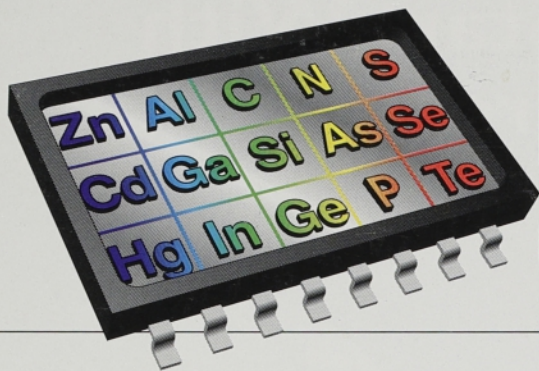




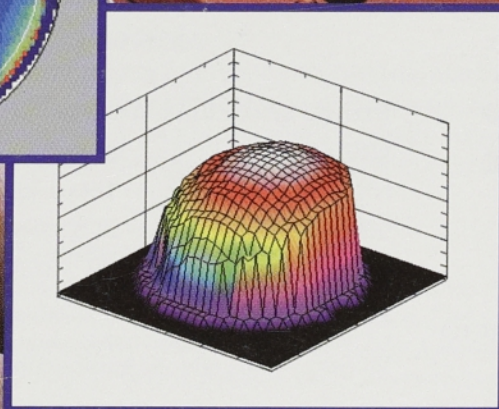
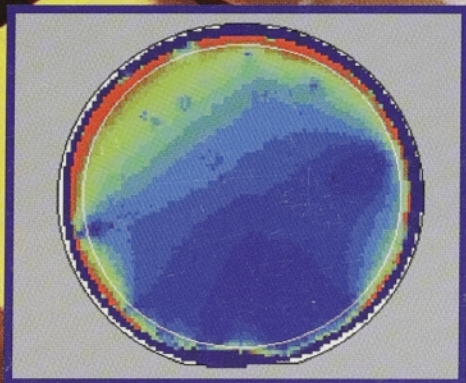
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March 2001

Volume 7 Number 2

CHARACTERIZATION of III-V Materials and Devices

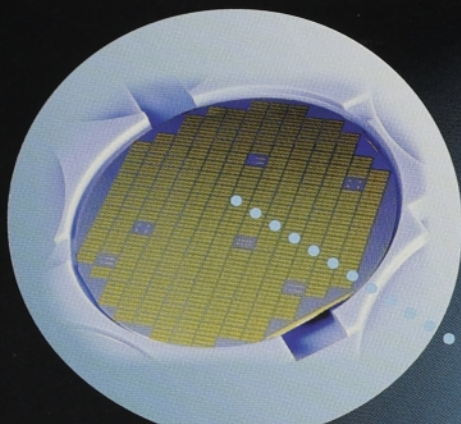


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GaAs IC Symposium Report
Nitride Lasers on Copper

The Best Devices Start With The Best Sources

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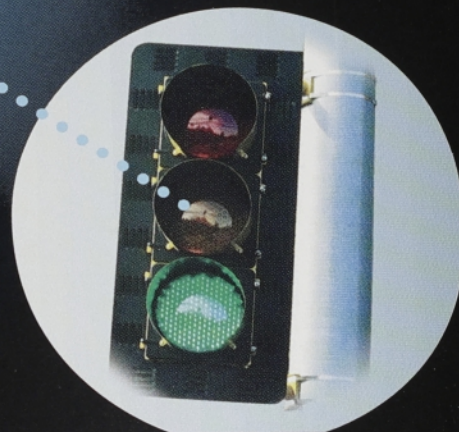
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PROCESS ENGINEER

Seeking a key member for our engineering team who will be responsible for the fabrication of semiconductor lasers using photolithography, dry and wet etching, dielectric deposition, metalization and lap and polishing of high power, highly reliable semiconductor lasers for telecommunications and graphics applications. Ph.D./Masters/Bachelor's degree with several years of industrial experience and knowledge of semiconductor lasers/optoelectronics.

SEMICONDUCTOR LASER ENGINEER

This position will be responsible for the design of new high power, highly reliable semiconductor lasers for telecommunication applications. Master's degree with minimum of 5 years of industrial experience, or Ph.D. in EE, physics or related discipline. Knowledge of semiconductor laser/optoelectronics, physics and device design.

OPTICAL ENGINEER

Will design and develop optical solutions for fiber optic telecommunication products, and participate in all phases of the program including feasibility, prototype, production evaluations, product certification and product launch. Must possess a M.S. or Ph.D. in optics, physics or related field and have experience with fiber optic subsystems, understand coupling issues for both single and multimode fibers.

TEST ENGINEER

Will develop testing and screening procedures for optoelectronic products for telecommunications market. Analyze test data for laser diode products and perform failure mode analysis. Specify requirements for test, burn-in, and life-test equipment. M.S. or equivalent educational degree, relating to electronics/photonics. Experience with design, implementation and use of automated test and data acquisition systems.

RELIABILITY ENGINEER

Will lead the reliability organization by setting standards and test procedures required for telecommunications qualifications as well as for continuous improvement of existing products; will provide an unbiased analysis for failure modes. Must possess a M.S. or Ph.D. in physics, material science or related field, with a thorough understanding of semiconductor physics with several years of experience in failure mode analysis and reliability assessment.

EPITAXIAL ENGINEER

This position will play a key role in product development through improvements in GaAs-and InP-based MBE-grown material and device structure optimization. B.S./M.S./Ph.D. in materials science, physics or electrical engineering. Expert-level mastery of the scientific and engineering aspects of compound semiconductor growth including material and structure characterization. Prefer hands-on experience with MBE/MOCVD or other UHV systems in an industrial environment.

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Manufacturing positions are also available: Optoelectronic Assembler/Operator, Process Engineering Technician, Epitaxial Technician, and Coating Technician.

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Compound Semiconductor has a circulation of more than 5,500 managers, engineers, scientists and technicians, the majority of which have valuable experience in III-Vs, IV-IVs, and II-IVs. We have subscribers at more than 900 compound semiconductor facilities around the world, including virtually every fab and R&D center in the compound semiconductor field. We deliver a very targeted audience that you won't be able to reach using any other publication.

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Marie Meyer
Managing Editor
Compound Semiconductor
Franklin Publishing
163 Cabot Street
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Innovation for the Future

Who we are

The GE Corporate Research & Development Center (CRD), located in Niskayuna, New York, is one of the most diversified industrial research laboratories in the world, dedicated to technological excellence and developing innovations that "change the game." Many of those game changes are currently happening within the Semiconductor Technology Program here at CRD where, "**Wide Band-Gap Exploration Fuses with the Blue Chip Application Frontier!**" Are you tired of worrying about the stability in a semi-conductor start-up or restrictions on technology because of funding sources? Well GE CRD is the place where the various applications that utilize Wide Band Gap material/device technology are ALL being addressed! The possibilities are almost endless with countless GE businesses supporting this technology, and the scientific standing to back it up. GE developed the first solid state laser and the world's first LED, and we are using that innovation excellence to drive our current nitride work and beyond. Please join us as we forge ahead into the new innovations of the semiconductor field!

Who we need

WIDE BAND GAP SEMICONDUCTOR DEVICE ENGINEER

As part of the Semiconductor Technology Program, this position requires a technically inclined individual. Using your device design and processing experience, take charge of programming and interaction for modeling, design, fabrication, and testing of microwave WBG semiconductor devices (SiC and GaN). This position focuses on commercial and military applications, and requires customer interaction, white paper and proposal generation, and possible business development activities. Interested candidates should have a Ph.D. with a minimum of 5 years experience in Wide Band Gap devices. Knowledge of microwave devices is required and the ability to manage several programs from conceptualization to completion, is highly desired. A solid knowledge of the WBG industry, experience as a WBG Project Engineer, and MOCVD epitaxial growth experience is also preferred. Job Code CRD/237564/AN000

NITRIDE SEMICONDUCTOR DEVICE ENGINEER

In this position, you will handle technical and programmatic interaction of the modeling, design, fabrication, and testing of III-Nitride-based optoelectronic devices (LEDs, photodetectors, etc.). The position will focus on commercial applications, requiring customer interaction, proposal generation, and possible business development activities. Interested candidates should have a Ph.D. and a minimum of 5 years experience with Wide Band Gap devices. Previous hands on involvement with device design, device processing, and GaN modeling and simulation is required. The ideal candidate must be able to manage many programs from conceptualization to completion, and have a solid understanding of the WBG industry. Experience as a WBG Project Engineer, as well as MOCVD epitaxial growth experience is highly desired. Job Code CRD/237569/AN000

SEMICONDUCTOR DEVICE TEST ENGINEER

This key position will involve the setup, calibration, and data analysis of DC parametric tests and small signal RF measurements for various RF devices made from Wide Band Gap material (SiC, GaN). You will supervise a semiconductor device test program for various internal optoelectronic device projects including photodiodes, power devices, high frequency devices, and LEDs. The successful candidate will have a BS/MS in EE, Physics, or Mat Sci, hands on experience with various electrical test instrumentation and software, and an understanding of solid state device physics. Experience in the setup and calibration of test systems for RF devices is preferred, as is proficiency in data acquisition and statistical analysis and experience in test and measurement of Wide Band Gap devices. Job Code CRD/237570/AN000

PROCESSING ENGINEER

This position involves the development and fabrication of Wide Band Gap semiconductor devices for various commercial and military applications. The successful candidate should have a thorough knowledge of the industry, including equipment, materials, wafers, and suppliers of Wide Band Gap services, a BS/MS in EE, Physics, Chemistry or Mat Sci., experience in semiconductor device fabrication, and 3+ years' cleanroom experience. Experience in fabrication or processing of Wide Band Gap devices and an understanding of solid state device physics is desired. Job Code CRD/237571/AN000

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For confidential consideration, please send an e-mail with the text of your resume to: opportunities@gecareers.com. Please reference Job Code (located at the end of each job description) in the subject line of your e-mail. You may also mail your resume to our processing center at: GE Resume Processing, 37 Whitcomb St., Waltham, MA 02453. An equal opportunity employer.



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Thermo VG Semicon is the world's leading supplier of molecular beam epitaxy (MBE) systems to the semiconductor industry. We are seeking a US-based sales manager. The successful applicant will be responsible for MBE system sales and marketing activities in North America and will manage all aspects of our business interactions with a defined number of major customers. Ideally applicants will have a BS or equivalent and have a minimum of five years postgraduate experience in semiconductor technology. Experience

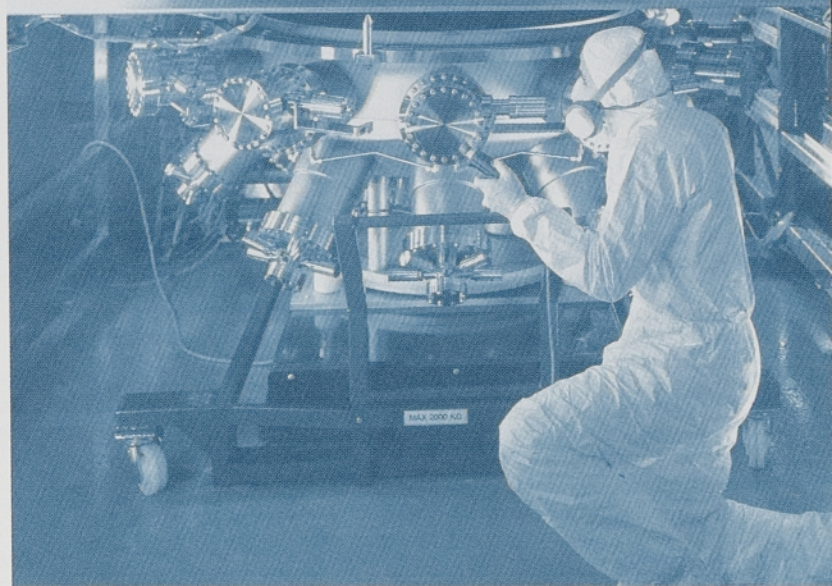
in technical sales would be advantageous. Applicants should have excellent communication skills (both verbal and written) and be able to demonstrate a successful track record in both the technical and commercial aspects of the telecommunications and/or semiconductor industry. Considerable travel is required, both within the USA and internationally. Thermo VG Semicon offers an excellent compensation and benefits package. To apply please submit a detailed resume including educational experience and job history.

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Thermo VG Semicon

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travel to customer sites to diagnose and rectify faults, installation of new systems and upgrades, maintenance and customer training. Self-motivation and the ability to work with minimal supervision are critically important.

Applicants should have a minimum of five years experience in the industry with a BS or B.Sc. in electronics or mechanical engineering or equivalent qualifications. These positions will be based in the USA and Europe and require significant levels of domestic and international travel.

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Test Manager: Responsibilities include management of small fabrication line, device test/analysis, implementation of ISO qualified procedures, SPC and documentation, data analysis, and developing and implementing tests to meet customer specifications. A Bachelors Degree in Electrical Engineering or related field with five years experience required. Experience with, IC fabrication, automated test and characterization are desired.

R&D Engineer: Research next-generation products, develop processes and transfer processes to Engineering. The ability to interact with applications engineers and manage R&D projects is critical. A strong understanding of crystal growth, materials and devices, and a Ph.D. in E.E. or related field is desirable.

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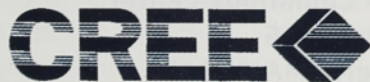
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You will be a key member of a group responsible for manufacturing the highest volume of high brightness nitride LEDs in the world. Your ongoing focus will be on yield improvement activities, developing analysis methodologies to address yield issues, and implementing new processes. Qualifications include a BS in electrical engineering, materials science, or the equivalent, with an advanced degree preferred, and 3+ years of work experience as a yield, test or process engineer. Solid working knowledge of SPC and industrial experimental design is a must. MOCVD experience strongly desired.

EQUIPMENT ENGINEER

We will rely on you to develop and implement plans for calibration schedules, preventative maintenance, adding capacity and increasing tool utilization in multiple manufacturing operations. Responsibilities will include directing the activities of the equipment technician team, assisting with troubleshooting, and responding to pages to support production in a 7X24 operation. We seek a hands on individual who has a BS in engineering, or the equivalent, and at least 1 year of semiconductor manufacturing experience. Training experience is highly desirable. Strong organizational and leadership abilities are a must.



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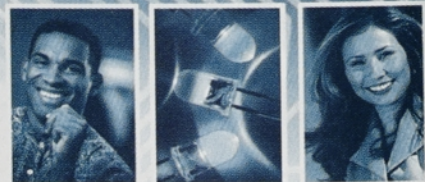
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LASER PKG. ENGINEER

In this key position, you'll work with a team of scientists & engineers to develop blue laser diode products. You'll develop internal capability to package blue laser diodes for demanding ambient conditions and help optimize packaged laser performance. Qualifications include a master's degree, or a Ph.D., in a technical field; expertise in analytical instrumentation; thermal modeling experience; and the ability to thrive in a high-pressure, deadline-oriented environment and work with minimal supervision. At least 2 years' semiconductor laser packaging experience in a manufacturing environment, including semiconductor laser testing & failure analysis experience, is preferred.

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Duties include monitoring the assembly and testing of diode bars, managing various yield improvement projects, and working in the test and assembly areas of the cleanroom. Requires at least 5–8 years of semiconductor engineering experience as well as the ability to collect and analyze yield data and trace failures to the source. Laser diode background a plus.

Development Tech (Job Code: CSD00-286)

Routine duties involve the collection and entry of lifetest data, failure analysis on devices from ongoing lifetest programs, and device testing in support of Engineering. Requires an AS degree or the equivalent and experience with device testing, preferably of opto-electronic devices and/or laser diodes. Familiarity with optical microscopes is essential; troubleshooting skills and cleanroom experience preferred.

Senior Staff Development Engineer (Job Code: CSG00-207HK)

Duties include troubleshooting existing laser diode burn-in and lifetest equipment; designing and developing laser diode control electronics and power supplies; serving as an in-house consultant on electrical engineering issues for CSG, Engineering, Manufacturing, and Marketing; and interfacing with EE groups in Finland and the Software Group in Santa Clara. Requires a BSEE with 5 years of experience. The proven ability to integrate electronic systems is essential, as is familiarity with opto-electronic systems. Experience integrating hardware with software preferred; knowledge of laser diodes and optical systems a plus.

Senior Development Engineer (Job Code: CSG00-29HK)

Duties include developing high new turn-key laser diode systems, supporting the existing systems product line and interacting with Sales/Marketing as well as customers on system issues. You will also interface with EE groups in Finland and our software group in Santa Clara, California. Requires a BS in Physics, Optics, Mechanical Engineering, Electrical Engineering, or a related field plus 3 years of experience. Prior experience with laser-based systems is preferred.

Applications Engineer (Job Code: CLG00-60HK)

Duties include creating new applications for ultra-fast and pulsed solid state lasers in the areas of material processing and process development, working closely with customers on specific application developments, and providing technical support for trade shows, marketing, and the worldwide sales force. Requires an advanced degree in Materials Science, Physics, Physical Chemistry, EE, ME or the equivalent.

Senior Development Engineer (Job Code: CLG00-254HK)

Duties include conducting tests on RF CO2 lasers (optical emphasis), organizing and performing complete qualification tests on pilot lasers, supporting the production group with training and testing as required, and supervising the lifetesting of CO2 lasers. Requires a BS or equivalent experience; MS in Physics, Optics, EE, or Chemistry preferred.

Director of Manufacturing (Job Code: CSD01-001JMP)

Oversee all manufacturing and planning activities involving revenue growth, workflow optimization, planning and purchasing, direct labor, capital equipment, and inventories management. Specific duties include enhancing shipment planning in line with divisional growth objectives, developing human resources and inventories, and streamlining supply chain management between all CSD sites. As an active member of the CSD staff, you will also be called upon to promote the group's strategy, and propose and implement business practices where applicable. Requires 6–10 years of relevant experience. Degree preferred.

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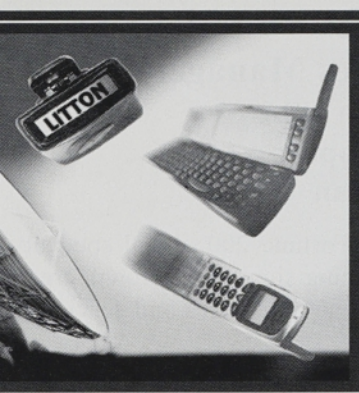
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The Components of Success

As a highly successful division of Litton Systems, Inc., Airtron is a leading manufacturer of compound semiconductor and laser materials to the global marketplace. Because of Airtron's scientific and engineering innovations and our ability to develop and deliver materials in a variety of applications for commercial, medical, industrial and military markets, we continue to experience significant growth as an organization. Airtron is seeking experienced scientific, engineering and technical talent in GaAs, SiC, GaN or any other semiconductor or photonic materials. To this end, our New Jersey and North Carolina operations have the following positions available immediately.

New Jersey Opportunities

Process Engineers

BS in Mechanical, Physics or Material Science Engineering. Positions have responsibilities for sustaining engineering requirements for crystal growth and fabrication manufacturing areas. Familiarity with six sigma concepts, crystal growth and machining skills are required. Experience in a semiconductor-manufacturing environment strongly preferred.

Mechanical Engineers

BA, BS, or MS with strong mechanical and electronic skills to design and build experimental apparatus, program and interface electronic and data acquisition equipment. It is essential that this individual interact professionally with the technicians, machinists and staff scientists.

Crystal Growth Scientists

Ph.D. with semiconductor crystal growth experience. Will be responsible for development of leading edge crystal growth processes and their transition into a full scale-manufacturing environment. Must be able to work independently, conduct scientific/engineering investigations, develop and test hypothesis and make conclusions based on data. DOE and SPC experience a definite plus. Good communication, organizational and planning skills are necessary.

Crystal Growth Engineering Technicians

Associates Degree with course work toward an engineering degree preferred. Good mechanical ability, organizational skills, and communication skills are necessary.

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Airtron Division, Litton Systems, Inc.

Director, Human Resources

200 East Hanover Avenue, Morris Plains, NJ 07950

Fax: (973) 539-6873, E-mail: nstubbs@littonairtron.com

North Carolina Opportunities

Process Engineers

BS in Chemical Engineering or Physics with some practical, hands-on working knowledge in the field of manufacturing of all optical products. Should have at least 5 years experience and be able to work effectively within time and budget constraints. Maintain computerized documentation of all processes.

Senior Manufacturing Engineer

MS/BS in Mechanical, Industrial, Robotic or Material Engineering with 5 years experience working with manufacturing processes. Will be responsible to transfer, implement and further refine development information into solid production capability for our Vanadate product line.

Senior Mechanical and Modeling Technologist

PhD in Mechanical Engineering or field related to modeling of crystal growth with demonstrated background in heat and flow modeling. Mathematical knowledge of thermodynamics related to crystalline solids is strongly desired.

Characterization Engineer

BS or higher in Scientific or Engineering discipline with a minimum of 3 years or more hands-on instrumentation experience required. Strong background in analytical characterization of materials and the ability to perform large-scale mechanization of these measurements for volume throughput.

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Airtron

OPTO JOBS!



TECSTAR INC., Applied Solar Division, is a privately held semiconductor R&D and manufacturing company in Southern California which operates a world leading III-V MOCVD growth foundry. Since 1954 we have produced photovoltaic solar cells for space satellite applications and are now leveraging our epitaxial growth expertise to enter the rapidly growing high brightness LED and VCSEL technology industries. The Optoelectronics Product Organization is a start-up division in an existing MOCVD facility that represents approximately 35% of the world's EPI manufacturing capability all under one roof. We are looking for fast paced, entrepreneurial, "think outside the box" type individuals with an interest in a commercial/ high production yet R&D intensive environment. We feel we have the best of all worlds coupling a start up venture with minimal downside risk as a result of being part of an existing established opto/photovoltaic leader in the industry.

- * Director of Optoelectronics Research and Product Development
- * Director of Epitaxial Growth Manufacturing
- * Optoelectronics Research Engineers

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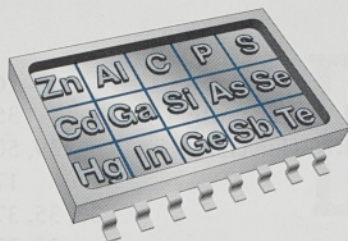
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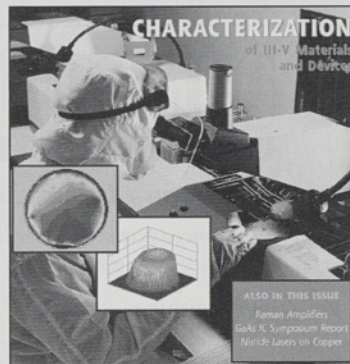
For more information, contact:

Marie Meyer
Managing Editor
COMPOUND SEMICONDUCTOR
Magazine
163 Cabot Street
Beverly, MA 01915
TEL [1] 978 927 9994
FAX [1] 978 927 9893
mmeyer@compsem.com
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TEL: [1] 978 927 9994

FAX: [1] 978 927 9893

Editor

Tim Whitaker

tim.whitaker@compsem.com

News Editor

Richard Dixon

rdixon@compsem.com

Managing Editor

Marie Meyer

mmeyer@compsem.com

SUBSCRIPTIONS

Please direct all subscription inquiries, changes of address etc., to Terri Bello, TEL: [1] 978 256 5421, FAX: [1] 978 256 1703;

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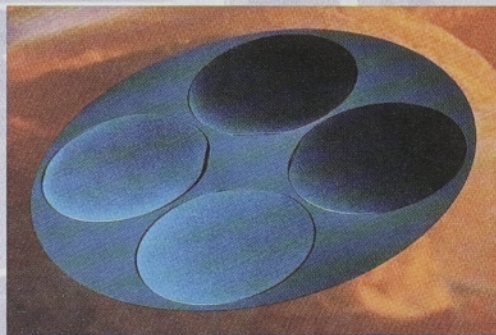
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JDSU Sells 980 nm Pump Laser Business to Nortel to Secure Approval for SDL Merger

The US Department of Justice gave its long-awaited approval for the merger of JDS Uniphase and SDL on February 6. As expected, JDSU was required to divest its Zurich-based 980 nm pump laser operation, which will be purchased by Nortel. Without this sale, according to the DOJ, the combined company would have controlled more than 80% of the market for this critical component. Nortel will pay \$2.5 billion for the business, and up to \$500 million in 2004 if it does not meet purchase commitments to JDSU. The Zurich operation was purchased by JDSU in 1995 from IBM for \$50 million.

Nortel is the world's largest consumer of 980 nm lasers, and could have easily scuppered the merger with a few well-placed objections. Analysts who follow both companies believe that Nortel received a very good deal from JDSU, perhaps in return for their compliance. JDSU said that several companies wanted to buy the plant. However, some analysts have questioned whether any of the other likely candidates—Lucent/Agere, Corning, Furukawa—had any deep-rooted interest.

nLight Photonics Joins Pump Laser Race

Optical amplifiers and the pump lasers that drive them are a crucial technology to support the continued capacity expansion of DWDM systems. nLight Photonics, a recent start-up based in Seattle, has just completed its second round of financing, providing \$44 million to accelerate the development of its innovative pump laser products. The funds will also facilitate the expansion of the company's manufacturing operations in Seattle and Vancouver, WA.

Predictably, precise details of the company's novel technology were not revealed. "We've developed a new way to make pump lasers, but we're also using a lot of standard approaches," says nLight President and CEO Scott Keeney, who adds that the company will have the capability to fabricate GaAs- and InP-based chips.

To support next generation optical transport systems, higher power EDFAs and fundamentally new Raman amplifiers will both be required, and in turn these will require advancements in pump lasers. nLight's technology is directed at achieving a "breakthrough in affordable bandwidth" by reducing cost and increasing functionality and integration levels. According to RHK, the pump laser market was the fastest growing segment in the optical component industry last year, growing at 170%, and is expected to continue growing at over 40% per year and to exceed \$4 billion by 2004.

nLight's second round was led by Menlo Ventures and Oak Investment Partners. The company raised \$9 million six months ago in a first round led by early-stage investor Mohr, Davidow Ventures. "nLight's high-performance pump modules address a unique opportunity to enable new optical amplifiers that will reduce system costs and increase data speeds to 40Gb/s," says Douglas Carlisle of Menlo Ventures. "What makes nLight so compelling is the team's execution in building high performance products that are also designed to be 'manufacturable,'" adds Bill Ericson of Mohr, Davidow Ventures.

The Zurich plant supplies around 40% of more than \$200 million in 2001 revenues, it will also provide Nortel with access to a renowned group of experts in the technology. This same group were the first to develop a facet passivation process that allowed production of reliable, high power 980 nm lasers, leading to widespread use of these devices in EDFAs. In turn, this enabled the explosive growth of DWDM networks.

Following completion of the transaction the Zurich site will become a wholly owned subsidiary of Nortel Networks. JDS Uniphase will retain several other European assets, including their source laser operation in the Netherlands and their laser packaging operations in the United Kingdom. "We are pleased that the agreement with Nortel Networks permits us to complete our merger with SDL," said Jozef Straus, CEO and co-chairman of JDS Uniphase. "We now look forward to quickly completing the transaction and moving ahead with the merger of our businesses in order to exploit the synergies that will enable us to serve our customers better.

Agility Ramps Laser Production to 1,000 per Week

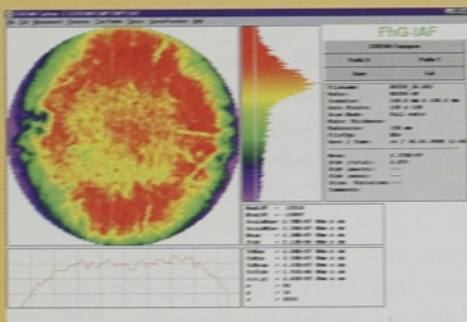
Agility Communications has finished the first phase of an expansion plan aimed at boosting capacity for packaged InP laser diodes to 1,000 per week by the end of the year. The 2-year-old spin off from UCSB has transferred all InP laser diode packaging from its original site at Santa Barbara to a 30,000 sq.ft. fully automated, high-volume manufacturing facility in Allentown, PA. The first products are expected this spring, and will include a tunable sampled grating DBR laser capable of producing 4 mW at any of 100 ITU channels across the entire C-band (1530–1565 nm).

The expansion is part of the company's intention to supply up to one million lasers per year by 2003. Agility's three-year manufacturing plan is to begin installing the necessary infrastructure to meet that goal, and the company anticipates completing phase two of the expansion to produce 10,000 lasers per week by the end of 2002. Agility is also evaluating additional manufacturing facilities worldwide to take it beyond an annual capacity of one million lasers.

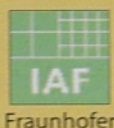
"Agility is recognized in the industry as being one of only a few companies in the world to have the expertise and facilities to manufacture these sophisticated, widely tunable lasers in desirable quantities at reasonable costs," said Ron Nelson, president and CEO. "Because Agility's high-power, widely tunable lasers have been exceptionally well received in the marketplace, we fully anticipate continuing to scale our manufacturing facilities to produce more than a million high-quality lasers per year to support the explosive growth in this industry."

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Alcatel Expands Component Production Capacity

Alcatel Optronics has invested more than 15 M Euro (\$14 M) to extend its production facility based in Lannion, Northern France. The new 20,500 sq.ft. production facility includes 12,100 sq.ft. of clean room space and will serve to increase Alcatel's manufacturing capacity for transmission lasers and submarine and terrestrial pump laser modules. The expansion will create more than 150 jobs.

"This investment plan illustrates our industrial strategy of developing the technological specialization of each of our production sites, allowing the flexibility to manufacture a variety of key components," said CEO Jean-Christophe Giroux. "In a period in which market demand evolves quickly, industrial processes and infrastructure must be modular, flexible, and intelligent."

Multiplex Opens High-Speed Design Center

Multiplex, a vertically integrated manufacturer of optoelectronic components based in South Plainfield, NJ, has announced the opening of a high-speed IC design center in San Jose, CA. The West Coast location will serve as an additional R&D arm to develop high-speed laser packages and receivers.

"With the addition of this design center, we will be able to dramatically cut our new product development times," says Multiplex president Won Tsang. "We currently offer end-to-end photonics

for 10 Gb/s applications, and the advancement of our R&D capabilities will greatly speed our entry into the world of 40 Gb/s transmission rates and other high-speed solutions."

Multiplex manufacturers high-speed electro-absorption modulated lasers for 2.5 and 10 Gb/s data rate applications, photoreceivers (including a variant that features an integrated limiting amplifier), high-power 980 nm pump lasers and electronically-tunable transmitters.

Optical Internetworking Forum Debuts VSR Specifications

The Optical Internetworking Forum, a non-profit group of 300 companies that promotes worldwide compatibility of optical internetworking products, has adopted two 10 Gb/s (OC-192) Very Short Reach (VSR) interface agreements. The two VSR standards are complementary and intended to help reduce the cost of OC-192/STM-64 links between equipment in a single central office.

VSR-1 is based on parallel optics and features twelve 850 nm lasers each operating at 1.25 Gb/s, such as used in commercially-available VCSEL arrays. Designed for distances up to 300 m, VSR-1 recommends the use of 62.5 μ m-core multi-mode ribbon fiber

and is potentially the lowest cost OC-192 link.

VSR-2 is a 1310 nm serial interface utilizing installed single-mode fiber over distances up to 600 m, which enables links within very large central offices. Compared to SONET Short Reach interfaces, this standard tolerates increased dispersion and reduced reach to enable cheaper devices to be used.

"Using existing interfaces designed for longer distances results in unnecessary cost," said Russ Tuck, chairman of Physical and Link Layer Working Group at OIF. "Carriers and network service providers can save thousands of dollars per interface by using OIF VSR interfaces to link co-located equipment."

Photodigm Receives \$2.5M in Funding

Photodigm (Richardson, TX) has closed an initial round of equity funding totaling \$2.5M. Backers included Corning Innovation Ventures and TriQuint. Founded early in 2000, Photodigm is developing a new type of hybrid device based on VCSELs and conventional edge-emitting lasers for use in telecom and datacom systems.

"Photodigm is developing a hybrid device that leverages the circular output and on-wafer test advantages of VCSELs, together with the high power and manufacturability of edge-emitting lasers," says Jack Mattis, VP of business development. "Essentially we use a sampled grating to reflect the light out of the surface of a conventional edge-emitting laser. This gives us the ability to test on-wafer and at the same time take advantage of the important telecom 1550 nm wavelength not yet available to VCSELs. It also leverages the high output power of edge-emitters and could lead to reduced manufacturing costs."

The company currently has a strategic relationship with Southern Methodist University (SMU) to use the wafer fabrication and grating facilities of the Photonics Laboratory. According to Mattis, Photodigm will initially produce devices at SMU and TriQuint, and may open its own limited fabrication/prototype facility in about a year's time.

Lucent Delivers High Capacity Networks to NTT and Time Warner

Lucent Technologies has installed two new optical networking systems that dramatically increase network capacity. A network installed by NTT Communications of Tokyo is Lucent's first commercial deployment that utilizes both the C- and L-bands for transmission. The WaveStar™ OLS 400GL DWDM system uses an L-band amplifier operating from 1565 to 1610 nm, while most current DWDM systems use only the C-band (1528–1563 nm). The system was designed to maximize the bandwidth potential of NTT's dispersion-shifted fiber, which can carry many more wavelengths in the L-band than in the C-band. The new system allows simultaneous transmission of up to 40 L-band wavelengths operating at data rates of 10 Gb/s.

In more news, Time Warner Telecom is to deploy Lucent's new 1.6 Tb/s optical networking system. Time Warner provides optical broadband networks and services to business customers, will be among the first to use the WaveStar™ OLS 1.6T DWDM system. Initially, Lucent will deliver and install the system with a capacity of 800 Gb/s (320 channels $\times$ 2.5 Gb/s or 80 $\times$ 10 Gb/s). However, the system includes a combiner/splitter that allows a carrier to double the network capacity without interrupting service when extra bandwidth is required. The installation is expected to be completed by mid-2001.

Tunable Lasers Finding Their Way into Networks

Two companies—Fujitsu and Atoga Systems—have introduced network products based on tunable lasers. Fujitsu Network Communications' new optical add drop multiplexing platform is the first to employ Fujitsu's tunable lasers as standard equipment. The system is capable of 1.76 Tb/s over an incredible 4,000 km without regeneration, which is achieved with optical amplifiers and spectrum analyzers. The system transmits at 10 Gb/s along channels with a spacing of 50 GHz.

Fujitsu's tunable lasers are currently offered in a 4-channel module, and the company plans to increase the number of tunable channels to 40 in future. The module responds to software commands that change the temperature and adjust the wavelength of the individual lasers. The laser sweeps across a range of pre-set frequencies, and when it reaches the desired one it is actively locked in place.

Atoga Systems (Fremont, CA) also claims to be first to market with a tunable laser product. Atoga's Optical Applications Router 5 enables flexible bandwidth provisioning and dynamic optical scaling. The system will offer 5 Gb/s of switching capacity, and allows dynamic scaling without hardware changes to simplify metro ring systems, which require manual tuning when extra wavelengths are needed to add capacity. The system is being beta tested with service providers and is expected to be on the market shortly.

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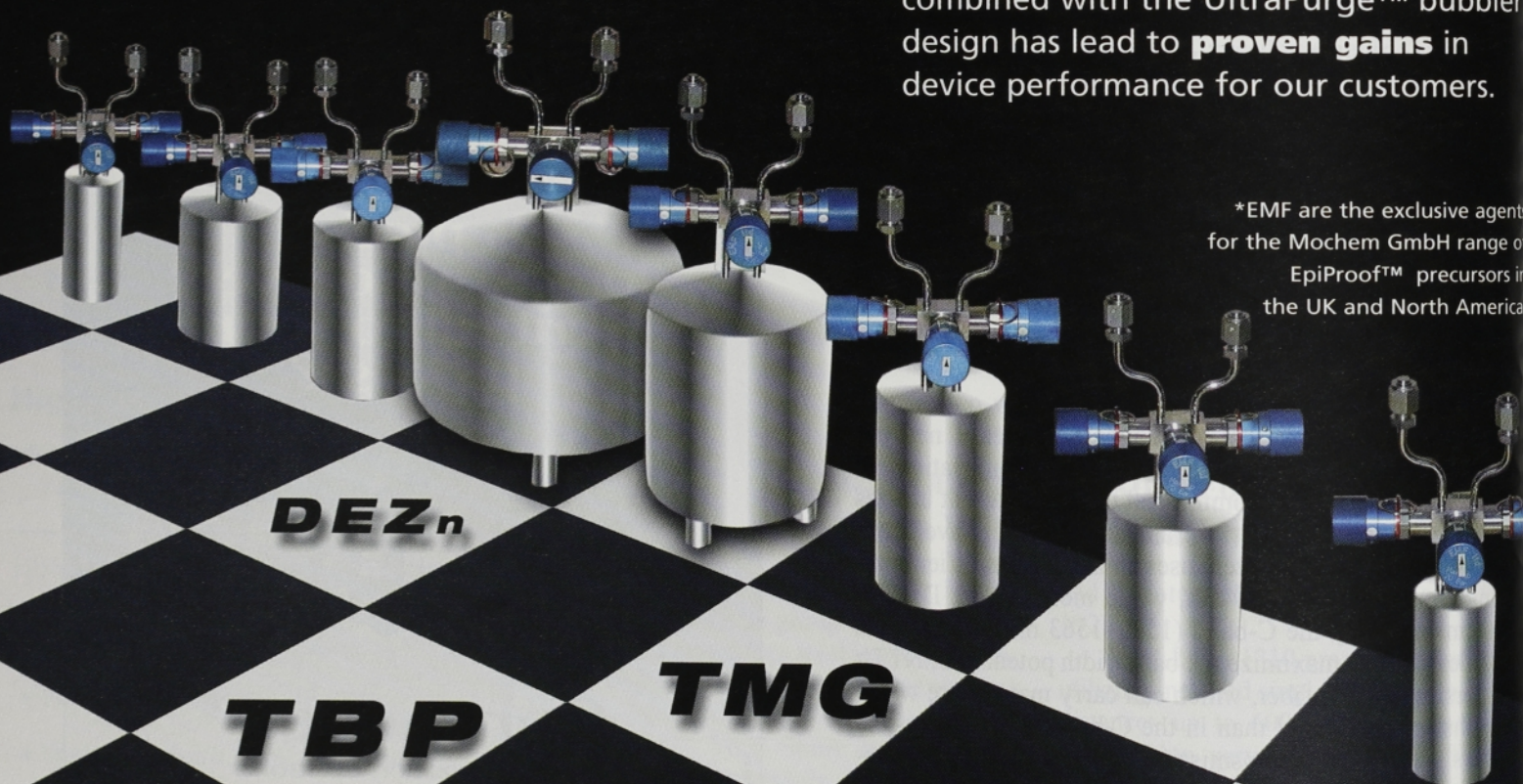
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Swedish Start-Up Optillion Receives More Funds

BRIDGET ADAMS

Swedish start-up company Optillion, currently based in Kista, has received second round funding of \$53 million. In what was one of last autumn's largest private placements in Sweden, Optillion raised the money through a new share issue. The company plans to develop, manufacture and market highly integrated, ultra-high bandwidth fiber-optic Ethernet transceivers for next-generation networks. Transmission capacity in the company's first transceiver is expected to be 10 Gb/s, for 10 Gigabit Ethernet, and future products will aim to enable even higher speeds.

Optillion is the brainchild of engineer turned business man Jan Nilsson. In all Nilsson has founded no less than 11 information technology companies, both in Europe and in the US, as part of an entrepreneurial career that spans 25 years. Starting in retail computer stores, he has moved through software companies, file-servers and into telecoms and datacoms components. In 1997, he founded Switch-Core, a company which specialized in silicon solutions for LAN switching and routing. Optillion was founded in December 1999 by Nilsson along with two leading Swedish academic researchers. Christer Svensson is a professor of electronic components at the University of Linköping and Lars Thylen a professor in photonics at the Royal Institute of Technology in Stockholm. In the company's first year they have put together a technologically strong team, with expertise in the fields of high-speed electronics, high-speed optics, automated manufacturing and encasing. The company currently employs 68 people, of whom 46 have M.Sc. degrees; 20 of those also have Ph.D. degrees in electronics or photonics.

Major seed investment for Optillion came from Itact, a Swedish venture capital provider specializing in early-stage hardware-related information technology

start-ups. The new second round funding comes from a group with lead partner Crescendo Ventures, and also includes Itact, Cisco Systems and Investor AB.

Products for 10 Gigabit Ethernet

The latest investment will help finance a new manufacturing facility currently being built in Stockholm, at which the company will manufacture high-performance transceivers in high volumes for 10 Gigabit Ethernet (10 GbE). The expected completion date is mid-2001, at which point it will become the center of Optillion's business operation. The financial boost will also enable Optillion to accelerate the development of its transceivers and open an office in the US.

The new production facility will fabricate optoelectronic chips, and encase and mount the transceivers. Indium phosphide wafers will be processed in order to fabricate lasers and detectors, and silicon wafers will be used to fabricate micro-mechanical optoelectronic chip carriers. Optillion will also be developing processes in the new plant, such as epitaxy, etching, lithography and metallization for the production of optoelectronic components. The devices they plan to make include DFB and DBR lasers, optical modulators, and detectors, for both 1310 and 1550 nm fiber-optic transmission at bit-rates of 10 Gb/s and higher.

Optillion is a principal member of the 10 Gigabit Ethernet Alliance, and is currently developing its first 10 GbE transceivers, which are designed to have lower power consumption and small size. Other criteria include design for automated manufacturing, which will ensure scalability, and field configuration for different transmission distances. The 10 GbE standard, IEEE n802a.e,

will be set by the first quarter of 2002; the modules are compatible with the proposals for the standard, and will be ready for launch in mid 2002. Prototypes will be ready by Q4 2001.

The transceivers are integrated, complete Ethernet PHY modules that provide high-speed serial links at a signaling rate of 10.3 GBaud. The physical (PHY) layer is a crucial part of the Gigabit Ethernet specification, and provides the interface between the media access control (MAC) layer and the transceivers in Gigabit Ethernet hardware. The PHY layer performs encoding, decoding, carrier sense, and link monitor functions.

Helène Wolpher, a spokesperson for Optillion, sees the company's strength in its team. "We have a team with world-class competence within high-speed electronic design, optical components, low-cost packaging and automated manufacturing. Moreover, the Optillion team has an excellent track record for 10 Gb/s and beyond, in providing low-cost, high performance products to the marketplace."

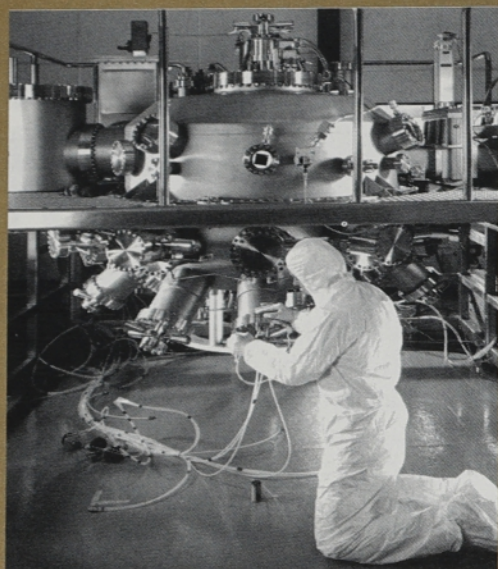
New C-Band EDFA Module from SDL

SDL has introduced a new range of low cost, small form factor EDFAs. The MA-C series is designed to provide cost effective amplification at specific points in the network to increase deployment flexibility. SDL is currently ramping volume shipments of this product to a number of customers.

These micro-amplifiers are well suited to the boosting of individual DWDM channels at the transmitter, as well as pre-amplifying signals at the receiver to increase effective distances or to better handle increasing bit rates. The MA-C can also be used to amplify single channels at an optical switch or wavelength router to compensate for losses, effectively making transparent switching possible.

Bridget Adams is a freelance writer based in the UK.

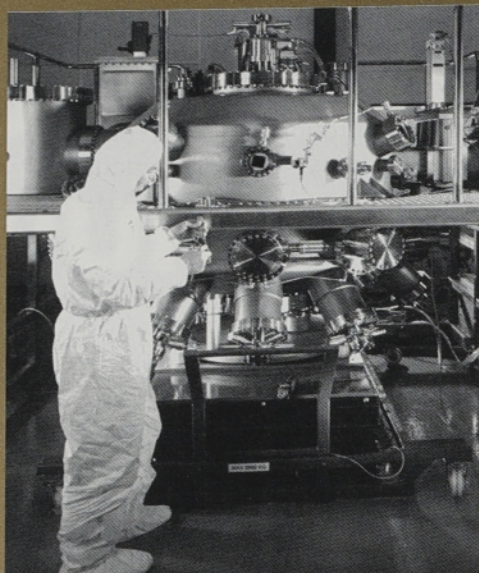
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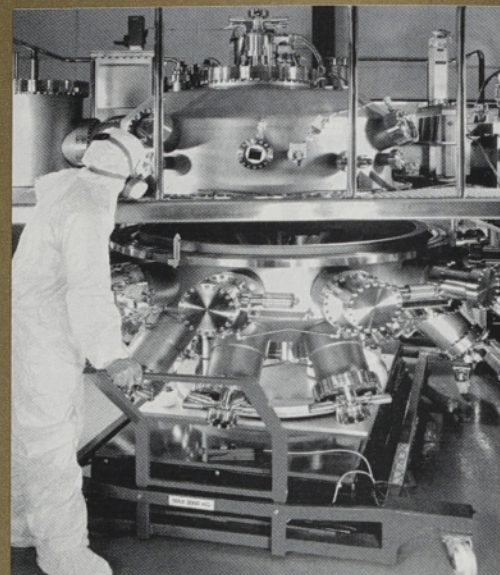
Now there's a way to significantly reduce this wasted downtime. VG Semicon's unique and exclusive chamber seal technology means the V150 is the first production MBE system ever that allows quick and easy removal of the entire source assembly.



2 *An hydraulic trolley is rolled underneath and takes the weight of the bottom half of the growth chamber. The four locating bolts are quickly removed.*

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3 *The trolley is lowered at the touch of a button and the entire lower section of the growth chamber is wheeled out for easy cleaning and source loading.*

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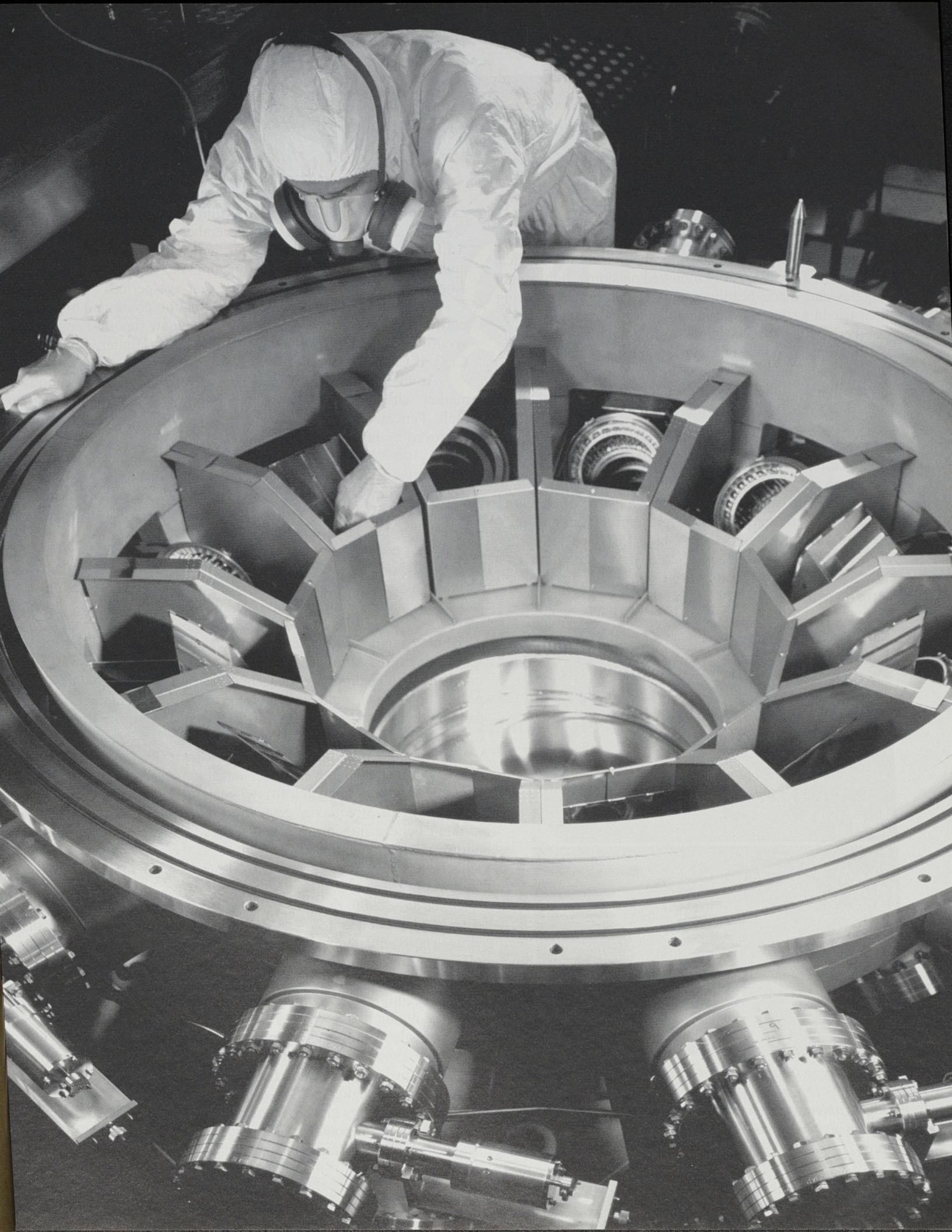
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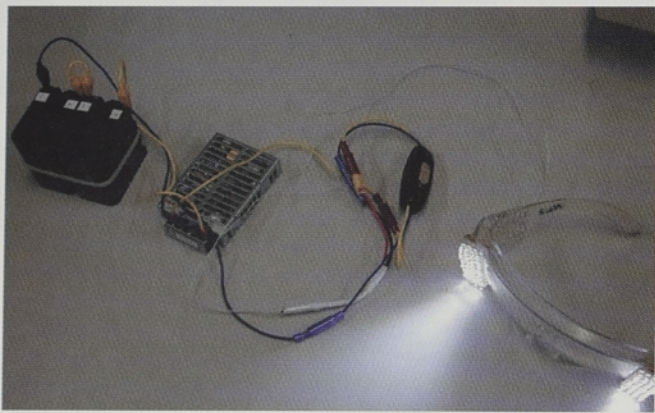


White LEDs Debut in Operating Theatre

Surgeons and scientists in Kyoto are collaborating on a head-mounted prototype white LED lighting system designed to provide directed illumination during surgical operations. The LEDs were mounted on simple lightweight goggles and made headlines in Japan recently following their use in a successful 2-hour forearm operation.

Performing surgery under normal halogen-based ceiling lighting fixtures can leave the surgeon's head casting shadow and even hindering the light source, but the head-mounted LEDs allow lighting under all operation conditions. The system uses 56 white Nichia LEDs on each side of the lenses to provide up to 450 lm of illumination, without overheating either the doctor or patient. Power is supplied by a relatively light 7.2 V waist-mounted battery.

Surgeon Junichi Shimada said that more sophisticated systems are currently being planned. One area of concern is the color rendering of the white emitters, which are based on standard 3 mm InGaN blue LEDs coated with yellow YAG phosphors. These 2-color devices do not correctly represent the red colors from skin, blood, tissue and internal organs.



Kyoto Prefectural Yosanomi Hospital

This prototype head-mounted light source uses 112 white LEDs to illuminate surgical operations, eliminating problems due to shadows and heating which are often experienced with standard overhead light sources.

Strong Results for Cree; LED Prices Decline

Bolstered by a 114% increase in sales of LED products, Cree's revenue grew 67% from \$24.8 million in the September quarter of 2000 to \$41.5 million in the December quarter. Average prices for LEDs declined 18% in the quarter, indicating a very large increase in unit volumes. The company's net income increased 145% to \$13.8 million compared to \$5.6 million in the year-ago period.

"We are particularly pleased with our continued revenue and earnings growth and the fact that we have now reported eighteen consecutive quarters of profitability," says Neal Hunter, Chairman and CEO of Cree.

Around 40% of Cree's LED chip production serves the automotive market, with displays and cellular handsets accounting for around 20% each. Penetration in these markets is very low, and will only be improved by tackling the key issues of cost and brightness. "The two primary drivers for our LED product line are higher brightness and lower pricing," says Hunter. "The recent introduction of our ultra-high brightness chip has closed the gap between SiC and sapphire, and Cree Lighting recently demonstrated a blue LED on SiC that is brighter than any device grown on sapphire."

Cree's new ultra-bright LEDs range from a 5.5 mW deep blue chip (460 nm) through to a 3.0 mW green chip (525 nm), and are two times brighter than the company's high-brightness devices [see CS 6(8), p.11]. Although only introduced in October of last year, the new ultra-high-brightness LEDs generated 8% of Cree's LED revenues during the December quarter. Because they offer a much lower cost per lumen, Cree expects the ultra-bright LEDs to replace demand for some of the company's older products. They may also allow Cree to gain greater penetration into the outdoor display and traffic signal market. The company predicts that the ultra-bright LEDs may account for up to 25% of LED sales in the March 2001 quarter.

Cree's goal is to reduce costs by at least 30% over the next six months through yield enhancement and automation. However, the company does not plan to switch from 2-inch to 3-inch wafers, partly due to the problems of epitaxial growth on larger diameter wafers. "Also, we don't believe moving to 3-inch offers us the best opportunity for short term cost reduction," says Hunter. "If we can get 20-30% higher yields from a 2-inch wafer, we can lower costs much more aggressively than by converting to 3-inch."

Since July 2000, the average sales prices (ASPs) of Cree's LEDs have already declined 13% due to expected contractual volume discounts. The company expects ASPs to decline approximately 25% in total during the fiscal year ending June 2001. Lower brightness products will experience more aggressive pricing declines. Interestingly, Cree has recently seen growth in demand for its oldest chip, which now sells in the region of 11 cents.

Cree is also gearing up to increase its production capacity. "Our facilities are expanding," says Hunter. "Our new epiwafer fab is partially operational and is coming on line in accordance with our needs, while our new packaging and test facility is now operational."

Sales of SiC wafers in the December quarter were up 40% compared to the previous three months. However, sales of SiC crystals for faux gemstone use appear to stagnating at around 5% of Cree's total revenues.

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III-Nitride Micro-Displays

Semiconductor micro-displays, which require the integration of a dense array of micro-size LEDs on a single semiconductor chip, have not been successfully fabricated to date. So far, large flat-panel LED displays, which are used on large buildings and in sports stadiums, are made up of a massive number of discrete LEDs.

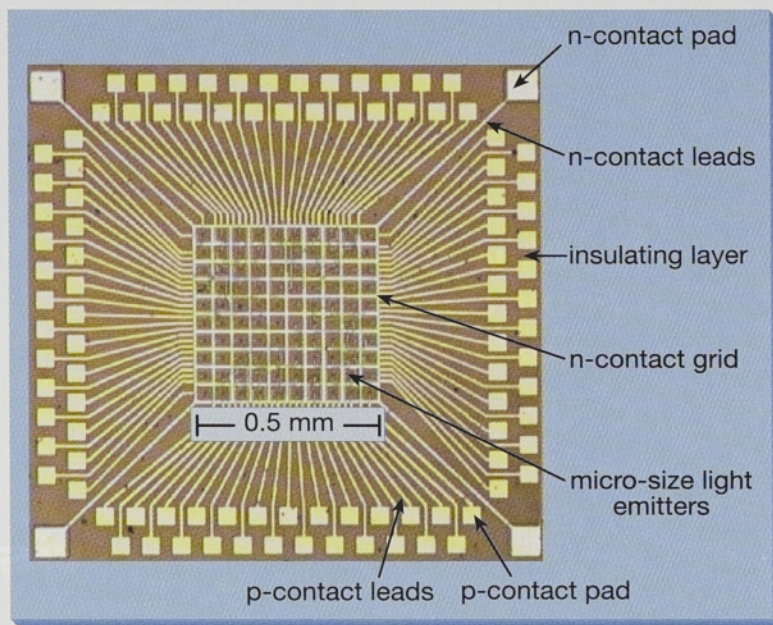
Last year, the group led by Hongxing Jiang and Jingyu Lin at Kansas State University (Manhattan, KS) demonstrated boosted emission efficiencies in interconnected microdisk LEDs [see *Compound Semiconductor* 6(8), p.14 and *Appl. Phys. Lett.* 2000, 77, p.3236]. Subsequently the successful fabrication of a prototype blue micro-display based on InGaN/GaN quantum wells was reported at the 2000 Fall MRS meeting in Boston. KSU's prototype device measures $0.5 \times 0.5 \text{ mm}^2$ and consists of 10×10 pixels, each being $10 \mu\text{m}$ in diameter (see Figures).

Although micro-displays are tiny, they can provide a virtual image comparable to viewing a 21-inch diagonal TV/computer screen when put into a headset and viewed through a lens system. Micro-displays can be used in a variety of devices such as head-mounted displays, camcorders and viewfinders, and are suitable for such diverse applications as computing, entertainment, military, law enforcement, fire fighting, medicine etc.

A New Display Technology

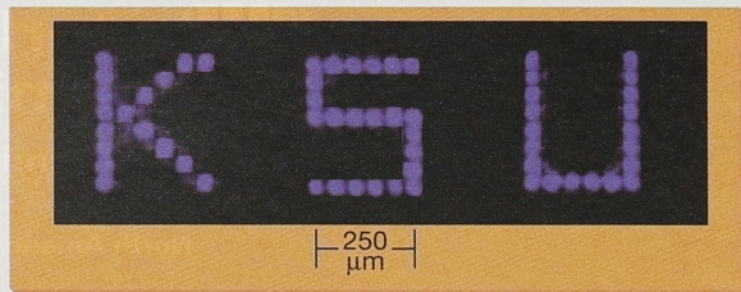
Current micro-displays are based on liquid crystal display (LCD) technology or organic light emitting diodes (OLEDs). Unlike LCDs, which require an external light source, III-nitride blue micro-displays are self-luminescent, resulting in both space and power savings. They also allow viewing from any angle without color shift and degradation in contrast. On the other hand, the current generation of OLEDs are only reliable when driven at current densities many orders of magnitude lower than semiconductor LEDs, and hence are not yet suitable for high-intensity (outdoor) use. Additionally, III-nitrides are grown on sapphire substrates that are transparent to light and hence can serve as a natural surface for image display, reducing the steps for device packaging.

Emission properties such as electroluminescence (EL) spectra, output power versus forward current (L-I) characteristic, viewing angle, uniformity, and speed of these III-nitride micro-displays have been measured. Due to the unique properties of



An optical microscope image of an individually addressed III-nitride microdisk array configured as a micro-display. The micro-display measures $0.5 \times 0.5 \text{ mm}^2$, and is made up of a 10×10 grid of $10\text{-}\mu\text{m}$ diameter pixels on a $50\text{-}\mu\text{m}$ pitch.

III-nitride wide bandgap semiconductors, micro-displays fabricated from these materials can potentially provide unsurpassed performance. Properties include high brightness, resolution and contrast; high temperature and high power operation; high shock resistance and wide viewing angles; and long life and low power consumption. All these features enhance the present capabilities of miniature display systems. It was also shown that the speed of these devices was very fast (around 0.3 ns). Since the fabrication of micro-size LEDs is much less sophisticated than VCSELs, the group believes that III-nitride blue micro-size LED arrays are also very attractive for inexpensive optical links.



Optical microscope image of the III-nitride blue micro-display in action; the letters K, S and U were displayed consecutively on the 10×10 display.

For more information, contact Hongxing Jiang at jiang@phys.ksu.edu. The group's paper entitled "III-Nitride Blue Micro-displays" by H. X. Jiang et al. is to be published in the February 26, 2001 issue of *Applied Physics Letters*.

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Nitronex Grows GaN HEMTs on 4-Inch Silicon Wafers

TIM WHITAKER

Nitronex, a wireless components supplier focusing on GaN-based devices, has announced that it is producing GaN-based HEMTs grown on 4-inch silicon substrates. In contrast, most other such devices have been grown on 2-inch diameter SiC or sapphire wafers. Furthermore, according to Bob Lynch, CEO of Nitronex, the room temperature mobility of the HEMT structures routinely exceeds 1600 cm²/Vs. "For production on a routine basis, this figure represents the highest mobility for GaN devices grown on such a large substrate," says Lynch. "We have also observed much higher mobility values in other samples."

"We expect to be able to demonstrate a 6-inch GaN-on-silicon wafer early next year."

"PendeoepitaxyTM" was a term coined by one of Nitronex's co-founders while at NCSU and refers to a process in which trenches are etched in a GaN layer and growth conditions are adjusted so that subsequent GaN growth occurs from the trench sidewalls. Although Nitronex has

licensed the relevant patent from NCSU, Bob Lynch says that Nitronex is not using this exact procedure,

and has in fact filed new patents on its proprietary approach.

Another key element is the novel MOCVD growth system developed by Nitronex. "We were unable to find a commercial MOCVD growth system that could grow on 4-inch wafers," says Bob Lynch. "Therefore, we built our own. These are multiwafer machines, and we have many of them." Among the unique design features of these machines are the gas distribution systems, along with the methods used to heat the large area substrates. "Uniformity of our epitaxial material is currently $\pm 5\%$, which we feel is excellent for such large wafers," says Lynch.

Products

As well as growing HEMT epitaxial wafers, Nitronex is building devices; Lynch reports that transistor performance has far exceeded expectations. "We have been working with outside partners all along, and they are now looking at our devices," he says. "Sampling on a wider scale will take place in April or May, and reliability tests are ongoing."

The devices are targeted towards a variety of markets in the 1.8–38 GHz range, including power transistors for cellular base stations. Other potential applications include MMDS (at fre-

The Pendeo Process

The high mobility is directly attributable to the quality of nitride material grown by Nitronex, which in turn results from the company's unique growth process combined with its specially designed MOCVD equipment. Precise details are not available at present, but a key feature is the nature of the layers deposited on the silicon substrate. "These layers are instrumental in reducing the strain between the substrate and epilayers, and alleviating the problems associated with lattice mismatches and different thermal expansion coefficients," explains Lynch. The result is a reduction in defect densities of many orders of magnitude compared to material grown by conventional techniques.

Nitronex uses the term "PendeoTM" to include its entire process from epitaxial growth to device fabrication, and has a number of patents in this specific area, including several licensed from North Carolina State University (NCSU).

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NITRIDE NEWS

quencies around 5 GHz), point-to-multi-point systems, and point-to-point radios.

Lynch feels that GaN devices grown on silicon are likely to offer considerable advantages over silicon carbide transistors, particularly in terms of processing. "We have some unique (and patented) backside processes to remove heat from the devices that will negate the advantages of silicon carbide's high thermal conductivity," he says. "SiC is a very difficult material to work with, while all our backside processes are done on silicon."

Multi-sourcing and Future Prospects

Nitronex has also been able to duplicate its manufacturing process at another company's fab in Europe. "This makes a big difference to our potential customers since it alleviates the risks of working with a single source," says Lynch. The fab in question was chosen since most of Nitronex's early customers are likely to be in Europe, and the facility has a good working knowledge of GaN.

Nitronex recently received \$9.5 million in its first round of funding, and plans to significantly increase the size of its facility in Raleigh, NC. Not content with the benefits of 4-inch wafers, the company is moving to still larger diameter substrates. "We expect to be able to demonstrate a 6-inch GaN-on-silicon wafer early next year," says Lynch.

This issue's Cover Theme:

CHARACTERIZATION

With high volume production a fact of life in the compound semiconductor field, characterization tools are critical to materials development and production. Coverage begins on page 54:

- FTIR Thin Film Metrology (page 54)
- Quantitative Mobility Spectrum Analysis (page 58)
- Thermal Conductivity Measurements (page 62)
- Photoluminescence Mapping (page 68)
- X-ray Characterization (page 72)
- Spectroscopic Ellipsometry (page 76)

Emcore Triples Manufacturing Capacity

Emcore has tripled the capacity of its manufacturing cleanrooms at the company's Albuquerque, NM facility. The site houses Emcore's solar cell division, which manufactures advanced triple junction solar cells for satellite applications, as well as the optical device division, which makes VCSELs, photodetectors and VCSEL arrays. An additional 36,000 sq.ft. of space was added to an existing 50,000 sq.ft. building.

"The additional cleanroom capacity is critical for us to serve our growing customer base, and provides an opportunity for Emcore to continually develop new product technologies for the rapidly increasing global communication markets," said Reuben Richards, president and CEO.

Opto Power Becomes Spectra-Physics Semiconductor Lasers

Opto Power (Tucson, Arizona), a manufacturer of high-power laser diodes originally acquired by Spectra-Physics in 1992, has been renamed Spectra-Physics Semiconductor Lasers (SPSL). The name change reflects the increasing importance of Opto Power's semiconductor lasers as critical components in the majority of Spectra-Physics' products. Spectra-Physics is a major supplier of high power multi-mode semiconductor lasers and solid-state laser systems. "Spectra Physics has been working for some time to make Opto Power a more fully integrated business unit within the company," said Alfred Feitisch of SPSL. "The name change marks the completion of that process."

The new identity follows the recent realignment of Spectra-Physics' business units to support growth in telecommunications and other markets deemed strategic to the company [see CS 6(8), p.23]. Along with its traditional high power laser markets in materials processing, biomedicine and graphics, SPSL will supply 915 nm and 975 nm multi-mode pumps for fiber lasers in telecom applications.

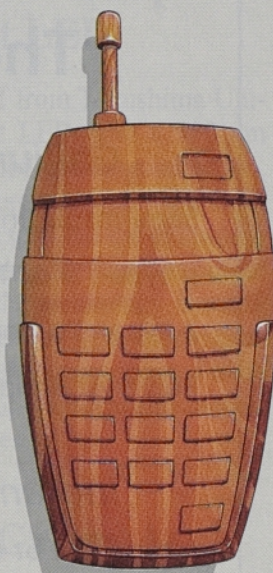
Quantum Cascade Lasers Warming Up

Applied Optoelectronics (Sugar land, TX) has demonstrated ACW operation in a quantum cascade laser up to a temperature of 210K (-63°C), around 35°C higher than the previous record held by Lucent Technologies. The company says the gain was achieved through improved material quality and thermal engineering of the laser structure to reduce the temperature rise of the active region during CW operation. Applications for the QC laser include spectroscopic chemical detection of trace gases, non-invasive medical diagnostics, industrial process control and environmental monitoring.

"Commercial applications demand CW operation near room temperature, and these results indicate that this is an achievable goal," said James Baillargeon, VP for Telecommunications Technologies.

The new laser demonstrated more than 8 mW of CW power at a wavelength of 5.2 μm , and AOI expects that the technology can also be rapidly applied to its 4.6 μm devices. The first commercial devices are planned for release this summer, a year after the company licensed the technology from Lucent [see CS 6 (6), p.21].

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Rohm To Build Major Manufacturing Base In China

Rohm Co. is to build a major device manufacturing complex, similar in size to its Kyoto factory, in the Chinese city of Tianjin, at an estimated cost of over ¥10 billion (~US\$85 million). The company aims to increase its overall production capacity for lasers and LEDs by 20–30%, to meet the growing demand for components used in cell phones and digital home appliances. Rohm has leased a 110,000 m² tract of land in a special economic development zone in Tianjin, and will start work building two factories at the site this spring.

Although the new facility, scheduled to begin operations in spring 2002, will export products globally, it will primarily target major Japanese and U.S. microchip and consumer-electronic companies with plants in China. Rohm will install its most advanced manufacturing equipment at the new plant, and will also close its smaller factories in other Tianjin locations and consolidate all manufacturing at the new site.

Ube Industries Quadruples Capacity for Metalorganics

Ube Industries Ltd. has quadrupled its production capacity for metalorganic compounds, and recently built new facilities for making these materials at a plant in Ube, Yamaguchi Prefecture. Equipped with synthesizing, refining and filling equipment, the plant can now produce up to about 1 ton of metallorganic compounds annually, around four times the level seen before the new facilities were built. The company will primarily produce methyl- and ethyl-based compounds of gallium, aluminum, indium and zinc. The new facilities will begin to operate at full capacity in two or three years at the earliest. The market for these compounds has been increasing at an annual rate of around 30%.

GaAs Quantum Dots Produced by Liquid Droplet Epitaxy

A way to fabricate large numbers of GaAs quantum dots of uniform size and shape has been developed by a joint team from the National Research Institute for Metals and the University of Tokyo. The method is named liquid-droplet epitaxy since the procedure involves spraying the starting materials to yield an arrangement of GaAs dots shaped like round droplets of water. Each tiny island of GaAs is just 5–20 nm in diameter and acts as a quantum dot, trapping electrons in a confined space and promising a future of extremely fast, low-power computing. The grains also emit

light at room temperature, suggesting new types of devices for the information society.

Starting with an AlGaAs thin film grown on GaAs, a liquid solution of gallium is sprayed onto the surface, creating numerous Ga droplets. Then As is sprayed over the wafer, creating GaAs quantum dots of common size and shape. Such features are thought to offer the potential for semiconductor lasers that emit light with one-hundredth the current of existing devices and quantum computers that operate at extremely fast speeds.

Nitride Semiconductors Develops 350 nm Ultraviolet LED

Nitride Semiconductors Co., a spin-off from Tokushima University, has developed an ultraviolet LED with a 350 nm wavelength and sufficient light output for commercialization. The wavelength of the devices, which were grown on sapphire, was achieved by optimizing the layer structure and the aluminum content of the GaN-based devices. Sample products can output 0.1 mW of light, and the company says the technology is ready to support outputs of up to 1 mW. Because they have short wavelengths and are easy to focus, ultraviolet LEDs are expected to be used in detecting microscopic quantities of chemical substances, as well as light sources for medical devices.

Furukawa to Recycle Ga and As

Furukawa is developing the technology for recovering gallium and arsenic from the GaAs semiconductors used in such products as cellular phones. The company intends to begin the service from around the middle of fiscal 2001, using the materials for its own production of GaP polycrystals, which are used for LEDs.

Advantest Develops Two-in-One Analyzer for Optical Networks

Advantest Corp. has developed a two-in-one measuring instrument for analyzing lasers and photodetectors used in fiber-optic systems. The single unit can test both the wavelength dispersion and polarization mode of light being sent and received, and is said to be the first such unit that can perform both of these tests.



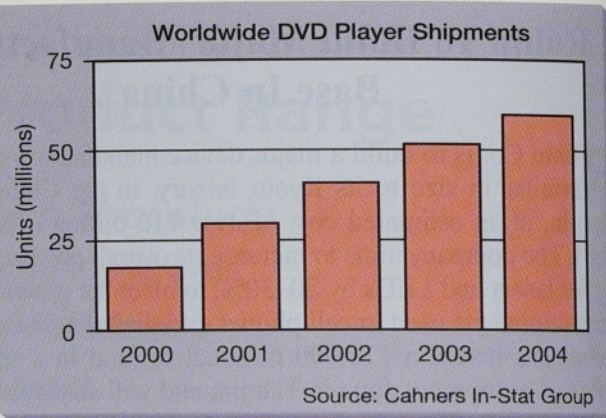
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DVDs Are Fastest Growing Consumer Electronics Product

DVDs are the fastest growing consumer electronics product in history and look set to continue this trend, says Cahners In-Stat, a market research firm based in Scottsdale, AZ.

DVD: More Than a Video Player forecasts the worldwide DVD market to grow from 28 million units in 2001 to more than 60 million units by 2004. This is being driven by new features such as DVD-Audio and new products such as TV/DVDs and DVD mini systems.

DVD players can read both DVD discs and CDs, which requires the use of lasers at different wavelengths. Typically DVD players employ AlInGaP lasers operating at 650 nm, and 780 nm AlGaAs lasers to read CDs.



Digital Satellite Will Continue to Lead Cable in Subscribers

Digital satellite transmission services such as digital Direct To Home (DTH) will continue to dominate digital cable TV in the race to replace analog transmissions, says a report by Cahners In-Stat.

According to *Worldwide Digital Satellite & Cable TV Services*, digital satellite subscribers will be almost twice as numerous as digital cable television subscribers in the next 5 years. The report also notes in the last decade the number of

worldwide cable TV subscribers has doubled to 280 million, but currently only 11.7 million subscribe to digital cable.

The growth of satellite and cable services is good news for GaAs. In satellite systems, GaAs MMICs are used to send and receive millimeter-wave signals. For cable systems, set-top boxes and cable modems require

components such as low noise up- and down-converters, as well as video and data tuners, which can be implemented using GaAs.

Subscribers to Digital TV Services

Subscribers (millions)	2000	2004
Digital Satellite	36	95
Digital Cable	11.7	48

Source: Cahners In-Stat Group

MATERIALS AND EQUIPMENT

Epigress Triples Capacity

Epigress AB has added a new production and office facility in Lund (Sweden) that will more than triple the company's annual capacity of CVD equipment. The new facility is designed to meet the demands of assembly and testing of single- and multi-wafer high temperature CVD and sublimation systems for SiC, in addition to UHV CVD systems for SiGe.

"This new facility will give us the long term expansion capacity to meet the increasing global market demand for our process equipment and services," said Jan-Olov Fornell, managing director of Epigress. "Epigress will further optimize its production work-flows in the new facility with the objective to shorten our lead times, from order to shipment. As a member of the Aixtron group, Epigress is now positioned for rapid growth, while overseas service will be increasingly be made available through the Aixtron network."

Aixtron Sells 500th Reactor

Aixtron recently sold an MOCVD system to Mitsubishi Electric (Itami, Japan), an AIX 2600G3 that will be used in the volume production of lasers. The order marks a milestone for Aixtron—it was the company's 500th system sale since the company's foundation in 1983. Aixtron says it has sold over 250 multiwafer production machines for compound semiconductors—around 190 machines over the last two years—including 30 multiwafer 6-inch machines for GaAs-based microelectronics applications.

E2O Selects Temescal Evaporation System

Temescal (Fairfield, CA) has been chosen to supply E2O Communications with a BJD-1800 evaporation system, to be used to process devices at E2O's 22,000 sq.ft. development facility based in Camarillo, CA. E2O sells VCSEL-based fiber-optic transceivers. According to E2O's director of marketing Mike Hartmann, the company is currently developing optoelectronic devices including long wavelength (1310 nm) VCSELs for all-optical communication networks. "Once developed, our devices will be manufactured at a new offshore manufacturing facility in Asia," says Hartmann.

Kopin Introduces InGaP/GaInAsN HBT Epiwafers

Kopin (Taunton, MA) is sampling InGaP/GaInAsN HBT epiwafers, designed to enhance the reliability, temperature stability and RF performance of HBT transistors based on existing GaAs manufacturing processes. The new process augments the company's recently announced C-doped InP HBT epiwafers.

"We are delighted to announce our success in incorporating indium and nitrogen into the base layers of our HBTs," said John Fan, president and CEO. "We have achieved substantial reductions in turn-on voltage of more than 150 mV with these InGaP/GaInAsN structures, while retaining excellent device characteristics. This major technical advance should enable significant improvements in GaAs-based HBT power amplifiers for advanced wireless handsets by lowering the operating voltage, increasing the efficiency and reducing power consumption."

Tegal Receives Etch System Orders

Tegal (Petaluma, CA) has received an order from Sumitomo Electric Industries (SEI) for a Tegal 901G diode plasma etcher—the third placed by SEI in the last 12 months. SEI will use the system to etch SiO₂, SiON and SiN films and photoresist, in order to increase its capacity for GaAs IC production for communication devices manufactured at the company's Yokohama plant. "As SEI continues to invest in its manufacturing facilities, Tegal's equipment has proven to be the most flexible and robust etching systems available for GaAs substrates," said Shigeru Nakajima, group leader of electron device technology for SEI.

Tegal has also received an order from a global supplier of broadband networks for multiple plasma etch systems. Scheduled for installation this month, the systems will be used for nitride and GaAs etching to support development and production of high speed ICs.

Suss Probe Tester

Operates up to 110 GHz

Karl Suss (Munich, Germany) has launched a very high frequency (VHF) test probe that enables phase-error-free measurement up to 110 GHz—a capability increasingly in demand for communications devices. In current systems, heavy tuners have to be placed away from the prober with long connecting cables that dampen the signals, says the company. By allowing the turners to be located at the ProbeHead, the Suss PH300HF probe reduces the potential for errors due to long cables or cable movement during testing.

"Although most components that are being tested right now are in the 20–40 GHz range, the market is seeing a rise in demand for higher frequencies in the research and development fields," said Claus Dietrich of Karl Suss. "This is due to the emergence of such technologies as distance sensors for cars which work in the 80 GHz range."

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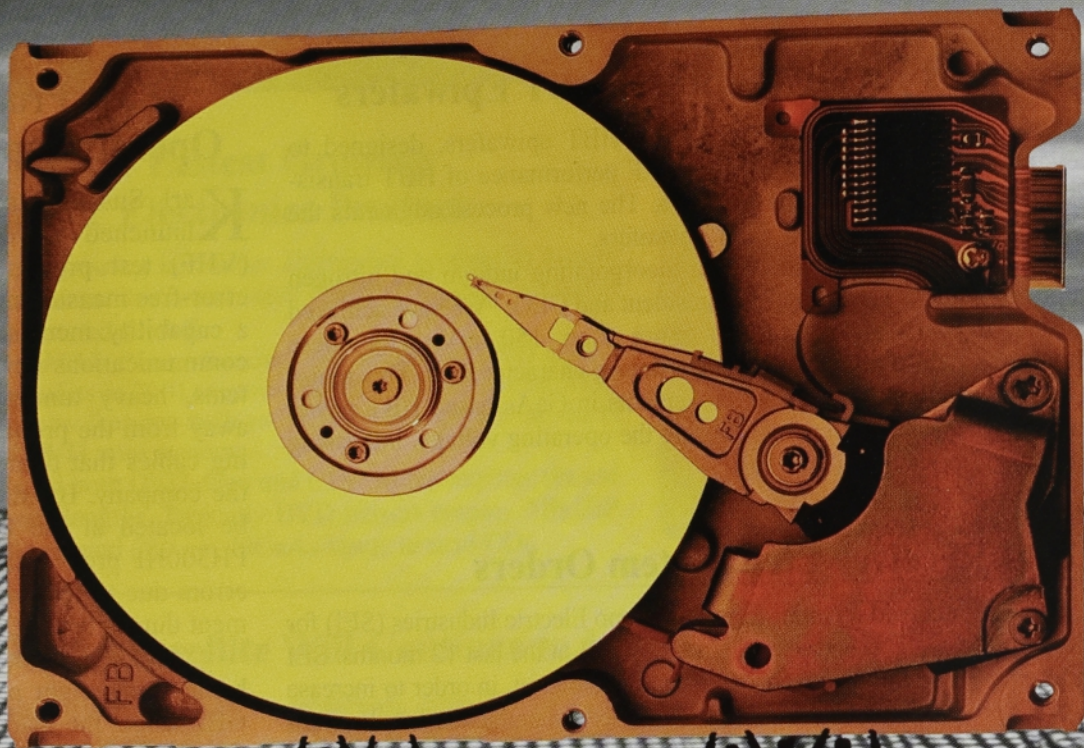


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Earnings Round Up for the December 2000 Quarter

MARIE MEYER

On January 30 Nokia warned that the entire wireless industry would slow this year, as consumers bide their time in expectation of next-generation services that will not come to market for several months. The Finnish giant said that global handset sales for 2001 might range between 500–550 million units, with the bottom end of the range being the most likely scenario.

Handset sales have been growing at a furious pace over the past several years, so much so that the *global* penetration rate for mobile phone subscribers is now believed to be around 12%. The key to moving that figure even higher was intended to be third generation (3G) digital services that would require new handsets. But the rollout of these services is taking longer than initially expected. In fact, operators are still working on the so-called 2.5G phones. Global Packet Radio Service, also called GPRS, is an upgrade of the Wireless Application Protocol currently in use to allow phones to make rudimentary connections to the Internet. GPRS was initially planned to be up and running late last year, but the absence of appropriate handsets has made that impossible. So far, only Motorola has presented a model. But Nokia is now saying that it will release GPRS phones in the third quarter of this year, with sales expected to reach millions of units by the fourth quarter.

The forecast proposed by Nokia—a current lull, with brighter prospects for the second half of the year—was also present in many of the earnings announcements by GaAs IC companies. And it seems to apply to the fiber-optic industry as well. As shown below, current market conditions are unfavorable for consumption of GaAs ICs, because manufacturers of wireless handsets, fiber-

Major News from December Quarter Earnings Announcements

- Broadband now accounts for 20% of Alpha's sales
- Anadigics' wireless business down 70% from last year
- Celeritek investing in a Taiwanese foundry
- Endwave angling for Ericsson outsourcing
- Filtronic seeks to contain losses from GaAs operation
- Module manufacturing said to be key for RFMD's revival
- Stanford Microdevices doubles sales in first year as a public company
- TriQuint tops \$300 million in revenues for 2000
- Vitesse one of the few semiconductor companies to actually beat earnings estimates

optic networks and CATV digital set-top boxes are sitting on top of large inventories that they need to work through before they can order new parts. But yet there is nearly universal optimism that the situation will correct itself in the second half of the year.

Alpha Industries

Alpha Industries announced record results for the December quarter, but warned that their book-to-bill ratio had dipped below 1.0, indicating a downturn ahead. For the quarter net sales increased to \$78.7 million, up 7% over the September quarter and up 64% compared to the

December 1999 quarter. Net income rose to \$11.6 million, compared to \$5.5 million for last year.

David Aldrich, Alpha's President and CEO noted that he was pleased with his company's performance, but also reported a decline in orders late in the quarter, which resulted in a book-to-bill ratio of 0.97. (The book-to-bill ratio compares the value of new orders received, or "booked", to the value of orders filled and shipped, or "billed".) Commenting on this turn of events, Aldrich said, "Our forecast is cautious and reflects the uncertainty that currently exists in the component supply chain." He went on predict that Alpha would show no growth in revenue for the next two quarters, but that it would maintain solid operating profit margins. But he also offered hope for improvement in the second half of the year, saying, "we expect order rates to rebound, along with a return to strong net sales gains . . . This forecast is based on our customers' projections for rising global handset growth in the second half of calendar 2001, our increased customer penetration and a reduction of inventory in the supply chain."

In the December quarter, Alpha's broadband sales exceeded forecast, topping \$16 million, or more than 20% of total sales. This category includes GaAs HBT and PHEMT products such as amplifiers and switches as well as ceramic filters. Applications include digital set-top boxes, cable modems, digital broadcast satellites, fixed wireless access and fiber-optic equipment. In the mobile wireless area, Alpha recorded "high levels of design and production activity" from emerging manufacturers of wireless handsets. In the quarter Alpha received their first production

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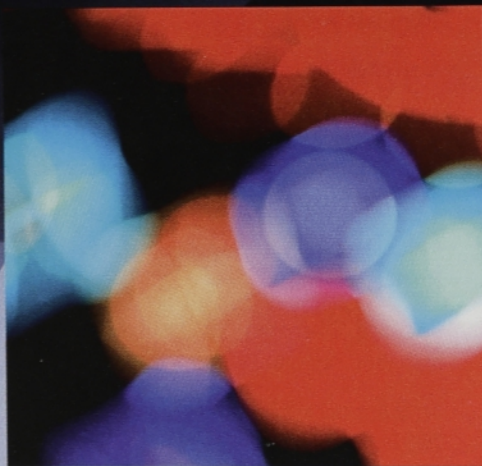
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order for RF semiconductors from Sony, and also made their first shipments of GaAs ICs for Siemens' newest dual-band GSM wireless handsets for the European market. Shipments to Motorola, Alpha's biggest customer, increased 14% over the previous quarter on the strength of power amplifier and switch shipments for Motorola's newest GSM phones.

Anadigics

As expected, Anadigics logged a disappointing December quarter. Late last year the company warned that its results were going to suffer due to inventory corrections at major customers and a slower than expected volume production ramp of the company's newly introduced HBT power amplifier products. The final figures, released on January 29, showed net sales of \$30.7 million, a 24% decline from the year-ago period and a 40% decline from the September 2000 quarter. The company reported a net loss of \$0.3 million, including \$1.3 million inventory write-off.

Sales to the CATV industry accounted for nearly 60% of sales, followed by wireless (22%) and fiber-optics (18.5%). The wireless segment showed the largest decline, dropping 67% from the previous quarter and 70% from the year-ago period [see Figure]. In comparison, broadband revenues (CATV + fiber optics) were down 22% from the third quarter.

"Our December quarter performance was affected by overall communications market conditions and inventory corrections at certain customers," said Bami Bastani, President and CEO. "We continue to focus on introduction of new products and diversification of our customer base and the results of our efforts are expected to materialize in first half 2001."

Celeritek

Celeritek reported record revenues and income for the December quarter (\$24.2 million and \$2.6 million, respectively). You might think that was good news. Unfortunately, the analysts who follow the company had been expecting

\$3.25 million or more in income. Moreover, the company reported that its gross margin fell to 24% of sales in the December quarter from 29% in the September quarter. It also announced that sales in the March quarter would show little growth. As a result, Celeritek shares lost nearly half of their value on the day following the announcement, in the heaviest day of trading ever for the stock.

But Celeritek is showing some growth in its semiconductor operation. For the December quarter sales of semiconductor products increased 12% to \$13 million, which equals 53% of total sales. Tamar Heusseini, President and CEO of Celeritek, indicated that semiconductor revenues are around 150% higher than last year. "We are confident of continued improvements in our semiconductor business, as we expand and diversify our customer base," he said. Celeritek received orders worth more than \$1 million for newly introduced fiber products in the December quarter, including a production contract from Vitesse for a driver amplifier for use in high bandwidth external fiber-optic modulators. Celeritek also reported \$2.6 million in new production orders for InGaP HBT modules, and subsequent to the close of the December quarter the company announced an additional \$15 million dollars in orders for these products.

"Both our orders and design wins demonstrate the expansion of our customer base and product offerings and the success of our technologies in various markets," said Husseini. As an example he cited receipt of a recent contract for \$4.5 million contract to "process wafers for millimeter wave applications".

The company is working to expand its semiconductor manufacturing capacity. One of the steps taken is a \$2.4 million investment in Sunket Compound Semiconductor Co. Ltd, a GaAs foundry being constructed in Taiwan. "It is our stated manufacturing strategy to outsource a portion of our foundry work and we expect this investment

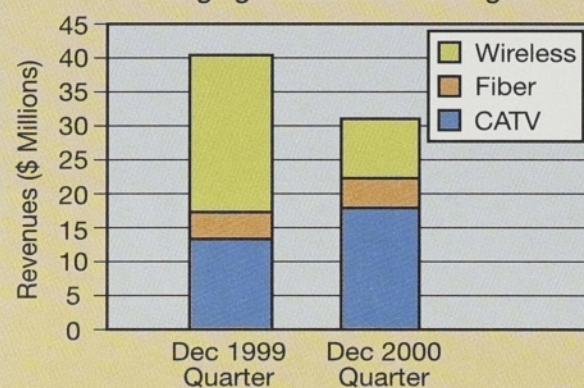
to secure increased semiconductor fabrication capacity for Celeritek in the future," said Husseini. The foundry is targeted to be in production in 18 to 24 months. In addition, Celeritek has added more semiconductor test capacity, and is in the process of expanding its own fab in Santa Clara, CA.

Endwave

Endwave Corporation reported revenues of \$13.3 million, more than double the results for the year-ago quarter. But the company recorded a net loss of \$9.2 million, which is also roughly double the year-ago results. These figures are based on a retroactive combination of the accounts for Endgate Corporation and TRW Milliwave, which were merged in March 2000 to form the current company.

Commenting on the news, Ed Keible, President and CEO, said, "Looking ahead to 2001, we anticipate strong demand from the cellular backhaul and point-to-point broadband access markets, and we are very pleased with our renewed agreements with Nokia and Allgon." In November Endwave announced a multi-million dollar contract with Nokia Networks for transceivers that Nokia plans to install in its FlexiHopper microwave radios. These will be used in broadband wireless networks over the next two-and-a-half years. And in late January Endwave announced a three year, multi-million dollar agreement with Allgon Microwave for 23, 26, 29, and 38 GHz transceivers for 2G and 3G cellular networks.

Changing Channels at Anadigics



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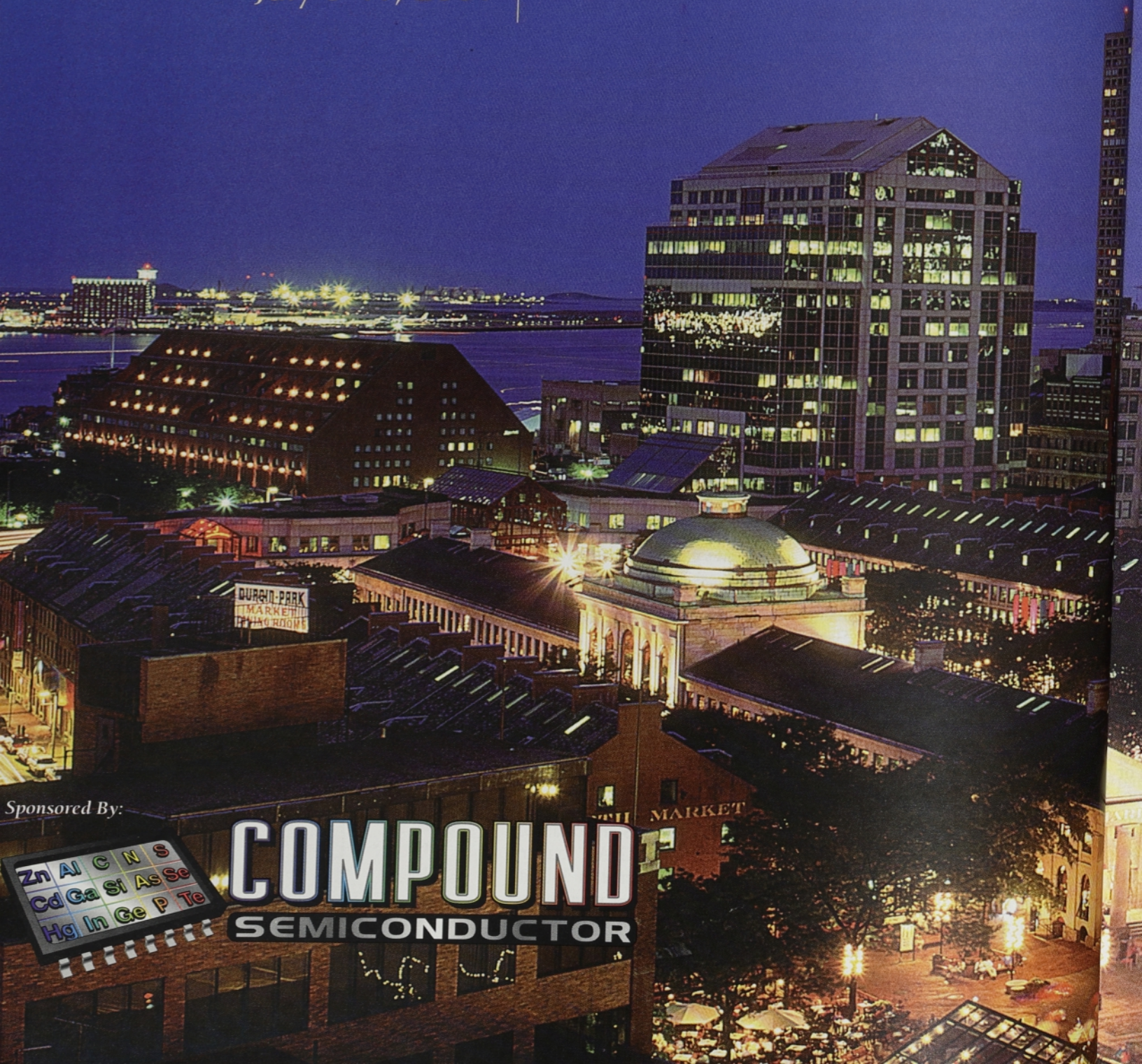
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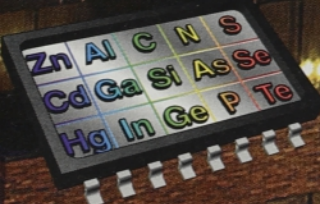
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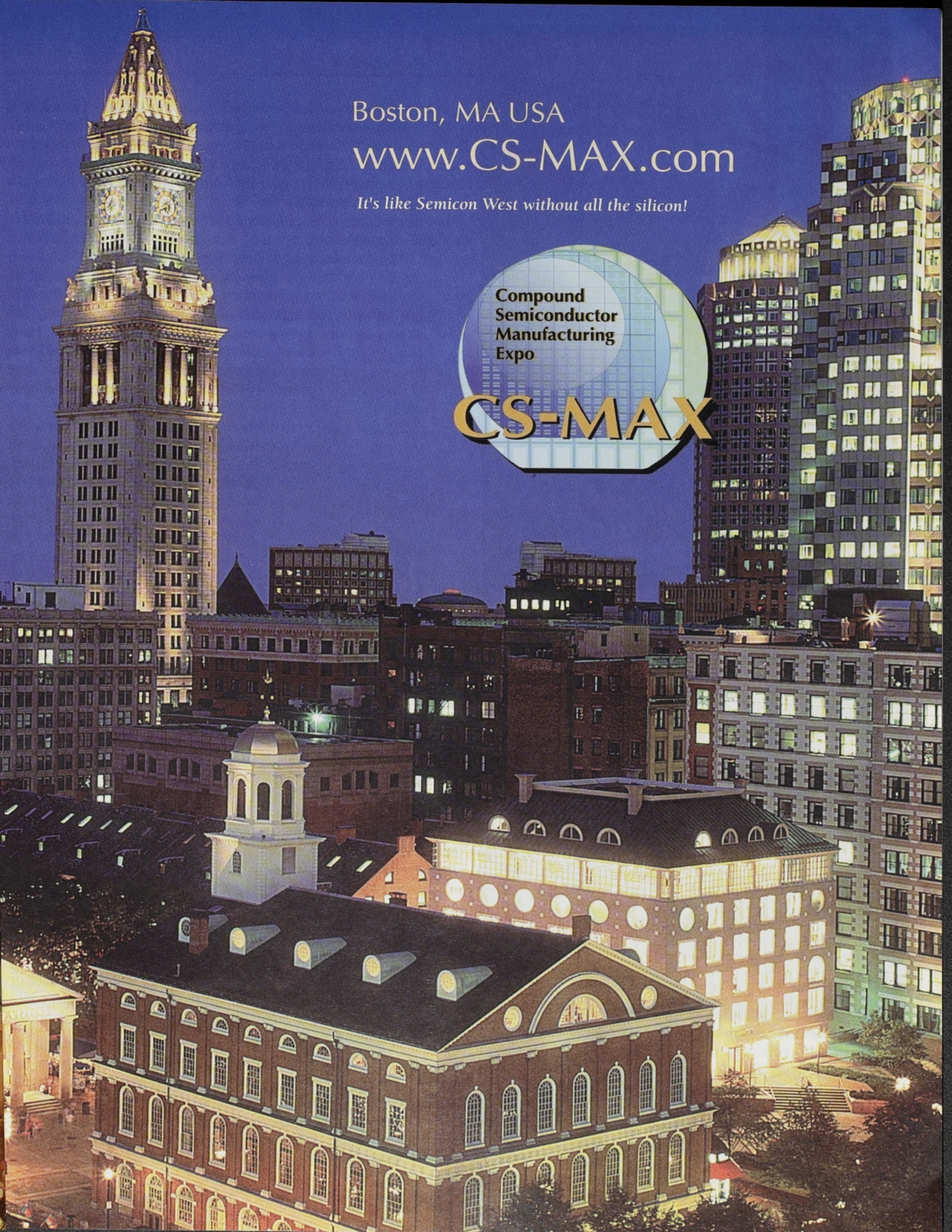
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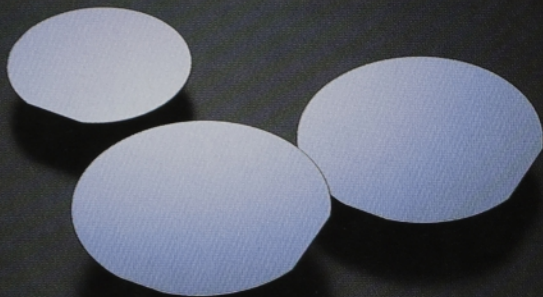
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GaAs NEWS

As Endwave tries to improve its profitability picture, it is making adjustments to its manufacturing strategy. In late January it opened a second volume manufacturing facility in Diamond Springs, CA, giving the company capacity to manufacture over 100,000 transceivers per year. Current production is running at a rate of approximately 40,000 units per year. Endwave will concentrate volume manufacturing for all of its electronic products—RF modules, mm-wave transceivers and outdoor units (ODUs)—at the new Diamond Springs facility, which has a lower cost structure than the company's other facility in Silicon Valley.

Endwave already has many of the major players in the wireless infrastructure business as customers. Nokia, Nortel, and Hughes are their top three customers, each accounting for more than 10% of Endwave's total revenues. In a conference call with investors, Endwave management hinted that they might be close to landing a few more "10% customers". The most promising candidate would like be Ericsson, in light of its recently announced decision to outsource the manufacturing of its mobile handsets. Ericsson is the last major captive manufacturer of millimeter-wave transceivers. If the company chooses to outsource this activity, analysts believe that Endwave—the largest merchant manufacturer—would be a logical choice.

Filtronic

Filtronic plc is taking steps to contain the losses stemming from its GaAs operation. A new group, Filtronic Compound Semiconductors, has been formed within the company. It consists of Filtronic's new 6" fab in Newton Aycliffe, England and the former Litton Solid State GaAs fab in Santa Clara, California. For the six months ended November 30 the company as a whole reported revenues of \$214.7 million, with an operating profit before goodwill of \$9.16 million. However, the Compound Semiconductors group generated a loss of \$10.76 million on \$7.4 million in sales.

According to a company statement, merchant sales from the Santa Clara operation have increased, mainly due to an increase in the production of PHEMT devices for photonics applications, but sales are still below the break-even point. With regard to the other facility, the company said that "the yields now anticipated from the Newton Aycliffe facility substantially exceed our early expectations and, as a result, will provide a capacity far in excess of that required for our foreseeable internal use. Additionally, the time scale required to establish and qualify products with customers was underestimated." The costs of operating the facilities are now more than \$1.5 million per month, and stemming from a cash outflow from the group "has assumed the highest priority."

Filtronic says it is looking for a strategy that will "reduce and eliminate the financial burden" of the Compound Semiconductors group as soon as possible, including discussions with potential commercial and financial partners.

RF Micro Devices

For the December quarter RF Micro Devices reported revenues of \$79.9 million, a decrease of more than 20% from the September quarter. Net income was \$7.8 million, compared to a loss of \$1.1 million in the September quarter.



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pared to net income of \$17.7 million for the previous quarter. RFMD management predicted that revenues for the March quarter would decline another 10%. The company will also suffer a hit of \$3–3.5 million stemming from their decision to delay opening their second fab until sales pick-up again.

Looking beyond the March quarter, RFMD is betting that the handset industry will grow at 25–35% in 2001, consistent with current industry estimates. RFMD hopes to post even higher growth rates by increasing its market share. To achieve this, it is emphasizing sales of multi-chip modules as opposed to the traditional single-chip power amplifier. RFMD's sales of modules in the December quarter increased 3X over the previous quarter, accounting for 16% of revenue. David Norbury, President and CEO of RFMD, said "We view the investment we've made in module technology to be as strategic to the company's future growth as the decision to adopt GaAs HBT technology several years ago." Analysts who follow RFMD had believed that the company was losing a significant portion of its business with Nokia to Hitachi, who took the early lead in module production. The impressive growth shown in the December quarter is believed to be a sign that RFMD is clawing its way back into the good graces of its largest customer.

The company is also hoping for gains in the CDMA market. In the December quarter revenues from sales to CDMA handset manufacturers grew 11% sequentially and comprised 24% of revenue for the quarter, versus 16% in the September quarter. RFMD is involved in a strategic alliance with Qualcomm, the leading developer of CDMA technology. During the quarter RFMD also announced that it had begun production shipments of a GaAs HBT power amplifier to be used in Motorola's popular Talkabout two-way pagers.

Norbury summarized the overall outlook for the company by saying that the disappointing results for the December quarter, and their extension into the March quarter, was largely a "near-term" problem. In the long run, Norbury said, "we believe we are extremely well positioned to exceed growth estimates for the

handset industry. Specifically, we anticipate our module technology will enable us to take additional share in GSM and CDMA while remaining strong in TDMA. Our customers tell us the transition to modules is mandatory, and we see tremendous potential for our module products across all air interface standards beginning at the end of the March quarter."

Stanford Microdevices

Stanford Microdevices reported net revenues of \$10.7 million, up 87% from the year-ago period and up 20% from the September quarter. Net income was \$1.3 million, a more than 5X improvement over the September quarter. These results were in-line with analysts' expectations, thus the company's stock did not get much of a "pop" from the announcement. Net revenues for the full year were \$34.6 million, nearly double the \$18.1 million reported for 1999.

"Solid revenue growth continued through the December quarter, driving sequential earnings momentum, as we fortified our market position and strengthened our business," said Robert Van Buskirk, president and CEO. "During the quarter, we expanded our product lines for current and next-generation (2G/2.5G/3G) mobile wireless infrastructure equipment, while extending our leadership in the design and marketing of broadly applicable, technology-enabled RF components. Overall, we're pleased with our first year's performance as a public company. Our current outlook for 2001 calls for continued growth in revenues and earnings, as we manage the business conservatively

through near-term uncertainty in the telecommunications market."

Looking forward, the company has indicated that revenue growth will be flat in the March quarter, but that they expect to resume double-digit sequential revenue growth in the following quarters of the year. In fact, management has gone so far as to say that sales are expected to ramp roughly at 15%, 25% and 30%+ on a sequential basis for the last three quarters of 2001. Some analysts, however, are taking a more conservative view and making their own forecasts that are a few percentage points lower.

TriQuint

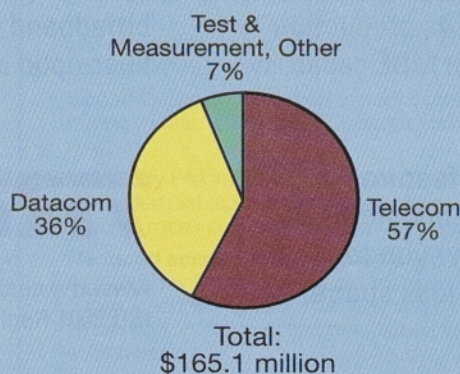
TriQuint reported record revenue and income results for the December quarter. Revenues were \$90.3 million, an 83% increase over the comparable period of 1999. Net income was \$23.2 million, a 127% improvement over the \$10.2 million reported for the December quarter 1999. Sequentially, revenues increased 12% and net income increased 10% over the September quarter.

In commenting on the results, Steven Sharp, TriQuint's Chairman, President and CEO stated, "This has been an unbelievable year for all of us at TriQuint, one that we will never forget. We have not only been involved in a number of rapidly growing markets but we have continued to diversify our products, our technologies, and our customer base while at the same time improving our business and operational processes."

Vitesse

Vitesse reported December quarter revenues of \$165.1 million, an increase of 85% over the year-ago period and an increase of 20% over the September quarter. Net income was \$47.6 million, compared with \$20.4 million for the December 1999 quarter and \$40.3 million for the prior quarter. The income figure was about 5% better than most Wall Street analysts expected, making Vitesse one of the few semiconductor companies to produce a pleasant surprise (continued on page 33)

Vitesse December Quarter Revenues



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(continued from page 31)

in an otherwise rather gloomy earnings season. Commenting on this fact, Vitesse President and CEO Lou Tomasetta said, "Despite the slowdown in some of our larger customers, we were able to provide significant growth through initial production ramps in our upper architectural layer product families and to numerous new customers in the optical transport and enterprise space."

Vitesse is seeing strong growth in OC-192 (10 Gb/s) shipments, which grew by 23% in the December quarter to reach \$24 million. OC-48 (2.5 Gb/s) revenue grew by 18% to reach \$71 million. Communications now account for 93% of Vitesse's total rev-

enue [see Figure on page 31], growing 21% over last quarter and 120% since last year. While GaAs is still the mainstay process at Vitesse, CMOS semiconductors accounted for 18% of Vitesse's total revenues for the quarter, and the company says this figure could rise to 33% or more within the next twelve months. Cisco (\$16 million) and Lucent (\$14 million) are the company's largest customers.

Looking forward, company management indicated that a 10–15% increased in revenue could be expected in the March quarter, and that "significant further acceleration" was likely in the second half of 2001.

New RFICs from WJ Communications

San Jose, CA. WJ Communications has introduced four new ICs for high linearity mobile infrastructure and fixed wireless applications. The AH101 is an internally-matched amplifier that extends the company's existing products out to 27 dBm output power at 1 dB compression, with an IP3 of 45 dBm, while consuming only 200 mA. The AG101 is a gain block, providing 14 dB gain from 250 to 3000 MHz with 27 dBm IP3.

The FP101 is a general-purpose, high dynamic range GaAs MESFET operating in the 50–3000 MHz frequency range for cellular, PCS, DCS1800, UMTS, ISM and MMDS applications, with an output power of 23 dBm and IP3 of 37 dBm. Finally, WJ's HMJ9 cellular-band mixer combines high dynamic range with high IF frequencies of 250 to 280 MHz, which simplifies the filtering of spurious products.

RFMD Unveils Modulator for TETRA Systems

Greensboro, NC. RF Micro Devices has introduced a GaAs MESFET-based quadrature modulator for Terrestrial Trunked Radio (TETRA) systems. Designed for use in the 200–600 MHz band and operating from a 5 V supply, the RF2485 features a broadband noise floor of –149 dBm/Hz at 5 MHz offset, along with an ACPR of –48 dBc at 25 kHz. The RF2485 is offered in a SOIC-14 package and priced at \$2.90 in quantities of 10,000 units.

New Relays from NEC

Santa Clara, CA. NEC has introduced new relays for use in telecommunications switching, ATE, industrial control and factory automation. Available from CEL, the PS7341B-1B telecom switch combines low output capacitance and R_{on} value with 400 V breakdown voltage. The one channel device features GaAs LEDs on the input side and MOSFETs on the output side.

The PS7200R-1A relay is suited to general high-speed switching applications and features a low capacitance and low current leakage (10 nA typical), for a breakdown voltage of 40 V.

Stanford RFICs for Cellular/PCS/3G

Sunnyvale, CA. Stanford Microdevices has unveiled a range of high-linearity PAs for cellular, PCS and 3G applications. Based on GaAs HBT technology, the SPA range covers the 850, 1950 and 2150 MHz frequency bands, and serve as driver amplifiers for base station and repeater applications. Featuring a 5 V supply voltage and offering an IP3 of typically 48 dBm, these devices are housed in standard surface-mount SOIC-8 plastic packages with backside metallization and priced at \$10.95 in quantities of 50,000.

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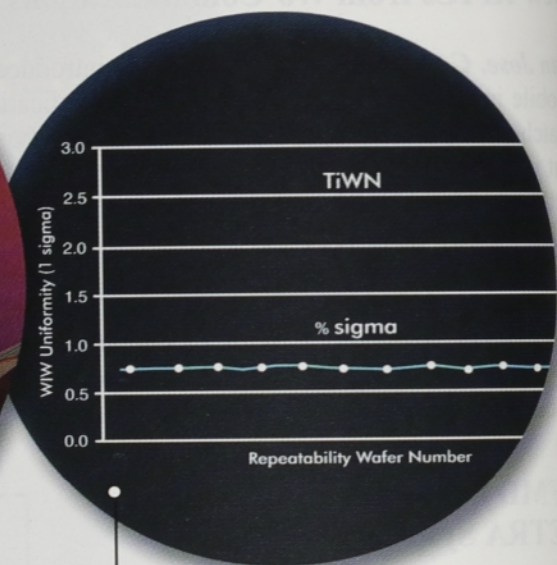
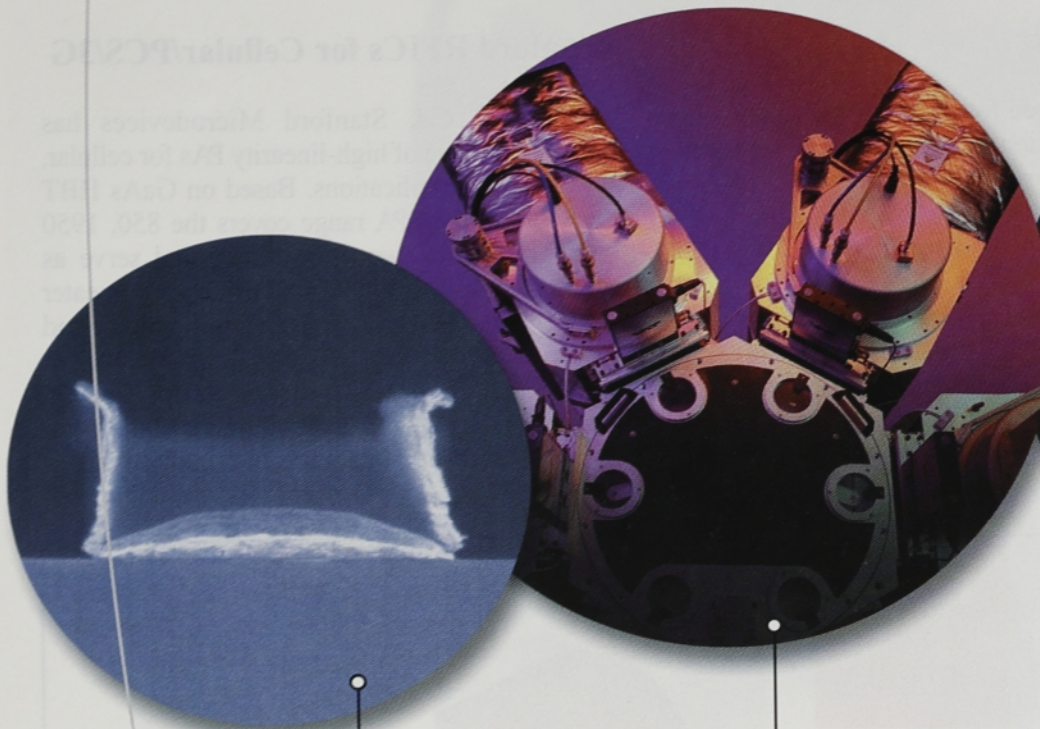


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TIM WHITAKER

As well as the technical talks, some of which are described below, the 2000 GaAs IC Symposium featured several Panel Sessions on topics including indium phosphide, 40 Gb/s systems, foundries and fabless companies, and the competition between E-mode PHEMTs and HBTs. These areas were all covered in the Things to Watch section of our February 2001 issue.

Handset Power Amplifiers

Third generation mobile communication systems such as W-CDMA require miniature power amplifiers with a combination of high efficiency and high linearity. A paper from **Sharp** described a two-stage PA MMIC, manufactured using a GaAs HBT process, which featured a novel linearizing bias circuit. The MMIC demonstrated 44% PAE, 27.6 dBm of output power and 21 dB gain with -37 dBc adjacent channel leakage power ratio (ACLR). The MMIC (see Figure 1) measured $1.16 \text{ mm} \times 0.75 \text{ mm}$, with an area of less than 1 mm^2 , meaning that more than 6,000 chips can be fabricated from a 4-inch wafer [see Technical Digest, page 25].

A late news paper from **NEC and Naito Densai Machida Mfg. Co.** described a multi-chip module (MCM) for 1.9 GHz W-CDMA that demonstrated a record 47.2% PAE and 22.3 dB gain with -35.5 dBc ACLR. The device was manufactured using a $0.5 \text{ }\mu\text{m}$ gate length enhancement-mode PHEMT featuring a 5 nm thick $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ barrier layer between the upper electron supply layer and the channel. This has the effect of raising the forward voltage V_F by 0.2 V to 0.9 V. Also, the thickness of the upper and lower electron supply

layers was optimized to obtain a high maximum drain current [see page 255].

Usually, different PAs are used for handsets that need to cover both PCS and cellular bands. **Fujitsu Quantum Devices** described a two-stage MMIC for cellular frequencies and a three-stage PCS MMIC that were co-packaged in a $4 \times 4 \text{ mm}^2$ quad leadless plastic package. The MMICs were fabricated using a $0.4 \text{ }\mu\text{m}$ gate length quasi enhancement-mode PHEMT process. The 2-stage MMIC exhibited 39.3% PAE at 836 MHz, with 30 dB gain and 28.0 dBm output power. At 1.88 GHz, the PCS MMIC demonstrated 34.6% PAE and 31 dB gain at 29.0 dBm output power [see page 29].

ISM and Base-Station PAs

Emerging radio systems such as Bluetooth require low cost, high performance integrated RF front-ends. Cost is driven not just by the RFIC itself, but also by the number of external components and the software requirements. A paper from **Hittite Microwave Corp.** described the smallest reported MMIC front-end at 2.4 GHz, measuring $0.7 \text{ mm} \times 1.15 \text{ mm}$. No external components are necessary because of the fully integrated features like power down, matching and logic control. The transceiver MMIC, fabricated using a $0.7 \text{ }\mu\text{m}$ MESFET process, incorporates a receiver LNA, a transmitter amplifier, RX/TX switches and control logic on a single chip [see page 37].

A paper from **Motorola** showed that GaAs PHEMT technology is highly competitive with silicon LDMOS for power amplifiers operating at 3.5 GHz, which are designed for use in highly linear base sta-

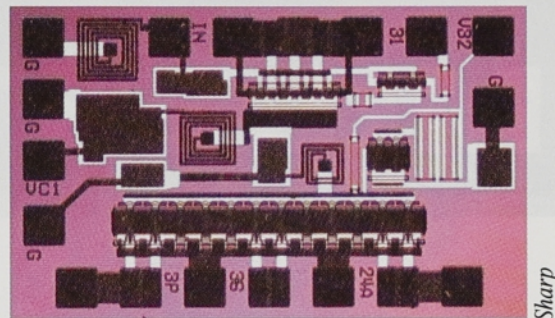


Figure 1. Photograph of a $1.16 \times 0.75 \text{ mm}^2$ HBT MMIC power amplifier for W-CDMA applications, which demonstrated 44% PAE at 1.95 GHz.

tion applications such as W-CDMA. Direct comparison of a 12 V GaAs PHEMT part and a 26 V LDMOS part showed a much higher PAE for the PHEMT (23% v. 11.5%), although gain and linear power were somewhat lower. The device structure was a $0.6 \text{ }\mu\text{m}$ gate length InGaAs/AlGaAs PHEMT grown by MBE [see page 71].

Millimeter-wave Devices

Gunn diodes have proven to be reliable solid-state mm-wave sources, and exhibit desirable characteristics such as low phase noise and $1/f$ noise. However, low cost mass production techniques are required. **New Japan Radio Co. Ltd.** has developed a flip-chip technique to bond GaAs Gunn diodes onto AlN microstrip substrates. The result was a Gunn oscillator with an output power of 134 mW at 34.5 GHz, with DC-to-RF conversion efficiency of 3.9%. Figure 2 shows the Gunn diode before flip-chip bonding. Anode and cathode contacts were formed on top of the MBE-grown device structure. Isolation was achieved by boron ion implantation between the contacts, and gold bumps were then added to the contacts to permit bonding to the AlN substrate [see page 165].

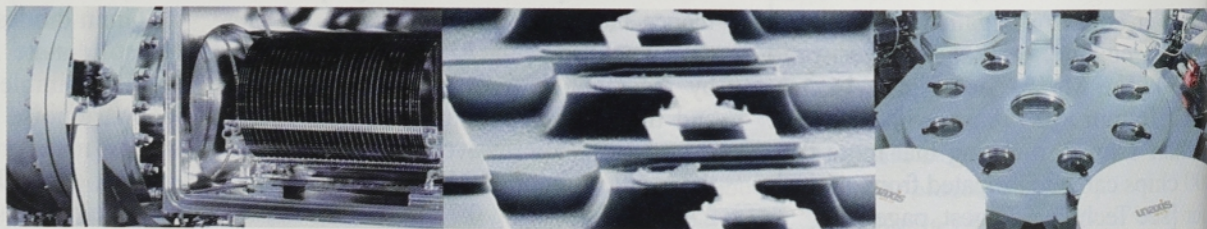
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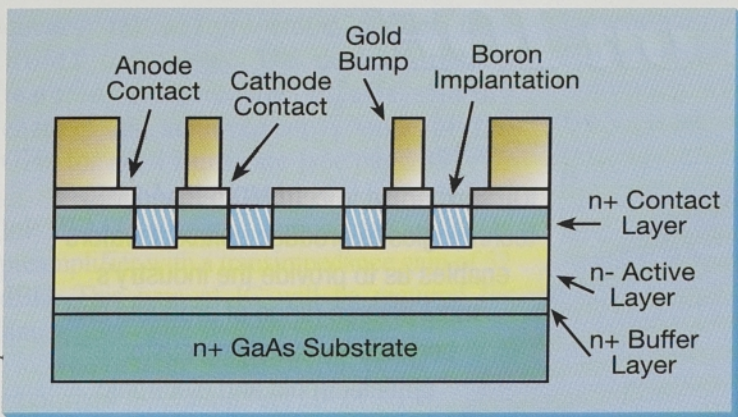


Figure 2. Schematic of a Gunn diode fabricated by boron ion implantation, prior to flip-chip bonding to an AlN substrate.

In a mm-wave transmit chain, the final upconversion to a mm-wave signal occurs at the highest level the mixer can sustain without distorting the modulation scheme. The mixer should have a high IP3 to increase its linearity and reduce the final mm-wave gain that is required. High IP3 is also very important in the receiver. A paper from **Hittite Microwave Corp.** described a 25–40 GHz sub-harmonically pumped mixer with an input IP3 of 20–24 dBm. The mixer is double balanced, the first such topology reported in this frequency band. Due to the use of lumped element matching techniques, the GaAs MMIC area was only 0.7 mm² [see page 171].

The V-band around 60 GHz is well suited for secure communications and wireless LANs. A paper from **DERA** in the UK reported what is believed to be the first single chip V-band receiver manufactured using a production foundry process (TRW's 0.15 μ m gate length PHEMT process). The 60 GHz MMIC, measuring 5.8 mm $\times$ 2.2 mm, consisted of a 4-stage LNA, a sub-harmonic diode mixer and a single-stage LO buffer amplifier. A packaged receiver module had a conversion gain of ≥ 8 dB across the 58–67 GHz frequency band and a typical noise figure of 5.8 dB [see page 175].

There is an increasing demand to link multimedia appliances using mm-wave wireless transceivers at data rates exceeding 100 Mb/s. **NEC** reported a 60 GHz chipset used for amplitude shift keying (ASK) transceivers operating at 500 Mb/s, which conform to the IEEE 1394 standard. Coplanar MMICs (MPA, modulator, LNA, detector) were fabricated using a 0.15 μ m HJFET

process, and packaged using flip-chip mounting onto multi-layer ceramic substrates [see page 179].

racy of ± 50 ps. GaAs technology has made possible the world's first 32-DUT (device-under-test) production tester for RAMBUS devices. **Vitesse Semiconductor** described a deskew IC, part of a 5-chip set used in ATE for RAMBUS devices, and currently shipping in high volume. The IC is fabricated in a 0.5 μ m GaAs E/D MESFET process and integrates 16 independent delay lines into one chip, which measures 4 mm $\times$ 4 mm and contains around 42,000 transistors (see Figure 3). The entire high-speed section of the 32-DUT RAMBUS tester fits into the test head, eliminating costly cables and their associated timing error [see page 89].

K- and Ka-band Power Amplifiers

Compared to microstrip MMICs, coplanar waveguide (CWP) technology has a poor power handling capability due to the high thermal resistance of thick GaAs substrates and the absence of via holes and backside metallization. However, CPW is compatible with flip-chip bonding, where thermal bumps can overcome these limitations. The **Fraunhofer IAF** reported coplanar PHEMT-based MMICs with excellent power handling characteristics, including a two-stage driver amplifier with a saturated output power (P_{sat}) of 500 mW at 35 GHz. A high power amplifier achieved a linear gain of 9.5 dB, with P_{1dB} of 725 mW and P_{sat} of more than 1 W, the highest output power for a Ka-band coplanar MMIC [see page 227].

Digital Memory Test ICs

Automatic test equipment (ATE) for evaluating digital memory circuits has reached speeds of 1 GHz and timing accu-

Emerging point-to-point and point-to-multipoint radio markets require high power, low cost K-band MMICs. **TriQuint** reported two 1 W power amplifiers operating at 18–27 GHz and 27–32 GHz, with areas of 3.91 mm² and 3.69 mm² respectively. Three key factors in achieving small die areas, which in turn drives down the cost, were extensive use of electromagnetic simulation, the process availability of MIM capacitors over vias, and the acceptance of a greater design risk. (A safer design approach would have been to focus on performance, then attempt to achieve a compact design in future iterations.) [See page 223.]

Indium Phosphide ICs

Two separate papers from **HRL Laboratories** reported impressive results for fully static frequency divider ICs manufactured using InP-based devices. M. Sokolich *et al.* reported a 72.8 GHz static 1/8 divider fabricated using an AlInAs/InGaAs/InP HBT process, the highest frequency of operation for a static divider in any technology. The power dissipation per flip-flop was 55 mW with a 3.1 V power supply, and the power-delay product was 94 fJ/gate, the lowest such value for any circuit operating above 50 GHz [see page 81].

G. Raghavan *et al.* described a 49.2 GHz divide-by-two IC, the highest fre-

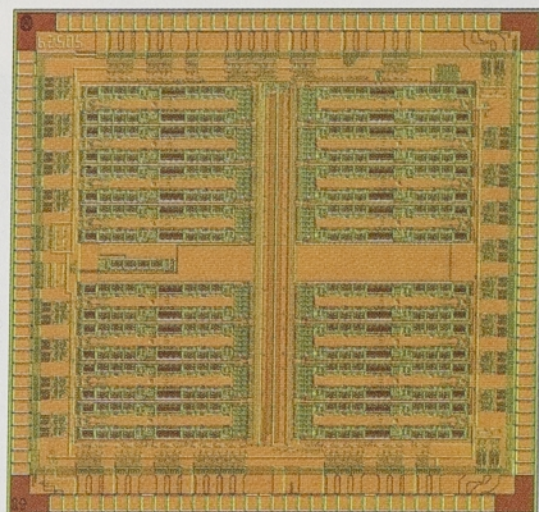


Figure 3. Die photograph of a 1 Gb/s deskew IC used to test RAMBUS memory devices. The die measures 4 $\times$ 4 mm², and contains approximately 42,000 transistors.

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quency for a fully static divider in a HEMT technology. The device structure featured a composite $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}/\text{InP}$ channel and achieved an f_T value of 150 GHz for a 0.15 μm gate [see page 85].

Fujitsu Laboratories used a 0.15 μm InP HEMT process to demonstrate a 49 GHz preamplifier with a transimpedance gain of 52 dB Ω . This type of IC will be required for future fiber-optic systems [see page 197].

The first InP-based DHBT MMIC power amplifiers operating at 22–24 GHz were described by **TRW**, **National Taiwan University** and **Stanford Microdevices**. The amplifiers combined four power cells, each made up of two $1.5 \times 30 \mu\text{m}^2$ emitter fingers, for a total emitter area of $360 \mu\text{m}^2$. A single-ended single stage PA demonstrated a record high output power density of 0.36 W/mm 2 at 22–24 GHz [see page 219].

Novel Approaches to HBTs

Improving the battery lifetime of portable electronics without sacrificing performance requires lower operating voltages without compromising PAE. In HBTs, a lower bandgap base layer reduces the turn-on voltage and in turn leads to greater efficiency at low bias conditions. InGaAsN is lattice matched to GaAs and has a much lower bandgap, making it a suitable choice for base layers in GaAs-based HBTs. **Sandia**, **Emcore** and the **University of Florida** described a P-n-P GaAs/InGaAsN/GaAs DHBT that has a turn-on voltage 0.27 V lower than a comparable AlGaAs/GaAs HBT [see page 63].

Externally biased Schottky potentiometers can be used to modulate and control the

current gain and 1/f noise in GaAs-based HBTs, according to a paper from the **University of California**, **Conexant** and **GCS**. As shown in Figure 4, a fourth electrode is placed in the center of the passivation ledge. The behavior of the gain modulation is determined by the extent to which the emitter ledge is depleted. Also, biasing the on-ledge Schottky diode at a high voltage ($V_L > V_{BE}$) allows the 1/f noise density of type-B HBTs to be minimized by eliminating the recombination of carriers in the extrinsic base region [see page 245].

Fiber-Optic Link ICs

A 10 Gb/s distributed driver IC containing a D-FF (flip-flop) function, for driving electroabsorption modulators, was described by **Mitsubishi Electric**. The IC, fabricated in a 0.2- μm PHEMT process, operated from a –5.2 V power supply with an output voltage of 2.9 V $_{pp}$ and a rise/fall time of 22/21 ps, and consumed 2.9 W [see page 205].

A paper from **Sandia** and others described driver and receiver ICs for use with an 8 $\times$ 8 array of VCSELs, each operating at 1 Gb/s. The receiver array consisted of an MSM photodetector, TIA, decision circuit and output buffer in each channel. A 16-channel driver array with programmable drive currents was also realized [see page 189].

Lucent Technologies presented a 10 Gb/s driver IC, fabricated using a 0.25 μm GaAs PHEMT process, that is capable of driving 120 mA of current into a laser, or 60 mA into an electro-absorption or Mach-Zehnder modulator. Rise and fall times were below 25 ps. Due to a novel dual-mode actively matched output buffer, the power consumption of the IC remains at a minimum, making it most suitable for co-packaging with uncooled lasers and EA modulators [see page 201].

Oki Electric Industry described a 10 Gb/s TIA, fabricated using a 0.1 μm gate PHEMT process, and driven by a single –5 V supply. The IC features an automatic gain control circuit, and had a transimpedance of 63 dB Ω , a bandwidth of 8 GHz and an optical sensitivity of –21.2 dBm [see page 193].

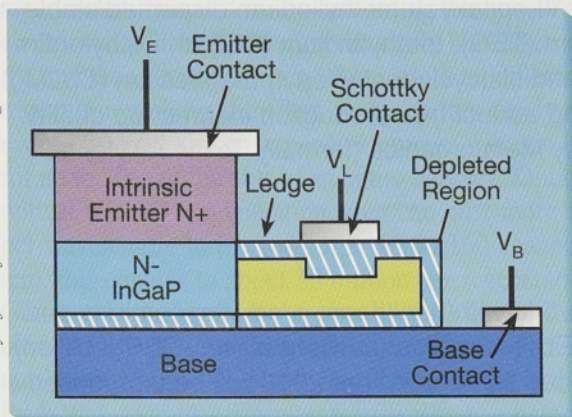


Figure 4. Cross-section of an HBT showing a passivation ledge with a Schottky potentiometer biased at V_L and the base contact biased at V_B .



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Deer Park, Texas, 7 December 2000 — Akzo Nobel, the only global, fully back-integrated high purity metalorganics producer, announced substantial investment in metalorganics production, distribution, and service capabilities at its Deer Park, Texas complex. Responding to rapidly growing demand for high purity metalorganics (HPMO) that underpin today's optoelectronics and wireless revolutions, Akzo Nobel is funding capacity expansion to meet foreseeable global HPMO demand.

This investment reflects Akzo Nobel's ongoing commitment to support the HPMO needs of the optoelectronics and wireless communities with attention to quality, quantity, consistency, and value.

Stated HPMO Business Manager Barry Cottrell,

"At Akzo Nobel, we take our responsibility to the compound semiconductor industry very seriously. We believe that for this industry to reach its full growth potential, it must be underpinned by a strong metalorganics supply base. Investment in manufacturing facilities, coupled with a streamlined organization and increased R&D, allows Akzo Nobel to respond to this challenge by making the highest purity metalorganic sources available on large scale."

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This investment is one of a series of Akzo Nobel actions designed to support compound semiconductor-based applications growth through global HPMO supply excellence. During 1999–2000, Akzo Nobel formed a new HPMO organizational unit enabling faster, targeted responses to market needs. Among the first of these responses was tripling of R&D resources dedicated to HPMO. Akzo Nobel plans additional investments beginning in 2002 to further enhance HPMO product quality, consistency, and capacity.

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Akzo Nobel HPMO specializes in high purity metalorganics for III-V and II-VI epitaxy: trimethylindium dispersed/stable flow (TMI), trimethylgallium (TMG), trimethylaluminum (TMA), triethylgallium (TEG), triethylindium (TEI), trimethylantimony (TMSb), dimethylzinc (DMZ), diethylzinc (DEZ), triethylborane (TEB), and bis(cyclopentadienyl) magnesium (Cp₂Mg) and other metalorganics available. Akzo Nobel's vertically integrated, ether- and adduct-free production insures top quality, value, and security of supply. The Deer Park site of Akzo Nobel High Purity Metalorganics (formally Texas Alkyls) has been supplying metalorganics to global epitaxy leaders since 1970.

About Akzo Nobel

Akzo Nobel, based in the Netherlands, serves customers throughout the world with healthcare products, coatings and chemicals. Consolidated sales for 1999 (excluding Acordis) totaled some EUR 12 billion (USD 13 billion, GBP 8 billion). Currently, the Company employs 68,000 people in 75 countries. Financial results for the year 2000 will be announced on February 23, 2001.

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Raman Amplification—Longer, Wider, Faster, Cheaper

RICK SCHAFFER and JAMES JUNGJOHANN
CIBC World Markets

In an effort to keep pace with bandwidth demands that are nearly doubling each year, WDM system designers are moving to more cost-effective solutions utilizing higher channel counts, higher transmission speeds and longer distances between regeneration sites. All these features require more power, and optical amplification is as crucial as ever. Attracted by unique power and distance-boosting attributes, including superior gain flatness, flexible gain profile and low noise figures, designers are looking to Raman amplification as the next generation technology for boosting optical signals.

For the most part complementary to erbium-doped fiber amps (EDFAs), Raman helps reduce overall network amplification costs by 40% or more, compared with traditional systems that are totally dependant on EDFAs. As a result, the Raman amplifier market could reach \$4.8 billion by 2005, from \$245 million in this year [see Figure 1].

For all its current popularity, diode-pumped Raman is made possible only through the recent commercial availability of high powered InP-based pump lasers operating in the 1400–1500nm wavelength range (hereafter referred to as 14XXnm). The market for 14XXnm pumps could explode over the next several years as Raman amp deployments aggressively ramp, jumping from just under \$110 million in 2000 to \$2.3 billion in 2005.

Why Use Raman?

As photons travel down an optical fiber, power and signal quality degrade. Power can be added to the signal with optical amplifiers, but at certain points in the network the signal must be regenerated. This is done by converting the optical signal into its electrical equivalent, restoring the signal back to its original quality, and then sending the signal back to a modulated laser for re-transmission along the fiber. Regenerators are typically placed every 400–600 km, an expensive process sometimes accounting for up to 50% of the cost of an entire network. Optical-electrical-optical (O-E-O) regeneration sites can cost more than \$50,000 per wavelength. In the case of a Nortel 160-channel WDM system, this equates to about \$8 million per regeneration site at 2.5 Gb/s (and roughly twice as much at 10 Gb/s). Raman enables ultra-long-haul WDM transmission by greatly reducing a system's noise figure. By deploying Raman amps in their networks, long-haul operators can increase the distance between regeneration sites to 4,000 km or more, leading to lower costs and, most importantly, a more efficient optical network.

Companies such as Corvis and Qtera developed ultra-long-haul WDM solutions that increased the distance between electrical regeneration sites to more than 3,000 km. Raman was one of two key elements of this accomplishment (the other was strong forward-error correction, or FEC). The potential savings are clear: for a 160-channel, 10 Gb/s (OC-192) network, the operator can replace more than six regeneration sites (cost ~\$75 million) with roughly 40 Raman amps costing less than \$1 million.

As channel counts in WDM systems increase from 16 to 80 or more, an incremental increase in amplification is required for each additional wavelength. Similarly, higher transmission speeds also require more amplification. When the photon stream is modulated at a higher data rate, each bit of data contains fewer photons. For a given photodetector to generate the same electrical signal at the higher data rate, the signal needs to be more powerful. The key is to do this without introducing signal distortions and crosstalk, which is where Raman comes in.

Raman—The Basics

Stimulated Raman scattering occurs when light waves interact with atomic vibrations in a crystalline lattice (or an optical fiber). The atom absorbs the light and then quickly re-emits a pho-

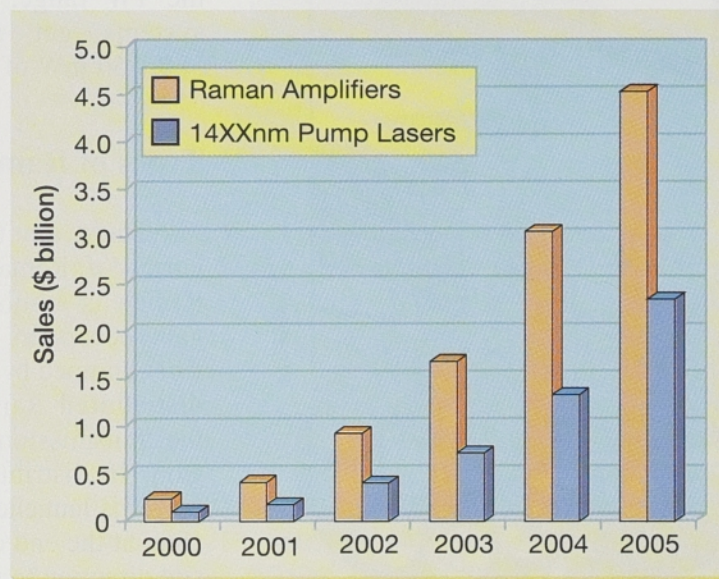


Figure 1. Market forecast for Raman amplifiers, and for pump lasers in the 1400–1500nm range (14XXnm) that are used in diode-based distributed Raman amplifiers.

ton with energy equal to the original photon energy plus/minus the atomic vibrational energy. Raman amplification occurs when higher energy (shorter wavelength) pump photons interact with the atomic vibrational modes in the optical fiber, thereby coherently "stimulating" or adding energy to the lower energy (longer wavelength) signal photons.

One major advantage of Raman is the ability to amplify over a broad spectral range, i.e. beyond the standard 1550 nm long-haul transmission window [see Figure 2]. This makes Raman potentially attractive for short-haul amplification, where 1310 nm transmission is common. Amplification of 1550 nm signals requires pump lasers operating at around 1450 nm, while 1310 nm amplification requires a 1240 nm pump source. Importantly, Raman can be used in any type of optical fiber, including the large installed base that is not optimized for WDM.

Because the power conversion efficiency of Raman amps averages 25%, compared to ~80% for EDFAs, a high pump energy is required. Normally, Raman requires output (launch) power in the 1W range, although some newer systems get adequate gain from 500–750 mW of output.

Types of Raman Amplifiers

There are two fundamental categories of Raman amplifiers: **discrete** Raman is similar to an EDFA, where gain occurs in a section of specialty fiber pumped by a 14XXnm laser, while **distributed** Raman amplifiers rely on the transmission fiber itself to achieve gain. In distributed Raman, the pump power is launched into the transmission fiber at the end of its span, in the opposite direction to the transmission signal: power is transferred from the pump photons to the transmission signal via the atomic vibrations in the optical

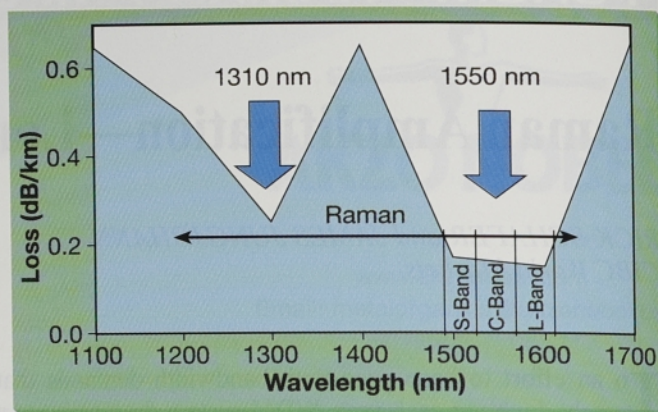


Figure 2. Stylized representation showing the low-loss transmission windows at 1310 nm and 1550 nm in optical fiber. While erbium-doped fiber amplifiers (EDFAs) are limited to the 1550 nm window, Raman amplification has a much broader range, as shown.

fiber. The distributed category is further broken down into **cascaded**, where a fiber laser provides the pumping, or **diode-based**, which uses 14XXnm diode laser pumps.

Diode based distributed Raman provides launch powers typically in the 500 mW–1 W range, and will come to dominate the terrestrial market as ultra-long-haul, high-channel-count, high-speed system deployments explode in 2001. Sales of diode-based distributed Raman could jump from about \$220 million in 2000 to roughly \$4.5 billion in 2005, or ~94% of the total Raman market.

Cascaded Raman using fiber pump lasers is typically utilized for undersea and remote amplification given its relatively high launch powers of 1.5–2 W. Cascaded Raman solutions should grow from \$25 million in 2000 to \$243 million in 2005 as undersea WDM system deployments proliferate.

In the long term, Raman amplification is likely to be a complement to, not a replacement for, traditional 980 nm/1480 nm EDFA amplification. However, in some new systems operating at 10 Gb/s speeds or less, where the amps are ~50 km apart, it is both possible and desirable to obviate the need for EDFAs provided the Raman power is high enough (~20 dB). As transmission speeds migrate to 40 Gb/s and higher, we believe Raman will likely be used in conjunction with EDFAs in all systems, including those with reduced hut spacings.

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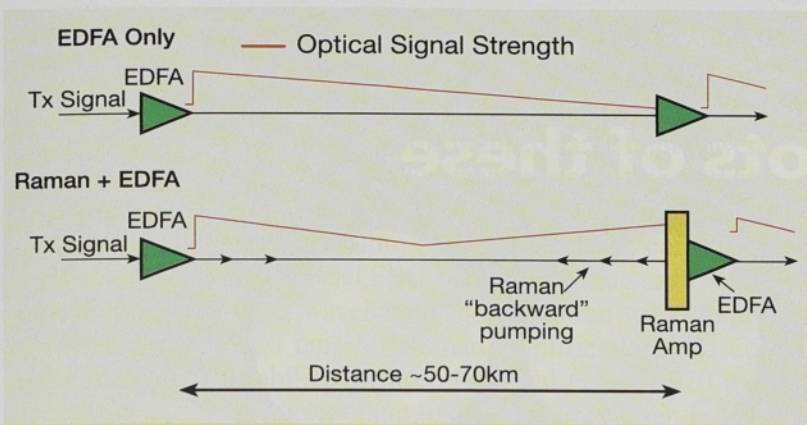


Figure 3. In a system amplified by EDFAs, the optical signal strength is attenuated in each fiber span before being boosted by the next EDFA. This process introduces noise, so the signal has to be regenerated every 400–600 km. Distributed Raman amplification, used before each EDFA, prevents the signal from becoming as weak as in an EDFA-only architecture, reducing the noise and allowing longer distances between regeneration sites.

Distributed Raman

Distributed Raman amplification reduces the gain required of an EDFA while providing a dramatic improvement in the overall noise figure. This translates to a six-fold or more improvement in distance traveled between O-E-O regeneration sites.

There are two major types of noise associated with fiber-optic transmission: amplifier noise, and noise due to signal attenuation in the fiber. In a system amplified exclusively by EDFAs, the signal attenuates after leaving the first amplification site, and reaches the next EDFA greatly weakened. The EDFA pounds this weakened signal with 30 dB-plus of pump power, introducing a disproportionate amount of noise into the signal as it is amplified. Thus, the signal-to-noise ratio (SNR) continues to fall span after span. After roughly 400–600 km, the signal needs to be cleaned up i.e. regenerated. Distributed Raman helps to reduce the noise figure, resulting in a much-improved SNR. Simply stated, the noise figure is improved because the signal is never allowed to become as weak between spans as in an EDFA-only architecture (see Figure 3). By maintaining a stronger signal at amplification (where the majority of noise is introduced), the overall SNR stays higher longer.

Raman is proving to be particularly attractive for 40 Gb/s systems. An increase in speed from 10 Gb/s to 40 Gb/s using normal EDFA amplification requires four times the amount of launched signal power, which can distort signals and induce channel crosstalk. Raman allows designers to reduce the launch power of the 1550 nm signal, therefore reducing non-linearities. In a typical one-one configuration, a Raman amp is used as a “pre-amp” for each EDFA in a given span, as shown in Figure 3.

Diode-Based Distributed Raman

As many as eight 14XXnm pumps are used per diode-based distributed Raman amplifier, for several reasons. First,

high-powered 14XXnm pumps are still relatively difficult to find in volume (and very expensive, once a supply can be secured). The second issue is reliability—the more pumps an amp has, the better it will be protected from the failure of any single laser. Third, the unique properties of InP-based 14XXnm pumps allow system architects to design Raman amps with pump lasers of varying wavelength, enabling a very flat gain shape without the need for lossy gain-flattening filters (GFFs). However, amps begin to get too complex beyond eight pumps, and higher-powered pumps will become more readily available in the future, keeping the average number of pumps per Raman amp at around five or six.

Figure 4 shows a schematic of a typical 1 W diode-pumped distributed Raman amplifier containing eight pump lasers of varying wavelengths, each with an output power of 125 mW. This example contains two polarization beam combiners (PBCs), which are passive optical components that combine the output of two lasers with the same wavelength but with orthogonal polarization modes. The amplifier also contains a multiplexer to combine the different pump laser wavelengths.

After each amplification, if gain flatness is not tightly controlled across the entire band (all 40 or 80 channels), the power of each channel can eventually vary widely introducing non-linear effects in higher power channels or signal degradation in lower powered channels. As WDM networks increasingly migrate to 10 Gb/s modulation rates and higher, power levels must be managed effectively. In the EDFA-only model, both gain flattening and dispersion compensation are needed immediately after signals are amplified. Aside from added equipment cost, gain flattening filters (GFFs) represent an additional cost in terms of efficiency by introducing another point of loss into the system. Some Raman amplifier designs do not require discrete GFFs, although others do employ these components.

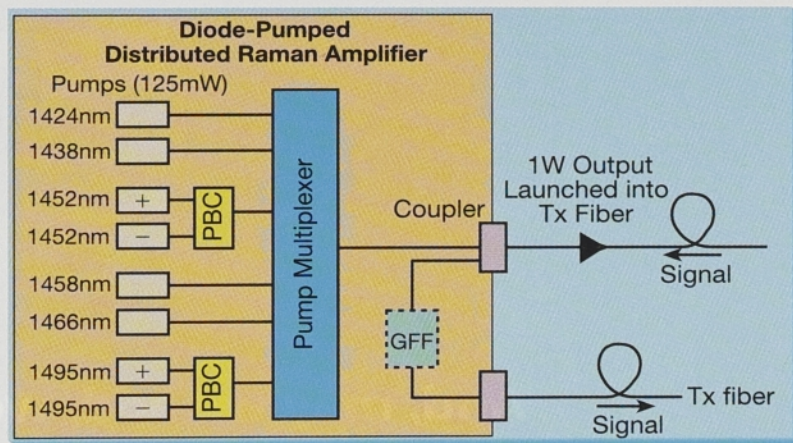
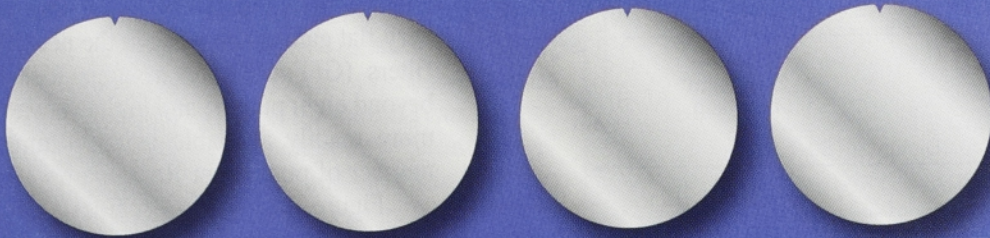


Figure 4. Representation of a typical diode-pumped distributed Raman amplifier. The output of eight 125 mW pump lasers is combined to provide around 1 W of pumping power, which is launched into the transmission fiber. A gain-flattening filter (GFF) is not always required provided that sufficient pump wavelengths are used to control the gain shape.

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Cascaded (Fiber Laser Pumped) Raman

Cascaded Raman amplification uses several fiber lasers with a combined output in excess of 1.5 W to pump the transmission fiber. In turn the fiber laser is pumped using high power, multimode diode lasers. SDL, the dominant player in this market, couples ten multi-mode one-watt 920 nm pump lasers together into a co-doped erbium ytterbium (Er/Yb) fiber. The combined output passes through a special FBG-based resonating cavity that shifts the final launched wavelength to the desired value (typically 1455 nm or 1480 nm) for Raman amplification [see CS 6(7), p.66]. The availability of more powerful (~2 W) 920 nm lasers could reduce the laser count to five per fiber laser, bringing down costs to achieve mass commercialization.

Cascaded Raman amps are well suited to remote pumping applications in the submarine (undersea) market. In a festooned WDM architecture, a fiber-optic cable is dropped just off the coast of a continent or island. Every 400–600 km, the cable is looped back to the shore into huts containing network elements like optical add-drop muxes (OADMs) and amplifiers. The benefit of this design is that no active components are located underwater. This helps reduce system costs and improve network reliability.

Discrete Raman and the Metro Opportunity

Discrete Raman is simply a stand-alone amplifier, similar to an EDFA in that the signal is piped into a discrete box and travels through a length of specialty fiber, where gain is achieved. This technology, yet to catch on commercially, is somewhat limited in its potential application. System designers will most likely deploy discrete Raman to overcome localized loss, which could occur in switches, OADMs, or in dispersion compensating fiber. We expect the market for discrete Raman could ramp from less than \$1 million this year to \$60 million in 2005.

One potential application for discrete Raman is to provide low-cost optical amplifiers, or "amplers," for the metro WDM market, where there are many potential sites for localized optical loss. Several other technologies, including scaled-down EDFA designs and semiconductor optical amplifiers (SOAs), will also compete. These amplifiers will sit on the outputs of switches and OADMs to rebalance powers, and the Raman and EDFA versions will be pumped by low-cost, low power 980 nm and 14XXnm pump lasers.

Pump Laser Diodes

InP-based 1480 nm and 14XXnm pumps met with early acceptance (for erbium-based and Raman amplification, respectively), because they offered a high degree of reliability relative to early generation GaAs-based 980 nm pumps. InGaAsP/InP 14XXnm lasers tend not to fail suddenly, but to degrade slowly and predictably over time, while 980 nm lasers failed frequently, suddenly, and unpredictably due to mirror degradation. However, the introduction of patented 980 nm mirror passivation processes at JDS Uniphase and SDL led to vastly improved 980 nm reliability,

with both companies producing 980's with failure in time (FIT) scores near 50, equating to a mean time to failure of 100-plus years. Because 980 nm pumps were inherently more powerful (and introduced less noise when used in the first stage of EDFAs), Raman and 14XXnm pumps were pushed to the back burner.

Raman amplification appears ready to blossom as supply of 14XXnm pumps has improved greatly over the past 12 months, led by ramping production at leading manufacturer Furukawa as well as Alcatel, Sumitomo and JDS Uniphase. Furukawa currently holds up to 90% of the capacity-constrained market for 14XXnm pumps, followed by Sumitomo, Alcatel, JDS Uniphase, Lucent, SDL, Corning, and Anritsu. Manufacturers are introducing modules with output powers exceeding 200 mW, and the introduction of 200–250 mW modules (containing 300 mW 14XXnm pump chips) will ensure high barriers to entry in this market. Packaging to dissipate heat is a big challenge; Furukawa has a novel solution to this challenge, using a "heat pipe" with exceptional thermal conductivity.

As shown in Figure 1, the market for 14XXnm pump lasers is expected to grow at a CAGR of around 85%, reaching \$2.34 billion in 2005. This assumes an average of 6 pumps per diode-pumped Raman amplifier. With average selling prices expected to decline from \$1800 in 2000 to \$1100 in 2004/5, unit sales of 14XXnm pumps will actually increase at a CAGR of over 100%, from around 60,000 in 2000 to over 2.1 million in 2005.



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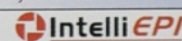
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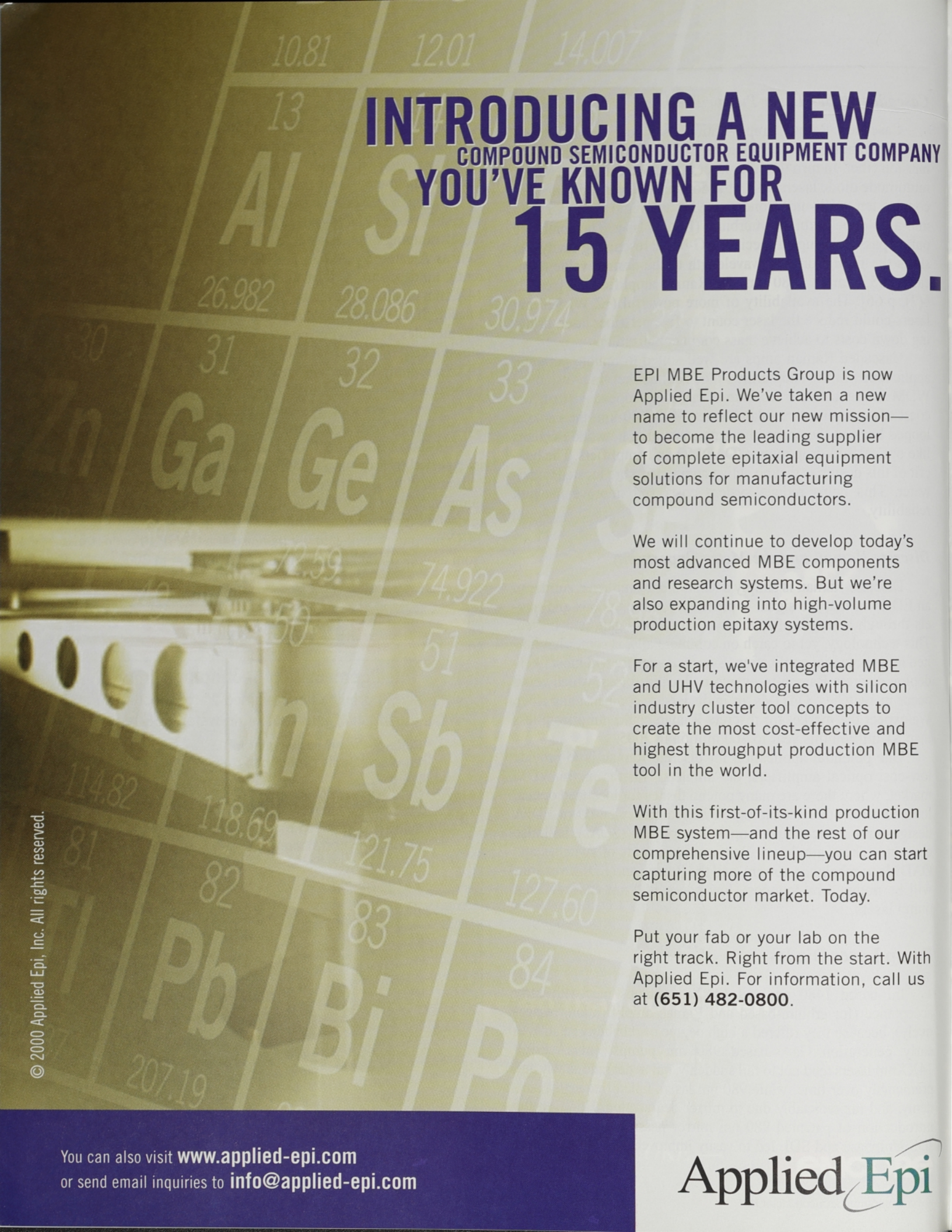
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Continuous-wave InGaN MQW Laser Diodes on Copper and Diamond Substrates

WILLIAM S. WONG, MICHAEL KNEISSL, DAVID W. TREAT, MARK TEEPE,
NAOKO MIYASHITA and NOBLE M. JOHNSON

XEROX Palo Alto Research Center
Electronic Materials Laboratory
Palo Alto, CA, USA

An effective means for improving blue laser performance can be achieved by thin-film lift-off and transfer of pre-fabricated, fully functional devices from sapphire onto another host substrate. Although high-performance CW (In,Ga,Al)N laser diodes possessing lifetimes greater than 10,000 hours have been realized on sapphire substrates [1], a major impediment to the development of III-nitride lasers still remains the efficient dissipation of heat generated from the active area of the device. The high thermal resistance of the sapphire substrate and the relatively high current densities combine to degrade the device performance and lifetimes due in part to excessive heating during operation. Substrates such as copper or diamond would be more ideal in terms of thermal and electrical conductivity, although direct deposition and fabrication of III-nitride-based laser devices on these materials are either unfeasible or result in poor-quality thin films.

Thin-film laser lift-off (LLO) techniques have recently been established as an effective tool for the integration of GaN thin films with a variety of dissimilar substrates [2]. The LLO process has successfully been used to fabricate vertical-structure InGaN-based LEDs on Si while showing no degradation to the device performance after the LLO and transfer process [3,4]. In addition, the integration of InGaN-based blue lasers with copper substrates have been demonstrated for lasers under pulsed operation [5]. Here, we describe the transfer of pre-fabricated CW InGaN MQW ridge-waveguide lasers from sapphire onto Cu and diamond substrates in order to enhance device performance through materials integration.

Device Fabrication and Transfer

The laser structures were grown on (0001) c-plane sapphire substrates by MOCVD. A 2 μm -thick GaN film was deposited, followed by a 100 nm thick SiO_2 layer, which was subsequently patterned. The patterning resulted in an 8 μm -wide stripe with a period of 11 μm parallel to the

GaN $\langle 10\bar{1}0 \rangle$ direction. MOCVD growth was then resumed with a 15 μm -thick, Si-doped GaN layer, followed by a standard laser heterostructure [6]. The device consisted of a 100 nm-thick Si-doped InGaN defect reducing layer; a 1 μm -thick Si-doped AlGaIn/GaN strained-layer-superlattice cladding layer; an active region comprised of three 3.5-nm-thick InGaIn QWs sandwiched between 100 nm-thick GaN waveguiding layers; a 20 nm Mg-doped AlGaIn tunnel barrier layer; a 500 nm-thick Mg-doped AlGaIn cladding layer; and finally, a 50 nm-thick Mg-doped GaN contact layer.

After MOCVD growth, 2 μm ridge-waveguide structures were formed by etching into the AlGaIn cladding layer using CAIBE, which was also used to fabricate mirrors. Metal contacts were then deposited on the top p-type GaN layer through openings in a silicon oxynitride overlayer. Finally, a highly reflective dielectric coating ($R=90\%$) was deposited on the backside facet in order to minimize the mirror loss.

The InGaIn MQW laser structures were then bonded onto the surface of a B-doped, p-type Si(100) wafer using an ethyl

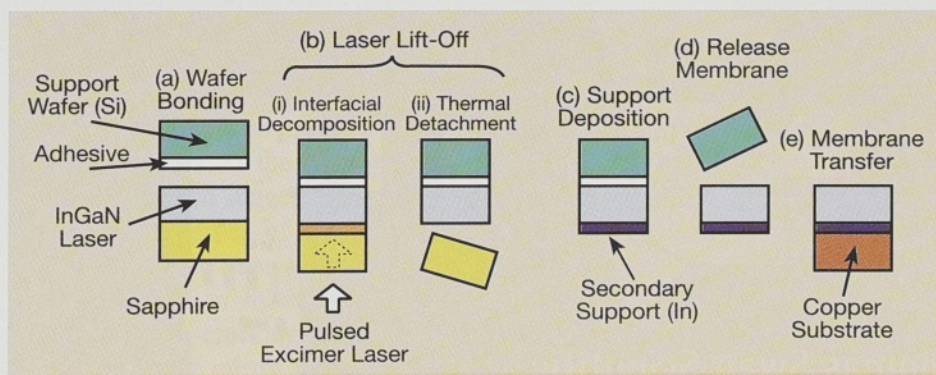
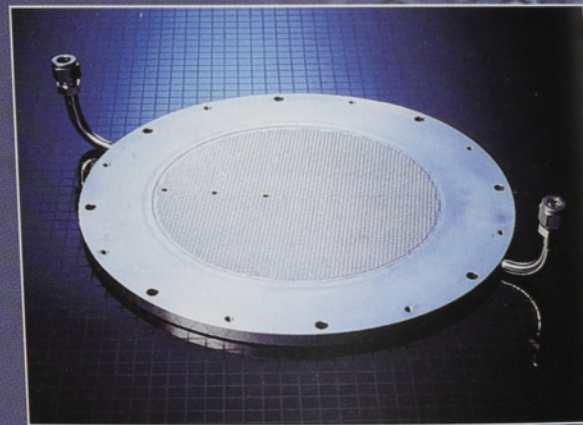


Figure 1. Process flow for fabricating an InGaIn MQW laser diode on Cu. (a) A pre-fabricated InGaIn MQW laser/sapphire is bonded to a Si supporting substrate. (b) Two step laser lift-off (LLO) process. Step (i): Irradiate the sapphire/laser/adhesive/Si structure through the transparent sapphire substrate with an excimer laser; Step (ii): heat post-laser processed structure above melting point of Ga to release sapphire substrate. (c) Deposit secondary support layer (indium). (d) Immerse InGaIn MQW laser/adhesive/Si structure in solvent to release laser membrane. (e) Bond laser to Cu substrate.

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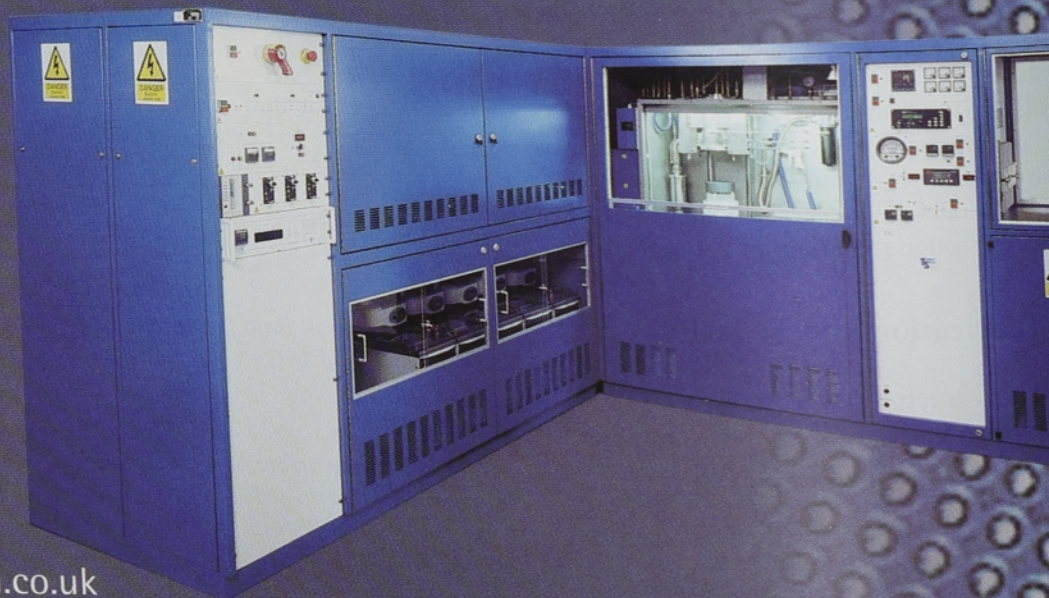
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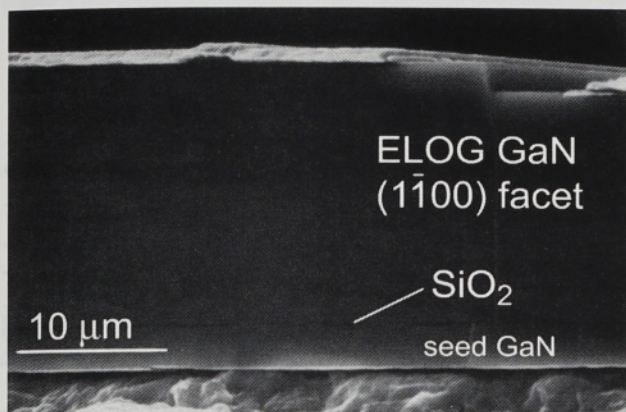


Figure 2. Cross-sectional SEM of a cleaved mirror facet on a free-standing InGaN ridge waveguide laser.

cianoacrylate ($C_6H_7NO_2$)-based adhesive [see Figure 1]. Lift-off and transfer of the laser structures from sapphire onto the receptor Si substrate were accomplished by using a single 20 ns, ~ 500 mJ/cm² pulse from a XeCl pulsed-excimer laser (308 nm) directed through the transparent sapphire substrate. After the laser irradiation, a low-temperature (40°C) anneal completed the separation process by melting the Ga-rich interface.

In order to improve the structural rigidity and minimize the mechanical failure of the laser membranes and the facet mirror coatings, a secondary supporting layer consisting of a 5 μ m-thick indium film was deposited onto the exposed GaN interface before removal of the Si support substrate. Immersion of the In/laser/adhesive/Si structure in acetone, to dissolve the adhesive bond, then

completed the fabrication of 1 cm² free-standing membranes. The membranes were then transferred and bonded at $\sim 200^\circ\text{C}$ onto a Cu or diamond substrate by using the indium layer first as a structural support and subsequently as a bond interface.

An advantage to removing the sapphire growth substrate is the ability to easily cleave mirror facets on the lasers before transfer [7].

Figure 2 shows a cross-sectional scanning electron microscopy view of a cleaved mirror facet for a typical ridge waveguide laser. The micrograph shows a very smooth topography along the surface of the facet with a surface roughness less than 0.5 nm measured by AFM over a 1×1 μm^2 area. The surface roughness was an order of magnitude smoother than typical CAIBE-etched facets.

Laser Performance

Figure 3 is a plot of the light output versus current and voltage (L-I-V) characteristics for a typical 2×800 μm^2 ridge waveguide device under room-temperature CW operation after transfer from sapphire onto diamond. The threshold current for a transferred device on diamond was 87 mA

at 5.2 V, with a 0.5 W/A differential slope efficiency. These devices showed no measurable degradation after the laser processing, which suggests that the optical properties of the transferred lasers were unaffected, and damage to the waveguide due to micro-cracking or deterioration of the mirror facet coatings had not occurred.

The effectiveness of using a thermally and electrically conductive Cu substrate to improve InGaN-based laser performance is demonstrated in the laser output-power performance. Figure 4 shows the L-I

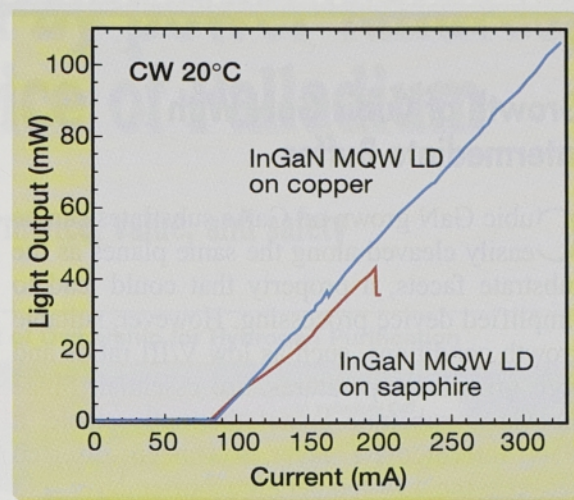


Figure 4. L-I characteristics for a typical laser on Cu (blue) compared to a laser on sapphire (red). Due to the lower thermal resistance, the maximum light output power is significantly improved for laser diodes on Cu substrates.

curve for a typical 3×500 μm^2 laser on sapphire compared to a laser on Cu with a backside n-contact. By using the Cu substrate as an efficient heat sink, it was possible to reduce the thermal resistance of the laser diode and raise the CW light output to more than 100 mW [7]. The enhanced device performance further establishes the use of LLO as a tool for integrating GaN-based optoelectronics with virtually any substrate material, allowing one to independently optimize the growth conditions and diode performance that can later be combined with other platforms.

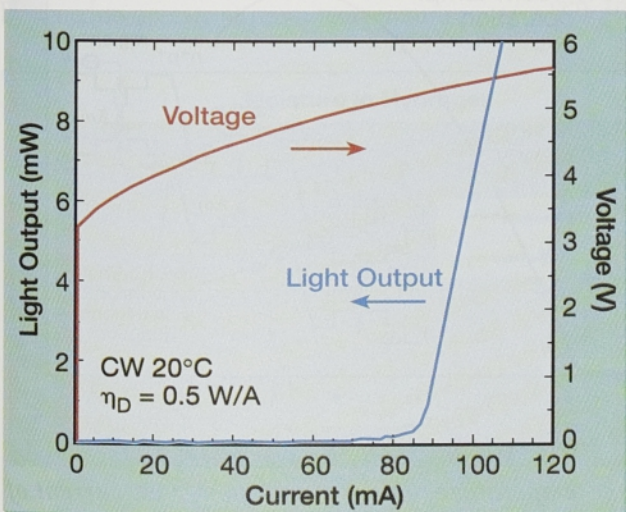


Figure 3. CW L-I-V characteristics for a 2 μ m ridge waveguide laser on diamond.

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Growth of Cubic GaN With Intermediate Buffer

Cubic GaN grown on GaAs substrates can be easily cleaved along the same planes as the substrate facets, a property that could lead to simplified device processing. However, suitable growth conditions, such as low V/III ratios and high growth temperatures, are essential. Since the GaAs substrate is not thermally stable, a GaN intermediate layer has been inserted between the low-temperature buffer layer and high-temperature GaN epilayer in order to achieve the growth of cubic GaN by MOVPE.

The intermediate layer was grown by MOVPE at moderate temperatures of 850°C both to avoid thermal damage to the substrate and to provide a flat cubic template. This approach was successful and enabled the growth of cubic GaN on GaAs at higher temperatures. Even at a growth temperature of 980°C, a smooth interface between the GaN layer and GaAs substrate was observed. Photoluminescence and X-ray diffraction measurements corroborated this, and revealed that the crystal quality of the cubic GaN layer was much improved compared to growth without the high temperature intermediate buffer.

*J. Wu et al, University of Tokyo, Japan
J. Cryst. Growth, 2000, 221, p. 276*

Multiplexer Using Cascaded 3D Vertical Couplers

A four-channel wavelength multiplexer/demultiplexer based on InGaAsP/InP has been demonstrated using cascaded 3D vertical couplers. The multiplexer featured a channel spacing of 17 nm with a cross-talk of less than 15 dB. The vertical couplers were used to couple different signals and were fabricated using wafer bonding to invert a conventionally processed epitaxial layer and bond it to a new host substrate. This approach enables a double sided wafer process, and makes it possible to fabricate 3D photonic ICs and multilevel optical interconnects.

*Bin Liu et al, University of California at Santa Barbara
Appl. Phys. Lett., 2000, 76(3), p. 282*

Evidence of Luminescence from InN Clusters

Quite surprisingly, in spite of large densities of threading dislocations, InGaN/GaN multiple QWs exhibit strong luminescence intensity at room temperature. And through a detailed study involving PL and PL excitation, Raman scattering and photoconductivity, the authors have found firm evidence of luminescence from InN clusters.

Careful examination of the low energy shoulders of the main peak luminescence reveals that the observed separation is in good agreement with the longitudinal optical phonon energy of a pure InN film measured by Raman scattering. A large Stokes-like shift between the emission peak and the absorption edge is also found, which increases with increasing indium content. In addition, after turning off the pumping light, the photoconductivity signal can persist for a very long period of time. All these observations can be explained as a result of localization of self-organized InN clusters within InGaN layers.

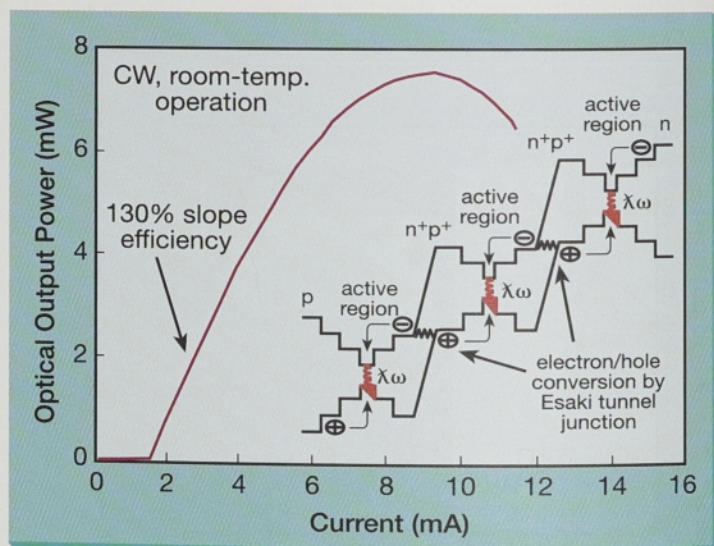
*Y. F. Chen et al, National Taiwan University, Taiwan
Appl. Phys. Lett., 2000, 76(25), p. 3712*

Cascade VCSEL with 130% Slope Efficiency

The relatively low roundtrip gain in VCSELs can be increased by monolithic stacking of active regions, electrically coupled by integrated Esaki tunnel junctions for carrier recycling (see inset in Figure). Thus, the threshold current density can be scaled down while simultaneously obtaining high differential quantum efficiency—even greater than unity. Lasers of this type are interesting solutions for optical links, low-noise devices and analog systems, to high-power applications and long-wavelength VCSELs.

The top-surface emitting InGaAs/AlGaAs quantum-well VCSEL contains three active pn-junctions in series, coupled by two highly doped GaAs tunnel junctions. The top and bottom mirror reflectivity is around 97 % and 99.95 %, respectively. The figure shows the optical output characteristic of a 9 μm active diameter device emitting at a wavelength centered on 980 nm. For the first time, a differential quantum efficiency above 100% is demonstrated for CW operation at room temperature. Optimizing the mirror doping levels and tunnel junctions will further improve the device performance.

*T. Knodl et al, University of Ulm, Germany
Elec. Lett., 2001, 37, p. 31*



CW room-temperature optical output power vs. current of a three-stage diode cascade VCSEL. The inset illustrates the carrier recycling mechanism.

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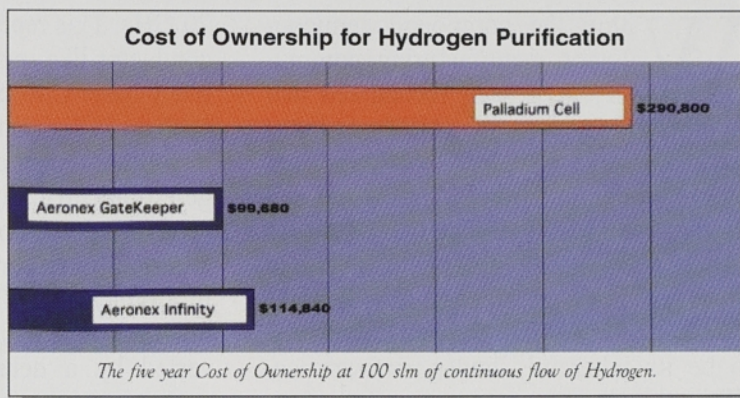
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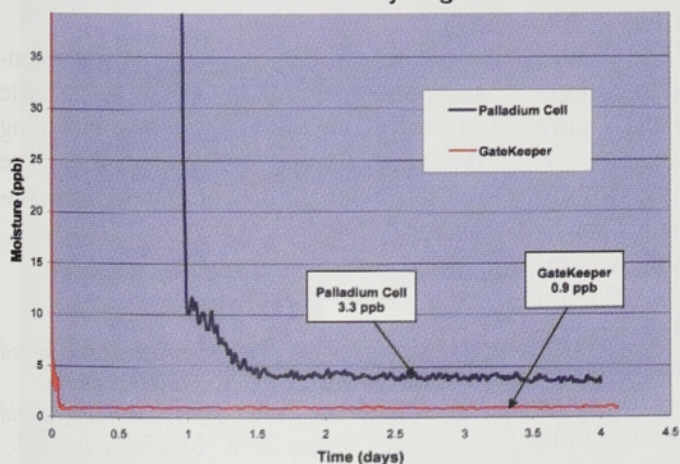
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High Performance CMOS

ROBERT A. METZGER

Within the compound semiconductor manufacturing community, it is well recognized that technologies such as SiGe HBTs, Si bipolar and even Si BiCMOS can represent stiff competition for both high speed and RF applications. But when it comes to basic CMOS, while most will concede to its intrinsic cost advantages, few consider it a serious threat due to what is believed to be its inherently lower performance. While this sentiment was true a few years ago, it certainly no longer is. Emerging from universities and research labs are a wide range of advanced CMOS circuits that can compete head-to-head with the most advanced compound semiconductor devices.

A team of researchers from the University of California San Diego, IBM and the Space and Naval Warfare Systems Center have reported on a bulk silicon divide-by-two dynamic frequency divider operating with a maximum clock speed of 26.5 GHz [1]. While the best III-V devices have pushed such dividers up to 80 GHz, performance in the 20 GHz range should be more than sufficient for the most demanding digital commercial applications.

Excepting the fact that smaller than standard CMOS gate-lengths were used (0.1 μm), the process itself was quite basic, using a single n-well process, a relatively lossy 1.2 ohm-cm p-type substrate, and only two levels of metallization. Using 3.0 nm gate oxides, and operating at a drain to source bias of 0.8 V and a gate to source bias of 0.8 V, the devices exhibited a breakdown voltage of over 3V and an f_t of 95 GHz. In order to achieve the maximum possible speed with the process, an all-NMOS design using source-coupled FET logic (SCFL) was used. The divider operated over a range of 6.5 to 26.5 GHz, and consumed only 26 mW of dc power at a clock frequency of

20 GHz. This represents compound semiconductor-like performance for a relatively basic CMOS process (note that not even an SOI substrate was used).

Other recent digital CMOS work targeted specifically at OC-48 SONET receiver applications (2.5 Gb/s) has been reported by researchers at Bell Labs [2]. In a typical SONET receiver, the incoming optical signal is received and converted by a detector (in this case an avalanche photodiode or APD) into a current signal. In turn, a transimpedance amplifier (in this case with a value of 1.5 k Ω) converts this current into a voltage signal. Before this signal can be passed along to the clock and data recovery circuit (CDR), and from there into the DEMUX, it must be amplified. This amplification can be done either by an automatic gain control amplifier (AGC), or a limiting amplifier, which by definition is used to limit amplification to avoid output saturation (and as a result the loss of the incoming signal).

Typically, a DFB laser would launch a signal into the fiber at a power level of -2 dBm, which after 100 km of travel would be attenuated to -28 dBm. To adequately amplify this signal a limiting amplifier with a gain of 30-32 dB is required. Furthermore, if implemented in CMOS, the limiting amplifier, CDR, DEMUX, MUX and SONET framer could potentially be fabricated in a single CMOS chip. This would then require only an external transimpedance amplifier (which typically is in close proximity to the APD to minimize parasitic capacitance) and the laser/modulator to complete the transceiver. Using a 0.25 μm bulk CMOS process, a CMOS limiting amplifier operating at 2.5 V was fabricated that exhibited a bandwidth of 3 GHz and a noise figure of 16 dB, while consuming only 53 mW. Such performance opens the way to an integrated CMOS SONET



OC-48 solution, and represents real competition in an application that is often implemented in GaAs MESFET technologies.

Driven by the need for wireless LANs operating at high data rates (i.e. 50 Mb/s) in the 5 GHz band (which the FCC has allocated for unlicensed national information infrastructure use), researchers at Bell Labs are also investigating the use of CMOS in the fabrication of a 5 GHz transceiver front-end chipset [3]. Using a 0.25 μm bulk CMOS process that features 5 layers of metal, and thick metal inductors with a Q of more than 10, the entire transceiver (full receiver and transmitter, except for a final external power amplifier needed on the transmitter side) is fabricated on two chips. The receiver contains an LNA with a 2.5 dB noise figure and 16 dB power gain and receiver mixer with 12.0 dB noise figure and 13.7 dB gain. The transmitter achieves an output power of -2.5 dBm at 5.7 GHz, with 33.4 side-band rejection by using an integrated quadrature VCO. By comparison, more advanced Si processes using BiCMOS or SiGe typically report less than -10 dBm of transmit power. Operating from a 3 V supply, the power consumption for the receiver and transmitter are only 114 and 120 mW, respectively.

These three examples clearly demonstrate the potential of CMOS to compete in a wide range of applications, including those which are often considered the exclusive domain of compound semiconductor devices.

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New Non-Destructive FTIR Thin Film Metrology for Optoelectronic Applications

SYLVIE BOSCH-CHARPENAY and PETER ROSENTHAL
On-Line Technologies, Inc
 East Hartford, CT, USA

STEVEN KWAN and MARK ITZLER
JDS Uniphase Corporation, Epitaxx Division
 West Trenton, NJ, USA

As complex compound semiconductor structures find an increasing variety of applications in the markets for optoelectronic, high frequency and high temperature devices, process control for wafer reproducibility and uniformity becomes critical. An example of a key optoelectronic device that will greatly benefit from improvements in epitaxial growth process control is the high-speed telecommunications photodiode. To detect light at the near infrared wavelengths most suitable for transmission of fiber-optic signals (1.3–1.6 μm), the most widely used device is the positive-intrinsic-negative (PIN) diode based on a double heterojunction structure in which an $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ absorption region is sandwiched between two layers of InP. Enhanced performance can be obtained from an avalanche photodiode (APD) based on a structure similar to the PIN diode but with additional epilayers designed to create internal avalanche gain. These diodes have become essential elements of all fiber-optic receivers and signal monitors designed for telecommunication applications. They are also instrumental in the test and measurement equipment designed for signal detection in this wavelength range.

The push for higher performance in many applications served by compound semiconductors makes it imperative that better epiwafer characterization tech-

niques are developed. For PINs and APDs, device performance is often critically dependent on wafer parameters such as layer thickness and doping. For instance, device bandwidths can be dictated by critical layer thicknesses, and more consistent device performance requires more consistent epitaxial growth. For the emerging generation of 10 Gb/s receiver products and next-generation 40 Gb/s devices, more challenging photodiode structures will mature in performance, yield, and throughput only if adequate wafer characterization tools are available.

Until now, the main characterization methods for measuring thickness and dopant concentrations of film stacks such as PINs or APDs were all destructive: thickness profiles were usually obtained by destructive chemical methods, and dopant concentrations were obtained using destructive CV. Moreover, these tests had to be performed on calibration samples or simultaneously grown witness samples with no option of carrying them out on the shippable wafers themselves. While visible ellipsometry and X-ray reflectometry are used to non-destructively characterize thin layers, the penetration depth at these wavelengths is usually not sufficient to probe thick (microns) layers, and measurements can be very slow. A new infrared metrology for thin film analysis was recently developed to perform fast optical measurements of thickness, free carrier concentration and index of refraction of multilayer compound semiconductor structures such as PINs and APDs.

New Infrared Optical Technology

The new technology employs state-of-the-art Fourier Transform Infrared (FTIR) reflection spectroscopy combined with advanced model-based analysis, and has been widely used for the characterization of epitaxial silicon [1]. The basis of the FTIR measurement lies in the different index of refraction (or complex dielectric function DF) in the infrared of the various films and the substrate. The index of refraction

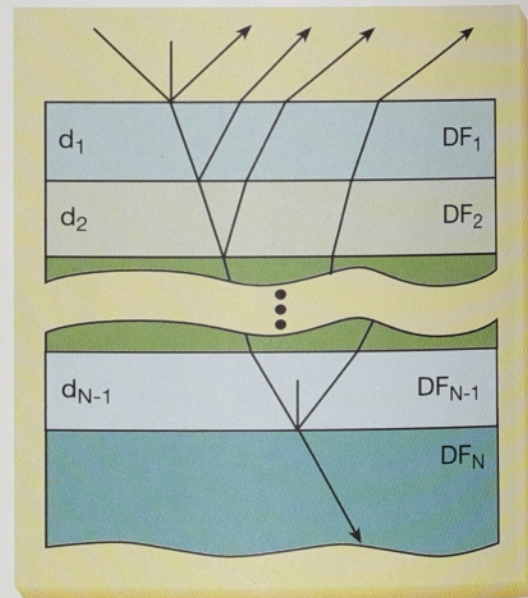


Figure 1. Schematic showing the multiple reflections of the infrared light in the film stack. The reflectance model uses as parameters the thickness d and spectral dielectric function DF (or spectral n and k) of each layer to calculate the predicted reflectance and match it to the measured reflectance.

[1] S. Charpenay et al., "Model-based analysis for precise and accurate epitaxial silicon measurements", *Solid State Technology*, July 1998 issue.

Layer	Nominal		Extracted	
	Doping ($\times 10^{18} \text{ cm}^{-3}$)	Thickness (μm)	Carrier conc. ($\times 10^{18} \text{ cm}^{-3}$) $\pm \sigma$	Thickness (μm) Min-Max $\pm \sigma$
Cap n-InP	0.02	1.11*	0 (fixed)	1.000–1.080 $\pm$ 0.005
Absorption layer i-InGaAs	Undoped	3.24*	0 (fixed)	2.992–3.172 $\pm$ 0.005
Buffer layer n ⁺ InP	>1	~1	2.6 $\pm$ 0.2	1.224–1.315 $\pm$ 0.005
Substrate n ⁺ InP	Unknown	–	14.8 $\pm$ 0.2	–

Table 1. Film stack description along with extracted film thicknesses and free carrier concentrations at the center of the wafer. σ represents the uncertainty of the extracted parameter. (*Measured by the epiwafer manufacturer on a simultaneously grown witness sample using a slow, destructive technique which does not allow wafer mapping.)

depends on material composition (e.g. InP, InGaAs) but also on free carrier concentration, as free carriers absorb infrared light. As a probing infrared beam interacts with stacked films with different dielectric functions, the reflected beam displays interference effects from the multiple reflections at the various film interfaces (see Figure 1). The spectrum obtained depends on the thickness and dielectric function of each film as well as of the substrate.

Advanced Analysis Algorithms

One innovation of the new FTIR metrology is to use powerful multi-layer, multi-parameter analysis algorithms [2] (similar to those typically used in visible ellipsometers) to extract parameters related to the films. This approach differs from “traditional” FTIR measurements, where simpler analysis models of the reflectance or absorbance spectra are used and cannot be applied to complex film stacks. Together with the multi-layer analysis algorithms, an automated solution routine simultaneously solves for the thickness, free carrier concentration and refractive index of the various layers and substrate by varying the model parameters to obtain a match between measured and theoretical reflectance spectra. The whole measurement, including the FTIR spectrum measurement and analysis, typically takes a few seconds per data point.

New Optics

Another key innovation of the new FTIR metrology is the use of special optics which allow the measurement of front surface reflections only, and eliminate the reflection from the backside of the wafer. This feature greatly simplifies the process of modeling of samples with transparent substrates and not well-controlled back surfaces (such as with glue residues) that would otherwise add artifacts to the measured spectrum. As a consequence, the measurements can be performed without requiring any special surface or backside treatments. The new

optics also provide a very small measurement spot (200 $\times$ 800 μm on the wafer, with an option for 50 $\times$ 50 μm), which is significantly smaller than the typical FTIR's spot size of around 5 mm diameter. The small spot allows measurements very close to the wafer edge, which is important when trying to optimize the wafer “real-estate”.

Example of PIN analysis

A multilayer PIN sample of InP/InGaAs/InP/InP was measured and analyzed. Table 1 shows the details of the film stack. The analysis was performed to extract the following parameters: cap InP thickness, InGaAs thickness, buffer InP thickness and free carrier concentration, and InP substrate free carrier concentration. A Drude model was used to represent the free carrier's absorption [3]. Literature spectra for the refractive index n and the extinction coefficient k were used for InP and the InGaAs alloy (note that while the overall shape of the refractive index spectrum does not usually vary significantly with alloy composition, n can however be adjusted linearly if found necessary to account for small differences in composition). Excellent fits were obtained, validating the film stack and dielectric function models used (see Figure 2). Table 1 shows the extracted parameters, which were in excellent agreement with the nominal values.

A 3-D thickness map of the InGaAs layer is shown in Figure 3, displaying a fairly radial distribution of thickness across the PIN wafer. Similar thickness maps were obtained for the other layers. Such information is extremely useful to improve the tuning of deposition chambers, ultimately increasing yields across the wafer. These data can also be of great value for optimizing subsequent processes carried out on the wafers, such as the timing of dopant diffusions to create p-n junctions.

Low Inter-Parameter Correlation

When several fitting parameters are used, correlations between the parameters should be estimated to assess the robustness of the measurements. We investigated the influence of each parameter on the reflectance spectrum for a film stack similar to that of the PIN sample described above. It was found that each parameter has a different influence on the spectrum, which translates into a mini-

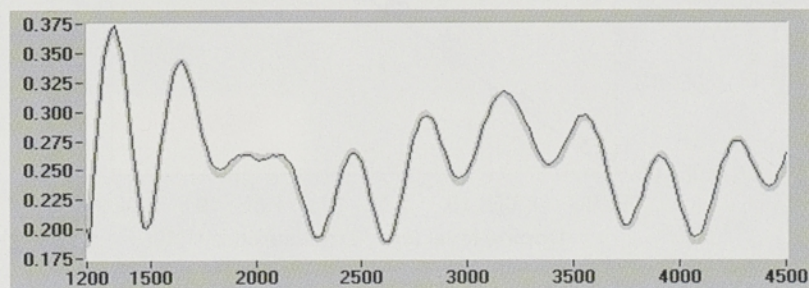


Figure 2. PIN wafer analysis. The thin black line shows the experimental spectrum, while the thick grey line shows the fitted spectrum.

[2] E. Hecht, “Optics”, Addison-Wesley Pub. (1987).

[3] C. Bohren et al., “Absorption and scattering of light by small particles”, John Wiley & Sons Inc (1998).

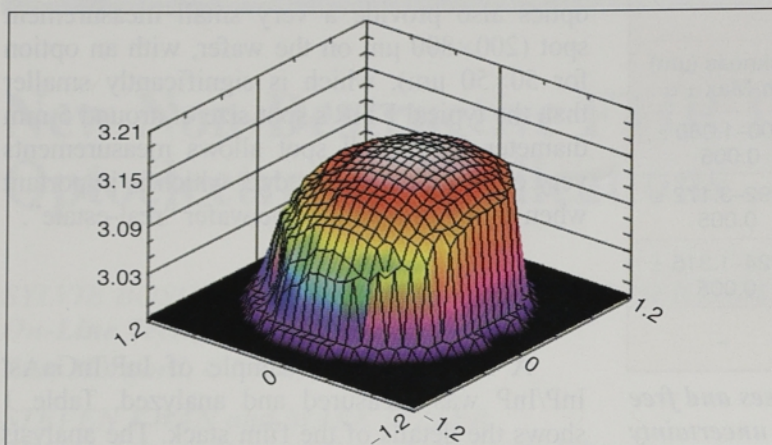


Figure 3. InGaAs thickness measurements across the PIN wafer (vertical axis in microns, horizontal axes in inches).

imum correlation. Quantitatively, it was determined that film thicknesses had uncertainties from 1 to 5 nm (1σ), and free carrier concentrations from 0.1×10^{18} to $0.2 \times 10^{18} \text{ cm}^{-3}$ (1σ). The repeatability for thickness was about 1 nm (1σ) and $0.1 \times 10^{18} \text{ cm}^{-3}$ (1σ) for free carrier concentration. These results are typical for PINs, APDs and similar structures.

Correlation with Independent Measurements

The accuracy of the FTIR measurements has been tested versus destructive measurements (SIMS, CV, etc.). Thicknesses as measured by SIMS typically agree closely with the FTIR results to better than 5%. An excellent correlation is also obtained between free carrier concentration as measured by the FTIR and CV doping measurements (see Figure 4).

Detection Limits

The detection limits for film thickness depend on the specific film stack to be analyzed. For example, if a thin layer (e.g. 20 nm) is next to a thick layer (microns) of significantly differ-

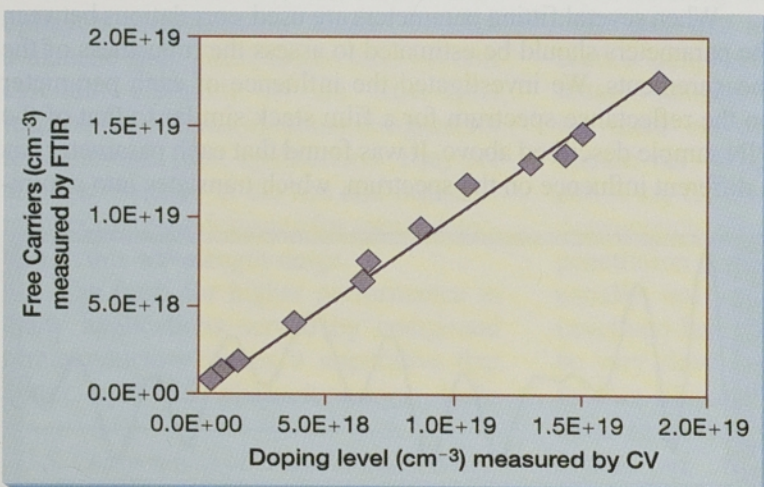


Figure 4. Correlation of free carriers measured by FTIR and doping measured by CV.

ent refractive index, there will be an internal reflection at the interface, which will clearly impact the reflectance spectrum. In such a case, the thicknesses of both layers can be extracted with accuracy. On the other hand, multiple layers which are very thin ($<10 \text{ nm}$) and/or with similar index of refraction may not be clearly distinguished from other thin neighboring layers. In that case, a "total equivalent" thickness can however be obtained for process control purposes. Typically, the detection limit for thickness can then be estimated to be from $\sim 10 \text{ nm}$ to $\sim 0.3 \mu\text{m}$. The detection limit for free carrier concentration is typically in the range $\sim 2 \times 10^{17}$ to $\sim 5 \times 10^{17} \text{ cm}^{-3}$ (depending on the material), as below this range the free carrier absorption is too weak.

Multiple Applications

Any application where one or more layers are deposited on a substrate can potentially benefit from the new FTIR metrology. Numerous applications are found in the optoelectronics industry, and include PIN diodes, APDs, infrared lasers, blue lasers, LEDs, high power applications, etc. Epitaxial film stacks including other materials such as SiC, GaN, MCT, etc. can be analyzed with similar levels of precision as for the InP/InGaAs/InP/InP PIN example above. Measurements can also be performed on transparent substrates such as sapphire or quartz without the typical complications due to backside reflections, as the proprietary optics eliminate backside reflections from the collected light.

The new FTIR metrology can also analyze advanced films for which chemistry is important, such as doped glass (i.e. boron- and phosphorus-doped glass, for waveguides applications), thick photoresist, and more. In these cases, critical parameters such as chemical composition and/or dopant concentration can be inferred from the extracted infrared dielectric function.

Conclusions

We have introduced a new FTIR metrology for the non-destructive wafer mapping of multiple parameters such as film thickness, film doping, etc. The new metrology yields the following features:

- Non-contact, non-destructive optical characterization;
- Ability to extract *multiple* parameters such as thickness, free carrier concentration and index of refraction of multiple layers;
- A small measurement spot $200 \times 800 \mu\text{m}$ (with an option for a $50 \mu\text{m}$ spot) which allows for a small edge exclusion;
- Measurement can be performed on opaque or transparent substrates as proprietary optics eliminate artifact backside reflections;
- Excellent thickness reproducibility measurements (i.e. precision) of typically 1 nm (1σ) and total uncertainty of typically 1–5 nm (1σ);
- Fast measurements of typically a few seconds (including analysis);
- Multiple applications in the compound semiconductor field.

Finally...

Optical Measurements of Dopants and Thickness!

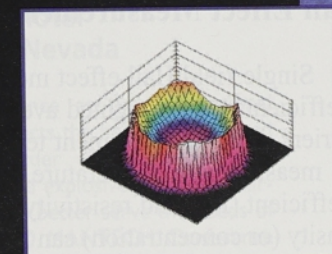
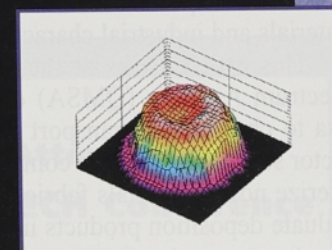
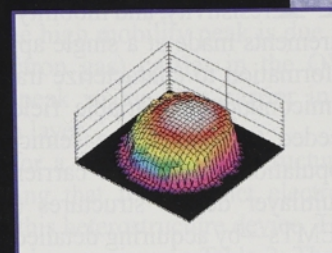
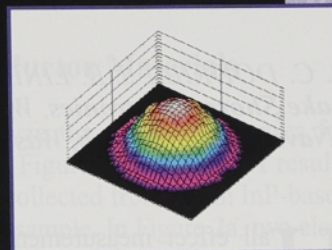


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Evaluation of Transport Properties Using Quantitative Mobility Spectrum Analysis

B. C. DODRILL, J. R. LINDEMUTH, B. J. KELLEY, G. DU and J. R. MEYER*

Lake Shore Cryotronics, Westerville, OH

*Naval Research Lab, Washington, DC

Hall effect measurements are the most commonly used method for determining the carrier type, concentration, resistivity, and mobility of semiconductor materials. Measurements made at a single applied field usually provide enough information to characterize transport properties of single carrier semiconductors. Variable field measurements provide the data needed to characterize semiconductor materials with multiple populations of distinct carrier species such as quantum wells, multilayer device structures (i.e. heterostructures), HBTs and HEMTs—by acquiring detailed information about transport properties of the *individual* carriers that make up a multi-carrier material. This is important for both research and development of new materials and industrial characterization and process control.

This article looks at the use of the Quantitative Mobility Spectrum Analysis (QMSA) of magnetic field-dependent Hall data to characterize transport properties of multilayer semiconductor structures. We also comment on the use of QMSA to characterize novel materials fabricated in R&D environments and to evaluate deposition products in quality control applications.

Hall Effect Measurements

Single field Hall effect measurements provide only the Hall coefficient and a weighted average of mobilities of all available carriers at the measurement temperature. Data collected include the measurement temperature, applied magnetic field (B), Hall coefficient (R_H) and resistivity (ρ), from which the mobility and density (or concentration) can readily be measured. Because both of these measurements refer only to the bulk average of all available carriers that make up the material, this data is of limited value. Furthermore, in the absence of measurements at other applied fields, it is impossible to determine whether more than one carrier species is present in the sample.

The measurement of Hall data from variable fields can provide additional information about multiple carrier semiconductors. Figure 1 shows the Hall coefficient and resistivity as a function of field for three different samples. Although the raw data does not allow extraction of any individual carrier's behavior, it may be used to distinguish one material from another. In Figure 1a, the R_H vs. B plots suggest that samples A and B are similar, while C is dissimilar. And in fact, A and B are closely

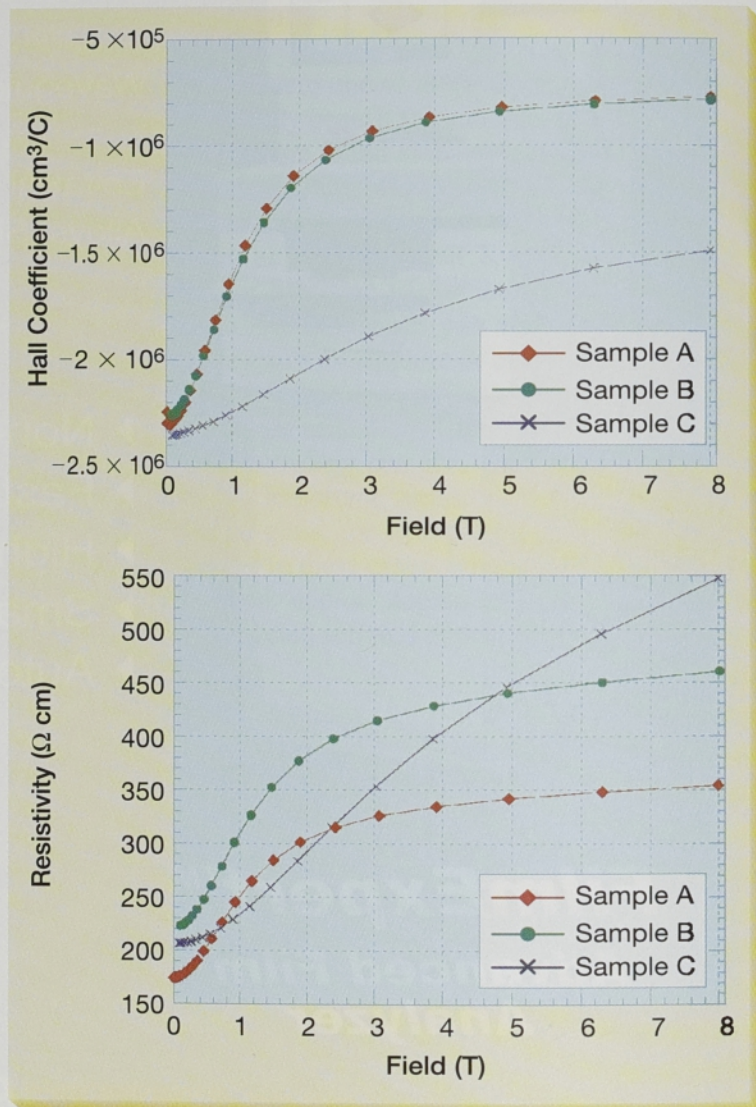


Figure 1. (a) Hall coefficient and (b) resistivity dependence on applied field for semiconductors with multi-carrier behavior. The raw data from Hall and resistivity measurements distinguishes different materials but does not reveal individual carrier behavior—a more sophisticated analysis such as quantitative mobility spectrum analysis (QMSA) is required.

related structures. In Figure 1b, the resistivity data show that samples A and B differ in conductance, although more specific

QMSA Results for Hall Data Presented in Figure 1.

Sample ID	Mobility 1 (cm ² /Vs)	Density 1 (cm ⁻³)	Mobility 2 (cm ² /Vs)	Density 2 (cm ⁻³)
Sample A	-1948	7.111e+12	-20538	1.067e+12
Sample B	-1609	6.767e+12	-17424	9.010e+11
Sample C	-1723	1.797e+12	-12826	2.051e+12

Table 1. Electron mobilities extracted by applying QMSA to the Hall data shown in Figure 1.

characteristics cannot be inferred. Thus, Hall coefficient and resistivity measurements provide general qualitative information about multi-carrier samples but do not identify individual carrier properties. To correctly characterize transport properties, a more sophisticated analysis, known as Mobility Spectrum Analysis, is required.

Quantitative Mobility Spectrum Analysis

Mobility Spectrum Analysis was developed by Beck and Anderson in 1987 [1] and was further expanded to Quantitative Mobility Spectrum Analysis (QMSA) by Meyer and Hoffman [2] of the Naval Research Laboratory and Antoszewski et al [3, 4] at the University of Western Australia in 1997. Lake Shore licensed the analytic method, and developed a QMSA software calculation package for use with its own Hall effect measurement systems [5]. This software may also be used to analyze Hall effect data from other systems. Due to the nature of the analysis, however, QMSA results are very sensitive to inherent R_H and ρ measurement errors, so that a high performance system such as the Lake Shore 7500 or 9500 series is required for the most reliable results.

In essence, QMSA correlates the measured Hall coefficient and resistivity to a unique mobility spectrum. The Hall coefficient and resistivity measurements in different applied magnetic fields are analyzed to extract a corresponding set of carrier mobilities and concentrations. QMSA takes as its input values the measured Hall coefficient and resistivity at various values of magnetic field. The elements of the field-dependent conductivity matrix are then calculated, and by numerically fitting these elements, QMSA is able to extract a spectrum of mobilities and densities for the individual carriers.

QMSA can be used to demonstrate that samples A and B contain low mobility carriers (see Table 1: Mobility 1, Density 1) with mobilities of -1948 and -1609 cm²/Vs respectively. Samples A and B also both have high mobility carriers (denoted Mobility 2, Density 2) with values of approximately -20,000 cm²/Vs, and densities of roughly 1×10^{12} /cm³ in both samples.

The structure of sample C appears to be entirely distinct from that of these two samples, evidenced by the fact that its high mobility carrier is far less mobile than those of sample A and B, while being present at twice the concentration. These findings suggest that samples A and B are very similar in the identity and

concentration of their high mobility carriers, and different with regards to their low mobility carriers. The identity and concentration of carriers in sample C differ from those in both samples A and B. These findings demonstrate the advantage of QMSA in characterizing multi-carrier materials, in contrast to the limited information available from the characterization depicted in the results of Figure 1.

Multi-Carrier Semiconductor Materials

QMSA can be used to analyze the carrier properties for single- and multi-carrier devices. Figure 2 show QMSA results for Hall effect measurement data collected from (a) an InP-based PHEMT and (b) a GaAs PHEMT sample. In Figure 2a, two electron carriers have been identified with mobilities of -427 cm²/Vs and -12,018 cm²/Vs and densities of 3.372×10^{17} /cm³ and 1.533×10^{18} /cm³, respectively. The high mobility peak is due to the 2DEG (two dimensional electron gas) carrier in the QW channel layer. The low mobility peak is due to a carrier in a highly-doped layer such as the cap layer.

Figure 2b shows the results for a GaAs PHEMT structure, with the QMSA spectrum revealing that four distinct electron carriers and a single hole populate this heterostructure device. The mobilities and densities of each carrier are given in Table 2. These mobility spectra clearly show the multi-carrier, mixed conduction

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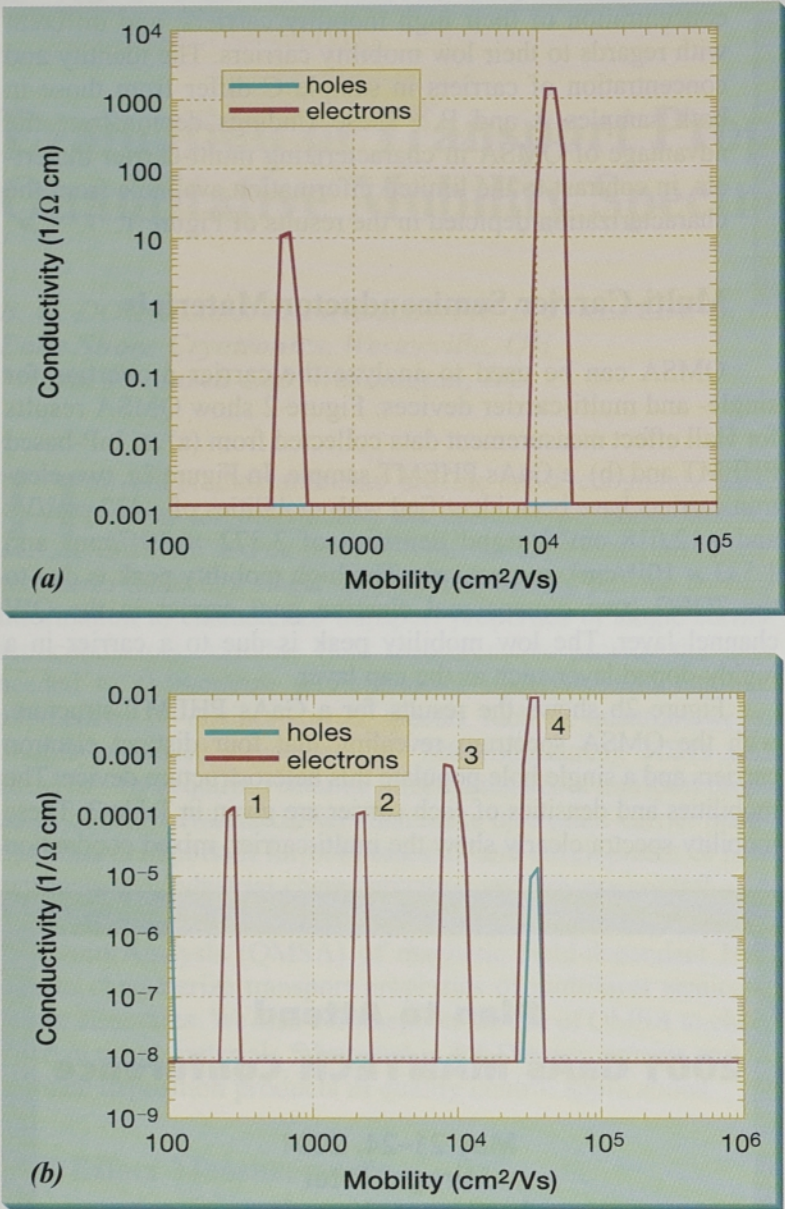


Figure 2. (a) Mobility spectrum calculated for the two carrier case for an InP PHEMT and (b) for a GaAs PHEMT sample. For the latter, the two high mobilities are due to 2DEG carriers in the QW channel layer (designated e Carrier 3 and 4), and the existence of two peaks suggests that two sub-bands in the QW layer are occupied.

nature of this sample. There are four electron peaks in Figure 2b. The two peaks at higher mobility are due to 2DEG carriers in the QW channel layer (designated e Carrier 3 and 4). In addition, the existence of two peaks suggests that two sub-bands in the QW layer are occupied.

The lowest mobility peak (e Carrier 1) is due to a carrier in the cap layer, while the intermediate mobility peak (designated e Carrier 2) is most likely due to a defect-induced carrier in a buffer layer, or an interface/surface carrier. The existence of this carrier implies poor device quality, and demonstrates the power of QMSA as a diagnostic tool for defect detection.

Although not shown here, the mobility of the 2DEG carriers is strongly temperature dependent and suggests thermally acti-

Carrier mobilities and densities for the pseudomorphic HEMT device.

	Mobility (cm²/Vs)	Density (1/cm³)
e Carrier 1	-269.07	-5.8436×10¹²
e Carrier 2	-2129.1	-6.53059×10¹¹
e Carrier 3	-8674.5	-1.14425×10¹²
e Carrier 4	-33436	-3.35793×10¹²
hole Carrier	34043	4.07967×10⁹

Table 2. Carrier mobilities and concentrations for the case of a multi carrier PHEMT device. The lowest mobility comes from a defect-induced carrier in a buffer layer or the cap layer.

vated scattering dominant charge transport. This dependence has been observed in all PHEMT devices studied thus far using QMSA. Conversely, the mobility of the cap layer carriers are virtually temperature independent, suggesting electron-impurity scattering dominant charge transport [6].

Conclusions

Quantitative Mobility Spectrum Analysis of variable field Hall effect measurements extracts significantly more information for electron transport characterization of semiconductor materials with multiple carrier species than is possible from single field Hall measurements alone, which determines only the bulk mobility and carrier concentration. QMSA is able to extend the data into studies of the individual carrier mobilities and concentrations for all carriers that comprise the material.

As an in-line metrology tool, QMSA allows the design of QA/QC procedures that will test the quantity of interest (e.g. the mobility and concentration of the high mobility electron carrier) in post-epitaxial products. This test procedure detects defective product early in the production cycle and prior to investment of additional capital in the wafer, and thus increases the yield. Testing may be performed on the wafer level and after dicing/slicing. Additionally, characterization of the 2DEG carrier mobility allows better estimation of the modeling parameters to be used in IC package design resulting in optimized performance, thus facilitating the efforts of the design engineer. Such measurements and analysis are also useful in fundamental research and development of novel heterostructures and HEMT devices.

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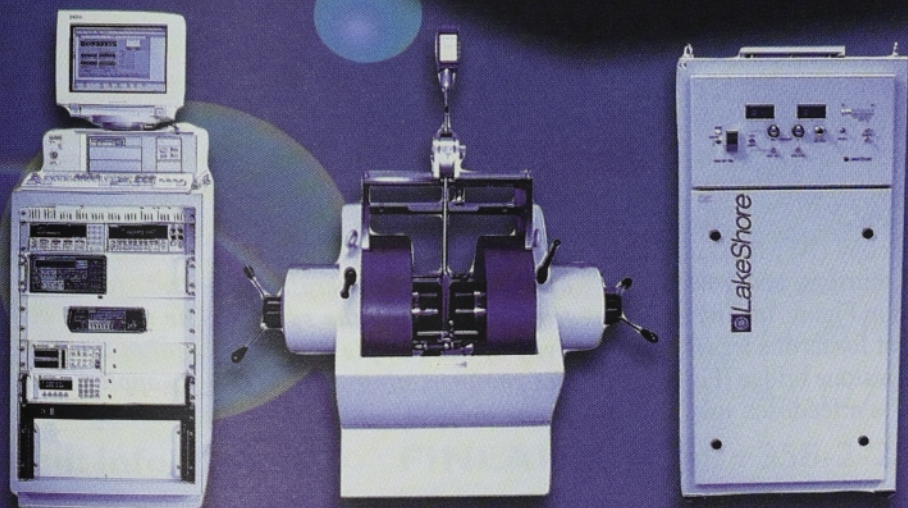
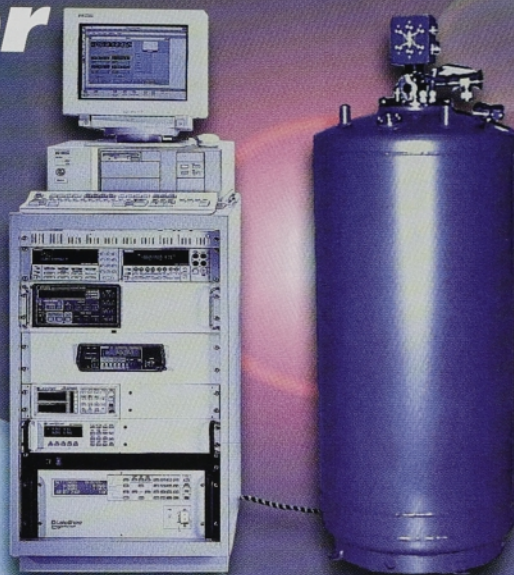
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Thermal Conductivity Measurements of GaN and AlN

D.I. FLORESCU, V.M. ASNIN and FRED H. POLLAK
Brooklyn College of the City University of New York*

Group-III nitride semiconductors (e.g. GaN, AlN, InN) have attracted considerable attention in recent years for their utilization in high power optoelectronic and electronic devices [1–4]. These high power/high temperature uses make thermal behavior, particularly the thermal conductivity (κ), an extremely important material property. The material's ability to dissipate heat directly affects its device performances.

The thermal conductivity is a function of both intrinsic and extrinsic effects [5]. The latter are related to thermal wave (i.e. phonon) scattering by generic crystal defects (dislocations, impurities, process-induced damage, etc.), while the former is due to anharmonic thermal wave-thermal wave scattering. For materials with free carrier concentrations $\leq 10^{19} \text{ cm}^{-3}$ the free carrier contribution to k is negligible. Thus k provides a measure of the material's quality. Therefore, the thermal conductivity is important from both applied (device modeling, sample quality) and fundamental (basic mechanisms of thermal wave propagation) perspectives.

However, despite the considerable body of work, both experimental and theoretical, on the electronic, optical, and structural properties of the group-III nitride semiconductors, relatively few investigations have been reported on thermal conductivity measurements [6–16] or theory [7,17–19].

Thermal Conductivity Measurement Methods

There are a number of ways to evaluate κ including steady-state longitudinal heat flow [5], modified Angstrom's method [5], optical pump-probe [20], laser flash [13], third-harmonic electrical method [9], scanning thermal microscopy (SThM) [8,10–12, 14–16], etc. With the exception of SThM most of these approaches require either contacts (destructive) and/or thick samples ($>100 \mu\text{m}$), and do not have high spatial resolution. On the other hand, SThM is essentially nondestructive, and has a micron range spatial/depth resolution. The latter is important for examining material fabricated by new, low defect density techniques such as lateral epitaxial overgrowth (LEO) and pendeo-epitaxy, in addition to mapping spatial variations of κ across a wafer.

In SThM [21] the probe consists of a "V" shaped (radius of curvature $\sim 1 \mu\text{m}$) resistive element (Pt/10%Rh wire) incorporated at the end of a flexible cantilever. The probe tip is positioned using an atomic force microscopy (AFM) arrangement (laser, mirrors, and detector) as shown in Figure 1a. The resistive element forms one leg (R_{probe}) of a Wheatstone bridge (Figure 1b). There is a feedback loop, which

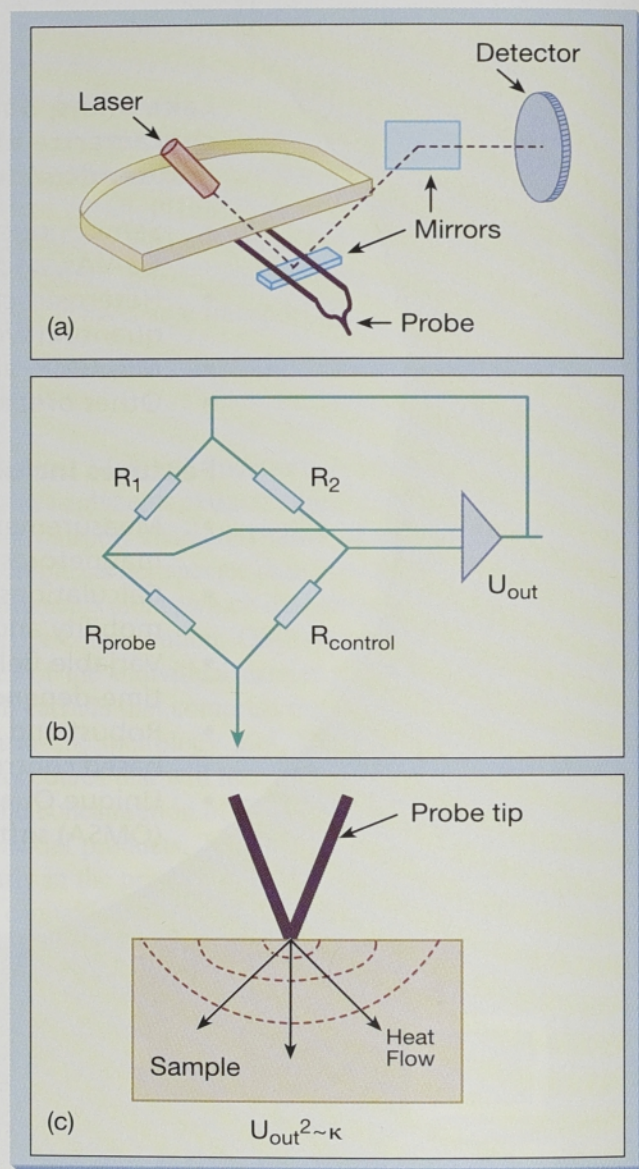
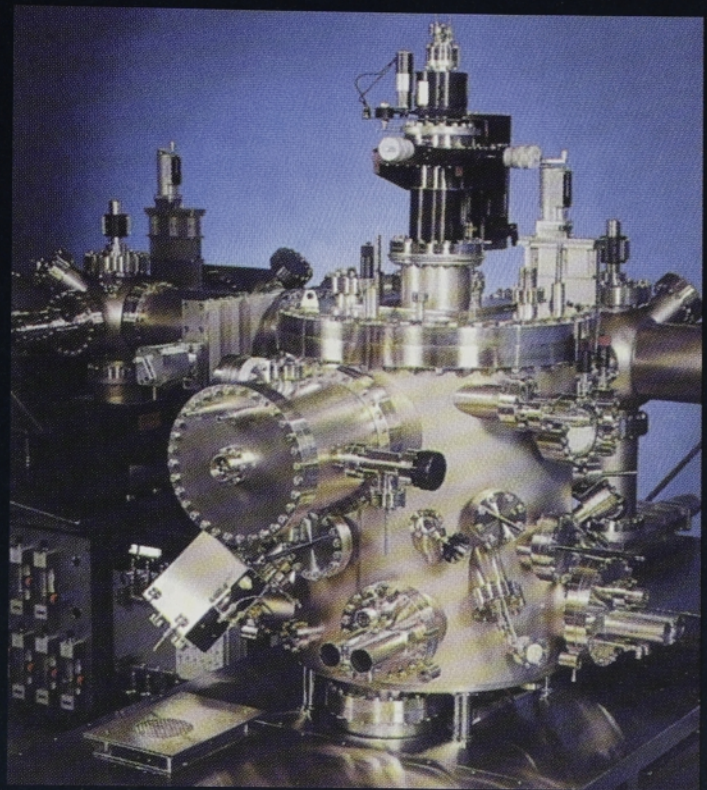


Figure 1. (a) Schematic diagram of the SThM probe and AFM arrangement (laser, mirrors and detector) used for positioning. (b) Circuit diagram of the probe temperature control. (c) Heat flow from the tip into the sample. The thermal conductivity of the sample is proportional to the square of the compensating voltage (U_{out}^2) applied when the probe tip is in contact with the specimen.

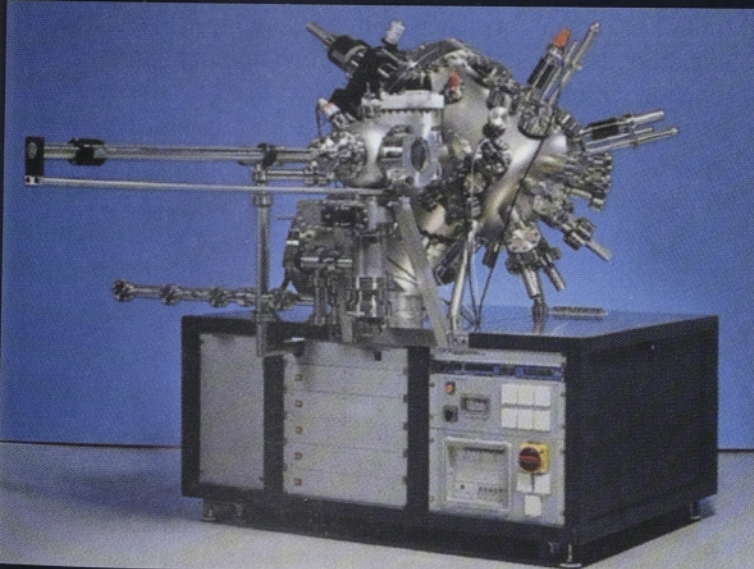
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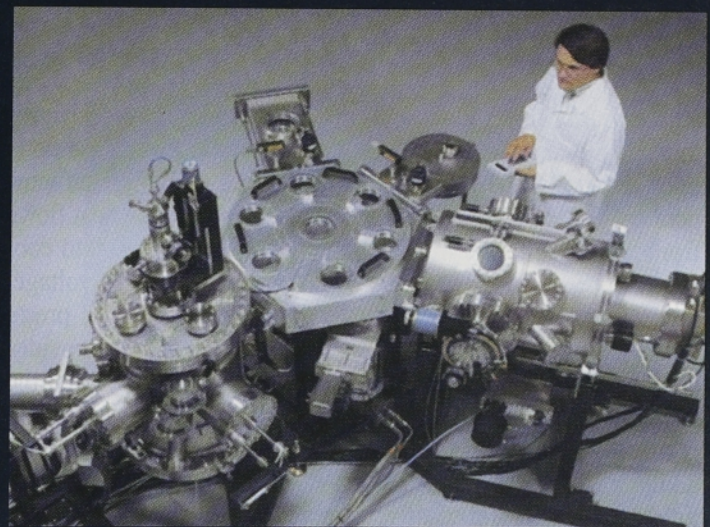
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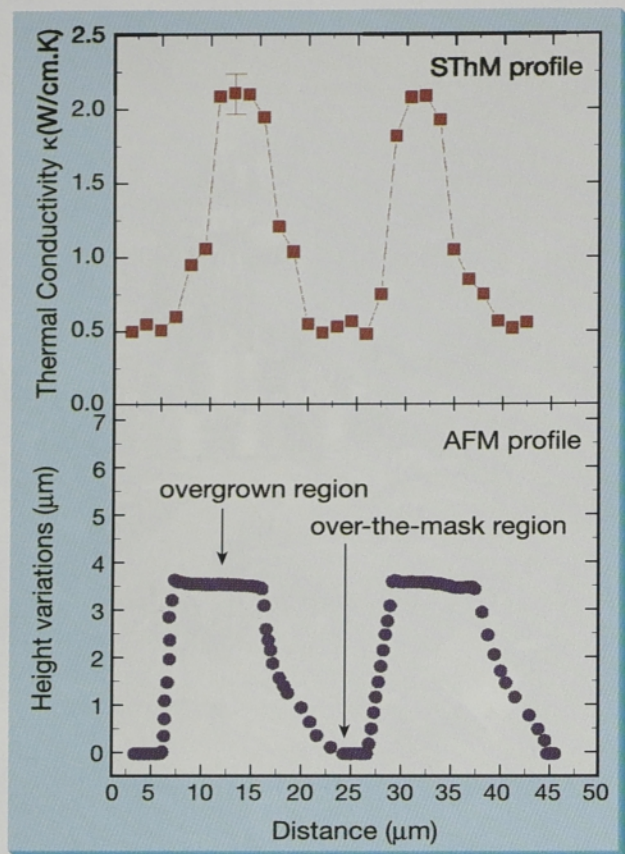


Figure 2. Thermal conductivity (solid squares) and AFM profile (solid circles) on two neighboring stripes of an LEO grown GaN sample. Representative error bar is shown for the SThM scan. The solid line is a guide for the eye.

adjusts the bridge voltage in order to keep the bridge balanced thus maintaining a constant probe temperature. The SThM tip is operated at a preset value ~ 40 – 50°C above the specimen temperature. When the heated probe contacts the sample heat flows from the probe to the material (Figure 1c), which tends to cool the tip. The feedback senses this shift and increases the voltage, thus returning the tip's resistance (temperature) to its preset point. The raw data from the SThM instrumentation provides only the voltage applied to the bridge (U_{out}). However, κ of the specimen is proportional to the heat flow (or U_{out}^2) when the tip is making contact. A simple calibration method was developed and implemented for absolute κ measurements [10,22]. The spatial/ depth resolution of this technique is estimated to be in the 2–3 μm range for GaN and AlN.

GaN and AlN Thermal Conductivity Results: Overview

1. GaN Material

Sichel and Pankove [6] performed the first measurement of κ of "bulk" GaN (400 μm of material fabricated by HVPE)

as a function of temperature ($25\text{K} < T < 360\text{K}$) with a room temperature $\kappa \sim 1.3 \text{ W/cm.K}$ (along the c -axis), a value less than Slack's estimation of $\sim 1.7 \text{ W/cm.K}$ [17].

More recently, Vaudo *et al.* [13] reported room temperature values of $2.2 \pm 0.2 \text{ W/cm.K}$ on 200–500 μm thick free-standing HVPE GaN using the laser flash method.

The Brooklyn College group, in collaboration with Emcore, measured the room temperature κ on partially and fully coalesced LEO GaN/sapphire (0001) using SThM [12]. A correlation between low/high threading dislocation density and high/low κ was established. High κ , comparable to the values subsequently reported by Vaudo *et al.* [13], were found on the overgrown regions of these samples. The solid squares in Figure 2 show the SThM profile and the solid circles depict an AFM profile on two neighboring stripes of a LEO GaN/sapphire (0001) sample. The overgrown and over-the-mask regions are also indicated on the AFM data. The SThM shape reveals high and low thermal conductivity regions. A direct correlation between the thermal conductivity values and the details of the overgrown patterning is established by plotting the SThM and AFM profiles on the same length scale. High κ readings, in the 2.00–2.10 W/cm.K range, correspond to the upper portion of the overgrown regions (low defect density) while the low κ values are found in the over-the-mask sections (high defect density).

Using a third-harmonic electrical technique Luo *et al.* determined a room temperature thermal conductivity on LEO material of at least 1.55 W/cm.K [9].

The thermal conductivity in HVPE-grown n -GaN/sapphire (0001) has been correlated with Si doping levels and sample thickness using SThM by the Brooklyn College group in conjunction with R.J. Molnar of MIT Lincoln Laboratories [10,11]. Plotted in Figure 3 are κ values as a function of doping level

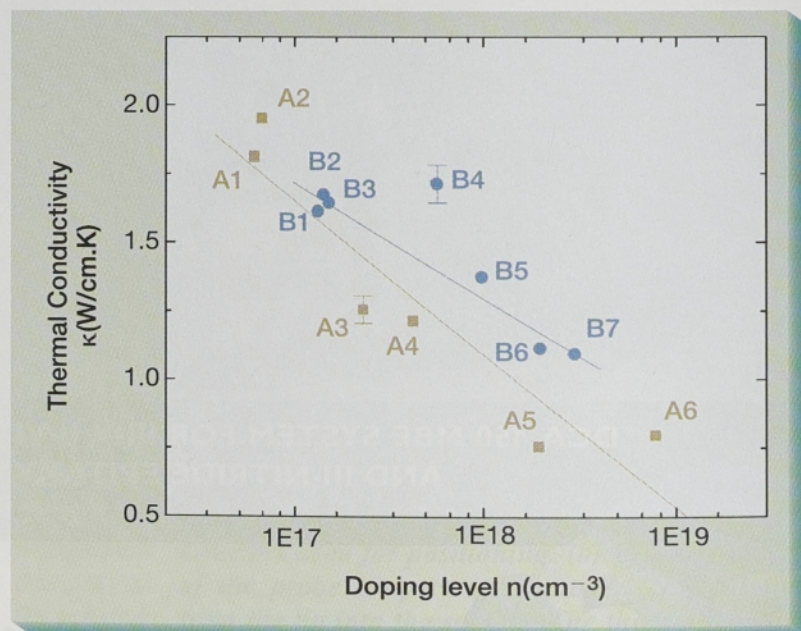


Figure 3. Thermal conductivity as a function of n for two sets of HVPE grown n -GaN. Representative error bars are shown. The solid lines are least-square fits to a linear function.

in two sets of HVPE n -GaN. In both groups the thermal conductivity decreased linearly with $\log n$, the variation being about a factor of two decrease in κ for every decade increase in n (in the measured range). Reference 11 has also reported the variation of κ (within 2–3 μm of the surface) with film thickness. There is a general trend of increasing thermal conductivity with thickness, consistent with the observed general reduction of both extended dislocations and point defects with film thickness.

The thermal conductivity behavior before and after plasma-induced effects was studied on a series of four HVPE n -GaN/sapphire (0001) samples by SThM in a joint project between Brooklyn College investigators and the Adesida group at the University of Illinois in Champaign-Urbana [14]. Before treatment κ was measured to be in the 1.70–1.75 W/cm.K range, similar to that

of HVPE GaN material with comparable carrier concentration and thickness [10,11]. The solid squares in Figure 4(a) show κ for the four samples measured before processing. The samples were processed under constant Ar gas flow and pressure for a fixed time period, the only variable processing parameter being the DC bias voltage (125–500 V). At 125 V the thermal conductivity was only slightly less ($\kappa \sim 1.65$ W/cm.K) compared to the untreated case. After the initial 125 V procedure κ exhibited a linear decrease with the DC voltage in the investigated range, with values ~ 0.3 W/cm.K for the 500 V situation [14]. Shown in Figure 4(b) is κ measured after each individual processing procedure as a function of the processing voltage. The observed linear decrease of κ at room temperature with increasing DC bias voltage could be attributed to the scattering of the thermal waves associated with additional "defects" being induced by the bias volt-

age. More defects are being generated with increasing bias voltages.

Using SThM the topographical variations in κ were correlated with plan-view transmission electron microscopy (TEM) and atomic force microscopy (AFM) imaging on a series of HVPE n -GaN samples [15]. Relatively low values of κ (~ 1.2 W/cm.K) were found in the regions near the edge dislocations, as identified by both TEM and AFM. On the other hand relatively high κ regions (~ 1.45 W/cm.K) were found in the sections between these defects.

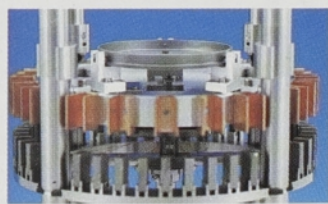
A theoretical prediction for κ for GaN at room temperature was initially estimated by Slack to be ~ 1.7 W/cm.K [17]. A simple expression to calculate the thermal conductivity of perfect dielectric crystals at "high temperatures" was derived by Witek [18]. Using this approximation he estimated the room temperature thermal conductivity of GaN to be ~ 4.10 W/cm.K. Subsequently



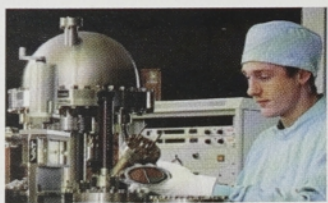
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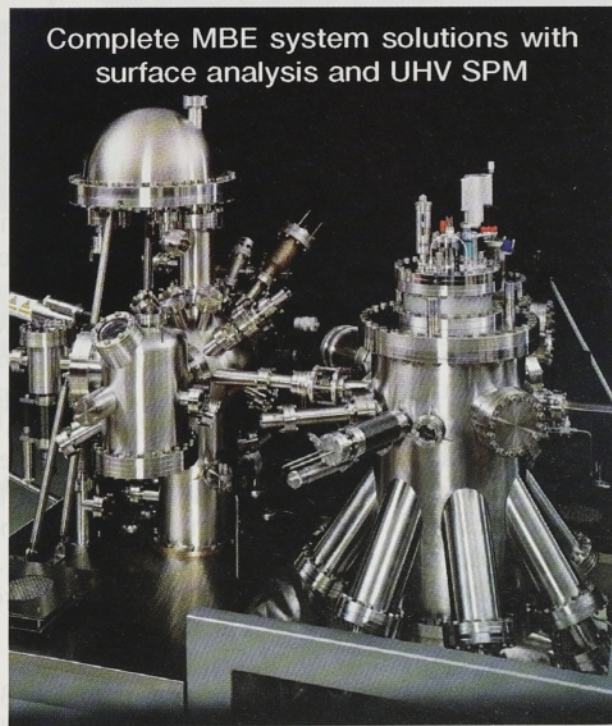
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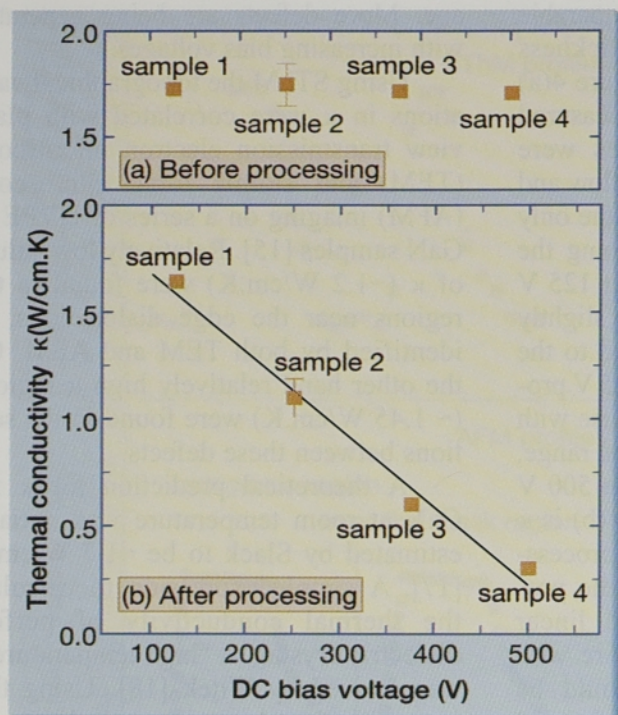


Figure 4. Thermal conductivity of the four samples (a) before processing, and (b) after processing, as a function of the processing voltage. Representative error bars are shown. The solid line in (b) is a least-square fit to a linear function.

Berman confirmed this value by evaluating the 300K thermal resistivity of GaN [19].

2. AlN Material

Slack *et al.* [7] measured the thermal conductivity of “single crystals” of AlN (340 ppm by weight oxygen) as a function of temperature ($0.4 \text{ K} < T < 1800 \text{ K}$) and found $\kappa \sim 2.85 \text{ W/cm.K}$ at 300 K, less than his own estimate of 3.19 W/cm.K for pure AlN (no oxygen).

Using SThM, Florescu *et al.*, in collaboration with TDI, Inc. (Gaithersburg, MD), determined the 300 K thermal conductivity on free standing AlN samples (thicknesses in the range of 300–800 μm) grown by HVPE on Si(111) substrates [16]. After growth the Si substrates were removed by chemical etching. The “as-grown surfaces” exhibited triangular patterns of about 10 μm on a side, probably due to misfit dislocations. At the center of these triangular portions the measured κ was in the range of $3.0\text{--}3.3 \text{ W/cm.K}$, higher than the 2.85 W/cm.K reported by Slack [7].

Slack estimated 300 K values of approximately 3.19 W/cm.K for the pure (no oxygen) AlN thermal conductivity [7]. More recently, Witek derived the room temperature thermal conductivity value for AlN finding a maximum value of $\sim 5.9 \text{ W/cm.K}$ [18].

Summary

This article has presented an overview of the experimental thermal conductivity (mainly at room temperature) of “bulk-like” and thin film GaN and “bulk-like” AlN as measured by a variety of techniques including nondestructive, high spatial/depth resolution SThM. The highest reported values were (a) for GaN $\kappa \sim 2.1 \text{ W/cm.K}$ found on both the overgrown regions of LEO films and free standing thick HVPE samples while (b) for AlN $\kappa \sim 3.3 \text{ W/cm.K}$ on free standing material. In GaN the influence on κ of dislocation density, n -doping, film thickness, and process-induced effects has been evaluated.

Acknowledgement

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Accent Optical Technologies,*
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The enormous demand for fiber optic and wireless communication components has been the main driving force behind the development and high volume production of compound semiconductors. Since the majority of optoelectronic device structures are manufactured using epitaxial growth methods, rapid, non-destructive and non-contact characterization techniques are required for quality control. Photoluminescence and photoluminescence mapping have become the most important process control tools for this early stage of production.

First Principles

When light of sufficient energy is incident on a semiconductor material, photons are absorbed and electronic excitations are created. Eventually, these excitations relax and the electrons return to the ground state. If radiative relaxation occurs, the emitted light is called photo-

luminescence (PL). This light can be collected and analyzed to yield a wealth of information about the material. The color (or wavelength) of the light provides information on transition energies, and the intensity is a measure of the relative rate of radiative and nonradiative recombination.

Excitation Wavelength

Since most optoelectronic and microelectronic devices are based on multilayer structures with different doping types and energy gaps, it is very important to choose a suitable excitation wavelength and power density to maximize the information obtained from PL. The energy of the excitation photon should be greater than the band gap of the layer of interest, and because the absorption coefficient of most materials increases with photon energy, the penetration depth of incident light reduces with increasing photon energy. In direct band gap semiconductors, the above band gap energy photons have penetration depths less than 1 μm .

Table 1 shows the absorption coefficient of GaAs at the wavelengths of the most commonly used excitation lasers and transmissions at thicknesses of 100 and 200 nm. Note that the transmission is reduced from 74% down to only 6% when the excitation wavelength is changed from 780 to 488 nm.

This does not take into account the 20–30% excitation power reflected at the surface. The diffusion of photo-generated carriers is strongly controlled by the energy band profile, and carriers can be confined within a thin layer or move up to 10 μm in bulk material. Thus, by carefully selecting the energy of excitation, the PL signal can be enhanced and buried layers within the device structures can be investigated.

In a typical AlGaAs/GaAs separate confinement QW laser structure such as shown in Figure 1, a narrower band gap GaAs cap layer is used in order to improve the ohmic contact. The electron-hole pairs generated in the cap layer can not reach the active region due to the high potential barrier present at the cap/cladding interface. Therefore, only the light absorbed in the cladding region would be capable of generating electron-hole pairs that could then reach the active region by diffusion. The PL signal from a top cladding layer can be eliminated by using an excitation source of photons with an energy between that of the band gap energies of cladding and waveguide layers.

However, the PL signals are not normally proportional to the efficiency of electroluminescence in LEDs and laser diodes, which is due to quenching of the emission of the QWs by the built-in electric field. The electric field also effectively stops diffusion of either electrons or holes generated near the surface into the active region.

Wavelength (nm)	Absorption Coefficient α (1/cm)	Transmission (%)	
		100 nm GaAs	200 nm GaAs
780.0	1.48E+04	86.22	74.33
632.8	4.10E+04	66.37	44.04
532.0	7.50E+04	47.24	22.31
514.5	9.00E+04	40.66	16.53
488.0	1.40E+05	24.66	6.08
325.0	7.35E+05	0.06	0.00

Table 1. Absorption coefficient and percent transmission of 100 and 200 nm thick GaAs at different laser wavelengths.

* Contact: Shouyin Wang. Tel: +44 20 8328 2290; E-mail: swang@accentopto.com or Gyles Webster. Tel: +1 650 934 8800; E-mail: gwebster@accentopto.com.

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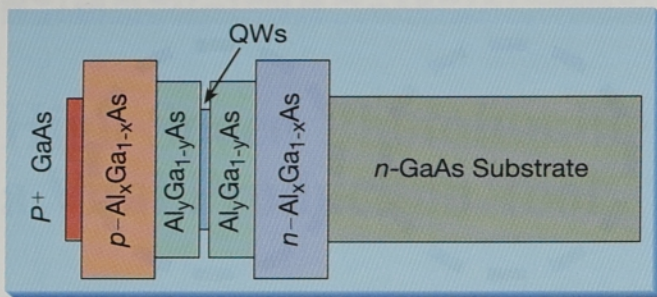


Figure 1. Schematic diagram of an AlGaAs/GaAs laser diode structure.

Excitation Intensity

The excitation intensity controls the density of photoexcited electrons and holes, which governs the behavior of these carriers. Each electron-hole recombination mechanism has a distinct functional dependence on the carrier density. For example, the number of interface and impurity states is finite, and recombination at these states will saturate at high excitation photon densities. When the excited carrier density is low, the recombination process is dominated by discrete defect and impurity sites at the interfaces and within the bulk of the material. For this condition the excitation power density is typically less than 10 W/cm², and repeatable peak

wavelength measurements are achieved at higher excitation power densities.

For example, good correlation between the PL intensity and leakage current has been reported for InGaAs-based PIN photodetector structures at very low excitation level. The less critical surface state effects can be minimized by direct excitation of the InGaAs region.

PL Mapping of Optoelectronic Devices

The optical transition energy obtained from PL analysis can be used to determine the key specifications for optoelectronic devices, the color of LEDs and the wavelength of laser diodes. Wafer level testing benefits manufacturers by detecting defective wafers at an early stage of device production, thus reducing production costs. An example of a PL analysis system is the Accent Rapid Photoluminescence Mapping (RPM) system. This system has been developed to meet such requirements and can provide image quality PL maps within minutes. Four key parameters define PL peaks: the peak wavelength, the peak intensity, the full width at half maximum (FWHM) and the area of the peaks (integrated PL intensity).

The simplest algorithm to determine the peak position is to choose the wavelength at which the intensity is a maximum. However, this algorithm is very noise sensitive over broad peaks. An alternative method is to use intersections. The wavelength can be chosen in the center for a symmetrical peak or at a fixed weighting ratio for an asymmetrical peak. Although both peak intensity and the area of the peaks can be used to measure the PL strength, the physics behind each can be different. For a multiple QW sample, broader peaks are

usually associated with the uniformity of well width or well composition. This would not be a problem for LEDs, providing the color changes were not recognizable to the human eye. But it could increase the threshold current dramatically for a laser diode, due to a reduction in peak gain.

In practice, it is necessary to develop a reliable analysis method to produce the useful statistical results from thousands of spectra in the mapping data. Using the Accent RPM system, a single recipe file has been used to set up all the variable parameters required, from data collection, storage statistical analysis and print out. Great care must be taken for all the measurement conditions, excitation wavelength, power density as well as the sample temperature. The PL peak parameters are all excitation power dependent.

Integrated PL Intensity Mapping

Integrated intensity maps are widely used as a quantitative measure of the quality of epitaxial wafers in production. Figure 2 shows an integrated PL map of the GaAs peaks at the interface of Al_xGa_{1-x}As/GaAs QWs grown on the GaAs substrate. The feature near the prime flat is probably due to the handling damage. The red "blobs" at the wafer's center and in the four-fold distribution were seen in all the results from wafers from an individual growth run and were caused by temperature hot spots. Some of the features seen on the top of the wafer map were not seen on the map of QW emission, indicating that these defects were restricted to the substrate and did not penetrate through to the epilayer.

Spectral Mapping

The most important parameter for the optoelectronic device is the emission spectrum, especially from the active region. The tolerance of devices such as Nd:YAG or Er-doped fiber pumping lasers is much tighter than that for LED wafers. The PL mapping results shown in Figure 3 were obtained from an wafer containing red LEDs that was rejected.

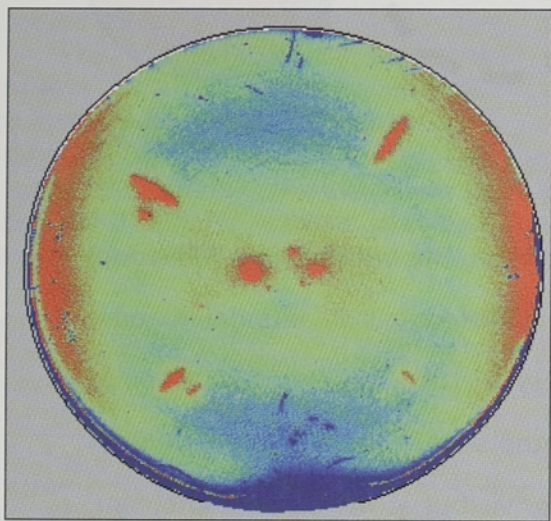


Figure 2. PL map from the GaAs peak at the interface of Al_xGa_{1-x}As/GaAs QWs grown on a GaAs substrate (2-inch wafer, 0.1mm spatial resolution, 202,580 points, data collected in 3 min, 53 s). The red blobs at the wafer's center and in the four-fold distributions result from temperature hot spots and were confined to the substrate.

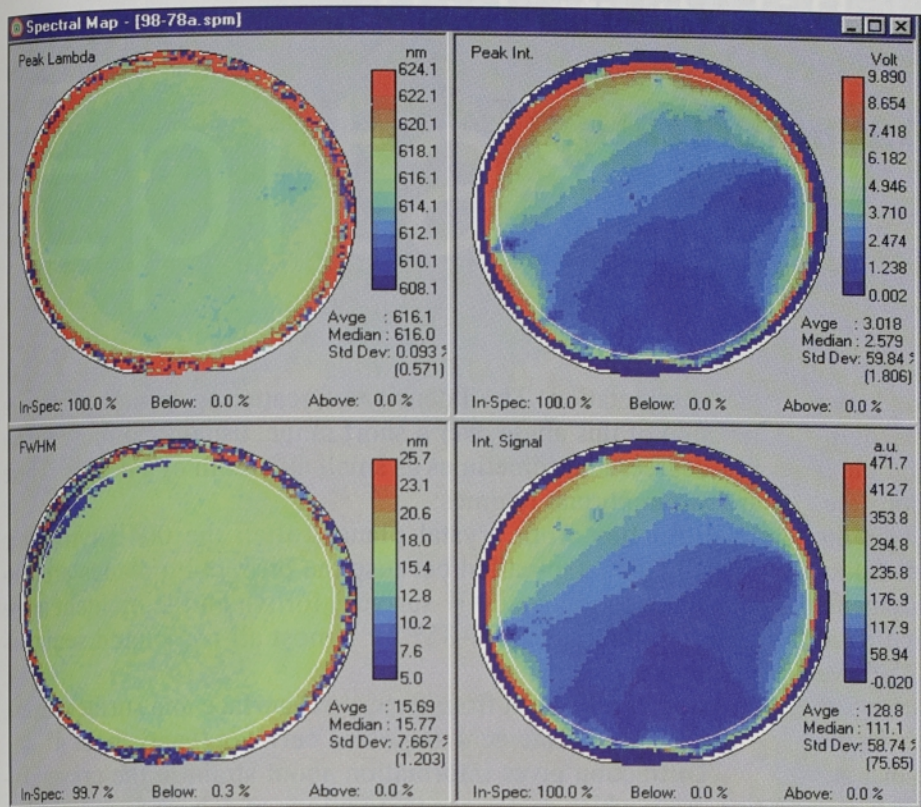


Figure 3. PL mapping for a 2-inch LED wafer that was subsequently rejected (7,642 full spectra, 0.5 mm spatial resolution, data collected in 1 min). The large variation in the PL intensity (shown by the blue areas) on the wafer was mainly due to non-uniformity in the thick window layers grown on the top surface.

Although the wavelength variation is very small—less than 0.6 nm—the average wavelength is too short compared to the specification of 625 ± 5 nm. The large variation in the PL intensity from this wafer was mainly due to non-uniformity in the thick window layers grown on top of the surface. All the statistical data shown in Figure 3 excluded data points less than 3 mm away from the edge of the wafer (indicated by the white line on the maps).

For a ternary material, PL measurements can be used to calculate the composition. In the case of AlGaAs, the resolution can be higher than that commonly achieved using x-ray diffraction, and PL has proved particularly useful for electronic devices that require better than 1% repeatability in the Al composition.

The Accent RPM system also allows white light reflectivity measurement. Reflectivity is employed in a production environment to control the composition and is useful in the analysis of Bragg mirror structures in VCSELs, and in LEDs.

Epitaxial structures are increasingly being used to manufacture optoelectronic devices. Characterization of these structures at wafer level using non-contact high-speed photoluminescence mapping increases yields and benefits QA in today's compound semiconductor production environments.

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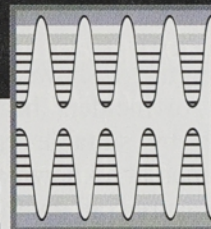


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How Accurate is X-ray Characterization?

D. KEITH BOWEN

Bede plc

Bowburn, UK and Englewood, CO, USA

Virtually all manufacturers of compound semiconductor materials invest large sums in X-ray diffraction equipment to develop their processes and to control their quality. Questions that they typically ask equipment vendors are, "How reproducible is this tool? How do I know that the results are reliable? How does it compare with other tools?" Manufacturers normally insist on stringent "tool matching" requirements so that a sequence of tools, in different locations and ordered at different times, will perform in the same way. However, I believe that equipment vendors should strive for a specified accuracy, as well as repeatability, of the information extracted, since in the long run the only stable measurement systems are those that are traceable to absolute intrinsic or international standards. This is a realistic possibility for X-ray characterization, since it depends upon simple parameters that can be made traceable. This article discusses these issues. A fuller discussion will be found in a recent paper [1].

Basics of X-ray Characterization

Figure 1 shows the general method of X-ray characterization. An incident beam, collimated and conditioned in wavelength by suitable crystal or multilayer optics, falls on the specimen at a known angle. The intensity of scattering of X-rays is measured at another known angle, but the incident angle, rather than the scattered angle, is usually the important one for

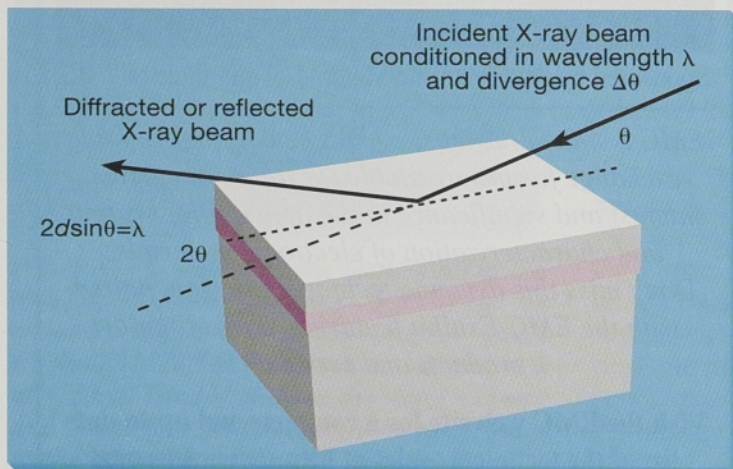


Figure 1. The general principles of X-ray characterization.

the interpretation. The intensity of scattering is measured as a function of this angle over a short range, usually no more than a few degrees and sometimes as small as a tenth of a degree. There are two important regimes:

- diffraction from crystal planes, often the 004 "symmetric reflection" (so-called because the diffracting planes are parallel to the typical 001 surface) for which the incident angle lies in the range 30° – 35° for almost all compound semiconductors
- external reflection from the crystal surface and surface layers, for which the incident angle lies between 0 and about 4°

Diffraction gives information about strain in the crystal lattice, from which material compositions may be inferred. Reflectivity gives information about electron density normal to the surface, from which densities, hence compositions and interface roughnesses may be inferred. Both regimes contain information about interferences between layer interfaces, from which layer thicknesses may be deduced. As a rule, diffraction is more sensitive to compositions and reflectivity to thicknesses and roughnesses, but there are exceptions. Fuller details of the theory and interpretation of diffraction [2] and reflectivity [3] may be found in the books cited.

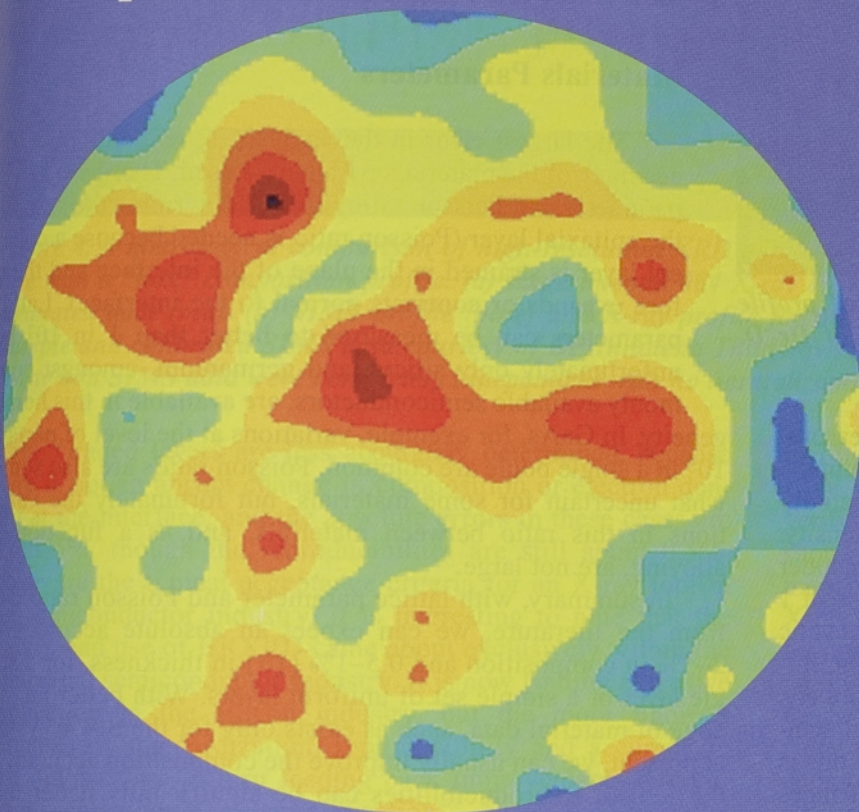
Traceable Measurements

It is important to understand the concept of a traceable measurement. While tool matching can and does satisfy the requirements of ISO 9000 quality control, it does not provide a metrologically stable system of measurement, nor one that can be used to compare results from tools and software made by different vendors. In contrast, "accuracy" entails coupling of the measurement in question to an invariant primary standard, or at least to a highly reproducible secondary standard that is well-connected to a primary invariant. For example, characteristic X-ray emission lines embody all of the needed features for the wavelength parameter. These lines are highly reproducible (within 1 part in 10^6), and have been linked to the base unit of length in the

Dr Keith Bowen is Group Director of Technology for Bede plc. He chairs the Atomic Physics sub-panel of the NAS-NRC Evaluation Panel for the NIST Physics Laboratory and, together with other industrial representatives, is advising the NIST Materials Laboratory on the production of X-ray SRMs for the semiconductor industry.

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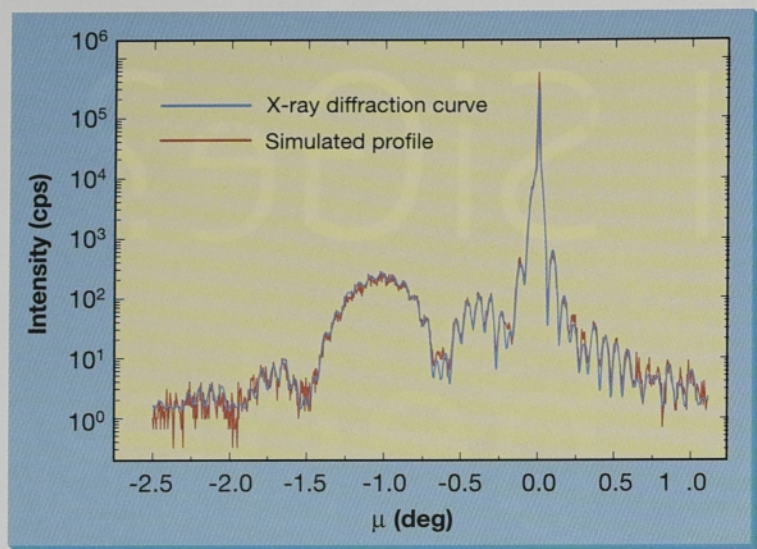


Figure 2. X-ray diffraction curve (blue) and simulated profile (red) for a GaAs-based PHEMT structure. Courtesy of Dr D. Braddock, Ovation Semiconductor.

International System of Units (the SI) by an unbroken measurement chain that does not degrade the indicated reproducibility.

Apart from wavelength, X-ray diffraction or reflectivity data depend only upon the measurement of angle and intensity. Angle is macroscopically self-calibrating if a full 360° encoder or gear train is used. We don't need a standard to tell us that 1 exact revolution is 360°. However, there are normally cyclic harmonic errors in linearity, especially in gear trains. The linearity of interpolation must therefore be determined separately. A rotary table can be calibrated for linearity at a national standards laboratory to a small fraction of an arc second, but this is inconvenient and laborious. The regularity of X-ray fringes from a sample such as a superlattice is a good test. In practice the best encoders that are currently used on diffractometers, taken together with their mounting and reading systems, give harmonic errors below 1 arc second over 360°, while 10 arc second accuracy over tens of degrees is relatively straightforward. This will typically contribute less than about 0.05% to the error in (for example) composition or thickness.

Intensity is less important for composition analysis but is important for analysis of graded layers such as are found in metamorphic buffer layers or in HBT structures. However, X-ray counters are inherently linear below the pulse pileup regime, and even then the non-linearity is easily calibrated. This is rarely a significant source of error.

Analytical software is very much in the accuracy loop when the data are interpreted. Automatic optimization (parameter fitting) programs that avoid being trapped in local minima [4] remove the subjectivity from the process. Grundmann and Krost [5] have made a detailed comparison of software interpretation programs demonstrating that there are substantial differences between vendors' programs. Given accurate structural models and materials

parameters the best programs are capable of calculating the X-ray scattering to a precision and accuracy that is significantly better than the measurement, and hence are not themselves a source of error. However, the poorest programs could give substantial error. For example, a common approximation in some programs is $\sin\theta = \theta$ at small angles, which gives significant error for larger-range scans such as for HEMTs or superlattices. Hence it is necessary for software to be tested and certified.

Materials Parameters

The largest error in the analysis is, without doubt, the accuracy of the materials parameters used. These are, lattice parameter and Poisson ratio, used to determine the strain in the epitaxial layer (Poisson ratio is needed because a coherent layer is strained in the plane of the interface and therefore expands or contracts normal to the interface). Lattice parameters can be measured to better than 1 in 10^7 but unfortunately only silicon and germanium, amongst commonly available semiconductors, are available in this homogeneity. In GaAs, for example, variations at the level of parts in 10^5 in a single boule are common. Poisson ratios are also somewhat uncertain for some materials, but fortunately the variations in this ratio between materials, and as a function of alloying, are not large.

In summary, with lattice parameter and Poisson ratio data from the literature, we can expect an absolute accuracy of 2–5% in composition and 0.5–1% (1σ) in thickness, for a single layer or a simple set of uniform layers. With better knowledge of material data, such as exists only for the Si-Ge system at present, we can usually improve the composition accuracy to 0.5% also. Reproducibilities can be significantly better than

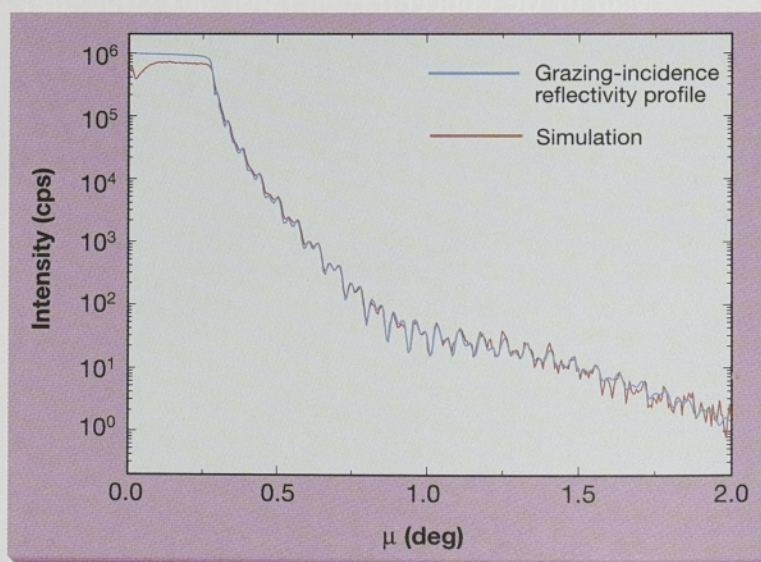


Figure 3. A grazing-incidence reflectivity profile (blue) of a GaAs/AlGaAs/GaAs structure together with a simulation based on reflectivity theory (red).

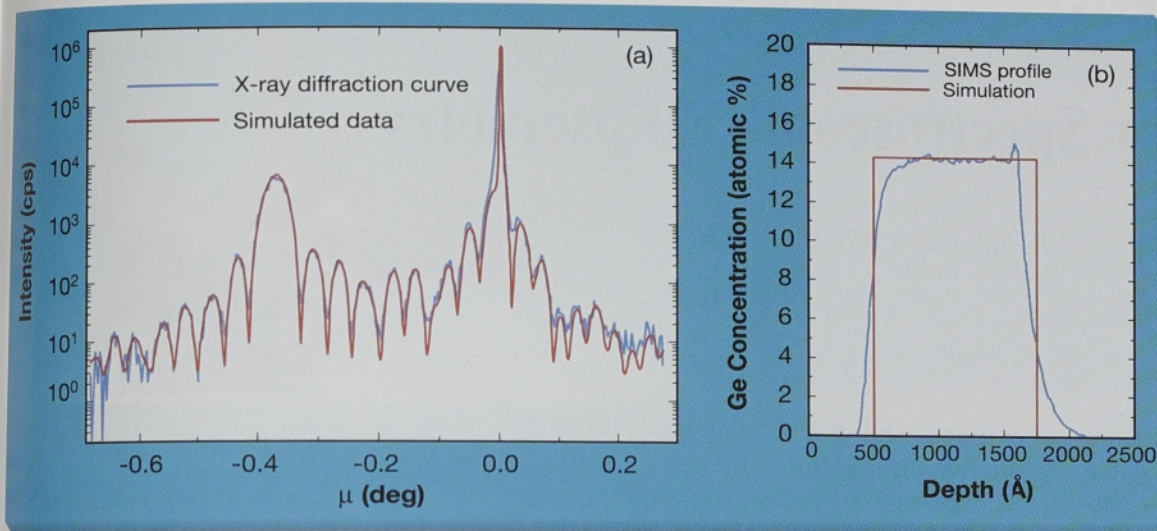


Figure 4. A metrological comparison of high-resolution XRD and SIMS for a Si/SiGe/Si structure with a "box" composition profile. (a) Experimental 004 X-ray diffraction curve (blue) and simulated data (red). (b) SIMS profile (blue) and X-ray profile for the simulation in (a) (red). Sample and calibrated SIMS data courtesy of Dr Annalena Thilderqvist, Applied Materials. The X-ray and SIMS data were completely independent with no normalization applied.

0.5%. Graded layers are less accurately determined, because there is not an abrupt change in composition or electron density at the interface, and the absolute errors in these cases are about 5%, though the reproducibilities are still about 0.5%. These are the typical acceptance criteria for an X-ray tool in the semiconductor industry. It is interesting to note that the widespread use of HRXRD came about exclusively within the compound semiconductor industry. It is now finding extensive application in the silicon industry, but the more rigorous demands of standardization, reproducibility and accuracy in that industry are in turn feeding back improvements to compound semiconductor characterization.

Choosing the Correct Type of Measurement

A couple of examples will show how important it is to do the right type of measurement. In general, diffraction is the choice if strained layers and large mismatches are expected. Figure 2 shows a GaAs-based PHEMT structure in which the 104 Å active In_{0.209}Ga_{0.791}As layer is determined to 1 Å in thickness and 0.1% in composition.

On the other hand, a thin AlGaAs/GaAs layer (say about 500 Å of each), is not at all well determined by diffraction because the peak from the thin, closely-matched layer cannot be distinguished from the intense substrate reflection. As shown in Figure 3, this material gives good fringe contrast in reflectivity, from which the thicknesses of these layers can be determined to better than 1%. Reflectivity is the choice if thin, closely-matched layers that show significant change in electron density are expected. It is also insensitive to dislocation content, and good reflectivity data can often be obtained with material that is too defective to give good diffraction data.

that they cover the diffraction range that is appropriate for most III-V materials, they are perfectly suitable for calibrating and verifying tools used for compound semiconductors. Figure 4 shows how good these standards can potentially be. The agreement between the X-ray data and the simulation, and between the X-ray interpretation and the SIMS profile is excellent. They differ only in the interface regions in which the well-known beam-mixing phenomenon gives artifacts in the SIMS profile. While the SRMs will first be issued simply with certified diffraction patterns, the plan is that later generations of SRMs (including compound semiconductors) will be issued with certified compositions and thicknesses. The equivalent performance of different tools will then be certifiable by tracing all measurements to the same set of national standards.

Standard Reference Materials

At present, the verification of calibration, linearity and correct set-up of an X-ray tool are up to the manufacturers and customers. This process, leading to the traceability of the tool, would be greatly aided by the provision of Standard Reference Materials and a program to establish SRMs for high performance X-ray systems has recently begun at NIST [6]. The first standards will be made of epitaxial silicon-germanium on silicon since this is the only material available in sufficient quality at present. However, since SiGe epilayers can be made so

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New Frontiers for Spectroscopic Ellipsometry

JAMES N. HILFIKER, THOMAS E. TIWALD and COREY L. BUNGAY

J. A. Woollam Co., Inc.

Lincoln, NE, USA

Traditional spectroscopic ellipsometry (SE) in the ultraviolet, visible, and near infrared is a well-established metrology technique for thin film characterization [1,2]. It offers a non-destructive method to accurately measure film thickness and optical constants. The power of SE is derived from its spectroscopic nature (range and number of wavelengths): in this area, bigger is considered better!

Wavelength coverage from 190 nm in the ultraviolet to 1.7 μm in the near infrared has been commercially available for over a decade. These instruments can precisely measure the thickness and composition of compound semiconductor devices. Variation in the alloy concentration of a material introduces a shift in optical constants. For instance, the fundamental bandgap of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ increases with increasing Al concentration. SE can be used to measure any material property that influences the optical constants within the measured wavelength range.

Recent hardware innovations have expanded commercial spectroscopic ellipsometry into both the infrared (IR) and vacuum ultraviolet (VUV). The IR and VUV are at opposite SE wavelength

extremes and thus provide new and distinctive information. The IR is sensitive to free-carrier concentrations, lattice vibrations, phonon absorptions, and molecular bond absorptions. At the other end of the spectrum, the VUV enhances sensitivity to ultrathin films and can characterize electronic transitions at higher energies. This article reviews both IR and VUV measurement capabilities, as they relate to semiconductor and insulator materials.

What is Ellipsometry?

Spectroscopic Ellipsometry measures the interaction of polarized light and a smooth surface. The light can either reflect or transmit from the surface, but is incident at an oblique angle, as shown in Figure 1. The change in polarization that occurs due to interaction with the sample is measured as two parameters, amplitude (Ψ) and phase (Δ), for each wavelength/angle combination. These terms are related to the complex Fresnel reflection coefficients [3]:

$$\rho = \tan \Psi e^{i\Delta} = \frac{\tilde{R}_p}{\tilde{R}_s}$$

This equation illustrates the advantages inherent in an ellipsometry measurement. First, Ψ and Δ are measured from a ratio, which allows ellipsometry to remain very accurate and precise. Second, ellipsometry measures both Ψ and Δ : two parameters are better than one, and the phase information happens to be highly sensitive to the surface condition of a material. Researchers have capitalized on this fact, as thin films reduce to a few nanometers

thick, hence the popularity of SE for thin gate measurements.

Like other optical measurements, SE does not directly measure the material properties. Instead, they are determined from a model-dependent regression of the experimental data. In this manner, ellipsometry has been used to characterize film thickness, optical constants, alloy concentration, doping concentration, crystallinity and many other properties. The spectral range of an ellipsometer determines its suitability for a particular application. We will highlight key applications of the new IR and VUV wavelength ranges.

Extending Ellipsometry to the Infrared

Although Beattie [4] developed an infrared spectroscopic ellipsometer (IR-SE) in 1955, the dispersive-monochromator's low throughput severely limited the instrument's capability. It was the advent of Fourier Transform Infrared (FTIR) spectrometers in the 1970's, with their high throughput and multiplex advantage, which made a practical IR-SE instrument possible. Röseler was the first to combine ellipsometry with FTIR [5,6]. In recent years, commercial instruments, including the IR-VASE® (J.A. Woollam Co., Inc.), have been developed with sufficient accuracy and precision to quantitatively determine the infrared optical response of bulk and multilayer semiconductors and dielectrics films.

The two most important infrared phenomena associated with semiconductor and dielectric materials are free carrier interactions and lattice vibrations (phonons). Thus, many new applications of the IR-VASE®

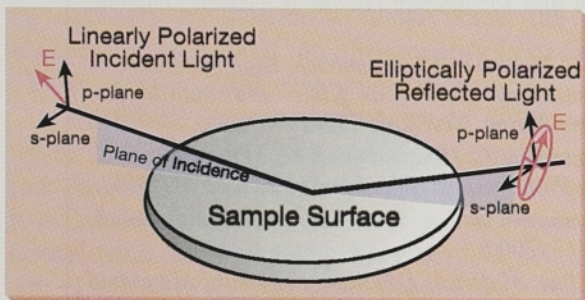


Figure 1. Configuration of a spectroscopic ellipsometry measurement.

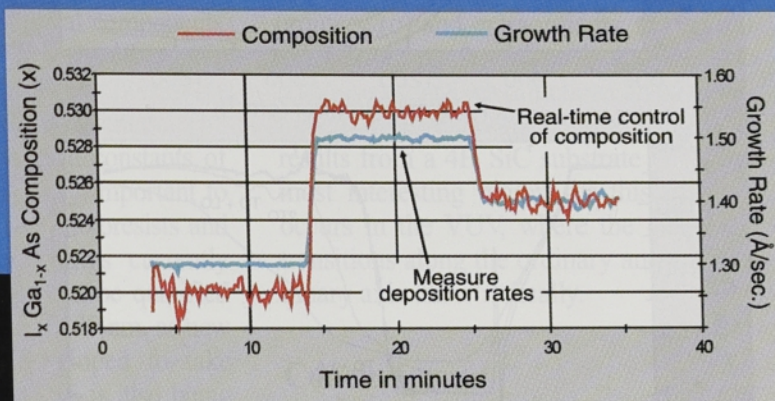


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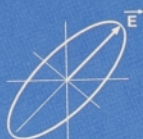
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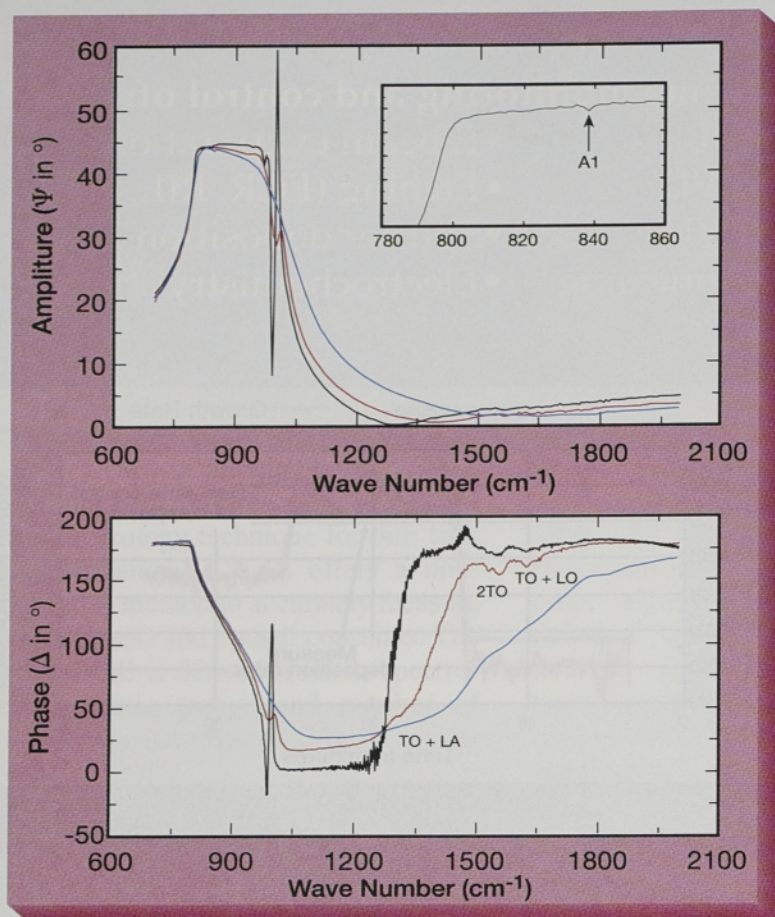


Figure 2. IR-VASE® data from *c*-plane 4H-SiC, centered on the strong planar (782 cm^{-1}) and axial (797 cm^{-1}) TO phonon modes. Doping concentration $<10^{15} \text{ cm}^{-3}$ (black), $3 \times 10^{18} \text{ cm}^{-3}$ (red), and $9 \times 10^{18} \text{ cm}^{-3}$ (blue). High-density free carriers screen the entire spectrum. Phonon anisotropy is visible near axial (964 cm^{-1}) and planar (970 cm^{-1}) LO phonon frequencies. Effects due to two-phonon summation bands are labeled. Inset shows weak A_1 phonon mode (838 cm^{-1}).

involve the semiconductor industry—epitaxial layer characterization, doping concentration, doping profiles, and phonon absorptions.

The interaction of free carriers with light is described by the Drude equation [7]. From that equation, we can determine the carrier concentration and mobility of semiconductors and metals, provided the effective mass is known. Resistivity can be directly determined from the Drude equation, without any independent knowledge of the effective mass.

We can exploit ellipsometry's high sensitivity to measure thin layers that are identical except for differences in carrier densities. In these instances, the only optical contrast between the layers results from free carrier effects. Examples of this include homoepitaxial layers [7] and surface depletion regions [8,9]. One can also determine carrier concentration profiles in ion-implanted materials [7].

Vibrational modes become infrared-active whenever there is an ionic component to the molecular bonds, which is typical for compound semiconductors. Crystalline materials often have one or more IR-active phonon lattice resonance. Materials containing light elements, such as C, N, and O, are particularly good examples because their phonon spectra contain strong features located at reasonably

high infrared energies. Therefore, IR ellipsometry has been particularly successful with wide bandgap semiconductors, such as GaN [9] and SiC [10], high- k gate dielectrics (e.g., SrTiO_3 [11]), and organic films on semiconductors.

Sometimes, second order vibrational resonance effects are detected, including summation bands (two or more phonons interacting with the incoming photon) and localized defect modes [9]. In low dimensional structures such as superlattices, folded modes can be observed. Free carrier/phonon interactions can also produce additional resonant effects, such as LO-phonon-plasmon modes [9] and Fano resonances [8].

Although LO-phonons are not infrared active, various effects occur at or near the LO phonon energy. These include the Berreman effect, surface polaritons, and spectral features related to phonon and free-carrier anisotropy. Interestingly, these effects can have dramatic impact on IR-SE, even with a dielectric response that is featureless. For many studies referenced here, the ellipsometric spectra provide sensitive and reliable measures of the broadening and frequency of LO-phonons and anisotropy of phonon and effective mass.

Examples of IR-SE

Hexagonal silicon carbide (polytype 4H-SiC) is prototypical of compound semiconductors in that its ellipsometric spectra readily show most of the effects described above. The data shown in Figure 2 were acquired from several bulk, *c*-plane 4H-SiC samples. The data are centered on the strong planar (782 cm^{-1}) and axial (797 cm^{-1}) TO phonon modes of *c*-plane 4H-SiC. The data also demonstrate how the screening effects of free carriers alter the ellipsometric response throughout the spectrum. The strong features seen in the region near axial (964 cm^{-1}) and planar (970 cm^{-1}) LO phonon energies are the result of phonon anisotropy. Several two-phonon summation bands are also visible.

A careful inspection of Ψ near 838 cm^{-1} reveals the weak A_1 phonon mode, which is IR-active due to zone folding (see inset Figure 2). Zone folding effects occur in artificial and naturally occurring superlattices (such as hexagonal SiC). Sensitivity to these effects depends on the orientation of the optic axis (data are from *c*-plane 4H-SiC only). In this case, a careful study provided the optic axis orientation, ordinary and extraordinary dielectric functions, free-carrier concentration, effective mass or mobility anisotropy, TO and LO phonon energies and broadenings, and 2-phonon summation bands [10].

IR-SE can also measure the thickness of ion-implanted doping profiles [7], carrier depleted surface regions and homoepitaxial layers [9,10]. Figure 3 compares free-carrier concentration profiles independently derived from IR-SE and spreading resistance probe (SRP) measurements. Note the excellent agreement between the two curves. As mentioned above, the Drude effect allows us to measure carrier profiles in otherwise homogeneous materials; including ion-implanted materials [8] and carrier depleted surface regions [8,9].

IR-SE has been applied to heteroepitaxial systems as well. These include systems with dielectric substrates such as sapphire. In these situations, ellipsometry can provide sufficient information to

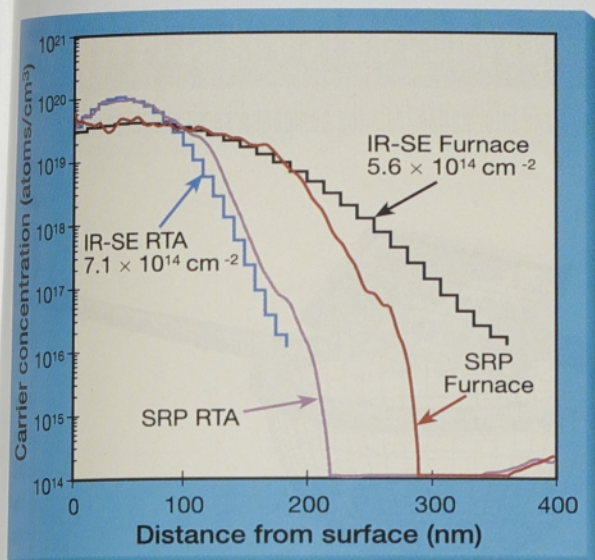


Figure 3. Comparison of free carrier profiles derived from IR-VASE® and spreading resistance probe (SRP) data. The total free-carrier doses (in cm^{-2}) were calculated by integrating the area under each curve.

determine the parameters of the semiconductor epilayers while accounting for all the optical effects of the substrate [9].

Ultraviolet and Beyond

Historically, commercial "tabletop" spectroscopic ellipsometers have been limited to wavelengths above 190 nm, as shorter wavelengths are completely absorbed by the atmosphere. The shift of optical lithography toward 157 nm has encouraged characterization of materials at this wavelength. This motivation led to the rapid development of commercial vacuum ultraviolet SE (VUV-SE). Unlike previous research VUV-SE tools that utilized ultrahigh vacuum and synchrotron radiation [12], the commercial

instruments are purged by dry nitrogen gas to avoid atmospheric absorption. Now, VUV-SE can reach wavelengths below 146 nm, or the equivalent to 8.5 eV, without the need for synchrotron-based measurements.

Lithography remains the primary application of VUV-SE [13]. Each aspect of lithography can benefit from accurate materials characterization. The optical components used in steppers are coated to optimize transmission or reflection at the lithographic wavelength. The thickness and optical constants of the coatings are very important to performance. The photoresists and anti-reflective coatings currently used for 193 nm can be qualified for potential use at 157 nm, as new materials are developed to take their place. VUV-SE is also being used to develop the coatings used for photomasks and pellicles [14]. In each case, accurate optical constants and film thickness are essential and can be obtained from a non-contact, non-destructive spectroscopic ellipsometry measurement.

Another application for VUV-SE involves the study of thin gate dielectrics. The short wavelengths of this spectral range provide increased sensitivity as the layer thickness decreases. Alternative materials with high dielectric constant, such as SrTiO_3 , are likely to replace current gate materials. VUV-SE can be used to study the material properties and provide more insight into its optical behavior [11].

III-Nitrides and other high-bandgap materials are important for both optoelec-

tronic devices and for high-power and high temperature applications. VUV-SE extends the study of critical points in these materials to larger photon energies [15,16]. The optical constants of AlN shown in Figure 4 have been measured from 0.73 to 8.5 eV. Notice that the interesting electronic transitions occur beyond 6.5 eV. The electronic transitions of hexagonal SiC are also located in the VUV. In this case, the optical response is anisotropic (different along the ordinary (o) and extraordinary (e) crystal axis). For in-plane substrates, the dielectric response along each direction can be determined from VUV-SE. Figure 5 presents results from a 4H SiC substrate [17]. The most interesting region for this material occurs in the VUV, where the electronic transitions along the ordinary and extraordinary axis differ radically.

Conclusion

The expansion of SE into both the IR and VUV is opening new doors for material characterization. Both wavelength extensions provide new information, and thus new applications. IR-SE is sensitive to free-carrier concentrations, lattice vibrations, phonon absorptions, and molecular bond absorptions. VUV-SE enhances sensitivity to ultrathin films and can characterize electronic transitions at higher energies. Both instruments have a good outlook for future semiconductor characterization.

References

See overleaf.

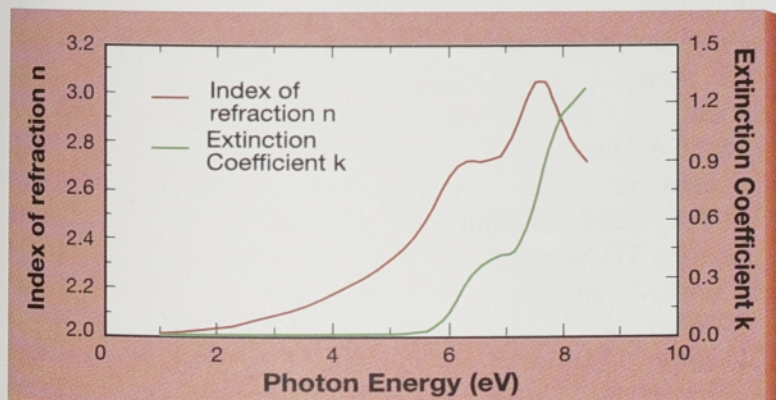


Figure 4. Optical constants of AlN film into the VUV, measured with spectroscopic ellipsometry.

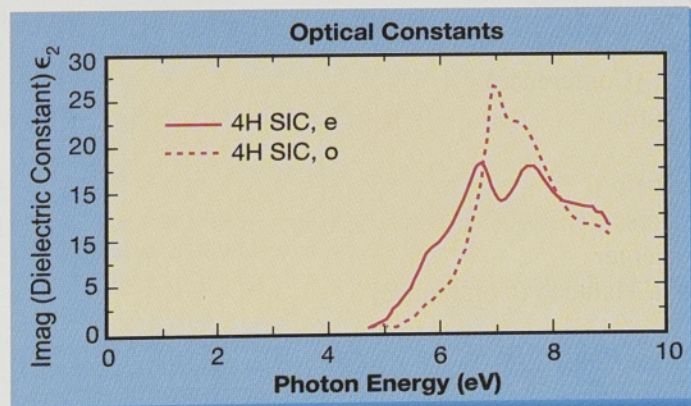


Figure 5. Ordinary and extraordinary imaginary dielectric function, ϵ_2 , measured from in-plane SiC substrate.

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Mixed Results in Optoelectronics for the Fourth Quarter

MARIE MEYER

Closely watched JDS Uniphase turned in a classic "good news/bad news" report for the December quarter. On the good news side, revenue more than doubled to \$925 million from \$354 million in the year-earlier period. Analysts had projected revenue of \$916 million to \$920 million. The company reported a substantial loss of \$895 million, but again, that was what the analysts were expecting. If one were to exclude JDSU's substantial merger & acquisition-related costs, as well as other accounting items such as gains on investments and payroll taxes on stock options, the company would have reported profit of \$208 million, more than double the "pro-forma" profit of \$84 million in the year ago period.

On the bad news side, JDSU said it expects its March earnings to be equal to or slightly better than the second quarter, with revenues 7–10% above the December quarter. This is a definite climb-down from a company that has been posting 20–25% growth quarter after quarter.

"This change in guidance from previous periods reflects uncertain near-term carrier capital spending plans, customer inventory adjustments and a somewhat lower level of near-term sales visibility than we and our customers had experienced in recent periods" JDS Uniphase chief financial officer Anthony Muller said in a conference call with analysts. President Jay Abbe said customers were working through inventories of components that are now more readily available. "We do not believe that this is a long-term trend or an across the board change," he said. "Our customers are in the process of finding the right inventory levels for each product and we may experience a temporary slowing in order flow for certain products until this adjustment is completed."

Commenting on the long-term outlook, JDSU CEO Jozef Straus told Reuters "We still firmly believe that fiber optics is an ongoing growth business—(carriers') capital expenditures, according to our information, are going to be continuing at 40% (growth)."

SDL

SDL reported revenue of \$175.6 million and earnings of \$48.2 million for the

December quarter. Nevertheless, the share price dropped, reflecting investors' disappointment over the continued delay in the closing date for the JDSU/SDL merger (approval was granted as this issue went to press—see page 5).

The revenue figure was three times higher than the year ago period, and 20% higher than the September quarter. Fiber optic communication products accounted for 92% of total revenue, with both the terrestrial (up 21%) and undersea (up 26%)

Company	Symbol	Closing Price Feb 2	52 Week Low - High	Market Cap*	P/E Ratio**
GaAs IC Companies					
Alpha	AHAA	30 7/8	22 3/8 - 78 1/4	1.327B	31.83
Anadigics	ANAD	16 13/16	13 5/16 - 112 1/8	504.8M	28.02
Celeritek	CLTK	15 7/8	15 5/16 - 85 1/4	188.0M	31.13
Conexant	CNXT	16 9/16	12 5/8 - 132 1/2	4.026B	N/A
Endwave	ENWV	4 3/4	2 1/2 - 20 5/8	162.1M	N/A
RF Microdevices	RFMD	19 5/16	12 1/16 - 92 1/4	3.133B	60.35
Stanford Microdevices	SMDI	23 1/2	13 3/4 - 60 1/4	619.2M	N/A
TriQuint	TQNT	31 3/16	21 - 67 3/4	2.448B	45.86
Vitesse	VTSS	67 1/8	35 5/8 - 115 11/16	12.118B	353.29
Opto Companies					
Agilent	A	52.20	38 - 162	23.823B	32.02
Alcatel Optronics	ALAO	51 1/2	38 1/8 - 71 3/4	849.8M	45.18
Coherent	COHR	49 7/16	25 - 107 3/8	1.351B	19.39
Cree	CREE	33 1/2	27 3/16 - 101	2.488B	53.17
JDS Uniphase	JDSU	50	37 - 153 7/16	48.077B	N/A
SDL	SDLI	185 39/64	117 5/8 - 460 1/2	16.227B	N/A
Uniroyal Tech.	UTCI	7 11/16	5 1/4 - 36 7/16	198.2M	N/A
Semiconductor Materials & Equipment Companies					
ATMI	ATMI	23 7/8	14 3/8 - 60 3/4	721.1M	19.73
AXT	AXTI	32 1/8	19 - 49 9/16	705.6M	76.49
Emcore	EMKR	37 7/8	20 - 86 1/2	1.288B	N/A
Kopin	KOPN	14 5/16	8 3/4 - 49 7/8	907.8M	89.45
Tegal	TGAL	3 5/8	1 5/16 - 9 11/16	45.3M	15.76
Trikon	TRKN	13 7/8	8 1/2 - 28 9/16	162.0M	12.07
European Shares (Currency Data in Euros)					
Aixtron	AIX	102.2	95 - 174.5	3.3B	172
Filtron	FTC	5.8	5.42 - 7.69	426.63M	N/A
IQE	IQE	3.56	2.70 - 4.278	366.2M	240
Picogiga	PICO NM	31.4	11.25 - 35.6	203M	62
Riber	RIBER	22	9 - 38.5	425.7M	N/A

*Market Capitalization = # shares × current share price

** Price/Earnings Ratio = (income for last 4 quarters ÷ # shares) ÷ current share price

sectors showing strong growth. The company recorded a net loss of \$122.8 million, but pro-forma income (excluding merger expenses and other non-core accounting items) was \$48.2 million, an increase of 20% over the September quarter.

In a conference call with analysts SDL's management predicted \$193 million to \$202 million in revenue for the March quarter, and raised expectations about profit margins. They also indicated that SDL would hit the \$1 billion mark in revenue in calendar year 2001.

Alcatel Optronics

Alcatel Optronics reported that sales in the December quarter increased 126% over the year ago period, to \$137 million. Net income was \$15.9 million, compared to \$10.5 million for the year ago period. However, gross profit declined somewhat to 34.8%, due to a change in product mix as well as a higher depreciation charge related to capital expenditures for capacity expansion.

"2000 has been a record year for Alcatel Optronics," said Jean-Christophe Giroux, CEO. "We set very high objectives and we have achieved them. Revenue and profitability have both grown significantly. We've been successful in moving up the vertical chain into integrated subsystems and in entering the passive market. We have leveraged our presence within our external customer base, which now represents over 30% of our sales. Our capacity has ramped up substantially and we will continue this effort throughout the year. Looking forward, we are still seeing strong demand across all product lines, driven by sustained growth in terrestrial and submarine DWDM systems and the widening acceptance of Raman technology, which was pioneered by Alcatel Optronics. Today, I have no reason to believe that we will not meet our 2001 targets of growing sales faster than the market to a range of 60 to 65% and of improving our profitability. The first quarter will be a bit slower than average, nevertheless, we are anticipating a growth in sales close to 100% over the corresponding period last year."

Uniroyal Technology

Uniroyal Technology Corporation reported net sales of \$14.3 million for the December quarter, down slightly from the year-ago results. Increased investment spending at the company's Compound Semiconductor and Optoelectronics business segment resulted in a net loss from continuing operations, excluding intangible amortization and unusual/non-recurring items, of \$3.1 million. The Compound Semiconductor division was formed through the acquisition of Sterling Semiconductor; the Optoelectronics business consists of a joint venture with Emcore for producing high brightness LEDs. Sales for the Compound Semiconductor and Optoelectronics business segment grew 90% versus the previous year, increasing to \$1.2 million versus \$614,000 last year. However, this segment generated a loss of \$8.3 million for the quarter.

AXT

AXT reported revenue of \$38.2 million, up 15% from the September quarter. 95% of this amount came from AXT's substrate division, with the remainder coming from the company's visible emitter division, which produces blue, green and cyan LEDs, and VCSEL wafers and chips. Production of 650nm laser diodes for laser pointers and other consumer-oriented applications was discontinued in the quarter. The company reported income from continuing operations of \$16.4 million, but when adjustments for one-time occurrences are made, the result is a net income of \$4.6 million. Still, this figure is more than double the net income gained in the year-ago quarter and is up 35% over the September quarter.

"The fourth quarter and fiscal year results were the strongest in the company's history, even without the net benefit of the one-time events recorded in the quarter," said Morris Young, president and CEO. "We are very pleased with the growth in our substrate division, which is being driven by the market demand for 5-inch and 6-inch gallium arsenide substrates and 3-inch and 4-inch indium phosphide substrates." He went on to say that company's near and long-term outlook continues to be strong. "We expect our substrate division to continue its consis-

tent growth throughout 2001, driven by the demand for higher performance wireless handsets and by the fiber-optic infrastructure build-out." In recent months AXT has been encouraging its substrate customers to make guaranteed long-term bookings with non-refundable advance payments—a testament to the scarcity of III-V substrates. As a result, AXT has more than \$91 million in substrate contracts on its books, and says that it will not be taking any new customers in 2001.

AXT predicted that revenues for the March quarter would increase 7–9%, but would then accelerate so that revenue for the entire calendar year would exceed 2000 revenue by 55–60%.

Emcore

Emcore reported revenue of \$40.1 million for the December quarter, up 143% from the year ago quarter and up 18% over the September quarter. Gross profit was a record \$16.5 million, although overall the company logged an operating loss of \$3.6 million and a net loss of \$6.3 million. Both of those figures are before charges for goodwill amortization are added in. Contributing to the losses were nearly \$7 million selling, general and administrative costs and just over \$13 million in R&D expenses.

Commenting on the results, Reuben Richards, President and CEO, said "During the quarter, we moved ahead with our previously-announced plans for accelerated investment in research and development in response to customer demand for fiber optic products, and the company is seeing substantial interest from its customer base relating to new product prototypes. This R&D investment strategy promises to significantly expand our wireless and fiber optic product lines and, at the same time, add further strength to our long-term customer relationships."

MOCVD equipment sales were up 126% and still dominate Emcore's sales, accounting for 66% of December quarter revenues. A breakdown of materials revenue by product type was not given, but the company did say that sales of electronic materials were up 172%, photovoltaics increased 251% and fiber optic sales grew 184% in comparison to the year-ago quarter.

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Web: www.picogiga.com

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Phone (707) 539-2508
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Aachen, Germany
AIXTRON AG
Kackertstr. 15-17
52072 Aachen
Germany

Phone: +49 (241) 89 09 - 0
Fax: +49 (241) 89 09 - 40
e-mail: info@aixtron.com

US Headquarters
Chicago, Illinois
AIXTRON Inc.
1670 Barclay Blvd.
Buffalo Grove
IL 60089, USA

Phone: +1 (847) 215 - 7335
Fax: +1 (847) 215 - 7341
e-mail: usinfo@aixtron.com

AIXTRON Taiwan
Hsinchu, Taiwan
Challentech International Corp.
Pateh Road No. 1, Lane 9
Hsinchu, 300
Taiwan R.O.C.

Phone: +886 (3) 5614 - 211
Fax: +886 (3) 5614 - 194
e-mail: hotos@challentech.com.tw

Sales and Service
Tokyo, Japan
Moritani & Co., Ltd /AIXTRON
4th Section, 12th Machinery Dept.
2nd Business Group
1-4-22 Yaesu, Chuo-Ku
Tokyo 103 - 8680, Japan
Phone: +81 (3) 3278 - 6131
Fax: +81 (3) 3278 - 6121
e-mail: mike@moritani.co.jp