (1982).

13. "Effects of Thermal Annealing on the Refractive Index of Amorphous Silicon Produced by Ion Implantation," J. E. Fredrickson, C. N. Waddell, W. G. Spitzer, and G. K. Hubler, App. Phys. Lett. 40, 172 (1982).

14. "Electrical and Structural Characterization of Implantation Doped Silicon by Infrared Reflection," G. K. Hubler, P. R. Malmberg, C. N. Waddell, W. G. Spitzer and J. E. Fredrickson, Radiat. Eff. 60, 35 (1980).

PROFESSIONAL PERSONNEL

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1. S. Prussin, Research Scientist

INTERACTIONS

1. G. K. Hubler, seminar given at SPIE meeting, Los Angeles, CA, January 1985.

2. W. G. Spitzer, seminar given at National Bureau of Standards, Washington, DC, December 1984.

3. L. Liou and K-W. Wang spent two weeks on this project at the Naval Research Laboratory with G. K. Hubler (23 July to 3 August, 1984).

4. L. Liou and K-W. Wang presented poster papers at the Ion Beam Modification of Materials Conference, Cornell University, July 1984.

5. K-W. Wang spent two weeks on this project at North Carolina State University with D. K. Sadana (2 July to 14 July, 1984).

6. C. N. Waddell worked at the Atomic Energy Research Establishment, Harwell, England in summer, 1984.

7. W. G. Spitzer, seminar given in SPIE meeting, Los Angeles, California, January 1984.

8. S-I. Kwun, seminar given in Anneal Physical Society Meeting, San Antonio, Texas, January, 1984.

9. W. G. Spitzer gave a series of lectures in Korea, May, 1983. The universities where lectures were given include: Seoul National University, KAIST; Yansee University; Jeonbuk University.

10. W. G. Spitzer, seminar given in February, 1982 to the Avionics Laboratory, Wright Patterson Air Force Base, Ohio.

11. W. G. Spitzer, seminar given in Februrary, 1982 to the Physics Department, University of Dayton, Dayton, Ohio.

12. C. N. Waddell, seminar at the Atomic Energy Research Establishment, Harwell, England, April, 1981.

13. C. N. Waddell, talk at Topical Meeting on Ion Implantation held at Liverpool, England by the Royal Society, May, 1981.

14. W. G. Spitzer spent two months working on this project at the Naval Research Laboratory with G. K. Hubler and T. Kennedy. The dates were from 24 September 1981 to 17 November 1981.

15. W. G. Spitzer spent one month at the Avionics Laboratory. AFWAL/AADR, Wright Patterson AFB working primarily on another research project. He worked with K Bajaj, C. Litton, and W. Theis. While at the Avionics Laboratory, he consulted with Dr. Peter Pronko and his group who are working on implanted semiconductors and employing RBS, PIXE, and electrical measurements.

DISCOVERIES/PATENTS

None

ELECTROOPTIC MATERIALS AND OPTICAL IMAGE STORAGE DEVICES

Armand R. Tanguay, Jr.

REPORT PERIOD: 1 April, 1981 - 31 March, 1985

RESEARCH OBJECTIVES

The principal objectives of the research program were as summarized below:

(1) To fully characterize the physical processes inherent in the operation of Electrooptic Spatial Light Modulators such as the Pockels Readout Optical Modulator (PROM), the PRIZ (a modified PROM), and the Microchannel Spatial Light Modulator, and to establish relationships between the relevant material properties and optimum device design parameters. These image storage devices are currently of interest for applications in coherent optical signal and image processing.

(2) To characterize the physical processes relevant to the operation of photorefractive volume holographic optical elements, for use in dynamic holography and spatial light modulator applications.

(3) To further develop the Czochralski growth technique for the production of large single crystals of optical quality bismuth silicon oxide $Bi_{12}SiO_{20}$, at present the most promising candidate for the active element of both Electrooptic Spatial Light Modulators and Photorefractive Volume Holographic Optical Elements.

(4) To determine the dependence of the electronic and optical properties of $Bi_{12}SiO_{20}$ (such as mobility, minority carrier lifetime, absorption coefficient, photoconductivity spectrum, intrinsic deep and shallow defect levels) on crystal growth parameters and fundamental physical properties of the material.

(5) To modify the absorption/photoconductivity spectrum of bismuth silicon oxide and/or bismuth germanium oxide by means of selective impurity incorporation.

STATUS OF RESEARCH EFFORT

During the contract period, the focus of this research program has been centered on crystal growth, material characterization, device fabrication, and device analysis specifically directed toward the improvement of electrooptic spatial light modulators (such as the PROM [3, 4] and PRIZ [5, 6]) for a wide range of applications in optical processing and computing. In the past year, emphasis has been placed primarily in the areas of crystal growth and characterization of the photorefractive material bismuth silicon oxide ($Bi_{12}SiO_{20}$ or BSO), and the development of a novel spatial light modulator (the Photorefractive Incoherent-to-Coherent Optical Converter) that combines the essential *features of volume holographic storage and incoherent-to-coherent image conversion.* Additional significant progress has been made in the application of electrooptic spatial light modulators to real-time synthetic aperture radar image formation, and in the prediction of phase nonuniformities in certain configurations of the Microchannel Spatial Light Modulator (MSLM). *Recently, a modification of the PRIZ-type spatial light modulator* has been discovered that potentially circumvents a number of performance limitations of both the PROM and the PRIZ [33]. Progress in these areas is described in this Section, along with other cumulative program results that provide context to the recent research directions.

A joint theoretical and experimental investigation of the factors affecting resolution and charge transfer dynamics in electrooptic spatial light modulators such as the Pockels Readout Optical Modulator (PROM) [3, 4], the PRIZ [5, 6], the Microchannel Spatial Light Modulator (MSLM) [7, 8], and the photo-DKDP [10] and electron-beam-DKDP [9, 10] image storage devices is now nearly complete. The theoretical approach to the resolution problem initially involved deriving the electrostatic field distribution from a fixed distribution of point charges located at the interface between two dissimilar dielectrics bounded by ground planes. The electric field modulation resulting from a longitudinal distribution of charges of given transverse spatial frequency can be directly related to the exposure-dependent modulation transfer function of the device. We obtained an analytic expression for the Fourier transform of the voltage distribution from a single point charge (which is also directly related to the modulation transfer function) for the full three layer dielectric problem, and extended the theory to include the dependence of the voltage distribution on the point charge location within the electrooptic crystal. The resultant analytic expression contains the dielectric constants of the blocking layers and electrooptic crystal, and the thicknesses of the three layers, as well as the location of the point charge. This formulation allows the effects of charge trapping within the bulk of the electrooptic crystal to be modeled. In particular, the low spatial frequency response decreases linearly, and the high spatial frequency response decreases exponentially with the distance of the point charge from the electrooptic crystal/dielectric blocking layer interface. Thus the overall sensitivity and resolution are degraded strongly by charge storage in the bulk away from the interface.

Utilizing superposition, this formulation was further extended to accommodate arbitrary charge distributions of significant physical interest. In particular, an iterative exposure-induced charge transfer and trapping model was formulated to calculate the charge distribution throughout the electrooptic crystal layer resulting from optical exposure at various wavelengths. The charge distributions so obtained were utilized to calculate the dependence of the device modulation transfer function on exposure level, exposure wavelength, device operational mode, mobility-lifetime product, and device configurational and constitutive parameters. The results indicate that very large variations in both sensitivity and resolution can result from differences in these parameters. For example, a substantial improvement in the resolution is achieved as the writing wavelength approaches the band gap of the electrooptic crystal. Such improvements are quite striking in experimental device resolution tests. In addition, it was shown that in the limit of high spatial frequencies, the modulation transfer function decreases as the inverse square of the spatial frequency regardless of the particular shape of the charge distribution. The shape of the charge distribution does, however, influence both the device exposure sensitivity and the spatial frequency above which the modulation transfer function asymptotically approaches the inverse square dependence on spatial frequency.

Application of these results has been made to a wide variety of PROM device design cases (including both symmetric and asymmetric devices) and specialized exposure conditions (particularly x-ray [40] and electron-beam [41] sources), as well as to other types of electrooptic spatial light modulators such as the MSLM and photo-DKDP devices. Furthermore, the theoretical formulation allows investigation of possible voltage-modulated recording techniques for resolution enhancement (such as the "superprime mode" [3]), and of flash erasure sensitivity and completeness. These results have numerous implications with regard to improving electrooptic spatial light modulator device resolution [JSEP Pubs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 16, 22, 23, 24].

During the past year, the potential formation of synthetic aperture radar images at extremely high frame rates has been investigated by employing a PROM as the input incoherent-to-coherent transducer. Theoretically computed SAR signals from a point target (which are two-dimensional anamorphic Fresnel zone plates) were optically recorded on film. These images were incoherently projected on a 1" diameter PROM, and the point target reconstructed with an anamorphic optical system. The preliminary results are extremely encouraging, in that high image definition and high signal-to-noise ratio were simultaneously achieved [JSEP Pub. 15, JSEP Conf. Pres. 21, 23].

PROM-like structures have been investigated [5, 6; JSEP Pubs. 5, 9, 10, 11, 16] that were reported to exhibit significantly enhanced resolution and sensitivity relative to traditional PROM structures. Such devices are fabricated from bismuth silicon oxide crystals oriented along <111> and <110> axes, as opposed to the usual <001> orientation. In these orientations, the longitudinal electrooptic effect does not contribute to the resultant image amplitude (as in the traditional <001> orientation). Instead, these novel configurations utilize the transverse electrooptic effect deriving from transverse fields within the bulk of the electrooptic crystal, induced by spatially varying components of the input image distribution. Since the electrooptic effect is antisymmetric under reversal of the electric field direction, transverse field contributions to the image are characterized by an antisymmetric point spread function. This implies that the device modulation transfer function will exhibit a bandpass character with no response at zero spatial frequency. This characteristic is useful in some optical processing applications requiring dc suppression. In addition, since field components in orthogonal transverse directions couple to different elements of the electrooptic tensor, the modulation transfer function will be sensitive in general to both the orientation of each spatial frequency component of the image (grating wavevector dependence) and to the polarization of the readout illumination. This orientation dependence is summarized in Figs. (1) through (3) and Table (1) [JSEP Pubs. 5, 10, 16]. Utilization of this effect allows for both one-dimensional and two-dimensional image reconstruction through appropriate choice of readout polarization.

We have modified our solution of the three layer dielectric problem to allow calculation of the integrated transverse potential drop (the integration is performed in the longitudinal or charge motion direction) for both point charge cases and continuous charge distributions. These calculations allow us to analyze potential PRIZ as well as PROM device performance. The results include the dependence of the modulation transfer function on device constitutive parameters, crystallographic orientation, and dielectric anisotropy in the electrooptic crystal layer [JSEP Pubs. 5, 9, 10, 11, 16]. Numerous <111> and <110> oriented devices have been fabricated in our laboratory with vapor-deposited parylene blocking layers and RF magnetron sputtered indium tin oxide transparent conductive electrodes. Primary characterization measurements have included diffraction efficiency as a function of spatial frequency, which can easily be related to the modulation transfer function of the device. Experiments to date confirm all of the essential model predictions.

During the measurement program described above, we have established a number of new observations about transverse field effect PROMs. First and foremost, the operational mode (direction of externally applied field during the writing sequence) utilized is critically important to the optimization of device characteristics. In this respect, the <001> PROMs and <111> PRIZs show essentially opposite behavior due to significant differences in response to similarly placed volume charge distributions [JSEP Pub. 9]. Hence the operational mode that optimizes <001> PROM performance is opposite from the operational mode that optimizes <111> PRIZ performance. Second, charge conservation within the photoconductive/electrooptic crystal layer in general enhances <001> PROM sensitivity, while diminishing <111> PRIZ sensitivity. Leaky parylene layers increase <111> PRIZ diffraction efficiency at the expense of device storage time. Numerous phase effects have been theoretically derived and experimentally demonstrated in the <111> PRIZ [JSEP Pub. 5, 10]. Although the longitudinal field does not contribute to the signal amplitude, it can be shown to induce a signal-dependent phase modulation that is present in concert with the transverse field-induced signal-dependent amplitude modulation (see Figs. 1-3 and Table 1). Such phase effects diminish the usefulness of the device for applications in which Fourier-plane processing is desired, as well as produce point-spread function anisotropies in the image plane in the presence of strain birefringence or imperfectly aligned polarizer/analyzer pairs. In a collaborative effort with Professor Cardinal Warde at the Massachusetts Institute of Technology, these concepts have recently been applied to the Microchannel Spatial Light Modulator [JSEP Pub. 24]. In this case, it has been shown that the 55° cut $LiNbO_3$ active layer (which optimizes the amplitude sensitivity) introduces phase nonuniformities similar to those observed in $Bi_{12}SiO_{20}$ [JSEP Pubs. 5, 10]. Finally, utilization of the exposure-induced charge transport model has allowed us to predict, and subsequently experimentally observe, striking nonlinearities in the transfer characteristics (output amplitude as a function of input exposure) of the <111> PRIZ [JSEP Pub. 11]. Such intriguing effects in <111> and <110> oriented PRIZs are under continuing investigation.

Quite recently, we fabricated a <111>-PRIZ-type device without blocking layers, which according to a Soviet research group [26] exhibited dynamic change detection, i.e., only that portion of the image that has recently changed appears in the output plane. On the contrary, using BSO crystals grown at USC, we found that excellent image storage characteristics were obtained in this device configuration. The advantages of this configuration are numerous: (1) the absence of dielectric blocking layers significantly enhances the measured (and theoretically predicted) resolution, as shown in Fig. 4 [33]; (2) the presence of parallel ground planes on opposite crystal surfaces ensures that the longitudinal voltage is space-invariant, which eliminates signal-dependent phase nonuniformities; (3) charge non-conservation is enhanced by allowing photo-induced electrons to reach the far electrode, which increases the device sensitivity; (4) high dielectric breakdown strength, high sensitivity blocking layers are no longer required, which eliminates a source of multiple reflections and significantly reduces the difficulty and expense of device fabrication; (5) the resolution, sensitivity, and linearity can be varied through proper choice of the device operating mode; and (6) monopolar (non-switching) power supplies can be used for device operation due to the constancy of the longitudinal applied voltage. A potential disadvantage is the accompanying reduction in image storage time, although the approximately fifteen second image decay time experimentally observed is more than adequate for a wide range of applications. This device clearly merits an intensive investigatory effort. In particular, it is of critical importance to ascertain the explanation for quite different observations of device performance between our device and that of the Soviet researchers.

An experimental determination of the charge carrier dynamics under both uniform and nonuniform exposure in a PROM structure by means of transverse electrooptic imaging has been undertaken to allow measurement of the appropriate exposure-induced electric field distribution function for refinements to the theoretical modulation transfer function calculations. Preliminary results suggested that the applied field distribution within the bulk of the electrooptic crystal prior to exposure is quite uniform longitudinally (as opposed to the distribution expected for the case of space-charge-limited current injection, for example). In addition, these measurements have been extended to the case of uniform exposure by fabrication of a PROM-structure 1.5 mm x 1.6 mm x 11 mm in size. Application of the external applied field under conditions of no exposure showed several interesting effects, including charge injection through the (dielectrically imperfect) parylene blocking layer, and the existence of periodically modulated resistivity fluctuations that are likely caused by rotation-induced striations during the crystal growth process. Exposure in forward mode (illuminated electrode negative) showed charge distribution effects throughout the bulk of the device, while exposure in reverse mode (illuminated electrode positive) showed strong charge confinement near the electrode. This result confirms an independent experiment that indicated a much larger mobility-lifetime product for electrons than for holes [42]. It also confirms semi-quantitatively the predictions of the charge transport model advanced earlier. This effort is extremely important to the design of new devices with improved resolution, and to investigations of novel voltage modulated recording techniques for enhanced device performance. In addition, it appears likely that this technique will allow accurate measurements of mobility-lifetime products to be made in low mobility-short lifetime electrooptic materials that are difficult to characterize otherwise. It is important to note here that this technique is currently the subject of intensive research in the Soviet Union [43, 44, 45, 46, 47, 48, 49], as applied to the case of BSO with no blocking layers under various types of optical exposure conditions.

During the contract period, numerous bismuth silicon oxide ($Bi_{12}SiO_{20}$) crystals have been grown by the top-seeded Czochralski technique. The growth apparatus includes a two-zone resistance heated furnace, which has been modified to incorporate precise and high stability set-point controllers interfaced to a programmable thermal cycle controller. This allows lengthy melting, annealing, and cool-down cycles to be controlled automatically. In one stability experiment, a Cr doped BSO crystal was grown 3 mm in diameter, 5 cm long with less than 0.5 mm diameter fluctuations. Crystals have been grown with both

<001> and <111> orientations for utilization in both optical device fabrication and crystal characterization experiments. Top-seeded crystals exhibit a high degree of optical uniformity and well-developed <100> facets for growth along the <001> axis.

Growth conditions have been established for the routine production of 1 cm diameter boules. These include a vertical growth rate of 1-3 mm/hr, a rotation rate of 5-20 rpm, a vertical gradient of approximately 10°C/cm at the melt surface, and a radial gradient less than 1°C/cm. The presence of axial coring, which results in optical density inhomogeneities as well as strain birefringence, has been observed in nearly all of the boules that we have grown (as well as in those of other laboratories and commercial enterprises). This problem has been addressed by a complete redesign of the multizone growth furnaces to simultaneously steepen the vertical gradient and flatten the horizontal gradient. This procedure is iterative in nature, and is being carried out in means of extensive thermal profiling of a test growth furnace. The interplay between the magnitude of the radial gradient and the rotation rate has been studied in order to optimize interface flatness during growth while still avoiding instabilities deriving from constitutional supercooling. A second Czochralski puller is presently under construction. This will represent a significant program upgrade, since the rate of achievable growth experiments will effectively double. The results of the furnace redesign experiments will be incorporated in the new puller, which will likely result in a three-zone configuration.

The photorefractive incoherent-to-coherent converter (described in succeeding paragraphs) application of $Bi_{12}SiO_{20}$ depends quite sensitively on the crystalline stoichiometry, and hence a series of experimental growth runs of undoped $Bi_{12}Si_{1-x}O_{20-2x}$ are being grown over a range of x to establish the existence or absence of an optimum stoichiometric defect density for photorefractive sensitivity.

In the area of photorefractive image storage device physics, a number of significant experiments have been performed in bismuth silicon oxide as well as the ferroelectric barium titanate. The experimental studies included formation and erasure of holographic gratings, and two-wave and four-wave mixing. These studies led to the proposal of a new theoretical model for the migration of charges mediating the photorefractive effect in these materials. Using this theoretical model, we are able to predict the observed dependence of wave mixing on the intensities and polarizations of the waves, and on the wave directions relative to each other and to the crystallographic axes. The effects of applied electric fields on the diffraction efficiency as a function of grating wavevector were predicted and verified experimentally [JSEP Pub. 13]. Extensions of both theory and experiment to the case of bismuth silicon oxide are under way, with emphasis on the correlation between observed photorefractive effects and characterization of fundamental material properties (defect density, trap energy levels, etc.). Applications in the areas of image phase conjugation, holographic data storage, programmable bandpass filtering, and dynamically programmable optical interconnects are being explored.

In addition, a study of the dependence of the diffracted order polarization on the simultaneous presence of optical activity and electric field induced birefringence in photorefractive materials such as BSO was extensively pursued. This study has allowed the prediction and experimental confirmation of the optimum orientational configurations for both diffraction efficiency and energy coupling in BSO [JSEP Pub. 12]. Furthermore, numerical solution of the analytical expressions in the limit of low exposures predicts the polarization behavior of the diffracted orders as a function of the experimental geometry and applied drift field. Experimental verification of the theoretical analysis is ongoing.

During the contract period, we have independently discovered and extensively characterized a new type of two-dimensional spatial light modulator that is capable of performing real-time incoherent-to-coherent image transductions with resolution and sensitivity comparable to those presently achieved with PROM and PRIZ devices [JSEP Pubs 18, 19, 20, 21]. This novel device, termed a Photorefractive Incoherent-to-Coherent Optical Converter (PICOC), is comprised of a single crystal of a photoconductive and electrooptic material such as bismuth silicon oxide with transversely deposited metal electrodes. The geometry is identical to that utilized in the photorefractive volume holographic storage experiments described above. The crystal is illuminated by two plane wave writing beams from an Argon ion laser that form a uniform diffraction grating in the photorefractive medium. An incoherent image is focused onto the crystal surface, which selectively erases the grating as a function of the local image intensity. Diffraction of a third (reading) beam from the grating results in creation of a coherent replica of the incoherent input image. The experimental geometry is as shown in Fig. 4. In preliminary experiments, a resolution exceeding 15 line pairs/mm was achieved without extensive optimization. We have since shown that the resolution can be extended to beyond 100 line pairs/mm by a simple wavevector matching geometry [JSEP Pubs. 20, 21], and the device sensitivity can be improved by a factor of 20 by a Schlieren readout technique in the positive image mode [JSEP Pub. 21].

Such a combination of volume holographic storage and spatial light modulator characteristics is unique, and suggests many novel optical processing configurations. In addition, such PICOC devices are easy to fabricate, durable, and inexpensive, all of which are potential advantages relative to currently available spatial light modulators.

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17. "Polarization Properties of Birefringent Phase Gratings", in preparation for Optics Letters.

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12. "Information Processing and Holography", Invited Panel Member, 1981 Annual Meeting of the Optical Society of America, Orlando, Florida, (1981).

13. "Materials Considerations for Electrooptic Spatial Light Modulators", American Vacuum Society Annual Meeting, Anaheim, (March, 1982) (Invited Paper).

14. "Recent Advances in Spatial Light Modulators for Coherent Optical Processing Applications", Conference on Lasers and Electro-Optics (CLEO), Phoenix, Arizona, (May, 1982) (Invited Paper).

15. "Recent Progress in Spatial Light Modulators for Coherent Optical Processing Applications", Gordon Research Conference on Optical Information Processing and Holography, Plymouth, New Hampshire, (June, 1982) (Invited Paper).

16. "Polarization Properties of Birefringent Phase Gratings", Gordon Research Conference on Optical Information Processing and Holography, Plymouth, New Hampshire, (June, 1982) (Invited Paper).

17. "Single Crystal and Thin Film Electrooptic Materials: Characterization for Optical Device Applications", DARPA Materials Research Council Symposium, La Jolla, California, (July, 1982) (Invited Paper).

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21. "Real Time Synthetic Aperture Radar Image Formation Utilizing an Electrooptic Spatial Light Modulator", NASA Spaceborne Imaging Radar Symposium, Jet Propulsion Laboratory, Pasadena, California, (1983), (Invited Paper), with I. Abramov and Y. Owechko.

22. "Fundamental and Materials Limitations of Electrooptic Spatial Light Modulators", SPIE International Symposium, Los Angeles, California, (1983), (Invited Paper), with Y. Owechko.

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26 "Photorefractive Incoherent-to-Coherent Optical Converter: Physical and Materials Considerations", SPIE International Symposium, Los Angeles, California, (1984), (Invited Paper), with D. Psaltis, A. Marrakchi, and Y. Shi.

27 "Materials Considerations for Optical Processing and Computing Devices", SPIE International Symposium Critical Review: Optical Computing, Los Angeles, California, (1984), (Invited Paper).

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30. "Programmable Optical Interconnections", DARPA Materials Research Council Symposium, La Jolla, California, (July, 1984) (Invited Paper).

31. "Optical Information Processing Components: Fundamental Issues", 1984 Annual Meeting of the Optical Society of America, San Diego, California, (October 31, 1984); (Invited Paper).

32. "Polarization Properties of Volume Phase Gratings in Optically Active Materials", 1984 Annual Meeting of the Optical Society of America, San Diego, California, (November 2, 1984), (with A. Marrakchi).

33. "Resolution and Sensitivity Enhancement of the Photorefractive Incoherent-to-Coherent Optical Converter", 1984 Annual Meeting of the Optical Society of America, San Diego, California, (November 2, 1984), (with A. Marrakchi, D. Psaltis, and J. Yu).

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III Theses

1. Owechko, Y., "Effects of Charge Transport and Crystallographic Orientation on Electrooptic Spatial Light Modulator Resolution and Sensitivity", May, 1983.

2. Marrakchi, A., "Real-Time Holography in Photorefractive Bismuth Silicon Oxide Crystals: Polarization Properties of Diffraction and Application to Spatial Light Modulation", August, 1985.

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1. Chavel, P., A.A. Sawchuk, T.C. Strand, A.R. Tanguay, Jr., and B.H. Soffer, "Optical Logic with Variable-Grating-Mode Liquid Crystal Device", Optics Letters, 5, 398-400, (1980).

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II. Patents

1. "Method and Apparatus for Optical Computing and Logic Processing by Mapping of Input Optical Intensity Into Position of an Optical Image", P. Chavel, A.A. Sawchuk, B.H. Soffer, T.C. Strand, and A.R. Tanguay, Jr., U.S. Patent No. 4,351,589, awarded September 28, 1982.

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PROFESSIONAL PERSONNEL

1. Armand R. Tanguay, Jr., Principal Investigator.

2. Yuri Owechko, Research Associate.

3. Abdellatif Marrakchi, Research Assistant.

4. Mark Garrett, Research Assistant

5. Leroy Fisher, Research Assistant.

6 Frank Lum, Senior Engineering Technician.

INTERACTIONS

Interaction With Other Work Units:

A significant interaction developed over several years with the Polychromatic Optical Information Processing project, directed by A. A. Sawchuk and T. C. Strand. Techniques for incorporating photorefractive real time image storage devices as programmable Fourier plane chromatic filters were jointly explored. This interaction has continued and expanded, even though the Polychromatic Processing project has not been continued under JSEP sponsorship.

An application common to both the JSEP project "Processing of Images With Signal-Dependent Noise" directed by A. A. Sawchuk, and to this project is the improvement of quality and processing speed of synthetic aperture radar images. This particular application has provided the focus for continued interaction of the two projects.

DOD Interactions:

1 During April, 1981 and 1982, visits to USC by Dr. John Neff of the Defense Advanced Research Projects Agency (formerly of the Air Force Office of Scientific Research) were arranged. Substantive discussions have also been held at numerous research conferences, including the Gordon Research Conference and the DARPA MRC Symposium in La Jolla, California (July, 1982) (see JSEP conference presentation #17), and the SPIE International Symposium (January, 1984). Dr. Neff will continue to be briefed on our progress as it relates to DARPA optical device and optical information processing programs.

2 Technical discussions concerning optimization and utilization of Photorefractive Image Storage Devices were held at USAF/RADC, Hanscom AFB Massachusetts with Ludman,

J. Horner, and W. Miceli in June, 1982. Dr Ludman has subsequently been briefed concerning recent research developments during visits to USC in July, 1982 and August, 1983, and during extensive meetings at the Gordon Research Conference and DARPA MRC Symposium. Dr. Chuck Woods of RADC visited USC in February, 1984 to discuss photorefractive materials and devices. Dr. Joe Hutta of RADC visited USC in February, 1984 to discuss crystal growth of bismuth silicon oxide. Dr. Carl Pitha of RADC visited USC in March, 1985 to discuss crystal growth and doping of bismuth silicon oxide, as well as electrooptic materials and devices.

3. Extensive discussions concerning utilization of spatial light modulators in synthetic aperture radar image reconstruction have been ongoing since May, 1980 with the Naval Ocean Systems Center, San Diego (M. Monahan, K. Bromley, W. Miceli), and with the Jet Propulsion Laboratory/NASA (T. Bicknell).

4. An invited paper detailing results on the PROM, PRIZ, and photorefractive devices was presented at the DARPA Materials Research Council Meeting on Spatial Light Modulators and Photorefractive Materials, July 19-20, 1982 in La Jolla, California. A second invited paper on the use of photorefractive materials in advanced programmable optical interconnects was presented at the DARPA Materials Research Council Meeting on Interconnection, July 18-19, 1984 in La Jolla, California.

5. The Principal Investigator was an invited participant in the AFOSR- and ARO-sponsored workshop "Optical Techniques for Multi-Sensor Array Processing", Pine Mountain, Georgia, May 9-11, 1983.

6. The Principal Investigator was an invited participant, workshop leader, and conference proceedings co-editor of an ARO-sponsored workshop on "Optical Switching Techniques", University of California at Irvine, Irvine, California, March 26-28, 1984.

7. The Principal Investigator was invited panel member at a USAF Foreign Technology Division Workshop on Foreign Optical Processing and Computing Technology, Wright-Patterson Air Force Base, Dayton, Ohio, May 8-9, 1984.

8. An invited paper was presented to the National Bureau of Standards on "Materials Requirements for Optical Processing and Computing Devices" in February, 1984. NBS is formulating a program on optical materials for optical signal processing and integrated optics applications, to be commenced in collaboration with several DOD agencies.

9. The Principal Investigator was an invited participant in a DOD-sponsored workshop on Signal Processing Devices, May 21-25, 1984, Santa Fe, New Mexico.

10 An invited paper was presented at the DARPA Annual Conference on Optical Processing and Computing, MacLean, Virginia, November 3, 1984, entitled "Single Crystal and Thin Film Electrooptic Materials: Characterization for Optical Device Applications".

DISCOVERIES/PATENTS

Discoveries during the contract period are as detailed in the "Status of Research Effort" Section. No patents were applied for during this contract.

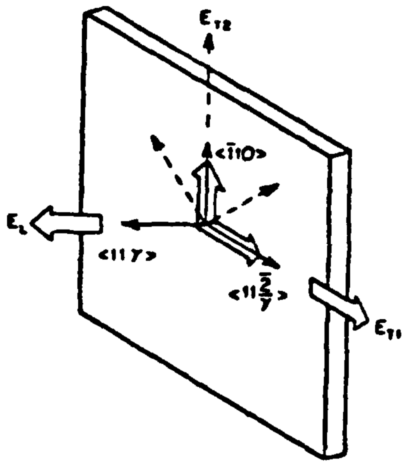

Fig. 1. Orientations of longitudinal and transverse electric fields, and their respective induced principal axes, for $Bi_{12}SiO_{20}$ (I23 symmetry). The longitudinal field (E_L) and one transverse field (E_{T1}) induce the same set of principal axes (open arrows), while the other transverse field (E_{T2}) induces a set of principal axes rotated by 45° (dashed arrows).

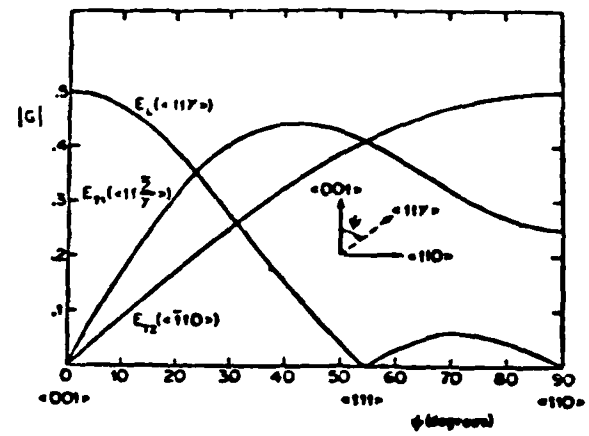

Fig. 2. Magnitude of retardation G induced by the three orthogonal field components defined in fig. 1 as a function of crystallographic orientation. The value of G is given in units of $\pi V_\alpha / V_\pi$ where α = L, T1, or T2; the quantities V_L, V_{T1}, and V_{T2} are defined in the text.

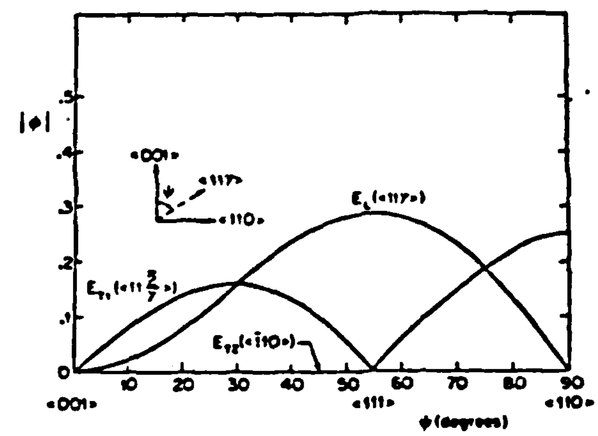

Fig. 3. Magnitude of phase ϕ induced by the three orthogonal field components defined in fig. 1 as a function of crystallographic orientation. The value of ϕ is given in units of $\pi V_\alpha / V_\pi$ where α = L, T1, or T2; the quantities V_L, V_{T1}, and V_{T2} are defined in the text.

Table 1

Values of G and ϕ for three orthogonal fields and three crystallographic orientations used in the PROM and PRIZ. The generalized voltages V_L, V_{T1}, and V_{T2} are defined in the text.

BSO orientation	⟨001⟩ (PROM)			⟨111⟩ (PRIZ)			⟨110⟩ (PRIZ)		
Field orientation	E_L ⟨001⟩	E_{T2} ⟨$\bar{1}$10⟩	E_{T1} ⟨110⟩	E_L ⟨111⟩	E_{T2} ⟨$\bar{1}$10⟩	E_{T2} ⟨11$\bar{2}$⟩	E_L ⟨110⟩	E_{T2} ⟨$\bar{1}$10⟩	E_{T1} ⟨00$\bar{1}$⟩
Phase ϕ	0	0	0	$\frac{\pi V_L}{2\sqrt{3} V_\pi}$	0	0	0	0	$\frac{\pi V_{T1}}{4 V_\pi}$
Signal G	$\frac{\pi V_L}{2 V_\pi}$	0	0	0	$\frac{\pi V_{T2}}{\sqrt{6} V_\pi}$	$\frac{\pi V_{T1}}{\sqrt{6} V_\pi}$	0	$\frac{\pi V_{T2}}{2 V_\pi}$	$\frac{\pi V_{T1}}{4 V_\pi}$

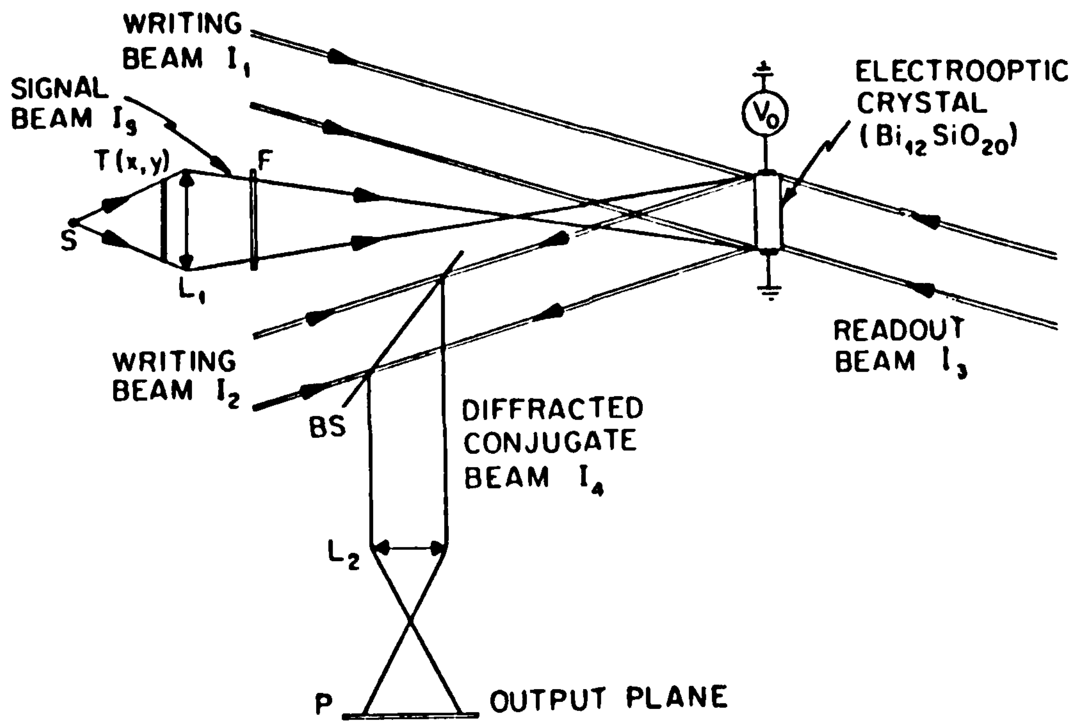

Fig. 4 Experimental set-up for incoherent-to-coherent conversion with phase conjugation in four-wave mixing. The writing beams I_1 and I_2, and the reading beam I_3 are generated from an argon laser (λ = 514 nm). The phase conjugate beam I_4 is diffracted at the same wavelength. The transparency T(x,y) is illuminated with a xenon arc lamp (S) and imaged on the BSO crystal with the optical system L_1, through a filter F (λ = 545 nm). BS is a beam-splitter and P a polarizer placed in the output plane.

STUDY OF THE TEMPERATURE DEPENDENCE OF THE GAIN AND SATURATION ENERGY IN GAINASP SEMICONDUCTOR LASERS

Work Unit QE4-1

E. Garmire

Report Period: 1 April 82 - 31 March 85

RESEARCH OBJECTIVES

The research group of Professor Garmire is studying the properties and improvements in devices for use in Lightwave Technology. This includes semiconductor lasers, optical logic elements and guided wave optical devices. Under JSEP sponsorship has been the growth and characterization of new laser structures for improved performance in applications of military significance. During the last three years this program has been directed toward reducing the temperature dependence of quatenary lasers in the 1.3 μm temperature region.

The intent of this program has been to determine the mechanism for the strong temperature dependence of the threshold of GaInAsP lasers. In particular, the relative roles of carrier confinement and auger recombination have been compared. Experimental investigations of the temperature dependence of the threshold for different laser structures and measurements of gain as a function of temperature allow these mechanisms to be separated.

STATUS OF RESEARCH EFFORT

Progress has been made along several directions toward the improvement of semiconductor lasers for military applications, all which will be outlined in separate sections below.

First, the JSEP program has allowed us to identify a new DCC structure (double carrier confinement) with improved high temperature performance. We have grown such structures and are currently evaluating them. In the process of device development it was necessary to develop a new ohmic contact to p-InP. We also developed a new method of determining laser gain, by placing the device in an external cavity and varying the external reflectivity. Also, under inspiration of the JSEP program, we identified a topic of interest which was not in the original proposal: a study of the temperature dependence of laser arrays, with particular emphasis on the effects of the heat sink. This theoretical effort was carried out in collaboration with The Aerospace Corporation, using their thermal resistance computer program. In addition, the JSEP program interacted very strongly with other research efforts in Professor Garmire's group. Of key importance was the demonstration of all-optical switches in the near-infrared at 3 μm. Finally, there was related work in integrated optics which will be very briefly described.

A. Identification of DCC Structure with High T_o

The development of a new laser structure, the Double-Carrier-Confinement (DCC) structure has demonstrated a lower temperature dependence than the conventional double heterostructure.

The temperature dependence of the laser threshold is usually described phenomeno - logically by the quantity T_o which is given by the following equation:

$$J(T) = J_o \exp(T/T_o)$$

which describes an exponential increase in threshold current density J with temperature T. D The smaller T_o, the larger the temperature dependence.

An example of a DCC epitaxial structure such as we grow in our laboratory by LPE (liquid phase epitaxy) is shown in Fig. I. Rather than a single active layer of thickness ~0.3 μm, there are double active GaInAsP layers separated by a thin p - InP layer. The second active layer acts to confine carriers which leak out of the first active layer. Preliminary work performed in Japan [1] demonstrated T_o = 180°K. This is in comparison to T_o = 70°K for a standard double heterostructure with a single active layer. The large increase in T_o proves that carrier leakage is more important than Auger recombination in GaInAsP lasers which operate at 1.3μm. Further corroberation of carrier leakage rather than Auger recombination as the source of low T_o comes from the increase of T_o from 70°K to 127°K by introducing transverse carrier confinement.[2]

The preliminary Japanese work demonstrated that, although T_o was higher, the DCC structure had two disadvantages: first, there was an increase in laser threshold due to spreading carriers out between two active layers, and second, there was a tendency for non-uniformities to cause the light emitted from each of the two active layers to have a different wavelength. The aim of the research at U.S.C. is to study and eliminate these disadvantages.

The three-year research project sponsored by JSEP is nearing completion with DCC lasers having been grown and fabricated and currently under test. The threshold and its temperature dependence are being investigated as a function of thickness of the two active layers and the separating InP layer. In addition, conditions under which single wavelength emission occurs are also being determined

B. LPE Growth of GnInAsP Lasers by LPE

Fig. 2 shows the apparatus for growth of double heterostructure lasers which we have constructed and is used in our laboratory. Fig. 3 shows the measured dependence of lattice mismatch on melt composition. Since good lasers require the percent lattice mismatch to be < 0.03%, it can be seen that careful weighing of melts before growth is critical to successful LPE. Fig. 4 shows the measured layer thickness as a function of growth time. Fig. 5 shows a typical light/current curve for our lasers, operating with 100 nsec pulses. These lasers were fabricated using SiN-defined stripes and a new Au/Be contact developed by us.

C. Development of Ohmic Contact To p-InP

A new kind of ohmic contact was developed and tested as part of the JSEP program. The standard ohmic contact to p-InP used in industry is Au-Zn. It was not possible to use this in a research environment because it requires a dedicated vacuum system, since Zn will contaminate the system for all other uses. We, therefore, developed a new ohmic contact with a measured resistance of only 7 ohms. The contact was fabricated using the following procedures: 800 Å of Au/Be (3% Be) is evaporated at low pressure, followed by 2000 Å of Au. This contact is alloyed at 450°C in flowing pure H_2 for two minutes and followed by a final evaporation of 200Å of Cr and 2500Åof Ace.

The overcoat layer of Cr/Au was found to be important to eliminate electrical degradation of the contacts. Without this overcoat, ohmic behavior was observed within a few hours of contact fabrication, but within a week of contacts ceased to conduct any current. Contact degradation occurs because of indium out-diffusion through the gold contact which is accelerated by alloying. This out-diffusion is followed by a slow oxidation of the indium at the surface of the contact, slowly building up an oxide layer which causes electrical conduction to cease after a while. The overcoat of Cr-Au protects the surface against indium out-diffusion and subsequent oxidation.

D. Measurements of Gain

In the last year, we have pioneered in a new technique to determine the gain and carrier life times in a semiconductor laser. The procedure is to place the laser in an external cavity with a varying reflectivity. The design for the external cavity laser used in these experiments is shown in Fig. 6. Because there was no access to the backside of a commercial semiconductor laser, and the other mirror was 100% reflective, the laser output was obtained by means of an etalon, as shown. Placed near Brewster's angle, it could reflect from the cavity as little power as needed.

The front facet of the diode combines with the external mirror to provide an effective reflectivity of the external cavity. When on resonance, this effective reflectivity is given by

$$R_{eff} = (\sqrt{R} + \sqrt{R_f}^2) + (1 + \sqrt{R_f R})^{-2}$$

Now, referring to the values labelled in Fig. 6, the overall reflectivity of the external optics is determined by

$$R_F = \eta T^2$$

where f is the efficiency with which light which is emitted by the laser returns into the laser cavity. This is given by

$$f = T_L^2 \, T_E^2 \, R_M \, \eta_C \, \eta_F$$

where η_C is the efficiency with which the microscope objective collimates the light emitted from the laser and η_F is the efficiency with which the microscope objective focuses the light back into the laser. T_E and T_L are the transmission of the etalon and the collimating lense, respectively.

The change in threshold due to the existence of the external cavity is given by

$$\Delta I_{th} = (edA/T_n a)(1/2L_d)\ln(R_{eff}/R)$$

where d is the thickness of the active region, A is the cross-sectional area of current flow, L_d is the length of the laser diode, L_d is the length of the laser diode, T_n is the lifetime of carriers, a is the gain coefficient, and e is the charge of the electron.

Thus, the slope of ΔI_{th} vs. $\ln(R_{eff}/R)$ gives the product of the gain coefficient and the carrier lifetime.

$$\frac{\Delta I_{the}}{\ln(R_{eff}/R)} = \left(\frac{1}{T_n a}\right)\left(\frac{edA}{2L_d}\right)$$

A measurement of this quantity as a function of temperature will determine the temperature dependence of $T_n a$, the product of the lifetime and gain coefficient.

We made a series of measurements for a laser diode in an external cavity with transmissions varying from 100% to 0%. The threshold varied by about 25%. Fig. 7 shows the experimental results and a theoretical fit to the above analysis. From this study, it can be determined that 38% of the light was recoupled back into the laser and that at room temperature

$$T_n a = 5\times10^{-17}\text{cm}^2\text{nsec}$$

A related experiment allows for the determination of T_n directly through a measurement of relaxation oscillations. Traditionally these are observed as transient oscillations when the current in a laser is abruptly switched on. We have observed that a semiconductor laser in an external cavity may sustain relaxation oscillations over a narrow range of currents and that a measurement of their frequency determines the carrier lifetime. Typical results are shown in Fig. 8, which gives the square of the relaxation oscillations frequency (normalized to 100 MHz) versus current normalized to threshold. The straight line is a theoretical fit to the standard rate equations for a semiconductor laser, represented by

$$W_r^2 = (1/\tau_e \tau_e)\ (J/J_{th} - 1) - (1/4\tau_e^2)\ ((J/J_{th})^2$$

The points are the experimental data, which are well-fit by a theory which includes a current-dependent lifetime. From an analysis of this type, the carrier dependence of the lifetime can be determined and carrier leakage effects and Auger recombination effects can be separately distinguished.

E Heatsink Requirements for Coherent Operation of High-Power Semiconductor Laser Arrays

This work was performed in collaboration with Michael Tavis at the Aerospace Corporation. We made an analysis of the requirements for coherent operation of laser diode arrays and considered the affects of the thermal properties of the heat sinks on phase-locking. It was shown analytically that mounting laser arrays at the edge of semi-infinite copper heatsinks results in temperature variations between individual laser diode elements that are too large to permit coherent operation except at relatively low power levels. It was also shown that, by use of diamond and/or shaped heatsinks, it will be possible to operate large arrays coherently to high optical output levels.

This work has already been published in IEEE Journal of Quantum Electronics, and a discussion of the use of shaped heatsinks has been published in Electronics Letters. This latter paper showed that the use of a thin diamond heat-spreading layer the same size as the laser array will substantially improve the temperature uniformity without substantially raising the operating temperature or threshold. This will guarantee phase-locking for laser arrays at all power levels. Since these papers have already been published, further details will not be presented here.

F. All-Optical Switching In InAs

An important result which has influenced the direction of our research for the coming few years is the demonstration of optical bistability, or all-optical switching in InAs at power levels as low as 3 mW (intensitivity levels of $75 W/cm^2$). These very low power levels, in a device which was not particularly optimized, make it possible to consider all-optical switching and logic elements for optical signal and image processing. Hysteresis was observed in the reflected signal from a Fabry-Perot etalon consisting of polished n-type InAs with silver deposited on the back surface. By using the 3.096μm line of an HF laser, which matches the bandgap at 77°K, bistable switching was achieved with power levels as low as 3mW Measurements of the nonlinear refraction at the absorption edge in InAs between 68 and 90°K taken with an HF laser were compared with those of a bandgap resonant model and good agreement between theory and experiment was obtained, with no free parameters. This made it possible to model the results to predict a threshold for all-optical switching in an optimized device. Such an analysis predicts a switching power of 100 nWatts. Further results are found in papers by Poole and Garmire listed in the Publications and in the Ph.D. thesis by Poole submitted June, 1984.

A scaling study has indicated that the 3μm wavelength regime is of particular interest for these devices, because of lower thresholds compared to the visible wavelengths. This study will be published by Garmire in Optical Engineering and its conclusions were discussed in the current JSEP proposal. The use of the 3 μm wavelength region at present is limited, however, since the HF laser is very awkward to use. We have been motivated, therefore, to consider the possibility of semiconductor lasers operating near 3 μm. This will be the direction of our future work sponsored under JSEP.

Other work on bistability in the past three years has included experimental studies of bistability in four-level dyes, which as BDN, using a pulsed Nd:YAG laser (Zhu and Garmire) and theoretical studies on bistability (Goldstone and Garmire). The work in these areas is of less direct relation to practical all-optical switching devices and is already published, so will not be further discussed here. These references are listed in publications.

G. Integrated Optics Studies

In the past few years, in addition to semiconductor laser and all-optical switching research, the laboratories of Professor Garmire have included several studies of integrated optics. In particular, $LiNbO_3$ directional couplers have been studied and are described in detail in the Ph.D. thesis of Craig Mueller, submitted December, 1983. We made the first measurements of photorefractive effects of $LiNbO_3$ at GaAs wavelengths, observing time dependent transmission at power levels as low as 32 μWatts. This has important implications for the use of these devices in fiber optic systems. Furthermore, we found evidence for two time constants in the device, on the order of minutes, and the other on the order of days. This work has been published in Applied Optics and is listed in Publications.

Integrated optics studies of a ring resonator were also performed, for possible sensor applications. We reported high sensitivity, but mode coupling and depolarization effects. The latter has led to a separate publication describing how to control depolarization. This work was performed by Honda and Garmire and is published in Journal of Lightwave Technology.

Other studies have involved measuring polymer film waveguides using a leaky waveguide method, published by Ding and Garmire. Finally, continuing research on high power transmissions through hollow metal waveguides has recently been reported by Garmire, with emphasis on single mode propagation.

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PUBLICATIONS

In Semiconductor Laser and Opto-Electronics Related Research

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3. E. Garmire. "The Emerging Technology in Opto-electronics". SPIE **380**, 340 (1983)

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In Optical Bistability

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3. C D. Poole and E. Garmire. "Nonlinear Refraction at the Absorptive Edge in InAs." Opt. Lett., **9**, 356 (1984).

4. Zh. Zhu and E Garmire. "Optical Bistability in Four Level Nonradiative Dyes." Optics Communic. **46**, 61 (1983).

5. Zh. Zhu and E Garmire. "Optical Bistability in BDN Dye." IEEE J> Quantum Electr. **QE-19**, 1495 (1983).

6. J A. Goldstone and E. Garmire. "Regenerative Oscillation in the Nonlinear Fabry Perot Interferometer." IEEE J. Quantum Electr., **QE-19**. 208 (1983).

7. Zhu and E. Garmire. "Theoretical and Experimental Study of Optical Bistability in Four Level Nonradiative Dyes." Optical Restability II, 337-44 ed. Gibbs, Plenum Press, NY (1984).

8. Poole and E. Garmire, "Nonlinear Refraction and Nonlinear Absorption in InAs." Optical Bistability II, ibid. 279-86.

9. E. Garmire, "Panel Discussion.", moderater, Optical Bistability II ibid. 479-96.

10. E. Garmire, C.D. Poole and J.A. Goldstone, "Bistability Experimental Observed and Theoretically Predicted." Phil. Trans. Roy. Soc. London **313** 257 (1984.

9. J.A. Goldstone and E. Garmire, "Intrinsic Polarization Bistability in Nonlinear Media"Phil. Trans. Roy. Soc. London A **313** 395 (1984).

10. E. Garmire. "Infrared All-Optical Image Processing in Semiconductors." Opt. Engineering (August 1985) accepted for publication.

11. C.D. Poole and E. Garmire, "Optical Bistability in InAs." IEEE J. Quantum Electr., accepted for publication (September 1985)

In Integrated Optics

1. E. Garmire. "Characteristics of an Integrated Optics Ring Resonator in Glass." J. of Lightwave Tech., **LT-2**, 714 (1984).

2. Ding and Garmire. "Measurement of Thin Film Parameters Using Substrate Excitation of Leaky Modes." Optics Communications. **48**, 113 (1983).

3. Ding and Garmire. "Measuring the Refractive Index and Thickness of Thin Films: A New Technique." Appl. Optics, **22**, 3177 (1983).

4. E. Garmire. "Hollow Metal Waveguides with Rectangular Cross Section for High Power Transmission." Proc. SPIE, **484**, (April 1984)

5. C.T. Mueller and E. Garmire. "Photorefractive Effect in $LiNbO_3$ Directional Couplers." Proc. SPIE., **460**, 109 (1984).

6. E. Garmire, K. Honda, T.N. Ding, K.E. Wilson. "Ring Resonator and Quasi Waveguides as Integrated Optics Devices for Measurements." Proc. SPIE, **408**, 102 (1983).

7. C.T. Mueller and E. Garmire. "Integrated Optics Components for Fiber Gyroscopes and Observation of the Photorefractive Effect in $LiNbO_3$ Directional Couplers at GaAs Wavelengths." Proc. SPIE., **412**, 37 (1983).

8. E. Garmire. "The Emerging Technology in Opto Electronics." Proc. Los Alamos Conf. on Optics, SPIE **380**, 340 (1983).

9. C.T. Mueller and E. Garmire. "Photorefractive Effect in Lithium Niobate Directional Couplers." Proc. SPIE, **445**, 128 (1984).

10. E. Garmire and K. Honda. "Depolarization in Glass Waveguides". Submitted to J. Lightwave Tech.

11. C.T. Mueller and E. Garmire. "Photorefractive Effect in $LiNbO_3$ Directional Couplers." Appl. Opt., **23**, 4348 (1984).

PROFESSIONAL PERSONNEL

JSEP Personnel

1. E. Garmire, Principal Investigator, Professor of Electrical Engineering
2. T. Hasenberg, Ph.D. candidate in Materials Science and research assistant
3. K. Tatah, Ph.D. candidate in Physics
4. T. Tsai, Masters student in Materials Science to June 1983
5. N. Jokerst, Graduate Assistant in Electrical Engineering
6. Vincent Ng, Work-Study Student
7. Steve Wallace, Undergraduate Assistant, summer 1982
8. Charles White, Student Assistant, summer 1983

Collaborating Personnel

1. M.T. Tavis, member technical staff, The Aerospace Corp
2. C.T. Mueller, member technical staff, The Aerospace Corp

Personnel in Related Research

1. Craig Poole, Ph.D. in Electrical Engineering, received June 1984
2. Craig Mueller, Ph.D. in Electrical Engineering, received December 1983
3. Jeff Goldstone, Research Scientist to October 1984
4. K. Honda, visiting scientist from Japan
5. Zh. F. Zhu, visiting scientist from China

6. T.N. Ding, visiting scientist from China

7. The JSEP program supported one Ph.D. student - T. Hasenberg, whose thesis is expected to be completed in August, 1985. The tentative title is: "Studies of DCC Lasers for Reduced Temperature Dependence."

8. During the JSEP program, there were two Ph.D. theses in related research; these are: 1) "Bandgap Resonant Optical Nonlinearities in InAs and their Use in Optical Bistability," C.D. Poole, June, 1984; 2) "A Study of $LiNbO_3$ Directional Couplers," C.T. Mueller, December, 1983.

9. There is a Ph.D. thesis in preparation in related research: "Dynamics and Instabilities in Semiconductor Lasers in External Cavities," Karim Tatah.

INTERACTIONS

1. Interaction continues with Electronics Research Laboratory, The Aerospace Corporation, through trading knowledge and materials for fabrication and testing of semiconductor lasers. Our experience with InP complements theirs with GaAs.

2. Talk given to DARPA at Materials Research Conference in July, 1983.

3. Talk given at DARPA in May 1983, entitle "Diode pumping for solid-state lasers."

4. Appearance on panel discussing emerging technology in optics at the Los Alamos Conference on Optics, April, 1983.

5. Appearance on panel discussing $LiNbO_3$ and GaAs technologies, SPIE, January, 1984, in Los Angeles.

6. Organizer and co-chair, "The Future of Lightwave Technology", NSF Workshop, March, 1984.

7. Chair, NSF panel on Small Business Initiatives, 1983.

8. Member, NSF panel on Lightwave Technology, 1985.

Other Interactions

1. Program Committee: International Electron Devices Meeting (IEDM), 1983.

2. Program Committee: Conference on Lasers and Electro-Optics (CLEO), 1984.

3. Invited Participant: IEEE Workshop on Semiconductor Lasers. San Diego, January, 1984.

4. Invited Participant and Session Chair: IEEE Workshop on Semiconductor Lasers, Baltimore. June, 1985.

5. Organizer and Session Chair: IEEE Workshop on Integrated Optics, San Diego, January, 1985

6. Program Committee: OSA Conference on Optical Bistability, 1983 and 1985.

Talks/Consulting at:

1. MIT Lincoln Laboratory, visit, December, 1983
2. Batelle Columbus Laboratories, visit, August, 1983
3. Kodak Research Laboratories, visit, June, 1983
4. Dupont Research Laboratories, visit, May 1983
5. University of Arizona, visit, October, 1983
6. Honeywell Corporation, Research and Technology Center, visit, January, 1984
7. TRW, January, 1985
8. Huges, April, 1985
9. Newport Research Corporation, July, 1985
10. Rockwell, October, 1984

Conference Presentations

1. A Comparison of $LiNbO_3$ and II-V Semiconductor Technologies. SPIE, Los Angeles, 1985.

2. Heatsink Requirements for Phase-locking Semiconductor Laser Arrays. IEEE Workshop on Semiconductor Lasers, New Orleans, February, 1984.

3. The Emerging Technology in Opto-Electronics. Los Alamos Conference on Optics, April, 1983.

4. Measurement of Mode Locked Semiconductor Laser Pulses. NSF Meeting on Optical Communication Systems, June, 1983.

5. Integrated Optics Device Studies. NSF Meeting on Optical Communicatation systems, June, 1982.

6. Observation of Optical Chaos in Semiconductor Lasers in External Cavities. NSF Meeting on Optical Communication Systems, June 1984.

7. Dynamics and Instabilities in Semiconductor Lasers in external Cavities. June, 1985.

8. Bistability - experimentally observed in 4 mW in InAs and theoretically predicted for a new class of nonlinear dielectrics. March 21,22, The Royal Society, London.

9. Single Mode Propagation of High Power Laser Light in Hollow Metal Waveguides. Referee. CLEO, Anaheim, June, 1985.

10. Macroscopic Manifestations of Microscopic Optical Bistability. IQEC, Anaheim, June, 1984.

11. Nonlinear Refraction at the Band Gap in InAs. Referree. IQEC, Anaheim, June 1984.

12. Reflective Optical Bistability at 3 mW in InAs. Referee. CLEO, Anaheim, June, 1984.

Patents

None

SEM MICROGRAPH OF DOUBLE CARRIER CONFINEMENT
LASER DIODE

BLOW UP OF ACTIVE REGIONS

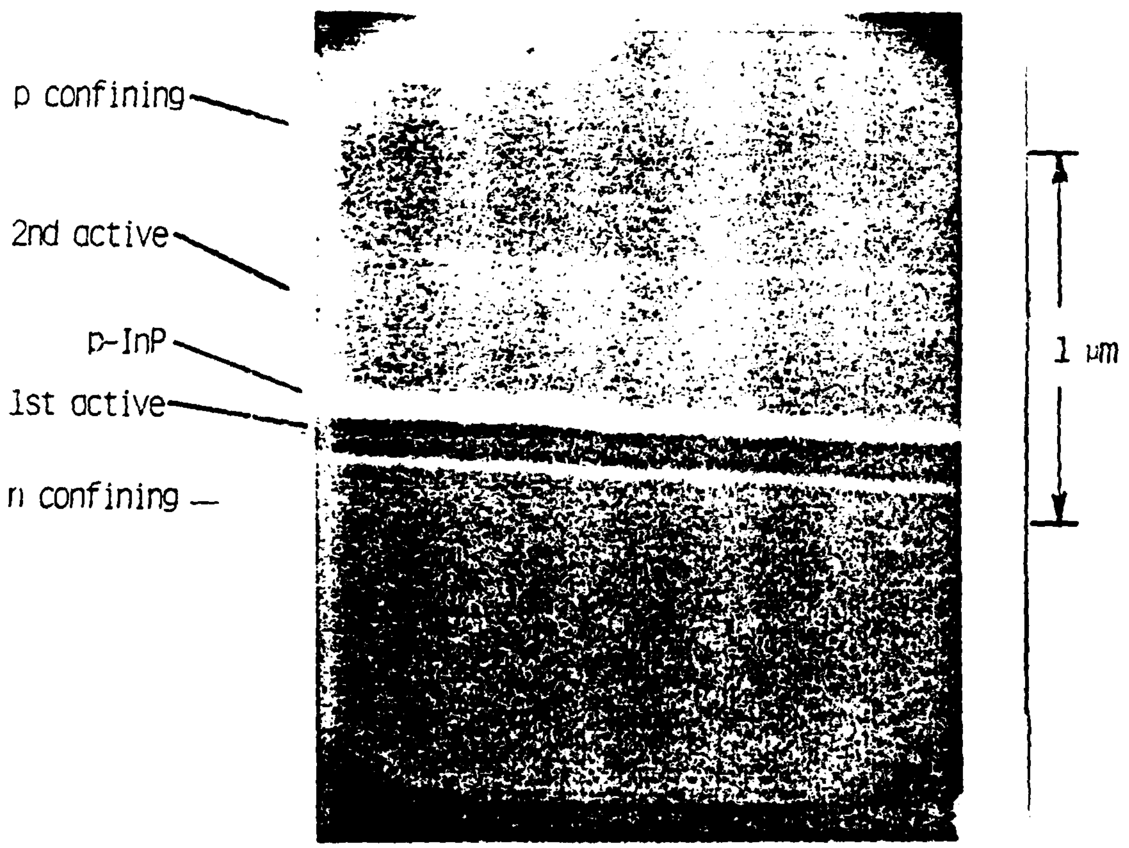
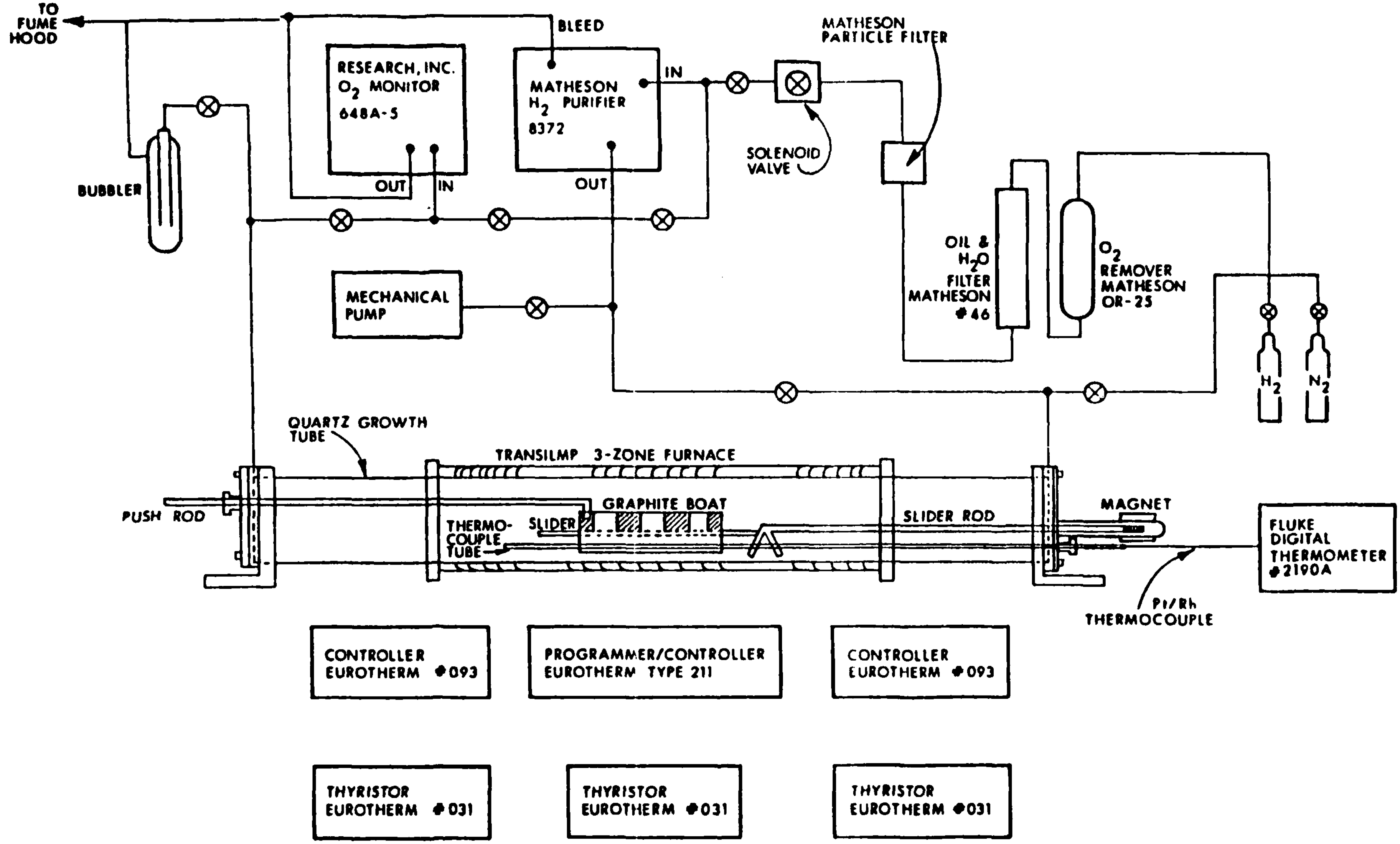
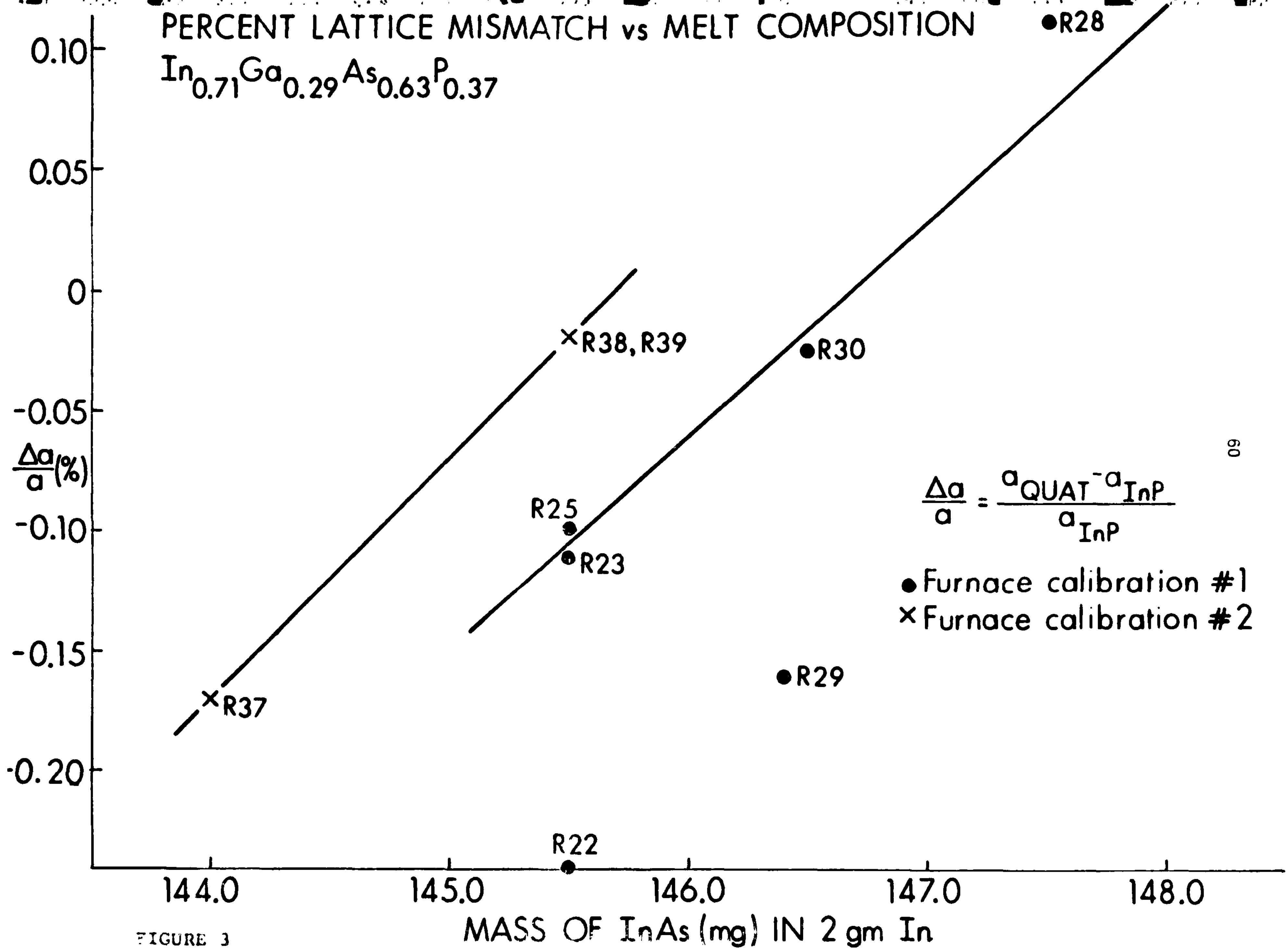


FIGURE 1.



APPARATUS FOR LIQUID PHASE EPITAXY OF DOUBLE HETEROSTRUCTURE MATERIAL FOR LASER DIODES

FIGURE 2



PERCENT LATTICE MISMATCH vs MELT COMPOSITION
$In_{0.71}Ga_{0.29}As_{0.63}P_{0.37}$
$\frac{\Delta a}{a}$(%)
0.10
0.05
0
-0.05
-0.10
-0.15
-0.20
144.0
145.0
146.0
147.0
148.0
MASS OF InAs (mg) IN 2 gm In
R28
R30
R38, R39
R25
R23
R37
R29
R22
$\frac{\Delta a}{a} = \frac{a_{QUAT} - a_{InP}}{a_{InP}}$
● Furnace calibration #1
× Furnace calibration #2

FIGURE 3

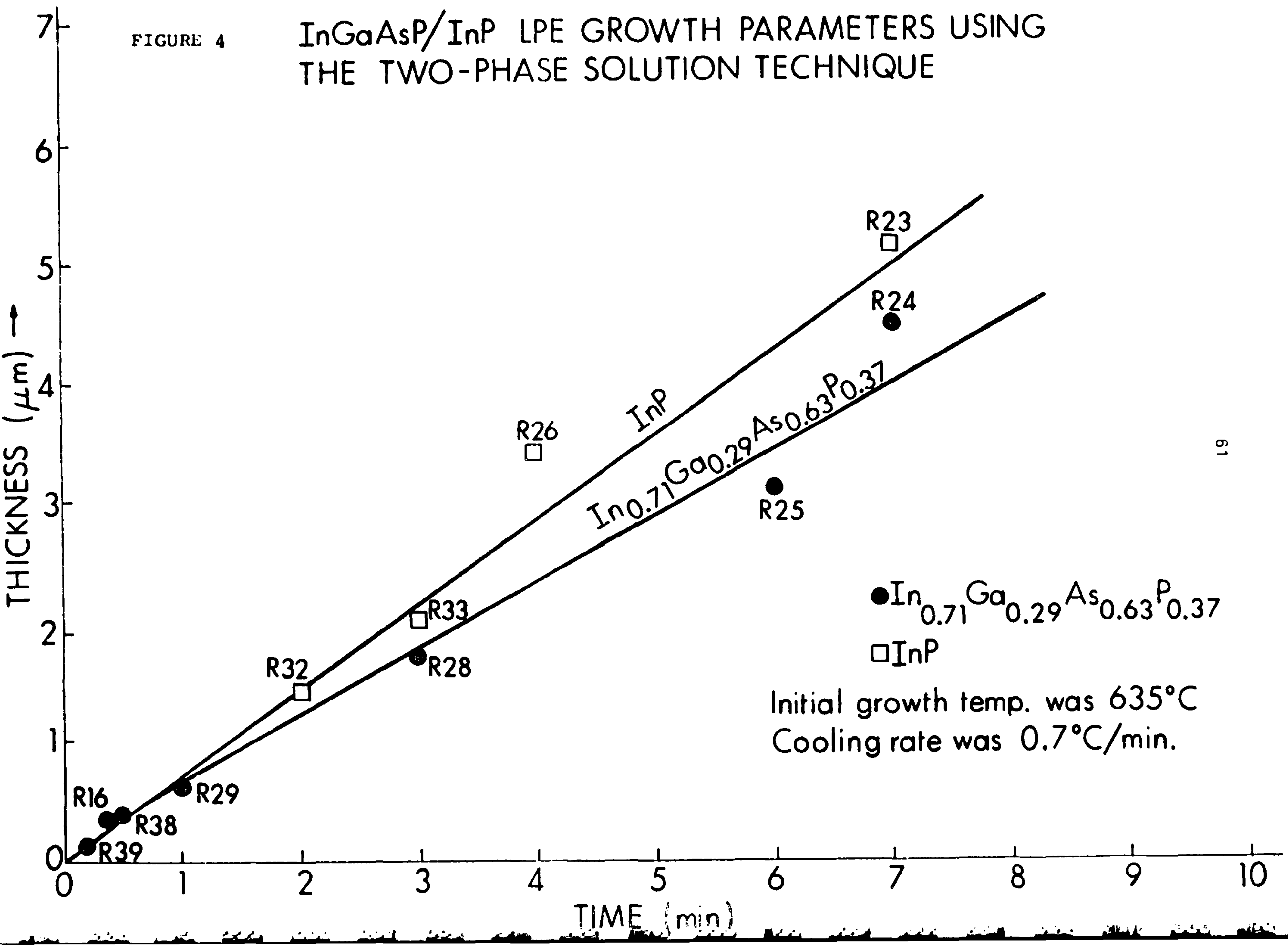
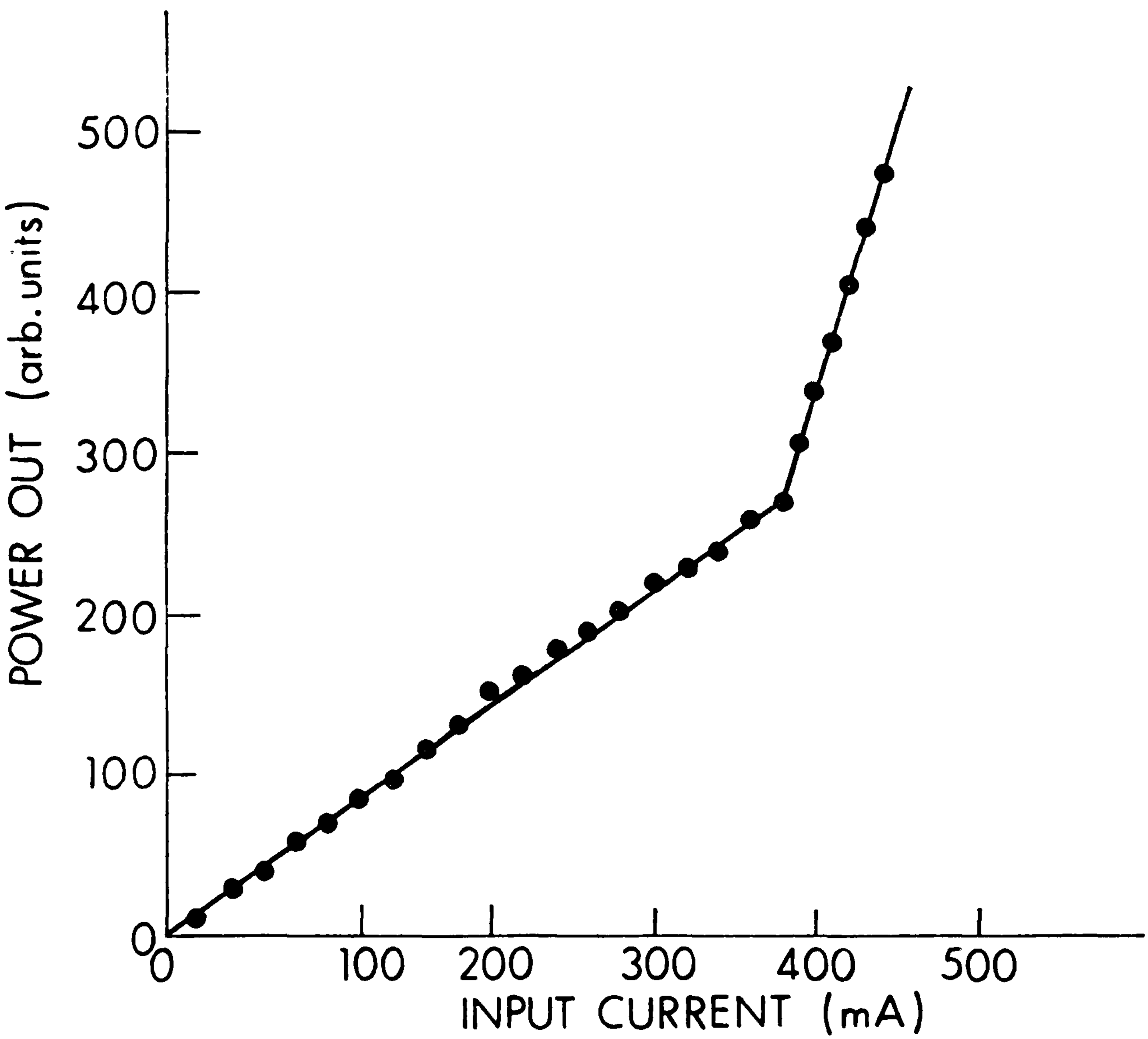


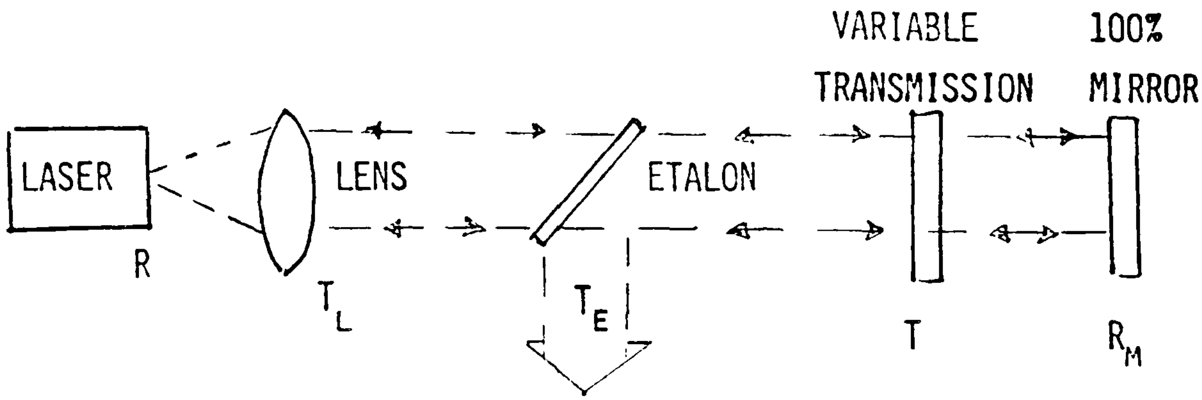
FIGURE 4 InGaAsP/InP LPE GROWTH PARAMETERS USING THE TWO-PHASE SOLUTION TECHNIQUE

FIGURE 5

LIGHT OUTPUT POWER vs INPUT CURRENT
FOR AN In/InGaAsP DHL (1.3 μm)



EFFECTIVENESS OF EXTERNAL CAVITY



$$R_{EFF} = \left(\frac{\sqrt{R} + \sqrt{R_F}}{1 + \sqrt{R_F R}} \right)^2$$

$$R_F = \eta T^2$$

$$\eta = T_L^{\ 2}\, T_E^{\ 2}\, R_M \eta_C \eta_F$$

η_C = COLLIMATION EFFICIENCY

η_F = FOCUSSING EFFICIENCY

$$\Delta I_{TH} = C \ \mathrm{LN}(R_{EFF}/R)$$

FIGURE 6. Experimental apparatus for measuring gain using an external cavity. Parameters are as expressed in the above formulas.

CHANGE IN THRESHOLD AS A FUNCTION OF AMOUNT OF EXTERNAL REFLECTION

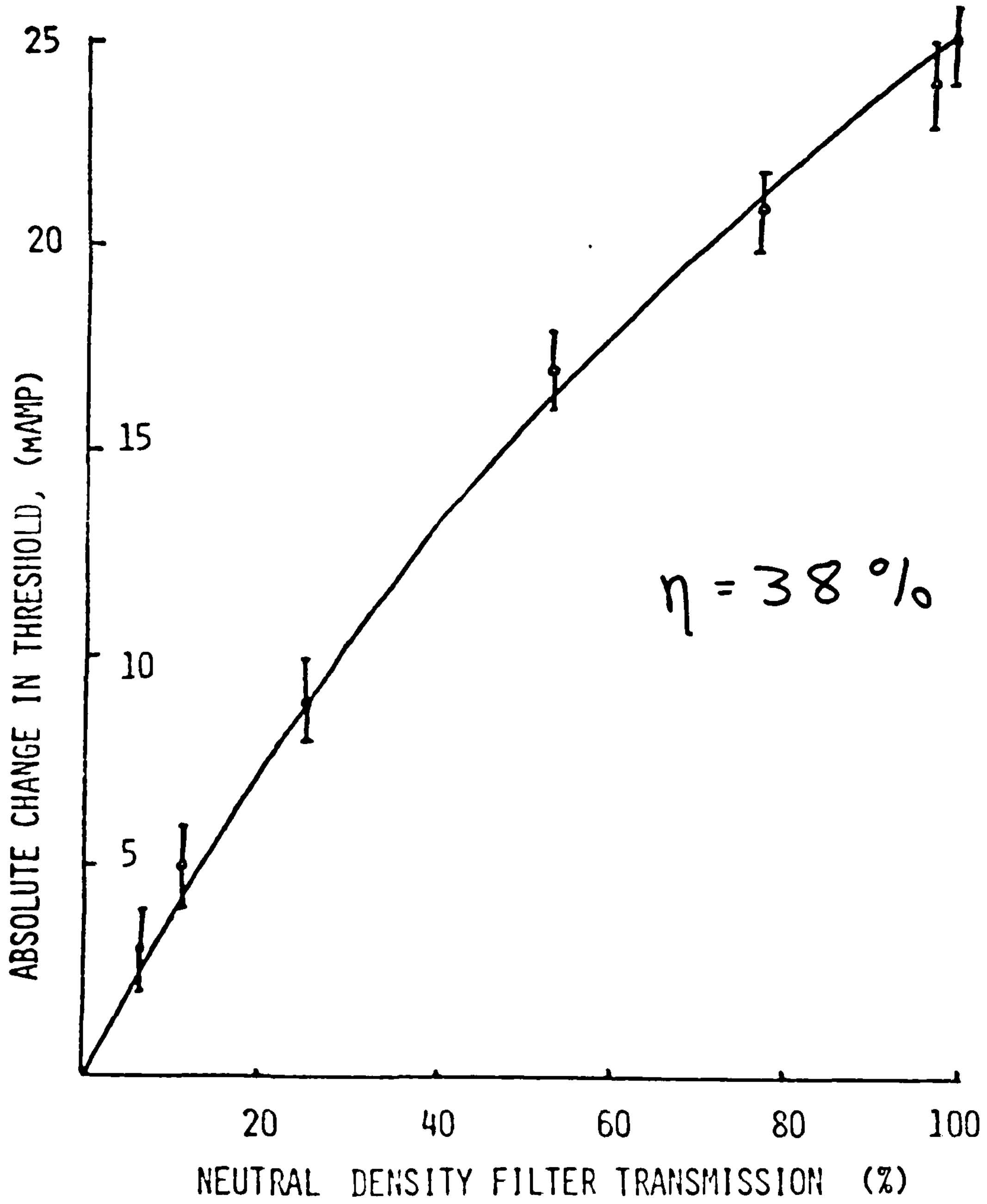


FIGURE 7.

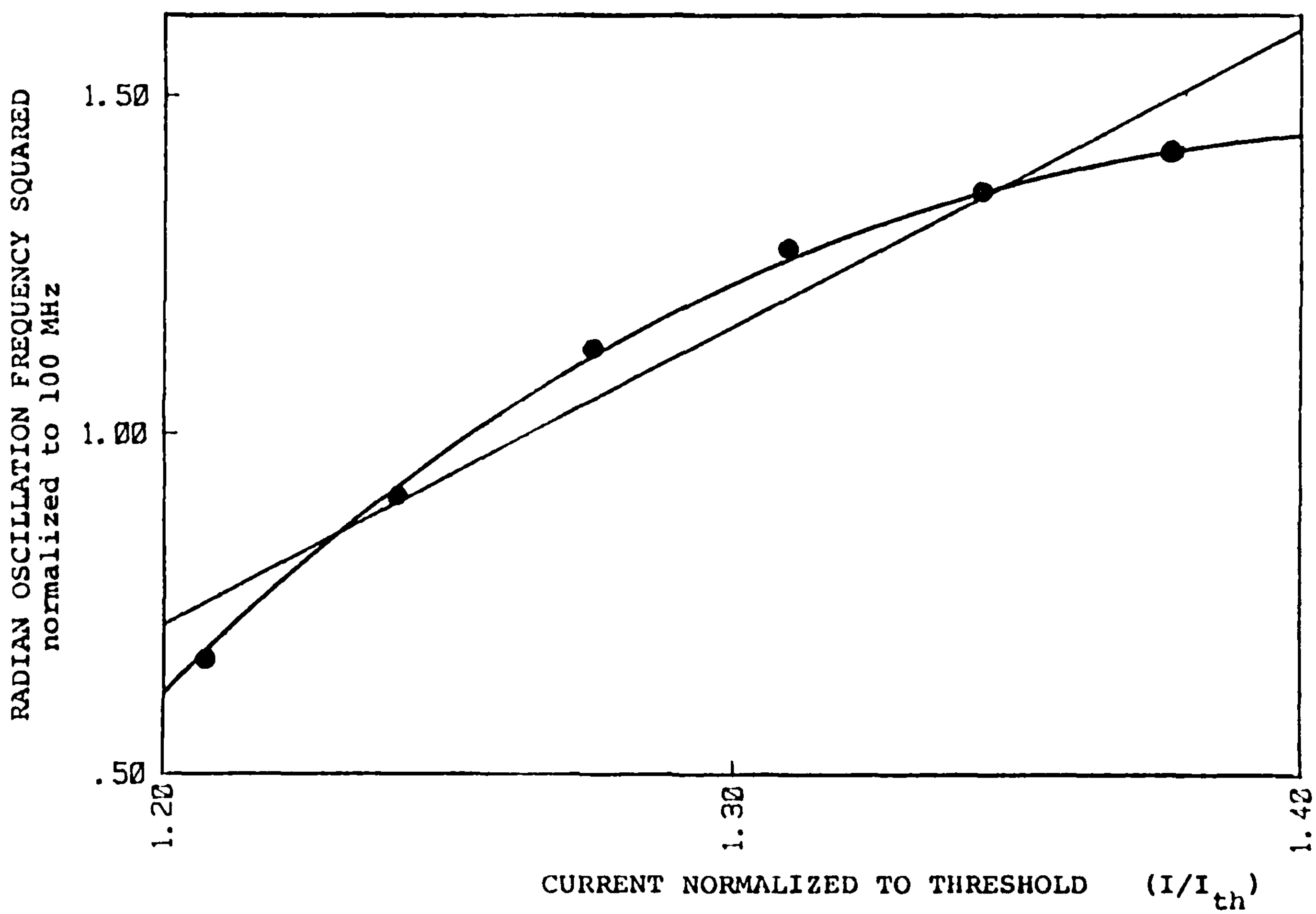


Figure 8. Square of the relaxation frequency as a function of injected current. Dots are experimental results, straight line is theory without considering the dependence of lifetime on injection current. Curve is the adjusted theory.

A SPECTROSCOPIC STUDY OF BASIC PROCESSES IN ELECTRICALLY EXCITED MATERIALS

Work Unit QE4-2

Martin A. Gundersen

Report Period: April 1, 1981 through March 31, 1985

RESEARCH OBJECTIVES

This work seeks to obtain through laser spectroscopic methods data to develop microscopic theories of electrical discharges. Such theories are needed to accurately describe conductivity, attachment, recovery, breakdown, etc., in discharges that are important in the operation of lasers, switches, optical pumping sources, optogalvanic devices, and other gas phase devices. At the present time the theoretical understanding of these phenomena is largely **qualitative**. It is the objective of this work to utilize spectroscopy to provide data that is needed to develop **quantitative** models.

This is to be accomplished by developing the necessary theory from and along with appropriate experimental data. In this JSEP project, support is to be used to obtain spectral data by developing and applying several methods. These include time resolved *spectral data, laser induced fluorescence, hook spectra, and streak camera data.*

STATUS OF RESEARCH EFFORT

Brief Outline of Group Recent Research Findings

1. It was found that helium is important for high power switches. It can be used in a thyratron with at least as high stand-off voltage capability, as high current handling capability, and faster recovery. Helium should be seriously considered for high power, high repetition rate switch requirements for applications such as excimer lasers.

2. A paper was published describing a cathode that operates at high currents in a field emission mode. This work suggests that field emission, along with a low work function material and an appropriate surface structure, may replace thermionic emitters for certain applications.

3. A quantitative theory of the plasma that exists during the steady-state or conductive phase in hydrogen thyratron was developed. This work included the following results:

* The production mechanism for electrons and ions is ionization of atomic hydrogen, rather than molecular hydrogen, as had previously been thought.

* The electron energy distribution function in this plasma was determined to be Maxwellian, based on a careful estimate of the role of electron-electron collisions.

* A method for determining the electron temperature was developed, through an analysis of all pertinent collisional and radiative processes. The electron temperature was found to be about 1.0 to 1.5 eV, substantially lower than previously reported.

* It is tentatively concluded that the presence of atomic hydrogen is a limitation to recovery in a hydrogen thyratron.

* Transport coefficients (such as the conductivity), are determined from an accurate model of collisional processes.

4. A major experimental effort has been undertaken to develop sophisticated diagnostic methods for partially ionized gases. This work is complemented by a theoretical project, and, in combination, is responsible for results such as those described in refs. 21 and 27.

5. Developed the theory describing the interaction between two fields and three levels with arbitrary 1) frequency mismatches, 2) lifetimes, and 3) field strengths. This has applications to the development of new lasers.

6. Completed a paper describing in detail the production of radiation in a thyratron plasma.

7. Developed a fairly general method that accounts for coulomb collisions in high current plasmas.

Spectroscopic studies of discharge kinetics, with applications to high power switching, are proceeding, as indicated by the progress during the past year, and by the publications, talks presented at technical meetings, and interactions with DoD. Thus, the research is successfully underway. The current status is largely described by the publications, of which there are 33 since 1981.

The research effort has demonstrated that a serious analysis of microscopic processes, including both data obtained by this project and a theoretical study of collisional and radiative processes, can produce important new results bearing on the operation of these devices--even in as common a device as the hydrogen thyratron. In addition, fallout is including new approaches to the problems of switching.

The hydrogen thyratron is presently a 'best' candidate for certain switch problems, such as high repetition rate excimer lasers. In its present form, it has reached certain limits of opration. However, it is essential to realize that the thyratron can be changed and improved, not by making incremental changes in the existing devices, but through an approach that considers fundamentally different approaches. This certainly should be pursued, because the development of a significantly improved thyratron-type switch will bring in its wake new applications. Improvements that are needed are in the areas of stand-off voltage, peak current, repetition rate, and cathode degradation and performance.

JSEP support was partially responsible for the following interactions (Talks Presented):

* "Optically Pumped Lasers," Army Research Office Meeting on Tunable Laser, Keystone, Colorado, April 2, 1981.

* "Optical Processes in the Recovery of Gas Phase Switches," 3rd International IEEE Pulsed Power Conference, June 1, 1981.

* "Formation of Metastable Species in Hydrogen Thyratrons," with S. Guha, 3rd International IEEE Pulsed Power Conference, June 2, 1981.

* "Optical Processes in Electrical Discharges," with S. Guha and H. Cole, 33rd Gaseous Electronics Conference, October 23, 1981.

* "Optical Processes in Laser Controlled Switches," Electro-Optics/Laser '81, November 17, 1981.

* "Pulsed Power Research Directed Towards Glow-Discharge Switches," presented at Sandia National Laboratory, interaction with W. Gerrardo, L. Pitchford, A. Owyung, C. Frost, J. Woodwards. February 19, 1982.

* "Pulsed Power at USC," Texas Tech Pulsed Power Review, May 19, 1982.

* "Fundamental Processes in Hydrogen Thyratrons," with S. Guha, H. Cole, and J.A. Kunc, 15th Power Modulator Symposium, June 14, 1982.

* "Basic Research in Hydrogen Thyratrons," presented at Math Sciences Northwest, Seattle, WA, July 10, 1982.

* "Plasma Processes in Hydrogen Thyratrons," with J.A. Kunc and S. Guha, 35th Gaseous Electronics Conference, October 19, 1982.

* "Optical Energy Extraction," Workshop on Optically Controlled Diffuse Discharge Switches, Eugene, Oregon, December 2, 1982.

* "Laser Related Research," presented to the Defense Contract Regional Administrative Officers Meeting at USC, December 6, 1982.

* "Pulse Power Physics," Quantum Electronics Seminar, USC, February 16, 1983.

* "Electronic Cross Section for Excitons Bound to ZnO Pairs in GaP," with P.G. Snyder and C.W. Myles, presented to the March 1983 APS Meeting, Bull. Am. Phys. Soc. **28**, 413 (1983).

* "A New Radiative Recombination in GaP," with P.G. Snyder, presented to the 1983 March APS Meeting, Bull. Am. Phys. Soc. **28**, 413 (1983).

* "Pulsed Power Physics," 1983 Industrial Associates Research Review, May 12, 1983.

* "Fundamental Processes in Thyratrons," with J.A. Kunc and S. Guha, Electron-Tubes, Nachrichtentechnische Gesellschaft im Verband Deutscher Elektrotechniker, Garmisch-Partenkirchen, May 18-20, 1983

* "A Theoretical Study of Steady-State Properties of a High-Current Hydrogen Discharge," with J.A. Kunc, presented to the 1983 IEEE Plasma Sciences Meeting, May 1983

* "Recent Thyratron Research," with J.A. Kunc, S. Guha, C. Braun, and D. Erwin, IV IEEE Pulsed Power Conference, Albuquerque, NM, June 8, 1983.

* "Metastable Quenching by Optical Pumping," with S. Guha, J.A. Kunc, and C. Braun, IV IEEE Pulsed Power Conference, Albuquerque, NM, June 8, 1983.

* "Spectroscopic Methods for Characterization of Microscopic Properties of a Diffuce Discharge," NATO Workshop on Fast Electrical and Optical Diagnostics, July 10-24, 1983, Castelvecchio, Italy.

* "Spectroscopic Methods for High Voltage Diagnostics," 1983 High Voltage Workshop, October 5, 1983, Adelphi, Maryland.

* "Formation of H^+, H_2^+, and H_3^+ in a Molecular Hydrogen Plasma with High Ionization Degree," with J.A. Kunc, 36th Gaseous Electronics Conference, Albany, New York, October 11-14, 1983

* "Transient Interaction of Two Electric Fields with a Three Level System," with S. Guha, 1983 Meeting of the Optical Society of America, October 16-22, 1983

* "Optical Energy Excitation in Molecular Hydrogen," with S. Guha, 1983 Meeting of the Optical Society of America, October 16-22, 1983.

* "Molecular Dissociative Processes in the Production of Atomic Emission in a Non-Equilibrium Hydrogen Plasma," J.A. Kunc and M.A. Gundersen, 1984 IEEE International Conference on Plasma Science, May 14-16, 1984, St. Louis, MO.

* "Gas Discharge Devices for High-Power High-Repetition Rate Applications: A Basic Approach," J.A. Kunc, C. Braun, D. Erwin, and M.A. Gundersen, 1984 Sixteenth Power Modulator Symposium, June 18-20, 1984, Washington, D.C.

PUBLICATIONS

Publications with JSEP support

1. "Formation of long-lived species in hydrogen thyratrons," M.A.Gundersen and S. Guha, Proceedings, 3rd IEEE International Pulsed Power Conference, 324 (1981).

2. "Optical processes in the recovery of gas-phase switches," M.A. Gundersen, Proceedings, 3rd IEEE International Pulsed Power Conference, 85 (1981).

3. "Optical processes in laser-controlled gas-phase switches," M.A. Gundersen, Proceedings, Electro-Optic/Laser '81, 34 (1981).

4. "Optical processes in laser-controlled gas-phase switches," M.A. Gundersen, Electro-Optic System Design, 24, June 1982.

5. *"Formation of metastable species in* hydrogen thyratrons," M.A. Gundersen and S. Guha, J. Appl. Phys. **53**, 1190 (1982).

6. "Fundamental processes in hydrogen thyratrons," S. Guha, H. Cole, J.A. Kunc, and M.A. Gundersen, Proceedings, 15th Power Modulator Symposium, 119 (1982).

7. "A review of some recent thyratron developments," J.A. Kunc, S. Guha, C. Braun, D. Erwin, and M.A. Gundersen, Proceedings IV IEEE Pulsed Power Conference, June 1983.

8. "A study of discharge processes in hydrogen thyratrons," S. Guha, H. Cole, and M.A. Gundersen, IEEE Trans. Plasma Sci. **PS-10**, 309 (1982).

9. "Thyratrons operating using helium for high power and high repetition rate applications," S. Guha, C. Braun, J.A. Kunc, and M.A. Gundersen, IEEE Trans. Electron Devices, accepted for publication.

10. "A fundamental theory for high power thyratrons I: The electron temperature," J.A. Kunc, S. Guha, and M.A. Gundersen, Laser and Particle Beams 1, 395 (1983).

11. "A fundamental theory for high power thyratrons II: The production of atomic hydrogen and positive ions," J.A. Kunc and M.A. Gundersen, Laser and Particle Beams **1**, 4 (1983).

12. "Gas discharge devices for high-power high-repetition rate applications: A basic approach," J.A. Kunc, C. Braun, D. Erwin, and M.A. Gundersen, Proceedings, 16th Power Modulator Symposium, June 18-20, 1984.

Other Related Publications

1. "Workshop on diffuse discharge opening switches," "Tammaron II", contributing author, U.S. AFOSR, January 1982.

2. "Optical processes in the performance and recovery of gas-phase switches," M.A. Gundersen, Appl. Opt. **21**, 1486 (1982).

3. "Fundamental processes in hydrogen thyratrons," S. Guha, H. Cole, J.A. Kunc, and M.A. Gundersen, Proceedings, 15th Power Modulator Symposium, 119 (1982).

4. "Fundamental processes in thyratrons," with J.A. Kunc and S. Guha, Proceedings, Electron-tubes Nachrichtentechnische Gesellschaft im Verband Deutscher Electrotechniker, May 1983.

5. "Metastable quenching by optical pumping," S. Guha, J.A. Kunc, C. Braun, and M.A. Gundersen, Proceedings, IV IEEE Pulsed Power Conference, June 1983.

6. "Summary of the workshop on the state-of-the-art of hydrogen thyratron," M.A. Gundersen, University of Southern California, held at the Air Force Weapons Laboratory, June 1983.

7. "Fundamental processes in thyratron developments," J.A. Kunc, S. Guha, and M.A. Gundersen, Proceedings, Electron-tubes Nachrichtentechnische Gesellschaft im Verband Deutscher Electrotechniker, May 1983.

8. "High voltage diagnostics: An experimental and theoretical approach," J.A. Kunc and M.A. Gundersen, Proceedings, 1983 NATO Meeting of Fast Optical and Electrical Diagnostics, July 1983.

9. "Gas Tube," M.A. Gundersen, prepared for McGraw-Hill Encyclopedia of Science and Technology, 1983.

10. "Plasma parameters characteristic of hydrogen thyratrons under steady-state conditions," J.A. Kunc and M.A. Gundersen, IEEE Trans. Plasma Sci. **PS-10**, 315 (1982).

11. "Scalar transport coefficients for the hydrogen plasma in the cathode-grid region of a thyratron," J.A. Kunc and M.A. Gundersen, J. Appl. Phys. **54**, 2761 (1983).

12. "Field emission cathode for high power beams," R. Petr and M.A. Gundersen, Laser and Particle Beams **1**, 207 (1983).

13. "Optical quenching and energy extraction involving metastable and dissociative states in hydrogen," S. Guha, J.A. Kunc, and M.A. Gundersen, IEEE J. Quantum Electron., accepted for publication.

14. "The transient and steady state interaction of two fields with a three level system," S. Guha and M.A. Gundersen, Phys. Rev. A, submitted.

15. "A fundamental theory for high power thyratrons III: The production of radiation," J.A. Kunc, D.E. Shemansky, and M.A. Gundersen, Laser and Particle Beams, accepted for publication.

16. "On the modeling plasma devices for pulsed power," J.A. Kunc and M.A. Gundersen, Appl. Phys. Lett., accepted for publication.

17. "Analytical expressions for H^+, H_2^+ and H_3^+ ion densities in a hydrogen glow discharge," J.A. Kunc and M.A. Gundersen, Phys. Fluids, submitted.

18. "An analysis of the asymmetry part of electron-electron Boltzmann integral," J.A. Kunc, J. Appl. Phys. **54**, 2687 (1983).

19. "Rate coefficients for some collisional processes in high current hydrogen discharges," D.A. Erwin and J.A. Kunc, IEEE Trans. Plasma Science **PS-11**, 266 (1983).

20. "Contribution of dissociative processes in the production of atomic lines in hydrogen plasmas," J.A. Kunc, J. Quantitative Spectros. and Rad. Transf., in press.

21. "Diffuse discharge switches," R. DeWitt, S. Friedman, R. Harvey, G. McDuff, D.V. Turnquist, W. Wright, and M.A. Gundersen, An assessment of Soviet Switch Technology, Tammaron IV, March 1984, Santa Fe, N.M. Copies may be obtained from M.A. Gundersen.

PROFESSIONAL PERSONNEL

1. Martin A. Gundersen, Professor - Electrical Engineering & Physics
2. Joseph A. Kunc, Research Associate Professor - Physics
3. Christopher Braun - Electrical Engineering
4. Daniel Erwin - Electrical Engineering

INTERACTIONS

* I am interacting on an ongoing basis with many people involved in high power switch research. These include, the U.S. Army ERADCOM, Ft. Monmouth, New Jersey, Steve Levy, et al.; Naval Surface Weapons Center, Larry Leussen, Frank Rose, Robert DeWitt; Lawrence Livermore National Laboratory, Earl Ault, Don Ball, Randall Ross; Air Force Weapons Laboratory, A.H. Guenther; ITT Electron Tube Division, Henry Grunwald; Los Alamos National Laboratory, Glen McDuff, C. Randy Jones, Steve Rockwood; EG&G, Inc., Steve Friedman; Maxwell Laboratories, Ed Chu; Physics International, Alan Toeppfer; Impulse Electronics, Dave Turnquist; Mathematical Sciences Northwest, Rodney Petr and Stan Byron.

* I have written parts of an assessment of Soviet Switch technology for T.R. Burkes, Inc. and the U.S. Army Foreign Technology Assessment Center. My work included contributions to the sections on solid state switches and thyratrons.

* I ran a workshop on the state-of-the-art of thyratrons, June 9, 1983, at the Air Force Weapons Laboratory. About 30 people attended, with representation for industry (ITT, EG&G, Hughes Aircraft Company, Maxwell Laboratories, Physics International), the Department of Defense (Naval Surface Weapons Center, U.S. Army ERADCOM, Air Force Weapons, Laboratory0, the Department of Energy (Los Alamos, Lawrence Livermore), and Universities (MIT, Texas Tech., USC). A summary is in preparation.

* I participated in a workshop on Foreign (Soviet) switch technology in Santa Fe, NM, March 6-8, 1984, and chaired a group that considered glow discharge switches.

DISCOVERIES/PATENTS

New application of helium to thyratron switching of high peak powers (described above).

See also Brief Outline of Recent Research Findings under Status of Research Effort.

Laser Devices & Applications

Work Unit QE4-3

W.H. Steier

Report Period: April 1, 1981 through March 31, 1985

RESEARCH OBJECTIVES

The object of this research is the study of non-linear materials and their applications in optical devices and systems. In the last four years, the effort on this task has been directed toward measuring the nonlinear properties of materials and in applying nonlinear optical materials to optical signal processing.

STATUS OF RESEARCH EFFORT

Measurement of the Short Pulse Saturation Properties of Ultraviolet Dyes with XeCl Laser

The measurements of the short pulse dye saturation properties of several UV dyes have been completed. The interest is in dyes for passive modelocking of the excimer lasers and for interstage isolation of UV amplifier chains. The detailed results are given in publication #2.

The experimental setup is shown in Figure 1. The XeCl laser has a pulse width of about 40 nsec. The one nsec pulses needed for the measurements were obtained as follows: A portion of the laser output triggers a switch (Lasermetrics SG201) which allows a 1.5 KV voltage wave front to propagate to one electrode of the KD* P modulator (Lasermetrics 1041). The other electrode momentarily remains at ground. This voltage is close to the half wave voltage for the modulator and rotates the incident laser polarization by 90° which then passes through a calcite polarizing prism. After the voltage wave front propagates to the other electrode of the modulator, the voltage falls to zero across the modulator and the XeCl laser output is blocked by the polarizer. The transmitted pulse length is the pulse transit time of the cable connecting the two electrodes on the modulator.

The results of the short pulse measurements are shown in Figure 2 and refer to (A) polyphenyl in ethylene glycol; (B) BPBD in cyclohexane. The solvents, ethylene glycol and cyclohexane, were measured and no saturation observed. The dye measurements are corrected for the absorption of the pure solvent filled cell. The saturation fluence, $J_s = h\nu/\sigma$, can be computed from the low intensity absorption of the dyes and are: 4.7 mJ/cm^2 for polyphenyl; 3.9 mJ/cm^2 for BPBD; and 3.1 mJ/cm^2 for BBQ. Up to about 10 mJ/cm^2, our data is consistent with these saturation fluences and a simple two level saturation; at higher fluence the observed transmission is lower than expected.

The energy available in the short pulse was not sufficient to show the limiting saturation, i.e., the plateau of the saturation curves. In order to determine if the dyes could be fully saturated at higher pulse intensities, the considerably higher pulse energies and peak intensities possible with the full 40 nsec laser pulse were used. However, this pulse length is considerably longer than the dye relaxation time which means the saturation is intensity controlled. Figure 3 shows the dye saturation long pulse measurements.

Earlier work indicated that photo-dissociation occurs in dyes at 193 nm Since many recombination processes are slow if significant photo-dissociation takes place, the dye may not be useable in modelocking because of this slow transmission recovery time. This may be another explanation for the lack of success in modelocking. To measure the transmission recovery times, an additional experiment was performed in which the nanosecond laser pulse was used to saturate the dye and a weaker 40 nsec pulse was used to measure the transmission of the dye. The two beams propagated at a small angle to each other in the dye.

The result was the same for all three dyes and is shown for the dye polyphenyl in Figure 4. The narrower peak riding on top of the broader pulse is due to the increased transmission of the dye that is coincident with the saturating pulse. The increased transmission of the dye follows the shape of the nanosecond saturating pulse within the accuracy of our detection system. Thus in all of the dyes, the transmission recovery time is no longer than one or two nanoseconds, and this is sufficient for most modelocking experiments.

All of the dyes show evidence of excited state absorption which cannot be saturated at the intensities achieved in this work. Even if the transmission of BPBD continues to increase, the shape of the curve is incorrect for a simple two level saturation. There is little data available on excited state absorption, but we might expect it to be more pronounced in the UV since the size of the photon makes it more likely that a higher lying singlet or triplet state can be reached.

The conclusion can be drawn from this work that passive modelocking of the excimer laser to achieve picosecond pulses will likely be difficult because of the unsaturable excited state absorption of the candidate dyes. A dye with a large UV absorption cross-section and without excited state absorption may be difficult to find.

Optical Signal Processing - Accuracy of Real Time Correlations via Four-Wave Mixing

As discussed in our earlier proposal, there are several 2-D analog mathematical operations which can be achieved using fourwave mixing in nonlinear optical materials. One of these operations, a 2-D correlation/convolution has been investigated in detail in this work to determine the accuracy and signal power possible. An analysis of the output correlation which demonstrates the amount and source of the inaccuracies has been completed and the results have been confirmed by experiment.

A typical application of the fourwave mixing correlations technique discussed here would be in the search of a scene for a given object. Peaks in the 2-D correlation between the scene and the object indicate the locations of the object. This work shows that the errors in the correlation increase as the size of the scene to be searched increases and these errors place a limit on the scene size. The results are given in detail in publication #3.

The first result of this analysis is the realization that a non-colinear interaction is considerably less accurate than the colinear. In the typical four wave mixing scheme, the two inputs B_1 and B_2 propagate at a small angle to each other within the non-linear medium, the pump wave is counter to one of the inputs. This angle between the beams results in a lateral translation between the patterns as they propagate through the non-linear material. The result is a correlation between smoothed versions of the inputs and a considerable error.

A colinear interaction is possible so long as the two inputs are distinguishable via either polarization or wavelength. A typical polarization scheme is shown in Figure 5. Input 2 interacts with the plane wave pump 3 to write a grating in the non-linear material. Input 1 reads the grating and results in the scattered output 4. Note that a true X_3 material such as CS_2 will not work in all cases since the output will contain the correlation and its complex conjugate. If the inputs are real, this is not objectionable.

The result for the colinear case is

$$B_4(x,y)=K_c\int\int_{-\infty}^{+\infty}dx'dy'B_1(x',y')B_2(x'+x,y'+y)\frac{1-\exp(i\gamma_c z_o)}{-i\gamma_c z_o}$$

where

$$\gamma_c=i\alpha\frac{k_0}{nF^2}(xx'+yy')$$

K_c = constant containing the nonlinear coefficient X_3
z_o = thickness of non-linear material
α = linear loss coefficient
F = Focal length of the F.T. lens.

The above expression differs from the desired 2-D correlation by the last bracketed term. The origin of this term is the k vector mismatch. Near the origin the correlation is relatively accurate, but the accuracy decreases as the size of the two input patterns increase. This is important in a typical case where a scene is scanned for a particular object. For large fields of scan, the accuracy decreases, and the possibility of false alarms increases. This is illustrated by the results shown in Figure 6. For this data, input 1 is a square aperture of side "a" located on the axis. Input 2 is similar square aperture but located Xo off axis. We are, therefore, searching over range 2Xo by 2Xo for the square aperture of side "a".

The vertical axis is the total integrated power in the correlation peak, relative to the power in the perfect correlation and would therefore be the relative detected power for a threshold detection scheme. Power above the threshold indicates a target has been located. The normalized parameters c, d, and b are indicated on the Figure. It is clear that, if one wishes to scan over a field 20 times the size of the target, the parameter c must be 0.1 or less. As a benchmark, for $\lambda = 1\mu$, $n = 2$, $z_o = 4$ mm, $a = 1$mm and $F = 20$ cm; $c = 0.1$.

To keep the accuracy high, the parameter "c" should be small; however the total power scattered in the output beam is proportional to c^2. We have shown that

$$P_{out} \propto P_1 P_2 P_3 \frac{c^2}{\lambda^4 d^2_{max} M}(RCP)$$

where

$$d_{max} = \frac{X_{o\,max}}{a}$$

M = space-bandwidth product $\alpha\ a^2 f^2_{max}$
P_1, P_2, P_3 = power in the three input beams

Thus there must be a design tradeoff analysis made between accuracy, power output, maximum scannable field, and the space-bandwidth product of the inputs. The power output is proportional to λ^{-4} which indicates a significant advantage in going to the ultraviolet if suitable non-linear materials can be found.

PUBLICATIONS

JSEP Publications

1. Christopher Sexton and W.H. Steier, "The Accuracy of Real Time Correlations Via Degenerate Optical Four Wave Mixing", CLEO '83, Baltimore, May 17-20, 1983.

2. Christopher Sexton and W.H. Steier, "Measurement of the Short Pulse Saturation Properties of Ultraviolet Dye with the XeCl Laser" IEEE J. Quant. Elect., QE-20, Oct. 1984, pp. 114-7

3. Christopher Sexton and W.H. Steier, "A Study of Real Time Correlations using Optical Four Wave Mixing", in preparation.

Other Related Publications

1. W.E. Stephens and W.H. Steier, "Hybrid Optical-Digital Signal Processing Applied to an Optical Nonlinear Phase Estimator", Applied Optics 22, March 15, 1984, pp. 787-95.

PROFESSIONAL PERSONNEL

1. William H. Steier, Professor - Electrical Engineering

2. Gregory Kavounas, Research Assistant - Electrical Engineering

3. Sergay Mnatzakanian, Research Assistant - Electrical Engineering

4. Christopher Sexton, Research Assistant - Electrical Engineering

INTERACTIONS

We have had several discussions and reviewed the measurements reported here with the ultraviolet laser research group at Northrop Research and Technology Center. This group has extensive DOD funding and is active in excimer laser applications. The ideas and results presented here have been extensively discussed with the USC Image Processing Group and other USC faculty active in phase conjugation and nonlinear optics. This represents an interaction with several DOD funded projects. Numerous seminars have been presented to industry and at other Universities.

DISCOVERIES/PATENTS

None.

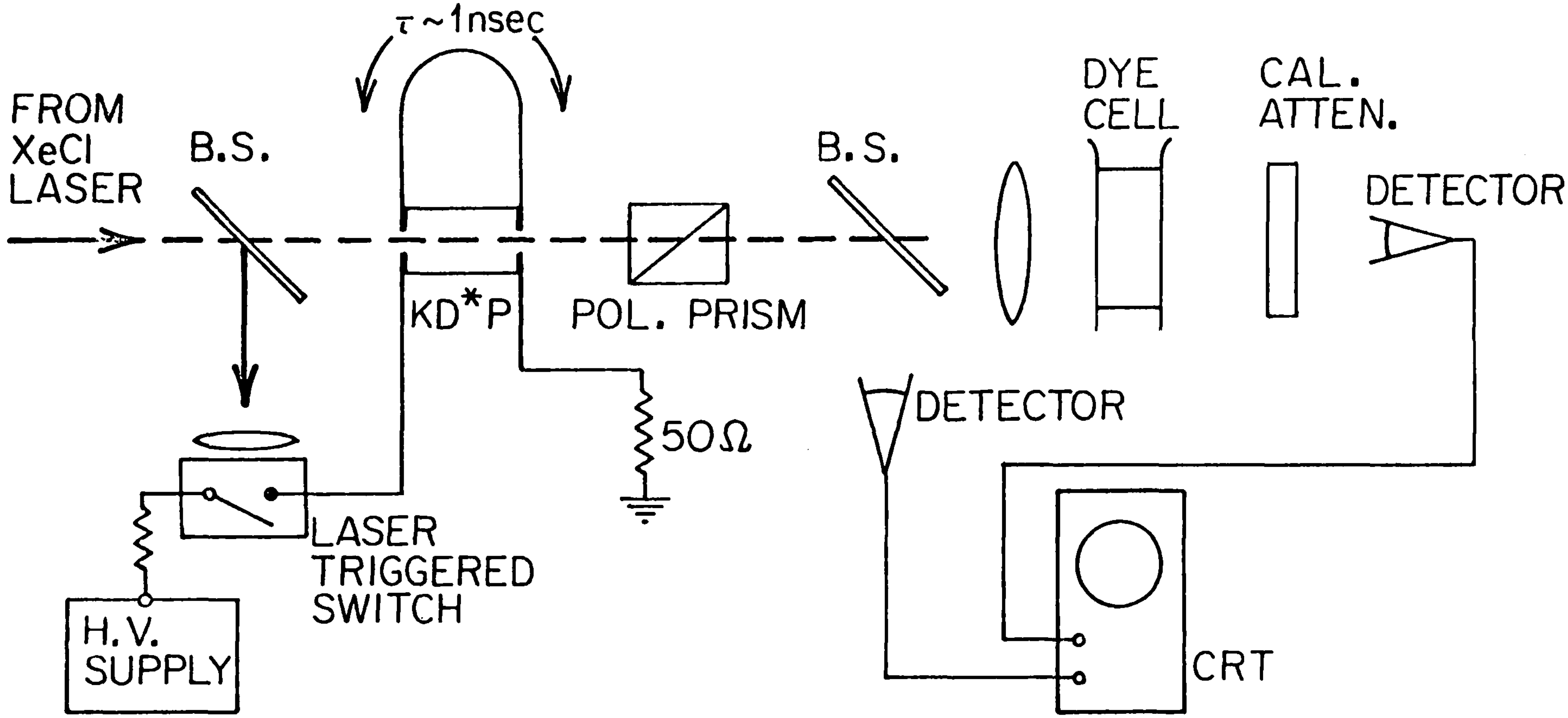


Figure 1. The experiment

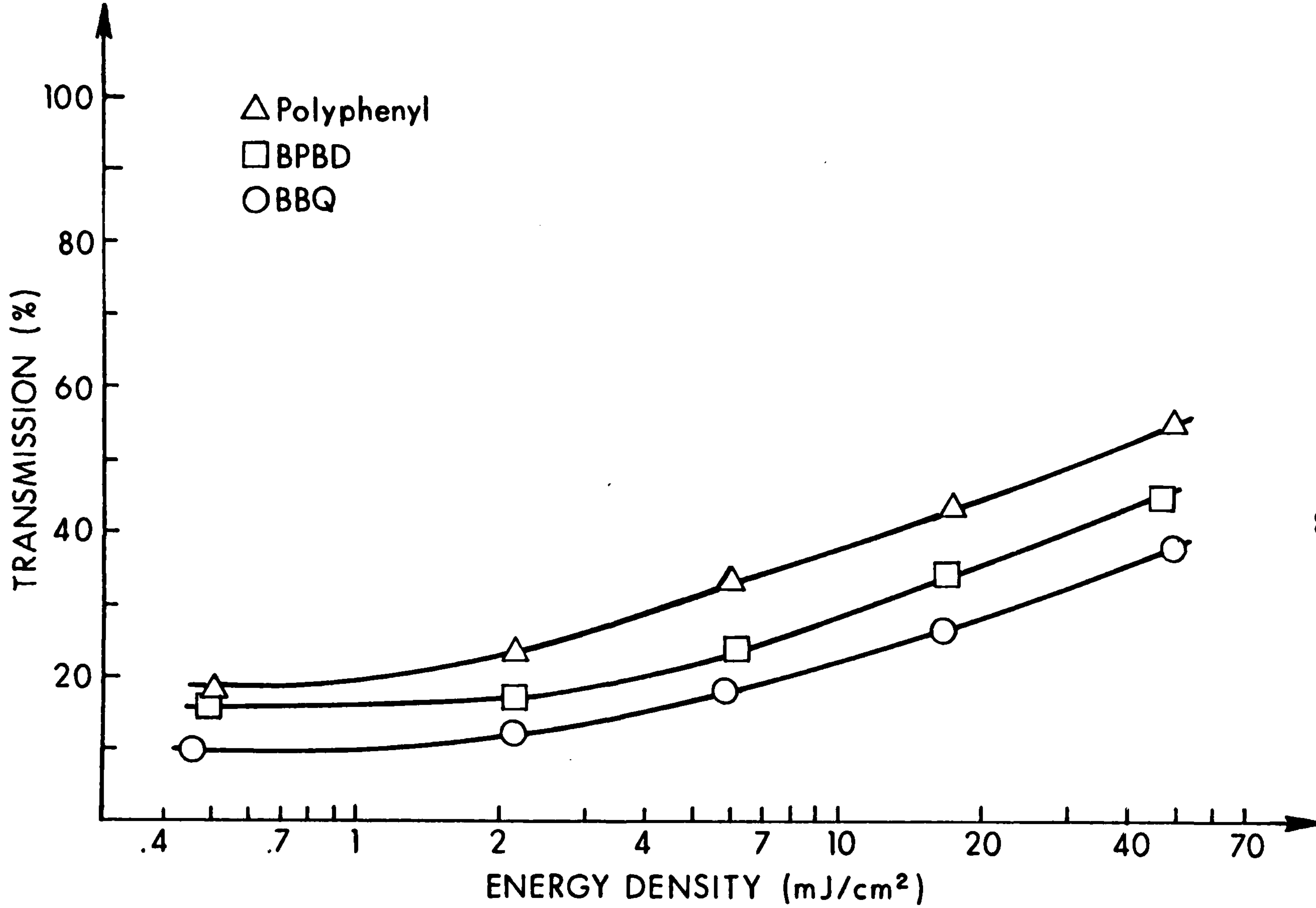


Figure 2. Short-pulse saturation measurements: Transmission of a 2ns pulse vs. the energy in the pulse. (Each data point is the average of 4-6 shots, and the curves are drawn to fit the data for illustration.)

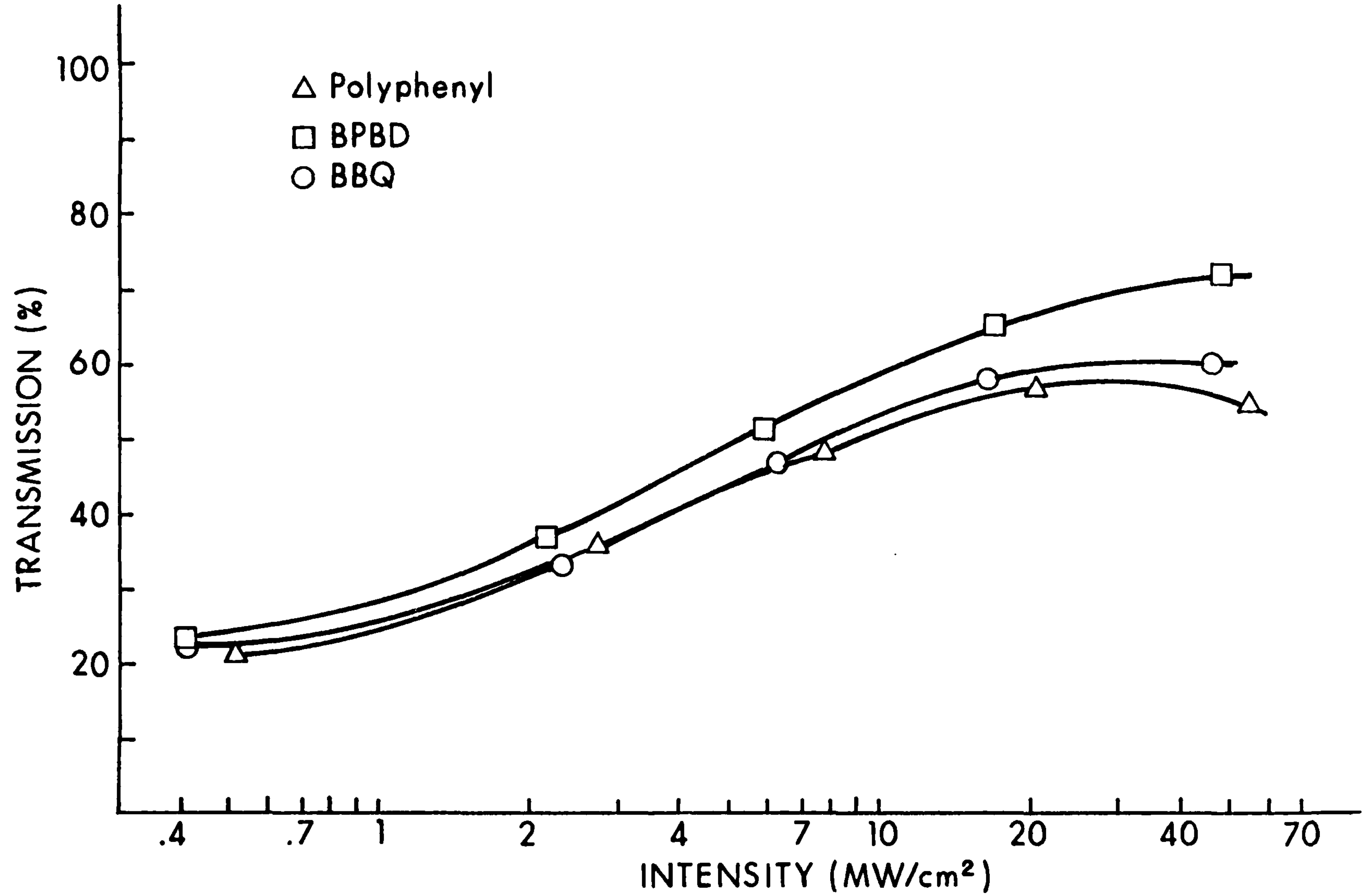


Figure 3. Long-pulse saturation measurements: Transmission of the peak of the laser pulse (~ triangular shaped; 10ns rise; 25ns fall) vs. the intensity of the peak. (Each data point is the average of 4-6 shots, and the curves are drawn to fit the data for illustration.)

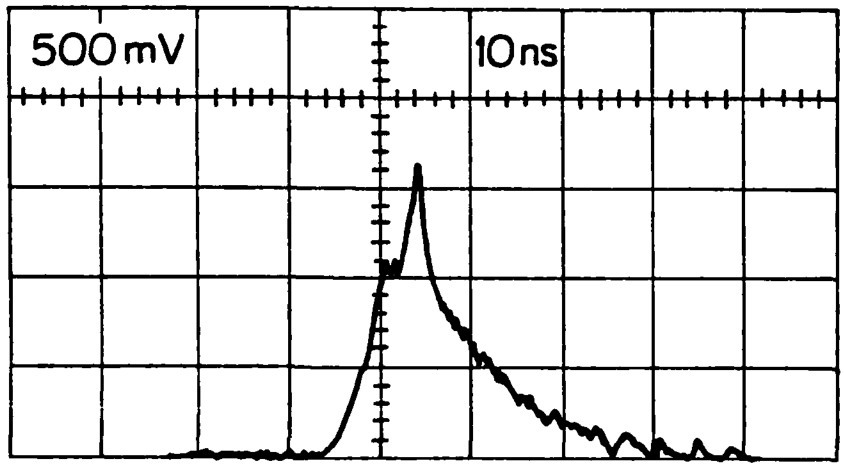
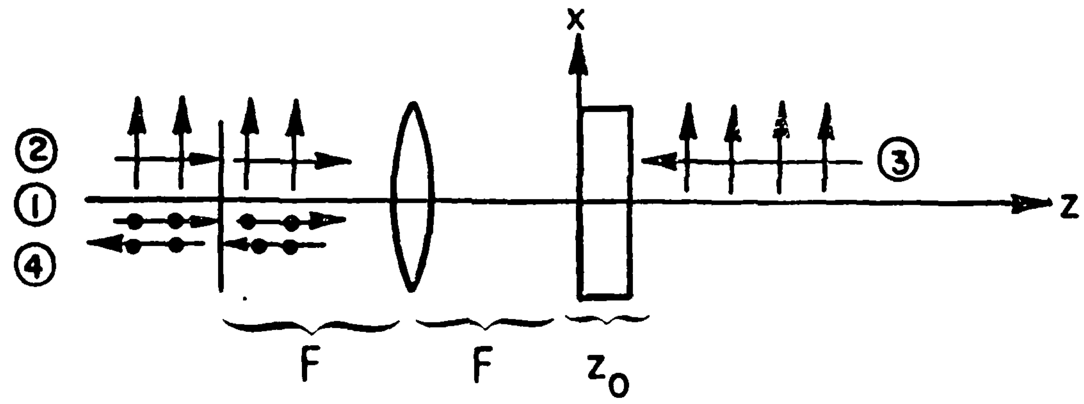


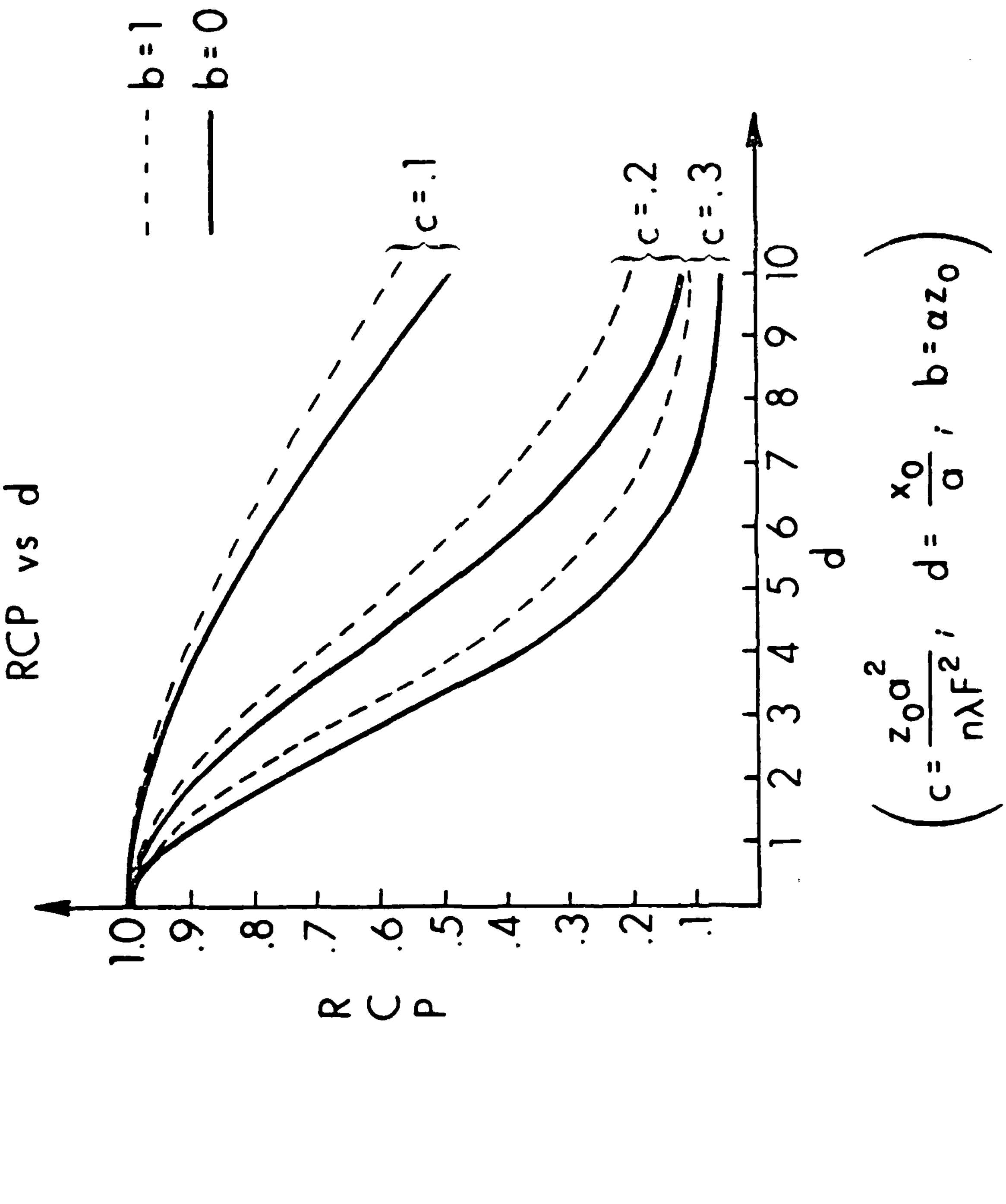
Figure 4. Polyphenyl dye recovery from saturation. The broad (~40nsec) low intensity laser pulse monitors the transmission of the dye. The narrow (~2nsec) peak occurring about 10 nsec after the start of the laser pulse is due to the increased dye transmission that is coincident with the saturating pulse.

- Collinear, degenerate FWM using orthogonal polarizations:



- 2 and 3 write a grating; 1 reads it
- Can't use a true $\chi^{(3)}$ material (e.g., CS_2)
- Strong noise at the input/output plane

Figure 5



RCP vs d
b=1
b=0
c=.1
c=.2
c=.3
R
C
P
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
1
2
3
4
5
6
7
8
9
10
d
$\left(c = \frac{z_o a^2}{n\lambda F^2},\ d = \frac{x_o}{a},\ b = a z_o \right)$

Figure 6

QUANTUM ELECTRONICS
SELF-PUMPED OPTICAL PHASE-CONJUGATING LASER RESONATOR CAVITIES

Work Unit QE1-4

J. Feinberg

Report Period: 1 April 1981 - 31 March 1985

NOTE: This work unit was added to JSEP in 1984

RESEARCH OBJECTIVES

The object of this research is to study the behavior and the applications of a new kind of phase conjugator that was recently discovered by the principal investigator. This device, called a self-pumped phase-conjugating mirror (SPPCM), is used to form novel laser-resonator cavities. In particular, l) Using a SPPCM, we have constructed a tunable dye laser that is self-aligning. This tunable dye laser can self-scan its own output wavelength. 2) We have also investigated the physical origin of the frequency shift caused by a SPPCM, and we discuss its implications for a variety of devices, including an optical gyroscope. 3) We have also completed preliminary experiments on the feasibility of using a SPPCM to injection-lock a high gain laser oscillator.

STATUS OF RESEARCH EFFORT

A. Dye laser with a self-pumped phase-conjugating mirror

A new kind of continuous-wave dye laser was constructed by replacing one of the mirrors of a conventional dye laser with a self-pumped phase-conjugating mirror (SPPCM). The resulting dye laser exhibited some remarkable properties: a) it was self-aligning, b) it could automatically correct for an optical distortion (a glass laboratory funnel) placed in the resonator cavity, and c) the output wavelength of the dye laser changed smoothly with time over the entire tuning range of the dye laser.

The SPPCM consisted of a single crystal of photorefractive barium titanate ($BaTiO_3$). Four-wave mixing of the incident beam in the crystal produced the phase-conjugate beam. However, in contrast to conventional four-wave mixing, there were no externally supplied pumping beams. Instead, the pumping beams were automatically derived from the incident beam itself inside the crystal, and were contained in the crystal by total internal reflection at the crystal faces. This phase conjugator operated even with a weak (milliwatt power) incident beam, and over the entire visible spectrum.

The dye laser was constructed by replacing the output mirror of a commercial dye laser with the SPPCM, as shown in Fig. 1. When the phase conjugator turned on, the spatial mode of the laser became uniform, and the spectral mode became a doublet separated by 1.5 GHz, as shown in Fig. 2

Self-scanning of the dye laser's output wavelength is shown in Fig. 3. The scanning could be either to the red or blue end of the spectrum, and covered the entire tuning range of the dye laser. The rate and the direction of the wavelength scan was affected by a number of experimental parameters, including the distance between the SPPCM and the rest of the dye laser, the geometry of the SPPCM, the presence of a lens or an aperture in the dye laser cavity, and table vibration. Further details can be found in publication #1.

Efforts to understand the cause of the self-scanning of the dye-laser's wavelength revealed that the SPPCM imparted a very small (~ 1 Hz) frequency shift to the phase-conjugated beam. This frequency shift occurred with each round trip of the optical beam in the laser cavity, i.e 10^8 times per second. The accumulation of these frequency shifts led to the easily observable change with time in the output color of the dye laser

A dye laser with a SPPCM has a number of useful features. Because the phase conjugator both spectrally narrows and scans the laser, there is no need for the complicated synchronization of the tuning wedges and etalons found in conventional dye lasers. The SPPCM also allows a spatially clean output mode, even with optical distortion in the laser resonator cavity. Although the 1 Hz frequency shift of the SPPCM explained the self-scanning of the dye laser, the physical origin of this frequency shift itself was unknown. Consequently, we initiated a series of experiments to determine the physical origin of the frequency shift observed in four-wave mixing in photorefractive $BaTiO_3$, as discussed in the next section.

B. Frequency shift in four-wave mixing in $BaTiO_3$

a) In order to understand the physical origin of the ~ 1 Hz frequency shift imparted to an optical beam by a SPPCM, we performed calculations and experiments on four-wave mixing in photorefractive $BaTiO_3$. The calculations revealed that, under some conditions, the phase-conjugate signal will be enhanced if the photorefractive grating is allowed to translate with a small velocity inside the $BaTiO_3$ crystal. This moving grating will Doppler-shift the incident beams and cause a small frequency shift in the phase-conjugate beam.

We verified our theoretical predictions by performing four-wave mixing experiments in which the writing beams were deliberately shifted from each other by a small frequency $\delta\omega$, causing the resulting photorefractive grating to translate in the $BaTiO_3$ crystal. We observed that the four-wave mixing efficiency was enhanced for two values of frequency shift $\delta\omega$, symmetrically placed around $\delta\omega=0$, as predicted by our theory. The optimum frequency shift scaled inversely with the optical intensity of the incident beams, as shown in Fig. 4. These results, which explain the self-scanning of the dye laser described above, are discussed in more detail in publication #2.

b) Similar frequency shifts will occur if a $BaTiO_3$ crystal is used in a ring resonator cavity. These shifts are deleterious for the operation of a ring laser gyroscope that uses two-wave mixing in $BaTiO_3$. Recent calculations and experiments have shown that the frequency of the light in the resonator cavity will depend critically on the cavity length, not because of the usual cavity mode condition, but because the phase delay in traversing the crystal depends very sensitively on the frequency difference $\delta\omega$ between the pump and the resonator beam.

c) We also studied a particularly interesting optical resonator formed by **two** $BaTiO_3$ *crystals as separate SPPCM's. One argon laser beam was split into two, and each beam* was directed into a separate SPPCM. As expected, the phase-conjugate output beam from each of the *SPPCM's was slightly shifted by a few Hz from the frequency of the* input beam, and the two phase-conjugate beams were slightly shifted in frequency from each other. However, when the two SPPCM's were placed near each other (~40 cm) on the optical table, a beam of light would spontaneously spring up between the two crystals! This self-generated optical beam would cause the output frequencies of the two SPPCM's to lock together in frequency. However, although the two SPPCM's were frequency locked, they were both emitting phase-conjugate beams that were frequency-shifted (together) from the frequency of the incident beam. These results are explained by analyzing the resonator condition on the beam between the two SPPCMS, and showing that this condition is identical to the condition for time reversal of an optical wave, as discussed in publication #3.

C. Pulsed lasers using a SPPCM

a) We completed preliminary experiments to determine whether a SPPCM would be useful for injection locking a high-gain pulsed laser. In these experiments a beam from a continuous-wave argon laser was directed into a SPPCM, and the phase-conjugate signal appeared within a few seconds. The SPPCM was then blocked, and the spatial mode of the laser was altered by changing its discharge current. It was found that, when the laser again illuminated the SPPCM, the instantaneous phase-conjugate reflectivity had decreased, due to the change in the mode of the incident laser beam. Further results are discussed in publication #4.

The above result implies that, for a SPPCM to be used in an optical resonator, any changes in the mode of the incident beam will have to occur slowly compared to the response time of the SPPCM. This has implications for the operation of a SPPCM in a pulsed laser system. For example, in the injection-locked dye laser shown in Fig. 5, the SPPCM is supposed to correct any optical distortion impressed on the optical wave by the laser amplifier. However, our experiments show that this scheme will only work if the SPPCM was previously illuminated by an optical wave having the <u>same</u> distortion. In practice, this can be accomplished by repeated operation of the pulsed laser: during the first few pulses the distorted wavefront will initiate self pumping of the phase conjugator, and subsequent pulses will then have their wavefronts restored (and further amplified) on the return pass through the distorter. However, this requires that the distortion in the laser amplifier by reproducible from shot to shot. We are currently performing experiments to demonstrate such a pulsed laser system.

REFEREED PUBLICATIONS (since April I, 1984)

1. Jack Feinberg and G.D. Bacher. "Self-scanning of a continuous-wave dye laser having a phase-conjugating resonator cavity," Optics Letters, **9**, 420 (1984).

2. Kenneth R. MacDonald and Jack Feinberg. "Enhanced four-wave mixing using frequency-shifted optical waves in photorefractive $BaTiO_3$," submitted April 1, 1985 to Physical Review Letters.

3. M.D. Ewbank, P. Yeh, M. Khoshnevisan, and Jack Feinberg. "Time reversal by an interferometer with coupled phase-conjugate reflectors," to be published in Optics Letters, June (1985).

4. F.C. Jahoda, P.G. Weber, and Jack Feinberg. "Optical feedback, wavelength response, and interference effects of self-pumped phase conjugation in $BaTiO_3$," Optics Letters **9**, 362 (1984).

PROFESSIONAL PERSONNEL

1. Jack Feinberg - Assistant Professor (Physics)
2. Kenneth R. MacDonald - Research Assistant (Physics)
3. Stephen P. Ducharme - Research Assistant (Physics)
4. Daniel Mahgerefteh - Research Assistant (Physics)
5. G. David Bacher - Undergraduate Research Assistant (Aerospace Engineering)

INTERACTIONS

We have had numerous interactions with Los Alamos National Laboratories on the applications of phase conjugation to plasma diagnostics; with Oak Ridge National Laboratories on the growth of photorefractive crystals; with Professor Leslie E. Cross at Penn State University on the characterization of photorefractive crystals; and with Honeywell Corporation and the Rockwell Science Center on the applications of phase-conjugation for position and rotation sensing. In addition, there have been collaborations and discussions with faculty here at USC in the material sciences laboratory, the electrical engineering laboratories, and the center for Laser Studies. A number of seminars and informal talks have also been presented at Universities and industrial research laboratories.

PATENTS

U.S. Patent #4,500,855 issued on February 19, 1985, to Jack Feinberg, "PHASE CONJUGATION USING INTERNAL REFLECTION."

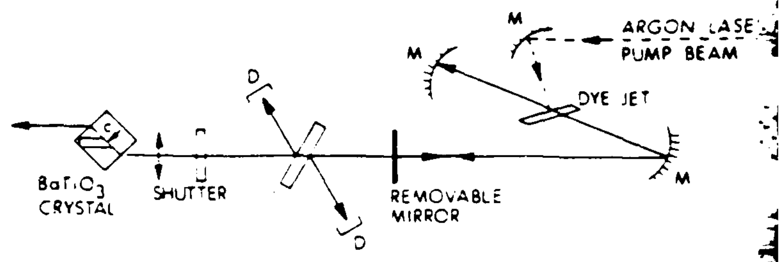


Fig. 1. A self-scanning dye laser with two curved mirrors and a $BaTiO_3$ crystal as the phase-conjugating front reflecto The removable mirror is needed to initiate lasing but can b removed once the phase conjugator has turned on. The detectors D monitor the power, reflected off a glass (wedged) fla of the optical beams going into and out of the $BaTiO_3$ crysta The light is polarized in the plane of the figure.

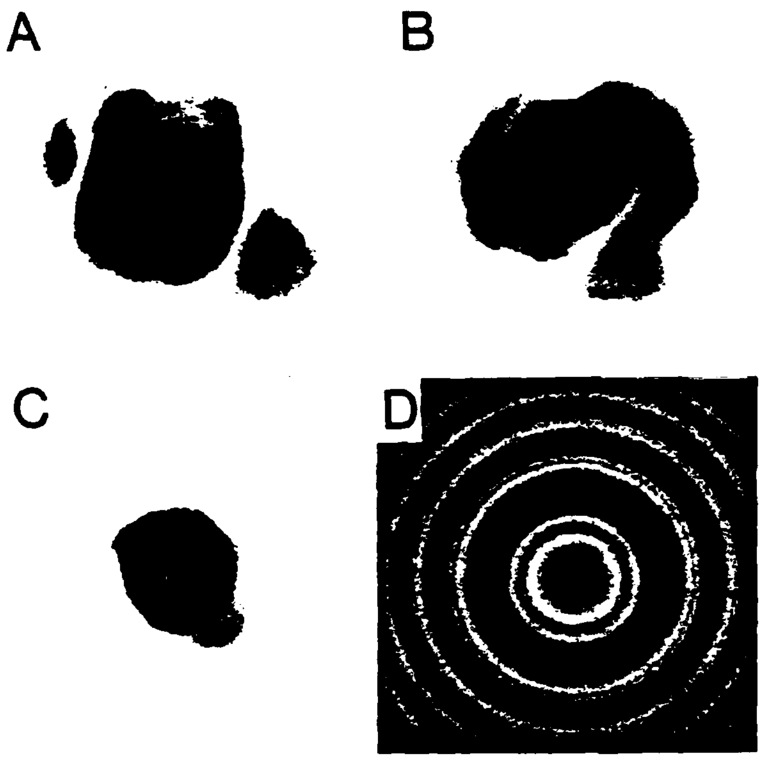


Fig. 2. Far-field spatial-mode patterns of the cw dye laser. The beam incident upon the $BaTiO_3$ phase conjugator is split off by the glass flat shown in Fig. 1 and photographed on a distant screen. The argon laser was deliberately misfocused on the dye jet so that high-order modes could oscillate: A, with the removable plane mirror in place, but before the phase conjugator has turned on; B, with the plane mirror *and* the phase conjugator; C, with the phase conjugator alone. D, Fabry–Perot pattern (free spectral range = 0.25 cm^{-1} = 7.5 GHz) of the dye laser operating with the phase conjugator alone. The spectral mode is a doublet separated by ~1.5 GHz.

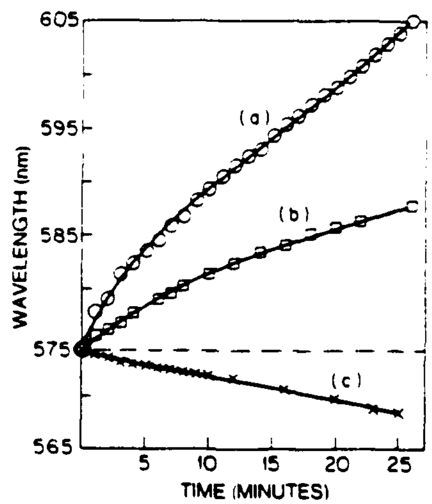


Fig. 3. Self-scanning of a cw dye laser having only a self-pumped phase conjugator as the front reflector. (a) Rapid scan toward the red. The optical table was lightly vibrated by a fish-tank motor during this scan. (b) Same as (a), but without deliberate table vibration. (c) Scan toward the blue. Blue scans were unaffected by table vibration.

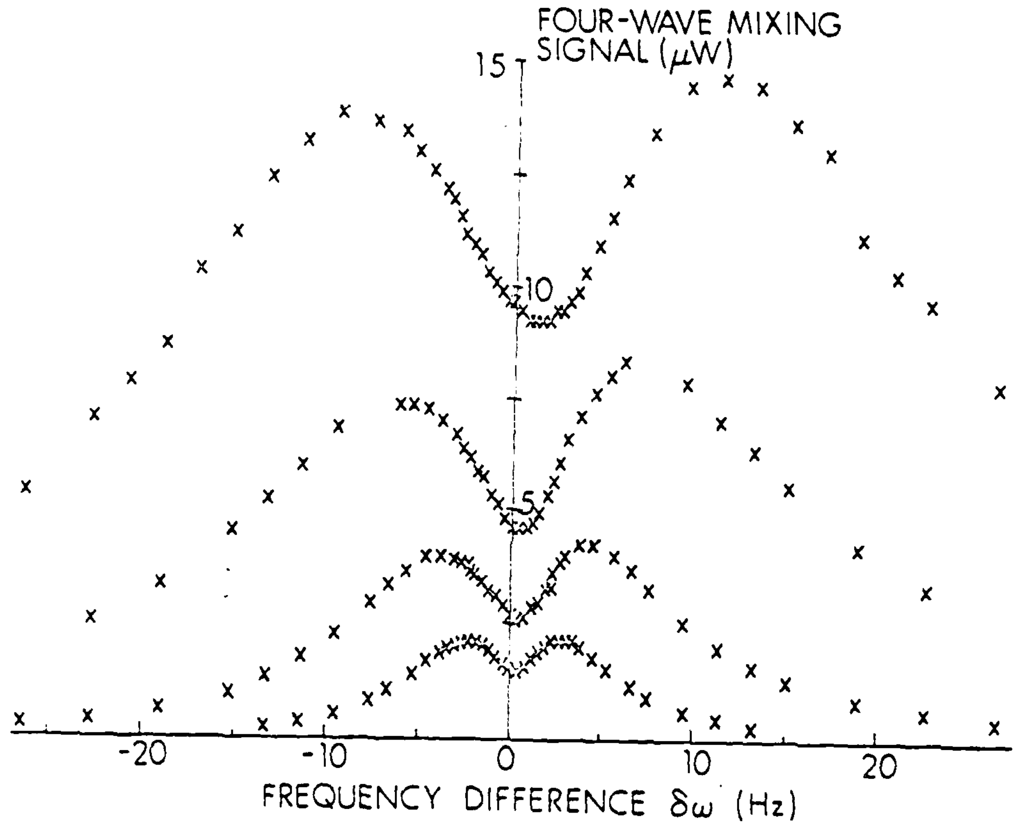


Fig. 4. Experimental four-wave mixing signal versus the frequency shift $\delta\omega$ between the two writing beams, for four different values of the total optical intensity. Note the two pronounced peaks for non-zero frequency shifts

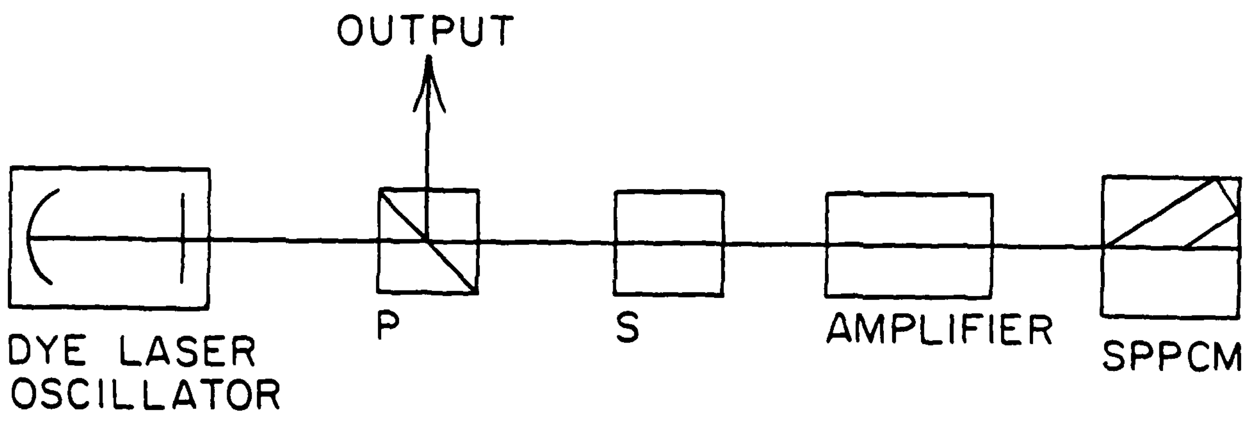


Fig. 5. An injection-locked dye laser that uses a self-pumped phase conjugating mirror (SPPCM). The output beam is coupled out by a polarization switch.

EFFICIENT MAPPING OF COMPUTATIONAL ALGORITHMS INTO VLSI STRUCTURES

Work Unit IE4-1

Dan I. Moldovan and George Bekey

1 September 1982 through 31 March 1985

RESEARCH OBJECTIVES

The overall goal of this project was to develop techniques for detecting parallelism in computational algorithms and mapping them into VLSI systolic arrays. In particular we considered algorithms with nested loop, which are frequently used in engineering applications such as signal processing, automatic control, robotics and others. Parallel processing of such algorithms, for the purpose of increasing the computational speed, required first transformation of algorithms from sequential forms to parallel forms suitable for VLSI architectures. Then, it was possible to develop a methodology for mapping algorithms into VLSI systolic arrays, and furthermore to perform tradeoffs between various design parameters.

STATUS OF RESEARCH EFFORT

1 Progress/Status

1.1 Summary

The research performed under the JSEP contract since this project started in September 1982, has focused on the mapping of numerical algorithms with nested loops on VLSI processing arrays. We developed new techniques to detect parallelism. For this purpose a new algorithm model was introduced as a five tuple (index set, set of dependences, set of computations, set of inputs and set of outputs). The parallelism analysis is based on the study of data dependencies. Conditions were given to detect non-interdependent computations. After the detection of parallelism in an algorithm, new execution orderings were derived to exploit this parallelism. By introducing the notion of τ-equivalent algorithms a mathematical framework was provided in which algorithm transformations were studied. Algorithm transformation techniques were introduced The purpose of these transformations is to modify the algorithm data dependencies such that the new algorithm can be processed on mesh-connected array processors Necessary and sufficient conditions for the existence of valid transformations were found for algorithms with constant data dependencies. A generalized technique for partitioning and mapping algorithms into systolic arrays was developed. Algorithm partitioning is essential when the size of a computational problem is larger than the size of the VLSI array intended for that problem. The approach used for partitioning algorithms was also based on the idea of algorithm transformation. We divide the algorithm index set into bands and map these bands into processor space. The partitioning is done with some hyperplanes such that the side effects are minimized

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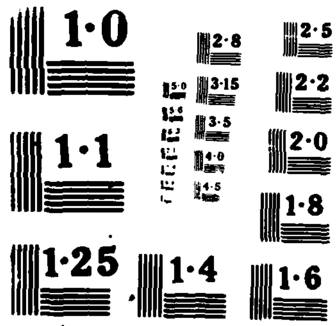


NATIONAL BUREAU
MICROCOPY RESOLU

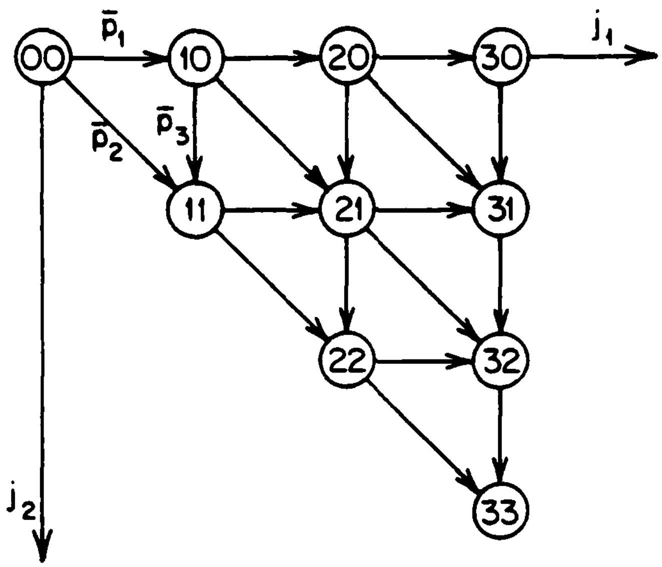


Figure 1: A triangular array with three interconnections

The structural details of the cells and the timing is derived from algorithms which are mapped into such arrays. For simplicity, we consider that all cells are identical. If an algorithm requires an array with several different types of cells, then the model can be easily modified by including another tuple describing the functions of each cell in index set J^{n-1}.

1.3 Algorithm Model

In this research we consider the class of algorithms with nested loops. In order to partition and to map algorithms into VLSI array processors it is convenient to define an algorithm model. The important information about an algorithm which we want to include in the model is the algorithm index set, the computations performed at each index point, the data dependencies which ultimately dictate the algorithm communication requirements and the algorithm input and output variables. In what follows, when we refer to an algebraic structure and its carrier, we will use the same symbol. Also, we use the fact that a mapping can be viewed as a set of ordered pairs with distinct first elements.

Definition 2: An algorithm A over an algebraic structure S and a set of predicates (or booleans) Q is a 5-tuple $A = (J^n, C, D, X, Y)$ where

J^n is a finite index set of A, $J^n \subset I^n$;

C is the set of computations of A, i.e., a mapping of J^n into the set of all total operations on $S \cup \Omega$ involving the operators of the algebra S;

X is the set of input variables of A;

D is the set of dependencies, i.e. a relation from Z^n to a set of all pairs (v,j) where $j \in J^n$ and $v \in X$ or v is a variable generated by some operation $(c,\bar{j}^*) \in C$ written $v \leftarrow c(\bar{j}^*)$.

Y is the set of output variables of A, i.e., a set of distinct variables on $S \cup \Omega$ such that if $y \in Y$ then $y \in X$ or $y \leftarrow c(\bar{j}^*)$ for some $(c,\bar{j}^*) \in C$

There are three types of dependencies in D:

1. input dependencies; $(\bar{d}, v, \bar{j})$ is an input dependence if $v \in X$ and v is an operand of C(j); by definition d = 0.
2. self dependence; $(\bar{d}, v, \bar{j})$ is a self dependence if $v \leftarrow C(\bar{j})$; by definition $\bar{d} = 0$.
3. internal dependence; $(\bar{d}, v, \bar{j})$ is an internal dependence if v is an operand of C(j) generated by $C(\bar{j}^*)$, $\bar{j}^* \in J^n$; by definition $\bar{d} = \bar{j} - \bar{j}^*$.

It is convenient to represent dependencies D as a matrix $D = [D^0 \;\; D^I]$ where D^0 is a submatrix of D containing all input and self dependencies, and D^I is the matrix of internal dependencies. Every column of D is the first element of the triple $(\bar{d}, v, \bar{j}) \in D$ and is labeled d_{vj}. If dependencies are valid almost in every point of the index set of the algorithm, the labels of the columns of D need not be shown. Also, for practical purposes self dependencies can be ignored.

Consider the algorithm:

```
        for j0 = 1 to N
            for j1 = 1 to N
                for j2 = 1 to N
S1:             a(j0,j1,j2) = a(j0-1,j1+1,j2)*b(j0-1,j1,j2+1)

S2:             b(j0,j1,j2) = b(j0-1,j1-1,j2+2)+b(j0,j1-3,j2+2)

                end j2
            end j1
        end j0                                                    (4)
```

The model for this algorithm is found using definition 2. The index set is $\{J^3 = (j_0, j_1, j_2,\ 1 \leq j_0 \leq N,\ 1 \leq j_1 \leq N,\ 1 \leq j_2 \leq N\}$. The set of computations C is $\{C\ (j_0, j_1, j_2) : a(j_0, j_1, j_2) = a(j_0-1, j_1+1, j_2) * b(j_0-1, j_1, j_2+1),\ b(j_0, j_1, j_2) = b(j_0-1, j_1-1, j_2+2) + b(j_0, j_1-3, j_2+2)\}$. In this example, at every point in the index space a multiplication and an addition are performed. Between the variables generated at different index points, there are some dependencies which actually dictate the *algorithm communication requirements*. For example $a(4,5,6) = a(3,6,6) * b(3,5,7)$. These dependencies can be described as difference vectors of index points where a variable is used and where that variable was generated. Four dependence vectors exist.

$\bar{d}_1 = (1,-1,0)^t$ for pair $<a(j_0, j_1, j_2,\ a(j_0-1, j_1+1, j_2)>$

$\bar{d}_2 = (1,-0,-1)^t$ for pair $<b(j_0, j_1, j_2,\ b(j_0-1, j_1, j_2+1)>$

$\bar{d}_3 = (1,1,-2)^t$ for pair $<b(j_0, j_1, j_2,\ b(j_0-1, j_1-1, j_2+2)>$

$\bar{d}_4 = (0,3,-2)^t$ for pair $<b(j_0, j_1, j_2,\ b(j_0, j_1-3, j_2+2)>$

With these dependencies we form a matrix D (the order of columns is not important).

$$D = [\bar{d}_1 \bar{d}_2 \bar{d}_3 \bar{d}_4] = \begin{array}{c} \begin{bmatrix} 1 & 1 & 1 & 0 \\ -1 & 0 & 1 & 3 \\ 0 & -1 & -2 & -2 \end{bmatrix} \\ \begin{matrix} a & b & b & b \end{matrix} \end{array} \qquad (5)$$

For this algorithm, all four dependence vectors exist in almost every point of the index set; d_1 is associated with variable a and the rest with variable b. Notice that the input dependencies were ignored here for the purpose of simplicity. The set of input variables X and the set of output variables Y are easily identified using indices and are ignored here.

The algorithm model from definition 2 is only a static model in the sense that it does not indicate an *execution ordering* on the index set. Notice that the index points in program (4) for example, are ordered in lexicographical order. This is an artificial ordering and can be modified for the purpose of parallelism extraction. Next, we define an execution ordering which must be associated to the algorithm model from definition 2 in order to guarantee the correctness of computation.

<u>Definition 3</u>: The execution of an algorithm $A = (J^n, C, D, X, Y)$ is described by

(i) the specification of a partial ordering $\underline{>}$ on J^n (called execution ordering) such that for all $(d, v, j) \in D^l$ we have $d > 0$ (i.e., d larger than zero in the sense of $>$);

(ii) the execution rule: until all_computations in C have been performed, execute all $C(\bar{j}^0) \in C$ such that all $C(j) \in C$, $j \neq j^0$ and $\bar{j}^0 > j$ have terminated

In this paper we use the ordering larger than zero $>$ in lexicographical sense. Thus, if $\bar{d} = j - j^* > \underline{0}$ it means that computations indexed by j must be performed before those indexed by j^*. One immediate application of the algorithm model presented here is to study the question of algorithm equivalency. Often, we desire to change the features of an algorithm while preserving its equivalence in computations. Two algorithms A and B are equivalent, written $A \equiv B$, if they map any set of input variables into the same set of output variables. The next definition introduces a stronger equivalence criterion than this input-output equivalence.

Definition 4: Two algorithms $A = (J_a{}^n, C_a, D_a, X_a, Y_a)$ and $B = (J^n{}_b, C_b, D_b, X_b, Y_b)$, are said to be τ-equivalent if and only if:

(i) algorithm B is input-output equivalent to A; $A \equiv B$

(ii) index set of B is the transformed index set of A;$J^n{}_b = T(J^n{}_a)$, where T is a bijection function

(iii) to any operation of A it corresponds an identical operation in B and vice-versa

(iv) dependencies of B are the transformed dependencies of A, written $D_b = T(D_a)$

We are interested in transformed algorithms for which the ordering imposed by the first coordinate of the index set is an execution ordering. The motivation is that if only one coordinate of the index set preserves the correctness of computation by maintaining an execution ordering, then the rest of index coordinates can be selected by the algorithm designer to meet some VLSI communication requirements. In what follows, we will indicate how a transformation T can be selected such that the transformed algorithm can be mapped into a VLSI array and moreover, how an algorithm can be partitioned.

1.4 MAPPING ALGORITHMS INTO VLSI ARRAYS

A transformation which transforms an algorithm A into an algorithm B is defined as

$$T = \begin{bmatrix} \Pi \\ S \end{bmatrix} \tag{6}$$

where mapping Π and S are defined as $\Pi : J_a^n \rightarrow J_b^1$ and $S : J_a^n \rightarrow J_b^{n-1}$. In this paper, we consider only linear transformations T, i.e., $T \in Z^{n \times n}$. Thus, algorithm dependencies D_a are transformed into $D_b = TD_a$. The mapping Π is selected such that the transformed data dependence matrix D_b has positive entries in the first row. This ensures a valid execution ordering, and can be written as:

$$\Pi \bar{d}_i > 0 \qquad \text{for any } \bar{d}_i \in D_a \tag{7}$$

The immediate gain of this setting is that we can regard correctly the first coordinate of the transformed algorithm as the time coordinate. Thus, a computation indexed by $j_a \in$

J_a^n in the original algorithm will be processed at the time $\Pi\ \bar{j}_a = j_b^0$. Moreover, the total running time of the new algorithm is usually $t = \max j_b^0 - \min j_b^0 + 1$. This assumes a unitary time increment. In general, the time increment may not be unitary; but it is given by the smallest transformed dependence, i.e. minimum Πd_i. Thus, the execution time of the parallel algorithm is the number of hyperplanes Π sweeping the index space J^n and is given by ratio

$$t = \frac{\max \Pi(\bar{j}^1 - \bar{j}^2)+1}{\min \Pi d_i}$$

for any $\bar{j}^1, \bar{j}^2 \in J_a^n$ and $\bar{d}_i \in D_a$. (8)

Transformation S can than be selected such that the transformed dependencies map into a VLSI array modeled as $(J_b^{n-1} P)$. This can be written as:

$$S \cdot D_a = P \cdot K \tag{9}$$

where matrix K indicates the utilization of primitive interconnections in matrix P. Matrix $K = [k_{ji}]$ is such that

$$k_{ji} > 0 \tag{10}$$

$$\sum_j k_{ji} < \Pi\ \bar{d}_i \tag{11}$$

Expression (10) simply requires that all elements of K matrix are non-negative and (11) requires that communication of data associated with dependence d_i must be done using some primitives p_j exactly $\sum_j k_{ji}$ times. It is possible that some interconnection primitives will not be used. These correspond to rows of matrix K with zero elements. Most often, many transformations S can be found, and each transformation leads to a different array. This flexibility apparently complicates matters, but in fact, it gives the designer the possibility to choose between a large number of arrays with different characteristics. As we will see, tradeoffs between time and space characteristics are possible.

Example: Consider again the high-level language algorithm (4); we want to map this algorithm into a VLSI array modeled by expressions (2) using the transformation technique outlined above.

We search for a transformation

$$T = \begin{matrix} \Pi \\ S \end{matrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix}$$

First, mapping Π is selected such that relation (7) is satisfied, and the parallel execution time given in (8) is minimized. Then mapping S is selected by solving for S the systems of diophantine equations (9). All possible utilization matrices K which satisfy relations (10) and (11) need to be considered. Since we do not have a technique which leads directly to the "optimal" transformation (mostly because we lack a performance index), we developed a software package which finds many valid transformations and then we pick the one which best fits our needs.

A large number of transformations $\Pi = [t_{11}\ t_{12}\ t_{13}]$ can be found to satisfy the relation $\Pi\, d_i > 0$. We have arbitrarily limited their number by imposing the condition.

$$\sum_{i=1}^{3} |t_{1i}| \leq 3$$

The program has found the following Π's:

$$\Pi_1 = [2 \quad 1 \quad 0]$$

$$\Pi_2 = [1 \quad 0 \ -1]$$

$$\Pi_3 = [1 \quad 0 \ -2]$$

$$\Pi_4 = [0 \ -1 \ -2]$$

$$\Pi_5 = [2 \quad 0 \ -1]$$

We found that Π_2 minimizes the parallel execution time given by expression (8). Thus,

$$\Pi = \Pi_2 = (1 \ 0 \ -1)$$

and

$$\Pi \ D = [\ 1\ 2\ 3\ 2\ ] \tag{12}$$

It can be seen from figure 2 that the index set for this example is a cube and Π contains the coefficients of a family of parallel planes. The first index points visited by Π are (1,X,N) and the last are (N,X,1), where X is don't care. The number of parallel planes Π necessary to cover all index points in the cube represents the parallel processing time and is found from (8)

$$t = \frac{(N-1) - (1-N)+1}{1} = 2N - 1 \tag{13}$$

All index points $\bar{j}$ which are contained in one plane Π at a given moment can be processed in parallel because there are no dependencies between them and they obey equation $\Pi \bullet j$ = constant.

The next step is to find transformation S. The program found twelve S matrices which satisfy conditions (9), (10) and (11). These S matrices, together with Π selected above form twelve distinct valid transformations of the form $T = \begin{bmatrix}\Pi \\ S\end{bmatrix}$ We list them here in order to discuss their merits.

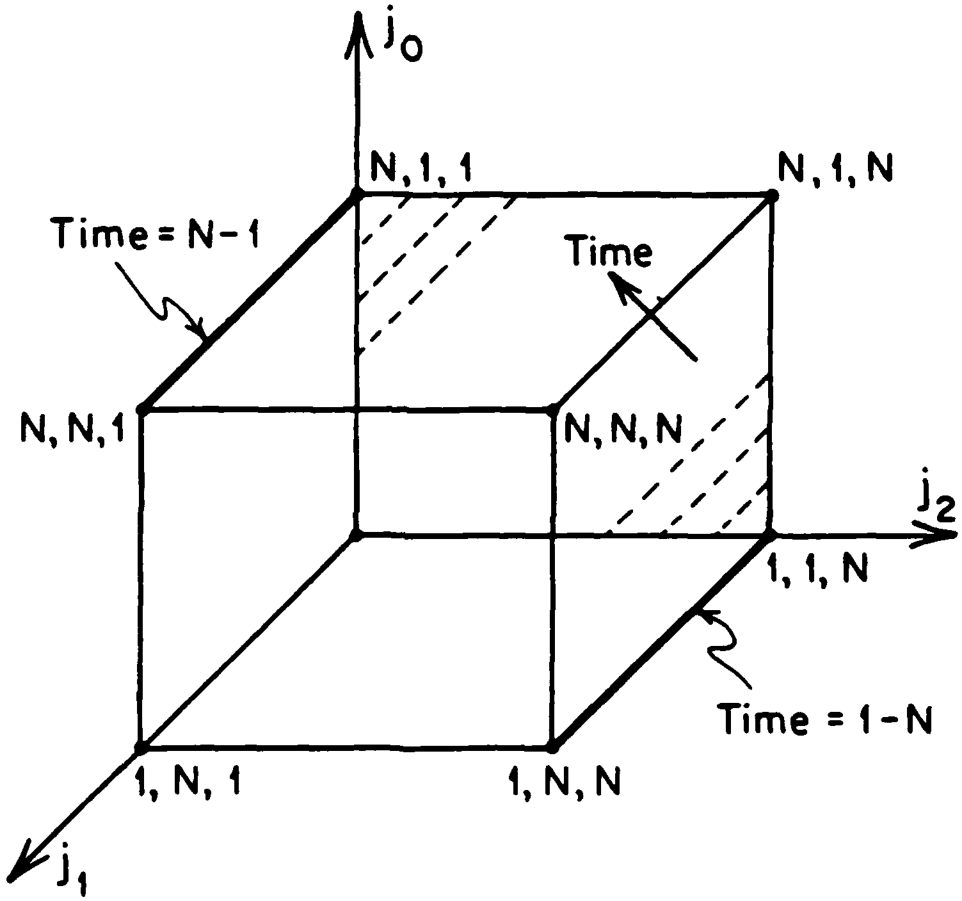


Figure 2: Index set and hyperplane Π

$$T_1 = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 1 & 1 \\ 2 & 2 & 3 \end{bmatrix} \quad T_2 = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & 2 \\ 2 & 2 & 3 \end{bmatrix} \quad T_3 = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 1 & 1 \\ 1 & 1 & 2 \end{bmatrix}$$

$$T_4 = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & 2 \\ 1 & 0 & 0 \end{bmatrix} \quad T_5 = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & 3 \\ 1 & 0 & 0 \end{bmatrix} \quad T_6 = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & 3 \\ 2 & 1 & 1 \end{bmatrix}$$

$$T_7 = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 1 & 1 \\ 1 & 0 & 0 \end{bmatrix} \quad T_8 = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & 2 \\ 1 & 0 & 0 \end{bmatrix} \quad T_9 = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 1 & 1 \\ 2 & 1 & 1 \end{bmatrix}$$

$$T_{10} = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & 2 \\ 3 & 2 & 2 \end{bmatrix} \quad T_{11} = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 0 & 0 \\ 2 & 1 & 1 \end{bmatrix} \quad T_{12} = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 0 & 0 \\ 3 & 2 & 2 \end{bmatrix}$$

For example, one possible utilization matrix K which satisfies (10) and (11) is:

$$K = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (14)$$

This utilization matrix leads to transformation T_7 because it satisfies equation $S_7D = PK$ and the transformation is $T_7 = \begin{bmatrix} \Pi \\ S_7 \end{bmatrix}$

Once a transformation is selected then the new parallel algorithm results immediately from definition 4. The original index set J_a is transformed into new index set J_b such that to every point $j_a \in J_a$ it corresponds a new index point $j_b = (j_b^0, j_b^1, j_b^2)^t \in J_b$

$$\bar{j}_b = T_7 \, \bar{j}_a \qquad (15)$$

Because of the way in which transformation was selected, the first coordinate j_b^0 indicates the time at which the computation indexed by corresponding j_a is computed and $(j_b^1, (j_b^2)$

indicates the processor when that computation is performed. For instance we want to know at what time and in what processor a computation indexed by (3,4,1) in algorithm (4) is performed. The transformed coordinates are $(j_b^0, j_b^1, j_b^2)^t = T(3,4,1)^t = (2,8,3)$ meaning that computation time is 2 and processor cell is (8,3). Notice that the transformed coordinates are offset by some initial values.

Next, we want to construct the entire array in which T_7 maps algorithm 4. The interprocessor communications result from the transformed data dependencies

$$D_b = T_7 D_a = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 1 & 1 \\ 1 & 0 & 0 \end{bmatrix} * \begin{array}{c} \begin{bmatrix} 1 & 1 & 1 & 0 \\ -1 & 0 & 1 & 3 \\ 0 & -1 & -2 & -2 \end{bmatrix} \\ \begin{array}{cccc} a & b & b & b \end{array} \end{array} = \begin{array}{c} \begin{bmatrix} 1 & 2 & 3 & 2 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \\ \begin{array}{cccc} a & b & b & b \end{array} \end{array}$$

The first row of the transformed dependencies is ΠD = [1 2 3 2]. Each element indicates the number of time units allowed for its respective variable to travel from the processor where it is generated to processor where is used. Only two interconnection primitives are required, namely $(0\ 1)^t$ and $(1\ 0)^t$. The VLSI array is shown in figure 3. This corresponds to the fact that the utilization matrix K is very sparse; and in general the simpler the K matrix is (less nonzero elements and unity if possible) the simpler the VLSI array we need. Notice that in this example we started with a rather complex VLSI network model as a tentative solution, but due to the transformation technique presented here we found that a much simpler array is actually needed. The computer program ADVIS detects which is the transformation leading to the simplest array and for this example T_7 was the "best".

Following the same procedure, the reader can verify that any other of the twelve transformations found above leads to a more complex VLSI structure.

All cells in the array shown in figure 3 are identical, and the structure of a cell results from the computations required by algorithm (4) as well as the timing and data communication dictated by transformed data dependencies (16). The structure of the cell is shown in figure 4. It consists of an adder, multiplier and delay elements. Notice that variable a which has a dependence d_1 moves from a cell to the next via a vertical channel with direction $(0\ 1)^t$, and it has one unit time delay in each cell (in the multiplier.) Variable b is used for three operands, and each one has its own direction and timing according to the dependence obtained from the algorithm. For example variable b which is the second multiplication operand has dependence d_2 and to this dependence it corresponds a vertical channel $(0\ 1)^t$ and a delay of two time units between the moment when variable is generated and used; that is one unit delay must be inserted in front of the multiplier for this operand. The operands for the adder are traced in the same way. It is important to remark here that tradeoffs are possible between the time and space characteristics of the VLSI array. By simply selecting another transformation, it results in different parallel execution time, different array dimensions, different delays inside processing cells and different interprocessing connections. The program we developed

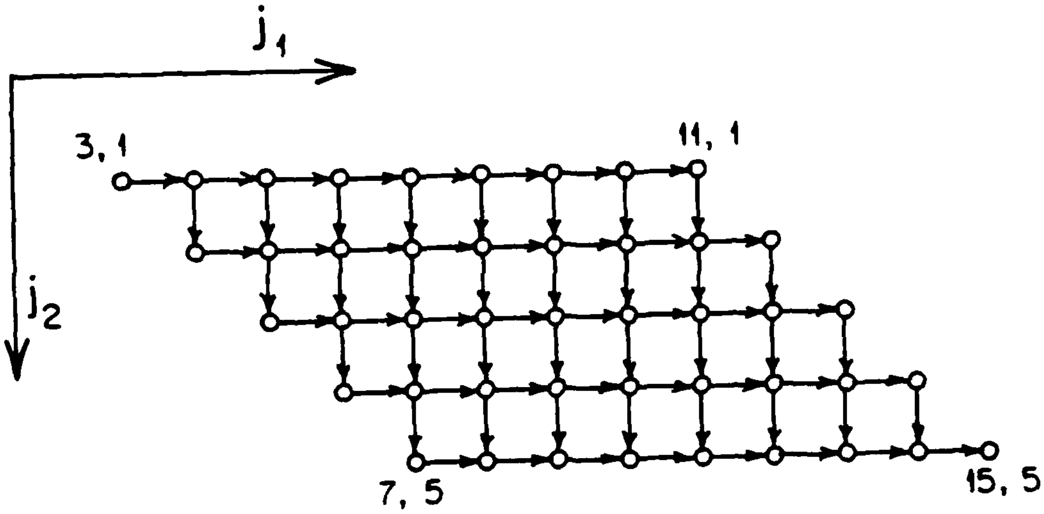


Figure 3: VLSI array

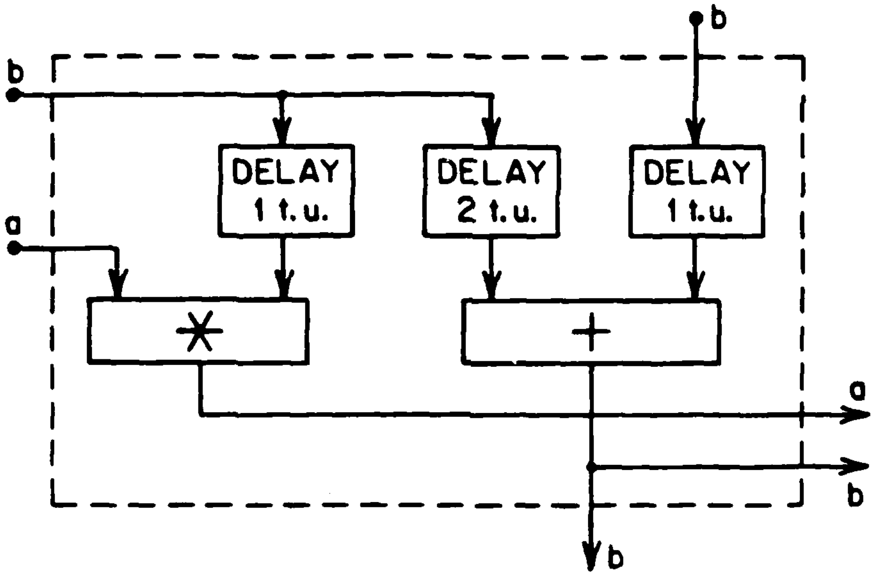


Figure 4: Cell structure

allows us to search for all possible transformations and to select the one which leads to the "optimum" array (in some selected sense.)

So far we assume arbitrarily large arrays. Next, we consider the case when the size of the array is fixed. As we will see, the mapping for this case can be done by the same transformation if an additional constant is satisfied.

Next we consider the partitioning of algorithm (4) which has a tridimensional index space. The problem we address now is to map this algorithm into a rectangular VLSI array of fixed size $M = m_1 \times m_2$. For simplicity we select $m_1 = m_2 = m = 3$. In the previous section an algorithm transformation T was found for this algorithm. This transformation can be used for partitioning the algorithm if we enhance its interpretation. Consider that the second and the third row of T are some partitioning hyperplanes. We define them

$$\Pi_{p1} = (1\ 1\ 1)$$

$$\Pi_{p2} = (1\ 0\ 0)$$

These two hyperplanes partition the index space into bands as shown in figure 5

The timing hyperplanes sweeps all the index points in each band before another band is processed. The band boundary must satisfy the equations

$$\begin{aligned} &\Pi_{p1}\ \bar{j} \bmod 3 = 0 \\ &\Pi_{p2}\ j \bmod 3 = 0 \end{aligned} \qquad (17)$$

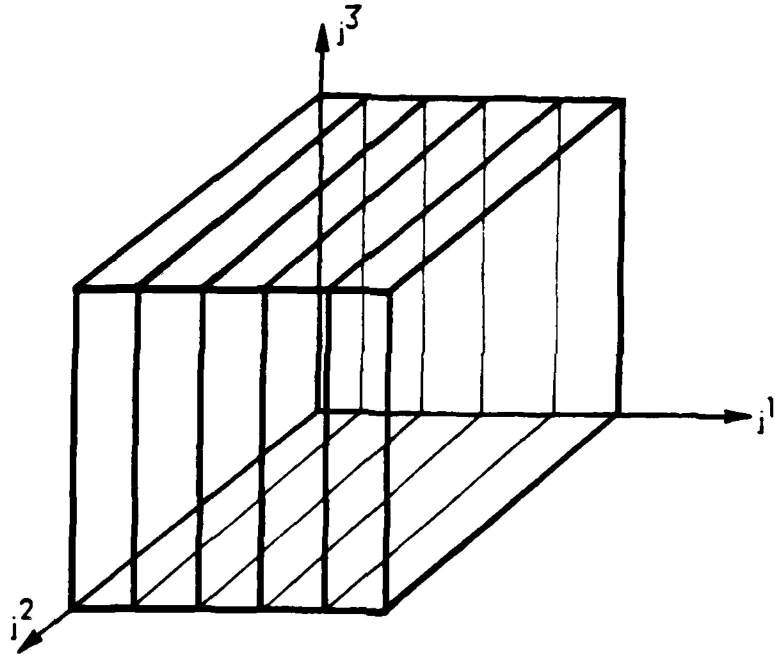
All index points inside one band are processed before another band is considered. Inside each band the index points are swept by a family of parallel time hyperplanes $\Pi = [1\ 0\ -1]$. Conditions (17) assume that at any given moment no more than m x m index points are processed. For each index point $j \in J_a$ we want to determine the band to which it belongs and in what processor it is mapped. In figure 6 it is shown the original index set for algorithm (4) and the allocation of indices to bands and to processors.

Based on this printout we constructed the array shown in figure 7 which illustrates how the nonpartitioned virtual array is partitioned into bands. Notice how the bands from figure 8 where allocated to the VLSI array.

In order to distinguish between different bands let's assign two coordinates (b_1, b_2) to each band, coordinate b_1 indicates the band number along the direction of Π_{p1} and b_2 indicates the band number along the direction Π_{p2} Thus an index point j will be assigned to a band

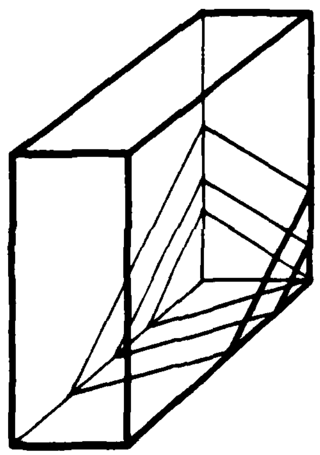
$$b_1 = \left\lceil \frac{\Pi_{p1}\ \bar{j}}{3} \right\rceil$$

$$b_2 = \left\lceil \frac{\Pi_{p2}\ \bar{j}}{3} \right\rceil \qquad (18)$$



The partitioning of the index set by hyperplane $\Pi_{p_2} = (1\ 0\ 0)$

(a)



The partitioning of one slice from Fig (a) by hyperplane $\Pi_{p_1} = (1\,1\,1)$
The space between planes forms a band

(b)

Figure 5: Partitioned index space

	band number		original index point			partitioned			transformed no partitioning	
	b_1	b_2	j^0	j^1	j^2	$\hat{j}^0$	$\hat{j}^1$	$\hat{j}^2$	$\hat{j}_1$	$\hat{j}_2$
	1	0	1	1	1	1	0	1	3	1
	1	0	1	1	3	1	2	1	5	1
	1	0	1	2	2	2	2	1	5	1
	1	0	1	1	2	2	1	1	4	1
B_{10}	1	0	2	1	2	3	2	2	5	2
	1	0	1	3	1	3	2	1	5	1
	1	0	1	2	1	3	1	1	4	1
	1	0	2	2	1	4	2	2	5	2
	1	0	2	1	1	4	1	2	4	2
B_{11}	1	1	3	1	1	5	2	0	5	3
	2	0	1	2	5	6	2	1	8	1
	2	0	1	1	5	6	1	1	7	1
	2	0	2	1	5	7	2	2	8	2
	2	0	1	3	4	7	2	1	8	1
	2	0	1	2	4	7	1	1	7	1
	2	0	1	1	4	7	0	1	6	1
	2	0	2	2	4	6	2	2	6	2
	2	0	2	1	4	8	1	2	7	2
	2	0	1	4	3	8	2	1	6	1
	2	0	1	3	3	8	1	1	7	1
	2	0	1	2	3	8	0	1	6	1
	2	0	2	3	3	9	2	2	8	2
	2	0	2	2	3	9	1	2	7	2
	2	0	2	1	3	9	0	2	6	2
	2	0	1	5	2	9	2	1	8	1
B_{20}	2	0	1	4	2	9	1	1	7	1
	2	0	1	3	2	9	0	1	6	1
	2	0	2	4	2	10	2	2	8	2
	2	0	2	3	2	10	1	2	7	2
	2	0	2	2	2	10	0	2	6	2
	2	0	1	5	1	10	1	1	7	1
	2	0	1	4	1	10	0	1	6	1
	2	0	2	5	1	11	2	2	8	2
	2	0	2	4	1	11	1	2	7	2
	2	0	2	3	1	11	0	2	6	2
	2	1	3	1	4	12	2	0	[illegible]	3
	2	1	3	2	3	13	2	0	8	3
	2	1	3	1	3	13	1	0	7	3
	2	1	4	1	3	14	2	1	8	4
	2	1	3	3	2	14	2	0	8	3
	2	1	3	2	2	14	1	0	7	3
	2	1	3	1	2	14	0	0	6	3
B_{21}	2	1	4	2	2	15	2	1	8	4
	2	1	4	1	2	15	1	1	7	4
	2	1	3	4	1	15	2	0	8	3
	2	1	3	3	1	15	1	0	7	3
	2	1	3	2	1	15	0	0	6	3
	2	1	5	1	2	16	2	2	8	5
	2	1	4	3	1	16	2	1	8	4
	2	1	4	2	1	16	1	1	7	4
	2	1	4	1	1	16	0	1	6	4
	2	1	5	2	1	17	2	2	8	5
	2	1	5	1	1	17	1	2	7	5
	3	0	1	5	5	18	2	1	11	1
	3	0	1	4	5	18	1	1	10	1
	3	0	1	3	5	18	0	1	9	1
B_{30}	3	0	2	4	5	19	2	2	11	2
	3	0	2	3	5	19	1	2	10	2
	3	0	2	2	5	19	0	2	9	2
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	3	1	4	2	5	24	2	1	11	4
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	3	1	3	4	4	24	2	0	11	3
	3	1	3	3	4	24	1	0	10	3
	3	1	3	2	4	24	0	0	9	3
	3	1	5	1	5	25	2	2	11	5
	3	1	4	3	4	25	2	1	11	4
	3	1	4	2	4	25	1	1	10	4
	3	1	4	1	4	25	0	1	9	4
B_{31}	3	1	3	5	3	25	2	0	11	3
	3	1	3	4	3	25	1	0	10	3
	3	1	3	3	3	25	0	0	9	3
	3	1	5	2	4	26	2	2	11	5
	3	1	5	1	4	26	1	2	10	5
	3	1	4	4	3	26	2	1	11	4
	3	1	4	3	3	26	1	1	10	4
	3	1	4	2	3	26	0	1	9	4
	3	1	3	5	2	26	1	0	10	3
	3	1	3	4	2	26	0	0	9	3
	3	1	5	3	3	27	2	2	11	5
	3	1	5	2	3	27	1	2	10	5
	3	1	5	1	3	27	0	2	9	5
	3	1	4	5	2	27	2	1	11	4
	3	1	4	4	2	27	1	1	10	4
	3	1	4	3	2	27	0	1	9	4
	3	1	3	5	1	27	0	0	9	3
	3	1	5	4	2	28	2	2	11	5
	3	1	5	3	2	28	1	2	10	5
	3	1	5	2	2	28	0	2	9	5
	3	1	4	5	1	28	1	1	10	4
	3	1	4	4	1	28	0	1	9	4
	3	1	5	5	1	29	2	2	11	5
	3	1	5	4	1	29	1	2	10	5
	3	1	5	3	1	29	0	2	9	5
B_{40}	4	0	2	5	5	30	0	2	12	2
	4	1	3	5	5	31	1	0	13	3
	4	1	3	4	5	31	0	0	12	3
	4	1	4	5	5	32	2	1	14	4
	4	1	4	4	5	32	1	1	13	4
	4	1	4	3	5	32	0	1	12	4
	4	1	3	5	4	32	0	0	12	3
B_{41}	4	1	5	4	5	33	2	2	14	5
	4	1	5	3	5	33	1	2	13	5
	4	1	5	2	5	33	0	2	12	5
	4	1	4	5	4	33	1	1	13	4
	4	1	4	4	4	33	0	1	12	4
	4	1	5	5	4	34	2	2	14	5
	4	1	5	4	4	34	1	2	13	5
	4	1	5	3	4	34	0	2	12	5
	4	1	4	5	[illegible]	34	0	1	12	4
	4	1	5	5	[illegible]	[illegible]	1	2	13	5
	4	1	5	4	[illegible]	[illegible]	0	2	12	5
	4	1	[illegible]	[illegible]	2	[illegible]	[illegible]	2	[illegible]	5
B_{51}	5	1	5	5	5	37	0	2	15	5

Figure 6: Partitioning and mapping the index set into a 3x3 VLSI array

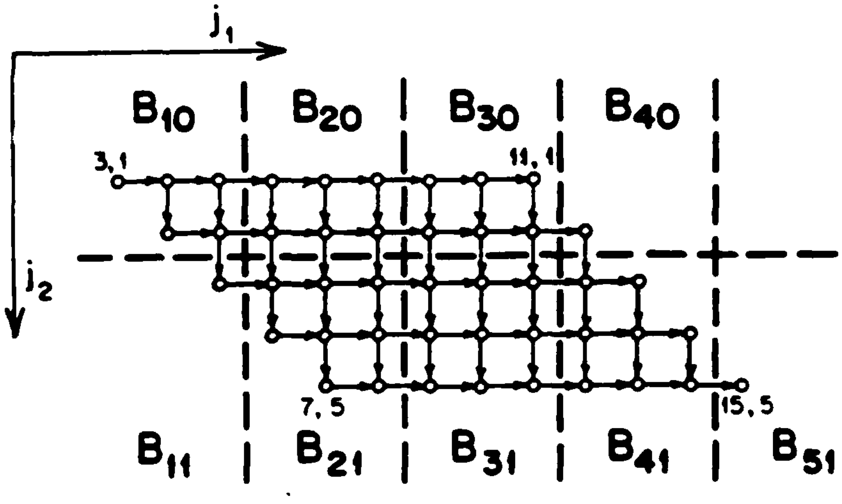

Figure 7: Mapping of partitioning bands into the array

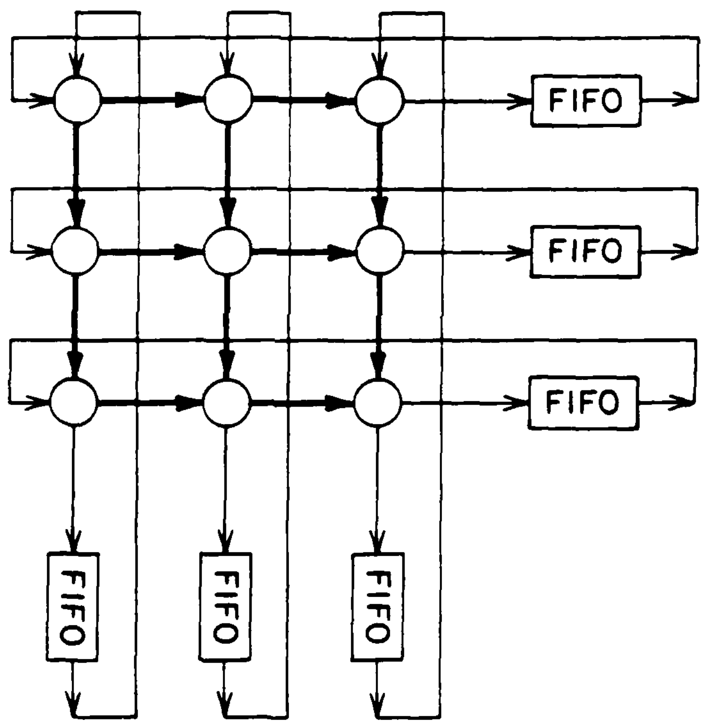

Figure 8: A 3x3 array with FIFO queue registers for partitioning

The allocation of computations to processors is done according with formulas

$$\hat{j}_b^1 = \Pi_{p1}\,\bar{j} \bmod 3$$
$$\hat{j}_b^2 = \Pi_{p2}\,\bar{j} \bmod 3 \qquad (19)$$

For instance index point (3,4,1) is allocated to processor (2,0) in band (2,1).

It remains now to determine the exact processing time for each index point $\bar{j}$. The processing time for the partitioned case depends on the order in which the bands are executed. many execution ordering are possible. In our example, we choose to execute the bands in order B_{00}, B_{10}, .. . Then the time coordinate j^0 from figure 6 was determined by first executing all points inside one band according with the ordering imposed by Π and then moving to the next band. The dependencies are mapped by the transformation such that only local communications are required inside each band. The communications between computations adjacent bands are performed via external FIFO queue registers, which temporarily store variables.

PUBLICATIONS

The following papers were written as a result of this JSEP sponsored research:

1. D.I. Moldovan and M.F.M. Tenorio, "Parallel Processing of Production Systems," submitted to *IEEE Trans. on PAMI*, in February 1985.

2. T.C. Lin and D.I. Moldovan, "Tradeoffs in Mapping Algorithms into Array Processors," *Proc. of 1985 International Conference on Parallel Processing*, also submitted to *IEEE Trans. on Computers*, in April 1985.

3. V. Dixit and D.I. Moldovan, "SNAP and Its Applications to Image Understanding," submitted to *IEEE Trans. on PAMI*, in January 1985.

4. Dan I. Moldovan and T.C. Lin, "Mapping of Algorithm Permutations into Mesh-Connected SIMD Computers", submitted to *IEEE Transactions on Computers*, in December 1984.

5. D.I. Moldovan and J.A.B. Fortes, "Partitioning of Algorithms for Fixed Size VLSI Architectures," revised version submitted to *IEEE Transactions on Computers*, in October 1984.

6. J.A.B. Fortes and D.I. Moldovan, "Data Broadcasting in Linearly Scheduled Array Processors," Proc. of the 11th Annual International Symposium on Computer Architecture, June 1984, (also submitted to *IEEE Trans. on Computers*, revised version submitted in March 1985).

7. Dan I. Moldovan and Yu-Wen Tung, "Bit Serial Techniques in VLSI Parallel Processing," *International Journal of Mini and Microcomputers*, accepted, scheduled to appear in Fall 1985.

8. J.A.B. Fortes and D.I. Moldovan, "Parallelism Detection and Algorithm Transformation Techniques Useful for VLSI Architecture Design," *Journal of Parallel and Distributed Computing*, scheduled August 1985

9. D.I. Moldovan and G.F. Lee, "Fast Solution of Differential Equations on Microprocessors," *Journal of Microcomputer Applications*, Vol. 3, No. 2, 1984.

10. D.I. Moldovan, "On the Design of Algorithms for VLSI Systems," *Proc. of the IEEE*, Jan. 1983.

11. D.I. Moldovan, "On the Analysis and Synthesis of VLSI Algorithms," *IEEE Trans. on Computers*, Nov. 1982.

12. F Tenorio and D.I. Moldovan, "Mapping Production Systems into Multiprocessors," *Proc. 1985 International Conf. on Parallel Processing*, August 1985.

13. H. Barad and D.I. Moldovan, "A Systems Approach to Mapping a Karhunen-Loeve Transform into a Systolic Array," to *Proc. 1985 International Conference on Parallel Processing*, August 1985.

14. Edward T. Chow and Dan I Moldovan, "Prime Factor DFT Parallel Processor using Wafer Scale Integration," to appear in *Proc. 7th Symposium on Computer Arithmetic*, June 1985.

15. Dan I. Moldovan, "Time and Space Tradeoffs in the Design of Systolic Arrays," to appear in *Proc. 1985 International Symposium on Circuits and Systems*, (invited paper for a special session on parallel processing).

16. D.I. Moldovan et. al, "Mapping an Arbitrarily Large QR Algorithm into a Fixed size VLSI Array," *Proc. of the 1984 International Conference on Parallel Processing*, Aug. 1984.

17. D.I. Moldovan, "Synchronization Mechanisms for Multimicroprocessor Systems," *Proc. International Symposium on Mini and Microcomputers*, pp. 172-179, Las Vegas, Dec. 1984.

18. D.I. Moldovan, "ADVIS: A Software Package for the Design of Systolic Arrays," *Proc. of the IEEE International Conf. on Computer Design: VLSI in Computers*, Oct. 1984.

19. D.I. Moldovan, "Partitioned QR Algorithm for Systolic Arrays," *Proc. of the Workshop on VLSI and Signal Processing*, Los Angeles, Nov 1984

20. D.I. Moldovan and Y.W. Tung, "Bit Serial Techniques in VLSI Parallel Processing," *Proc. of the 23rd International Symposium on Mini and Microcomputers*, San Antonio, Texas, Dec 1983.

21. D.I. Moldovan, "A VLSI Algorithm and Architecture for Linear Recurrence Systems," *Proc. of the 23rd International Symposium on Mini and Microcomputers*, San Antonio, Texas, Dec 1983.

22. D.I. Moldovan and A. Varma, "Design of Algorithmically Specialized VLSI Devices," *Proc. of the IEEE International Conf. on Computer Design: VLSI in Computers*, Oct 1983

Book Chapters

1. "Towards a Computerized Optimal Design of VLSI Systolic Arrays," Advances in CAD for VLSI, vol 6. Design Methodology, North-Holland Publishing Company, S. Goto (Japan) editor, to appear in September 1985.

2. "On the Design of Algorithms for VLSI Systems," reprinted in Interconnection Networks for Parallel and Distributed Processing, IEEE Computer Society, Aug. 1984, C.L. Wu, and T.Y. Feng, editors.

PROFESSIONAL PERSONNEL

Principal Investigator:	Dr. Dan Moldovan
Graduate Students:	J.A.B. Fortes
	T.C. Lin
	Y.W. Tung
	A. Varma

INTERACTIONS

All papers listed in the previous section published in conference proceedings have been presented in the respective conference. In summary, these research results have been presented at the following conferences:

1. International Conference on Parallel Processing, August 1984 and 1985.

2. International Symposium on Computer Architecture, June 1984.

3. Symposium on Computer Arithmetic, June 1985.

4. International Symposium on Mini and Microcomputers, Dec. 1983, Dec 1984.

5. IEEE International Conference on Computer Design: VLSI in computers, Oct. 1984, and Nov. 1983.

6. Workshop on VLSI and Signal Processing, Nov. 1984

Ph.D. Thesis Completed

Jose Fortes was partly supported by this JSEP project. He completed his Ph.D. thesis in December 1983 and is currently on the faculty of Purdue University. The title of his thesis is: "Algorithm Transformations for Parallel Processing and VLSI Architecture Design."

Dr. Moldovan was a consultant for Hughes Research Labs on Technical problems related to this research.

BASIC RESEARCH IN C³ DISTRIBUTED DATABASES

Work Unit IE4-2

VICTOR O.K. LI

REPORT PERIOD: 1 April 1981 - 31 March 1985

RESEARCH OBJECTIVES

The development of a distributed database performance model which will enable one to compare the performance of concurrency control, query processing and file allocation algorithms, and to propose better, more efficient algorithms.

STATUS OF RESEARCH EFFORT

A distributed database (DDB) consists of copies of datafiles (often redundant) distributed on a network of computers. Numerous concurrency control algorithms have been proposed. (See Rothnie and Goodman [22] and Bernstein and Goodman [1] for excellent surveys.) However, little has been done to compare the performance of the different proposals. Bernstein and Goodman [1] analyzed the performance of principal concurrency control methods in qualitative terms. The analysis considers four cost factors: communication overhead, local processing overhead, transaction restarts, and transaction blocking. The assumption is that the dominant cost component is the number of messages transmitted. Thus, location of database sites, topology of network, and *queueing effects are ignored.* A quantitative comparison is described in Garcia-Molina [9]. He compared several variants of the centralized locking algorithm with Thomas' Distributed Voting Algorithm [23] and the Ring Algorithm of Ellis [7]. The major assumptions are (1) a fully redundant database and (2) the transmission delay between each pair of sites is constant. The first assumption requires that the whole database be fully replicated at each node. This is necessary because Garcia-Molina did not want to model query processing, which would have been necessary for a general (not fully redundant) database. The second assumption means that the topology, message volume and queueing effects of the communication subnetwork will be ignored. More recently, some Ph.D. theses which study the performance issues in distributed databases have been published. Ries [21] considered four locking-based algorithms and evaluated them by simulation. Analyses were performed for both a centralized and a distributed database. Dantas [6] developed simulation and analytic models of Thomas' Distributed Voting Algorithm. His approach is similar to that of Garcia-Molina's and he made similar assumptions, i.e., a fully redundant database and constant transmission delay between sites. Cheng [5] studied the performance of a centralized locking algorithm, and a distributed timestamp ordering algorithm. The system model and the parameters are similar to those used in [9]. Ozsu [19] proposed to model a distributed database by a Petri Net model(see, for example, [20]). To analyze this Petri Network model, however, Ozsu argued that the only viable way would be by simulation. This research report will describe the development of a five-component modeling framework of distributed databases. In the next section, we shall describe this modeling framework. Our research results will be summarized in section 2.

1 THE MODELING FRAMEWORK

The basic architecture of a DDB consists of database sites connected to each other via a communication subnetwork. At each database site is a computer running one or both of the software modules: Transaction Module (TM) and Data Module (DM). The TM supervises user interactions with the database while the DM manages the data at each site.

We propose a 5-component performance model (see Figure 1):

1. Input Data Collection - Given a DDB managed on an arbitrary communication network, we have to determine the following:

   a. topology of network, i.e., the connectivity and capacity of links between computer sites

   b. locations of all copies of files

   c. arrival rates of different transactions

2. Transaction Processing Model - Consider transaction T arriving at database site i and processed by TM_a. Suppose T reads data items X,Y and writes items U,V, where U=f(X,Y), V=g(X,Y). This transaction will be performed in two steps.

   a. Query Processing- TM_a will devise a query processing strategy to access X and Y and to produce the values of U and V at database site i. To model concurrency control algorithms accurately, we have to model query processing. Previous researchers got around the query processing problem by assuming a fully redundant database, in which case all queries will be addressed to the local site and incur zero communication delay. We do not believe this is a realistic assumption, and we are confronted with the problem of modeling query processing. This was done in Li [15].

   b. Write - The new values of U and V will be written into the database. This is accomplished by the two-phase commit algorithm (See Bernstein and Goodman [1] and Gray [10].):

      i. Pre-commits - TM_a sends new values of U and V to all DM's having copies of U and V, respectively. The DM's then copy the new values to secure storage and acknowledge receipt.

      ii. Commits - After all DM's have acknowledged, TM_a sends commit messages, requesting the DM's to copy the new values of U and V from secure storage into the database.

   Using our Transaction Processing Model, we can determine, for each particular transaction, the file transfers, read and write messages that are necessary.

This information, together with the transaction arrival rates and the file locations, lets us generate estimates for f_{ij}, the arrival rate of messages at site i destined for site j.

3. Communication Subnetwork Model - Using the message flow requirements between database sites, f_{ij}, and the network topology, as input to a routing strategy, such as Gallager's Minimum Delay Routing Strategy [8], we can determine the total traffic on each channel of the network. We can then find the average service time at each channel.

4. Conflict Model - Given transaction generation rates and the intersite transmission delay obtained in steps 2 and 3, respectively, we can calculate the probability of transaction restarts, transaction blockings, and the associated delay.

5. Performance Measures - We emphasize the performance measure most visible to the users, namely response time, which is the sum of the local processing delay at the database sites, the transmission delay and the delay due to conflicts.

Our performance model is a modeling framework which allows us to consider the interactions between the different components. For example, the conflict model lets us estimate the number of transaction restarts. The restarts lead to increased loads on the Communication Subnetwork. Based on the new loads, the Communication Subnetwork Model determines the revised transmission delay between sites. In addition, since each component is totally self-contained, each user has the flexibility of designing his own models for each of the five components, to match a particular database system.

2. RESEARCH RESULTS

During the past four years the following specific research tasks were pursued:

1. Determine Message Delay in a Computer Network with Unreliable Components

2. Develop Conflict Models for Concurrency Control Algorithms

3. Develop New Query Processing Strategies Amenable to Distributed Implementation

2.1 Determine Message Delay in a Computer Network with Unreliable Components

Existing research results in computer network delay assume that the communication channels and computers are failsafe. This is unrealistic. Attempts to analyze the impact of failures on network delay have always been doomed by the "state space explosion" problem --- in a network with n unreliable components, there are 2^n different ways for the network to fail. Even for moderate-sized network, it is impossible to analyze all the possible states.

We have developed an efficient technique for analyzing the performance of communication networks with unreliable components. This technique does not suffer from the "state-space explosion" problem since we avoid the traditional state-space enumeration technique. An algorithm, called ORDER, has been perfected to generate the most probable states of the network. The computational complexity of this algorithm is polynomial in the number of unreliable components. Accurate estimates of network performance, i.e. connectivity, survivability, message delay, etc., can be obtained using our approach. More detailed discussion of our approach, and illustrative examples, can be found in [18]. We are presently attempting to modify our algorithm to accommodate network with multimode failures.

A related research problem which we have studied is the reliability analysis of networks with dependent failures. Most existing research results in network reliability assume that the component failures are independent. In reality, network component failures are dependent. We have developed a Colored Network Model and an Event Network Model which allow us to model and analyze the reliability of network with dependent failures. Our research results are documented in Lam and Li [13], [14].

2.2 Develop Conflict Models for Concurrency Control Algorithms

While the literature abounds in concurrency control methods, most of them are variations of two basic approaches, namely, timestamp-ordering and two-phase locking. We have developed conflict models for both of these approaches. Our research results for timestamp-ordering algorithms are documented in [17] and a conflict model for the Two-Phase Locking Algorithm is documented in [16]. We found that waiting is built inherently into timestamp ordering algorithms, while the performance of locking algorithms depends on the particular deadlock solution technique used.

2.3 Develop New Query Processing Strategies Amenable to Distributed Computation

We have developed an effective approach to distributed query processing problems. It has been shown that a general query processing problem is N-P hard ([11], [12]). Therefore, to obtain the optimal solution is computationally expensive. The alternative would then be the development of heuristics. We have proved several important optimality properties of query processing programs [2]. These optimality properties let us check whether a given query program (generated by a heuristic, for example) is optimal. We have also developed improvement algorithms which allow us to improve a given program if it is not optimal ([3]). In addition, we have been able to identify a subset of all possible solutions for solving queries which dominate (i.e. cost less than) the rest of the solutions [4]. In other words, we can restrict our search for the optimal solution to this dominating subset. An algorithm has been developed for generating this dominating group of solutions and hence finding the optimal solution for star queries [4]. We are presently trying to estimate the size of this dominating subset, and to extend the algorithm to more general queries.

PUBLICATIONS

JOURNAL PUBLICATIONS

1 Li, V.O.K., and Silvester, J.A., "Performance Analysis of Networks with Unreliable Components," IEEE Trans. on Communications, Vol. COM-32, No. 10, Oct. 1984, pp. 1105-1110.

2. Chen, A.L.P. and Li, V.O.K, 'Improvement Algorithms for Semi-Join Query Processing Programs in Distributed Databases." IEEE Trans. on Computers, Vol. C-33, No. 11, Nov. 1984, pp. 959-967.

3 Li, V.O.K., "Performance Models of Timestamp Ordering Synchronization Algorithms in Distributed Databases,' submitted for publication.

4. Chen, A.L.P and Li, V.O.K., 'Optimizing Star Queries in Distributed Databases," submitted for publication.

CONFERENCE PUBLICATIONS AND REPORTS

* Li, V.O.K., "Message Delay in a Communication Network with Unreliable Components,' Proc. 5th MIT/ONR Workshop on Distributed Information and Decision Systems, Naval Postgraduate School, Monterey, California, August 1982.

* Li, V.O.K., and Silvester, J.A., "An Approach for Studying the Performance of Networks with Unreliable Components," Technical Report No. CSI-83-02-01, Communication Sciences Institute, University of Southern California, 1983.

* Li, V.O.K., and Silvester, J.A., "Performance Analysis of Networks with Unreliable Components", Proc. IEEE International Conference on Communications, Boston, Mass., June 1983.

* Lam, Y.F. and Li, V.O.K., "On Reliability Calculations of Networks with Dependent Failures," Proc. IEEE Global Communications Conference, San Diego, CA, December 1983.

* Lam, Y.F. and Li, V.O.K., "A Network with Generalized Cost Function and Some Applications," Proc. IEEE Intl. Conf. on Comp., Systems and Signal Processing, Bangalore, India, December 1984, pp. 241-243.

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* Li, V.O.K., "End-To-End Delay in a Message-Switched Network," Technical Report No. CSI-83-02-02, Communication Sciences Institute, University of Southern California, 1983.

* Chen, A.L.P. and Li, V.O.K., 'Properties of Optimal Semi-Join Programs for Distributed Query Processing," Proc. IEEE Seventh International Computer Software and Applications Conference, Chicago, Illinois, November 1983.

* Chen, A.L.P. and Li, V.O.K., "Deriving Optimal Semi-Join Programs for Distributed Query Processing," Proc. IEEE INFOCOM, San Francisco, California, April 1984.

* Chen, A.L.P. and Li, V.O.K., "Improving Semi-Join Programs for Distributed Query Processing," Proc. IEEE Eighth International Computer Software and Applications Conference, Chicago, Illinois, November 1984.

* Chen, A.L.P and Li, V.O.K., "Optimizing Star Queries in a Distributed Database System," Proc. Tenth International Conference on Very Large Data Bases, Singapore, August 1984.

* Chen, A.L.P and Li, V.O.K., "Performance Analysis of Distributed Query Optimization Algorithms," Proc. International Computer Symposium, Taipei, Taiwan, December, 1984.

* Li, V.O.K., "A New Approach to Query Processing in Distributed Databases", Proc. Mediterranean Electrotechnical Conference, Athens, Greece, May 1983.

* Li, V.O.K., "Conflict Models of Locking Algorithms in Distributed Databases," Proc. IEEE Sixth International Computer Software and Applications Conference, Chicago, Illinois, November 1982.

* Li, V.O.K., "Performance Models of Distributed Databases," Proc. IEEE National Telecommunication Conference, New Orleans, Louisiana, December 1981.

* Li, V.O.K., " Performance Models of Distributed Databases," Proc. 4th MIT/ONR Workshop on Distributed Information and Decision Systems, San Diego, California, June 1981.

PROFESSIONAL PERSONNEL

Principal Investigator - Victor O.K. Li

Research Assistants - Arbee L.P Chen, Chieh-Hsien Shu, Mohammad Tassoji, Yuen-Fung Lam.

Ph D. thesis completed:

Arbee L.P Chen, "Query Optimization in Distributed Database Systems," Ph.D. thesis, Department of Electrical Engineering, University of Southern California, December, 1984

Chieh-Hsien Shu, "Data Management in a Distributed Computer Network," Ph.D. thesis, Department of Electrical Engineering, University of Southern California, May, 1984.

INTERACTIONS

* Li, V.O.K., "Message Delay in a Communication Network with Unreliable Components," Proc. 5th MIT/ONR Workshop on Distributed Information and Decision Systems, Naval Postgraduate School, Monterey, California, August 1982.

* Li, V.O.K., and Silvester, J.A., "Performance Analysis of Networks with Unreliable Components", Proc. IEEE International Conference on Communications, Boston, Mass., June 1983.

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* Li, V.O.K., " Performance Models of Distributed Databases," Proc. 4th MIT/ONR Workshop on Distributed Information and Decision Systems, San Diego, California, June 1981.

DISCOVERIES/PATENTS

No patents have been applied for.

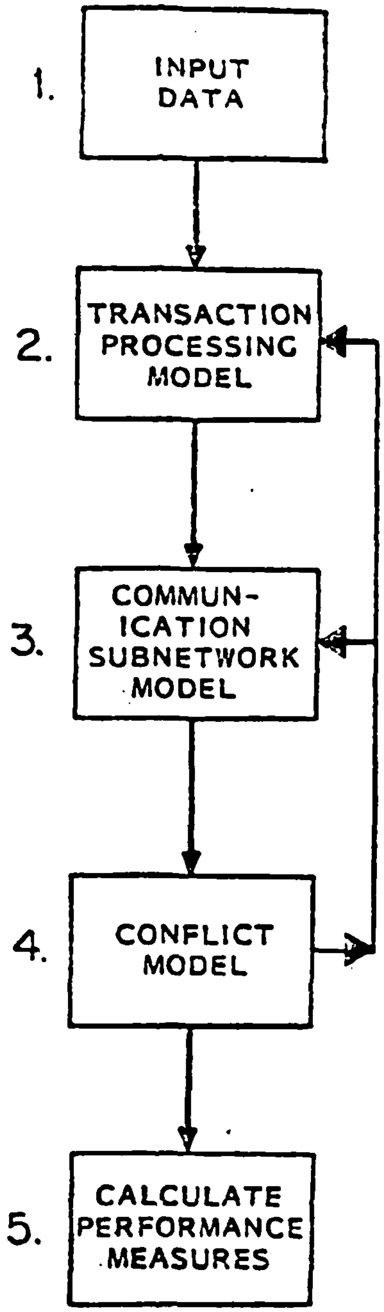

Figure 1: Five-Component Modeling Framework for Distributed Databases

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Processing of Images with Signal-Dependent Noise; Image Texture Analysis and Restoration Using Nonstationary Models

Work Unit IE4-3

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1 April 1981 - 31 March 1985

RESEARCH OBJECTIVES

To accurately model optical phenomena that lead to signal-dependent noise in images, including speckle effects from coherent illumination in synthetic aperture radar (SAR), sonar and acoustic imaging systems, holography and active infrared systems. To reduce the effects of this noise for imaging and pattern recognition applications by the use of advanced image restoration and fast filtering algorithms. Specific restoration techniques include Kalman filtering, local linear minimum mean-square error (LLMMSE) filters, maximum a posteriori (MAP) and maximum likelihood estimation. Nonstationary statistical image models are used to more accurately account for image structure. Various adaptive, recursive, and non recursive techniques are used to improve image restoration. An additional scientific objective is to improve image analysis and vision systems using new methods of texture analysis and texture segmentation. These techniques may involve: the use of spatially nonstationary (position-varying) models for image statistics; and the use of hierarchical structures containing texture features and other image information obtained over several levels of resolution (several window or scale sizes). Applications include image segmentation for vision and identification systems; image analysis systems for counting, sorting, sizing, etc.; and noise suppression and image sharpening as a preprocessing step for feature extraction, pattern recognition and machine vision.

STATUS OF RESEARCH EFFORT

In the fields of image processing and analysis, it is widely recognized that better results can be obtained when better models are available for degradations due to random noise and blurring. Also, it is widely recognized that images are themselves random processes with nonstationary statistics [1]. The recent trend has been to use this detailed information to improve image restoration, analysis, and segmentation.

In the field of image restoration, we have concentrated on signal-dependent noise models for the speckle that results from coherent imaging systems [2]-[9]. Such systems include synthetic aperture radar (SAR) on satellite and aircraft platforms, sonar and acoustic imaging systems; active infrared imaging systems; coherent optical information processing and holographic systems. Other examples of signal-dependent noise in imaging systems include Poisson noise occurring in photon-counting sensors in low light level imaging, astronomy, and nuclear delay imaging.

Effective imaging and image processing applications such as target classification and detection of scene variations in the presence of speckle depend strongly on accurate models for object statistics, background clutter, system noise and bandwidth. Our recent work has been on the statistical modeling of coherent imaging systems such as digital SAR in which full complex (real and imaginary) data is available [2]-[4]. We have developed accurate models for higher-order statistical properties of speckle, especially in digital coherent systems. Second-order statistics (e.g., covariance) have been found to be of fundamental importance. Furthermore, signal-dependent noise inherently implies non-stationary statistics in all cases except the relatively uninteresting case of a constant signal. We have recently concentrated on the modeling and processing of nonstationary signals. These approaches are very new and are just beginning to appear in the literature. We have also developed signal-dependent models for speckle image formation valid for intensity detection (no phase information present) and for complex detection (phase and magnitude information present) [5], [6]. Much past work on speckle suppression and restoration has assumed a multiplicative model valid only under a very restricted set of conditions.

Another part of this work has been directed at improving statistical models for image data. Conventional image models have assumed a constant mean and stationary covariance, with Gaussian statistics often assumed for computational simplicity. In recent work a nonstationary mean has been included to better describe the low-frequency gross features of the image [7]-[9]. A residual image containing the statistics of high frequency details is described in the covariance structure. This model takes the important step of recognizing that images are locally stationary, but globally nonstationary. In our recent work, these models have been extended to include nonstationary variance in addition to nonstationary mean. These models for signal-dependent image formation and nonstationary image statistics have been used with success in the new image restoration algorithms to be described.

A two-dimensional recursive image restoration filter has been developed for images degraded by blur and a class of uncorrelated, signal-dependent noise [5], [8]. Unlike conventional image restoration techniques, the filter does not require any a priori information about the original image and uses the nonstationary image model. All the parameters needed for the filter are estimated from the noisy image. The filter has a simple recursive structure, and is able to adapt itself to the nonstationary content of the image and to different types of signal-dependent noise.

A local linear minimum mean square error (LLMMSE) speckle reduction filter has been developed for intensity speckle images, where only the speckle intensity is observable. Unlike other existing approaches, this filter considers the second order statistics of speckle and also uses the nonstationary image model. The two-dimensional recursive implementation of this filter is also developed as a fast computation algorithm. In some applications, both the amplitude and phase of the speckle image are observable. In the past, the additional phase, the additional phase information has been ignored in designing the speckle reduction filter. A nonlinear maximum a priori (MAP) filter for complex amplitude speckle images has been developed. The MAP equations can be expressed in terms of the filtered estimate and filtered covariance matrix of a nonstationary two-dimensional recursive filter and a cubic equation. Thus the MAP estimate can be solved iteratively by using the cubic equation as a constraint to optimize the estimate at each iteration [8].

We have extended the ideas of nonstationary image and noise models to problems of image texture analysis, segmentation and boundary finding. As discussed previously, images are known to be highly nonstationary in both first-order and second-order statistics. Over a small spatial area (typically extending over a few pixels) these statistics can be considered stationary, but over a large area (comparable to the scale size of gross features and regions in an image) these statistics change. In a sense, the problem of segmenting images on the basis of brightness becomes a problem of identifying regions of homogeneous first-order statistics. The real problem comes in segmenting images and analyzing their structure on the basis of second-order statistical properties such as texture, edges, etc. In general, finding these statistics requires a great deal more computing and judicious choice of region shape and size over which data must be gathered. The regions must be chosen large enough to assure good statistical reliability of the data, yet small enough to avoid overlap into yet another region with different statistics.

One of the major problems with segmenting textured images is that the spatial window used to extract the texture features may overlap several different regions with different textures [10],[11]. In most pattern classification applications, it can be assumed that a feature point results from a single statistical model. However, when using operators in a local spatial window to generate features for texture classification, the operator will often overlap more than one texture and the resulting feature will be a mixture of several statistical models. The probability density of the feature point is then a mixture density [12] with the degree of the contribution from each class determined by the location of the operator in the image. This implies that the features are nonstationary even though the statistics of the individual textures are stationary. One reason that the presence of the mixture density can cause problems when doing the classification is that in many cases the mixture of two or more classes will result in features that are nearly identical to the features of a different legitimate class. If this happens, it will be impossible for the classifier to differentiate between points from the mixture density and the legitimate class. There does not appear to be any direct solution to this problem. The best that can be done is to recognize that the problem exists and to develop ways to minimize its impact.

An approach that has been tried with varying degrees of success involves using operators of different sizes. The size of an operator has a significant effect on the features generated for particular point in the image When a large spatial area operator is used to generate the features it is more likely that it will be overlapping more than one texture at any place in the image. This increases the probability of errors due to the mixture density. If we could be assured that the operator was only over a single texture then the features generated by it will generally be more accurate since more data is available for analysis. When a small spatial area operator is used over a single texture the resulting features will have a larger variance and resulting higher error rate than those from the larger operator However the smaller operator has the advantage that it is less likely to overlap multiple textures. If a texture mosaic is classified using a large averaging window, the large regions of homogeneous texture are classified accurately while erroneous non-existent textures appear between the boundaries of the regions due to the mixture of two sets of statistics within the window. If the same texture mosaic is classified with a small operator, evidence of the higher error rate can be seen in the interior of the larger regions, although the boundaries between regions are more accurate. This difference in the way the operators react in the image leads to a simple rule for classifying textures: when analyzing data away from boundaries between textures, use the larger operator, and when analyzing data near boundaries use the smaller operator. Unfortunately this rule cannot be implemented as stated since it is not known a priori where the boundaries between textures are located.

The different behavior of the multiple-size operators can be exploited in a hierarchical manner to achieve much the same effect. The basic concept here is to use the large operator classification unless there is reason to doubt its accuracy, in which case the small operator classification will be used. They key to this technique is developing a criterion for determining when the large operator classification is likely to be incorrect due to the mixture density problem Two techniques have been tried which allow a classification to be made only for image points which are not likely to be products of a mixture density.

The first and simplest method involves surrounding each mean with a hypersphere with a class dependent radius. If a feature point is within a hypersphere, it is classified to that class. If a feature point is not within any of the hyperspheres, it is left unclassified and will be classified using the smaller operator. Selecting the proper radius for each hypersphere is done prior to doing the classification. The radius is determined by two criteria: the hypersphere for a particular class should not encompass any points that would not be classified to that class by an unrestricted classification, and the hypersphere should not encompass any points which could be the generated by mixing two classes. The first rule implies that the hypersphere is completely within the Bayesian boundaries of the class region. The second rule ensures that any point in the feature space which coincides with an expected location of a point from a mixture of two classes is also outside the hypersphere. An advantage of this method is its simplicity in that the test may be done by comparing the distance to the mean to a single threshold. The major disadvantage is that is it is overly restrictive. Depending on circumstances, the hypersphere for a class could be very small and most of the points for the class could end up unclassified.

The second method involves using hyperplanes to reduce the size of the classification region for each class. The hyperplanes are selected in such a manner that the expected locations of mixture points lies outside the classification region. As with the hypersphere, the determination of the necessary hyperplanes for each class can be done prior to doing the classification. This method is less restrictive than the hypersphere method. The hypersphere method is essentially a omni-directional threshold around the mean which is applied to points which may or may not be closer to the mixture points than the mean. By using the hyperplanes we are assured that only points that are in the vicinity of the mixture points will be affected. A disadvantage is the higher amount of computations needed for each point classified. The suggested class for each point must first be determined and then a second classification test must be made determine if the point is within the hyperplanes region for that class

Both of these methods have worked at acceptable levels in preventing incorrect classifications when using the large operator features The advantage of using the multiple-size operators for generating features and the hierarchical classification method is that we are free to leave points unclassified after the first pass through the data if we have reason to believe that the second pass will do a more accurate classification.

A drawback of the two methods described previously for detecting mixture densities corresponding to texture boundaries is the lack of a theoretical basis. The selection of parameters (the radius of the hypersphere, the location of the hyperplanes) should be made to minimize the probability of error for that type of region. The theoretically correct way to separate a mean from mixture of other means is to use a Bayesian classifier to assign a class to either the single mean or the mixture. To do this, the probability density of the mixture must be known. We have worked on determining the density of the mixture of more than one class in an analytically useful way. Some initial results show that while the shape of the mixture density is a function of the densities of the classes contributing to the mixture, it is unlikely that a generalized closed-form solution can be found. It is known that the mixture does not have a Gaussian form, which would be desirable for ease of classification. It also appears that using the actual expression for the density in classification would be undesirable due to extreme computational costs. To avoid this problem, we have investigated computationally acceptable approximations to the mixture density. This approach appears feasible because a good approximation of the density is only needed in a limited area of the feature space between the mean and the mixture. Various types of approximations are being studied to examine the tradeoff between error rate and computational cost.

The work described is the first phase of the multiple-size operator texture segmentation study. The goal of the first phase is minimize the number of incorrect classifications while classifying as many points and possible. Once this is done, the second phase of the classification must be done to fill in the areas of the image which are not classified. This second phase uses data from the smaller operators and also from the results of the first classification phase. The major problems are how to use spatial information to improve accuracy and how to combine the results from the large operator and small operator classifications to take advantage of the differing strengths and weaknesses.

Segmentation of an image can be viewed as a classification with spatial constraints. When segmenting a textured image, it is a safe (and probably necessary) assumption that the textures will be present in cohesive regions of some minimum size as opposed to scattered and intermixed pixels. The likelihood that two pixels belong to the same class should be a function of the distance between them in the image. The classification techniques which were used with a single size operator did not use any spatial information. The classification decision for one pixel was not dependent on the decision made for any neighboring pixel. This is obviously different from the way that a human observer would classify textures. A human would probably rely greatly on the classification of the area surrounding the pixel in order to make the best possible one that should be implemented in any texture classification technique. If there is some evidence that a point belongs to class 1 but all the neighboring pixels in a surrounding region have been classified to class 2, then we should strongly consider classifying the pixel to class 2.

The use of available spatial information is one topic to be studied in the future. One possible approach is by measuring the "coherence" between a pixel and its neighbors. Because we face a multi-class problem, the measurement must examine the coherence between a pixel and its neighbors for each possible class assignment for the pixel in question. The resulting vector of coherence values represents a "coherence histogram" in which the value in each histogram bin indicates the coherence of the center pixel with the pixels around it under a different assumption for its class assignment. Due to the nature of the coherence histogram in that it contains information about the spatial distribution of the texture classes, it will be a major component in the final decision process. Area with a few highly coherent classes should be treated differently that areas with very low coherence in all classes. Proposed used of the coherence information is to use it for limiting the allowable classification choices for the small operator classifier. If a small number of classes have a high coherence then the unclassified pixel should be classified into one of those classes. If no class has a dominant coherence then any class should be considered for selection.

The final step in the segmentation process is to combine the previously developed information to select a final classification for the texture points. These source of information include:

* The classification choice using the large window operators.

* The coherence histogram giving spatial information about the surrounding area.

* The classification features from the small window operators.

The basic decision process can be stated as follows: If the pixel was classified with the large operator features, use that classification, otherwise classify using the small operators with the allowable class assignments determined by the spatial information from the coherence histogram. The key to implementing this process is in developing a method for interpreting the results of the coherence histogram measurement. Work is currently in progress to develop an acceptable decision rule which uses all the information listed above.

Even without the use of a complex decision rule, the desirability of using multiple resolution features has been demonstrated by using the results of the hypersphere method of restricting classification with the large window features, in combination with the small window operator classification results. A simple multiple resolution classifier can be implemented by using the following rule: use the result of the large window classification if a class was selected (feature point inside a hypersphere), otherwise use the result of the small window classification. The results of using this very simple rule have been compared with the classification results using a single size operator and indicate that the multiple size operator approach holds significant promise of improving the overall classification accuracy.

We are extending work on nonstationary statistics for image restoration by using a more sophisticated nonstationary boundary model that retains directionality as well as magnitude information. This requires the use of the segmentor described earlier or an edge detector that finds boundaries and splits boundary regions within a window into two parts, forming a directional nonstationary boundary. We are also experimenting with various averaging window sizes for the nonstationary statistics. Preliminary experiments show that the size of these windows and the exact method of computing the statistics has a significant effect on the restored image quality

We expect that these current and projected results in texture analysis and restoration will be very beneficial toward the overall goal of improving machine vision and image understanding systems. Significant progress has been made in improving the statistical accuracy and refining boundaries in texture segmentation. The texture mosaics used for the experimental tests in this project are difficult to segment because the individual textures making up the mosaic all are histogram equalized to have the same first-order statistics. Thus, these mosaics are not distinguishable on the basis of mean brightness or any first-order measurement. In natural scenes, this first-order information combined with texture could improve overall segmentation greatly. The important noise suppression and detail enhancement functions of restoration also improve image quality as a preprocessing step prior to feature extraction. The application of these new restoration techniques based on nonstationary image models may enable real-world images from noisy sensors to be effectively processed in machine vision systems in situations where they might fail otherwise.

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ADVANCED DEGREES AWARDED:

1. D. Kuan Ph.D. in Electrical Engineering, awarded August 1982, thesis title, "Nonstationary Recursive Restoration of Images with Signal-Dependent Noise with Application to Speckle Reduction".

INTERACTIONS:

Papers presented at Meetings, Conferences, and Seminars:

1. P. Chavel, D. Kuan, A.A. Sawchuk, and T.C. Strand, "Approaches to Effective A Priori Processing of Single Speckle Patterns", 1980 Annual Meeting Optical Society of America, Chicago, October 1980.

2. D. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, Discrete Speckle Image Modeling and Restoration," 1981 Annual Meeting Optical Society of America Orlando, Florida, October, 1981.

3. D. Kuan and A.A. Sawchuk, "Nonstationary 2-D Recursive Image Restoration", 1981 Annual Meeting Optical Society of America, Orlando, Florida, October, 1981.

4. A.A. Sawchuk, "Modeling of Signal-Dependent Noise," Second ASSP Workshop on Two-Dimensional Signal Processing, New Paltz, New York, October 1981, (invited paper).

5. A.A. Sawchuk, "Recent Developments in Optical and Digital Processing", Workshop on Optical Information Processing", Workshop on Optical Information Processing, Centro de Investigaciones en Optica, Cuernavaca, Mexico, January, 1982, (invited paper)

DISCOVERIES/PATENTS

None

INFOBASE: AN INFORMATION MANAGEMENT ENVIRONMENT FOR PERSONAL WORKSTATIONS

Work Unit IE4-4

DENNIS MCLEOD

1 APRIL 1981 THROUGH 31 MARCH 1985

RESEARCH OBJECTIVES

The principal scientific objective of this research is to devise, formally specify, and experimentally demonstrate principles and techniques to allow end-users of database systems (with limited database expertise) to directly design, use, evolve, and interconnect databases. The specific context of this research in the past two years has been personal workstation database systems. In particular, information management requirements of a well-defined class of users of personal workstation computers has been studied and analyzed; this study has focused on the areas of office information systems, software development and maintenance environments, and VLSI design. Based upon the requirements of these target users, and upon an assessment of the limitations of contemporary database technology to address them, this research has proceeded to develop and experimentally test concepts, mechanisms, and techniques to support several important aspects of personal database management. Experimental prototypes have been constructed to demonstrate and test these techniques; these prototypes have not been intended in any sense to be production systems, but rather to serve as experimental test vehicles.

STATUS OF RESEARCH EFFORT

During the past decade, significant progress has been made in devising and applying concepts and techniques to provide effective general-purpose data management capabilities for commercial-type application domains. Relational database technology has emerged as a viable tool to provide high-level data management facilities for database application programmers and end-users. Existing research prototype and commercial record-oriented database management systems are principally intended to accommodate centralized collections of uniformly structured data, requiring database experts to establish and maintain their organization.

Contemporary database technology is however limited in its ability to address certain aspects of the information management problem for commercial application domains. Further, current technology has significant limitations vis-a-vis the specific requirements of currently emerging database application environments, specifically office information systems, and systems to support design engineering (e.g., software and VLSI). In contradistinction to commercially-oriented database application environments, these application domains require that:

* The database must capture more of the meaning of the data, e.g., multiple

overlapping classifications of information objects, a rich variety of kinds of inter-relationships among objects, rules for deriving/deducing facts from the data explicitly present in the database, and historical information concerning past states of the database.

* Support must be provided for end-users to dynamically explore and modify the conceptual structure (schema) of a database, and to find and introduce new kinds of information objects, inter-relationships among object types, deduction rules, etc. The need for database expertise to support this task must be reduced.

* Concepts, techniques and mechanisms are required to support information sharing and coordination in a distributed database environment. In an environment consisting of a number of inter-connected database systems, possibly including large databases and smaller, personal databases, it must be possible for users to establish and evolve inter-database information sharing patterns. Database users must be able to explore remote databases (subject to access control restrictions), to transfer information between databases, to establish information inter-relationships that span database boundaries, to specify inter-database consistency constraints, to coordinate concurrent database manipulation in a network environment, etc.

* Facilities must be provided to avoid the need for database and data structure expertise in determining an internal, physical database organization that realizes the desired conceptual database schema. While an optimal physical organization is not required, performance must be adequate given a set of (informal) performance requirements.

During the four year JSEP contract period, this research has focused on several of the key open problems central to the general goals stated above, in an attempt to remove some of the limitations of current database technology. The specific focus has been on techniques to support the direct design, use, evolution, and interconnection of databases. More precisely, we have developed principles, concepts, and techniques to provide these functions for a generalized class of collections of information that might be termed "information bases", and to make them directly accessible to users who are not database experts. An information base is a generalized database, in that it can include elements that are classically considered external to a database, such as a structural description of the meaning of data (data dictionary), derived data specifications (deduction rules), specifications for transactions associated with the data, program modules, text, and a variety of other modalities of information. To experimentally test and refine the principles, techniques, and mechanism devised in this research, prototype implementations have been produced. While no single integrated prototype system has been developed, the prototyping efforts have been directed towards the goal of an *INFOrmation BAse Support Environment (INFOBASE)*.

Information Management Requirements of the Target Application Environments:

An investigation has been conducted the purpose of which was to determine the information management requirements of the target class of users <7, 9, 13, 18, 19>. In particular, a detailed study has been conducted to determine the distinctive information management requirements of VLSI designers <7, 9, 18>. Includes in this study was a "rapid prototype" implementation of a database for VLSI design using an existing relational database system (INGRES), and an assessment of the limitations and problems of such an approach. A similar study has been being conducted vis-a-vis information management in the software engineering domain <19>. A goal here is to generalize to the domain of information management for the design and evolution of a complex engineered system over its life-cycle. Further, the *information management requirements of professionals* and sophisticated office workers has been investigated <11, 13, 14>.

This assessment of information management requirements has resulted in this research focusing on the following specific technical issues:

* a generally-applicable, extensible information model that allows various kinds of information objects to be conceptually specified/structured;

* a prescriptive, stepwise methodology to aid the designer in the complex process of generating and evolving a specific conceptual schema from an informal set of requirements;

* an approach to a structured user interface to support end-user database design, evolution, and access;

* *an approach to dynamic interconnection and sharing* of data among databases;

* a prescriptive, stepwise methodology for mapping high-level information descriptions into a physical implementation.

Semantic Data Modelling and Database Design/Evolution:

As noted *above, a generally-applicable, extensible information model* is required to support the conceptual specification of the contents of a database; this model must capture much more of the meaning of data than is possible with conventional data models (e.g., the hierarchical, network, and relational models). In particular, the semantic *data model must* be capable of accommodating specific data objects, meta-data, operations on data, and derived data.

In this research, a rich semantic data model, termed *SDM* (for "semantic data model) has been devised <1>. In the course of research on the SDM model, a comprehensive survey and of related research on data models has been produced, and published in <12, 15>. Relevant information modelling concepts from research on abstract datatypes (in the programming languages area) and knowledge representation techniques (in the artificial intelligence domain) have been incorporated into SDM. SDM provides modelling primitives to allow a database designer to specify classes (classifications) of information objects, generic kinds of inter-relationships among object classes, and semantic connections among object classes themselves; in particular, SDM supports the notions of object aggregation, generalization/specialization, and classification. SDM also provides a language for defining derived data specification, and directly incorporating them in a structured manner into the conceptual structure (schema) of a database. SDM has been used as a database design specification mechanism, and also as a basis for an interactive, browsing-oriented, prescriptive query formulation tool <3>.

Drawing on experience in the use of SDM to support conceptual database design, a prescriptive, stepwise methodology to aid the designer in the complex process of generating and evolving a specific conceptual schema from an informal set of requirements has been devised and a prototype implemented <4, 5, 16>. This approach and tool, termed the *event database specification model* (*event model*) is significantly simpler than SDM, and it provides a prescriptive methodology to guide its use, thereby reducing the expertise required to design and evolve databases. The event model database design and evolution methodology allows a designer to specify the information and process content of a database at a very high level of abstraction, and to refine it into a specific database conceptual schema. The event model has been experimentally applied to design and evolve office system databases <16>.

End-User Database Interfaces:

The intended users of databases to which this research is addressed cannot be assumed to be "query language" experts; thus, existing formal query languages are inadequate. In particular, it is essential to provide prescriptive (guided) facilities for end-users to dynamically explore and modify the conceptual structure (schema) of a database, and to find and introduce new kinds of information objects, inter-relationships among types of objects, derived data objects (deduction rules), etc.

An initial experiment was conducted to devise a user interface methodology based upon SDM, and a prototype was implemented <3>. The semantic information in an SDM conceptual database schema was used to drive a domain independent methodology for database browsing and query formulation; this guides an end-user in determining the content of a database, and assists the user in formulating a query or database modification operation.

Based upon this initial experiment with an SDM interface, the *3DIS (3 Dimensional Information Space)* was devised <12, 18> The 3DIS is a simple yet extensible framework in which to uniformly handle information at various levels of abstraction. The 3DIS represents and treats data (of different modalities), properties of data, classifications of data, and operations on data (events) uniformly, and within a homogeneous object-oriented framework. The 3DIS constructs are defined formally through simple mathematical notions of set theory. The 3DIS representation framework is a cube wherein discrete points, lines, planes, etc., and geometric relations among them represent objects and their relationships. This provides a simple framework for a user to view data, and a set of geometric 3D space exploration primitives for information object browsing, retrieval, and manipulation. A prototype prescriptive, stepwise 3DIS user interface has been built for a personal workstation, using a personal workstation computer (an IBM

PC/XT) with a mouse and graphics capabilities. The 3DIS has been applied in detail to a VLSI design database, which has also demonstrated the built-in extensibility of the 3DIS model; a specific overview of the 3DIS is provided in the Appendix.

Database Interconnection and Sharing:

As noted above, in an environment consisting of a number of inter-connected database systems, possibly including large databases and smaller, personal databases, it must be possible for users to establish and evolve inter-database information sharing patterns. Database users must be able to explore remote databases (subject to access control restrictions), to transfer information between databases, to establish information inter-relationships that span database boundaries, to specify inter-database consistency constraints, to coordinate concurrent database manipulation in a network environment, etc.

Current approaches to "distributed databases" and "heterogeneous database systems" are inadequate for the target environment of this research, in that they require a centralized logical organization and centralized control. In virtually all "distributed database systems", users and applications access data via a single dictionary (conceptual schema), although the data may be distributed over a network of computers. "Heterogeneous database systems" embody a similar approach, in that they form a single, centralized catalog of the contents of a collection of databases. The essential problems of logical centralization are: a complete merge of the data associated with individual users and applications is required; user/application autonomy must be sacrificed; global optimality is often inadequate for the most important users of certain data; and a performance bottleneck often results.

In response to the limitations observed with current approaches to integrated and distributed databases, the design of a new database system architecture (*federated database systems*) was devised and implemented in prototype form <2, 6, 17> The goal of this new database structural concept is to accommodate logical decentralization and partial sharing of data among (autonomous) users and applications.

A federation consists of components (of which there may be any number) and a single federal dictionary The components represent individual users, applications, or information systems. The federal dictionary is a distinguished component that maintains the topology of the federation and oversees the entry of new components. Each component in the federation controls its interactions with other components by means of an export schema and an import schema. The export schema specifies the information that a component is willing to share with other components. The import schema specifies the information in the federation that a component wishes to access. As a counterpoint to the autonomy of components, the federated architecture provides mechanisms for sharing data, for sharing transactions (via message types), for combining information from several components, and for coordinating activities among autonomous components (via negotiation). A prototype implementation of the federated database mechanism is currently operational on an experimental basis.

Based upon the results of the federated database concept, further research has been conducted on the problem of supporting sharing and coordination among distributed, autonomous databases <8, 10, 14>. A principal goal of this work has been to simplify the powerful but somewhat complex federated database mechanism, and to further increase database autonomy and avoid centralized information/control. An information object sharing mechanism has been designed, and applied specifically to office information system applications, and to the context of a collaborating collection of design engineers.

User-Assisted, Semi-Automatic Physical Database Design and Evolution

As there is no database design expert available in the environment which this research addresses, it is necessary for the high-level, meaning-based specification of a database to be (semi-) automatically transformed into an executable, physical implementation. Since it is necessary to hide the actual details of the data structures from the naive or uninterested user, the approach taken in this project has been to present the user with an initial canonical physical design, along with a prescriptive design methodology to guide the user in refining the implementation when the initial implementation proves inadequate. The key to allowing non-experts to effectively perform this task is to base the physical design process on a few powerful heuristics, and embed these heuristics in an interactive, stepwise, prescriptive physical design methodology.

The physical design approach and methodology provides a small set of physical data structure types that can enhance the performance of a database system. When performance is inadequate, the user is asked to identify problems (e.g., which transactions/events are too slow); the system then adjusts the physical design to address these problem areas. Of course, this process is not guaranteed to produce and optimal implementation, but it does allow a user and system to cooperate on improving performance, and it does not require database expertise of the user. The results of this work on user-assisted, semi-automatic physical database design and evolution are described in <20>.

PUBLICATIONS

1. Hammer, M., and D. McLeod, "Database Description with SDM: A Semantic Database Model", *ACM Transactions on Database Systems*, Volume 6, Number 3, September 1981, Pages 351-386.

2. Heimbigner, D., and D. McLeod, "Federated Information Bases", in *Infotech State-of-the-Art Report on Databases* (editor M. Atkinson), Pergamon Infotech Ltd., 1981.

3. McLeod, D., "A Database Transaction Specification Methodology for End-Users", *Information Systems*, Volume 7, Number 3, 1982, Pages 253-264.

4. King, R., and D. McLeod, "The Event Database Specification Model, *Proceedings of Second International Conference on*

Databases: Improving Usability and Responsiveness, Jerusalem, Israel, June 1982.

5. King, R., *A Semantics-Based Methodology for Database Design and Evolution*, Technical Report (Ph.D. Thesis), Computer Science Department, University of Southern California, Los Angeles CA 90089-0782, June 1982.

6. Heimbigner, D., *A Federated Architecture for Database Systems*, Technical Report (Ph.D Thesis), Computer Science Department, University of Southern California, Los Angeles CA 90089-0782, August 1982.

7. McLeod, D., K. Narayanaswamy, and K. V. Baparao, "An Approach to Information Management for CAD/VLSI Applications", *Proceedings of ACM SIGMOD International Conference on the Management of Data*, San Jose CA, May 1983.

8. Lyngbaek, P., and D. McLeod, "An Approach to Object Sharing is Distributed Database Systems", *Proceedings of International Conference on Very Large Databases*, Florence, Italy, October 1983.

9. McLeod, D., K. Narayanaswamy, and K. V. Baparao, "Information Management for CAD/VLSI Applications" *Proceedings of IEEE Spring COMPCON*, San Francisco CA, February 1984.

10. Lyngbaek, P., and D. McLeod, "Object Sharing in Distributed Information Systems", *ACM Transactions on Office Information Systems*, Volume 2, Number 2, April 1984, Pages 96-122.

11. King, R., and D. McLeod, "A Unified Model and Methodology for Information System Design and Evolution", in *Perspectives on Conceptual Modelling* (editors M. Brodie, J. Mylopoulos, and J. Schmidt), Springer-Verlag, 1984.

12. Afsarmanesh, H., and D. McLeod, "A Framework for Semantic Database Models", *Proceedings of NYU Symposium on New Directions for Database Systems*, New York NY, May, 1984.

13. Lyngbaek, P., and D. McLeod, "A Personal Data Manager", *Proceedings of International Conference on Very Large Databases*, Singapore, August 1984.

14. Lyngbaek, Peter, *Information Modelling and Sharing in Highly Autonomous Database Systems*, Technical Report (Ph.D. Thesis), Computer Science Department, University of Southern California, Los Angeles CA 90089-0782, August 1984.

15. King, R., and D. McLeod, "Semantic Database Models", in *Principles of Database Design* (editor S. B. Yao), Prentice Hall, 1985.

16. King, R., and D. McLeod, "A Database Design Methodology and Tool for Information Systems", *ACM Transactions on Office Information Systems*, Volume 3, Number 1, January 1985.

17 Heimbigner, D., and D. McLeod, "A Federated Architecture for Information Management", *ACM Transactions on Office Information Systems*, Volume 3, Number 2, April 1985.

18. Afsarmanesh, H., D. Knapp, D. McLeod, and A. Parker, "An Extensible, Object-Oriented Approach to Databases for VLSI/CAD", *Proceedings of International Conference on Very Large Databases*, Stockholm, Sweden, August 1985 (to appear).

19. Narayanaswamy, K., W. Scacchi, and D. McLeod, "A Database System to Support the Design and Evolution of Large Software Systems", Technical Report, Computer Science Department, University of Southern California, Los Angeles CA 90089-0782, April 1985 (submitted to *International Conference on Very Large Databases*, Stockholm, Sweden, August 1985).

20. Ahad, R., and D. McLeod, *User-Assisted Semi-Automatic Design of Physical Databases*, Technical Report, Computer Science Department, University of Southern California, Los Angeles CA 90089-0782, April 1985 (submitted to *ACM Transactions on Database Systems*).

PROFESSIONAL PERSONNEL

* Dr. Dennis McLeod, Faculty Investigator, Associate Professor of Computer Science.

* Dr. Roger King, Ph.D. in Computer Science granted May 1982. Thesis title: "A Semantics-Based Methodology for Database Design and Evolution"

* Dr. Dennis Heimbigner, Ph.D. in Computer Science granted August 1982, Thesis title: "A Federated Architecture for Database Systems".

* Dr. Peter Lyngbaek, Ph.D. in Computer Science granted August 1984, Thesis title: "Information Modelling and Sharing in Highly Autonomous Database Systems".

* Dr. Rafiul Ahad, Ph.D. in Computer Science granted May 1985, Thesis title: "User-Assisted Semi-Automatic Design of Physical Databases".

* Ms. Hamideh Afsarmanesh, Ph.D. Candidate in Computer Science (degree expected June 1985), Thesis title: "3DIS: An Extensible, Object-Oriented Framework for Information Modelling and Access".

* Mr. K. V. Baparao, Ph.D. Candidate in Computer Science (degree expected August 1985). Thesis title: "A Model and Methodology for the Design and Evolution of Engineering Databases".

INTERACTIONS

* McLeod, D., "Object Management and Sharing in Distributed, Autonomous Database Systems", Computer Science Colloquium, Stanford University, Palo Alto CA, April 1985 (invited talk).

* McLeod, D., "On Semantic Data Models", NYU Symposium on New Directions for Database Systems, New York NY, May 1984 (invited talk).

* McLeod, D., "An Approach to Information Management for CAD/VLSI Applications", COMPCON 1984, San Francisco CA, February 1984 (conference presentation).

* McLeod, D., "Information Management for CAD/VLSI", Microelectronics and Computer Technology Corporation, Austin TX, February 1984 (invited talk).

* Lyngbaek, P., "A Personal Data Manager", International Conference on Very Large Databases, Singapore, August 1984 (conference presentation).

* Lyngbaek, P., "An Approach to Object Sharing in Distributed Database Systems", International Conference on Very Large Databases, Florence, Italy, October 1983 (conference presentation).

* Baparao, K. V., "An Approach to Information Management for CAD/VLSI Applications", ACM SIGMOD International Conference on the Management of Data, San Jose CA, May 1983 (conference presentation).

* King, R., "The Event Database Specification Model, Second International Conference on Databases: Improving Usability and Responsiveness, Jerusalem, Israel, June 1982 (conference presentation).

* McLeod, D., "A Unified Model and Methodology for Information System Design and Evolution", NSF Symposium - Perspectives on Conceptual Modelling, Intervale NH, June 1982 (invited talk).

* McLeod, D., "Personal Database Systems", ACM SIGMOD International Conference on the Management of Data, Orlando FL, June 1982 (panel presentation, chaired by D. McLeod).

* McLeod, D., "Database Integration", National Computer Conference, Houston TX, June 1982 (panel presentation, chaired by D. McLeod).

APPENDIX

This appendix provides a more detailed overview of the 3DIS information model and user interface, and an example of its application to the application environment of VLSI component (chip) design. The examples are selected from a complete database which has been defined to support VLSI design applications <18>.

As noted above, the 3 Dimensional Information Space (3DIS) is a simple but extensible information management framework. It is mainly intended for applications that have dynamic and complex structures, and whose designers, manipulators, and evolvers are *non-database-experts*. As a step towards addressing the modeling needs of such application environments, the 3DIS unifies the view and treatment of all kinds of information including the description and classification of data (meta-data).

3DIS databases are collections of interrelated objects, where an object represents any identifiable piece of information, of arbitrary kind and level of abstraction. For example, a component **H42padder**, an attribute **Designer-Names**, a string of characters **Low-Order-Bit**, a structural component (meta-data) **OEM-Component**, and a procedure **Insert-an-OEM-Component** are all modeled uniformly as objects in a homogeneous framework. Therefore, what distinguishes different kinds of objects is not how they are modeled, but rather the set of structural and non-structural (data) relationships defined on them.

Each object has a globally unique *object-id* that is an identifier generated by the system. An object can also have several user-specified surrogate *object-names* which also uniquely identify it. Objects may be referred to via their unique object-ids, object-names, or via their relationships with other objects. The 3DIS model supports atomic, composite, and type objects:

* *Atomic* objects serve as the symbolic identifiers for atomic constants in databases. These objects carry their own information content in their object-ids. Atomic objects cannot be decomposed into other objects. The contents of atomic objects are uninterpreted by 3DIS databases, in the sense that they are either displayable or executable without any further interpretation of their information content. Strings of characters, numbers, booleans, text, audio, and video objects, as well as behavioral (procedural) objects, are examples of atomic objects. Text objects represent long character strings, while audio and video objects represent digitized images and voices. Behavioral objects represent the routines that embody database activities, modeling an object that is executable. Behavioral objects accomplish modeling of data definition, manipulation, and retrieval primitives, e.g., **Insert-an-OEM-Component**.

* *Composite* objects describe (non-atomic) entities and concepts of application environments. The information content of these objects can be interpreted meaningfully by the 3DIS database through decomposition into

further objects. Mapping objects are a kind of composite objects. Each may be decomposed into a domain type object, a range type object, an inverse mapping object, and the minimum and maximum number of the values it may return. Mappings represent both the descriptive characteristics of an object, e.g., **Model-Name**, and the associations defined among objects, e.g., **Has-Model-Constituents**. Mappings model both single and multi-valued relationships.

* *Type* objects contain the descriptive and classification information of a database. Every type object is a structural specification of a group of atomic or composite objects. It denotes a collection of database objects, called its *members*, together with the shared common information about these members. A type object can be a *subtype* of another type object (*supertype*). Subtypes inherit all of their supertypes' properties. A type object can be the subtype of more than one type object. Therefore, the subtype/supertype relationships among type objects can be represented by a directed acyclic graph (DAG). Examples of type objects are **In-House-Component** and **Dataflow-Model**.

Basic relationships among objects are defined through the three fundamental abstraction mechanisms of classification, aggregation, and generalization:

* *Classification* represents member/type relationships by relating an atomic/non-atomic object, e.g., **H42padder**, to its generic type object(s), e.g., **In-House-Component**.

* *Aggregation* represents member-mapping/type relationships by relating a type object, e.g., **In-House-Component**, to the mappings that define its members, e.g., **Designer-Names, Realization-Bindings**, etc.

* *Generalization* represents subtype/supertype relationships by relating a type object, e.g., **In-House-Component**, to a more general type object, e.g., **Component**.

The 3DIS model has also been extended to accommodate other kinds of abstractions that are useful in VLSI design applications. For example, abstraction primitives to support the definition of recursively defined entities and concepts such as sets, lists, and binary trees are included in the model. In particular, for a VLSI design database, the 3DIS supports the recursive definition of VLSI cells.

An integral part of the 3DIS model is its simple and multi-purpose geometric representation. This geometric framework graphically organizes both structural and non-structural database information in a 3-D representation space. It reflects a mathematically founded definition for 3DIS modeling constructs in terms of the geometric components that represent them. The three axes in the space represent the domain (**D**), the mapping (**M**), and the range (**R**) axes. Relationships among objects are modeled by (domain-object, mapping-object, range-object) triples that represent specific points in the geometric space.

Figure 1 illustrates a perspective view of the geometric representation of a 3DIS database for VLSI design.

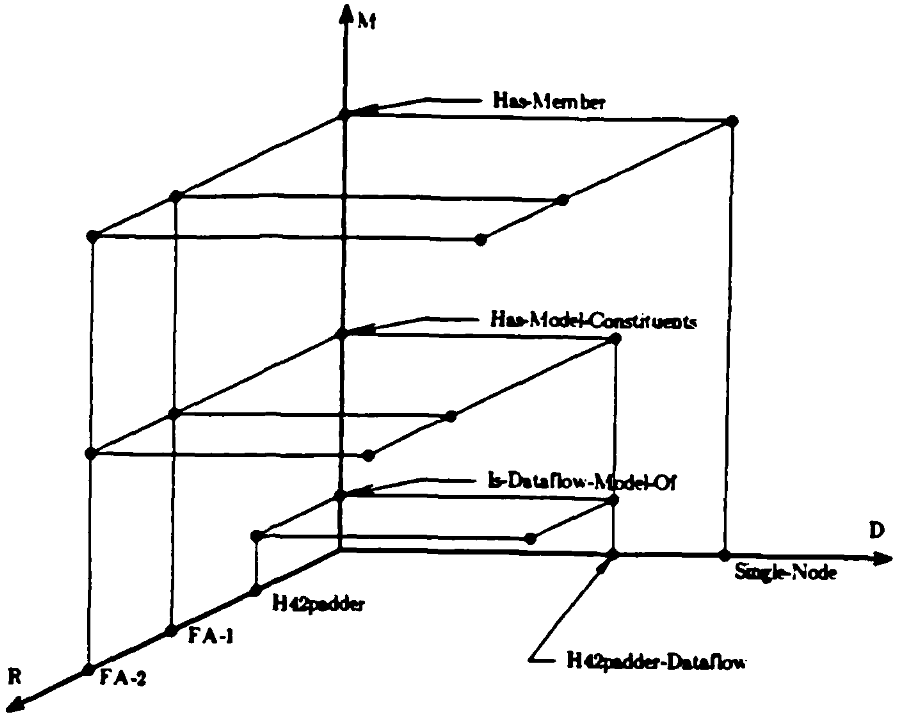

Figure 1: Perspective View of Part of an Example 3DIS Database

In this figure, **FA-1** and **FA-2** are members of the type object **Single-Node**, while they are also the **Model-Constituents** of **H42padder-Dataflow**. Figure 2 illustrates the right view of the simplified geometric representation for the **H42padder-Dataflow**.

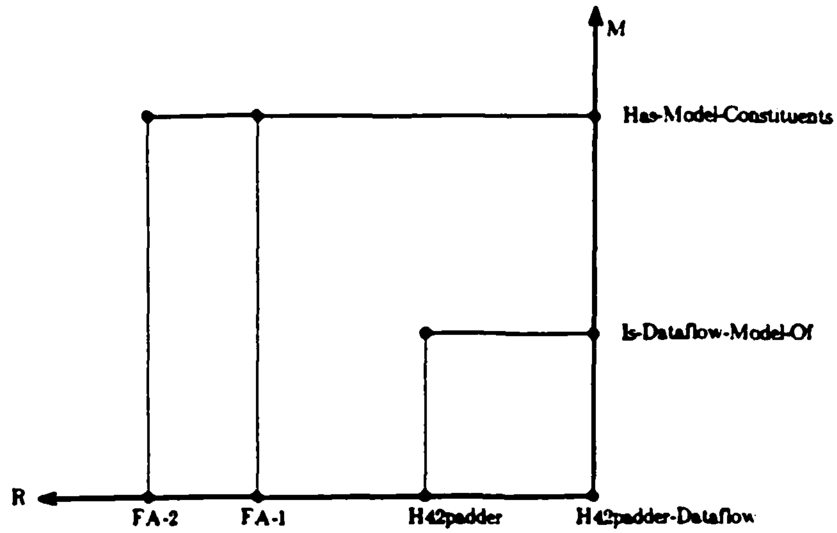

Figure 2: Right View of H42padder-Dataflow

The figures have been simplified to represent only a part of the information in the database.

Several geometric components such as points, lines, and planes encapsulate database information at several levels of abstraction, which has an advantage of enhancing the readability of the display. For instance, in Figure 1, the vertical line emanating from the object **H42padder-Dataflow** corresponds to all mappings defined on that object. Similarly, an orthogonal plane passing through the same object, which is also represented as the right view in Figure 2, contains the information about all objects directly related to **H42padder-Dataflow**. The variety and level of information encapsulation supported by the geometric *representation* is a *unique* feature of the 3DIS data model.

The geometric representation also provides an appropriate foundation for information browsing and serves as an environment for a simple graphics-based user interface. Database browsing is supported by a "display window" to the geometric framework, through which users may focus on and investigate an object or an 'information neighborhood' of their interest. A further description of the 3DIS user interface, and the prototype implementation is given in <18>

REDUCED MODELLING

Work Unit IE4-5

Edmond A. Jonckheere and Leonard M. Silverman

1 April 1981 - 31 March 1985

RESEARCH OBJECTIVES

The overall goal of this research unit has been the development of algorithms for computing reduced models for large scale, distributed systems.

A reduced model should be accurate enough to capture the essence of the dynamic behavior of a complex system, yet it should be simple enough to make the large scale system predictable and controllable through the simplified mathematical model. Systematic techniques for reducing models are also essential in stochastic modelling, since in this kind of applications the identification is performed through the gathering of a rather formidable amount of data and this usually results in overly complicated Markov or power spectral density models

Another area where model reduction is essential is the reduction of a feedback compensator, computed through a complex analytical procedure, down to a size that can be real-time computer implemented.

Over the past four years, we have developed numerous model reduction techniques. Both stochastic and deterministic model reduction techniques have been developed. Both state space and frequency domain algorithms have been considered. Both the reduction of a physical system model as well as the simplification of feedback compensators have been looked at. Mathematical softwares have been developed and computer implemented. Regarding the applications of the developed theory, we have especially concentrated on the reduced modelling and the reduced compensation of Large Space Structures.

STATUS OF RESEARCH EFFORT

As said in the RESEARCH OBJECTIVES Section, we have been working on many model reduction techniques. We therefore split this section into several paragraphs, each paragraph describing one of the many research directions we have taken.

Chronologically, we have first looked at balanced and Hankel norm model reductions We have discovered several hidden links between these two seemingly unrelated model reduction procedures. Further, we have formulated the state space approach to optimal Hankel norm reduction; see the work of Bettayeb (1981). While we did this for the monovariable case, our early work has had a dramatic impact on the future evolution of the field and has been quoted in numerous subsequent articles

Regarding the concrete applications of the theory of balancing and Hankel norm reduction, which we helped develop, we were the first researches to formulate the problems of balanced reduction and optimal Hankel norm reduction of Large Space Structures. In a few words, these is the essence of the results: The balanced state space representation of a flexible large space structure coincides with the modal representation, asymptotically as the structural damping goes to zero. Further, the balanced and optimal Hankel norm reduced models coincide with the modally truncated model, asymptotically as the damping goes to zero. However, in case of finite but nonvanishing damping, balanced or Hankel norm reduction is no longer equivalent to modal truncation. Therefore, in case of nonzero damping, which is the case with real flexible structures, balanced and optimal Hankel norm reductions provide different and better models that those obtained through modal truncation. Our early work on balancing flexible structures has been quoted and picked up by other researches in the aerospace field.

In the course of our effort directed towards a better understanding of balancing and Hankel norm reductions, the asymptotic stability of the full order model to be reduced, a required assumption in both balancing and Hankel norm reductions, appeared to be a severe restriction. We therefore attempted to relax this condition and formulated a model reduction procedure for open loop unstable plants. The idea is to prestabilize the system with a standard Linear-Quadratic-Gaussian (LQG) feedback loop, and then reduce both the unstable open loop model and the compensator in the coordinate system in which the filtering and control algebraic Riccati equations have the same diagonal solution. We have subsequently referred to this technique as the "Riccati balancing." Again, many researches have quoted this work.

The application of the Riccati balancing to Large Space Structures has also been investigated. It was proved that through Riccati balancing one could robustly stabilize a large flexible structure with a very low order compensator. Typically, for a structure with 12 vibration modes and co-located sensors/actuators, a compensator of order two was able to do the job.

In the standard Linear Quadratic Gaussian design, the compensator has the same degree as the original plant. However, if some cost or noise matrices become singular, then the degree of the LQG compensator naturally drops. This is another approach to compensator reduction which we have explored; see the Ph. D. thesis of Kitapci (1985).

Over the past twelve months, we have formulated and solved a fundamental generic problem--reduced modelling by optimal phase matching. In a few words, this is the problem: Given a high order stable, minimum phase transfer function $w(s)$, compute a reduced order stable, minimum phase transfer function $w_r(s)$ such that the phases of w and w_r closely match. The difficulty in this approach is to reduce the model while at the same time preserving the stable, minimum phase property. With both $w(s)$ and $w_r(s)$ stable and minimum phase, then by the Bode phase/gain relation, "good" matching of the phases will imply "good" matching of the amplitudes, and hence good matching between the transfer functions themselves. If $w(s)$ is thought of as the spectral factor of a stochastic process power spectral density, then the stochastic interpretations of this procedure are obvious. Actually, we derived this phase matching problem from Akaike's canonical correlation; we were indeed the first to prove that Akaike's canonical correlation operator is the Hankel operator induced by the phase of the process spectral factor, and this discovery has open the road to the investigation of many hitherto hidden links between canonical correlation and Hankel operators. On the other hand, w(.) can also be thought of as a compensator to be reduced with a minimum amount of phase disturbance in order to preserve stability and phase margin. This "phase matching" problem is still the object of intensive investigations; such specific problems we are currently looking at are i) the multivariable extension, ii) the multivariable Bode phase/gain relation, iv) the notion of phase margin in multi-loop feedback systems.

PUBLICATIONS

In this part are listed those publications that have appeared or are under process to appear in refereed journals. Conference papers are listed in the "Interactions" section.

1. E.A. Jonckheere and L.M. Silverman, "Singular value analysis of deformable systems," Journal of Circuits, Systems, and Signal Processing; Special Issue on Rational Approximation for Systems, vol. 1, pp. 447-470, 1982.

2. E.A. Jonckheere and L.M. Silverman, "A new set of invariants for linear systems--application to reduced-order compensator design," IEEE Transactions on Automatic Control, vol. AC-28, pp. 953-964, October 1983.

3. L.M. Silverman and A. Kitapci, "System structure at infinity," Systems&Control Letters, vol. 3, pp. 123-131, August 1983.

4. P. Harshavardhana, E.A. Jonckheere, and L.M. Silverman, "Stochastic balancing and approximation--stability and minimality," IEEE Transactions on Automatic Control, Vol. AC-29, pp. 744-746. August 1984.

5. E.A. Jonckheere and J.W. Helton, "Power spectrum reduction by optimal Hankel norm approximation of the phase of the outer spectral factor," IEEE Transactions on Automatic Control, to appear, 1985.

6. P. Harshavardhana and E.A. Jonckheere, "Spectral factor reduction by phase matching--the continuous time SISO case," International Journal of Control, to appear, 1985.

PROFESSIONAL PERSONNEL

Edmond A. Jonckheere and Leonard M. Silverman have been the key persons involved in this work unit.

Here, we list the students, along with their Ph.D. dissertation titles and graduation dates, who have been supported by JSEP

M. Bettayeb, "Approximation of linear systems: new approaches based on singular value decomposition," August 1981.

P. Harshavardhana, "Model reduction in control and signal processing," October 1984.

S. Lele, "Minimum variance deconvolution for 1-D and 2-D systems with colored noise input," April 1984.

Ph. C. Opdenacker, "Balanced model order reduction techniques and their applications to large space structure problems," May 1985.

A. Kitapci, "System structure and singular problems," May 1985.

INTERACTIONS

Here are listed, among other things, the papers that have been presented at refereed conferences and that have appeared in the proceedings.

1. E.A. Jonckheere and L.M. Silverman, "A new set of invariants for linear systems--Application to approximation," International Symposium on the Mathematical Theory of Network and Systems, Santa Monica, California, August 5-7, 1981, pp. 129-133.

2. E.A. Jonckheere and L.M. Silverman, "Singular value analysis of deformable systems," IEEE Conference on Decision and Control, San Diego, California, December 16-18, 1981, pp. 660-668.

3. E.A. Jonckheere, P. Crespo, and L.M. Silverman, "A closed-loop principal component analysis of singularly perturbed systems," in Proceedings IEEE Conference on Decision and Control, Orlando, Florida, Dec. 1982, Session FA6, pp. 1095-1096.

4. L.M. Silverman and A. Kitapci, "System structure at infinity," IEEE Conference on Decision and Control, Orlando, Florida, Dec. 8-10, 1982, pp. 420-421.

5. P. Harshavardhana, E.A. Jonckheere, and L.M. Silverman, "Open & closed loop balanced approximation techniques--an overview," IEEE International Symposium on Circuits and Systems, Newport Beach, California, May 2-4, 1983, pp. 126-129.

6. P. Harshavardhana, E.A. Jonckheere, and L.M. Silverman, "Stochastic balancing and approximation--stability and minimality," International Symposium on the Mathematical Theory of Networks and Systems, Ben Gurion University of the Negev, Beer Sheva, Israel, June 1983; Lecture Notes in Control and Information Sciences, Springer-Verlag, vol. 58, pp. 406-420.

7. E. Jonckheere, "Principal component analysis of flexible systems-- Open-loop

case,' International Symposium on the Mathematical Theory of Networks and Systems, Ben Gurion University of the Negev, Beer Sheva, Israel, June 1983; Lecture Notes in Control and Information Sciences, Springer-Verlag, vol. 58, pp. 494-512.

8. E. Jonckheere, P. Opdenacker, and L. Silverman, "Reduced-compensator design via LQG-balancing -- a case study," International Symposium on the Mathematical Theory of Networks and Systems; Special Session on Numerical Methods in System Theory, Beer Sheva, Israel, June 1983; Lecture Notes in Control and Information Sciences, Springer Verlag, vol. 58, pp. 523-520.

9. P. Harshavardhana, E.A. Jonckheere, and L.M. Silverman, "Stochastic balancing and approximation--stability and minimality," in Proceedings IEEE Conference on Decision and Control, San Antonio, Texas, December 14-16, 1983, Session FP1, pp.1260-1265.

10. E.A. Jonckheere and J. W. Helton, "Power spectrum reduction by optimal Hankel norm approximation of the phase of the outer spectral factor," in Proceedings American Control Conference, San Diego, CA, June 6-8, 1984, Paper FA6-1, pp. 1352-1359.

11. A. Kitapci and L.M. Silverman, "Determination of Morse's canonical form using the structure algorithm," IEEE Conference on Decision and Control, Las Vegas, Nevada, December 12-14, 1984, pp. 1752-1757.

12. Leonard M. Silverman has had over the past five years consulting interaction with Lockheed-California.

13. Edmond A. Jonckheere has had interaction with the Aerospace Corporation, El Segundo, California and with TRW, Redondo Beach, California. He has also had a consulting affiliation with the Honeywell Systems Research Center, Minneapolis, Minnesota, during the summer of 1983.

DISCOVERIES/PATENTS

None.

ELECTRICAL TECHNIQUES FOR MATERIALS CHARACTERIZATION

WORK UNIT SS1-3

C.R. CROWELL

Report Period: 1 April 1982 to 31 March 1983

RESEARCH OBJECTIVES

The primary research objective was to develop non-destructive electrical techniques which aid in semiconductor materials and device characterization. Studies undertaken included: 1) ohmic contact evaluation; 2) a development of the understanding of capacitive evaluation of deep impurity levels from the frequency dependence of junction impedance; 3) supplementing (2) with a study of differential deep level transient spectroscopy, DDLTS; 4) an analysis of multiple level systems and sample inhomogeneity by Hall measurements; 5) charge effects associated with current transport in insulators; 6) photo- conductance semiconductor interfaces.

STATUS OF RESEARCH EFFORT

1. We are currently extending our previous work [1] in which the contact effects on both resistivity and Hall measurements were characterized. We are investingating structures that will be able to model effects of interface resistance as well as bulk effects in a relatively straightforward diagnostic form. The resulting guidelines should be of special interest in VHSIC work, where the problem of small area ohmic contacts is expected to become crucial with progressively smaller dimensions.

During the past year the greater part of our effort has been directed in this field because of the level of program support and the available personnel. An optimized structure for ohmic contact evaluation and guidelines for measurement interpretation are nearing completion [2]. We have also performed some calculation on the diagnostics of distributed resistance effects in the bulk and surface layers of solar cells [3].

2. We have made a detailed study of bias, frequency and temperature dependence of the complex capacitance of In doped Si in Hf-p type Schottky barriers [4,5,6]. The measurements constitute the most complete characterization to date of a Schottky barrier system with deep level doping. We have, however, wanted to complete an error analysis of the results before publishing the manuscript. We have also performed a calculation of the spatial distribution of generation and recombination of gold doped Pt on n type Si Schottky barrier. In both the above the details of the boundary conditions are handled in a unique and physically more meaningful fashion than is current practice. The techniques developed here are especially applicable to the analysis of heavily compensated or nearly semi-insulating semiconductors in a way which is less ambiguous than DLTS. This analysis will be given JSEP acknowledgment when completed.

3. We have completed an analysis that compares DLTS and DDLTS analysis of deep level transients [7]. This manuscript has considered tradeoffs in sensitivity versus time

constant selectivity for a number of DLTS "correlators" and sets up other guidelines for the time- efficient acquisition of spectra. A third major contribution of this work is an analysis of the effects of deep levels large in concen- tration relative to the bulk majority carrier concentration. In this situation a strong distortation of the transient behavior occurs if the transients are not analyzed at constant high frequency capacitance. Since this is not always possible the above analysis is pottentially very useful.

A companion analysis of the analogous MOS system has been completed with a consideration of both charge storage and charge release modes of measurement. In each of the measurements there is a character- istically different spatial response that permits information about trap location and type (hole of electron) to be determined [8].

An experimental system to perform a variety of DLTS measurements is being constructed: 16 channel gated analyzer for determination of the spectral content of a signal is operational [9] and a unique feedback system for control of capacitance and measurement of bias transients at constant capacitance is nearing completion. This latter will permit the "drive" portion of the transient analysis to be set for a given constant capacitance as well as controlling the "read" capacitance. The capacitance "bridge" has been demonstrated to be operational but requires an evaluation of its sensitivity.

An analysis of the slow restoration technique, a heralded "optimum" system for data acquisition, has been analyzed and shown to be no better than simple signal gating techniques [10]. A far more powerful technique for improving the figure of merit of the system is shown to be inherent in the choice of mode for the temporal analyzing of the output signal.

4. Techniques for analysis of the Hall effect data from materials that have multiple deep levels are being investigated and have been used to support the In studies discussed above.

Presentation of the data in the form of an activation energy plot versus fermi energy has been shown to be very revealing [11]. We are currently trying to set up an analysis system that will also yield error criteria for the fitting parameter, and that does not require tailored controls on the choice of initial estimates.

5. Some work has been done with W. Patterson on the Frenkel- Poole characterization of traps in silicon nitride [12]. The approach features a generalization of the Frenkel-Poole model that permits analysis of a multi-break F-P plot. Some guidelines for analysis of charge migration in silicon nitride were developed with D. Crain. These were later incorporated in the ongoing program conducted by K. Lehovec.

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PROFESSIONAL PERSONNEL

C R CROWELL, Principal Investigator, Professor of Electrical Engineering.

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D. LUCEY, Ph.D. proposed Fall 1982

M.W. CHIANG, Research Assistant

INTERACTIONS

Seminar at NOSC on Ohmic Contact Evaluation, May 1981.

MBE GROWTH OF GA AS/AL GA AS TUNNELING DEVICES

Work Unit SS2-2

M. GERSHENZON

REPORT PERIOD: 1 April 1982 to 30 September 1983

RESEARCH OBJECTIVES

A. BACKGROUND

This task has evolved from a former JSEP program which investigated physical properties and device parameters of GaP/Si heterojunctions. As described in previous reports, potential applications of such structures, grown by MOCVD, were limited by interface imperfections which could not be identified or controlled by the MOCVD method of preparation. It was then proposed to transfer the project to our newly acquired MBE system, where the on-board analytical capabilities and the high degree of crystal growth control might identify the interface problems clearly. During the period that the MBE system was being installed and tested (by growing standard GaAs multilayer structures) our own continued MOCVD experiments, as well as the results of two other groups using MBE techniques to grow GaP/Si interfaces, indicated that our original device and physics expectations from the GaP/Si system were, unfortunately, greatly exaggerated. This was explained in our last JSEP report. Accordingly, in order to take maximum advantage of the ultimate capabilities of the MBE system, it became desirable to change the thrust of our research objectives, while still retaining device potential of heterostructure systems as the ultimate goal. At the 1982 triennial review of our JSEP program, we proposed a major MBE research effort aimed at elucidating device potential of interfaces and quantum wells in the metastable alloy system (Ga,In) (As,Sb,Bi), as well as a more modest alternative program, focusing on devices based on tunneling across interfaces and between quantum wells in the (Ga Al) (As) system, a system we were already using to test our new facility. It became obvious, from the comments of the JSEP review members, that support for our more ambitious program was not forthcoming. Thus, we reformulated this JSEP task to comply with the more restrictive constraints of the alternative proposal.

B. SPECIFIC TASKS

In our most recent (September, 1982) JSEP proposal, the specific goals of this project were outlined in detail. Briefly, most of the previous transport work in the GaAs/AlGaAs system, involving single interfaces, quantum wells and superlattices, was concerned with transport parallel to the interfaces. Our focus, however, is to be on transport perpendicular to the interfaces. Three-dimensional circuitry is feasible if carriers confined near an interface or in a quantum well are allowed to tunnel to an underlying quantum well or confining interface barrier. Resonant (and non-resonant) tunneling would be controlled by application of an external bias to a Schottky barrier on each underlying GaAs confining layer. The barrier layers would be AlGaAs. Carrier detection in each confining layer would be by a reverse biased Schottky barrier, or by observing radiative recombination in doped confining layers. Ohmic contacts and Schottky gates would be prepared by lithography and differential (GaAs vs AlGaAs) etching to contact each layer individually. In addition confining layers consisting of superlattices were also proposed. Such a structure, a superlattice of a superlattice, offers more degrees of freedom in defining the confining electronic states.

The immediate goals were the preparation of two types of structure. The first structure would permit an investigation of tunneling between two bulk GaAs layers. The structure would consist of an n+ GaAs substrate, 1 m n (10^{17}) GaAs buffer, undoped $Al_xGa_{1-x}As$ barrier, with x = 0.3, 1 m n(10^{17}) GaAs, 0.5 m n^- GaAs, and an MBE grown Al contact. The barrier layers would be 200, 100, 5 and 0 Å thick, the latter for establishing contact resistance, and the viability of the subsequent processing steps. In the second structure, two AlGaAs barriers would be grown with a thin 50-100 Å GaAs layer sandwiched between to form the quantum well. In both cases, the devices would be defined laterally either into mesas, by etching through the barrier layers, or by proton bombardment isolation using the covering metal as a mask. Photolithographic techniques would be used to establish the lateral geometry. For establishing Schottky contact to the quantum well in the second structure, differential (GaAs vs AlGaAs) etching would be employed.

C. PREVIOUS WORK

In our last report, we described why our initial MBE program was aimed at achieving controlled growth of state-of-the art structures in the GaAs (only) system. Over 60 structures were grown consisting of single and multiple layers of varying doping and thickness. Growth on (100) substrates was at 560-580°C, with a As_4 to Ga flux ratio of 3:1 and proceeding at a rate of 1 m/hr. Growth rate and growth rate uniformity over a 1 cm^2 substrate of better than 5% could be obtained. Crystal morphology (RHEED, X-ray diffraction, optical microscopy) was good. The background doping was p-type (carbon?) at about 10^{15} cm^{-3} grown with a base pressure of 10^{-10} torr. Donor doping was by Si and Sn, acceptor doping by Be. Controlled doping to within 20% could be achieved up to 10^{19} (Be) and 5×10^{18} (Si). From Hall measurements and C-V profiling, the 77°K electron mobility at low donor doping was quite acceptable, and the interfaces between differently doped layers exhibited a sharpness of at least 100 Å Some of the these structures were fabricated into IMPATT and TED diodes.

In last year's report we also discussed our first experiments with the GaAs-AlGaAs system. Bulk uniform layers (thickness, composition and doping) of $Al_xGa_{1-x}As$, ($0<x<0.3$) were grown on (100) GaAs substrates, but no acceptable multilayered structures had been prepared.

STATUS OF RESEARCH EFFORT

Although we had achieved reasonable control of thickness, composition and doping in bulk (single layer) AlGaAs, the first multilayered structures grown exhibited effects which could only be due to poor interfaces: lack of sharpness, non-planarity, impurity incorporation, or the presence of morphological defects. As a consequence, the preliminary experiments aimed at achieving control of bulk properties in the AlGaAs system were repeated and extended, this time aimed at achieving interface perfection.

The first task involved achieving good control of the Ga,Al and As_4 fluxes. A nude Bayard-Alpert ion gauge was installed just below the sample position to monitor the fluxes from each source, when the shutters were opened, one at a time. The Ga flux was calibrated against the growth rate of pure GaAs, already established by profilometry across shadowed regions of the substrate. The Al flux was established by depositing Al on glass substrates at room temperature, and measuring the thickness by profilometry. The As_4 flux was obtained from the predicted relative sensitivity of the ion gauge and cross-checked by noting the As_4 flux dependent phase transitions of the surface reconstructed phases on pure GaAs and comparing with the phase boundaries reported in the literature. Secondly, cross-correlation standards were transferred to measurements of the temperatures of the source cells, the total power delivered to the source ovens and to the quadropole mass spectrometer mounted just above the sample. The latter was particularly effective in defining the Al:Ga flux ratio. Both the on-board auger analyzer and subsequent electron probe microanalysis provided confirmation of the results. Finally a wire was used as a shadow mask. The Al and Ga Knudsen cells were positioned at 180° positions in the source flange. Thus the Al and Ga fluxes reached the substrate from maximum differing angles. Thus, in the shadowed region only, GaAs grew as a step on one side, AlAs on the other side, and nothing in the center. Profilometry of the resultant stepped structure provided the most conclusive definition (on the growing sample itself) of the separate Ga and Al-fluxes.

The ideal growth temperature for GaAs *already established was 560-580°C. However,* at a growth rate of l m/hr., this is too low for AlGaAs because of the increased bonding strength of Al compared with Ga, and hence to the lower surface mobility of Al. From the literature, the optimum growth temperature of $Al_3 Ga_7 As$ is 650°C, about 100° higher than the growth temperature we had been using for GaAs. Because it was not desirable to interrupt growth between GaAs and AlGaAs in order to change the temperature of the sample, during which time, impurities from the ambient vacuum could be collected at the interface, the growth of pure GaAs was re-optimized for 650°. This simply meant an increased As_4 flux (to 3.5:1) to compensate for increased re-evaporation of As. The GaAs so grown was as good morphologically and electrically (mobility) as that previously grown at lower temperatures. Both GaAs and $Al_3 Ga_7 As$ grown under these conditions, at l m/hr., showed RHEED streak patterns (As-stabilized c(8x2) surfaces), and subsequent sharp line X-ray photographs as good as our best previous GaAs results.

The substrate temperature was established and controlled by the reading of a chromel-alumel thermocouple contacting the Mo substrate holding block, by the power fed to the block and, most significantly, by the use of an infrared pyrometer, which viewed the sample through a sapphire window in an unused source port. Absolute temperature calibration was achieved by visually observing the reflectivity change on melting of a eutectic Al-Si alloy mounted on a Si substrate on the sample block.

Our first GaAs/AlGaAs interfaces were grown by stopping growth and readjusting substrate temperatures. Profiling with Auger spectroscopy and sputtering showed that about 0.1 monolayer of oxygen had built up at the interface during this waiting period.

Thus, we first concentrated on learning how to grow without interrupting growth at the interface (by increasing the growth temperature of GaAs as explained above). But, second, we also investigated the rate of incorporation of oxygen from the vacuum ambient of our MBE system (10^{-0} torr). Our on-board auger system has a detectability limit of 1% for oxygen. By observing the increase of the oxygen signal with time, we concluded that a monolayer of oxygen developed on a Al_3Ga_7Ab surface in 20 minutes at room temperature and in 40 minutes at 200°C. Since desorption of oxygen does not proceed at higher temperatures as quickly for AlGaAs as for GaAs due to the stronger Al-O bonds, this gave us an upper bound on the length of time we could allow a surface to sit at the growth temperature, but without growth, in order to minimize oxygen contamination at the interface. With uninterrupted growth, while crossing the interface, this meant a maximum oxygen concentration at the interface of less than 10^{13} cm^{-2}. Sputtered Auger analysis of interfaces so grown, did indeed show that the oxygen content at the interface was below this level, comparable to the best GaAs:AlGaAs interfaces reported in the literature. At the growth temperature for AlGaAs used, 650°, oxygen desorbs as fast as it is absorbed.

Thus, oxygen contamination at the GaAs:AlGaAs interface has been minimized. Morphological studies (RHEED, optical microscopy, x-ray diffraction, TEM is still to be done) show that the structure near the interface is "perfect". Most recently, multi-layer GaAs-AlGaAs structures, with layers of 25-100 Å have been grown under the growth conditions described. If the interfaces are sharp and free of oxygen, the simple one-barrier tunneling structures and more complicated quantum-well tunneling structures, described earlier, will be fabricated and evaluated.

PUBLICATIONS:

None.

PROFESSIONAL PERSONNEL

M. GERSHENZON, Principal Investigator

Y.H. WU, Research Assistant

T.C. LEE, Research Assistant

DOD INTERACTIONS:

None.

DISCOVERIES/PATENTS

None.

TANDEM TIME OF FLIGHT LASER MASS SPECTROMETER

Work Unit QE2-4

Curt Wittig

Report Period: 1 April 1981 to 31 March 1984

RESEARCH OBJECTIVES

One of the earliest and most intriguing observations associated with the IR multiple photon excitation and dissociation (MPE and MPD) of polyatomic molecules was the detection of small fragments {e.g. C_2, CH} which could only derive from extensive fragmentation of the parent species.{1-3} Since then, it has been shown that dissociation follows low energy pathways, {4,5} and sequential laser driven unimolecular reactions are responsible for the fragments which require a large amount of energy for their production. {6} However, for neutral species, it is an arduous task to monitor the intermediate steps which transpire to convert a large precursor molecule into rather small fragments, since there exist no straightforward, universal detection methods for these purposes. Laser induced fluores (LIF) is sensitive and state specific, but is adequate for only a limited number of fragments. Electron impact ionization of neutral photofragments, which is a quite general technique, makes interpretation difficult when more than one fragment is involved, and has limited sensitivity in the environments where it is most useful. {5}

The IRMPD of molecular ions allows one to scrutinize the low energy reaction pathways without most of the difficulties associated with monitoring neutrals since ions are easily monitored under collision free conditions. Moreover, both parent and daughter ions can be studied quantitatively, and thus the method is particularly suitable for studying the IRMPD of large molecular ions, where several competitive and sequential processes can be involved. The IRMPD of ions has been studied previously using ion cyclotron resonance (ICR) spectroscopy, {7,8} and in molecular beams. {9} In addition, MPI has recently been introduced in this laboratory as a means of preparing ions for such studies. {10} In contrast to other methods, MPI produces ions with excellent spatial and temporal resolution, making it possible to use focused CO_2 laser radiation, while interacting with the entire ion population. This method can be used to address directly the issue of overall; dissociation efficiency, under truly collision free conditions. In the example studied here, we find that complete removal of the parent ion produced by MPI is possible under straightforward experimental conditions.

In the present MPI/IRMPD study, triethylamine (TEA) was chosen as the neutral precursor for several reasons. Parker et. al. have shown that the MPI mass spectra at a particular wavelength are independent of laser intensity over a wide range, {11} and this is of great experimental value, since pulse to pulse intensity fluctuations in the laser output do not affect the MPI cracking pattern. The wavelength dependence of the mass spectra can be understood in terms of competition between 3 and 4-photon ionization processes producing, respectively, as major peaks, the parent ion (m/e=101), or the parent ion minus a methyl group (m/e=86). The latter species can be made dominant by the proper choice of the wavelength of the MPI radiation. In the wavelength region 400-520 nm, ionization is facilitated by a 2-photon transition to a bound state which has been observed by 2-

photon LIF. {12} At wavelengths shorter than 400 nm, this intermediate state undergoes a rapid radiationless transition (possibly predissociation). In general, the photophysics of tertiary amines, including TEA, has been well studied, {11, 13, 14} and this is a decided advantage in our work. Finally, fragmentation patterns for electron impact ionization of TEA, and aliphatic amines in general, are well documented, {15} thus serving as a guide in this first extension of the MPI/IRMPD technique to the use of tunable laser radiation for the preparation of molecular ions.

STATUS OF RESEARCH EFFORT

* The MPI/IRMPD technique is a general method for the study of unimolecular reactions of molecular ions under collision free conditions. MPI provides an efficient method for preparing large concentrations of ions, with excellent temporal and spatial resolution, and thus, the entire ion population can interact with the focused output of the CO_2 laser. The method provides a convenient way of monitoring all ionic reaction products, and of directly determining the dissociation efficiency of the parent ions.

* In the present work we demonstrate that complete dissociation of large molecular ions by IRMPD can be achieved at sufficiently high CO_2 laser fluences. In addition, the TEA parent ion prepared by MPI absorbs the CO_2 radiation throughout the entire CO_2 laser tuning range (in contrast with the neutral TEA, which absorbs significantly only around 9.4 μm).

* IRMPD follows the lowest available energy dissociation pathways, and in the case of TEA, the extensive fragmentation observed is compatible with a sequential dissociation mechanism.

* By using a TOF mass filter, it should be possible to increase the data acquisition rate by at least an order of magnitude. Also, product kinetic energy and unimolecular reaction rate measurements are straightforward when using such an arrangement, and we will use a TOF mass filter in many of our future experiments.

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PROFESSIONAL PERSONNEL

1. Curt Wittig, Professor of Electrical Engineering, Physics and Chemistry, USC.
2. Hanna Reisler, Research Associate Professor of Chemistry and Physics, USC.
3. Yehuda Haas, Associate Professor of Chemistry [Jerusalem], sabbatical leave at USC during 1981-82.
4. David Sumida, Graduate Student [Physics], USC.
5. Joe Catanzarite, Graduate Student, [Electrical Engineering], USC.

FURTHERING DATA ABSTRACTION VERIFICATION

Work Unit IE1-1

LAWRENCE FLON

Report Period: 1 April 1981 to 31 March 1982

RESEARCH OBJECTIVES

Research during the reporting period has been concentrated on two efforts:

1) A design methodology for large systems aimed at transforming system requirements into an implementation meeting those requirements;

2) An investigation of a software design methodology and support system, called "metaprogramming".

STATUS OF RESEARCH EFFORT

Research on topic [1] over the last several years has been brought to a successful conclusion at this time. Using our methodology, a system is derived incrementally from the initial statement of its requirements. The resulting hierarchy of system designs is one of detail, not one of system structure or functionality. Each level in the hierarchy is a complete, self-contained description of the system. Each level is derived from, and is more detailed than, the previous level. A level consists of a model of the system and requirements constraining the model. The methodology defines verification steps that must be taken as new levels are produced. This highlights one of the benefits of using this design strategy. It might be quite difficult to show that a system implementation satisfies some high level requirement such as fault-tolerance. It is easier to show that the high level requirement is satisfied by a somewhat lower level specification, that each lower level specification is satisfied by a still lower level specification, and finally that a specification is satisfied by the implementation.

The major by-product of this research has been the successful PhD dissertation [1], authored by Dr. Deborah Baker, now on the faculty of the University of Colorado. In this dissertation, the methodology is developed and applied to the major example of (re-)designing the SIFT computer system, a fault-tolerant avionics system developed by SRI International under contract from NASA Langley. Also in the process of development is [2], a joint paper between the Principal Investi- gator and Dr. Baker, summarizing the results in a more terse form.

Research on topic [2] has been underway for about one year. A metaprogram is the simultaneous denotation of a class of implementations with the same abstract behavior. Because metaprograms are not tied to particular execution environments, they can be stored in a library from which a programmer can effectively choose those relevant to his/her task, supply them with appropriate information about the desired execution environment, and incorporate the resulting actual programs into a larger system. The benefits of such an approach to system construction include significantly reduced development time and significantly enhanced reliability.

The developing research includes the design of a metaprogramming language, i.e. one in which one can conveniently denote metaprograms. This metaprogramming language is based upon the Ada programming language. We are currently implementing an Ada front-end and interpreter which we will use as the vehicle to test out our metaprograms. We are also actively involved in the design of the environment that a programmer would use to interact with the metaprogram database. We have in progress a paper summarizing our research thus far [3]. This research effort is now being supported directly by AFOSR, with the conclusion of our JSEP support.

PUBLICATIONS

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2. Baker, D., and Flon, L., "Requirements-Driven System Design", in preparation.

3. Flon, L. and Cooprider, L. W., "Metaprogramming - Prospects for the Practical Reuse of Software", in preparation.

PROFESSIONAL PERSONNEL

LAWRENCE FLON, Principal Investigator

DEBORAH BAKER, Research Assistant (through December 1981)

ANNE CURRAN, Research Assistant (half-time, January-March 1981)

THIERRY PARADAN, Research Assistant (half-time, January-March 1981)

INTERACTIONS

Dr. Baker gave presentations concerning her Ph.D. research at the University of Colorado, the University of Michigan, Washington University, St. Louis, the University of Virginia, and Ohio State University. Dr. Flon gave a presentation on metaprogramming at USC's Information Sciences Institute.

DISCOVERIES/PATENTS

None.

DESIGN OF EASILY MAINTAINABLE DIGITAL SYSTEMS

Work Unit IE2-4

JOHN P. HAYES

Report Period: 1 April 82 to 31 March 1983

RESEARCH OBJECTIVES

The overall goal of this project is to develop efficient design methods for digital systems to simplify the tasks of fault detection and location. During the reporting period, the CSA approach to fault simulation and testing of complex MOS VLSI circuits was further developed. A simulation program to test CSA theory was successfully implemented.

STATUS OF RESEARCH EFORT

The CSA (connector-switch-attenuator) methodology for digital circuit analysis in the VHSIC/VLSIC context (8, 9, 10) was substantially developed during the reporting period. New techniques were obtained for modeling charge - storage phenomena and complex failure modes. A computer program CSASIM was designed for simulation of both good and faulty CSA circuits. A prototype version of CSASIM was implemented in the Pascal language, and successfully tested on some sample circuits. We also extended our model for fault tolerance of interconnection networks (5, 6, 7) in several new directions. Because of the departure of the Principal Investigator from USC, no further effort on this project is planned.

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PROFESSIONAL PERSONNEL

J.P. Hayes, Principal Investigator

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INTERATIONS

None.

DISCOVERIES/PATENTS

None.

MULTIVARIABLE FEEDVACK SYSTEM DESIGN

Work Unit IE2-6

M.G. SAFONOV

Report Period: 1 April 1982 to 31 March 1983

RESEARCH OBJECTIVES

To develop engineering techniques suitable for use in the modern computer-aided design environment, which are applicable to the design of dynamical multiloop feedback control systems to meet specifications calling for a robust tolerance of paramenter variation, nonlinearity and noise within specified bounds.

STATUS OF RESEARCH EFFORT

Since the last annual report, significant progress has been made in the development of several robust multiloop feedback design tools. First the completion of the Ph.D Thesis of B.S. Chen [1] was a significant milestone. The thesis includes a number of useful results concerning the inverse problem of Linear Quadratic Gaussian (LQG) optimal control in the general stochastic setting with a Kalman-Bucy filter for optimal state estimation. The results enable one to determine the LQG cost and noise intensity matrices that lead to a given control law. They are useful in providing a means for adjusting the LQG design parameters so as to improve the robustness of multiloop feedback control systems.

Another area where significant progress was in the reduction of the conservativeness of multivariable stability margin estimates for systems subject to parameter uncertainty having a known structure. A technique involving the use of Perron eigenvalues was developed and found to be substantially less conservative than standard singular value techiques when dealing with structured uncertainty [2].

A systematic technique for optimizing the stability margin singular values of multiloop feedback systems was developed and reported in [3].

Finally, a technique for analyzing the stability of feedback systems with hysteresis nonlinearities has been developed which generalizes the Popov stability criterion.

PUBLICATIONS

1. B.S. Chen, Ph.D. Thesis, University of Southern California, June 1982.

2. M.G. Safonov and B.S. Chen, "Multivariable Stability Margin Optimization With Decoupling and Output Regulation", Proc IEEE Conf. on Decision and Control, Orlando, Fla, December 8-10, 1982; also, IEE Proc., Pt. D, Control Theory and Applications, Vol. 129, pp. 276-282, 1982.

3. M.G. Safonov, "Stability Margins of Diagonally Perturbed Multivariable Feedback Systems", IEE Proc., Pt. D. Control Theory and Applications, Vol. 129, pp. 251-256, 1982.

4. M.G. Safonov and K. Karimlou, "Input-Outp;ut Stability Analysis with Hysteresis Nonlinearities", short paper summary submitted 3/83 to IEEE Conf. on Decision and Control, San Antonio, TX, December, 1983.

PROFESSIONAL PERSONNEL

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INTERACTIONS

None.

DISCOVERIES/PATENTS

None.

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