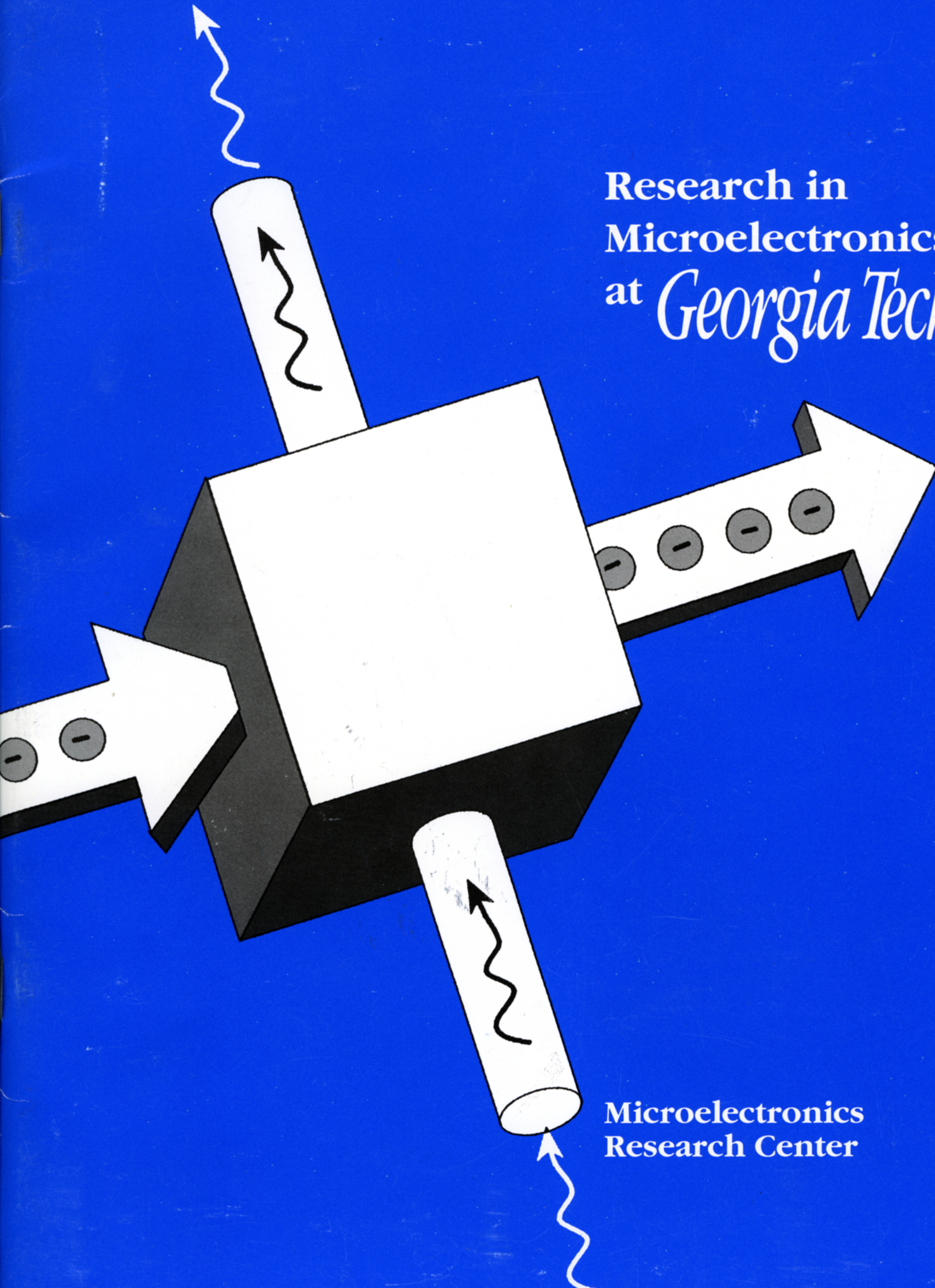
Research in Microelectronics at *Georgia Tech*



Microelectronics Research Center

Research in Microelectronics at Georgia Tech

Atlanta is scheduled to host the 1996 Summer Olympic Games. Georgia Tech researchers are currently involved in computer and communications advanced multi-media demonstration projects for this event.

The cover depicts a 3-dimensional optoelectronic integrated circuit that incorporates both electronic and photonic (optical) pathways for communication and information processing.

The Pettit Building

CONTENTS

Microelectronics Challenges:

- **Merging Computers and Communications**
- **Merging Electronics with Photonics**

Computing and communications technology are merging through the development of information "superhighways" on which voice, video, text, and data travel. As the demand increases for graphical information at higher definition and at video framerates, gigabit/ second networking has become a national expectation. One vision for the future workplace involves a distributed network of "superworkstations" which can support not only text and data exchange but also simultaneous voice and video dialogue. The audio information will pass at the bandwidth of compact disk recording. The video will have high-definition resolution while supporting dial-up access to people and library resources.

Optical pathways for information, already pervasive in long-distance communications, are being brought closer to the consumer. For example, optical fibers can support the gigabit/ second bandwidth requirements of high-speed computer networking and networked high-definition graphics. Photonics and integrated optics are going inside computer, communications, and consumer products through optical backplanes and interconnects in computers, and optical switching in telecommunications to support this requirement. The most common solid-state photonic consumer product is rarely seen but often "heard"—the semiconductor laser in the compact disk (CD) player. The next wave in microelectronics will replace such discrete optical devices with optics integrated with microelectronics.

Achieving this vision requires the development of enabling technologies to support:

- Electron-photon interconversion at multigigabit rates
- Light controlling light at bit rates above electronic limits
- Higher speed electronics to interface with photonics and to provide electronic pathways to VLSI chips
- Computer and communication system development to incorporate the new electronic and photonic devices;

The Georgia Tech Microelectronics Research Center (MiRC) is positioned to make pivotal contributions to these enabling technologies.

Center Objectives and Scope

Missions of the Georgia Tech Microelectronics Research Center

The purpose of the Georgia Tech Microelectronics Research Center is to

- provide major facilities for research in microelectronics and integrated optics that would otherwise be too expensive for individual faculty and student use;
- provide an interdisciplinary environment that will stimulate wide and successful collaboration of faculty and students from many disciplines;
- promote economic development in microelectronics associated industry in the region and contribute to national competitiveness in microelectronics, and
- educate students who will implement next generation microelectronics and integrated optics strategies.

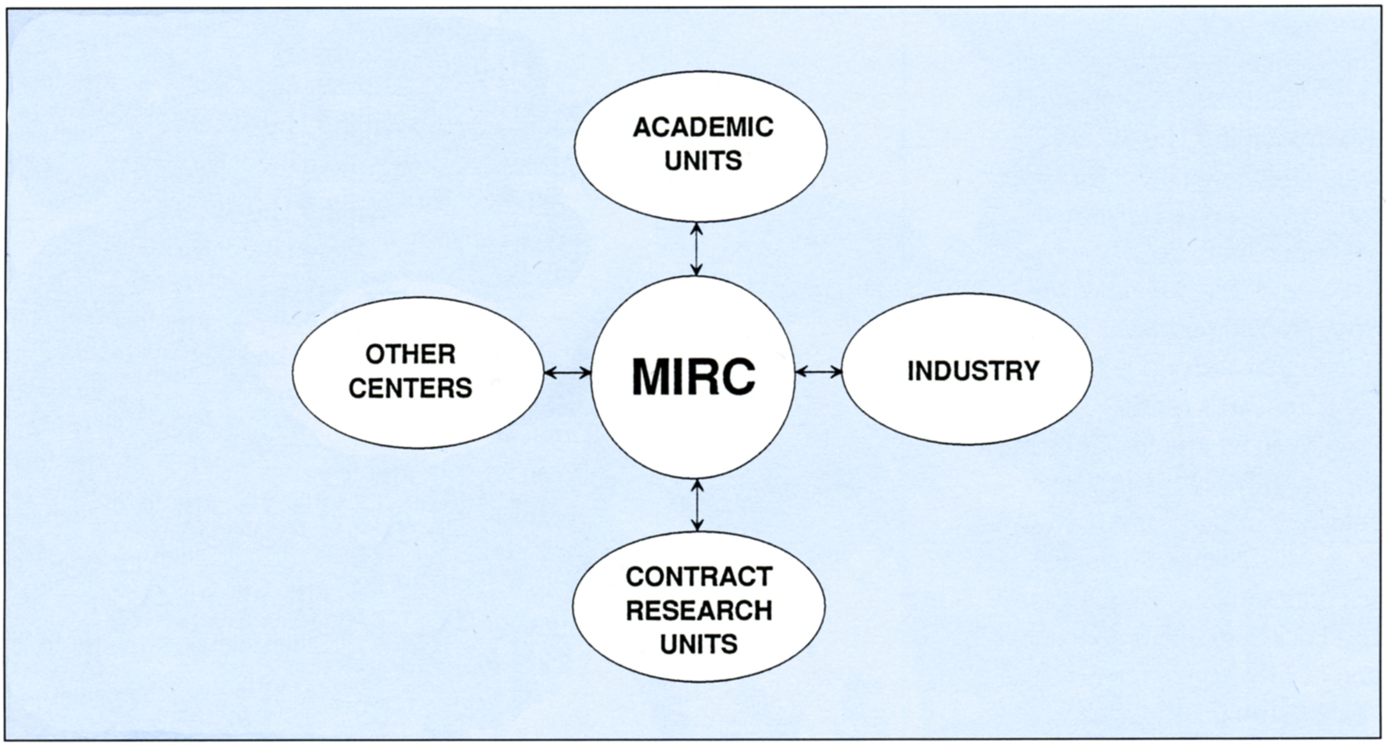
Initiated in the early 1980s and stimulated by a $15 million award from the state of Georgia in 1984, the Center's programs now are located predominately in the 100,000 square-foot Joseph Pettit Building, dedicated in January 1990. The Pettit Building includes the following:

- A 7,000 square-foot clean room chip-fabrication lab. Half is class 100, half class 10, and other clean rooms bring the total to 10,000 square feet.
- 18 general purpose laboratories. Half of the labs emphasize electronics, and half emphasize photonics. There is office space for 40 faculty researchers plus 80 student researchers and industrial visitors.

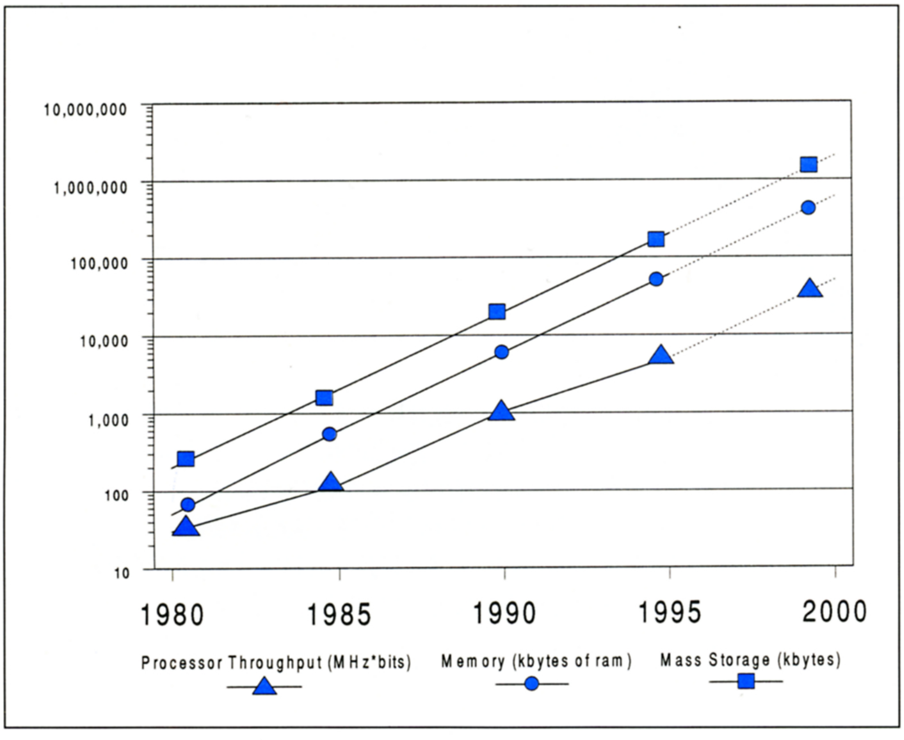
The Center maintains a small staff for its administration and technical operation. Center research participants come from the academic departments and from the Georgia Tech Research Institute, an on-campus contract research organization. Participating academic Schools include Electrical Engineering, Chemical Engineering, Mechanical Engineering, Computer Science, Physics, Chemistry, and Materials Engineering. The Pettit Building is a key element of Georgia Tech's vital academic and research environment. The participating departments and research organizations are within easy walking distance. Technology transfer is facilitated by close links to the Manufacturing Research Center, which emphasizes electronic manufacturing, and to the new Georgia Center for Telecommunications.

CAPITAL INVESTMENTS

Electronic Materials	Building	$	01.0 M
	Equipment	$	05.0 M
Microfabrication and Testing	Building	$	11.5 M
	Clean room	$	04.5 M
	Test labs	$	04.0 M
	TOTAL	$	26.0 M



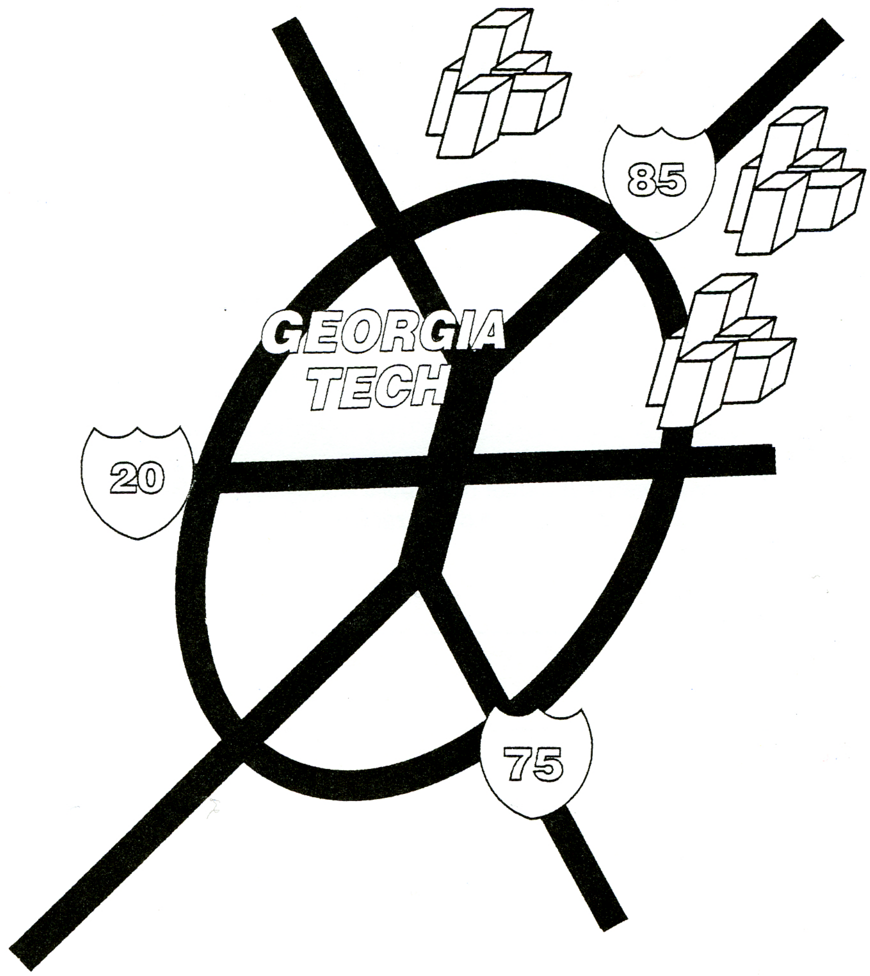
The Microelectronics Research Center helps build interdisciplinary bridges between several academic units, the Georgia Tech Research Institute (a contract research organization), other closely allied centers (such as manufacturing and communication) and industry.



A projection of personal computer performance measures to the year 2000 gives a capacity that challenges today's microelectronics.

Georgia Tech is located at the hub of Atlanta's dynamic communications and high-technology community. The 50-story regional headquarters for IBM and ATT, as well as national headquarters for Bell South and CNN are within a mile of the campus. The perimeter highway (I-285) that surrounds Atlanta is the Southeast's center of high-tech business and for companies such as DEC, HP, Northern Telecom, Contel, Hayes, NRC, DCA, MCI, Pactel, Rockwell, Scientific Atlanta, Oki, Hitachi, and Lockheed. This concentration of high-tech strengths provides a strong connection between Georgia Tech students and faculty researchers and real-world high-tech issues.

ATLANTA AREA TECHNOLOGY FIRMS



GEC • MCI • IBM • NCR • AT&T • HAYES
PACTEL • CONTEL • DIGITAL • HITACHI
OKIDATA • SIEMENS • LOCKHEED
BELL SOUTH • HEWLETT PACKARD
SCIENTIFIC ATLANTA • NORTHERN TELECOM
ELECTROMAGNETIC SCIENCES

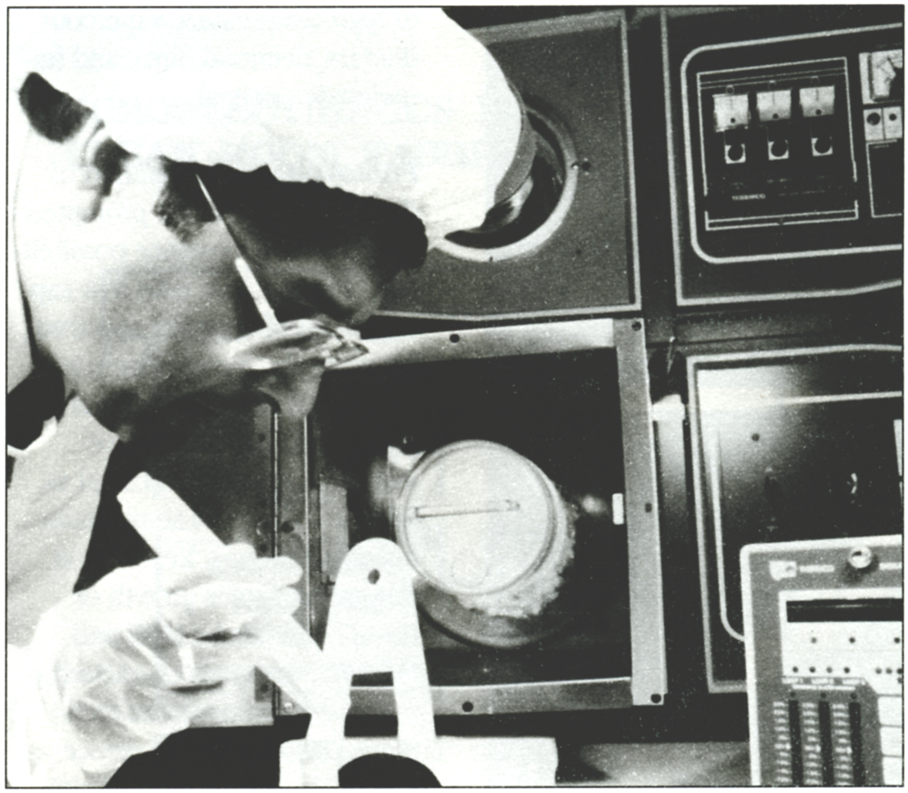
The Atlanta industrial-educational complex ranks among the most dynamic emerging high-tech regions in the U.S.

Strengths of the Program

In support of the goal of excellence in microelectronics that emphasizes optoelectronics as well as integrated optics, the Center has developed major facilities and programs in

- Atomically structured materials
- Microfabrication and nanofabrication
- Integrated circuits that are smaller, faster, and smarter
- Quantum devices
- Packaging: multichip and micro-grafting
- Modeling and simulation for all of the above

The mastery of all phases of the microelectronics cycle, from materials through modeling, is an explicit Center strategy because all are crucial to a "food chain" of electronics products in which microelectronics plays the role of the plankton. As optical methods become increasingly important to communications and computers, the Center is developing novel methods for incorporating powerful optical functions into affordable silicon microelectronics.

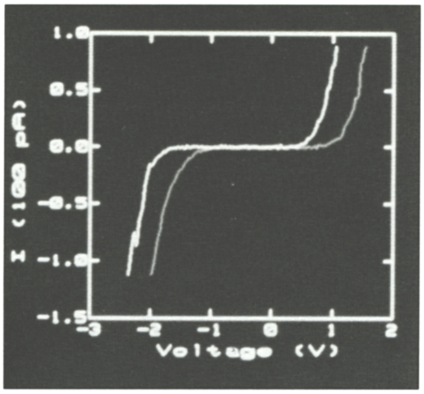


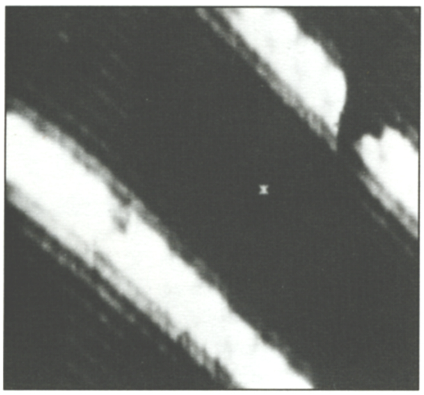
Multilayer photovoltaic cell structure and performance.

Atomically Structured Materials

The decision to emphasize optoelectronics and photonics led the Georgia Tech Microelectronics Research Center to build strong capabilities in molecular beam epitaxy (MBE) as well as metal-lorganic chemical vapor deposition (MOCVD). This program has led to a variety of electronic and photonic material advances utilizing compound semiconductors and the development of new vapor-deposited materials such as diamond films, ferroelectrics, and high-temperature superconductors. The MiRC places particular emphasis on the integration of dissimilar materials as well as atomically structured multilayer materials.

Epitaxial Growth: Thanks to inhouse MBE (both III-V and II-VI compounds) as well as MOCVD, Georgia Tech researchers are accomplished in epitaxial growth of diverse material combinations, such as wide-band-gap II-VI compounds on GaAs, for dielectric layers in a metal-insulator-semiconductor circuit family. Chemical vapor deposition methods mastered for semiconductor work have been applied as well





Scanning tunneling microscopy makes it possible to measure the electronic response of individual atoms on a surface.

to high-temperature superconductors, diamond films, and ferroelectric material.

Photovoltaics: Integration of dissimilar materials is prompted by higher performance possibilities. Photovoltaic cells that capture more of the solar spectrum, for example, incorporate layers of material of differing band gaps. MiRC programs have included both silicon-based as well as compound semiconductor combinations. Research in this area includes growth of novel materials by MBE and MOCVD, materials characterization using sophisticated techniques, modeling and device design, and fabrication of high efficiency Si, CdTe, CdZnTe, and GaAs solar cells.

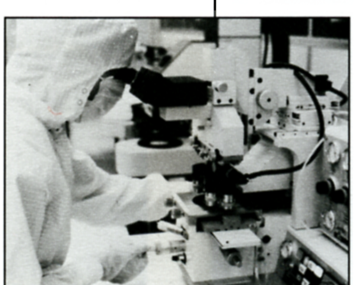
Superconductors: Since their discovery in the late 1980s, high-temperature superconductors have attracted strong interest. At Georgia Tech, several high-Tc superconductor programs are underway. One program has led to an improved understanding of material combinations and materials growth conditions for thin-film layers with high current capability needed for electronic applications. Another program has emphasized continuous film growth onto polymer substrates, for solenoid magnet applications.

Diamond and Ferroelectrics: Diamond films recently have been synthesized by remarkably simple chemical vapor deposition methods. In film form, diamond is useful not only for its hardness but also for a high thermal conductivity comparable to that of copper. It is ideal as a heat-sink material for multilayer electronics at high density. The Center's MOCVD expertise has led to a program in growth of ferroelectric thin films. These are directly applicable to higher density computer memory that is also non-volatile since a ferroelectric film can take on two states of polarization.

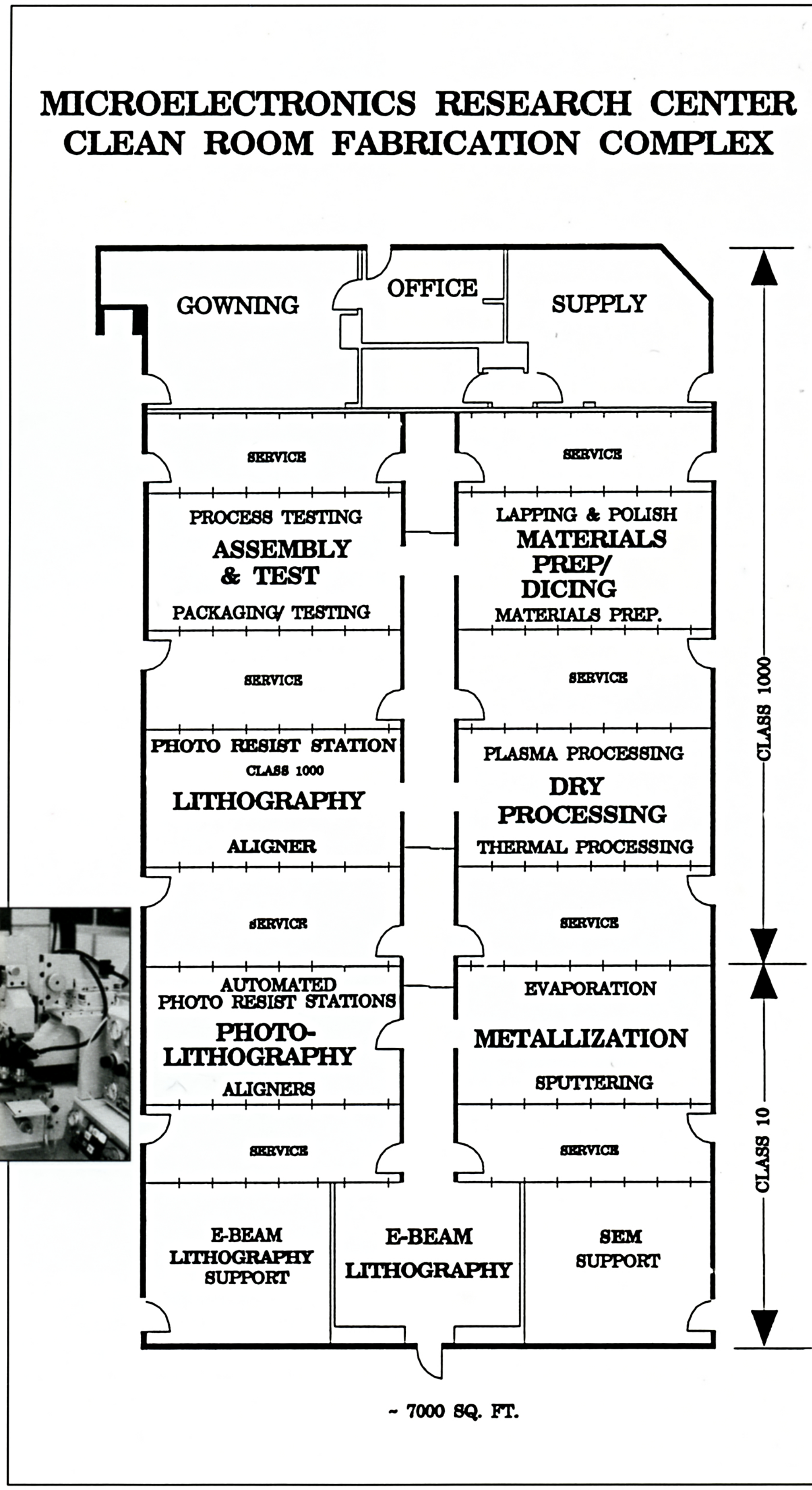
Materials Analysis: Microelectronics Research Center researchers also have developed outstanding materials analysis strengths, including in-house SIMS, ESCA, and Auger. A scanning tunneling microscope facility makes it possible to image at the atomic scale, as well as to study the electronic transport properties of devices at atomic dimensions.

Microfabrication and Nanofabrication

All stages of integrated circuit research from concept through fabrication and testing can be done either in-house or through outside foundries. In-house fabrication is chosen for unusual materials or unusual devices and microstructures, such as heterostructure quantum wells or microactuators. When the task can be accomplished with industry-standard fabrication, an outside foundry is employed. We have explicitly chosen not to set up a standard process line for a specific technology, but instead to provide standard process tools and a variety of standard process steps. The Center provides the "pots and pans" for creative "chefs" in microelectronics and integrated optics.

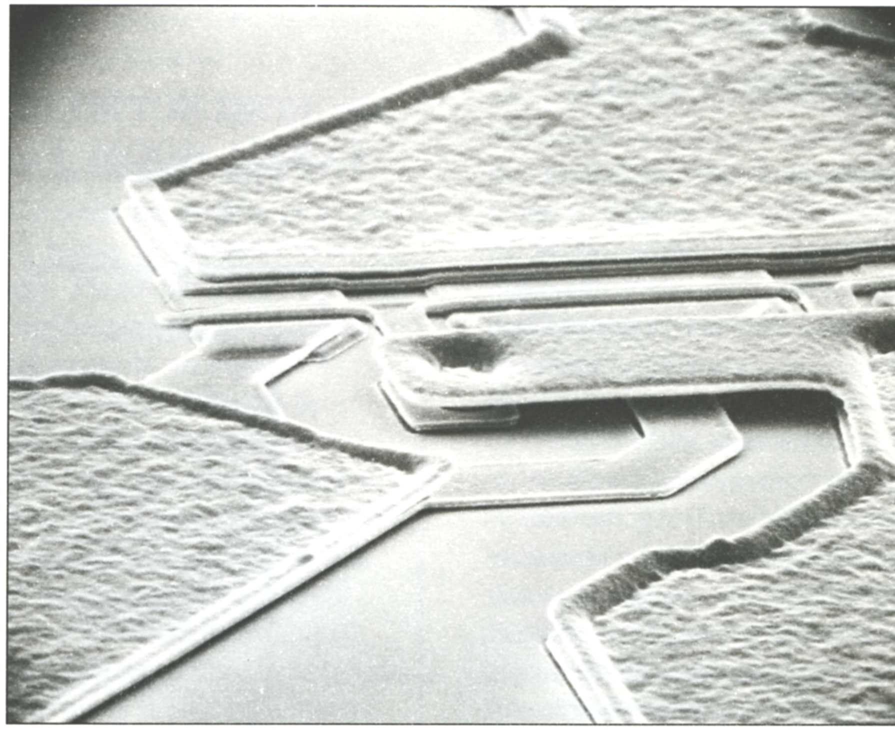


A "mix-and-match" approach may be used, as in the fabrication of optical interconnection chips with conventional silicon circuits fabricated in foundries and hybrid optical components developed in-house. Georgia Tech's emphasis on photonics challenges and extends the state of the art in circuit fabrication.

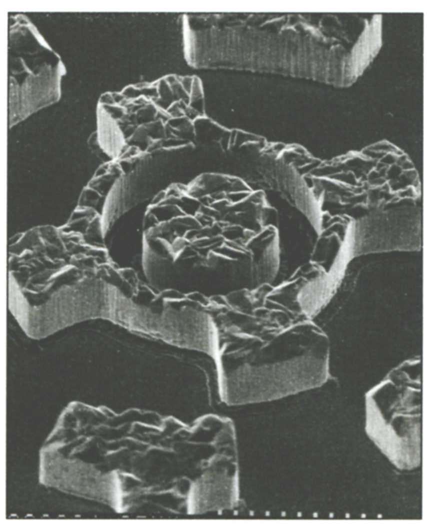


Microfabrication of sensors and actuators is a new application domain of micro-lithography. On-board electronics (linearization, signal processing, memory) may be included to pre-process sensor outputs and actuator inputs, providing distributed processing that communicates only needed information or changes to or from a central processor.

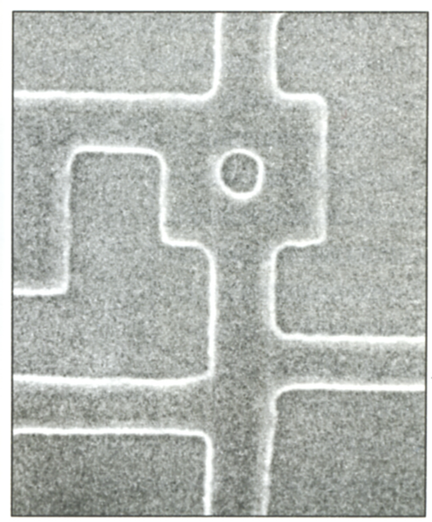
In-house electron-beam lithography permits us to fabricate feature sizes below 0.1 micrometer. This research probes the limits of conventional transistor design, where individual defects can spoil threshold control and yield. In-house processing research is directed at achieving process tools, such as low-damage reactive ion etching, which will be compatible with 0.1 micrometer designs.



GaAs-based high electron mobility transistor (HEMT) with integral air bridge crossover. Unity current gain frequency of greater than 35 GSz was demonstrated early in the history of this recent new circuit family.



This micro-machined motor has superior strength and torque to earlier designs because it is fabricated in a strong metal rather than in a brittle semiconductor, and embodies a proprietary process developed at Georgia Tech to micro-machine unusually thick parts with thickness/feature size ratios > 1.



Nanometer-scale feature

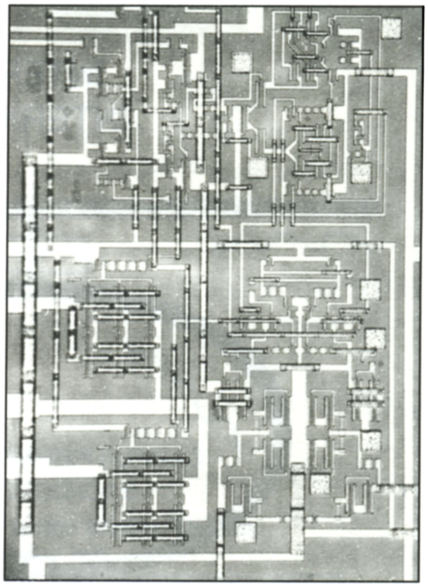
Integrated Circuits: Smaller, Faster, Smarter

The escalating capital cost of manufacturing ICs at shrinking scales puts a premium on designs with extremely high performance and reliability. Georgia Tech researchers and their industrial colleagues have forged partnerships that produce both analog and digital circuits that are not only smaller and faster but also smarter.

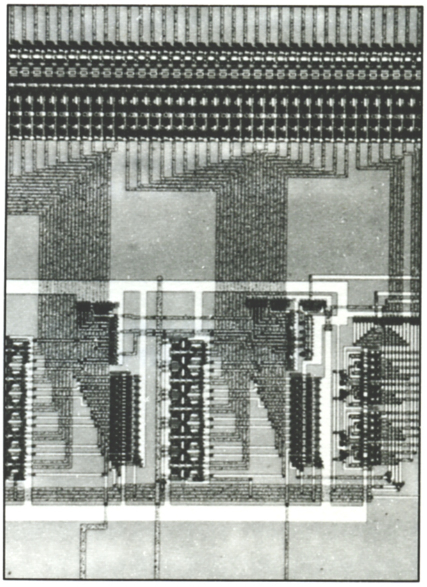
Analog ICs: The analog IC group has pioneered a family of op amps, comparators, and sample and hold circuits with gigahertz performance for instrumentation and communications systems. Designs perfected earlier in silicon are transferred to GaAs for higher speeds, and fabricated in several industrial partnerships.

Smart Circuits: Neural Networks Smarter circuits designed at Georgia Tech use neural network methods for higher performance. Built-in self-check and weak links provide early in-situ predictors of processing problems or in-service reliability. Neural network circuits designed here incorporate highly parallel arrays of simple neuron-like elements that, acting together, can be highly accurate and yet also extremely fast. Neural circuits may also incorporate a training loop to learn from experience, reducing the need for ultra-precise processing steps.

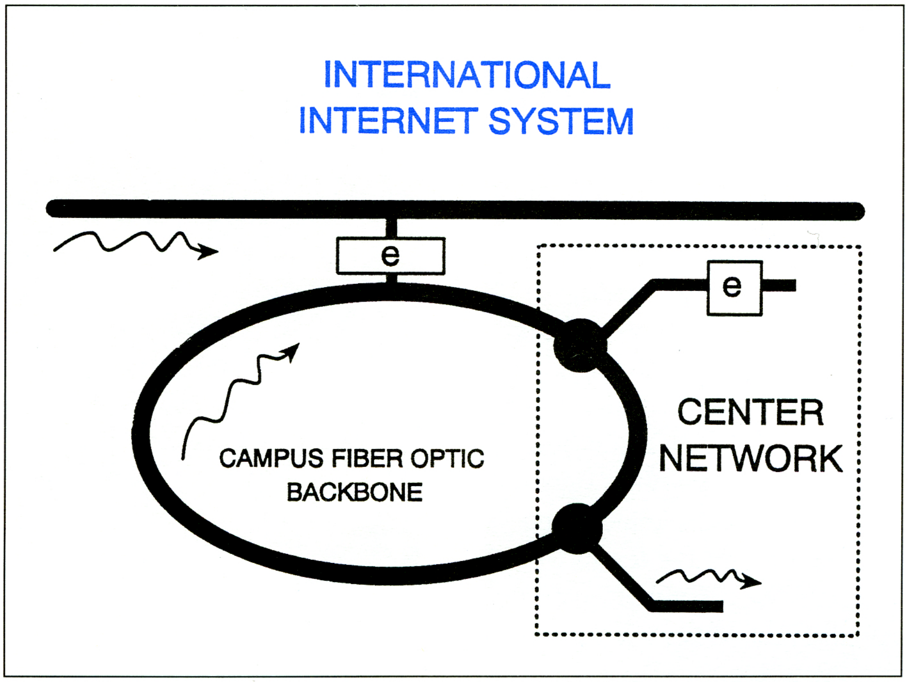
Digital Signal Processing: Towards Gigabit Networking. Georgia Tech's Digital Signal Processing group has an international reputation in algorithms for speech and graphics signal processing. With the increased importance of these topics for integrated voice, video, and data communications in telecommunications and in computer networking, Georgia Tech microelectronics researchers are working with DSP researchers to implement some of their powerful algorithms. The challenge is significant. A high-definition digital TV signal, for example, demands nearly 1 GBit/s, while a conventional TV channel has available only a 6 MHz bandwidth. This consumer-electronics challenge is accompanied by longer term research objectives, such as simultaneous voice, graphic or video, data, and text processing on sophisticated workstations, as well as its networking. Georgia Tech researchers are involved in a national initiative: the "superhighway for supercomputers," aimed at gigabit/s rate networking of supercomputers and superworkstations by the year 2000.



Analog GaAs Test Chip



Neural Net Analog Multiply Chip



The Center's networking capability includes direct optical access to a campus-wide fiber network that serves as a testbed for new device or system concepts.

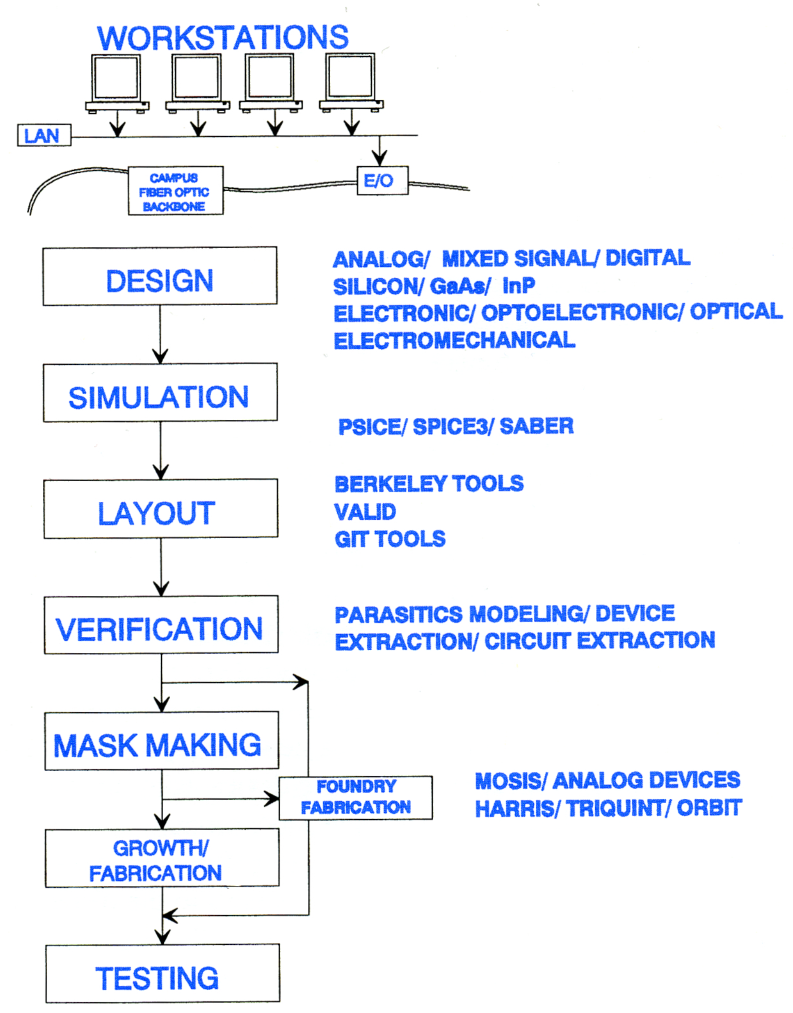
High Frequency Microelectronics: Microwave and millimeter wave integrated circuits require both advanced materials and processes to achieve efficient operation. Center researchers are combining high electron mobility gallium arsenide and aluminum gallium arsenide materials with advanced optical and electron beam lithography to produce transistors and circuits that operate at frequencies in excess of 35 gigahertz.

Design Resources: Designs are implemented on a variety of platforms ranging from specialized layout tools to increasingly common workstation platforms. Our design resources can handle design, simulation, and layout of compound semiconductor designs on the same footing as silicon to facilitate the design of highest speed circuits as well as the integration of photonic devices.

Design software includes both industrial-strength packages (e.g., VALID) and university standard (e.g., MAGIC) systems. Recent projects include analog, digital, and mixed-signal integrated circuits. Reflecting the Center's strength in integrated optics, the mix of projects spans electronic, photonic, and optoelectronic projects.

Testing: Circuit testing resources include low-noise analog and microwave testing to over 100 GHz. Digital VLSI testers are available that permit chips to be exposed to hostile environments including temperature extremes and radiation, and sampling of both electrical and optical pulse response down to picoseconds.

The Pettit Building local area network links distributed computing resources and is a gateway to both campus and national networks. The campus fiber optic backbone is connected to the building for experiments in high data-rate optical communications. Typical design cycles involve a combination of in-house resources and chip foundry operations. The Center has in-house resources for all phases from design through fabrication and testing.



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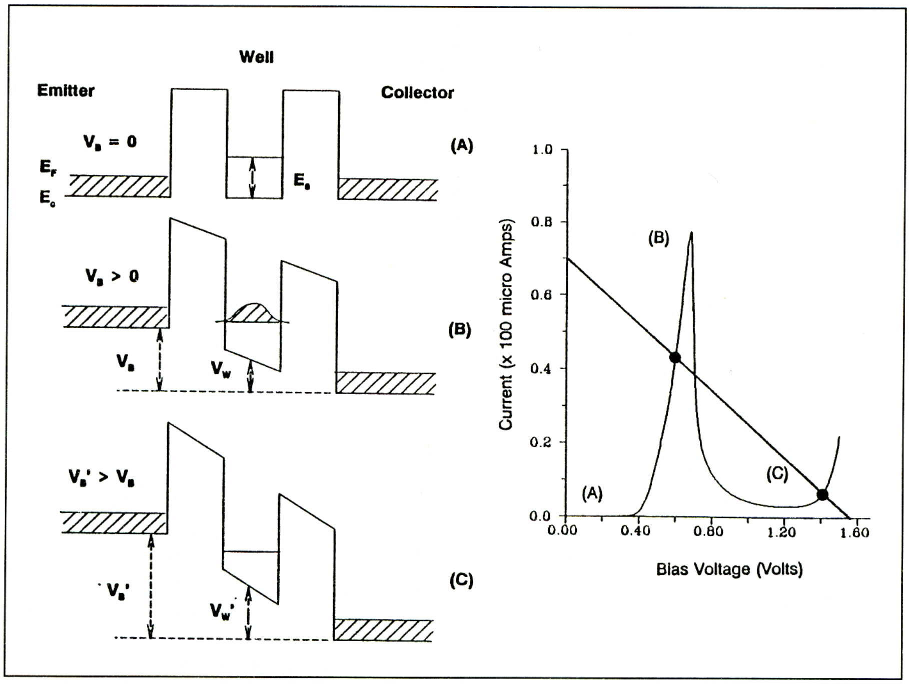
Quantum Devices and Circuits

As feature sizes shrink towards 0.1 micrometer, conventional device designs risk extreme yield sensitivity to defect and process parameters. The internal electric fields become so large that conventional gate control becomes less effective, and performance can suffer. Quantum device designs have an advantage at this scale. They actually perform better as scales shrink, since quantum effects become stronger at smaller feature sizes. At Georgia Tech, several groups have developed quantum device concepts.

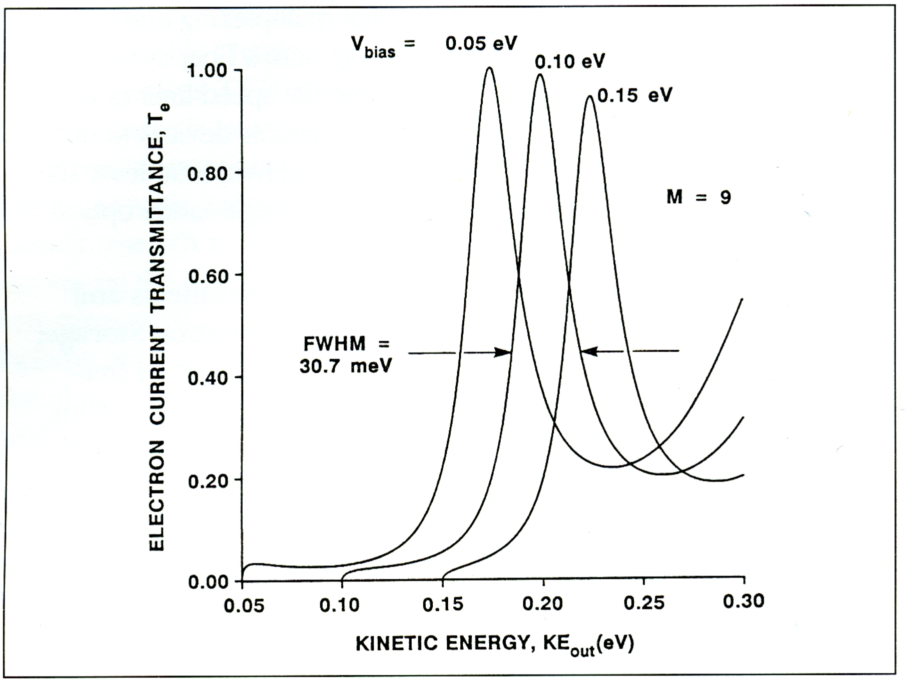
For example, faster transistors can result from incorporation of hot electron emitters. A novel Georgia Tech design, the variably spaced superlattice filter (VSSF), provides a hot-electron injector whose energy is precisely tuned by the layer design and turns on sharply at certain bias voltages.

Resonant tunneling through quantum wells that are defined by narrow barriers have been actively developed, since this device family promises terahertz speeds. MBE and MOCVD permit atomic-scale control of structural features that define performance. The performance is predictable and the yield more reasonable than the earlier Esaki diode family. Research is now directed at development of a third control electrode to help generate a complete quantum transistor circuit family.



Resonant tunneling devices based on quantum wells mimic earlier Esaki diodes, but with higher speed potential and better manufacturability.

A new concept, the electron wave device, takes account of the wave properties of the electron to design a full device family analogous to the dielectric interference filters of optics. Because the electrons are propagating (rather than trapped in a quantum well such as the above), current-carrying capability and fan-out is superior. A design methodology invented at Georgia Tech permits complete circuit functions to be performed within the quantum wave function scale. This eliminates an objection to earlier quantum devices combined with conventional electronics whose parasitic loading lessened the performance enhancement.



Electron current transmission of a 9-layer AlGaAs superlattice interference filter/emitter as a function of electron output kinetic energy for three values of applied bias.

Integrated Optics and Photonics

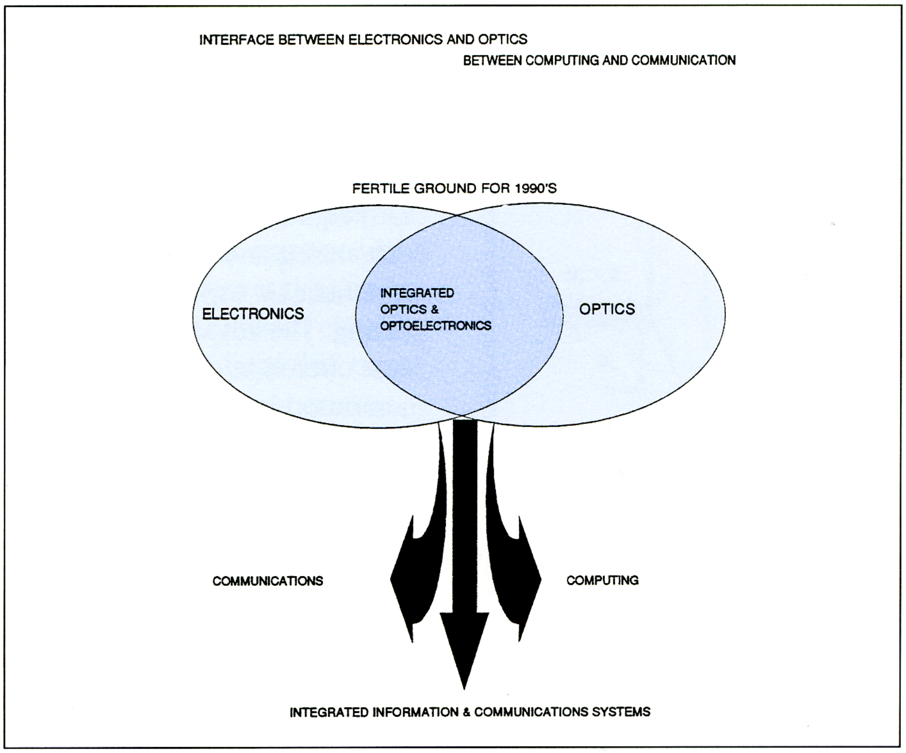
In telecommunications, nearly 100 percent of new long lines are fiber optic. Light-wave or "photonic" interconnects also are being explored in computer research, not only for enhanced speed but also for enormously enhanced parallelism. Finally, as fiber optic links extend into the home and office network, communications and computer research share common issues. The interface between electronics and optics, as well as the interface between computing and communications, is fertile ground for R&D in this decade.

Integrated optics is playing a role comparable to that which integrated electronics played in the 1970s to bring high performance at reasonable cost.

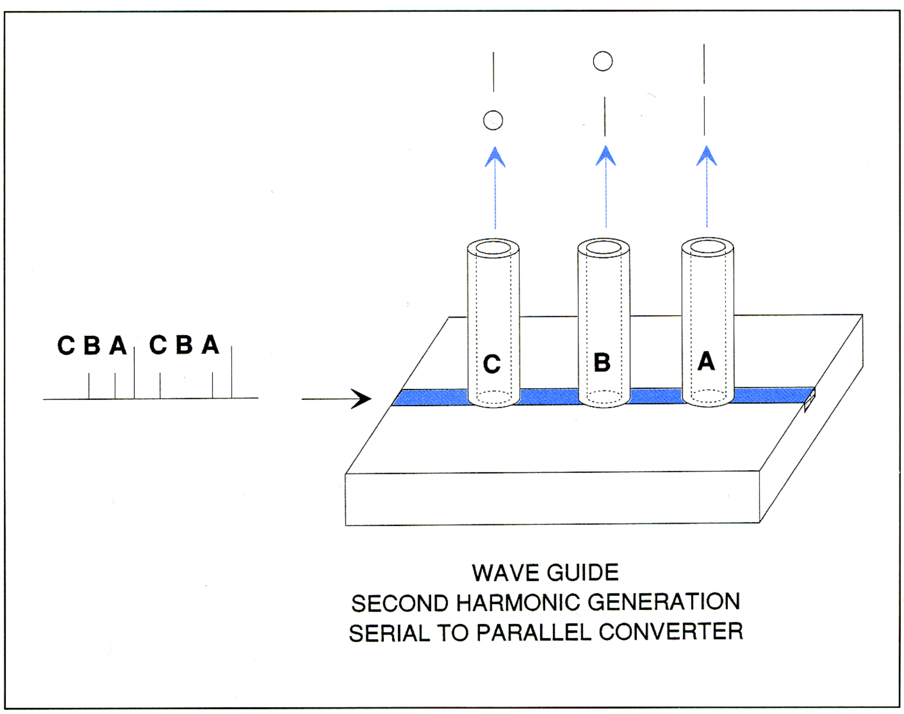
Georgia Tech microelectronics researchers are taking a leading role in this photonic revolution. Lightwave technology for information processing and communications plays a role in more than half of the research at the Georgia Tech Microelectronics Research Center, due to an intentional buildup of strength in compound semiconductors and to the development of internationally recognized optics programs in electrical engineering and physics.

Optoelectronic Telecommunications: Georgia Tech researchers and their industrial partners are experimenting with simultaneous transmission of many signals (in some cases both analog and digital) on the same fiber by wavelength multiplexing. The advantages are the same offered in electronic communications except that the frequency of the light wave is thousands of times higher, permitting many more channels to be multiplexed and also permitting higher bandwidth per channel. Researchers are exploring crosstalk due to modification of the fiber's response to one signal by the another - a weak effect, but reliable communications demands extremely low bit error rate. Increased bandwidth per channel is also a target, since the transmission of video-rate images at high definition (HDTV-quality) on fibers challenges the speed of electronic and electro-optic switching devices. Georgia Tech researchers bring a long history of experience to the study of microwave electronics, particularly with GaAs and other compound semiconductors. They are developing semiconductors notable not only for their speed but also for their natural interface to and from light waves.

All Optical Devices: Georgia Tech researchers have invented novel all-optical schemes that



Interface between electronics and optics, and between computers and communications.

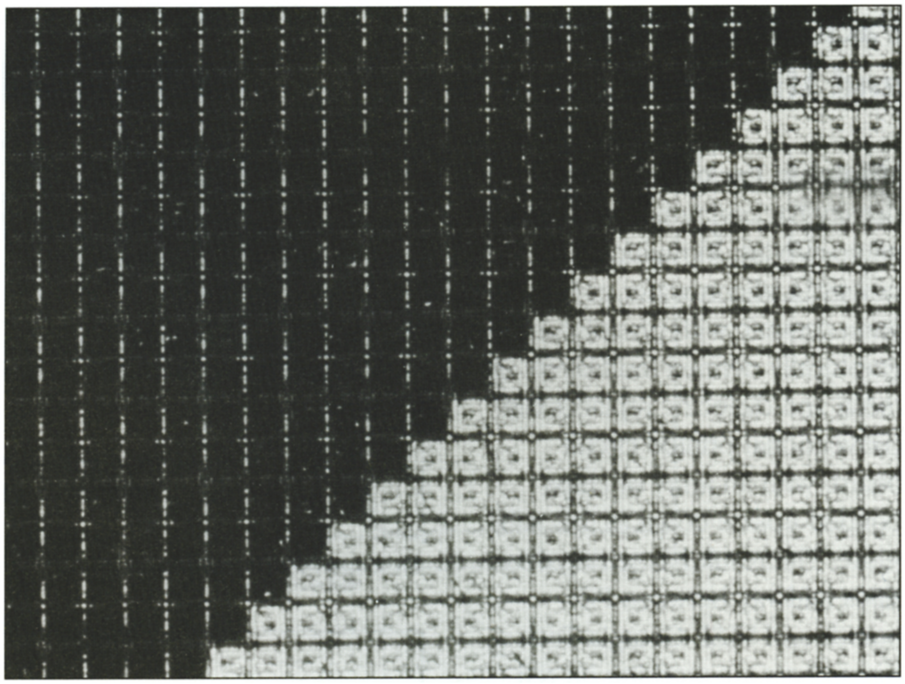


All-Optical Devices.

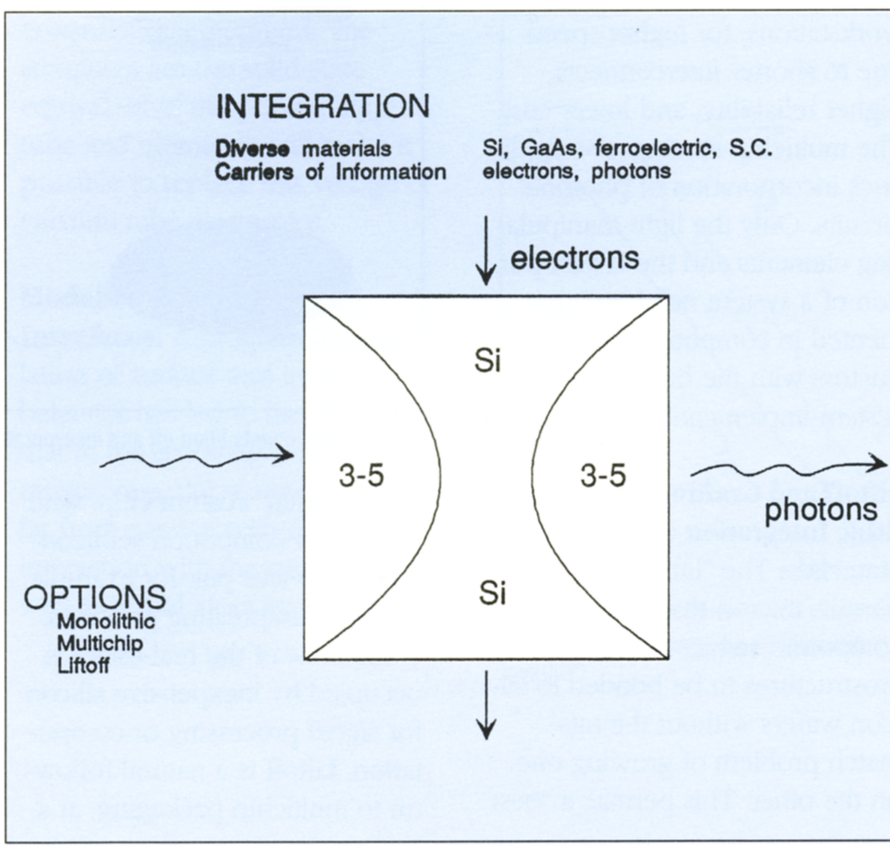
permit multiplexing and demultiplexing onto a fiber at rates beyond the speed limit of common electronic devices to utilize the full bandwidth (at least 100 GHz) of a single-mode optical fiber.

Optical Interconnects and Optical Information Storage: If chips talk to chips by free-space light beams, then wiring delays are lessened and highly parallel and reconfigurable multiprocessor schemes can be realized. Optical interconnects were demonstrated at Georgia Tech in a project that combined a silicon microprocessor with a spatial light modulator array. The spatial light modulator reflects the results of a previous output beamed onto it, modulates them by the results of that processor's computations, and bounces them optically to another processor in the chain. Parallelism is limited only by the size of the SLM array (N2) rather than by a bus width (N). In another project, an entire RAM array is flash addressed by an optical image, for extremely rapid parallel transfer of data from optical memory to electronic chip. This scheme has potential for fully parallel optoelectronic correlators.

Acoustic Charge Transport: Interest is growing in a relatively new type of device known as acoustic charge transport (ACT) devices that can be utilized for analog signal processing. These devices resemble Charge Coupled Devices (CCD) except that the charge is transported by the potential propagating with a surface acoustic wave (SAW). Current research at Georgia Tech focuses on the development of new types of ACT devices. This includes experimental and theoretical work on the details of SAW propagation in AlGaAs heterostructures and in II-VI compound semiconductors as they pertain to the performance of proposed ACT devices. Of particular interest is the impact of acoustic considerations on the design of new device structures, such as focal plane arrays. Interface between electronics and optics, and between computers and communications.

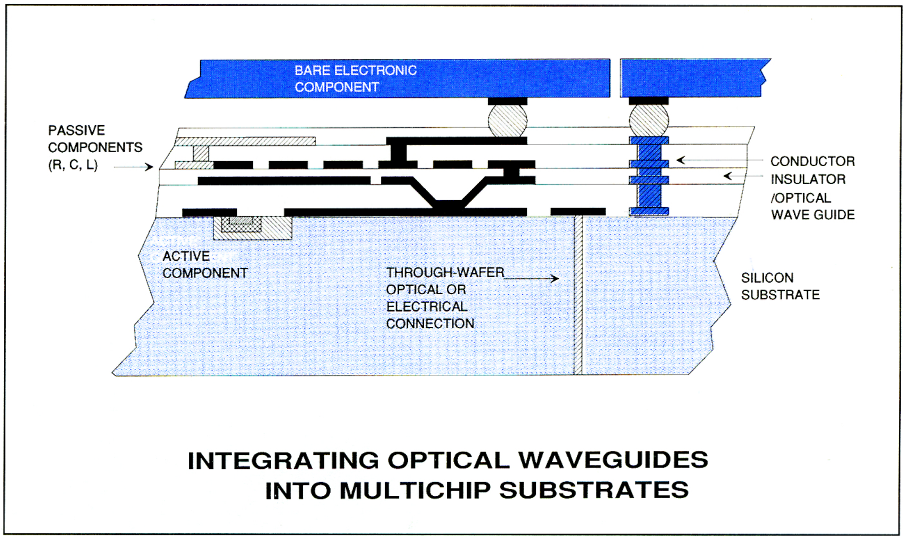


Optical integration projects combine materials best for optical function with silicon microelectronics.

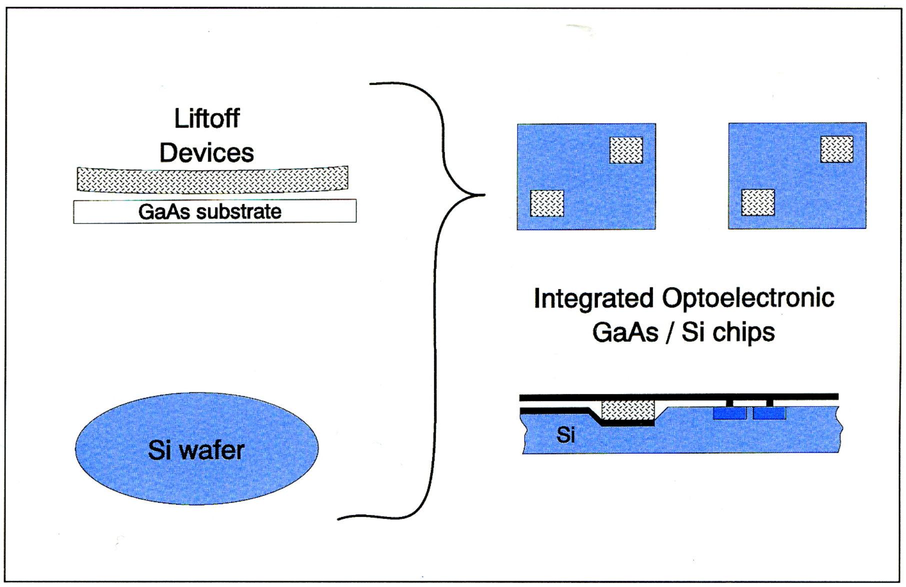


Packaging: Multichip and Micro-grafting

Multichip Packaging: High-density packaging has become a microchip art. In multichip technology, a silicon wafer or fine-grain ceramic with photolithographically defined multilayers of metal and dielectric replaces the conventional printed circuit board, with an array of chips bonded upside down to this substrate. The result has wiring densities midway between PC-boards and VLSI. Georgia Tech researchers are working on reliable ways to implement multichip packaging for high-end supercomputers, and desktop workstations, for higher speed due to shorter interconnects, higher reliability, and lower cost. The multichip strategy also facilitates incorporation of photonic circuits. Only the light-manipulating elements and the fastest portion of a system need be implemented in compound semiconductors with the balance of the system implemented in silicon.



Multi-chip hybrid cross-section.



Optical components lifted off and incorporated onto silicon IC wafers.

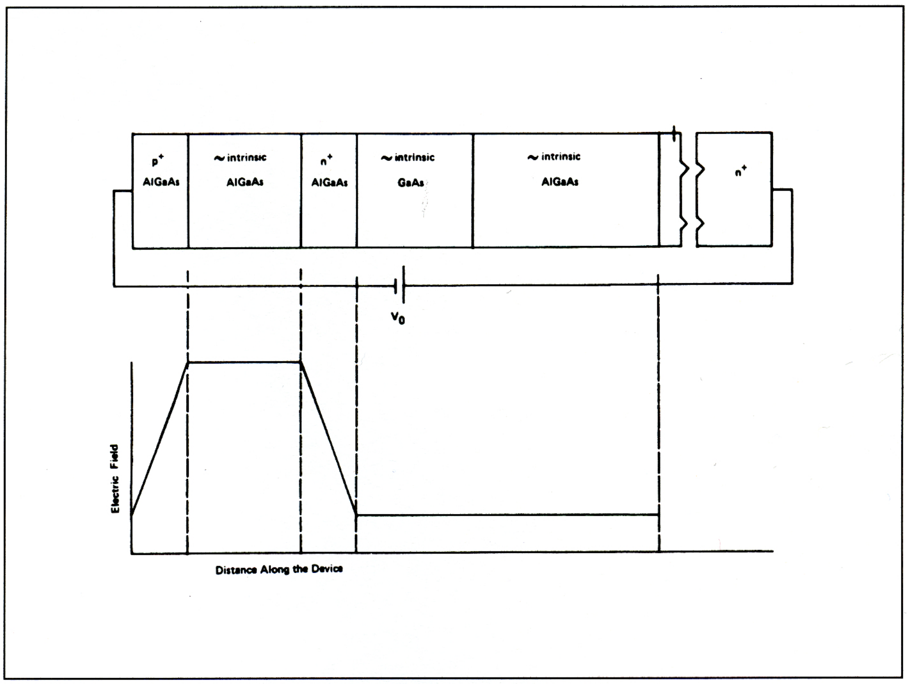
Liftoff and Grafting — Monolithic Integration of Dissimilar Materials: The "liftoff" technique permits micron-thick layers of compound semiconductor heterostructures to be bonded to silicon wafers without the mismatch problem of growing one on the other. This permits a "best of all worlds" custom chip, with chiplets of compound semiconductor devices put, for example, at light-manipulating positions, while most of the real-estate is occupied by inexpensive silicon for signal processing or computation. Liftoff is a natural follow-on to multichip packaging, at a still finer scale. Georgia Tech researchers have advanced the liftoff technique to produce inexpensive manufacturable OEICs pre-patterning and post-patterning of the hybrid. This permits a true monolithic result with associated cost reduction and performance enhancement.

Modeling and Simulation

The performance of new electronic and optical semiconductor devices is modeled using in-house minisupercomputers as well as national supercomputer resources. Modeling permits optimization of existing designs prior to expensive fabrication and also leads to design of totally new devices.

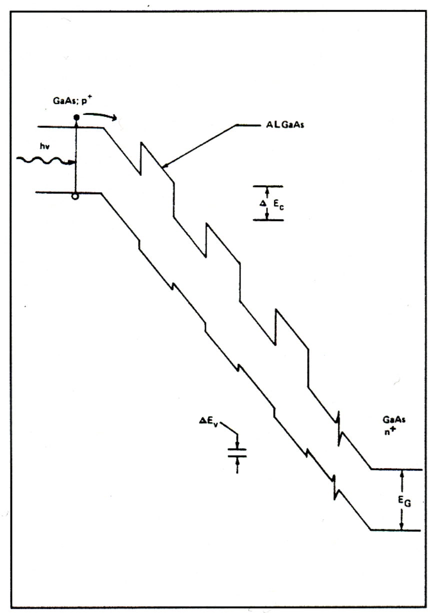
Next-Generation Modeling Tools: Submicron heterostructure transistors must be modeled with new tools, since classic modeling methods fail when an electron may travel through the active region without a single scattering event. MiRC researchers use Monte Carlo and full quantum modeling techniques to predict unusually high drift velocities that have been verified by actual transconductance measurements. "Beyond Boltzmann equation" modeling permits Center researchers to design optimized multilayer heterostructures that confine the channel to ultra-high mobility layers for highest speeds at lowest power.

Modeling of Photonic Devices: A particular strength has developed in the design and modeling of photonic detectors such as avalanche photodiodes that incorporate superlattice heterostructure multilayers. The structures are the solid-state equivalent of the photomultiplier tube and ultimately will make it possible to replace this vestige of vacuum tube electronics.



Schematic representation of a p-i-n heterojunction APD and the corresponding electric field profile.

Modeling of Surfaces and Interfaces: A program in simulation of surface and interface behavior has led to the discovery that in the scanning tunneling microscope, the scanning tip is far from passive with significant interaction with the surface as well as actual atom exchange.



Energy band diagram of a multi-quantum well APD.

Educational Programs

Students are perhaps the most important "product" of MiRC research. The Center typically serves about 80 graduate students and 50 undergraduate research participants.

Students apply for admission and register in the academic department closest to their degree interests. The Microelectronics Research Center itself grants no degrees, serving instead as a facilitator for students in their research projects. The Center provides equipment and office space for students working on the projects of faculty members who are Center participants. Our faculty participants (some 40 in number) include representatives from electrical engineering (about 50 percent) as well as chemical, materials, and mechanical engineering, the College of Computing, and, in the sciences, from physics and chemistry. Our students gain access to state-of-the-art-facilities for microelectronic materials, devices, and circuits, and access to interdisciplinary faculty expertise that transcends departmental boundaries.

How Can Your Company Interact?

Companies can participate in Microelectronics Research Center activities via

- Graduate Fellowships
- Equipment Gifts
- Focused Projects
- Strategic Alliances

Company participation in Center programs is strongly encouraged, and companies play an important role in shaping our research programs. Benefits to participation include early information on results, in some cases developing and licensing proprietary technologies, and identifying the most talented students as potential employees.

Companies find that Center projects are a highly effective way to explore a new technology or develop a new knowledge base, since Georgia Tech is known for its applied approach to research. The linkage of microelectronics research to manufacturing is particularly effective at Georgia Tech, since strong research Centers exist in both domains. Our faculty participate in programs that transition from research to development to manufacturing.

Company participation is highly leveraged, by other companies in strategic alliances, and with government agencies in partnership projects. Some 25 major U.S. companies have participated in Center programs during the past five years. Corporate-supported research constitutes typically 1/4 to 1/3 of the external microelectronics research budget in any given year.

The costs and benefits of these interactions are outlined in a separate PROSPECTUS, which may be obtained by contacting the Center at the following address:

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