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All modern high speed devices deal with small structures (nanometers) and high-fields (several hundred kilovolt/cm). The relevant time constants involved in the carrier transport are typically in the subpicosecond domain. Under the URI contract, with techniques based on ultrashort laser pulses, we have studied the dynamics of carriers in the 100-1000 GHz regime in bulk, low-temperature grown, and quantum-size semiconductors. In addition, because of the relevance of high-speed electronics, we have studied the carrier dynamics in high T_c superconductors in the same frequency regime. During the course of the URI a number of technological innovations have been demonstrated and have found their way to the commercial world. The URI is at the origin of two spin-off companies, Medox Research and Picotronix, now selling products first demonstrated in our laboratories. Also a license is being granted to a laser company to develop a laser amplifier product demonstrated during the course of the URI last year. It is important to note that the URI has helped to orginate a large grant from NSF that was awarded to our group to pursue and expand our activity in the ultrafast science and technology domain.

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TRANSPORT IN MICROSTRUCTURES IN THE MICROWAVE AND MILLIMETER-WAVE REGIME

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URI Highlights 1991-92

Motivations and Objectives

All modern high speed devices deal with small structures (nanometers) and high-fields (several hundred kilovolt/cm). The relevant time constants involved in the carrier transport are typically in the subpicosecond domain.

Under the URI contract, with techniques based on ultrashort laser pulses, we have studied the dynamics of carriers in the 100-1000 GHz regime in bulk, low-temperature grown, and quantum-sized semiconductors. In addition, because of the relevance to high-speed electronics, we have studied the carrier dynamics in high-T_c superconductors in the same frequency regime.

During the course of the URI a number of technological innovations have been demonstrated and have found their way to the commercial world. The URI is at the origin of two spin-off companies, Medox Research and Picotronix, now selling products first demonstrated in our laboratories. Also, a license is being granted to a laser company to develop a laser amplifier product demonstrated during the course of the URI last year. It is important to note that the URI has helped to originate a large grant from NSF that was awarded to our group to pursue and expand our activity in the ultrafast science and technology domain.

The URI last year has helped to support 12 graduate students. We will describe now some of the achievements of the URI-supported personnel.

Science

The following projects were carried out in the past year in the area of fundamental studies of the physics of high-field transport.

1) Femtosecond optical spectroscopic techniques were used for the first time to probe directly the nonequilibrium distribution functions of electrons under conditions of high-field transient transport. This culminated in the first time-resolved observation of ballistic acceleration of electrons in a semiconductor in an external electric field. Spectroscopic techniques were also used to probe the resulting electric field dynamics, and it was found that the field and carrier dynamics were closely coupled, with both radiation and space charge contributing to the field dynamics.

2) Femtosecond optical techniques were used to observe the THz radiation emitted by carriers undergoing high-field transport in several semiconductor structures. By coupling this work with that described in (1), we have made the first unambiguous experimental correlation of terahertz radiated waveforms with electron transport dynamics.

3) We have performed a comprehensive study of ultrafast optical response of low-temperature MBE-grown semiconductors, including:

- transient photoconductivity and reflectivity of LT-GaAs, InGaAs, and AlInAs. Picosecond response of LT-InGaAs was observed for the first time.
- femtosecond optical absorption characterization of LT-GaAs.
- characterization of response of all materials over a range of growth conditions.

We have also undertaken the investigation of semiconductors doped with rare earths other than chromium, observing photoconductive-switch responses of ~ 10 ps in erbium doped GaAs.

4) We have performed a nonlinear optical study of exciton transport in quantum wells, and observed of the role of disorder.

5) We have continued an investigation of the dynamics of the formation of high-field domains in superlattices. In the course of performing photoluminescence experiments on the superlattices, we have observed for the first time a giant electro-pleochroism in a semiconductor heterostructure, which we term the quantum-confined Pockels effect.

6) We began a theoretical investigation of high-field transport to complement the experimental work. The focus has been the development of a Monte-Carlo code to calculate carrier dynamics under very high electric fields (up to 300 kilovolt/cm), including impact ionization effects.

7) We were the first to measure the temperature-dependence of the relaxation time of the non-equilibrium electron distribution in an *n*-doped high-critical-temperature superconductor, NdCeCuO. The occurrence of a peak in the relaxation time near the critical temperature, also observed in several p-doped high-Tc materials ($YBa_2Cu_3O_7$ and $Bi_2Sr_2Ca_2Cu_3O_{10}$), will hopefully enhance the understanding of carrier scattering and the condensation of quasi-particles into Cooper pairs for all these materials. It is already significant that the n- and p-doped superconductors behave in a very similar fashion.

8) At Cornell, MBE growth and processing of multiple-quantum-well structures and low-temperature materials (LT-GaAs, InGaAs, and InAlAs) was carried out for high-speed optical measurements. Also, the first DLTS measurements on the LT material, relating deep centers, recombination times, and growth conditions, were performed.

Technology

1) A 100-GHz network analyzer based on the electro-optic sampling technique was demonstrated. It has been used to determine all four *S*-parameters and the maximum unilateral gain (f_{max}) for a 0.15-μm-gate-length pseudomorphic HFET supplied by the Electronics Laboratory at General Electric. The 40-GHz measurement bandwidth of the conventional frequency-domain network analyzer was extended to 100 GHz in this optically-based system.

2) We have begun work on a program to refine a technique for the epitaxial liftoff and subsequent Van der Waals bonding of MBE-grown semiconductor films on arbitrary substrates. This technique, originally demonstrated at Bellcore, has been applied using low-temperature-grown GaAs lifted off from a layer of AlGaAs grown at MIT Lincoln Lab. The GaAs was removed, bonded to a quartz substrate, and covered with patterned coplanar transmission lines in order to produce a photoconductive element on a substrate with much lower permittivity, and thus much lower dispersion and radiation, than GaAs.

3) Picosecond large-signal transient measurements were made on an AlGaAs/InGaAs HEMT device so that the device switching from cut-off to saturation and saturation to cut-off could be directly observed. Rise times as fast as 6.2 ps and the delay times associated with capacitive feedthrough were also obtained.

4) The fastest high-sensitivity photodetectors produced to date have been fabricated using low-temperature-grown GaAs and a pattern having 200-nm interdigitated finger spacings and finger widths. These detectors were demonstrated to have a 375-GHz bandwidth and a responsivity of 0.1 A/W. While the latter property compares favorably with MSM photodiodes, the bandwidth represents a 50-100% improvement over even the fastest MSM technology reported.

5) High-speed photoconductive switches, fabricated on low-temperature-MBE InGaAs-grown at General Electric, were tested using the electro-optic sampling technique. Response times as short as 2 ps were found for detectors having both 25% and 35% In compositions, although these times increased with higher growth temperatures, and efficiencies varied with growth temperature and annealing conditions. While more study is needed, we believe that demonstrations of ultrafast, highly sensitive InGaAs detectors for the communications wavelengths of 1.3 and 1.5 μm will be made soon.

6) We have generated, for the first time, kilovolt electrical pulses with picosecond durations. We have also demonstrated a concept for generating >100 kV/cm picosecond electrical transients on transmission lines. These pulses will be extremely important in the study of the dynamics of electrons in semiconductors in the high-field, high-frequency regime.

7) We have developed a completely novel detector for coherent detection of THz pulses. Previous detectors have until now been based on photoconductive sampling, and have therefore been limited by the carrier lifetime (about 0.4 ps at best). Our new detector is based instead on the excitonic electro-absorption effect in quantum wells, and therefore should be capable of 10-THz bandwidth. This detector is the fastest THz detector yet demonstrated, but has not achieved its full potential bandwidth.

8) Two novel short-pulse amplification techniques were demonstrated allowing the generation of femtosecond pulses with average power a hundred times what was previously available. The first one produces femtosecond pulses at the millijoule energy level and kilohertz repetition rate. The second one is producing femtosecond pulses at microjoule energy level but at a much higher repetition rate, 0.5 MHz. Both systems will be extremely important in the study of the semiconductor transport in the high-field/high-frequency regime. (See photograph showing the generations of white-light continuum with this laser system which was used for the front cover of *Laser Focus*. Both laser systems are now commercially available). They are sold by two laser companies and will be the workhorse of many laboratories working in the ultrafast domain.

9) At Cornell, investigation of growth of strained InGaAs/GaAs structures for application to high speed laser modulation was carried out.

10) Also at Cornell, strained-layer quantum well laser growth, fabrication, packaging, characterization, and theoretical analysis were carried out. The highest 3-dB modulation bandwidth lasers fabricated to date were made.

1992-93 Research Plan

Science

1) The time-resolved optical techniques demonstrated last year as probes of high-field transport dynamics in quantum wells will be extended to the study of other structures of importance to semiconductor devices, namely real-space transfer structures, LT-GaAs material, as well as bulk GaAs. The development of the new Ti:sapphire laser systems will

allow us to probe the carrier dynamics at much lower carrier densities than before, thereby enabling us to elucidate the role of carrier-carrier scattering on ballistic carrier dynamics.

2) The waveforms of the coherent THz radiation emitted by carriers undergoing high-field transport will be investigated as a probe of the carrier acceleration. Velocity overshoot dynamics will be studied for the first time at fields up to 200 kV/cm.

3) We will investigate several ways (including optical probes and THz radiation) of studying for the first time the *dynamics* of impact ionization.

4) We will continue to develop techniques for probing carrier dynamics under transient (subpicosecond) high electric fields, including the coherent time-domain mobility technique, and optical probes of the distribution functions.

5) We will continue the relaxation-time studies of the n- and p-doped high-critical-temperature superconductors, expanding the samples to be tested to include YBCO films fabricated using a variety of techniques on a variety of substrates, as well as single crystals of the 'second-generation' high-T_c superconductors, such as BaSrCaCuO and TlBaCaCuO. We also plan to establish a link between the all-optical carrier-relaxation-time measurements and terahertz-beam measurements which allow observation of the peaks in the real part of the conductivity of superconducting materials versus temperature below T_c. It is hoped that speculation regarding an enhanced quasi-particle relaxation time for the superconducting high-T_c cuprate materials can be verified.

6) The investigation of the response of low-temperature-grown GaAs and InGaAs to short optical pulses will continue. Materials fabricated under a wide variety of growth parameters will be tested to gain a greater understanding into the high-speed response of the materials. Examples of LT-materials to be studied include GaAs of varying thicknesses, GaAs epi-liftoff layers bonded to various substrates, and InGaAs both lattice-matched and mismatched.

7) We will continue to investigate the dynamics of high-field domain formation in superlattices.

8) Development of growth and fabrication of quantum-well and LT-semiconductor material will be carried out at Cornell in support of the tasks described above.

Technology

1) We will continue our investigation of low-temperature-grown semiconductors applied as high-sensitivity, high-speed photodetectors. This work will focus primarily on the use of lattice-matched and mismatched InGaAs with interdigitated detector patterns for detection of 1.3 and 1.55-mm wavelengths.

2) Erbium-(or other rare-earth-)doped InGaAs will also be explored as an alternate material for high-speed detection of long wavelengths.

3) A cryogenic electro-optic sampling capability will be developed for the investigation of the behavior of LT-GaAs and InGaAs at low temperatures. This work will be expanded to include the study of the step-response and/or the *S*-parameters of semiconductor and superconductor devices across a wide range of temperature.

4) The bandwidth of the electro-optic network analyzer will be extended to a frequency between 200-250 GHz. This objective will be pursued in two independent ways.

a) The first will be to develop a new test fixture based on the Van der Waals bonding of LT-GaAs onto a quartz substrate. The low permittivity of the quartz test fixture compared to the old GaAs-substrate test fixture diminishes the effects of dispersion and radiation and will allow higher frequencies to travel from the pulse generator to the device under test. Improved propagation characteristics will first be demonstrated, followed by device measurements.

b) The second technique will involve the integration of a high-speed HEMT with the required test fixture for electro-optic measurements. This structure will eliminate the inductive wire-bonds otherwise needed to connect the device under test to the transmission lines of the fixture, while providing the short-pulse source from an LT-GaAs epilayer on the GaAs device substrate. The fixture will be designed to allow either Cascade-probe connection to an HP8510 or electro-optic network analysis.

5) A new external photoconductive-sampling probe will be developed and applied to measurements of high-speed electronic devices and circuits. This high-impedance contacting probe will have picosecond temporal resolution, microvolt sensitivity, and few-micron spatial resolution.

6) The THz spectroscopy system will continue to be used for measurements of the millimeter- and submillimeter-wave complex conductivity of high-T_c superconductors. This non-contact technique will be used for the determination of the high-frequency surface impedance of superconducting thin films.

7) The excitonic electro-absorption THz detector will be refined, with the goal of demonstrating its anticipated bandwidth of 10 THz.

8) Dynamics of carriers in high-speed quantum-well lasers will be studied.

9) An LT-GaAs switch will be integrated under MODFET structures for s-parameter measurements. Material growth and integrated device design and fabrication are taking place at Cornell.

Technology Transfer

Two companies spun off from our laboratory during the course of the URI program are offering products based on research supported by the URI.

1) Medox Research: This company is successfully selling the laser system (femtosecond, millijoule, kilohertz) mentioned in paragraph four of *Technology.*

2) Picotronix: This company is offering a product based on low-temperature-grown GaAs for ultrafast light detection as well as ultrafast electrical gating.

3) Coherent Laser: This company has negotiated an agreement with the University to sell the microjoule, megahertz laser system mentioned in item 6 of the Technology section.

4) General Electric: New detectors based on InGaAs and AlInAs are jointly developed with this company.

Awards

It is because of the URI program that we were able to obtain a very large and prestigious grant from NSF to establish a Center for Science and Technology in the ultrafast domain. The grant is from 5 to 11 years, the amount is 1-to-1.7 million/year from NSF, and over 750 thousand/year from the University, the State of Michigan and private sponsors.

Scientists & Faculty

Faculty (teaching): Gerard Mourou, Theodore Norris, Roberto Merlin Duncan Steel, Jasprit Singh, Lester F. Eastman (Cornell).
Faculty (research): John F. Whitaker, Steven L. Williamson, William J. Schaff (Cornell).

Interactions with Air Force Laboratories

1) MIT-Lincoln Laboratories: This interaction involves the characterization of devices and materials, especially those using low-temperature MBE processing. (R. Calawa and F. Smith)

2) Rome-Air Force Development Laboratories: This interaction covers the characterization of ultrafast electrical probe detectors and modulators. (B. Hendrickson)

3) Hanscom: This interaction involves the applications and characterization of photoconductive switches. (R. Payne, B. Thaxter)

Education

Last year four students sponsored by URI have received Ph.D. degrees.

December 1991, Yi Chen, Ph.D., Development of Detectors and Modulators for Multi-Hundred Gigahertz Operation
July 1992, Michael Y. Frankel , Ph.D, Ultrafast Device Characterization
August 1992 James Chwalek, Ph.D., Subpicosecond Time-Resolved Spectroscopy of High Transition-Temperature Superconductors
December 1991, Shantanu Gupta, Ph.D., Carrier Dynamics in III-V Materials and Heterostructures Studied by Ultrafast Laser Techniques

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M.Y. Frankel, J.F. Whitaker, G.A. Mourou, and J.A. Valdmanis, "Ultrahigh-bandwidth vector network analyzer based on external electro-optic sampling," *Solid-State Electronics*, 35, 325-332 (Mar. 1992).

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S. H. Kwok, E. Liarokapis, R. Merlin, H. T. Grahn, H. Schneider, and K. Ploog, "Raman Scattering Studies of Resonant Tunneling Domains in Quantum Well Structures," to be published in *Proceedings of the 20th International Conference on the Physics of Semiconductors*, ed. J. Joannopoulos (World Scientific, Singapore).

Y. Chen, S. L. Williamson, T. Brock, and F. W. Smith, "1.9 Picosecond Optical Temporal Analyzer Using 1.2 Picosecond Photodetector and Gate," submitted to International Electron Device Meeting (meeting in Boston, 12/91).

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W. Sha, T.B. Norris, J W. Burm, D. Woodard, and W.J. Schaff, "A New Coherent Detector for Terahertz Radiation Based on Excitonic Electroabsorption," to be published in Appl. Phys. Lett.

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J.M. Chwalek, J.F. Whitaker, and G.A. Mourou, "Submillimeter-Wave Properties of High-Temperature Superconductors and Dielectrics Using Coherent Time-Domain Spectroscopy," presented at the IEEE Lasers and Electro-Optics Society 1991 Summer Topical Meeting on Optical Millimeter-Wave Interactions, Newport Beach, CA (July 1991).

J.F. Whitaker, "Ultrafast Optics for High-Speed Electronics Measurements," lecture at the Ontario Laser and Lightwave Research Center Summer School, Toronto, Ontario, Canada (May 1991).

G. Mourou, "LT GaAs: Characterization and Applications," at the Low Temperature Grown GaAs Symposium (Boston), Dec. 5, 1991

S. H. Kwok, H. T. Grahn, K. Ploog, and R. Merlin, "Giant In-Plane Optical Anisotropy in Biased GaAs-AlAs Structures: the Quantum-Well Pockels Effect," presented at the 21st International Conference on the Physics of Semiconductors, Beijing, China.

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T.B. Norris, W. Sha, and J. Rhee, "Time-Resolved Observation of Ballistic Electrons in a Quantum Well," invited paper QWB1 at the Quantum Electronics and Laser Science Conference, Anaheim, CA, 1992.

W. Sha, J. Rhee, and T.B. Norris, "Transient Electron Transport in GaAs Quantum Wells: from the Ballistic to the Quasi-equilibrium Regime," presented at the Eighth International Conference on Ultrafast Phenomena, Antibes, 1992.

W. Sha, J. Rhee, T.B. Norris, and W.J. Schaff, "Photoconductive Switching: Field and Carrier Dynamics," presented at the XVIII International Quantum Electronics Conference, Vienna, 1992.

T.B. Norris, W. Sha, and W.J. Schaff, "Time-Resolved Optical Studies of High-Field Electron Transport in GaAs Semiconductor Structures," presented at the SPIE Symposium on Compound Semiconductor Physics and Devices, Somerset, NJ, 1992.

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