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UNIVERSITY PARK

LOS ANGELES, CALIFORNIA 90007

SCHOOL OF ENGINEERING
ELECTRONIC SCIENCES LABORATORY

30 June 1982

Lt. Colonel Clarence Gardner
Air Force Office of Scientific Research
Bolling Air Force Base
Washington, D.C. 20332

AFCOR-TR. 89-1706

Dear Colonel Gardner:

Enclosed are sixteen [16] copies of our Annual Technical Report covering the period 1 April 1981 through 31 March 1982 under contract F49620-81-C-0070. Also enclosed is the Significant Accomplishments Report for this same period. I am sending copies of these reports to everyone on the JSEP Distribution List.

Sincerely,

William H. Steier
William H. Steier
Director

Enclosures

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UNIVERSITY OF SOUTHERN CALIFORNIA

JOINT SERVICES ELECTRONICS PROGRAM

SIGNIFICANT ACCOMPLISHMENTS

1 April 1981 - 31 March 1982

WORK UNIT SS1-1

OPTICAL PROPERTIES & THERMAL/LASER ANNEALING
OF ION IMPLANTED SEMICONDUCTORS

WILLIAM G. SPITZER & C.N. WADDELL

It has been demonstrated that infrared reflection measurements of Si samples which have been heavily implanted with Si or P ions can be used to determine many of the implantation-related parameters of physical interest. Moreover, it has been shown that computer fitting of the infrared measurements for samples being annealed can yield values for (i) the regrowth rate of the amorphous layer (produced by the implantation), (ii) the refractive indices of the amorphous and recrystallized regions, and (iii) the 1st, 2nd, and 3rd moments of the carrier distribution (where P⁺-ions are the implanted species) in the annealed material. One result of considerable interest is that the infrared measurements have shown that amorphous Si has two reproducible states of different optical properties: one the as-implanted state and the other produced by annealing at 500 degrees C for one hour or longer. The optical properties of these two states are each essentially independent of the implanted ion (Si or P), the ion energy (300 keV to 2.7 MeV), or the ion fluence (as long as the fluence is sufficient to produce an amorphous layer). The two states differ from one another in their refractive indices (both different than crystalline Si) and dangling bond concentrations (EPR measurements) but have very nearly the same density.

WORK UNIT IE1-3

DESIGN OF EASILY MAINTAINABLE DIGITAL SYSTEMS

JOHN P. HAYES

Major advances have been made in the analysis of faults in complex MOS VLSI circuits and in the synthesis of fault tolerant interconnection networks for multi computer systems. An important class of interconnection networks (beta networks) have been studied and several new classes of fault-tolerant beta-networks have been discovered. It has been demonstrated that faults such as short circuits, open circuits, and delay faults in MOS VLSI circuits can be best modeled by a new approach developed by Prof. Hayes.

WORK UNIT IE1-2

A SUPPORT ENVIRONMENT FOR INFORMATION BASES

DENNIS MCLEOD

The long-term objective of this research is to devise and demonstrate techniques to support the design, evolution, and interconnection of computerized databases, improving the state-of-the-art in function and reducing the expertise required by database designers/users. Toward this end, a high-level specification language and formalism (termed "SDM" for semantic database model) has been developed and applied to the design and documentation of database systems. A tool that serves as a database transaction specification advisor has been designed and implemented based on SDM, guiding an end-user in understanding the content and structure of a database, and formulating a transaction on that database. Experience with SDM has supported the design and prototype implementation of the "event model": a database design and evolution methodology coupled with a semantic database model that accommodates both statics (data objects) and dynamics (process). The prototype event model implementation prescriptively guides a designer, reducing the expertise required to design and maintain databases.

To address the important problem of database interconnection and sharing, the "federated database" architecture has been developed. While most approaches to "distributed databases" require a centralized logical organization and substantial centralized control, the federated database approach provides a mechanism for specifying and negotiating the information exchange requirements among component databases, an approach to the effective processing of information exchange requests among components (transaction processing), and a methodology to support the design and evolution of a federated database system.

The above specific results will provide strong input into the new specific direction of this research, namely workstation information management environments. "INFOBASE" (for information base support environment) is being designed and a prototype is planned, the goal of which is to enable an end-user directly to define, classify, interrelate, manipulate, and share a universe of information objects, and provide an access port onto a network of large databases and information sources. Intended applications of INFOBASE include handling the data necessary to support the activities of a professional, manager, and engineer (in software engineering, VLSI design, and computer-aided design and manufacturing (CAD/CAM)).

FOREWORD

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

JSEP research projects at USC are currently in three areas: Solid State Electronics, Quantum Electronics, and Information Electronics. This report presents summaries of the accomplishments and progress for each of the projects [work units] which were active during the contract period of 1 April 1981 to 31 March 1982 under contract F49620-81-C-0070.

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OPTICAL PROPERTIES AND THERMAL/LASER ANNEALING
OF ION IMPLANTED SEMICONDUCTORS
[Work Unit SS1-1]

WILLIAM G. SPITZER and C.N. WADDELL
in collaboration with
J.E. FREDRICKSON
California State University at Long Beach
and
GRAHAM HUBLER
Naval Research Laboratory, Washington, D.C.

REPORT PERIOD: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

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

STATUS OF RESEARCH EFFORT

In our previous annual report(4/1/80 - 3/31/81) we reviewed a series of measurements of the infrared reflection as a function of frequency for implanted Si samples and a computer model which was used to fit the observed measurements. As a result of the fitting procedure a number of parameters of physical interest were obtained. These parameters included the depth of the amorphous--crystalline interface, the epitaxial regrowth rate produced by annealing samples, the widths of any transition layers, the dielectric properties of the amorphous and the recrystallized materials, carrier activation when the implanted ion is an electrically active dopant, and the spatial characteristics of the free carrier plasma in the recrystallized material.

One of the more interesting results obtained from the above measurements is that the refractive index of the as-implanted, amorphous Si is significantly larger than that for crystalline Si and is independent of the implanted ion (Si or P), the ion fluence, or the ion energy. Moreover, after short annealing times at either 500 or 550 degrees Celcius, the amorphous material refractive index drops approximately one-third of the way back towards the crystalline value and remains at this value with further annealing time until the material recrystallizes. These two states of amorphous Si (a-Si) have been called the defect-saturated (as-implanted) and thermally stabilized (annealed) states. Further measurements have shown that the epr signal from the "dangling bonds" in the a-Si undergoes a large decrease between the defect-saturated and thermally stabilized states with little change in the a-Si spin density with further annealing

SS1-1(2)

until recrystallization occurs. On the other hand, the change in density of the Si as a result of the amorphization shows no significant change when the a-Si is annealed between the two states although the changes are too small to be quantitatively interpretable with any reliability.

In order to study the two a-Si states further and to obtain additional regrowth data, a series of new implantations have been done. These implants include <100> and <111> Si samples implanted with Silicon (mass 29), with Carbon (mass 12), and with Tin (mass 120). Using these samples we intend to determine whether there is any dependence of the refractive index, the microstructure (voids), the dangling bond densities, or the density of the a-Si on the mass of the implanted ion. Radial distribution measurements (X-ray) will be made to compare the two states. We also intend to anneal samples at temperatures below 500 degrees Celcius in order to determine if the thermally stabilized state is a unique state or one of a continuum of such states. We will also explore annealing cycles which might produce even lower spin densities and hence a potentially interesting electronic material.

PUBLICATIONS

1. "Effects of Thermal Annealing on the Refractive Index of Ion Implanted Silicon" by J.E. Fredrickson, C.N. Waddell, W.G. Spitzer, and G.K. Hubler, Appl. Phys. Letters 40, 172 (1982).
2. "Electrical and Structural Characterization of Implantation Doped Si by Infrared Reflection" by G.K. Hubler, R.P. Malmberg, C.N. Waddell, W.G. Spitzer, and J.E. Fredrickson, Rad. Eff. (in press).
3. "Isothermal Annealing of Ion-Implanted Silicon: Refractive Indices, Regrowth Rates, and Carrier Profiles" by C.N. Waddell, W.G. Spitzer, G.K. Hubler, and J.E. Fredrickson, J. Appl. Phys. (in press).
4. "Properties of Amorphous Si produced by Ion Implantation: Thermal Annealing" by W.G. Spitzer, G.K. Hubler, and T.A. Kennedy, to be submitted to the International Conference on Ion Implantation, September, 1982 in Grenoble, France.

PROFESSIONAL PERSONNEL (alphabetical order)

1. J.E. FREDRICKSON, Professor of Physics, California State University at Long Beach (work done at USC).
2. G.K. HUBLER, Research Scientist, Naval Research Laboratory, Washington, D.C.

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

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

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

INTERACTIONS

A. Papers at Meetings, Seminars, etc.

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

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

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

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

B. Consultative and Advisory Functions

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

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

Work Unit SS1-2

Electrooptic Materials and Optical Image Storage Devices

Armand R. Tanguay, Jr.

Report Period: April, 1981 - April, 1982

Research Objectives:

(1) To fully characterize the physical processes inherent in the operation of Pockels Effect and Photorefractive Image Storage Devices, and to establish the relationship between the relevant material properties and optimum device design parameters. These image storage devices are currently of interest for applications in incoherent-to-coherent conversion and coherent optical signal and image processing.

(2) To further develop the Czochralski growth technique for the production of large single crystals of optical quality bismuth silicon oxide ($\text{Bi}_{12}\text{SiO}_{20}$), at present the most promising candidate for the active electrooptic element of both Pockels Effect and Photorefractive Image Storage Devices.

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

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

Status of Research Effort:

Substantial progress has been achieved in a joint theoretical and experimental investigation of the factors affecting resolution and charge transfer dynamics in electrooptic spatial light modulators such as the Pockels Readout Optical Modulator (PROM) [1], Microchannel Spatial Light Modulator (MSLM) [2], photo-DKDP

[3], and electron-beam-DKDP [4] image storage devices. The theoretical approach to the resolution problem initially involved deriving the electrostatic field distribution from a fixed distribution of point charges located at the interface between two dissimilar dielectrics bounded by ground planes. The electric field modulation resulting from a longitudinal distribution of charges of given transverse spatial frequency can be directly related to the exposure-dependent modulation transfer function of the device. We have obtained an analytic expression for the Fourier transform of the voltage distribution from a single point charge (which is also directly related to the modulation transfer function) for the full three layer dielectric problem, and have extended the theory to include the dependence of the voltage distribution on the point charge location within the electrooptic crystal. The resultant analytic expression contains the dielectric constants of the blocking layers and electrooptic crystal, and the thickness of the three layers, as well as the location of the point charge. This formulation allows the effects of charge trapping within the bulk of the electrooptic crystal to be modeled. In particular, the low spatial frequency response decreases linearly, and the high spatial frequency response decreases exponentially with the distance of the point charge from the electrooptic crystal/dielectric blocking layer interface. Thus the overall sensitivity and resolution are degraded strongly by charge storage in the bulk away from the interface. Utilizing superposition, this formulation has been further extended to accommodate arbitrary charge distributions of particular physical interest. In particular, an iterative exposure-induced charge transfer and trapping model has been formulated to calculate the charge distribution throughout the electrooptic crystal layer resulting from optical exposure at various wavelengths. The charge distributions so obtained have been utilized to calculate the dependence of the device modulation transfer function on both exposure level and exposure wavelength. The results indicate a substantial improvement in the resolution as the wavelength

approaches the band gap of the electrooptic crystal. Such improvements are quite striking in preliminary experimental device resolution tests. In addition, it has been shown that in the limit of high spatial frequencies, the modulation transfer function decreases as the inverse square of the spatial frequency regardless of the particular shape of the charge distribution. The shape of the charge distribution does, however, influence both the device exposure sensitivity and the spatial frequency above which the modulation transfer function asymptotically approaches the inverse square dependence on spatial frequency. Application of these results has been made to a wide variety of PROM device design cases (including both symmetric and asymmetric devices) and specialized exposure conditions (particularly x-ray [5] and electron-beam [6] sources), as well as to other types of electrooptic spatial light modulators such as the MSLM and photo-DKDP devices. Furthermore, the theoretical formulation allows investigation of possible voltage-modulated recording techniques for resolution enhancement (such as the "superprime mode" [1]), and of flash erasure sensitivity and completeness. These results have numerous implications with regard to improving device resolution [JSEP Pubs. 2,3,4,5,6,7].

In the past year, PROM-like structures have been investigated [7,8; JSEP Pubs. 8,9] that can exhibit significantly enhanced resolution and sensitivity relative to traditional PROM structures. Such devices are fabricated from bismuth silicon oxide crystals oriented along $\langle 111 \rangle$ and $\langle 110 \rangle$ axes, as opposed to the usual $\langle 001 \rangle$ orientation. In these orientations, the longitudinal electrooptic effect does not contribute to the resultant image amplitude (as in the traditional $\langle 001 \rangle$ orientation). Instead, these novel configurations utilize the transverse electrooptic effect deriving from transverse fields within the bulk of the electrooptic crystal, induced by spatially varying components of the input image distribution. Since the electrooptic effect is antisymmetric under reversal of the electric field direction, transverse field

contributions to the image are characterized by an antisymmetric point spread function. This implies that the device modulation transfer function will exhibit a bandpass character with no response at zero spatial frequency. This characteristic is useful in some optical processing applications requiring dc suppression. In addition, since field components in orthogonal transverse directions couple differently to the electrooptic tensor, the modulation transfer function will be sensitive in general to both the orientation of each spatial frequency component of the image (grating wavevector dependence) and to the polarization of the readout illumination. Utilization of this effect allows for both one-dimensional and two-dimensional image reconstruction through appropriate choice of readout polarization. We have modified our solution of the three layer dielectric problem to allow calculation of the integrated transverse potential drop (the integration is performed in the longitudinal or charge motion direction) for both point charge cases and continuous charge distributions. The results include the dependence of the modulation transfer function on device constitutive parameters, crystallographic orientation, and dielectric anisotropy in the electrooptic crystal layer [JSEP Pubs. 5,8]. Numerous $\langle 111 \rangle$ and $\langle 110 \rangle$ oriented devices have been fabricated in our laboratory with vapor-deposited parylene blocking layers and RF magnetron sputtered indium tin oxide transparent conductive electrodes. Primary characterization measurements have included diffraction efficiency as a function of spatial frequency, which can easily be related to the modulation transfer function of the device. Experiments to date confirm all of the model predictions.

During the measurement program described above, we have established a number of new observations about transverse field effect PROMs. First and foremost, the operational mode (direction of externally applied field during the writing sequence) utilized is critically important to the optimization of device characteristics. In this respect, the $\langle 001 \rangle$ and $\langle 111 \rangle$ PROMs show

essentially opposite behavior due to significant differences in response to similarly placed volume charge distributions. Hence the operational mode that optimizes $\langle 001 \rangle$ PROM performance is opposite from the operational mode that optimizes $\langle 111 \rangle$ PROM performance. Second, charge conservation within the photoconductive/electrooptic crystal layer in general enhances $\langle 001 \rangle$ PROM sensitivity, while diminishing $\langle 111 \rangle$ PROM sensitivity. Leaky parylene layers increase $\langle 111 \rangle$ PROM diffraction efficiency at the expense of device storage time. Finally, numerous phase effects have been theoretically derived and experimentally demonstrated in the $\langle 111 \rangle$ PROM. Although the longitudinal field does not contribute to the signal amplitude, it can be shown to induce a signal-dependent phase modulation that is present in concert with the transverse field-induced signal-dependent amplitude modulation. Such phase effects diminish the usefulness of the device for applications in which Fourier-plane processing is desired, as well as produce point-spread function anisotropies in the image plane in the presence of strain birefringence or imperfectly aligned polarizer/analyzer pairs. Such intriguing effects in $\langle 111 \rangle$ and $\langle 110 \rangle$ oriented PROMs are under continuing investigation.

An experimental determination of the charge carrier dynamics under both uniform and nonuniform exposure in a PROM structure by means of transverse electrooptic imaging has been undertaken to allow measurement of the appropriate exposure-induced electric field distribution function for refinements to the theoretical modulation transfer function calculations. Preliminary results have been obtained which suggest that the applied field distribution within the bulk of the electrooptic crystal prior to exposure is quite uniform (as opposed to the distribution expected for the case of space-charge-limited current injection, for example). In addition, these measurements have been extended to the case of uniform exposure by fabrication of a PROM-structure 1.5 mm x 1.6 mm x 11 mm in size. Application of the external

applied field under conditions of no exposure showed several interesting effects, including charge injection through the (dielectrically imperfect) parylene blocking layer, and the existence of periodically modulated resistivity fluctuations that are likely caused by rotation-induced striations during the crystal growth process. Exposure in forward mode (illuminated electrode negative) showed charge distribution effects throughout the bulk of the device, while exposure in reverse mode (illuminated electrode positive) showed strong charge confinement near the electrode. This result confirms an independent experiment that indicated a much larger mobility-lifetime product for electrons than for holes. It also confirms semi-quantitatively the predictions of the charge transport model advanced earlier. This effort is extremely important to the design of new devices with improved resolution, and to investigations of novel voltage modulated recording techniques for enhanced device performance. In addition, it appears likely that this technique will allow accurate measurements of mobility-lifetime products to be made in low mobility-short lifetime electrooptic materials that are difficult to characterize otherwise.

During the contract year, numerous bismuth silicon oxide ($\text{Bi}_{12}\text{SiO}_{20}$) crystals have been grown by the top-seeded Czochralski technique. The growth apparatus includes a two-zone resistance heated furnace, which has been modified to incorporate high precision and stability set-point controllers interfaced to a programmable thermal cycle controller. This allows lengthy melting, annealing, and cool-down cycles to be controlled automatically. In one recent experiment, a Cr doped BSO crystal was grown 3 mm in diameter, 5 cm long with less than 0.5 mm diameter fluctuations. Crystals have been grown with both $\langle 001 \rangle$ and $\langle 111 \rangle$ orientations for utilization in both optical device fabrication and crystal characterization experiments. Top-seeded crystals exhibit a high degree of optical uniformity and well-developed $\langle 100 \rangle$ facets for growth along the $\langle 001 \rangle$ axis.

Doping experiments are proceeding in concert with photoconductivity, photoluminescence, and thermally stimulated current measurements to determine the optical and thermal levels induced by incorporated impurities. Such experiments are being undertaken in hopes of modifying the band edge absorption to increase readout gain, and of broadening the photoconductivity spectrum to permit sensitive exposure in the visible (450 - 550 nm).

In the area of photorefractive image storage device physics, a number of significant experiments have been performed in bismuth silicon oxide as well as the ferroelectric barium titanate. The experimental studies included formation and erasure of holographic gratings, and two-wave and four-wave mixing. These studies led to the proposal of a new theoretical model for the migration of charges mediating the photorefractive effect in these materials. Using this theoretical model, we are able to predict the observed dependence of wave mixing on the intensities and polarizations of the waves, and on the wave directions relative to each other and the crystallographic axes. The effects of applied electric fields on the diffraction efficiency as a function of grating wavevector were predicted and verified experimentally [JSEP Pub. 10]. Extensions of both theory and experiment to the case of bismuth silicon oxide are under way, with emphasis on the correlation between observed photorefractive effects and characterization of fundamental material properties (defect density, trap energy levels, etc.). Applications in the areas of image phase conjugation, holographic data storage, and programmable bandpass filtering are being explored.

In addition, a study of the dependence of the diffracted order polarization on the simultaneous presence of optical activity and electric field induced birefringence in photorefractive materials such as BSO has been undertaken. Preliminary results have explained the optimum orientations for diffraction efficiency and energy coupling, and have as well provided closed form solutions

for the diffracted order polarizations in the limit of low exposures.

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1. B.A. Horwitz and F.J. Corbett, "The PROM-Theory and Applications for the Pockels Readout Optical Modulator", Opt. Eng. 17, 353-364 (1978).
2. C. Warde, A.D. Fisher, D.M. Cocco and M.Y. Burmawi, "Micro-channel Spatial Light Modulator", Opt. Lett. 3, 196-198 (1978).
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4. G. Marie, J. Donjon and J.P. Hazan, "Pockels Effect Imaging Devices and Their Applications", in Advances in Image Pickup and Display, Vol. 1, B. Kazan, Ed. Academic Press, New York (1974), 225-302.
5. G.J. Berzins and M. Graser, Jr. "Response of a $\text{Bi}_{12}\text{SiO}_{20}$ Pockels Readout Optical Modulator to X-rays", Appl. Phys. Lett., 34(8), 500-502 (1979).
6. J.C.H. Spence and A. Olsen, "Use of Pockels Readout Optical Modulators (PROMs) for Atomic Resolution Electron Image Processing", Proc. SPIE :os Angeles Technical Symposium, 218, 154-160 (1980).
7. M.P. Petrov, "Diffraction and Dynamic Properties of Photo-sensitive Electrooptic Media", Proc. Optics in 4-Dimensions, CICEFE, Mexico, (1980).
8. M.P. Petrov, "Electrooptic Photosensitive Media for Image Recording and Processing", in Current Trends in Optics, F. Arecchi and F. Aussenegg, Eds., Taylor and Francis, London, 161-172 (1981).
9. R.A. Sprague, "Effects of Bulk Carriers on PROM Sensitivity", J. Appl. Phys. 46(4), 1673-1678 (1975).
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Cumulative Publications List (JSEP Sponsorship:)

I. Journal Publications and Proceedings Manuscripts

1. "Crystal Chirality and Optical Rotation Sense in Isomorphous $\text{Bi}_{12}\text{SiO}_{20}$ and $\text{Bi}_{12}\text{GeO}_{20}$ ", Solid State Communications, 30, 293-295 (1979), with S.C. Abrahams and C. Svensson.
2. "Effects of Charge Dynamics and Device Parameters on the Resolution of Electrooptic Spatial Light Modulators", Proceedings of the SPIE International Symposium, San Diego, August (1979), 202, 110-121, with Y. Owechko.
3. "Exposure-Induced Charge Distribution Effects on the Modulation Transfer Function (MTF) of Electrooptic Spatial Light Modulators", Proceedings of the SPIE International Symposium, Los Angeles, February (1980), 218, 67-80, with Y. Owechko.
4. "Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators. I. Fundamental Considerations", in preparation for Journal of the Optical Society of America, with Y. Owechko.
5. "Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators. II. Effects of Crystallographic Orientation and Dielectric Anisotropy", in preparation for Journal of the Optical Society of America, with Y. Owechko.
6. "Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators. III. Effects of Continuous Charge Distributions", in preparation for Journal of the Optical Society of America, with Y. Owechko.
7. "Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators. IV. Effects of Device Operational Mode", in preparation for Journal of the Optical Society of America, with Y. Owechko.
8. "Effects of Operating Mode on Electrooptic Spatial Light Modulator Resolution and Sensitivity", submitted to Optics Letters, with Y. Owechko.
9. "Dependence of Electrooptic Spatial Light Modulator Phase Response on Crystallographic Orientation", submitted to Optics Letters, with Y. Owechko.
10. "Photorefractive Effects and Light-Induced Charge Migration in Barium Titanate", J. Appl. Phys. 51, 1297-1305 (1980), with J. Feinberg, D. Heiman and R.W. Hellwarth.

11. "Spatial Light Modulators for Real Time Optical Processing", Proc. ARO Workshop on Future Directions for Optical Information Processing, Texas Tech. Univ., Lubbock, Texas (1980), (Invited Paper).
12. "EPR Characterization of Czochralski Grown $\text{Bi}_{12}\text{SiO}_{20}$ Single Crystals", submitted to Applied Physics Letters, with H.J. von Bardeleben.
13. "Polarization Properties of Birefringent Phase Gratings", submitted to Optics Letters.

II. Conference Presentations

1. "Effects of Charge Dynamics and Device Parameters on the Resolution of Electrooptic Spatial Light Modulators", SPIE International Symposium, San Diego, August (1979), with Y. Owechko.
2. "Exposure-Induced Charge Distribution Effects on the Modulation Transfer Function (MTF) of Electrooptic Light Modulators", SPIE International Symposium, Los Angeles, February (1980), with Y. Owechko.
3. "Theoretical Resolution Limitations of Electrooptic Spatial Light Modulators", 1979 Annual Meeting of the Optical Society of America, Rochester, N.Y., (1979), with Y. Owechko.
4. "Four-Wave and Two-Wave Mixing Theory and Experiments in Barium Titanate", 1979 Annual Meeting of the Optical Society of America, Rochester, N.Y., (1979), with J. Feinberg, D. Heiman and R.W. Hellwarth.
5. "Four-Wave and Two-Wave Mixing Theory and Experiments in Barium Titanate", 1979 Gordon Conference on Nonlinear Optics, Brewster Academy, New Hampshire, (1979), with J. Feinberg, D. Heiman and R.W. Hellwarth.
6. "Spatial Light Modulators for Real Time Optical Processing", ARO Workshop on Future Directions for Optical Information Processing, Lubbock, Texas, May (1980) (Invited Paper).
7. "Progress in Pockels Readout Optical Modulators and Variable Grating Mode Liquid Crystal Devices", U.S. Army Research Office, Durham, North Carolina, May (1980).
8. "Modulation Transfer Function Model for Electrooptic Spatial Light Modulators", 1980 Annual Meeting of the Optical Society of America, Chicago, Illinois, (1980), with Y. Owechko.

9. "Real-Time Spatial Light Modulators for Coherent Optical Processing Applications", Second SPSE Symposium on Optical Data Display, Processing, and Storage, Las Vegas, Nevada, (1981), (Invited Paper).
10. "Exposure-Induced Charge Transport Model of Electrooptic Spatial Light Modulator Sensitivity", 1981 Annual Meeting of the Optical Society of America, Orlando, Florida, (1981), with Y. Owechko.
11. "Electrooptic Spatial Light Modulators: Effects of Operational Mode and Crystallographic Orientation", 1981 Annual Meeting of the Optical Society of America, Orlando, Florida, (1981), with Y. Owechko.
12. "Information Processing and Holography", Invited Panel Member, 1981 Annual Meeting of the Optical Society of America, Orlando, Florida, (1981).
13. "Materials Considerations for Electrooptic Spatial Light Modulators", American Vacuum Society Annual Meeting, Anaheim, (March, 1982) (Invited Paper).
14. "Recent Advances in Spatial Light Modulators for Coherent Optical Processing Applications", Conference on Lasers and Electro-Optics (CLEO), Phoenix, Arizona, (May, 1982) (Invited Paper).
15. "Recent Progress in Spatial Light Modulators for Coherent Optical Processing Applications", Gordon Research Conference on Information Processing and Holography, Plymouth, New Hampshire, (June, 1982) (Invited Paper).
16. "Polarization Properties of Birefringent Phase Gratings", Gordon Research Conference on Information Processing and Holography, Plymouth, New Hampshire, (June, 1982) (Invited Paper).
17. "Single Crystal and Thin Film Electrooptic Materials for Optical Device Applications", DARPA Materials Research Council Symposium, La Jolla, California (July, 1982) (Invited Paper).

Professional Personnel:

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

Interactions:

Interaction With Other Work Units:

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

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

DOD Interactions:

1. During the contract period an important collaboration agreement was continued with the Itek Corporation, Lexington, Massachusetts (Dr. Ralph Aldrich, Project Manager). The agreement provides for advanced technology and device fabrication support from Itek, while the USC effort is focused on device evaluation and understanding. The advanced PROM development work at Itek has been supported by several DOD agencies. In particular, a program on

development of new PROMs with improved resolution characteristics was supported by Dr. Robert Leighty of the Army Engineering Topographical Laboratory through the Army Research Office, Durham. Dr. Ralph Aldrich of Itek Corporation visited USC in June, 1979, and in April, 1980, for technical discussions. Dr. Leighty visited USC in February, 1980, and was briefed at ETL (Fort Belvoir) about current research progress in April, 1980. He has subsequently been briefed concerning recent research developments.

2. During April, 1978, 1979, and 1980 and 1981, visits to USC by Dr. John Neff of the Air Force Office of Scientific Research were arranged. Dr. Neff will continue to be briefed on our progress as it relates to Air Force optical device and optical information processing programs.

3. An invited paper on recent progress in spatial light modulators was presented at the ARO sponsored Workshop on Future Directions in Optical Information Processing, Lubbock, Texas, May (1980). Recent progress on spatial light modulator research at USC was presented at the Army Research Office, Durham, in May, 1980.

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

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

ELECTRICAL TECHNIQUES FOR MATERIALS CHARACTERIZATION
[Work Unit SS1-3]

C.R. CROWELL

Report Period: 1 April 1982 - 31 March 1982

RESEARCH OBJECTIVES

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

STATUS OF RESEARCH EFFORT

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

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

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

3. We have completed an analysis that compares DLTS and DDLTS analysis of deep level transients [7]. This manuscript has considered tradeoffs in sensitivity versus time constant selectivity for a number of DLTS "correlators" and sets up other guidelines for the time-efficient acquisition of spectra. A third major contribution of this work is an analysis of the effects of deep levels large in concentration relative to the bulk majority carrier concentration. In this situation a strong distortion of the transient behavior occurs if the transients are not analyzed at constant high frequency capacitance. Since this is not always possible the above analysis is potentially very useful.

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

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

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

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

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

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

REFERENCES AND PUBLICATIONS

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2. D. Lucy, "Ohmic Contact Evaluation", Ph.D. Thesis, in preparation.
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6. C.H. Huang, M.M. Beguwala and C.R. Crowell, "Capacitive Evaluation of Concentration, Energy Level and Hole Captive Cross-section of In in p Type Si," manuscript in preparation.
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9. C.R. Crowell, presented at JSEP Topical Review, USC, Jan. 1981, manuscript planned for publication.
10. C.R. Crowell and S. Alipanahi, "Figure of Merit for Slow Restoration DLTS Filters," accepted for publication in Applied Physics, manuscript being revised.
11. R. Chwang and C.R. Crowell, "Activation Analysis and Recursive Parameter Estimation of Hall Data," presented at JSEP Review, USC, manuscript in preparation.
12. W.P. Patterson and C.R. Crowell, "Poole-Frenkel Effects in Silicon Nitride," presented at JSEP Review, USC, Jan. 1976, manuscript in preparation; W.P. Patterson, Ph.D. Thesis, USC.

SS1-3(4)

PROFESSIONAL PERSONNEL

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

S. ALIPANAHI, Ph.D., Jan. 1981, "A Signal Acquisition Technique for Transient Spectroscopy of Semiconductor Bulk and Interface Deep Levels."

D. LUCEY, Ph.D. proposed Fall 1982

M.W. CHIANG, Research Assistant

INTERACTIONS

A GAP ON SI INTEGRATED OPTICS CHIP:
MOLECULAR BEAM EPITAXY
[Work Unit SS1-4]

MURRAY GERSHENZON

Reporting Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

A. MOCVD Program

Several years ago, we embarked on a JSEP sponsored program to grow GaP epitaxially on Si, noting that (1) epitaxial growth of high quality semiconductors depends on the availability of a good substrate; (2) large area, single crystals of Si of high quality are readily available and relatively inexpensive; and (3) GaP is the best simple semiconductor crystallographic lattice match to Si, although, even here, the match is not perfect; GaP is 0.4% larger than Si, and the discrepancy increases above room temperature.

If good epitaxial layers of GaP could be grown on Si, the device goals were obvious. 1) Considering the GaP layer only, we could envision a wave guide for visible light (from which this project derived its title), as well as a large area LED display. 2) Focussing on the Si substrate, the GaP could act as a Fermi level controllable passivation layer or as an FET gate insulator. 3) With light allowed to penetrate the interface, we could fabricate a (GaP) filtered photodetector (Si) or an optical isolator (GaP LED's, Si photodiodes). 4) With majority carriers passing through the interface, we proposed coupled opto-electronic devices, such as a GaP LED array driven by Si circuitry. 5) Finally, with minority carriers traversing the interface, we envisioned various heterostructure devices, such as a high efficiency GaP emitter on a Si bipolar transistor, designed for very high speed response.

The results of our experimental program have been given in previous reports, and are here summarized briefly.

1. LPE growth of GaP on Si is chemically incompatible; growth by halide VPE is almost incompatible. MBE was not available. MOCVD growth was shown to be feasible and was demonstrated to be the method of choice.

2. It was essential to remove the oxide from the Si substrate in order to obtain good single crystal growth. The method devised was to preheat the Si in H_2 to 1150° , expose the surface to PH_3 , then cool to 800° , where GaP growth from trimethyl gallium and PH_3 then ensued.

3. Antiphase twin boundaries appeared because the Si substrate is of higher crystallographic symmetry than the GaP and cannot uniquely establish the epitaxial relation. This problem was solved by using a misoriented substrate; a $2-4^\circ$ misorientation (towards a $\langle 111 \rangle$ direction) of a (100) Si substrate proved effective.

4. On cool-down from the growth temperature of 800° , the GaP contracts more than the Si and is therefore in tension. GaP layers thicker than $5\mu\text{m}$ then crack on cooling. Below $5\mu\text{m}$, stresses at intermediate temperatures are great enough to cause plastic deformation. These layers do not crack, but they contain a high dislocation density. Layers grown on Si predeposited on sapphire (SOS) are always in compression. They do not crack and no thermal contraction dislocations are generated.

5. Because of the significant lattice mismatch between GaP and Si at the growth temperature (0.64% at 800°), nucleation was by an island mechanism. This led to a non-planar surface morphology.

6. At the high growth temperature, significant interdiffusion across the heterostructure was noted, doping the Si with Ga and P, and doping the GaP with Si out to $1\mu\text{m}$ from the interface. The solution to the last two problems lay in obtaining growth at lower temperatures. The growth temperature of 800° was used because PH_3 does not crack until 750° . Hence, we were preparing to precrack the PH_3 or substitute trimethylphosphorus, when the project suddenly changed course.

B. Acquisition of MBE System

Through the generosity of the JSEP program, the University Of Southern California was able to purchase a modern, sophisticated MBE system, a Perkin-Elmer, PHI Model 400. The instrument was delivered during the summer of 1980 and became operational in the Fall. The system was new to us. Having no previous hands-on experience with UHV and with surface analytic equipment, with no trained students or technicians, and with a limited amount of funding, the system was down much of the fall and winter of 1980-81. During an annual JSEP review in February 1981, we were strongly advised to shift our MOCVD program to the MBE system. At university expense, we hired a full-time technician with extensive experience with MBE and its sub-systems. He arrived in May 1981.

C. Initial MBE Research Objectives

As reported at the last triennial JSEP review in January 1982, in cooperation with Prof. A. Madhukar, we devised a plan to teach us how to make effective use of the MBE system. This was a one year plan, based upon the well established GaAs/GaAlAs materials system, that has been at the heart of MBE work.

1. We first proposed to grow GaAs on GaAs substrates, aiming for maximum control of growth rate, uniformity of growth rate over a one inch substrate, and quality control, consisting of minimal background doping and maximum mobility.

2. The ability to dope the grown GaAs was to be addressed next, aiming for absolute control and for uniformity across the substrate. Here, two donors and one acceptor were envisioned.

3. The ability to grow with sharp doping steps was to be demonstrated.

4. GaAlAs was to be grown next, with good control over the alloy composition and its uniformity over the substrate.

5. The ability to dope the GaAlAs alloys both n-type and p-type, over a wide range of dopant concentration was to be shown next.

6. Finally, the ability to produce sharp steps and ultra-thin layers in the GaAlAs/GaAs system was to be demonstrated.

STATUS OF RESEARCH EFFORT

A. Epitaxial Growth of GaAs

The initial goals of the project were the achievement of controlled, high quality GaAs growth involving control over the growth rate, uniformity of deposition over the entire substrate area and the attainment of crystallographically perfect epitaxial layers with low background doping and high mobility. Semi-insulating (Cr), (100) GaAs substrates were used so that Hall Effect and resistivity measurements could be used to evaluate the grown layers. Chemically polished substrates were cleaned organically, etched with an acidic H_2O_2 etch, washed and blown dry with N_2 just prior to insertion into the UHV system. The native oxide was removed by heating to $590^\circ C$ in UHV, following the removal with Auger spectra. In the growth chamber, with a base pressure of less than 10^{-10} torr, growth was achieved at a substrate temperature between 550° and 650° , at a rate of $1 \mu m/hr$ and with a Ga/As flux ratio of 1:3 using an As_4 source of As. Sharp HEED streak diffraction patterns indicated good crystallographic structure and morphology during growth.

Initially the fluxes during growth were set by first establishing the As_4 flux using an ion gauge not in a direct line with the primary beam, and then adjusting the Ga flux to be a set fraction of the As_4 flux using the quadrupole mass spectrometer to set the ratio. This led to growth rate control of no better than $\pm 30\%$. To improve on this, we installed a nude ion flux gauge just below the substrate position, so that the Ga flux could be set directly just before growth. This improved growth rate control to $\pm 10\%$. However, the beam divergence changes as the Ga effusion cell slowly empties with time and the flux gauge measures the flux away from the center line of the beam. Thus, we always kept the Ga crucible almost full. To alleviate this, we plan to install a movable flux gauge, to measure the flux on the center line, in the substrate position, just prior to growth.

Growth rates and growth rate uniformities, were obtained by using shadow masks (wires) during growth, then measuring step heights after growth with a profilometer. With the substrate tilted towards the Ga effusion cell, growth control and uniformity were better than $\pm 10\%$ over a 1×2 cm substrate. Hall effect and resistivity measurements indicated that the background doping was low (p-type, low 10^{15} cm^{-3} range) and the electron mobility (after low n-type doping, see below) was high both at 300° and 77°K , comparable to the state of the art for MBE grown GaAs.

B. Doping of GaAs

Two donors (Sn and Si) and one acceptor (Be) were used to establish doping capabilities. Sn is an easy donor dopant in bulk layers, but its surface segregation obviates its use in fabricating sharp doping steps. Thus Si was added for this function. Hall effect measurements, again on semi-insulating substrates, established the relationship between carrier density and dopant effusion cell temperature. The flux gauge could only be used at the higher flux values. On an Arrhenius plot the observed data were parallel to the published vapor pressure curves of the three dopants. For Sn the calibrated range was 5×10^{15} to 10^{18} cm^{-3} , for Si it was 10^{16} to $6 \times 10^{18} \text{ cm}^{-3}$ and for Be it was 5×10^{15} to $2 \times 10^{19} \text{ cm}^{-3}$. Doping control of $\pm 20\%$ was achieved, with part of the error being due to the deviation in layer thickness control.

C. Doping Steps in GaAs

In order to test our overall ability for controlled growth rate and uniformity, doping control, and, especially, the ability to grow sharp planar steps in doping profile we grew a series of IMPATT structures. These included both single drift [$n 2 \times 10^{18} \text{ cm}^{-3}$ substrates $n 2 \times 10^{17}$ ($0.25 \mu \text{ m}$), $n 5 \times 10^{16}$ ($0.4 \mu \text{ m}$), $n 2.5 \times 10^{17}$ ($0.1 \mu \text{ m}$) and $p 2 \times 10^{18}$ ($0.2 \mu \text{ m}$)] and double drift [$(n 2 \times 10^{18}$ substrates $n 2 \times 10^{17}$ $10.25 \mu \text{ m}$), $n 5 \times 10^{16}$ ($0.4 \mu \text{ m}$), $n 2.5 \times 10^{17}$ ($0.1 \mu \text{ m}$), $p 8 \times 10^{16}$ ($0.35 \mu \text{ m}$) and $p 2 \times 10^{18}$ ($0.2 \mu \text{ m}$)] Read structures. Evaluation was done by C-V profiling with controlled etching steps. Layer thickness control and uniformity over a 1×2 cm substrate and doping control were as expected from the tolerances deduced above on single layers. For these multi-layer structures, approximately 80% of them fell in the overall $\pm 10\%$ range for thickness control of all layers simultaneously and 25% fell in the $\pm 20\%$ doping control range for the entire structure. The C-V measurements also indicated sharp doping steps, at least down to 100-200 Å. Microfabrication of these structures into IMPATT diodes, and evaluation of their microwave properties, is being done at the Electron Dynamics Division of Hughes Aircraft.

D. Growth of GeAlAs

We envision using GeAlAs layers primarily as barrier layers to GaAs rather than as active layers themselves. Thus growth and doping control as stringent as that for GaAs is not necessary. We focused on

two compositions, 0.2 and 0.3 mole per cent AlAs. These were grown on semi-insulating GaAs substrates at an overall rate of $1\mu\text{m/hr}$. The flux gauge and the mass spectrometer were used to set the Ga/Al ratio. The composition of the grown layers was measured by Auger spectra, EXDAC and an electron microprobe. The layers were easy to grow, with good morphology, growth control and composition control. Material quality evaluation based upon photoluminescence is waiting to be completed.

E. Doping of GaAlAs

Both n-type (Si) and p-type (Be) doping control was demonstrated by layers at both 0.2 and 0.3 mole fraction AlAs, by using Hall Effect measurements in epitaxial layers grown on semi-insulating GaAs substrates, no attempt was made to reach the same degree of doping control as achieved previously on GaAs, because such control of barrier layers is not necessary.

F. Sharp, uniform, doping and composition steps in the GaAs/GaAlAs system.

The final step in calibrating the MBE system, in learning how to use it, and in preparing some structures for additional investigation, consists of three parts which are now being done. First, we have grown several DH laser structures, with a $0.1\mu\text{m}$ GaAs layer as the active layer. These await fabrication into striped geometry lasers. Thresholds and C-V probing should demonstrate our ability to grow uniform and high quality layers of both GaAs and GaAlAs. Second, we will grow multiquantum well structures (~ 100 layers) with GaAs active layers and 30% Al barrier layers of varying layer widths, down to $10\text{\AA}$. These will be evaluated by x-ray diffraction, Auger profiling, C-V profiling and photoluminescence, to establish the limits to alloy and doping composition control to ultra-thin layers. Finally, we will grow some single heterostructure modulation doped FET structures, for demonstration of both interface sharpness and layer control. These three phases should be completed during the summer of 1982, allowing completion of our calibration and learning experience with the MBE system, as well as supplying the structures that will be used for our early MBE related research effort.

G. Future Direction

Long range research objectives were discussed during the last triennial JSEP review. We described two basic programs. The first program contemplated laying the basis for an MBE-based science and technology involving thin layers and heterojunctions in a new III-V materials and alloys system, the antimonides, including interfaces with II-IV compounds (CdTe). Here an investigation of the physics of the interfaces and several novel device concepts were proposed. However, the limited nature of this contract, both in time and in manpower, prohibits embarkation on such an ambitious project. Instead

we will implement the second, more limited program. This is based upon the GaAs/GaAlAs system, in which we have already demonstrated competence. There are two objectives here. First, we will fabricate FET structures using single quantum wells and small superlattices (multiple quantum wells), and study electron transport in these structures. Such devices offer the high mobility characteristics of single interface, modulation doped structures, the high electron mobility transistor (HEMT), as well as providing predetermined, uniform control of the electron density in the channel. Second, we will grow loosely coupled quantum well structures and study the characteristics of tunneling between wells, as a first step towards a three-dimensional device technology. These goals, already discussed at the triennial review, will be outlined in greater detail in our next proposal.

PUBLICATIONS

M. Gershenson and B.C. Chung, "Metal-organic Epitaxial Chemical Vapor Deposition of Semiconductors: A Tutorial Perspective", International Optoelectronics Workshop, Tainan, Taiwan, December 1981.

PROFESSIONAL PERSONNEL

MURRAY GERSHENZON, Principal Investigator, Professor of Electrical Engineering & Materials Science

B.C. CHUNG, Research Assistant

C. SHANNON, Technician

A SPECTROSCOPIC STUDY OF BASIC PROCESSES
IN ELECTRICALLY EXCITED MATERIALS
[Work Unit QE1-1]

MARTIN GUNDERSEN

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

The objective of this work was the investigation by optical techniques of the basic processes that occur in highly electrically excited materials. Through this approach it was intended to achieve a deeper understanding of the physics of high energy switches, and thus provide knowledge for the next generation of switches.

Objectives achieved during the previous year include:

1. Characterization of the plasma in a low-pressure glow discharge switch such as a hydrogen thyatron.
2. Measurement of electron densities using spectroscopic methods.
3. Collection of data for other research projects related to this problem, including a theoretical study of the thyatron switch plasma, and a study of optical interactions in switches.
4. Development of a laser-induced-fluorescence (LIF) experiment for the detection of metastable species.
5. Spectroscopic data on molecular fluorescence in the gas-phase switch, leading to information pertinent to switch recovery (high repetition rate operation).

STATUS OF THE RESEARCH EFFORT

This project has demonstrated that spectroscopy plays an essential role in studies related to pulsed power. The project for spectroscopic studies has achieved results that have significantly affected the pulsed power research program which is investigating gas-phase glow-discharge switches. These include the following.

1. Spectral data providing a determination of electron densities in situ in hydrogen thyatrons. Electron densities in thyatrons under high power operation are of the order $2 \times 10^{14} \text{ cm}^{-3}$. These results are described in more detail in Ref[1]. With this diagnostic tool it is possible to obtain extremely good spatial resolution ($\sim 1 \text{ mm}^2$). In addition, it is possible to obtain temporal resolution of the order 1 nsec. Further, the method is non-interfering, and thus suitable for various pulsed power applications. The method is based on measurement of Stark-broadened Balmer hydrogen line widths (Ref[2]).

Using this method it has been possible also to develop an experimental criterion for the glow-to-arc transition in the switch. In addition, data has been developed for a comprehensive theoretical analysis (Ref[3]).

2. These data were supplied to a study of the thyatron plasma based on the Boltzmann transport equation (Ref[3]). Figures are now available for various plasma parameters. These include typically:

average electron energy	≤ 1 eV
electric field	5 to 10 V/cm
ionization rate	10^{-10} cm ³ /sec
electron density	10^{14} cm ⁻³
current density	~ 30 A/cm ²

3. These methods are suitable for use in a high power facility, and they are non-interfering, have high spatial and temporal resolution, and work very well at high currents.

4. Streak camera data have demonstrated several features of the breakdown process in the thyatron (Ref[1]). These include observation of a delay between breakdown in the grid-cathode region and breakdown in the grid-anode region, and measurement of the velocity of a Townsend breakdown, 10^7 cm/sec.

5. The spectroscopic study has provided direct evidence of the formation of metastable species in the thyatron (Ref[4]). This is important because this neutral species has ~ 11.75 eV, and a lifetime of 10^{-3} sec, and thus may affect recovery of the device between pulses. The presence of this species had not been previously recognized.

6. We have also demonstrated that an intrinsic atomic or molecular species is affecting recovery of hydrogen thyatrons (Ref[1]).

7. A study of gases other than hydrogen is underway. Preliminary data indicating that helium can improve the rate of recovery has been obtained (Ref[5]).

8. A study of optical and laser processes as they affect switch performance has been undertaken (Ref[6]). This study suggests that the laser can play an important role in switch recovery as well as in breakdown.

9. An LIF experiment to measure the presence of metastable species during switch recovery is being undertaken.

A. Experimental

In order to obtain information on the molecular excited states formed during the discharge in thyratron devices spectra were obtained from glass-enclosed thyratrons including the EGG model 5C22 and ITT-Kuthe model 5949. The grid and anode in these devices are typically disks approximately 5 cm in diameter and separated by approximately 2 mm. A bluish-white emission from the narrow grid-anode region was studied. Pulse currents were obtained by discharging capacitors charged to voltages between 15 and 25 kV, thereby varying the emission intensity, and were monitored with a pulse current transformer. Peak currents were varied from 1 to 300 A in the 5C22 and 10 to 500 A in the 5949.

Light emitted from the grid anode region during the discharge pulse was collected by a lens and focused on the input slit of a monochromator with a resolution of approximately 0.03 nm. A photomultiplier tube attached to the output slit measured the light intensity. Detailed spatial resolution of the grid-anode region was limited by the tube geometry in that the grid structure, a restricted optical access. The response of the photomultiplier (~20 ns) limited the temporal resolution of the observed spectra to approximately 40 ns. The glow from the filament heater interfered with the spectra taken continuously only below 450 nm and was not observed at all in the time-resolved spectrum. The filament continuous emission is eliminated if the photomultiplier is terminated properly (typically several k Ω).

Spectra were obtained over the range 400--600 nm. Many lines and the corresponding molecular levels were readily identified, and the relative strengths of the observed lines corresponded well when the spectral response of the monochromator and the photocathode were taken into account.

With this apparatus it is also possible to make estimates of electron densities and electric field strengths as a function of current. This can be done by measuring the line width of the atomic Balmer emission as a function of current and determining the corresponding field and/or electron density from Stark broadening. The highest electron density was observed at high current levels (~500 A) in the 5949, and was approximately 3×10^{14} cm³.

B. The Hydrogen Metastable $c^3\Pi_u$

The dominant feature of the molecular emission is a cluster of lines due to transitions into $c^3\Pi_u$. The $c^3\Pi_u$ state is metastable. Relaxation of $c^3\Pi_u$ state is complex. Briefly, the lower Λ component of the vibrational and rotational states within $c^3\Pi_u$ can predissociate via $b^3\Sigma_u^+$ following selection rules $\pm \rightarrow \pm, a, s \rightarrow a, s$, and conservation of angular momentum. This process is fast (~10 ns) and accounts for the decay of 1/2 of $c^3\Pi_u$ molecules. For the remainder this transition is very strongly selection rule disallowed. These molecules (except $v = 0$)

relax through a dipole allowed infrared transition to $a^3\Sigma_g^+$, a non-metastable state, with lifetimes of approximately $100\ \mu\text{s}$.⁹ The $c^3\Pi_u$ $v=0$ state is lower in energy than all $a^3\Sigma_g^+$ states, and decays by quadrupole or magnetic dipole emission in $10^{-3}\ \text{s}$ to $b^3\Sigma_u^+$.

Processes involving excited species in gas-phase switches such as thyratrons are not well characterized, and details of energy transfer between excited species relating to breakdown, conduction, and recovery are generally not well understood in switches. For example the presence of long-lived species in a low pressure gas-phase switch following electrical excitation deserves consideration because these species may provide an intrinsic limitation to switch recovery rates. In hydrogen, molecular metastable species have only recently begun to be understood in detail. The physical processes occurring during the recovery phase that are a function of collisions involving metastables have not been investigated, and in particular the relative roles of ambipolar diffusion and metastable collision processes deserve study. As switches are required to provide higher repetition rates, faster rise times, and higher pulsed current and power handling capability, it will be necessary to develop devices based on an understanding of fundamental aspects of medium behavior.

In a gas at 300 mTorr collision rates between molecules will be of the order $3 \times 10^6\ \text{s}^{-1}$, e.g., approximately 3 per microsecond. This suggests that collision processes involving long-lived species deserve consideration. Collisions with walls should play a role in quenching of metastables; however, this process has not been characterized. Penning ionization should be efficient. Thus for example assuming an initial concentration of metastables of $10^{10}\ \text{cm}^{-3}$ and a typical gas kinetic rate of $10^{10}\ \text{cm}^{-3}\ \text{s}^{-1}$, one obtains for a rate of electron and ion generation, r ,

$$r \approx 10^{10}\ \text{s}^{-1}\ \text{cm}^{-3}.$$

This number is only an estimate and cannot be used to characterize an actual device; in particular it is difficult to make an accurate estimate of initial concentrations, and to account accurately for collisions with walls and other quenching processes.

It should be possible to study the temporal behavior of these states using laser-induced fluorescence. For example, using tunable dye laser at approximately 580 nm one may excite molecules in various ro-vibrational states of $c^3\Pi_u$ to $s^3\Delta_g$ then observe emission back to $c^3\Pi_u$. By varying the delay between the current pulse and the dye laser excitation, it will be possible to measure the metastable lifetime. Good spatial resolution could be obtained by modifying the grid structure, although in lieu of this it is possible to make observations in specially constructed optical cells.

These results demonstrate that long-lived species are being formed in hydrogen thyratrons, and suggest that some further understanding of the subsequent behavior of these species would be useful, and is probably important for the development of improved switches.

C. Electron Energy Measurements

For an atomic transition from upper level m to a lower level n the emissivity of a line of central wavelength λ_{mn} integrated over the entire line profile is given by

$$I_{mn} = 2hc^2 r_0 \frac{g_n}{g_m} \frac{f_{mn}}{\lambda_{mn}^3} N(m) (Wm^{-3} sr^{-1}) \quad (1)$$

where g_i denotes the degeneracy of the level i ; f_{mn} , the transition oscillator strength; r_0 , the classical electron radius; and $N(m)$, the population density of the upper state. For the three successive Balmer transitions observed, $n=2$ and $m=3,4,5$.

The ratios $I_{32}:I_{42}$ and $I_{42}:I_{52}$ were measured for various values of current. $N(m)$, the population density of the upper level, appearing in the right hand side of equation 1 is calculated based on various assumptions of the average energy and the energy distribution function of the electrons. In the following a discussion of three different approaches to characterizing the electron energy is presented.

First, the strong assumption that the plasma is in local thermal equilibrium is considered; in this model not only the free electrons, but also the bound electrons are required to populate the discrete energy levels in accordance with Maxwell-Boltzmann velocity distribution, so that

$$\frac{N(m_1)}{N(m_2)} = \frac{g_{m_1}}{g_{m_2}} e^{-(E_{m_1} - E_{m_2})/kT} \quad (2)$$

where the subscripts m_1 and m_2 refer to the upper levels of two Balmer lines and T denotes the electron temperature. The ratios $I_{32}:I_{42}$ and $I_{42}:I_{52}$ are now calculated from the right hand side of equation 2 for different values of T . It is found that typical electron temperatures are 0.5 ± 0.2 eV.

Second, it is assumed that only the free electrons have a Maxwellian velocity distribution and that the upper Balmer levels are populated by excitation of the ground state hydrogen molecules. This assumption is supported by the electron collision rate, $\sim 6 \times 10^9$ p (p in torr), and the Balmer emission data. During the conduction phase the ratio of Balmer emission intensities remains constant, for periods greater than a few nsec to well over 100 nsec. This suggests that the free electrons are in at least quasi-equilibrium, and can be characterized by a distribution function. It should be noted that it is unlikely that the molecules are in equilibrium, because the molecular collision rate is very low ($\sim 5 \times 10^6$ p (p in torr)).

Using the cross sections $\sigma(\epsilon)$ for excitation of atomic states from the molecular ground state it was assumed

$$N(m) = \text{constant} \int_{\epsilon_{\text{threshold}}}^{\infty} \sigma f(\epsilon) \epsilon \, d\epsilon \quad (3)$$

and the integral on the right hand side of (3) numerically evaluated for different values of T, and various distribution functions. Here $f(\epsilon)$ is the electron energy distribution function. If one assumes a Maxwellian distribution, evaluating the ratios $I_{32}:I_{42}$ and $I_{42}:I_{52}$ as functions of T from equation 1 results in an electron temperature that does not correlate well with reported excitation cross sections.

Third, if the average electron energy is low, then a two step procedure for the excitation of the Balmer lines and ionization should be considered. Electrons of energy 8.8 eV or higher were assumed to cause molecular dissociation into ground state hydrogen atoms and subsequently electrons with more than 12.03 eV caused excitations of these ground state atoms into the upper Balmer levels. The atomic excitation cross sections have been evaluated analytically. With these values of $\sigma(\epsilon)$ and $\epsilon_{\text{threshold}}$ substituted in equation 1 the are evaluated as a function of T. This work is in progress and results are to be published. In addition, a more thorough analysis using the Boltzmann transport equation, including elastic cross sections is in progress. These results indicate a relatively low electron energy.

D. Summary & Conclusion

The atomic and molecular emission from the different regions in glass enclosed hydrogen thyratron tubes have been studied spectroscopically. The formation of excited atomic and molecular species have been observed and various mechanisms which contribute to long lived ionization processes have been discussed. The average electron energy during the conduction phase is estimated to be about 0.5 eV, and the average electron density to be $\sim 10^{14} \text{ cm}^{-3}$. The propagation of the discharge across the tube has been photographed and its velocity estimated to be $\sim 10^6 \text{ cm/sec}$. The temporal behavior of the Balmer emission intensities show that even several hundred of nanoseconds after the end of the current pulse, the Balmer transitions are taking place. Because the lifetime of the Balmer emission is only $\sim 20 \text{ nsec}$, this demonstrates that excited atomic levels are being formed after the conduction phase. The mechanisms for the formation of these excited states is possibly through the long lived excited metastable molecular states.

We conclude that the spectroscopic study of gas phase switches such as the hydrogen thyratron yields useful information regarding the basic processes limiting switch operation. Further fundamental investigations of the role of metastable and other species, the role of other gases, and of other approaches to improved switches are currently in progress.

References:

1. S. Guha, H. Cole, and M.A. Gundersen, "A Study of Discharge Processes in Hydrogen Thyratrons", submitted to IEEE Trans. Plasma Science (invited).
2. S. K. Dhali, P.F. Williams, R. Crumley, M.A. Gundersen, "Electron Densities in Laser Triggered Hydrogen Sparks", IEEE Trans. Plasma Science. PS-8, 164 (1980).
3. J. Kunc and M.A. Gundersen, "Plasma Parameters Characteristic of Hydrogen Thyratrons", submitted to IEEE Trans. Plasma Science.
4. S. Guha and M.A. Gundersen, "Formation of Metastable Species in Hydrogen Thyratrons," J. Appl. Phys., 53, 1190 (1982).
5. S. Guha and M.A. Gundersen, submitted to IEEE Trans. Plasma Science.
6. M.A. Gundersen, "Optical Processes in the Performance and Recovery of Gas-phase switches," Appl. Opt., April 1982.

PUBLICATIONS

1. M.A. Gundersen, "Optical Processes in the Recovery of Gas-Phase Switches," Proc. 3rd IEEE International Pulsed Power Conf., 85 (1981).
2. M.A. Gundersen and S. Guha, "Formation of Long-lived Species in Hydrogen Thyratrons," Proc. 3rd Int'l. Pulsed Power Conference, 324 (1981).
3. M.A. Gundersen, "Optical Processes in Laser Controlled Switches," Proc. Electro-Optics/Laser 81, 34 (1981). (Invited)
4. R.A. Dougal, M.A. Gundersen and P.F. Williams, "Simple Powerful Tunable Single-mode and Mode-locked TEA CO₂ Laser," Rev. Sci. Instrum. 53, 181 (1982).
5. M.A. Gundersen and S. Guha, "Formation of Metastable Species in Hydrogen Thyratrons," J. Appl. Phys. 53, 1190 (1982).
6. M.A. Gundersen, T.A. Yocom, P.G. Snyder and P.F. Williams, "Efficient Infrared Upconversion in GaP," J. Appl. Phys. 53, 19 769 (1982).
7. T.A. Yocom, M.A. Gundersen and A.H. Bushnell, "Simple Pulsed HF Laser for Optical Experiments," Appl. Opt., to appear in March 1982.

8. M.A. Gundersen, "Optical Processes in the Performance and Recovery of Gas-phase Switches," Appl. Opt., April 1982.

9. M.A. Gundersen and T.A. Yocom, "Tunable Pump Laser Stabilization of the Optically Pumped CF_4 Laser," to appear in IEEE J. Quantum Electron.

10. M.A. Gundersen, "Optical Processes in Laser Controlled Gas-phase Switches," to appear in EOSD, June 1982.

PAPERS CURRENTLY UNDER REVIEW

1. P.G. Snyder and M.A. Gundersen, "A New Nitrogen Related Recombination in GaP," Phys. Rev. B, Rapid Commun.

2. P.G. Snyder, C. Myles, E.G. Bylander, and M.A. Gundersen, "A Non-radiative Recombination in GaAs.61 P.39:Ge," submitted to J. Appl. Phys.

3. S. Guha, H. Cole and M.A. Gundersen, "A Study of Discharge Processes in Hydrogen Thyratrons," submitted to IEEE Trans. Plasma Science (invited).

4. J. Kunc and M.A. Gundersen, "Plasma Parameters Under Discharge Conditions Characteristic of Hydrogen Thyratrons," IEEE Trans. Plasma Science.

PROFESSIONAL PERSONNEL

MARTIN A. GUNDERSEN, Principal Investigator

SHEKHAR GUHA, Research Associate

HOWARD COLE, Research Assistant

INTERACTIONS

A. Presentations

"Optically Pumped Lasers"

Army Research Office Meeting on Tunable Lasers
Keystone, Colorado, April 2, 1982

"Pulsed Power and Laser Research"

Advanced Nuclear Systems and Projects Division
Department of Energy
Germantown, MO, April 1981

~Laser Induced Recovery~

Texas Tech Pulsed Power Review
Lubbock < TX, May 1981

~Optical Processes in the Recovery of Gas Phase Switches~

Third International IEEE Pulsed Power Conference
June 1, 1981

~Formation of Metastable Species in Hydrogen Thyratrons~

Third International IEEE Pulsed Power Conference
June 2, 1981 (with S. Guha)

~Some Properties of Hydrogen Thyratrons~

AP Division, Los Alamos National Laboratory
June 3, 1981

~Optical Processes in Electrical Discharges~

33rd Gaseous Electronics Conference
October 23, 1981 (with S. Guha and H. Cole)

~Optical Processes in Laser Controlled Switches~

Electro-Optics/Laser 81
November 17, 1981 (Invited)

~Fundamental Properties of Hydrogen Thyratrons~

Naval Surface Weapons Center
Dahlgren, VA, February 17, 1982

~Pulsed Power Research Directed Towards Glow-Discharge Switches~

Sandia National Laboratory
February 19, 1982

B. Consultative and Advisory Functions

Consultant for Los Alamos National Laboratory

The Naval Surface Weapons Center and the Pulsed Power Group at
Ft. Monmouth have requested that our data be communicated to
companies involved in thyatron research and development.

C. Specific interactions during the last year

Advanced Nuclear Systems and Projects Division,
US Department of Energy, Germantown, MO,
April 28, 1981, W. Polansky, N. Haberman

Air Force Office of Scientific Research, Physics Division,
April 29, 1981, H. Schlossberg, L. Kravitz.

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The Air Force Weapons Laboratory, Kirtland AFB, A.H. Guenther

US Army MIRADCOM

Ft. Belvoir, VA, April 30, 1981, R. Buser

MIT Lincoln Laboratory

Lexington, MA, May 1, 1981, P.L. Kelley, H. Fetterman,

P. Tannenbaum, R. Osgood

EGG Inc.

Salem, MA, May 1, 1981, S. Goldberg, S. Friedman

Los Alamos National Laboratory

AP Division, June 3, 1981, C.R. Jones, S.D. Rockwood

Los Alamos National Laboratory

AP Division, August 1981, C.R. Jones, P. Mace, C. Tallman,

L. Radziems

ITT Electron Tube Division

Allentown, PA, October 22, 1981, H. Grunwald, A.J. Kelley

MIT Plasma Fusion Laboratory

October 23, 1981, R. Temkin, B. Blackwell

SRI International

November 1981, J. Peterson, L.C. Lee

Pulsed Power Group

Ft. Monmouth, N.J., December 14, 1981

S. Levy, M. Weiner, Sol Schneider

Workshop on Opening Switches

Tamarron, CO, January 12-15, 1982

Participated in editing and preparation of materials
for report.

A. H. Guenther, A. K. Hyder, A. Garscadden, P. Bletzinger,
from the Air Force, B.D. Guenther

Air Force Office of Scientific Research

Physics Division, February 16, 1982, A. K. Hyder

Naval Research Laboratory, February 16, 1982, W.L. Faust

Office of Naval Research

Physics Branch, February 17, 1982, B. Junker

Naval Surface Weapons Center

February 17, 1982, L. Leussen, F. Rose

Sandia National Laboratory

February 19, 1982, L. Pitchford, A. Owyung, C. Frost,

J. Woodworth

NEW DISCOVERIES AND SPECIFIC APPLICATIONS

1. Achievement of a modern theory of thyatron behavior.
2. Discovery of metastable species in the thyatron.
3. Demonstration of the applicability of spectroscopy to pulsed power physics.
4. Recommendation of specific mechanisms for improvement of thyatron operation.

LASER DEVICES AND APPLICATIONS
[Work Unit QE1-2]

WILLIAM H. STEIER

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

The objective of this work is to investigate non-linear materials in ultraviolet and to consider the uses of these materials in novel UV devices. During this period our work has included: (A) completion of the measurements on the two photon generated color centers and its uses in picosecond pulsewidth measurements in the UV; (B) measurement of the absorption of ZnS in UV and some unsuccessful attempts at phase conjugation using the XeF laser; (C) start up of an experiment to measure the saturation parameters of dyes in the UV using nanosecond pulses.

STATE OF THE RESEARCH

A. Two Photon Generated Color Center Gratings in KBr.
Proposed Picosecond Pulse Width Measuring Technique for the Ultraviolet.

Using the XeCl laser, measurements of the parameters of color center generation in KBr have been made. By interfering two UV beams we have written a grating pattern in the KBr using two photon generated color centers and we have measured the diffusion distance of the electrons before they become attached to impurities and form color centers. We have related these measurements to a proposed picosecond pulse width measuring technique. The results are given in detail in the article listed under PUBLICATIONS, and will not be repeated here.

B. Attempts at UV Phase Conjugation in ZnS.

Over the past several months we have been attempting to observe phase conjugation in ZnS using the XeF laser. The bandgap of ZnS (3.74 eV) is close enough to the XeF laser wavelength (353 nm) that considerable free carrier generation is expected at room temperatures. The expected phase conjugation is due to the plasma effect of these free carriers similar to the effect in Si at 1060 nm.

We have measured the absorption spectra of ZnS and observe a loss coefficient of $\sim 10 \text{ cm}^{-1}$ at 353 nm at room temperature. We have not been successful in observing phase conjugation. This is a difficult experiment because the path lengths of the two interfering beams must be equal to or less than the coherence length of the laser (0.6 mm). We now believe that to observe phase conjugation we must greatly improve the coherence of the laser. Techniques are available using an oscillator-amplifier combination that have significantly improved the coherence of excimer lasers. We have decided not to pursue this effort further and to concentrate on the dye saturation measurements described below.

C. Dye Saturation Measurements in the Ultraviolet

We have initiated a program to measure the saturation fluence of dyes using the excimer laser. Recent measurements on dyes in the UV have reported no saturation or have reported a decreased saturation at very high fluences due to excited state absorption. The motivation for this work is to understand the role of excited state absorption and possibly photo-dissociation in the UV absorption and to identify candidate dyes for mode locking in the UV or to identify dyes for preventing gain depletion due to spontaneous emission in amplifier chains.

To obtain results which apply to the picosecond pulsewidth regime, one must use pulses with pulsewidths less than the recovery time of the dyes. Several of the candidate dyes have recovery times of several nanoseconds and we believe we can obtain sufficient pulse energy from our system for pulse widths on the order of one nanosecond.

We have set up an experiment to obtain one nanosecond pulses from the XeCl laser with sufficient energy to saturate the candidate dyes. The output of the laser is normally a 10 nanosecond pulse with 30-40 millijoules of energy. Using a laser triggered spark gap and a KD^xP modulator we are able to chop out of the laser pulse a one nanosecond pulse.

The experiment works as follows. A portion of the laser output is focused into the spark gap and closes the switch. A high voltage wave front propagates thru the switch to one electrode of the KD^xP modulator. The remainder of the laser pulse propagates to the modulator and is timed to have peak intensity at the time the voltage wavefront arrives. The voltage wavefront opens the combination modulator-prism polarizer and allows the UV to pass thru. The modulator-prism remains open until the voltage wavefront propagates to the other modulator electrode. The modulator therefore remains open for the transit time of the cable connecting the two electrodes of the modulator.

We have succeeded in generating pulse of less than 2 nanoseconds but with energies of less than one millijoule. We believe we are oscilloscope limited in our pulsewidth measurements and believe we have a pulse in the order of one nanosecond. We have found several optical components in the experiment with unexpectedly high UV losses. One window on the modulator had above 50% loss and is being replaced. The calcite polarizing prism has 40% loss for the wanted polarization and we believe this is due to the quality of the calcite and cannot be improved. We still expect to get sufficient pulse energy with minor changes in the setup. We have found no difficulty in getting a rapidly rising voltage of greater than the half wave voltage on the modulator.

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Reliable and repeatable closing of the spark gap requires about 4 mJ of laser energy. We have also found that argon gas in the switch produces the fastest closing and the most reliable delay time between application of the laser pulse to the switch and the closing of the switch.

We have measured the focusability of the laser output and found that the 2 cm x 0.5 cm output beam can be focused to a 0.5 mm x 0.2 mm spot by a 5 cm focal length lens. Hence a one millijoule pulse could be focused to 10^3 mJ/cm² which should be more than sufficient to saturate the dyes.

Recent work by Muller et al [1] has shown dye saturation at 193 nm using longer pulses. The saturation is believed due to photo dissociation of the molecules and hence has a relatively long recovery time. This type of saturation is useful for preventing spontaneous emission in a chain of pulse amplifiers when the repetition rate between the pulses is low. However this saturation is not useful in modelocking where the dye must recover in nanoseconds. We are therefore considering a modification of our saturation experiments to get some measure of the recovery time to determine if photo dissociation is present. A small portion of the saturating pulse is delayed by several nanoseconds and used to probe the dye after the saturating pulse.

[1] D.F. Muller, M. Rothschild, K. Boyer, and C.K. Rhodes, "Saturable Absorbers at 193 nm" CLEOS, Phoenix, Arizona, April 1982.

PUBLICATIONS

Heungsup Park and William H. Steier, "Two Photon Generated Color-Center Grating in KBr: Proposed Picosecond Pulsewidth Measuring Technique for the Ultraviolet," IEEE J.Q.E., May 1981.

PROFESSIONAL PERSONNEL

WILLIAM H. STEIER, Principal Investigator, Professor of Electrical Engineering

CHRIS SEXTON, Research Assistant
EDWARD VAN GIESON, Undergraduate Student

INTERACTIONS

We have worked closely with the UV laser group at the Northrop Research and Technology Center where the work is largely funded by DOD. If our work succeeds in identifying a candidate dye we propose a joint experiment with NRTC to attempt passive modelocking of an e-beam pumped excimer laser.

QE1-2(4)

NEW DISCOVERIES

A novel new technique for making pico-second pulse width measurements in the ultraviolet using two photon generated color centers in alkali halides.

**TANDEM TIME OF FLIGHT LASER MASS SPECTROMETER USING
MULTIPHOTON AND VUV IONIZATION (QE9-2)**

INVESTIGATOR: C. WITTIG

REPORT PERIOD: APRIL 1981 - MARCH 1982

RESEARCH OBJECTIVES: OUR OBJECTIVES ARE TWOFOLD. FIRST, WE WILL DEVELOP A LASER MASS SPECTROMETER WHICH USES TANDEM TOF MASS FILTERS, TAKES AN ENTIRE SPECTRUM FOLLOWING A SINGLE LASER FIRING, AND CAN SELECT IONS ONE AT A TIME FOR FURTHER STUDY. THIS DEVICE WILL HAVE CONSIDERABLE ANALYTICAL POTENTIAL. WE WILL THEN USE THIS APPARATUS IN ORDER TO STUDY ELEMENTARY GAS PHASE PROCESSES INVOLVING IONS.

PROGRESS DURING PAST YEAR: As discussed in last year's proposal, our efforts during this period have been directed toward the development of advanced analytical instrumentation involving laser multiphoton ionization of molecules, as well as optical pumping and probing of the ions thus produced. We have used quadrupole and time-of-flight (TOF) mass filtering, in order to identify ions, and are presently developing instrumentation which involves advanced electronics design concepts, and which we believe will be the precursor to modern analytical devices in this area. During the past year, we have made progress toward these goals along two fronts, and these results are summarized here.

"SINGLE SHOT" LASER MULTIPHOTON IONIZATION DETECTION OF NASCENT FRAGMENTS FOLLOWING THE PHOTODISSOCIATION OF UF_6

The detection of free radicals by laser multiphoton ionization (MPI) is an attractive application of this technique, particularly under collision free conditions, since the method is extremely sensitive and is often state specific. It is also possible to detect species which absorb radiation but do not fluoresce, since the absorption can define a signature which is then manifest in the production of ions.^{1,2} In this communication, we report the results of experiments which address these issues for the technologically important case of UF_5 . Despite its significance in laser isotope separation schemes, the diagnostics available for monitoring the nascent UF_5 which derives from the photodissociation of UF_6 are primitive to say the least.^{3,4} In a previous publication, we demonstrated that UF_5 could be ionized via MPI in the presence of large backgrounds of UF_6 , and we pointed out that this method of detection allows the isotopic composition of the UF_5 to be determined.⁵ We also pointed out that by using a time-of-flight (TOF) mass filter, it would be possible to obtain such information very rapidly, allowing important parameters to be monitored continuously during experiments. We have now extended our experiments to include a TOF mass filter, and the use of tunable dye laser radiation for MPI of the nascent UF_5 photofragments, following the 266 nm photodissociation of UF_6 . The sensitivity is improved by at least two orders of magnitude over our previous results, and the entire MPI spectrum can be obtained following a single laser firing. Signal averaging will produce very high signal to noise ratio (S/N) in just a few seconds. This is the most promising diagnostic for monitoring UF_6 dissociation in an isotopically selective environment that has been developed to date.

The experimental arrangement is straightforward, and will be described in detail in a future publication. Both photodissociation and MPI are done with radiations which derive from a Quanta Ray Nd:YAG laser system. In the present experiments, we use the 266 nm 4th harmonic from the Nd:YAG laser to prepare nascent species which are then acted on with the dye laser radiation. The lasers overlap in an interaction region located between mesh electrodes, and positive ions are

accelerated toward a 2 mm dia. hole which is the entrance to the field free region of the TOF mass filter. The mesh electrode system consists of two regions in series. One region is 0.95 cm long and the potential difference between meshes is 700 V, and in the other region the meshes are 1.0 cm apart and the potential difference is 4000 V. The ions are formed in the region of low electric field, and pass through the region of higher electric field on the way to the drift tube. The counterpropagating 266 nm and dye laser radiations are both focused, with 50 and 30 cm focal length lenses respectively, in order to prevent radiation from striking surfaces near the accelerating grids. The 266 nm radiation is attenuated ($\sim 50 \text{ mJ cm}^{-2}$) in order that no more than a few percent of the UF_6 molecules are dissociated, as in our previous report.⁵ An optical delay of 20 ns between the 266 nm and dye laser pulses insures that the action of these two pulses is sequential, and that multiphoton processes involving the simultaneous annihilation of 266 nm and dye laser photons do not occur.

Ions which enter the field free region travel 1 m and are then detected with a tandem microchannel plate array (Varian). Signals from the plates are amplified, digitized (Biomation 8100), and either stored or averaged, depending on the experiment. The TOF/detection region is pumped separately from the sample chamber, and is maintained at $\sim 10^{-7}$ Torr during experiments.

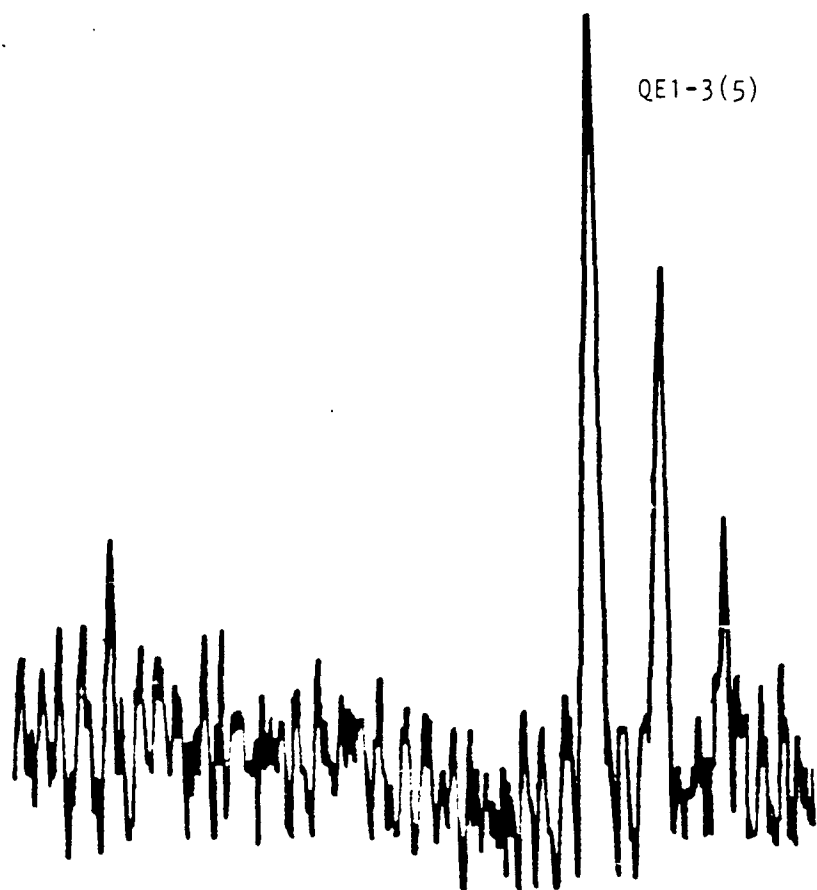
Using the arrangement described above, it was possible to reproduce the results of ref. 5, but under experimental conditions which seriously compromised the performance of the microchannel plate detectors. These detectors are adversely affected by high pressures of UF_6 vapor (10^{-5} Torr), and the ionization efficiency at 532 nm is quite low, therefore requiring more differential pumping than was possible with our arrangement. Even with 100 mJ of 532 nm radiation, MPI signals were small and required uncomfortable amounts of UF_6 vapor in the sample chamber. We were thus led to peruse shorter wavelengths for MPI, while trying to maintain the same high discrimination against undesirable MPI of UF_6 which we achieved in our earlier work.⁵ All of the results reported below were obtained using low energy tunable dye laser radiation (2-3 mJ, 433-474 nm), which proved quite superior to 532 nm radiation for ionizing the nascent photofragments. We estimate that the ionization efficiency at the shorter wavelengths exceeds that at 532 nm by approximately two orders of magnitude.

Typical experimental results are shown in fig. 1 for "single shot" as well as averaged mass spectra, taken with 3 mJ of 450 nm ionizing radiation. Averaging 256 signals requires less than half a minute, and produces very high S/N spectra. The mass spectra reported here are quite similar, but not identical, to those reported earlier. Since the cracking patterns for MPI excitation depend on the wavelength and intensity of the ionizing radiation, this behavior is to be expected.⁶ Although the (S/N)

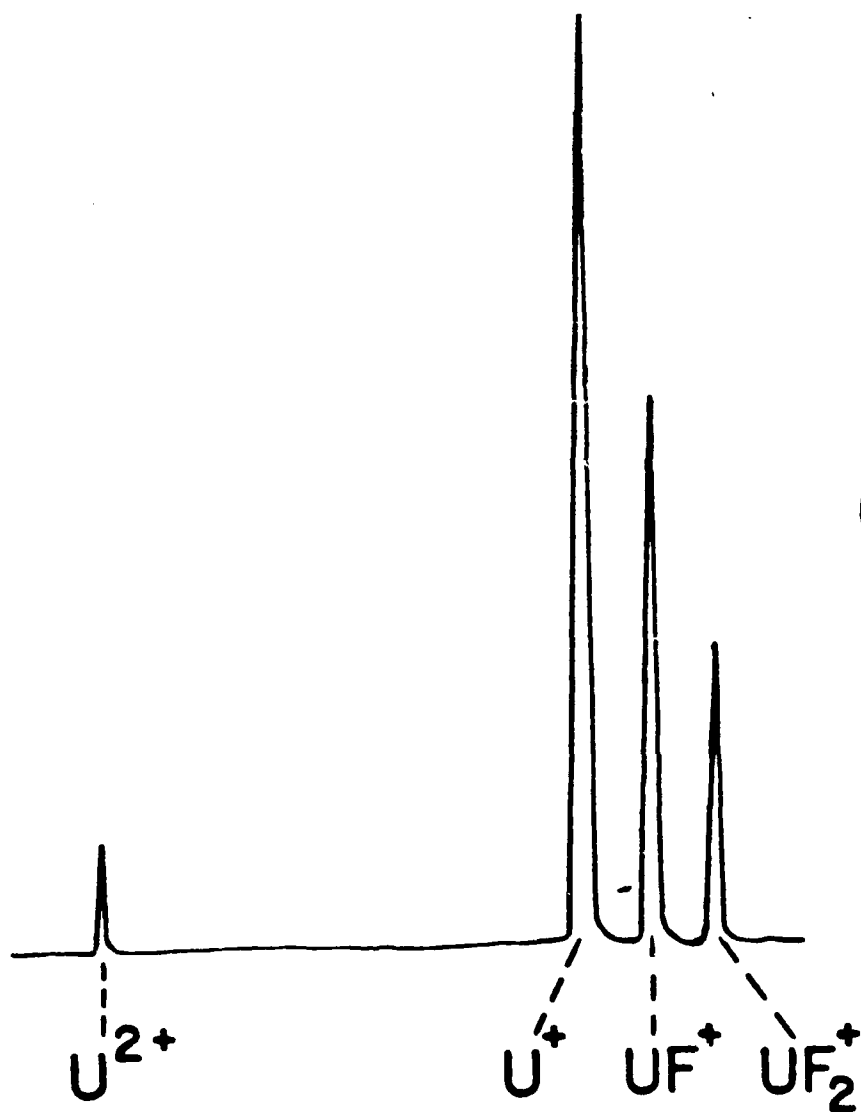
Figure 1. TOF mass spectra following MPI of the nascent photofragments from the 266 nm photodissociation of UF_6 . There is no detectable signal with either laser blocked, and there is a 20 ns delay between the onsets of the 266 and 450 nm pulses. The pressure in the sample chamber is 10^{-5} Torr, and the laser energies at 450 and 266 nm are 3 and <0.5 mJ respectively.

QE1-3(5)

SINGLE PULSE



AVERAGED
(256 PULSES)



for a single laser firing was not particularly high in the present experiments, we are confident that modest technological changes can improve this markedly. We estimate that only $\sim 10^{-3}$ of the nascent photofragments are ionized via MPI under the present experimental conditions,⁷ and this can be improved by using higher energy laser pulses. The laser energy used for MPI can be increased until parent ionization begins, at which point further increases in the intensity of the ionizing radiation are pointless for diagnostic purposes. The use of a pulsed supersonic expansion nozzle operating synchronously with the lasers enables high densities to be achieved under collision free conditions, and we hope to include this in our apparatus in the future. Also, another stage of differential pumping would be beneficial to the detection system.

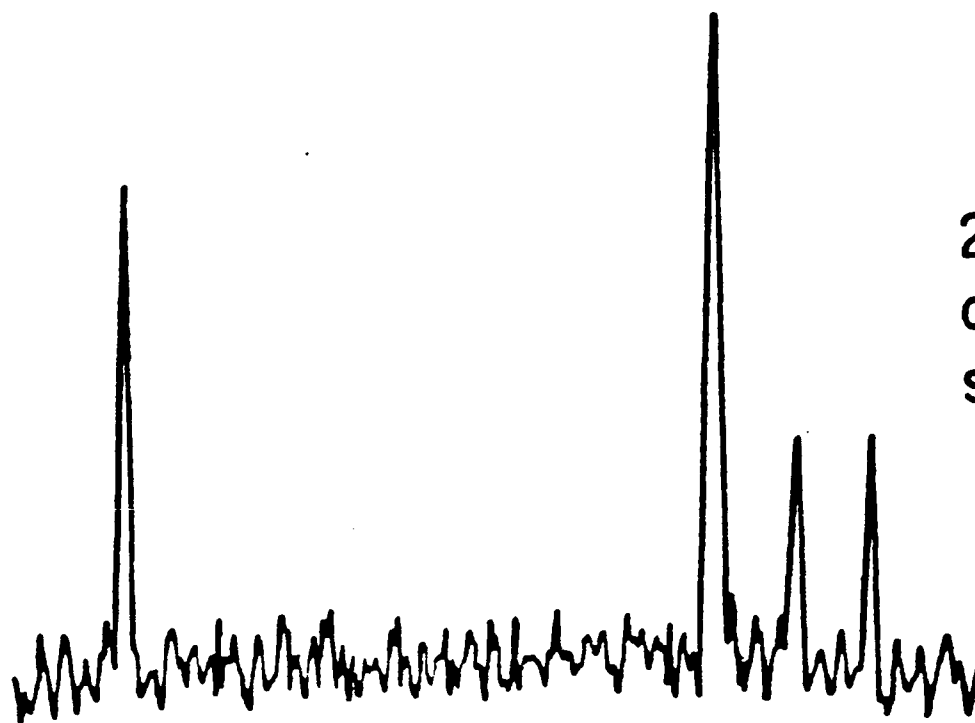
Data which were qualitatively similar to those shown in Fig. 1 were also obtained using 433 and 474 nm ionizing radiation. In all cases, the ionizing radiation was < 3 mJ, and the signals increased markedly with the intensity of the ionizing radiation. As before, there was no detectable signal with either the 266 nm or ionizing radiation blocked, showing that ions formed by the direct dye laser MPI of UF_6 are negligible.

With larger 266 nm fluences, it was possible to produce ions in addition to neutrals, and to further act on this ensemble of neutral and ionic species with dye laser radiation. A typical result from such an experiment, under single shot conditions, is shown in fig. 2 for the case of 433 nm dye laser radiation. As before, there is no MPI using 433 nm radiation alone. Clearly, there are ions formed by MPI at both 266 and 433 nm. The ion distribution following 433 nm irradiation is the result of ionization and fragmentation at both 266 and 433 nm, and it is difficult to determine unambiguously the respective roles of 433 nm MPI of neutrals, and 433 nm fragmentation of the ions already present. This difficulty can be overcome by delaying the 433 nm radiation with respect to the 266 nm radiation. With suitable delay, the ions deriving from 266 nm MPI will have been swept out of the interaction region before the 433 nm radiation arrives, thereby ionizing the remaining neutrals. A convenient, adjustable delay between the two groups of ions (e.g. 500 ns) will separate species in the TOF spectrum and allow the separate groups of ions to be determined without resort to messy manipulations of the data. Such experiments will be carried out in the future in our laboratory.

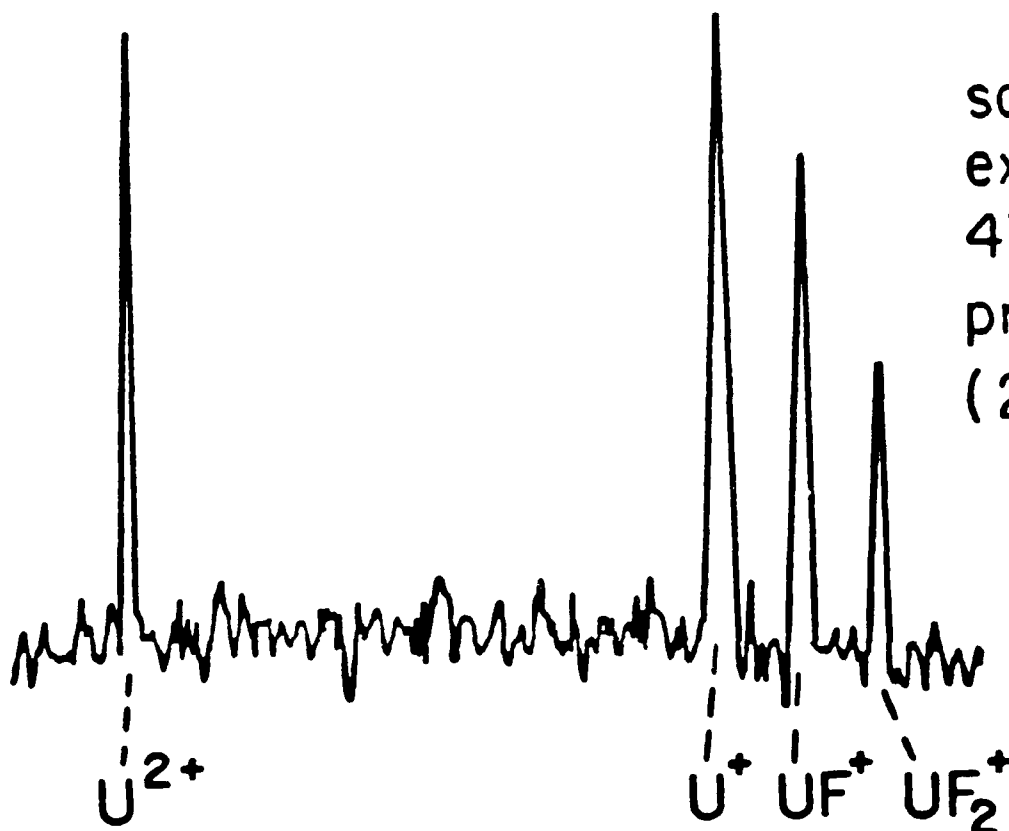
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Figure 2. TOF mass spectra for the case when the 266 nm fluence is high enough to produce some ionization in the absence of the dye laser radiation. The 433 nm radiation may now fragment the ions as well as ionize the neutrals (see text for details).



266nm radiation
alone produces
some ionization



same as above,
except with
433nm also
present
(20 ns delay)

U^{2+}

U^{+}

UF^{+}

UF_2^{+}

—→ t, m/e

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LASER MULTIPHOTON IONIZATION OF TRIETHYLAMINE FOLLOWING COLLISION FREE IR MULTIPLE PHOTON EXCITATION

Laser multiphoton ionization¹ (MPI) can, in principle, be used for the selective detection of any species involved in a chemical reaction. Selectivity can be greatly enhanced by using an intermediate resonant electronic transition to enhance the ionization efficiency of a given species, a variant of MPI called REMPI (resonance enhanced MPI).² Its sensitivity is better than that of laser induced fluorescence (LIF), and its use is not limited to fluorescing species.^{1,3} It has been shown that it may be used for quantitative estimates of molecular concentrations, both under collision free conditions and with high pressure gaseous samples,⁴ and recently MPI has been used to monitor transient species such as free radicals (e.g. CH_3)^{5,6} and nascent products of unimolecular reactions induced both by IR multiple photon excitation and dissociation (MPD and MPE)⁷ and by visible and UV radiation.^{6,8,9} Recently,¹⁰ the technique was extended to include the MPI of vibrationally excited molecules, prepared via IRMPD under collision free conditions, using the output from a pulsed CO_2 laser. A significant enhancement of the ionization signal was obtained for all the major species appearing in the MPI mass spectrum of 1,1,1 trichloroethane. In this communication we show that vibrational excitation can be used to extensively change the MPI fragmentation patterns, and our results also suggest that it may be possible to detect large organic free radicals in a facile, straightforward manner.

The experimental arrangement is described in detail elsewhere,¹¹ and only features deemed essential to the present report are discussed here. The output from a pulsed CO_2 laser (Lumonics 103, 100 ns fwhm spike, 1-2 μs tail) is focused into the center of the modified ionizer region of a quadrupole mass spectrometer (UTI 100C), and overlaps the focused, counterpropagating output from a pulsed dye laser (Quanta Ray), which is used for MPI. The dye laser interrogates the molecules $1.40 \pm 0.05 \mu\text{s}$ after the peak of the CO_2 laser pulse, and the ions thus produced are sent to the separately pumped mass filter, and detected with a channeltron. The ion signal is sent to a boxcar integrator (PAR 162/165) whose output is averaged by a computer. Typically, results from 10-50 laser firings are averaged at a repetition frequency of 0.5 Hz.

Triethylamine (TEA) was chosen for the present study because its MPI has been extensively studied,^{12,13} and this species offers several advantages in the experiments reported here. The REMPI fragmentation pattern consists primarily of only two peaks, the parent ion at $m/e=101$ and the parent-minus-methyl ion at $m/e=86$. The branching ratio depends strongly on the laser wavelength throughout the 400-500 nm region, but not on the dye laser power.¹² In particular, REMPI with 490 nm radiation produces mainly $m/e=86$ (a 4-photon process), even though the parent ion is energetically accessible via a 3-photon channel. Unfavorable Franck-Condon (FC) overlap in the electronic transition connecting the ground state to the ionization continuum via a 2-photon allowed intermediate state was suggested

as the cause for the inefficiency of the 3-photon route.¹² Thus, using 490 nm radiation for MPI, the 4-photon process dominates, thereby favoring $m/e=86$ over the lower energy channel. TEA absorbs quite strongly near 9.3 μm , and vibrational excitation is easily achieved using the pulsed CO_2 laser.

We find that upon vibrational excitation, the $m/e=101$ signal increases dramatically (Fig. 1), but only at low fluences. The maximum signal is obtained at approximately 1 J/cm^2 . The $m/e=86$ signal is also enhanced, but to a much lesser extent at low fluences. Increasing the CO_2 laser fluence beyond 1 J/cm^2 causes a sharp decrease in $m/e=101$, and a further increase in $m/e=86$, reaching a maximum at about 10 J/cm^2 . We note that the $m/e=86$ maximum occurs when the $m/e=101$ signal is smaller than the signal observed with the dye laser only. Above 10 J/cm^2 the $m/e=86$ signal decreases, displaying a qualitatively similar behavior to that of $m/e=101$. At fluences above 16 J/cm^2 , a $m/e=58$ signal appears, and at higher fluences also an $m/e=30$ signal. These signals (indicating further fragmentation) increase with fluence, but remain small compared to $m/e=86$ even at 40 J/cm^2 . The total ion current is thus significantly reduced at high fluence levels.

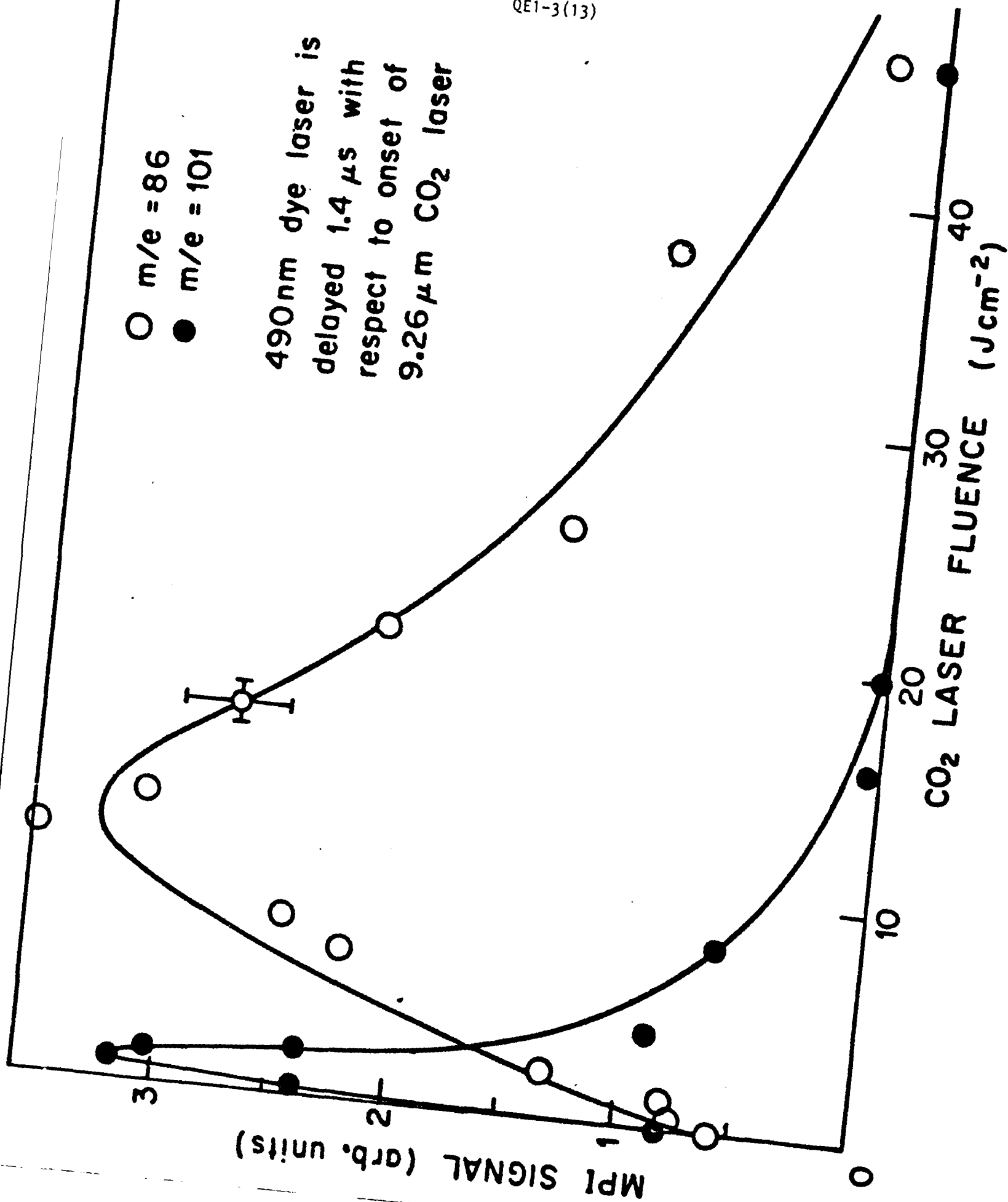
The sharp increase in the $m/e=101$ signal following IRMPE is consistent with a mechanism wherein vibrational excitation of the neutral enhances the overall electronic transition probabilities, (here, the 3-photon REMPI). Poor FC overlap near ionization threshold is a well known feature in many molecules, causing a considerable decline in ionization efficiency, and ambiguities in the precise determination of adiabatic ionization potentials. In REMPI this problem is compounded by FC factors for transitions to intermediate states. For TEA, these are known to be small near the origin of the transition, as is evident from the large Stokes shift between the absorption and fluorescence spectra.¹³ This phenomenon is expected to be quite general.

The loss of $m/e=101$ signal and the concurrent increase in $m/e=86$ signal at fluences $\geq 1 \text{ J/cm}^2$ is striking, and may derive from several mechanisms. Firstly, as TEA is vibrationally excited via IRMPE, its vibrational partition function increases rapidly and its spectral features broaden and shift in ways that are well documented.² The MPI ion signal decreases because of this, but not to the extent observed in our measurements. Also, this mechanism is not consistent with the $m/e=86$ signal enhancement. Secondly, if TEA molecules acquire sufficient vibrational excitation, three 490 nm photons can promote these species to energies in excess of those required to produce $m/e=86$, via the unimolecular decay of $m/e=101$ excited above its dissociation threshold. Finally, neutral TEA molecules which dissociate cannot contribute to the $m/e=101$ signal, but may enhance the $m/e=86$ signal. Molecules that acquire large amounts of vibrational energy but not enough for IRMPD to occur, contribute to the second mechanism. This mechanism is therefore feasible at intermediate CO_2 laser fluences. It is also quite consistent with the enhancement of the $m/e=86$ signal. At high

Figure 1. The relative amplitude of the MPI signal as a function of the CO₂ laser fluence. Data are not corrected for different transmission coefficients through the mass filter. The m/e=86 signal was approximately 8 times larger than the m/e=101 signal with the CO₂ laser blocked.

○ $m/e = 86$
● $m/e = 101$

490nm dye laser is
delayed 1.4 μ s with
respect to onset of
9.26 μ m CO₂ laser



fluences ($\geq 10 \text{ J/cm}^2$) dissociation of TEA is very likely to be increasingly significant. This has been observed with most large organic molecules that display strong absorption feature overlapping CO_2 laser lines.^{2,14,15} The dissociation pattern of TEA may be complex, since several routes involving simple bond fission appear to have similar thresholds. The bond energies are about equal ($72\text{--}74 \text{ kcal mol}^{-1}$) for both the C-C and C-N bonds, and dissociation of TEA with a loss of a CH_3 group gives rise to a radical $(\text{C}_2\text{H}_5)_2\text{NCH}_2$ (mass 86) that may contribute to the observed $m/e=86$ signal at high CO_2 laser fluences. The overall loss of ion signal at very high fluences is most easily accounted for by efficient dissociation to smaller fragments, not readily ionized using 490 nm radiation.

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see A.M. Halpern, Mol. Photochem. 5, 517 (1973).

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16. F. Kong, H. Reisler, and C. Wittig, "The unimolecular reaction of isolated CF_3CN near dissociation threshold", J. Chem. Phys. **76** (1982), in press.
17. F. Shokoohi, A.M. Renlund, H. Reisler, and C. Wittig, "Reactions of C_2H with small molecules", in preparation.
18. T. Fischer and C. Wittig, "Frequency tuning and high energy operation of the C_2D_2 laser," Appl. Phys. Lett., (1982), in press.
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22. T.A. Watson, M. Addison, and C. Wittig, "Reactions of atomic oxygen with CF_3I : sequential processes leading to the formation of $\text{IF}(\text{X})$," in preparation.
23. Y. Haas, H. Reisler, and C. Wittig, "Laser multiphoton ionization of triethylamine following collision free IR multiple photon excitation," J. Chem. Phys., submitted.

THESES 1981/1982

Thomas Fischer (1981)
 Donald Spencer (1981)
 Henry Helvajian (1981)

PRESENTATIONS, 1981

Intramolecular processes in polyatomic molecules, USC, Chemical Physics Seminar.	6 Jan.
Laser multiphoton ionization as a means of detecting nascent UF₅, DOE, Germantown MD, contractors meeting.	9 Jan.
Precise studies of unimolecular reactions using state specific diagnostics, Berkeley CA, Workshop on fundamental research concerning energetic materials.	22 Jan.
Intramolecular processes in polyatomic molecules, The Aerospace Corp., Los Angeles CA, Chemical Kinetics Seminar.	26 Jan.
Unimolecular reactions of isolated molecules, Harvard Univ., Chemical Physics Seminar.	16 March
Time of flight mass spectroscopy studies DOE, Germantown MD, LIS Seminar.	17 March
Unimolecular reactions: statistics and dynamics, Naval Research Labs, Washington DC, Physics Seminar.	18 March
n-center chemical reactions, Yale Univ., Chemical Physics Colloquium.	27 March
Reaction dynamics of unimolecular processes Brookhaven Natl. Labs, Upton NY, Chemistry Seminar.	28 April
The 4-center reaction of diatomic carbon with NO, and other oddities, Harvard Univ., Chemical Physics Seminar.	12 May
Laser diagnostics: from industrial processes to the transition state, Exxon Research Labs, Linden NJ, Laser Chemistry Seminar.	22 May
Dynamics and elementary processes, MIT Lincoln Laboratories, Applied Photochemistry Group Seminar.	26 May
The era of the chemical laser, Univ. of Illinois, Urbana IL, Commemoration for Prof. Paul Coleman.	9 June
Product V,R,T excitations in laser driven unimolecular reactions, Univ. of Oxford, informal Chemical Physics Seminar.	16 June

*on sabbatical leave, Spring 1981.

Laser multiphoton ionization , Gordon Conference on Molecular Dynamics, Wolfeboro NH.	30 July
Detailed studies of elementary gas phase processes , Gordon Conference on Non-linear Optics, Wolfeboro NH.	6 Aug.
Reactions of gaseous free radicals , AFOSR sponsored colloquium on chemical dynamics, Albuquerque NM.	9 Nov.
Laser diagnostics , SPIEE symposium on laser processing of materials, Anaheim CA.	16 Nov.
Reactions of the ethynyl radical , Combustion Symposium, USC.	16 Nov.
Dealing with product energy disposal in unimolecular reactions , Univ. of Utah, Chemistry Seminar.	24 Nov.
The physics of dissociation and desorption , Calif. State Univ., Northridge CA, Physics Seminar.	25 Nov.
Detailed studies of gas phase chemical reactions , Aberdeen proving grounds MD, Chemistry Seminar.	15 Dec.
Collisional deexcitation of $\text{Hg}(6^3\text{P})$ by HgBr and Br: the $\text{HgBr}(\text{B})$ product channel , Lasers 81 Conference, New Orleans LA.	16 Dec.
Selective production of $\text{Br}(^2\text{P}_{1/2})$ via the "spin wave" reaction of $\text{I}(^2\text{P}_{1/2})$ with Br_2 , Lasers 81 Conference, New Orleans LA.	17 Dec.

PRESENTATIONS, 1982

1. 14 January **Nonlinear optical processes in chemical physics**, Winter Colloquium on Quantum Electronics, Snowmass, UT.
2. 26 January **Laser time of flight mass spectrometer**, Joint Services Electronics Program Review, USC.
3. 17 February **Surface desorption: a sensible approach to product V,R,T excitations**, Quantum Electronics Seminar, USC.
4. 25 February **Reaction dynamics of unimolecular and bimolecular processes**, Laser Chemistry, Seminar, Exxon Research Labs, Linden, NJ.
5. 3 March **Microscopic details of combustion processes**, Combustion Division Seminar, Sandia Labs, Livermore, CA.
6. 24 March **The nature of chemical change involving devious intermediates**, Chemistry Department Colloquium, Illinois Institute of Technology, Chicago, IL.
7. 25 March **Product energy disposal in unimolecular reactions**, Chemistry Colloquium, Argonne National Labs, Argonne, IL.
8. 25 March **The chemistry of the ubiquitous ethynyl radical**, Theoretical Chemistry Group Seminar, Argonne National Labs, Argonne, IL.
9. 29 March **The chemistry of $C_2H(X,A,...)$** , ACS meeting (poster), Las Vegas, Nevada.
10. 31 March **The unimolecular decomposition of CF_3CN : product V,R,T excitations**, ACS meeting (poster), Las Vegas, Nevada.
11. 1 April **Unimolecular reactions of isolated polyatomic ions**, ACS meeting (poster), Las Vegas, Nevada.

12. 12 April **The elusive and hungry ethynyl radical,**
Chemistry Department Colloquium, University
of California, Irvine, CA.
13. 4 May **Quantum level measurements of unimolecular**
reactions of nitrites and nitroso compounds,
Energetic Materials Workshop, Eastern Shore, MD.
14. 12 May **Advanced diagnostics using laser**
spectroscopy: the next generation,
Industrial Associates Review, USC.
15. 18 May **Experimental studies concerning microscopic**
details in chemical reactions, Chemical
Physics Colloquium, California Institute of
Technology.

PROFESSIONAL PERSONNEL 1981/1982

Curt Wittig
Hanna Reisler
Yehuda Haas
Henry Helvajian
Thomas Fischer
Michael Stuke
Joseph Catanzarite
Delroy Baugh
Frough Shokoohi
Thomas Watson
Fanao Kong
David Sumida
Jim-Son Chou
Julio Caballero
Francisco Pessine
Milan Trtica
Donald Spencer

FURTHERING DATA ABSTRACTION VERIFICATION
[Work Unit IEL-1]

LAWRENCE FLON

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

Research during the reporting period has been concentrated on two efforts:

- 1) A design methodology for large systems aimed at transforming system requirements into an implementation meeting those requirements;
- 2) An investigation of a software design methodology and support system, called "metaprogramming".

STATUS OF RESEARCH EFFORT

Research on topic (1) over the last several years has been brought to a successful conclusion at this time. Using our methodology, a system is derived incrementally from the initial statement of its requirements. The resulting hierarchy of system designs is one of detail, not one of system structure or functionality. Each level in the hierarchy is a complete, self-contained description of the system. Each level is derived from, and is more detailed than, the previous level. A level consists of a model of the system and requirements constraining the model. The methodology defines verification steps that must be taken as new levels are produced. This highlights one of the benefits of using this design strategy. It might be quite difficult to show that a system implementation satisfies some high level requirement such as fault-tolerance. It is easier to show that the high level requirement is satisfied by a somewhat lower level specification, that each lower level specification is satisfied by a still lower level specification, and finally that a specification is satisfied by the implementation.

The major by-product of this research has been the successful PhD dissertation [1], authored by Dr. Deborah Baker, now on the faculty of the University of Colorado. In this dissertation, the methodology is developed and applied to the major example of (re-)designing the SIFT computer system, a fault-tolerant avionics system developed by SRI International under contract from NASA Langley. Also in the process of development is [2], a joint paper between the Principal Investigator and Dr. Baker, summarizing the results in a more terse form.

Research on topic (2) has been underway for about one year. A metaprogram is the simultaneous denotation of a class of implementations with the same abstract behavior. Because metaprograms

are not tied to particular execution environments, they can be stored in a library from which a programmer can effectively choose those relevant to his/her task, supply them with appropriate information about the desired execution environment, and incorporate the resulting actual programs into a larger system. The benefits of such an approach to system construction include significantly reduced development time and significantly enhanced reliability.

The developing research includes the design of a metaprogramming language, i.e. one in which one can conveniently denote metaprograms. This metaprogramming language is based upon the Ada programming language. We are currently implementing an Ada front-end and interpreter which we will use as the vehicle to test out our metaprograms. We are also actively involved in the design of the environment that a programmer would use to interact with the metaprogram database. We have in progress a paper summarizing our research thus far [3]. This research effort is now being supported directly by AFOSR, with the conclusion of our JSEP support.

PUBLICATIONS

1. Baker, D., "The Use of Requirements in Rigorous System Design", PhD Dissertation, Computer Science Department, University of Southern California, December 1981. (Available as a USC-CSD Technical Report.)
2. Baker, D., and Flon, L., "Requirements-Driven System Design", in preparation.
3. Flon, L. and Coopridier, L. W., "Metaprogramming - Prospects for the Practical Reuse of Software", in preparation.

PROFESSIONAL PERSONNEL

LAWRENCE FLON, Principal Investigator

DEBORAH BAKER, Research Assistant (through December 1981)

ANNE CURRAN, Research Assistant (half-time, January-March 1981)

THIERRY PARADAN, Research Assistant (half-time, January-March 1981)

INTERACTIONS

Dr. Baker gave presentations concerning her Phd research at the University of Colorado, the University of Michigan, Washington University, St. Louis, the University of Virginia, and Ohio State University. Dr. Flon gave a presentation on metaprogramming at USC's Information Sciences Institute.

A SUPPORT ENVIRONMENT FOR INFORMATION BASES
[Work Unit IE1-2]

DENNIS MCLEOD

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

The principal purpose of this research is to develop and demonstrate techniques to support the design, evolution, and interconnection of databases. A major goal is to devise an approach that will allow users with little or no database expertise to perform these functions directly.

A new specific research direction, initiated in early 1982, involves the design and implementation of an experimental prototype information management environment for a personal (workstation) computer. The goal of this specific project, called INFOBASE (for INFOrmation BASE Support Environment), is to enable an end-user to directly define, classify, interrelate, manipulate, and share a universe of information objects, and provide an access port onto a network of large databases and information sources. The term "information base" is used here in place of "database" to stress that INFOBASE must handle information objects of a variety of modalities, such as formatted data, communication messages, algorithms, documentation, images, descriptive/structural information, and so forth.

STATUS OF RESEARCH EFFORT

During the past contract year, several subtasks of this JSEP research project were completed.

1. A new technique has been developed to support the design and structuring of computerized databases, which optimizes their understandability and usability. The design and refinement of this "semantic database model" (named SDM) has been completed, and the results are detailed in <Hammer+McLeod 1981>.

2. A general survey and framework for the comparative evaluation of semantic database models has been produced. This includes a comprehensive overview of relevant research on semantic database models as well as the relationships of semantic database modelling techniques with related research on abstract datatypes (in the programming languages area) and knowledge representation techniques (in the artificial intelligence domain). The results of this analysis are published in <King+McLeod 1982a>.

3. A design and implementation of the "event database specification model", an integrated model and methodology for conceptual database design, has been produced <King+McLeod 1982b, King+McLeod 1982c>. This work has drawn upon our prior work on SDM and our experience in using it. In particular, the event model is much simpler than SDM, and it provides integrated facilities for database specification, evolution, and access. The event model includes a prescriptive methodology to guide its use, thereby reducing the expertise required to design and document databases.

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

5. The design of the "federated database" architecture has been completed <Heimbigner+McLeod 1981>. This approach supports both the logical and physical decentralization required to support a network of databases. While contemporary approaches to "distributed databases" and "heterogeneous database systems" require a centralized logical organization, and centralized control, the federated database architecture addresses many problems associated with logical centralization by providing flexible sharing of information, but maintaining substantial autonomy for the component databases (viz., those constituting the federation). The federated database architecture provides a mechanism for specifying and negotiating the information exchange requirements among components, an approach to the effective processing of information exchange requests among components (transaction processing), and a methodology to support the design and evolution of a federation. The prototype federated database system will be completed by July 1982.

The above specific results will provide strong input into the new specific direction of this research, namely the INFOBASE project.

As stated above, the goal of the INFOBASE project is to enable an end-user to directly define, classify, interrelate, manipulate, and share a universe of information objects, and provide an access port onto a network of large databases and information sources. An experimental INFOBASE prototype is being designed, and an implementation is planned on a powerful but relatively inexpensive personal workstation computer. INFOBASE will provide a framework in which to devise and demonstrate the principles and techniques required to allow end-users to directly design, use, evolve, and dynamically interconnect information bases.

Intended applications of INFOBASE include handling the data necessary to support the activities of a professional, manager, and engineer (in software engineering, VLSI design, and computer-aided design and manufacturing (CAD/CAM), etc.). These applications, while varied in nature, share the common underlying information management requirement to allow end-users to directly design, use, evolve, and dynamically interconnect information bases.

PUBLICATIONS

1. <Hammer+McLeod 1981> Hammer, M. and D. McLeod, "Database Description with SDM: A Semantic Database Model", ACM Transactions on Database Systems, 1981 (to appear).
2. <Heimbigner+McLeod 1981> Heimbigner, D. and D. McLeod, "Federated Information Bases (A Preliminary Report)", Infotech State-of-the-Art Report on Databases, Pergamon Infotech Ltd., 1981.
3. <King+McLeod 1982a> King, R. and D. McLeod, "Semantic Database Models", Database Design, editor S. B. Yao, Prentice-Hall, 1982 (to appear).
4. <King+McLeod 1982b> King, R. and D. McLeod, "The Event Database Specification Model", Proceedings of Second International Conference on Databases: Improving Usability and Responsiveness, Jerusalem, Israel, June 1982 (to appear).
5. <King+McLeod 1982c> King, R. and D. McLeod, "A Unified Model and Methodology for Conceptual Database Design and Evolution", Perspectives on Conceptual Modelling, editors M. Brodie, J. Mylopoulos, and J. Schmidt, Springer Verlag, 1982 (to appear).
6. <McLeod 1982> "A Database Transaction Specification Methodology for End-Users", Information Systems, Volume 7, Number 3, 1982 (to appear).

PROFESSIONAL PERSONNEL

DENNIS MCLEOD, Principal Investigator, Assistant Professor
of Computer Science

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

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

INTERACTIONS

ARPA Information Processing Technologies Office, discussion of
database systems research issues, Washington, D.C.

TRW Defense and Space Systems, advisor on SAFE CIA/DIA project,
Redondo Beach CA.

DESIGN OF EASILY MAINTAINABLE DIGITAL SYSTEMS
[Work Unit IE1-3]

JOHN P. HAYES

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

The overall goal of this project is to develop efficient design methods for digital systems to simplify the tasks of fault detection and location. The following specific research tasks were pursued during the reporting period.

1. A comprehensive study of easily testable and self-testing bit-sliced digital systems was completed.
2. New methods for synthesizing fault-tolerant interconnection networks (beta-networks) for multicomputer systems were developed.
3. A new approach to fault simulation and testing of complex MOS VLSI circuits was developed.

STATUS OF RESEARCH EFFORT

Final documentation was completed on an investigation of the testability properties of bit-sliced systems [1-5]; a comprehensive description of this work appears in T. Sridhar's Ph.D. thesis, which is available as a University Of Southern California report [3]. The major technical results of this research effort were: development of an efficient high-level circuit and fault modeling methodology; design of a family of easily testable processor slices; theoretical characterization of easily testable arrays using on the properties of C- and I-testability; a new self-testing technique based on I-testing.

In previous JSEP-sponsored work [6-7], a new approach to the analysis of the fault-tolerance properties of an important class of interconnection networks was developed. These networks are called beta-networks, and are composed of 2 x 2 crossbar switches. During the past year, our earlier analytical results were applied to the synthesis of fault-tolerant beta networks [8-9]. Two parameters were employed in this synthesis process: the maximum number of beta-element faults that can be tolerated (FT parameter), and the worst-case communication delay (CD parameter) of the network. The tradeoffs between the FT and CD parameters were studied. Several new classes of fault-tolerant beta-networks were discovered, including DPR networks, which are unique in achieving the maximum fault tolerance, and MISE networks, which are minimally fault-tolerant but also have the minimum communication delay. Our research in this area is fully documented in J. P. Shen's Ph.D. thesis, which is also available as a University Of Southern California technical report [8].

We have continued our research into a high-level approach to representing the test requirements of complex systems using the concept of a vector sequence (VS), which is a flexible array representation of test data [10]. In related work, we have applied a new switching theory that we developed called CSA (connector-switch-attenuator) theory to problems of fault simulation and testing [11]. CSA circuit models have been shown to allow the layout and logical behavior of an IC to be accurately represented under both faulty and fault-free conditions. We have demonstrated that faults such as short circuits, open circuits, and delay faults affecting MOS VLSI circuits can be more efficiently and more accurately modeled via the CSA approach than using conventional methods. A generalized single-stock-line fault model was proposed which allows many faults of interest to be simulated in a uniform manner [11].

PUBLICATIONS

1. T. Sridhar & J.P. Hayes: "Testing Bit-sliced Microprocessors", Digest Ninth Fault-Tolerant Computing Symp., Madison, pp. 211-218, June 1979.
2. T. Sridhar & J.P. Hayes: "Self-testing Bit-sliced Microcomputers", Proc. Spring COMPCON 81, San Francisco, pp. 312-316, Feb. 1981.
3. T. Sridhar: "Easily Testable Bit-sliced Digital Systems", Ph.D. Thesis, University Of Southern California, Aug. 1981. Also available as University Of Southern California DISC Tech. Rept. No. 81-4, Oct. 1981.
4. T. Sridhar & J.P. Hayes: "A Functional Approach to Testing Bit-sliced Microprocessors", IEEE Trans. Computers, Vol. C-30, pp. 563-571, Aug. 1981.
5. T. Sridhar & J.P. Hayes: "Design of Easily Testable Bit-sliced Systems", IEEE Trans. Circuits & Systems, Vol. CAS-28, pp. 1046-1058, Nov. 1981. Also in IEEE Trans. Computers, Vol. C-30, pp. 842-854, Nov. 1981 (Joint Special Issue on Design for Testability).
6. J.P. Shen & J.P. Hayes: "Fault Tolerance of a Class of Interconnection Networks", Proc. Seventh Computer Architecture Symp., La Baule, France, pp. 61-71, May 1980.
7. J.P. Shen & J.P. Hayes: "Fault Tolerance of Dynamic-full-access Interconnection Networks", Jan. 1982, submitted for journal publication.
8. J.P. Shen: "Fault Tolerance of Beta-networks in Inter-connected Multicomputer Systems", Ph.D. Thesis, University of Southern California, Aug. 1981. Also available as USCEE Tech. Report No. 510, Aug. 1981.

9. J.P. Shen & J.P. Hayes: "Synthesis of Fault-tolerant Beta-networks", Digest Twelfth Fault-Tolerant Computing Symp., Santa Monica, June 1982, to appear.

10. J.P. Hayes: "A Calculus for Testing Complex Digital Systems", Digest Tenth Fault-Tolerant Computing Symp., Kyoto, pp. 115-120, Oct. 1980.

11. J.P. Hayes: "A Fault Simulation Methodology for VLSI", Proc. 19th Design Automation Conf., Las Vegas, June 1982, to appear.

PROFESSIONAL PERSONNEL

J.P. HAYES, Principal Investigator, Associate Professor of Electrical Engineering and Computer Science

T. SRIDHAR, Research Assistant

J.P. SHEN, Research Assistant

A. JOHARY, Research Assistant

S. GOPALAKRISHNAN, Research Assistant

ADVANCED DEGREES AWARDED

1. J.P. SHEN, Ph.D., Dept. of Electrical Engineering, University Of Southern California, Aug. 1981. Thesis title: "Fault Tolerance of Beta-Networks in Interconnected Multicomputer Systems".

2. T. SRIDHAR, Ph.D., Dept. of Electrical Engineering, U.S.C., Aug. 1981, Thesis title: "Easily Testable Bit-sliced Digital Systems".

INTERACTIONS

J.P. Hayes served as a consultant to Aerospace Corporation, El Segundo, California (contact: A. Carlan) in the area of design for testability.

IDENTIFICATION AND MODEL DEDUCTION VIA SINGULAR
VALUE DECOMPOSITION OF THE HANKEL MATRIX
[Work Unit IEL-4]

LEONARD SILVERMAN & S.Y. KUNG

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

To develop numerically stable and fast algorithms for low order approximation of complex systems (model reduction) and identification of systems from noisy input-output data.

STATUS OF RESEARCH OBJECTIVES

A. SVD Algorithms for System Identification

1. Principal Hankel Component Approximation. In [1], [10] it was shown that a pair of approximate controllability and observability matrices derived by SVD on the Hankel matrix lead to a useful approximate realization of discrete input-output data. Several important features of the algorithm have been theoretically verified, including reliable numerical performance, assured model stability and error analysis. Moreover, it has been shown that the A-matrix of the realization has spectral norm < 1 , which is very desirable in digital filter implementation.

2. Comparison Study. For infinite data, the algorithms of Moore, Zeiger and McEwen and Kung [1], [10] have all been shown to be equivalent in the infinite data case [2], [10]. However, with finite data substantial differences are observed in stability and accuracy for the different methods. Simulation results and comparisons are made in a recent paper [10].

3. Computer Software Package. We have completed a software package for the SVD algorithm. The package can accept impulse-response data as input, and will output approximants of different orders along with accuracy measures and curves of comparisons. The package has been used in many geophysical data processing experiments.

B. Optical Hankel Norm Approximation

1. Scalar System Optimal Hankel Norm Approximation. An optimal approximation scheme (AAK) was obtained [2], [3]. Several efficient algorithms for model reduction are obtained including (1) a generalized eigenvalue formulation for the minimum norm problem, and (2) a fast algorithm on an adjoint system matrix equation for solving the related minimum degree approximation problem.

2. Multivariable System Approximations. In Kung and Lin [6],[8], a closed-form (Hankel-norm) optimal solution for multivariable system reductions is given. The major contribution is a minimal-degree-approximation theorem and a fast multivariable system reduction algorithm. The main theorem presents a simple formulation for the approximation solution, with optimality verified by a complete mathematical analysis.

3. State-Space and Continuous-Time System Approximations. Following our first work on optimal Hankel Norm Approximation, a new state space formulation was obtained allowing a model reduction directly in state space terms. This work is reported in [7]. Optimal approximation has also been generalized in the continuous time case [5],[9],[10],[12] and the correspondence between discrete and continuous-time SVD has been explored.

C. Other Related Works

1. We have also proposed a scheme to deal with frequency-weighted approximation problems. This involves a pre-weighting and de-weighting filter before and after the approximation procedure [10].

2. We have also been looking recently at the approximation problem in a stochastic content. One application of this work has been in the low rank approximation of Toeplitz systems [11] in which a resolution spectral line estimation problem is imbedded.

3. Another application has been made to flexible space structure control [12]. For such systems a comparison of several approximation algorithms was made.

PUBLICATIONS OVER PAST 3 YEARS

1. Kung, S., "A New Identification and Model Reduction Algorithm via Singular Value Decompositions," Proceedings of 12th Annual Asilomar Conference on Circuits, Systems and Computers, November 1978.

2. Silverman, L.M., and Bettayeb, M., "Optimal Approximation of Linear Systems," Proc. of JACC, San Francisco, 1980.

3. Kung, S., "Optimal Hankel-norm Model Reductions: Scalar Systems," Proceedings, 1980 JACC, San Francisco, CA.

4. Kung, S., "Optimal Hankel-norm Model Reductions: Scalar Systems," submitted to IEEE Trans. on Automatic Control.

5. Bettayeb, M., Silverman, L.M., and Safonov, M., "Optimal Approximation of Continuous-Time Systems," Proceedings of 1980 IEEE CDC, Albuquerque, New Mexico.

IEI-4(3)

6. Kung, S.Y., and Lin, D., "Optimal Hankel-Norm Model Reductions: Multivariable Systems," IEEE Trans. Automat. Contr., Vol. AC-26, August 1981.
7. Kung, S.Y., and Lin, D., "A State-Space Formulation for Optimal Hankel-Norm Approximations," IEEE Trans. Automat. Contr., Vol. AC-26, August 1981.
8. Kung, S., and Lin, D.W., "Optimal Hankel-Norm Model Reductions - Multivariable Systems," submitted to 19th CDC & IEEE Trans. on Automatic Control.
9. Lin, D., "Multivariable Linear Systems Approximation via Singular Value Analysis," Ph.D. dissertation, University of Southern California, Los Angeles, CA, 1981.
10. Kung, S.Y., and Lin, D., "Recent Progress in Linear System Model Reduction via Hankel Matrix Approximation," Proceedings of ECCTD 1981, The Hague, The Netherlands.
11. Kung, S.Y., "An Application of Approximation Method to High Resolution Spectral Estimation," to be presented at the 20th IEEE CDC, San Diego.
12. Jonckheere, E., and Silverman, L.M., "Singular Value Analysis of Deformable Systems," to be presented at 20th IEEE CDC, San Diego, 1981.

PROFESSIONAL PERSONNEL

L.M. SILVERMAN, Principal Investigator
S.Y. KUNG, Principal Investigator
D. LIN, Research Assistant
M. BETTAYEB, Research Assistant

ADVANCED DEGREES AWARDED

D. LIN, Ph.D.
M. BETTAYEB, Ph.D.

INTERACTIONS

Lockheed - California Co.

TRW

MULTIVARIABLE FEEDBACK SYSTEM DESIGN
[Work Unit IE1-5]

M.G. SAFONOV

REPORT PERIOD: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

To develop engineering techniques suitable for use in the modern computer-aided design environment, which are applicable to the design of multiloop feedback systems to meet specifications calling for a robust tolerance of parameter variation, nonlinearity, and noise within specified bounds. Such robust feedback design tools are needed to improve the precision of control systems operating in an uncertain environment and to help determine whether or not control objectives can be achieved without resorting to more complex, less reliable adaptive control methods.

STATUS OF RESEARCH EFFORT

Techniques based on "cyclic sector conditions" and "singular values" have been developed for evaluating the stability margins of multiloop feedback systems. The techniques give frequency domain conditions that guarantee stability despite the simultaneous occurrence of parameter variations, unmodeled nonlinearity, etc., in several or all of the system's components, provided only that the stability margins determined for individual components are not exceeded [1,4,8].

Techniques have been developed for evaluating how bounded subsystem modeling uncertainties (parameter variations, unmodeled nonlinearities, etc.) propagate in interconnected systems to affect the precision within which it is possible to control the overall system's response [2,6].

An improved formula has been developed for characterizing the sensitivity of multivariable feedback control systems to plant and sensor transfer function matrix variations [7]. The technique permits direct calculation of a closed-loop transfer function "percent-variation matrix" as a simple linear function of open-loop plant and sensor "percent variation matrices," even when plant and sensor variations are large.

A robust method for state-space realization of discrete-time multivariable system impulse responses was developed by applying singular value decomposition to the Hankel matrix associated with the impulse response [3]. The realization is always stable and, moreover, has the important property that the associated state transition matrix has norm less than one, i.e., $1 > \|A\| \max(\|Ax\|/\|x\|)$. The property ensures that the realization will remain stable with reasonable perturbations in the parameters of A . It is useful for digital signal processing applications where finite-word-length effects are of much concern.

A methodology based on the frequency-response properties of stochastic linear-quadratic optimal output-feedback regulators has been devised for the synthesis of multiloop feedback control designs to meet inequality specifications of sensitivity, disturbance attenuation, and stability margin [5]. The methodology permits manipulation of the frequency-response singular values that determine multivariable feedback system performance by systematic off-line tuning of the quadratic cost and noise matrices.

A technique for optimally selecting previously unspecified "multipliers" has been developed, leading to a substantial reduction in the conservativeness of stability margin bounds for linear time-invariant multivariable feedback systems having several uncertain components [10].

A "separation principle" has been developed proving that one can with complete rigor decompose linear multivariable controller design problems into two independent steps: (1) select a realizable nominal response, and (2) design the feedback based on sensitivity and stability margin considerations [9].

The problem of designing decoupled multivariable feedback controllers for maximal stability margin singular values has been mathematically posed and solved, providing a useful new feedback design tool [11].

PUBLICATIONS

1. M.G. Safonov and M. Athans, "A Multiloop Generalization of the Circle Stability Criterion", Proc. Twelfth Annual Asilomar Conference on Circuits, Systems, and Computers, Pacific Grove, CA, November 6-8, 1978.
2. M.G. Safonov, "Tight Bounds on the Response of Multivariable Systems with Component Uncertainty", Proc. Sixteenth Annual Allerton Conf. on Communication, Control, and Computing, Monticello, IL, October 4-6, 1978.
3. S. Kung, "An Identification and System Reduction Algorithm Via Singular Value Decompositions", Proc. Twelfth Annual Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, CA, November 6-8, 1978.
4. M.G. Safonov, "Singular Values, M-Matrices, Diagonal Dominance, and the Stability Margins of Multivariable Feedback Systems," presented at Optimization Days 1979, Montreal, Quebec, Canada, May 23-25, 1979.
5. M.G. Safonov, "Choice of Quadratic Cost and Noise Matrices and the Feedback Properties of Multiloop LQG Regulators", Proc. Thirteenth Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, CA, November 5-7, 1979.

6. M.G. Safonov, "Frequency-Domain Design of Multivariable Control Systems for Insensitivity to Large Plant Modeling Errors", Proc. IEEE Conf. on Decision and Control, Fort Lauderdale, FL, December 12-14, 1979.

7. M.G. Safonov, "The Sensitivity Problem in Multivariable Feedback Design Revisited", Fourteenth Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, CA, November 1980.

8. M.G. Safonov and M. Athans, "A Multiloop Generalization of the Circle Criterion for Stability Margin Analysis," IEEE Trans. on Automatic Control, vol. AC-26, no. 2, 1981.

9. M.G. Safonov and K. Karimlou, "A Separation Principle for Linear Control Systems with Large Plant and Sensor Uncertainty," Proc. Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, CA, November 9-11, 1981.

10. M.G. Safonov, "Stability Margins of Diagonally Perturbed Multivariable Feedback Systems," Proc. IEEE Conf. on Decision and Control, Orlando, FL, December 8-10, 1982.

11. M.G. Safonov and B.S. Chen, "Multivariable Stability Margin Optimization with Decoupling and Output Regulation", submitted to IEEE Conf. on Decision and Control, Orlando, FL, Dec. 8-10, 1982.

12. B.S. Chen, "The Inverse Problem of LQG Control via Frequency Dependent Cost/Noise Matrices", Ph.D. Thesis, University of Southern California, Los Angeles, CA, May 1982.

PROFESSIONAL PERSONNEL

1. MICHAEL G. SAFONOV, Principle Investigator
2. Mr. KAMRAN KARIMLOU, Graduate Research Assistant
3. Mr. BOR-SEN CHEN, Graduate Research Assistant

ADVANCED DEGREES

B.S. CHEN, Ph.D. Electrical Engineering, May 1982
Thesis: "The Inverse Problem of LQG Control via Frequency Dependent Cost/Noise Matrices"

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

A.A. SAWCHUK & T.C. STRAND

Report Period: 1 April 1981 - 31 March 1982

RESEARCH OBJECTIVES

To accurately model optical phenomena that lead to signal-dependent noise in images, including speckle effects from coherent illumination in synthetic aperture radar (SAR), sonar and acoustic imaging systems, holography and active infrared systems. To reduce the effects of this noise for imaging and pattern recognition applications by the use of advanced image restoration and fast filtering algorithms. Specific restoration techniques include Kalman filtering, local linear minimum mean-square error (LLMMSE) filters, maximum a posteriori (MAP) and maximum likelihood estimation. Nonstationary statistical image models are used to more accurately account for image structure.

STATUS OF THE RESEARCH EFFORT

The problems of signal-dependent noise in imaging and pattern recognition systems are becoming more significant as new techniques and new wavelength sensors are introduced. An important example of signal-dependent noise is the speckle that appears in coherent imaging systems when illumination from an optically diffuse object interferes, giving a noisy, granular appearance to the image that reduces the resolution capability. Such systems include synthetic aperture radar (SAR) on satellite and aircraft platforms; sonar and acoustic imaging systems; active infrared imaging systems; coherent optical information processing and holographic systems. Other examples of signal-dependent noise in imaging systems include poisson noise occurring in photon-counting sensors in low light level imaging, astronomy, and nuclear decay imaging. Effective imaging and image processing applications such as target classification and detection of scene variations in the presence of speckle depend strongly on accurate models for object statistics, background clutter, system noise, and bandwidth.

The first phase of this work has been to develop signal-dependent models for speckle image formation valid for intensity detection (no phase information present) and for complex detection (phase and magnitude information present). Much past work on speckle suppression and restoration has assumed a multiplicative model valid only under a very restricted set of conditions. A detailed model for signal-dependent speckle has been developed that more accurately models the imaging process according to the physical mechanism of coherent image formation. Second-order statistics (e.g., covariance) have been found to be of fundamental importance in characterizing speckle images. Furthermore, signal-dependent noise inherently implies nonstationary statistics in all cases except the relatively uninteresting case of a constant signal.

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

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

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

A number of paper presentations and publications describing some aspects of this work have been made. The Ph.D thesis of D. Kuan to be published soon will contain many of the experimental and analytical details.

PUBLICATIONS

1. P. Chavel, D. Kuan, A.A. Sawchuk, and T.C. Strand, "Approaches to Effective A Posteriori Processing of Single Speckle Patterns," Journal of the Optical Society of America, vol. 70, p. 1581, December, 1980.
2. D. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Discrete Speckle Image Modeling and Restoration," Journal of the Optical Society of America, vol. 71, pp. 1585-1586, December, 1981.
3. D. Kuan and A.A. Sawchuk, "Nonstationary 2-D Recursive Image Restoration," Journal of the Optical Society of America, vol. 71, pp. 1641-1642, December, 1981.
4. D.T. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Nonstationary 2-D Recursive Filter for Speckle Reduction," Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, Paris, May, 1982.
5. D.T. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "MAP Speckle Reduction Filter for Complex Amplitude Speckle Images," Proceedings IEEE Patt. Recog. and Image Processing Conf., Las Vegas, Nevada, June, 1982.
6. D. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Adaptive Restoration of Images with Speckle," Proc. SPIE Conf. Applications of Digital Image Processing IV, San Diego, August, 1982.

PROFESSIONAL PERSONNEL

1. T. Strand, Research Assistant Professor, Department of Electrical Engineering-Systems, Image Processing Institute.
2. A.A. Sawchuk, Associate Professor, Department of Electrical Engineering-Systems, Director, Image Processing Institute.
3. D. Kuan, Research Assistant, Image Processing Institute, Ph.D. candidate, Department of Electrical Engineering-Systems.
4. P. Chavel, Visiting Research Scientist, Image Processing Institute, from Institut d'Optique, Orsay, France.

ADVANCED DEGREES AWARDED

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

INTERACTIONS

A. Papers Presented at Meetings, Conference, and Seminars

1. P. Chavel, D. Kuan, A.A. Sawchuk, and T.C. Strand, "Approaches to Effective A Priori Processing of Single Speckle Patterns," 1980 Annual Meeting Optical Society of America, Chicago, October, 1980.
2. D. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Discrete Speckle Image Modeling and Restoration," 1981 Annual Meeting Optical Society of America, Orlando, Florida, October, 1981.
3. D. Kuan and A.A. Sawchuk, "Nonstationary 2-D Recursive Image Restoration," 1981 Annual Meeting Optical Society of America, Orlando, Florida, October, 1981.
4. A.A. Sawchuk, "Modeling of Signal-Dependent Noise," Second ASSP Workshop on Two-Dimensional Signal Processing, New Paltz, New York, October, 1981, (invited paper).
5. A.A. Sawchuk, "Recent Developments in Optical and Digital Processing," Workshop on Optical Information Processing, Centro de Investigaciones en Optica, Cuernavaca, Mexico, January, 1982, (invited paper).

B. Interactions with Other Laboratories

1. Several discussions of this project of this project have been held with Dr. Harold Szu and Dr. Jong-Sen Lee of the Naval Research Laboratory, Washington, D.C.
2. Several discussions on this work have been held with Dr. James Fienup and Dr. Robert Powers of the Environmental Research Institute of Michigan (ERIM), a DOD contractor investigating digital SAR imaging techniques.
3. Several technical discussions with Dr. Dan Held, Dr. Fuk Li, and Dr. Charles Elachi of JPL regarding SEASAT SAR systems have been held. They have supplied some experimental data to be used in this research.