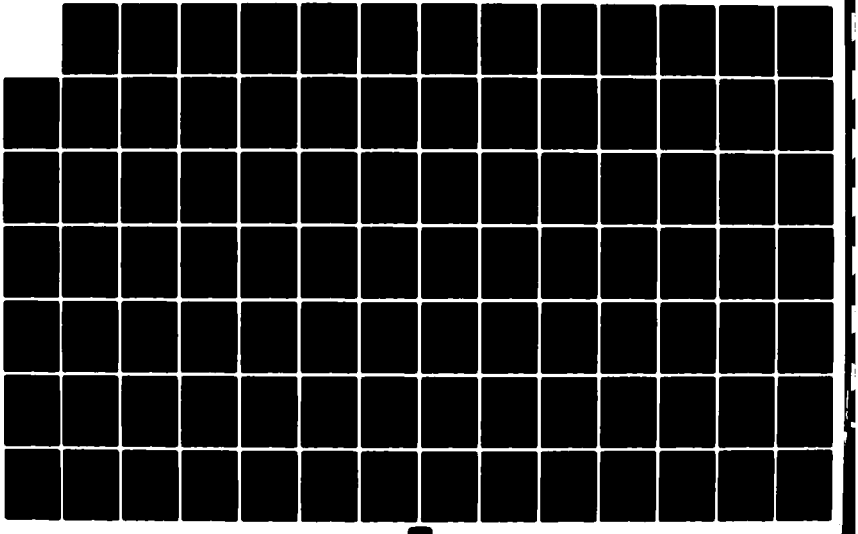
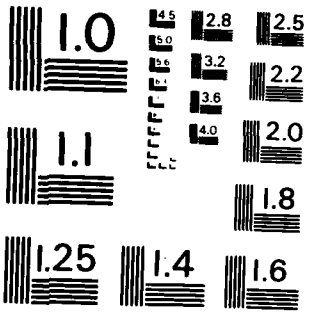
AD-A130 791 RESEARCH IN ELECTRONICS: JOINT SERVICES ELECTRONICS PROGRAM(U) UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES ELECTRONIC SCIENCES LAB W H STEIER 30 APR 83 1/2

UNCLASSIFIED AFOSR-TR-83-0617 F49620-81-C-0070 F/G 5/1 NL





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SCHOOL OF ENGINEERING
ELECTRONIC SCIENCES LABORATORY

(6)

30 April 1983

Gerald L. Witt
Program Manager
Air Force Office of Scientific Research
Bolling Air Force Base
Washington, D.C. 20332

Dear Dr. Witt:

Enclosed are six [6] copies of our Annual Technical Report covering the period 1 April 1982 through 31 March 1983 under contract F49620-81-C-0070. Also enclosed is the Significant Accomplishments Report for this same period. I am sending copies of these reports to those on the JSEP distribution list.

Sincerely,

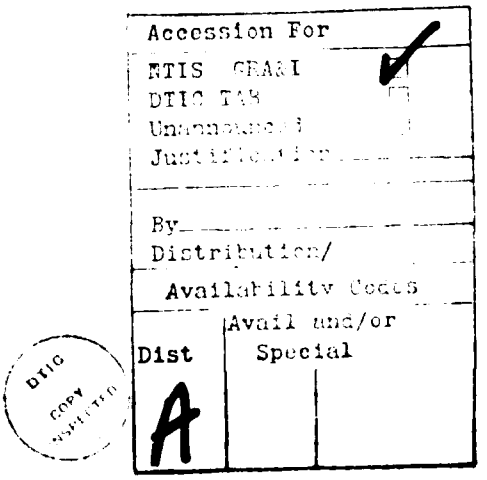
W H Steier
William H. Steier
Director

Enclosures

FOREWORD

The Joint Services Electronics Program [JSEP], a mutual undertaking of the Army, the Navy, and the Air Force, is organized to provide the Department of Defense with basic research capabilities in electronics and related sciences areas. The University of Southern California has been participating in the JSEP since 1963. Faculty in the departments of Electrical Engineering, Materials Science, Computer Science, and Physics participate in this program.

JSEP research projects at USC are currently in three areas: Solid State Electronics, Quantum Electronics, and Information Electronics. This report presents summaries of the accomplishments and progress for each of the projects [work units] which were active during the contract period of 1 April 1982 to 31 March 1983 under contract F49620-81-C-0070.



Chief, Technical Information Division

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

This annual technical report summarizes accomplishments and progress of fifteen (15) projects (work units) which were active during all or part of the reporting period of 1 April 1982 to 31 March 1983 under contract F49620-81-C-0070 at the Electronic Sciences Laboratory of the University of Southern California under the Joint Services Electronics Program.

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UNIVERSITY OF SOUTHERN CALIFORNIA

JOINT SERVICES ELECTRONICS PROGRAM

SIGNIFICANT ACCOMPLISHMENTS

1 April 1982 - 31 March 1983

WORK UNIT IE2-2

OPTICAL INFORMATION PROCESSING: PROCESSING OF IMAGES WITH SIGNAL-DEPENDENT NOISE

A.A. Sawchuk and T.C. Strand have developed several techniques for modeling systems with signal-dependent noise such as coherent speckle and Poisson noise. The models include first and higher-order statistics. They have also developed several image models that incorporate nonstationary mean, variance, and covariance. These models have been used in several novel restoration and recursive filtering schemes to reduce the effects of noise in imaging and pattern recognition applications. These filtering methods include a local linear minimum mean-square error (LLMMSE) processor, a recursive LLMMSE processor, maximum a posteriori (MAP) and maximum likelihood (ML) estimators. Applications of these techniques include synthetic aperture radar (SAR), sonar, acoustic imaging, active IR imaging, and low light level imaging.

WORK UNIT QE2-2

LASER SPECTROSCOPIC STUDIES OF FUNDAMENTAL PROCESSES IN ELECTRICALLY EXCITED GASES

During the past year, Martin Gundersen and his team developed a theory for the steady-state behavior of the hydrogen thyratron switch, and obtained additional results bearing on the use of other gases and switch materials. Thus, for the first time, a fundamentally correct theory of the plasma processes occurring during the conductive phase of an important high power switch has been developed. This was made possible by a theoretical study that utilized data obtained from spectroscopic studies of operating hydrogen thyratrons. These results are expected to lead to significant improvements in the switches that the Department of Defense uses for pulsed power applications, such as lasers and particle beams. These results will encourage the further development of the understanding of the role of microscopic processes, as they occur during the operation of real devices, either through the use of Monte Carlo codes, or other analytical methods. There will be continued development of these spectroscopic studies in the coming year, particularly with

regard to the study of very fast processes, such as those occurring during electrical breakdown.

Several additional aspects of this work, related to the spectroscopic studies, deserve mention. Helium was studied as a thyratron gas, and was found to be a serious candidate for use as a high voltage, high power, fast recovery switch. A study of cathode materials indicates that high current cold cathodes should be possible, employing field emission as a mechanism. A spectroscopic method of determining the electron temperature was developed, and a theory describing the production of atomic hydrogen was obtained. The transport properties of the hydrogen thyratron plasma were determined. These results should significantly impact the development of pulsed power for Department of Defense applications.

HETEROJUNCTION MATERIALS WITH REDUCED DIMENSIONALITY

GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION

Work Unit SS2-1

P.D. DAPKUS

REPORT PERIOD: 1 September 1982 to 31 March 1983

RESEARCH OBJECTIVES

The objectives of this project are to grow, optimize and utilize in new devices, heterojunction materials containing thin quasi two dimensional layers of selected semiconductor materials. Central to these studies is the use of metalorganic chemical vapor deposition (MOCVD) as a means to grow the layers. The near term objective of the project is the establishment of a state of the art MOCVD facility at USC and the initiation of growth studies to better understand and characterize the initial stages of growth of heterojunctions. To accomplish these tasks the design of a reactor, gas handling system, and waste gas disposal system were required. In addition, the renovation of existing laboratories to meet safety standards was required. To facilitate the analysis of the gas composition and the composition of the crystal surface apparatus for mass spectroscopy, laser induced flourescence and ellipsometry were required. Other ancillary analysis and measurement equipment will also be established to characterize the materials and devices fabricated in this project.

STATUS OF THE RESEARCH EFFORT

Significant progress towards the establishment of a state of the art facility for the growth of heterojunction materials by MOCVD has been made since September when this project began. Laboratory space has been allotted for epitaxial growth, materials analysis, device processing and device testing. The crystal growth facility has been designed and equipment ordered to facilitate the storage of the required gases. A plan to increase the ventilation in the laboratory to meet the safety standards has been approved and construction is to begin soon. A high purity water supply has been ordered and will be installed in a newly-purchased process hood. Laminar flow work benches have been added to the facility to improve cleanliness and complement the crystal growth activities.

A state of the art MOCVD gas handling system has been designed and ordered from Nav-Tec, Inc. The system is unique in that it is designed to operate two separate reactor chambers and is equipped to grow compounds containing any combination of Ga, Al, In, As and P. The system is designed to be fully automated by an Apple computer with an Isaac interface. The time resolution for process steps is determined by the switching time of the pneumatic valves and is less than 1 sec. All the ancillary valves and tubing to construct the injection manifold for the reactor have been received and construction of the InGaAs-InP reactor will begin soon. The system will be capable of atmospheric or reduced pressure growth.

Bubblers have been designed that facilitate etching and cleaning prior

to filling and are being constructed. All gases and organometallics required for growth have been ordered following a careful screening of vendors. As soon as the gas flow panel has arrived interfacing of the computer will be completed and final assembly of the injection manifold will be completed.

In addition to the crystal growth facility described above a laboratory for materials characterization and device processing is being established. Photoluminescence, Hall effect and C-V profiling as well as optical microscopy are being installed as the fundamental characterization tools. A station for the CVD deposition of Si_3N_4 and SiO_2 has been designed and built and a sputtering unit is being retrofitted for deposition of Si_3N_4. The aim of this activity is the ability to fabricate simple devices such as lasers, detectors and FET's. Photolithography, metal deposition and device separation capabilities presently exist.

Proposals and white papers have been submitted in support of this project. Recently a grant for the purchase of equipment to analyze the chemical kinetics of MOCVD growth in the DoD-University equipment program was awarded to USC. This equipment will be used on this project to analyze the kinetic processes involved in the growth of heterostructures.

It is expected that growth of crystals will begin in the summer and will begin by the growth of GaAs and InGaAs. We will then progress to InP and superlattices.

PUBLICATIONS

None. (Note: this project began 1 September 1982.)

PROFESSIONAL PERSONNEL

1. P.D. DAPKUS, Principal Investigator, Professor of Electrical Engineering and Materials Science
2. ALLEN DANNER, Research Assistant
3. MARK INNOCENZI, Research Assistant
4. VIJAYA WICKREMARACHCHI, Research Assistant

DOD INTERACTIONS

None. (Note: this project began 1 September 1982.)

MBE GROWTH OF GA AS/AL GA AS TUNNELING DEVICES

Work Unit SS2-2

M. GERSHENZON

REPORT PERIOD: 1 April 1982 to 31 March 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 superlatices 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, $1\,\mu m$ n (10^{17}) GaAs buffer, undoped $Al_xGa_{1-x}As$ barrier, with x = 0.3, 1 μm n(10^{17}) GaAs, 0.5 μm 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 ^{o}C, with a As$_4$ to Ga flux ratio of 3:1 and proceeding at a rate of 1 μm/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 ^{o}K electron mobility at low donor doping was quite acceptable, and the interfaces between differently doped layers exhibited a sharpness of at least 100 ^{o}A. 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 transfered 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^{o} 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 1 μm/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 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 1 μm/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^{-10} 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 $Al_{.3}Ga_{.7}As$ 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

OPTICAL PROPERTIES & THERMAL ANNEALING OF ION IMPLANTED SEMICONDUCTORS

Work Unit SS2-3

WILLIAM G. SPITZER & C.N. WADDELL

in collaboration with

J.E. FREDRICKSON

California State University at Long Beach

GRAHAM HUBLER

Naval Research Laboratory, Washington, D.C.

REPORT PERIOD: 1 April 1982 to 31 March 1983

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

In previous reports we have emphasized the use of computer models of the dielectric properties as functions of depth for heavily implanted Si samples in order to fit the observed reflection spectra. In cases where the implantation was such as to produce a continuous a-Si layer the

modeling produces several physically interesting parameters and constitutes a method for non-destructive diagnostic testing. For this information and method of analysis, please consult the earlier progress reports.

It was also pointed out in the last progress report (4/1/81-3/31/82) that a-Si produced by ion implantation appears to have two metastable states. The first state is the as-implanted one which is characterized by a large infrared refractive index [$n_D(\nu)$ approximately 12% larger than that for crystalline material], a large EPR measured dangling density [approximately 2×10^{19} cm^{-3}], and a mass density about 2% less than that for the crystalline material. The second state is achieved after a short annealing time at 500 °C and is characterized by a significant reduction in both $n_D(\nu)$ and the dangling bond density but no change in the mass density from that of the first state.

We have just completed measurements of a set of Si samples which substantiate the prior results and demonstrate the independence of the results of almost all implantation related parameters. Samples were implanted with 400 keV ions of ^{12}C, 400 keV ions of ^{29}Si, and 2 MeV ions of ^{120}Sn. In the ^{12}C and some ^{29}Si cases the energy given is the maximum value of a multienergy implantation. The fluences were such that a continuous a-Si layer was formed from the front surface of the sample. It was found that $n_D(\nu)$, the EPR deduced dangling bond densities, the fundamental absorption edge, and the change in mass density for the a-Si, were each the same for all three implanted ion species. Annealing experiments were done for annealing temperatures of

400 °C and 500 °C and the changes in n_D and spin densities, as well as the lack of change in mass density, were the same for all three cases. Moreover, measurements for anneal temperatures between 400 °C and 600 °C showed that the anneal-stabilized value of $n_D(\nu)$, called $n_D'(\nu)$, is the same. These results are being prepared for publication. At the present time we are measuring a series of ^{120}Sn implanted samples to determine the role of the ion fluence on the metastable state properties. The infrared measurements will be compared directly with transverse TEM micrographs for both as-implanted and annealed samples. (The TEM work is being done by Dr. Devendra Sadana at U.C. Berkeley).

Some measurements of the infrared reflection and transmission of GaAs implanted with large fluences Be ions have been made in collaboration with Prof. Sook-Il Kwun of Seoul National University in Korea. It is observed that annealing up to 400 °C results in decreases in the lattice disorder responsible for changes in the dielectric constant. Unlike similarly implanted Si or thin amorphous layers in GaAs, the dielectric constant recovery is non-epitaxial. Annealing for 2 h at 400 °C returns the refractive index to essentially the pre-implanted value with no carrier activation being observed (Be is an acceptor in GaAs). Carrier activation is observed only after prolonged annealing at 400 °C, i.e. >50 h. These observations are being extended to determine whether the removal of the disorder induced changes in the dielectric constant and the carrier activation processes involve the same or different annealing mechanisms.

PUBLICATIONS

1. "Electrical and Structural Characterization of Implantation Doped Si by Infrared Reflection" by G.K. Hubler, R.P. Malmberg, C.N. Waddell, W.G. Spitzer, and J.E. Fredrickson, Rad. Eff. 60, 35 (1982).

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

3. "Properties of Amorphous Si produced by Ion Implantation: Thermal Annealing" by W.G. Spitzer, G.K. Hubler, and T.A. Kennedy, 16th International Conference on Ion Implantation, September 1982 in Grenoble, France, also Nucl. Inst. and Methods (in press).

4. "Low Temperature Annealing of Be-Implanted GaAs" by Sook-Il Kwun, Chong-Han Hong, and W.G. Spitzer, J. Appl. Phys. (in press).

5. "Amorphous Silicon Produced by Ion-Implantation: Effects of Ion Mass and Thermal Annealing" by C.N. Waddell, W.G. Spitzer, J.E. Fredrickson, G.K. Hubler, and T.A. Kennedy, submitted to J. Appl. Phys.

PROFESSIONAL PERSONNEL

alphabetical order

1. J.E. FREDRICKSON, Professor of Physics, California State University at Long Beach (work done at USC).

2. G.K. HUBLER, Research Scientist, Naval Research Laboratory, Washington, D.C.

3. T. A. KENNEDY, Research Scientist, Naval Research Laboratory, Washington, D.C.

4. SOOK-IL KWUN, Professor of Physics, Seoul National University.

5. W.G. SPITZER, Principal Investigator, Professor of Materials Science and Physics, USC.

6. C.N. WADDELL, Associate Professor of Physics, USC.

ELECTROOPTIC MATERIALS AND OPTICAL IMAGE STORAGE DEVICES

WORK UNIT SS2-4

A.R. TANGUAY, JR.

Report Period: 1 April, 1982 to 31 March, 1983

RESEARCH OBJECTIVES

(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, the Microchannel Spatial Light Modulator (MSLM), and Photorefractive Volume Holographic Storage Devices, and to establish the relationship between the relevant material properties and optimum device design parameters. These image storage devices are currently of interest for applications in incoherent-to-coherent conversion, and coherent optical signal and image processing.

(2) 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 Storage Devices.

(3) 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.

(4) 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

Substantial progress has been achieved in 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], Microchannel Spatial Light Modulator (MSLM) [25], photo-DKDP [26], and electron-beam-DKDP [27] image storage devices. 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 have 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 have 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 has been further extended to accommodate arbitrary charge distributions of significant physical interest. In particular, an iterative exposure-induced charge transfer and trapping model has been formulated to calculate the charge distribution throughout the electrooptic crystal layer resulting from optical exposure at various wavelengths. The charge distributions so obtained have been 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 a substantial improvement in the resolution as the wavelength approaches the band gap of the electrooptic crystal. Such improvements are quite striking in preliminary experimental device resolution tests. In addition, it has been 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 [28] and electron-beam [29] 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 device resolution [JSEP Pubs. 2,3,4,5,6,7,8,9,10,11,16].

In the past year, PROM-like structures have been investigated [31,32; JSEP Pubs. 5,9,10,11,16] that can 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 differently to 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,

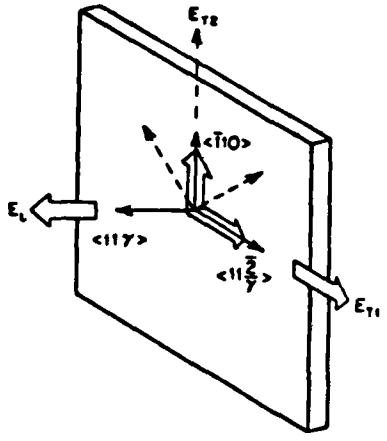

Fig. 1. Orientations of longitudinal and transverse electric fields, and their respective induced principal axes, for $Bi_{12}SiO_{20}$ (I23 symmetry). The longitudinal field (E_L) and one transverse field (E_{T1}) induce the same set of principal axes (open arrows), while the other transverse field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

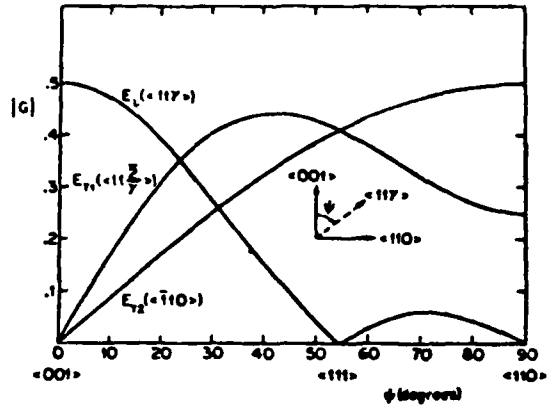

Fig. 2. Magnitude of retardation G induced by the three orthogonal field components defined in fig. 1 as a function of crystallographic orientation. The value of G is given in units of $\pi V_\alpha / V_\pi$ where α = L, T1, or T2; the quantities V_L, V_{T1}, and V_{T2} are defined in the text.

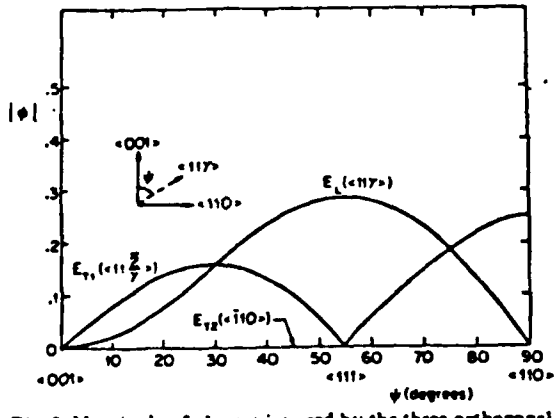

Fig. 3. Magnitude of phase ϕ induced by the three orthogonal field components defined in fig. 1 as a function of crystallographic orientation. The value of ϕ is given in units of $\pi V_\alpha / V_\pi$ where α = L, T1, or T2; the quantities V_L, V_{T1}, and V_{T2} are defined in the text.

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	$\frac{\pi V_{T1}}{4V_\pi}$
Signal G	$\frac{\pi V_L}{2V_\pi}$	0	0	0	$\frac{\pi V_{T2}}{\sqrt{6}V_\pi}$	$\frac{\pi V_{T1}}{\sqrt{6}V_\pi}$	0	$\frac{\pi V_{T2}}{2V_\pi}$	$\frac{\pi V_{T1}}{4V_\pi}$

which can easily be related to the modulation transfer function of the device. Experiments to date confirm all of the 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. 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. 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. 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.

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 have been obtained which suggest that the applied field distribution within the bulk of the electrooptic crystal prior to exposure is quite uniform (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. 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.

During the contract year, 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 high precision and 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 recent 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. Doping experiments are proceeding in concert with photoconductivity, photoluminescence, and thermally stimulated current measurements to determine the optical and thermal levels induced by incorporated impurities. Such experiments are being undertaken in hopes of modifying the band edge absorption to increase

readout gain, and of broadening the photoconductivity spectrum to permit sensitive exposure in the visible (450 - 550 nm).

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 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, and programmable bandpass filtering 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 has been undertaken. Preliminary results have explained the

optimum orientations for diffraction efficiency and energy coupling, and have as well provided closed form solutions for the diffracted order polarizations in the limit of low exposures [JSEP Pub. 12].

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I. Journal Publications and Proceedings Manuscripts

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3. "Exposure-Induced Charge Distribution Effects on the Modulation Transfer Function (MTF) of Electrooptic Spatial Light Modulators", Proceedings of the SPIE International Symposium, Los Angeles, February (1980), 218, 67-80, with Y. Owechko.

4. Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators. I. Fundamental Considerations", accepted for publication in Journal of the Optical Society of America, (in press), with Y. Owechko.

5. "Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators. II. Effects of Crystallographic Orientation", accepted for publication in Journal of the Optical Society of America, (in press), with Y. Owechko.

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II. Conference Presentations

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III. Theses

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PROFESSIONAL PERSONNEL

1. Armand R. Tanguay, Jr., Principal Investigator.
2. Yuri Owechko, Research Assistant.
3. Leroy Fisher, Research Assistant.
4. Frank Lum, Senior Engineering Technician.

INTERACTIONS

Interaction With Other Work Units:

A significant interaction has 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 are being 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 T.C. Strand, 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 the contract period an important collaboration agreement was continued with the Itek Corporation, Lexington, Massachusetts (Dr. Ralph Aldrich, Project Manager). The agreement provides for advanced

technology and device fabrication support from Itek, while the USC effort is focused on device evaluation and understanding. The advanced PROM development work at Itek has been supported by several DOD agencies. In particular, a program on development of new PROMs with improved resolution characteristics was supported by Dr. Robert Leighty of the Army Engineering Topographical Laboratory through the Army Research Office, Durham. Dr. Ralph Aldrich of Itek Corporation visited USC in June, 1979, and in April, 1980, for technical discussions. One of us (ART) has visited Itek on numerous occasions for collaborative interaction, most recently following the Gordon Research Conference on Information Processing and Holography in New Hampshire, June, 1982. Dr. Leighty visited USC in February, 1980, and was briefed at ETL (Fort Belvoir) about current research progress in April, 1980. He has subsequently been briefed concerning recent research developments, most recently at the Gordon Research Conference.

2. During April, 1978, 1979, 1980, 1981, and 1982, visits to USC by Dr. John Neff 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). Dr. Neff will continue to be briefed on our progress as it relates to Air Force optical device and optical information processing programs.

3. An invited paper on recent progress in spatial light modulators was presented at the ARO sponsored Workshop on Future Directions in Optical

Information Processing, Lubbock, Texas, May (1980). Recent progress on spatial light modulator research at USC was presented at the Army Research Office, Durham, in May, 1980.

4. Technical discussions concerning optimization and utilization of Photorefractive Image Storage Devices were held at USAF/RADC, Hanscom AFB, Massachusetts with J. Ludman, J. Horner, and W. Miceli in August, 1980, and in June, 1982. Dr. Ludman has subsequently been briefed concerning recent research developments during a visit to USC in July, 1982, and during extensive meetings at the Gordon Research Conference and DARPA MRC Symposium.

5. 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), and with the Jet Propulsion Laboratory/NASA (T. Bicknell).

6. 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.

7. One of us (ART) will be an invited participant in an AFOSR and ARO-sponsored workshop "Optical Techniques for Multi-Sensor Array Processing", Pine Mountain, Georgia, May 9-11, 1983.

STUDY OF THE TEMPERATURE DEPENDENCE OF THE GAIN & SATURATION ENERGY IN GA IN AS P SEMICONDUCTOR LASERS

Work Unit QE2-1

E. GARMIRE

REPORT PERIOD: 1 April 1982 to 31 March 1983

RESEARCH OBJECTIVES

The principal objectives of this research effort are to: 1) determine the limitations which temperature effects place on the performance of semiconductor lasers operating at 1.3 - 1.6 μm wavelengths, which are currently being developed for use in optical communications; and 2) investigate ways to decrease this temperature dependence and to improve the lasers' performance. This will be done by direct measurement of gain and saturation energy in GaInAsP lasers as a function of temperature from 77 ^{o}K to above room temperature. Double heterostructure lasers will be fabricated by LPE. Composition will be varied to provide operating wavelengths throughout the range of interest for optical communications.

STATUS OF RESEARCH EFFORT

1982-83 was the first year of this program, and the experimental effort concentrated on completing the in-house laser fabrication and test facility. We have completed the LPE fabrication facility, which is operational and is growing laser-quality wafers at a rate of one per

week, when required. Figure 1 is a schematic of this system.

We have grown a number of wafers designed to operate as lasers at 1.3 μm. Their layer structure is shown in the following table:

TABLE - PROPERTIES OF LASER WAFERS GROWN

$In_{1-x}Ga_xAs_yP_{1-y}$

layer	x	y	dopant	thickness	carrier concentration
n-isolation	0.03	0.10	Sn	3.3 μm	2×10^{18} n-type
active	0.29	0.63	none	0.2 μm	intrinsic
p-isolation	0.03	0.10	Zn	2.6 μm	5×10^{18} p-type

This structure has been shown[1] to make excellent lasers at 1.3 μm.

The quality of the epitaxial material which this new system is producing is exceedingly high, and there are no problems with lattice matching. This system was developed with the assistance of Navin Patel, Visiting Professor from the University of Campinas, Brazil. The procedure which we have implemented in our laboratory is based on work reported in the thesis of F.C. Prince, entitled "Fabrication and Characterization of Semiconductor Lasers in InGaAsP at 1.3 μm" submitted to the University of Campinas, Brazil, May, 1981.

The fabrication procedure for laser diodes from epitaxial wafers has recently been completed. We are using evaporated contacts. The n-side has 3000 $\mathring{A}$ of Au-Ge, followed by 700 $\mathring{A}$ of Ni, and the p-side has 1400 $\mathring{A}$

of Au-Zn. The contacts are annealed in flowing H_2 for two minutes at 400 °C. We are using traditional cleaving and bonding techniques. The first diodes have been fabricated and are currently waiting to be tested.

Finally, we have completed assembling the apparatus for analyzing the properties of these laser diodes. A diagram of the facility is shown in Figure 2. Particular emphasis is placed on spectral measurements as well as near and far field intensity profiles for pulsed, as well as cw, excitation. This apparatus has been tested with 0.83 μm laser diodes, and we are currently preparing to make long-wavelength measurements.

An important step achieved this year was a comparative study of the best way to measure gain in GaInAsP lasers to determine its temperature dependence. We considered five techniques:

1. Studies of spontaneous emission spectra from laser diodes.[2]
2. Studies of amplified spontaneous emission from optically pumped samples of variable length.[3]
3. Measurements of gain in diodes with multiply segmented contacts by measuring spontaneous emission as a function of the length of carrier injection.[4]
4. Amplification in cleaved-substrate diodes, which separate the laser from the amplification regime.[5]
5. Discrete diode amplification, in which light from a laser is focussed into an amplifier.[6]

After careful study, we selected technique #3 as the one we will use.

Technique #1 was eliminated because the determination of gain from spontaneous emission spectra requires very careful measurement of the intensity ratio between maxima and minima of the Fabry-Perot resonances in spontaneous emission. Without an automated data acquisition system, we decided these measurements would be difficult to implement over a range of temperatures.

Measurements of amplified spontaneous emission as a function of gain length give the gain directly. This has been demonstrated by optical pumping in InGaAsP over a wide temperature range.[3] Technique #3 is a direct extension of this method to current injection pumping. The multiply segmented contacts we are designing make possible a variation in gain length both below and above threshold for laser action. In addition, it will be possible to make an independent measurement of absorption loss in unpumped regions, which is not possible with technique #1. We believe this planned experiment will give accurate information on gain in GaInAsP lasers over a wide variety of temperatures and wavelengths.

We have eliminated technique #4 from consideration because the introduction of an additional cleave to form a laser-amplifier is not necessary and introduces problems with coupled oscillators.[5] Finally, use of a discrete amplifying diode requires careful optical alignment between laser and amplifier[6], as well as a careful frequency match which is difficult to obtain over a range of temperatures.

The multiply segmented contact method requires separately pumping various portions of the laser stripe. We have designed our initial

experiments to take place with three-segment contacts, mounted p-side up. The reason for the third segment is to avoid laser oscillation during the injection pumping of two adjacent segments. These experiments will, of necessity, be with pulsed excitation. In order to study gain during cw operation, it will be necessary to design segmented contacts which may be mounted p-side down with the individual segments separately contacted. In order to implement this requirement, we have studied the possibility of using an electrically insulating heat sink. Either type II diamond or highly resistive silicon may be used in a design such as that shown in Figure 3. The regions where the multiply segmented contacts will be formed are opened up as windows in a protective oxide layer. The contacts are plated, rather than evaporated, which will ensure metal only inside the windows. This is followed by plating a thick layer of indium in the contact windows, which will act as a bonding and heatsinking medium to connect the ohmic contacts to the semi-insulating silicon heat sink. Finally, the heat sink is prepared with an electrode pattern which will allow electrical contact to be made to the three separate segments. The diode is attached p-side down to the heat sink, with thermo-compression, so that the thick indium pads soften and wet the electrodes on the insulating heat sink. Care must be taken so that the separate indium contacts do not fuse. Our studies show that this bonding is best done under a reducing atmosphere. Preliminary studies indicate that spacings of 25 μm between contacts are sufficient to maintain the integrity of the separate contacts.

At the end of this first year, we have mounted diodes p-side up and

experiments are just beginning to measure gain and laser action under pulsed conditions.

REFERENCES

1. F.C. Prince, N.B. Patel, D.J. Bull, "Three Layer 1.3 μm InGaAsP DH Laser With Quaternary Confining Layers", IEEE J. Quantum Electr., QE-17, 597 (1981).

2. J.N. Walpole, T.A. Lind, J.J. Hsieh, and J.P. Donnelly, IEEE J. Quantum Electr., QE-17, 186 (1981).

3. E.O. Goebel, G. Luz, E. Schlosser, IEEE J. Quantum Electr., QE-15, 697 (1979).

4. J.K. Carney, C.G. Fonstad, Appl. Phys. Lett. 38, 303 (1981).

5. M.B. Chang, E. Garmire, IEEE J. Quantum Electr., QE-16, 997 (1980), "Amplification in Cleaved Substrate Lasers."

6. T. Mukai, Y. Yamamoto, IEEE J. Quantum Electr. QE-17, 1028 (1981).

PUBLICATIONS

There were no publications in this technical area by Garmire and co-workers in the past year since this was a new-start.

PROFESSIONAL PERSONNEL

ELSA GARMIRE, Principal Investigator

TOM HASENBERG, Graduate Research Assistant

TONY TSAI, Graduate Research Assistant

STEVE WALLACE, Undergraduate Assistant

CHARLES WHITE, Student Assistant

INTERACTIONS WITH OTHER WORK UNITS

We have been working with researchers from the Molecular Beam Epitaxy laboratory of Professor Gershenzon, supported partly by JSEP, collaborating on contacting and testing laser diode material fabricated by MBE.

We developed our proposed procedure for fabrication of multiply- segmented contacts on highly resistive silicon by discussing with Professor Tanguay, whose research is also supported in part by JSEP, electro-optics devices which use proximity-coupling of fields from silicon driver chips into LiNbO modulators.

DOD INTERACTIONS

- Wafer material and contacting and bonding techniques have been traded and compared with the Electronics Research Laboratory - The Aerospace Corporation. This interaction has speeded our progress and also given useful suggestions to their laboratory.
- A talk entitled "Improved Semiconductor Lasers" was given at the BMD/ATC meeting on "Applications of Opto-Electronics" at La Jolla Institute, March, 1982.
- A talk entitled "Studies of Integrated Optics Devices" was given at the NSF Grantee-User Meeting on Optical Communications, June, 1982 at Berkeley.
- Consulting to DARPA through La Jolla Institute, preparation of report entitled "Potential of Very Large Arrays of Semiconductor Sources" delivered October, 1982.

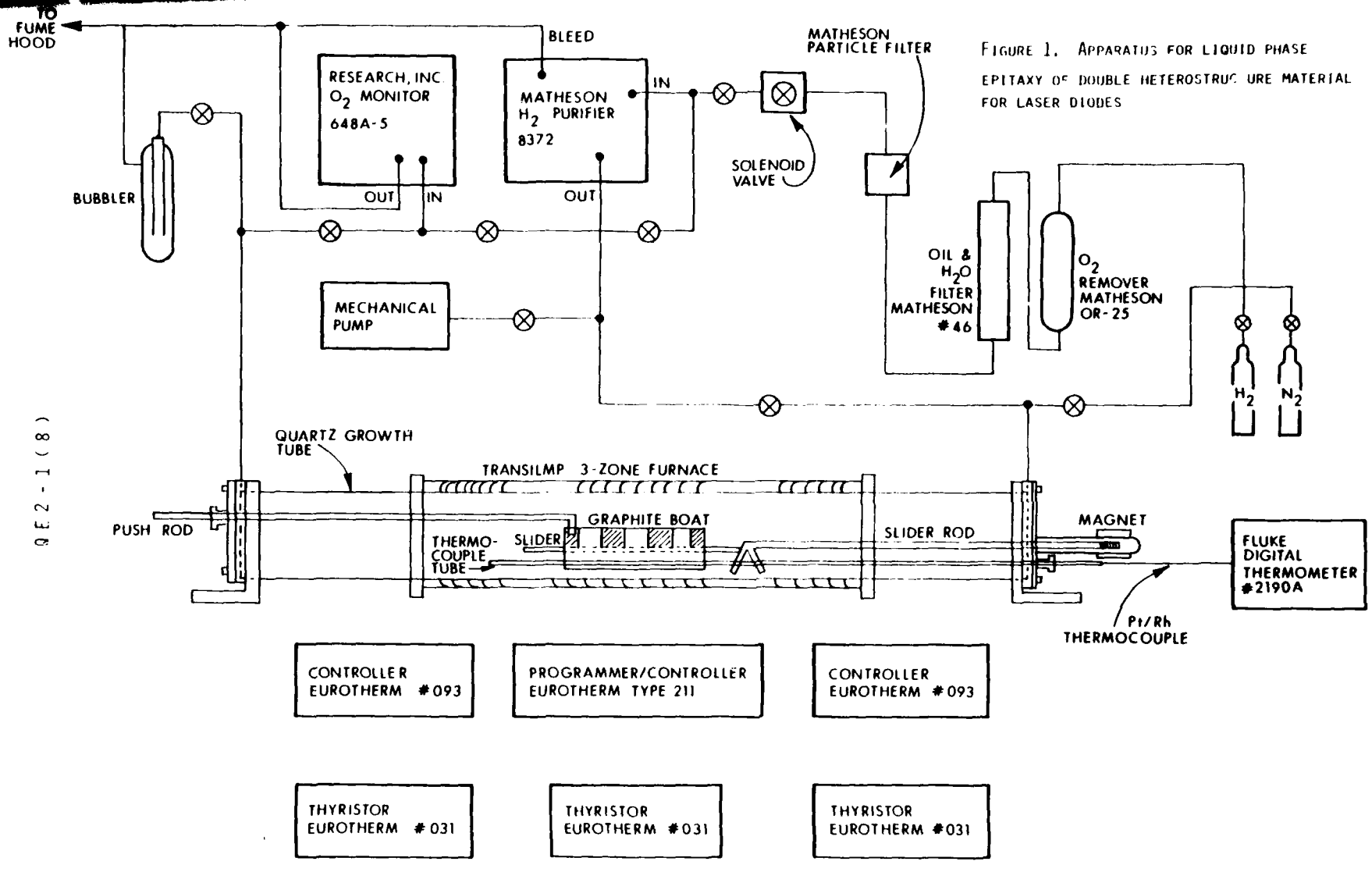


FIGURE 1. APPARATUS FOR LIQUID PHASE EPITAXY OF DOUBLE HETEROSTRUCTURE MATERIAL FOR LASER DIODES

QE2-1(8)

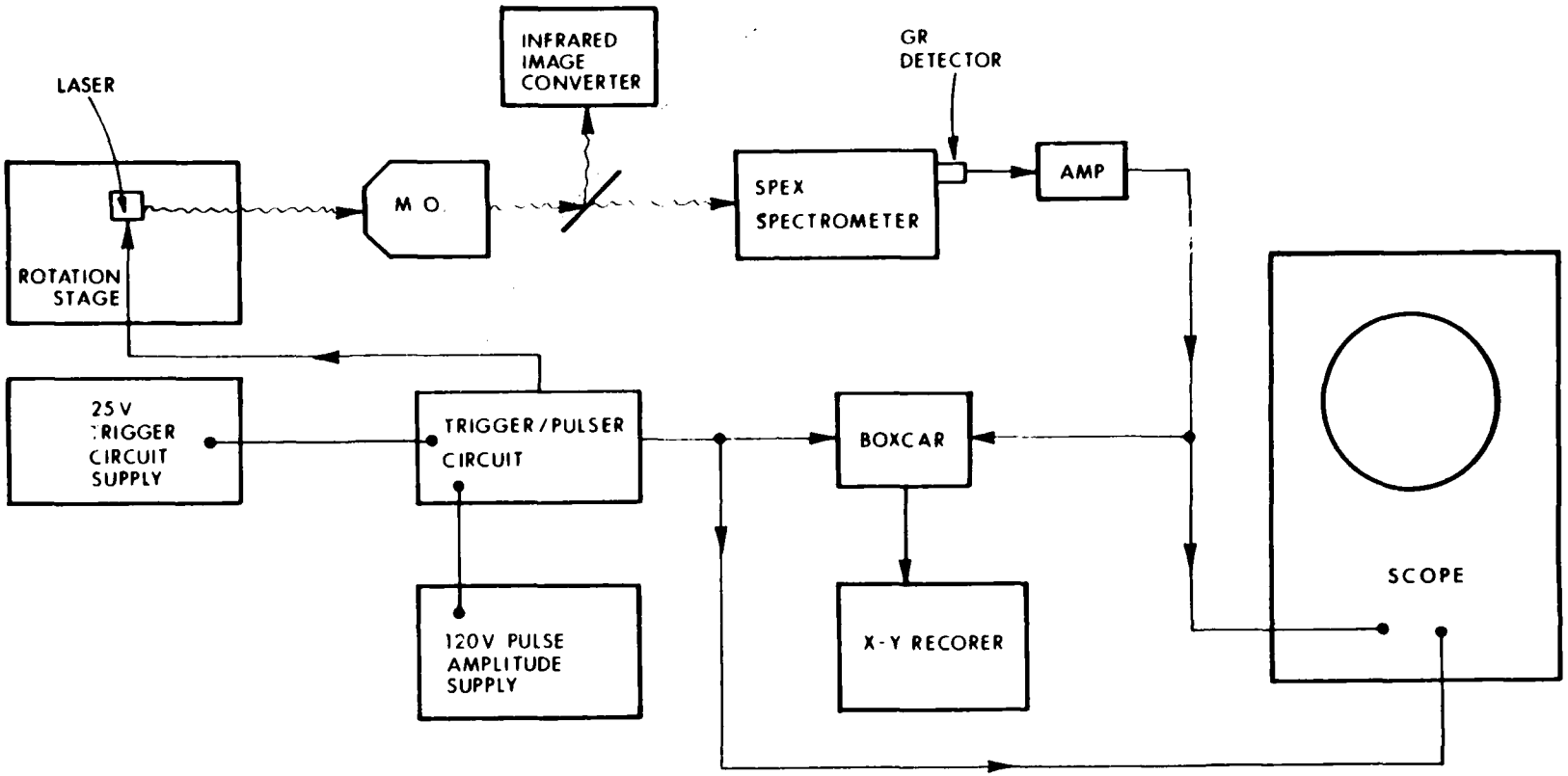


FIGURE 2. APPARATUS FOR THE STUDY OF THE GAIN IN SEMICONDUCTOR LASERS

JSEP ANNUAL REPORT

March 31, 1983

(1) **A SPECTROSCOPIC STUDY OF BASIC PROCESSES IN ELECTRICALLY EXCITED MATERIALS**

(2) Martin Gundersen
April 1, 1982 - March 31, 1983

(3) **RESEARCH OBJECTIVES**

This work has as its objective a scientific understanding of processes that are important in electrically excited materials and in the area of pulsed power. In order to accomplish this, it is necessary to develop specific spectroscopic data needed to understand gas phase switches. These data are used to develop theoretical models of plasma and cathode behavior in switching. An example is the characterization of the hydrogen plasma processes in a hydrogen thyratron. This work complements in an essential way other research directed towards the development of new switches for pulsed power.

(4) **STATUS OF RESEARCH EFFORT**

The following accomplishments are of importance to DoD programs:

1. The helium thyratron.
2. The field emission cathode model.
3. The theory of the glow-discharge switch, which we have developed for the steady-state phase of the hydrogen thyratron.

These results should impact the problem of high repetition rate, high power switching.

During this period, we have

- Developed a spectroscopic method of measuring electron temperatures in the thyratron discharge.

- Determined pertinent transport coefficients (diffusion, mobility, conductivity) in the thyratron-type glow discharge.

- Developed a model for a new field emission cathode. This cathode is very important for high current switches.

- Operated thyratrons with helium, as well as other gases. The properties of helium in the thyratron are important for the development of improved high power switches. We have observed a more rapid recovery using helium.

- Developed a theory for the production of atomic hydrogen in a thyratron discharge.

We have published considerable material relating to the fundamental processes occurring in hydrogen thyratrons. Recent experimental data pertaining to electron densities, energies, and excitation processes occurring in devices during their normal operation have been presented. Electron densities are observed to be lower than 2×10^{14} cm^{-3}, corresponding to (higher) current densities of 50 to approximately 100 A/cm^2. The presence of both molecular and atomic species affecting recovery and voltage reerection were reported. Streak camera data showing a delay in breakdown of the grid-anode relative to the grid-cathode region were also presented.

The scalar conductivity, electron diffusion and mobility have been calculated for a hydrogen plasma in the cathode-grid region of a hydrogen thyratron, assuming neutral pressure about 0.5 Torr, electron temperature 1 eV, electron density $N_e \sim 10^{14}$, and electric field E_p = 5-10 V/cm. the role of coulomb collisions is considered, and it is shown that coulomb collisions are important in the plasma.

Results of a study of helium as a thyratron medium were reported. Data was presented suggesting that for some applications helium will have advantages over hydrogen, including faster recovery.

Field emission was identified as a mechanism responsible for high current emission from a dispenser-type cathode. This particular cathode has significant advantages over thermionic cathodes and other field-emitter cathode, especially for high power operation.

The net production of atomic hydrogen in a hydrogen plasma with $\sim 10^{16}$ cm^{-3} neutral, 10^{14} cm^{-3} electron and an electron temperature $T_e \sim 1$ eV was analyzed. It was found that the dissociation degree $y = N_H/N_{H_2}$ is equal to about 0.1 - 0.2. The production of atomic hydrogen in devices such as hydrogen thyratrons is an important factor in determining the operational limitations.

The electron temperature in hydrogen plasmas that are characteristic of hydrogen thyratrons was considered. The electron temperature is dependent on several different collisional and radiative processes, and its determination by measurement of the ratio of Balmer line intensities is

complicated by this. These processes were considered in detail, and the electron temperature was determined for conditions that apply to operating thyratrons. The results were summarized so that they may be used as an in situ measurement method.

(5) WRITTEN PUBLICATIONS IN TECHNICAL JOURNALS

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

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

"Tunable pump laser stabilization of the CF_4 laser," M.A. Gundersen and T.A. Yocom, IEEE J. Quantum Electron. **QE-18**, 1237 (1982).

"A simple pulsed HF laser for optical experiments," T.A. Yocom, M.A. Gundersen, and A.H. Bushnell, Appl. Opt. **21**, 757 (1982).

"A new nitrogen related recombination in GaP." P.G. Snyder and M.A. Gundersen, Phys. Rev. B, Feb. (1983).

"A non-radiative recombination in $GaAs_{.61}P_{.39}$:Ge," P.G. Snyder, M.A. Gundersen, C.W. Myles, H.G. Henry, and E.G. Bylander, J. Phys. Chem. Sol., accepted for publication.

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

"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).

"Scalar transport coefficients for the hydrogen plasma in the cathaode-grid region of a thyratron," J. Kunc and M. Gundersen, J. Appl. Phys., accepted for publication.

"Field emission cathode," R. Petr and M. Gundersen, Laser and Particle Beams, accepted for publication.

"A fundamental theory for high power thyratrons in the electron temperature," J.A. Kunc, S. Guha, and M.A. Gundersen, Laser and Particle Beams, accepted for publication.

"Production of atomic hydrogen in a hydrogen thyratron," J.A. Kunc and M.A. Gundersen, Laser and Particle Beams, submitted.

"Fundamental processes in thyratrons," M.A. Gundersen, J.A. Kunc, and S. Guha, accepted for Proceedings Electron-tubes, Nachrichtentechniscum Gesellshaft in Verband Deutscher Electrotechniker, May 1983, submitted.

"Optical processes in laser-controlled gas-phase switches," M.A. Gundersen, Electro-Optic System Design, 25, June 1982.

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

A number of manuscripts will be submitted soon.

(6) **PERSONNEL**

Martin A. Gundersen
Christopher Braun
Daniel Erwin
Howard Cole

(7) **INTERACTIONS**

Consultative Interactions:

Consultant to Los Alamos National Laboratory and Mathematical Sciences Northwest.

Participant in a review of the state-of-the-art of certain aspects of High Power Switching.

Other Interactions:

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

"Fundamental processes in hydrogen thyratrons," Fifteenth Power Modulator symposium, June 14, 1982, with S. Guha, H. Cole, and J. Kunc.

"Basic research in hydrogen thyratrons," presented at Math Sciences Northwest, Seattle, WA, July 20, 1982.

Air Force Weapons Laboratory, Shiva and Trestle programs, August 1982.

"Plasma processes in hydrogen thyratrons," 35th Gaseous Electronics Conference, October 19, 1982, with J.A. Kunc and S. Guha.

"Optical energy extraction," Workshop on Optically Contrlled Diffuse Discharge Switches, Eugene, Oregon, December 2, 1982.

"Laser related research," Defense Contract Regional Administrative Officers meeting at USC, December 6, 1982.

Helped arrange for Engineering students to visit White Sands Missile Range, Yuma, and Fort Huachucha. This trip was organized by Major General Koehler (WSMR) and Lt. Col. Knapp (USC).

"A new radiative recombination in GaP," P.G. Snyder and M. Gundersen, March 1983, American Physical Society Meeting, Bull. Am. Phys. Soc. **28**, 412 (1983).

"Electronic cross section for excitons bound to ZnO pairs in GaP," P.G. Snyder, M. Gundersen, and C.W. Myles, March 1983, American Physical Society Meeting, Bull. Am. Phys. Soc. **28**, 413 (1983).

(8) **NEW DISCOVERIES**

The helium thyratron. This offers certain advantages for very high power, high repetition rate applications.

LASER DEVICES AND APPLICATIONS

Work Unit QE2-3

WILLIAM H. STEIER

REPORT PERIOD: 1 April 1982 to 31 March 1983

RESEARCH OBJECTIVES

The object of this research is the study of non-linear materials in the ultraviolet and their use in devices and systems. The current emphasis is on saturable dyes for the UV.

STATUS OF RESEARCH EFFORT

During the past period we have continued the short pulse saturation measurements on dyes in the ultraviolet. These dyes would be candidates for modelocking of UV excimer lasers and for interstage isolation of large UV amplifier chains.

In the experimental setup a portion of the XeCl laser (308 nm) output triggers a switch (Lasermetrics SG201) which allows a 1.5 KV voltage wave front to propagate to one electrode of $KD^{x}P$ 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^{o} 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. This

system chops a pulse from the ~40 n sec laser output. The pulse length is the pulse transit time of the cable connecting the two electrodes on the modulator.

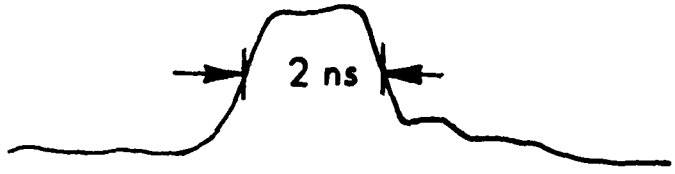


Fig.1 Laser pulse used in short pulse dye saturation measurements

Figure 1 shows the output pulse when the cable length is set for ~1 nanosecond. The pulse energy is typically 0.1 millijoules; limited by losses in the various optical components in the chain. The pulse energy to leakage background energy ratio was typically 8:1.

Two different setups for measuring the dye transmission as a function of the pulse energy were tried. In the single detector scheme the reference pulse was delayed so that both the transmitted and reference pulse can be resolved by one detector. In the second, two detectors were used and the system carefully calibrated to correct for detector differences. The data from both setups was very similar but the two detector setup was finally selected for the measurements because of

convenience and higher accuracy. In our initial measurements, a consistent error was found due to the fluorescence of the dye. The UV attenuators were found to be low loss to the visible fluorescence and this gave an artificially large saturated dye transmission. This was corrected by using different attenuators and placement of the detectors. Much of the dye fluorescence occurs too close in wavelength to the exciting 308 nm to be blocked by filters. The dye cells were 0.5 mm thick with a 2 cm dia. aperture and used fused quartz windows.

Saturation measurements have been made on three UV dyes that are known to have large crossections at 308 nm and calculated relaxation times around 1 n sec. The results are shown in Figure 2 and refer to (A) Polyphenyl in ethylene glycol; (B) BPBD in cyclohexane, and (C) BBQ 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, $J_s = \frac{h\nu}{\sigma}$, 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. Given J_s, a theoretical 2 level short pulse saturation curve can be calculated. All of the measured dyes showed considerably more high energy loss than predicted. In each case however the short pulse energy density was not sufficient to show the limiting saturation, i.e. the plateau of the saturation curves could not be reached in the experiments.

Considerably higher pulse energies and peak intensities could be reached

if the full 40 n sec laser pulse is 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. In this case the limit on the high intensity transmission is reached and is never larger than 60-70%.

The data clearly show that some form of excited state absorption is present in all of the dyes measured. No dye showed the predicted degree of saturation in long or short pulse measurements. There is little data available on excited state absorption but we might expect it to be more pronounced in the UV. The size of the photon makes it more likely that a S1-->S2 or perhaps a T1-->T2 transition can be excited.

There is an alternate explanation that part of the saturation observed is due to photo-fragmentation of the dye molecules. The resulting fragments then show absorption in the UV. We are now setting up an experiment to determine if photo-fragmentation is occurring.

It seems clear that the excited state absorption will have a serious effect on attempts to mode-lock the excimer laser with these dyes and we suspect that most dyes will have similar properties to the three measured here. We are now working on an extension of the theory of passive mode locking to include excited state absorption. Excited state absorption may explain the lack of success by several laboratories to passively mode-lock in the UV.

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. W.E. Stephens and W.H. Steier, "Hybrid Optical-Digital Signal Processing Applied to an Optimal Nonlinear Phase Estimator", Applied Optics, 22, 15 March 1983, pp 787-95.

PROFESSIONAL PERSONNEL

WILLIAM H. STEIER - Professor of Electrical Engineering

CHRISTOPHER S. SEXTON - Research Assistant

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. We have discussed the implications of our results on several proposed systems applications of UV excimer lasers.

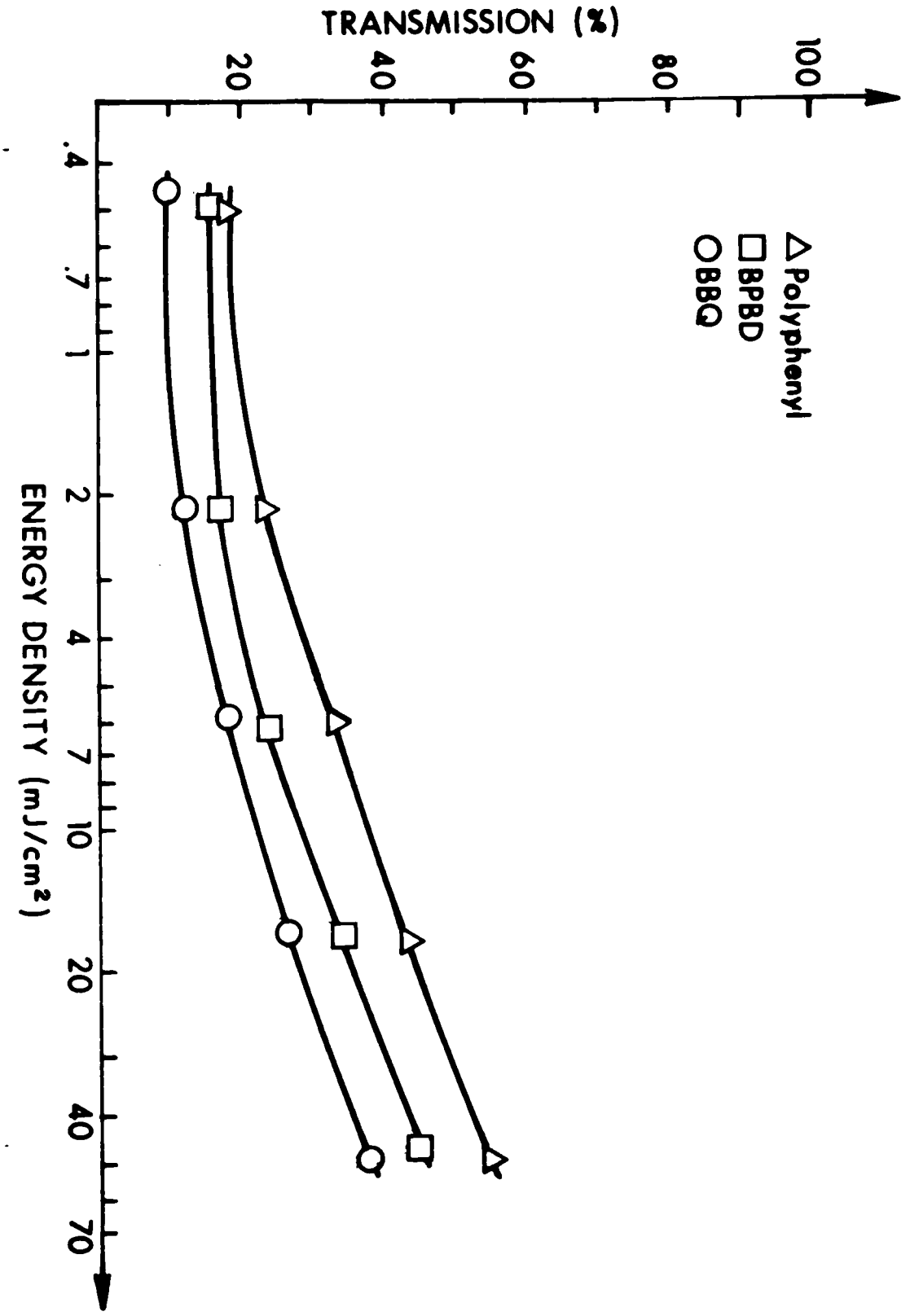


Figure 2. Short-pulse saturation measurements: Transmission of a 2ns pulse vs. the energy in the pulse. (Each data point is the average of 4-6 shots, and the curves are drawn to fit the data for illustration.)

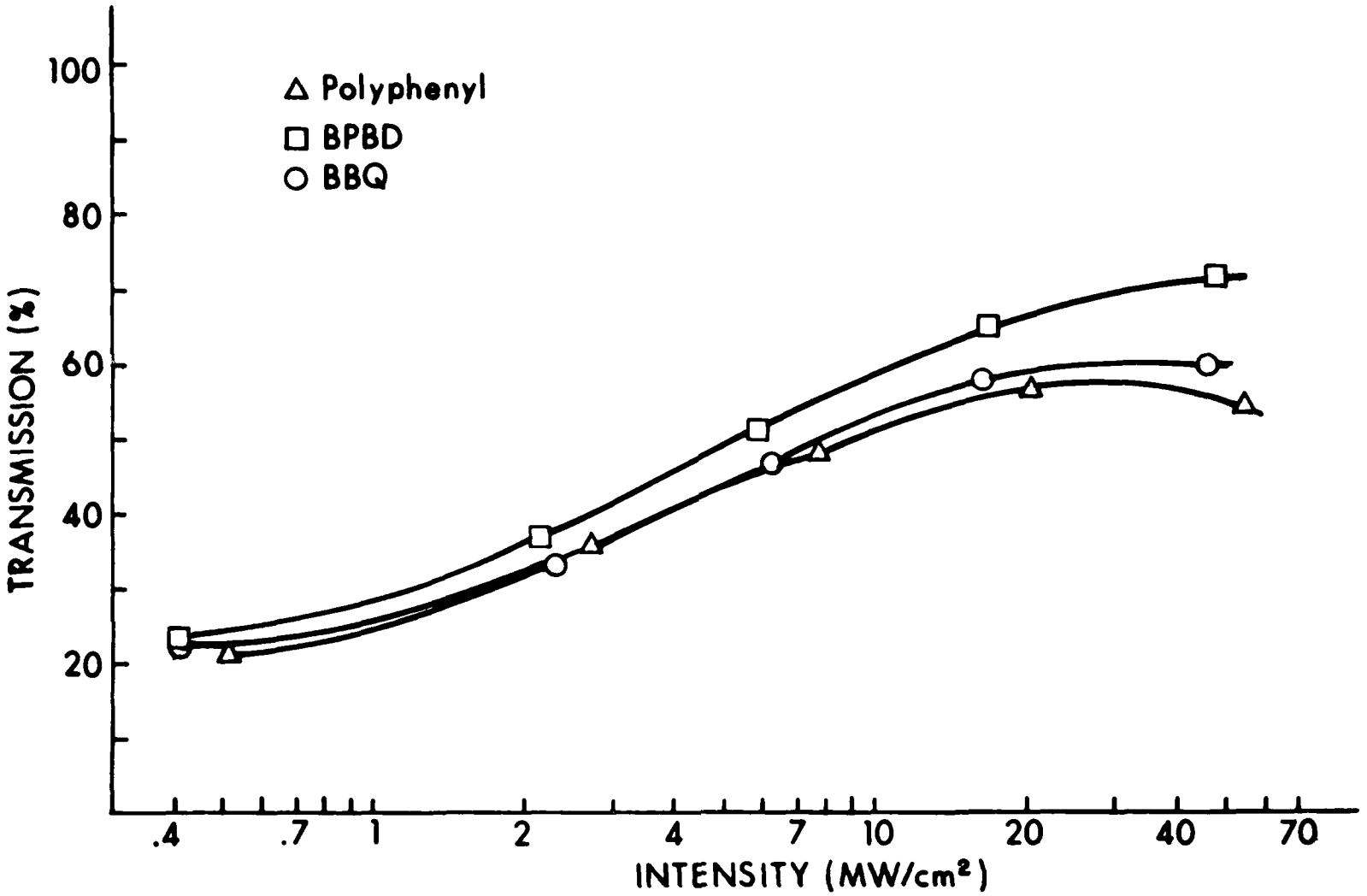


Figure 3. Long-pulse saturation measurements: Transmission of the peak of the laser pulse (~ triangular shaped; 10ns rise; 25ns fall) vs. the intensity of the peak. (Each data point is the average of 4-6 shots, and the curves are drawn to fit the data for illustration.)

TANDEM TIME OF FLIGHT LASER MASS SPECTROMETER

CURT WITTIG

Technical report for the USC Joint Services Electronics Program, prepared by

Curt Wittig
University of Southern California
Los Angeles, CA 90089

I. OBJECTIVES AND BACKGROUND

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 fluorescence (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.

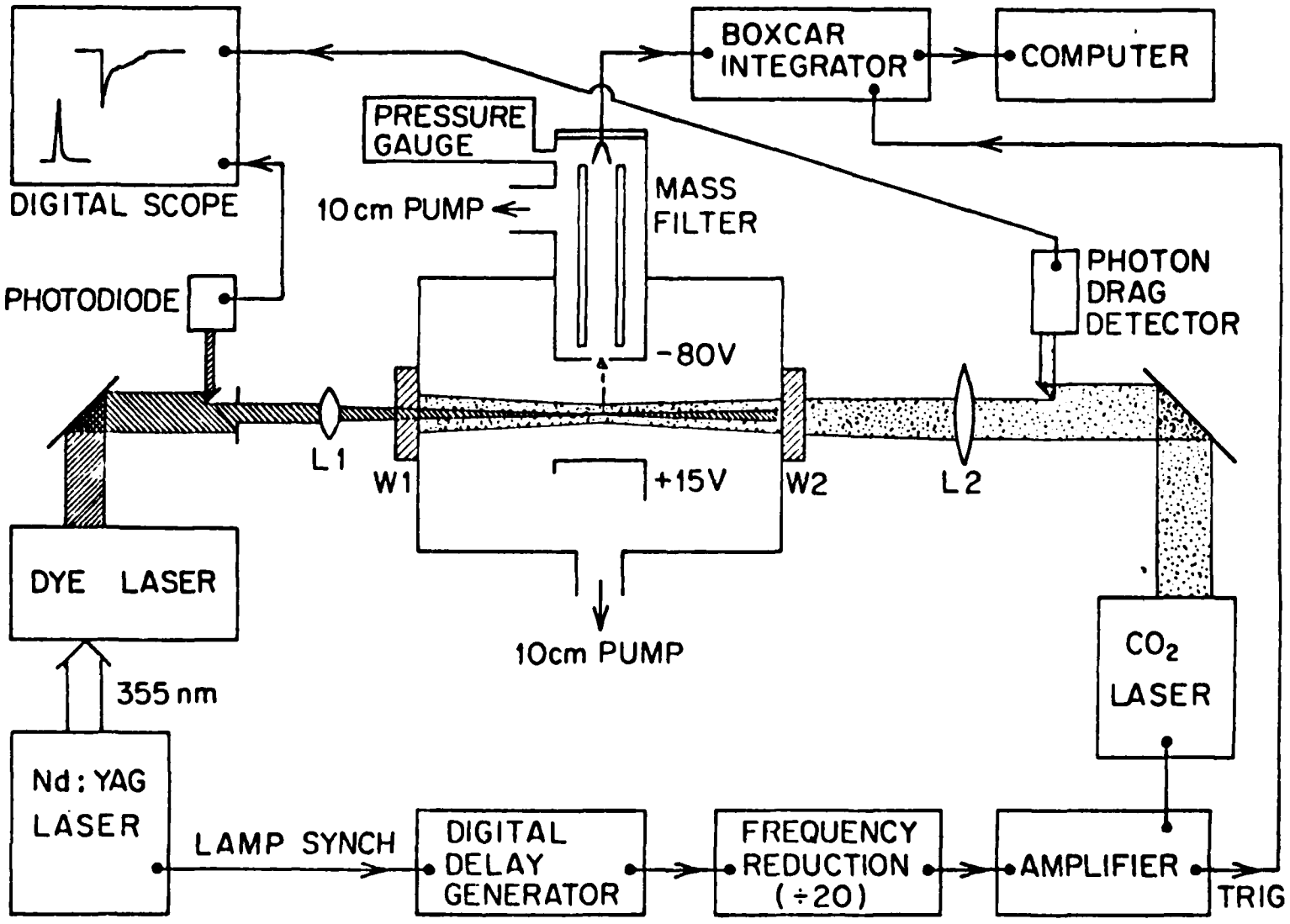
In the present MPI/IRMPD study, triethylamine (TEA) was chosen as the neutral precursor for several reasons. Parker **et al.** have shown that the MPI mass spectra at a particular wavelength are independent of laser intensity over a wide range,[11] and this is of great experimental value, since pulse 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.

II. STATUS OF EXPERIMENTAL APPROACH

The previously described experimental arrangement used in this laboratory for the IRMPD of ions[10] was modified slightly so that a dye laser could be used as the MPI source. A schematic description is shown in Fig. 1. A stainless steel vacuum chamber houses a quadrupole mass filter (UTI 100C), whose ion source was modified by cutting holes in the wire mesh surrounding the ionization region, thereby allowing the laser beams to propagate through the source region without hitting a metal surface. Ions are formed using a pulsed dye laser (Quanta Ray PDL 1) pumped by the third harmonic of a Nd:YAG laser (Quanta Ray DCR-1). The dye laser radiation is focused with a 25 cm focal length quartz lens, and enters the vacuum chamber through a BaF_2 window. Ions are formed only in the focal region, directly below the 5 mm

Figure 1. Schematic drawing of the experimental arrangement. L_1 and L_2 are 25 cm focal length quartz and BaF_2 lenses, respectively. W_1 and W_2 are BaF_2 windows. See text for details.


BOXCAR INTEGRATOR
COMPUTER
PRESSURE GAUGE
DIGITAL SCOPE
10 cm PUMP
MASS FILTER
PHOTODIODE
PHOTON DRAG DETECTOR
-80V
L1
W1
+15V
W2
L2
DYE LASER
10cm PUMP
CO_2 LASER
355 nm
Nd:YAG LASER
LAMP SYNCH
DIGITAL DELAY GENERATOR
FREQUENCY REDUCTION (÷20)
AMPLIFIER
TRIG

aperture leading to the separately pumped mass filter and detection assembly. The ions are sent to the mass filter with properly biased repeller and aperture plates, and are detected with a channeltron (Galileo 4717), whose output is sent to a boxcar integrator (PAR 162/165) and subsequently processed with a computer. The ions are dissociated with the focused output from a pulsed CO_2 laser (Lumonics 103) that overlaps the focused dye laser radiation at the ion source. A 25 cm focal length BaF_2 lens is used to focus the IR radiation, and the CO_2 and dye laser beams are counterpropagating and overlap throughout the entire length of the cell. Alignment, which is quite critical, is facilitated by using BaF_2 optics, which are transparent to both the IR and dye laser outputs. The CO_2 laser beam waist is appreciably larger than that of the dye laser, so that all of the ions formed by the dye laser can be excited with the IR laser.

Pulse to pulse stability is optimum at 10 Hz in the case of the Nd:YAG laser, and 0.2-0.3 Hz in the case of the CO_2 laser. The flashlamps in the Nd:YAG laser are fired 250 us prior to the internally triggered Q-switch, and a digital delay generator (Berkeley Nucleonics, 7055) is triggered synchronously with the flashlamp firing. The digital delay generator triggers an oscilloscope with an adjustable time base. The gate output of the oscilloscope then initiates the triggering of the CO_2 laser. The delay between the two lasers is controlled with the digital delay generator, and the jitter between the two laser pulses was $\pm$50 ns, due largely to the jitter in the spark gap triggered CO_2

laser. The boxcar integrator is triggered synchronously with the CO_2 laser, sampling only the ion signal affected by **both** lasers.

The sample chamber and the detector assembly are each pumped with 10 cm diffusion pumps, maintaining a base pressure of approximately 10^{-7} Torr near the channeltron. Operating pressures were in the range $3\text{-}50 \times 10^{-6}$ Torr, as measured with an ionization gauge. The pressures quoted were measured near the detector, and we estimate that the pressure at the ion source was higher by a factor of two or three.

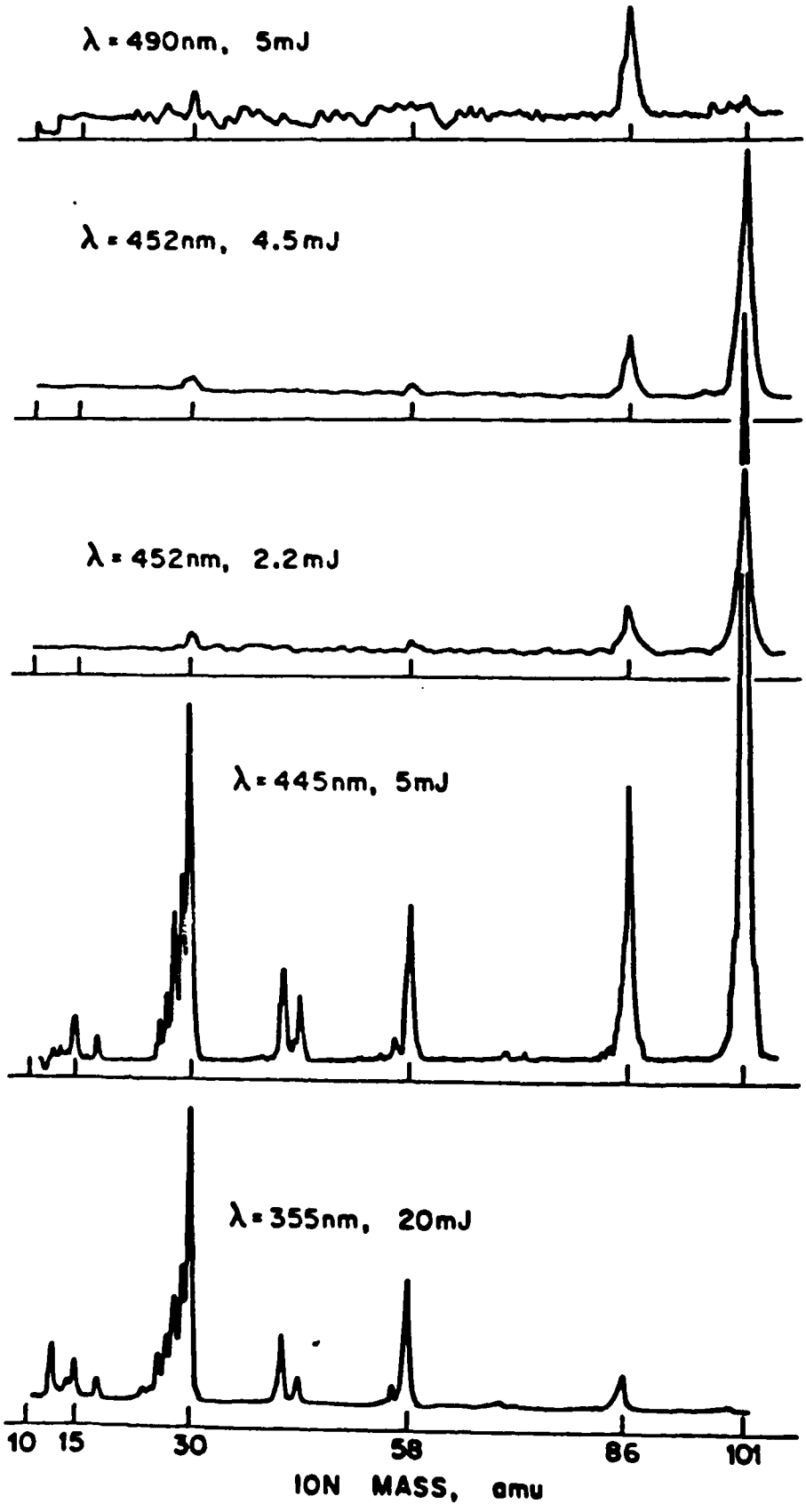
Triethylamine (Aldrich, 99.0%) was degassed before use, and checked for impurities using electron impact mass spectrometry.

III. STATUS OF EXPERIMENTAL RESULTS

The MPI spectra of TEA were extensively discussed by Parker et al.,[11] and we have essentially reproduced their results for a wide range of excitation frequencies. Representative spectra are shown in Fig. 2, in order to demonstrate the resolution and the signal to noise ratio (S/N) of our experiments. The main peaks are the parent ion at m/e=101 and the parent-minus-methyl peak at m/e=86. Further fragmentation, leading to peaks at m/e=58 and m/3=30, is common but yields are quite low. Only at very high dye laser fluences do these processes become dominant. Our main interest in the present work was to cause fragmentation via IRMPD, and therefore we chose two dye laser wavelengths for the

Figure 2. MPI spectra of TEA, obtained under different excitation conditions. The pressure in all cases was 5×10^{-6} Torr.

MPI SPECTRA OF TRIETHYLAMINE

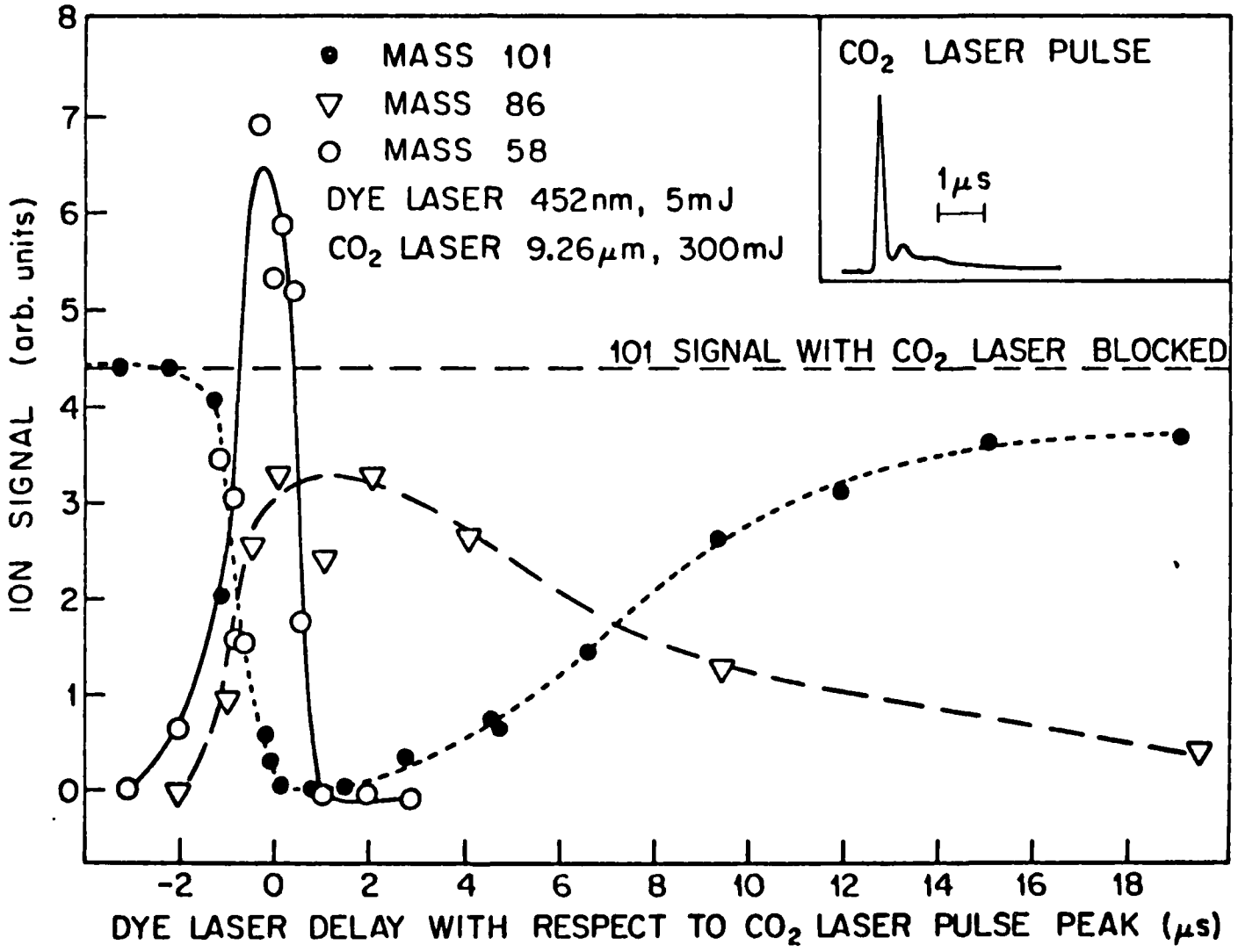


present study: 452 nm, yielding mostly the parent ion (m/e=101), and 490 nm, for which the largest peak is parent-minus-methyl (m/e=86).

Extensive fragmentation of m/e=101 was observed using several CO_2 laser frequencies in the R branch of the (001)-(020) band, and most results reported below were obtained with the R(22) line at 9.26 um. Fragmentation depends strongly on the spatial overlap, the CO_2 laser fluences, and the timing of the two laser pulses. The latter point is illustrated in Fig. 3.

When the CO_2 laser follows the dye laser by more than 2 us, the ion signals are essentially unaffected by the IR radiation. At shorter delays all the major peaks (m/e 101, 86, 58, 30 and 28) show strong time dependences. These strong variations with the delay time are due to the rapid removal of ionic species from the interaction region by the repeller field. With the CO_2 laser **preceding** the dye laser, a different effect is observed. At 9.3 um, the m/e 101 and 86 ion intensities vary as a function of the delay time, when the dye laser follows the CO_2 laser by up to 25 us. However, when using 10.2 um CO_2 radiation (which is not absorbed by TEA) the ion signals are unaffected by the preceding CO_2 laser pulse. The IR radiation affects MPI by vibrationally exciting/dissociating parent molecules, thereby altering the MPI signature. This effect can be quite striking, as shown in Fig. 3, and we find that ~25 us is required before effects due to IR MPD are gone. Again, this is consistent with neutral species moving into and out of the interaction region.

Figure 3. Relative ion signal intensities as a function of the delay between the onsets of the CO_2 and dye lasers. The signal intensities at different m/e are not corrected for instrumental sensitivity, and therefore the signals do not reflect directly the ion concentrations. Ion signal variations for m/e=30 and m/e=28 are the same as for the case of m/e=58. The data were taken at an intermediate IR laser fluence (37 J cm^{-2}), so that parent ions are not completely dissociated (see Fig. 4). The insert shows the CO_2 laser pulse shape. The pressure was $7x10^{-6}$ Torr.


MASS 101
MASS 86
MASS 58
DYE LASER 452nm, 5mJ
CO2 LASER 9.26μm, 300mJ
CO2 LASER PULSE
1μs
101 SIGNAL WITH CO2 LASER BLOCKED
ION SIGNAL (arb. units)
DYE LASER DELAY WITH RESPECT TO CO2 LASER PULSE PEAK (μs)
0
1
2
3
4
5
6
7
8
-2
0
2
4
6
8
10
12
14
16
18

The mass spectrum of TEA was measured at several CO_2 laser fluences, with the dye laser preceding the peak of the CO_2 laser pulse by 200 ns. The major peaks were at m/e of 101, 86, 58, 30, and 28. At high IR fluences (> 100 J cm^{-2}), m/e of 27 and 26 were also obtained, but we never observed m/e < 26. Some evidence for formation of masses 44 and 72 was found at intermediate IR laser fluences, but these were too weak for quantitative estimates. Figure 4 shows the results of fragmentation via IRMPD, for IR laser fluences < 42 J cm^{-2}. The TEA parent ion is completely dissociated at fluence $\geq$ 40 J cm^{-2}, while the relative abundances of smaller fragments becomes successively larger with increasing IR laser fluences. This trend is also present when using other CO_2 laser wavelengths, and Fig. 5 shows results obtained using the (001)-(100)P24 CO_2 laser transition at 10.63 um (neutral TEA is practically transparent at this wavelength). Detailed quantitative comparisons of dissociation efficiencies at different laser wavelengths cannot be made at this time, since the slight misalignment that accompanies tuning the CO_2 laser may affect the intensities of the observed signals. Our measurements indicate that 9.26 um radiation is more effective than 10.63 um radiation insofar as producing fragmentation is concerned, but further work is needed if quantitative comparison is desired.

The extensive fragmentation evident in Figs. 4 and 5 suggests the possibility of daughter ion dissociation via IRMPD. By tuning the dye laser to 490 nm, we were able to produce m/e=86 as

Figure 4. Fragmentation patterns of TEA ions, prepared by MPI, and rradiated with various fluences of 9.26 um radiation from a pulsed CO_2 laser. MPI was done at 452 nm, using the focused output from a dye laser (5 mJ). The relative signal intensities of the major masses observed (at m/e=101, 86, 58, 30, and 28) are shown as a function of the CO_2 laser fluence. The sample pressure was 10^{-5} Torr, and the delay between the dye laser and the onset of the CO_2 laser was 200 ns.

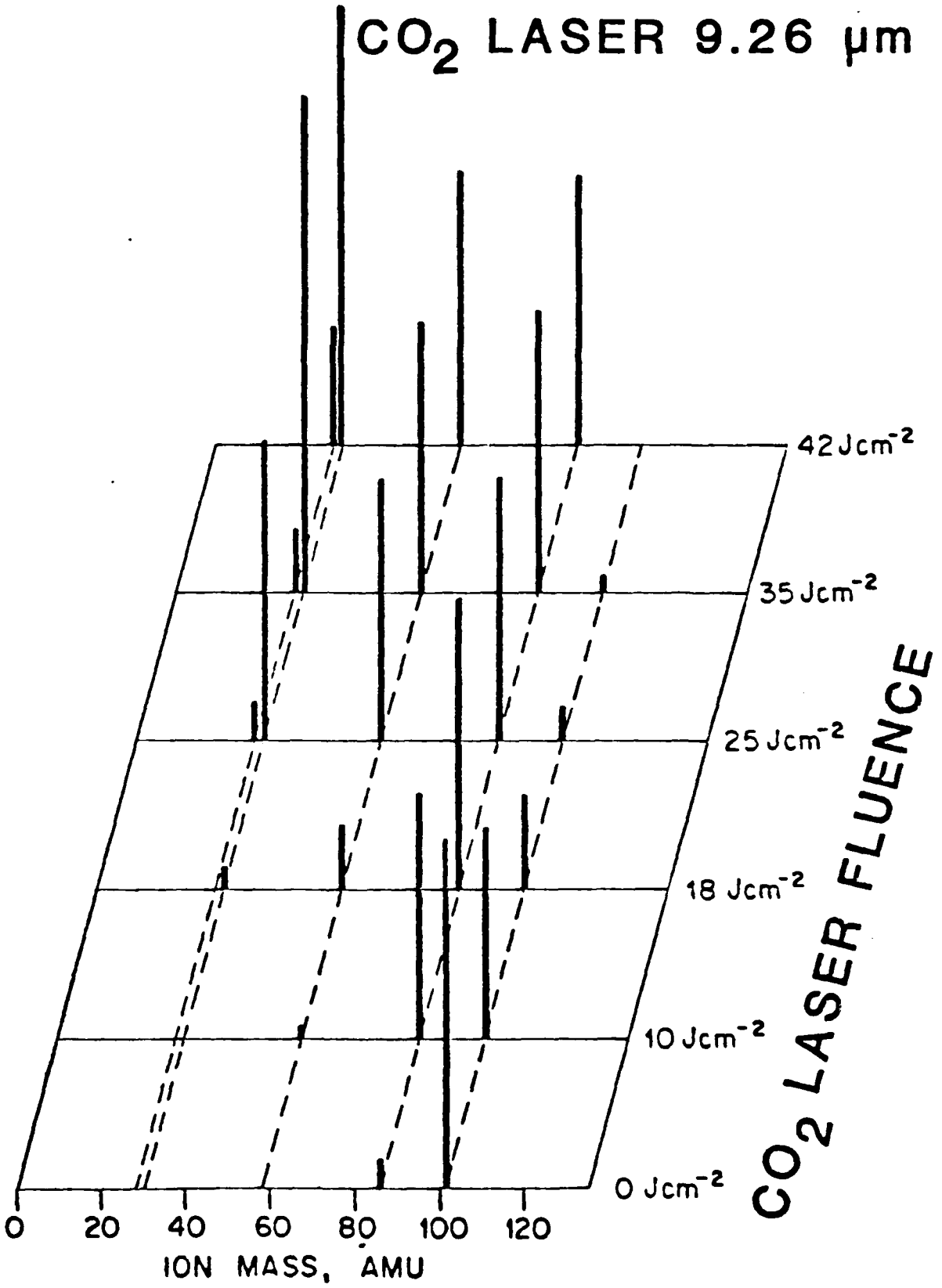
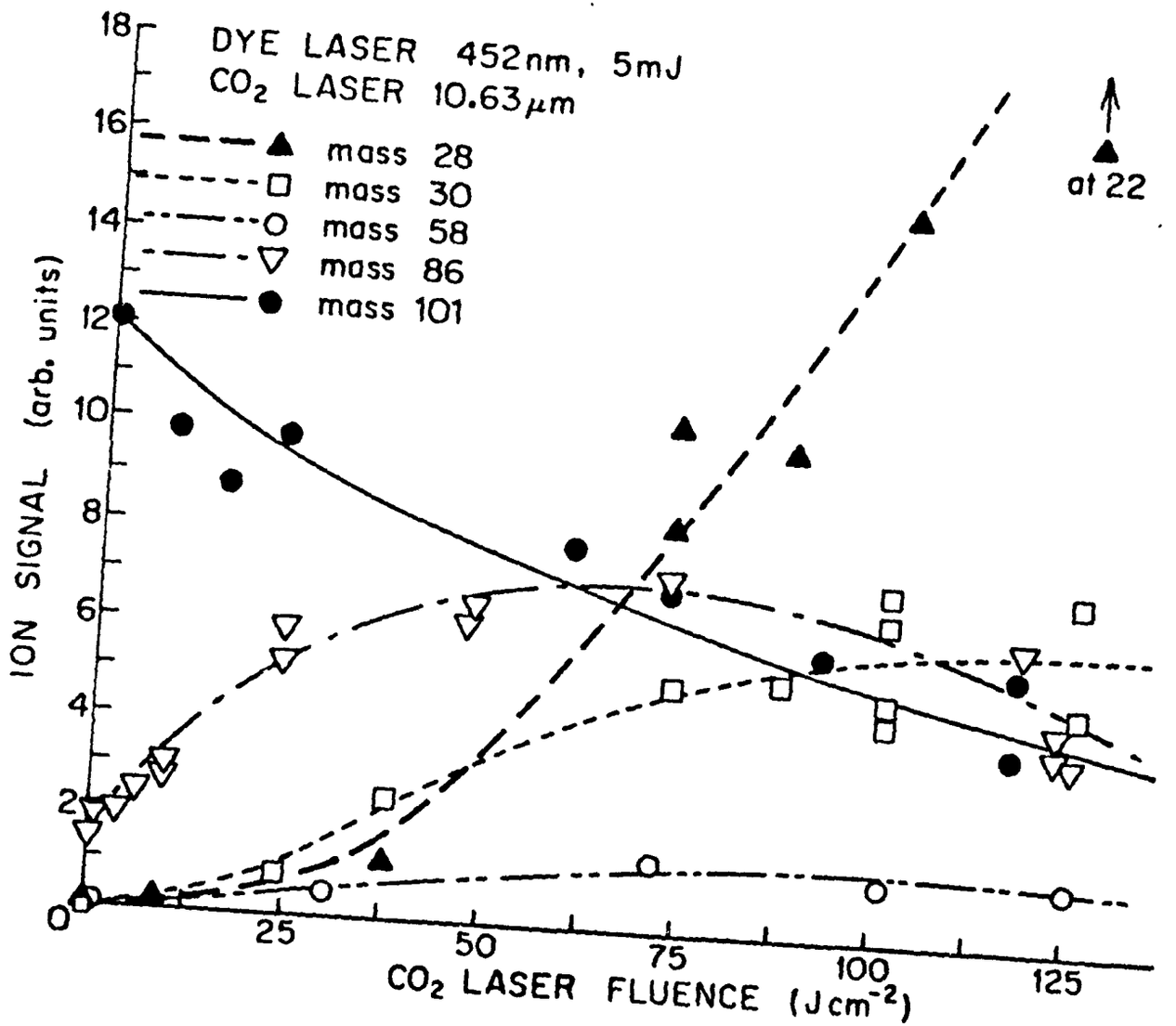

DYE LASER 452 nm, 5 mJ
CO_2 LASER 9.26 μm
42 Jcm^{-2}
35 Jcm^{-2}
25 Jcm^{-2}
18 Jcm^{-2}
10 Jcm^{-2}
0 Jcm^{-2}
CO_2 LASER FLUENCE
0
20
40
60
80
100
120
ION MASS, AMU

Figure 5. Fragmentation pattern of ions prepared by MPI at 452 nm, and fragmented via IRMPD at 10.63 um. The lines connecting the different data points are only for convenience when viewing the figure. The pressure was 10^{-5} Torr.

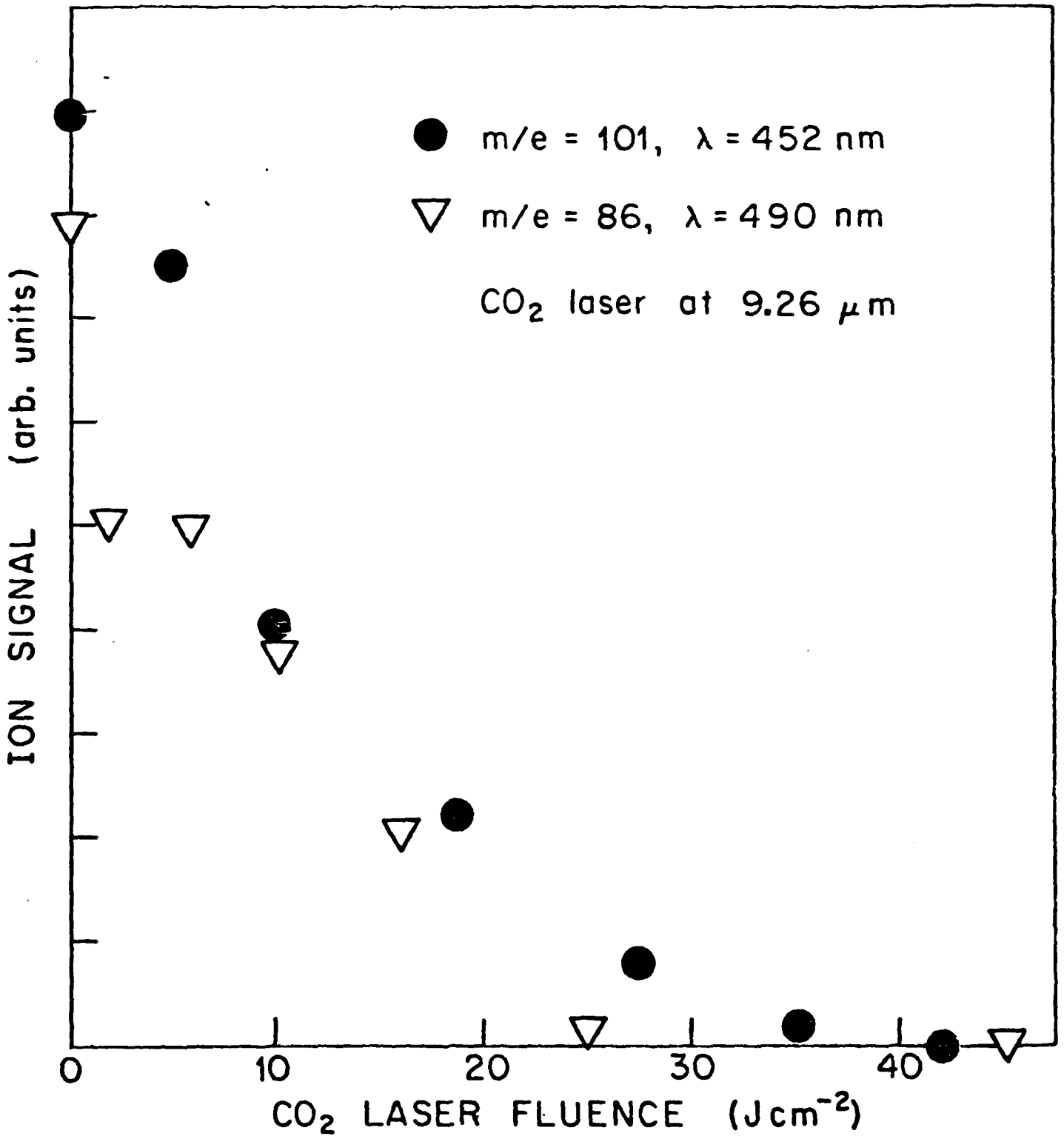

DYE LASER 452nm, 5mJ
CO_2 LASER 10.63μm
mass 28
mass 30
mass 58
mass 86
mass 101
at 22
ION SIGNAL (arb. units)
CO_2 LASER FLUENCE ($J cm^{-2}$)
0
2
4
6
8
10
12
14
16
18
25
50
75
100
125

the dominant MPI ion product, in order to monitor the fragmentation of this species via IRMPD. Efficient dissociation is obtained, as shown in Fig. 6. The major fragments are again m/e = 58, 30, and 28, and the signal intensity vs. fluence dependence is very similar to those shown in Figs. 4 and 5. The ionic fragments were only observed when the dye laser preceded the onset of the CO_2 laser by 0-2 us, as with the data shown in Fig. 3. The m/e=86 signal displayed a more complicated dependence on the timing between the two lasers when the CO_2 laser was operated at 9.26 um and preceded the dye laser.[16] With the CO_2 laser operating at 10.6 um, TEA molecules are not excited, and there is no effect due to the CO_2 laser preceding the dye laser.

At a particular IR laser frequency and fluence, the IRMPD fragmentation pattern was independent of the dye laser energy over the range 1-6 mJ (fluences of about 1-6 J cm^{-2}). The signal amplitude at a particular m/e increased significantly with dye laser energy, as is expected for an unsaturated multiphoton process.

The pressure dependences of all ion signals were checked periodically, and the signal intensities varied linearly with pressure throughout the range 3-30 x 10^{-5} Torr. This check was considered essential in view of recent experiments reporting bimolecular reactions involving ions, even at pressures of 10^{-6} - 10^{-5} Torr.[17]

Figure 6. The decrease in concentration of the nascent ions produced via MPI, upon increasing the CO_2 laser fluence. The dye laser preceeded the onset of the CO_2 laser by 200 ns.


m/e = 101, λ = 452 nm
m/e = 86, λ = 490 nm
CO2 laser at 9.26 μm
ION SIGNAL (arb. units)
0
10
20
30
40
CO2 LASER FLUENCE (Jcm-2)

IV. DISCUSSION OF RESULTS/PROGRESS TO DATE

The quantitative removal of parent ions via IRMPD is a straightforward, direct demonstration of the dissociation efficiency that can be realized using this excitation method. Within the accuracy of our measurements, the dissociation yields in the present experiments are unity, at sufficiently high IR laser fluences. In contrast with previous studies reporting high dissociation yields,[18-21] the present method provides a direct way of monitoring the removal of the parent, and the appearance, as well as subsequent disappearance, of many product ions. Before discussing the present results in the context of IRMPD processes, several comments concerning the merits and problems associated with this new MPI/IRMPD technique are in order.

The present experimental techniques complement nicely other IRMPD studies of ions,[7-9] and also offer several advantages. The IR radiation can interact with **all** of the ions initially formed, under conditions wherein collisions do not influence the experimental results, and we estimate that under the present conditions, ions are removed from the interaction region in approximately 10^{-6} s. Figure 3 shows that ions prepared earlier than 2 us prior to the onset of the CO_2 laser pulse are unaffected by it, since they have been removed from the interaction region. The strict linear dependence of all ion signals with pressure, even at the highest pressures used in this study, lends further support to the suggestion of collision free conditions.

MPI is sufficiently selective so that the electronic ground states of molecular ions can be produced without interference from electronic metastable states. Vibrational excitation can also be contained within a rather narrow energy range,[11,22] thereby providing well characterized species for subsequent excitation via IRMPD. Producing vibrationally cold ions may be difficult due to unfavorable Franck-Condon factors, however, and seeded expansions may be more suitable if truly "cold" ions are required.[23] When ions are formed via MPI in the so-called "quasi-continuum", their IR absorptions are broadened considerably and shifted to lower frequencies,[21] Thus, although the spectrum will remain structured, the oscillator strength can be sufficiently smeared by the high density of vibrational states that excitation is possible at many or all of the CO_2 laser frequencies, albeit with varying cross sections. Based on the absorption spectrum of neutral TEA, we expect 9.3 um radiation to be more effective than 10.6 um radiation, and our experiments confirm this qualitative trend.

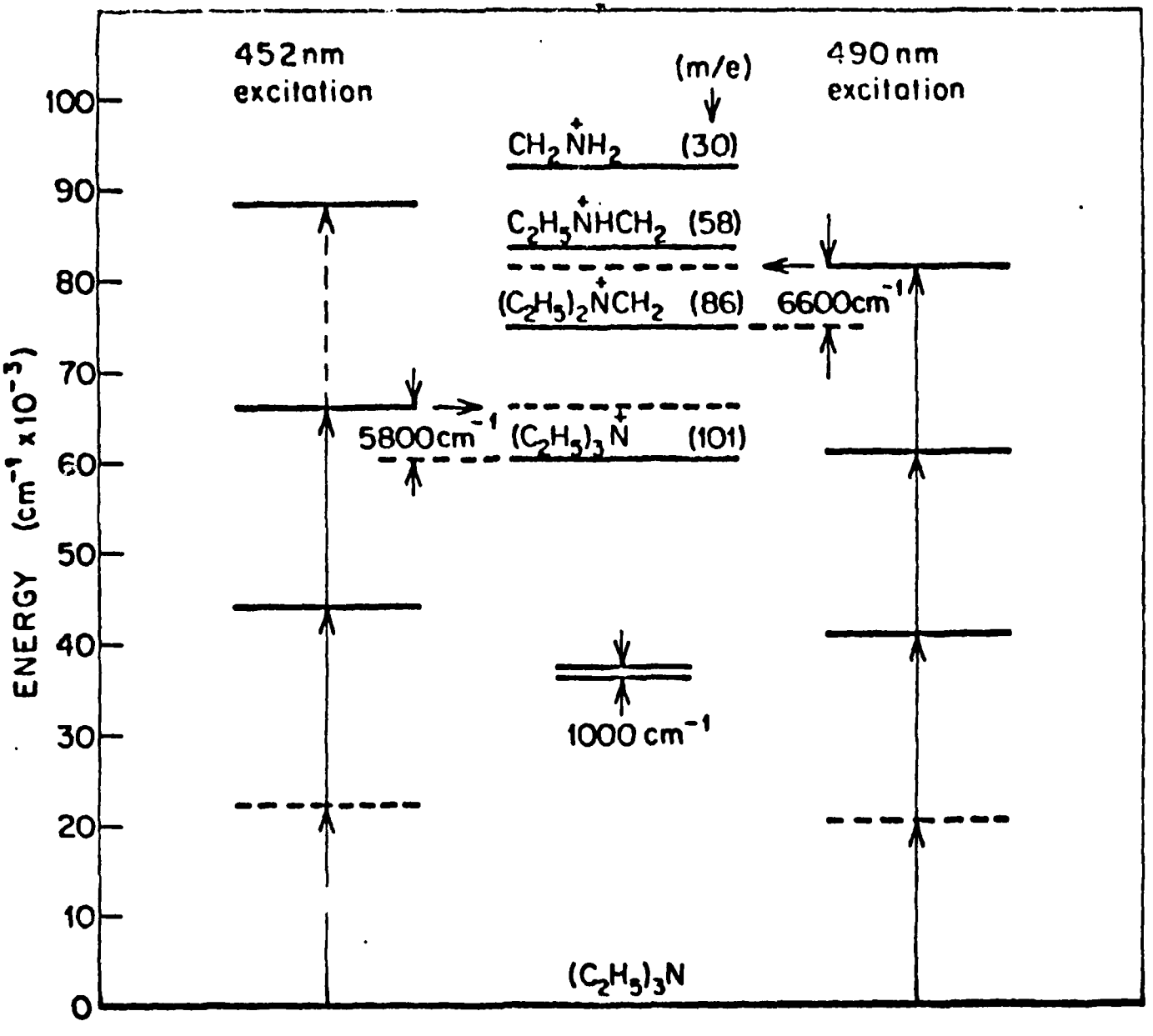
IRMPD is commonly scrutinized in terms of statistical theories of unimolecular reaction,[5,21] assuming fast randomization of vibrational energy compared to the rate of dissociation. As energy is accumulated in a molecule, reaction channels are sampled as they become available, and subsequent to dissociation the fragments may continue the absorption/dissociation sequence until excitation ceases. Excitation stops because either the exciting pulse terminates, or the molecular entity has too small an absorption cross section to be significantly excited. In the

present work, several chemically distinct products are observed, providing an opportunity to check the consistency of this model. Figure 7 shows a partial energy level diagram pertinent to the experiments.[24-27] Thermochemical data are not available for all the species involved (e.g. $C_2H_5NH{=}CH_2^+$ and CH_2N^+), and in constructing this diagram, we used appearance potential data[24] and assumed that the sequence of ion dissociations follows the pattern revealed in electron impact (EI) mass spectrometry:[15]

$$\underset{(C_2H_5)_3N^+}{(m/e=101)} \xrightarrow{-CH_3} \underset{(C_2H_5)_2N{=}CH_2^+}{(m/e=86)} \xrightarrow{-C_2H_4} \underset{C_2H_5NH{=}CH_2^+}{(m/e=58)} \xrightarrow{-C_2H_4} \underset{CH_2{=}NH_2^+}{(m/e=30)} \qquad (1)$$

We also assumed that successive eliminations of C_2H_4 are equally endothermic. Note that m/e=28 (CH_2N^+) is not an important species in EI mass spectra, although we observe this species at high IR laser fluences in our experiments. The alternative assignment of the m/e=28 peak to $C_2H_4^+$ cannot be ruled out on the basis of the mass spectrum alone with the low resolution of our measurements. We consider this to be unlikely, in view of the preferred formation of positive ions containing a nitrogen atom. Figure 7 shows that MPI at 452 nm leads to parent ions with a maximum of 5800 cm^{-1} of vibrational energy. The small, but measurable, amounts of lower m/e fragments are due presumably to higher order MPI processes. At 490 nm, 3-photon MPI would lead to vibrationally unexcited parent ions. Apparently, because of Franck-Condon considerations,[11] the 4-photon process dominates, forming the parent-minus-methyl ion with a maximum of 6600 cm^{-1} of vibrational energy.

Figure 7. Partial energy level diagram pertinent to the MPI/IRMPD dissociation of the TEA ion. The ionization potential of TEA (7.5 eV) was taken from Ref. 25, and the appearance potential of m/e=86 (9.3 eV) from Ref. 24. The exothermicity of m/e=86 formation was calculated from the heats of formation of $CH_2{=}NH_2^+$ (178 kcal mol^{-1}),[26] CH_3 (35 kcal mol^{-1}),[27] and C_2H_4 (12.5 kcal mol^{-1}). The exothermicity of m/e=58 formation was estimated by assuming that the same energy is required to eliminate C_2H_4 from m/e=86 as from m/e=58. Data for m/e=28 are not available. The approximate energy carried by a CO_2 laser photon (1000 cm^{-1}) is shown for comparison. The horizontal arrows indicate the maximum internal energy in the ion prepared by MPI.



Energy level diagram for Triethylamine MPI/IRMPD. The sizes of the visible and IR photons are indicated.

*The alternative assignment of the m/e=28 peak to C_2H_4 cannot be ruled out on the basis of the mass spectrum alone with the low resolution employed by us. We consider this to be unlikely, in view of the preferred formation of positive ions containing a nitrogen atom.

IR radiation also causes dissociation of ionic fragments which are themselves produced via IRMPD, and the dependence of the fragmentation pattern(s) on the IR laser fluence indicates that the lowest energy pathways are preferred. In the case of 452 nm excitation, -elimination of CH_3 is the dominant product of the IRMPD of TEA^+, and the resulting m/e=86 species is dissociated by the CO_2 laser output, as shown in Fig. 6. In separate experiments,[28] $C_2H_5NH{=}CH_2^+$(m/e=58) was prepared independently using a diethylamine precursor, and dissociated by IRMPD (at 10.6 um) to yield m/e=30 and 28. Also, $CH_2NH_2^+$ was prepared using a methylamine precursor, and we find that 9.26 um radiation causes fragmentation, yielding CH_2N^+. Thus, all our results are compatible with a sequential dissociation mechanism.

In order to check the possibility of competitive production of m/e=58 and m/e=30 directly from m/e=86, we carried out several straightforward calculations using the QRRK formalism.[29] Production of m/e=58 and 30 requires the elimination of one and two C_2H_4 groups, respectively, processes which are expected to have low frequency factors.[30] Using the energies shown in Fig. 7, we find that the A-factor for the higher energy process must be larger than tnat for the lower energy process by a factor of 10^2 - 10^3, and the excitation must be $\sim$ 40,000 cm^{-1} above the lowest dissociation threshold, in order to make the reaction

rates similar. This is quite unreasonable, since the elimination of two C_2H_4 groups can hardly be more facile than the elimination of one, and the very high unimolecular rates at an energy of 40,000 cm^{-1} above reaction threshold are incompatible with the optical pumping rates which can be achieved via IRMPE using conventional CO_2 lasers, even with the largest transition dipole moments known.[5,21,31]

V. SUMMARY OF PROJECT RESULTS

1. 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.

2. 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 neutral TEA, which absorbs significantly only around 9.4 um).

3. 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.

4. 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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4. "Low energy pathways" refers to those with the lowest activation energies. These are not necessarily those with the smallest enthalpy changes.

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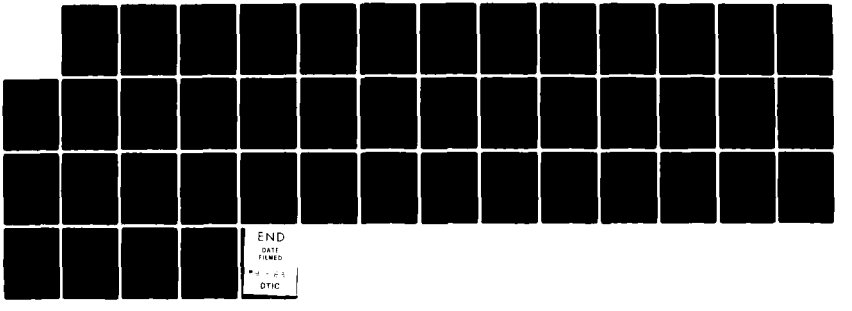

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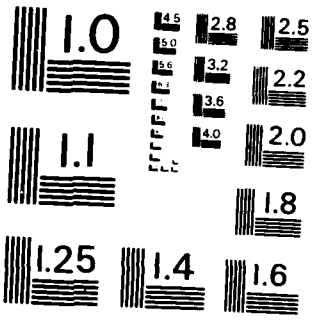

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31. H. Reisler, F. Kong, C. Wittig, J. Stone, E. Thiele, and M.F. Goodman, J. Chem. Phys., **76**, in press.

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 leve at USC during 1981-1982.
4. David Sumida, graduate student (Physics), USC.
5. Joe Catanzarite, graduate student, (E.E.), USC.

Degrees

Thomas Fischer, Ph.D. E.E., Fall 1981, "Optically pumped infrared molecular lasers."

Henry Helvajian, Ph.D. E.E., Fall 1981, "Kinetic studies of mercury halides."

WITTIG GROUP PUBLICATIONS: 1981 - PRESENT

1. H. Reisler and C. Wittig, "Electronic luminescence resulting from ir multiple photon excitation", Adv. Chem. Phys., Vol. XLVI: Photoselective Chemistry, J. Jortner, R. Levine, and S. Rice, eds. (Wiley, 1981), pp. 679-711.

2. A.M. Renlund, H. Reisler, and C. Wittig, "The influence of laser intensities on the rotational distribution of CN(X) produced via ir multiple photon dissociation", Chem. Phys. Lett. **78**, 40 (1981).

3. J.F. Caballero and C. Wittig, "IR multiple photon excitation of C_2H_5F and 1,1-$C_2H_4F_2$ near dissociation threshold: vibrational emissions from parent and product species", Chem. Phys. Lett. **82**, 63 (1981).

4. T.A. Watson, M. Mangir, M.R. Levy, and C. Wittig, "Optical detection of photoproducts using a pulsed supersonic molecular beam: application to intramolecular V-E coupling in ir laser excited polyatomics", J. Chem. Phys. **25**, 5311 (1981).

5. H. Helvajian and C. Wittig, "Vibrational quenching of HgBr(X)", Appl. Phys. Lett. **38**, 731 (1981).

6. T.A. Watson, M. Mangir, C. Wittig, and M.R. Levy, "The origin of the electronic emission which accompanies ir multiple photon excitation of CrO_2Cl_2", J. Phys. Chem. **85**, 754 (1981).

7. T.A. Fischer and C. Wittig, "16 micron laser action in propyne", Appl. Phys. Lett. **39**, 6 (1981).

8. M. Stuke and C. Wittig, "Multiply charged atomic and molecular ions from laser multiphoton ionization of UF_6", Chem. Phys. Lett. **81**, 168 (1981).

9. M. Stuke, H. Reisler, and C. Wittig, "Monitoring UF_5 photodissociation via laser multiphoton ionization", Appl. Phys. Lett. **39**, 201 (1981).

10. 74. A.M. Renlund, F. Shokoohi, H. Reisler, and C. Wittig, "Gas phase reactions of $C_2H(X)$ with O_2, H_2, and CH_4", Chem. Phys. Lett. **84**, 293 (1981).

11. 75. H. Reisler, F. Kong, A.M. Renlund, and C. Wittig, "The unimolecular reaction of isolated CF_3CN: energy disposal into CN product degrees of freedom", J. Chem. Phys. **76**, 997 (1982).

12. M. Stuke and C. Wittig, "The IRMPD of molecular ions prepared by laser multiphoton ionization," J. Phys. Chem. **86**, 438 (1982).

13. H. Helvajian and C. Wittig, "Collisional deexcitation of $Hg(6^3P_0)$ by HgBr(X), $Br(4^2P)$", and $Br_2(X)$: evidence for ion-pair formation in the entrance channel," J. Chem. Phys. **76**, 3505 (1982).

14. 78. A. Renlund, F. Shokoohi, H. Reisler, and C. Wittig, "The reaction of C_2H with O_2: chemiluminescent products," J. Phys. Chem. **86**, 4165 (1982).

15. 79. H. Reisler, F. Kong, C. Wittig, J. Stone, E. Thiele, and M.F. Goodman, "The unimolecular reaction of isolated CF_3CN: The influence of laser fluence/intensity on the rovibronic excitation of CN(X) produced via infrared multiple photon dissociation," J. Chem. Phys. **77**, 328 (1982).

16. T. Fischer and C. Wittig, "Frequency tuning and high energy operation of the C_2D_2 laser," Appl. Phys. Lett. **77**, 328 (1982).

17. 81. Y. Haas, H. Reisler, and C. Wittig, "Laser Multiphoton ionization of triethylamine following collision free IR multiple photon excitation," Chem. Phys. Lett. (1982), **92**, 109 (1982).

18. 82. Y. Haas, H. Reisler, and C. Wittig, "Infrared multiple photon dissociation of molecular ions formed by the laser multiphoton ionization of triethylamine," J. Chem. Phys. **77**, 5527 (1982).

19. 83. J.S. Chou, D. Sumida, M. Stuke, and C. Wittig, "Single shot laser multiphoton ionization detection of UF_5 following the 266 nm photodissociation of UF_6," Laser Chem. **1**, 1 (1982).

20. 84. T.A. Watson, M. Addison. and C. Wittig, "Reactions of atomic oxygen with CF_3I: sequential processes leading to the formation of IF(X)," Chem. Phys., in press.

21. M.R. Levy, A. Renlund, T.A. Watson, M. Mangir, H. Reisler, and C. Wittig, "Intramolecular processes in isolated polyatomic molecules", J. Hinze, ed. (Plenum), in press.

22. H. Reisler, F.B.T. Pessine, Y. Haas, and C. Wittig, "The unimolecular reaction of $(CH_3)_3$ CNO following n-pi* excitation with a tunable dye laser," J. Chem. Phys. **78**, xxxx (1983).

23. J.H. Catanzarite, Y. Haas, H. Reisler, and C. Wittig, "Dissociation of benzylamine ions following infrared multiple photon absorption, electron impact ionization, and uv multiphoton ionization," J. Chem. Phys., xxxx (1983).

24. F. Shokoohi, T. Watson, A.M. Renlund, H. Reisler, and C. Wittig, "Reactions of C_2H with small molecules", in preparation.

25. J.F. Caballero and C. Wittig, "IR multiple photon dissociation of C_2HCl_3: Efficient dissociation of the C_2Cl_2 product," J. Chem. Phys., in press (1983).

26. F. Kong and C. Wittig, "The chemiluminescent reaction of $C_2H(A^2A")$ with NO," in preparation.

27. J.R. Beresford, G. Hancock, A.J. MacRobert, J. Catanzarite, G. Radhakrishnan, H. Reisler, and C. Wittig, "Energy distributions in the CN(X) fragment from the infrared multiple photon dissociation of CF_3CN: a comparison between experimental results and the predictions of statistical theories," J. Chem. Soc. Faraday Disc. (1983).

28. H. Reisler, F.B.T. Pessine, and C. Wittig, "The unimolecular reaction of benzylamine on the ground electronic potential surface," J. Chem. Phys., submitted.

29. J.S. Chou, D. Sumida, and C. Wittig, "A time-of-flight mass spectrometer using multiphoton ionization and infrared multiple photon dissociation," in preparation.

RESEARCH IN PERFORMANCE OF C^3 DISTRIBUTED DATABASES

VICTOR O.K. LI

Report Period: 1 April 1982 - 31 March 1983

RESEARCH OBJECTIVES

The development of a performance model of C^3 distributed databases that will enable one to compare the performance of concurrency control, query processing and file allocation algorithms, and to propose better, more efficient algorithms. The following specific research tasks were pursued during the reporting period:

1. Determine Message Delay in a Computer Network with Failing Nodes and Links
2. Develop New Concurrency Control Algorithms
3. Develop New Query Processing Strategies Amenable to Distributed Computation
4. Develop New File Allocation Algorithms

STATUS OF RESEARCH EFFORT

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 that other researchers run into if they use 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, can be obtained using our approach. More detailed discussion of our approach, and illustrative examples, can be found in [1]-[4]. We are presently attempting to modify our algorithm to accommodate failure dependencies of the various components.

We have developed a new concurrency control algorithm for distributed databases. Very briefly, instead of using the traditional approach of locking or timestamp-ordering, we schedule transactions by first constructing the conflict graph, and then executing the transactions corresponding to the maximum independence set (MIS) concurrently. The MIS algorithm is free from deadlocks, can be implemented in a distributed fashion and is resilient to computer and communication link failures. An earlier version of the algorithm, which is centralized, will be documented in [9]. We are presently working on a distributed computation version of the algorithm.

We have developed an effective approach to query processing problems. It has been shown that a general query processing problem is N-P complete. Therefore, the optimal solution must be obtained by exhaustive enumeration, which is computationally expensive. We have proved several important properties of query processing problems, and have been able to identify a subset of all possible solutions which dominate (i.e. cost less) than the rest of the solutions. In other words, we can restrict our search for the optimal solution to a much smaller subset. An algorithm has been developed for generating this dominating group of solutions. Our approach for single-target queries will be documented in a Ph.D. thesis proposal [10]. We are presently trying to estimate the size of this dominating subset, and to extend the algorithm to multiple target queries.

PUBLICATIONS OVER PAST YEAR

1. Li, V.O.K., and Silvester, J.A., "Performance Analysis of Networks with Unreliable Components," Technical Report No. CSI-83-03-01, Communication Sciences Institute, University of Southern California, 1983. (submitted for journal publication)

2. 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.

3. 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.

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

5. 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. (submitted for journal publication)

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

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

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

9. Li, V.O.K., and Shu, I.C.S., "A New Concurrency Control Algorithm for Distributed Databases," (in preparation).

10. Chen, A.L.P., "Query Processing in Distributed Databases." (Ph.D. thesis proposal: in preparation)

PROFESSIONAL PERSONNEL

1. VICTOR O.K. LI, Principal Investigator, Assistant Professor of Electrical Engineering.

2. YUEN FUNG LAM, Research Assistant

3. IGNATIUS SHU, Research Assistant

4. MOHAMMAD TASOOJI, Research Assistant

INTERACTIONS

Dr. Li interacts with faculty and students of the C^3 project at MIT (sponsored by ONR). He has attended all the MIT/ONR Sponsored Workshops on Distributed Information and Decision Systems. He also serves as a referee for the Army Basic Research Committee of the National Academy of Sciences.

OPTICAL INFORMATION PROCESSING: PROCESSING OF IMAGES WITH SIGNAL-DEPENDENT NOISE [Work Unit IE1-6]

A.A. SAWCHUK AND T.C. STRAND

Report Period: 1 April 1982 - 31 March 1983

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.

STATUS OF THE RESEARCH EFFORT

The problems of signal-dependent noise in imaging and pattern recognition systems are becoming more significant as new techniques and new wavelength sensors are introduced. An important example of signal-dependent noise is the speckle that appears in coherent imaging systems when illumination from an optically diffuse object interferes, giving a noisy, granular appearance to the image that reduces the resolution capability. 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 decay 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.

A fundamental component of this research has been to develop signal-dependent models for speckle image formation for the cases of intensity detection and complex amplitude detection. Past

work in speckle processing has often relied upon models that assume speckle can be treated as multiplicative noise. The multiplicative noise model is valid only for a very limited set of conditions and only provides first order statistical properties of fully developed speckle. We are interested in more general models that provide also some second-order statistics (e.g., covariance). Of the more general models that have been developed in the past, many have neglected the effects of aliasing introduced by improper sampling in the speckle generation process. We have developed three speckle models where these effects are explicitly considered. The first technique is a general speckle model which is an exact model of a physical system with a known surface phase profile. This approach requires significant oversampling of the phase function to avoid aliasing. This general model can be used to study the statistical properties of general speckle (including non-fully developed speckle). The model can be used to obtain either complex amplitudes or intensity speckle patterns.

Two additional techniques have been developed which are less general, but which also require less computation. Both are restricted to fully developed speckle. The first is a single phase model which, like the general model, can be used to generate complex amplitudes or intensities. The system is however no longer an exact model of a real physical situation. Although the computational burden is significantly less than in the general speckle model, oversampling of the phase functions involved is still required. The third technique is called a multiple phase model. This is essentially a multiplicative noise model followed by a low-pass filter (note the noise at the output is no longer multiplicative). This model does not require oversampling. This approach is limited to producing speckle intensity images.

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. 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 several new image restoration algorithms that have been explored.

Several algorithms were developed for processing speckle intensity images. First, a MAP approach was developed for images with uncorrelated speckle. This case is analogous to the

multiplicative speckle model. The MAP filter utilizes the nonstationary mean and nonstationary variance (NMNV) of the image. Because these parameters are difficult to estimate from the original noisy data, an iterative technique was used where new mean and variance estimates were obtained after each iteration. The iteration process performed significantly better than a single pass.

A major development in this work was the introduction of techniques which handle correlated speckle. All previous work has ignored the second order statistics of the noise and image. A local linear MMSE filter based on a NMNV image model was derived. This filter adapts to the signal-dependent noise and the nonstationary content of the image. More importantly, the correlation properties of the speckle are taken into account. However, since correlation information is utilized, this technique is computationally demanding. To help alleviate this problem a reduced update recursive algorithm was developed which includes correlation information and approximates the local linear MMSE filter.

Finally, several techniques were developed for processing speckle information where the complex amplitude data is available. This is true for the important case of synthetic aperture radar (SAR) imagery. Previous work with speckle reduction SAR imagery has ignored the phase information because of the difficulty in incorporating it in the speckle reduction process. A maximum likelihood algorithm was developed but it was computationally impractical because of the need to invert large matrices in an iterated routine. A simplified MAP equation was developed which incorporated the local linear MMSE concept to obtain an equation which could easily be solved iteratively. The MAP filter is nonlinear and can be decomposed into two parts, a deconvolution component and a one-point MAP component. The deconvolution component can be implemented with a nonstationary 2-D recursive filter. The one-point MAP estimate is a real root of a cubic equation. This decomposition not only simplified the computation but also leads to a simple constrained iteration algorithm to solve the MAP equation. The structure of this algorithm has shown the optimal way of processing complex amplitude speckle images.

WRITTEN PUBLICATIONS:

1. P. Chavel, D. Kuan, A.A. Sawchuk, and T.C. Strand, "Approaches to Effective A Posteriori Processing of Single Speckle Patterns," Journal of the Optical Society of America, vol. 70, p. 1581, December, 1980.

2. D. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Discrete Speckle Image Modeling and Restoration," Journal of the Optical Society of America, vol. 71, pp. 1585-1586, December, 1981.

3. D. Kuan and A.A. Sawchuk, "Nonstationary 2-D Recursive Image Restoration," Journal of the Optical Society of America, vol. 71, pp. 1641-1642, December, 1981.

4. D.T. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Nonstationary 2-D Recursive Filter for Speckle Reduction," Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, pp. 1561-1564, Paris, May, 1982.

5. D.T. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "MAP Speckle Reduction Filter for Complex Amplitude Speckle Images," Proceedings IEEE Patt. Recog. and Image Processing Conf., pp. 58-63, Las Vegas, Nevada, June, 1982.

6. D. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Adaptive Restoration of Images with Speckle," Proc. SPIE Conf. -Applications of Digital Image Processing-IV, San Diego, August, 1982.

7. D.T. Kuan, "Nonstationary Recursive Restoration of Images with Signal-Dependent Noise with Application to Speckle Reduction," Ph.D. dissertation, Department of Electrical Engineering, Univ. of So. Calif., Los Angeles, August 1982; USCIPI Report 1060.

PROFESSIONAL PERSONNEL:

1. T. Strand, Research Assistant Professor, Department of Electrical Engineering-Systems, Image Processing Institute.

2. A.A. Sawchuk, Professor, Department of Electrical Engineering-Systems, Director, Image Processing Institute.

3. D. Kuan, Research Assistant, Image Processing Institute, Ph.D. graduate, Department of Electrical Engineering-Systems.

4. P. Chavel, Visiting Research Scientist, Image Processing Institute, from Institut d'Optique, Orsay, France.

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, Conference, 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, Centro de Investigaciones en Optica, Cuernavaca, Mexico, January, 1982, (invited paper).

Interactions with Other Laboratories:

1. Several discussions of this project of this project have been held with Dr. Harold Szu of the Naval Research Laboratory, Washington, D.C.

2. Several discussions on this work have been held with Dr. James Fienup and Dr. Robert Powers of the Environmental Research Institute of Michigan (ERIM), a DOD contractor investigating digital SAR imaging techniques.

3. Several technical discussions with Dr. Dan Held, Dr. Fuk Li, and Dr. Charles Elachi of JPL regarding SEASAT SAR systems have been held. They have supplied some experimental data to be used in this research.

DISCOVERIES, INVENTIONS, PATENT DISCLOSURES:

None

A SUPPORT ENVIRONMENT FOR INFORMATION BASES

Work Unit IE2-3

DENNIS MCLEOD

Report Period: April 1982 - March 1983

RESEARCH OBJECTIVES

The principal overall goal of this research is to devise and demonstrate principles and techniques to allow end-users to directly design, access, manipulate, evolve, and interconnect computerized databases. The current focus of the project is on information management facilities for personal (workstation) computers. The principal specific goals are: (1) to study the information management requirements of a well-defined class of users of personal workstation computers; (2) to devise techniques and mechanisms that allow such users to directly define, classify, interrelate, manipulate, and dynamically share a universe of information objects (object space); and (3) to design, implement and test an experimental prototype personal information management environment on a network of personal workstation computers.

STATUS OF THE RESEARCH EFFORT

During the past contract year, progress in this research has included new work in the area of personal information management (as outlined above), as well as the completion of work initiated in previous contract years. In the area of personal information management, the following milestones have been reached:

- An initial investigation has been conducted to determine the information management needs of a well-defined class of potential users of personal workstation computers, for whom current database technology and tools are inadequate. The class of end-users that have been the principal target of study include the professional or sophisticated office worker, and the design engineer (specifically the CAD/VLSI designer or software engineer). A detailed study has been conducted to determine the information management requirements for support

VLSI design <McLeod+Narayanaswamy+Rao 1983>; included in this study is a "quick prototype" implementation of a database for VLSI design using a relational database system, and an assessment of the limitations and problems of such an approach. At present, a similar study is being conducted vis-a-vis information management for software engineering. A goal here is to generalize to information management to support the design and evolution of a complex engineered system over its life-cycle. Finally, the information management requirements to handle "office data" for professionals and engineers (e.g., reports, memos, calendars, messages, etc.) is under investigation. These classes of users, while somewhat varied in nature, have similar core information management needs; further, these needs are not satisfied by current database technology and tools.

- Research has been initiated to establish technical approaches to the four principal subtasks that have been determined critical to providing a personal information management environment:

  1. A simple information model is required to uniformly accommodate all information objects, which may be of a variety of modalities (e.g., formatted data, communication messages, programs, documentation, images, etc.). To stress this required generality, the term "information base" is used here in place of "database" to refer to the collection of information objects associated with some personal workstation. The model must allow such information objects to be defined, classified, interrelated, and manipulated. While program objects are to be stored in an information base, this research does not specifically focus on the specification of algorithms; rather, programs are simply objects with behavior. The information model must also treat meta data and specific data in in a similar manner. In this way, an end-user can use the same model to conduct routine data manipulations, as well as to define, access, and manipulate object classifications (types, subtypes), inter-object mappings (relationships), and other information that is traditionally outside the "database" per se. During the past contract year, an initial definition of such a model, called the 3D information space model (3DIS), has been produced. A complete specification will be completed during 1983.

  2. A user interface is required to accommodate object search, definition, manipulation, and invocation (for program objects). Initial work is underway in defining such an interface, and on using the capabilities of a

high-resolution bit-map display to allow a user to browse and modify an information base defined with the 3DIS model. This interface will also employ prescriptive guidance to assist users in utilizing features of the systems with which they are not familiar <McLeod 1982>.

3. An information object management kernel will manage the physical storage and access of an information base. The approach taken here is to provide a canonical, default physical implementation, which is appropriately extended as an information base evolves (e.g., as new objects and inter-object relationships are defined). For cases in which the canonical implementation proves inadequate, a prescriptive (user-assisted) physical design methodology will be utilized. This methodology will employ a very small (but generally useful) set of physical storage structures, along with a small number of performance improvement heuristics, to iteratively improve performance. A tentative initial design of the kernel has been specified, and a prototype implementation will be developed and tested during 1983.

4. An interconnection mechanism is required to support the controlled sharing of information objects among a logical network of information bases. Specifically, a collection of workstation computers will be interconnected by a communication channel, and an interconnection and sharing mechanism will provide a small set of operations for object definition, manipulation, and retrieval in a distributed environment. An initial specification of such a mechanism is provided in <Lyngbaek+McLeod 1983>. In this approach, relationships among objects can be established across information base boundaries, objects are relocatable within the distributed environment, and mechanisms are provided for the controlled sharing of objects between individual information bases. An object naming convention supports location transparent object references; that is, objects can be referenced by user-defined names rather than by address. A refined sharing mechanism will be completed in 1983, along with a prototype implementation.

- An experimental prototype implementation of a personal information management environment, called INFOBASE (for "INFOrmation BAse Support Environment"), will be designed and implemented to serve as a vehicle to test and refine the research techniques devised in this project. While initial design of this prototype is well underway, implementation will not begin until mid-to-late 1983.

During the past contract year, the following milestones have been reached concerning aspects of this project initiated in prior contract years:

- A design and implementation of the "event database specification model", an integrated model and methodology for conceptual database design, has been produced <King+McLeod 1982, King+McLeod 1983a, King+McLeod 1983b, King 1982>. It provides integrated facilities for database specification, evolution, and access. The event model includes a prescriptive methodology to guide its use, thereby reducing the expertise required to design and document databases.

- A "transaction specification advisor" (TSA) has been designed and implemented, the purpose of which is to guide an end-user in understanding the content and structure of a database, and formulating a transaction on that database <McLeod 1982>. As such, the TSA provides prescriptive guidance to the user in browsing a databases and querying it. An experimental prototype TSA has been implemented.

- The design of the "federated database" architecture has been completed <Heimbigner 1982, Heimbigner+McLeod 1983>. This approach supports both the logical and physical decentralization required to support a network of databases. While contemporary approaches to "distributed databases" and "heterogeneous database systems" require a centralized logical organization, and centralized control, the federated database architecture addresses many problems associated with logical centralization by providing flexible sharing of information, but maintaining substantial autonomy for the component databases (viz., those constituting the federation). The federated database architecture provides a mechanism for specifying and negotiating the information exchange requirements among components, an approach to the effective processing of information exchange requests among components (transaction processing), and a methodology to support the design and evolution of a federation. A prototype federated database system was completed in August 1982.

JSEP PUBLICATIONS

1. <McLeod+Narayanaswamy+Rao 1983> McLeod, D., K. Narayanaswamy, and K. V. Bapa Rao, "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 (to appear).

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

3. <Lyngbaek+McLeod 1983> Lyngbaek, P. and D. McLeod, "An Approach to Object Sharing is Distributed Database Systems", submitted to International Conference on Very Large Databases, Florence, Italy, October 1983.

4. <King+McLeod 1982> 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+McLeod 1983a> 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, 1983 (to appear).

6. <King+McLeod 1983b> "Semantic Database Models", in Principles of Database Design (editor S. B. Yao), Prentice Hall, 1983 (to appear).

7. <King 1982> King, R., A Semantics-Based Methodology for Database Design and Evolution, Ph.D. Dissertation (Technical Report TR-115), Computer Science Department, University of Southern California, Los Angeles CA, May 1982.

8. <Heimbigner 1982> Heimbigner, D., A Federated Architecture for Information Bases, Ph.D. Dissertation (Technical Report TR-114), Computer Science Department, University of Southern California, Los Angeles CA, August 1982.

9. <Heimbigner+McLeod 1983> Heimbigner, D. and D. McLeod, "A Federated Architecture for Database Systems", to be submitted to ACM Transactions on Database Systems, 1983.

PROFESSIONAL PERSONNEL

- DENNIS MCLEOD, Principal Investigator, Assistant Professor of Computer Science

- ROGER KING, Ph.D. in Computer Science, received May 1982.

- HAMIDEH AFSARMANESH, Ph.D. Candidate in Computer Science, expected May 1984.

- K. V. BAPA RAO, Ph.D. Candidate in Computer Science, expected May 1984.

DESIGN OF EASILY MAINTAINABLE DIGITAL SYSTEMS

Work Unit IE2-4

JOHN P. HAYES

REPORT PERIOD: 1 April 1982 to 31 August 1982

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 EFFORT

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

1. J.P. HAYES, Principal Investigator

2. A. JOHARY, Research Assistant

3. G. SRINATH, Research Assistant

4. M. KAWAI, Visiting Scholar

EFFICIENT MAPPING OF COMPUTATIONAL ALGORITHMS INTO VLSI ARCHITECTURES
[Work Unit IE1-3]

DAN I. MOLDOVAN

REPORT PERIOD: 1 SEPTEMBER 1982 - 31 MARCH 1983

RESEARCH OBJECTIVES

The overall goal of this project is to develop a methodology for the efficient implementation of computational algorithms on Very Large Scale Integration (VLSI) processing arrays. The following specific research tasks were pursued during this period.

1. Study of parallelism in computational algorithms: parallelism detection and algorithm transformation.
2. Design of algorithmically - specialized VLSI devices.

STATUS OF RESEARCH EFFORT

Significant progress has been made in studying parallelism in algorithms. The results related to task 1 were documented in papers [1-3]. A new model to represented algorithms was introduced in technical report [3] as a five-tuple (index set, set of dependences, set of computations, set of inputs and set of outputs). Using this model we can classify algorithms into classes of equivalence and study parallelism properties for such classes. Our approach for parallelism analysis is based on the study of data dependences. These represent some precedence relations in

computations and are mathematically represented as vectors defined on algorithm index space. The research under task 1 has focused on the following two questions:

Q1. For an algorithm A with a given set of data dependences can we identify sets of noninterdependent operations in A?

Q2. For an algorithm A with a given set of data dependences can we device execution orderings of computations that sets of noninterdependent operations in algorithm A can be executed in parallel?

Positive answers were found to both questions for some classes of algorithms. A solution to the first question allows us to identify operations that can be executed in parallel and require no interconnections between processors that execute them. A solution to the second question allows us to take advantage of potential parallelism, thus achieving shorter execution time. More theoretical work is needed to extend these results to broader classes of algorithms.

The results related to research task 2 were documented in papers [2, 4-6]. Our approach to the design of algorithmically - specialized VLSI devices was to divide the design process into two main steps: 1 the mapping of algorithm into a global model describing the overall structure and operation of VLSI array and 2 the design of processing cells of the array based on the information contained in the global model. The design of the overall VLSI structure, including communication requirements was documented in [2]. The second step of the design, namely the detail design of processing cells was documented in technical report [4]. Several suggestive examples were given in order to illustrate the techniques proposed for the design of cell architectures. The case of algorithms with

variable data dependences was also considered, i.e. data dependences are functions of the algorithm index set. This class of algorithms is more difficult to synthesize, and generally leads to more complex cell structures. Dynamic programming algorithms are part of this class. Overall, technical papers [2,4] demonstrate that it is feasible to replace the heuristics used to design algorithmically - specialized VLSI devices with a precise methodology which ultimately can be automated.

Another type of algorithms considered were combinational algorithms for graph isomorphism. This was documented in [5]. The problem of graph matching occurs frequently in many fields of engineering and computer science and it is known to be computation and communication intensive. It was estimated that using the parallel algorithm proposed in [5], a real-time solution to subgraph isomorphism problem is possible with present VLSI technology for graphs with more than 20 nodes.

Another focus of the research was the study of bit-serial processing techniques for VLSI processing arrays. The main motivation for using bit-serial processing as opposed to word - parallel processing is to alleviate the I/O bottleneck problem in VLSI structures. By feeding and processing the data serially, the amount of hardware and data communication for each device is reduced; thus, more computing elements can be integrated in one VLSI chip. Moreover, bit-serial schemes offer speed-up advantages over the word-parallel schemes by means of bit level pipelining. The design philosophy for bit-serial adders and multipliers are presented in [6].

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6. D.I. Moldovan and G.R. Nudd, "A VLSI Algorithm and Architecture for Subgraph Isomorphism," (USC, Tech. Rep. PPP 83-4).

PROFESSIONAL PERSONNEL

D.I. MOLDOVAN, Principal Investigator,
Assistant Professor of Electrical Engineering

J.A.B. FORTES, Research Assistant

A. VARMA, Research Assistant

INTERACTIONS

D.I. Moldovan served as a consultant to Hughes Research Laboratories, Malibu, California in the area of VLSI computer architectures.

MODEL REDUCTION FOR REDUCED-ORDER ROBUST COMPENSATOR DESIGN

Work Unit IE2-5

L.M. SILVERMAN β E.A. JONCKHEERE

REPORT PERIOD: 1 April 1982 to 31 March 1983

RESEARCH OBJECTIVES

To achieve a deeper understanding of model reduction in the context of feedback systems. To derive "canonic" forms for linear multivariable feedback control sytems, allowing one to "measure" the "importance" of each "subsystem", under varying stability margin and robustness requirements. To derive from these canonic forms reduced plant models and reduced compensators. To derive streamlined, easy-to-use criteria for stability of the full plant closed up by a reduced compensator which ignores the "unessential subsystems". To assess the amount of robustness lost in the process of reducing the compensator. To implement numerically the developed theory.

STATE OF THE ART

There has been increasing interest over the past few years in model reduction, with in mind the ultimate objective of designing low-order, stabilizing, robust, feedback loops. The philosophy of this research can be described, in a few words, as follows: Given a high-dimensional, or large scale, plant G(s), one derives a "canonic" (or "balanced") state space realization of G(s), in which each state variable can be assigned a "measure" of its "dynamical importance". Since model reduction should be an external, or state coordinate free problem, it is essential that these measures be similarity invariants. If, in the appropriate balanced realization, some state components, some "subsystems", or some "modes" have "low" dynamical importance, then the

deletion of that part of the system characterized by "low" dynamical importance yields a reduced-order plant model. Finally, an obvious reduced-order compensator can be designed as the nominal compensator of the reduced plant.

Renewed interest in model reduction came with Moore's formulation [Ref.7] of the singular value decomposition for linear systems. In this technique, a measure, called singular value, is assigned to every state variable of the plant in a canonic (balanced) realization. A plant reduced-order model is derived by simply deleting, in the balanced realization, those state components with low singular values. However, it soon became evident that this procedure is not appropriate for feedback systems, for reasons explained in detail in [Ref.17].

Along a parallel line of ideas, Skelton [Ref.9] developed the "cost decomposition" for linear systems. This technique centers around the idea of connecting a white noise source at the input of the (open-loop or closed-loop) system and of defining a cost as the amount of noise at the output. In a suitably defined realization, one measures the contribution of each state coordinate to the cost; deletion of the less costly state coordinates yields the reduced-order model. The problem with this approach is that the quantities measuring how much each state coordinate participates in the cost are not always similarity invariants; also, some state components in a minimal realization can be assigned zero measure of importance, which apparently contradicts minimality. Hence more work needs be to done before the full potential and limitation of the "cost decomposition" can be assessed.

Finally, one should mention the stochastic approach [Ref.20], where model

reduction is thought as "approximate covariance realization".

STATUS OF RESEARCH EFFORT

Background material

Our research has centered around what we have called the "closed-loop principal component analysis", which is briefly summarized here below...

Consider a minimal state space representation

$$dx/dt = Ax + Bu \qquad (5.1)$$
$$y = Cx$$

of the plant transfer matrix

$$G(s) := C(sI-A)^{-1}B$$

y is an output available for feedback purposes, while u is the available control action.

The basic philosophy of the "closed-loop principal component analysis" is to measure how much each "mode", "subsystem", or state component participates in the inherent closed-loop behavior of the system. Model reduction and reduced compensation then follow by deleting the unessential part. There are many ways, depending on the specifications, of closing up a system by a feedback loop, but it is attractive to do this in an optimal way using the Linear-Quadratic-Gaussian approach. This approach is indeed systematic and fairly well understood. It also has the advantage of endowing the design with fairly general robustness properties. More interestingly, the LQG design can be tuned to optimal sensitivity properties by correct adjustment of the the quadratic criterion and the noise covariances. To formulate the problem within the LQG setup, a disturbance Gaussian white noise d(t) is added at the input

and a measurement Gaussian white noise n(t) is added at the output. To tune the LQG design to optimal robustness properties, it is convenient to introduce the quadratic criterion

$$r_o u'u + q_o y'y \tag{5.2}$$

together with the noise statistics

$$E(d(t)d'(\tau)) = q_m I\delta(t-\tau) \tag{5.2}$$

$$E(d(t)n'(\tau) = 0$$

$$E(n(t)n'(\tau)) = r_m I\delta(t-\tau)$$

The q's and the r's are (positive) parameters which must be tuned so as to reach satisfactory robustness properties. To understand how this can be done, let K(s) be a causal, stabilizing, strictly proper compensator. A crucial result, apparently due to Youla [Ref.1, Ref.2], connects up the performance $E(q_o y'y + r_o u'u)$ of the compensator K(s) with robustness matrices as follows:

$$\begin{aligned} &E(q_o y'y + r_o u'u) = \\ &1/(2\pi j) \int_{-j\infty}^{+j\infty} \text{Trace } \{ \\ &q_o r_m (I-GK)^{-1} GKK_* G_* (I-K_* G_*)^{-1} \\ &+ q_o q_m (I-GK)^{-1} GG_* (I-K_* G_*)^{-1} \\ &+ r_o q_m (I-KG)^{-1} KGG_* K_* (I-G_* K_*)^{-1} \\ &+ r_o r_m (I-KG)^{-1} KK_* (I-G_* K_*)^{-1} \} \, ds \end{aligned} \tag{5.3}$$

($K_*(s) := K'(-s)$, that is, the paraconjugate transpose of K(s).) The matrices

$$(I-GK)^{-1}GK,\ (I-GK)^{-1}G,\ (I-KG)^{-1}KG,\ (I-KG)^{-1}K$$

are well known to be related to the robustness properties of the loop; the smaller they are, the better the robustness properties. Intuitively speaking, Equality (5.3) says that minimizing the expected value $E(q_o y'y + r_o u'u)$ is equivalent to minimizing the integral over all frequencies of "sizes" of

"robustness" matrices. More intuitively, this says that minimizing a quadratic criterion boosts robustness. In the weighted average of the right side of Equation (5.3), the matrices $(I-GK)^{-1}GK$ and $(I-KG)^{-1}KG$ are of particular importance; they are indeed related to the stability margin of the feedback system [Ref.3]; the smaller these matrices, the more the feedback system can accomodate variations of GK and KG, respectively, before the loop becomes unstable. In closed-loop model reduction, the reduction error is considered as plant variation and is expected to be taken care of by the stability margin property of the loop. Hence, for this to be the case, it is imperative that the LQG problem underlying model reduction boosts the stability margin. This can be accomplished by assigning the following values to the parameters:

$$q_o=1,\ r_o=\varepsilon,\ q_m=\varepsilon,\ r_m=1$$

and by taking ε arbitrarily small.

Invoking the Separation Principle, one can split the design into an optimal filtering and an optimal control problem. It is well known [Ref.4, Ref.5] that these optimization problems involve in a crucial way the <u>filtering algebraic Riccati equation</u>

$$AP_m + P_mA' + q_mBB' - P_mC'CP_m/r_m = 0,\ P_m=P_m'>0$$

and the <u>control algebraic Riccati equation</u>

$$A'P_o + P_oA + q_oC'C - P_oBB'P_o/r_o = 0,\ P_o=P_o'>0$$

The optimal LQG controller consists of the cascade of the optimal filter

$$dw/dt = Aw + Bu + r_m^{-1}P_mC'(z-Cw)$$

and the optimal control gain

$$u=-r_o^{-1}B'P_ow$$

This leads to the following state space representation of the compensator K(s):

$$dw/dt = Fw + Gz$$

$$u = Hw$$

where

$$F := A - Br_o^{-1}B'P_o - P_mC'r_m^{-1}C$$

$$G := P_mC'/r_m$$

$$H := -B'P_o/r_o$$

The following is a fundamental result [Pub.2, Pub.4, Pub.7, Ref.21].

Theorem. Let (A,B,C) be a minimal realization of G(s). Then the eigenvalues of P_oP_m are similarity invariants. Further, these eigenvalues are real and strictly positive. If $\mu_1^2 \geq \mu_2^2 \geq \ldots$ denote the eigenvalues of P_oP_m in decreasing order, then there exists a "balancing" transformation $\underline{T}$ and a "balanced" state space realization $(\underline{A},\underline{B},\underline{C}) := (\underline{T}A\underline{T}^{-1}, \underline{T}B, C\underline{T}^{-1})$ in which

$$\underline{P}_o = \underline{P}_m = M$$

where

$$M := \text{diag}\ \{\ \mu_1,\ \mu_2,\ \ldots\ \}$$

The physical interpretation of the abovedefined quantities (the "closed-loop singular values") should be clear. Assume, for example, that μ_k is "small"; then the balanced state component $\underline{x}_k$ is "easy" to filter ($\underline{P}_m$ "small" along the kth direction) and "easy" to control ($\underline{P}_o$ "small" along the kth direction); hence, intuitively, $\underline{x}_k$ is an unessential state component; it is not significantly involved in the closed-loop LQG behavior of the system, and it can be discarded. Technically, this model reduction is done as follows:

Assume

$$M = \text{block diag } \{ M_{11}, M_{22} \}$$

with M_{11} "much larger than" M_{22}. Partition both the plant state equations

$$d\underline{x}_1/dt = \underline{A}_{11}\underline{x}_1 + \underline{A}_{12}\underline{x}_2 + \underline{B}_1 u$$

$$d\underline{x}_2/dt = \underline{A}_{21}\underline{x}_1 + \underline{A}_{22}\underline{x}_2 + \underline{B}_2 u$$

$$y = \underline{C}_1\underline{x}_1 + \underline{C}_2\underline{x}_2$$

and the controller state equations

$$d\underline{w}_1/dt = \underline{F}_{11}\underline{w}_1 + \underline{F}_{12}\underline{w}_2 + \underline{G}_1 z$$

$$d\underline{w}_2/dt = \underline{F}_{21}\underline{w}_1 + \underline{F}_{22}\underline{w}_2 + \underline{G}_2 z$$

$$u = \underline{H}_1\underline{w}_1 + \underline{H}_2\underline{w}_2$$

conformably with M. The obvious reduced-order model is $(\underline{A}_{11}, \underline{B}_1, \underline{C}_1)$, and it is easily proved that its optimal LQG controller is the obvious reduced-order compensator $(\underline{F}_{11}, \underline{G}_1, \underline{H}_1)$. Intuitively, stability of the full plant G(s) closed up by the reduced compensator should be guaranteed if M_{22} is "sufficiently small".

Besides its interest for reduced compensator design, the balanced realization enjoys some remarkable properties. In the SISO case, one can define a signature S := diag { s_1, s_2, ... }, with $s_k = \pm 1$, such that $\underline{A}' = S\underline{A}S$ and $\underline{b} = S\underline{c}'$. Such a realization is called signature symmetric [Ref.19]. Further, it can be shown that S conveys a phase information. Finally, it can be shown that $(M, S, \underline{b})$ is a parametrization of all SISO systems; see [Pub.2, Pub.4, Ref.19].

The intuitive feeling that stability of the full plant/reduced compensator loop should be guaranteed if M_{22} is small enough has received analytical confirmation in the form of a sufficient condition on M and S for stability

[Ref.2].

A few words about computations. The main computational burden is the solution to both algebraic Riccati equations. However, there is a fast and reliable procedure for solving the algebraic Riccati equation: the technique of Laub [Ref.6], which proceeds via the quasi-upper triangular form of the Hamiltonian matrix. A more recent procedure consists in solving the algebraic Riccati equation via an associated generalized eigenvalue problem. Once P_m and P_o are computed, their simultaneous diagonalization proceeds via the factorization of one of them, say, $P_m=LL'$, followed by the eigenanalysis of $L'P_oL$; see [Ref.8].

Results and accomplishments

Over the past twelve months, several (more or less concrete) examples have been considered, in an attempt to achieve a better understanding of the significance of the principal component analysis in the real-world.

The singular perturbation problem has been looked at as a case-study of the closed-loop principal component analysis. The major result [Pub.4] is that, under some conditions on the perturbation, the closed-loop balancing is consistent with the splitting of the singularly perturbed system into a slow (principal) and a fast (parasitic) subsystem; the largest μ's are related to the slow mode, and the lowest μ's are related to the parasitic mode. Somehow, this was a confirmation of the fact that, under some circumstances, unmodeled parasitic phenomena cannot destabilize a feedback loop.

The closed-loop principal component analysis has been numerically implemented on a computer program. The input to this program is the (A,B,C) data as well as the q's and the r's. The software computes the solution to the Riccati

equations, balances the state space realization, and computes the μ's. Further, it computes the reduced compensators of all orders, checks their stability properties, and examines via efficient frequency response computations their robustness properties. This program is still being updated; we consider it as a "prototype" of a more advanced software yet to be written in its final form.

A large space structure example -- the tetrahedral truss of Draper Lab [Pub.7, Ref.16] -- has been considered. The main conclusion is that the balancing transformation picks up the modal coordinates, but reorders them, not necessarily by order of decreasing eigenfrequencies. For example, some potentially overlapping fast modes can be assigned large μ's, under stringent stability margin requirements on the underlying LQG design. The resulting reduced-order compensator actively controls the high μ modes and leaves the low μ modes be damped by the structural dissipation without creating spillover.

Another example which has recently been considered is the roll-yaw control of the F-4 fighter aircraft [Pub.9, Pub.10]. The plant model (A,B,C) is six-dimensional and incorporates the dutch roll as well as the actuator dynamics. The input vector u consists of the rudder/aileron command signals; the output vector y consists of inertial and aerodynamic measurements. The numerical explorations have shown that it is possible to design compensators, of very low orders (even one), yet retaining stability and good frequency response properties. This case-study has allowed us to understand how the frequency-response properties are affected by compensator reduction: typically, compensator reduction <u>decreases</u> the bandwidth but <u>increases</u> the

gain so that, interestingly enough, the product "gain x bandwidth" remains a constant for all controller orders. In other words, there is an identifiable amount of robustness lost in the process of reducing the compensator.

Probably the most important result of all is that these numerical explorations have confirmed many intuitive feelings we had developed along the path of the theoretical establishment of this design technique.

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PROPOSED PROGRAM

The main thrust of future research effort will be in software development and numerical investigation of real-world examples. Aerospace control problems

will received top priority.

Our SISO stability criteria suffer some conservativeness. The reason is that they involve a restricted number of parameters (the μ's and the signature) and as such they must accomodate the worst possible combination of the other parameters (the $\underline{p}$'s). It is intended to derive less concervative criteria by using the stability margin property of the full order design. Somehow, the the reduction of the controller can be considered as a perturbation of an element of the feedback loop; if the "size" of this perturbation is smaller than the stability margin of the full design, then stability of the full plant/reduced compensator loop should be preserved. Whether this intuitive argument can be translated in terms of a precise, tractable stability criterion is an issue left for further research.

It is well known that a LQG design leads to some robustness properties. More interestingly, the quadratic criterion and the noise statistics can be tuned so as to boost some preselected robustness properties. As our simulation studies have shown, most of these robustness properties are preserved under the reduction of the controller. But the way the noises and the quadratic criterion have been chosen, more generally, the way the underlying LQG problem has been formulated, lead to some <u>very specific</u> robustness properties. Even better and more general robustness properties can be achieved by i) considering colored noises and frequency-dependent weightings, and ii) by injecting the noises at other nodes along the loop. This can be exploited in order to take care of sensor and actuator bandwidths. The details are left for further research.

Other "closed-loop balancing" techniques will be considered. For example, we

have recently formulated a new balancing procedure, inspired from Popov's theory and conventional frequency-response techniques [Pub.5, Pub.8]. It is still too early to predict where this is going, but this will retain part of our attention.

INTERACTION WITH OTHER WORK UNIT

Interaction with Dr. Safonov's work unit.

DOD INTERACTIONS

None.

MULTIVARIABLE FEEDBACK 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 parameter 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. The 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 made 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 techniques when dealing with structured uncertainty [2].

A systematic technique for optimizing the stability margin singular values of multiloop feedback systems was developed in 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, FL, 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-Output 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

1. **M. G. SAFONOV** (Principal Investigator)

2. **KAMRAN KARIMLOU** (Graduate Research Assistant)

3. B. S. CHEN (Graduate Research Assistant)

DOD INTERACTIONS: None

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