THREE YEAR FINAL REPORT

FEMTOSECOND CARRIER PROCESSES IN COMPOUND SEMICONDUCTORS AND REAL TIME SIGNAL PROCESSING

MAY 1, 1990 - APRIL 30, 1993

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This report is the final 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 tolerance architectures, and architectures with multiple functional units for signal processing are given under the second theme.
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Directors Overview

This document is the final report of the Cornell Joint Services Electronics Program for the period from May 1, 1990 to April 30, 1993. This program carried two themes: femtosecond carrier processes in compound semiconductors, and real time signal processing. Seven task investigators, Profs. R. Shealy, C. Tang, C. Pollock, P. Krusius, G. Bilardi, A. Bojanczyk, F. Luk, and H. Torng, with their graduate students have contributed to JSEP research during this period. A substitute task for G. Bilardi’s effort with Prof. Adam Bojanczyk was started in September 30, 1991. F. Luk was on a leave of absence from Cornell University during the academic year 1991/92. He resigned from Cornell during the fall of 1992 in order to take a position of the chairman of the computer science department at Rensselaer Polytechnic Institute, but continued to supervise his JSEP graduate students to the end of this program. 13 graduate students have been partially, or fully, supported by JSEP during this three year period. A total of 69 publications and 12 theses were prepared in this period and are now various stages of processing. One MS and 11 PhD degrees have been awarded to JSEP supported students during this three year period.

Femtosecond Carrier Processes in Compound Semiconductors

Two major events have dominated the activities under the compound semiconductor theme. First, the successful multi-university optoelectronics proposal submitted to DARPA under the leadership of Prof. C. Tang, one of the JSEP investigators, resulted in the establishment of the Optoelectronics Technology Center (OTC) in September 1990 with primary participant from Cornell University, University of California Santa Barbara, and University of California San Diego. The Cornell part of the OTC proposal leveraged past JSEP research. The OTC had its "kick-off" meeting in December 1990 in Santa Barbara. C. Tang served as the overall director of the OTC, while Profs. R. Shealy and H. Craighead, in addition to C. Tang, served on the executive committee. All solid state JSEP investigators, Profs. R. Shealy, C. Tang, C. Pollock, and P. Krusius, are involved in the OTC research program. This program terminates in July 1993. In the proposal, "The Optoelectronics Technology Center-Phase 2", submitted to ARPA in June 1993, the participating universities detail the continuation of this research. This time the overall principal investigator is Prof. L. Coldren from the University of California at Santa Barbara with Prof. R. Shealy serving as the co-principal investigator. Prof. C. Pollock is one of the task leaders. Second, the new off-campus organometallic vapor phase epitaxial (OMVPE) compound semiconductor materials growth facility has been completed under the leadership of R. Shealy. The facility has a total area 5,000 sq. ft, with 1,800 sq. ft of class 10,000 clean room, and houses 3 OMVPE reactors, the first of which became operational during the second year of this period. The two other reactors are being readied for operation. The facility design sets new standards
for handling highly toxic hydride source and process gases including full secondary containment. This facility is operated within the School of Electrical Engineering under a Dean's oversight committee. It serves the compound semiconductor materials growth needs for a variety of research programs including JSEP, DARPA OTC, ONR and SDIO/IST.

Using the first OMVPE reactor Prof. Shealy and his students have perfected the flow modulation epitaxial (FME) process for the synthesis of advanced III-V structures. The FME process has been optimized for GaInP and GaInAs alloys lattice matched to GaAs and InP respectively. A new selective epitaxial technology has also been developed. Selectivity is achieved via an evaporated graphite mask patterned with deep UV ablation. Prof. Tang in his research has successfully demonstrated the first broadly tunable femtosecond source. This femtosecond parametric oscillator is continuously tunable in the wavelength range from 900 nm to 4 μm. With additional intracavity doubling ultrashort pulses from the near UV to the near IR at power levels of hundreds of mW have been generated. Technology transfer from this work has lead to the first commercial broadly tunable femtosecond sources. Profs. Pollock and Krusius have explored near band gap femtosecond carrier relaxation in the InGaAs/InP system using tunable femtosecond dual pulse correlation spectroscopy and self-consistent Monte Carlo simulation respectively. Band gap renormalization and dynamic screening have been identified as the most dominant phenomena affecting the details of electron and hole relaxation under these conditions.

Real Time Signal Processing

The four investigators involved in the real time signal processing theme, Prof. G. Bilardi, F. Luk, H. Torn and later A. Bojanczyk, have performed their work in a synergistic mode. H. Torn organized three "Project 2000" meetings at Cornell, June 1990, 1991, and 1992 respectively, to discuss computer engineering advances with academic and industrial researchers. Typically about 25 industrial representatives attend this two day meeting. F. Luk organized an SPIE meeting on real time signal processing in July 1990. These JSEP faculty, together with other computer engineering and systems faculty of the School of Electrical Engineering moved into the new Engineering and Theory Center (E&TC) building with new accommodations for graduate students and faculty. F. Luk and A. Bojanczyk were awarded a Warp computer by DARPA. This GE built machine was installed at the E&TC building in September 1990.
Listing of Principal Investigators

Task #1  J.R. Shealy, Professor of Electrical Engineering
         OMVPE Growth of III-V Alloys for New High Speed Electron Devices

Task #2  C.L. Tang, Professor of Electrical Engineering
         Femtosecond Laser Studies of Ultrafast Processes in Compound Semiconductors

Task #3  C.R. Pollock, Professor of Electrical Engineering
         Ultrafast Interactions of Carriers and Phonons in Narrow Bandgap Semiconductor Structures

Task #4  J.P. Krusius, Professor of Electrical Engineering
         Femtosecond Dual Carrier Transport and Optical Interactions in Compound Semiconductor Heterostructures

Task #5  G. Bilardi, Professor of Computer Science
         Parallel Structures for Real-Time Adaptive Signal Processing

Task #6  F. Luk, Professor of Electrical Engineering
         Fault Tolerant Beamforming Algorithms

Task #7  H.C. Torng, Professor of Electrical Engineering
         Interrupt and Branch Handling for Real-Time Signal Processing Systems

Task #5' A. Bojanczyk, Professor of Electrical Engineering
        Parallel Structures for Real-Time Adaptive Signal Processing
        (Substituted for task #5)
OMVPE GROWTH OF III-V ALLOYS FOR NEW HIGH SPEED ELECTRON DEVICES

Task #1

Task Principal Investigator: James R. Shealy
(607) 255-4657

DEGREES AWARDED

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

2. James Singletery
"Promising Solutions to Indium Phosphides Low Schottky Barrier"
Ph.D., 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"
Ph.D., Applied Physics, August 1991

4. Bobby Pitts
"Flow Modulation Epitaxy Using a Multichamber Organometallic Vapor Phase Epitaxy System"
Ph.D., Electrical Engineering, May 1993

ISEP PUBLICATIONS


3. S. O'Brien, J. R. Shealy, and G. W. Wicks, "Monolithic Integration of an (Al)GaAs Laser and an Intracavity Electroabsorption Modulator Using


13. B.L. Pitts, D.T. Emerson, M.J. Matragrano, and J.R. Shealy, "The influence of the Al-precursors, Trimethylamine Alane and Trimethylaluminum,


**REPORTABLE INVENTION(S)**

None.
FEMTOSECOND LASER STUDIES OF ULTRAFAST PROCESSES
IN COMPOUND SEMICONDUCTORS

Task #2

Task Principal Investigator: C. L. Tang
(607)255-5120

DEGREES AWARDED

1. E. S. Wachman
"Ultrafast Spectroscopy with a Novel Broadly Tunable cw Femtosecond Source"
Ph.D., Applied Physics, 1991

2. W. H. Loh
"Polarization Self-Modulation in Semiconductor Lasers"
Ph.D., Electrical Engineering, August, 1991

3. Y. Ozek:
"Study of Two-mode Optical Bistable Semiconductor Laser Diodes with Intra-cavity Saturable Absorbers"
Ph.D., Electrical Engineering, August, 1991

4. Wayne Pelouch
"Multi-wavelength Ultrafast Source Development and Spectroscopy"
Ph.D., Applied Physics, January, 1993

ISEP PUBLICATIONS


**REPORTABLE INVENTION(S)**


ULTRAFAST INTERACTION OF CARRIERS AND PHONONS IN NARROW BANDGAP SEMICONDUCTOR STRUCTURES

Task #3

Task Principal Investigator: C. R. Pollock
(607) 255-5032

DEGREES AWARDED

1. Timothy Carrig
"Characterization of New Color Center and Transition Metal Ion Lasers"
Ph.D., Applied and Engineering Physics, August 1992

ISEP PUBLICATIONS


7. A. Sennaroglu, C. R. Pollock, and H. Nathel, "Generation of Tunable Femtosecond Pulses in the 1.21-1.27 μm and 605-635 nm Wavelength..."


**REPORTABLE INVENTION(S)**

None.
FEMTOSECOND DUAL CARRIER TRANSPORT AND OPTICAL INTERACTIONS IN COMPOUND SEMICONDUCTOR HETEROSTRUCTURES

Task #4

Task Principal Investigator:  J. P. Krusius
(607) 255-3401

DEGREES AWARDED

1. Steven Richard Weinzierl
   "Two-Dimensional Monte Carlo Simulations of Submicron Unipolar and Bipolar Compound Semiconductor Devices with Ballistic Injection Cathodes"
   Ph.D., Electrical Engineering, January 1992

ISEP PUBLICATIONS


REPORTABLE INVENTION(S)

None.
NOVEL VLSI ALGORITHMS AND ARCHITECTURES
FOR HIGH DATA RATE DIGITAL FILTERING

Task #5 (Terminated 1991)

Task Principal Investigator: Gianfranco Bilardi

DEGREES AWARDED

None.

ISEP PUBLICATIONS


REPORTABLE INVENTION(S)

None.
PARALLEL STRUCTURES FOR REAL-TIME ADAPTIVE SIGNAL PROCESSING

Substitute Task #5

Task Principal Investigator: Adam W. Bojanczyk
(607) 255-4296

DEGREES AWARDED

None.

ISEP PUBLICATIONS


REPORTABLE INVENTION(S)

None.
FAULT TOLERANT BEAMFORMING ALGORITHMS

Task #6

Task Principal Investigator: F. T. Luk
(607) 255-5075

DEGREES AWARDED

None.

ISEP PUBLICATIONS


REPORTABLE INVENTION(S)

None.
INTERRUPT AND BRANCH HANDLING FOR REAL-TIME SIGNAL PROCESSING SYSTEMS

Task #7

Task Principal Investigator: H. C. Torng
(607) 255-5191

DEGREES AWARDED

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

2. Deborah T. Marr
   "A Block-Based Dispatch Window for Multiple Out-of-Order Instruction Issue"
   M.S., Electrical Engineering, June 1992

ISEP PUBLICATIONS


REPORTABLE INVENTION(S)

None.
JSEP
HIGHLIGHT TRANSPARENCIES
FOR THE FOLLOWING TASKS:

J. R. Shealy - Task 1
C. L. Tang - Task 2
C. R. Pollock - Task 3
J. P. Krusius - Task 4
Coherency Range of GaInP/GaInAsP on GaAs and GaInAs on InP

- Coherency range of GaInP over 10% In composition.
- Defect free surfaces observed with proper treatment of the reaction chamber.
- Cathodoluminescence reveals low dark line density over the entire coherency range.
- Tetragonal distortion range of GaInAsP is similar to GaInP.
Cornell JSEP (F49620-90-C0039) Task: C. L. Tang
Femtosecond Laser Studies of Ultrafast Processes in Compound Semiconductors

Objective: Development and applications of new broadly tunable femtosecond optical sources and techniques for studying ultrafast processes in semiconductors and quantum well structures.

Results: - Developed the first broadly tunable high repetition rate femtosecond optical source: the femtosecond optical parametric oscillator.
- Demonstrated the first intracavity doubling of the femtosecond optical parametric oscillator to cover the visible to near IR spectral range [see Fig. 1].
- Demonstrated the first femtosecond optical parametric oscillator using the new nonlinear optical crystal KTiOAsO₄ which can operate in the important 3 to 5 μm spectral range.
- Application of tunable femtosecond sources to study the relaxation dynamics of nonequilibrium carriers in GaAs and InGaAs [see Fig. 2].

Spectra of Intracavity-doubled OPO

(a) [Graph showing multiple peaks]
(b) [Graph showing a single peak]

Fig. 1
- Demonstrated tuning range of the intracavity frequency-doubled OPO from 580 to 657 nm.
- Tuning is accomplished by rotating phase-matching angle of KTP, and optimizing output coupler and cavity length.
- Total power generated in second harmonic varies between ~80 and 240 mW over range shown.

Fig. 2. Representative time-resolved luminescence spectra for the 4000-Å bulk GaAs sample at room temperature at each excitation power (squares, 1x10¹⁹ cm⁻³; circles, 5x10¹⁸ cm⁻³; triangles, 2x10¹⁸ cm⁻³). The carrier temperature fits (straight lines) and values are shown for each carrier density at delay times of (a) 100 fs, (b) 1 ps, (c) 20 ps, and (d) 100 ps.
Objective: Testing of the Monte Carlo modeling of Prof. Krusius (Task #4).

Results: Using pump-probe measurements of doped and undoped samples of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, we have confirmed the predicted effects of excess carrier concentration on the carrier relaxation time. The presence of excess carriers dramatically slows down the energy relaxation process.

Fig. 1. Carrier relaxation in a sample with $8.75 \times 10^{17} \text{ cm}^{-3}$ n-type dopant. The photon energy is 51 meV greater than the bandgap. The autocorrelation trace is of the probe without a semiconductor sample.

Fig. 2. Carrier relaxation in a sample with $8.75 \times 10^{17} \text{ cm}^{-3}$ n-type dopant. The photon energy is 17 meV greater than the bandgap.

Fig. 3. Carrier relaxation in an undoped sample. The photon energy is 16 meV greater than the bandgap.
Objective: Monte Carlo Modeling of Femtosecond Optical Probing

Results: Reproduced experimental data for a wide range of near band gap photon energies for InGaAs/InP

Provides foundation for quantitative understanding of carrier scattering and many body effects in compound semiconductors

Fig(s): Simulated pulse-probe vs. experimental dual-pulse correlation
Band Gap: 0.750 eV for InGaAs