AD-A196 788

COORDINATED SCIENCE LABORATORY

PROGRESS REPORT
FOR THE
JOINT SERVICES
ELECTRONICS PROGRAM

FOR THE PERIOD
APRIL 1, 1987, THROUGH MARCH 31, 1988
FOR
CONTRACT N00014-84-C-0149

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
Unclassified	None

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
N/A	Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
N/A	

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
Second Annual Progress Report	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
Coordinated Science Lab University of Illinois	N/A	Office of Naval Research

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
1101 W. Springfield Ave. Urbana, IL 61801	800 N. Quincy St. Arlington, VA 22217

8a. NAME OF FUNDING/SPONSORING ORGANIZATION Joint Services Electronics Program	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
		N00014-84-C-0149

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
800 N. Quincy St. Arlington, VA 22217	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Second Annual Progress Report

12. PERSONAL AUTHOR(S) Professor William Kenneth Jenkins

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM 4/1/87 TO 3/31/88	6/30/88	93

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

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

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	**22b. TELEPHONE (Include Area Code)** **22c. OFFICE SYMBOL**

DD FORM 1473, 84 MAR   83 APR edition may be used until exhausted.   SECURITY CLASSIFICATION OF THIS PAGE
All other editions are obsolete.

OFFICE OF NAVAL RESEARCH

PROGRESS REPORT

For the Period

1 April 1987 through 31 March 1988

for

Contract N00014-84-C-0149

Title of Contract
Joint Services Electronics Program

Name of Principal Investigator
William Kenneth Jenkins
Coordinated Science Laboratory

Name of Organization
THE BOARD OF TRUSTEES OF THE UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
Grants and Contracts Office

Address of Organization
506 S. Wright Street
Urbana, IL 61801

TABLE OF CONTENTS

RESEARCH AREA: Information Systems

RESEARCH AREA: Electronics Research

EXECUTIVE SUMMARY

I. Summary of tne Program

This report summarizes the research that was carried out under the Joint Services Electronics Program at the Coordinated Sciences Laboratory, University of Illinois at Urbana–Champaign, during the period April 1, 1987, through March 31, 1988. The current JSEP contract that began on October 1, 1986, contains 22 work units (Unit 3 of the new contract was withdrawn and Unit 6 has been replaced by Unit 24). In all, there are 9 units in Physical Electronics, 2 units in Electromagnetics, 10 units in Information Electronics, and 1 discretionary unit used by the Director to seed new projects.

As of October 1, 1987, a new unit (Unit 24) entitled "Electronic and Transport Properties of Ultra-Low-Dimensional Structures" was added to the program as a replacement for Unit 6. Unit 6, entitled "Optical Properties of MBE-Grown Structures," was phased out from October 1, 1987, to March 31, 1988, since Professor Morkoc became overcommitted and was no longer able to participate in this research. The Senior Investigators on Unit 24 are Professors Leburton, Kolodzey, and Adesida. The objective of this new unit is to explore the potential of ultra-low-dimensional semiconductor structures for electronic and optical device applications. This research represents a team approach, with Professor Leburton providing theoretical expertise, Professor Adesida providing experimental expertise, and Professor Kolodzey providing the skills in high-speed measurements.

After the death of Professor Thornton, Professor Mark Kushner joined the program to carry on the work of Unit 9, "An Investigation of Plasma Chemistry Processes in Cylindrical Magnetron Plasma Discharges." Professor Kushner has assumed the responsibility for the supervision of the graduate research assistants on this unit and is carrying out the research in accordance with the original objective.

Professor Jessy Grizzle has left the university and is no longer participating in the work of Unit 20. However, three new faculty have been added: Professor Yoram Bresler has joined the Digital Signal and Image Processing Group; Professor Wen-Mei Hwu has joined the Computer Systems Group; and Professor Bang-Sup Song has joined the VLSI Circuits Group. Although none of these young faculty is currently receiving direct support from the JSEP program, they are working with the graduate students in the corresponding areas, and it is anticipated that they will play important roles in future JSEP work.

In general, work on all of the units not mentioned above has been proceeding on schedule and according to the plans that were outlined in the original 3-year proposal. The progress on each of these units is summarized in the body of this report.

During the second year of this JSEP contract, all of the discretionary funds provided to the Director under Unit 23 were allocated for equipment purchases for the new MBE facility (Epi-Center) that has been established in CSL under a college-wide cooperative effort. This new facility is described more fully under Unit 23.

After serving as the Acting Director of CSL from August 1986, Professor W. Kenneth Jenkins was named Director in May 1987 and has undertaken the responsibility for managing the JSEP program. During the last year, he has named a JSEP Advisory Committee to help establish direction and policy for the JSEP-sponsored research. Professor Karl Hess and Professor Michael Pursley are serving as Technical Advisors for Physical Electronics and Information Electronics, respectively. Professor Timothy Trick, Head of the Electrical and Computer Engineering Department, is serving as an Advisor-at-Large in order to integrate the interests of JSEP with the capabilities of the ECE Department. It is anticipated that the JSEP Advisory Committee will be quite active next year as the faculty in CSL prepare for the next major proposal.

University of Illinois at Urbana–Champaign   Coordinated Science Laboratory

II. JSEP Outstanding Accomplishments

During the last year three JSEP accomplishments stand out as particularly significant, each of which is described briefly below. These are: (1) a new CAD program called iSMILE for the modeling and simulation of new microelectronic and optoelectronic devices and circuits; (2) a first-time experimentally observed charge density wave (CDW) discommensuration domain structure in the nearly commensurate phase of $1T-TaS_2$; and (3) new progress in achieving controlled doping in MBE silicon.

(1) Modeling and Simulation of New Microelectronic and Optoelectronic Devices and Circuits with the iSMILE Program (Unit 7)

During the last few years Professors S. M. Kang and T. N. Trick, with graduate students K. Cioffi and A. T. Yang, have collaborated on the development of circuit models for High Electron Mobility Transistors (HEMT) under the JSEP sponsorship. Traditionally, the task of developing new circuit models has been time consuming, mainly due to the intensive line-by-line modification of generic circuit simulators like SPICE or SLATE. As a result, the progress in computer-aided simulation of new microelectronic devices and circuits has been hampered by the slow model development process.

Under the JSEP sponsorship, Professor Kang and his Research Assistant A. T. Yang initiated the development of a new CAD tool, iSMILE (Illinois Simulator for Modeling of Integrated-circuit Level Elements). This program was first tried by Dr. Cioffi, now at Rockwell International, for his development of HEMT models. To iSMILE, circuit models are described by using a simple input file containing model topology descriptions and element characteristic equations. The iSMILE program then builds a circuit simulator based on circuit models shielding the user from the laborious line-by-line program modifications. Owing to this unique feature, the model development time is reduced significantly from several months to a few weeks once the model developer has a clear understanding of underlying device physics.

Further development of the iSMILE program has been continued under the sponsorship of the National Science Foundation (NSF) Engineering Research Center for Compound Semiconductor Microelectronics. iSMILE has been used to develop lossy transmission models, multiple quantum well laser diode models, optical waveguide models, and photodetector circuit models in cooperation with Professors J. J. Coleman, T. A. DeTemple, and G. E. Stillman. Using these models and HEMT models, we have been able to simulate the speed performance of optical interconnect systems, which would not have been possible in such a short time without iSMILE.

The unique capability of the iSMILE program has been well recognized by industry visitors and, at their request, we have ported the iSMILE program to industrial researchers at Hewlett Packard. Our work on circuit modeling and simulation will be presented at the 1988 International Conference on Circuits and Systems and the 1988 International Conference on Computer Design. Further details of our work will be published in professional journals.

It was through the interdisciplinary team effort provided under the sponsorship of JSEP, NSF, and industry that enabled our development of new circuit models, as well as the novel CAD tool, iSMILE.

(2) Scanning Tunneling Microscopy of the CDW Discommensuration Domain Structure in the Nearly Commensurate Phase of $1T-TaS_2$ (Unit 8)

It has been known for some time from bulk NMR and XPS measurements that the nearly commensurate CDW phases exhibited by some of the layered transition metal dichalcogenides actually consist of relatively small commensurate regions separated by CDW phase kinks or discommensurations (DCs). Their existence and microscopic domain structure have previously been predicted by the Ginzburg Landau approaches of McMillan and Nakanishi; however, no direct observation of the DC domain structure has been made until now.

Recently, Professor Joe Lyding and one of his students, Mr. Stephen Skala, have been able to use their new variable temperature STM (thermal drift < 1 Å/hour) to study the nearly commensurate phase of $1T-TaS_2$. Shown in Figure 1a is a representative STM image in which the larger period CDW is superimposed against the sulfur rows of the atomic lattice. From images like this, the commensurability of the CDW relative to the lattice can be studied. Shown in Figure 1b is their proposed model for the DC structure for Figure 1a and for $1T-TaS_2$ in general. The small dots denote the sulfur atoms, the large dots are the CDW maxima, and the lines are the DCs between commensurate regions. Here it is seen that the domains are rhombohedral with a characteristic length of 60 Å along each edge. The bold line to the right of Figure 1b represents a DC with a larger phase kink than the other DCs. The observed domain structure is not the hexagonal domain structure predicted by Nakanishi but one in which there are two equivalent CDW wavevectors (parallel to the DC boundaries), while the third wavevector passes through more DCs per unit length. This model also yields the correct average orientation of the incommensurate CDW wavevector relative to the lattice, as determined by bulk measurements.

(3) Controlled Doping in MBE Si: Chemistry at the Atomic Level (Unit 1)

Fabrication of modern microelectronic devices requires precise control of dopant concentrations and depth distributions. Molecular beam epitaxy (MBE) is presently employed in many critical applications, such as the growth of superlattices and modulation-doped structures. However, most of the common dopants used in bulk Si wafers present serious problems during film growth by MBE due to low incorporation probabilities and/or pronounced surface segregation giving rise to uncontrolled profile broadening.

Under JSEP Unit 1, Professor Joe Greene has been investigating the use of low-energy (50-500 eV) accelerated-ion doping during MBE Si growth. The experiments are carried out using new ultrahigh-vacuum compatible low-energy ion sources, which were developed as part of the research program. Sb, an important shallow donor in Si, and In, a deep acceptor, were chosen as model dopant materials.

Thermal Sb_4 and In, obtained from standard effusion cells, have low incorporation probabilities σ in MBE Si. σ_{Sb} ranges from 10^{-3} to 10^{-5} at growth temperatures T_s between 700 and 850 °C, while σ_{In} is $< 10^{-5}$ at $T_s > 550$ °C. These dopants also exhibit severe surface segregation with, in the case of Sb, steady-state surface accumulations during growth of up to a full monolayer. This not only gives rise to broad doping profiles but also limits the maximum usable doping concentrations. For example, obtaining Sb concentrations higher than $\approx 5 \times 10^{17} - 10^{18}$ cm^{-3} with thermal-doping requires the use of extremely large Sb_4 fluxes, which results in the production of a high concentration of structural defects and a corresponding decrease in electron mobilities.

The University of Illinois Thin Film Physics Group is employing a combination of Auger electron spectroscopy (AES), low-energy and reflected high-energy electron diffraction (LEED and RHEED), plan-view and cross-sectional transmission electron microscopy (TEM and XTEM), secondary-ion mass spectrometry (SIMS), and temperature-dependent Hall measurements to investigate the growth, structure, dopant distribution, and electrical properties of Si films grown at $T_s =$ 800 °C with 150 eV Sb^+ and 200 eV In^- dopant beams. Sb and In were found to incorporate, with unity probability, into substitutional, electrically active sites at concentrations up to at least 3×10^{19} cm^{-3} and 1×10^{18} cm^{-3}, respectively. The films were essentially dislocation free with no indication of residual ion-induced damage. Data show that carrier mobilities of Sb and In ion-doped films are equal to the best reported values for bulk Si even at doping concentrations extending well above those attainable by thermal-beam MBE. In fact, the hole mobilities are the highest ever reported for In-doped Si, whether bulk or thin film. Doping profiles in accelerated-beam modulation-doped structures were extremely abrupt. There was no indication from *in situ* AES and RHEED analyses of significant dopant surface accumulation during growth.

4

1T–TaS$_2$

100x100 Angstroms   T–298 K

a)
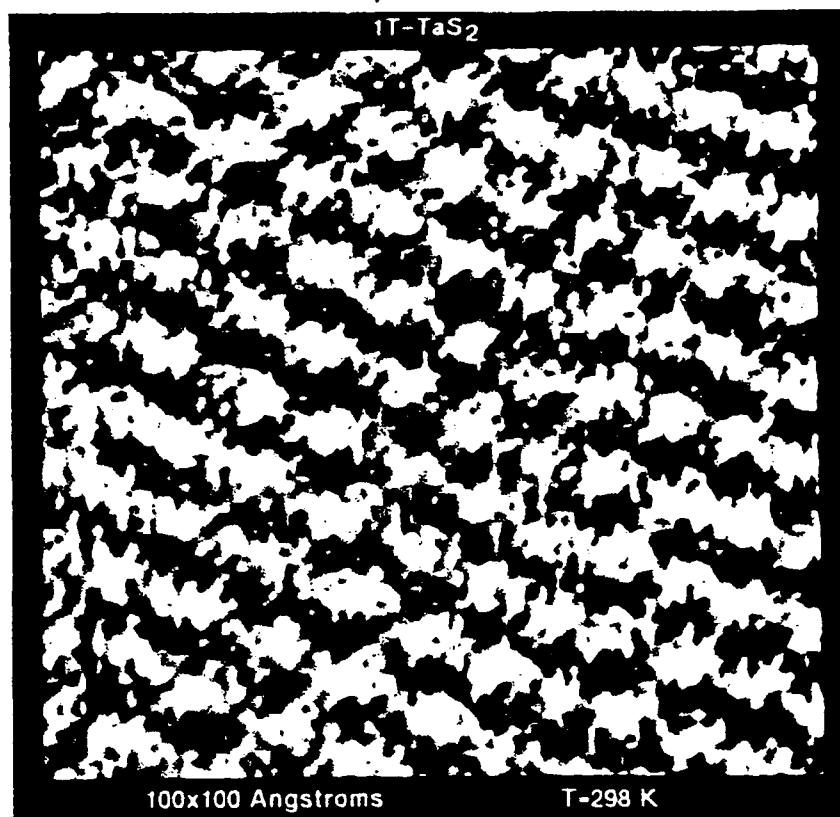
b)
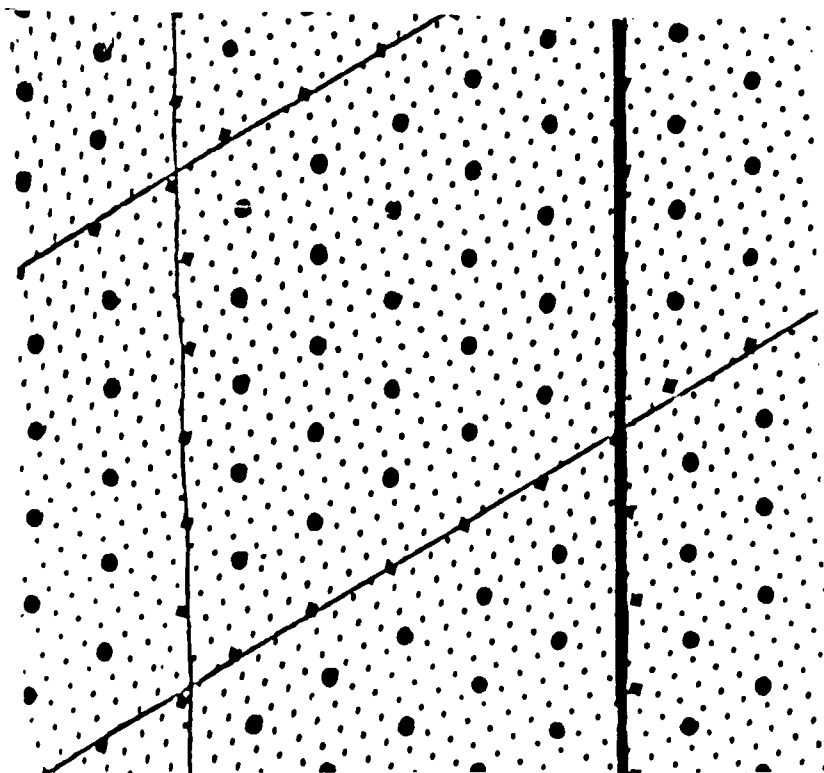
Fig. 1   a) STM image of the nearly commensurate phase of 1T–TaS$_2$ showing the orientation of the CDW (large period) relative to the atomic sulfur rows of the lattice. b) Discommensuration model constructed from a where the small dots are atoms, large dots are CDW maxima and the lines are discommensurations. The bold line is a discommensuration having a larger phase kink.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

WORK UNIT NUMBER 1

TITLE: Crystal Growth from the Vapor Phase and Controlled Doping of Equilibrium and Metastable Semiconductor Alloys: Ion-Surface Interactions

SENIOR INVESTIGATORS:

J. E. Greene, Research Professor
D. Lubben, Research Associate

SCIENTIFIC PERSONNEL AND TITLES:

F. Adibi, Research Assistant
P. Fons, Research Assistant
B. Kramer, Research Assistant
L. Markert, Research Assistant
D. McIntyre, Research Assistant
D. Mei, Research Assistant
J.-P. Noël, Research Assistant
M.A. Ray, Research Assistant

SCIENTIFIC OBJECTIVE:

The primary objective of this research program is to investigate energetic particle-surface interactions that control the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconductors during vapor phase crystal growth by UHV ion beam sputtering and accelerated-beam molecular beam epitaxy. In both of these growth techniques, low energy ion-surface interactions allow an efficient coupling of kinetic energy to the growth surface upon condensation, thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing single crystal film growth at lower temperatures, much more precise control over dopant incorporation probabilities and depth distributions, and the growth of unique metastable alloys. This work is being pursued from both an analytical and an experimental point of view in order to establish a detailed understanding of fundamental film growth mechanisms.

SUMMARY OF RESEARCH:

Incorporation Probabilities and Depth Distributions of Thermal and Accelerated Dopants in Semiconductors Grown by MBE

Most common n- and p-type dopants used in bulk Si technology and many dopants used in bulk GaAs provide problems in MBE film growth due to either low dopant incorporation probabilities and/or high surface-segregation rates. The problem is especially acute in MBE Si. We have attacked these problems on two fronts. (1) As discussed in the last two annual reports, we have developed a general time-dependent model, which combines thermodynamic and kinetic elements, for describing the incorporation of thermal dopants into films during deposition. (2) We have investigated the use of low-energy primary and secondary accelerated-ion doping during MBE growth to demonstrate increases in σ by more than five orders of magnitude, abrupt doping profiles with no indication of segregation-induced broadening, and excellent electrical properties. Primary-ion doping experiments were carried out using a new ion source that was designed and constructed as part of this research project.

dopant incorporation model accounts for dopant surface segregation and allows elemental incorporation probabilities σ and depth-dependent concentration profiles $C(x,t)$ to be calculated as a function of experimental parameters such as film and dopant material, deposition rate, incident dopant flux, film growth temperature, etc. Calculated profiles from arbitrarily complex doping schedules for both thermal and accelerated dopants are in good agreement with experimental results for dopants in MBE Si, GaAs, and $Ga_{1-x}Al_x$ As. In addition, we have used the model to predict critical temperatures for transitions in dopant segregation regimes, dopant-induced surface structural phase transitions, and changes in dopant/surface reaction paths leading to large changes in surface binding energies and hence incorporation probabilities. All of these effects have now been observed experimentally. We have recently predicted that there should exist a narrow growth-temperature range over which abrupt doping profiles can be obtained for Al, a p-type dopant which exhibits severe surface segregation, in MBE Si. Our preliminary experimental results are in agreement showing, for the first time, abrupt modulation-doped Al profiles.

We have recently designed, constructed, and tested a second-generation single-grid optics, electron impact, ultrahigh vacuum compatible, low-energy ion source capable of operation with low vapor-pressure solid source material. The ion optics are well characterized, very reproducible, and provide uniform beam profiles with current densities of up to 0.3 mA cm^{-2}. The gun has been operated for long periods of time at acceleration energies ranging from 50 e to 500 eV.

Using ion sources such as described above, we have investigated the incorporation of accelerated-In, a deep level acceptor, and accelerated-Sb, a shallow donor, in MBE Si. The incorporation probability of thermal In in MBE Si(100) is too low to be usable with $\sigma_{In} < 10^{-5}$ for film-growth temperatures $T_s > 550$ °C . σ_{Sb} is also low and ranges from 10^{-3} to 10^{-5} for T_s between 700 and 850 °C. Both dopants exhibit severe surface segregation with steady-state surface accumulations during growth of up to a full monolayer. This not only gives rise to broad profiles but also limits the maximum usable doping concentrations to rather low values due to the necessity of using extremely large dopant fluxes that result in the production of high concentrations of structural defects and a corresponding decrease in carrier mobilities.

We have carried out a detailed investigation of the incorporation of accelerated-In^+ in MBE Si(100) using ion acceleration energies E_{In^+} of 50, 75, 100, 200, 300, 400, and 500 eV at growth temperatures between 500 and 1050 °C. σ_{In^-} was found to be unity for $E_{In^+} \geqslant 200$ eV at growth temperatures up to approximately 900 °C where bulk diffusion becomes appreciable giving rise to surface segregation and hence dopant loss by desorption. Even at $E_{In^-} = 50$ eV, σ_{In^+} ranged from ≈ 0.2 at 500 °C to 2×10^{-4} at 1050 °C. increases of ≈ 3 to 5 orders of magnitude! Doping profiles in modulation-doped structures were found to be abrupt, at all acceleration energies, to within the depth resolution of SIMS. Thermally-stimulated desorption (TSD) and modulated-beam mass spectrometry (MBMS) have been used in combination with an extension of our thermal dopant incorporation model to understand the mechanisms associated with accelerated-dopant incorporation. Initial results clearly show that the mechanisms are quite different for acceleration energies above and below 200 eV. Structural and electronic properties of accelerated-In^+ doped films are discussed in the next section.

We have modeled thermal Sb incorporation in MBE Si based upon incorporation data and detailed analyses of our TSD and MBMS data to determine Sb_4 dissociative chemisorption kinetics and surface binding energies and lifetimes as a function of coverage and T_s. The first experiments on accelerated-Sb doping have also been carried out with $E_{Sb^+} = 50$ and 150 eV at T_s between 500 and 950 °C. σ_{Sb^-} was increased by up to three orders of magnitude and doping profiles in the accelerated-Sb^+ doped films were found to be abrupt.

Electronic Properties of Accelerated-Ion Doped MBE Si Films

A combination of in situ low-energy and reflected high energy electron diffraction (RHEED and LEED), plan-view and cross-sectional transmission electron microscopy (TEM and XTEM), secondary-ion mass spectrometry (SIMS), and temperature-dependent Hall measurements were

used to investigate the structure. dopant distribution, and electrical properties of MBE Si(100) films grown at 800 °C with either 200 eV In$^+$ or 150 eV Sb$^+$ accelerated-dopant beams. The incorporation probabilities were found to be unity. A comparison between total dopant concentrations determined by calibrated SIMS measurements and dopant concentrations obtained from Hall data shows that both In and Sb were incorporated into substitutional. electrically active sites. The concentration ranges examined so far are $5 \times 10^{15} - 2 \times 10^{18}$ cm^{-3} for In. well above the equilibrium solid-solubility limit. and $10^{16} - 3 \times 10^{19}$ cm^{-3} for Sb. more than an order of magnitude above the highest values obtainable by thermal doping without introducing high structural defect concentrations. In all cases. the films were found by TEM and XTEM analysis to be dislocation free with no indication of residual ion-induced damage.

Carrier mobilities were found to be equal to. or higher than. the best reported values for bulk Si. In fact. hole mobilities measured in In$^+$-doped films were the highest ever reported for In-doped Si and were much higher than mobilities for annealed In-implanted Si. Doping profiles in modulated structures were abrupt and *in situ* AES and RHEED analysis showed no indication of significant dopant surface accumulations as were observed during the growth of thermally-doped films. Thus. under the present growth conditions. radiation-induced defects were annealed out at a faster rate than they were produced resulting in no residual damage. We have. in addition. begun to investigate the parameter space over which damage-free material can be grown as well as the nature of residual damage in films deposited under conditions outside this growth parameter window.

Effects of Low-Energy Ion/Surface Interactions on the Nucleation and Growth Kinetics of Films Deposited from the Vapor Phase

The increasingly stringent requirements of sophisticated thin-film device and processing technologies provide a strong impetus for obtaining better control over the microchemistry and microstructure of as-deposited layers as well as for devising lower-temperature growth techniques. Low-energy ion irradiation of the substrate and film <u>during</u> deposition is presently being used by laboratories across the world in a variety of beam and plasma-based film growth techniques in order to provide an efficient coupling of kinetic energy to the growth surface to alter reactivity as well as adsorption. adatom diffusion. nucleation. and growth kinetics.

Our group has been modeling low-energy ion/surface interaction effects that are common to a variety of growth techniques and has carried out some of the first definitive experiments under well-controlled ultrahigh vacuum environments to probe fundamental mechanisms. A few highlights are described briefly below.

● We have demonstrated in experiments involving the deposition of both thermal In and accelerated-In$^+$ on Si(100)2x1 surfaces that low-energy (50-300 eV) primary-ion deposition changes not only the kinetics of nucleation but also the mechanism. That is. thermal In deposited at $T_s \leq 150$ °C grows by a Stranski-Krastanov mechanism to form quasi-one-dimensional wires along [011] directions. Surface tension is extremely high leading to very low island coverage. In fact. only about 7% of the Si surface is covered after the deposition of 200 monolayers! The use of accelerated primary ions increases the nucleation density by several orders of magnitude. enhances surface diffusivity. and leads to essentially complete coverage by 200 ML.

● We have previously predicted that low-energy ion irradiation might lead to much higher nucleation rates. as in the experiments described above. due to the production of preferential adsorption sites provided by charged surface vacancy complexes and trapping. The key feature necessary to test these ideas was the development of techniques to measure preferential adsorption energies. We have recently done this for both Sb and In on Si(100) surfaces using TSD and MBMS. The initial results show not only the production of enhanced binding sites but that the nature of the sites changes at critical energies. ≈ 200 eV for In$^+$.

● We have also investigated mechanisms leading to ion-induced enhanced surface diffusion during nucleation and film growth. For these experiments. In was deposited to nominal thicknesses

ranging from 1 to 10 nm on thin, electron-transparent, Si_3N_4 substrates in a UHV system and then investigated by TEM. The use of accelerated condensing species resulted in larger average island sizes (for a given nominal film thickness), more uniform island size distributions, and the suppression of secondary nucleation. We have proposed a model to explain these results in which the primary effect of ion irradiation is to break up small clusters to form still smaller clusters and adatoms which can diffuse much more rapidly on the surface to feed larger stable islands.

The loss of these small clusters (incipient islands) explains the decrease in the secondary nucleation rate and leads to large changes in growth kinetics. In the accelerated-beam case, island growth continues to be dominated by surface diffusion to much higher nominal film thicknesses than in thermal-beam deposits where coalescence of small islands at an early stage of growth leads to less uniform island size distributions. Other effects associated with collision-cascade dynamics are also important and have been shown by molecular dynamics simulations to be related to the development of preferred orientation in polycrystalline films and may allow decreased epitaxial temperatures. Such effects cannot, however, account for long-range "enhanced diffusion."

JSEP-SPONSORED PUBLICATIONS

[1] S. A. Barnett, H. F. Winters, and J. E. Greene, "Influence of ion bombardment on the interaction of Sb with the Si(100) surface," *Surf. Sci.*, vol. 181, pp. 596-603, 1987. (JSEP/SRC)

[2] S. I. Shah, J. E. Greene, L. L. Abels, Q. Yao, and P. M. Raccah, "Growth of single-crystal metastable $Ge_{1-x}Sn_x$ alloys on Ge(100) and GaAs(100) substrates, *J. Cryst. Growth*, vol. 83, pp. 3-10, 1987. (JSEP/DOE)

[3] J. E. Greene, "Crystal growth, atomic ordering, and physical properties of epitaxial metastable semiconductors," *J. Vac. Sci. Technol. A*, vol. 5, pp. 1947-1948, 1987. (JSEP)

[4] J. E. Greene, T. Motooka, J.-E. Sundgren, D. Lubben, S. Gorbatkin, and S. A. Barnett, "The role of ion-surface interactions and photo-induced reactions during film growth from the vapor phase." *J. Nucl. Instr. Methods B*, vol. 27, pp. 226-242, 1987. (JSEP/DOE/ONR/SRC)

[5] J. E. Greene, "Low-energy ion bombardment during film deposition from the vapor phase: effects on microchemistry and microstructure." *Sol. St. Technol.*, vol. 30, pp. 115-122, 1987. (JSEP/DOE/SRC)

[6] M.-A. Hasan, S. A. Barnett, J.-E. Sundgren, and J. E. Greene, "Nucleation and initial growth of In deposited on Si_3N_4 using low-energy ($\leqslant$ 300 eV) accelerated beams in ultra-high vacuum." *J. Vac. Sci. Technol. A*, vol. 5, pp. 1883-1887, 1987. (JSEP/SRC)

[7] M.-A Hasan, J. Knall, S. A. Barnett, A. Rockett, J.-E. Sundgren, and J. E. Greene, "A low-energy metal-ion source for primary-ion deposition and accelerated-ion doping during molecular beam epitaxy." *J. Vac. Sci. Technol. B*, vol. 5, pp. 1332-1339, 1987. (JSEP/SRC)

[8] N. Hirashita, J.-P. Noel, A. Rockett, L. Markert, J. E. Greene, M.-A. Hasan, J. Knall, W.-X. Ni, and J.-E. Sundgren, "Indium ion doping during Si molecular beam epitaxy," in *Materials Modification and Growth Using Ion Beams*, U. Gibson, P. P. Pronko, and A. E. White, Eds. Pittsburgh: Materials Research Society, in press. (JSEP/SRC)

[9]   J. Knall, M.-A. Hasan, J.-E. Sundgren, A. Rockett, L. Markert, and J. E. Greene, "Indium incorporation in MBE Si(100) layers using low-energy secondary and primary ion implantation during growths," in *Silicon Molecular Beam Epitaxy II*, J. C. Bean and L. J. Showalter, Eds. Electrochemical Society, in press.   (JSEP/SRC)

[10] J. E. Greene, S. A. Barnett, J.-E. Sundgren, and A. Rockett, "Ion/surface interactions during film growth from the vapor phase," in *Ion Beam Assisted Film Growth*, T. Itoh, Ed. Elsevier, in press.   (JSEP/SRC)

WORK UNIT NUMBER 2

TITLE: Studies of Transport Phenomena in Semiconductors

SENIOR INVESTIGATOR:

K. Hess, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

I. C. Kizilyalli, Research Assistant
J. Higman, Research Assistant
S. Manion, Research Assistant

SCIENTIFIC OBJECTIVE:

This research involves the study of basic properties of semiconductors, semiconductor-heterolayers, new device concepts, and device simulation. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance. The experimental studies concern mainly electronic transport in heterolayers in high electric and high magnetic fields, while the theoretical studies are based on Monte Carlo methods and, generally speaking, the use of large computational resources.

SUMMARY OF RESEARCH:

Our research in the last year has centered on several new phenomena in heterolayer transport. We have continued our theoretical studies of the S-shaped current voltage characteristic in the H^2ED heterolayer structure [1,2], and we have found a satisfactory analytical theory which explains the switching mechanism and the parameter range (doping) fairly well. We have shown that the mechanism by itself is extremely fast (subpicosecond range), although practical limitations arise from resistance-capacitance consideration. A description is given also by Professor Coleman who guided the experimental effort.

We have continued to investigate the use of heterolayer structures in problems related to impact ionization and avalanche photodiodes. On the side of impact ionization over the band gap in superlattices, we have found an analytical approach in cooperation with Brennan (Georgia Tech) and Capasso (AT&T Bell Laboratories) [3]. The work with Chuang on ionization of electrons out of heavily doped quantum wells has basically been completed and is summarized in [24].

A series of investigations has been devoted to the idea (Sakaki) of velocity modulated transistors. These field effect transistors intend to capitalize on the fast transfer between the two heterolayer interfaces in a (quantum) well. One interface is assumed to be ideal, while the other interface contains defects that lower the mobility considerably. Transferring the electrons from one interface to the other then modulates the electron velocity and results in fast switching. We have verified by Monte Carlo simulations that this concept is essentially valid. However, there is a

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

long-time component in the switching mechanism that still corresponds to approximately the source-to-drain transit time and needs to be taken into account. Overall, however, these structures do promise extremely high speed [4,5,6].

Using high magnetic fields, we have been able to demonstrate clearly that real-space transfer can be viewed as a transition from two- to three-dimensional behavior of an electron gas. A NER-FET fabricated in the group of J. J. Coleman was immersed into liquid helium and subjected to a magnetic field parallel to the interface. At low electric fields the magnetoresistance was negligible, as expected, for a two-dimensional electron gas, while at high electric fields a considerable magne-toresistance indicated the change of dimensionality to three [7]. More recent work has concentrated on energy loss in degenerate quasi-two-dimensional systems [8].

INTERACTION AND/OR TECHNOLOGY TRANSFER:

The investigations in references [4,6] have been developed in cooperation with the U. S. Army Electronics Technology and Devices Laboratory, Ft. Monmouth. The work described in reference [3] has been performed in cooperation with Federico Capasso from AT&T.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] T. K. Higman, J. M. Higman, M. A. Emanuel, K. Hess, and J. J. Coleman, "Theoretical and experimental analysis of the switching mechanism in heterostructure hot electron diodes", *J. Appl. Phys.*, vol. 62, no. 4, pp. 1495-1499, Aug. 15, 1987. (ONR/JSEP)

[2] M. A. Emanuel, T. K. Higman, J. M. Higman, J. M. Kolodzey, J. J. Coleman, and K. Hess, "Theoretical and experimental investigations of the heterostructure hot electron diode," *Solid-State Electron.*, vol. 31, no. 3/4, pp. 589-592, 1988; also, *Proc. Fifth Int. Conf. on Hot Carriers in Semiconductors*, Boston, 1987. (ONR/JSEP)

[3] K. Brennan, K. Hess, and F. Capasso, "Physics of the enhancement of impact ionization in multiquantum well structures," *Appl. Phys. Lett.*, vol. 50, no. 26, pp. 1897-1899, 1987. (JSEP/ONR/NSF)

[4] I. C. Kizilyalli and K. Hess, "Electron transfer between adjacent channels simulated by ensemble Monte Carlo methods," *J. Appl. Phys.*, vol. 61, no. 6, pp. 2395-2398, 1987. (ARO/JSEP)

[5] I. C. Kizilyalli, and K. Hess, "Ensemble Monte Carlo simulation of a velocity-modulation field effect transistor (VMT)", *Japanese J. of Appl. Phys.*, vol. 26, no. 9, pp. 1519-1524, 1987. (ARO/JSEP)

[6] I. Kizilyalli and K. Hess, "Ensemble Monte Carlo simulation of velocity modulation (VMT) and real space transfer (NERFET, CHINT) devices," presented at the Third International Conference on Superlattices, Microstructures and Microdevices (1987); proceedings to be published in *Superlattices and Microstructures*. (ARO/JSEP)

[7] T. K. Higman, S. J. Manion, I. C. Kizilyalli, M. A. Emanuel, K. Hess, and J. J. Coleman, "Observation of the transition associated with real-space transfer of two-dimensional electron gas to a three-dimensional electron distribution in semiconductor heterolayers," *Phys. Rev. B*, vol. 36, no. 17, pp. 9381-9383, Dec. 15, 1987. (JSEP/ONR/NSF)

[8] S. J. Manion and K. Hess, "Phonon energy dependence of scattering in quasi-two-dimensional electron gases at low temperature," *J. Appl. Phys.*, vol. 62, no. 12, pp. 4942-4944, 1987. (JSEP)

[9] I. C. Kizilyalli, K. Hess, T. Higman, M. Emanuel, and J. J. Coleman, "Ensemble Monte Carlo Simulation of Real Space Transfer (NERFET/CHINT) Devices," *Solid-State Electron.*, vol. 31, no. 3/4, pp. 355-357, 1988. (ARO/JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[10] D. Arnold and K. Hess, "Barrier height fluctuations in very small devices due to the discreteness of the dopants," *J. Appl. Phys.*, vol. 61, no. 11, pp. 5178-5180, 1987. (ONR/NSF)

[11] K. Hess and G. J. Iafrate, "Modern aspects of heterojunction transport theory," in *Heterojunctions - Band Discontinuities*, F. Capasso and G. Margaritondo, Eds. The Netherlands: North Holland Publishing Co., 1987, pp. 451-487. (ARO/ONR)

[12] B. Mason, K. Hess, R. E. Cline, Jr., and P. Wolynes, "A new technique for the calculation of real-time path integrals and applications to electron transport," *Superlattices and Microstructures*, vol. 3, no. 4, pp. 421-428, 1987. (NSF/Cray/ARO/ONR)

[13] K. Hess, "Non-stationary transport in MODFET's and heterojunction devices," in *Picosecond Electronics and Optoelectronics II, Proc. OSA-IEEE (LEOS)*, F. J. Leonbarger, C. H. Lee, F. Capasso, and H. Morkoc, Eds. Incline Village, Nev., Jan. 14-16, 1987, pp. 79-81. (ARO/ONR)

[14] K. Kim, K. Hess, and F. Capasso, "New effects of structure in momentum and real space on nonlinear transport across heterojunction band discontinuities," *Appl. Phys. Lett.*, vol. 51, no. 7, pp. 508-510, 1987. (ONR/NSF/Cray/IBM)

[15] D. Arnold and K. Hess, "The effect of reflecting contacts on high-field transport," *IEEE Trans. Electron Dev.*, vol. ED-34, no. 9, pp. 1978-1982, 1987. (ONR/NSF/Cray)

[16] K. Kim, B. A. Mason, and K. Hess, "Inclusion of collision broadening in semiconductor electron transport simulations," *Phys. Rev.*, vol. B36, pp. 6547-6550, 1987. (ONR)

[17] D. Arnold, K. Kim, and K. Hess, "Effects of field fluctuation on impact ionization rates in semiconductor devices due to the discreteness and distribution of dopants," *J. Appl. Phys.*, vol. 61, no. 4, pp. 1456-1459, 1987. (NSF/Cray/ONR)

[18] D. W. Bailey, M. A. Artaki, C. J. Stanton, and K. Hess, "Ensemble Monte Carlo simulations of femtosecond thermalization of low-energy photoexcited electrons in GaAs quantum wells," *J. Appl. Phys.*, vol. 62, no. 11, pp. 4638-4641, 1987. (NSF/Cray/ONR)

[19] I. C. Kizilyalli and K. Hess "Simplified device equations and transport coefficients for GaAs device modeling", *IEEE Trans Electron Dev.*, vol. 34, no. 11, pp. 2352-2354, 1987. (ARO)

[20] K Hess. "Real space transfer: Generalized approach to transport in confined geometries." *Solid-State Electronics*, vol. 31, no. 3/4, pp. 319-324, 1988; also in *Proc. Fifth Int. Conf. on Hot Electron Carriers in Semiconductors*, Boston, 1987. (ONR/ARO)

[21] M. Artaki and K. Hess, "Transient and steady-state electron transport in GaAs/Al$_x$Ga$_{1-x}$ As heterojunctions at low temperatures: the effects of electron–electron interactions." *Phys. Rev. B.*, vol. 37, no. 6, pp. 2933-2945, 1988. (ARO/NSF/Cray)

[22] D W. Bailey, C. J. Stanton, M. A. Artaki, K. Hess, F. W. Wise, and C. L. Tang, "Ensemble Monte Carlo simulations of femtosecond energy relaxation of photoexcited electrons in bulk GaAs." *Solid-State Electron.*, vol. 31, no. 3/4, pp. 467-470, 1988. (ONR)

[23] K. Hess. *Advanced Theory of Semiconductor Devices.* New York: Prentice Hall, Series in Solid State Physical Electronics, 1988. (not funded)

REFERENCE:

[24] S. L. Chuang and K. Hess "Tunneling-assisted impact ionization for a superlattice." *J. Appl. Phys.*, vol. 61, no. 4, pp. 1510-1515, 1987. (NASA/JSEP)

WORK UNIT NUMBER 4

TITLE: Basic Studies of the Optical and Electronic Properties of Defects and Impurities in Compound Semiconductor Epitaxial Layers and Related Superlattices

SENIOR INVESTIGATOR:

G. E. Stillman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. S. Bose, Research Assistant
B. Lee, Research Assistant
M. H. Kim, Research Assistant
M. A. Haase, Research Assistant
N. Pan, Research Assistant
A. Reed, Research Assistant
V. M. Robbins, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this research unit is to contribute to our understanding of impurity incorporation mechanisms, sources, and defects and to improve our understanding of the influence of growth conditions on impurities and defects in semiconductor materials that will be important for new multiple-layer heterostructure devices. It includes developing new characterization techniques that will extend the range of impurity concentrations over which quantitative analysis is possible. These techniques will lead to better control of high-purity growth and accurate doping levels in epitaxial layers grown by metalorganic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), and chemical beam epitaxy (CBE) or gas source molecular beam epitaxy (GSMBE) growth techniques that are most important for the preparation of multiple layer heterostructures for high-speed electronic and optoelectronic devices.

SUMMARY OF RESEARCH:

The capability of making low-temperature magneto-photoluminescence measurements using a superconducting solenoid was established, using a one-meter, double-slit grating spectrometer. By correlating photothermal ionization measurements with the magneto-photoluminescence measurements on the same samples, the $1s-2p_0$ and $1s-2p-1$ two-electron transitions of the neutral donor bound excitons $(D^\circ.X)$, corresponding to the common donor species in GaAs, have been identified.

This technique has been extended to the identification of the residual donor species, Si, S and Ge, in high-purity undoped p-type epitaxial GaAs, grown by metalorganic chemical vapor deposition and arsenic trichloride vapor phase techniques, using the magnetic splittings of "two-electron" replicas of donor-bound exciton transitions at low temperature (~ 1.8K) and at a high magnetic field (9.0 T). This technique permits identification of donors in certain high-purity p-type GaAs samples that have sufficient neutral donor-bound exciton recombination but in which donor species cannot be identified by photothermal ionization spectroscopy or any other technique.

Both the PTIS and MPL measurement techniques for identification of donors, as well as low-temperature photoluminescence for the identification of acceptors, have been applied to the study

of the incorporation of Si in high-purity lightly Si-doped GaAs grown simultaneously on (100), (311)A, and (311)B GaAs substrates by molecular beam epitaxy (MBE). Photothermal ionization spectroscopy shows that Si is incorporated predominantly as a donor for growth on (100) and (311)B substrates, whereas low-temperature photoluminescence shows that Si is incorporated predominantly as an acceptor for growth on (311)A substrates. Spectroscopic and Hall effect measurements show that the dominance of Si donors in the samples grown on the (100) and (311)B substrates renders these samples n-type, while the dominance of Si acceptors in the sample grown on the (311)A substrate renders that sample p-type. The behavior of Si can be understood in terms of the bonding arrangement on the A and B surfaces, but the observation in these measurements that the C acceptor concentration is higher on the B face as compared with 100 orientation can only be understood by considering the kinetic effects of the growth and impurity species on the different growth faces. Figure 1 shows the experimentally determined donor and acceptor incorporation behavior for the (100), (311)B, and (311)A orientations in GaAs.

In characterization of high-purity epitaxial layers, it is often impossible to make Hall effect measurements because the layer is fully depleted. We have used the well-known persistent photoconductivity effect in GaAs to electrically characterize thin high-purity GaAs, which is fully depleted at low temperatures due to increasing surface and interface depletion effects. At 4.2 K, the sample is momentarily illuminated by above band gap light. This allows electrons to be energetically excited from the surface and interface states, thus forming a charge neutral region. After illumination, the effect of this photo-induced charge neutral region persists until, at moderately high temperature, the sample relaxes back to the original state. Results of temperature-dependent Hall measurements performed on samples under these conditions show that the sheet carrier concentration increases from that measured in the dark, but the mobility remains unchanged. Since the mobility remains constant, this effect does not change the transport properties of the material. The increase in the sheet carrier concentration results from the decrease of the depletion widths after illumination. Due to the increasing need for the analysis of thin, high-purity layers, such measurements provide an important new method of judging the quality of layers when samples are fully depleted of carriers. The mobility of a high-purity MBE sample that becomes depleted of carriers at low temperatures was measured to be 180,000 cm^2/Vs at 77 K by this method.
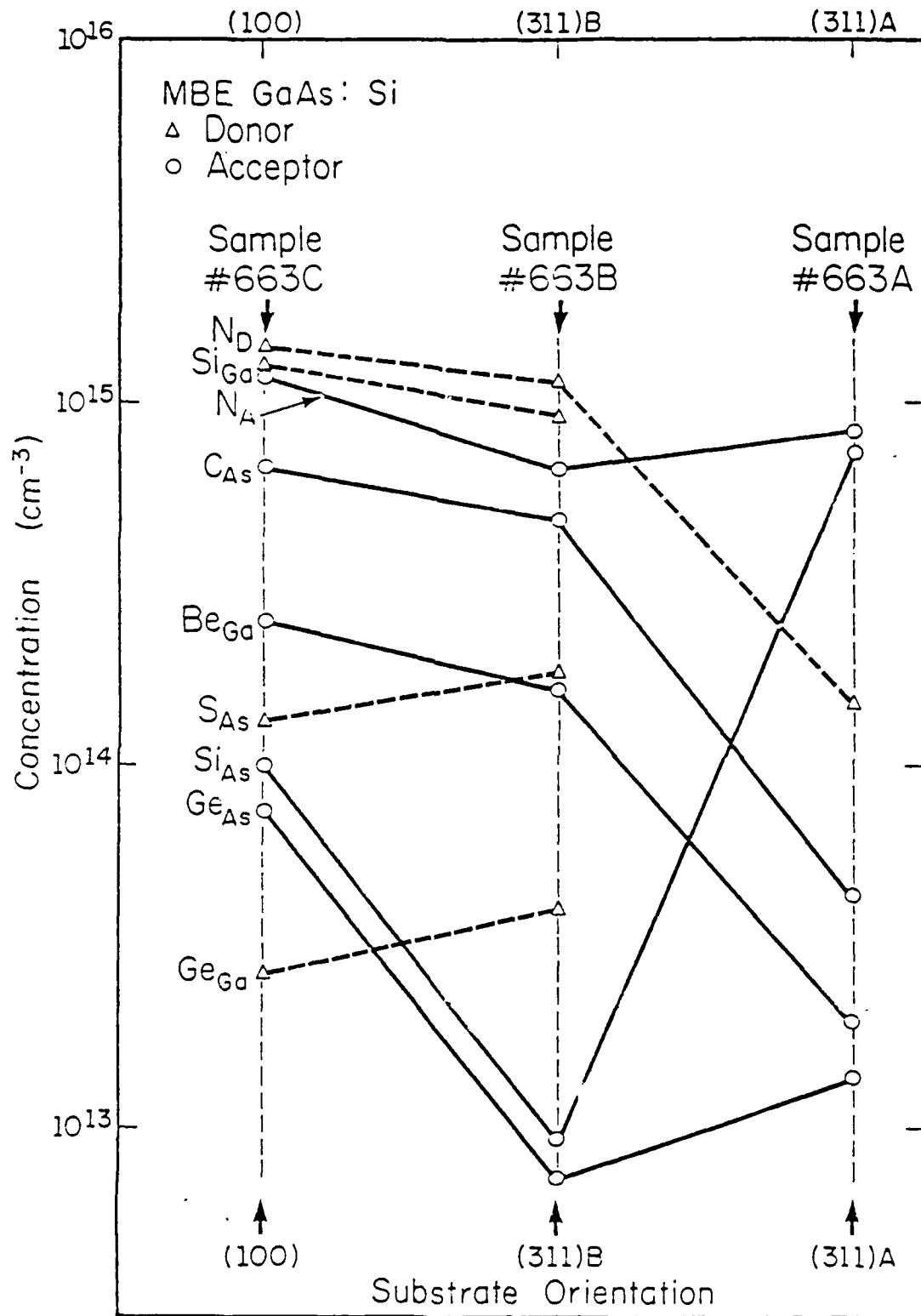
Fig. 1. Plot of concentrations of the total donor and acceptor impurities and the individual impurities for the three orientations (100), (311)A, and (311)B. The dashed lines indicate donor concentrations and the solid lines indicate acceptor concentrations.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] N. Pan, B. Lee, S. S. Bose, M. H. Kim, J. S. Hughes, G. E. Stillman, and K. Arai, "Si donor neutralization in high purity GaAs," *Appl. Phys. Lett.*, vol. 50, pp. 1832-1834, June 22, 1987. (NSF/JSEP)

[2] S. S. Bose, B. Lee, M. H. Kim, G. E. Stillman, and W. I. Wang, "Influence of the substrate orientation on Si incorporation in MBE GaAs," *J. Appl. Phys.*, vol. 63, pp. 743-748, Feb. 1988. (NSF-CDR JSEP AFOSR/DARPA/IBM/ARO)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[3] T. R. Lepkowski, R. Y. DeJule, N. C. Tien, M. H. Kim, and G. E. Stillman, "Depletion corrections in variable temperature hall measurements," *J. Appl. Phys.*, vol. 61, pp. 4808-4811, May 15, 1987. (AFOSR ONR NSF-DMR/NSF-CDR)

[4] B. Lee, N. Pan, and G. E. Stillman, "Neutron transmutation doping of high purity InP," *J. Appl. Phys.*, vol. 62, pp. 1129-1132, Aug. 1, 1987. (AFOSR/DARPA/NSF-CDR)

[5] N. Pan, S. S. Bose, M. H. Kim, G. E. Stillman, F. Chambers, G. Devane, C. R. Ito, and M. Feng, "Hydrogen passivation of C acceptors in high purity GaAs," *Appl. Phys. Lett.*, vol. 51, pp. 596-598, Aug. 24, 1987. (NSF-DMR/NSF-ECS/SDIO-IST-ARO)

[6] S. S. Bose, B. Lee, M. H. Kim, and G. E. Stillman, "Identification of residual donors in high purity epitaxial GaAs by magneto-photoluminescence," *Appl. Phys. Lett.*, vol. 51, pp. 937-939, Sept. 21, 1987. (DARPA/AFOSR/NSF-CDR)

[7] G. S. Jackson, N. Pan, M. S. Feng, G. E. Stillman, N. Holonyak, Jr., and R. D. Burnham, "Stripe geometry $Al_xGa_{1-x}As$—GaAs quantum well lasers via hydrogenation," *Appl. Phys. Lett.*, vol. 51, pp. 1629-1631, Nov. 16, 1987. (NSF-CDR/NSF-DMR/ARO/SDIP/IST)

[8] V. M. Robbins, S. C. Smith, and G. E. Stillman, "Impact ionization in $Al_xGa_{1-x}As$— for x=0.1 to 0.4," *Appl. Phys. Lett.*, vol. 52, pp. 296-298, Jan. 25, 1988.

[9] M. A. Plano, W. E. Plano, M. A. Haase, S. S. Bose, N. Holonyak, Jr., and G. E. Stillman, "Generation of an anomalous hole trap in GaAs by As overpressure annealing," *Appl. Phys. Lett.*, vol. 52, pp. 1077-1079, Mar. 28, 1988. (NSF-CDR/NSF-DMR)

WORK UNIT NUMBER 5

TITLE: Heterostructure Electronic Devices by Metalorganic Chemical Vapor Deposition (MOCVD)

SENIOR INVESTIGATOR:

J. J. Coleman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. A. Emanuel, Research Assistant
M. E. Favaro, Research Assistant
T. K. Higman, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this program is to extend to electronic devices the enormous impact that metalorganic chemical vapor deposition (MOCVD), as a sophisticated epitaxial growth method, has had on optical device research. This involves fundamental studies of the MOCVD process itself for electronic materials, studies of the electronic properties of heterostructure electronic materials, and studies of devices made from these materials. Two specific areas of interest for this research are (1) continuation of electronic materials analysis including deep-level transient spectroscopy (DLTS) and Shubnikov-de Haas measurements of quantum well heterostructure and superlattice structures, and (2) development of MOCVD-grown real-space transferred electron devices, the heterostructure hot electron diode (H^2ED), and other electronic devices.

SUMMARY OF RESEARCH:

In the past two years, we have developed the heterostructure hot electron diode (H^2ED), a new two-terminal device that exhibits S-shaped negative differential resistance (NDR) due to a field-dependent transition between the current conduction modes of tunneling and thermionic emission of hot electrons in a two-layer AlGaAs-GaAs heterostructure. In the past year, experimental results obtained for various single period and multiple period H^2ED structures fabricated from wafers grown by metalorganic chemical vapor deposition (MOCVD) have been extended to demonstration of significant NDR at room temperature and development of all-binary AlAs-GaAs H^2ED devices. Continued investigations of the H^2ED on nonoptimized structures have resulted in room temperature test-fixture-limited oscillation at frequencies greater than 26 GHz. These results indicate that, as reported previously, the H^2ED should be capable of transit time-limited high-speed performance. In the past year, we have also continued our research on real-space transferred electron transport phenomena in negative resistance field effect transistors. In high magnetic field studies, we have shown that real-space transfer in these structures is associated with a transition of the two-dimensional electron gas to a three-dimensional electron distribution at the onset of real-space transfer. We have recently begun a transport study of structures incorporating MOCVD-grown higher mobility InGaAs strained layers at the interface of negative resistance field effect transistors.

JSEP-SPONSORED PUBLICATIONS

[1] S. J. Manion. M. Artaki. M. A. Emanuel, J. J. Coleman, and K. Hess, "Electron energy loss rates in AlGaAs/GaAs heterostructures at low temperatures." *Phys. Rev. B*, vol. 35, p. 9203, 1987. (JSEP)

[2] T. K. Higman, J. M. Higman, M. A. Emanuel, K. Hess, and J. J. Coleman, "Theoretical and experimental analysis of the switching mechanism in heterostructure hot electron diodes." *J. Appl. Phys.*, vol. 62, p. 1495, 1987. (JSEP)

[3] M. A. Emanuel, T. K. Higman, J. M. Higman, J. M. Kolodzey, J. J. Coleman, and K. Hess, "Theoretical and experimental investigations of the heterostructure hot electron diode, *Solid State Electron.*, vol. 31, no. 3 4, pp. 589-592, 1988; also, *Proc. Fifth Int. Conf. on Hot Carriers in Semiconductors*, Boston, 1987. (JSEP)

[4] T. K. Higman, S. J. Manion, I. C. Kizilyalli, M. A. Emanuel, K. Hess, and J. J. Coleman, "Observation of the transition associated with real-space transfer of a two-dimensional electron gas to a three-dimensional electron distribution in semiconductor heterolayers." *Phys. Rev. B*, vol. 36, p. 9381, 1987. (JSEP)

WORK UNIT NUMBER 6

TITLE: Optical Properties of MBE-Grown Structures

SENIOR INVESTIGATOR:

M. V. Klein, Research Professor
H. Morkoc, Research Professor

SCIENTIFIC PERSONNEL:

D. Levi, Research Assistant

SCIENTIFIC OBJECTIVE:

Objectives are twofold. The first is to characterize and understand the optical and vibrational properties of novel semiconductor superlattices and multiple quantum wells. The second is to study and understand the dynamics of photopumped carriers in quantum wells.

SUMMARY OF RESEARCH:

Empasis during the past year has been on broadening the parameters of our previous work on dynamics of photopumped carriers. Understanding the processes wherein the carriers lose their energy is essential to understanding the action of fast photoelectronic devices. These measurements are carried out in the Laser Laboratory of the Materials Research Laboratory using two independently tunable picosecond dye lasers, one to excite carriers and the other to measure the intersubband Raman scattering from the carriers. Through intensity measurements and other spectral measurements, the populations of the carriers on the various subbands can be determined as a function of time. Earlier work established that we could measure and understand intersubband relaxation between bands with low energy spacing. We have since been trying to measure the relaxation between bands with greater spacing than the energy of an LO phonon, so far with no positive results. We have also studied the relaxation between closely spaced subbands under conditions when carriers are initially given kinetic energy in excess of the LO phonon energy. There is a temporal regime when population of low energy states of the second subband is enhanced by this process. Implications of these results will bear further experimental and theoretical examination. The latter is being done in collaboration with C. Stanton (Prof. Karl Hess's group).

JSEP-SPONSORED PUBLICATIONS

[1] D. Y. Oberli, D. R. Wake, M. V. Klein, J. Klem, T. Henderson, and H. Morkoc, "Time-resolved Raman scattering in GaAs quantum wells," *Phys. Rev. Lett.*, vol. 59, pp. 696-699, 1987; also, *Proc. SPIE*, vol. 793, 1987, pp. 58-61. (NSF/AFOSR/JSEP)

[2] D. Levi, S.-L. Zhang, M. V. Klein, J. Klem, and H. Morkoc, "Raman study of the effects of annealing on folded LA and confined LO phonons in GaAs-AlAs superlattices," *Phys. Rev. B*, vol. 36, pp. 8032-8037, 1987. (NSF/JSEP/AFOSR/DOE)

[3] V. K. Arora, D. S. L. Mui. and H. Morkoc, "Mobility degradation in a quantum well heteros-tructure of GaAs AlGaAs prototype." *Appl. Phys. Lett.*, vol. 50. no. 16. pp. 1080-1082, Apr. 20. 1987. (JSEP/AFOSR)

[4] C. Choi. N. Otsuka. G. Munns. R. Houdré. H. Morkoc. S. L. Zhang. D. Levi. and M. V. Klein. "Effect of *in situ* and *ex situ* annealing on dislocations in GaAs on Si substrates." *Appl. Phys. Lett.*, vol. 50, no. 15, pp. 992-994, Apr. 13, 1987. (AFOSR/JSEP/NSF)

[5] V. K. Arora, D S. L. Mui. and H. Morkoc. "High-field electron-drift velocity and temperature in gallium phosphide." *J. Appl. Phys.*, vol. 61. no. 9. pp. 4703-4704, May 1. 1987. (JSEP/AFOSR)

[6] U. K. Reddy. G. Ji. T. Henderson. H. Morkoc. and J. N. Schulman. "Investigation of GaAs (Al.Ga)As multiple quantum wells by photoreflectance." *J. Appl. Phys.*, vol. 62. no. 1. pp. 145-151, July 1, 1987. (JSEP/AFOSR)

[7] R. Houdré. G. Munns. H. Morkoc. C. Choi. N. Otsuka. S. L. Zhang. D. Levi. and M. V. Klein. "Dislocation reduction via annealing of GaAs grown on Si substrates." *SPIE*, vol. 796. pp. 27-31. 1987. (AFOSR/JSEP/NSF)

[8] U. K. Reddy. R. Houdré. G. Munns. G. Ji. H. Morkoc. M. Longerbone. L. Davis. B. P. Gu. and N. Otsuka. "Investigation of GaAs/(Al.Ga)As multiple quantum wells grown on Ge and Si substrates by molecular-beam epitaxy." *J. Appl. Phys.*, vol. 62. no. 12. pp. 4858-4862. Dec. 15. 1987. (JSEP/AFOSR)

[9] U. K. Reddy. G. Ji. R. Houdré. H. Unlu. D. Huang. and H. Morkoc. "Study of GaAs/AlGaAs and InGaAs/GaAs multiple quantum wells grown on non-polar substrates by photoreflectance." *SPIE*, vol. 794. pp. 116-120. 1987. (NASA/JSEP/AFOSR)

[10] D. Y. Oberli. D. R. Wake. M. V. Klein. T. Henderson. and H. Morkoc. "Intersubband relaxation of photoexcited hot carriers in quantum wells." *Solid-State Electron.*, vol. 31. no. 3/4. pp. 413-418. 1988. (NSF/AFOSR/JSEP)

[11] Z. Shulin. T. A. Gant. M. Delaney. M. V. Klein. J. Klem. and H. Morkoc. "Resonant behavior of GaAs LO phonons in a GaAs-AlAs superlattice." *Chinese Phys. Lett.*, vol. 5. no. 3. pp. 113-116. 1988. (NSF JSEP/AFOSR)

[12] M. V. Klein. T. A. Gant. D. Levi. and S.-L. Zhang. "Raman studies of phonons in GaAs AlGaAs superlattices." in *Laser Optics of Condensed Matter. Proc. Third Binational USA-USSR Symp. Laser Optics of Condensed Matter*, Leningrad. USSR. June 1-6. 1987. J. L. Birman. H. Z. Cummins. and A. A. Kaplyanski. Eds. New York and London: Plenum Press. 1988. pp. 119-126. (NSF/JSEP/AFOSR)

[13] D. Y. Oberli. D. R. Wake. and M. V. Klein. "Picosecond Raman and luminescence studies of carrier relaxation in quantum wells." *Laser Optics of Condensed Matter. Proc. Third Binational USA-USSR Symp. Laser Optics of Condensed Matter*, Leningrad. USSR. June 1-6. 1987. J. L. Birman. H. Z. Cummins. and A. A. Kaplyanski. Eds. New York and London: Plenum Press. 1988. pp. 95-101. (NSF JSEP AFOSR)

WORK UNIT NUMBER 7

TITLE: Computer-Aided Design of High-Performance Integrated Circuits with Ultra-Small Features

SENIOR INVESTIGATORS:

I. N. Hajj, Research Professor
S. M. Kang, Research Associate Professor
V. B. Rao, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

D. Smart, Research Assistant
A. T. Yang, Research Assistant
T. K. Yu, Research Assistant

SCIENTIFIC OBJECTIVE:

The continuing evolution of integrated circuit processing technology toward ultra-small feature sizes and new compound semiconductor materials and devices demands new computer-aided design (CAD) tools and design methods. One of the basic issues is to develop efficient circuit models for new devices such as the High-Electron Mobility Transistor (HEMT) and important parasitics of interconnects in high-speed integrated circuits. With such models, integrated circuits can be simulated accurately. During the last two years, we have developed HEMT models and a time-domain circuit model for lossy transmission lines. Our next goal is to develop CAD tools for evaluating the effects of statistical process variations on chip yield, reliability, and design verification of Ultra-/Very-Large Scale Integrated (U/VLSI) circuits. Novel parallel computation algorithms and optimization in view of yield and reliability will also be investigated.

The main objectives of this research unit are:

(1)   to develop accelerated circuit simulation methods for U/VLSI circuits by exploiting hierarchy and parallelism; and

(2)   to develop rigorous design optimization techniques and programs for yield and reliability enhancement.

SUMMARY OF RESEARCH:

This past year, the HEMT model and the lossy transmission line model have been fully implemented in the Illinois Simulator for Modeling of Integrated-circuit Level Elements (iSMILE) program. HEMT circuits can now be simulated accurately including the parasitic effects of up to three parallel interconnects without resorting to the indirect, frequency-domain methods. After exploiting the unique capability of the iSMILE program, especially for developing new circuit models for new novel devices, we have technology-transferred the iSMILE program to the optical interconnect project (NSF Engineering Research Center) for the development of circuit models for optical sources, photodetectors, and optical waveguides. iSMILE can now be used to simulate HEMT optoelectronic circuits.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

In the area of CAD tools for enhancement of circuit performance, we have developed a hierarchical design aid system iJADE [5] for optimizing high-performance CMOS VLSI circuits. It has four novel features. First, it combines analytic tools with a rule-based expert system to take advantage of timely on-line information to administer rules and to verify actions. Secondly, the program can detect latches, trace clock paths, accurately simulate voltage waveforms in the circuit, and tune synchronous circuits to satisfy the clock timing constraints [24]. Furthermore, a functional pattern recognition ability is implemented in the rule-based expert system. Finally, the program uses a hierarchical approach that saves a considerable amount of memory space and also speeds up calculations, especially for large circuits.

The input to the iJADE system is a SPICE-like transistor level description of the circuit along with interconnect resistances and capacitances. A hierarchical frame data base is constructed according to the hierarchy of the circuit description. The program begins by detecting the worst-case critical paths using a timing simulator JADE [23]. The algorithms for delay reduction and the rules are then applied to optimize the timing in the circuit. The entire circuit is then re-simulated to check whether further optimization is necessary. This process is repeated until either the design meets the timing specifications or the design cannot be improved further. Since the execution time is slow for an expert system, an algorithmic-based approach is used to speed up the execution, whenever possible, while special cases are handled by the rule-based expert system. The main function of the delay reduction algorithms and the rule-based expert system is to speed up the critical paths by tuning the transistors in slow blocks and/or subcircuits while satisfying other constraints. The iJADE system is written in Franz LISP and runs on a VAX-11/780 machine with the UNIX operating system.

Experimental results on a 4-bit CMOS ALU with 142 transistors show that the circuit optimized by iJADE performed better than the design manually sized in industry. The propagation delay times as determined by the falling edge of the waveforms were found to be smaller in the iJADE-sized circuit configuration. The active area used in the iJADE-sized circuit is only $1750\,\mu m^2$ as compared with $3118\,\mu m^2$ in the industry-sized circuit.

Several other circuits have been optimized by running iJADE. The above results show that iJADE performs CMOS circuit optimization competitively or sometimes even better than conventional approaches in terms of glitch avoidance, propagation delay time, and chip area. The overall execution time appears to grow linearly with the number of transistors.

As the feature sizes of Very-Large-Scale-Integrated (VLSI) circuits continue to decrease, the timing performance of a design cannot be estimated accurately without introducing the signal delay due to interconnect parasitics. Modeling interconnect parasitics directly from a circuit layout is therefore very crucial. To this end we have focussed our research in the following areas: (1) interconnect modeling, (2) hierarchical parasitic circuit extraction, and (3) collapsing technique for interconnects. In the modeling area we have developed FEMRC [25] as a two-dimensional, finite-element program which computes the resistance or capacitance from the user-specified geometry. Since the equation formulation for FEMRC is based on a finite-element method, there is no shape restriction on dielectric interfaces or conductor geometries. In resistance calculation, a quasi-three-dimensional effect of contact resistance is also taken into account. We have also developed a program HPEX [26] that is a hierarchical parasitic circuit extractor that takes the CIF layout description as an input and generates a SPICE input with different details of interconnect parasitics. In this extractor, analytical formulas fitted from numerical data are used to model interconnect parasitics of VLSI circuits in order to compromise between the accuracy and the computation time. Simulations show that by carefully fitting data, analytical formulas can be very accurate, especially when the interconnect region is fairly regular. A layout partition technique, which facilitates the interconnect modeling, is also implemented in HPEX. Finally, a new node reduction technique [27] that accurately reduces parasitic RC networks has been developed. This technique is capable of reducing a large volume of interconnect data into a manageable size, thereby substantially reducing the effort needed in verification.

To simulate the effect of statistical process variations without excessive amount of CPU time, we have developed a non-nested experimental design method. In this method, we model the statistical circuit performance as a function of transistor channel widths and a noise parameter and select the simulation points in the design space by an experimental design method. The fitted performance model was then used to optimize the worst-case performance function and the squared-error loss function. Compared with Tagushi's method, which is practiced widely, our non-nested experimental design method reduces the required number of circuit simulations by more than 50%.

In our research work on parallel circuit simulation, we have studied waveform relaxation (WR) and focused on 4 different parallel WR algorithms, which utilize the natural parallelism of WR to reduce the run time of a circuit simulation when the simulation is run on parallel processors. Each of the algorithms uses either the Gauss-Seidel (GS) or Gauss-Jacobi (GJ) relaxation method in combination with either the full window technique (FWT) or the time point pipelining (TPP) technique for the coordination of parallel tasks [28].

We have recently obtained a theoretical result that states that parallel GJ is faster than parallel GS if the number of processors is sufficiently large, when these relaxation methods are applied to the solution of a class of linear algebraic problems that arise at each time point in the simulation of MOS integrated circuits [29]. Our experimental results using GS and GJ in waveform relaxation support the same conclusion: that if the number of processors is large enough, GJ is faster than GS.

During the past year we have implemented the TPP algorithm in a parallel WR program. Like our previously developed FWT program, this program runs on an Alliant FX/8 multiprocessor using up to 8 processors. Performance measurements [30] of these programs demonstrate that GJ-TPP is the fastest of the algorithms on 8 processors for the smaller of our benchmark circuits. For the larger benchmark circuits which approach 1000 nodes, the extra parallelism of GH-TPP is not beneficial on 8 processors because the processors are already nearly fully utilized by GJ-FWT. Estimates of the potential performance of the different algorithms obtained with our PARASITE parallel simulation time estimator show that GH-TPP offers the greatest potential performance of the different methods for all the circuits when the number of processors is large enough, and that speedups of about 1 order of magnitude should be possible for 1000-node circuits on 32 processors.

Since different algorithms produce the fastest results in different situations, we have developed a presimulation selection procedure to select the fastest of the 4 algorithms prior to simulating a given circuit on a given number of processors. The choice between the different methods is based on a computationally inexpensive analysis of the subcircuit interconnection structure and subcircuit sizes.

Time latency (when a subcircuit is in a dc steady state) and iteration latency (when a circuit's inputs match the previous iteration) can be exploited to reduce the number of computations in WR. However, the degree of parallelism is also reduced when latency is exploited. We are currently implementing latency exploitation in our parallel WR programs to measure its impact on multiprocessor speedup.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] S. M. Kang, "Physical design of microprocessors," *IEEE Des. and Test of Comput.*, vol. 4, no. 3, pp. 10-11, June 1987. (JSEP/SRC)

[2] S. M. Kang and J. P. Ebner, "Accurate I/O timing measurement of high-speed VLSI devices," *Proc. 30th Midwest Symp. on Circuits and Systems*, Aug. 1987, pp 532-535. (JSEP SRC)

[3] J. L. Krysl and S. M. Kang, "The metastability properties and optimization of CMOS memory devices," *Proc. European Conf. on Circuit Theory and Design.* Sept. 1987, pp. 759-763. (JSEP/SRC)

[4] S. M. Kang, "Metal-metal matrix (M^3) for high-speed MOS VLSI layout," *IEEE Trans. Comput.-Aided Des.*, vol. CAD-6, no. 5, pp. 886-891, Sept. 1987. (SRC/JSEP)

[5] F. P. Lai, S. M. Kang, T. N. Trick, and V. B. Rao, "iJADE: A rule-based hierarchical CMOS VLSI optimizer," *Proc. Int. Conf. on Computer Design*, Oct. 1987, pp. 38-41. (JSEP/SRC)

[6] D. C. Yeh, S. M. Kang, and V. B. Rao, "Logic circuit partitioning with complexity-based gate weighting," *Proc. Int. Conf. on Computer Design.* Oct. 1987, pp. 358-361.

[7] F. P. Lai, S. M. Kang, and T. N. Trick, "A timing error corrector for VLSI synchronous path circuits," *Proc. Int. Conf. on Computer-Aided Design*, Nov. 1987, pp. 48-51. (JSEP/SRC)

[8] O. Tejayadi and I. N. Hajj, "Dynamic partitioning method for piece-linear MOS design," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1987, pp. 102-105. (JSEP/SRC)

[9] M. Y. Wu and I. N. Hajj, "Modified sequential CMOS circuit design," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1987, pp. 460-463. (JSEP)

[10] T. K. Yu, S. M. Kang, I. N. Hajj, and T. N. Trick, "Statistical performance modeling and parametric yield estimation of MOS VLSI," *IEEE Trans. Comput. Aided Des.*, vol. CAD-6, no. 6, pp. 1013-1022, Nov. 1987. (JSEP/SRC)

[11] I. N. Hajj, G. DeMicheli, and H. Hsieh, "Decomposition techniques for large-scale circuit simulation," in *Circuit Analysis, Simulation and Design*, North-Holland Publishing Co., A Ruehi, Editor, 1987. (JSEP)

[12] M. E. Mokari-Bolhassan and S. M. Kang, "Analysis and correction of VLSI delay measurement errors due to transmission line effects," *IEEE Trans. Circuits and Syst.*, vol. CAS-35, no. 1, pp. 19-25, Jan. 1988. (JSEP/SRC)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[13] I. N. Hajj and F. Najm, "Test generation for physical faults in MOS VLSI circuits," *COMPEURO '87: VLSI and Computers*, Hamburg, Germany, May 1987, pp. 386-389. (SRC)

[14] S. M. Kang, "Domino CMOS barrel switch for 32-bit VLSI processors," *IEEE Circuits and Dev.*, vol. 3, no. 3, pp. 3-8, May 1987. (SRC)

[15] M. E. Mokari-Bolhassan and S. M. Kang, "VLSI device characterization for accurate delay measurements under transmission line effects," *Proc. Int. Symp. on Circuits and Syst.*, May 1987, pp. 526-529. (SRC)

[16] H. Y. Chen and S. M. Kang, "Performance optimization for domino CMOS circuit modules," *Proc. Int. Conf Comput. Des.*, Oct. 1987, pp. 522-525. (SRC)

[17]   P. Gee. M. Y. Wu. S. M. Kang. and I. N. Hajj. "Metal-metal matrix (M^3) CMOS cell generator with compaction." *Int. Conf. Comput.-Aided Des.*, Santa Clara. CA. Nov. 1987. pp. 184-187.   (SRC/TI)

[18]   Y. Leblebici. S. M. Kang. C. T. Sah. and T. Nishida. "Modeling and simulation of hot electron effects for VLSI reliability." *Proc. Int. Conf. Comput.-Aided Des.*, Nov. 1987, pp. 252-255. (SRC)

[19]   D. K. Hwang. W. K. Fuchs. and S. M. Kang. "An efficient approach to gate matrix layout." *IEEE Trans. Comput.-Aided Des. of Integrated Circuits and Syst.*, vol. CAD-6. no. 5, pp. 802-809. Dec. 1987.

[20]   P. Gee. M. Y. Wu. S. M. Kang. and I. N. Hajj. "Symbolic compaction of metal-metal matrix layout for double-metal VLSI." *IEEE Trans. Comput.-Aided Des.* (to appear).   (SRC/TI)

[21]   D. Overhauser and I. N. Hajj. "Multilevel circuit partitioning for switch-level timing simulation." *IEEE Int. Symp. on Circuits and Syst.*, Espoo, Finland (to appear).   (SRC/INTEL)

[22]   W. Shu. M. Y. Wu. and S. M. Kang. "Improved Net Merging Method for Gate Matrix Layout." to appear in *IEEE Trans. Comput.-Aided Des.*   (SRC)

REFERENCES:

[23]   F. Lai. V. B. Rao. and T. N. Trick. "JADE: A hierarchical switch-level timing simulator." *Proc. ISCAS-87*, Philadelphia. PA. May 1987.

[24]   F. Lai. S. M. Kang. and T. N. Trick. "A timing error corrector for VLSI synchronous path circuits." *Proc. of ICCAD-87*, Santa Clara. CA. Nov. 1987.

[25]   S.-L. Su. "Extraction of MOS VLSI circuit models including interconnect parasitics." Ph. D. dissertation. University of Illinois at Urbana-Champaign. Sept. 1987.

[26]   S. L. Su. "HPEX: A hierarchical parasitic circuit extractor." *Proc. 24th Des. Automation Conf..* June 1987.

[27]   S.-L. Su. V. B. Rao. and T. N. Trick. "A simple and accurate node reduction technique for interconnect modelling in circuit extraction." *Proc. ICCAD-86*, Santa Clara. CA. Nov. 1986.

[28]   D. W. Smart and T. N. Trick. "Increasing parallelism in multiprocessor waveform relaxation." *IEEE Int. Conf. Comput.-Aided Des.*, Santa Clara. CA. Nov. 1987.

[29]   D. Smart and J. White. "Reducing the parallel solution time of sparse circuit matrices using reordered Gaussian elimination and relaxation." *IEEE Int. Symp. on Circuits and Systems.* Espoo. Finland. June. 1988.

[30]   D. W. Smart and T. N. Trick. "Waveform relaxation on parallel processors." to appear in *Int. J Circuit Theory and Applications.*

WORK UNIT NUMBER 24

TITLE: Electronic and Transport Properties of Ultra-Low-Dimensional Structures
(no previous unit)

SENIOR INVESTIGATORS:

J. P. Leburton, Research Associate Professor
I. Adesida, Research Assistant Professor
J. Kolodzey, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. Boor, Research Assistant
D. Jovanovich, Research Assistant
A. Ketterson, Research Assistant

SCIENTIFIC OBJECTIVE:

This unit work explores the potential of ultra-low-dimensional semiconductor structures for electronic and optical device applications. The emphasis is placed on fast transient and the research is concerned with the conception, design, and investigation of nonconventional devices characterized by extreme quantization of the electronic system.

Our method involves an integrated theoretical and experimental approach including various technological components from material growth, processing, and testing to numerical simulation of nanostructures. In addition, we are conducting a fundamental investigation of new physical effects in ultra-low-dimensional systems.

SUMMARY OF RESEARCH:

Novel FET-Device Configuration and New Injection Mechanism

We have conceived a new device configuration for modulation doping structures and proposed a new tunnel injection mechanism into the channel of FET devices [4,5]. This novel configuration is a generic structure that combines a MODFET with a tunnel junction and can be modified for various device purposes. We have proposed two new three-terminal devices--the BITFET and the TIFET--that operate with tunnel injection through the homojunction and capitalize on the occurrence of negative differential resistance (NDR) and its modulation by the gate field. Abrupt NDR transitions and large peak-to-valley ratio are anticipated. Theoretical estimates of the relevant time constants indicate frequency operation in the 100 GHz range.

Modulation-doped compound semiconductor layers of two material systems, AlGaAs/GaAs and InAlAs/InGaAs/Inp, have been grown by MBE and processed into active tunnel structures. A mask set for the TIFET has been designed and made using electron beam lithography.

A patent disclosure form has been filed for the discovery of the new devices.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

Investigation of Quasi-One Dimensional Structures

Nanostructure Fabrication and Device Processing

AlGaAs/GaAs and InAlAs/InGaAs/InP modulation-doped structures for quantum-wire devices have been grown by MBE in collaboration with AT&T Bell Laboratories, Murray Hill. Using Nomarski's interference contrast microscopy, the surface morphology of the layers have revealed an oval defect density of only 740/cm2 for AlGaAs/GaAs materials. We have started with the fabrication of the ultra-small structures on the Cambridge EBMF 6.5 lithography system (at the Center for Compound Semiconductor Microelectronics), using the PMMA/P(MMA-MAA) multilayer resist approach. The Cambridge system is capable of a maximum accelerating beam energy of 30 keV with a beam diameter of $\sim$ 70 nm. To date, we have realized isolated metals with line width of $\sim$ 100 nm and metal gratings with the same line width dimensions at 400 nm periodicity. Figure 1 shows these metals (50 nm Ti/100 nm Au) gratings fabricated on GaAs.

Current efforts are directed toward the realization of grating structures with smaller periodicity. However, it is our estimation that the results achieved so far are perhaps very close to the best that can be realized with the Cambridge System given its characteristics. We have recently ordered a Cambridge S360 scanning electron microscope (40 keV beam energy and 5 nm beam diameter) that will be used as a lithography system to realize structures down to $\sim$ 20 nm dimensions.

Major efforts have been expended in setting up the processing methodologies in our laboratory for GaAs and modulation-doped systems. Using these techniques along with electron beam lithography, we have fabricated GaAs FETs and modulation-doped FET's. Figure 2 shows a $\sim$ 150 nm recessed gate GaAs FET. Transconductance as high as 420 mS/mm with an f_{max} of 43 GHz have been obtained on these devices. For high frequency measurement, a cascade microwave probe station has been modified to operate over wide range of temperature from 300 K down to 77 K.

Transport Simulation of Quantum-Wire Structures

We have investigated the transport properties of multi-subband quasi-one dimensional systems by a particle Monte Carlo simulation and found that the transport parameters are a sensitive function of the confinement conditions. For optimum confinement, the 1-D carrier mobility is over twice the bulk value at room temperature. We attribute this excess value to the reduction of the phase-space that enhances the average carrier velocity.

We have also investigated Resonant Inter-Subband (polar) Optic Phonon Scattering (RISOPS), which is the analog effect of magneto-phonon in magnetic field. RISOPS is, however, more general than its magnetotransport analog since it occurs with anisotropic y-z confining potential that results in nondegenerate unequally spaced 1-D energy levels. Under RISOPS conditions, we have observed significant population-inversion between the second and third quantum level.

INTERACTION AND/OR TECHNOLOGY TRANSFER

A solid collaborative effort on the MBE growth of modulation-doped structures for low dimensional transport has been established with A. Y., Cho. R. Fisher, and D. Sivco at AT&T Bell Laboratories, Murray Hill, NJ.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory
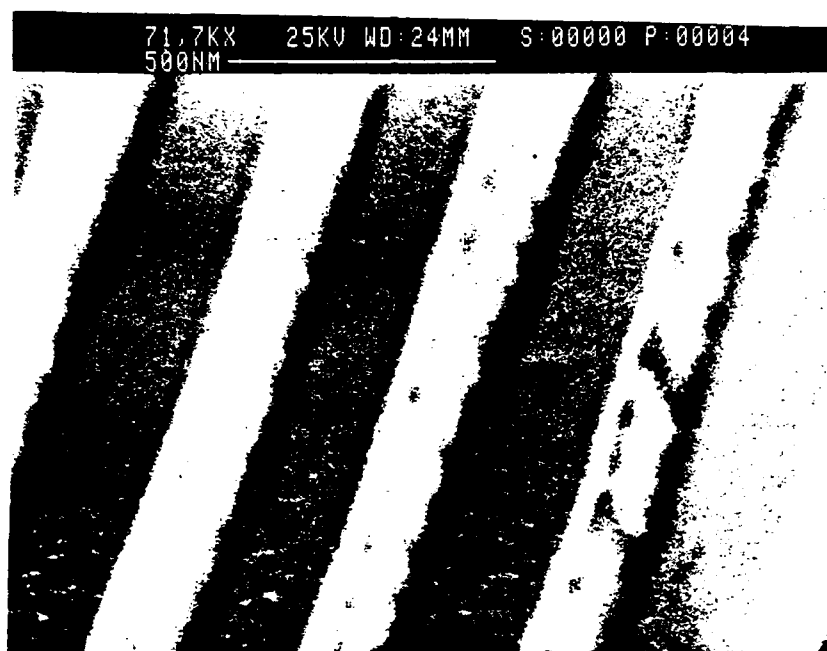
Fig. 1. 100 nm metal grating line with a pitch of 400 nm on GaAs.

Fig. 2. 150 nm recessed gate GaAs field effect transistor.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] J. P. Leburton, "Anomalous current oscillations in semiconductor-insulator-semiconductor structures and related devices," in *The Physics of the Two-Dimensional Electron Gas*, J. T. Devreese and F. M. Peeters, Eds. Plenum Pub., 1987, pp. 227-257. (JSEP)

[2] J. P. Leburton, "Microscopic interpretation of the current oscillations in $GaAs^+-AlGaAsGaAs^-$ tunnel junctions," *Proc. 18th Int. Conf. on the Physics of Semiconductors*, Stockholm, Sweden, 1986, Engstrom, Ed.: World Scientific Press, 1987, pp. 1623-1626. (JSEP)

[3] M. A. Emanuel, T. -K. Higman, J. M. Higman, J. S. Kolodzey, J. J. Coleman, and K. Hess, "Theoretical and experimental investigations of the heterostructure hot electron diode," *Solid-State Electron.*, vol. 31, pp. 589-592, 1988. (ONR/JSEP/NSF)

[4] J. P. Leburton "Phonon ionization of neutral donors in lightly doped GaAs: A model for the conductance oscillations in semiconductor-insulator-semiconductor tunnel structures," to appear in *Phys. Rev.* (JSEP)

[5] J. P. Leburton, J. Kolodzey, and S. Briggs, "Bipolar tunneling field effect transistor: a three-terminal negative differential resistance device for high-speed applications," *Appl. Phys. Lett.* (in press.) (JSEP/NSF)

[6] J. Kolodzey, J. Laskar, T. K. Higman, M. A. Emanuel, J. J. Coleman, and K. Hess, "Microwave frequency operation of the heterostructure hot electron diode," *IEEE Electron Device Lett.* (in press). (NSF/JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP

[8] K. B. Kahen and J. P. Leburton, "Index of refraction of GaAs-AlGaAs superlattices and multiple quantum wells," *Superlattices and Microstructures*, vol. 3, p. 251, 1987. (NASA)

[9] R. Schwarz, J. Kolodzey, R. T. Kouzes, and S. Wagner, "Simultaneous depth profiling of constituents and impurities by elastic proton scattering in amorphous hydrogenated silicon films," *Appl. Phys. Lett.*, vol. 50, pp. 188-190, 1987. (EPRI/Kodak)

[10] Z. E. Smith, V. Chu, K. Shepard, S. Aljishi, D. Slobodin, J. Kolodzey, S. Wagner, and T. L. Chu, "Photothermal and photoconductive determination of surface and bulk defect densities in amorphous silicon films," *Appl. Phys. Lett.*, vol. 50, pp. 1521-1523, 1987. (EPRI/Kodak)

[11] J. Kolodzey, S. Boor, P. Saunier, J. W. Lee, and H. -Q. Tserng, "Microwave performance of InAlAs/InGaAs high electron mobility transistors at 77 K," *Proc. IEEE Cornell University Conf. on Advanced Concepts in High Speed Semiconductor Devices and Circuits*, New York, Aug. 1987. (NSF/Texas Instruments)

[12] S. Aljishi, V. Chu, Z. E. Smith, D. -S. Shen, J. P. Conde, D. Slobodin, J. Kolodzey, and S. Wagner, "Steady state and transient transport in Si,Ge:H,F alloys," *J. Non-Crystalline Solids*, vol. 97 & 98, pp. 1023-1026, 1987. (EPRL Kodak)

[13] J. Kolodzey, R. Schwarz, S. Aljishi, V. Chu, D. -S. Shen, P. M. Fauchet, and S. Wagner, "Optical and electronic properties of an amorphous silicon-germanium alloy with a 1.28 eV optical gap," *Appl. Phys. Lett.*, vol. 52, pp. 477-479, 1988.   (EPRI/Kodak)

[14] J. L. Educato, M. Wagner, and J. P. Leburton, "Multijunction upper subcell cascade photovoltaics for space applications," *J. Appl. Phys.*, vol. 63, p. 540, 1988.   (NASA)

WORK UNIT NUMBER 8

TITLE: Collective Electronic Transport in Quasi One-Dimensional Systems

SENIOR INVESTIGATORS:

J. R. Tucker. Research Professor
J. W. Lyding. Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

W. G. Lyons. Research Assistant

SCIENTIFIC OBJECTIVE:

The goal of this research is to understand the basic mechanism of charge density wave (CDW) transport in the linear chain conductors $NbSe_3$. TaS_3. $(TaSe_4)_2I$. $K_{0.3}MoO_3$. and related compounds. The motion of CDWs in these materials represents the only known example of electric current flow by a moving quantum ground state. apart from superconductivity. The response of CDWs to applied electric fields is nonlinear in both field and frequency, and novel electronic devices may become possible if the basic properties of these systems can be understood. An extensive experimental and theoretical effort is conducted in our laboratory to characterize the dynamics of CDW motion and to test theoretical predictions.

SUMMARY OF RESEARCH:

The past year has seen enormous progress in our understanding, to the point where we would now tentatively claim to have achieved a complete solution to the problem of CDW dynamics. This work has its origins in the diverse experimental findings we have obtained over the past two years and represents a total break with our previous theoretical ideas.

CDW's experience a periodic pinning potential due to impurities and defects as they move along. since displacement by an integral number of wavelengths produces an identical configuration. The deformable phase-only model of weak pinning. proposed by Bell Laboratories' theorists several years ago [6]. predicts that this periodic pinning potential should vanish at high electric fields where the average drift frequency $\omega_d = \overline{d\phi/dt}$ exceeds the dielectric relaxation frequency ω_o. Our systematic experimental studies [1.2.4.7.8] of the current oscillations accompanying dc CDW motion. and the resulting ac-dc interference effects with an external ac potential. culminated last year in a clear demonstration [9] that all the basic predictions of the Sneddon. Cross. and Fisher [6] model are fundamentally incorrect. This was a very important result. since it overthrew the theoretical model which had long served as the paradigm for most workers in this field.

While our former collaborators. John Bardeen and R. E. Thorne. took this as conclusive proof of Bardeen's quantum tunneling hypothesis. we began to consider another possible explanation. Strong impurity pinning. in which the CDW phase is pinned to a particular optimal value at each impurity site. had long ago been dismissed on the basis that phase correlation was known to exist over volumes much larger than the average n_i^{-1} associated with each impurity. We were able to show. however. that for typical dilute impurity concentrations $n_i \leq 1000ppm$. the average CDW phase $\overline{\phi(r)}$ will indeed remain correlated over large volumes. with very tiny regions of rapid phase interpolation between $\overline{\phi}$ and the pinned value ϕ_o^i surrounding each impurity site. The resulting

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

theoretical model that we have constructed [5] on the basis of Ginzburg-Landau arguments turns out to be particularly simple. The average pinning frequency is directly determined by the average spacing between impurities along the conducting chains. Because dc CDW motion must involve phase-slip at the impurity sites, the pinning potential persists to arbitrary drift frequencies and the threshold electric fields can be calculated in terms of the Peierls energy gap. Quantitative estimates are easily extracted for virtually every measured property, and all of these are found to be in excellent agreement with experiment. A number of unique properties of the model are also found to explain outstanding mysteries, for which not even a qualitative interpretation had previously been possible.

At the present time, we are immersed in the interpretation of experimental data across the widest possible spectrum, including NMR, broad-band noise, specific heats, far-infrared and millimeter wave data, and much more. The range of our success thus far is so far beyond what we could have imagined six months ago that we are tempted to declare victory, although much remains to be done over the next one to two years.

Our previous working theoretical hypothesis, that CDW acceleration represents some kind of macroscopic quantum tunneling analogous to Zener breakdown, has been found after several years to be incorrect, in our opinion. Professor Bardeen has chosen to dissociate himself from our group, since he vehemently disagrees.

A development related to this research program is the successful construction of a new scanning tunneling microscope by one of us (JWL) under NSF funding through the Materials Research Laboratory. The design of this instrument is doubly revolutionary: (1) it needs no vibration isolation and can thus be placed in experimental environments that were previously impossible for STM, and (2) it is fully temperature-variable, with a thermal drift $\leq 1\text{\AA}$/hour so small that detailed spectroscopy of individual adsorbates on surfaces is now feasible, for example. The following figure illustrates these remarkable capabilities in images of the 2D CDW material $1T\text{-}TaS_2$. The large-scale images show the regular array due to the CDW charge modulation, while in the smaller scale images one can see the individual atoms underneath. We intend to exploit the unique properties of this new STM in our future JSEP research.
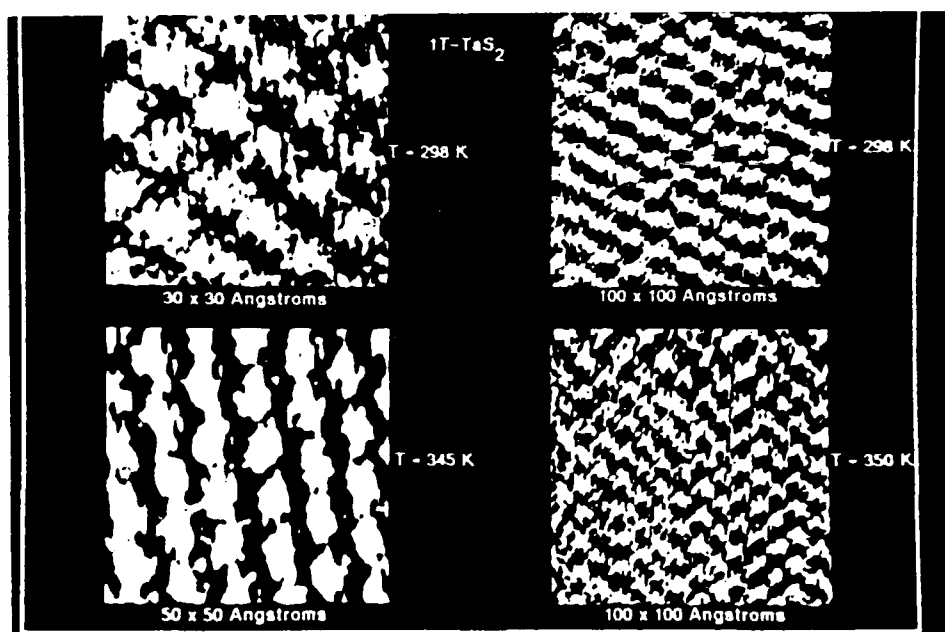
Fig. 1. Scanning tunneling microscope (STM) images of the charge density wave (CDW) structure in the 2-dimensional layer compound $1T\text{-}TaS_2$, at two different temperatures.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] R. E. Thorne, W. G. Lyons, J. W. Lyding, J. R. Tucker, and J. Bardeen, "Charge density wave transport in quasi one-dimensional conductors: I. Current oscillations," *Phys. Rev.*, vol. B35, no. 12, pp. 6348-6359, Apr. 15, 1987. (JSEP/NSF)

[2] R. E. Thorne, W. G. Lyons, J. W. Lyding, J. R. Tucker, and J. Bardeen, "Charge density wave transport in quasi one-dimensional conductors: II. Ac-dc interference phenomena," *Phys. Rev.*, vol. B35, no. 12, pp. 6360-6372, Apr. 15, 1987. (JSEP/NSF)

[3] J. R. Tucker, "Proposed NMR test of strong pinning and phase-slip in sliding charge density wave systems," *Phys. Rev. Lett.*, vol. 60, pp. 1574-1577, 1988. (JSEP/NSF)

[4] R. E. Thorne, J. S. Hubacek, W. G. Lyons, J. W. Lyding, and J. R. Tucker, "Ac-dc interference, complete mode-locking, and origin of coherent oscillations in sliding charge density wave systems," *Phys. Rev. B* (to appear). (JSEP/NSF)

[5] J. R. Tucker, W. G. Lyons, and G. Gammie, "Theory of charge density wave dynamics," *Phys. Rev. B* (to appear July 15, 1988). (JSEP/NSF)

REFERENCES:

[6] L. Sneddon, M. C. Cross, and D. S. Fisher, *Phys. Rev. Lett.*, vol. 49, p. 292, 1982.

[7] R. E. Thorne, J. R. Tucker, J. Bardeen, S. E. Brown, and G. Grüner, "Phase-locking in charge density wave transport," *Phys. Rev.*, vol. B33, pp. 7342-7345, 1986. (JSEP)

[8] R. E. Thorne, W. G. Lyons, J. H. Miller, Jr., J. W. Lyding, and J. R. Tucker, "Current oscillations in charge density wave transport," *Phys. Rev.*, vol. B34, pp. 5988-5991, 1986. (JSEP/NSF)

[9] R. E. Thorne, J. R. Tucker, and J. Bardeen, "Experiment versus the classical deformable model of charge density waves," *Phys. Rev. Lett.*, vol. 58, pp. 828-831, 1987. (JSEP/NSF)

WORK UNIT NUMBER 9

TITLE: An Investigation of Plasma and Chemistry Processes in Cylindrical Magnetron Plasma Discharges

SENIOR INVESTIGATORS:

M. J. Kushner, Assistant Professor
J. A. Thornton (Deceased), Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

G. Y. Yeom, Research Assistant
M. J. McCaughey, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this program is to investigate fundamental plasma and chemistry processes in radio frequency (rf) magnetron discharges as applied to plasma etching and deposition of electronic materials. This type of discharge has the potential to reduce damage by ion impact and radiation during processing while maintaining high etching or deposition rates.

This research program has the following specific objectives:

(1) To investigate the basic plasma behavior of rf driven cylindrical magnetron discharges and to assess the delivery of activation energy from the plasma to processing surfaces.

(2) To examine the plasma chemistry of low pressure rf-driven magnetron etching plasmas using CH4-H2 and CF4-O2 gas mixtures.

(3) To investigate magnetron reactive ion etching of Si with particular emphasis on the damage mechanisms and on the basic surface chemistry that establishes selectivity and anisotropic etching.

(4) To assess the applicability of these discharges to plasma deposition.

SUMMARY OF RESEARCH:

Our research activities are progressing according to the program plan and the statement of work in the original proposal. We anticipate no change in the program objectives.

The construction and characterization of the experimental apparatus have been completed, and we are now collecting data toward satisfying our research goals. The experimental apparatus is a plasma discharge chamber having a cylindrical central electrode, which may be of user selected diameter, and a cylindrical housing that serves as the outer electrode. Standard high vacuum systems are used for gas supply and exhaust. The discharge is excited by either dc or rf (1.8 MHz, 13.56 MHz) power supplies and is sustained in a dc magnetic field generated by external coils. The magnetic field (0-250 Gauss) is uniform to within 15% throughout the discharge chamber. The following diagnostics are being utilized in this study: (1) electrostatic probe measurements of the plasma and floating potentials, plasma density, and electron temperature; (2) retarding grid electrostatic analyzer to measure ion energies incident on surfaces; (3) optical emission spectroscopy to assess the rate of electron impact excitation; and (4) mass spectroscopy of the species produced in the plasma.

Significant progress has been made toward characterizing rf cylindrical magnetron discharges (CMD's). We have found that rf CMD's do not, in general, obey the same current-voltage relationships, as do dc magnetron discharges, and appear more resistive. Magnetron discharges are usually

characterized by $I \sim V^n$, and rf CMD's generally have lower n. By measuring the plasma potential distribution in the plasma using electrical probes, we have determined that this behavior results from the discharge losing its ability to confine electrons in the magnetron "trap" on the anodic part of the cycle. In fact, the discharge may not be self-sustaining during the anodic half cycles. In spite of these conditions, though, rf CMD's still maintain the highly desirable feature of developing a low dc self bias on the electrodes and, therefore, will not be as damaging to electronic material being processed as conventional rf diode discharges.

Electrical probe measurements of plasma density have been performed as a function of position in the discharge chamber, rf power, and applied magnetic field to determine the manner of power deposition. As expected, we found that the plasma density increases with increasing magnetic field, an indication of more efficient electron trapping. We also found that the spatial distribution of plasma density shifts toward the inner electrode with increasing magnetic field. These results correlate with our observations of lower dc self bias at higher magnetic fields and indicate fewer highly energetic electrons.

Studies are presently in progress to assess the applicability of rf CMD's to etching electronic materials. We have begun to parameterize etching rates and the selectivity of etching Si vs SiO2. We have obtained high etch rates (1000's Å/min) and found that the selectivity of the etch is a function of the applied magnetic field; higher selectivity is obtained with higher magnetic fields. Optical emission spectroscopy has been performed to determine the relative rates of excitation and fragmentation and, perhaps, to determine the cause for the change in selectivity. We have found that the fraction of CF_3/F is a strong function of magnetic field, with the ratio increasing with increasing field at constant power deposition. Since the selectivity of etching is dependent on the C F ratio of radicals in the plasma, this change in dominant plasma species may explain our observed changes in selectivity.

PUBLICATIONS

[1] M. J. McCaughey and M. J. Kushner, "A model for the surface morphology of a-Si:H films," presented at the Fall 1987 Meeting of the Materials Research Society. (ARO)

[2] M. J. Kushner, "A phenomenological model for surface deposition kinetics during plasma and sputter deposition of amorphous hydrogenated silicon," *J. Appl. Phys.*, vol. 62, p. 4763, 1987. (ARO)

[3] M. J. Kushner, "A model for the discharge kinetics during PECVD of amorphous silicon," to be published in *J. Appl. Phys.* (ARO)

WORK UNIT NUMBER 10

TITLE: Excited State Chemistry in Gases

SENIOR INVESTIGATORS:

J. G. Eden. Research Professor
J. T. Verdeyen. Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

C. C. Abele. Research Assistant
C. J. Kiely. Postdoctoral Research Associate
L. Overzet. Research Assistant

SCIENTIFIC OBJECTIVE:

Excited states and/or free radicals. produced by a gas discharge or an intense laser beam. play a critical role in the etching and deposition of semiconductor material. One case. dry processing with plasmas. has become the "standard" industrial tool. and much of the imaginations involving laser interactions are beginning to bear fruit. Inasmuch as these sources of radicals and excited states produce an environment that is far from that described by equilibrium thermodynamics. one can expect unique. puzzling. and yet most interesting processes resulting from the use of these techniques. Our goals have been and continue to be the understanding of the complex processes responsible for those actions and a development of a scientific model that quantifies the interaction between the source (electrons or photons). the donor gas. and the semiconductor surface. We will continue the basic study of the kinetic processes occurring in these environments. but we also plan to combine the two technologies.

To gain further insight into these complex processes. a specific target for this next period is to combine the discharge. with its ability to produce copious quantities of free radicals in almost anything rather easily. with the laser. which has the advantage of energy selectivity and directionality.

SUMMARY OF RESEARCH:

Plasma Processing Discharges

A major thrust of this work has been on the physics of discharges used for the deposition of materials (amorphous silicon) or for the etching of the common semiconductors. We had found that the simple expedient of modulating the rf excitation of the gases with a low audio frequency square wave (10 Hz → 50 kHz) made a significant difference in both the microscopic properties of the plasma and the macroscopic characteristics of the films. Table 1. taken from our paper at the MRS meeting in San Diego. 1987. illustrates that the effect is not just a small perturbation. Our efforts have focussed on obtaining a physical explanation.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

Table 1. The optical and electrical properties of films produced in CW and SQWM discharges (200 Hz modulation frequency). (* data unavailable)

CW/ SQWM	Substrate Temperature (°C)	Refractive Index (at 1μm)	Optical Bandgap (eV)	Dark Conductivity $(\Omega*cm)^{-1}$	AM1 Conductivity $(\Omega*cm)^{-1}$	Activation Energy (eV)
CW	160	2.71	2.00	4.6 E-13	3.0 E-07	0.92
SQWM	155	3.09	1.82	6.8 E-12	1.8 E-07	0.87
CW	200	3.01	1.89	*	1.7 E-0.6	0.85
SQWM	200	3.08	1.84	2.2 E-11	3.9 E-06	0.85
CW	235	3.04	1.94	3.1 E-12	1.9 E-06	0.88
SQWM	255	3.15	1.81	1.2 E-11	1.3 E-06	0.84
CW	300	3.11	1.82	4.9 E-11	7.5 E-06	0.84
SQWM	300	3.13	1.82	1.3 E-11	1.3 E-06	0.83

The complicated time evolution of the bulk electron densities in 98% He, 2% SiH_4 suggested that attachment (to a radical) was playing a significant role in controlling the plasma density, which appears to be directly correlated with the change in film properties (i.e., lower bandgap, high mass density). Consequently, we have attempted to detect the negative ions with a mass spectrometer.

In order to obtain "practice" toward this goal, we have used CF_4 and 97.3% He + 2.7% F_2 mixture as the donor gases. We find dramatic enhancements of the F⁻ signal with modulation rate, as shown in Figure 1. We have succeeded in modeling this enhancement by recognizing that the sheath polarity in most discharges is such to confine the negative charges (electrons and negative ions) and enhance the outward flux of the positive charges, otherwise the electrons would escape to the walls and electrodes far too rapidly and extinguish the discharge. By clamping the excitation to zero for 50% of the time, the sheaths disappear and the negative ions can reach the electrodes. This may have a significant effect on etching or the deposition of the materials. Shown in Figure 2 is the relative ion signal as a function of RF power. Notice that the F⁺ signal scales directly with power (as expected) whereas the F⁻ appears to saturate. These two figures are the basis for a publication being prepared at this time.

Laser Growth of Films

Photoenhancement of Surface Mobilities

Considerable progress has been made in the last year in applying laser material interactions to the growth of metal or semiconductor films. Two parallel research efforts are involved. The first is concerned with illuminating surfaces with low fluence visible or ultraviolet (UV) coherent radiation in order to improve adatom mobilities and, hence, improve film quality (morphology, structure, etc.) and permit film growth at lower substrate temperatures. At the time of our last annual report, experiments in which disilane (Si_2H_6) was being pyrolyzed were just under way. These experiments will be completed later this year and the results to date are gratifying. Figure 3 illustrates the effect of surface irradiation on the growth of Si from Si_2H_6. In acquiring these data, the total He/Si_2H_6 pressure was maintained at 9.6 Torr ($p_{Si_2H_6} = 0.5$Torr) and film growth rate data were taken with and without surface illumination ($\lambda = 193$ nm, ArF laser). In order to avoid significant transient heating of the substrate, the average ArF laser power was fixed at ~125 mW for a PRF of 100 Hz (e.g., only 1.25 mJ/pulse). While, as expected, the presence of laser radiation makes little difference at high substrate temperatures ($T_s > 750°$ C) where surface mobilities are

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

F ions (+ & -) from a 2.7% F_2 in helium glow.
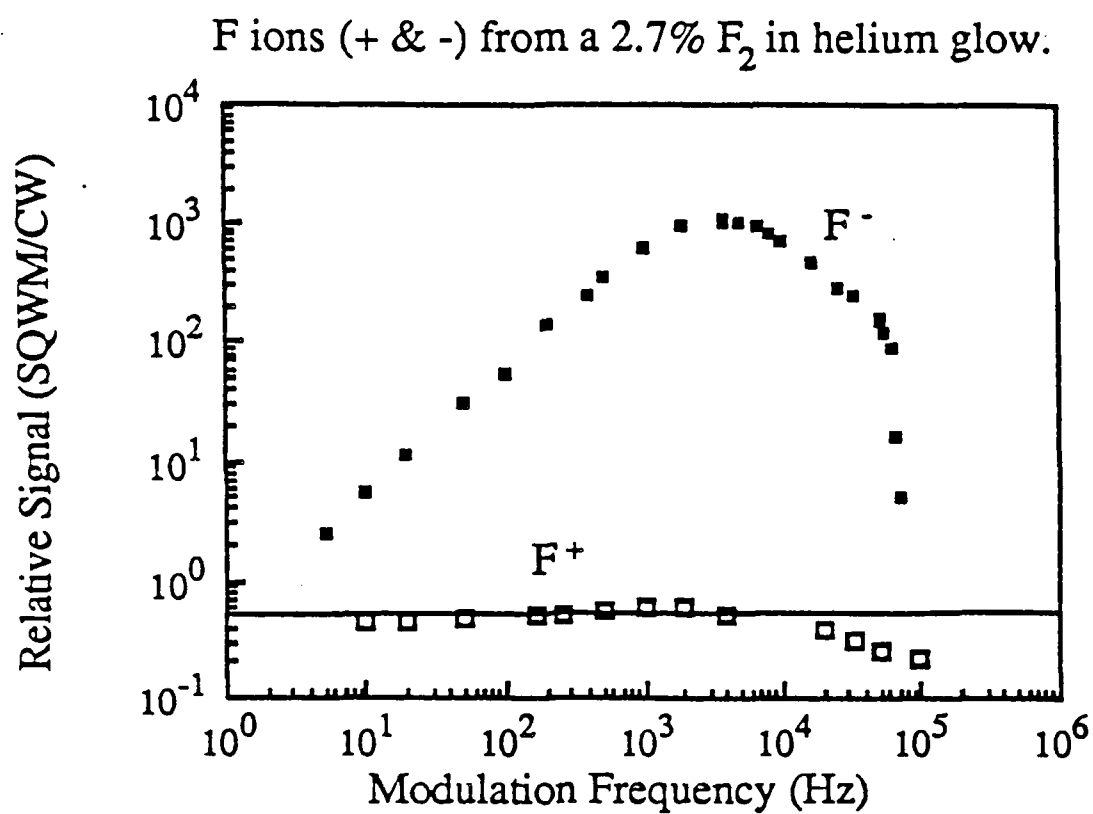
Fig. 1.   Variation of the relative ion signal with modulation frequency. The power was 7.5 watts with a total pressure of 0.7 Torr.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory
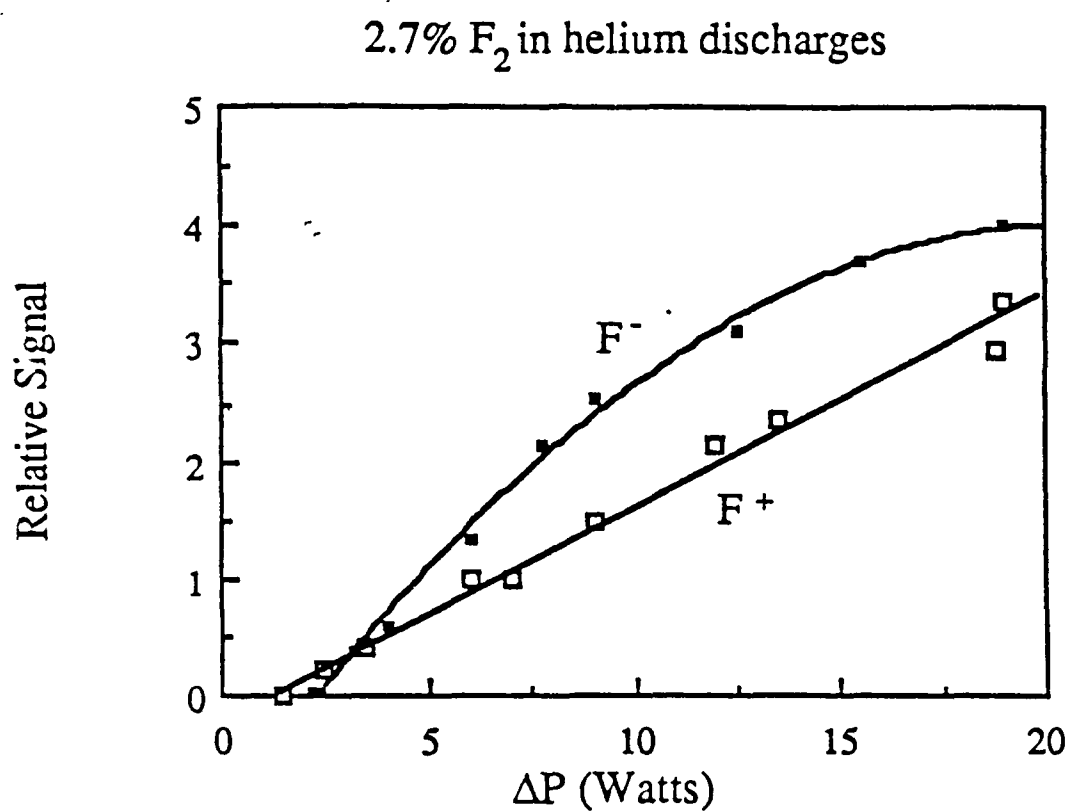
Fig. 2.   Variation of the ion signals with the peak power exciting the discharge.
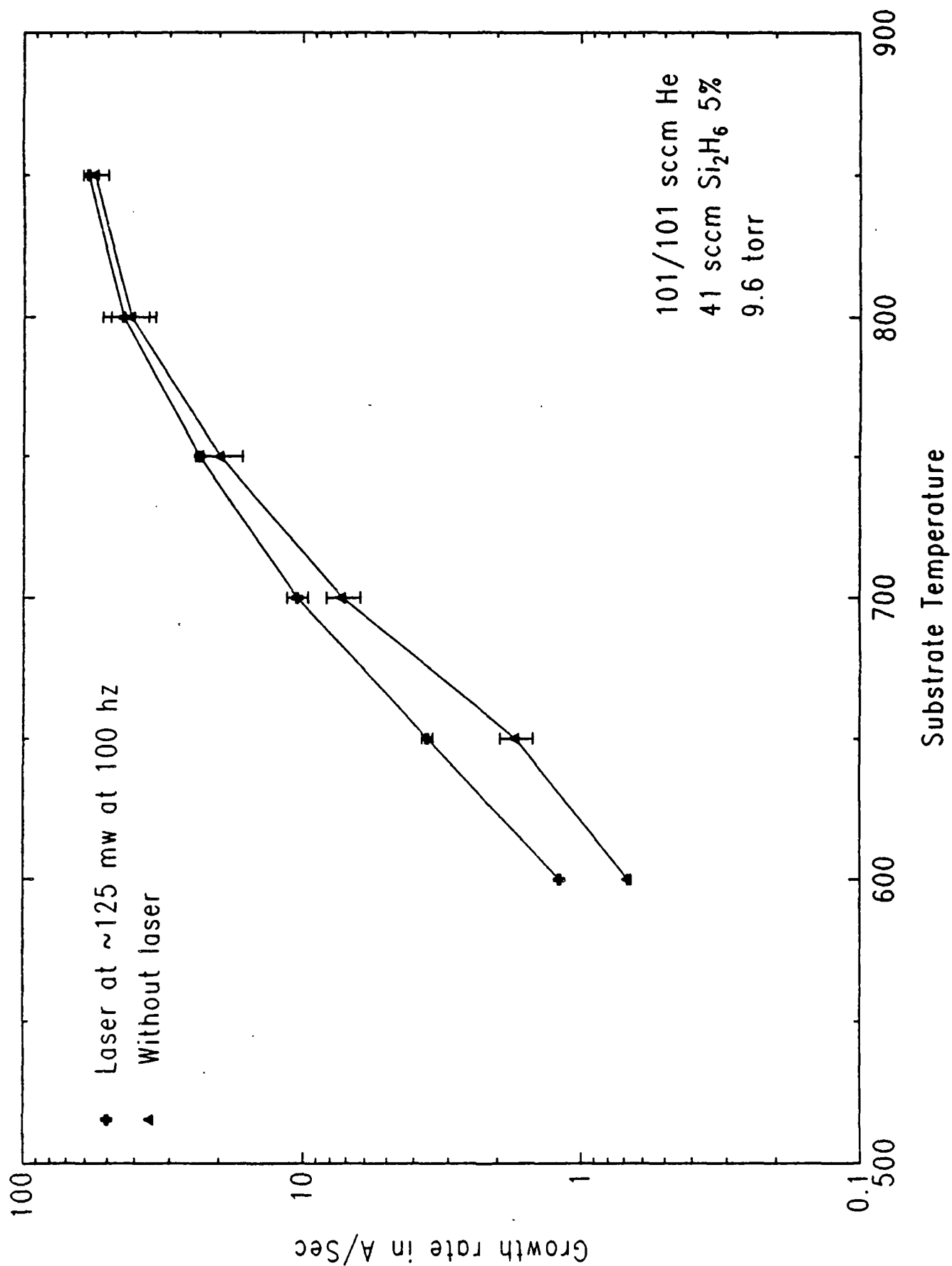
Fig. 3. Rates for the growth of Si films from Si_2H_6 as a function of substrate temperature (T_s) in the absence or presence of UV ($\lambda = 193$ nm) radiation impinging on the substrate at 90°.

adequate. the impact at lower T_s ($< 650°$ C) is quite dramatic. In particular. the Si film growth rate in the absence of external UV irradiation is roughly half that measured when the laser is "on." In passing. it should be noted that each point in Figure 3 represents the average of several (at least 3 and in many cases. > 6) experimental trials, and the error bars represent one standard deviation in the data.

Also. the film growth rate enhancement is only part of the story. The improvement in surface morphology that is observed in the presence of the UV beam is equally dramatic. More detailed studies of the properties of the films are presently being carried out by Dr. Kiely at the Center for Microanalysis (here at the U. of I.) using transmission electron microscopy.

Metal Ion Production by Multiphoton Ionization of Molecules

One of the most promising applications of laser physics and technology that has received little attention is the generation of high brightness. pulsed beams of singly charged metal ions. If successful. this technique would provide a relatively simple and inexpensive means for producing beams of a wide variety of metal or semiconductor ions. For such a technique to be practical. however. will require that the fragmentation pathways of the precursor molecule be better understood.

Our initial experiments have centered on Al^+ or Ga^+ ions produced by the multiphoton ionization of precursors such as trimethylaluminum (TMA). Little is known of the processes involved and. although the A^+ production rate is dramatically enhanced in the vicinity of a three photon resonance in atomic aluminum. the products of and mechanisms responsible for ionization off-resonance are poorly understood. Similar comments hold for the production of Column IIIA ions by dissociative ionization of metal halides in the VUV (such as In^+ from InI).

To more closely investigate this process. we have recently constructed a time of flight (TOF) mass spectrometer and have carried out several experiments involving the fragmentation of $Ga(CH_3)_3$ by tunable blue dye laser radiation. The apparatus is shown schematically in Figure 4. Representative time-of-flight (TOF) spectra that have been obtained with this system are presented in Figure 5. Such data demonstrate that the system resolution is sufficiently high to resolve peaks associated with the two most abundant isotopes of gallium. It is a simple matter to select a particular mass peak for study. and preliminary experimental results show that the spectral dependences for the Ga^+ peaks differ considerably from those for the other fragments. In particular. the atomic ion spectra display strong resonant structure whereas the other fragments yield essentially continua. These experiments are continuing with the goal of elucidating fragmentation patterns for the molecule. both on and off a gallium $2 + 1$ resonance.

Our primary goal is to study the scaling of the Ga^+ ion production rate and determine if the obtainable Ga^+ current makes this process competitive with current ion production techniques. These experiments will also be extended to other metal atom precursors such as the metal-halides.
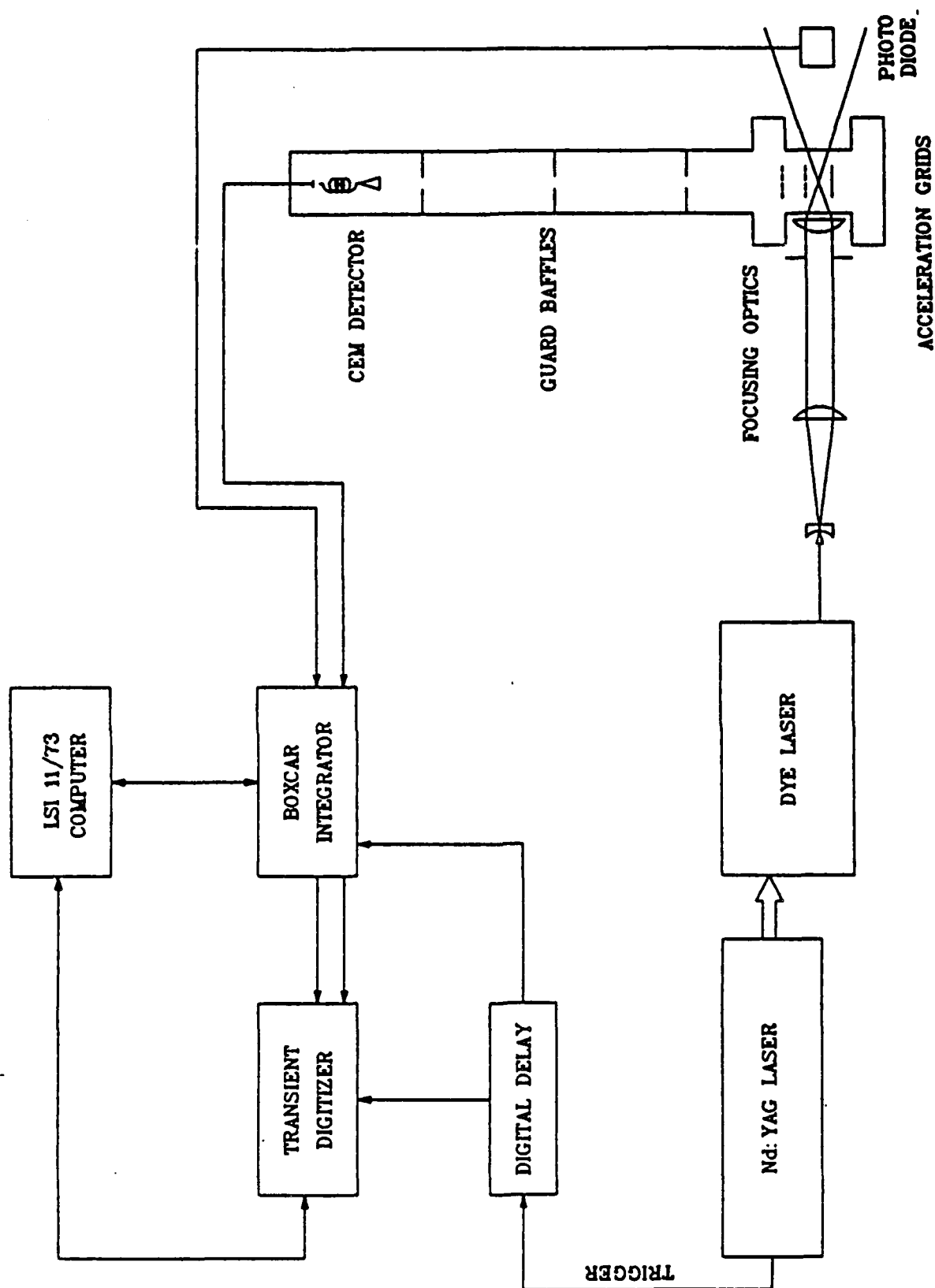
Fig. 4. Schematic diagram of the apparatus used in studying the photofragmentation of trimethylgallium by time of flight mass spectrometry.
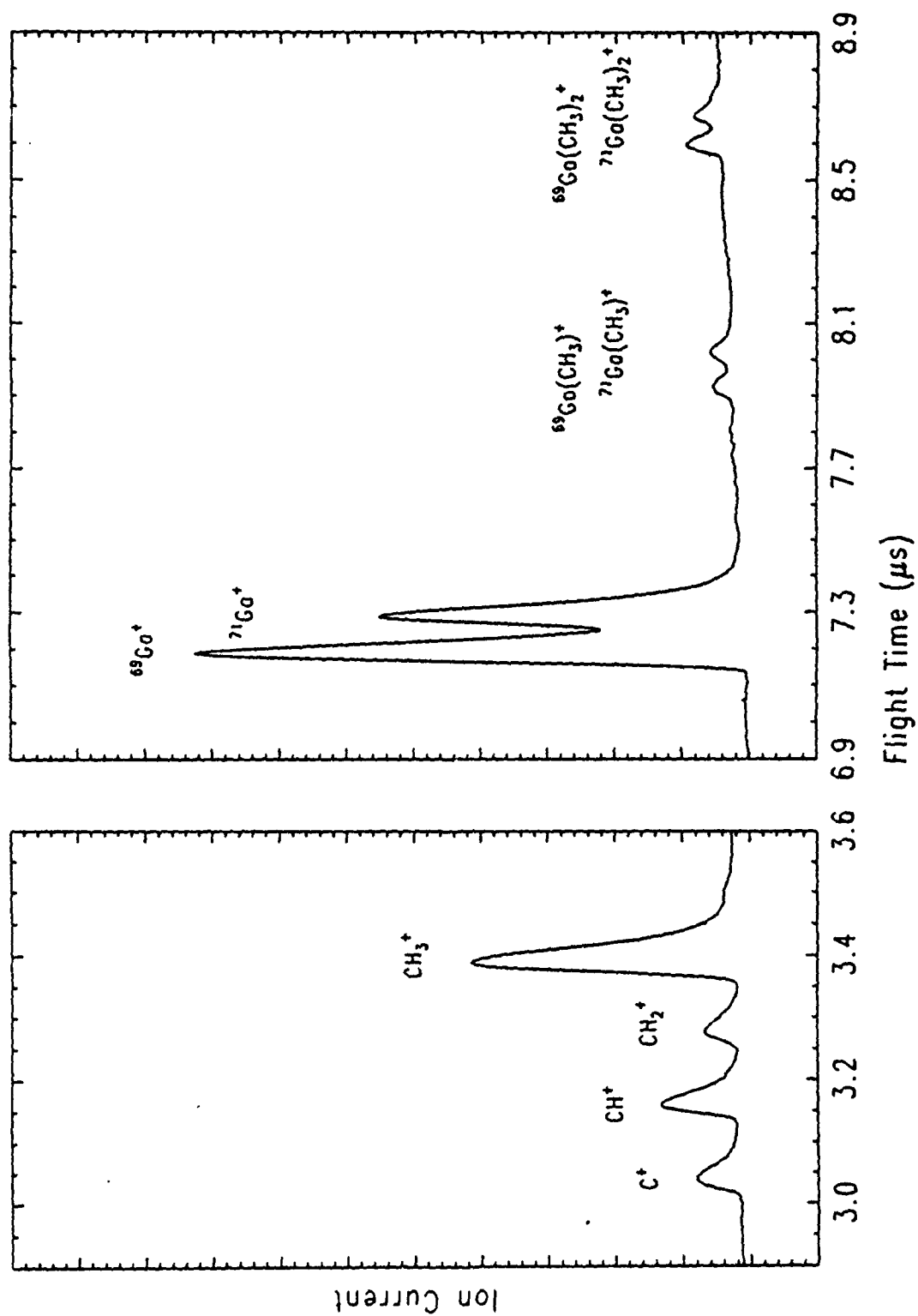
Fig. 5. Selected segments of the TOF spectrum obtained by the photoionization of TM Ga. Note the ability to isotopically resolve the mass peaks.

JSEP-SPONSORED PUBLICATIONS

[1] L. J. Overzet, J. T. Verdeyen, R. M. Roth, and F. F. Carasco, "The effects of modulation on an RF discharge in Silane and on the deposited a-Si:H," *Proc. MRS Symp. K: Plasma Processing and Synthesis of Material*, San Diego, CA, Apr. 20-24, 1987, vol. 98, pp. 321-327. (JSEP)

[2] G. A. Hebner, J. T. Verdeyen, and M. J. Kushner, "An experimental study of a parallel-plate radio-frequency discharge: measurements of the radiation temperature and electron density," *J. Appl. Phys.*, vol. 63, no. 7, pp. 2226-2236, Apr. 1, 1988. (JSEP)

[3] V. Tavitian, C. J. Kiely, D. B. Geohegan, and J. G. Eden, "Epitaxial growth of Ge films on GaAs (285-410°C) by laser photochemical vapor deposition," to appear in *Appl. Phys. Lett.*

[4] D. B. Geohegan and J. G. Eden, "Absorption spectrum of $Kr_2F(4^2\Gamma)$ in the near ultraviolet and visible ($335 \leqslant \lambda \leqslant 600$ nm): Comparison with $Kr_2^+1(\frac{1}{2})_u$ measurements," to appear in *J. Chem. Phys.*

WORK UNIT NUMBER 11

TITLE: · Monolithic Millimeter-Wave Integrated Circuits with Microstrip Antennas

SENIOR INVESTIGATORS:

S. L. Chuang, Assistant Professor
Y. T. Lo, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. I. Aksun, Research Assistant
B. Do, Research Assistant

SCIENTIFIC OBJECTIVE:

Our principal goal on the investigation of monolithic microwave integrated circuits (MMIC) is to integrate active solid state devices with microstrip antennas. It includes the study of propagation characteristics of guidance structures and transmission line discontinuities, the coupling between waveguides, and the integration of solid-state amplifiers with microstrip antennas.

SUMMARY OF RESEARCH:

(a) Study on Guidance Structures and Transmission Line Discontinuities Using Supercomputer

Dielectric waveguides, transmission lines, and discontinuities are the canonical parts of millimeter-wave integrated circuits. Therefore, the propagation characteristics of rectangular dielectric waveguides, microstrip lines, and coplanar lines have been studied. The discontinuities, such as open microstrip line and open and shorted coplanar lines, have been characterized.

To fully understand the operational condition of the rectangular dielectric waveguides, one must obtain the relationship for the propagation constant and the mode pattern inside the waveguide in terms of the frequencies and the waveguide geometry. The purpose of this research is to derive such a relationship using the analytical effective index method and the numerical finite element method. The computer program developed using the finite element method can also be applied as a CAD tool for dielectric as well as nondielectric waveguide designs.

A computer program using the method of moments in the spectral domain has also been developed to analyze the propagation characteristics of the microstrip line, coplanar line, and their aforementioned discontinuities. A large amount of computation time is required when executing the program. Thirty hours of supercomputer CPU time have been granted to work on this project.

(b) Coupling Between Anisotropic Waveguides and the Electro-optical Effect

During the past year, the applications of the strongly coupled-mode theory to a reciprocal anisotropic multiwaveguide system and multiple quantum-well channel waveguides have been studied. The general reciprocal anisotropic medium is described by a symmetric permittivity tensor that can have nonzero off-diagonal elements. The derivation was based on the generalized reciprocity relation, and the derived coupled-mode equations are applicable to both lossy (gain) and lossless systems. The improved coupled-mode theory in an anisotropic multiwaveguide system has also been illustrated with numerical examples. Furthermore, the quadratic electrooptic effect in the multiquantum-well structures has been considered. It has been shown that only a moderate electric field for multiquantum-well is necessary to achieve the optical power switching compared with

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

that required for a bulk GaAs waveguide. These results are useful for both millimeter-wave dielectric waveguides and integrated optical circuits.

(c) Experimental Study on the Integration of Microstrip Antennas

We have been working on the components of the integrated circuits and their integrations. We have studied experimentally an aperture-coupled microstrip antenna and are comparing it with coplanar-fed microstrip antennas. Specifically, the aperture-coupled microstrip antenna consists of an aperture in the ground plane which couples a microstrip line below the ground plane to the patch above. An experimental model of this antenna was designed at 3.6 GHz. It was found that the back radiation and the return loss at f=3.6 GHz are lower than 20 dB and 15 dB, respectively. When the return loss was measured over the frequency range of 3-10 GHz, another frequency, 6.8 GHz, was found with a return loss lower than 15 dB. This is believed to be due to the presence of the aperture. It is known that if slots are cut in the patch where the magnetic field of the (0,3) mode is maximum, they can have a strong effect on the (0,3) modal field, in particular, to lower the operating frequency for the (0,3) mode. In addition, 2-by-2 aperture-coupled and coplanar/slot line feed microstrip arrays were designed to investigate the possibility of beam steering. The dimensions of the patches and the distances between patches were chosen for the operation frequency at 3.6 GHz. The feeding system of the aperture coupled array was designed using Wilkinson's power divider to reduce the effect of the reflection from the branches. The input impedances, co-polarization and cross-polarization characteristics were measured.

The amplifier was designed using the coplanar-line matching network. This was necessary for the integration of the amplifier with the coplanar-fed microstrip antenna. First of all, S-parameters of the FET-transistor (packaged NEC 700) to be used in the amplifier were measured. Then input and output matching networks using coplanar lines were designed to match the input and output of the transistor to a 50-ohm line and to antenna, respectively. Although this is a hybrid integration, it helps us in the development of the theory and software programs for the monolithic integration.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] S. L. Chuang and B. Do, "Electron states in two coupled quantum wells--A strong coupling-of-modes approach," *J. Appl. Phys.*, vol. 62, pp. 1290-1297, Aug. 1987. (JSEP/Air Force)

[2] S. L. Chuang and B. Do, "Application of an improved coupled-mode theory to optoelectronic devices," *Optical Society of America Ann. Mtg*, Rochester, Oct. 18-23, 1987. (JSEP/Air Force)

[3] S. L. Chuang, "Integrated optical devices," *1988 National Radio Sci. Mtg.*, January 5-8, 1988. (JSEP)

[4] I. Tsang, D. Ahn, and S. L. Chuang, "Electric field control of optical second-harmonic generation in a quantum well," *Appl. Phys. Lett.*, vol. 52, pp. 697-699, Feb. 1988. (JSEP/Air Force)

[5] I. Tsang and S. L. Chuang, "Improved coupled-mode theory for reciprocal anisotropic waveguides," *J. Lightwave Technol.*, vol. LT-6, pp. 304-311, Feb. 1988. (JSEP/NASA/NSF)

[6] L. Tsang and S. L. Chuang. "Coupled GaAs multiple-quantum-well channel waveguides including quadratic electrooptic effect." Joint special issue on Integrated Optics. *IEEE J. Quantum Electron.* and *J. Lightwave Technol.* (to appear). (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[7] S. L. Chuang. "Application of the strong coupled-mode theory to integrated optical devices." *IEEE J. Quantum Electron.*, vol. QE-23, pp. 499-509, 1987. (NASA)

[8] D. Ahn and S. L. Chuang. "Intersubband optical absorption in a quantum well with an applied electric field." *Phys. Rev. B.*, vol. 35, pp. 4149-4151, 1987. (NASA/Air Force)

[9] D. Ahn and S. L. Chuang. "Nonlinear intersubband optical absorption in a semiconductor quantum well." *J. Appl. Phys.*, vol. 62, pp. 3052-3054, 1987. (NASA/Air Force)

[10] D. Ahn and S. L. Chuang. "Calculation of linear and nonlinear intersubband optical absorptions in a quantum well model with an applied electric field." *IEEE J. Quantum Electron.*, vol. QE-23, pp. 2196-2204, 1987. (Air Force)

[11] D. Ahn and S. L. Chuang. "Nonlinear intersubband optical absorption in a quantum well with an applied electric field." *Optical Society of America Ann. Mtg.*, Rochester, Oct. 18-23, 1987. (Air Force)

[12] P. Aoyagi, J. Brenneman, S. L. Chuang, and Y. T. Lo. "Novel integration of a coplanar waveguide fed microstrip antenna with amplifier." *1988 National Radio Sci. Mtg.*, Jan. 5-8, 1988. (RADC)

[13] Y. T. Lo, M. L. Oberhart, J. S. Brenneman, P. Aoyagi, J. Moore, and R. Q. H. Lee. "Slotline fed microstrip antenna array modules." *Microwave and Optical Technol. Lett.*, vol. 1, pp. 26-29, Mar. 1988. (RADC)

[14] D. Ahn and S. L. Chuang. "Electric field dependence of intersubband polar-optical phonon scattering in a quantum well." *Phys. Rev. B*, vol. 37, pp. 2529-2535, 1988. (Air Force)

[15] D. Ahn and S. L. Chuang. "Electric field dependence of the intersubband optical absorption in a semiconductor quantum well." *Superlattice and Microstructures* (accepted for publication). (Air Force)

[16] D. Ahn and S. L. Chuang. "A field effect quantum well laser with lateral current injection." *J. Appl. Phys.* (accepted for publication). (Air Force)

[17] Y. T. Lo, B. Engst, and R. Q. Lee. "Simple design formulas for circularly polarized microstrip antennas." to appear in *Proc. IEE. Part H. Microwaves, Antennas, and Polarization.* (NASA)

[18] M. Oberhart, Y. T. Lo, and R. Q. Lee. "A question of microstrip antenna impedance." to appear in *Proc. IEE. Part H. Microwaves, Antennas, and Propagation.* (RADC and NASA)

WORK UNIT NUMBER 12

TITLE: Investigation of Radar Scattering Characteristics of Controllable Surface Shapes with Application to Low Observable Targets

SENIOR INVESTIGATOR:

R. Mittra, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

A. Peterson, Visiting Assistant Professor
C. Chan, Visiting Assistant Professor
A. Chang, Graduate Student
R. Gordon, Fellow
R. Jorgenson, Graduate Student
J. Joseph, Graduate Student
K. Merewether, Fellow

SCIENTIFIC OBJECTIVE:

There are three principal objectives of this effort. The first is to develop efficient integral equation and differential equation techniques for solving the problems of electromagnetic scattering and coupling into complex structures. The second is to study techniques for reducing the radar cross-section of targets of different shapes. The third is to analyze frequency selective surfaces (FSS) for radomes and other antenna applications.

SUMMARY OF RESEARCH:

During the last twelve months we have solved the problem of scattering by resistive honeycomb structures that are useful for fabricating low observable vehicles. The problem of computing the effective complex dielectric constants of such structures has been solved, up to the resonance region. Next, the problem of complex modes in periodic resistive structures has been addressed and these modes are being employed to represent the fields inside the honeycomb structure and to compute the scattering characteristics of truncated honeycombs.

We have also considered the problem of scattering from a body of revolution (BOR), which can be quite large compared to the wavelength. We have developed an efficient algorithm for computing the RCS of BORs that is ten times faster than the conventional methods. Furthermore, we have studied the problem of reducing the radar cross-section of a BOR by coating it with one or more layers of lossy dielectric media.

During this period we have initiated the study of Absorbing Boundary Conditions (ABCs) with the objective of substantially reducing the mesh size associated with the PDE approaches to solving open region scattering problems. The FEM approach appears to be quite promising for complex targets that are inhomogeneously loaded.

We have continued our investigation of the frequency selective surfaces (FSSs) and have focused our attention on the problem of scattering from curved and truncated FSSs. Both singly and doubly truncated FSSs have been considered, and structures with dimensions quite large compared to the wavelength have been investigated by using a technique that allows one to handle over

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

1000 cells. each one requiring several unknowns for the accurate representation of the current distribution on the cell patch. We are currently considering the finite FSS geometry with a dielectric substrate and we plan to study multiple, truncated screens in the near future.

As for the curved surface FSS. we are investigating the problem of scattering (both in-band and out-of-band) by a parabolic surface comprised of frequency selective cells. The curved surface problem is being investigated as an extension of the planar problem by using a locally planar approximation. The investigation of this problem will be continued.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] T. Cwik. R. Mittra. K. C. Lang. and T. K. Wu. "Frequency selective screens." *IFEE Antennas Propagat. Society Newsletter*. vol. 29. no. 2. pp. 6-10. Apr. 1987. (JSEP)

[2] C. H. Chan and R. Mittra. "Comparative study of iterative techniques, moment method and spectral Galerkin approach for solving the problem of electro-magnetic scattering by a rectangular plate." *IEE 5th Int. Conf. on Antennas and Propagation ICAP 87*. York. Mar. 30 - Apr. 2, 1987. pp. 443-446. (JSEP)

[3] T. Cwik and R. Mittra. "Frequency selective surfaces of constant curvature." *IEE 5th Int. Conf. on Antennas and Propagation ICAP 87*. York. Mar. 30 - Apr. 2, 1987. pp. 67-70. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[4] T. Kitazawa. Y. Hayashi. and R. Mittra. "Asymmetrical coupled coplanar-type transmission lines with anisotropic substrates." *IEE Proc. H*. Aug. 1986. vol. 133. no. 4. pp. 265-270. (ONR ARO)

[5] Z. Pantic and R. Mittra. "Quasi-TEM analysis of microwave transmission lines by the finite-element method." *IEEE Trans. Microwave Theory and Tech.*. vol. MTT-34. no. 11. pp. 1096-1103. Nov. 1986. (ONR ARO)

[6] C. H. Chan and R. Mittra. "Analysis of a class of cylindrical multiconductor transmission lines using an iterative approach." *IEEE Trans. Microwave Theory Tech.*. vol. MTT-35. no. 4. pp. 415-424. Apr. 1987. (ONR)

WORK UNIT NUMBER 13

TITLE: High-Performance Testable Electronic Systems

SENIOR INVESTIGATORS:

J. A. Abraham, Research Professor
J. H. Patel, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. Fu, Graduate Research Assistant
C. Gura, Graduate Research Assistant
J. Gerstenberger, Graduate Research Assistant
S. Laha, Graduate Research Assistant

SCIENTIFIC OBJECTIVE:

This unit seeks to develop, model, and analyze efficient, high-performance, and testable computer architectures which will exploit compound semiconductor technology. There has been increasing interest in the use of compound semiconductor technologies, such as gallium arsenide (GaAs), as a vehicle to develop high-performance electronic systems. Various studies have indicated that GaAs devices will become a larger share of the semiconductor market in the coming years. In addition to the high performance possible, the capability for greater radiation hardness in the compound semiconductor technology is of great interest to military systems. We have identified several aspects of computer architecture for particular attention, due both to their emerging importance from a technology-driven point of view and to the lack of known structures or analysis techniques for meeting our objective.

SUMMARY OF RESEARCH:

Memory Organizations

Chip area is a critical resource in the design of VLSI processors, and careful allocation of available area will help maximize chip performance. This research compares several different local memory organizations applicable for single-chip processors. Several cache types—instruction, data, split, unified, stack, top-of-stack—were considered. These are compared to multiple register set architectures to which various caches can also be added. The performance metric of interest is effective access time, since a wide variety of register and cache organizations is used. A model for access time and a model for chip area required for each organization form the basis for comparison. Extensive simulations of several register-memory organizations were performed. Address traces from a VAX-11/780 running systems programs were used in the simulation. The results are somewhat surprising for very small on-chip memories: in particular, stack caches and instruction caches performed better than the conventional wisdom of adding more registers or a companion data cache.

Trace-driven simulation is a simple way of evaluating cache memory systems with varying hardware parameters. To evaluate realistic workloads, simulating even a few million addresses is not adequate and such large-scale simulation is impractical from the consideration of space and time requirements. Therefore, simply reporting more simulation results on cache memories, which are found in profusion in existing literature, is not the goal of this research. The goal of this research is to develop new methods of cache simulation based on statistical techniques for

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

decreasing the need for large trace measurements and to predict true program behavior. In the proposed method. sampling techniques are applied while collecting the address trace from a workload. The cost of the sampling-based simulation method in terms of both memory space and computer time is significantly lower than conventional techniques. For a trace length of 5 million references, this method typically requires collecting only 7% or less of the trace for smaller caches. For large caches. much longer segments of traces are required by conventional methods. The new method estimates the true value of miss ratio with much lower overhead. This technique gives accurate estimates of both the mean value and the distribution of the miss ratio.

Last year we reported the success of the sampling method for small cache. We have continued this work for large caches. The large caches are becoming very common and their behavior can only be studied by using massively long traces. However, the above sampling-based methods are not directly applicable to large caches where significant amounts of data are retained across the context switches. Therefore a new concept of primed cache was introduced to simulate large caches by the sampling-based method. This is achieved by simulating only those portions of the cache whose true state can be recreated even from the sampled trace. Both direct-mapped and set-associative caches. as large as 128 Kbytes. have been studied using these methods. Extensive verification experiments were carried out and the results obtained indicate that the primed cache concept with sampled simulation method gives very accurate miss ratios.

Improved Methods of Simulating Transmission Lines

This research addresses the accurate assessment of interconnection delay in high-performance integrated circuit technologies. The models for the interconnections between devices can generally be divided into two categories. In the first category the signal transition time is sufficiently longer than the delay of the signal propagation through the interconnection. Interconnect models in the first category include the lumped capacitor and the distributed RC line. In the second category the transition time is less than twice the delay of the signal propagation. thus a transmission line model must be considered. Models in the second category include single (uncoupled) lossless and lossy (RLC) transmission lines and coupled lossless and loss transmission lines.

We have developed new techniques for simulating lossy (RLC) transmission lines based on the method of characteristics. For uncoupled lossy transmission lines. a method is presented that speeds up the simulation time by a factor of two compared with existing techniques. A method is also presented for the transient analysis of coupled lossy lines in an inhomogeneous medium. Previously. simulation techniques were limited to coupled lossy lines in a homogeneous medium. Results in this area will be used to develop techniques and tools to evaluate the performance of high-performance computer systems implemented with new packaging technologies.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] S. G. Abraham and J. H. Patel. "Parallel garbage collection on a virtual memory system." *Proc. 1987 Int Conf. on Parallel Processing.* St. Charles. IL. Aug. 1987. pp. 243-246. (JSEP)

[2] R. J. Eickmeyer. "Performance evaluation of on-chip register and cache organizations." *Proc. 15th Int. Ann. Symp. on Computer Architecture.* Honolulu. Hawaii. May 1988 (to appear. 'JSEP SRC'

[3] C. V. Gura and J. A. Abraham, "Improved methods of simulating RLC coupled and uncoupled transmission lines based on the method of characteristics," *Proc. 25th Design Automation Conf.*, Anaheim, CA, June 1988 (to appear). (JSEP)

[4] S. Laha, J. H. Patel and R. K. Iyer, "Accurate low-cost methods for performance evaluation of cache memory systems," *IEEE Trans. Comput.* (to appear). (JSEP/NASA)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[5] N. K. Jha and J. A. Abraham, "Techniques for efficient MOS implementation of totally self checking checkers," *Int. J. Comput. and Math.*, vol. 13, no. 5/6, pp. 555-566, Apr. 1987. (SRC)

[6] V. S. S. Nair and J. A. Abraham, "Average checksum codes for fault-tolerant matrix operations on processor arrays," (invited paper) *Proc. 2nd Int. Conf. on Supercomputing*, San Francisco, CA, May 1987, pp. 284-290. (NASA)

[7] A. Chatterjee and J. A. Abraham, "Test generation for arithmetic units by graph labelling," *Proc. 17th Int. Symp. on Fault-Tolerant Computing*, Pittsburgh, PA, July 1987, pp. 284-289. (SRC/GE)

[8] R. J. Eickemeyer and J. H. Patel, "Performance evaluation of multiple register sets," *Proc. 14th Annual Symp. on Computer Architecture*, Pittsburgh, PA, June 1987, pp. 264-271. (SRC)

[9] S. J. Chandra and J. H. Patel, "A hierarchical approach to test vector generation," *Proc. 24th ACM/IEEE Design Automation Conf.*, Miami Beach, FL, June 1987, pp. 495-501. (SRC)

[10] P. Mazumder and J. H. Patel, "Design and algorithms for parallel testing of random access and content addressable memories," *Proc. 24th ACM/IEEE Design Automation Conf.*, Miami Beach, FL, June 1987, pp. 688-694. (SRC)

[11] P. Mazumder and J. H. Patel, "Methodologies for testing embedded content addressable memories," *Proc. 17th Int Symp. on Fault-Tolerant Computing*, Pittsburgh, PA, July 1987, pp. 270-275. (SRC)

[12] W.-T. Cheng and J. H. Patel, "A minimum test set for multiple-fault detection in ripple-carry adders," *IEEE Trans. Comput.*, vol. C-36, pp. 891-895, July 1987. (SRC)

[13] J. A. Abraham, P. Banerjee, W. K. Fuchs, C.-Y. Chen, S.-Y. Kuo, and A. L. N. Reddy, "Fault tolerance techniques for systolic arrays" (invited paper), *IEEE Computer Magazine (Special Issue on Systolic Arrays: From Concept to Implementation)*, vol. 20, no. 7, pp. 65-75, July 1987. (SRC)

[14] M. M. Yen, W. K. Fuchs, and J. A. Abraham, "Designing for concurrent error detection in VLSI: application to a microprogram control unit," *IEEE J. Solid-State Circuits*, vol. SC-22, no. 4, pp. 595-605, Aug. 1987. (VHSIC/SRC)

[15] W. K. Fuchs, C.-Y. Chen, and J. A. Abraham, "Concurrent error detection in highly structured logic arrays," *IEEE J. Solid-State Circuits*, vol. SC-22, no. 4, pp. 583-594, Aug. 1987. (SRC/VHSIC)

[16] C.-Y. Chen and J. A. Abraham, "Concurrent error detection in VLSI processor arrays," *Proc. SPIE 2nd Conf. on Advanced Signal Processing Algorithms and Architectures*, San Diego, CA, vol. 826, Aug. 1987, pp. 205-214. (SDIO/IST)

[17] H. P. Chang and J. A. Abraham, "Use of high-level descriptions for speedup of fault simulation," *Proc. Int. Test Conf.*, Washington, DC, Sept. 1987, pp. 278-285. (SRC/GE)

[18] P. Mazumder and J. H. Patel, "An efficient built-in self testing for random access memory," *Proc. Int. Test Conf.*, Washington, DC, Sept. 1987, pp. 1072-1077. (SRC)

[19] W. A. Rogers, J. F. Guzolek, and J. A. Abraham, "Concurrent hierarchical fault simulation: a performance model and two optimizations," *IEEE Trans. Comput.-Aided Des., Special Issue on ICCAD-86*, pp. 848-862, Sept. 1987. (SRC)

[20] A. Chatterjee and J. A. Abraham, "On the C-testability of generalized counters," *IEEE Trans. Comput.-Aided Des., Special Issue on ICCAD-86*, vol. CAD-6, no. 5, pp. 713-726, Sept. 1987. (GE/SRC)

[21] P. Mazumder and J. H. Patel, "A novel fault-tolerant design of testable dynamic random access memory," *Proc. Int. Conf. on Computer Design (ICCD '87)*, New York, NY, Oct. 1987, pp. 306-309. (SRC)

[22] K. A. Hua and J. A. Abraham, "Design and evaluation of executable assertions for concurrent error detection," *Proc. Computer Software and Applications Conf.*, Tokyo, Japan, Oct. 1987, pp. 324-330. (IBM/NASA)

[23] W. C. Carter and J. A. Abraham, "Design and evaluation tools for fault-tolerant systems," *Proc. AIAA Computers in Aerospace VI Conf.*, Wakefield, MA., Oct. 1987, pp. 70-76. (U of I)

[24] D. S. Brahme and J. A. Abraham, "Knowledge based test generation for VLSI circuits," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1987, pp. 292-295. (ONR)

[25] H. P. Chang and J. A. Abraham, "The complexity of accurate logic simulation," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1987, pp. 404-407. (SRC/GE)

[26] A. Chatterjee and J. A. Abraham, "Testability of generalized counters under sequential and multiple faults," *Proc. Int. Symp. on Electronic Devices, Circuits, and Systems*, Kharagpur, India, Dec. 1987, pp. 624-626. (GE/SRC)

[27] P. Mazumder, J. H. Patel, and W. K. Fuchs, "Methodologies for testing embedded content addressable memories," *IEEE Trans. Comput.-Aided Design*, vol. 7, pp. 11-20, Jan. 1988. (SRC)

[28] P. Banerjee, J. Rahmeh, C. Stunkel, S. Nair, K. Roy, and J. Abraham, "An evaluation of system-level fault tolerance on the Intel hypercube multiprocessor," *Proc. 18th Int. Symp. on Fault-Tolerant Computing*, Tokyo, Japan, June 1988 (to appear). (NSF/SRC Shell)

[29] V. S. S. Nair and J. A. Abraham, "General linear codes for fault-tolerant matrix operations on processor arrays," *Proc. 18th Int. Symp. on Fault-Tolerant Computing*, Tokyo, Japan, June 1988 (to appear). (NASA)

[30] P. A. Duba. R. K. Roy. J. A. Abraham, and W. A. Rogers, "Fault simulation in a distributed environment," *Proc. 25th Design Automation Conf.*, Anaheim, CA, June 1988 (to appear). (SRC)

WORK UNIT NUMBER 14

TITLE: New Directions in Fault-Tolerant Computing

SENIOR INVESTIGATORS:

P. Banerjee, Research Assistant Professor
W. K. Fuchs, Research Assistant Professor
R. K. Iyer, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. Patil, Research Assistant
C. C. Li, Research Assistant
S. Subramani, Research Assistant
M. C. Hsueh, Research Assistant/Visiting Professor

SCIENTIFIC OBJECTIVE:

This unit is concerned with exploring new directions in fault-tolerant computing that will be useful in understanding the basic principles in design, testing, error prediction, and circumvention for reliable complex computer systems. Basic research is being performed in the three areas of parallel test pattern generation, reliable distributed database systems for real-time applications, and intelligent error prediction and circumvention.

SUMMARY OF RESEARCH:

Parallel Algorithms for Automatic Test Generation

In the past year, we have performed research into the investigation of algorithms for automatic test pattern generation (ATPG) in a parallel processing environment. We have identified several techniques for partitioning a large circuit into blocks. We have also studied the effect of assigning circuit blocks to processors in a multiprocessor environment on the algorithm performance. In conventional test generation algorithms, during the decision-making process, we may have more than one way to satisfy our current objective. In a parallel environment, we can evaluate the alternate choices in parallel and avoid backtracking. This sort of parallelism is called OR-parallelism. In satisfying an objective, there may be some necessary subgoals that must be solved. These subgoals can be solved in parallel, and this form of parallelism is called AND parallelism. The proposed test generation algorithm uses AND/OR parallelism. We can get further speedups by parallelizing the forward implication steps. Apart from an algorithm based on decision trees such as PODEM or FAN, we are also working on a simulation-based algorithm that uses a cost function to guide the search for a test vector. The proposed test generation algorithm also uses parallelism at a higher level. Given a list of faults, we can generate tests for different faults in parallel. The test generation step is usually followed by fault simulation. We are at present investigating different partitioning techniques for fault sets so that communication between processors for fault simulation is reduced.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

Reliable Distributed Database Systems

A new technique, based on virtual backpointers, has been developed for local concurrent error detection in linked data structures. Two new data structures, the Virtual Double-Linked List and the B-Tree with Virtual Backpointers, have been designed and implemented based on this technique. The data structures are appropriate for real-time applications since they allow concurrent error detection in O(1) time with little or no storage overhead and few extra node accesses. For purposes of analyzing local concurrent error detection strategies, a checking window metric has been developed. Checking windows define the dimension of the locality and are a function of the cost of performing local concurrent error detection. These techniques have been implemented in a data structure software package and are currently undergoing experimental performance and reliability analysis.

We have also developed a strategy for reliable storage reclamation in distributed object-oriented systems. A distributed garbage collection algorithm that does not require global state information has been developed. The algorithm exhibits the property of graceful degradation and functions in the presence of inactive processor nodes. Compaction of objects is supported and object locality is exploited to reduce overhead. An implementation utilizing the operating system MACH and the transactions facility CAMELOT is currently under way.

Intelligent Error Prediction and Circumvention

A new technique for extracting behavioral models that characterize jointly, system resource and error activity, has been developed. This technique has now been adapted to develop models of system behavior in real-time. The model extraction system takes, as input, measured data of resource usage and error occurrence. Statistical clustering is then used to identify recurring patterns of usage and failures for the set of applications or workload under consideration. The identified patterns are then used to define a state transition model of system behavior. This model extraction approach is now being used to investigate real-time resource reconfiguration for both optimum performance and optimum availability.

It has been shown that such analyses are not only capable of accurately predicting system performability, but error prediction based on the past occurrence patterns as well. A new approach for utilizing the identified failure and resource usage patterns for system failure diagnosis is now under investigation.

JSEP-SPONSORED PUBLICATIONS

[1] M. C. Hsueh, R. K. Iyer, and K. S. Trivedi, "A measurement-based performability model for a multiprocessor system." *Proc. 2nd Int. Wkshp. on Applied Mathematics and Performance Reliability Models of Computer/Communications Systems*. Rome, Italy, May 25-29, 1987. (JSEP)

[2] R. Chillarege and R. K. Iyer, "Measurement-based analysis of error latency." *IEEE Trans. Comput.*, vol. C-36, no. 5, pp. 529-537, May 1987. (JSEP)

[3] P. McGuire and R. K. Iyer, " A measurement-based study of concurrency in a multiprocessor." *Proc. 1987 Int. Conf. on Parallel Processing*. St. Charles, IL, Aug. 17-21, 1987. (JSEP)

[4] M. C. Hsueh and R. K. Iyer, "Measurement-based model of software reliability in a production environment." *Computer Software and Applications Conf.*, Tokyo, Japan, Oct. 5-9, 1987. (JSEP)

[5]   P. Banerjee. M. Jones. J. Sargent. R. J. Brouwer. K. P. Belkhale. A. Hagin. and S. Patil. "Parallel algorithms for placement. routing. extraction. simulation and test generation on hypercube multiprocessors." in *Advances in VLSI Computer-Aided Design*. vol. 2. I. N. Hajj. Ed. England: JAI Press. 1988. (JSEP)

[6]   S. Laha. J. Patel. and R. K. Iyer. "Accurate low-cost methods for performance evaluation of cache memory systems." *IEEE Trans. Comput.* (to appear). (JSEP)

[7]   S. Mitra and R. K. Iyer. "A measurement-based analysis of multiple error and near-coincident fault discovery in a shared memory multiprocessor." *Proc 1988 Int. Conf. on Parallel Processing*. Aug. 1988 (to appear). (JSEP)

[8]   R. Chillarege and R. K. Iyer. "An experimental study of memory fault latency." *IEEE Trans. Comput.* (to appear). (JSEP)

[9]   D. B. West and P. Banerjee. "On the construction of communication networks with bounded degree of output ports." *IEEE Trans. Comput.* (to appear). (JSEP)

[10]   P. Banerjee and A. Dugar. "The design. analysis and simulation of a fault-tolerant interconnection network supporting the fetch-and-add primitive." *IEEE Trans. Comput.* (to appear). (JSEP)

[11]   M. Sharma and W. K. Fuchs. "Applicative environments for reliable multiprocessor systems." *Algorithm. Architecture and Technology Issues in Concurrent Computation*. Tewksbury. Ed. 1988 (to appear). (JSEP)

WORK UNIT NUMBER 15

TITLE: Efficient Computation Techniques

SENIOR INVESTIGATORS:

D. J. Brown, Research Associate Professor
M. C. Loui, Research Associate Professor
F. P. Preparata, Research Professor
V. L. Ramachandran, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

A. Kanevsky, Research Assistant
M. L. Prastein, Research Assistant
R. Tamassia, Research Assistant
I. Tollis, Research Assistant
J. L. Trahan, Research Assistant

SCIENTIFIC OBJECTIVE:

For several years one of the most vigorous areas of research in information processing has been the analysis and design of efficient computation techniques. Its impact has been not only on the availability of better computational methods for a number of significant applications, but also on the awareness in the computing community of the crucial importance of algorithmic design. By investigating both upper and lower bounds to the resource requirements of specific applications, this discipline effectively develops a methodology aiming at a quantitative formulation of the inherent difficulty of problems in the appropriate computation models.

The involvement of our research group with this topic is well established and dates back to the early seventies. Our record over this period shows that our focus (as well as that of our peer community) has been adjusting dynamically, as changes in technologies have modified the general research horizon and the perception of relevance. The most significant change of this type has been the advent of Very-Large-Scale-Integration (VLSI), which has profoundly influenced essentially every facet of our current research interests. The advent of VLSI is important in two major respects: one is the present possibility to realize massively parallel computers: the other is the introduction of criteria of complexity (the VLSI "model"), which takes into account the design rules dictated by the new technology. Therefore, while maintaining our interest for problems in the more traditional areas (Von Neumann computations), our current work emphasizes research on the potentially revolutionary domain of concurrent computation.

SUMMARY OF RESEARCH:

Parallel Computation and Graph Algorithms

We have continued our investigation of efficient parallel algorithms for graph problems. We have developed a new algorithm for testing graph four-connectivity and for finding all separating triplets of a tri-connected graph. This algorithm has both sequential and parallel implementations that are better than previous algorithms for the problem. On an n-node graph, the parallel algorithm runs in $O(\log^2 n)$ parallel time with n^2 processors on a CRCW PRAM.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

We have developed an improved sequential algorithm for determining the vertex connectivity of graphs. As an aid to developing good parallel algorithms for graph connectivity, we have studied the structure of separating k-sets in a graph. We have obtained a $\Theta(c^k n^2)$ bound on the worst-case number of separating k-sets in a k-connected graph, with exact results for k=2 and 3. We have also obtained a compact, linear-size representation for these separating k-sets.

We have improved the running time for efficient parallel triconnectivity testing to $O(\log n)$ from $O(\log^2 n)$ by developing two new parallel algorithmic techniques. We have developed fast parallel algorithms for several problems on reducible flow graphs, and we have obtained an interesting minimax arc theorem for them. We have also obtained fast and efficient circuits for the problem of integer division.

We have spent a substantial portion of the last year in preparing a survey article with R. M. Karp at University of California, Berkeley, on parallel algorithms for shared memory machines. This survey was invited for the *Handbook of Theoretical Computer Science*, by the editor, J. van Leeuwen, and will be published by North-Holland.

Models of Parallel Computation

We have significantly strengthened our time and space bounds for simulation of PRAMs with unit-cost multiplication and with unit-cost shift instructions. Let PRAM[*] (PRAM[↑,↓]) denote a PRAM with a unit-cost multiplication instruction (respectively left shift and right shift instructions). For convenience we use PRAMs with the concurrent-read-concurrent-write capability. Every PRAM[*] of time complexity $T(n)$ can be simulated by an ordinary PRAM in time $O(T^2(n)/\log T(n))$ and by a Turing machine in space $T^2(n)$. Every PRAM [↑,↓] of time complexity $T(n)$ can be simulated by an ordinary PRAM in time $O(T^2(n))$ and by a Turing machine in space $T^3(n)$. We have obtained analogous results for PRAMs with unit-cost division.

Parallel Implementation of Signal Processing (in VLSI)

Signal processing is a most typical candidate for high-efficiency dedicated parallel computation. For increasing input rate, processing is feasible only by resorting to massive parallelism, i.e., to an nq-th extension of the original order-n filter. We have shown that the operation is reducible to convolutions with fixed n-vectors and propose to realize the computation by means of the twisted-reflected-tree, a network naturally suited for prefix computation. The fact that digital filtering is structurally in the class of prefix computations has motivated an in-depth study of space-time trade-offs for circuits for parallel-prefix computations. We have shown that inherently different trade-offs exist depending upon the structure of the operation semigroup [6].

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] A. Kanevsky and V. Ramachandran, "Improved algorithms for graph four-connectivity." *Proc. 28th Ann. IEEE Symp. on Foundations of Comp. Sci.*, Los Angeles, CA, 1987, pp. 252-259. (JSEP SRC)

[2]   M. C. Loui and H. H. Abu-Amara, "Memory requirements for agreement among unreliable asynchronous processes," in *Advances in Computing Research*, vol. 4, F. P. Preparata, Ed. JAI Press, 1987, pp. 163-183.   (JSEP/ONR/Kodak)

[3]   N. Shankar and V. Ramachandran, "Efficient parallel circuits and algorithms for division," CSL Technical Report UILU-ENG-87-2235, ACT-77, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, May 1987; also, submitted to *Inform. Proc. Lett.* (JSEP/NSF/SRC)

[4]   V. Ramachandran, "Fast parallel algorithms for reducible flow graphs," *Proc. 1987 Princeton Wkshp. on Algorithm, Architecture and Technology Issues in Models of Concurrent Computations*, Princeton, NJ, Oct. 1987.   (JSEP/NSF/SRC)

[5]   V. Ramachandran, "A minimax arc theorem for reducible flow graphs," Technical Report 87-001, International Computer Science Institute, Berkeley, CA, Dec. 1987; also, submitted to *SIAM J Discrete Math.*   (JSEP)

[6]   G. Bilardi and F. P. Preparata, "Size-time complexity of Boolean networks for prefix computations, to appear in *J. Assoc. Comput. Mach.*   (JSEP/NSF)

[7]   H. Edelsbrunner and F. P. Preparata, "Minimum polygonal separation," *Inform. and Computation* (to appear).   (JSEP/NSF)

[8]   R. M. Karp and V. Ramachandran, "Parallel algorithms for shared memory machines," *Handbook of Theoretical Computer Science*, J. van Leeuwen, Ed., 1988 (to appear).   (JSEP)

[9]   V. Ramachandran and U. Vishkin, "Efficient parallel triconnectivity in logarithmic time," *Proc. Aegean Workshop on Computing*, Corfu, Greece, June-July 1988, Springer-Verlag Lecture Notes in Computer Science (to appear).   (JSEP/SRC)

[10] J. Trahan, M. C. Loui, and V. Ramachandran, "Multiplication, division, and shift instructions in parallel random access machines," *Proc. 22nd Ann. Conf. on Inform. Sci. and Sys* Princeton, NJ, Mar. 1988.   (JSEP).

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[11] H. Alt, T. Hagerup, K. Mehlhorn, and F. P. Preparata, "Deterministic simulation of idealized parallel computers on more realistic ones," *SIAM J. Comput.*, vol. 16, no. 5, pp. 808-835, Oct. 1987.   (NSF)

[12] W. Lipski, Jr., and F. P. Preparata, "A unified approach to layout wirability," *Math. Syst. Theory*, vol. 19, pp. 189-203, 1987.

[13] K. Mehlhorn and F. P. Preparata, "Area-time optimal division for $T = \Omega ((\log n)^{1+\epsilon})$," *Inform. and Computation*, vol. 72, no. 3, pp. 270-282, 1987.   (NSF)

[14] V. Ramachandran, "The complexity of minimum cut and maximum flow problems in an acyclic network," *Networks*, vol. 17, pp. 387-392, 1987.   (NSF/IBM)

[15] M. Sarrafzadeh and F. P. Preparata, "A bottom-up layout technique based on two rectangle routing," *Integration*, vol. 5, pp. 231-246, 1987.

[16] R. Tamassia, "On embedding a graph in the grid with the minimum number of bends," *SIAM J. on Comput.*, vol. 16, no. 3, 1987, pp. 421-444.

[17] A. Kanevsky and V. Ramachandran, "A characterization of separating pairs and triplets in a graph," CSL Technical Report UILU-ENG-87-2242, ACT-79, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, June 1987; also submitted to *Discrete Applied Math.* (NSF/SRC)

[18] M. Ben-Or, E. Feig, D. Kozen, and P. Tiwari, "A fast parallel algorithm for determining all roots of a polynomial with real roots," *SIAM J. Comput.* (to appear). (IBM/ONR)

[19] G. Bilardi and M. Sarrafzadeh, "Optimal VLSI circuits for discrete Fourier transform," *Advances in Computing Research* (to appear). (SRC/NSF/IBM)

[20] P. Czerwinski and V. Ramachandran, "Optimal VLSI graph embeddings in variable aspect ratio rectangles," *Algorithmica*, vol. 3, no. 4, 1988 (to appear). (SRC/IBM)

[21] A. S. Hodel and M. C. Loui, "Optimal dynamic embedding of X-trees into arrays," *Theoretical Computer Science* (to appear). (Kodak)

[22] G. L. Miller, V. Ramachandran, and E. Kaltofen, "Efficient parallel evaluation of straight-line code," *SIAM J. Comput.*, vol. 17, no. 4, 1988 (to appear). (NSF/SRC)

[23] P. A. Peterson and M. C. Loui, "The general maximum matching algorithm of Micali and Vazirani," *Algorithmica* (to appear). (ONR)

[24] V. Ramachandran, "Finding a minimum feedback arc set in reducible flow graphs," *J. Algorithms*, vol. 9, no. 3, 1988 (to appear). (NSF/IBM)

[25] M. Sarrafzadeh, "On the complexity of the channel routing problem in the knock-knee model," *IEEE Trans. CAD* (to appear). (SRC)

WORK UNIT NUMBER 16

TITLE: High-Resolution Sensor Array Processing

SENIOR INVESTIGATORS:

T. S. Huang, Research Professor
W. K. Jenkins, Research Professor
D. C. Munson, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

C. W. Chen, Research Assistant
R. P. Faust, Teaching Assistant
A. W. Hull, Research Assistant
G. Kakazu, Research Assistant

SCIENTIFIC OBJECTIVE:

The term "sensor array system" refers to a large class of remote sensing systems in which data are collected and recorded by many independent sensors, or by one sensor that is moved to different spatial positions. The recorded data are processed by a digital array algorithm to produce a high-resolution object function. Some of the more important multi-sensor array systems now in use are synthetic aperture radar (SAR), computer-aided tomography (CAT), and beam-forming sonar. The objective of the research in this unit is to develop both the theory and computer verification of new signal processing methods with the goal of overcoming current limits on resolution and data throughput rates for these systems. Specifically, we propose to develop reconstruction algorithms that: (1) can achieve high resolution from a limited amount of sampled data; (2) have small enough computational complexities that real-time implementation is feasible; and (3) can be partitioned into sets of elementary operations suitable for VLSI realization.

SUMMARY OF RESEARCH:

During the past year our JSEP research has concentrated on two aspects of high-resolution sensor array processing: adaptive filtering and beamforming algorithms, and signal and image recovery from incomplete observations. In the adaptive area we have continued studying discrete orthogonal transforms for improving convergence properties in adaptive finite impulse response (FIR) digital filters that operate in colored noise environments. Also, we have extended the principles of 1-D adaptive filtering into 2-D by creating a new 2-D adaptive filter structure having reducing computational complexity. In the area of signal and image recovery from incomplete observations, we have developed a new algorithm based on the Hankel transform for inversion of polar format Fourier data in tomography and synthetic aperture radar. We have also performed extensive comparison tests on several Fourier phase retrieval algorithms, and we have developed a new algorithm for discrete band-limited signal extrapolation.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

1D and 2D Adaptive Signal Processing

The least-mean-square (LMS) adaptive algorithm is the best known and most widely used real-time adaptive FIR filtering algorithm due to its simple computational requirements. However, as VLSI digital processors become cheaper and more readily available, the question arises as to whether more effective real-time algorithms can be found that take advantage of increased computational resources as they become available. It is well known that a real-time decomposition of the incoming signal into a set of nearly orthogonal components leads to faster convergence rates when the adaptive systems trains on colored noise inputs. In this work, transform domain processing was characterized by the effect of the transform on the shape of the mean-square error surface. It was shown that the effect of an ideal transform is to convert equal error contours, which are initially hyperellipses in the parameter space, into hyperspheres. Four real-valued orthogonal transforms were experimentally compared and evaluated in terms of learning characteristics for different classes of input signals. The discrete Hartley transform, a relatively obscure real-valued ortnogonal transform, was shown to perform very well in comparison to the Walsh Hadamard transform, discrete cosine transform, and a custom-designed, power-of-2 transform.

In the area of 2D signal processing, a new 2D adaptive digital filter was created by applying an LMS adaptive algorithm to the parameters of a McClellan-Chan 2D digital filter. By applying the adaptation to only the 1D prototype coefficients, while keeping the parameters of the McClellan mapping fixed, a constrained adaptive filter resulted that requires the update of only $M+1$ parameters at each iteration (as opposed to $(M+1)^2$ for a conventional 2D structure), where $M=(2N+1)/2$ and N is the length of the 1D FIR prototype. Three features make this design particularly useful: (1) the classes of achievable designs include many important types of filters that are useful in practical image processing; (2) the computational complexity is sufficiently reduced compared to a direct form LMS structure that implementation in real-time applications becomes an economic possibility; and (3) the convergence rate of the new structure is much faster than a direct form 2D LMS filter.

Signal and Image Recovery from Incomplete Observations

We have developed a new algorithm for reconstructing a 2-D image from a finite set of its sampled projections. The algorithm, which we have named the Hankel Transform Reconstruction (HTR) algorithm, is polar-coordinate based. The algorithm expands the polar form Fourier transform $F(r,\theta)$ of an image into a Fourier series in θ; calculates the appropriately ordered Hankel transform of the coefficients of this series, giving the coefficients for the Fourier series of the polar-form image $f(\rho,\phi)$; resolves this series, giving a polar-form reconstruction; and finally, if desired, interpolates this reconstruction to a rectilinear grid. We have developed both the theory and discrete implementation of the HTR algorithm and have investigated errors arising in its implementation. We have also compared it with the popular convolution back-projection algorithm and found that the HTR algorithm can take a factor of 2 less computation.

We have performed extensive computer simulations to compare several phase-retrieval algorithms with respect to noise sensitivity and computational requirements. Specifically, the following algorithms were studied: (a) solving a set of nonlinear equations based on autocorrelation functions; (b) iteratively going back and forth between the spatial and frequency domains and imposing given constraints in each domain; (c) doing many 1-D spectral factorizations and then searching for a consistent 2-D solution; (d) doing 2-D spectral factorization directly by zero-tracking in the complex plane. It has been found that method (b) is superior to the others.

Finally, in the area of extrapolation we have developed a new algorithm for discrete band-limited signal extrapolation that outperforms existing algorithms. This new algorithm recursively changes the weighting function in the frequency domain to make the energy of the weighted signal concentrate in the subspace of basis functions used to represent the unknown signal.

65

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] T. S. Huang, K. A. Rinaldi, and H. Lee, "Comparison of phase retrieval algorithms," in *Digital Signal Processing*, V. Cappellini and A. G. Constantinides, Eds., North Holland, 1987. (JSEP)

[2] W. K. Jenkins, "Analog signal processing," in *The Encyclopedia of Physical Science and Technology*, Robert A. Meyers, Ed., Academic Press, Inc., pp. 571-598, 1987. (JSEP/NSF)

[3] H. Lee, D. P. Sullivan, and T. S. Huang, "Improvement of discrete band-limited signal extrapolation by iterative subspace modification," *Proc. IEEE Int. Conf. Acoustics, Speech, Signal Processing*, Dallas, TX, Apr. 6-9, 1987, pp. 1569-1572. (NSF, Motorola, Hughes, JSEP)

[4] D. C. Munson, Jr., "An introduction to strip mapping synthetic aperture radar," *Proc. IEEE Int. Conf. Acoustics, Speech, Signal Processing*, Dallas, TX, Apr. 6-9, 1987, pp. 2245-2248. (ARO, JSEP)

[5] W. K. Jenkins, M. Nayeri, D. F. Marshall, and W. Hull, "An important research problem: Alternate realizations of adaptive digital filters," *Proc. 30th Midwest Symp. on Circuits and Syst.*, Syracuse, NY, Aug. 16-17, 1987, pp. 721-724 (Invited). (JSEP/AT&T)

[6] W. K. Jenkins, J. J. Murphy, and D. F. Marshall, "The use of the discrete Hartley transform for improving convergence rates in adaptive FIR digital filters," *Proc. Int. Symp. on Electronic Devices Circuits and Systems*, Karagpur, India, Dec. 1987, pp. 761-763. (JSEP/AT&T)

[7] W. E. Higgins and D. C. Munson, Jr., " A Hankel transform approach to tomographic image reconstruction," *IEEE Trans. Medical Imaging*, vol. 7, pp. 59-72, Mar. 1988. (Shell Oil Co. JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[8] E. J. Diethorn and D. C. Munson, Jr., "Linear, time-varying system characterization and design of discrete-time bandlimited extrapolation algorithms," *Proc. IEEE Int. Symp. Circuits and Syst.*, Philadelphia, PA, May 4-7, 1987, pp. 839-842. (NSF)

[9] M. Nayeri, D. F. Marshall, and W. K. Jenkins, "Relationships between error surfaces and adaptive architectures in adaptive filters," *Proc. IEEE Int. Symp. Circuits and Syst.*, Philadelphia, PA, May 4-7, 1987, pp. 777-780. (AT&T)

[10] O. Arikan and D. C. Munson, Jr., "An analysis of keystone format spotlight mode synthetic aperture radar," *Proc. Twenty-first Asilomar Conf. Signals, Systems, Computers*, Pacific Grove, CA, Nov. 2-4, 1987, pp. 690-694. (ARO)

WORK UNIT NUMBER 17

TITLE: Parallel VLSI Structures for Sensor Array Processing

SENIOR INVESTIGATORS:

W. K. Jenkins, Research Professor
A. S. Karalamangala (a.k.a. K. S. Arun), Research Assistant Professor
B. W. Wah, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. Aboelaze, Graduate Research Assistant
K. Baumgartner, Graduate Research Assistant
J. C. Chen, Graduate Research Assistant
J. V. Krogmeier, Graduate Research Assistant
G. J. Li, Graduate Research Assistant
D. R. Wagner, Graduate Research Assistant

SCIENTIFIC OBJECTIVE:

The research in this unit is motivated by the observation that modern signal processing cannot be done in real-time on a single sequential processor. To achieve real-time operation, signals generated by sensor-array systems must be processed in a pipelined and/or parallel mode using a large number of fast, dedicated processors working in unison. The objective of this work unit is to develop high-throughput, VLSI structures for the real-time implementation of high-resolution algorithms developed in Unit 16 for sensor-array systems such as synthetic aperture radars, beam-forming sonars, direction finders, and x-ray CAT scanners.

SUMMARY OF RESEARCH:

Research on this unit for the period April 1987 through March 1988 has concentrated on (1) parallel and pipelined VLSI structures for fast digital filtering, (2) systematic design methodologies for mapping algorithms to VLSI structures, and (3) the application of RNS arithmetic to modular VLSI design.

Earlier, we reported the development of new parallel VLSI structures for high-speed FIR and IIR digital filtering [2]. The structures we have studied are block versions of the sequential direct-form, cascade-form, and parallel-form. These block structures produce multiple outputs per multiplication cycle (unlike the classical sequential structures that generate one output in the time required for one multiplication); and are, therefore, capable of achieving throughput rates much higher than the clock rate of the chip. In this reporting period, we have studied the effects of finite wordlength on these structures and have concluded that the finite-precision behavior of the new structures (as measured by conventional means such as the variance of round-off noise, or the sensitivity of the transfer function to coefficients) is superior to sequential structures. However, block structures have other problems (that are unique to them) caused by finite wordlengths. Stability of the realization can become a problem when the parameters are quantized. Moreover, the overall system might behave as a time-varying system as a result of coefficient quantization. We have developed a new block structure that is guaranteed to be time-invariant and stable even in the presence of coefficient quantization errors [3]. We are currently working on schemes to

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

incorporate pipelined coefficient multipliers in the block structures and thus further increase throughput rates [4].

During the past year, our research on systematic design methodologies for mapping algorithms to structures has focussed on three related issues: (a) complexity of layouts in VLSI circuits, (b) design of buffers for macropipelines of systolic arrays, and (c) design of systolic arrays for evaluating dynamic programming algorithms. We have examined the complexities in volume and maximum wire length of mapping circuits represented as undirected graphs to three-dimensional VLSI systems [6, 16]. Tighter bounds than those previously known were obtained for various families of graphs in both the one-active-layer and the unrestricted layouts. A cost model was also developed to optimize the cost of implementation with respect to the third dimension. In the design of a macropipeline of systolic arrays, one major problem is the conversion of outputs of one systolic array in one given format to inputs with a possibly different format to be fed to another systolic array in the macropipeline. A common memory is a potential bottleneck and may limit the number of systolic arrays that can be connected together. We have studied designs of buffers to convert data from one format to another [5]. The maximum number of buffers was determined by a dynamic programming algorithm with $O(n^2)$ computational complexity, where n is the problem size. A general-purpose convertor to convert data from any distribution to any other from a subset of the possible data distributions was also proposed. Buffer designs for a macropipeline to perform feature extraction and pattern classification were used to exemplify the design process. In the design of systolic arrays for problems formulated in dynamic programming, we have classified these problems as monadic-serial, polyadic-serial, monadic-nonserial, and polyadic-nonserial [7]. Problems in serial formulations can be implemented easily in systolic arrays; however, nonserial problems may have to be transformed into a serial one before an efficient implementation can be found. A monadic-serial dynamic programming problem can be solved as the search of an optimal path in a multistage graph and can be computed as a string of matrix multiplications. Three efficient systolic-array designs were presented. A polyadic-serial dynamic programming problem can be solved by either a divide-and-conquer algorithm or the search of optimal solutions in a serial AND OR graph. We have evaluated the asymptotically optimal architecture for divide-and-conquer algorithms and have developed efficient methods of mapping a regular AND/OR graph into systolic arrays. Cases were studied for transforming a problem in a nonserial formulation into a serial one.

We have continued to study the application of RNS arithmetic to designing VLSI modules that can be used for high-resolution sensor array processing [8]. It was discovered that an interesting trade-off between speed and hardware complexity (i.e., silicon area) can be achieved with an RNS digital-serial scheme that has been called a serial-by-modulus (SBM) architecture. With this scheme the residue digits $x_1, x_2, \ldots, x_L$ are processed sequentially one after the other, but the processing of each residue digit is bit-parallel. Roughly, the SBM architecture operates L times slower than a fully bit-parallel architecture, but the required silicon area is reduced by a factor of L. If the moduli are each b-bit integers so that there are b parallel bit lines through the entire processor, then roughly the SBM architecture will operate b times faster than a fully bit-serial architecture, while requiring b times the silicon area. SBM represents a compromise between the low speed of bit-serial arithmetic and the high cost of bit-parallel arithmetic. In [10] and [17], the theory of processor design based on SBM-RNS arithmetic was developed. In particular, standard cell design was proposed and the design of a mixed radix convertor with SBM-RNS arithmetic was presented. It is anticipated that although SBM circuits will be slower than fully parallel circuits, they will be more amenable to testing and fault tolerant design. We intend to continue our investigation of these new VLSI structures.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] W. K. Jenkins and J. V. Krogmeier. "The design of dual-mode complex signal processors based on quadratic modular number codes." *IEEE Trans. on Circuits and Syst.*, Special Issue on Complex Signal Processing. CAS vol. 34, no. 4, pp. 354-364, Apr. 1987. (ARO/NSF/JSEP)

[2] M. Aboelaze and B. W. Wah. "Complexities of layouts in three-dimensional VLSI circuits." *Proc. Int. Symp. on Circuits and Systems.* Philadelphia, PA, May 1987, pp. 543-546 (invited). (JSEP)

[3] W. K. Jenkins and S. F. Lao. "The design of an RNS digital filter module using the IBM MVI-SA VLSI design system." *Proc. Int. Symp. on Circuits and Systems.* Philadelphia, PA, May 1987, pp. 122-126 (invited). (JSEP/NSF)

[4] W K. Jenkins and S. F. Lao. "The design of an integrated RNS digital filter module based on serial-by-modulus residue arithmetic." *Proc. 1987 Int. Conf. on Signals, Systems, and Computers.* Port Chester, NY, Oct. 1987, pp. 634-638. (JSEP/ARO)

[5] W. K. Jenkins and J. T. Chen. "New architectures for VLSI digital signal processors using serial-by-modulus RNS arithmetic" *Proc. 21st Asilomar Conf. on Signals, Systems, and Computers.* Pacific Grove, CA, Nov. 1987 (invited). (JSEP/ARO)

[6] B. W. Wah, M. Aboelaze, and W.-J. Shang. "Systematic design of buffers in macropipelines of systolic arrays." *J. Parallel and Dist. Computing.* vol. 5, pp. 1-25, 1988. (JSEP)

[7] B. W. Wah and G.-J. Li. "Systolic processing for dynamic programming problems." *Circuits, Systems, and Signal Processing,* vol. 7, no. 2, pp. 119-149, 1988. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[8] B. W. Wah and G.-J. Li. "A survey of special purpose architectures for artificial intelligence." in *Parallel Computation and Computers for Artificial Intelligence.* J. S. Kowalik, Ed. Kluwer, 1987, pp. 263-291. (NSF)

[9] J. A. B. Fortes and B. W. Wah. "Guest-editors' introduction: systolic arrays: from concepts to implementation." *Computer,* vol. 20, no. 7, July 1987. (NSF/ONR).

[10] K. M. Baumgartner and B. W. Wah. "Window protocols for load balancing in a local computer system with a multiaccess bus." *Proc. Int. Conf. on Parallel Processing.* St. Charles, IL, Aug. 1987, pp. 851-858. (NSF).

[11] W. K. Jenkins and E. J. Altman. "Self-checking properties of residue number error checkers based on mixed radix conversion." *IEEE Trans. on Circuits and Syst.,* vol. CAD-35, no. 2, pp. 159-167, Feb. 1988. (ARO NSF)

[12] J. A. B. Fortes, K. S. Fu, and B. W. Wah, "Systematic approaches to the design of algorithmically specified systolic arrays," in *Computer Architecture: Concepts and Systems*, V. M. Milutinovic, Ed. Elsevier, 1988. (NSF)

[13] B. W. Wah and G.-J. Li, "Design issues of multiprocessor systems for artificial intelligence applications," in *Scientific Supercomputers and Artificial Intelligence Machines*, K. Hwang and D. DeGroot, Eds. McGraw-Hill, 1988. (NASA)

[14] B. W. Wah and G. J. Li, "A survey on the design of multiprocessing systems for artificial intelligence applications," *IEEE Trans. Syst., Man, and Cybernetics*, 1988 (to appear). (NASA)

REFERENCES:

[15] K. S. Arun and D. R. Wagner, "A study of parallel and pipelined VLSI structures for fast digital filtering," CSL Technical Report, Coordinated Science Lab., University of Illinois at Urbana-Champaign, 1988 (in preparation). (JSEP)

[16] B. W. Wah, "Guest editor's introduction: New computers for artificial intelligence processing," *Computer*, vol. 20, no. 1, pp. 10-15, Jan. 1987. (NSF).

WORK UNIT NUMBER 18

TITLE: Adaptive Algorithms for Identification, Filtering, Control, and Signal Processing

SENIOR INVESTIGATORS:

P. V. Kokotovic, Research Professor
P. R. Kumar, Research Professor
J. V. Medanic, Research Professor
W. R. Perkins, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

R. Gerth, Research Assistant
S.-F. Lin, Research Assistant
J. Perkins, Research Assistant
R. Ramaker, Research Assistant
D. Schoenwald, Research Assistant

SCIENTIFIC OBJECTIVE:

Our group has been and is in the forefront of research on a wide array of problems in adaptive systems; some of the problem formulations, methods and results which have originated in our research group have been accepted by leading researchers worldwide and are being experimentally tested. This accumulated experience and knowledge in the field puts us in the best position to address the underlying fundamental issues and to develop a theory for adaptive algorithms which operate in partially modeled environments.

Our approach embodies the philosophy that adaptive systems, be they adaptive filters, estimators and controllers, or diagnostic and tuning software for automatic quality control and maintenance, are logical on-line extensions of well-tested off-line algorithms and, as such, should inherit their robustness properties. To achieve this level of realism, we allow our convergence and stability conditions to be signal-dependent and guarantee them in the domain of interest, rather than globally. This closes the gap separating the realistic conditions from the mathematically appealing global results derived under unrealistic and unverifiable modeling assumptions. The robustness properties guaranteed by our approach will compensate for the loss of fictitious globality.

Toward this general objective, one of our goals in this research project is to investigate the key question of whether there are *self-tuning* algorithms with the important feature that the algorithm will automatically tune itself to a correct regulator for a given unknown system. Earlier versions of such algorithms have had a big impact on the practical control of a certain class of systems and are also beginning to be fabricated on chips and installed in industrial plants, vehicles, ships, and other communication and control equipment.

Our second goal is to examine the behavior of the algorithms in a variety of environments where precise modeling assumptions are violated. Following the first encouraging results, one of our objectives is to develop a methodology to design algorithms that are capable of using the available *a priori* information about systems to be identified, estimated and/or controlled, and to avoid limitations imposed by preselected parameterizations. We instead plan to use existing physical parameters and thus enhance not only robustness but also serviceability of the control instrumentation.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

SUMMARY OF RESEARCH:

A major objective in this research unit is to develop a design methodology for robust adaptive control and estimation. To enhance robustness of these algorithms in incompletely known or varying environments. it is important to make them capable of using the available *a priori* information and to evaluate bounds for their robust operation.

A significant accomplishment in this direction is our result on robust adaptive regulation of nonlinear systems with unmodeled dynamics. This result combines recent advances in the three hitherto separate areas: feedback linearization, adaptive control. and asymptotic analysis. A novel use of these techniques has led to a guaranteed region of robust operation in the presence of both parametric and dynamic uncertainties. Moreover. the analytical bounds are in the form which allows a robustness comparison of adaptive and nonadaptive control strategies. A semiquantitative trade-off is established showing when an adaptive approach is superior to a nonadaptive design.

We have studied the issue of designing adaptive controllers which combine good performance along with robustness. Specifically, for linear stochastic systems we seek performance as measured by a minimum variance criterion that is optimal under ideal conditions: i.e., when the plant is of the order assumed. is of minimum phase. the delay is as assumed. and the noise polynomial satisfies a positive real condition. Moreover. we seek stability of the adaptively controlled system when these assumptions are violated to some degree. We have been successful in exhibiting an adaptive control algorithm that achieves optimal performance under ideal conditions as above and also

i)   maintains stability when the positive realness assumption is dropped.

ii)   maintains stability in a graph topological neighborhoods (of computable size) of ideal systems. and

iii) maintains stability in a similar neighborhood when the adaptive controller is used in a non-vanishing gain mode.

Work has also continued on the design of dynamic controllers (filters) using the projective controls methodology. This method is based on an extension of the basic linear-quadratic optimization approach of control system theory. Emphasis has been placed on incorporating **frequency weighting** into the optimized index to provide increased robustness properties in the final design. A parameterized design approach has resulted that yields good performance in the presence of unmodeled dynamics.

Robust-adaptive control using low-order controllers. without on-line plant identification. is being explored and preliminary results for a one-link flexible joint robot have been obtained. The approach describes the nonlinear robust arm by multiple linear models corresponding to multiple operating points and seeks a low-order controller using a three-stage procedure: (i) a class of parameterized controllers is determined for a nominal operating point using the projective controls approach: (ii) a robust controller is determined for the entire range of operation characterized by linear models at multiple operating points by using Hankel singular values-based approach to select the free controller parameters to achieve robust performance; and (iii) an adaptive controller is obtained by allowing critical free controller parameters. identified in the robust design phase. to adapt to improve system performance. A decentraliz.d control strategy with robust. or adaptive. controllers will be sought using the decentralized projective controls approach to obtain the collection of parameterized low-order controllers.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] D. Schoenwald, P. Kokotovic, and S. Dasgupta, "A boundedness conjecture for locally unstable adaptive estimation of non-SPR transfer functions," *Proc. Conf. on Inform. Sci. and Syst.*, Johns Hopkins University, Baltimore, MD, Mar. 1987. (NSF/JSEP).

[2] B. D. Riedle and P. V. Kokotovic, "Stability of slow adaptation for non-SPR systems with disturbances," *IEEE Trans. Automat. Contr.*, vol. AC-32, no. 5, pp. 451-454, May 1987. (NSF/JSEP)

[3] J. V. Medanic, H. S. Tharp, and W. R. Perkins, "Structural decomposition approach to design of robust decentralized controllers for a large scale systems," *Proc. 1987 American Contr. Conf.*, pp. 976-981, June 1987. (JSEP)

[4] P. R. Kumar and L. Praly, "Self tuning trackers, *SIAM J. Contr. and Optim.*, vol. 24, no. 4, pp. 1053-1071, July 1987. (JSEP/NSF)

[5] Z. Uskokovic and J. Medanic, "New parameterization of decentralized dynamic regulators designed by projective controls," *Proc. 26th IEEE Conf. on Dec. and Contr.*, Los Angeles, CA, Dec. 1987, pp. 2289-2294. (JSEP)

[6] H. S. Tharp, J. Medanic, and W. R. Perkins, "Eigenstructure retention with frequency weighting," *Proc. 26th IEEE Conf. on Dec. and Contr.*, Los Angeles, CA, 1987, pp. 1720-1725. (JSEP)

[7] B. D. O. Anderson and P. V. Kokotovic, "Optimal control problems over large time intervals," *Automatica*, vol. 23, no. 3, pp. 355-363, 1987. (JSEP)

[8] R. Marino and P. V. Kokotovic, "A geometric approach to nonlinear singularly perturbed control systems," *Automatica*, vol. 24, no. 1, pp. 31-41, 1988. (JSEP)

[9] P. R. Kumar, "Recent advances in the theory of stochastic adaptive control," in *Stochastic Differential Systems, Stochastic Control Theory and Applications*, vol. 10, IMA Volumes in Mathematics and Its Applications, W. Fleming and P. L. Lions, Eds. New York: Springer-Verlag, 1988, pp. 241-254. (JSEP/NSF)

[10] D. K. Lindner and W. R. Perkins, "The generalized Hessenberg representation and near aggregation," *Automatica*, Mar. 1988 (to appear). (JSEP)

[11] J. Medanic, H. S. Tharp, and W. R. Perkins, "Pole placement by performance criterion modification," to appear in *IEEE Trans. on Automatic Control*, 1988. (JSEP)

[12] H. Tharp, J. Medanic, and W. R. Perkins, "Parameterization of frequency weighting for a two-stage linear quadratic regulator based design," *Automatica*, May 1988 (to appear). (JSEP)

WORK UNIT NUMBER 19

TITLE: Distributed and Decentralized Systems

SENIOR INVESTIGATORS:

T. Basar. Research Professor
P. R. Kumar, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

R. Bansal. Research Assistant
D. Connors. Research Assistant
J Perkins. Research Assistant
M Shor. Research Assistant
R. Srikant. Research Assistant
R. Veillette. Research Assistant

SCIENTIFIC OBJECTIVE:

Attempts to harness several newly emerging technologies. which lead naturally to large-scale. computer-controlled systems. have given rise to a significant interest in the underlying field of distributed and decentralized systems. Most of these systems incorporate task decomposition. multilevel coordination and control. and distributed estimation and computation. Some of them diverge from classical systems in that the basic phenomena governing them are event-driven and discrete. Examples of such event-driven systems are many and include automated VLSI production systems for making printed circuit boards or fabricating wafers in large volumes in flexible electronic assembly systems. communication networks for data transmission. and interconnected computer systems. They require descriptions in terms of discrete quantities such as the number of PC boards to be retested. or other dynamic. logical and linguistic variables; and they operate as event-driven. asynchronous. largely nondeterministic processes, and hence must be analyzed as such. The basic goal in studying such large. complex. and. typically. distributed and decentralized systems is. firstly. to design them for efficiency and then to control and coordinate them to attain this efficiency. Important issues that arise in the modeling. control. and coordination of such systems are information flow. learning. aggregation. time scale separation. decentralized estimation. and distributed computation. The principal objective of this research unit is to study such issues in order to enhance our understanding of the behavior and control of large-scale. computer-controlled systems in a distributed network. under uncertainty and decentralization.

SUMMARY OF RESEARCH:

We have continued our study of distributed systems under decentralized nonclassical information from the points of view of optimum strategy design, performance evaluation. and computational algorithms. Such systems arise in practice when the controller memory is limited. requiring each action to depend on the most recently available information. or when the physical system is of large size and involves various subsystems that are individually responsible for specific control actions and there is a delay in the transmission of measurement and control information from one subsystem to another. In general. neither analytical tools nor numerical methods are known to exist for such problems. During this past year we have shown that indirect techniques (based on

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

bounds from information theory or constructed from related zero-sum games) can be used to obtain the optimal solution for some classes of such problems, defined on both finite and infinite horizons. For other classes of problems, we have made performance evaluations using nonlinear strategies for basically linear-quadratic problems. We have also considered the situations when the communication medium has unknown statistical description and have solved for worst case performances under a variety of fidelity criteria. On the algorithmic side, we have studied the design of decentralized asynchronous algorithms for on-line computation of optimum controllers, under minimum information-sharing among the subsystems of a distributed system.

We have made some fundamental advances in the control of large discrete-event systems, such as flexible manufacturing/assembly/disassembly systems or systems for VLSI wafer fabrication. Such systems typically involve a large number of machines, interconnected by a transportation network, that are required to produce a specified mix of part-types at a desired rate. A major problem in running such automated systems is that of "scheduling," where decisions must be made at each point in time on what part-type a given machine is to work on. Classical approaches have treated this problem as an optimization problem, but this approach quickly becomes intractable due to the large number of decisions involved. We have developed a new "closed-loop" scheduling approach that provides real-time scheduling algorithms that can be implemented in a distributed fashion at the various machines based only on local information possessed by the machine regarding the contents of its own buffers. This scheduling algorithm guarantees the stability of the overall manufacturing system in the sense that all buffers are guaranteed to remain bounded and the overall production rate of the entire manufacturing system equals the desired production rate for every part-type.

We have also investigated the simulated annealing algorithm for global optimization, which is a Monte-Carlo method that is essentially a modification of standard descent algorithms so as to allow for occasional uphill moves. This probabilistic modification is introduced to allow the algorithm to escape from local minima and reach a global minimum. A critical question here is the rate at which the probabilistic modification should be reduced to zero, i.e., the rate of "cooling" in order to guarantee that such a global minimum is hit with probability one. We have developed a new theory for Markov processes and determined necessary and sufficient conditions to guarantee that the algorithm reaches a global minimum. This new theory allows the study of asymptotic behavior of a class of Markov processes where the transition probabilities are proportional to powers of a diminishing time varying parameter, i.e., singularly perturbed Markov chains with vanishing small parameter.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] R. Bansal and T. Basar, "Solutions to a class of linear-quadratic (LQG) stochastic team problems with nonclassical information," *Syst. and Contr. Lett.*, vol. 9, pp. 125-130, June 1987. (JSEP AFOSR)

[2] S. L. and T. Basar, "Asymptotic agreement and convergence of asynchronous algorithms," *IEEE Trans. Automat. Contr.*, vol. AC-32, no. 7, pp. 612-618, July 1987. (JSEP/AFOSR)

[3] R. Bansal and T. Basar, "Communication games with partially soft power constraints," to appear in *J. Optimization Theory and Applications*, 1988-89. (JSEP/AFOSR)

[4] T. U. Basar and T. Basar. "Optimum linear causal coding schemes for stochastic processes in the presence of correlated jamming," to appear in *IEEE Trans. Inform. Theory*, 1988. (JSEP)

[5] T. Basar and S. Li. "Distributed computation of Nash equilibria in linear-quadratic stochastic differential games," to appear in *SIAM J. Contr. and Optimization*, 1989. (JSEP/AFOSR)

[6] T. Basar. "Solutions to a class of nonstandard stochastic control problems with active learning," to appear in *IEEE Trans. Automat. Contr.*, 1988/89. (JSEP/AFOSR)

[7] T. Bielecki and P. R. Kumar. "Optimality of zero inventory policies for unreliable manufacturing systems," to appear in *Operations Research*. (JSEP/USARO)

[8] D. P. Connors and P. R. Kumar. "Balance of recurrence order in time-inhomogeneous Markov chains with application to simulated annealing," to appear in *Probability in the Engineering and Information Sciences*. Apr. 1988. (JSEP/USARO)

[9] T. Bielecki and P. R. Kumar. "Optimality of zero inventory policies for unreliable manufacturing systems," to appear in *Operations Research*. (JSEP/USARO)

[10] D. P. Connors and P. R. Kumar. "Balance of recurrence order in time-inhomogeneous Markov chains with application to simulated annealing," to appear in *Probability in the Eng. and Inform. Sci.*, Apr. 1988. (JSEP/USARO)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[11] S. Li and T. Basar. "Distributed algorithms for the computation of noncooperative equilibria," *Automatica*. vol. 23. no. 4. pp. 523-533. July 1987. (AFOSR)

[12] R. Bansal and T. Basar. "Stochastic teams with nonclassical information revisited: When is an affine law optimal?" *IEEE Trans. Automat. Contr.*, vol. AC-32, no. 6, pp. 125-130, June 1987. (AFOSR)

[13] T. Basar. "Relaxation techniques and asynchronous algorithms for on-line computation of noncooperative equilibria." *J. Economic Dynamics and Contr.*, vol. 11, no. 1, 1988. (AFOSR)

WORK UNIT NUMBER 20

TITLE: Robust Feedback Control of Nonlinear Systems

SENIOR INVESTIGATORS:

P. V. Kokotovic, Research Professor

K. Poolla, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

K. Beuscher, Research Assistant

R. Gerth, Research Assistant

A. S. Hodel, Research Assistant

K. Otto, Research Assistant

M. Shor, Research Assistant

T. Ting, Research Assistant

SCIENTIFIC OBJECTIVE:

For physical devices running the gamut from rotating machinery to opto-electronic laser positioning systems, nonlinearities constitute an essential part of any reasonable model. Revolutionary developments in microelectronics, coupled with recent breakthroughs in the understanding of the structural properties of nonlinear dynamic systems, open up new possibilities for the synthesis and implementation of feedback controllers in order to meet the steadily rising needs for higher performance and increased efficiency. However, even the most powerful analytical tools that are available today, such as exact linearization via feedback, nonlinear input-output characterizations, and geometric conditions for noninteracting control and disturbance rejection, still require that exact nonlinear models be available. This is in direct conflict with the fact that the mere presence of nonlinearities makes accurate modeling and identification difficult. Consequently, controllers based upon the currently available theory could be highly unreliable.

To remedy this situation, some fundamentally new lines of research are needed for the design of realistic robust controllers for nonlinear systems. Driven by this need, our research program has two key objectives. The first is to develop a fundamentally new *geometric-asymptotic* approach for the synthesis of robust nonlinear controllers: this approach will combine the advantages of exact geometric notions with estimates of sensitivity and robustness obtained from an asymptotic analysis and will build upon synergisms of two types of expertise available within our research team. The second objective is to deal with circumstances where desired levels of performance *cannot* be achieved by feedback; it is then necessary to restructure the nonlinear systems. Our objective here is to develop a methodology for reconfiguring nonlinear systems for robustness enhancement.

SUMMARY OF RESEARCH:

Over the past year, we have made remarkable progress in the study of robust feedback control for nonlinear discrete-time systems. In particular, we have developed an entirely new approach to adaptive robust control for such systems. The essential idea involved is to fragment modeling uncertainty in a physical plant into "small" families of plant models for which robust

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

LTI controllers can readily be designed. We refer to these smaller families as "operating points." We then adapt between these robust controllers K_i by implementing a convex combination of the K_i, the parameters of which are tuned based on error measurements. One of the most endearing features of this approach is that the particular methodology used to design the individual controllers K_i is not prescribed. One could use H^∞-optimal control or LQG/LTR methods. We have been able to construct a tuning algorithm for these adaptive robust controllers that yields input-output stability in the sense of Desoer. This stability notion is much stronger than that of state or Lyapunov stability and permits us to treat disturbance rejection problems for nonlinear plants.

Using this approach we have been able to determine an **absolute, computable, tight** band on the ability to adaptively stabilize a plant against unmodeled dynamics. This result, in our opinion, represents a definitive answer to the question of determining the extent to which unmodeled dynamics jeopardizes feedback system stability.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] K. Khorasani and P. V. Kokotovic, "Feedback linearization of a flexible manipulator near its rigid body," *Syst and Contr Lett.*, vol. 6, no. 3, pp. 187-192, 1987. (JSEP/Illinois Office of Advanced Engineering Study)

[2] J. R. Winkelman, S. T. Hung, and P. V. Kokotovic, "Self-tuning of conflicting oscillatory modes in a power system stabilizer," *Proc Fifth Yale Wkshp. on Applications of Adaptive Systems Theory*. New Haven, CT, May 1987, pp. 31-36. (NSF/JSEP)

[3] T. Ting and K. Poolla, "Suboptimal solutions for multi-disk problems," *Proc. American Control Conf.*. Minneapolis. MN, June 1987. (JSEP)

[4] D. G. Taylor and P. V. Kokotovic, "Reduced order adaptive design for linearizable systems," *Proc Wkshp on Current Trends in Adaptive Control*. Cavtat, Yugoslavia, July 1987. (NSF JSEP)

[5] J. R. Winkelman, S. T. Hung, and P. V. Kokotovic, "Self-tuning of conflicting oscillatory modes: A case study," *Proc. 10th IFAC World Congress vol. 2*. Munich, W. Germany, July 1987, pp. 108-113. (NSF JSEP)

[6] S. Cusumano, K. Poolla, and T. Ting, "On robust stabilization problems for plants with block-structured modeling uncertainty," *Proc. 26th IEEE Conf on Dec. and Contr.*, Los Angeles, CA, Dec. 1987, pp. 423-428. (JSEP)

[7] T. Ting and K. Poolla, "Upper bounds and approximate solutions for multi-disk problems," *IEEE Trans. Automat Contr.* (to appear). (JSEP)

[8] T. Ting, S. Cusumano, and K. Poolla, "On robust stabilization problems with additive block-structured uncertainty," *IEEE Trans. Automat. Contr.* (to appear). (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[9]   P. V. Kokotovic and P. W. Sauer. "Integral manifold as a tool for reduced-order modeling in nonlinear systems: A synchronous machine case study." *Proc. 26th IEEE Conf. on Dec. and Contr.*, Los Angeles, CA, Dec. 1987, pp. 873-878.

[10] M. W. Spong, K. Khorasani, and P. V. Kokotovic, "An integral manifold approach to the feedback control of flexible joint robots," *IEEE J. Robotics and Automation*, vol. RA-3, no. 4, pp. 291-300, 1987. (NSF)

WORK UNIT NUMBER 21

TITLE: Multiple-Terminal Digital Communication Systems

SENIOR INVESTIGATORS:

B. Hajek. Research Professor
M. B. Pursley. Research Professor
D. V. Sarwate. Research Professor

SCIENTIFIC PERSONNEL A O TITLES:

K. K. Chawla, Research Assistant
M. Chen. Research Assistant
C. D. Frank, Research Assistant
A. Krishna. Research Assistant
U. Madhow, Research Assistant
B. Radosavljevic. Research Assistant
S. D. Sandberg. Research Assistant

SCIENTIFIC OBJECTIVES:

Problems involving the interaction of the elements of a multiple-user communication network are among the most important and most challenging problems in electronic communications. The performance of a communication network depends in a very complex way on the routing algorithm. flow control mechanism, acknowledgment procedure, channel access protocol, error-control code. signaling scheme. receiver processing method, and synchronization technique employed in the lower three layers (network layer, data link layer, and physical layer) of the ISO-layered model for the network. The objective of our research in multiple-terminal digital communications is to gain a better understanding of the interplay between these elements. Our research will focus on the issues that arise in mobile radio networks. particularly spread-spectrum radio networks, that must operate in hostile environments that include jamming and fading. This imposes additional requirements on the network in terms of robustness and survivability that will be accounted for in our research.

One of the objectives of our research is to develop new signaling methods and receiver processing techniques that will exploit the implicit and explicit redundancy that is present in the signals and messages. Such redundancy exists in the physical layer (diversity transmission. multipath signals. and modulation), the data link layer (error-control coding), and the network layer (redundant packets and messages). We are particularly interested in the efficient use of implicit and explicit diversity in spread-spectrum radio transmissions to improve communication performance under stressed conditions (e.g., jamming or heavy network traffic). Another objective is to develop network protocols that are compatible with and take advantage of the features of spread-spectrum modulation. Of particular interest are algorithms for distributed scheduling of transmissions. A third objective is to examine the synchronization problem for spread-spectrum radios. Efficient network operation requires fast acquisition of the spread-spectrum signals. Moreover. the acquisition and synchronization systems must be able to operate in the presence of multiple transmissions. jamming. and fading to be of any use in a military communications network.

SUMMARY OF RESEARCH:

Adaptive Coding for Meteor Burst Communication Links

The trade-off between error rates and transmission time was identified in our proposal as a key issue in the design and development of meteor burst communication systems and networks. Because we feel that adaptive error-control coding can play a very important role in this trade-off, we have conducted an extensive investigation of adaptive coding for meteor burst communication links. Because of the nature of the meteor burst channel, it is clear that higher throughput and lower error rates can be achieved by adapting the code to the channel.

There are two approaches to adaptive coding in this context: adaptive selection of a fixed-rate code from one trail to the next and adaptive variable-rate coding. Even if the code rate is fixed throughout the lifetime of a meteor trail, the fact that some trails decay faster than others should be accounted for in the selection of the code rate. The simplest method uses a code of fixed rate throughout the life of the trail but varies the code rate from one trail to the next, which is inter-trail adaptation using fixed-rate codes. Use of this type of adaptation requires estimation of the decay rate for each meteor trail.

There is also an advantage in varying the rate of the error-correcting code during the lifetime of a meteor trail. Typically, the reflected signal is very strong when the trail is first formed so that a code with a small amount of redundancy is sufficient for correcting the few errors that occur. Such codes will provide high throughput in the early phases of the meteor trail. As the trail expands and breaks up, however, the reflected power is reduced, so that it is necessary to correct a larger number of errors. As a result, more redundancy must be used during the latter phases of the trail's existence. To some extent, the sequence of rates for the variable-rate code can be selected at the beginning of the trail by estimating the signal strength and the decay rate.

The potential improvement for inter-trail adaptation using fixed-rate and variable-rate Reed-Solomon coding on the meteor burst channel was investigated in [30]. The model used in [30] assumes exponential decay in the received power as a function of time. The approach used for adaptation in this paper is based on a selection of the code rates for a packet to send a fixed number of information symbols. The rates selected depend on the estimates of the received power and decay rate obtained during the initial part of the packet.

An optimal algorithm is given in [30] for selecting the set of code rates to be used to transmit a fixed number of information symbols on a given meteor trail. In comparisons of variable-rate codes and fixed-rate codes for inter-trail adaptation, the former were found to give performance improvements in the range of 0.5 to 1.0 dB over the latter. We found that the selection of the rates for the variable-rate code does not depend very strongly on the initial value of E_b/N_0 for the trail; it does, however, depend critically on the decay rate.

More general code-rate adaptation can be implemented if the transmitting terminal continually monitors the signal strength at the receiver and adapts the code rate throughout the packet. This can be based on power measurements on the return channel or on feedback information from the receiver. Both of these require full duplex operation. The former requires the link to be symmetrical and bidirectional, while the latter only requires the link to be bidirectional. The method developed in [30] can be applied at several stages during the decay of the meteor trail to give continual adaptation throughout the packet. A trade-off exists between the performance of the resulting variable-rate code and the amount of computation required by the algorithm. More frequent application of the algorithm during the transmission of the packet requires more computation but also gives a code that is closer to the optimum.

Synchronization of Direct-Sequence Spread-Spectrum Systems

We have studied the acquisition of synchronization in a direct-sequence spread-spectrum system via a sequential search technique with adaptive time-varying thresholds and varying dwell times. This scheme allows for false hypotheses about the signal epoch to be discarded relatively

quickly and still achieves the same miss probability as schemes with fixed thresholds. Critical to the operation of this scheme is a uniform bound on the aperiodic autocorrelation of a PN sequence that allows false hypotheses to be rapidly discarded. We have also obtained considerable experimental evidence that our bound is quite weak and that our estimates of the time required to acquire synchronization are rather pessimistic; actual system performance should be much better than our estimates.

We have studied parallel acquisition techniques that consider multiple hypotheses about the signal epoch in order to reduce the acquisition time. In the case of a PN sequence code of period N, one correlator with an integration time of one chip can be used to compute N single chip correlations. The decision statistics are then just the Hadamard transform of these correlations. If a complete period of the PN sequence is available, this scheme can be viewed in the context of orthogonal signalling and the well-known results on orthogonal signalling used to obtain results on system performance. However, we are interested in the effectiveness of this approach when fewer than N chip correlations are available. as would be the case when the PN sequence has a very large period and the delay in computing all N chip correlations is prohibitively large. This problem is complicated by the fact that when the Hadamard transform of a partial period is computed, the decision statistics are no longer independent random variables. The results on nonorthogonal signalling are, of course, applicable but not particularly useful in that the bounds obtained on system performance are rather weak. We have obtained some simple and better results by more detailed considerations of the structure of the PN sequence.

Graph Algorithms for Independent Sets

Significant progress was made during the past year on the average case performance analysis of simple greedy algorithms for finding maximum cardinality independent sets in graphs and for other problems. An independent set of an undirected graph is a set S of nodes such that no two nodes in S are neighbors of each other. The problem arises in many contexts, for example, independent sets in the hearing graph of a radio network correspond to sets of stations that can simultaneously transmitted and, in certain iterative concurrent algorithms, independent sets in problem-related graphs correspond to sets of variables that can be simultaneously updated. Since the problem is widely believed to be difficult (not just because it is NP-hard), it is desirable to use fast, though approximate, algorithms. For example, one heuristic is to search for minimum degree nodes and add those to the independent set sought. We analyzed the average performance of this algorithm for large random graphs by observing that its behavior tends to be predictable and is, moreover, described by certain differential equations when applied to large random graphs. Numerical analysis of the differential equations suggests that the algorithm is, with high probability, optimal for large random graphs with mean node degree less than $e = 2.718\dots$. We have found that our method of analysis is useful for studying the average case behavior of more complicated algorithms for scheduling transmissions in a spread spectrum packet radio network as well.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] A. C. Blumer. "Minimax universal noiseless coding for unifilar and Markov sources." *IEEE Trans. Inform. Theory.* vol. IT-33, pp. 925-930, Nov. 1987. (JSEP/NSF)

[2] J. S. Lennert and M. B. Pursley. "Multipath diversity reception of spread-spectrum multiple-access communications." *IEEE Trans. Commun..* vol. COM-35, pp. 1189-1198, Nov. 1987. (DARPA JSEP)

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

[3] P. K. Enge and D. V. Sarwate, "Spread spectrum multiple-access performance of orthogonal codes: Linear receivers," *IEEE Trans. Commun.*, vol. COM-35, pp. 1309-1319, Dec. 1987. (JSEP)

[4] C. M. Keller and M. B. Pursley, "Clipped diversity combining for channels with partial-band interference -- Part I: Clipped-linear combining," *IEEE Trans. Commun.*, vol. COM-35, pp. 1320-1328, Dec. 1987. (JSEP)

[5] B. Hajek, "Average case analysis of greedy algorithms for Kelly's triangle problem and the independent set problem," (Invited Paper) *Proc. IEEE Conf. on Dec. and Contr.*, Los Angeles, CA, Dec. 9-11, 1987), pp. 1455-1460. (JSEP)

[6] P. K. Enge and D. V. Sarwate, "Spread-spectrum multiple-access performance of orthogonal codes: Impulsive noise," *IEEE Trans. Commun.*, vol. 36, pp. 98-107, Jan. 1988. (JSEP)

[7] F. D. Garber and M. B. Pursley, "Performance of differentially coherent digital communications over frequency-selective fading channels," *IEEE Trans. Commun.*, vol. 36, pp. 21-31, Jan. 1988. (JSEP)

[8] B. Hajek and G. Sasaki, "Link scheduling in polynomial time," accepted for publication in *IEEE Trans. Inform. Theory*, vol. IT-34, Nov. 1988. JSEP)

[9] D. V. Sarwate, "Computation of cyclic redundancy checks via table look-up," accepted for publication in *Commun. of the ACM*, 1988. (JSEP)

[10] J. C. Kieffer, "Sturmian minimal systems associated with the iterates of certain functions on an interval," to appear in *Springer-Verlag Lecture Notes in Mathematics: Proc. of the Special Year on Dynamical Systems, University of Maryland, 1986*, New York: Springer Verlag, 1987. (NSF, JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[11] B. Hajek and R. Cruz, "Delay and routing in interconnection networks," in *Flow Control of Congested Networks*, A. Odoni and G. Szego, Eds., New York: Springer-Verlag, pp. 235-242, 1987. (NSF/AT&T)

[12] B. Hajek, "Multiple access and a conjectured generalized permanent inequality," in *Fundamental Problems in Communication and Computation*, T. M. Cover and B. Gopinath, Eds. New York: Springer-Verlag, pp. 127-129, 1987.

[13] B. Hajek, "Cooling schedules for simulated annealing," in *Fundamental Problems in Communication and Computation*, T. M. Cover and B. Gopinath. Ed. New York: Springer-Verlag, pp. 147-150, 1987.

[14] B. Hajek, "Ergodic process selection," in *Fundamental Problems in Communication and Computation*, T. M. Cover and B. Gopinath, Ed. New York: Springer-Verlag, pp. 199-203, 1987.

[15] B. Hajek, "Gambler's ruin: A random walk on a simplex," in *Fundamental Problems in Communication and Computation*, T. M. Cover and B. Gopinath. Ed. New York: Springer-Verlag, pp. 204-207, 1987.

[16] A. W. Lam and D. V. Sarwate. "A comparison of two methods for generation of side information in frequency hop spread-spectrum multiaccess communications." *Proc. 1987 Conf. on Inform. Sci. and Syst.*, The Johns Hopkins University, Baltimore, MD, Mar. 25-27, 1987, pp. 426-431. (ARO)

[17] S. D. Sandberg and M. B. Pursley. "Simulation of delay in frequency-hop packet radio networks." *Proc. 1987 Conf. on Inform. Sci. and Syst.*, The Johns Hopkins University, Baltimore, MD, Mar. 25-27, 1987, pp. 137-142. (ARO)

[18] M. B. Pursley. "Tradeoffs between side information and code rate in slow-frequency-hop packet radio networks." *Conf. Record, 1987 IEEE Int. Conf. on Commun.*, Seattle, WA, June 7-10, 1987, vol. 2, pp. 947-952. (ARO)

[19] U. Madhow. "Bounds and asymptotic results for the performance of asynchronous frequency-hop packet radio networks." Report UILU-ENG-87-2236, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, June 1987; also, M. S. thesis, Department of Electrical and Computer Engineering, M. B. Pursley, adviser. (ARO)

[20] R. L. Cruz. "A calculus for network delay and a note on topologies of interconnection networks." Report UILU-ENG-87-2246, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, July 1987; also Ph.D. dissertation, Department of Electrical and Computer Engineering, B. Hajek, adviser. (NSF)

[21] B. Hajek and T. Berger. "A decomposition theorem for binary Markov random fields." *Ann. of Probability*, vol. 15, pp. 1112-1125, July 1987. (NSF)

[22] G. Sasaki. "Optimization by simulated annealing: a time complexity analysis." Report UILU-ENG-87-2261, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, October 1987; also Ph.D. dissertation, Department of Electrical and Computer Engineering, B. Hajek, adviser. (NSF/ONR)

[23] R. L. Cruz and B. Hajek. "Mechanisms for controlling delay in communication networks." (Invited Paper) *Conference Bulletin ORSA-TIMS*, (St. Louis: October 25-27, 1987), p. 85.

[24] B. Hajek. "Locating the maximum of a simple random sequence by sequential search." *IEEE Trans. Inform. Theory*, vol. IT-33, pp. 877-881, Nov. 1987. (ONR/ARO)

[25] G. Sasaki and B. Hajek. "Optimal dynamic routing in single commodity networks by iterative methods." *IEEE Trans. Commun.*, vol. COM-35, pp. 1199-1206, Nov. 1987. (ONR)

[26] A. W. Lam and D. V. Sarwate. "Optimum time-hopping patterns." *IEEE Trans. Commun.*, vol. 36, pp. 380-382, Mar. 1988. (ARO)

[27] G. Sasaki and B. Hajek. "The time complexity of maximum matching by simulated annealing." accepted for publication in *J. Assoc. Comput. Machinery*, 1987. (NSF/ARO)

[28] R. G. Ogier. "Minimum delay routing in continuous-time dynamic networks with piecewise continuous capacities." accepted for publication in *Networks*, 1988. (ONR)

[29] B. Hajek. "Cooling schedules for optimal annealing." accepted for publication in *Math. Oper. Res.*, 1987. (NSF/ONR)

REFERENCE:

[30] M. B. Pursley and S. D. Sandberg. "Adaptive-rate coding for meteor-burst communications." to be presented at MILCOM '88. San Diego. Oct. 1988.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

WORK UNIT NUMBER 22

TITLE: Statistical Signal Processing in Communication Systems

SENIOR INVESTIGATORS:

H. V. Poor, Research Professor
A. R. Barron, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

B. Clarke, Research Assistant
S. Zabin, Research Assistant

SCIENTIFIC OBJECTIVE:

Statistical signal processing functions such as signal detection, estimation, and identification play a key role in the development of effective communications, radar, and sonar systems. For example, advanced statistical methods are emerging as being particularly important in digital communications systems operating in channels corrupted by interference from such phenomena as multiple-access noise, intentional jamming, and impulsive noise sources. Conventional demodulation methods, such as coherent matched filtering, often suffer serious performance degradation when subjected to interference of these types; however, this degradation can frequently be eliminated through the use of more sophisticated signal processing techniques.

A central issue in the design of effective signal processing procedures for systems operating in channels such as those noted above is that of channel identification. Although certain aspects of channel identification have been studied extensively, one area in which there is a pressing need for further research is that of identification of impulsive channels. Natural impulsive phenomena are major noise sources in many types of channels including ELF electromagnetic and under-ice acoustic channels. Moreover, man-made impulsive phenomena are a principal background noise source in the environments in which military radio networks must operate. Thus, since it is well established that impulsive noise can be extremely detrimental to the performance of communications, radar, and sonar systems if not properly suppressed and since impulsive channels often exhibit nonstationary characteristics, the development of effective techniques for identification and tracking of the characteristics of impulsive noise channels is an important problem in the development of systems that can approach the performance limits set by such channels.

The overall objective of this research project is to study the general problems of identification and tracking of impulsive channels. A thorough study of this area is planned, including the development of suitable channel models, the derivation and analysis of optimum batch and recursive nonlinear estimation algorithms for identification tracking, and the application of these algorithms to develop adaptive techniques for the reception of signals passing through impulsive channels. It is anticipated that the results of this study will find application in a broad class of areas including digital communications, sonar, and radar.

SUMMARY OF RESEARCH:

Our research efforts during this reporting period have focused on two principal aspects of the problem of identifying impulsive channels. These are: (1) parameter estimation in canonical statistical/physical models for impulsive channels and (2) probability density estimation for general parametric channel noise models.

Our work in the first of these areas has focused on the Class A Middleton model, which is a physically based model that is known to accurately characterize a wide variety of impulsive phenomena. including under-ice acoustic noise and man-made electromagnetic interference. This model has two basic parameters. A and Γ. that characterize the frequency and severity of the impulses. In this reporting period. we have explored several techniques for estimating these parameters from channel measurements. This work. which is reported in [3,4,18]. has considered both batch and decision-directed recursive algorithms for this purpose. For each type of algorithm. we have found efficient and practical global techniques for estimating these parameters, and we have verified the favorable performance characteristics of these algorithms through extensive simulations.

In the second of these two areas, we have undertaken a theoretical analysis of the rates of convergence of probability density function estimates for situations in which the density function can be assumed to be a member of a smooth parametric family. These convergence rates lead to performance approximations that are applicable to a wide range of stochastic models including. in particular. impulsive noise models. In [17] precise asymptotics are obtained for the cumulative risk of Bayes estimators of density functions in smooth finite dimensional families using an entropy-based loss function. In other research [1] rates of convergence are obtained for maximum likelihood density estimation based on sequences of exponential families of growing dimension.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] A. R. Barron. "The convergence in information of probability density estimators." *Abstracts of Papers: 1988 IEEE Int. Symp. on Inform. Theory*, Kobe. Japan. June 1988 (to appear). (JSEP)

[2] H. V. Poor. "Fine quantization in signal detection and estimation." *IEEE Trans. Inform. Theory*, vol. IT-34, 1988 (to appear). (JSEP)

[3] S. Zabin and H. V. Poor. "New algorithms for the identification of impulsive noise." *Abstracts of Papers: 1988 IEEE Int. Symp on Inform. Theory*, Kobe, Japan, June 1988 (to appear). (JSEP)

[4] S. Zabin and H. V. Poor. "Recursive estimation of the Class A noise model parameters." *Proc. 22nd Ann. Conf. on Inform. Sci. and Syst.*, Princeton University. Princeton. NJ. Mar. 1988 (to appear). (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[5] S. Verdú and H. V. Poor. "Abstract dynamic programming models under commutativity conditions." *SIAM J. Contr. and Optim.*, vol. 25, no. 4, pp. 990-1006, July 1987. (NSF/ONR)

[6] B. Aazhang and H. V. Poor. "Performance of DS/SSMA communications in impulsive channels - Part I: Linear correlations receivers." *IEEE Trans. Commun.*, vol. COM-35, no. 11. pp. 1179-1188, Nov. 1987. (ARO)

[7] A. R. Barron. "Are Bayes rules consistent in information?" in *Open Problems in Communication and Computation*. T. M. Cover and B. Gopinath, Eds., New York: Springer-Verlag, 1987, pp. 85-91. (ONR)

[8] E. A. Geraniotis and H. V. Poor. "Robust matched filters for optical receivers." *IEEE Trans. Commun.*, vol. COM-35, no. 12, pp. 1289-1296, Dec. 1987. (ONR)

[9] H. V. Poor. *Advances in Statistical Signal Processing - Vol.1: Estimation*. Greenwich, CT: JAI Press. 1987.

[10] H. V. Poor. "Robust filtering." in *Advances in Statistical Signal Processing - Vol. 1: Estimation*. H. V. Poor. Ed. Greenwich, CT.: JAI Press, 1987, pp. 329-360. (ONR)

[11] H. V. Poor. *An Introduction to Signal Detection and Estimation*. New York: Springer-Verlag, 1988.

[12] B. Aazhang and H. V. Poor. "Performance of DS/SSMA communications in impulsive channels - Part II: Hard-limiting correlation receivers." *IEEE Trans. Commun.*, vol. COM-36, no. 1, pp. 88-97, Jan. 1988. (ARO)

[13] H. V. Poor and S. Verdú. "Single-user detectors for multi-user channels." *IEEE Trans. Commun.*, vol. COM-36, no. 1, pp. 50-60, Jan. 1988. (ARO)

[14] R. Vijayan and H. V. Poor. "Improved algorithms for the rejection of narrowband interferences from direct-sequence signals." *Proc. 22nd Ann. Conf. on Inform. Sci. and Syst.*, Princeton University, Princeton, NJ, Mar. 1988 (to appear). (ARO)

[15] A. R. Barron and T. M. Cover. "A bound on the financial value of information." to appear in *IEEE Trans. Inform. Theory*. (ONR NSF)

[16] R. J. Barton and H. V. Poor. "Signal detection in fractional Gaussian noise." to appear in *IEEE Trans. Inform. Theory*. (NSF)

REFERENCES:

[17] A. R. Barron and B. Clarke. "Information-theoretic asymptotics of Bayes methods" (in preparation). (JSEP)

[18] S. Zabin and H. V. Poor. "Parameter estimation in the Middleton Class A interference model." *IEEE Trans. Commun.* (undergoing review). (JSEP)

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

WORK UNIT NUMBER 23

TITLE: Basic Research in Electronics

PRINCIPAL INVESTIGATOR:

W. K. Jenkins, Director and Research Professor

SCIENTIFIC OBJECTIVE:

The objective of this research is to sponsor new initiatives on basic problems of electronic materials, devices, and systems in a timely manner and to provide early funding on the start-up of projects that present immediate opportunities of high scientific merit.

SUMMARY OF RESEARCH:

A total of $250K of JSEP discretionary funds has been committed for a new MBE "Octopus" facility that is housed in the Coordinated Science Laboratory (CSL) and which is supported and operated jointly by CSL, the Materials Research Laboratory (MRL), and the Microelectronics Laboratory. The JSEP commitment is $100K for the first year, $100K for the second, and $50K for the third year of the current JSEP contract. A team of researchers from the University of Illinois at Urbana-Champaign designed this unique facility in which state of the art surfaces, interfaces, and multilayers can be synthesized. This new facility is called the **EpiCenter**, an abbreviation for the U of I CSL-Microelectronics Joint Center for Epitaxial Growth and Surface Science. About $500K is scheduled from University of Illinois at Urbana-Champaign DOE Program funds for the purchase of the MBE equipment over FY 86, 87, and 88. The remaining funds for the $6M facility have been contributed by NSF/Materials Research Laboratory ($500K), NSF/Engineering Research Center ($200K), JSEP ($250K), AFOSR ($600K), and the University of Illinois at Urbana-Champaign, together with a gift from the Perkin Elmer Corporation of approximately $2.3M.

Seven MBE machines in the EpiCenter are interconnected by uhv (5×10^{-11} torr) stainless steel transfer lines. From the same vacuum environment, it is possible to access advanced instrumentation for surface modification and sample characterization. The crystal growth equipment forms a cross at one end of the 80' x 40' facility. Access to the clean environment of the facility from an observation area is attained through an air lock, as indicated in Figure 1. A sample preparation room providing class 100 clean space in laminar flow hoods is accessible only from the main area. A lounge is provided for planning, discussion, computation, etc., during facility-related activities.

Both the MBE machines and the uhv transfer lines were fabricated by the Perkin Elmer Co. Figure 1b shows the configuration of the system. Machines 1 and 2 on Arm I are III-V compound machines with 2 adapted to gas-source research of Morkoc. Machines 3 and 4 on Arm II are designed for work with metals (3), with both effusion and e-beam sources, and for polar ceramic materials (4). Machine 5 is contributed by the University of Illinois at Urbana-Champaign Engineering Research Center for device work, and the other machine, 6, on Arm III is custom designed with e-beam hearths for research into growth of the group IV materials Si, Ge, etc. Finally, machine 7 on Arm IV is specially adopted to Greene's research using ion beam mixing to select particular growth paths of metastable structures. The complex thus contains a wide variety of crystal growth environments that are not ordinarily compatible with one another. Columns III and V elements, for example, are electrically active dopants in group IV semiconductors and must, therefore, be employed with selective care in group IV synthesis.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

(a)

(b)

Fig. 1.   Schematics showing (a) the EpiCenter facility for epitaxial growth and (b) the approximate layout of the MBE machines.

University of Illinois at Urbana-Champaign   Coordinated Science Laboratory

A special feature of the complex is that the seven machines are interconnected by uhv transfer lines held at a pressure of 5×10^{-11} torr. The purpose is to permit transfer of a given substrate from one growth chamber to a second without surface contamination. This makes it possible to grow on a given fresh substrate an epitaxial layer which is not compatible with the environment needed to grow the substrate. The growth of GaAs on Si is a particular example of an important synthesis problem of this type. The seven machines offer a unique flexibility for research of this type into heteroepitaxy. In particular, the MBE and sample transfer equipment throughout is adapted to 3" wafers so that any sample may receive successive processing in any desired sequence of the seven growth chambers.

A variety of characterization and processing instruments are designed to attach on the ends of the arms. These, also, are fully adapted to the 3" wafer size of the synthesis complex. This permits *in situ* modification of samples and structure characterization within the common vacuum environment so that surface contamination is avoided. A substrate preparation chamber is attached to the end of Arm I so that substrates can be oxydized, sputtered, annealed, tested, etc. Opposite, on the end of Arm III, a rotating anode x-ray source and diffractometer are being set up by Zabel for *in situ* studies of surfaces and multilayers. On Arm IV a PHI XPS unit is being installed for surface studies; its diagnostic capabilities are enhanced by added ion scattering spectroscopy, ultra-violet photoemission, and LEED capabilities. These are in addition to the RHEED and mass spectroscopy diagnostics in each MBE machine. Further, MBE machines 1, 3, and 7 are being specially equipped for ellipsometry, fluorescence, and other optical probes of film growth. Efforts are now being made to obtain Rutherford backscattering equipment for interface and surface studies on Arm IV of the system. A planned future development is the installation of focussed ion beam materials modification and an electron microscope on Arm I. Plans call for the experimental area at the end of Arm IV to become a surface science complex to which freshly grown surfaces from the complex can be transferred.

At the present time, the building remodeling has been completed and all the equipment has been installed in the room. Representatives from Perkin Elmer are now working together with faculty and staff of the university to bring the equipment to a fully functioning state. During the fall semester of 1987, Professor James Kolodzey spent a semester in residence at AT&T Bell Laboratories, Murray Hill, NJ, working with Dr. Alfred Cho to learn more about MBE processes. It is expected that the EpiCenter will become fully operational during the summer of 1988. An official dedication ceremony is being arranged for the fall of 1988.