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ANNUAL REPORT

FEMTOSECOND CARRIER PROCESSES IN COMPOUND SEMICONDUCTORS AND REAL TIME SIGNAL PROCESSING

MAY 1, 1991 - APRIL 30, 1992

CONTRACT #F49620-90-C-0039

CORNELL UNIVERSITY

SCHOOL OF ELECTRICAL ENGINEERING
ITHACA, NEW YORK 14853

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Joint Services Electronics Program
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March 25, 1992

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approval for public release. Distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Cornell University 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research
6c. ADDRESS (City, State, and ZIP Code) 119 Phillips Hall Ithaca, NY 14853-5401	7b. ADDRESS (City, State, and ZIP Code) Building 410, Bolling Air Force Base, Washington, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-90-C-0039
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Femtosecond Carrier Processes in Compound Semiconductors and Real Time Signal Processing

12. PERSONAL AUTHOR(S)
J. Peter Krusius

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Annual Report	FROM 5/1/91 TO 4/30/92	92/03/25	45

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Compound semiconductor, organometallic vapor phase epitaxy, femtosecond laser probing, Monte Carlo simulation, VLSI, fault tolerance, computer architecture

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

This report is the annual report on research conducted under the auspices of the Joint Services Electronics Program at Cornell University. The research is grouped under two themes: (a) femtosecond carrier processes in compound semiconductors, and (b) real time signal processing. Results on OMVPE materials growth, femtosecond laser probing of hot carriers, and ensemble Monte Carlo simulations are reported on under the first theme. Accomplishments on VLSI algorithms, fault tolerant architectures, and architectures with multiple functional units for signal processing are given under the second theme.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL J. Peter Krusius	22b. TELEPHONE (Include Area Code) (607) 255-3401 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

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A. DIRECTOR'S OVERVIEW

This document is the second year annual report of the Cornell Joint Services Electronics Program for the period from May 1, 1990 to April 30, 1993. The present Cornell program carries two themes: femtosecond carrier processes in compound semiconductors, and real time signal processing. The program has advanced according to the plan. Eight task investigators, Profs. R. Shealy, C. Tang, C. Pollock, P. Krusius, G. Bilardi, F. Luk, A. Bojanczyk, and H. Torng, with their graduate students have contributed to JSEP research this year. Early during this year G. Bilardi left Cornell University in order to take a position at the Italian University, Universita' di Padova, Dipartimento di Electtrotechnica ed Informatica. A substitute task proposed by Prof. Adam Bojanczyk was approved starting September 30, 1991. The integration of research under each of the two themes has progressed according to plan and joint publications are appearing. Eleven graduate students have been partially, or fully, supported by JSEP this year. A total of 29 publications and eight theses were prepared in this period and are now various stages of processing. Eight PhD degrees have been awarded to JSEP supported students during this reporting period.

B. DESCRIPTION OF SPECIAL ACCOMPLISHMENTS AND TECHNOLOGY TRANSITION

B.1. *Femtosecond Carrier* Processes in Compound Semiconductors

Several significant achievements have been reached in the research performed under the compound semiconductor theme. The new off-campus organometallic vapor phase epitaxial (OMVPE) compound semiconductor materials growth facility has been completed and outstanding OMVPE films have been grown under the leadership of R. Shealy. The facility has a total area of 5,000 sq ft, with 1,800 sq ft of class 10,000 clean room, and will house 3 OMVPE reactors, the first of which became operational during this reporting period. The facility design sets new standards in New York State for handling highly toxic hydride process gases by exceeding even the stringent code set by the State of California. Undoped GaAs films have been grown in this multi-chamber OMVPE reactor using triethylgallium (TEG) and arsine source gases with at very low V/III flow ratios. Films grown above 600 C are n-type and have carrier concentrations typically less than $5\times10^{14}cm^{-3}$ with 77K mobilities exceeding 101,000 cm^2/V-s. The second OMVPE reactor is being readied for deep UV stimulated selective OMVPE growth for exciting new structures. Very high average power of high repetition rate femtosecond pulses in the blue have for the first time been generated by C. Tang's group via intra-cavity doubling of a mode-locked Ti:sapphire laser using a BaB_2O_4 crystal. The same group has also set-up a hot luminescence based sensitive time-resolved spectrometer. This technique has been used to study the relaxation dynamics of hot carriers in III-V compound semiconductors. C. Pollock's group has perfected its unique tunable color center laser based femtosecond pump-and-

probe characterization system for narrow band gap semiconductors. Carrier relaxation data for excitations from the band edge up to a few optical phonon energies in InGaAs thin films is being measured. The Monte Carlo simulation group of J. P. Krusius has completed the dual carrier code for the time-dependent simulation of non-equilibrium transport in two-dimensional heterostructure devices, such as heterojunction bipolar transistors. In parallel this group has been collaborating with C. Pollock's efforts to develop and analyze the femtosecond pump-and-probe measurements on narrow band gap semiconductors. Most recently the ability to model the effect of dynamic screening on carrier-optical phonon and carrier-carrier scattering has been added. A qualitative agreement between theory and experiment for InGaAs thin films has been reached.

The Optoelectronics Technology Center (OTC), established in September 1990 under DARPA support, with primary participant from Cornell University, University of California Santa Barbara, and University of California San Diego is in its second year. C. Tang continues as one of the leaders of this multi-university program. The Cornell part of the OTC proposal leveraged past JSEP research. The OTC had its first annual review meeting at Cornell University in October 1991. In addition to C. Tang, R. Shealy, C. Pollock, and P. Krusius of the JSEP investigators, are involved in the OTC research program.

Further special accomplishments are listed in the description of research under each of the tasks.

B.2 Real Time Signal Processing

The investigators involved in the real time signal processing theme, Profs. G. Bilardi, A. Bojanczyk, F. Luk, and H. Torng, have continued the synergistic work. F. Luk's group discovered the relationship between the Berlekamp-Massey algorithm for decoding the Reed-Salomon code and the well known Lanczos algorithm. H. Torng's group has made significant progress in the instruction issuing mechanism, interrupt handling, branch prediction and multi-stream processing, all problems arising in efforts to design faster superscalar computing machines. While A. Bojanczyk is new to this group, he will bring a more hardware oriented approach and longer term impact the program considerably.

H. Torng organized the third "Project 2000" meeting in June 1991 at Cornell to report on computer engineering advances in the past year. About 15 industrial representatives attended this two day meeting. F. Luk organized an SPIE meeting on advanced signal processing algorithms, architectures, and implementations. The proceedings, which he edited, included 46 papers and covered 494 pages. F. Luk together with A. Bojanczyk were awarded a Warp computer by DARPA. This GE built machine was installed at the Cornell Engineering and Theory Center building in September 1990. Also a group of

INMOS transputers has been installed at the E&TC for exploratory computation.

Further special accomplishments are listed in the description of research under each of the tasks.

C. DESCRIPTION OF INDIVIDUAL WORK UNITS

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C.1 Femtosecond Carrier Processes in Compound Semiconductors

Task #1 OMVPE Growth of III-V Alloys for New High Speed Electron Devices 4
Task #2 Femtosecond Laser Studies of Ultrafast Processes in Compound Semiconductors 13
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OMVPE GROWTH OF III-V ALLOYS FOR NEW HIGH SPEED ELECTRON DEVICES

Task #1

Task Principal Investigator: James R. Shealy
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OBJECTIVE

The program objective for the materials task is to explore the use of OMVPE to produce novel epitaxial structures for new high speed electron devices. The emphasis is to extend the capabilities of the OMVPE process to include sub-micron selective growth of high mobility electron channels, as well as, to use conventional OMVPE techniques to produce high quality III-V alloys, both lattice matched and pseudomorphic, for the device fabrication and carrier relaxation studies ongoing in other related JSEP program tasks (2-4). The program objectives are currently proceeding in a series of stages involving the operation of the new OMVPE facility at Cornell (which includes environmental testing) , the construction of an additional OMVPE reactor for the selective growth studies, and the development of advanced optical probing techniques for the non-destructive characterization of 2 dimensional epitaxial structures.

DISCUSSION OF STATE-OF-THE-ART

The following discussion of the state-of-the-art is organized into separate sections on photo-stimulated selective OMVPE, the properties of phonons in strained semiconductor short period superlattices, and the operation of a safe OMVPE process with hydrides.

Selective OMVPE Deposition with Deep UV Radiation

Deep UV photo-assisted OMVPE growth is one of the most promising paths to realizing in situ submicron selective growth. The proposed approach for selective OMVPE on the submicron scale utilizes tunable, coherent deep UV radiation in contrast to all previous attempts. The reactants used in OMVPE are generally transparent in the visible and infrared portion of the spectra. Optical activation of the growth has been achieved using visible laser radiation, where the reactants on the growth surface are <u>not</u> directly excited. The growth is apparently activated by local thermal heating or by carrier generations near the growth surface [1]. These intermediate steps will most likely prevent a high resolution selective growth process due to thermal and/or carrier diffusion prior to the activation of the growth. The deep UV approach also has its limitations. Previous studies using an ArF excimer laser

excitation (193 nm) have found at best a 2:1 growth ratio in the illuminated:dark regions of the substrate. Also, substantial carbon concentrations [@ (10^{17}) cm^{-3}] are observable in the selectively deposited GaAs films [2]. The laser enhanced growth was found to be severely limited by absorption in the gas phase. In spite of this, enhanced growth was observed using 10 Hz pulse trains with energies as low as 10 mJ/cm^2/pulse with trimethylgallium (TMG) and arsine.

With other approaches, a visible laser stimulated Atomic Layer Epitaxial (ALE) process, the selectivity has been dramatically improved [3]. Unfortunately, this process suffers from limited dimensional control for the reasons stated above and considerable carbon contamination. In all previous studies the dimensional resolution of the selective growth process (best linewidth) exceeds 10 μm.

With a tunable deep UV source it becomes feasible to perform selective deposition where the radiation is incident on the growth surface, and also to selectively excite reactant species in the vapor phase or in the adlayers on the surface. Furthermore, the Ga, or Al sources may be selectively excited as the absorption edges are distinctly separated in the UV spectrum. To illustrate these excitations, the absorption spectra of TMG, trimethylaluminum (TMA), and the surface chemisorbed species using TMG/AsH_3 exposures are presented in figure 1 [4].

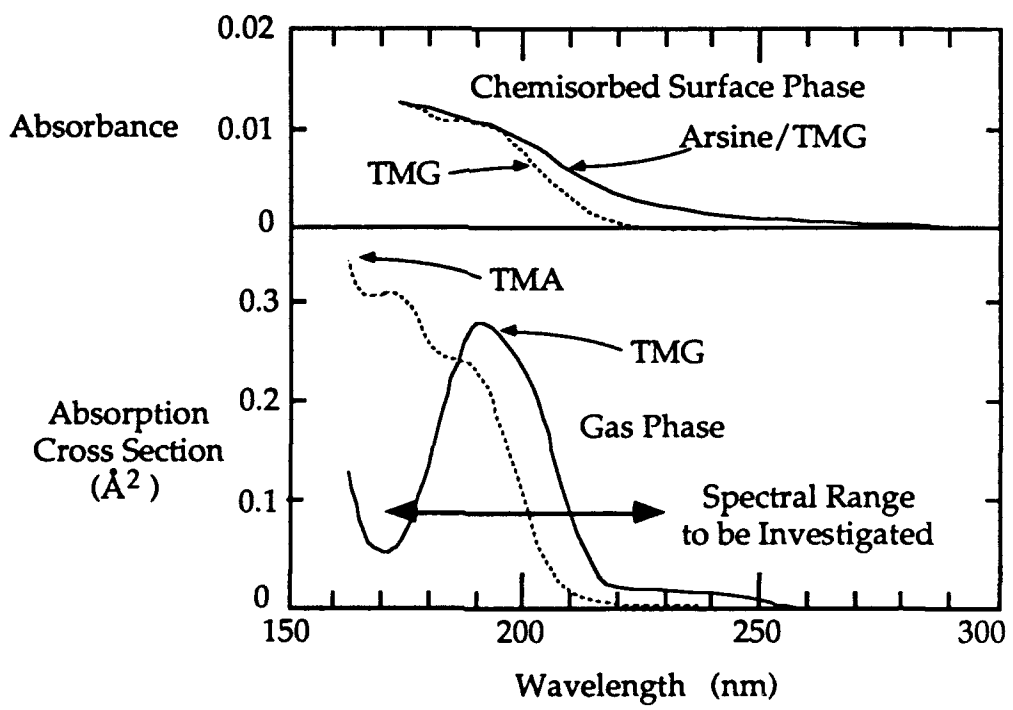

Figure 1. Room temperature UV absorption spectra for TMG, TMA, and the chemisorbed surface layers caused by TMG and AsH_3 exposures on a silica substrate surface. The chemisorbed surface adlayers' spectra were obtained by subtracting the TMG vapor phase spectrum from the measured data (Ref. 4).

As is evident in figure 1, at an excitation wavelength of 220 nm, the surface phase may be excited without appreciable absorption in the vapor phase. Note that previous studies using 193 nm excimer laser radiation resulted in excitation of both the vapor and surfaces phases, a problem which was cited to degrade the stimulated growth rate and the dimensional selectivity of the process[2]. The tunable deep UV source (frequency doubled, excimer pumped, dye laser system) will allow the use of coherent radiation from 170 to 220 nm. By selecting the laser wavelength, it becomes feasible to selectively excite the Ga or Al vapor species using TMG and TMA by operation at 170 and 210 nm, respectively. These experiments may allow a modulation in the alloy composition x in $Al_xGa_{1-x}As$ films under the proper growth conditions. It should be noted that the absorption feature for the TMA vapor near 175 nm is due to the presence of the dimer species (not seen with TMG) which transports near room temperature from the bubbler. As the vapor heats in the boundary layer above the substrate, where the photo-excitation takes place, the dimer species partial pressure is substantially reduced (observed by a diminishing 175 nm absorption feature). This may prevent selective excitation of the TMA on or near the substrate surface. For the best dimensional control however, it appears that for wavelengths longer than 220 nm will offer the advantage of a transparent vapor over the substrate.

Phonons in Short Period (AlAs)(InAs) and (GaAs)(InAs) Superlattices

The use of strained layer, short period superlattices has been considered an attractive alternative for conventional lattice matched bulk ternary layers in heterostructure devices. Possible attributes of the superlattice approach are lower thermal spreading resistance of laser cladding layers and improved impurity activation, especially in n-type high bandgap alloys.

The most straight forward implementation of this concept has been using (AlAs)(GaAs) structures in heterostructure lasers emitting in the IR [5] and the visible [6]. In the former study, graded index regions are synthesized with graded superlattice periods and selectively doped cladding layers are used. The visible laser structures have benefited from superlattice active regions as demonstrated by a reduction of laser threshold currents at wavelengths as short as 680 nm.

More recently, strained layer superlattices latticed matched (nominally) to InP have been studies in the (GaAs)(InAs) system [7]. Improved structural and optical properties are associated with structures produced by Migration Enhanced Epitaxy (MEE). Besides their potential device applications, these short period strained layer structures are interesting from a fundamental viewpoint. Phonons and electrons in layered media display the effects of zone folding and quantum confinement which are, in turn, sensitive indicators of material structure and quality. Depending on the nature of the bulk dispersion in each region of a superlattice the resulting vibrational modes are either confined or propagative as. In all cases, the acoustic branches fold in the

superlattice, giving rise to new Raman active phonons at the reduced zone center. These modes are commonly observed to be as sensitive a measure of periodicity as X-ray rocking curves of TEM diffraction data. It is interesting to note that where the optical branches overlap, folding of the optic branches occur indicating propagative modes. The region of overlap is substantially increased in the (GaAs)(InAs) case if strain corrections are included in a 1D linear chain calculation.

Safety Issues Concerning the OMVPE Process Using Hydrides

A few significant features commonly found in the OMVPE process and related facilities are described here. Also the latest N.Y. State guidelines (as set by their Department of Environmental Conservation - DEC) for emissions into the environment are given to indicate the need for good process control from the arsine source to the exhaust stack. Most of the information given is obtained through private communications and, as a result, is not referenced.

Generally, conventional vented gas cabinets are used to house the hydride tanks which are fitted with a flow limiting orifice. If vented gas cabinets are to be used, dilution exhaust flow required to meet the 1/2 Immediately Dangerous to Human Life (IDLH) toxicity level as required the California building code are over 35,000 and 300,000 cfm for arsine cylinders with and without a standard flow limiting orifice. It should be noted that no arsine installation in the U.S. meets the 1/2 IDLH requirement when a catastrophic cylinder failure occurs and few can handle the controlled release through the orifice. New technology is needed to allow the OMVPE technique to be used in production environments in the near future. Furthermore, recent changes in the DEC code in N.Y. State are more stringent than the California code. For example, the ambient guide line concentrations for arsine emissions into the environment are $6.5(10^{-2})$ and $7.4(10^{-5})$ parts per billion (ppb) for short term release (1 hour) and annual averages, respectively. These numbers are many orders of magnitude less than the TLV value of 50 ppb. This requires that spills be contained and the exhaust from reactors be treated prior to release up the stack. An approach taken at Cornell will be described in the discussion of progress below.

It is worth noting that the use of ethyl-organometallic sources generally reduce the amount of hydride consumption by as much as 2 orders of magnitude for acceptable quality films. As a result, a safer OMVPE process emerges using ethyl sources. For example, workers have reported high purity GaAs grown at 10 torr using triethylgallium (TEG) and arsine with a V/III ratio of unity [8]. Recent results on low V/III ratios used in GaAs growth will be presented below.

PROGRESS

In this section, progress on the OMVPE growth and characterization of undoped GaAs is presented, as well as, the MEE growth and characterization of GaInAs and AlInAs structures. A brief update on the status of the selective growth reactor and the deep UV laser system will follow. Finally, a discussion of the the secondary hydride containment system in use in the OMVPE facility and results on stack testing are presented.

OMVPE Growth of Undoped GaAs

The operation of Cornell's new OMVPE facility began in late 1991. A multichamber reactor [9] is currently in use for the growth of GaAs using TEG and arsine. A table which summarizes the first 9 growth runs of undoped GaAs is given below.

Table 1. Summary of the growth experiments performed on undoped GaAs giving the growth parameters and measured layer thickness (by angle bevel and stain). The TEG flow rate is calculated from published vapor pressure data and measured pressure and flow data.

Experiment	Growth Temp. (°C)	Group III flow (sccm)	Group V flow (sccm)	V/III ratio	Pressure (torr)	Thickness (mm)
II1	577	0.9	66	75	76	1
II2	577	2.6	66	25	76	2.46
II3	577	2.6	34	13	76	3.14
II4	577	2.6	49	19	76	6
II5	577	2.6	13	5	76	3
II6	577	2.6	19.5	7.5	76	3
II7	635	2.6	80	30	76	4.5
II8	577	2.6	13	5	76	3.5
II9	635	2.6	42	20	76	6

We have explored the best growth conditions for ultra-high purity layers at low arsine flows (alternatively low V/III ratios). The layers have been characterized using 77 K and room temperature hall measurements, capacitance-voltage (CV) measurements, and low temperature photoluminescence (PL). Several interesting features have emerged from this series of experiments including the inter-related effects of gas phase stochiometry and growth temperature. At sufficiently high growth temperatures (> 600 °C), the normal p/n conversion apparently does not occur, which is attributed to the total lack of carbon contamination in many films. All the films grown above 600 °C are n-type and the carrier concentration is typically less than $5(10^{14})$ cm^{-3}. Mobilities at 77 K have been measured to exceed 101,000 cm^2/v sec. This corresponds to a total ionized donor and acceptor concentration of $5(10^{14})$ cm^{-3}. Low temperature PL data for several films grown at 577 °C are presented in figure 2.

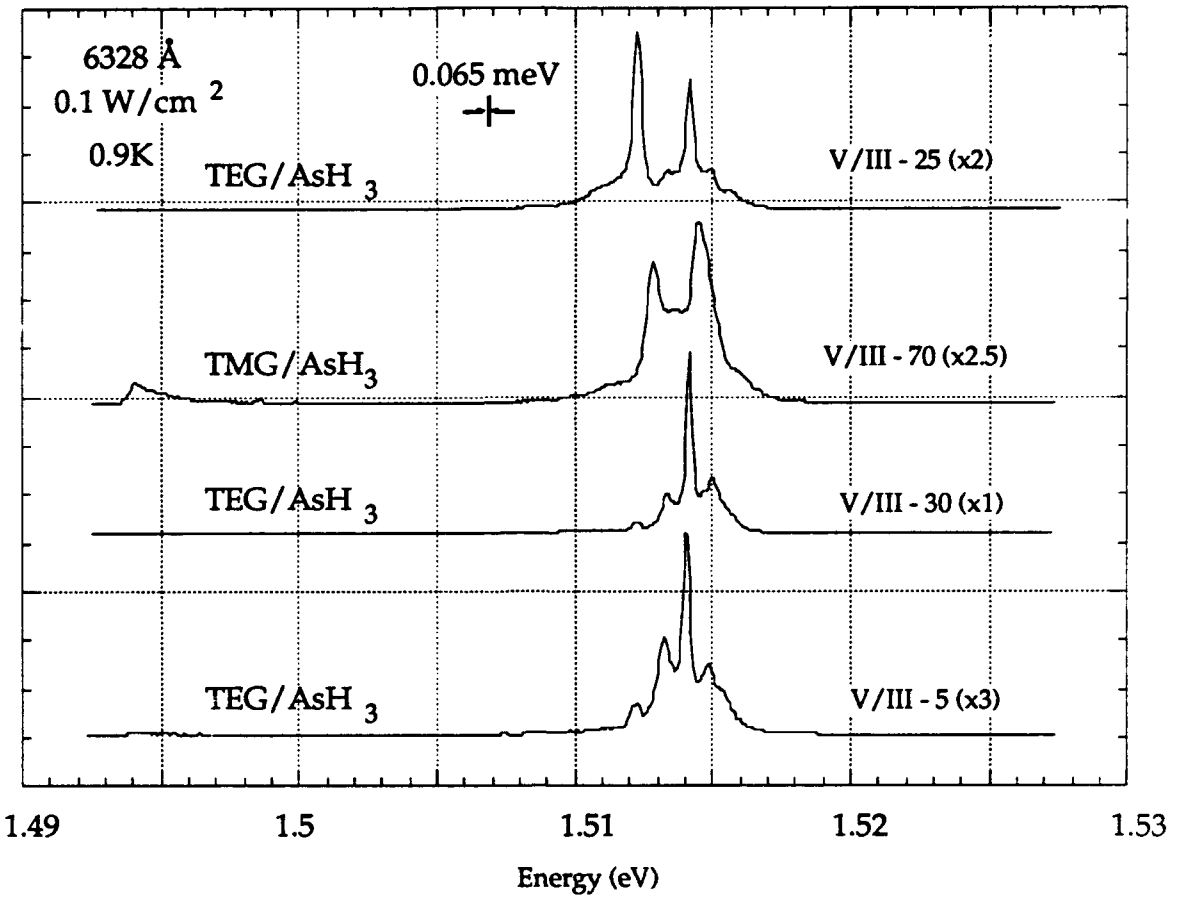

Figure 2. Low temperature (0.9 K) photoluminescence spectra of undoped GaAs grown with TEG and arsine at 577 °C and at the indicated gas phase stochiometry. A spectrum of a sample grown using TMG and arsine at 650 °C in the same reactor is shown for comparison. The excitation conditions and experimental resolution are indicated.

The most striking features in this PL data is the lack of donor-carbon acceptor pair transitions which appear near 1.495 eV for samples grown with the TEG source. This is observed even at the low V/III ratios meaning the ethyl source requires at least an order of magnitude less hydride consumption for high quality films. The bound excitons and free excitons transitions are readily resolved at photon energies near 1.515 eV and is a sensitive indicator of material quality. Finally excitons bound to neutral acceptors are barely visible in this spectral range indicating low acceptor concentrations are present in the recently grown samples.

OMVPE Reactor for Deep UV Stimulated Selective Growth

A second OMVPE reactor is currently nearing the end of its construction and will be used to perform photo-stimulated growth using a coherent, tunable laser source. The reaction cell is integrated onto an optical table and a piezoelectric 3 axis drive will allow scanning of a focused submicron spot across the growth surface. We have tested the laser performance and the

results look encouraging. When the dye laser is pumped at 25 Hz, the average power of the second harmonic exceeds 80 mW (1.7 mJ/pulse) and is tunable over the spectral range from 230 to 255 nm with peak power available at 240 nm. This performance is expected to allow excitation of the surface reactants without absorption in the gas phase at sufficient energy to stimulate the growth over 1 cm^2 areas. This projection is based on data from reference 2 and the absorption spectra in figure 1. The first selective growths are planned for late summer in 1992.

Test Results on Arsine Containment and Emissions

The arsine cylinders are housed in a secondary containment system which has fully pressure tested at the extreme limits of its intended use. These containment systems (one for arsine, one for phosphine) are now able to handle a catastrophic cylinder failure. The exhaust from this containment system and from the reactor is passed through a high temperature incinerator for destruction of residual arsine. We have been monitoring arsine emissions on the exhaust stack since the first run of the multichamber OMVPE reactor. The level of detection is less than 3 ppb prior to dilution and dispersion at the top of the stack. After the first several runs it was found that the incinerator required modifications to meet emission standards. Oxygen/air mixtures are used to insure complete combustion of hydrogen and arsine. The procedures used for each growth experiment were modified to eliminate "spikes" of arsine at the beginning and end of each run. We (including a representative from the DEC) are able now to observe undetectable emissions throughout a given growth run. Given the 10^4 dilution which occurs at the stack and the level of detection, Cornell's lab meets the most stringent environmental protection standards. Some aspects of the design are currently under consideration for a patent application.

SCIENTIFIC IMPACT OF RESEARCH

The scientific impact of this research task can be summarized in two major points. First, an OMVPE facility can be designed and implemented to insure a minimal level of risk to personnel, the general public and the environment. Furthermore, using certain combinations of organometallic precursors, the amount of arsine consumption is substantially reduced. The PL data on films grown with low arsine anf TEG show the absence of acceptors, in particular carbon and zinc, which is commonly found in OMVPE materials. When used in combination with a new Al precursor, trimethylamine alane, we anticipate high quality Al containing alloys can be grown in the near future. Second, the development of the submicron selective OMVPE growth process, using a high power deep UV coherent source, will potentially revolutionize the development of III-V based integrated circuits including those with optoelectronic elements. The laser system is commercially available and can be readily integrated into an OMVPE reaction cell to stimulate the reactions on the growth surface without photo decomposition in the vapor phase.

DEGREES AWARDED

1. Steve O'Brien
   "Interdiffusion of III-V Semiconductor Quantum Well Heterostructure and its Application to Integrated Electro-Optical Devices"
   PhD, Electrical Engineering, January 1991

2. James Singletery
   "Promising Solutions to Indium Phosphides Low Schottky Barrier"
   PhD, Electrical Engineering, May 1991

3. James T. Bradshaw
   "Characterization by Raman Spectroscopy of Graded Index-Separate Confinement Heterostructure Lasers and Short Period Strained Layer Superlattices"
   PhD, Applied Physics, August 1991

REFERENCES

[1] N.H. Karam, N.A. El-Masry and S.M. Bedair,"Laser Selective Deposition and Direct Writing of Single Crystal III-V Compound Films," *13th International Symposium on Gallium Arsenide and Related Compounds Abstracts,* Las Vegas, Nevada., (1987), 171-6.

[2] P. Balk, M. Fischer, D. Gundmann, R. Luckerath, H. Luth and W. Richter, "Ultraviolet-Assisted Growth of GaAs," *J. Vac. Sci. Technol.,* **B5**(1987), 1453-9.

[3] S.P. DenBaars, P.D. Dapkus, C.A. Beyler, M. Zandian, A. Hariz, and K. Dzurko," Thermal and Laser Assisted Atomic Layer Epitaxy of Compound Semiconductors,"*15th International Symposium on Gallium Arsenide and Related Compounds Abstracts,* Atlanta, Ga., (1988), 60-1.

[4] M.Sasaki, Y. Kawakyu, H. Ishikawa, and M. Mashita, "UV Absorption Spectra of Adlayers of MOCVD Source Gases," *Appl. Surface Sci.,* **41/42** (1989), 343-45.

[5] J.R. Shealy, "High-Efficiency Superlattice Graded-Index Separate Confining Heterostructure lasers with AlGaAs Single Quantum Wells," *Appl. Phys. Lett.,* **52** (1988), 1455-7.

[6] T. Hayakawa, T. Suyama, K.Takahashi, M. Kondo, S. Yamamoto, and T. Hijikata, "Low Current Threshold AlGaAs Visible Laser Diodes with an $(AlGaAs)_m(GaAs)_n$ Superlattice Quantum Well," *Appl. Phys. Lett.,* **49** (1986), 636-8.

[7] J.M. Gerard, J.Y. Marzin, B. Jusserand, F. Glas, J. Primot, "Structural and Optical Properties of High Quality InAs/GaAs Short-Period Superlattices Grown by Migration-Enhanced Epitaxy," *Appl. Phys. Lett.*, **54** (1989), 30-2.

[8] K. Kimura, S. Takagishi, S. Horiguchi, K. Kamon, M. Mihara and M. Ishii, "Low Pressure OMVPE Growth of GaAs Using TEG," *Jap. Jour. Appl. Phys.*, **25** (1986), 1393-6.

[9] J.R. Shealy, "Characterization of AlGaAs/GaAs Heterostructures Grown in a Multichamber OMVPE Apparatus," *J. Crystal Growth*, **87** (1988), 350-356.

ISEP PUBLICATIONS

1. "Monolithic Integration of an (Al)GaAs Laser and an Intracavity Electroabsorption Modulator Using Selective Partial Interdiffusion," S. O'Brien, J. R. Shealy, and G. W. Wicks, *Appl. Phys. Lett.*, 58 (13), April 1, 1991.

2. "Tunable (Al)GaAs Lasers Using Impurity-Free Partial Interdiffusion," S. O'Brien, J. R. Shealy, F. A. Chambers, and G. Devane, *J. Appl. Phys.*, **71** (2), January 1992.

3. "Characterization by Raman Scattering X-Ray Diffraction and Transmission Electron Microscopy of $(AlAs)_m(inAs)_m$ Short Period Superlattices Grown by Migration Enhanced Epitaxy," J. Bradshaw, X. J. Song, J. R. Shealy, and H. Ostergaard, to appear in *J. Appl. Phys.*

FEMTOSECOND LASER STUDIES OF ULTRAFAST PROCESSES IN COMPOUND SEMICONDUCTORS

Task #2

Task Principal Investigator: C. L. Tang
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OBJECTIVE

The objective of this task is to develop new femtosecond sources and measurement techniques and to use such sources and techniques to study ultrafast processes in compound semiconductors and related structures. On source development, current emphasis is on high repetition rate all-solid-state femtosecond sources and in extending the tuning range of such sources. On optical measurement techniques, current emphasis is on developing optical sampling techniques with femtosecond time resolution based the up-conversion processes. These sources and techniques are being successfully applied to studying the relaxation dynamics of non-equilibrium carriers in III-V compounds and quantum wells. The capture problem and the problem of tunneling of coherent wave packets in quantum wells are of particular interest at the present time.

DISCUSSION OF THE STATE-OF-THE-ART

Almost all the work on femtosecond optics and ultrafast processes in the past has been based on the use of the mode-locked Rh6G femtosecond dye laser as the primary source of short pulses of light. The trend recently has been to move away from the dye lasers to all-solid-state short pulse sources. CW mode-locked Ti-doped sapphire laser has been most widely used new primary femtosecond laser source. The Ti:sapphire laser is tunable over the range of 720 nm to about 1 mm. The emphasis of our work has been to extend the useful range of all-solid-state femtosecond lasers to beyond this range through nonlinear optical techniques. Very significant progress has been made in this effort during the past year and the results are discussed below in the Progress section.

In the case of femtosecond optical measurement techniques, most of the past studies of ultrafast phenomena have been based upon some sort of pump-probe measurement, including the related correlation spectroscopic techniques. All these techniques suffer from the fact that during the probing process, the system being measured is also disturbed to some extent. To avoid perturbing the system being measured, the time-resolved hot luminescence up-conversion technique has been developed to study the relaxation

dynamics of non-equilibrium carriers in semiconductors at a number of laboratories recently, including Cornell. This technique allows optical sampling with a time resolution on the order of 50 fs of the very weak hot luminescence emitted by the carriers during the relaxation process. This technique has now been well developed where the dark noise count is down to half a photon per second and has been used successfully to yield unambiguous data on the cooling rates of hot carriers in bulk GaAs and GaAs/AlGaAs quantum wells at high carrier densities. An earlier controversy on this issue is thus resolved unambiguously and put to rest.

The relative hot-electron cooling rates for bulk and quantum well (QW) structures is an important, basic question that affects many applications of quantum well structures and has inspired a large number of theoretical studies. It is well known that the hot-carrier cooling rate decreases with increasing carrier concentration in both QW and bulk structures. The first study comparing GaAs/AlGaAs QW's and bulk GaAs reported similar cooling rates at a carrier density (n) of 2.5×10^{17} cm^{-3} [1]. Subsequent studies reported a much slower cooling rate in QW's than in the bulk at higher carrier densities ($n>10^{18}cm^{-3}$) [2-5]. Nevertheless, in a number of recent publications Leo et al. [6, 7] have cited these previous results as being contradictory and concluded that the cooling rates of bulk GaAs and GaAs/AlGaAs QW's are equivalent. These comparisons, however, were based on comparisons limited to the carrier density range of $10^{15}<n<10^{18}$ cm^{-3}, generalizing that the independence of carrier cooling with dimensionality is also independent of carrier density. The former studies [2-5] were carried out using nonlinear intensity correlation spectroscopy. The latter study was carried out using a time-resolved streak-camera with a time resolution of ~20 ps. Using the more accurate time-resolved hot-luminescence spectroscopic technique we have now shown conclusively [8] that the cooling rates of the quantum-well structures are significantly slower than that of the bulk for $n\geq5\times10^{18}$ cm^{-3} and similar at $2\times10^{18}cm^{-3}$ or lower thus confirming the earlier observations [2-5] of the difference in the cooling rates between the bulk and quantum well structures. This difference could not have been seen in the carrier density range studied by Leo et al. [7, 8].

PROGRESS

High repetition rate femtosecond pulse generation in the blue [9] - We have succeeded in generating very high average powers of high repetition rate femtosecond pulses in the blue for the first time by intracavity doubling of a mode-locked Ti:sapphire laser using b-BaB_2O_4 (BBO). To reduce the pulse broadening effect of group velocity mismatch, an extremely thin BBO crystal is used. Pumping the Ti:sapphire laser with 4.4 W from an Ar^+ laser, up to 230 mW of 430 nm light is produced at 72 MHz repetition rate and 89 fs pulsewidth. This represents an effective conversion efficiency of ~75% from the typical infrared output to the second harmonic. Pulse widths as short as

54 fs are achieved for the blue output. Recent conversion to a higher power Ar^+ laser pump has led to blue output in the range of 400 mW. We expect eventually to reach the 1 W level. When this is reached, we expect to be able to generate femtosecond uv pulses near 200 nm at a substantial power level, which should open up many ultrafast processes in a variety of materials and structures for study in the femtosecond time domain. Work is also under way to achieve extra-cavity pumping of the femtosecond OPO by the Ti:sapphire laser. This should make it much easier for others to operate the fs OPO's than in the case of intracavity pumped OPO demonstrated by us earlier. This should open up the broad mid ir range up to 4.5 mm for studies in the femtosecond time domain by many laboratories.

Hot luminescence spectroscopy [9] - A very sensitive time-resolved upconversion spectroscopic setup has been built in our laboratory. This time-resolved spectrometer has a time resolution on the order of 50 fs, spectral range from approximately 400 nm to 2.5 mm, and noise of 0.5 Hz. It has been successfully used to study the relaxation dynamics of hot carriers in III-V compounds and will be applied to the quantum well carrier-capture problem and the coherent electron-wavepacket tunneling problem.

Comparison of hot-carrier relaxation in quantum wells and bulk GaAs at high carrier densities [8] - An investigation of the hot-carrier relaxation in GaAs/(Al,Ga)As quantum wells and bulk GaAs in the high-carrier-density limit is completed. Using a time-resolved luminescence up-conversion technique with $\leq$ 80 fs temporal resolution, carrier temperatures are measured in the 100 fs to 2 nsec range. Our results show that the hot-carrier cooling rates in the quantum wells are significantly slower than in the bulk for carrier densities greater than 2×10^{18} cm^{-3}. A comparison is made with previous publications to resolve the confusion concerning the difference in cooling rates in quasi-two and three dimensional systems.

SCIENTIFIC IMPACT OF RESEARCH

The femtosecond sources and measurement techniques developed should be of great use to others in the scientific community. The results obtained on the dynamics of nonequilibrium carriers in III-V compounds and structures are of fundamental importance to the understanding of the physics and the design of ultra-high speed semiconductor electronic and optical devices.

DEGREES AWARDED

1. E. S. Wachman
   "Ultrafast spectroscopy with a novel broadly tunable cw femtosecond source"
   PhD, Applied Physics, 1991.

2. W. H. Loh

"Polarization Self-Modulation in Semiconductor Lasers"
PhD, Electrical Engineering, August, 1991.

3. Y. Ozeki
"Study of two-mode optical bistable semiconductor laser diodes with intra-cavity saturable absorbers"
PhD, Electrical Engineering, August, 1991.

REFERENCES

[1] C. V. Shank, R. L. Fork, R. Yen, J. Shah, B. I. Greene, A. C. Gossard, and C. Weisbuch, *Solid State Commun.* **47**, 981 (1983).

[2] Z. Y. Xu and C. L. Tang, *App. Phys. Lett.* **44**, 692(1984).

[3] H. Ukichi, Y. Arakawa, H. Sakaki, and T. Kobayashi, *Solid State Comm.* **55**, 311 (1985).

[4] S. A. Lyon, J. Lumm. **35**, 121 (1986).

[5] A. J. Nozik, C. A. Parsons, D. J. Dunlavy, B. M. Keyes, and R. K. Ahrenkiel, *Solid State Comm.* **75**, 297 (1990).

[6] K. Leo, W. W. Ruhl, and K. Ploog, Phys. Rev. **B 38**, 1947(1988); *Solid. State Elect.* **32**, 1863 (1989).

[7] K. Leo, W. W. Ruhl, H. J. Queisser, and K. Ploog, App. Phys. **A 45**, 35(1988); *Phys. Rev.* **B 37**, 7121 (1988).

[8] W. S. Pelouch, R. J. Ellingson, P. E. Powers, C. L. Tang, D. M. Szmyd, and A. J. Nozik, *Phys. Rev.* **B 45**, 1450(15 January, 1992); 7th International Conference on Hot Carriers Conference in Semiconductors, Nara, Japan, (July, 1991).

[9] "High Repetition Rate Femtosecond Pulse Generation in the Blue," R. J. Ellingson and C. L. Tang, *Optics Letters* (scheduled for March, 1992); also to be presented at CLEO '92, Anaheim, CA (May, 1992).

ISEP PUBLICATIONS AND TALKS

1. "Broadly tunable cw femtosecond optical parametric oscillators," C. L. Tang, W. Pelouch, and P. Powers, invited talk, CLEO '91, Baltimore, MD (May, 1991).

2. "Polarization bistability in semiconductor lasers," C. L. Tang, Y. Ozeki, and J. Johnson, CLEO '91, Baltimore, MD (May, 1991).

3. "Femtosecond optical parametric oscillators," C. L. Tang, invited talk, American Physical Society March Meeting, Cincinnati, OH (March 18-21, 1991).

4. "Femtosecond optics," International Workshop on Lasers in Chemistry and Physics, Dalian, China, sponsored by UNESCO and the Chinese Academy of Sciences (May 22-28, 1991).

5. "CW femtosecond pulses tunable in the near- and mid-infrared," E. W. Wachman, W. S. Pelouch, and C. L. Tang, *J. App. Phys.*, **70**, 1893 (1 August, 1991).

6. "Comparison of hot-carrier relaxation in quantum wells and bulk GaAs at high carriers densities," W. S. Pelouch, R. J. Ellingson, P. E. Powers, C. L. Tang, D. M. Szmyd, and A. J. Nozik, *Phys. Rev.* **B 45**, 1450 (15 January, 1992).

7. "Investigation of hot carrier relaxation in quantum well and bulk GaAs at high carrier densities," W. S. Pelouch, R. J. Ellingson, P. E. Powers, C. L. Tang, D. M. Szmyd, and A. J. Nozik, *Proceedings of 7th International Conference on Hot-Carriers in Semiconductors*, Nara, Japan (July 1991).

8. "High Repetition Rate Femtosecond Pulse Generation in the Blue," R. J. Ellingson and C. L. Tang, *Optics Letters* (scheduled for March, 1992); also to be presented at CLEO '92, Anaheim, CA(May, 1992).

9. "Polarization bistability in semiconductor lasers with intracavity multiple quantum well saturable absorbers", Y. Ozeki, J. E. Johnson, and C. L. Tang, App. Phys. Lett., **58**, 1958 (1991).

10. "Polarization switching and bistability in an external cavity laser with a polarization-sensitive saturable absorber," Y. Ozeki and C. L. Tang, *Appl. Phys. Lett.*, **58**, 2214 (1991).

11. "Dynamics of hot carriers in quantum wells and bulk GaAs at high carrier densities: femtoseconds to naoseconds," invited talk, SPIE Conference on Ultrafast Laser Probe Phenomena in Bulk and Microstructures in Semiconductors and Superconductors, Somerset, NJ (22-26 March, 1992).

12. "Optical parametric oscillators," C. L. Tang, invited talk, International School on Optics and Optical Physics, Capri, Italy (1992).

ULTRAFAST INTERACTIONS OF CARRIERS AND PHONONS IN NARROW BANDGAP SEMICONDUCTOR STRUCTURES

Task #3

Task Principal Investigator: Clifford Pollock
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OBJECTIVE

Our goal is to provide experimental data that can be used to confirm or refute the current models used to describe hot electron relaxation in narrow bandgap semiconductors. In this manner, we are measuring the carrier relaxation in various samples and providing the results of the measurements to Prof. Krusius for comparison with his groups simulations of the scattering process.

DISCUSSION OF STATE-OF-THE-ART

Most of the ultrafast work in InGaAs has been on quantum well structures, such as laser diode amplifiers. One motivation for doing femtosecond studies of diode amplifiers is "gain compression", which refers to a decrease in gain at high modulation rates. Most pump-probe work on amplifiers attempts to characterize this effect. Working in a semiclassical picture (carrier/photon rate equations), one can model the recovery. The debate in the field is about the importance of different forms of carrier relaxation. Spectral hole burning has been suggested to explain the transient gain decrease. Others advocate carrier heating: carrier transitions occur away from the bandgap due to the wideband nature of the femtosecond pulses, while stimulated emission occurs preferentially at the bandgap [1]. The effect occurs because carriers need to cool down to reach the bandgap and be more readily available for stimulated emission.

Recently, a new candidate for the gain nonlinearity has been proposed. Weiss [2] considered an InGaAs/InGaAsP MQW structure similar to Hall's paper above. They proposed that spatial transport of carriers from the boundary layers cladding the MQW structure. The experiments appear identical, the difference lies in the models used to fit the data by the two groups. Hall uses rate equations with a phenomenological heating term, while Weiss fits the gain decay rate to a carrier diffusion model. A third amplifier gain compression paper deals with the same issues [3].

Carruthers [4] at NRL examined a vertical stack heterojunction bipolar transistor. He used a modelocked Er-fiber laser to generate 1.6 ps pulses at

1.53um. Shining the light on the emitter contact layer (which was the InGaAs layer that absorbed most of the light and injected photocarriers into the InP/InGaAs/InP transistor structure below), with the collector grounded, the emitter photocurrent was observed with a 40GHz scope. This revealed a 12ps electrical pulse. The author attributes the width to RC effects, but the experiment in principle could measure transit times.

Knox [5] laid down parallel stripline on top of the quantum well. A pump beam at the appropriate energy to generated excitons which were rapidly ionized by an applied electric field. The electrical transient this generated propagated rapidly inside the stripline. Because the exciton creation time is very fast, and the exciton absorption line is Stark shifted by an E field, the exciton absorption strength was a sensitive measure of the field inside the stripline. Knox used a pump at one end of the line to generate an initial phototransient, and used a probe beam at the same energy but displaced along the line to measure the electric field strength, with 100 fs time resolution and 1um spatial resolution. He observed signals propagating near the speed of light (since the QW was very thin, with no substrate, the electrical group velocity is extremely large in these structures).

PROGRESS

We found through comparison of data to simulation that an experimental accuracy and repeatability of 1 part in 1000 was required. This is not simply a Signal/Noise issue, but a problem of removing all systematic errors from the data to this level. The search for systematic errors has been the thrust of most of our work in the past year.

Much of the error in our signals was traced to the variable delay arm of the spectrometer. We found that our data was slightly asymmetric, at least on the scale of parts per thousand. The source of the asymmetry was found to lie in a slow creep of the galvonometer that was used to scan the retroreflecting mirror of the delay arm. In response, we improved the galvanometer-driven optical delay device by using a lightweight translation stage to insure linearity, and by using position sensitive feedback to monitor and control the galvo itself.

We have evaluated several different noise reduction techniques. We found that the weak reflection of the pump laser from our femtosecond laser led to amplitude instabilities in the output power, and this caused excess noise in our signal. We implemented a new feedback amplitude stabilizer using acousto-optic (AO) modulation of the pump for our ultrafast laser. The AO cell both amplitude stabilizes the pump beam, and further it acts as an optical isolator between the two systems, reducing the deleterious feedback. In addition, we have refined the existing feedback control of cavity length. Finally, we have mapped out a larger range of operating parameters of the APM laser, allowing us to generate a more stable train of femtosecond pulses.

Our data shows the recovery time of the measured transmission fits a single exponential decay, which is a simplification of the process, but describes the data very well. Data is being collected as a function of wavelength, and we are just setting up a temperature stage to measure the effects of increased temperature on the scattering rates.

SCIENTIFIC IMPACT OF RESEARCH

These measurements will provide a test of the models used by designers to simulate the performance of InGaAs devices. They will be invaluable for refining and improving present theory and simulation of hot carriers in narrow bandgap materials.

DEGREES AWARDED

None.

REFERENCES

[1] "Femtosecond Gain Dynamics and Saturation Behavior in InGaAsP Multiple Quantum Well Optical Amplifiers," K. Hall, Y. Lai, E. Ippen, G. Eisenstein, U. Koren, *APL* 57, 27, (1990)

[2] "Carrier Capture Times in 1.5um Multiple Quantum Well Optical Amplifiers," S. Weiss, J. Wiesenfeld, D. Chemla, G. Raybon, G. Sucha, M. Wegener, G. Eisenstein, C. Burrus, A. Dentai, U. Koren, B. Miller, H. Temkin, R. Logan, T. Tanbun-Ek, *APL* 60, 1, (1992)

[3] "Gain Compression and Recovery Dynamics in Multiple Quantum Well Optical Amplifiers," in Ultrafast Phenomena VII, Springer-Verlag '90, J. Wiesenfeld, G. Eisenstein, M. Wegener, D. Chemla, G. Raybon, U. Koren, S. Weiss

[4] "Responses of an InP/InGaAs/InP Heterojunction Bipolar Transistor to 1530 and 620 nm Ultrafast Optical Pulses," T Carruthers, I. Duling III, O. Aina, M. Mattingly M. Serio, APL 59, 3, (1991)

[5] "Ultrafast Dynamical Response of Quantum Well Excitons in Applied Fields," W. Knox, Workshop on Optical Properties of Mesoscopic Semiconductor Structures, Snowbird, Utah, April 1991

ISEP PUBLICATIONS

1. "Femtosecond Electron Relaxation in InGaAs Lattice-Matched to InP," D. Cohen and C. R. Pollock, to be presented at SPIE conference 1677, March 25, 1992, Somerset, New Jersey.

FEMTOSECOND DUAL CARRIER TRANSPORT AND OPTICAL INTERACTIONS IN COMPOUND SEMICONDUCTOR HETEROSTRUCTURES

Task #4

Task Principal Investigator: **J. P. Krusius**
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OBJECTIVE

The objective in this work unit is to explore non-equilibrium carrier processes governing electron and hole transport and optical interactions in inhomogeneous compound semiconductor heterostructures theoretically. Electron and hole interactions among themselves, the semiconductor lattice, optical fields, and external electric fields are described using self-consistent ensemble Monte Carlo formulations including quantum well phenomena. This work is done collaboratively with femtosecond optical measurements and materials growth efforts. In the area of femtosecond optical probing with tunable lasers, joint work is performed together with C. Pollock's research group in order to design samples, optical experiments, analyze measured data, and extract microscopic information of femtosecond carrier processes. Two PhD graduate students, J.E. Bair and S. Weinzierl, have worked on this task in addition to the principal investigator.

DISCUSSION OF STATE-OF-THE-ART

A variety of ballistic injection cathodes have been built into the structure of compound semiconductor devices in order to enhance their high speed performance. These include the n+/n homojunction [1], the p+/n heterojunction [2], the abrupt heterojunction [3], and the Schottky barrier [4]. It has been experimentally demonstrated that these injection cathodes can generate a significant quasi-ballistic electron fraction in compound semiconductor devices, but despite such observations there is no conclusive evidence on whether such injection structures substantially increase device performance. The first published observation of the probing of the non-equilibrium electron distribution was made on the planar doped barrier transistor (PDBT), which was used as a hot electron spectrometer [5]. Another device structure used at about the same time was the tunneling hot electron transfer amplifier (THETA), first in its vertical form [6] and later in its lateral form [7]. Several attempts to fabricate unipolar FET devices with hot electron cathodes to generate ballistic electrons were also made but results were ambivalent [8, 9]. However, because of the complexity of designing and fabricating three terminal devices with hot electron cathodes, it was not clear whether fabricated devices suffered from materials growth or processing

related non-idealities, incorrect device designs, or the insignificant impact of ballistic electron processes on the terminal characteristics of devices. In order to resolve these fundamental questions it is necessary to explore the microscopic physics of the transport in such devices via sophisticated simulation techniques, which can resolve the underlying microscopic processes, including non-equilibrium carrier transport in inhomogeneous devices. Consequently a two-dimensional time-dependent self-consistent ensemble Monte Carlo method has been developed by this group and used to examine the impact of the above and many other hot carrier processes on the terminal characteristics.

The relaxation of carriers excited by ultra-short optical pulses has been intensely studied both experimentally and theoretically for several years. Despite this a full understanding of the complex carrier dynamics in these highly non-equilibrium situations is still lacking. Current Monte Carlo models of carrier relaxation have achieved considerable success in explaining many qualitative features of experimental observations [10, 11]. However, a great deal of uncertainty remains. At the heart of these uncertainties lies the role of carrier-carrier scattering. Models to this point have almost unanimously assumed that free carrier screening can be adequately described by using long wavelength static approximations. However, recent results have indicated carrier-carrier scattering may be seriously underestimated in a static screening limit [12, 13]. Theoretical calculations also have shown that carrier-carrier scattering rates are significantly enhanced, if dynamic screening effects are taken into account [14, 15]. Since the two most important scattering processes in compound semiconductors, polar optic phonon scattering and carrier-carrier scattering, are both heavily dependent on free carrier screening, this issue is critical in the understanding the role of these scattering mechanisms. Significant progress must be made in this area before the details of femtosecond optical experiments can be understood. Progress in this area has recently been made through a joint ensemble Monte Carlo/molecular dynamics approach [16] which has some success in correlating with measured data. However, this method appears limited to homogenous systems due to limitations arising from the size of the area that can be simulated. Thus it is unlikely that this method can be applied more widely to the modeling of other highly non-equilibrium phenomena, such as is found in state of the high speed compound semiconductor devices.

PROGRESS

Non-Equilibrium Carrier Transport

Work in this subtask has built on our past efforts with progress made in the following areas: dual carrier transport formulation and software development, and understanding of carrier launching across electron launchers subject to interactions with two-dimensional space charges.

The bipolar part of our previous software package, OPTMC developed by J.E. Bair, has been incorporated into the existing 2DMC transport code. The new code, M^2EDUSA, for Multi-dimensional Monte carlo Ensemble Simulation for Detailed Unipolar and bipolar heterojunction Semiconductor device Analysis, implements a two conduction band k.p band valleys, Γ-L, and two hole bands, Γ, including warping. All the usual scattering mechanisms are included. Any number of ternary compound layers, with either donor or acceptor doping, can be specified along one spatial dimension. A material homogeneity is assumed in the lateral direction. Either rectangular or mesa type devices can be simulated, and ohmic or Schottky contacts of any length can be placed anywhere around the two-dimensional periphery. Quantum mechanical reflection due to the potential step at the abrupt heterojunctions is included to first order. The entire implementation was constructed with the goal of having the simulations run as accurately as possible in a workstation computing environment without the use of supercomputing resources. This required, for example, the of analytic energy bands in order to decrease run time memory requirements and the exclusion of carrier scattering in order to keep execution times acceptable. A typical M^2EDUSA run for a vertical FET with an abrupt heterojunction, zero applied bias, charge neutral initial state, 256x64 point spatial mesh, 50000 particles, and 1000 time steps takes about 8:45, 2:54, and 2:26 hrs:min on an HP9000/380, a DEC 5000/200, and an HP 9000/720 engineering workstation respectively. As a calibration, the HP-RISC station 9000/720 is 37.4 times faster than the DEC VAX 11/780, an early 1980's CISC computer, which has often been used a benchmark.

M^2EDUSA has been calibrated and verified against physics principles, other simulators, and experiments. The simulated velocity field curve for GaAs matched with measured data within the experimental error. M^2EDUSA accurately resolves the transient phenomenon of the formation and propagation of a stable Gunn domain. M^2EDUSA also accurately models the dynamics of carrier heating and cooling, the time-dependence of the electron phonon interaction and the average momentum relaxation time. The correlation of M^2EDUSA simulated current-voltage characteristics with measured device data for a vertical FET with an imbedded heterojunction shows an excellent overall agreement. M^2EDUSA was also used to simulate significant characteristics of the homojunction pn diode and the homojunction bipolar junction transistor with a direct comparison with the drift-and-diffusion simulator PISCES-II with excellent results. Further verification and calibration studies are documented in detail in S. Weinzierl's PhD thesis (see degrees awarded).

To date M^2EDUSA has been used to simulate the following unipolar and bipolar compound semiconductor devices: the abrupt vertical field effect transistor with an abrupt heterojunction launcher, HJ-VFET; the modified planar doped barrier vertical FET transistor (PBD-VFET); and the ballistic

heterojunction bipolar transistor (BHBT). As an example, Figure 1 shows the simulated average electron drift velocity in an npn AlGaAs/GaAs BHBT device for three different base doping levels. The unipolar devices have been analyzed to the end resulting in a full understanding of device operation and the role of imbedded ballistic electron injectors. The bottom line is that ballistic electron injectors indeed do enhance device performance, measured e.g. with the cut-off frequency and current drive capability, but only if the device has been designed correctly. The design is tricky because many tradeoffs have to be considered simultaneously, a task rather impossible without the microscopic insight and optimization provided by M^2EDUSA. Although only preliminary results are available for the BHBT at this time, the same conclusion seem to apply.

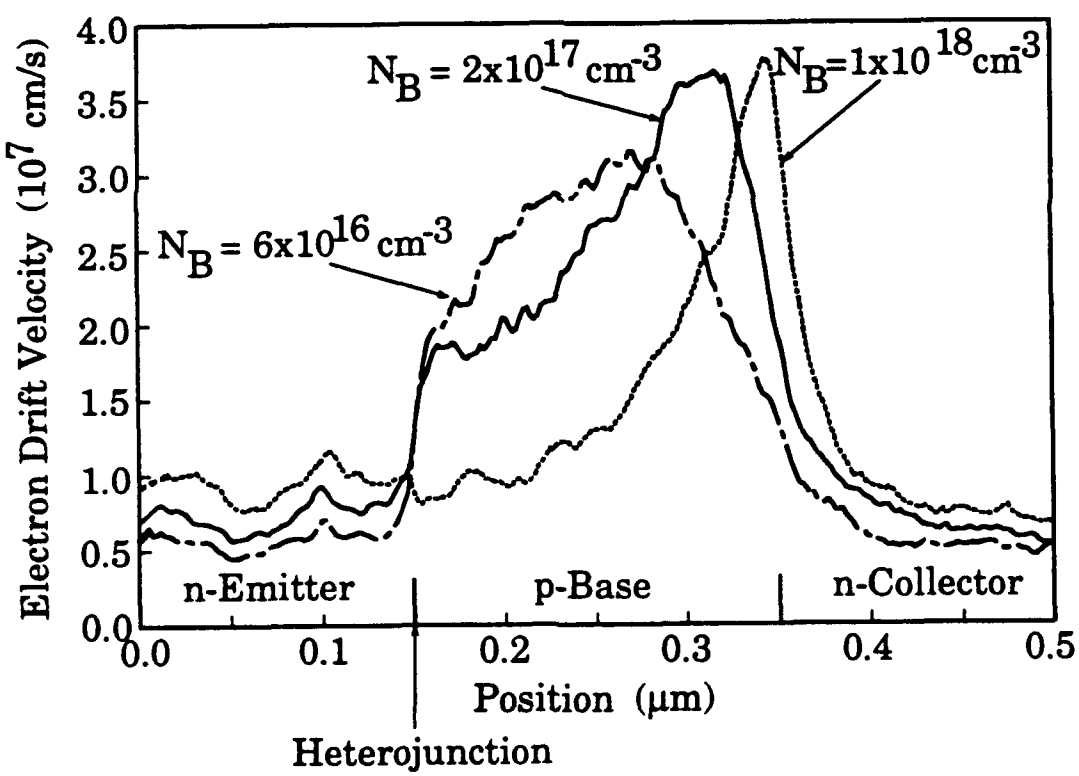

Figure 1. Simulated steady state average electron drift velocity for npn AlGaAs/GaAs +BHBT device as a function of position at 300K. Three base doping levels are given. The applied voltages as V_{CE} = +1.0V and V_{BE} = +0.1V not including the built in junction potentials.

Femtosecond Optical Interactions

Femtosecond thermalization of optically excited carriers in thin films has been explored using a self-consistent Monte Carlo technique fully modeling the interaction of conduction band electrons and light hole and heavy holes with femtosecond optical pulses. The electron and hole bands are described using a **k.p** formulation, with corrections for higher bands included through second order perturbation theory. The interaction of optical pulses with the evolving carrier distribution function is handled self-consistently through Fermi's golden rule. All important scattering mechanisms are included. Polar optic phonon scattering and carrier-carrier scattering are screened using a static screening model calculated self-consistently from the distribution function. Carrier transport along the normal to the thin film is included through a self-consistently calculated electric field.

The dependence of ultrafast carrier relaxation on each of the carrier scattering processes and on several experimental parameters has been investigated. The latter included the frequency and intensity of the excitation pulse, as well as the temporal width of the excitation and probe pulses, and the film thickness. Optical phonon scattering was found to dominate the relaxation processes, with carrier-carrier scattering of secondary importance and other scattering processes playing only a minor role. For carrier-carrier scattering this was contrary to expectations, since carrier-carrier scattering is thought to be a dominant process at the carrier densities in question. In this model carrier-carrier scattering is largely suppressed by free carrier screening due to the large carrier densities excited by the pulse.

Transmission data from pulse-probe experiments were found to depend on several experimental parameters. The energy of the exciting photons was found to be particularly important, since the simulated relaxation times significantly decrease with increasing photon energy. This is largely due to a step at the first electron-phonon threshold, and correlates closely with an increase in electron-optical phonon scattering rate at that photon energy. Conversely, simulated relaxation times were found to increase with the intensity of the excitation pulse. This is due to the suppression of both the optical phonon and carrier-carrier scattering rates resulting from increased free carrier screening and degeneracy as the carrier density increases. A complex relationship between the widths of the excitation and probe pulses and overall relaxation times was observed. Also a significant decrease in the fitted relaxation times with increasing sample thickness was found for samples with thickness equal or greater than the optical absorption length.

Due to the critical role screening plays in femtosecond experiments, it was concluded that the consequences of the approximations made in the static screening model needed to be examined in greater detail. To this end a new more accurate dynamic screening model has been developed and

implemented in our Monte Carlo code. The new model is derived from the Lindhard dielectric function and fully incorporates the energy dependence of the free carrier screening. The use of an approximate parabolic band structure and neglecting anisotropy for the bands, carrier distributions, and dielectric function are the only simplifications made. Improvements are being considered to incorporate a more accurate band structure with anisotropy into the model.

The new dynamic screening model resulted in a dramatic change in the effect of free carrier screening. Polar optical phonon scattering appears largely unscreened and carrier-carrier scattering rates are substantially enhanced. Also, several unexpected features of the highly non-equilibrium dielectric function result in a spectacular enhancement in the carrier-carrier scattering of electrons and light holes at early times. The result is a model of carrier relaxation, for which relaxation times are substantially shorter than those obtained using static screening, and where carrier-carrier scattering plays a much enhanced and perhaps dominant role.

Investigations are currently underway to determine the effects of photon energy, excitation pulse intensity and the role of each scattering mechanism using the dynamic screening model These results will then be compared to those obtained using static screening. Preliminary results for the effect of photon energy dependence indicate not only substantially reduced relaxation times for dynamic screening, but a qualitatively different relationship between photon energy and relaxation time in the two cases. This facilitates the correlation of both models with the experiment and the rejection of one model over the other. Further investigations on doped samples are being planned.

SCIENTIFIC IMPACT OF RESEARCH

Non-equilibrium carrier transport and optical interactions in high speed electronic and optoelectronic device structures are examined in this work unit using time-dependent self-consistent ensemble Monte Carlo particle simulation techniques. We have now completed the simulation software development for two-dimensional unipolar and bipolar heterojunction devices with graded structures and built-in heterojunctions. Microscopic aspects of high speed electron transport phenomena in several high speed devices have been investigated. A detailed understanding of unipolar and bipolar non-equilibrium carrier transport, including steady state and transient ballistic carrier launching, subject to self-consistent space charges has now been established. We are able , for example, to explain why fabricated devices in the past have not reached expected high cut-off frequencies and to design optimum devices (layer sequence, materials composition and geometrical dimensions) for highest frequency large signal operation. From this work it is very clear that the full exploitation of non-equilibrium carrier transport in high speed compound semiconductor devices requires microscopic insight

and optimization that can only be provided by sophisticated particle codes such as M^2EDUSA.

Free carrier screening has been shown to be a critical mechanism in developing accurate models of carrier relaxation and to this end a new dynamic carrier screening model has been developed. It much more accurately models the free carrier dielectric functions than previous static models. Static screening appears inadequate in modeling femtosecond carrier relaxation. The inclusion of dynamic screening provides a much more accurate understanding of the microscopic processes involved. Further, the increased importance of carrier-carrier scattering, when combined with dynamic screening, seems to require that the effect of carrier-carrier scattering be reassessed in other situations where highly non-equilibrium distribution functions are involved. Such conditions are found in state of the art high speed heterojunction devices.

DEGREES AWARDED

1. Steven Richard Weinzierl
   "Two-Dimensional Monte Carlo Simulations of Submicron Unipolar and Bipolar Compound Semiconductor Devices with Ballistic Injection Cathodes," pp. 1 - 243, Cornell University.
   PhD, Electrical Engineering, January 1992.
   PhD Advisor: Prof. J.P. Krusius.

REFERENCES

[1] "A proposal and numerical simulation of of n+nn+ Schottky device for ballistic and quasi-ballistic electron spectroscopy," P. Hesto, J. Pone and R. Castagne, *Applied Physics Letters*, 40, (#5), 405-406 (1984).

[2] "Planar doped barriers in GaAs by molecular beam epitaxy," R.J. Malik, T.R Aucoin, R.L. Ross, K. Board, C.E.C. Wood, and L.F. Eastman, *Electronics Letters*, 16, (#22), 836-838 (1980).

[3] "n-n semiconductor heterojunctions," W.G. Oldham and A.G. Milnes, *Solid State Electronics*, 6, 121-132 (1963).

[4] "Hot carrier transport effect in Schottky barrier diode grown by MBE," C.G. Hwang and R.W. Dutton, *IEEE Transactions on Computer Aided Design*, 7, (#5), 578-583 (1985).

[5] "Hot electron spectroscopy," J.R. Hayes, A.F.J. Levi, and W. Wiegman, *Electronics Letters*, 20, (#21), 851-852 (1984).

[6] "Direct observation of ballistic transport in GaAs," M. Heiblum, M.I. Nathan, D.C.Thomas, and C.M. Knoedler, *Physical Review Letters*, 55, (#20), 2200-2203, (1985).

[7] "High gain lateral hot electron device," A. Pavlevski, C.P. Umbach, and M. Heiblum, *Applied Physics Letters*, 55, (#15), 1421-1423 (1989).

[8] "Gallium arsenide planar doped barrier diodes and transistors grown by molecular beam epitaxy," R.J. Malik, PhD Thesis, Cornell University, Ithaca, New York, 1981.

[9] "The Effects of hot electron injection cathodes on the performance of gallium arsenide vertical field effect transistors," J.R. Wendt, PhD Thesis, Cornell University, Ithaca, New York, 1988.

[10] "Femtosecond-Pump, Continuum-Probe Nonlinear Absorption in GaAs," C. J. Stanton, D. W. Bailey, and K. Hess, *Physical Review Letters*, 65, (2), 231 (1990).

[11] "Monte Carlo simulation of electron-hole thermalization in photo-exited bulk semiconductors," R. P. Josh, R. O. Grenadine, and D. K. Ferry, *Physical Review B*, 42, (9), 5685 (1990)

[12] "Carrier-carrier scattering in GaAs: Quantitative measurements from hot (EPA) luminescence," J. A., *Physical Review B*, 40, (5), 3455 (1989).

[13] "Initial Thermalization of Photo-Excited Carriers in GaAs Studied by Femtosecond Luminescence Spectroscopy," Thomas Elsaesser, Jagdeep Shah, Lucio Rota, and Paolo Lugli, *Physical Review Letters*, 66, (13), 1757 (1991).

[14] "Full Dynamic Screening Calculation of Hot Electron Scattering Rates in Multicomponent Semiconductor Plasmas," Jeff F. Young, Norm L. Henry, and Paul J. Kelly, *Solid State Electronics*, 32, (#12), 1567 (1989).

[15] "Carrier-carrier scattering and optical dephasing in highly excited semiconductors," R. Binder, D. Scott, A. E. Paul, M. Lindberg, K. Hennebergerger, and S. W. Koch, *Physical Review B*, 45, (3), 1107 (1992).

[16] "Role of electron-electron scattering on ultrafast probe phenomena of photoexcited carriers in GaAs," M. J. Kann, A. M. Kriman, and D. K. Ferry, Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors III, Robert R. Alfano, Editor, *Proc. SPIE 1282*, 98 (1990).

ISEP PUBLICATIONS

1. "Heterojunction Vertical FET's Revisited: Potential for 225 GHz Large Current Operation," S.R. Weinzierl and J.P. Krusius, accepted for publication in *IEEE Transactions on Electron Devices*, September 1991, in press.

2. "Space Charge Effects on Ballistic Injection Across Heterojunctions," S.R. Weinzierl and J.P. Krusius, submitted for publication in *IEEE Transactions on Electron Devices*, revised manuscript submitted February 1992.

3. "Design of the Modified Planar Doped Barrier for Maximizing the Effects of Ballistic Acceleration," S.R. Weinzierl and J.P. Krusius, manuscript in progress, to be submitted for publication in April 1992.

4. "Ballistic Injection Cathodes in High Speed Three Terminal Devices: Do They Really Make a Difference," S.R. Weinzierl and J.P. Krusius, manuscript in progress, to be submitted for publication in May 1992.

5. "Simulation of Ultrafast Carrier Relaxation Processes in Pulse/Probe and Dual Pulse Correlation Probing of InGaAs Type Narrow Band Gap Semiconductors," J. E. Bair, and J. P Krusius, Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors III, Robert R. Alfano, Editor, *Proc. SPIE 1282*, 162-169 (1990).

6. "Investigation Of The Role Of Free Carrier Screening During The Relaxation Of Carriers Excited By Femtosecond Optical Pulses," J. E. Bair and J. P. Krusius, to be presented at the Ultrafast Laser Probe Phenomena in Semiconductors and Superconductors, Paper No. 1677, manuscript submitted for publication in *Proceedings of SPIE's 1992 Symposium on Compound Semiconductor Physics and Devices.*

8. "Observation of Phonon Threshold in InGaAs using Femtosecond Optical Probing," J. E. Bair, J. P. Krusius, D. Cohen, and C. R. Pollock, manuscript in progress, to be submitted for publication April 1992.

PARALLEL STRUCTURES FOR REAL-TIME ADAPTIVE SIGNAL PROCESSING

Task #5

Task Principal Investigator: **Adam W. Bojanczyk**
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OBJECTIVE

This proposal is concerned with parallel adaptive computational schemes for real-time processing of data collected from the environment which rapidly changes in time. A basic step in adaptive processing is to discard a portion of the "old" data which no longer represents the environment, add new data, and then "adapt" the current knowledge about the environment according to the change in the data. Such processing arises for example in sensor array processing. Our three major objectives are: (i) development of strategies for adding and deleting information from the covariance matrix in multi-direction beamforming (least squares), (ii) development of strategies for tracking the eigenstructure of the array data after addition and deletion of data (covariance differencing), (iii) evaluation of procedures in (i) and (ii) on emerging parallel processor architectures.

DISCUSSION OF STATE-OF-THE-ART

Least squares problems are ubiquitous in engineering, science, operations research, etc. The linear least squares problem can be posed as a problem of finding the vector x which minimizes the quadratic form $(A\mathbf{x} - \mathbf{b})^{\dagger}(A\mathbf{x} - \mathbf{b})$ where A and b are given data.

In applications various constraints are imposed on the weight vector x. Typical constraints are linear equality constraints, linear inequality constraints, or quadratic constraints.

The method of choice for solving full rank least squares equations is to proceed by a unitary transformation Q that "compresses" the data matrix A to the "information equivalent" triangular matrix U. This triangular matrix is known as a Cholesky factor of $A^T A$. The desired least squares solution is next determined by solving the corresponding triangular system of linear equations.

In recursive least squares equation the minimization problem needs to be solved repeatedly after some rows of A are removed and additional rows are added. This happens if, for example, the data to be deleted is unrepresentative of the data at large and so its effects on the weight vector (or parameter

estimate) x must be excised (robust statistics). Or perhaps the data is changing with time and old data must be deleted (adaptive beamforming) [8, 11]. The addition and the deletion are known as updating and downdating the Cholesky factor, respectively, or simply as a modification of the Cholesky factor.

The combined process of updating and downdating the Cholesky factor is called a *sliding rectangular window* process, and is one of the topics of the proposed research.

Processing of recursive least squares problems on sequential machines is now well understood. It is known that while the updating process is numerically sound, the downdating can be very sensitive to rounding errors [3]. Thus if the problem is expected to be ill-conditioned downdating requires formation of Q and downdating Q itself ([7]). This however results in quite high computational cost, and additional memory requirements for storing Q. If ill-conditioning is not expected (this can be checked concurrently with processing the data), the downdating of the Cholesky factor can be realized via so-called *Stabilized Hyperbolic Householder* scheme [5] (see also [14]) which is the least expensive (for multiple vector updating/downdating problems), in terms of number of operations and hence the preferable method for sequential rectangular sliding window process. In the case when the downdating of the covariance matrix results in the sign indefinite matrix, the recently proposed in [12] method of hyperbolic singular value decomposition can be used to deal with this sign indefiniteness.

In parallel computing the additional cost of interprocessor communication has to be taken into account in assessing the cost of executing algorithms. Most discussions surrounding multiprocessor computers for signal processing have centered on planar (triangular) arrays [4, 6, 9, 10, 16, 15]. Perhaps the sole exception has been the important contribution by Rader in [13]. Both triangular and linear arrays considered in [10] or [13] are designed to implement efficiently the exponential weighting method. The exponential weighting method is very attractive for parallel implementation as it can be realized by a single updating process. On the other hand, the sliding window process is a composite task in the sense that each recursive step involves updating and downdating of the triangular factor followed by solving the resulting triangular systems of linear equations. None of the architectures proposed in [9] or [13] can efficiently deal with the sliding window process described above. A preliminary study on the behavior of a simple variant of the sliding window process on a linear array of processors have been recently reported in [2].

In this task we will extend the problem of implementing the sliding rectangular window process investigated in [2] to other parallel architectures and more general least squares problems.

One of the tasks in sensor array processing is to compute the noise subspace of the data matrix derived from the array of sensors. In this case the data matrix can be considered as having a low (numerical) rank and then the standard recursive updating/downdating approach may lead to unsatisfactory results. One way to circumvent this problem is by computing the singular value decomposition, or recently proposed URV decomposition of A. The advantage of the URV over the SVD is that a complete decomposition can be updated at a much lower cost than the corresponding SVD decomposition. This is particularly attractive for adaptive processing and can be used in the recursive least squares problems [1, 17].

We plan to address the question under what conditions matrix updating techniques for the URV type decompositions are preferable to restarting the singular value decomposition of the matrix when implemented on parallel architectures.

PROGRESS

New task started September 30, 1991.

SCIENTIFIC IMPACT OF RESEARCH

The research in this task will aid in developing real-time sensor arrays systems. The contributions will be twofold. Firstly, new highly concurrent algorithms amenable to efficient parallel implementation will be proposed and their numerical properties will be analyzed. Secondly, a parametric model will be developed so, given the user's specified requirements, solid recommendations can be made as to the applicability of the techniques discussed in this proposal. The accuracy of the model will be thoroughly tested on existing parallel architectures. Part of the research will also address the question of fault tolerance, and multiprocessor organization for real time signal processing systems.

DEGREES AWARDED

New task.

REFERENCES

[1] C. Bischoff, G. Shroff, "On Updating Signal Subspaces," *IEEE Trans. Signal Processing*, Jan. 1992.

[2] A. W. Bojanczyk and J-Y. Choi, "Recursive LLSP on Distributed Memory Multiprocessors," Technical Report, School of Electrical Engineering, Cornell University, June 1990.

[3] A. Bojanczyk, R. Brent, P. Van Dooren, and F. De Hoog, "Downdating the Cholesky factorization," *Algorithms and Applications on Vector and Parallel Computers*, H. J. J. de Riele, Th. J. Dekker and H. A. van der Vorst, eds., Elsevier Science Publishers, 1987.

[4] A. W. Bojanczyk and F. T. Luk, "A Unified Systolic Array for Adaptive Beamforming," *J. Parallel and Distributed Computing*, vol 8, no 4, pp 388-392, April 1990.

[5] A. W. Bojanczyk and A. O. Steinhardt, "Stabilized Hyperbolic Householder Transformations," *IEEE ASSP*, vol 37, no 8, pp 1286-8, 1989.

[6] W. M. Gentleman and H. T. Kung, "Matrix Triangularization by Systolic Arrays," *SPIE Proceedings*, vol 298, pp 12-26, 1982.

[7] G. Golub and C. Van Loan, Matrix Computations, John Hopkins Press, 2nd edition, 1989.

[8] S. Haykin, Adaptive Filter Theory, Prentice-Hall, 1986.

[9] J. V. McCanny and J. G. McWhirter, "Some Systolic Array Developments in the United Kingdom," *IEEE Computer*, vol 20, pp 51-63, July 1987.

[10] J. G. McWhirter, "Algorithmic Engineering - an Emerging Discipline," *Proceedings of the SPIE*, vol 1152, pp 2-15, 1989.

[11] R. Monzingo and T. W.Miller, Introduction to Adaptive Arrays, Wiley, 1980.

[12] R. Onn, A. Steinhardt, and A. Bojanczyk, "The Hyperbolic SVD and Applications," *IEEE Trans. on Signal Processing*, to appear May, 1991.

[13] C. M. Rader, "Wafer-Scale Integration of a Large Systolic Array for Adaptive Nulling," *The Lincoln Laboratory Journal*, vol 4, no 1, pp 3-29, 1991.

[14] C. Rader and A. Steinhardt, "Hyperbolic Householder Transformations," *IEEE ASSP*, pp. 1589-1602, Dec. 1986.

[15] R. Schreiber, "Implementation of Adaptive Array Algorithms," IEEE ASSP, vol 34, no 5, October 1986.

[16] R. Schreiber and W. P. Tang, "On Systolic Arrays for Updating Cholesky Factorization,"*BIT*, vol 26, pp 451-66, 1986.

[17] G. W. Stewart, "An Updating Algorithm for Subspace Tracking," To appear in *IEEE Trans. Signal Processing*.

JSEP PUBLICATIONS

New task.

FAULT TOLERANT BEAMFORMING ALGORITHMS

Task #6

Task Principal Investigator: Franklin T. Luk
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OBJECTIVE

Multidimensional signal processing in the context of processing signals received by an array of sensors has many important applications. The type of filtering that can be conveniently applied to signals carried by propagating waves is beamforming, which seeks to isolate signal components that are propagating in a particular direction. Although computationally expensive, the beamforming procedure has been rapidly rising in popularity due to advances in both matrix algorithms and systolic arrays. Most systolic arrays will be deployed in harsh environments and thus susceptible to frequent transient errors. The principal objective of this task is to develop systolic fault tolerant beamforming techniques. Special attention will be paid to computing complex matrix decompositions, avoiding numerical overflows, differentiating between errors arising from numerical roundoff buildups and those from hardware failures, and interrupting the operation of systolic arrays for error correction.

DISCUSSION OF STATE-OF-THE-ART

The compatibility of systolic arrays and algorithms with both matrix computations and today's VLSI and wafer-scale technology guarantees their future use as key components in any signal processing system. An especially important systolic algorithm is the orthogonal triangulation algorithm (the QR decomposition) for least squares minimization, a crucial step in most adaptive antenna processing algorithms. The importance of these problems is evidenced by two major systolic array projects; one at MIT's Lincoln Laboratory [1] and the other at the United Kingdom's Royal Signals and Radar Establishment (RSRE) [2]. However, traditional fault tolerance techniques such as modular redundancy have been regarded as too costly and unwieldy to implement on these systolic arrays. In [3], a JSEP supported work, we presented a simple fault tolerance scheme for the QR decomposition and showed how it can be easily incorporated into the RSRE systolic arrays for recursive least squares minimization. Our work, scarcely one year old, has already won recognition at the RSRE as a possible fault tolerance technique for their systolic arrays [4].

Data matrices that are ill-conditioned call for a more robust and more expensive numerical technique known as the singular value decomposition (SVD). An SVD systolic array designed by us has been adopted for hardware implementation at both the RSRE [5] and Computational Engineering, Inc. [6]. The implementation of the latter will be used for real time system control; its application in the wing flutter analysis of supersonic planes has been proven in a wind tunnel test at an Air Force Laboratory in Ohio. The problem of fault tolerant computation of the singular value decomposition awaits a nice solution. Schemes were reported in [7], but they are so complicated that triple modular redundancy may well be a better choice.

Existing fault tolerance schemes have often been ignored by systolic array designers because they are too costly and unwieldy to implement. An attractive new idea came in the form of algorithm-based fault tolerance. This approach employs three steps; encode the input data, execute the algorithm on the encoded input to produce encoded output, and decode the output to detect and perhaps correct errors. Both checksum and weighted checksum encoding schemes have been developed by Abraham et al. [8, 9], who showed that a variety of matrix operations preserves the checksum property.

In [9, 10] a linear algebraic interpretation of the weighted checksum scheme was proposed. Such a model allows parallels to be drawn between algorithm-based fault tolerance and coding theory, and makes it possible to examine in detail the difficulties in choosing weight vectors such that the correction vector can be explicitly resolved. The hard problem of how to determine the exact number of errors that have occurred has been solved in [11]. For error correction, prior to [11], it was known only how to correct a weighted checksum scheme for the cases of one error [9] and two errors [10]. In [11] a theoretical framework was given which would enable one to solve the correction problem for the general case.

The weighted checksum technique has been demonstrated to be effective in multiple error detection. It has been shown that, in order to guarantee error detection, the chosen weight vectors must satisfy some very specific properties about linear independence. Previously, appropriate sets of weight vectors have been proposed which are powers of integers [9, 12]; these suffer from the fact that the weights can become very large. In [13, 14] a new scheme was presented that generates weight vectors to meet the requirements about independence and to avoid the difficulties with overflow.

PROGRESS

In [15] we introduced a new algorithm-based fault tolerance technique specifically designed for use on passive antenna arrays. This work is significant in that it is joint with an industrial researcher with access to real world data and problems.

Error correction has proved to be a much more difficult problem to solve than error detection when using weighted checksums. In [16] we provided a theoretical basis for the correction problem and showed how the correction procedure can be greatly simplified via the Lanczos recursion.

To avoid numerical overflows, in [8] and [9], two methods were proposed that use modular arithmetic to compute weighted checksums. A new scheme was derived by us in [13, 14]. A real breakthrough was achieved by us in [17] where we showed how small weights can be derived via the use of orthogonal polynomials.

SCIENTIFIC IMPACT OF RESEARCH

Our work is making a significant impact in that it is getting lots of attention so that many researchers are attempting to improve on our work. We are most proud of our result in discovering the relationship between the famous Berlekamp-Massey algorithm for decoding the Reed-Solomon code, and the well known Lanczos algorithm in numerical computing [16].

DEGREES AWARDED

None.

REFERENCES

[1] "Wafer-Scale Systolic Array for Adaptive Antenna Processing," C. M. Rader, *Proceedings IEEE ICASSP*, New York, NY, 2069-2071 (1988).

[2] "Some Systolic Array Developments in the United Kingdom," J. V. McCanny, and J. G. McWhirter, *IEEE Computer*, **20**, 51-63 (July 1987).

[3] "A Novel Fault Tolerance Technique for Recursive Least Squares Minimization," C. J. Anfinson, F. T. Luk, and E. K. Torng, *Proceedings of SPIE Vol. 975, Advanced Algorithms and Architectures for Signal Processing III*, 268-276 (1988).

[4] I. K. Proudler, Private communication at Conference on Mathematics in Signal Processing, Warwick, England, December 1988.

[5] "Simulation of Luk's SVD Array Using a Transputer," G. de Villers, Paper presented at Conference on Mathematics in Signal Processing, Warwick, England, December 1988.

[6] "A Transputer Implementation of System Identification and Control Using SVD's," W. E. Larimore, J. Galdos, D. Martin, and F. T. Luk, *Proceedings SPIE, Vol. 1069, Advanced Algorithms and Architectures for Signal Processing IV*, Paper 11 (August 1989).

[7] "Fault-Tolerant Systems for the Computation of Eigenvalues and Singular Values," C. Y. Chen and J. A. Abraham, *Proceedings SPIE, Vol. 696, Advanced Algorithms and Architectures for Signal Processing I*, 228-237 (1986).

[8] "Algorithm-Based Fault Tolerance for Matrix Operations," K. H. Huang and J. A. Abraham, *IEEE Transactions on Computers*, **C-33**, 518-528 (1984).

[9] "Fault-Tolerant Matrix Arithmetic and Signal Processing on Highly Concurrent Computing Structures," J. Y. Jou and J. A. Abraham, *Proceedings IEEE*, **74**, 732-741 (1986).

[10] "A Linear Algebraic Model of Algorithm-Based Fault Tolerance," C. J. Anfinson and F. T. Luk, *IEEE Transactions on Computers*, **C-37**, 1599-1604 (1988).

[11] "A Theoretical Foundation for Weighted Checksum Methods," C. J. Anfinson, R. P. Brent, and F. T. Luk, *Proceedings of SPIE Vol. 975, Advanced Algorithms and Architectures for Signal Processing III*, 10-18 (1988).

[12] "Algorithm-Based Fault Tolerance for Parallel Matrix Equation Solvers," F. T. Luk, *Proceedings SPIE*, **564**, Real Time Signal Processing VIII, 49-53 (1985).

[13] Choosing Small Weights for Multiple Error Detection," R. P. Brent, F. T. Luk, and C. J. Anfinson, *Proceedings of SPIE*, **1058**, High Speed Computing II, 130-136 (1989).

[14] "Checksum Schemes for Fault Tolerant Systolic Computing," R. P. Brent, F. T. Luk, and C. J. Anfinson, Paper presented at Conference on Mathematics in Signal Processing, Warwick, England (December 1988).

[15] "Algorithmic Sensor Failure Detection on Passive Antenna Arrays," J. Chun and F. T. Luk, *Proceedings of SPIE Vol. 1566, Advanced Signal Processing Algorithms, Architectures and Implementations II, SPIE - The International Society for Optical Engineering*, Bellingham, Washington, 1991, 483-492.

[16] "Algorithmic fault tolerance using the Lanczos method," D. L. Boley, R. P. Brent, G. H. Golub and F. T. Luk, *SIAM Journal on Matrix Analysis and Applications*, **13** (1992), 312-332.

[17] "A Well Conditioned Checksum Scheme for Algorithmic Fault Tolerance," D. L. Boley and F. T. Luk, *Integration, the VLSI Journal*, **12** (1991), 21-32.

JSEP PUBLICATIONS

1. "A well conditioned checksum scheme for algorithmic fault tolerance," D. L. Boley and F. T. Luk, Integration, *the VLSI Journal,* **12** (1991), 21-32.

2. "Algorithmic sensor failure detection on passive antenna arrays," J. Chun and F. T. Luk, *Proceedings of SPIE Vol. 1566, Advanced Signal Processing Algorithms, Architectures and Implementations II, SPIE - The International Society for Optical Engineering,* Bellingham, Washington, 1991, 483-492.

3. F. T. Luk, Editor, *Proceedings of SPIE Vol. 1566, Advanced Signal Processing Algorithms, Architectures and Implementations II, SPIE - The International Society for Optical Engineering,* Bellingham, Washington, 1991, 46 papers/494 pages.

INTERRUPT AND BRANCH HANDLING FOR REAL-TIME SIGNAL PROCESSING SYSTEMS

Task #7

Task Principal Investigator: H. C. Torng
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OBJECTIVE

The objective of our task is to address two important issues that confront the deployment of superscalar processors, processors with multiple functional units, which issue and execute multiple, and possibly out-of-order, instructions from an instruction stream, for real-time signal processing tasks. The two vexing issues are:

1. Interrupt handling: A critical requirement for real-time signal processing computation is that the computer system has to be able to provide *prompt* and *precise* interrupt handling capabilities. Interrupt requests have to be promptly handled because tasks that initiate these requests have to be processed as soon as possible. Responding to an interrupt request, the processor first stores its processor state; this has to be done precisely so that the interrupted process can be resumed at the point of interruption later.

The presence of multiple functional units enables the concurrent execution of multiple instructions from the same instruction stream. Since these instructions are at various stage of execution, it is a challenging task to identify and then store a precise processor state quickly.

2. Branch handling: The presence of conditional branch instructions invariably introduces disturbances into a dynamic instruction stream. On the other hand, branch instructions appear quite frequently in dynamic instruction streams. It can be safely stated that these undesirable effects are magnified in computer systems with multiple functional units.

The objective of the proposed investigation is to seek solutions to these two problems, which are important for real-time signal processing systems as well as for general applications.

In addition, we have extended our investigation into a new and exciting area: the processing of multiple instruction streams with a single superscalar processor. This means that multiple signal processing tasks can be processed efficiently and concurrently with one chip.

DISCUSSION OF STATE-OF-THE-ART

An important and indispensable feature of any processor is its ability to handle properly interrupts and exceptions, which can be classified into three types: external interrupts, exception traps, and software traps. External interrupts are generated from or by the environment -- such as the processing of a newly arrived task. Abnormalities encountered in system processing, such as division by zero, overflow, or illegal operations, generate exception traps. Software traps are instructions which initiate interrupt requests; these traps provide a means of controlling and monitoring program executions.

When an interrupt request is received, the processor must save its processor state, then load and execute an appropriate interrupt handler. Upon completion of the interrupt handling routine, the saved processor state is restored, and the interrupted process can then be restarted.

A processor state should contain enough, and preferably only enough, information so that the interrupted process can be restarted at the **precise** point where it was interrupted. To be able to resume an interrupted process, the processor state should consist of the contents of the general purpose registers, the program counter, the condition register, all index registers and the relevant portion of the main memory.

The classical approach to identifying precisely the point where a process is interrupted is to save, among other vital items, the address of a specific instruction, say instruction a, when the processor state is saved. All instructions that precede instruction a have been executed. And instruction a and those that follow it have not. Instruction a thus provides a **precise** interrupt point.

For superscalar processors, which execute instructions concurrently and possibly out-of-order, the identification of a precise interrupt point when an interrupt request is made may become very costly.

In order to evaluate interrupt handling schemes, a framework must be established. Three factors have been identified:

1) Latency:

   An interrupt handling approach must be judged by the latency between the receipt of an interrupt request and the completion of saving the processor state. Clearly, any acceptable interrupt handling scheme should yield a latency, that is appropriate for the interrupt request, which may be generated internally or externally.

2) Component Cost:

The cost of additional hardware and software incurred by the installation of an interrupt handling scheme must be considered.

3) Performance Degradation:

The presence and operation of an interrupt handling scheme may bring about performance degradation; its extent should be critically examined.

There are three sources of degradations:

i. Abort -- In response to an interrupt request, some instructions that have already been partially or even completely executed are "aborted";

ii. Execution inhibition -- the need to maintain a "consistent" processor state prevents some instructions which have been executed out-of-order from depositing their results; this in turn inhibits the execution of subsequent instructions which use these results as operands;

iii. Update -- Certain schemes, such as checkpointing, require run-time continuous updating operations, which have to be performed by the processor.

The CDC and CRAY machines [1, 2] all have multiple functional units and do allow instructions executed out-of-order. They generally allow instructions under execution to complete before the processor state is stored; a penalty in long latency is consequently exacted. In the IBM 360/91 [3], a precise interrupt is supported by allowing all issued instructions to complete their execution; this results in considerable latency. If an imprecise interrupt is generated, the processor state of the system is lost and the system cannot be restarted precisely at the interrupted point.

More recently, machines -- which allow multiple and out-of-order -- instruction issuances, executions, and completions have been proposed. The HPSm [4] implements the "High Performance Substrate" model of execution. In order to respond to interrupt requests, checkpointing has been proposed to allow precise handling [5]. In such a scheme, a minimum of two checkpoints and hence two additional processor states have to be maintained.

Clearly, the approach proposed for HPS will degrade system performance, both in processor speed, and in the time required to restore to a consistent processor state upon receiving an interrupt request. The speed of the system will be slowed down by the movement of state information as the states change, and by the additional read instruction which must precede all instructions which alter the memory. A performance penalty has to be taken

to correct the memory to a consistent state when an interrupt request is received.

Several interesting methods were presented in [6] to realize the classical precise interrupts. Again certain amount of performance degradation results.

Branching is an indispensable ingredient in any meaningful program; it however injects performance damping turbulences into the instruction stream. How to handle conditional branching efficiently remains a difficult challenge for computer architects. A clear survey of possible techniques in handling conditional branches can be found in [7]. The proposed and implemented systems discussed previously do not approach this opportunity aggressively. Pre-fetching, small and tentative, is implemented in some. Checkpointing can again be applied to allow instruction execution on an assumed path. If the assumption made is proven incorrect, a consistent processor state can be restored through the processor state corresponding to the checkpoints implemented [5]. In most cases, the supply of instructions is usually disrupted by the presence of conditional branch instructions.

Our investigation indicates that due to inter-instruction dependencies and branching turbulences, a single instruction stream may not be able to make full advantage of the execution resources of a superscalar processor. The notion that such a processor can concurrently execute several independent instruction streams is NEW and exciting.

PROGRESS

We have made considerable progress in the following three investigations:

INTERRUPT HANDLING: We have improved upon the "instruction window" approach, reported previously, to implementing efficient and prompt interrupt handling.

The factors that must be considered in evaluating the effectiveness of interrupt handling schemes have been modified to be: latency, cost, and performance degradation. We have introduced a new parameter: No Return Point (NRP), which provides machine designer with a means of achieving flexible responses to various types of interrupts and exceptions. Further, the implementation of the requisite Instruction Window (IW) has been studied in detail.

A paper presenting the results has been accepted for publication by the IEEE Trans. on Computers. And a patent application has been been pending since January 1990.

We are completing the study of a Fast Dispatch Stack (FDS) system, which will provide another approach to fast, precise interrupt handling.

BRANCH PREDICTION: The Fast Dispatch Stack (FDS) system under active investigation also will facilitate speculative execution -- Instructions preceding and following one or more predicted conditional branch instructions may issue and execute to achieve high performance. When necessary, their effects are undone in one machine cycle. In other words, a processor can execute speculatively on predicted paths to gain superior performance and the penalty for incorrect guesses is not significant.

MULTIPLE STREAM PROCESSING: We have continued our work on boosting superscalar performance: the processing of two or more independent instruction streams on a superscalar processor, creating an MIMD system. A paper has been presented at the 1991 International Conference on Parallel Processing in August, 1991.

SCIENTIFIC IMPACT OF RESEARCH

Our task has addressed several issues that computer designers will face in the next few years.

We have made considerable progress in the instruction issuing mechanism, interrupt handling, branch prediction and multi-stream processing. These features enhance significantly the performances of superscalars without raising the clock rate. And we believe that our study provides timely and much needed investigation into areas that are vital to the further development of such systems.

We have active ongoing discussions with IBM, Intel and AMD. Dr. Harry Dwyer, who has just completed his degree in August 1991, is working with IBM/Austin on their superscalar processor development.

DEGREES AWARDED

1. Harry Dwyer
   "A Multiple, Out-of-Order, Instruction Issuing System for Superscalar Processors"
   PhD, Electrical Engineering, September 1991.

REFERENCES

[1] R. M. Russell, "The CRAY-1 Computer System," *ACM Communications*, 21, 1, January 1978, pp. 63-72.

[2] J. E. Thornton, DESIGN OF A COMPUTER: The Control Data 6600, Scott Foresman, 1970.

[3] R. M. Tomasulo, "An Efficient Algorithms for Exploiting Multiple Arithmetic Units," *IBM Journal*, vol 11, January 1967, pp. 25-33. and related articles in the same issue.

[4] W. Hwu and Y. N. Patt, "HPSm, a High Performance Restricted Data Flow Architecture Having Minimal Functionality," Proceedings of the 13th International Symposium on Computer Architecture, June 1986, pp. 297-306.

[5] Hwu, Y. N. Patt, "Checkpoint Repair for High Performance Out-of-Order Execution Machines," IEEE Trans. Computer., vol C-36, no. 12, Dec. 1987, pp 1496-1514, .

[6] J. E. Smith and A. R. Pleszkun, "Implementing Precise Interrupts in Pipelined Processors," *IEEE Trans. Computer.*, vol C-37, no. 5, pp. May 1988, 562-573, .

[7] J. K. F. Lee and A. J. Smith, " Branch Prediction Strategies and Branch Target Buffer Design," *IEEE COMPUTER*, vol. 17, no. 1, January 1984, pp. 6-22, .

ISEP PUBLICATIONS

1. H. C. Torng and Martin Day, "Interrupt Handling Approach for Out-of-Order Execution Processors," accepted by *IEEE Transactions on Computers* for publication.

2. George E. Daddis Jr. and H. C. Torng, "The Concurrent Execution of Multiple Instruction Streams on Superscalar Processors," *Proceeding of the 1991 International Conference on Parallel Processing*, August 1991, pp. I-76 to I-83.