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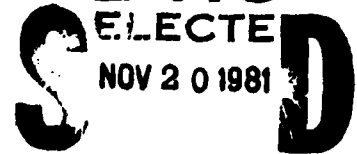
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RESEARCH IN ELECTRONICS - JSEP

Z. A. Kaprielian  
Principal Investigator

Final Report for the Period 1 April 1976 - 31 March 1981  
(Program Initiated in September 1963)

Prepared for the Air Force Office of Scientific Research  
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**ELECTRONIC SCIENCES LABORATORY**

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## 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 a hardcore research capability in the electronics and related sciences areas of the basic research spectrum. The University of Southern California has been participating in the JSEP since 1963 within the framework of the Electronic Sciences Laboratory which involves research activities of the faculty in the departments of Electrical Engineering, Materials Science, Computer Science and Physics.

JSEP research projects at USC are currently in three areas: Solid State Electronics, Quantum Electronics and Information Electronics (Communications and Signal Processing, Controls and Computers). The report presents summaries of the accomplishments and progress for each of the projects (work units) which were active during the contract period of April 1, 1976 - March 31, 1981, under Contract F44620-76-C-0061.

The report is organized in three sections as follows:

- Section I: Contains reports for the 13 projects which were still active at the close of the report period and which are being continued on into the new contract year.
- Section II: Contains reports for the 18 projects which were concluded during the report period.
- Section III: Contains the significant accomplishments report submitted to the JSEP Coordinating Committee for the most recent period of the contract.

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SECTION I

ACTIVE PROJECTS AT CLOSE OF REPORT PERIOD

## 1. SOLID STATE ELECTRONICS

### 1.1 Optical Properties and Thermal/Laser Annealing of Ion Implanted Semiconductors

(PI) C. N. Waddell and W. G. Spitzer

Report Period: April 1979 - April 1981

Research Objectives: a) To study the physical changes occurring during thermal and laser annealing of high fluence, ion-implanted, semiconducting materials. The principal technique utilizes infrared interference measurements to determine the changes in the dielectric constant profiles occurring during the annealing process. These dielectric changes result from recrystallization, electrical activity of the implanted ions, and changes in the structure of the amorphous region. The purpose is to establish the annealing mechanisms in sufficient detail that it will be possible to determine the conditions necessary to recrystallize the implanted region without substantially altering the distribution of the implanted ions and achieve a high doping efficiency. b) To perfect the model for calculating i. r. reflection and transmission spectra so that infrared dielectric profiling can become a practical, non-destructive tool for determining the structural and electrical properties of ion-implanted semiconductors.

#### Status of Research Effort:

In close cooperation with Dr. Graham Hubler of the Naval Research Laboratories we have implanted a large number of  $\langle 100 \rangle$  and  $\langle 111 \rangle$  oriented Si samples with different ions and different implantation energies. Detailed and precise infrared reflection measurements of these samples have been made during periods of isothermal annealing at  $500^{\circ}\text{C}$  and  $550^{\circ}\text{C}$  during which the implantation-induced amorphous Si layer recrystallizes. As a result of these studies, we have demonstrated that simple computer modeling permits one to fit the experimental data to an extraordinary degree of precision (typically a few tenths of 1% reflection at any frequency). The modeling produces information concerning the following quantities of physical interest:

- (1) the depth of the amorphous layer produced by implantation both before and during isothermal annealing when epitaxial regrowth occurs,
- (2) the thickness of the recrystallized layer,
- (3) the widths of any transition layers,
- (4) the dielectric properties of both the amorphous and the epitaxially recrystallized layers,
- (5) the relative roles of regrowth by epitaxy and polycrystalline grain nucleation,
- (6) the characteristics of the free carrier plasma in the recrystallized material for those cases where the implanted ion is an electrical dopant,
- (7) and the carrier activation efficiency.

As a result of these studies a number of specific facts concerning heavily-implanted and thermally annealed systems have been obtained. These facts include (see publications for details).

- (1) The infrared refractive index of heavily implanted amorphous Si is independent of the implanted ion (Si or P), the fluence, the ion energy or the initial sample orientation.
- (2) With relatively short annealing times at 500°C and 550°C the refractive index of the amorphous material decreases to that reported for thermally stabilized amorphous Si. The refractive index remains constant with further annealing until recrystallization takes place.
- (3) The amorphous-crystalline interface in the as-implanted samples has a finite width, typically 0.03 to 0.05  $\mu\text{m}$  for the standard deviation of a half-Gaussian used to fit the refractive index, which becomes smaller than 0.02  $\mu\text{m}$  with the shortest anneal times used at 500°C (approximately 2 hrs.).
- (4) Epitaxial regrowth rates at 500°C for  $\langle 111 \rangle$  samples are in reasonable agreement with those reported by Mayer et al., while the rates observed for  $\langle 100 \rangle$  regrowth at both 500°C and 550°C are below that of Mayer et al. by a factor of  $\sim 2.5$ .
- (5) Free carriers produced by the electrical doping of the implanted ions are present only in that portion of the implanted amorphous material which has recrystallized.
- (6) The fitting procedures are sufficiently sensitive that the asymmetry in the carrier distribution (3d moment correction of the Gaussian) can be detected. Approximations in which two half-Gaussians of different standard deviations are joined at their peaks are used to fit the data and the fitted standard deviations are in reasonable agreement with theoretical values.

Publications:

1. G. K. Hubler, C. N. Waddell, W. G. Spitzer, J. E. Fredrickson, S. Prussin, and R. G. Wilson, High Fluence Implantations of Silicon: Layer Thicknesses and Refractive Indices, J. Appl. Phys. 50, 3294 (1979).
2. W. G. Spitzer, J. S. Ko, C. N. Waddell, G. K. Hubler, and J. E. Fredrickson, Plasma Region in High Fluence Implants of Phosphorous in Amorphized Silicon, J. Appl. Phys. 50, 3775 (1979).
3. G. K. Hubler, P. R. Malmberg, C. A. Carosella, T. P. Smith III, W. G. Spitzer, C. N. Waddell, and C. N. Phillippi, Optical Effects Resulting from Deep Implants of Silicon with Nitrogen and Phosphorus, Rad. Effects 48, 81 (1980).
4. G. K. Hubler, P. R. Malmberg, C. N. Waddell, W. G. Spitzer and J. E. Fredrickson, Electrical and Structural Characterization of Implantation Doped Silicon by Infrared Reflection, accepted for publication by Rad. Effects.

5. J.E. Fredrickson, C.N. Waddell, W.G. Spitzer, and G.K. Hubler, Effect of Annealing on the Infrared Refractive Index of Amorphous Silicon Produced by Ion Implantation, in preparation for submission to Appl. Phys. Letters.
6. C.N. Waddell, W.G. Spitzer, J.E. Fredrickson, G.K. Hubler and P.R. Malmberg, Infrared Studies of Thermal Annealing of Amorphous Silicon Layers Produced by Ion Implantation, in preparation.

Professional Personnel:

J.S. Ko - graduate student  
L. Liou - graduate student  
J.E. Fredrickson - Professor of Physics, California State University at Long Beach, Calif. (spent sabbatical leave and two summers at USC)  
W. G. Spitzer (PI)  
C. N. Waddell (PI)

Interactions:

Work carried out in collaboration with the Naval Research Labs, Washington, D. C. (See Hubler and Malmberg in publication list.)

Discoveries/Patents:

We have developed a non-destructive analytical technique useful for obtaining many properties of physical interest and of interest to the device engineer when dealing with heavily implanted Si samples. No inventions or patent disclosures.

1.2 A GaP on Si Integrated Optics Chip

M. Gershenzon (PI)

Report Period: April 1977 - March 1981

Research Objectives: It was proposed to grow thin, planar layers of device quality GaP on Si substrates to develop an alternative system for integrated optics, wherein the GaP would be used for optical processing (wave-guiding, modulation, mixing) and the Si would serve for optical detection and as a base for standard electronics integrated circuitry. The light generator would be a hybrid. Since the cost of large area, single crystal Si substrates is being reduced rapidly as a result of the solar photovoltaic cell program, and since GaP is the only simple semiconductor that is at all compatible with epitaxial growth on Si, the development of a viable GaP on Si technology could lay the basis for many other types of semiconductor devices. The GaP layer only could be used (large area LED displays as well as integrated optics). The Si alone could be used (the GaP acting as a passivating layer or as a gate insulator). Light could pass through the interface (a GaP LED-Si photodiode optical isolator). Majority carriers could pass through the interface (a GaP display

driven by circuitry on the Si). Finally, minority carriers could traverse the interface (a high speed bipolar heterostructure transistor with a wide gap GaP emitter allowing heavy doping in the Si base).

#### Status of Research Effort:

1. GaP and Si are chemically incompatible with each other using the most common semiconductor crystal growth techniques (LPE, halide CVD) and, to minimize thermal contraction and interdiffusion problems, growth should occur at the lowest temperature possible. Vapor growth using organometal transport, which involves the pyrolysis of  $(\text{CH}_3)_3\text{Ga}$  in a  $\text{H}_2$  stream containing  $\text{PH}_3$ , is the most practical solution. Single crystals of GaP have been grown by this method epitaxially on (100) Si at temperatures as low as  $800^\circ\text{C}$ .
2. Single crystal GaP will not grow on the  $\text{SiO}_2$  layer normally covering the Si. The  $\text{H}_2\text{O}$  content of the  $\text{H}_2$  from our purifier is about 1-2 ppm. This is low enough to allow the  $\text{H}_2$  to reduce the  $\text{SiO}_2$  at  $1100^\circ\text{C}$ , but it is high enough to re-oxidize the Si at  $800^\circ$ . After an alkaline HF etch to minimize the oxide thickness just prior to growth, the substrate is heated in  $\text{H}_2$  to  $1150^\circ$  to remove the oxide. The  $\text{PH}_3$  flow is initiated at this temperature and the substrate cooled to  $800^\circ$  where growth is initiated. The P-containing surface layer so formed apparently prevents readsorption of oxygen as the sample is brought to the growth temperature and single crystal epitaxial growth of GaP then follows.
3. The lattice constant of GaP is larger than that of Si by 0.37% at room temperature and the disparity increases to 0.57% at  $800^\circ$ , the growth temperature. On cooldown from the growth temperature, differential contraction puts the GaP in tension. GaP layers greater than  $5\ \mu\text{m}$  in thickness grown on much thicker Si substrates always crack on cooldown. An analysis of the net tensile stress in the GaP at the interface, from which the cracks originate, shows that for the thinner layers the stress during cooldown is sufficient to cause plastic flow relieving most of the stress and avoiding eventual fracture, whereas for the thicker layers the interface stress is insufficient to produce plastic deformation and the net unrelieved stress leads finally to fracture at temperatures below those at which plastic relief can occur. As a result, the thin crack-free layers contain a high density of dislocations. If the GaP is grown on Si predeposited on sapphire (SOS) the fact that sapphire has a higher coefficient of thermal expansion than both Si and GaP, places the GaP in compression on cooldown and crack-free GaP layers as thick as  $60\ \mu\text{m}$  have been grown on such substrates.
4. GaP has lower crystal symmetry than Si. As a result, a Si substrate cannot completely determine the orientation of the GaP, and twins result. GaP grown on (100) Si consists of many twins. By orientating the Si substrate slightly away from a (100) plane,  $1-4^\circ$  towards a  $\langle 110 \rangle$  direction, one of the two sets of GaP orientations is eliminated and a single crystal results.
5. The GaP growth morphology is not planar, although it is a single

crystal. We have focused on this problem recently, because for the devices we envision, planar technology requires planar material. Nucleation of the GaP on the Si occurs discretely, and as the growing nuclei merge, the surface toplogy continues to reflect the island nature of the early growth stages. Multiple island nucleation occurs because the interface energy between the Si and the GaP is large. Thus, at the start of GaP growth, it is energetically more favorable to minimize the interface energy by minimizing the interface area, i. e., growth does not commence over the entire surface of the substrate. This interface energy is high because of chemical reasons (bonding between Si and GaP at the interface or in some thin transition region), because of physical reasons (there is a lattice constant difference between Si and GaP at the growth temperature) and because of possible impurity "poisoning" at the interface (some oxide may remain on the substrate at the start of growth). It was deemed desirable to re-optimize the early stages of growth in order to increase the density of nucleation. Even though planar nucleation probably is not inherently possible because of the chemical difference, a larger density of nuclei would merge together at an earlier stage of growth leading to a more planar surface. In principle, the kinetics of the MO-CVD reaction are favorable for producing GaP down to temperatures less than 500°C. By reducing the current growth temperature of 800°, we should be operating under conditions where the lattice mismatch between the Si and the GaP will be reduced, hence, resulting in fewer misfit dislocations, possibly planar nucleation, thus a planar growth morphology, and a lower stress differential due to thermal contraction while cooling down to room temperature, hence less cracking. Furthermore, diffusional intermixing should be reduced significantly. We first attempted to grow at 700°. No successful growth was achieved. Only non-oriented nuclei formed on the surface of the Si. This type of nucleation was characteristic of our early experiments, where growth was occurring on the amorphous SiO<sub>2</sub> layer on Si. We concluded that the procedure we had developed for removing the oxide and keeping the surface clean down to 800° was no longer effective at 700°C. In fact, the equilibrium H<sub>2</sub>O pressure needed to keep the surface free of SiO<sub>2</sub> is about a decade lower at 700° than it is at 800°. Thus, we attempted to reduce further the O<sub>2</sub> and H<sub>2</sub>O content in the reactant gas streams. A hygrometer capable of measuring H<sub>2</sub>O contamination down to 0.001 ppm (dew point of -110°C) was installed to monitor the moisture in the H<sub>2</sub> stream used as the carrier gas in the growth system. The Pd diffusion cell in the H<sub>2</sub> purifier was replaced and a tank of PH<sub>3</sub> of ultra-high purity is on order. So far, with only the H<sub>2</sub> source cleaned up, nucleation at 800° seems improved and the measured H<sub>2</sub>O contamination is low enough so that we may be successful in growth attempts at 700° or even lower temperatures.

6. Interdiffusion mixing at the growth temperature could be a problem, since Si in GaP and Ga and P in Si are all shallow dopants. We already have observed such diffusion tails up to 1 μm from the interface. We have not yet faced up to this problem, although the solutions, minimum growth temperature and minimum period of time at the growth temperature, appear obvious.

7. The lattice mismatch at the growth temperature should lead to the incorporation of interface misfit dislocations. These could degrade the lifetime of minority carriers traversing the interface. We have not yet tried to measure this effect. Again, lower growth temperatures, where the lattice constants become more nearly equal, may be the obvious solution.

Publications:

1. R. K. Tsui and M. Gershenson, Appl. Phys. Lett. 37, 218 (1980).
2. J. K. Abrokwah and M. Gershenson, J. Elect. Mats. 10, 379 (1981).

Professional Personnel:

1. M. Gershenson
2. R. K. Tsui, Ph.D., Sept., 1979, "The Characterization of GaP/Si Heterostructures Grown by Organometallic Vapor Phase Epitaxy."
3. J. K. Abrokwah, Ph.D., Sept. 1979, "Liquid Phase Epitaxial Growth and Characterization of  $\text{InAs}_x\text{Sb}_{1-x}$  and  $\text{In}_{1-x}\text{Ga}_x\text{Sb}$  on III B InSb Substrates for Infrared Detectors and Heterojunction Lasers."

Invention Disclosures: None

1.3 Electrooptic Materials and Optical Image Storage Devices

A. R. Tanguay, Jr.

Report Period: September 1977 - April 1981

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 investigate the effects of multiple internal reflections and space charge redistribution on the measurement of the electrooptic coefficient of high index and high resistivity electrooptic materials.

(3) 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.

### 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 periodic array of charges of given spatial frequency can be directly related to the exposure dependent modulation transfer function of the device. We have obtained an analytic expression for the Fourier transform of the voltage distribution from a single point charge (which is also directly related to the modulation transfer function) for the full three layer dielectric problem, and have extended the theory to include the dependence of the voltage distribution on the point charge location within the electrooptic crystal. The resultant analytic expression contains the dielectric constants of the blocking layers and electrooptic crystal, and the thicknesses of the three layers, as well as the location of the point charge. This formulation allows the effects of charge trapping within the bulk of the electrooptic crystal to be modeled. In particular, the low spatial frequency response decreases linearly, and the high spatial frequency response decreases exponentially with the distance of the point charge from the electrooptic crystal/dielectric blocking layer interface. Thus the overall sensitivity and resolution are degraded strongly by charge storage in the bulk away from the interface. Utilizing superposition, this formulation has been further extended to accommodate arbitrary charge distributions of 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].

Recently, PROM-like structures have been investigated [7, 8] that exhibit significantly enhanced resolution and sensitivity relative to traditional PROM structures. Such devices are fabricated from BSO crystals oriented along  $\langle 111 \rangle$  and  $\langle 110 \rangle$  axes, as opposed to the usual  $\langle 100 \rangle$  orientation. We have applied our comprehensive model to such structures, and have been able to predict both the reported experimental results, as well as several new effects. Such structures appear to be quite promising for coherent optical processing applications requiring dc-suppressed band pass spatial frequency characteristics.

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). These measurements are in the process of being extended to the cases of uniform exposure, and exposure to one-dimensional sinusoidally varying intensity distributions of different spatial frequencies. 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.

An existing Czochralski crystal pulling apparatus has been overhauled and modified for growth and doping experiments with bismuth silicon oxide and other optical materials. The growth furnace consists of two independently controlled zones for adjustment of the furnace thermal profile and post-growth annealing. Detailed thermal profiling (measurement and furnace optimization) has been completed, and numerous crystal growth runs have been accomplished. Bismuth silicon oxide ( $\text{Bi}_{12}\text{SiO}_{20}$ ) single crystals have been grown (both doped and undoped) both from Pt wire nucleation and by top-seeding. 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. The origin of growth-axis oriented microvoid "strings" with associated microcrack patterns and strain birefringence is under investigation.

The fundamental origin of the widely observed photochromic effects in bismuth silicon oxide (and related compounds) was investigated utilizing a highly sensitive liquid helium cryostat electron paramagnetic resonance spectrometer. Well resolved lines were observed for chromium doping levels in bismuth silicon oxide of only a few parts per million atomic. It has been tentatively concluded that the chromium is selectively incorporated in the (nearly) octahedral bismuth site (as opposed to the tetrahedral silicon site), and that the distortion of the octahedral site is sufficient to account for the observed enormous enhancement of the optical transition cross sections relative to those expected from atoms incorporated in a nominally spin-forbidden site. Experiments to determine the valence state

of chromium dopant atoms in BSO in both absorbing and non-absorbing photochromic states are in progress, and similar experiments for other transition metal dopants are planned as soon as appropriate doped samples can be grown in the Czochralski system.

The crystal chirality (absolute handedness of the spatial atomic arrangement) and optical rotation sense were determined for crystals of isomorphous bismuth silicon oxide and bismuth germanium oxide. The results not only detail the correlation between the absolute atomic configuration and optical rotation sense of each crystal (known for only a few optically active materials), but also demonstrate identical behavior in the case of both isomorphous materials. This result contrasts with the case of isomorphous  $\text{NaClO}_3$  and  $\text{NaBrO}_3$ , wherein the relationship between chirality and rotation sense is exactly opposite (spatially right handed  $\text{NaClO}_3$  rotates the polarization opposite to that of spatially right handed  $\text{NaBrO}_3$ ). This experiment has a number of important implications for fundamental theories of optical activity, as well as the useful pragmatic benefit of absolute atomic configuration determinations in BSO and BGO samples by means of simple optical measurements (as compared with the usual tedious and expensive x-ray analysis techniques) [JSEP Pub. 1].

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. 8]. 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 polarizations 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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6. J. C. H. Spence and A. Olsen, "Use of Pockels Readout Optical Modulators (PROMs) for Atomic Resolution Electron Image Processing," *Proc. SPIE Los Angeles Technical Symposium*, 218, 154-160 (1980).
7. M. P. Petrov, "Diffraction and Dynamic Properties of Photosensitive Electrooptic Media," *Proc. Optics in 4-Dimensions, CICEFE, Mexico*, (1980).
8. A. V. Khomenko (private communication).
9. R. A. Sprague, "Effects of Bulk Carriers on PROM Sensitivity," *J. Appl. Phys.* 46(4), 1673-1678 (1975).
10. A. A. Ballman, H. Brown, P. K. Tien, and R. J. Martin, "The Growth of Single Crystalline Waveguiding Thin Films of Piezoelectric Sillenites," *J. Cryst. Growth* 20, 251-255 (1973).

Cumulative Publication 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, 293-5, (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 Continuous Charge Distributions," 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 Crystallographic Orientation and Dielectric Anisotropy," 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. "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.
9. "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).

## 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 Spatial 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, ILL, (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, NV, (1981), (invited paper).

Professional Personnel:

1. Armand R. Tanguay, Jr., Principal Investigator.
2. Yuri Owechko, Research Assistant.
3. Leroy Fisher, Research Assistant.
4. LiCheng Hou, Research Assistant.

Interactions:

Interactions 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.

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 current program on development of new PROMs with improved resolution characteristics is supported by Dr. Robert Leighty of the Army Engineering Topographic 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.
2. Technical discussions of a classified nature were arranged by Dr. R. Gerhartz of the U. S. Army Night Vision Laboratories in April, 1980.
3. During April, 1978, 1979, and 1980, 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.

4. 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.

5. Technical discussions concerning optimization and utilization of Photorefractive Image Storage Devices were held at USAF/RADC, Hanscomb AFB, Massachusetts and J. Ludman, J. Horner, and W. Miceli in August, 1980.

New Discoveries, Inventions, or Patent Disclosures:

A new comprehensive theoretical model of the sensitivity and resolution of electrooptic spatial light modulators has been developed, as particularly applied to Pockels Readout Optical Modulators (PROMs). Such devices are candidate incoherent-to-coherent image transducers for applications in coherent optical processing. The theoretical model provides a mechanism for optimization of device design and operational mode.

1.4 Electrical Techniques for Materials Characterization

C. R. Crowell

Report Period: April 1976 - May 1981

Scientific Objective: To develop non-destructive electrical techniques which aid in semiconductor materials and device characterization. Studies undertaken are: (a) a development of the understanding of capacitive evaluation of deep impurity levels from the frequency dependence of junction impedance; (b) to supplement (a) with a study of differential deep level transient spectroscopy, DDLTS; (c) an analysis of multiple level systems and sample inhomogeneity by Hall measurements; (d) charge effects associated with current transport in insulators; (e) photoconductance analysis of deep levels; (f) charge transfer and impedance at metal-semiconductor interfaces.

Status of Research Effort:

a) We have made a detailed study of bias, frequency and temperature dependence of the complex capacitance of In doped Si in  $H_f$ -p type Schottky barriers [1, 2, 3, 4]. 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 a 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.

b) We have completed an analysis that compares DLTS and DDLTS analysis of deep level transients [5]. 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 [6].

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 [7] 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.

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 [8]. A far more powerful technique for improving the figure of merit of the system is shown to be inherent in the temporal analyzing of the output signal.

c) 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 in a).

Presentation of the data in the form of an activation energy plot versus fermi energy has been shown to be very revealing [9, 10]. We are currently trying to set up an analysis system that will also yield error criteria for the fitting parameter.

d) Some work has been done with W. Patterson on the Frenkel-Poole characterization of traps in silicon nitride [11]. 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. Lehovc.

e) Photoconductance analysis of deep levels using a modulated light source and phase sensitive detection was undertaken with R. M. Madden. We demonstrated the desirability of using phase-quadrature response (as opposed to the in-phase response) to provide selectivity in measuring the response times constants. Mr. Madden did not complete the Ph. D. thesis,

but aside from a few unexplained parts the material did indicate the usefulness of the approach. One of the major outgrowths of the work was, however, that this was a precursor of the development of the ideas we have developed for controlled selectivity in DLTS measurements (see (b) above).

f) We have conducted a number of studies directed towards characterization of metal-semiconductor interfaces. The supposedly anomalous  $T_0$  effects in Schottky barriers were analyzed and shown to be consistent with counter doping under the metal-semiconductor interface. The emergence of the  $T_0$  parameter was shown to be largely an artifact of the way some of the early researchers' measurements were taken (12).

Another interface study was of photojunction of carriers at a Schottky barrier. In this study an intensive analysis was undertaken of the validity of the modelling assumptions inherent in the interpretation of the Fowler model [13]. Excellent agreement was obtained over a wide range of field and temperature with the only fitting parameter being the zero temperature mean free path for optical phonon scattering and the temperature dependence of the barrier height at zero electric field.

We are currently extending older work used [14] in which the contact effects on both resistivity measurements were characterized. We are investigating structures that will be able to model effects of interface resistance as well as bulk effects relatively straightforward diagnostic form. The resulting guidelines should be of special interest in VHSIC work.

Related work was also performed (not JSEP supported) on the Auger characterization of Schottky barriers [16]. We have also performed some calculation on the diagnostics of distributed resistance effects in the bulk and surface layers of solar cells [16].

#### References and Publications:

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2. "Electrical Techniques for Semiconductor Characterization," JSEP Topical Review, Stanford Univ., August 4, 1977.
3. C. H. Huang, Ph.D. Thesis, January 1978.
4. 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.
5. C. R. Crowell and S. Alipanahi, "Transient Distortion and nth Order Filtering in Deep Level Transient Spectroscopy ( $D^n$ LTS)," 24, 25-36 (1981).

6. C. R. Crowell and S. Alipanahi, "Charge Storage and Charge Release Modes for D<sup>n</sup>LTS Studies of MRS Interface States and Deep Level Impurities," presented at VIth PCSI Conference, manuscript in preparation.
7. C. R. Crowell, presented at JSEP Topical Review, USC, Jan. 1981, manuscript planned for publication.
8. C. R. Crowell and S. Alipanahi, "Figure of Merit for Slow Restoration DLTS Filters," accepted for publication in Applied Physics, manuscript being revised.
9. R. Chwang and C. R. Crowell, "Activation Analysis and Recursive Parameter Estimation of Hall Data," presented at JSEP Review, USC, manuscript in preparation.
10. C. R. Crowell and R. Chwang, "Configurational Effects on Hall and Resistivity Measurements," invited paper presented at the International Conference on Metallurgical Coatings, at San Francisco, CA, April 1976.
11. 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.
12. C. R. Crowell, "The Physical Significance of the T<sub>0</sub> Anomalies in Schottky Barriers," Solid St. Electron. 20, 171-175 (1977); initially presented as an invited paper at PCSI II.
13. C. W. Kao, C. L. Anderson and C. R. Crowell, "Photoelectron Injection at Metal-Semiconductor Interfaces," Surface Science, 95, 321-339 (1980); initially presented at PCSI III.
14. R. Chwang, B. J. Smith and C. R. Crowell, "Contact Size Effects on the van der Pauw Method for Resistivity and Hall Coefficient Measurements," Solid St. Electron. 17, 1217-1227 (1974).
15. J. Roth and C. R. Crowell, "Application of Auger Electron Spectroscopy to Studies of the Silicon/Silicide Interface," J. V. S. T. 15, 1317-1325 (1978).
16. R. Chwang and C. R. Crowell, "Bulk and Surface Distributed Resistance Effects in Solar Cells," manuscript in preparation.

Professional Personnel:

1. C. H. Huang, Ph.D., Jan. 1978, "Deep Level Elastance Spectroscopy: Indium and Gold Doped Silicon Schottky Barriers."
2. S. Alipanahi, Ph.D., Jan. 1981, "A Signal Acquisition Technique for Transient Spectroscopy of Semiconductor Bulk and Interface Deep Levels."

3. D. Lucey, M.S., Jan. 1979.
4. S. J. Lee.
5. M. W. Chiang.

Interactions:

Consulting, Hughes Research Laboratories, Malibu: Chemical Physics Division, MIS, DLTS, Impact Ionization, C. L. Anderson. Auger Spectroscopy, J. Roth, Hall Effect Characterization, R. Brom, 1976-1980.

Informal ongoing communications with H. Wieder, NELC, Interactions with respect to DLTS system development and impact ionization in InP.

ARO supported research on Impact Ionization, 1976-1980 (ongoing proposal in preparation), Contract Monitor, H. Wittmann.

Several informal contacts with ARO and ONR personnel from membership on the committee for the Conferences on the Physics of Compound Semiconductor Interfaces, 1975-1980, Chairman, 1976.

Presently Chairman, Electronic Materials and Processing Division of the A. V. S.

Discovered a dual-path multichannel approach to determining improved selectivity in DLTS.

Proposal reviews for ARO, ONR, NSF, JSEP Presentations at U.S. C.

Reviewer for Phys. Rev., Phys. Rev. Letters, J. Appl. Phys., Applied Phys. Letters, Solid State Electronics, J. V. S. T., Electrochemical Society, IEEE Trans. on Electron Devices, IEEE Electron Device Letters.

## 2. QUANTUM ELECTRONICS

### 2.1 Laser Devices and Applications

William H. Steier (PI)

Report Period: April 1976 - March 1981

#### Research Objectives:

a) Rare Gas Halide Lasers. The goal of this work was to develop methods for modelocking, transverse mode control and increasing the lasing pulse width. A second goal was the development of compact capillary discharge excimer laser device.

b) Wave Guide Modes. The goal of the work was to complete the analysis of the modes in a square crosssection hollow dielectric waveguides for use at optical wavelengths.

c) Two Photon Ionization. The objective is the study of two photon ionization in the alkali halides for possible new ultraviolet devices. The use of this phenomena for pico-second pulsewidth measurements in the UV was investigated.

#### State of the Research:

##### a) Rare Gas Halide Lasers:

- i) XeF Laser Modelocking. We have successfully demonstrated modelocking in the excimer laser and have analyzed the problems of attaining gain bandwidth limited pulses. Using an acousto-optic modulator, we have actively modelocked the XeF laser to produce optical pulses of 1.5 ns duration.
- ii) High-Repetition Rate XeF Laser. We have investigated the gas recycling and gas purification problems in realizing a high repetition rate excimer laser. We have extended the repetition rate to 200 Hz using a longitudinal gas flow.
- iii) Capillary Lasers. The capillary laser has been made to oscillate using KrF, XeF and XeCl. The typical average output energy per pulse was  $0.5 \text{ mJ/cm}^3$  with a pulse length of 10-20 nsec.
- iv) Transverse Electrode-less R-F Discharges. Application of this excitation technique to pumping of Ar-Xe, He-Xe, F, XeF, and  $\text{CO}_2$  laser transitions has been studied. We find this arrangement to be very well suited to excitation of  $10.6 \mu$   $\text{CO}_2$  transitions and have obtained pulse energies of 5 mJ., peak power in excess of 1 kW and a laser efficiency of 6%. Neutral xenon transitions at  $2.02 \mu$  and  $2.65 \mu$  have been excited in a quasi-cw manner, and pulse durations in excess of  $25 \mu\text{s}$  have been observed. Although peak powers

are limited to the 0.1 - 1 watt range by the inherently lower efficiency of this system ( $< 10^{-3}$ ). We find that addition of a small amount ( $\sim 0.1\%$ ) of SF to Ar/Xe and He/Xe mixture enhances the laser output and promotes long pulse operation. Both the Xe(1) and CO<sub>2</sub> transitions operate well at fill pressures extending above one atmosphere.

b) Waveguide Modes:

We have completed an analysis of modes in a square cross section hollow dielectric waveguide. This configuration is currently used in several waveguide lasers now being developed.

c) Two Photon Ionization:

We have studied two-photon generated color centers in the alkali halides. Measurements in KBr using the XeCl laser show that the color center density varied as  $I^{1.5}$  and that intensities less than 10 MW/cm<sup>2</sup> are sufficient for color-center generation. Two-photon generated color-center gratings were produced by a UV interference pattern and were used to measure the diffusion distance of the electrons before becoming color centers. The measured distance of 25  $\mu$  limits the minimum resolvable pulsewidth to about 0.25 ps.

Publications:

1. C. P. Christiansen, L. W. Braverman, W. H. Steier, and C. Wittig, "Active Modelocking of the XeF Laser," Appl. Phys. Lett. 29, 424 (1976).
2. C. P. Christiansen, "High-Repetition-Rate XeF Laser with Gas Recycling," Appl. Phys. Lett. 30, 483 (1977).
3. C. P. Christiansen, "High-Repetition-Rate XeF Laser with Gas Recycling," presented at Symposium on High-Power Lasers and Applications, June 1977, Munich, West Germany.
4. C. P. Christiansen, "High-Repetition-Rate XeF Laser with Gas Recycling," presented at 1977 March meeting of American Physical Society, San Diego, California.
5. L. W. Braverman, C. P. Christiansen, W. H. Steier, and C. Wittig, "Active Modelocking of the XeF Excimer Laser," presented at the October 1976 meeting of the Optical Society of America, Tuscon, Arisona.
6. K. D. Lackman and W. H. Steier, "Characteristic Modes of Hollow Rectangular Dielectric Waveguides," Appl. Opt. 15, 1334 (1976).
7. C. P. Christiansen, "High-Repetition-Rate XeF Laser with Gas Recycling," Appl. Phys. Lett. 30, 483 (1977).

8. C. P. Christiansen (USC), N. Djeu (NRL) and F. X. Powell (NRL), "High Pressure Laser Excitation by Transverse Electrodeless Discharge," submitted.
9. 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:

C. P. Christiansen (Research Assistant Professor)

Heungsup Park (Research Associate)

Chris Sexton (Research Assistant)

Katherine Laackman (Research Assistant/Received Ph. D. 1976  
"Propagation in Hollow Waveguide Amplifiers Filled with an  
Inhomogeneous Medium")

Tom Pacala (Research Assistant/Received Ph. D. 1980, "Sub  
Nanosecond Pulse Amplification in Rare Gas Halide Media")

Interactions:

During this time Dr. Christiansen has had extensive contacts with other scientists at the Naval Research Laboratories. To further these contacts Dr. Christiansen spent 6 months (9/1/78 - 3/1/79) as a visiting scientist at NRL working on new programs involving excimer lasers.

Extensive interactions have taken place with the UV laser group at the Northrop Research and Technology Center. This work is partially supported by DOD.

New Discoveries:

- a) The capillary discharge laser.
- b) The r-f electrodeless discharge laser.
- c) Pico-second pulsewidth measuring technique for the ultraviolet using two photon generated color centers.

2.2 A Spectroscopic Study of Basic Processes in Electrically  
Excited Materials

M. Gundersen (PI)

Report Period: September 1980 - March 1981

Research Objectives: The objective of this work is the investigation by optical techniques of the basic processes that occur in highly electrically excited materials.

### State of the Research:

Since the initiation of this new work unit in September 1980, most of the effort has been directed to establishing a new laboratory for the research group to pursue the program described in the September 1980 proposal. The following briefly describes the status of the laboratory and some research which has been started.

A laboratory including tunable dye laser, CO<sub>2</sub> laser, electrically shielded screen room, optical multichannel analyzer and other apparatus has been started. With the exception of the dye laser and optical multichannel analyzer, the laboratory is in good operating condition.

Additionally, research into the physics of electrically excited gases has begun. We have observed for the first time the formation of long-lived molecular states in hydrogen thyractions [1]. Work on approaches to optical energy extractors has also been undertaken [2].

### Publications:

1. M. Gundersen and S. Guha, "Formation of Metastables in Hydrogen Thyractions," to be submitted to IEEE Trans. Plasma Sci.
2. M. Gundersen, "Optical Processes in the Recovery of Gas Phase Switches," to be submitted to IEEE Trans. Plasma Sci.

### Other Professionals:

S. Guha and S. J. Lee (Research Assistants)

### Interactions:

The principal investigator is a consultant to Los Alamos Scientific Laboratory.

## 2.3 Dynamic Processes in Chemically and Collisionally Pumped Lasers

Curt Wittig

Report Period: April 1976 - March 1981

Research Objectives: During this period, we studied elementary physical and chemical processes that occur in the gaseous phase. These processes are germane to many applications in the area of quantum electronics, and the work resulted in the development of several unique laser systems as well as leading to a more clear understanding of several existing, technologically significant laser systems. Several diagnostic techniques were developed which helped very much in our measurements of cross sections for relevant processes. We emphasized this aspect of the work, since we felt that such information could not be obtained by measurements of a "working laser medium," since under these circumstances a plethora of relevant processes occur simultaneously. Below, specific projects are listed along with their individual objectives.

(a) Collisionally Pumped Lasers. These devices were pumped by energy transfer from a metastable "reservoir" of molecules which can be produced in large quantities, and which transfer their excitation in a specific way, thereby providing selective excitation of the desired lasing species. In this work, it is important both to uncover such selective processes, and also to analyze the relevant physical processes in sufficient detail so that something definitive can be said about the laser system under question.

(b) Inverse Electronic Relaxation. This work was concerned with understanding what is responsible for this phenomenon, which species are participants (in our experiments), and whether significant population inversions can be achieved using this technique.

(c) The Reaction of  $C_2(a^3\Pi_u)$  with NO: Electronic Specificity in the CN Product. In this work, we studied the specificity of the reaction  $C_2(a^3\Pi_u) + NO(X^2\Pi) \rightarrow CO(X^1\Sigma) + CN(X, A, \text{ and } B \text{ states})$ . Adiabatic correlations between reagents and products suggest that the excited A and B states can be formed in this reaction, but the ground state can not. We decided this issue by measuring nascent X, A, and B state populations. Also, the possibility of laser oscillation on CN transitions was scrutinized.

(d) The HgBr Laser. This work was concerned with reactive and energy transfer processes of concern to the HgBr laser. We measured relaxation of upper and lower laser levels, and chemical reactions which form HgBr in the excited B state.

(e) Laser Multiphoton Ionization (MPI). The objectives of this work were (i) to develop a diagnostic technique which could be used with species which do not fluoresce, and (ii) to optically produce highly ionized species which could be used subsequently to selectively excite collision partners via near resonant processes. The work has been successful, and is ongoing in our research program (see below).

Status of Research Effort: This section summarizes our progress on the separate research items which are listed in the previous section. For the sake of brevity, publications are referenced for details.

(a) Collisionally Pumped Lasers. In experiments where Br ( $4^2P_{1/2}$ ), hereafter referred to as Br\*, acts as the metastable reservoir species, our research resulted in a large number of new and interesting laser systems operating at ir frequencies [1, 4-6, 9]. These lasers provided new and desirable frequencies, high pressure operation for certain applications, and the possibility of unique means of exciting certain transitions (e. g., solar pumped CO<sub>2</sub> laser). A parallel set of diagnostic measurements, in which we measured rate coefficients for all relevant kinetic processes [7, 10-12, 14], allowed us to make critical statements concerning system efficiency, potential laser power, cooling requirements, etc.

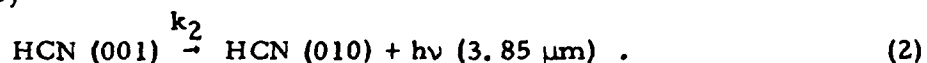
This work was rather productive and reached an unusually happy conclusion approximately three years ago. In looking back, we can now assess these E → V pumped molecular lasers with reasonable accuracy.

The opportunity for efficient operation, compared with competing technologies, of a laboratory scale device seems remote. However, after several careful analyses, we feel that the solar pumped Br\*/CO<sub>2</sub> E → V transfer laser is competitive with any of the other solar pumped lasers which have been proposed/demonstrated to date. This is an area that remains to be exploited, and which may hold a number of applications for laser devices which are not restricted to operate within the confines of the earth's atmosphere.

We also studied the HF/HCN energy transfer system. In addition to being an intellectual curiosity, this system was thought to hold promise as an energy transfer laser analogous to the DF/CO<sub>2</sub> laser, but operating near 3.85 μm. The inversion occurs via



followed by



Our approach was to measure  $k_1$  as well as rate coefficients for deleterious processes, and on the basis of these measurements to critically evaluate a scheme for a laser based on (1) and (2). We did this, and concluded that such a laser would work, but not well. Thus, we did not try to construct a laser based on reactions (1) and (2). Other groups (e. g., Hughes, Culver City) pursued this idea subsequently using expansion nozzle technology, as this can improve matters somewhat. They succeeded in obtaining 3.85 μm laser oscillation, but at modest power levels.

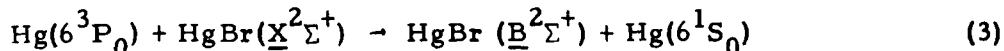
(b) Inverse Electronic Relaxation, V ↔ E Coupling. This occurs because of a coupling between electronic and vibrational degrees of freedom. With a polyatomic species, vibrational excitation can be imparted, rather straightforwardly and efficiently, with ir lasers (e. g., CO<sub>2</sub>). Due to V ↔ E coupling, emission occurs at frequencies which correspond to electronic transitions of the polyatomic. The spontaneous

emission rate for the electronic transition is diluted by the vibrational character of the state, but as long as this rate is  $\gg$  the spontaneous emission rate for vibrational transitions, the photon quantum yield may approach unity.

It was the purpose of our research to identify candidate species which undergo  $V \approx E$  coupling following CO<sub>2</sub> TEA laser excitation, and to see whether or not a vapor phase laser, similar in many respects to a dye laser, could be pumped by this method. This led to several papers which established the collision free nature of the excitation process, found a large number of suitable precursors, and led ultimately to the proper identification of the emitting species [15, 18, 21, 23]. Laser action from such a system seems rather unlikely, however, due to the very efficient  $V \rightarrow T$  collisional relaxation of the excited polyatomics. Even Ar was an efficient collision partner, and thus there is little chance that a high density medium could be inverted by this technique. Also, dissociation was found to be very facile, and this does not help matters.

(c) The Reaction of C<sub>2</sub>(a<sup>3</sup>π<sub>u</sub>) With NO: Electronic Specificity in the CN Product. In this work, we found a chemical reaction which produces electronically excited products in preference to ground state products. The reaction occurs in C<sub>8</sub> symmetry and the experimental results are in accord with an adiabatic correlation of products with reactants via A' and A'' potential surfaces. The reaction produces the B and A states of CN, but not the X state [16]. It is possible that such an inversion between product electronic states could find application in the quantum electronics area.

(d) The HgBr Laser. This work was initiated with JSEP support in order to study kinetic processes which are germane to the electrically excited HgBr blue-green laser. We obtained encouraging initial results which showed that the proposed experiments would work, and, due to a very specific interest in the research, ONR began supporting this work shortly thereafter. We measured cross sections for collisional relaxation of HgBr (B), for collisional relaxation of HgBr (X) vibrational levels, and several reactive processes involving radical-radical encounters [17, 19, 22]. These results impacted thinking about the HgBr laser, particularly with respect to fundamental limitations. Finally, we measured the reactive process



and were able to explain the results using an electron jump model wherein the  $\text{Hg}^+(\text{HgBr})^-$  charge transfer complex acts as a reaction intermediate.

(e) Laser Multiphoton Ionization (MPI). These experiments were begun during summer, 1980, and are now among the most active experiments in the group. MPI is extremely attractive as a diagnostic tool, since it can be used with very minute samples which do not fluoresce. Identification is via the spectral signature of an absorptive system, despite the lack of fluorescence, and therefore both mass and optical spectra are obtained in a single experiment. This has been demonstrated in our lab by detecting UF<sub>5</sub> radicals via MPI in the presence of a large background

of UF<sub>6</sub> vapor [25].

We have also been successful with using MPI to generate multiply charged ions via sequential ionization and fragmentation of parent molecules. These are very energetic species, and can be used as donors in excitation transfer schemes. For example, we have generated U<sup>+</sup>, U<sup>2+</sup>, and U<sup>3+</sup> in high concentration using a 5 ns pump pulse duration. U<sup>+</sup> and U<sup>2+</sup> are present in equal concentration, and under different circumstances it should be possible to peak the ion distribution near U<sup>3+</sup> or possibly more highly charged ions [26]. Note that charge transfer processes of the form  $M^{n+} + N \rightarrow M^{(n-1)+} + N^{+*}$  are capable of producing very highly excited species N<sup>+\*</sup>. Our preliminary results have been written up and are in press. Future experiments will be concerned with resonant charge transfer of highly charged species and associated product state distributions. Such distributions can be measured by LIF, since high ion concentrations can be prepared and analyzed in 5-10 ns, before Coulomb scattering can diffuse the charged species.

Publications:

1. A. B. Petersen and C. Wittig, "Chemically Pumped N<sub>2</sub>O Laser," Chem. Phys. Lett. 32, 274 (1975).
2. A. B. Petersen and C. Wittig, "NaCl Surface Reaction in Chemical Laser Devices," IEEE J. Quant. Electron. QE11, 110 (1975).
3. A. B. Petersen, C. Wittig and P. D. Coleman, "CW Chemical Lasers Pumped by Vibrational Energy Transfer: CO/CO<sub>2</sub> and CO/N<sub>2</sub>O," J. Appl. Phys. 46, 4570 (1975).
4. A. B. Petersen, C. Wittig, and S. R. Leone, "Infrared Molecular Lasers Pumped by Electronic-Vibrational Energy Transfer from Br(4<sup>2</sup>P<sub>1/2</sub>): CO<sub>2</sub>, N<sub>2</sub>O, HCN, and C<sub>2</sub>H<sub>2</sub>," Appl. Phys. Lett. 27, 305 (1975).
5. A. B. Petersen, C. Wittig, and S. R. Leone, "E-V Pumped CO<sub>2</sub> Laser Operating at 4.3, 10.6, and 14.1 μm," J. Appl. Phys. 47, 1051 (1976).
6. A. B. Petersen, L. W. Braverman and C. Wittig, "H<sub>2</sub>O, NO, and N<sub>2</sub>O Infrared Lasers Pumped Directly and Indirectly by Electronic-Vibrational Energy Transfer," J. Appl. Phys. 48, 230 (1977).
7. A. Hariri, A. B. Petersen, and C. Wittig, "Electronic-to-Vibrational Energy Transfer from Br(4<sup>2</sup>P<sub>1/2</sub>) to HCN, and the deactivation of HCN (001)," J. Chem. Phys. 65, 1872 (1976).
8. C. P. Christensen, L. W. Braverman, W. H. Steier, and C. Wittig, "Active Modelocking of the XeF Laser," Appl. Phys. Lett. 29, 424 (1976).
9. A. B. Petersen and C. Wittig, "Line Tunable CO<sub>2</sub> Laser Operating in the Region 2280-2360 cm<sup>-1</sup> Pumped by Energy Transfer from Br(4<sup>2</sup>P<sub>1/2</sub>)," J. Appl. Phys. 48, 3665 (1977).

10. A. Hariri and C. Wittig, "Electronic to Vibrational Energy from (Br( $4^2P_{1/2}$ )) to CO<sub>2</sub>, COS, CS<sub>2</sub>," J. Chem. Phys. 67, 4454 (1977).
11. A. Hariri and C. Wittig, "Electronic to Vibrational Energy Transfer from Br( $4^2P_{1/2}$ ) to H<sub>2</sub>O," J. Chem. Phys. 68, 2109 (1978).
12. H. Reisler and C. Wittig, "Temperature Dependence of Electronic to Vibrational Energy Transfer from Br( $4^2P_{1/2}$ ) to CO<sub>2</sub> and HCl," J. Chem. Phys. 68, 3308 (1978).
13. D. Coulter, D. Dows, H. Reisler, and C. Wittig, "Laser Photodissociation of s-Tetrazine: Product Vibrational Energies," Chem. Phys. 32, 429 (1978).
14. H. Reisler and C. Wittig, "Temperature Dependence of Electronic to Vibrational Energy Transfer from Br( $4^2P_{1/2}$ ) to <sup>12</sup>CO<sub>2</sub> and <sup>13</sup>CO<sub>2</sub>," J. Chem. Phys. 69, 3756 (1978).
15. M.H. Yu, H. Reisler, M. Mangir, and C. Wittig, "Collisionless Production of Electronically Excited Species Via IR Laser Photolysis," Chem. Phys. Lett. 62, 439 (1979).
16. H. Reisler, M. Mangir, and C. Wittig, "The Kinetics of Free Radicals Generated by IR Laser Photolysis: I. Reactions of C<sub>2</sub>( $a^3\Pi$ ) with NO, Vinyl Cyanide, and Ethylene," J. Chem. Phys. 71, 2109 (1979).
17. H. Helvajian and C. Wittig, "Collisional Quenching of HgBr( $B^2\Sigma_{1/2}^+$ )," Opt. Commun. 30, 189 (1979).
18. H. Reisler and C. Wittig, "Electronic Luminescence Resulting from IR Multiple Photon Excitation," in 'Photoselective Chemistry, Part I,' J. Jortner ed., Wiley, 1981.
19. H. Helvajian, M. Mangir and C. Wittig, "Vibrational Relaxation in HgBr ( $X^2\Sigma_{1/2}^+$ )," Chem. Phys. Lett. 77, 177 (1980).
20. A. M. Renlund, H. Reisler and C. Wittig, "The Influence of Laser Intensities on the Rotational Distribution of CN ( $X^2\Sigma^+$ ) Produced via IR Multiple Photon Distribution," Chem. Phys. Lett., 78, 40 (1981).
21. T. A. Watson, M. Mangir, M.R. Levy and C. Wittig, "Optical Detection of Photoproducts Using a Pulsed Supersonic Molecular Beam: Application to Intramolecular V E coupling in IR Laser Excited Polyatomics," J. Chem. Phys., in press.
22. H. Helvajian and C. Wittig, "Vibrational Quenching of HgBr ( $X^2\Sigma_{1/2}^+$ )," Appl. Phys. Lett., in press.
23. T. A. Watson, M. Mangir, C. Wittig and M.R. Levy, "The Origin of the Electronic Emission which Accompanies IR Multiple Photon Excitation of CrO<sub>2</sub>Cl<sub>2</sub>," J. Phys. Chem., 85, 754 (1981).

24. H. Helvajian and C. Wittig, in preparation.
25. M. Stuke, H. Reisler and C. Wittig, "Monitoring UF<sub>5</sub> Photo-dissociation via Laser Multiphoton Ionization," J. Appl. Phys., in press.
26. M. Stuke and C. Wittig, "Multiply Charged Atomic and Molecular Ions from Multiphoton Ionization of UF<sub>6</sub>," Chem. Phys. Lett., in press.

Professional Personnel (April 1976 - March 1981):

1. Alan Petersen, Research Assistant, Ph.D.E.E., November, 1976.
2. Akban Hariri, Research Assistant, Ph.D. Physics, September, 1977.
3. Dong Shim, Research Assistant, Ph.D.E.E., June, 1978.
4. Leonard Braverman, Research Associate, 1976-1977.
5. Hanna Reisler, Research Assistant, Professor, 1977-present.
6. Joe Tice, Research Assistant, Ph.D.E.E., January, 1979.
7. Jean-Pierre Morand, Visiting Scholar, 1977-1978.
8. C. Robert Quick, Jr., Research Assistant, Ph.D.E.E., January, 1979.
9. Metin Mangir, Research Associate, 1977-1980.
10. Ming-Hsing Yu, Research Assistant, Ph.D. Chemistry, September, 1978.
11. Henry Helvajian, Research Assistant, Ph.D.E.E., expected September, 1981.
12. Thomas Fischer, Research Assistant, Ph.D.E.E., expected September, 1981.
13. Michael Stuke, Visiting Professor, 1980-1981.

### 3. INFORMATION ELECTRONICS

#### 3.1 Furthering Data Abstraction Verification

PI: L. Flon

Report Period: April 1979 - March 1981

#### Research Objectives:

The identification and investigation of methodologies designed to deal with the construction of correct and high quality software systems. This has included:

- a) methods for reasoning about abstract data types;
- b) a design methodology for large systems aimed at transforming system requirements into an implementation meeting those requirements;
- c) a beginning investigation of a software design methodology and support system, called "metaprogramming."

#### Status of Research Effort:

Initial investigation of topic (a) above led to [1], and subsequently our interest broadened to the design analysis of complete systems. We have investigated the nature of requirement specification and analysis, in an attempt to formulate a design methodology that takes account of system requirements as a basic principle of the design, thus greatly reducing the herculean task of after-the-fact validation against user requirements. Using the SIFT computer system (SRI project funded by NASA, Langley) as a guiding example, we have identified a methodology which organizes system design into a hierarchy of levels. In this case, a level consists of a model of the system and a set of requirements governing the behavior of that model. Levels are connected via design decisions. A design decision made at level  $i$  causes the model and/or the requirements at that level to become partially undefined. Level  $i+1$  is made consistent with level  $i$  by resolving these "perturbations." In this way the original system requirements are satisfied as early as possible in the design process, giving more freedom of implementation to lower levels and allowing validation of those original requirements at a much higher level than that of the actual code.

This work is being completed in the form of a Ph. D. dissertation [2] by Ms. Deborah Baker. Ms. Baker is expected to receive her degree later this year. A joint paper will be published in addition [3].

The research effort is now moving into the area of "metaprogramming."

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.

Publications:

1. Flon, L. and Misra, J., "A Unified Approach to the Specification and Verification of Abstract Data Types," Proceedings of the IEEE Conference on Specification of Reliable Software, 1979.
2. Baker, D., "The Use of Formal Requirements in the Design of Integrated Systems," Ph.D. Thesis, University of Southern California, in preparation.
3. Baker, D. and Flon, L., "Requirements-driven System Design," in preparation.

Professional Personnel:

(PI) - Prof. L. Flon

Research Assistant - Deborah Baker, Ph.D. Thesis in preparation, expected 1981 (see [2]).

Interactions:

A major example used in investigating the design methodology was the Software Implemented Fault Tolerance System (SIFT) at SRI, funded by NASA, Langley. Interactions with members of the SRI laboratory (J. Goldberg, P. G. Neumann) led to later discussions between Prof. Flon and Brian Lupton of NASA, Langley. Mr. Lupton is involved in the design of Airlab, a NASA project designed to support a unification of the electronic systems in aircraft. Airlab is interested in looking at the design methodology for this purpose.

Invention Disclosures: None

3.2 User-Oriented Database Structure and Access

(PI) Dennis McLeod

Report Period: April 1979 - March 1981

Research Objectives: The objectives of this project have been to devise: (1) a database structuring and description formalism (database model) describing the logical content and organization of databases; (2) a disciplined, structured database design and evolution methodology (to reduce the cost of developing new database systems, and improve the quality and evolvability of the resulting software systems); (3) to devise and demonstrate a new approach to logically linking multiple database systems, with controlled sharing among the interconnected databases.

### Status of Research Effort:

During the contract period, three main research results have been produced:

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 (SDM) has been completed during the contract period, and the results of this research are detailed in [5]. A survey and framework for the comparative evaluation of other semantic database models was also produced [6]. Finally, a short overview was prepared, which analyzes 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) [7].
2. After a careful analysis of the deficiencies of contemporary software architectures for general-purpose database management systems [4], we have developed a new database system architecture, termed federated database systems [2]. This new database system architecture supports the decentralization of databases, provides a basis for partial integration and sharing of data, and accommodates the interconnection of heterogeneous databases.
3. Progress has been made towards a database design and evolution methodology, which is intended to aid in the problem of developing and maintaining a database. Preliminary results of this research are described in [1]. Our approach is to base the methodology on a semantic database model (similar to SDM), as it can support a high-level, implementation-independent structural specification of a database. (A detailed design and evolution methodology will be complete by August 1981 [9]).

### JSEP Publications:

1. "Applying a Semantic Database Model," with R. King, Proceedings of International Conference on the Entity-relationship Approach to Systems Analysis and Design, Los Angeles, CA, 10-12 December 1979.
2. "A Federated Architecture for Database Systems," with D. Heimbigner, Proceedings of National Computer Conference, Anaheim, CA, 1980.
3. "A Database Transaction Specification Methodology for End-Users," Technical Report 79-6, Computer Science Department, University of Southern California, Los Angeles, CA, 1980 (accepted for journal publication).
4. "On the Architecture of Database Management Systems," with M. Hammer, Infotech State of the Art Report on Data Design, 1979.
5. "Database Definition with SDM: A Semantic Database Model," with M. Hammer, to appear in ACM Transactions on Database Systems, 1981.

6. "Abstraction in Databases," with J. Smith, Proceedings of Workshop on Data Abstraction, Databases, and Conceptual Modelling, Pingree Park, CO, 23-26 June 1980.
7. "On Conceptual Database Modelling," Proceedings of Workshop on Data Abstraction, Databases, and Conceptual Modelling, Pingree Park, CO, 23-26 June 1980.
8. "Semantic Database Models," with R. King, to appear in Principles of Database Design, S. B. Yao, editor, Prentice Hall, 1981.
9. "The Event Database Support Model," with R. King, in preparation, 1981.

Professional Personnel:

(PI) - Dennis McLeod, Assistant Professor of Computer Science

Roger King, Ph.D. Candidate in Computer Science, M.S. received June 1979, Ph.D. expected January 1982.

Interactions:

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

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

ARPA/SAC/USC-ISI, advisor on SAC data management problems and possible research directions.

Discoveries, Patents, etc.: None

3.3 Design of Easily Maintainable Digital Systems

(PI) John P. Hayes

Report Period: April 1976 - March 1981

Research Objectives:

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

1. Design of combinational logic networks to maximize fault resolution.
2. Development of graph models to analyze the requirements for fault tolerance in multiprocessor systems.
3. Evaluation of transition counting and related methods for testing

digital logic circuits.

4. Development of a high-level calculus for testing complex digital systems.
5. Determining the testing requirements of bit-sliced designs, and their use in self-testing systems.
6. Analysis and synthesis of fault-tolerant interconnecting networks for computer systems.

Status of Research Effort:

A study of fault resolution and fault equivalence in combinational logic networks was completed [2, 8, 15, 20]. Two faults are said to be equivalent or non-resolvable if they cannot be distinguished by externally applied tests. We introduced the concept of S-equivalence which extends the usual definition of fault equivalence from gates to circuit elements of arbitrary complexity. We developed several techniques for designing networks in which equivalent faults can be confined to a small area of the network.

We introduced a new model for analyzing fault-tolerant computing systems [4]. A computing system S is defined by a graph G whose nodes represent computing facilities, including spares. Faults are associated with the removal of nodes from G. S is said to be k-fault tolerant (k-FT) with respect to a basic system A if S can reconfigure to the structure of A with up to k faults present. We developed techniques for designing optimally k-FT systems where A is a single loop or a simple tree structure [4]. We have also applied this graph model to the characterization of dynamic reconfiguration and recovery strategies in multiprocessor systems [9]. The concept of a t-step recoverable (t-SR) system was introduced as a way of measuring recovery efficiency. A simple class of optimally t-SR designs was discovered [9]. Work is continuing on characterization of more general recovery and reconfiguration strategies for multiprocessors.

An investigation of transition counting and other unconventional testing methods was carried out [1, 3, 6, 7, 13]. Transition counting (TC) is a data compaction technique in which a test response sequence is represented by the number of 0/1 transitions it contains. It requires little test equipment, and is particularly suited to field maintenance by unskilled personnel. A thorough analysis of TC testing was carried out [1, 7] which demonstrated that TC testing can, in principle, provide essentially the same fault coverage as conventional testing with very little increase in test length. We generalized TC testing to a hierarchy of testing methods which we term "check sum" methods [3, 6]. We showed that check sum tests involve some basic tradeoffs between tester complexity and fault resolution. We are currently considering the use of check sum methods in the design of built-in test equipment. We also completed a brief study of an algebraic approach to testing called the ENF method [13]. In this we solved a 15-year old problem (Armstrong's Conjecture) concerning the coverage of ENF testing.

A study of the use of high-level algebraic expressions (recurrence equations) to describe the interconnection structure of digital systems was carried out [11]. This formed the starting point for the development

of a high-level calculus for representing the test requirements of complex systems [19].

The goal of this work is to treat high-level components such as registers, multiplexers and ALU's, and their associated signals as primitives in testing. This is motivated by the need to manage the complexity of testing VLSI-based systems. In [19] the use of general symbolic matrices called vector sequences (VS's) is described. We have demonstrated that the VS approach allows an enormous compression in test data. For example, the following VS expression

$$[(1, 1, 1, d_9)^{256}, C_8] \times [0_7^{8192}, C_{13}]^{258}$$

represents an input test sequence containing over two million 21-bit test patterns, which detects all functional faults in the ALU of a typical 8-bit microprocessor [19]. Much work remains to be done in this area, including the development of test generation algorithms that employ VS's rather than conventional bit patterns.

We have carried out a comprehensive study of the testability of bit-sliced systems [12, 21, 22, 23, 25]. A bit-sliced system is composed of uniform elements (slices) which are interconnected as a one-dimensional array. We developed a model for a general-purpose microprocessor slice which contains most of the features of commercial devices. We have analyzed the test requirements of this and other slices with respect to functional faults. We have shown that in most cases the tests for a single slice can be easily extended to a bit-sliced array of arbitrary length. In many cases no increase in the number of tests needed is required, a property called C-testability. We have developed new methods for making arbitrary slices C-testable. We have shown that bit-slicing can also be exploited in the design of self-testing systems [21]. Current work in this area is concerned with the characterization of self-testing designs. We are also using our results to provide data for the VS testing project discussed above.

We are also completing an investigation of the fault tolerance properties of a class of interconnecting networks called  $\beta$ -networks intended for use in multicomputer systems [18, 24]. A  $\beta$ -network is composed of  $2 \times 2$  programmable crossbar switches called  $\beta$ -elements. Using a fault model in which a  $\beta$ -element can be stuck in any two of its normal states, we have developed a new criterion for fault tolerance called dynamic full access (DFA). A fault is said to be critical if it destroys DFA. We have derived a complete mathematical characterization of the critical faults in  $\beta$ -networks [18]. Using this work, we are currently investigating ways of synthesizing  $\beta$ -networks with specified bounds on their fault tolerance and communication delay.

#### JSEP Publications (1976-1981):

1. J. P. Hayes, "Transition count testing of combinational logic circuits," IEEE Trans. on Computers, vol. C-25, pp. 613-620, June 1976.
2. J. P. Hayes and A. Goundan, "Partitioning logic circuits to maximize fault resolution," Proc. Thirteenth Design Automation Conf., San Francisco, pp. 271-277, June 1976.

3. J. P. Hayes, "Check sum test methods," Proc. Sixth Fault-Tolerant Computing Symp., Pittsburgh, pp. 114-120, June 1976.
4. J. P. Hayes, "A graph model for fault-tolerant computing systems," IEEE Trans. on Computers, vol. C-25, pp. 875-884, Sept. 1976.
5. J. P. Hayes, "On the properties of irredundant logic networks," IEEE Trans. on Computers, vol. C-25, pp. 884-892, Sept. 1976.
6. J. P. Hayes, "Check sum methods for test data compression," Journal of Design Automation and Fault-Tolerant Computing, vol. 1, pp. 3-17, Oct. 1976.
7. J. P. Hayes, "Generation of optimal transition count tests," IEEE Trans. on Computers, vol. C-27, pp. 36-41, Jan. 1978.
8. A. Goundan, "Fault equivalence in logic networks," Ph. D. Dissertation, Dept. of Electrical Eng., U. S. C., Feb. 1978.
9. J. P. Hayes and R. Yanney, "Fault recovery in multiprocessor networks," Digest Eight Fault-Tolerant Computing Symp., Toulouse, pp. 123-128, June 1978.
10. J. P. Hayes, "Path complexity of logic networks," IEEE Trans. on Computers, vol. C-27, pp. 459-462, May 1978.
11. J. P. Hayes, "Component expansion techniques in computer design," Digital Processes, vol. 4, pp. 295-312, Winter 1978.
12. T. Sridhar and J. P. Hayes, "Testing bit-sliced microprocessors," Proc. 1979 Internat. Symp. on Fault-Tolerant Computing, pp. 211-218, Madison, Wisconsin, June 1979.
13. J. P. Hayes, "Test Generation Using Equivalent Normal Forms," Journal of Design Autom. & Fault-Tolerant Computing, Vol. 3, pp. 131-154, Winter 1979.
14. J. P. Hayes and E. J. McCluskey, "Testability Considerations in Microprocessor-Based Design," Computer Systems Laboratory Technical Report No. 179, Stanford University, November 1979.
15. A. Goundan and J. P. Hayes, "Design of Totally Fault Locatable Logic Networks," IEEE Trans. Computers, Vol. C-29, pp. 33-44, January 1980.
16. J. P. Hayes and E. J. McCluskey, "Testability Considerations in Microprocessor-Based Design," Computer, Vol. 13, No. 3, pp. 17-26, March 1980.
17. J. P. Hayes, "Testing Memories for Single-Cell Pattern Sensitive Faults," IEEE Trans. Computers, Vol. C-29, pp. 249-254, March 1980.

18. J. P. Shen and J. P. Hayes, "Fault Tolerance of a Class of Connecting Networks," Proc. Seventh Annual Symp. on Computer Architecture, pp. 61-71, LaBaule, France, May 1980.
19. J. P. Hayes, "A calculus for testing complex digital systems," Digest Tenth Fault-Tolerant Computing Symp., Kyoto, pp. 115-120, Oct. 1980.
20. A. Goundan and J. P. Hayes, "Identification of Equivalent Faults in Logic Networks," IEEE Trans. on Computers, vol. C-29, pp. 978-985, Nov. 1980.
21. T. Sridhar and J. P. Hayes, "Self-Testing Bit-Sliced Microcomputers," Digest of 22nd IEEE Computer Society Conf. (Spring COMPCON 81), San Francisco, pp. 312-316, Feb. 1981.
22. T. Sridhar and J. P. Hayes, "A Functional Approach to Testing Bit-Sliced Microprocessors," IEEE Trans. on Computers, to appear.
23. T. Sridhar, "Easily Testable Bit-Sliced Digital Systems," Ph. D. Dissertation, Dept. of Electrical Eng., U.S.C., 1981, in preparation.
24. J. P. Shen, "Fault Tolerance of  $\beta$ -Networks in Interconnected Computer Systems," Ph. D. Dissertation, Dept. of Electrical Eng., U.S.C., 1981, in preparation.
25. T. Sridhar and J. P. Hayes, "Design of Easily Testable Bit-Sliced Systems," IEEE Trans. on Computers, to appear.

Professional Personnel:

Faculty: J. P. Hayes

Students:

- A. Goundan, (Ph. D., 1978, Thesis: "Fault Equivalence in Logic Networks").  
 J. P. Shen, (Ph. D. expected 1981, Thesis: "Fault Tolerance of  $\beta$ -Networks in Interconnected Systems").  
 T. Sridhar, (Ph. D. expected 1981, Thesis: "Easily Testable Bit-Sliced Digital Systems")  
 R. Yanney  
 C. S. Yeh

Interactions:

J. P. Hayes visited Rome Air Development Center, Rome, New York, in May 1978. He met with M. Kesselman and M. Troutman and discussed research problems of mutual interest in the areas of computer architecture and fault-tolerant computing.

J. P. Hayes spent a sabbatical at the Center for Reliable Computation, Computer Systems Laboratory, Stanford University, January - June 1979. He interacted with Prof. E. J. McCluskey and his group on research problems in testing and fault tolerance.

J. P. Hayes acted as a consultant to Aerospace Corporation, El Segundo, California, during the period 1980-81. He worked with A. Carlan and his associates on design for testability.

J. P. Hayes acted as a consultant to the Research Triangle Institute, Research Triangle Park, North Carolina, in September 1980. He served as a member of a Working Group to evaluate the NASA-sponsored CARE III program for computer reliability calculation. His main contact at RTI was J. Clary.

#### New Discoveries:

A new graph theoretical model for the study of fault-tolerant systems was introduced. A classical problem in testing theory known as Armstrong's Conjecture was solved; it is false. A powerful new tool (vector sequences) for analyzing the test requirements of complex digital systems was developed. There were no invention disclosures.

### 3.4 Multivariable Feedback Design

(PI) M. G. Safonov

Report Period: April 1978 - March 1981

Research Objectives: To develop engineering techniques suitable for use in the modern computed-aided design environment, which are applicable to the design of dynamical multiloop feedback control systems to meet specifications calling for a robust tolerance of parameter variation, nonlinearity and noise within specified bounds.

#### Status of Research Effort:

Techniques based on "conic 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 systems 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.,  $1 > \|A\| \triangleq \max(\|\underline{Ax}\|/\|x\|)$ . The property ensures that the realization will remain stable with reasonable perturbations in the parameters of  $\underline{A}$ . 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 on 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 [9].

#### JSEP 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, "Stability Margins of Diagonally Perturbed Multivariable Feedback Systems," submitted 3/81 to IEEE Conf. on Decision and Control, San Diego, CA, December 16-18, 1981, and to IEEE Trans. on Automatic Control.

Professional Personnel:

Dr. Michael G. Safonov (Principal Investigator)  
 Dr. Sun-Yuan Kung (Senior Investigator)  
 Mr. Yadolah Hadaegh (Graduate Research Assistant)  
 Mr. Kamran Karimlou (Graduate Research Assistant)

DOD Interactions:

The Principal Investigator (M. G. Safonov) served as a consultant to Honeywell Systems and Research Center, Minneapolis, MN, in conjunction with ONR Contract N00014-75-C-0144.

The Principal Investigator was an invited participant in the ONR Workshop on Robustness, MIT, Cambridge, MA, April 1979.

The Principal Investigator was an invited participant in the AFOSR Workshop on Adaptive Control, Campaign-Urbana, IL, May 1979.

Discoveries/Inventions Disclosures: None

3.5 Identification and Model Reduction Via Singular Value Decomposition Analysis on the Hankel Matrix

L. Silverman and S. Kung

Report Period: April 1979 - May 1981

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

Status of Research Effort:

I. SVD Algorithms for System Identification

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  $\leq 1$ , which is very desirable in digital filter implementation.

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].

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.

## II. Optimal Hankel Norm Approximation

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.

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.

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 to the continuous time case [5], [9], [10], [12] and the correspondence between discrete and continuous-time SVD has been explored.

## III. Other Related Works

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].

We have also recently been looking 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.

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

Publications:

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," Proceedings 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.
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 '81, The Hague, The Netherlands.
11. Kung, S.Y., "An Application of Approximation Method to High Resolution Spectral Estimation," submitted to the 20th IEEE CDC, San Diego, 1981.
12. Jonckheere, E. and Silverman, L.M., "Singular Value Analysis of Deformable Systems," submitted to 1981 IEEE CDC.

### Professional Personnel

1. S. Y. Kung, Assistant Professor, Department of Electrical Engineering, U.S. C.
2. David Lin, Ph. D., Department of Electrical Engineering, U.S. C., 1981.
3. Harry Y.H. Hu, Ph. D. Candidate, Department of Electrical Engineering, U.S. C.
4. L. M. Silverman, Professor .
5. B. Lashgari Ph. D. Candidate.
6. S. Shokoohi, Ph. D. Candidate.

### 3.6 Polychromatic Optical Information Processing

A. A. Sawchuk and T. C. Strand

Report Period: April 1976 - March 1981

Research Objectives: The objective is to extend the capabilities of optical information processing by the use of polychromatic light in coherent, incoherent, and partially coherent systems. Specific systems encode spatial frequency dependent information in a multidimensional input function as chromatic (wavelength) variations in a polychromatic output function, or they can be used for space-variant linear filtering. These abilities can be used to enhance human/machine detection and interpretation in pattern recognition, multidimensional signal processing and image analysis. Applications include texture analysis and change detection tasks such as cloud cover identification, land use discrimination, and photointerpretation. A final objective is to compare various systems and determine limits on sensitivity, space-bandwidth product, flexibility and real-time operation. In addition, new types of color selective filters, such as volume holographic filters were developed.

#### Status of Research Effort:

Significant accomplishments in several areas were made during the course of this work. Several theoretical papers on polychromatic processing have been published [1, 2]. These papers discuss the relationships between and the problems associated with both the coherent and incoherent approaches to optical pseudocoloring of spatial frequency information. This theoretical work describes the results for a particular one-dimensional object and a particular filter. The results show that the color saturation and number of different hues that can be obtained from a given filter depend strongly on the degree of coherence of the illumination.

An experimental system was assembled for polychromatic spatial frequency filtering [2]. The system consists of a white light source of

adjustable size, an illumination system for the monochromatic object transparency and an imaging system whose Fourier plane contains color filters. The system was used for one-dimensional and two-dimensional filtering of several different types of input targets, including 3 bar targets, sinusoidal targets with different fundamental spatial frequencies, natural gray level scenes, and synthesized texture patterns. Several different types of color filters were synthesized, including linear 1-D filters and circularly symmetric filters. The filters were made by photographing computer generated patterns on color films, and by assembling them in pieces from Wratten color gelatin filters.

The system has proven extremely effective in enhancing subtle texture changes [1-5]. In one experiment, the system made a very difficult texture discrimination target much more visible to the human observer. The system also made small natural texture differences in a gray-level scene much more observable. Various source sizes have been studied in a preliminary way for their effect on hue and saturation. A source image which is approximately the same size as the smallest element of the Fourier plane filter produces best results.

The spatial-frequency polychromatic filtering concept for pseudocoloring was applied to the problem of cloud identification from weather satellite pictures with very good results [3-5]. The idea of the cloud-typing experiment is that clouds which appear in weather satellite pictures can be categorized on the basis of their textural differences. If an effective means can be developed for machine detection of these textural differences, the need for time consuming and expensive human evaluation could be greatly reduced. By optically pseudocolor encoding the spatial frequency information, the various textures, and thus the various cloud types, can be color coded. This color coding can be easily input to a machine for numerical pattern classification.

Texture feature extraction on the basis of spatial frequency signatures is well suited to optical analysis whereas such global features are expensive to compute digitally. The optical pseudocolor system generates a color image where color differences indicate textural differences. These color differences are easily read and analyzed directly without further processing.

To test this idea a number of weather satellite photographs were obtained showing several different cloud types. These photographs were processed in the optical pseudocolor system to produce color images where the color conveyed textural information. These color images were photographed and the resulting color transparencies were digitized. The digitized data was brightness normalized so that only chromaticity information was retained. A cluster analysis was performed on the chromaticity data. It was found that in one particular photograph, seven distinct cloud types were identified by this cluster analysis. These results were then compared to a photointerpreter's analysis to verify their validity. The conclusion is that the cluster analysis accurately distinguished the different cloud types in the photographs, and that the segmented regions matched the photointerpreter's analysis very well. On the basis of these encouraging results the cloud-typing project has continued so that the exact color mapping of the various cloud types can be established and the system can be tried on a larger selection of satellite images.

Another area of significant contribution has been a system for space-variant processing involving a simple optical spatial filtering system with several wavelength multiplexed spatial filters [6]. Each spatial filter operates in a space-invariant manner. The space-variance is achieved by utilizing spatially varying color information in the input. This color information may be inherent in the object (i. e. , a normal color or pseudo-colored image) or may be introduced via a color mask placed either in the input or output plane. Details of the system are given in a reference [6].

Several experiments were performed to demonstrate space-variant filtering. In the first experiment, a dot array was used as a test object so that the space-variant impulse response could be seen directly. A color mask was generated that coded two vertical rows of dots red, two horizontal rows green and all other dots blue. A filter was made which performed as a low-pass filter in the horizontal direction for green with essentially no filtering of the blue. In the output image the dots which were color coded red were smeared into vertical lines while the dots that were color coded green were transformed into horizontal lines. In a second experiment the lower-half of the object was high-pass filtered and the upper half simultaneously low-pass filtered. The upper half of the input plane was passed through a red color filter while the lower half was covered with a blue color filter. The red component was low-pass filtered while the blue component was high-pass filtered in the Fourier plane.

In contrast to many previous techniques, this method of space-variant processing works for 2-D images and imposes no severe restriction on the space-bandwidth product of the input. The experiments were done using standard color transparency film for the input mask and for the multiplexed spatial filter.

To aid in the pseudocolor encoding and in the space-variant processing system described, new means of implementing narrowband color filters with controllable amplitude and phase response are needed. A study of plane-wave volume holograms for these applications was initiated. The idea is to combine computer generated holograms with the desired amplitude and phase information as a mask in the recording of a plane-wave volume hologram. By itself, the plane-wave volume hologram effectively serves as a narrowband color filter. Together the computed generated hologram mask it forms a highly selective, accurately controllable color filter.

#### Publications:

1. J. Bescos and T. C. Strand, "Optical Pseudocoloring of Spatial-Frequency Information," 1977 Annual Meeting, Optical Society of America, Toronto, October 1977; Journal Optical Society of America, vol. 67, p. 1407 (October 1977).
2. J. Bescos and T. C. Strand, "Optical Pseudocolor Encoding of Spatial Frequency Information," Applied Optics, vol. 17, pp. 2524-2531 (August 15, 1978).

3. T. C. Strand, A. A. Sawchuk and J. Mantock, "Hybrid Optical-Digital Texture Analysis," First ASSP Workshop on Two-Dimensional Digital Signal Processing, Berkeley, California, October 1979 (invited paper).
4. J. Mantock, A. A. Sawchuk, and T. C. Strand, "Hybrid Optical/Digital Texture Analysis," *Optical Engineering*, 19, pp. 180-185 (1980).
5. J. Mantock, A. A. Sawchuk, and T. C. Strand, "An Optical Processor Applied to Cloud Classification," *SPIE Proceedings*, vol. 218 (1980).
6. T. C. Strand and A. A. Sawchuk, "Space-Variant Processing with Polychromatic Light," *Proc. International Commission for Optics Congress, Madrid, Spain*, pp. 269-272 (1978).
7. S. K. Case and W. J. Dallas, "Volume Holograms Constructed from Computer-Generated Masks," *Appl. Opt.*, 17, 2537-2540, 1978.
8. E. N. Leith, A. Kozma, J. Upatnieks, J. Marks, and N. Massey, "Holographic Data Storage in Three-Dimensional Media," *Appl. Opt.*, 5, 1303-1311 (1966).
9. A. A. Friesem and J. L. Walker, "Thick Absorption Recording Media in Holography," *Appl. Opt.* 9, 201-214 (1970).
10. V. V. Aristov and V. Sh. Shekhtman, "Properties of Three-Dimensional Holograms," *Sov. Phys. Vp.*, 14, 263-277 (1971).
11. T. K. Gaylord and T. K. Tittel, "Angular Selectivity of Lithium Niobate Volume Holograms," *J. Appl. Phys.* 44, 4771-4773 (1973).
12. R. Magnusson and T. K. Gaylord, "Use of Dynamic Theory to Describe Experimental Results from Volume Holography," *J. Appl. Phys.*, 47, 190-199 (1976).
13. T. Kubota, "Characteristics of Thick Hologram Grating Recorded in Absorptive Medium," *Optica Acta*, 25, 1035-1053 (1978).

Professional Personnel:

1. A. A. Sawchuk, Associate Professor, Electrical Engineering.
2. T. C. Strand, Research Assistant Professor, Electrical Engineering.
3. A. R. Tanguay, Jr., Assistant Professor, Electrical Engineering and Materials Science.
4. J. Bescos, Visiting Scientist, Image Processing Institute (from Instituto de Optica, Madrid, Spain).

5. I. Glaser, Visiting Scientist, Image Processing Institute (from Dept. of Electronics, Weizmann Institute of Science, Rehovot, Israel).
6. P. Chavel, Visiting Scientist, Image Processing Institute (from Institut d'Optique, Orsay, France).
7. J. Mantock, Graduate Student, Electrical Engineering.
8. D. D. Garber, Graduate Student, Ph. D. degree in EE received June 1981, Thesis title: "Computational Models for Texture Analysis and Texture Synthesis."
9. M. Muha, Undergraduate Student, Physics, BS degree received June 1979.

Interactions:

1. Several discussions with George E. Lukes, U.S. Army Engineering Topographic Laboratories, Ft. Belvoir, Virginia 22060, regarding applications of polychromatic spatial frequency processing to cloud cover and terrain identification from aerial and satellite photographs.
2. Discussion with John R. Parsons, Manager, Digital Image Processing Section, Optical Systems Department, Aerospace Corp., 2350 E. El Segundo Blvd., El Segundo, California, regarding applications of polychromatic preprocessing for feature extraction in pattern recognition. Possible applications include cloud cover recognition.
3. Several technical discussions on this project and others of related mutual interest have been held with Dr. Robert Leighty of the U.S. Army Engineering Topographic Laboratories, Ft. Belvoir, Va. 22060.
4. Discussions on polychromatic processing and hybrid optical/digital systems have been held with Dr. Harold Szu of the Naval Research Lab., Washington, D. C.

SECTION II  
PROJECTS CONCLUDED DURING REPORT PERIOD

## 1. SOLID STATE ELECTRONICS

### 1.1 A Transmission Electron Microscope Study of Radiation Damage Induced by Ion-Implantation in GaAs Single Crystals

G. H. Narayanan and B. Hughes

Report Period: March 1976 - September 1979

Objective Summary: To investigate the structural characteristics of the radiation damage induced by ion-implantation in GaAs single crystals by transmission and scanning electron microscopy techniques.

#### Conclusions:

1. Amorphous layers produced in heavily damaged implanted layers recrystallize epitaxially, however, the layers contain a high concentration of  $\langle 111 \rangle$  microtwins. Twins are not desirable, therefore, driving the GaAs amorphous should be avoided.
2. Light damage implants contain black dot defects. This damage anneals out above  $600^{\circ}\text{C}$  as small perfect, interstitial type, dislocation loops on  $\{110\}$  planes. These implants should have acceptable electrical properties.
3. Moderately damaged implants contain a high concentration of black dot defects and dark diffuse linear defects, which have not been identified. These unidentified defects are stable even after an  $800^{\circ}\text{C}$  anneal. These defects are undesirable.
4. Restoring the stoichiometry of a Si implant by an additional implantation of P ions significantly increased the annealing rate of damage.
5. Electron channeling patterns are a fast non-destructive technique which can be used to monitor lattice damage.

#### Publications:

1. G. H. Narayanan and W. G. Spitzer, "The Structural Characteristics of Radiation Damage Produced by High Energy (2.7 MeV) Ion-Implantation in GaAs," J. Mat. Sci. 13, p. 2418 (1978).
2. B. Hughes and G. H. Narayanan, "On Annealing-Induced Dislocation Loops and Electrical Changes in Heavily Te-Doped GaAs," Phys. Stat. Sol. (a) 46, 627 (1978).
3. G. H. Narayanan and R. G. Wilson, "The Influence of Crystal Orientation on the Residual Defects in Ion-Implanted Si," in preparation.

4. B. Hughes and G. H. Narayanan, "An Investigation of Ion-Implantation-Induced Damage in GaAs Single Crystals," paper presented at 1978 WESTEC Technical Conference, held in Los Angeles, March 21, 1978.
5. B. Hughes and G. H. Narayanan, "Ion Implantation Damage in GaAs," paper presented at Ninth Western Regional Meeting of Electron Microscopists, held in Palm Springs, CA, May 3, 1979.
6. B. Hughes and G. H. Narayanan, "Transmission Electron Microscopy Study of Si Ion Implanted GaAs," paper presented at 155th Electrochemical Society Meeting, held in Boston, Mass., May 10, 1979.
7. B. Hughes, "A Transmission Electron Microscopy Study of Ion Implanted GaAs," Ph. D. dissertation,

## 1.2 Plasmon-Phonon Coupling in Mixed III-V Compound

Crystals--GaAs<sub>1-x</sub>P<sub>x</sub> and Ga<sub>1-x</sub>Al<sub>x</sub>As

W. G. Spitzer

Report Period: April 1977 - March 1979

Objective Summary: To study the free carrier effects including plasmon-phonon coupling in GaAs<sub>1-x</sub>P<sub>x</sub> and Ga<sub>1-x</sub>Al<sub>x</sub>As by using primarily optical techniques (infrared spectroscopy and Raman scattering) supplemented by electrical measurements.

### Progress/Accomplishments:

Most of the effort during the early part of the project was spent on the growth of thick and uniform Ga<sub>1-x</sub>Al<sub>x</sub>As layers on GaAs substrates by a temperature gradient liquid phase epitaxial growth technique. After growth, substrates were lapped off and the remaining epi-layers were polished chemically on the first grown sides. The composition (x) and its depth profile were evaluated for each layer by using an electron microprobe. In a depth of 12 μm or more the compositional variation in a given layer was less than 10%. Each growth run reproduced the x values when the same growth conditions were used.

Infrared reflectivity spectra were measured in frequency range 1000 cm<sup>-1</sup> to 50 cm<sup>-1</sup> for both undoped and Te-doped Ga<sub>1-x</sub>Al<sub>x</sub>As. The least square curve fitting of reflectivity spectra to a classical dielectric function has been done in terms of two resonance oscillators and a plasmon where the complex susceptibilities are assumed to be additive. The undoped samples give the composition dependence of the near q = 0 lattice mode frequencies. A theoretical model was used to fit this observed dependence which required the inclusion of a composition dependent "charge exchange" between GaAs and AlAs dipoles.

For Te-doped samples with  $x = 0.14$ , measured Hall data disagree with the  $n_e$  obtained from the plasma frequencies ( $\omega_p$ ) to 30 - 40% if the effective mass value obtained from the  $\bar{k} \cdot \bar{p}$  theory is used. Consideration of conduction-valence band-mixing of various energy bands at the  $\Gamma$ -point in the  $\bar{k} \cdot \bar{p}$  calculation does not remedy this discrepancy. The value of  $m^*$  determined from the measured  $\omega_p$  and  $n_e$  is  $(0.12 \pm 0.01) m_e$  for  $x = 0.14$ . For sets of samples with higher  $x$  ( $x = 0.30$  and  $x = 0.45$ ), plasma terms and Hall data have to be analyzed on the basis of the multi-valency contribution of electrons in three different types of conduction band minima, the  $\Gamma$ , L, and X minima. Due to the low mobilities of electrons in L and X minima, the plasma terms are insensitive to some degree to changes in damping constants in the curve fitting procedure as well as Hall effect measurements.

Raman scattering measurements have been made for six undoped samples. Each sample has a different composition from the others and the samples are the same pieces used in the infrared study. The LO modes contribute to the Raman intensity for a (100) surface in the backscattering geometry and the LO frequencies in Raman scattering found to be in good agreement with those obtained from infrared spectra and dispersion analysis. Other probably disorder-induced Raman-active modes were also observed. The infrared reflectivity spectra and Raman spectra for the undoped  $\text{Ga}_{1-x}\text{Al}_x\text{As}$  were analyzed and discussed in a paper recently submitted for publication. The infrared study of the plasmon-phonon interaction in  $\text{Ga}_{1-x}\text{Al}_x\text{As}$  has also been submitted for publication. O. K. Kim used this work as the basis of a Ph. D. dissertation submitted to and accepted by the Physics Department. With the completion of Dr. Kim's work this project was terminated.

#### Publications:

1. O. K. Kim and W. G. Spitzer, "Infrared Reflectivity Spectra and Raman Spectra of  $\text{Ga}_{1-x}\text{Al}_x\text{As}$  Mixed Crystals," J. Appl. Phys., 50(6), June 1979, pp. 4362-4370.
2. O. K. Kim and W. G. Spitzer, "Infrared Reflectivity Study of Heavily Te-Doped  $\text{Ga}_{1-x}\text{Al}_x\text{As}$ ," submitted for publication in Phys. Review B2.
3. O. K. Kim, Dissertation to Department of Physics, University of Southern California, April 1979.

### 1.3 Surface Wave Propagation Studies

K. M. Lakin

Report Period: April 1976 - March 1978

#### TASK A: Surface Wave Interactions with Gas Plasmas

1. Objective: To study the interaction of gas plasmas with surface acoustic waves on piezoelectric substrates and also with periodic metal stripes on the surface of an insulator in order to define a new class of active devices.

#### 2. Accomplishments:

a) This was a new task initiated in April, 1977. Further investigation into the feasibility of building useful devices using the interaction of gas plasmas with surface waves has been carried out. The available voltage at the surface of a piezoelectric crystal was found to be given by

$$v = C(P/w)^{1/2}$$

where P is the power per unit width of the acoustic beam,  $C = 1.45 \times 10^4$  for YZ LiNbO<sub>3</sub> and  $C = 8.73 \times 10^3$  for YX quartz. Thus at 10 MHz the peak potential is approximately 26 volts. This voltage level is sufficiently large to trigger a biased plasma into conduction.

b) This task was still very much in the early stage of planning and research with no experimental effort prior to conclusion of the total project. However, the implications of such an effort suggest a wide range of display and signal processing devices which exploit the non-linear interaction between SAW and the gas plasma.

#### 3. Publications:

No publications have resulted from this new task.

#### TASK B: Effect of Static Strain on Surface Acoustic Wave Propagation

1. Objective: To determine the effect of static strain on surface acoustic wave propagation and the subsequent effect on device performance.

2. Accomplishments: Work on this project has yielded a paper given at the 30th Annual Symposium on Frequency Control, 2-4 June 1976, Atlantic City, N. J. [1]. This paper gives calculated values of surface wave velocity versus all possible free-surface uniform stress elements for YX quartz, ST-X quartz, and YZ LiNbO<sub>3</sub>; the calculated coefficients are also compared with theory and experiments of other authors. All research results are described in a dissertation [2].

#### 3. Publications:

1. R. B. Stokes and K. M. Lakin, "Static Strain Effects on Surface Acoustic Wave Delay," 30th Annual Symposium on Frequency Control, 2-4 June 1976, Atlantic City, N. J.

2. R. B. Stokes, "The Effect of Uniform Static Strain on Surface Acoustic Wave Velocity," Ph. D. dissertation, University of Southern California, Los Angeles, Ca.

#### 1.4 Thin Film Crystal Filters

K. M. Lakin

Report Period: March 1979 - August 1980

Objective Summary: To study the materials growth device fabrication and analytical circuit modeling problems of a new class of thin film crystal filters. These filters are unique in that they offer a physical size reduction of 100 to 1000 over existing crystal filters, could be designed for the frequency range 1 to 1000 MHz, and could significantly affect the design of military and commercial communications systems.

#### Progress/Accomplishments:

A thickness mode composite resonator having a fundamental resonant frequency of near 435 MHz and a Q of 5000 was demonstrated. This device was fabricated using the selective etching techniques developed for Si and a sputtered ZnO film over P<sup>+</sup> silicon as the resonator element. Several such resonators have been built and tested. Results are described in the Ph. D. thesis referenced below.

This work represents a significant accomplishment in the field of microwave acoustics and in microelectronics since future devices can be integrated with active circuits on the same chip.

#### Publications:

1. Jin Wang, Ph. D., Electrical Engineering, June 1981, "Zinc Oxide on Silicon Bulk-Acoustic-Wave Composite Resonators."

#### 1.5 Negative Resistance Punched-Through-Diode Devices

B. J. Gordon

Report Period: April 1976 - March 1977

Objective Summary: To investigate the punched-through-diode, or BARITT, as an oscillator and an amplifier and to maximize device negative resistance using novel structures. The results are directly applicable to low and medium power, low-noise source and amplifier requirements.

Progress/Accomplishments: Work has continued from the past contract period with the fabrication and testing of multilayer BARITT structures. Particular emphasis has been placed on the effects of phase delay in the injection and low field regions of the device. Careful design of this region has led to substantial increases in device negative resistance in theoretical analyses. Experimental efforts are underway to verify this. Results will be reported in Y. J. Chang's dissertation.

Publications:

1. Y. J. Chang, Ph.D., Electrical Engineering, 1977, "Microwave Punch-Through (BARRITT) Diode."

## 2. QUANTUM ELECTRONICS

### 2.1 Low Frequency Dispersion of the Nonlinear Index of Refraction

M. D. Levenson and J. J. Song

Report Period: April 1976 - March 1979

Objective Summary: To observe and parametrize the contributions to the nonlinear index of refraction due to dynamical processes in ions or molecules interacting with an intense laser field.

Progress/Accomplishments: Experiments in the past year have focussed on the dynamics of the absorption process in dyes used as passive Q-switches and mode lockers. The dynamics are best described in the density matrix formalism. We have found that the dominant population relaxation times in these dyes is in the picosecond range, while the coherence decay occurs on a femtosecond time scale. This results justifies the usual rate equation treatment of saturable absorption.

This work unit was discontinued in its past form of direction and was replaced, 1979, by a new work unit, "Frequency Dispersion of Third-Order Nonlinear Optical Susceptibility," (J. J. Song).

#### Publications:

1. J. J. Song and M. D. Levenson, "Electronic and Orientational Contributions to the Optical Kerr Constant Determined by Coherent Raman Techniques," J. Appl. Phys. 48, 3496-3501 (1977).
2. G. L. Eesley, M. D. Levenson, W. M. Tolles, "Optical Heterodyne Detection of Coherent Raman Signals," J. Quant. Elec. QE-14, 45-49 (1978).
3. G. L. Eesley, Ph.D. Thesis, 1978, Univ. of So. Calif., "Engineering Development of Coherent Raman Spectroscopy."

### 2.2 Frequency Dispersion of Third-Order Nonlinear Optical Susceptibility

J. J. Song

Report Period: April 1979 - June 1980

Objective Summary: (1) Improve the sensitivity, spectral resolution of our nonlinear optical spectrometer; (2) Investigate the frequency dispersion of third-order nonlinear electric susceptibility  $X^{(3)}$  to extract the important parameters for opto-electronic application.

### Progress/Accomplishments:

1. By analyzing the lineshape of  $X^{(3)}$  spectra we have determined the picosecond-range dephasing and depopulation time constants of  $\text{Sm}^{2+}$  transitions in  $\text{CaF}_2$  [3].
2. Nonlinear spectroscopy becomes easy to carry out with a Faraday rotator we devised. Also, it is simple and cheap to make this device [2].
3. From the low frequency dispersion of  $X^{(3)}$  in  $\text{CS}_2$  we could derive (a) the reorientational time constant of the molecules, (b) nonlinear index of refraction, (c) two-photon absorption coefficients [4].

### Publications:

1. J. H. Lee, "Relaxation Time Measurements in Condensed Matter by Polarization Spectroscopy," Ph. D. Thesis, Physics, November 1979.
2. "Improved Geometry for Polarization-Sensitive Nonlinear Spectroscopy," Appl. Phys. Lett. 35, 490 (1979).
3. "Coherent Population Oscillations and Hole Burning Observed in  $\text{Sm}^{2+}:\text{CaF}_2$  using Polarization Spectroscopy," Opt. Lett. 5, 196 (1980).
4. "Coherent Rayleigh Wing Spectroscopy in  $\text{CS}_2$ ," in preparation.

### Interactions: The following papers were presented at conferences:

1. "Polarization Spectroscopy Applied to  $\text{Sm}^{2+}:\text{CaF}_2$ , CLEA Conference on Laser Engineering and Applications), May 1979, Washington, D. C.
2. "Polarization Sensitive Nonlinear Spectroscopy with a Faraday Rotator," Annual Meeting of Optical Society of America, Oct., 1979, Rochester, New York.

### 2.3 Bistable Optical Devices

J. H. Marburger, M. D. Levenson and E. Garmire

Report Period: April 1977 - March 1979

Objective Summary: To demonstrate bistable operation of a variety of optical devices employing electronic feedback to enhance the intensity dependence of the index of refraction and to investigate, experimentally and theoretically, ways in which such bistable optical devices can be developed into useful logic elements.

### Progress/Accomplishments:

1. In many crystals, the Pockels effect causes applied d. c. electric fields to alter the index of refraction. Such crystals are used, for example, in Pockels cell switches. If this d. c. field is controlled by a photodetector, an electronically enhanced nonlinear index of refraction results. Such feedback controlled Pockels cells are capable of bistable operation without the need for a delicately aligned Fabry Perot resonator. A related device employs the electric field dependence of the coherence length of a second harmonic generation crystal. Bistable operation has been demonstrated in both proposed devices. Unfortunately, theoretical analysis presently indicates that all such devices operate too slowly when consuming little power and too inefficiently when adjusted for maximum switching speed. A paper describing these results was presented at the Ninth International Quantum Electronics Conference, May 29, 1978.

2. As a follow-on to the above JSEP supported research, E. Garmire and S. D. Allen directed a USC supported project with the specific objective to develop an incoherent, mirrorless, bistable optical switch using hybrid electrical/optical feedback. The device was demonstrated in a bulk LiNbO<sub>3</sub> modulator and in a waveguide modulator, using a CdS detector as the detector and feeding the signal back onto the modulator. Bistability was observed and good agreement was seen between experiment and theory.

### Publications:

1. E. Garmire, S. D. Allen, J. Marburger, Appl. Phys. Lett. 32, 320 (1978).
2. E. Garmire, J. Marburger, S. D. Allen, Proc. SPIE, Washington, D. C., March 1978.
3. E. Garmire, Bistable Optical Device Conference, ARO, Philadelphia, Nov. 1977.

### 2.4 Theory of Electromagnetic Scattering Processes at Resonance and with Intense Fields

R. W. Hellwarth

Report Period: April 1976 - March 1978

Objective Summary: To be able to interpret and predict the nature of the electromagnetic radiation that is scattered by matter from a strong incident monochromatic wave whose frequency is at or near a resonance of the scattering medium. The problems to be attacked include those that arise in mode-locking, saturable absorption, saturation spectroscopy, high-energy optical amplifiers, infrared-laser window failure, and optical image and frequency converters.

## Progress/Accomplishments:

### TASK A: Two-Photon Amplifiers and Two-Photon Interactions

In order to evaluate the third order non-linear susceptibility for hydrogen-like atoms, we sought an analytical form for a triple sum over continuum and discrete states of a product of hydrogenic matrix elements and energy denominators. We have proceeded along lines suggested by Schwartz and Tiemann [Annals of Physics: 2, 178-187, 1959] where a part of the sum is removed by the introduction of a function defined by a separate differential equation. By use of a Laplace transform technique, we obtained a closed form integral solution to this equation which may be solved numerically. However, results of this method were found to be inconsistent with previously published limiting values, and in some cases do not seem to be physically realistic. We have begun a different approach to this calculation, using instead a Green's function method following that of Karule (J. Phys. B 4, 267, 1971), which, however, appears to require more lengthy numerical evaluations.

We obtained preliminary experimental verification (using borrowed apparatus) of the concept of an energy-reservoir level to supply population to a level from which stimulated two-photon emission is possible. Experiments monitored the non-exponential fluorescent decay from the 13s level of potassium vapor excited by 2-photon absorption for a tunable dye laser.

### TASK B: Theory of Ultra-High Optical Field Interactions

1. Nonlinear Counter-Propagating Pulses (NCP). The first portion of our proposed project studying chirp compensation with counter-propagating pulses has been completed. A report of the work has been accepted for publication as an Applied Physics Letter [2]. In this study, only plane wave situations were analyzed. The result of our study is that forward chirp developed by pulse propagation in a nonlinear medium can be removed near the pulse peak by allowing the pulse to overlap with a backward pulse at the exit of the medium. Details of the calculation are reported in ref. [2].

Beams of finite aperture tend to self-focus in non-linear medium, and this alters the self-phase modulation process. We have developed approximate equations to describe counter-propagating pulses of finite aperture and are designing a computer code for their numerical solution. Some analysis is possible for steady state counterpropagating beams, but even in this case complete solutions require numerical analysis.

2. Self-Trapped Propagation Excitations. The nonlinear Maxwell equations which govern propagation of electromagnetic waves at high intensities in plasma were examined for solutions which are self-trapped balls of energy in three dimensions. Such solutions were found to exist, but at field strengths beyond those presently obtainable in laser beams. A computational algorithm for their differential equation has been found for monochromatic stationary excitations of spherical symmetry. By computer analyses we have established that the number of such solutions (in the classical regime) is a function of the difference between the

plasma frequency and e-m wave frequency. It remains to determine if these solutions are stable to center-of-mass motion and angular variations.

3. Polarization Spectroscopy. A study of the relative merits of several laser-spectroscopy techniques for plasma diagnostics was continued. The first results have shown that the Raman-induced Kerr effect (discovered previously in this project) has unique advantages [1]. The results are being used by experimentalists elsewhere.

4. Phase-Conjunction and Beam Restoration by Stimulated Scattering. From recent experiments by Nosach et al. [4] and Zel'lovich et al. [5] it is apparent that both stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) in the backward direction can produce waves that are remarkably close to being "phase-conjugate" to the pump beam, and therefore to being a time-reversed replica of it. Such a replica can back-track through a distorting medium to emerge restored to the condition of the entering pump beam. We completed the first theory of the degree to which stimulated waves are phase-conjugates under various experimental conditions, and the powers required for efficient generation of replica waves by this process [6]. The conditions under which stimulated scattering can usefully produce a phase-conjugate wave are found to be very wide.

Publications/References:

1. R. W. Hellwarth, "Nonlinear Optical Effects for Plasma Diagnostics," Appl. Phys. 11, 147 (1976).
2. J. Marburger, R. Shockley, "Nonresonant Chirp Compensation with Counterpropagating Optical Pulses," Appl. Phys. Letters 30, 441 (1977).
3. A. T. Georges, P. Lambropoulos, J. Marburger, "Theory of Third Harmonic Generation in Metal Vapors Under Two-Photon Resonance Conditions," Phys. Rev. A15, 300 (1977).
4. O. Nosach, V. Popovichev, V. Ragul'skii, and F. Faisullov, "Cancellation of Phase Distortions in an Amplifying Medium with a 'Brillouin Mirror'," Sov. Phys. JETP Lett. 15, 109 (1972).
5. B. Ya. Zel'lovich, N. Mel'nikov, N. Pilipetskii, and V. Tagul'skii, "Observation of Wavefront Inversion in Stimulated Raman Scattering of Light," Sov. Phys. JETP Lett. 25, 36 (1977).
6. R. Hellwarth, "Theory of Phase Conjugation by Stimulated Scattering in a Waveguide," July 1978, Journ. Opt. Soc. Am.

2.5 Intense Phase Matched Picosecond Third Harmonic Generation, Using Coherent Propagation and Two-Photon Resonance Enhancement

J. C. Diels

Report Period: April 1976 - March 1978

Objective Summary: To demonstrate a new method of third harmonic generation, which would generate picosecond pulses of GW peak power in the wavelength range between 1800 Å and 2000 Å.

Progress/Accomplishments:

1. A theoretical analysis of the propagation and tripling of Rh6G laser pulses in lithium vapor, under conditions of two photon resonance, was made. The conversion efficiency can exceed 8%. The latter figure pertains to the tripling of a 70 ps duration (FWHM), 80 mJ/cm<sup>2</sup> energy density "90° phase shifted pulse" in a 1 m cell containing lithium vapor at a pressure of 1 torr. An abstract has been submitted to the Multiphoton Rochester Conference [1].

2. Computer calculations showed that the third harmonic generated by the "90° phase shifted pulse" is a smooth, unmodulated bell shaped pulse. In contrast, in conditions of "two photon self-induced transparency" [2], a wildly modulated (in phase and amplitude) third harmonic pulse is generated. Although the energy of the input pulse in the latter scheme is 130 mJ as against 50 mJ for the 90° phase shifted pulse, the highest conversion efficiency is only 2%.

3. The pulse shaper that generates 90° phase shifted pulses [3] provides two complementary outputs. More recent calculations show that the second output can be used for parametric complication of the third harmony created by the first one, yielding still higher conversions than the area reported above. Efficiency of the harmonic generation at 115 nm also occurs in this process and is currently under investigation. The results of this theory are summarized in a letter [3] and detailed in a manuscript in preparation [5].

4. The theoretical work has now contoured fairly accurately the physical parameters required for the experimental demonstration. The laser source should include:

- a) an oscillator generating pulses shorter than 50 ps;
- b) amplifiers stages to reach an energy of at least 10 mJ/pulse;
- c) a device forming a "phase shifted pulse."

Items (1) and (3) have now been successfully developed. The laser amplifiers will be built.

A heat pipe oven to produce an homogeneous mixture of Mg and Li has been constructed, together with a pump station.

Publications/References:

1. J. C. Diels and A. T. Georges, International Conference on Multiphonon Processes, University of Rochester, June 609, 1977.
2. J. C. Diels, Optical and Quantum Electronics 8, 513 (1976).
3. J. C. Diels and A. T. Georges, Optics Letters, 1, 158 (1977).
4. J. C. Diels and A. T. Georges, 10th Int. Quantum Electr. Conf., paper L5, Atlanta, June 1978.
5. J. C. Diels and A. T. Georges, manuscript in preparation.

### 3. INFORMATION SCIENCES

#### 3.1 Software Reliability and the Application of Axiomatic Data Structure Specifications

J. Guttag

Report Period: April 1977 - March 1979

Objective Summary: To investigate the application of the axiomatic specification of data structures to enhance software reliability. We hope to demonstrate that formal program verification techniques can be effectively combined with testing procedures in the development of reliable software.

#### Progress/Accomplishments:

A primary goal was to study the mathematical foundations of this formalism with respect to determining completeness and consistency. This work was begun earlier and was further expanded in [4]. Based upon this work a completeness "checker" for algebraic axioms has been implemented by D. Baker, a graduate student supported by the current grant. This piece of software will be used in conjunction with the Data Type Verification System (DTVS) which we have built jointly with Drs. Ralph London and David Musser at USC's Information Sciences Institute (ISI).

Another research goal was to investigate how one might use an algebraic axiomatization of a data type to participate in the verification of its implementation. This was the major thrust of [2]. In that work it is shown how to take (i) an algebraically axiomatized data type; (ii) an implementation of the data type; and (iii) an equality interpretation, and to use these to construct a proof of the validity of the implementation. The proof proceeds as a series of substitutions. Though the reductions can become tedious they are simple in nature and are readily susceptible to machine aids.

This led us to an automated data type verification system which we have now implemented in INTERLISP on a PDP/10. This system serves dual purposes: testing and verification. The input to DTVS is a collection of algebraically axiomatized data types and an arbitrary LISP-like program which makes use of any subset of these data types. DTVS will permit the program to be executed despite the fact that these data types have not been implemented. An implementation is automatically devised which uses the axioms as the semantics of the operations. Though the automatic implementation may be inefficient, its virtue is that testing of a very high level design of a software system is possible without the effort of implementing possibly complex data types. Once the testing phase has been completed an implementation of one or more data types can be supplied to DTVS. The system will then automatically generate the verification conditions which need to be established for correctness. It will then attempt to prove each one in turn, using the reduction process explained in [2].

The development of DTVS and its underlying theory led to other questions of more practical significance. One such question was how to specify error conditions. This was dealt with in [3]. Another area of second investigation was the question of how to combine the use of algebraic axioms with the use of Floyd-Hoare like specifications of programs. One approach to this is discussed in [5].

Also we completed a paper [6] comparing our approach to data abstraction to that taken in the programming language Euclid.

Publications/References:

1. J. V. Guttag, "Abstract Data Types and the Development of Data Structures," Communications of the ACM (June 1977).
2. J. V. Guttag, E. Horowitz, and D. R. Musser, "Abstract Data Types and Software Validation," Communications of the ACM, 1977.
3. J. V. Guttag, E. Horowitz and D. R. Musser, "Some Extensions to Algebraic Axioms," Proc. of an ACM Conference on Language Design for Reliable Software (March 1977).
4. J. V. Guttag and J. J. Horning, "The Algebraic Specification of Abstract Data Types," Acta Informatica, V. 10, N. 1, pp. 26-52, 1978.
5. J. V. Guttag and J. Staunstrup, "Algebraic Axioms, Classes, and Program Verification," University of Southern California, Computer Science Department, Working Report (February 1978).
6. J. V. Guttag, "Notes on Data Abstraction," NATO International Summer School on Program Construction (August 1978).

3.2 Checkpoint Recovery in Computer Systems

D. L. Russell

Report Period: April 1977 - March 1979

Objective Summary: Develop techniques for the construction of highly reliable computing systems that are able to tolerate both hardware and software errors. Investigate the use of checkpoint recovery in single-processor and multi-processor systems. Investigate the effects of error propagation among systems of concurrent processes and find methods of limiting that error propagation.

Progress/Accomplishments:

Optimum checkpoint intervals for systems with non-zero error latencies and where errors may be detected during checkpoint or recovery have been obtained [2], extending the preliminary results of [1]. Delayed

detection of errors drastically increases the optimum checkpoint interval and the run-time overhead. In particular, when error latencies are very large, a "repeated retrial" approach to recovery becomes impractical and better diagnosis is necessary. It has proved very difficult to obtain closed form solutions, particularly with more realistic extensions of the model of [1, 2]. Alternate models have therefore been examined with the hope of realizing more tractable analyses. Some success has been obtained with a language-directed model of state restoration and backup [3]. The model describes recovery in multiprogramming systems; the recovery activity undergone by the system is shown to be directly related to the system interconnections and internal process structures.

The language-directed model of system state restoration has been studied. Two papers [4, 5] describing application of the MARK-RESTORE-PURGE model of state restoration are in preparation. In [4] the producer-consumer system is studied in depth; necessary and sufficient conditions are found for bounds on recovery activity to exist and complete solutions are found. In [5] arbitrary systems of interconnected processes are considered; sufficient conditions are found for the avoidance of the domino effect. The importance of these results is that a methodology is proposed that allows a priori determination of system performance in the presence of error recovery.

The conversion language construct, proposed by Randell to control state restoration in systems of concurrent processes, has been examined in [6]. Two possible implementations of conversions are proposed; name-linked recovery blocks and multiprocess recovery blocks. Name-linked recovery blocks are considered in detail and it is shown that their use can lead, under certain circumstances, to the domino effect and to deadlock. Multiprocess recovery blocks are considered briefly and seem to avoid many difficulties of name-linked recovery blocks. Both methods, however, imply design techniques which are far removed from current trends in multiprocess system design; it remains unclear whether conversions are a viable means of coordinating multiprocess recovery.

#### Publications/References:

1. D. L. Russell and K. R. Babu, "Optimum Inter-Checkpoint Intervals," (unpublished notes), August 1976.
2. D. L. Russell and K. R. Babu, "Optimum Checkpoint Intervals with Delayed Error Detection," in preparation.
3. D. L. Russell, "Process Backup in Producer-Consumer Systems," Proc. Sixth Symposium on Operating Systems Principles, Purdue, November 16-18, 1977, pp. 151-157.
4. D. L. Russell, "The Domino Effect in Producer-Consumer Systems," in preparation.
5. D. L. Russell, "Restoration of Asynchronous Communicating Processes," IEEE Trans. of Software Eng., V. 6, N. 2, March 1980.

6. D. L. Russell and M. J. Tiedeman, "Multiprocess Recovery Using Conversation," Fault-Tolerant Computing Symposium, Madison, Wisconsin, June 1979.

### 3.3 Reliable Microprocessor Networks

P. Brinch-Hansen

Report Period: April 1977 - March 1978 (During the period, sponsorship was transferred from JSEP to ONR)

Objective Summary: To work towards a design methodology that will make the software and hardware of microprocessor networks simple, reliable, and efficient. Although the digital technology for such networks is available now the system architecture and the programming methodology are not. The objective is to make it possible to build real-time systems that one can understand fully, depend on for months without failure, and adapt easily to changing requirements.

Progress: We have invented a new language concept, called Distributed Processes, for microprocessor networks and have proposed a multi-processor architecture for the programming language Concurrent Pascal. In addition, we have compared the efficiency of existing 16-bit microcomputers.

#### Publications:

1. P. Brinch-Hansen, "Network - A Multiprocessor Program," IEEE Transactions on Software Engineering, May 1978.
2. P. Brinch-Hansen, "Distributed Processes - A Concurrent Programming Concept," to appear in Communications of the ACM.
3. P. Brinch-Hansen and C. Hayden, "Microcomputer Comparison," submitted to the IEEE CompSac 78 Conference.
4. P. Brinch-Hansen, "Multiprocessor Architectures for Concurrent Programs," submitted to the ACM 78 Conference.

3.4 Enhancement of Computing System Reliability through  
Fault-Tolerant Programming and Multiprocessor  
System Architecture

K. H. Kim

Report Period: April 1976 - March 1978

Objective Summary: The objective of this project is to find effective methods of using program redundancy for the purpose of tolerating both residual program errors and hardware faults in real-time applications. It specifically aims at the development of computing system architectures capable of efficiently executing programs containing redundancy and at the development of software tools aiding structured incorporation of redundancy into a program.

Progress/Accomplishments:

1. Among the early results obtained were (1) a parallel (dual processor) system structure containing a novel memory organization, termed a duplex memory, for efficient execution of fault-tolerant programs, and (2) the evaluation of the performance gain by a parallel system over a sequential system (that performs the main-stream computation and the validation in non-overlapped mode). These results were slightly refined and presented during the period covered in this report [1, 2].

2. Application of the parallel execution approach to the systems which establish checkpoints at regular intervals in a manner transparent to the program designer, was studied. This study produced a new rollback and retry scheme, termed a two-level rollback, which establishes two types of checkpoints for reduction of both time overhead and rollback distance. The scheme establishes one type of checkpoint with high frequency but with negligible time overhead by utilizing the parallel execution concept and establishes the other type of checkpoints less frequently (and thus with less time overhead) than checkpoints in existing time overhead. Sometimes a multi-step rollback, i. e., backing up past the most recent checkpoint, is executed to recover from a long latent error. An analytic model of this scheme was also developed to facilitate the determination of an optimal checkpoint interval and an optimal multistep rollback strategy. These results are summarized in [3].

3. Efficient rollback and retry in real-time multiprogrammed systems was studied. This study aimed at optimal checkpointing, i. e., minimization of the time overhead incurred by checkpoint establishment, under the constraint that once an error is detected, the subsequent rollback and retry must be done within a given time limit. We attempted to extend the approach developed by Chandy and Ramamoorthy [IEEE Trans. on Computers, June 1972] for uniprogrammed situations so that it may be applicable to multiprogrammed situations. This required the development of a new inter-process communication protocol. It was then learned that truly optimal checkpointing in general multiprogrammed situations is not feasible. Various classes of systems in which optimal checkpointing

becomes feasible, have been identified. These results will be summarized in [4].

4. A survey of recent developments in the area of fault-tolerant software was carried out and its results are summarized in [5].

Publications:

1. K. H. Kim and M. J. Jenson, "Performance Evaluation of a Parallel System Processing Fault-Tolerant Program," Proc. 1977 International Conference on Parallel Processing, August 1977, pp. 131-138.
2. K. H. Kim and C. V. Ramamoorthy, "Structure of an Efficient Duplex Memory for Processing Fault-Tolerant Programs," Proc. the 5th Annual Symposium on Computer Architecture, April 1978, 11. 131-138.
3. K. H. Kim, "A Two-Level Rollback Scheme and Its Optimization," to be submitted for publication.
4. N. Daouk, "Error Recovery Among Communicating Processes," Ph. D. Dissertation.
5. K. H. Kim and C. V. Ramamoorthy, "Recent Developments in Software Fault Tolerance Through Program Redundancy," Proc. 10th Hawaii Int'l Conf. on System Sciences, Jan. 1977, pp. 234-238.

3.5 Automated Systems for Computer Software Development

E. Horowitz

Report Period: April 1976 - March 1977

Objective Summary: A set of tools for the design of computer systems will be defined and developed. The tools will satisfy 3 broad criteria: (i) they should be robust enough so that specification changes can be easily incorporated, (ii) they should be easy to use and cost-effective to run, and (iii) they should allow control and data flow to be clearly expressed.

Progress/Accomplishments: During the close of the last contract period we had designed a programming language called SPARKS and built a translator for it. The translator was programmed and tested and is completely described in [1]. During the current period the development of the SPARKS language was completed and distribution to all requesting institutions was made. Further investigation of language features was studied and these are included in the current version. The system for program structuring was simulated on several programs indicating about a 10% reduction in code would result.

Publications:

1. SPARKS User Manual, Computer Science Technical Report, U.S.C., Los Angeles, August 1976.
2. J. Guttag, E. Horowitz, D. Muser, "The Design of Data Type Specifications," Proc. 2nd Symposium on Software Engineering, IEEE, San Francisco, October 1976.

3.6 Multiple User Information Theory

A. A. El Gamal

Report Period: April 1979 - August 1980

Objective Summary: The ultimate goal of this research is to determine the theory of information transmission in communication networks with arbitrary interference among the transmitters and arbitrary noise at the receivers. The approach is information theoretic in the Shannon sense of information theory. Results are expressed in terms of entropy and mutual information bounds on rates of information transmission.

Progress:

1. The Capacity of the Deterministic Relay Channel: In earlier work [1] we established the capacity of the degraded relay channel, the reversely degraded relay channel and the relay channel with feedback. We have been able to show that Theorem 7 in [1] is the capacity when the relay channel is deterministic, i. e., when  $y = f(x_1, x_2)$  and  $y_1 = g(x_1, x_2)$ . This result was presented at the IEEE International Symposium on Information Theory, Grignano, Italy, 1979. A paper [2] has been submitted for publication.
2. A Proof for Marton's Coding Theorem for the Broadcast Channel: A simple proof, using partitions and joint typicality, for Marton's important theorem has been established jointly with van der Meulen [3]. This proof contains a new typicality lemma. A paper containing this proof has been accepted for publication in the IEEE Information Theory Transactions.
3. Multiple User Information Theory (An invited paper): The Principal Investigator has been invited to submit an overview paper on multiple user information theory for a special issue on allocation of radio spectrum in the Proceedings of IEEE. This paper, which was written jointly with T. Cover, has already been submitted for publication [4].
4. Multiple Access Channel with Correlated Sources: The work mentioned in our previous report [5] has been accepted for publication in the IEEE Trans. on Information Theory.
5. Statistical Modeling for Interconnections in Integrated Circuits:
  - (i) In [6] two-dimensional stochastic models for interconnections in

master slice LSI are described. Several limit theorems are derived for estimating the wiring area on large chips in terms of average wire length  $\bar{R}$ , average number of wires emanating from each logic block  $\lambda$ , and wire trajectory parameters. The expected value of the maximum number of tracks per channel on an  $N \times N$  chip is shown to be less than  $O(\ln N)$  as long as  $\bar{R}$  does not grow faster than  $O(\ln N)$ . If  $\bar{R} > O(\ln N)$ , then the expected maximum number of tracks is  $O(\bar{R})$ . Simple bounds on the expected wiring area are given and numerical results compared to the earlier work by Heller et al.

(ii) In [7] a stochastic model for interconnections in integrated circuits composed of unequal size logic blocks separated by routing channels is described. An algorithm, based on the model, is given for estimating channel widths and chip area. The effectiveness of the algorithm is tested through an example. Applications of the model to placement and routing of integrated circuits are discussed.

#### Publications:

1. T. Cover and A. El Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Information Theory*, Sept. 1979.
2. A. El Gamal, "The Capacity of the Deterministic Relay Channel with Feedback," submitted to *IEEE Trans. on Information Theory*.
3. A. El Gamal, E. van der Meulen, "A Proof of Marton's Coding Theorem for the Discrete Memoryless Broadcast Channel," to appear in the *IEEE Trans. on Information Theory*, January 1981.
4. A. El Gamal, T. Cover, "Multiple User Information Theory," invited paper, to appear in *Proceedings of IEEE*.
5. T. Cover, A. El Gamal, and M. Salehi, "An Achievable Rate Region for the Multiple Access Channel with Correlated Sources," to appear in *IEEE Trans. on Information Theory*, Nov. 1980.
6. A. El Gamal, "Two-Dimensional Stochastic Model for Interconnections in Master Slice Integrated Circuits," to appear in the *IEEE Trans. on Circuits and Systems*.
7. A. El Gamal and Z. Syed, "A Stochastic Model for Interconnections in Custom Integrated Circuits," submitted to the *IEEE Trans. on Circuitry and Systems*.

### 3.7 Coherent Multiple-Frequency Systems

R. A. Scholtz

Report Period: June 1977 - February 1978

Objective Summary: To develop a digital communication system configuration using constant energy signals which are linear combinations of several free-running oscillators, having the property that (a) performance is comparable to coherent communications using the same data rate, and (b) spread-spectrum processing gain is developed to provide immunity to various types of interference including signals from other similar systems.

Progress/Accomplishments: Although this project was terminated after 8 months duration, considerable progress was made as follows:

- (a) characterized the statistical properties of an intermittent tone observed in Gaussian noise,
- (b) developed the maximum likelihood estimator of the tone's phase during a fixed observation interval,
- (c) configured the decision-directed loop which effectively mechanizes a serial search for the maximum likelihood estimator,
- (d) generalized the results to allow tone duration and probability of occurrence to be variables in the design,
- (e) created an open loop simulation of the system to determine statistical properties of the phase detector, and
- (f) made comparisons with continuous-tone-tracking phase-locked loops.

At this point research efforts were being directed to configure a coherent spread-spectrum frequency-hopping system using several such phase tracking devices.

Publications: None

### 3.8 Multiple Access/Spread Spectrum Communication Systems

C. L. Weber

Report Period: April 1976 - March 1977

Objective Summary: To develop the theory of multiple access/spread spectrum techniques through a satellite repeater which must communicate with a set of receivers. Of particular interest is the more complex case wherein the terminals are mobile, thereby considering the problem of simultaneously communicating with a large number of aircraft and/or ships. Of particular interest is to determine improved acquisition techniques and

to determine the environments wherein asynchronous multiple access techniques are more advantageous than synchronous multiple access techniques.

Progress/Accomplishments: Progress during 1975 and on into this reporting period led us to consider continuous phase-frequency-shift-keying in the development of a design theory for spread spectrum/multiple access (SSMA) communication systems. This new signal format has specific advantages in view of its spectral concentration, its constant envelope, and its inherent coding capability. Taking advantage of these characteristics with implementable systems entails simple suboptimal receivers which closely approximate the very complicated optimal receiver. Several simple receivers and their corresponding error rate performance have been developed and documented [1-5], and submitted for publication [6].

Publications:

1. C. Weber, R. Scholtz, U. Von der Embse, "Signal Design for Totally Phase-Incoherent Communications," IEEE Trans. on Communications, vol. COM-23, No. 2, Feb. 1975, pp. 213-221.
2. C. Weber, G. Huth, "Minimal Weight Convolution Codewords of Finite Length," IEEE Trans. on Information Theory, March 1976.
3. C. Weber, "Analysis of Quadrature Receiver Operating in a Burst Data SSTDMA Environment," Proc. of the AIAA Conf. on Communications, April 1976, Montreal.
4. C. Weber, "Candidate Receivers for Unbalanced QPSK," Proc. of the Int'l Telemetry Conference, Sept. 1976, Los Angeles.
5. S. A. Minium, "Design and Performance of Continuous-Phase FSK Receivers," Ph. D. Dissertation, Dept. of Elec. Engr., USC, Sept. 1976.
6. C. Weber, "Performance of Implementable Receivers for CPFSK," IEEE Trans. on Communications, submitted.

3.9 Structural Aspects of System Identification

L. M. Silverman

Report Period: April 1976 - March 1977

Objective Summary: To increase the understanding of the theory governing the modeling and identification of dynamical systems, and subsequently improve the performance of existing system identification algorithms, as well as generate new ones.

Progress/Accomplishments:

Conditions for the identifiability of nonlinear dynamical systems have been derived [1] using the concepts of output distinguishability.

The problem of identifying the deformable modes in a class of non-rigid satellites has been considered and the results presented [2].

A new approach to deterministic identification has been developed using ideas from the geometric theory of linear systems. This approach is quite general and includes identifiability tests from input-output data [3, 4].

Publications:

1. M. S. Grewal and K. Glover, "Identifiability of Linear and Nonlinear Dynamical Systems," IEEE Trans. on A. C., pp. 833-836, Dec. 1976.
2. E. Jonkheere, "On the Observability of the Deformable Modes of Non-Rigid Satellites," Symposium on the Dynamics and Control of Non-Rigid Space Vehicles, Frascati, Italy, 1976.
3. E. Emie, "Design and Identification of Linear Multi-Variable Control Systems," Ph. D. Dissertation, Dept. of EE, USC, 1976.
4. E. Emie, L. M. Silverman and K. Glover, "Generalized Dynamic Covers for Linear Systems with Application to Deterministic Identification and Realization Problems," IEEE Trans. on A. C., pp. 26-35, Feb. 1977.

SECTION III  
SIGNIFICANT ACCOMPLISHMENTS REPORT (1980-81)

## SIGNIFICANT ACCOMPLISHMENTS

Electronic Sciences Laboratory  
University of Southern California  
October 1980 - September 1981

1. Dr. Martin Gunderson (Work Unit QE 1-1) has demonstrated that long-lived neutral molecular and atomic species are formed during pulse excitation of  $H_2$  thyratrons. These species are highly energetic and are of interest because of their role in limiting recovery of high repetition rate high power electrical switches. This work is directing towards the need for understanding electrically excited gases.
2. Dr. W. H. Steier and Dr. H. Park (Work Unit QE 1-2) have developed a new technique for making pico-second pulse width measurements in the ultraviolet using two photon generated color centers in the alkali halides. Their measurements in KBr using XeCl laser indicates that pulse widths as short as 0.25 ps could be measured and that pulse energies of only 100 nJ are required. Pulse width measuring techniques used in the visible such as second harmonic generation and two photon fluorescence are not possible in the ultraviolet because of material limitations. This new technique of two photon generated color centers should be applicable at all of the wave-lengths in the ultraviolet produced by the excimer lasers.
3. Dr. J. Hayes and Dr. T. Sridhar (Work Unit IE 1-3) have developed a new technique called I-testing for the design of self-testing integrated circuits. The technique is based on bit-slicing, and requires very little hardware or software overhead. A self-testing microprocessor has been designed using this approach.
4. Dr. A. A. Sawchuk and Dr. T. C. Strand (Work Unit IE 1-6) have developed an automated data acquisition system for measuring the wavelength dependence of diffraction efficiency for volume holograms. Volume holograms with multiple wavelength reconstructions and high diffraction efficiency have been made and measured. A computer analysis which gives a rigorous solution of the diffraction from a volume hologram of arbitrary thickness has been produced. With these two experimental and theoretical tools, new applications of volume holograms to spatial filtering can be quickly analyzed in computer simulation and experimentally verified. In related work, a Talbot depth measurement technique has been implemented in real-time. This technique offers high speed depth extraction in a simple system that is ideally suited to many robotics and other computer vision applications.

5. Dr. M. Safonov (Work Unit IE 1-5) has developed improved techniques for evaluating multivariable feedback sensitivity and less conservative methods for estimating the stability margins for multiloop feedback systems subject to large parameter variations and transfer functions uncertainties occurring simultaneously in multiple feedback paths. The sensitivity results have also led to the establishment of a "separation principle" that guarantees that complicated linear multivariable servomechanism design problems can always be decomposed into two separate, simpler design problems.