

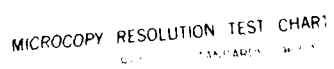
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MICROCOPY RESOLUTION TEST CHART  
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*Dr Witt.*

UNIVERSITY OF SOUTHERN CALIFORNIA  
SCHOOL OF ENGINEERING

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**JOINT SERVICES ELECTRONICS PROGRAM  
RESEARCH IN ELECTRONICS**

**CONTRACT NO. F49620-85-C-0071**

**1987 ANNUAL TECHNICAL REPORT**

**For the Period 1 January 1987 through 31 December 1987**

**Submitted to:**

**Air Force Office of Scientific Research  
Building 410  
Bolling Air Force Base, DC 20332**

**Submitted by:**

**University of Southern California  
School of Engineering  
University Park  
Los Angeles, CA 90089-0483**

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**Joint Services Electronics Program  
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## DIRECTOR'S OVERVIEW

This report summarizes the progress made under the Joint Services Electronics Program for the period 1 January 1987 through 31 December 1987. It is the third annual technical progress report on the three-year contract, F49620-85-C-0071. This report covers the thirteen research projects being supported: four in solid state electronics, four in quantum electronics, and five in information electronics. This report also summarizes the significant accomplishments that have been achieved during this research period.

## SIGNIFICANT ACCOMPLISHMENTS

*Totally Planar Pnp Heterojunction Bipolar Transistor - P.D. Dapkus - Research Unit SS3-1.*

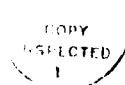
The first totally planar pnp heterojunction bipolar transistor has been fabricated and tested. The devices were grown by MOCVD. The decreased base resistance of the pnp design and the planar geometry have significant circuit advantages, especially when used in complementary circuits with npn devices.

*Transient Detection Microscope - Jack Feinberg - Research Unit QE3-4.*

A new device which displays only moving objects in a microscope scene has been demonstrated. This all-optical device operates in real time by using the nonlinear coupling of optical beams in a photorefractive crystal of barium titanate.

*Radio Frequency Electric Field Enhancement of Photorefractive Effects - W.H. Steier - Research Unit QE3-3.*

It has been demonstrated that r.f. electric fields can be used to increase the nonlinearity in photorefractive materials. This approach has significant practical advantages over the conventional d.c. electric fields. The r.f. field approach can be used with almost all photorefractive materials and will find wide application in nonlinear optical devices for optical signal processing.



|                           |   |
|---------------------------|---|
| Administrative Codes      |   |
| Project Number            | 1 |
| Project Title             |   |
| Project Status            |   |
| Project Manager           |   |
| Project Sponsor           |   |
| Project Reviewer          |   |
| Project Approval          |   |
| Project Date              |   |
| Project Location          |   |
| Project Contact           |   |
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**HETEROJUNCTION MATERIALS AND DEVICES  
EMPLOYING ULTRATHIN LAYERS GROWN  
BY METALORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD)**

P.D. Dapkus

Research Unit SS3-1

**ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987**

**PROGRESS**

This program was designed to investigate the fundamental properties of ultrathin layers and the devices that would be fabricated from them. We have concentrated our investigations on the influence of growth conditions on the interfaces between AlGaAs and GaAs and the effect these properties have upon device performance. This has allowed us to optimize the techniques for interface formation to the point that low interface state densities can be achieved for both "normal" and "inverted" heterojunctions. We have also determined the optimal conditions for the growth of quantum well structures and have achieved state of the art low temperature PL linewidths for MOCVD-grown quantum wells (QW). We also investigated and analyzed the design of heterojunction bipolar transistors during the course of this program. Our studies pointed out that a significant opportunity to increase the capabilities of bipolar circuits through the use of complementary device designs had been overlooked. We developed a methodology for device analysis that showed that Pnp HBT's could be designed that were comparable in performance to the Npn designs used by most workers. The realization of this analysis would allow designers to consider low power complementary bipolar circuits in GaAs for the first time. We have proceeded to fabricate Pnp devices that show the expected performance and will continue to optimize them until the current program ends.

In our studies of heterojunction quality, we have used PL as the most sensitive tool to analyze the quality of heterojunctions. We have completed a study of both horizontal and vertical reactor designs to determine the effect of growth interruption on the interface of AlGaAs/GaAs QW's. We have determined that **the highest quality interfaces are formed by continuous growth in MOCVD.** Using the results of these studies, quantum well lasers with threshold current densities in the range of 200A/cm<sup>2</sup> are routinely grown in our vertical reactor

system. This system was also used to fabricate MQW nonlinear materials with the lowest saturation intensity reported to date, 250 W/cm<sup>2</sup>.

A continuing activity on this program has been the investigation of heterojunction bipolar transistor designs through analysis and fabrication. The motivation for this study came from the observation that the base resistance of Npn transistors limits the operating characteristics of these devices. Furthermore the fabrication of Npn designs is limited by the high diffusivity of acceptors in the heavily doped base. A Pnp design by contrast has the **n-type** base as the most heavily doped layer. The low diffusivity of donors in III-V compounds alleviates the base layer out diffusion problems. The lower solid solubility of donors compared to acceptors eases the problem of making a planar devices by diffusing a p+ contact to the collector. We performed an analysis of the performance potential of Pnp transistors by developing an optimization procedure that properly weighted carrier transport in both the electron and hole current paths. We chose as a criterion for optimization of microwave devices the requirement that the current gain cutoff frequency,  $f_T$ , and the maximum oscillation frequency,  $f_{max}$ , were related by  $f_T = 2 \times f_{max}$ . This was strongly motivated by practical circuit considerations. Switching transistor designs were optimized by *SPICE* simulation of the switching time of the transistor. We developed a compact model that includes all parasitic resistive and capacitive elements inherent to the structure. The conclusion we have reached from our studies is that nearly equivalent device performance can be achieved from Npn and Pnp designs if the designs are properly optimized. This conclusion is also valid when one considers various enhancements to the device design including self aligned contacts, graded base regions and suppression of the extrinsic collector capacitance. The designs of all optimized structures were analyzed with our physical simulator to ensure that the designs yielded sufficient gain for the application.

The major question to be answered about the viability of Pnp designs is the current gain achievable from such a device. We have successfully fabricated both mesa and **totally planar** Pnp HBT's grown by MOCVD to test this question. The incremental gain at high current levels is of the order 100. Mesa devices show a strong dependence of gain on current that is due to surface recombination at the edges of the emitter-base region. This component is absent from the planar structures in which the contact to the emitter, base and collector are made with concentric contacts. These device structures were intentionally grown with a thicker base region than optimal to ease the problem of making base contact to the

exposed base region in the mesa design. Thus we expect to be able to achieve higher gains with thinner base regions. The achievement of a totally planar device structure has been done while at the same time improving the device characteristics. These results open the way to achieving complementary devices on the same wafer.

### List of Publications

1. D. A. Sunderland and P. D. Dapkus, "Optimizing Npn and Pnp Heterojunction Bipolar Transistors for Speed," Trans. Electron Dev. **ED-34**, 367 (1987).
2. H. C. Lee, A. Hariz, P. D. Dapkus, A. Kost, M. Kawase, and E. Garmire, "Nonlinear Absorption in AlGaAs-GaAs Multiple Quantum Wells Grown By Metalorganic Chemical Vapor Deposition," Appl. Phys. Letters **50**, 118 (1987).
3. A. Kost, M. Kawase, E. Garmire, H. C. Lee, A. Hariz, and P. D. Dapkus, "Spectral Dependence and Diffusion Effects in the Nonlinear Absorption of GaAs/ AlGaAs Multiple Quantum Wells," Proc. IQEC '87, 30 (1987).
4. S. P. DenBaars, C. A. Beyler, A. Hariz, and P. D. Dapkus, "GaAs/AlGaAs Quantum Well Lasers with Active Regions Grown by Atomic Layer Epitaxy," Appl. Phys. Letters **51**, 1530 (1987).
5. H. C. Lee, K. Dzurko, P. D. Dapkus, and E. Garmire, "Electroabsorption in AlGaAs/GaAs Multiple Quantum Wells Grown on a Transparent GaP Substrate," Appl. Phys. Lett., **51**, (1987).
6. H. C. Lee, A. Kost, M. Kawase, A. Hariz, P. D. Dapkus, and E. Garmire, "The Nonlinear Absorption Properties of AlGaAs/GaAs Multiple Quantum Wells Grown by Metalorganic Chemical Vapor Deposition," Invited Paper to be published in IEEE J. Quant. Electron.
7. A. D. Danner, P. D. Dapkus, A. Kost, and E. Garmire, "Nonlinear Absorption Coefficient of GaAs Doping Superlattices," To be Published in J. Appl. Phys.
8. A. Kost, E. Garmire, A. D. Danner, and P. D. Dapkus, "Nonlinear Optical Absorption in Quantum Well-NIPJ Structures," Accepted for publication in Appl. Phys. Letters.
9. D. A. Sunderland, J. M. Haden, W. E. Stanchina, K. M. Dzurko, H. C. Lee, A. D. Danner, and P. D. Dapkus, "A Fully Planar PNP Heterojunction Bipolar Transistor," Accepted for publication in Electron Devices Letters.
10. S. P. DenBaars, A. Hariz, C. A. Beyler, B. Y. Maa, Q. Chen, and P. D. Dapkus, "The Growth of AlGaAs/GaAs heterostructures by Atomic Layer Epitaxy," Proceedings of *The Symposium on Semiconductor Multilayer Heterostructures*, Materials Research Society (1987).

### List of Presentations

1. H. C. Lee, A Hariz, P. D. Dapkus, A. Kost, M. Kawase, and E. Garmire, "Nonlinear Absorption in AlGaAs-GaAs Multiple Quantum Wells Grown By Metalorganic Chemical Vapor Deposition," Talk Presented at the Topical Meeting on Photonic Switching, March 1987 Incline Village, NV.
2. P.D. Dapkus, " Decomposition Kinetics Of Organometallic Precursors" Talk presented at the Winter Gordon Conference on Crystal Growth, January 1987, Santa Barbara, CA.
3. P. D. Dapkus, "MOVPE Growth Processes," Talk presented at the First European Workshop on MOVPE, April 1987, Aachen, Germany.
4. P. D. Dapkus, "Kinetics of Growth in MOCVD," Talk Presented AACG West Meeting, May 1987, Los Angeles, CA.
5. D. A. Sunderland and P. D. Dapkus, "The Performance Potential of P-n-p Heterojunction Bipolar Transistors" Talk presented at the Device Research Conference, University of Mass. 1986.
6. H. C. Lee, A. Hariz, P. D. Dapkus, A. Kost, M. Kawase, and E. Garmire, "The Growth and Characterization of AlGaAs-GaAs Multiple Quantum Well Nonlinear Materials By MOCVD," Talk presented at the Electronics Materials Conference , Santa Barbara, CA, June 1987.
7. A. D. Danner and P. D. Dapkus, " The Growth and Characterization of Doping Superlattices by MOCVD," Talk presented at the Electronics Materials Conference , Santa Barbara, CA, June 1987. (Manuscript in Preparation for submission to J. Electron. Mater.)
8. S. P. DenBaars, H. C. Lee, A. Hariz and P. D. Dapkus, "The Effects of Hydrodynamics, Interrupted Growth and Growth Temperature on the Interface Properties of AlGaAs/GaAs Quantum Wells Grown by Metalorganic Chemical Vapor Deposition," Talk presented at the Electronics Materials Conference , Santa Barbara, CA, June 1987. (Manuscript in Preparation for submission to J. Electron. Mater.)
9. S. P. DenBaars, A. Hariz, C.A. Beyler, B. Y. Maa, Q. Chen, and P. D. Dapkus, " The Growth of AlGaAs/GaAs heterostructures by Atomic Layer Epitaxy," Talk presented at the Materials Research Conference, Boston, MA, December 1987

## SOME INVESTIGATIONS OF THE KINETICS AND MECHANISMS OF MOLECULAR BEAM EPITAXIAL GROWTH

A. Madhukar

Research Unit SS3-2

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

During this year, we implemented growth of a variety of GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As quantum well structures under conditions indicated by our earlier reflection high energy electron diffraction (RHEED) intensity studies to be near optimal and away from optimal. The objective was, of course, to examine the types of correlations that may exist between RHEED measurements and the atomistic nature of the corresponding interfaces as revealed in optical and electrical measurements.

A major finding from systematic growth of single quantum wells under RHEED determined identical and optimized conditions was that the photoluminescence linewidth ( $\Gamma$ ) as a function of the well width ( $d_w$ ) in GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As system goes nearly like  $\Gamma \propto d_w^{-1}$ . This is totally contrary to the  $\Gamma \propto d_w^{-3}$  behavior unquestioningly used to analyze such data over the past decade on the assumed notion of fluctuations in the well width. We were also able to offer an explanation for the  $\Gamma \propto d_w^{-1}$  behavior based upon fluctuations in the depth of the well arising from in-plane, non-uniformity in the Al concentration distribution on the length scale of the exciton size. This non-uniformity was shown to be tied to the growth kinetics and the attendant surface morphology as revealed in RHEED studies. An important point we showed is that, while RHEED is sensitive only to the surface/interface morphology, the optical and electrical properties are sensitive also to the chemical distribution.

Finally, systematic RHEED studies of the GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As(100) surface were carried out to examine the possible growth conditions which may lead to high quality inverted high-electron-mobility-transistor (HEMT). It was found that the high reactivity of Al with As and background impurities are the inherent surface processes responsible for loss of good surface smoothness, quite apart from the Si dopant out-diffusion towards the inverted HEMT surface, thus limiting the mobility. We thus concluded that optimal growth conditions for inverted HEMT are (i) low substrate temperature, (ii) slow growth rate, (iii) use of growth interruption after

"capping" AlGaAs surface with a mono-layer to two of GaAs, and (iv) change of substrate temperature from quite low ( $\sim 500^{\circ}\text{C}$ ) during growth of doped AlGaAs to moderate ( $\sim 600^{\circ}\text{C}$ ) during growth of the undoped AlGaAs spacer layer. We have grown a few such structures, including single square quantum well structures, and are presently analyzing their properties. Preliminary results indicated that we are on the right track.

#### List of Publications

1. P. Chen, A. Madhukar, J.Y. Kim, and N.M. Cho, "The nature of surface migration during MBE growth of III-V compounds: a study via the RHEED specular beam intensity dynamics," Proc. 18th Int. Conf. Phys. Semiconductors, (Stockholm, Sweden, August 11-15, 1986) **1**, 109 (1987).
2. F. Voillat, J.Y. Kim, W.C. Tang, A. Madhukar, and P. Chen, "Near band-edge luminescence studies of the effect of interfacial step distribution and alloy disorder in ultrathin GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ (100) single quantum wells grown by MBE under RHEED determined conditions," Superlattices and Microstructures, **3**, 313 (1987).
3. J.Y. Kim, P. Chen, F. Voillat, and A. Madhukar, "Photoluminescence and reflection high energy electron diffraction dynamics study of the interfaces in molecular beam epitaxially grown GaAs/ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$  (100) single quantum wells," Appl. Phys. Lett., **50**, 739 (1987).
4. N.M. Cho, P. Chen, and A. Madhukar, "Specular beam intensity behavior in reflection high energy electron diffraction during molecular beam epitaxial growth of  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  on GaAs(100) and implications for inverted interfaces," Appl. Phys. Lett., **50**, 1909 (1987).

## **ELECTROOPTIC MATERIALS FOR OPTICAL PROCESSING AND COMPUTING DEVICES**

Armand R. Tanguay, Jr.

Research Unit SS3-3

**ANNUAL TECHNICAL REPORT**  
**For the Period 1 January 1987 through 31 December 1987**

### **PROGRESS**

During the most recent contract period, the research emphasis has been placed on a continued evaluation of the properties of electrooptic materials, specifically those that impact components necessary for the implementation of optical information processing and computing systems. Requisite components include spatial light modulators such as the Photorefractive Incoherent-to-Coherent Optical Converter [JSEP Publ. 1] and the Total Internal Reflection Spatial Light Modulator. Also of considerable interest are volume holographic optical elements such as birefringent phase gratings stored via the photorefractive effect in bismuth silicon oxide, and Stratified Volume Holographic Optical Elements [JSEP Publ. 2].

Bismuth silicon oxide ( $\text{Bi}_{12}\text{SiO}_{20}$ ) has proven to be a most versatile electrooptic material for such device applications, in that it can be employed in all of the device applications listed above (in addition to a long list of others). One critical material property that strongly affects device performance (particularly for relaxation semiconductors, for which the minority carrier lifetime is much shorter than the dielectric relaxation time) is the volume resistivity, which establishes both image storage times in spatial light modulators and grating decay times in volume holographic optical elements. We have developed an experimental technique that allows measurement of the very high volume resistivities characteristic of  $\text{Bi}_{12}\text{SiO}_{20}$  ( $> 10^{15}$  ohm-cm) as well as those of other electrooptic materials. The technique is based on the direct electrooptic measurement of the voltage decay across a transparent capacitor of the electrooptic material, by utilizing phase sensitive detection techniques and extremely low duty cycle probe illumination to minimize photoinduced charge decay [JSEP Publ. 3]. Studies have been performed on both doped and undoped crystals [JSEP Publ. 3], with further studies on stoichiometric variations in progress.

The polarization properties of diffraction from volume gratings in materials such as bismuth silicon oxide that are characterized by concomitant natural optical activity and electric field induced linear birefringence were further examined during

the contract period. In particular, the photorefractive charge transport model developed during the previous year was extended to incorporate the effects of self-diffraction on the formation of the volume grating. In addition, the striking effects of enhanced self-diffraction that can occur for example with running gratings were analyzed in detail [JSEP Publ. 4]. These results indicate that both the phase and the amplitude (modulation depth) of photorefractively written gratings can vary dramatically as a function of the grating depth due to periodic scattering of the writing beams from the forming diffraction grating. These studies have strong implications for the optimization of grating formation parameters, polarization selectivity, and ultimate diffraction efficiency achievable in each principal crystallographic orientation.

In related studies, the fundamental origins of the quantum efficiency of photorefractive grating formation were examined in detail [JSEP Publ. 5]. For a number of reasons, photorefractive gratings are highly quantum inefficient compared with the optimum grating structure that can be formed from a given volume density of photoexcited charge species. This yields an estimate of the maximum number of full volume hologram reconfigurations that can be achieved per watt of optical input power, an extremely important parameter in the determination of overall computational throughput in optical processing and computing architectures that rely on highly parallel weighted interconnections.

#### List of Publications

1. J. Yu, D. Psaltis, A. Marrakchi, A. R. Tanguay, Jr., and R. V. Johnson, "The Photorefractive Incoherent-to-Coherent Optical Converter", in Photorefractive Materials and Applications, J. P. Huignard and P. Gunter, Eds., Springer-Verlag, New York (in press).
2. R. V. Johnson and A. R. Tanguay, Jr., "Stratified Volume Holographic Optical Elements", submitted for publication in *Optics Letters*, (1987).
3. D. A. Seery, M. H. Garrett, and A. R. Tanguay, Jr., "Electrooptic Measurement of the Volume Resistivity of Bismuth Silicon Oxide ( $\text{Bi}_{12}\text{SiO}_{20}$ )", accepted for publication in *Journal of Crystal Growth* (in press), (1987).
4. A. Marrakchi, R. V. Johnson, and A. R. Tanguay, Jr., "Polarization Properties of Enhanced Self-Diffraction in Sillenite Crystals", accepted for publication in *IEEE Journal of Quantum Electronics*, Special Issue on Electrooptic Materials and Devices (in press), (1987).

5. R. V. Johnson and A. R. Tanguay, Jr., "Fundamental Physical Limitations of the Photorefractive Recording Sensitivity for Grating Structures", submitted to Applied Optics, Special Issue on Optical Computing, (1987).

#### List of Presentations

1. K. Rastani, Z. Karim, R. V. Johnson, and A. R. Tanguay, Jr., "Optical Information Processing Components", Gordon Research Conference on Optical Information Processing and Holography, Santa Barbara, California, (1987); (Invited Paper).
2. C. Kyriakakis, P. Asthana, R. V. Johnson, and A. R. Tanguay, Jr., "Fundamental Physical Limitations of Optical Information Processing and Computing", 1987 Optical Society of America Topical Meeting on Optical Computing, Incline Village, Nevada, (1987); (Invited Paper).
3. A. R. Tanguay, Jr. and R. V. Johnson, "Stratified Volume Holographic Optical Elements", 1987 Conference on Lasers and Electro-Optics (CLEO), Baltimore, Maryland, (1987).
4. A. R. Tanguay, Jr., "Fundamental Physical Limitations of Optical Information Processing and Computing", NATO Collaborative Award Colloquium, University College London, London, England, (1987); (Invited Colloquium).
5. A. R. Tanguay, Jr., "Materials Requirements for Optical Information Processing and Computing Devices", Seventh American Conference on Crystal Growth (ACCG-7), Monterey, California, (1987); (Invited Paper).
6. M. H. Garrett, D. A. Seery, and A. R. Tanguay, Jr., "Electrooptic Measurement of the Volume Resistivity of Bismuth Silicon Oxide ( $\text{Bi}_{12}\text{SiO}_{20}$ )", Seventh American Conference on Crystal Growth (ACCG-7), Monterey, California, (1987).

## **ELECTRONIC SURFACE ANALYSIS USING NON-DESTRUCTIVE ORGANIC-ON-INORGANIC SEMICONDUCTOR CONTACTS**

**S. R. Forrest**

**Research Unit SS3-4**

**ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987**

### **PROGRESS**

During the last year, two significant results were obtained which greatly increase our understanding of the nature of organic-on-inorganic (OI) semiconductor contacts. These results are:

**Measurement, for the first time, of the valence band discontinuity energy between certain crystalline organic materials (such as PTCDA) and inorganic substrates (e.g. Si, Ge, GaAs, GaSb and InP).** The direct measurement of this quantity was done by analysis of the temperature dependent current-voltage (I-V) characteristics as well as by photoemission spectroscopy done at mid-IR wavelengths. The measured discontinuity energies were consistent with a theory regarding OI transport via diffusion and drift which was developed during this past year. To our knowledge, this is the first time that OI contacts have been theoretically considered as a new class of semiconductor heterojunctions, and the theory thus developed represents an important advance in our understanding of transport across energy barriers formed between molecular and inorganic semiconductors. In addition, the measurement of the "intrinsic energy band discontinuity" as opposed to previously reported "apparent barrier heights" is fundamental to our analysis of the transport mechanisms, as well as to our interpretation of surface defect data obtained by the semiconducting organic-on-inorganic surface analysis spectroscopic (or SOISAS) method.

One additional result arising from our theoretical study was determination of the carrier velocities and the non-equilibrium Fermi energies (or imrefs) throughout the OI diode bulk. Surprisingly, we calculated very high carrier velocities (between 1000 and 10<sup>6</sup> cm/s) in the organic bulk under all bias conditions, and were able to test this calculation experimentally. All of these results are necessary in the interpretation of surface analysis data as obtained via SOISAS.

**Determination of the Non-Destructive Nature of the OI contact.** A central aspect to the SOISAS method is the assumption that formation of the OI contact is largely non-destructive of the underlying inorganic semiconductor

surface. To test this hypothesis, we measured the surface state density on a p-Si substrate in contact with different organic materials including two dianhydrides (PTCDA and NTCDA), and two porphorin films (metal free phthalocyanine-Pc, and CuPc). This was the first demonstration of the formation of a rectifying HJ contact with a crystalline organic semiconductor other than a dianhydride. Our findings were that the density of interface states for the anhydride-based OI diodes was very small, whereas peaks existed in the surface state spectrum within the Si band gap when the Si wafer was in contact with one of the Pc's. We developed a model indicating surface reactions occur between the Pc's and the semiconductor, thereby inducing a high density of surface states. The peak of the defect density distribution for the CuPc sample was at 0.5 eV above the Si valence band maximum. This is at the same energy as observed for bulk Cu acceptor-like defects in Si, thus lending corroborative support to our surface reactivity model.

#### **List of Publications**

1. F. F. So and S. R. Forrest, "Dependence of the Electrical Characteristics of Organic-on-Inorganic Semiconductor Contact Barrier Diodes on Organic Thin Film Composition", J. Appl. Phys. (Jan. 1, 1988).
2. S. R. Forrest and F. F. So, "Organic-on-Inorganic Semiconductor Heterojunctions: Energy Band Discontinuities, Quasi-Fermi Levels and Carrier Velocities", To be submitted to J. Appl. Phys., Dec., 1987.

#### **List of Presentations**

1. S. R. Forrest, "Semiconductor Contacts Using Organic Thin Films", invited paper at PCSI, Salt Lake City, UT, January 27-29, 1987.

## TOWARD ROOM TEMPERATURE LASERS IN THE $3\mu\text{m}$ WAVELENGTH REGION

Elsa Garmire

Research Unit IE3-1

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

A final paper, outlining the results of the previous three year's work on p-DCC lasers and summarizing Hasenberg's thesis was published. Some continuing work on the efficiency of the p-DCC lasers is still underway at a low level.

Liquid phase epitaxy of quaternaries has been refined and we are able to grow GaInAsP layers to order. Recent results have been obtained on material which has a bandgap at  $1.06\mu\text{m}$ . Growth of a thin quaternary n layer on a p substrate of InP allowed some new exciting research to be performed. This was the development of a new nonlinear medium, consisting of a metal/n-Quaternary/p-InP depletion region structure. The application of light causes photo-induced carriers which migrate in the presence of the depletion region fields. The migrating charges cause a space charge field which cancels the built-in depletion region field, flattening the bands. The reduction of the junction field changes the electro-absorption and band filling, which increases the transmission of the device. Thus the depletion region electro-absorption modulator (DREAM) acts as a saturable absorber. What is exciting is that 50% modulation has been seen at power levels of only  $0.2 \text{ W/cm}^2$ , much higher sensitivity than any other nonlinear effects. A YAG laser was used.

The liquid phase epitaxial facility made possible by the JSEP funding has allowed us to fabricate this material. Plans are underway to create pnp material which should have even larger effects. In addition, experiments are underway to make semi-insulating quaternary material, as well as long-wavelength material which is applicable to long wavelength lasers.

### List of Publications

1. T. Hasenberg and E. Garmire, "An improved Au/Be contact to p-InP," J. Appl. Phys., **61**, 808 (1987).
2. T. Hasenberg and E. Garmire, "Characteristics of InGaAsP/InP p-DCC lasers grown by three-melt technique," IEEE J. Quant. Elect., **QE-23**, 948 (1987).

3. N. M. Jokerst and E. Garmire, "The depletion region electric-field absorption modulator," submitted to Appl. Phys. Lett., November 1987.
4. H.C. Lee, A. Hariz, P.D. Dapkus, A. Kost, M. Kawase, and E. Garmire, "Nonlinear absorption in AlGaAs/GaAs multiple quantum well structures grown by metalorganic chemical vapor deposition," Appl Phys. Lett., **50**, 1182 (1987).
5. H.C. Lee, K.M. Dzurko, P.D. Dapkus, and E. Garmire, "Electro-absorption in AlGaAs/GaAs multiple quantum well structures grown on GaP transparent substrate," Appl. Phys. Lett., **51**, (1987).
6. H.C. Lee, A. Kost, M. Kawase, A. Hariz, P.D. Dapkus, and E. Garmire, "The nonlinear absorption properties of AlGaAs/GaAs multiple quantum wells grown by metalorganic chemical vapor deposition," Invited paper, IEEE J. Quant. Elect., submitted December 1, 1987.

#### List of Presentations

1. N. M. Jokerst and E. Garmire, "Nonlinear absorption in InGaAsP epitaxial layers," Opt. Soc. of America Annual Meeting, Rochester, NY, October, 1987.
2. H.C. Lee, A. Hariz, P.D. Dapkus, A. Kost, M. Kawase, and E. Garmire, "Room temperature excitonic nonlinear absorption in GaAs/GaAlAs multiple quantum well structures grown by metalorganic chemical vapor deposition" OSA Topical Meeting on Photonic Switching, Lake Tahoe, Nevada, March, 1987.
3. A. Kost, M. Kawase, E. Garmire, H.C. Lee, A. Hariz, and P.D. Dapkus, "Spectral dependence and diffusion effects in nonlinear absorption of GaAs/AlGaAs multiple quantum wells", IQEC, Baltimore, MD, April, 1987.
4. H.C. Lee, P.D. Dapkus, A. Kost, M. Kawase, and E. Garmire, "AlGaAs/GaAs multiple quantum well nonlinear optical materials grown by metalorganic chemical vapor deposition," Electronic Materials Conference, Santa Barbara, CA June, 1987.
5. A. Kost, M. Kawase, E. Garmire, H.C. Lee, A. Hariz, and P.D. Dapkus, "Contributions to optical absorption in GaAs/AlGaAs multiple quantum wells," Opt. Soc. of America Annual Meeting, Rochester, NY, October, 1987.

## A SPECTROSCOPIC STUDY OF BASIC PROCESSES IN ELECTRICALLY EXCITED MATERIALS

Martin Gundersen

Research Unit QE3-2

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

New experimental methods have been developed and demonstrated (Appl. Phys. Lett. **48**, 1773 (1986) and references therein). A considerably improved understanding of thyatron physics has been achieved (Appl. Phys. Lett. **48**, 1727 (1986), Appl. Phys. Lett. accepted for publication, and references therein). Efforts have been made to develop communication between scientists and engineers (Power Conditioning Workshop, Dec. 1986 at USC). An improved thyatron-type switch, the back-lighted thyatron (BLT) has been developed (Appl. Phys. Lett. **49**, 494 (1986). This switch is important because it may make possible the development of certain types of power pulse generators and beam devices.

Optical diagnostic methods for high current discharges, including laser induced fluorescence, have been developed and applied to devices such as the thyatron. It has been possible to combine theory and experiment in developing quantitative models of processes in high power thyatrons. It is particularly of interest to develop new devices based on predictive, microscopic models.

Parallel to the physics effort, results include the development of a new high power glow discharge switch. In 1986 we demonstrated a light activated glow discharge switch (the back-lighted thyatron, or BLT, Appl. Phys. Lett. **49**, 494 (1986)) that is now a candidate to replace thyatrons for a number of applications. Since 1986, BLT results include new methods to fabricate high power modulators for accelerator, lasers, and other high power applications. Thus, we have developed a new method to switch devices such as linear accelerators.

The BLT conductive phase is initiated by light. The light is incident on the back of the cathode. Typical operating parameters are 10-50 Pa H<sub>2</sub> or He, 3mm electrode separation, and a few millijoules of ultraviolet radiation. Over 35 kV stand off and 10 kA peak current have been obtained, with circuit-limited  $di/dt \sim 4 \cdot 10^{11}$  A/sec. Optical triggering has been demonstrated by 1) using an unfocused laser (Xe Cl @ 308 nm and KrCl @ 222nm) directly incident on the back of the cathode, 2) a flashlamp, 3) radiation from a spark generated in air, and 4) by coupling laser radiation into the BLT cathode area through an optical fiber.

The unfocused light initiates the discharge through photoemission, rather than through the formation of a plasma at the surface of the cathode. This is ordinarily not possible with a high current switch, as it has not been possible to fabricate devices that have both photosensitive cathodes and have the cathode in a region where either the laser or arcing produce permanent cathode damage. Although circuit limited, the compact structure of the anode and cathode as well as the pseudo-spark and BLT results suggest that extremely high  $di/dt$  should be possible. A two-gap construction achieved stand-off voltages in excess of 60 kV. It should be straightforward to connect several BLTs in parallel in order to lower the inductance and increase peak current capability. Because several switches can be triggered by the same laser, pulse-to-pulse jitter should be minimal.

Characterization of the laser triggered switch revealed that only a few millijoules of light energy was required to initiate the discharge, prompting the design of a switch using a UV flashlamp. This version has significantly improved power gain and is a simpler device. The flashlamp-switched BLT has operated at hold-off voltages  $>37$  kV, peak currents of more than 37 kA in 2  $\mu$ sec pulses, and at a repetition rate of 100 Hz. This repetition rate was limited by available power supplies and not the switch. The power gain, measured as the ratio of switched energy to trigger energy, was  $\sim 1400$ . High repetition rates should be achievable, partially because energy loading restrictions will be somewhat relaxed as a result of the simpler structure.

It is also possible to use a fiber optic waveguide to deliver a UV light pulse to the cathode. Advantages of using an external light source for triggering include complete electrical isolation, serviceability of the trigger separate from the switch, and ease of triggering multiple gaps/switches simultaneously. At a wavelength of 308 nm (XeCl excimer laser), consistent triggering was found with as little as 1.5 mJ of laser energy incident in a 15 ns pulse on the cathode. The pressure was 15-26 Pa of  $H_2$  and the switch was operated at a repetition rate of 1 to 10 Hz at voltage up to 25 kV and a pulse duration of 1.5  $\mu$ s. The circuit was not designed to test the switch for high peak currents and  $di/dt$ 's, and consequently these numbers are rather modest. The best jitter and delay times to date are 0.8 ns FWHM and 78 ns, respectively, operating at a pressure of 27 Pa of  $H_2$ , 10 kV anode charging voltage, 4.4mJ/308 nm light from the fiber, and molybdenum electrodes.

Research in semiconductor physics has most recently been directed towards development of a model for calculating phonon sideband structure in radiative recombination in GaP:N. This model provides a means of testing impurity

wavefunctions, and is a method for studying the physics of deep traps. Furthermore, and especially pertinent to the proposed program, the model has provided information about electron scattering process, particularly through phonons. It has also been possible to determine the role of several processes in recombination that have not previously been recognized.

Semiconductor switch research is following an approach that is analogous to the gas phase switch research effort. A twofold approach, including an investigation of basic physics problems related to junction and surface breakdown and other issues related to device failure, and an effort to select, design, and fabricate a device, is underway.

### List of Publications

1. C. G. Braun, D. A. Erwin and M.A. Gundersen, "Fundamental processes affecting recovery in hydrogen thyratrons", Appl. Phys. Lett. **50** (19), 1325 (1987).
2. K. Frank, E. Boggasch, J. Christiansen, A. Goertler, W. Hartmann, C. Kozlik, G. Kirkman, C. G. Braun, V. Dominic, H. Riege and M.A. Gundersen, "High power hollow electrode thyatron-type switches," Proceedings, Sixth IEEE Pulsed Power Conference, June 1987.
3. K. Frank, E. Boggasch, J. Christiansen, A. Goertler, W. Hartmann, C. Kozlik, G. Kirkman, C. G. Braun, V. Dominic, M.A. Gundersen, H. Riege and G. Mechtersheimer, "High power hollow electrode thyatron-type switches," IEEE Trans Plasma Science submitted.
4. C.G. Braun, W. Hartmann, V. Dominic, G. Kirkman, M. Gundersen and G. McDuff, "Fiber optic triggered high-power low-pressure glow discharge switches", IEEE Trans. Electron Devices submitted.
5. G. Kirkman, W. Hartmann and M.A. Gundersen, "A flashlamp triggered high power thyatron type switch with remarkable plasma characteristics", App. Phys. Lett. submitted.

### List of Presentations

1. "A new high power switch", Sandia National Laboratory, May 19, 1987.
2. "Plasma dynamics of a new high power switch and application to plasma accelerators", presented to PS division, C.E.R.N., Geneva Switzerland, June 10, 1987.
3. "High power hollow electrode thyatron-type switches," K. Frank, E. Boggasch, J. Christiansen, A. Goertler, W. Hartmann, C. Kozlik, G. Kirkman, C. G. Braun, V.

Dominic, H. Riege and M.A. Gundersen, Sixth IEEE Pulsed Power Conference,  
Washington D. C., July 2, 1987.

## OPTICAL SWITCHING

William H. Steier

Research Unit QE3-3

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

*Measurement of the photorefractive properties of GaAs:Cr* - Photorefraction in the oxides such as BSO, LiNbO<sub>3</sub>, and BaTiO<sub>3</sub> has been widely studied in several laboratories. The compound semiconductors (GaAs, InP, CdTe, etc.) exhibit photorefraction and are relatively fast with grating formation times of less than one microsecond because of their high electron mobility. These materials are, therefore, of particular interest for fast opto-optical switching. We have completed a series of measurements on the photorefractive properties of GaAs:Cr which, taken in total, fairly well define the merit and, therefore, the potential applications of this material.

Measurement of the D.C. electric field assisted two wave gain show a maximum gain of  $\sim 0.9\text{cm}^{-1}$  and a grating formation time of one microsecond for an incident intensity of  $\sim 50\text{W/cm}^2$  (publication 1). The experimental results agree with the published theories of photorefraction when the difficulties of determining the electric field within the illuminated regions of the sample are taken into account. From these measurements, the Debye length was determined to be 0.9 microns.

Radio frequency electric fields can also be used to enhance the photorefractive effect, and this approach has some significant advantages over the use of D.C. fields. The r.f. fields are much easier to get into the illuminated regions, and the gain is much less affected by vibrations than the D.C. case. We have completed a series of measurements of the effect of r.f. electric fields (publication 2) and derived a theory to describe the effect (publication 4). Peak gains of  $0.9\text{cm}^{-1}$  using an applied frequency of either 7.7 MHz or 3.75 MHz were measured. Comparing the data to the theory yields a value of the diffusion length of 0.3 microns.

The "moving grating" technique has been used in several materials to enhance the photorefractive effect, and we have completed a series of measurements of the effect in GaAs:Cr (publication 6). The measurements agree very well with the published theories when the earlier measured values of the Debye length and the diffusion length are used.

*Cavity Enhanced Opto-Optical Switching* - In the faster photorefractive materials, the four wave mixing type of opto-optical switching normally can yield a switch with only a few percent transmission into the switched beam. This is essentially due to the relatively small index changes possible ( $\Delta n \approx 10^{-5}$ ). Only in the slower materials, such as  $\text{BaTiO}_3$ , can a higher efficiency be achieved. If, however, the opto-optical switch is used to couple into a resonant cavity, the coupling into the switched beam can be significantly increased. We have completed the analysis of this approach and can predict the efficiency improvement for both the linear and ring resonators.

An experiment using  $\text{LiNbO}_3$  as the photorefractive material has confirmed the theory. For the linear cavity, the theory predicted a factor of 4.9 increase in efficiency; the experiment showed 4.8. For the ring cavity the theory predicted a factor of 5.8; the experiment showed 5.6. The details are given in publication 7.

*Waveguiding in MQW Structures* - A waveguide with a  $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$  guiding layer, a  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  lower cladding, and an upper MQW cladding has been fabricated by MOCVD in Professor P.D. Dapkus' laboratory. The guide is designed so that approximately 1% of the guided mode power resides in the MQW. In preliminary experiments, we have observed waveguiding by butt coupling the output of the Styral 9 dye laser into the cleaved input face of the guide. Preliminary spectra shows the exciton resonance. We are now preceding to accurately measure the loss and optical non-linear effects on the long wavelength side of the resonance. In later experiments, we will attempt to observe optical switching.

### List of Publications

1. G. Albanese, J. Kumar, and W.H. Steier, "Investigations of Photorefractive Behavior of Chrome-doped GaAs by using Alternating Electric Fields," *Optics Lett.*, **11**, 650 (1986).
2. J. Kumar, G. Albanese, W.H. Steier, and M. Ziari, "Enhanced Two Beam Mixing Gain in Photorefractive GaAs using Alternating Electric Fields," *Optics Lett.*, **12**, 120 (1987).
3. J. Kumar, G. Albanese, and W.H. Steier, "Measurement of Two-wave Mixing Gain in GaAs with a Moving Grating," *Optics Comm.*, August, 1987.
4. W.H. Steier, G. Kavounas, R.T. Sahara, and J. Kumar, "Enhanced Opto-Optical Light Deflection using Cavity Resonance", submitted to *Appl. Optics*.

### List of Presentations

1. J. Kumar, G. Albanese, and W.H. Steier, "Photorefractive Two Beam Coupling in GaAs:Cr with Applied r.f. Fields and Moving Gratings," Presented CLEO, Baltimore, MD., April, 1987.
2. J. Kumar, G. Albanese, W.H. Steier, "Enhancement of Photorefractive Two Beam Coupling Gain by Radio Frequency Fields: Theory and Experiment," JOSA-B, July, 1987.
3. G. Kavounas and W.H. Steier "Fast Hologram Erasure in Photorefractive Materials," to be presented at OSA Topical Meeting on Photorefractive Materials, Effects, and Devices, UCLA, August, 1987.

## SELF-PUMPED OPTICAL PHASE-CONJUGATING LASER RESONATOR CAVITIES

Jack Feinberg

Research Unit QE3-4

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

We demonstrated a new device: a crude optical computer that transforms one image into another. The device is based on a "ring" self-pumped phase conjugator, which usually produces the phase-conjugate replica of any input pattern. However, we demonstrate that the device can be altered to compute different optical patterns other than the phase-conjugate pattern. phase conjugator that can change a high-order, distorted laser mode into a low-order, undistorted mode. Placing a Faraday cell in the ring of the conjugator breaks the time-reversal symmetry of the ring, and makes the optical path length different for light propagating in different directions around the ring. A barium titanate crystal in the ring compensates for for the asymmetry by choosing an output mode that has a slightly different propagation constant from the input mode. By varying the asymmetry caused by the Faraday cell, the shape of the output mode can be reproducibly controlled.

The principal investigator made a 16mm movie, titled "Dancing Modes," of these effects. A paper describing the device was published in the April, 1987 issue of Optics Letters.

We remeasured the Pockels and piezoelectric coefficients of two widely used photorefractive crystals: barium titanate and strontium barium niobate. Accurate values of the Pockels coefficients are necessary for choosing between competing models for the photorefractive effect, and, in particular, for determining the magnitude of the hole and electron densities in these crystals. We found that previous measurements by others produced significantly smaller values for the Pockels coefficients because they had ignored the piezoelectric effect in their measurement. Our results imply that there is more competition than previously suspected between holes and electrons in barium titanate. These results will be published in the December, 1987 issue of the IEEE Journal of Quantum Electronics.

We demonstrated a new device which displays only moving objects in a microscopic scene. Called a "transient detection microscope," the device preferentially displays any moving objects, and suppresses stationary images. This all-optical device operates in real time by using the nonlinear coupling of optical beams in a photorefractive crystal of barium titanate. The device does not use any electronics, so it is a single-task, all-optical computer. We made a short video using the device, which illustrates the 30-to-1 enhancement of any moving protozoa against a background of stationary algae. A manuscript describing the device has been submitted to Nature.

#### **List of Publications**

1. J.P. Jiang and J. Feinberg, "Dancing modes and frequency shifts in a phase conjugator," Optics Letters **12**, 266-268 (1987)
2. S. Ducharme, J. Feinberg, and R.R. Neurgaonkar, "Electrooptic and piezoelectric measurements in photorefractive barium titanate and strontium barium niobate," IEEE J. Quantum Electronics, December, (1987).
3. R.S. Cudney, R.M. Pierce, and J. Feinberg, "Transient Detection Microscope," submitted to Nature on October 29, 1987.

#### **List of Presentations**

1. Invited paper "Optical Phase Conjugation," at the USA-USSR Symposium on Lasers in Condensed Matter, June 1-10, 1987, Leningrad, USSR.
2. Invited paper "Probing Stimulated Scattering in Photorefractive Crystals, " at the Gordon Research Conference on Nonlinear Optics and Lasers, July 27-31, Wolfeboro, New Hampshire.
3. Invited paper "Applications of Optical Phase Conjugation," at the Winter Colloquium on Quantum Electronics, January 5-8, Snowbird, Utah.
4. Contributed paper with Daniel Mahgerefteh, "Nanosecond response and "coasting" in photorefractive barium titanate at the OSA Topical meeting on Photorefractive Materials, Effects, and Devices, August 12-14, Los Angeles, California.

## ANALYSIS AND SYNTHESIS OF PARALLEL PROCESSING SYSTEMS

D.I. Moldovan

Research Unit IE3-1

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

During this period, the research effort has been on parallel processing of real based system. The following main results were obtained:

1. Development of a technique for reducing search spaces
2. Development of a scheme for firing rules in parallel
3. Identification of the way to map rule-based systems into multi processors.

The multi processor called RUBIC (Rule-based inference computer) was designed to implement parallel processing of rule-based systems.

### List of Publications

1. D.I. Moldovan, "RUBIC; multiprocessor for rule-based systems," to appear in IEEE Trans. on Sys. Man and Cybernetics, 1988.
2. D.I. Moldovan and C.I. Wu, "Parallel processing of knowledge based visions systems," to appear in IEEE Trans on Software Eng., 1988.
3. D.I. Moldovan, "Multi processor for rule-based systems", Proc. 2nd Int. Conf. on Super Computing, May 1987.
4. D.I. Moldovan, "Systolic array for optimal binary research three algorithm, Proc. 20 Hawaii Int. Conf. Systems Sciences, Jan. 1987.

## BASIC RESEARCH IN C<sup>3</sup> DISTRIBUTED DATABASES

VICTOR O.K. Li

Research Unit IE3-2

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

In the past year, we have focused on three areas of basic research in distributed databases, namely, performance modeling of concurrency control algorithms, query processing, and termination protocols. In Pub. 4, we have developed a performance model for timestamp-ordering algorithms. We believe our work represents the first successful attempt to model timestamp-ordering algorithms without resorting to simulations. The model for locking algorithms that we have developed (Pub. 10) allows one to include the effect of deadlocks. The Precedence-Assignment model (Pub. 6) is a unified model of most existing concurrency control algorithms. Based on this model, a unified concurrency control algorithm has been developed (Pub. 3). In the area of query processing, we have developed the domain-specific semijoin for distributed query processing (Pub. 9), and a query processing algorithm applicable to distributed databases managed on local area networks (Pub. 1 and 5). We have also developed termination protocols in distributed databases managed on networks with unreliable components (Pub. 2 and 7).

### List of Publications

1. Chen, J.S.J. and Li, V.O.K., "Optimizing Joins in Fragmented Database Systems on a Broadcast Local Area Network." To appear in the IEEE Trans. on Software Engineering.
2. Huang, C.L. and Li, V.O.K., "A Quorum-Based Termination Protocol for Distributed Database Systems," Proc. IEEE Data Engineering Conference, Culver City, California, February 1988.
3. Wang, C.P. and Li, V.O.K., "A Unified Concurrency Control Algorithm for Distributed Database Systems," Proc. IEEE Data Engineering Conference, Culver City, California, February 1988.
4. Li, V.O.K., "Performance Models of Timestamp-Ordering Synchronization Algorithms in Distributed Databases," IEEE Trans. on Computers, **C-36(9)**, 1041 (1987).

5. Chen, S.J. and Li, V.O.K., "Optimizing Joins in Fragmented Database Systems on a Broadcast Local Area Network," Proc. IEEE International Conference on Distributed Computing, Berlin, Germany, September 1987.
6. Wang, C.P. and Li, V.O.K., "The Precedence-Assignment Model for Distributed Database Concurrency Control Algorithms," Proc. ACM Symposium on Principles of Database Systems, San Diego, California, March 1987.
7. Huang, C.L. and Li, V.O.K., "A Termination Protocol for Simple Network Partitioning in Distributed Database Systems," Proc. IEEE Data Engineering Conference, Culver City, California, February 1987, pp. 455-465.
8. Chen, S.J. and Li, V.O.K., "Minimum-Weight Vertex Cover Problem for Two-Class Resource Connection Graphs," submitted for publication.
9. Chen, S.J. and Li, V.O.K., "Domain-Specific Semijoin: A New Operation for Distributed Query Processing," submitted for publication.
10. Shyu, S.C. and Li, V.O.K., "Performance Analysis of Static Locking in Distributed Database Systems," submitted for publication.

## IMAGE TEXTURE RESTORATION AND ANALYSIS USING NONSTATIONARY MODELS

Alexander A. Sawchuk

Research Unit IE3-3

ANNUAL TECHNICAL REPORT  
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### PROGRESS

Image sequence analysis is an area of image processing and computer vision which has attracted the interest of many researchers in recent years. An image sequence is a sampling in time of a time-varying scene. Each sample is a 2-D image. The image sequence contains moving parts which we call targets and nonmoving parts which we call background. An important problem is the segmentation of these images into moving and stationary components and the 2-D motion estimation of the targets. The segmentation and motion estimation are strongly related to each other because motion is a cue to the segmentation and motion estimation is improved in a well segmented image sequence. Our overall approach is to combine estimation and segmentation in mutually beneficial algorithms which take advantage of this interdependence.

Two different methods of using motion information in order to segment an image sequence have been described previously. The first method begins by accumulating difference pictures to give a crude segmentation; then it employs a region growing algorithm to produce a finer segmentation. In the second method, a 2-D motion estimation algorithm is used and motion parameters such as displacement or velocity are estimated. Then the segmentation is based on the simple idea that points with the same motion parameters most likely belong to the same target.

All these methods use dynamic features such as difference images and motion parameters to segment the image sequence. If we also consider the static features of each single frame then the segmentation will be improved.

Our method incorporates all the available static and dynamic information about the image sequence. More specifically, we use a statistical segmentation algorithm which is a statistical edge detector or equivalently a boundary estimator. This estimator uses the information we have about the motion, which is really a motion prediction, as a priori information. After segmenting the current frame we estimate the target motion which took place between the previous and the current

frame. This 2-D motion estimation uses the segmented images. As a result, the estimate is greatly improved. We then predict the motion for the next frame and this prediction is used as a priori information for the statistical segmentation of that frame.

We have developed an algorithm which performs the segmentation assuming that the motion information (prediction) is given. This segmentation algorithm has been analyzed in [1]. This paper contains some experimental results of boundary estimation under different conditions of signal-to-noise ratio, prediction variance (confidence) and prediction accuracy.

We are now working on the 2-D motion estimation problem assuming that the segmentation has been done. Existing methods of 2-D motion estimation can be divided into two categories: pixel-based methods and feature-based methods. In pixel-based methods the displacement of each pixel is estimated separately. The separation is based on the relation of time differences to spatial differences. In feature-based methods, features are matched between frames and then their motion is estimated. An appropriate feature could be the boundary. Our 2-D motion estimation algorithm and its interaction with our segmentation algorithm will be presented in [2].

### List of Presentations

1. D.S. Kalivas, A.A. Sawchuk and R. Chellappa, "Estimation and Segmentation of Image Sequences," Proc. SPIE's 31st Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, August 1987.
2. D.S. Kalivas, A.A. Sawchuk and R. Chellappa, "Segmentation and 2-D Motion Estimation of Noisy Image Sequences," to be presented in ICASSP '88, New York, April 1988.

## REDUCED MODELLING THROUGH OPTIMAL PHASE MATCHING

Edmond A. Jonckheere

Research Unit IE3-4

ANNUAL TECHNICAL REPORT  
For the Period 1 January 1987 through 31 December 1987

### PROGRESS

This research unit is essentially concerned with large space flexible plates coated with a piezoelectric material, e.g. polyvinylidene fluoride, that acts as a distributed sensor/actuator.

Both the Aerospace Corporation (El Segundo) and Rockwell (Seal Beach) are currently conducting experiments whose very purpose is to demonstrate the feasibility of active control of large space structures with piezoelectric material.

The shorter term objective of this research unit is to identify the transfer function from the piezo-actuator input to the piezo-sensor output. Indeed, this relationship is poorly known, and accurate pointing control, figure control, disturbance isolation, etc. of large space structures precisely require accurate knowledge of the actuator-sensor transfer function. To be a little more specific, a source of great uncertainty in the Aerospace Corporation experiment is what happens at the interface where the piezo film is glued on the plate.

Over the past twelve months, our main thrust of research effort has been directed towards technology transfer -- i.e., how to apply the theoretical material that has been developed over the past few years in the course of this JSEP work unit to the real problem of mathematical modelling from real, experimental data.

As said in the proposal, the real problem is to construct the so called phase function from the experimental frequency response of the structure. This has been, at least partially, solved through some FFT analysis of the data. However, this has revealed yet another problem -- The construction of the phase function by FFT analysis of the data is possible, provided the data is complete, in other words, the experimental frequency response must cover the entire bandwidth of the structure. In case the experimental frequency response data is insufficient, which happens if for example the bandwidth of the instruments is not wide enough to cover the bandwidth of the structure, then the construction of the phase function appears to be an even more challenging problem. The key to the solution appears to be the mathematical notion of "extension."

Another significant progress that has been accomplished over the past twelve months of this JSEP work unit is the extension of the basic single-input-

single-output ideas to the multi-input-multi-output case. Namely, we have found the way to extract the multivariable phase information from the experimental frequency response data. The key idea is polar decomposition of the experimental frequency response.

### List of Publications

1. E. A. Jonckheere and J.C. Juang, "Fast computation of achievable performance in mixed sensitivity H-infinity design," IEEE Transactions on Automatic Control, **AC-32**, 896 (1987).
2. E. A. Jonckheere and Chingwo Ma, "Combined sequence of Markov parameters and moments in linear systems," IEEE Transactions on Automatic Control, submitted, 1987.
3. Ph. C. Opdenacker, E.A. Jonckheere et al, "Reduced order compensator design for a flexible structure," Journal on Guidance, Control and Dynamics, to appear, 1987.
4. J.C. Juang and E.A. Jonckheere, "Data reduction in the mixed sensitivity H-infinity design problem," IEEE Transactions on Automatic Control submitted and accepted, 1987.
5. J.C. Juang and E.A. Jonckheere, "On computing the spectral radius of the Toeplitz plus Hankel operator," IEEE Transactions on Automatic Control, submitted and accepted, 1987.
6. E.A. Jonckheere and Rongsheng Li, "L-infinity error bound for phase matching approximation--the one step at a time Hankel norm model reduction version," International Journal of Control, **46**, 543 (1987).
7. E.A. Jonckheere and J.C. Juang, "Hankel and Toeplitz operators in linear quadratic and H-Infinity designs," Modelling, Robustness and Sensitivity Reduction in Control Systems, Edited by R. F. Curtain, Springer Verlag, NATO ASI Series, Vol. F34, pp. 323-356.

### List of Presentations

1. E. Jonckheere, "H-infinity control system design for directed energy weapons," Lawrence Livermore National Laboratory, Livermore, CA, March 1987.

## RESEARCH IN COMPUTER VISION

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Research Unit IE3-5

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### PROGRESS

The goal of this research unit is to develop model based algorithms for some computer vision problems. We have made significant progress over the last twelve months in developing algorithms for edge detection in noisy images, for topographical feature extraction in noise free images and texture segmentation. The potential applications of this research are in smart interpretation of aerial images.

A unified framework for smoothing and edge detection based on an autoregressive (AR) random field model has been developed for edge detection in noisy images. An edge is detected, if the first and second directional derivatives and a local estimate of the variance at each point satisfy certain criteria. Due to the modeling assumptions, the directional derivatives become functions of the model parameters and of the neighboring pixels in a (3x3) window. When noise is present, a good estimate of the original from the noisy images improves the Signal-to-Noise-Ratio (SNR) and this results in better estimates of the directional derivatives. To avoid excessive computations the problem of estimation of the original image and the model parameters is presented as a combination of a Reduced Update Kalman filter (RUKF) and an adaptive Least Square (LS) parameter estimation algorithm. The restoration process is completed with a min-max replacement scheme to enhance edge strength. Since the edge detector operates on the processed image, restoration and edge detection cannot be performed simultaneously and the edge detector lags behind the restoration filter.

An oriented detector resulting from the use of an AR model may not detect edges of significantly different orientations. This is overcome by running four edge detectors on the four interior pixels of a (4x4) window and this corresponds to rotating the window in successive multiples of 90 degrees. These intermediate results are stored at each point and the final result is the union of the outputs of the four edge detectors. Results of applying this edge detector on noisy real aerial images have shown that a unified model based approach produces better results than the heuristic approaches often used in the literature.

We have developed methods for extracting topographical features such as flatness, peakness, pit, convex, concave hills, valley and pit using the directional derivatives estimated from the AR model. We first construct a matrix of partial derivatives as

$$\begin{pmatrix} \frac{\partial^2 g}{\partial x^2} & \frac{\partial^2 g}{\partial x \partial y} \\ \frac{\partial^2 g}{\partial x \partial y} & \frac{\partial^2 g}{\partial y^2} \end{pmatrix} \quad (1)$$

where  $g(x,y)$  is the gray level at position  $(x,y)$ . The topographical classification of each pixel is then done using the eigenvalues and eigenvectors of the above given matrix. For instance, a peak is detected if the gradient magnitude is zero and eigenvalues of the matrix given above are strictly negative. The main advantage of using topographic symbols is their invariance to monotonically increasing gray tone transformations.

We have also developed a local algorithm for maximizing the expected proportion of correctly labelled pixels for texture segmentation. This algorithm finds the optimal label configuration with respect to the maximum posterior marginal (MPM) criterion. We assign two random variables for the observed image pixel, one for characterizing the underlying intensity and the other for labeling the texture corresponding to the pixel location. A fourth order Gauss Markov random field is used to represent the image intensity distribution given its texture labels. The texture labels are assumed to obey a first order Markov model with a single parameter  $\beta$ , which measures the amount of cluster between adjacent pixels. Let  $\Omega$  denote the set of grid point in the  $M \times M$  lattice,  $L(s)$ ,  $s \in \Omega$  and  $y(s)$ ,  $s \in \Omega$  the label and gray level arrays respectively.

We then maximize

$$p(L(s)/y(s), s \in \Omega) = p(L(s)/y(s+r) \quad r \in N)$$

where  $N$  is the fourth order neighbor set. The optimal algorithm is implemented by sampling out of the posterior distribution of the texture labels given the intensity. A Gibbs sampler has been used for this purpose. The algorithm can be implemented sequentially or in parallel, with a deterministic or stochastic decision rule for the

order of visiting the pixels. Excellent results have been obtained for a 6 class texture mosaic image.

### List of Publications

1. R. Chellappa, "Model Based Approaches for Some Image Understanding Problems", Proc. SPIE Conference, Los Angeles, Jan. 1987. (Invited Paper), was presented by Chellappa.
2. Y.T. Zhou and R. Chellappa, "Linear Feature Extraction Based on an AR Model Edge Detector," Proc. Intl. Conf. on Acoust, Speech and Signal Proc., Dallas, Texas, April 1987 (was presented by Yitong).
3. Y.T. Zhou, A. Rangarajan and R. Chellappa, "A Unified Approach for Filtering and Edge Detection in Noisy Images", Proc. 21st Annual Asilomar Conf. on Signals, Systems and Computers, Pacific Grove, CA, Nov. 1987 (Invited Paper, was presented by A. Rangarajan)
4. Y.T. Zhou, V. Venkateswar and R. Chellappa, "Edge Detection and Linear Feature Extraction Using an AR Model," Accepted for Publication, IEEE Trans. Patt. Anal. Mach. Intelligence.

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