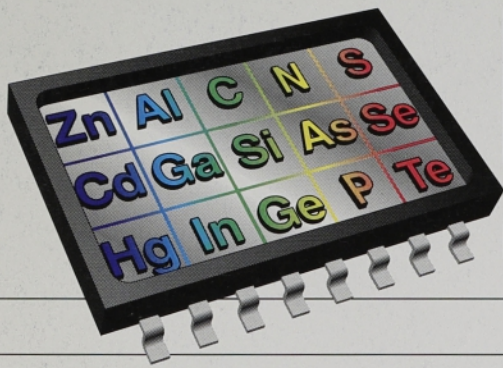
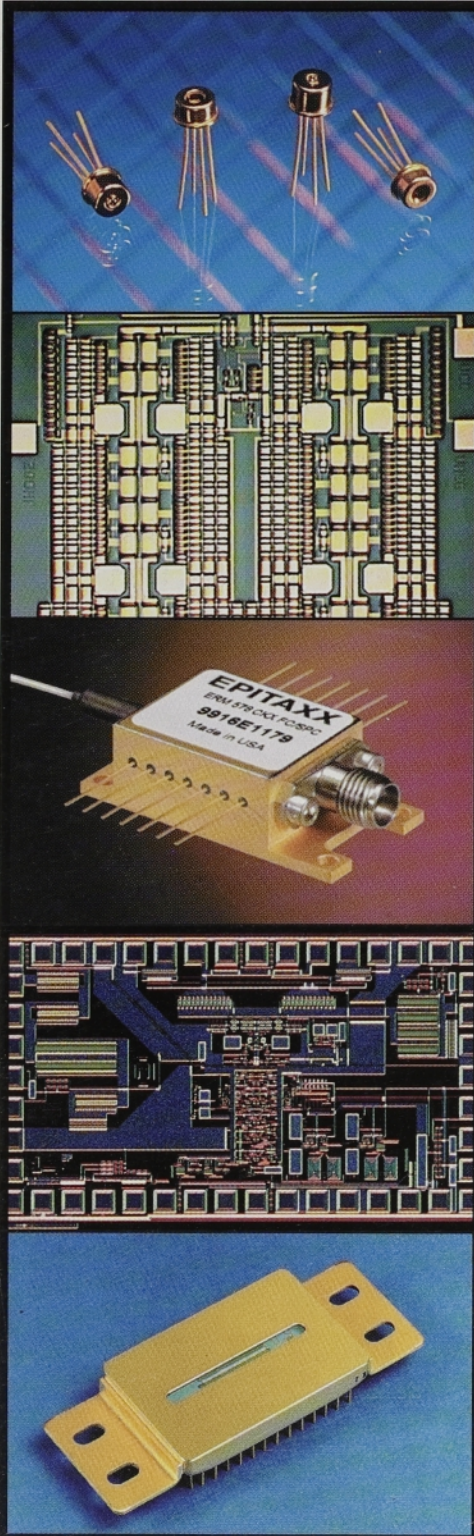




COMPOUND SEMICONDUCTOR

April 2000

Volume 6 Number 3



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- InP Microelectronics: Poised to Change the Competitive Landscape
- Future Opportunities For Optoelectronic Components
- Progress in GaAs OEICs for Datacommunications
- 10 Gb/s Detectors at Epitaxx
- Optical Fiber Communications Conference Report

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Mid IR Lasers...SiC Gas Sensors

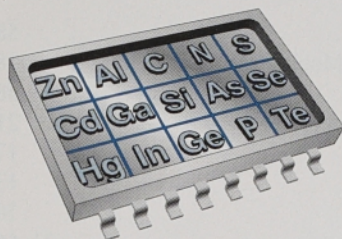
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This issue begins a series of articles presented at the "Compound Semiconductors in Communications" conference (Key West, March 13-14) focusing on optical communications. Components for this market represent the hottest field in compound semiconductors today - a fact also evidenced by the very dynamic Optical Fiber Communications meeting recently. Coverage begins on page 23.

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Vitesse Eyes Indium Phosphide for 40 Gb/s Products

TIM WHITAKER

Indium phosphide ICs will play a major role in Vitesse Semiconductor's future plans as the company develops next generation products for 40 Gb/s fiber-optic communication networks. In an interview with *Compound Semiconductor*, Vitesse outlined its technology roadmap, and revealed that a 1-micron InP HBT process will be used to implement several 40 Gb/s functions. These products are expected to begin shipment two years from now. InP was chosen over all other options - including SiGe and GaAs HBTs - because of its favorable characteristics such as high speed and low power consumption.

In the long term, Vitesse will leverage its experience in the volume production of GaAs ICs and will establish partnerships to implement an InP HBT fabrication line, but plans to use foundry services in the short term. Although the foundry partner was not revealed, several companies, including TRW, NTT and HRL Labs, are very close to commercializing InP ICs [see CS 6(1), p. 88]. TRW may be the obvious choice as they are particularly focused on InP HBT technology.

Not Just a GaAs Company

Vitesse is a major player in the fiber-optic IC market, and claims to have a 50% market share for SONET/SDH products at OC-48 (2.5 Gb/s). Revenues were \$281.5 million in 1999, up 59% compared to the previous year. The company operates two GaAs fabrication facilities: Fab1 in Camarillo runs 4-inch GaAs wafers, while Fab2 in Colorado Springs was the world's first 6-inch GaAs fab.

Vitesse was founded with the aim of developing a manufacturable GaAs IC process for physical layer (PHYS) functions in fiber-optic networks such as multiplexers (MUX) and demultiplexers (DEMUX), as well as clock data recovery (CDR) and clock multiplication unit (CMU) ICs. Applications for these ICs include high-speed SONET/SDH networks, and Fibre Channel and Gigabit Ethernet systems.

Vitesse's first proprietary MESFET process, named H-GaAs I, was introduced in 1987. With 9 mask levels, 2 metal layers and a maximum of 15,000 transistors, this process (which is still in use today) has an f_T of 15 GHz. H-GaAs IV, introduced in 1996, has 15 mask levels, 4 metal layers and an f_T of 45 GHz, and can be used to design ICs with more than 1.5 million transistors. The

latest generation, H-GaAs V, is focused at OC-192 PHY layer products and exhibits an f_T of over 80 GHz.

In addition to continually improving its GaAs MESFET processes, the company has evolved its product portfolio into other areas. These include analog and optical front-end functions such as laser drivers, transimpedance amplifiers (TIAs) and post amplifiers, and ICs for "upper layer" functions such as framing, processing and switching, as well as enclosure management for storage area networks.

Perhaps most importantly, in their own words, Vitesse is now "not just a GaAs company". In 1998, introduced its first CMOS products, manufactured through external foundry relationships. CMOS enables relatively low cost products with extremely high levels of integration, and is ideal for the upper layer processing and framing functions. "Over 60% of the Vitesse design staff are involved in CMOS product development," says Vitesse's Ken Jones.*

New H-GaAs Process

Vitesse is currently in the process of introducing its latest GaAs MESFET process, H-GaAs V, which will allow the integration of additional functionality while at the same time provid-

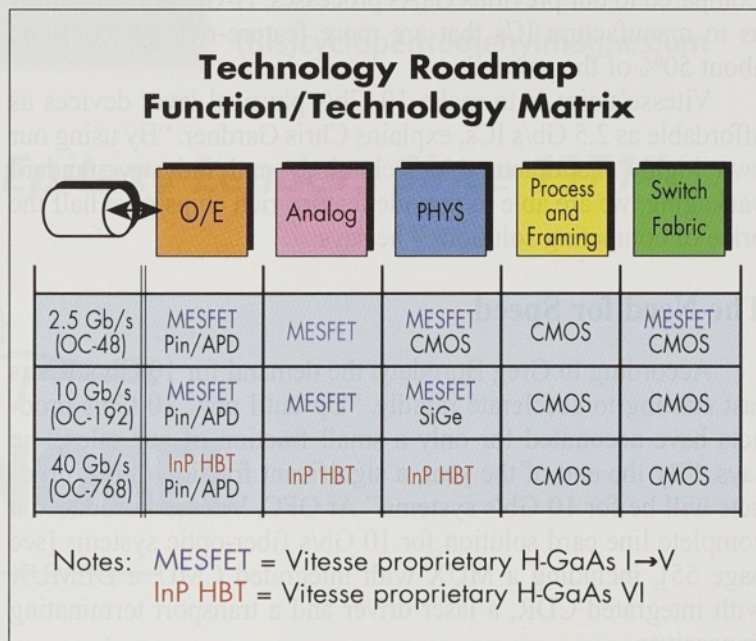


Figure 1. Vitesse's technology roadmap calls for the use of a 1-micron InP HBT process to implement several functions in next-generation 40 Gb/s fiber-optic networks.

* Ken Jones is VP and General Manager of Vitesse's Advanced Transmission division.

Chris Gardner is VP and General Manager of Vitesse's Telecom division.

Greg Borodaty is director of Telecom Product Marketing.

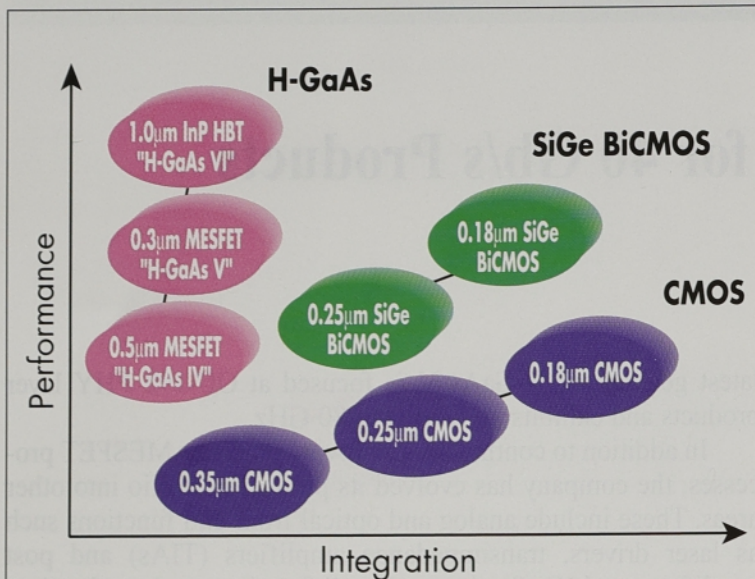


Figure 2. Vitesse's new H-GaAs V MESFET process and the planned InP HBT process (H-GaAs VI) offer very high performance, while CMOS will be used for functions requiring very high levels of integration.

ing a significant reduction in operating power. The company will introduce the first H-GaAs V parts later this year. The 0.25 µm MESFET process has 4 metal layers, 16 mask levels and an f_T of 80 GHz, and will run on the 6-inch GaAs fabrication line in Colorado Springs.

The main difference between H-GaAs IV and H-GaAs V is that the new process has much smaller dimensions and allows the design of ICs that dissipate much less low power. "The key is that H-GaAs V is a relatively simple process, which provides excellent yields in combination with the use of 6-inch wafers," explains Ken Jones. "In comparison, SiGe processes use as many as 30 mask levels, introducing more complexity and cost. Compared to our previous GaAs processes, H-GaAs V will allow us to manufacture ICs that are more feature-rich yet consume about 50% of the power."

Vitesse's aim is to make 10 Gb/s physical layer devices as affordable as 2.5 Gb/s ICs, explains Chris Gardner. "By using our own highly manufacturable technology and industry-standard packaging, we are able to provide feature-rich chipsets at half the price of competing solutions," he says.

The Need for Speed

According to Greg Borodaty, the demand for 10 Gb/s ICs is just starting to accelerate rapidly. "Up until now, 10 Gb/s products have accounted for only a small fraction of our sales," he says. "By the end of the year, a significant fraction of our products will be for 10 Gb/s systems." At OFC, Vitesse introduced a complete line card solution for 10 Gb/s fiber-optic systems [see page 55], including a MUX with integrated CMU, a DEMUX with integrated CDR, a laser driver and a transport terminating transceiver.

Vitesse predicts that a similar ramp in demand for 40 Gb/s systems will occur around two years from now. The company has

assessed the technologies that provide the best match to the various functions in fiber-optic networks operating at different data rates [see Figure 1]. GaAs MESFET technology will continue to be used for optoelectronic, analog and physical layer functions in 2.5 Gb/s and 10 Gb/s systems. As shown in Figure 2, CMOS offers very high levels of integration with reasonable performance, and will be used extensively for processing, framing and switching functions. Vitesse expects to utilize SiGe parts for certain niche physical layer applications and ultimately exploit the feasibility of BiCMOS integration using this technology.

Next-generation 40 Gb/s systems require a new, higher performance process for functions with a low level of integration, and Vitesse has chosen InP HBT technology. So why InP? Vitesse has also assessed SiGe and AlGaAs/GaAs HBT technology, but found significant advantages to using InP. One is that the higher mobility of InP results in an f_T of 160 GHz for a 1 µm InP HBT process, compared to typical values of 90 GHz for SiGe and 50-60 GHz for AlGaAs. This allows the design of ICs capable of operating at 50 Gb/s, providing the necessary margin for bandwidth overhead that permits the implementation of forward error correction in an OC-768 system.

Another advantage of InP HBTs is their lower supply voltage: the base-emitter voltage (V_{be}) is 0.7 V for InP HBTs, compared to 1.4 V for GaAs HBTs. This will translate into devices operating at lower voltage and therefore consuming less power. Furthermore, InP HBTs have a breakdown voltage of around 10 V, while the much lower breakdown voltage of SiGe means this technology is difficult to use for functions such as laser drivers.

Vitesse intends to become one of the first companies to install a purpose-built InP HBT line. "Our initial strategy is to work with foundry relationships, but eventually the work will be done in-house," says Ken Jones. Given Vitesse's track record manufacturing GaAs-based fiber-optic ICs, this news is a resounding endorsement of InP as a production-ready technology for microelectronics.

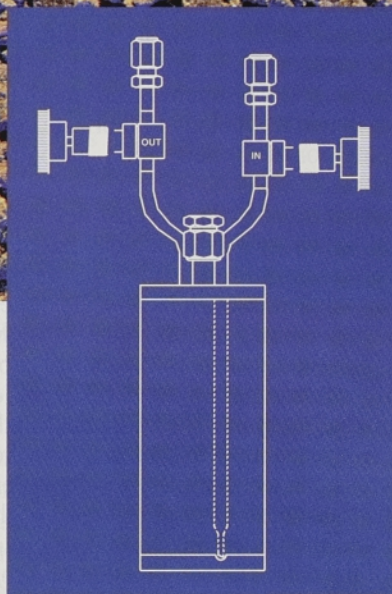
Intel Buys High Speed IC Design House

Intel, the world's largest chip manufacturer, has established an immediate presence in the rapidly accelerating OC-192 fiber-optics market by acquiring GiGA in a transaction valued at \$1.25 billion. GiGA, based in Copenhagen, Denmark, designs high speed ICs and is a leading supplier of silicon-based 2.5 Gb/s (OC-48) and 10 Gb/s (OC-192) components. The ICs are fabricated through GiGA's external foundry relationships.

Intel is apparently debating whether to establish in-house manufacturing for 40 Gb/s ICs. Although CMOS may eventually be able to run at 40 Gb/s, the early generation of ICs will require more "exotic" processes such as GaAs, SiGe or InP. Intel does not have any of these processes at present, and will almost certainly work with foundry partners in the short term.

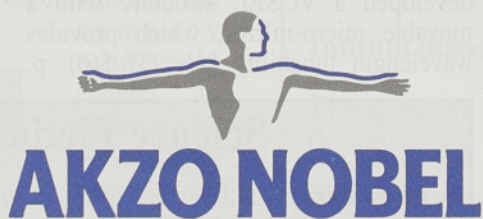


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FIBER OPTICS NEWS

Samsung Forms Optoelectronics Division

In order to meet the increasing market demand for optoelectronic components, Samsung Electronics recently launched its Optoelectronics Division. The new division will manufacture components such as electroabsorption-modulator lasers (EMLs), DFB and FP lasers, semiconductor optical amplifiers (SOAs) and VCSELs. A new 100,000 sq. ft. facility is under construction near Seoul,

Korea, and is due to be completed in June 2000. The company predicts that its state-of-the-art manufacturing lines should provide a module production capacity of 400,000 units per year. Facilities will include MOCVD and MBE epitaxy, a 2-inch full wafer fabrication process, automatic, high throughput assembly and low cost plastic packaging for access network and datacom modules.

Nortel Goes Shopping – Again

After splashing out \$3.25 billion to purchase Qtera, a developer of ultra-long-haul optical network systems, Nortel Networks has committed a further \$4.68 billion to acquire two more companies – Xros and CoreTek. Both use MEMS (micro-electromechanical systems) technology to fabricate components for next generation all-optical networks.

Xros (Sunnyvale, CA) has developed an all-optical switch technology based on silicon micro-mirrors, which allows data to be switched through large-scale optical networks entirely in the form of light. Xros' X-1000 switch is capable of arbitrarily connecting up to 1152 pairs of inputs and outputs. The all-optical pathway from each input to each output makes the cross-connect completely independent of the transmission speed (bit rate) of the data and the underlying format or protocol of the data. The combination of Xros' photonic switches and Qtera's ultra-long-reach networks should give Nortel the capability to deliver the world's first all-optical network.

Another key piece of the puzzle is provided by the acquisition of CoreTek (Burlington, MA). The company has developed a VCSEL structure with a movable micro-mirror, which provides wavelength tunability [see CS 5(6), p.

32]. The ability to change the wavelength of light in real-time as it travels through a network provides the flexibility to dynamically monitor and re-route traffic.

"CoreTek's capabilities are an important building block in our vision to transform today's Internet into the all-optical Internet of tomorrow," says Clarence Chandran, president, Service Provider and Carrier Group, Nortel Networks. "This will deliver the power and flexibility needed to support new applications, instantly reroute traffic in response to bandwidth demand, and provision new high-speed services in a matter of minutes."

CoreTek was purchased for up to \$1.43 billion, a portion of which is contingent upon CoreTek achieving certain milestones, while Xros cost Nortel \$3.25 billion. Although these are huge sums of money, the market for optical bandwidth management systems in 2004 has been estimated as \$15 billion, and Nortel clearly intends to be a major player. "By aggressively employing a mix of alliances, acquisitions, and R&D," says Chandran, "we can answer the ever-growing bandwidth demands of our customers, while at the same time exponentially driving down the cost of delivering services and driving up profitability."

Science Fiction or Fact? - #1

Our industry will be very different in the future, if a recent film and a science-fiction novel are to be believed:

- From the film "Galaxy Quest" - A group of actors from a TV science fiction series are transported into space to try to prevent an aggressive alien race from destroying its peaceful neighbors.

"They are very bad," explains the leader of the oppressed race. "They tortured our scientists and sent them to work in the gallium arsenide mines."

Sumitomo to Offer GaN Single Crystal Products

Sumitomo Electric recently announced the development of a process for producing single crystal GaN substrates in diameters up to 2 inches. The company is investing 5 million yen (\$4.7 million) to establish a GaN wafer production plant, and plans to begin shipping wafers in commercial quantities next year.

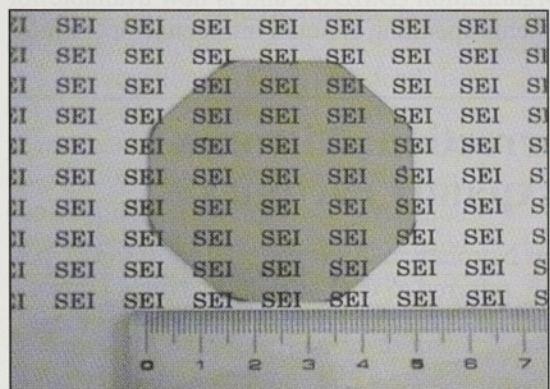
The availability of large diameter GaN substrates could have a dramatic impact on the production of GaN-based devices. Sapphire substrates are commonly used now, largely because no suitable alternatives exist. But they suffer from well known drawbacks, including a large lattice mismatch with GaN and poor thermal conductivity. Sapphire is an insulator, which complicates device design, and it is also difficult to cleave, which complicates processing. But all of these problems would be removed if GaN substrates can be made cheaply and reproducibly.

The traditional melt-growth methods that are used to produce other types of compound semiconductor substrates do not work with GaN. Ultra-high-pressure solutions and sublimation methods have been tried, but only very low growth rates and very small crystals have been realized thus far.

Sumitomo says that its process is based on thermodynamic developments achieved by Professors Seki and Koukitu at the Tokyo University of Agriculture and Technology. Further details were not provided. The substrates are said to be conductive, and suitable for cleaving. The company estimates that GaN-laser diodes grown on these substrates could be up to 50% smaller in size than their counterparts grown on sapphire, and will cost half as much to produce. The company plans "to confirm the practicality of single-crystal for epitaxial growth for lasers; to establish a mass production system which will include process technology; and to begin sales by 2001." Sumitomo says that "GaN single-crystal substrate will not only accelerate movement towards common use of blue lasers, but will also promote new developments in electronic devices which employ GaN." However, the company did not offer any opinions as to whether the new substrates will find use in the production of GaN-based LEDs.

Earlier this year, Sumitomo Electric announced plans to mass-produce a ZnSe-based white LED (see CS 6(2), p. 21). The

company reportedly expects to generate 12 billion yen (\$113.2 million) from sales of white light LED and GaN wafer sales in fiscal 2002.



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OPTOELECTRONICS NEWS

Applied Optoelectronics Announces Mid-IR Laser

Applied Optoelectronics (Sugar Land, TX) has reported high-efficiency mid-IR interband cascade lasers. Mid-IR lasers are expected to find applications in medical diagnosis and chemical detection, and in pulsed mode, these 4.42 μm emitters have achieved an efficiency as high as 580% (i.e. every electron injected into the laser creates on average nearly 6 photons).

The interband cascade design uses a series of type-II band alignment quantum wells, in which the electron and hole quantum confinement are in different material layers. This structure allows the recycling of carriers, similar to the quantum cascade laser (QCL); but, unlike the type-I band alignment QCL, the lasing transition remains inter-band. This has the benefit of increasing the carrier lifetime in the upper laser state, leading to a lower threshold current for the type-II devices.

Applied Optoelectronics uses an MBE-grown ridge-type structure based on an MQW active region of InAs/InGaSb/InAs/AlSb/InGaSb/AlSb/GaSb/AlSb on GaSb substrates. These are separated by superlattice injection regions to efficiently channel the recycled carriers into the next active region. For cw operation at 4.42 μm , the output power was 50 mW per facet at a temperature of 80 K. The threshold current was 35 A/cm², and the external quantum efficiency was 193%. In pulsed mode, the peak power was 150 mW with 580% external quantum efficiency.

"The interband cascade laser represents a real technological breakthrough," says Thompson Lin, president of Applied Optoelectronics. "It will enable compact and efficient devices for performing chemical leak detection in refineries and gas pipelines, process control in factories and chemical plants, and monitoring environmental air quality, as well as a host of other applications."

The interband cascade laser offers improvements to many medical diagnostic techniques, says Lin. Blood glucose monitoring can be performed without taking samples from patients, while levels of oxygen in the blood and carbon dioxide in the breath can also be monitored using these lasers, he says.

The mid-IR interband cascade laser was developed with support from the Air Force Research Laboratory and the Ballistic Missile Defense Organization (BMDO), and is now available for use in prototype systems operating at liquid nitrogen temperatures.

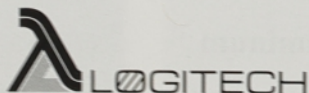
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Correction: Nitronex Expands Facilities

In an article about Nitronex in our last issue [see CS 6(2), p. 18], we mistakenly referred to the company as Nitres on two occasions. We apologize for the confusion caused by these errors.

AXT Ships Blue LEDs

American Xtal Technology (AXT) has begun shipping AlInGaP-based blue LEDs in pilot quantities. The 470 nm high-brightness devices provide around 1.5 mW of output power at 20 mA, making them suitable for full-color signs, LCD backlighting, automobile instrument panels and white light LED illumination. The new device augments the company's current offering of AlInGaP-based high-brightness red, amber and yellow LEDs. These are manufactured by AXT's Lyte Optonics subsidiary, acquired in May 1999, which is also a leading producer of diodes for laser pointers.

Cree Receives LED and Laser Funding

Silicon materials and device manufacturer Cree, Inc. has received an additional \$10 million funding commitment from Microvision (Bothell, WA). Microvision's retinal scanning display technology replaces conventional displays with a rapidly scanned beam of LED light to project images on the eye's retina, allowing the viewer to see large, full-motion images [CS 5(5), p. 11].

Cree intends to use the funds for further development of blue and green LEDs as well as CW lasers. Cree's chairman and CEO Neal Hunter stated: "This additional funding will help us to expand our technology for inclusion in new state-of-the art applications, including mobile Internet handsets and other applications."

Microvision says it will extend the development program for another two years, instead of the original agreement (signed in May 1999) for a one-year commitment and one-year extension option. Cree has also agreed to expand its equity position in Microvision. Cree and General Electric Pension Trust will each make a \$12.5 million investment in the company's common stock.

Gentex, LumiLeds Win Auto Awards for LED Designs

Gentex recently received an Automotive News PACE (Premier Automotive Suppliers' Contributions to Excellence) award for its white light LED technology, which uses additive color mixing to provide replacements for incandescent bulbs in vehicles. The additive mixing approach uses amber and blue LEDs to synthesize white light without the use of a phosphor converter [see CS 6(2), p. 40].

Gentex's white LED illuminators first appeared as map lamps in the automatic-dimming rearview mirrors of the 1998 Oldsmobile Intrigue GLS, and have since gained wider acceptance. "This award is especially significant to Gentex because it affirms and lends credence to this new technology," said Ken La Grand, Gentex's executive VP.

LumiLeds Lighting was also a recipient of a 2000 PACE award for its SnapLED automotive LEDs, which uses high power AlInGaP LEDs attached to a metal substrate. This method provides automotive manufacturers such as Cadillac with a robust, thin lighting solution for exterior lighting applications [see CS 5(9), p. 76].

The SnapLED gives automotive manufacturers design flexibility, and trunk sizes are increasing as a result of the reduced space requirements of LEDs for tail lighting. LEDs also provide lower power consumption and superior reliability. In addition, LED center high mount stop lights offer a safety benefit by turning on faster than incandescent lights, which translates into an additional car-length of stopping distance at 60 mph.

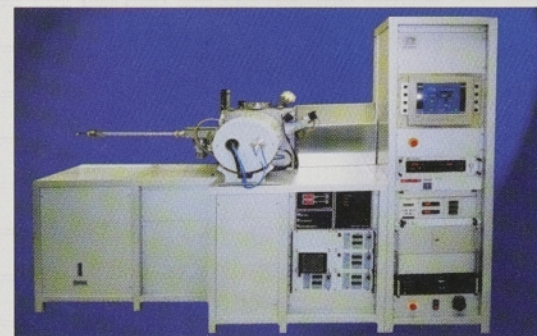
The Society of Automotive Engineers (SAE) Congress included an unprecedented number of LED lighting presentations, which augers well for the market adoption of LEDs in automotive lighting applications.

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Compound Semiconductor Leaders Honored by IEEE

The IEEE recently elevated 248 members to "Fellow" status. The list includes several prominent members of the compound semiconductor community. Here is a partial list:

Peter M. Asbeck, University of California, San Diego, La Jolla, CA.
For development of heterostructure bipolar transistors and applications.

Werner Bachtold, Swiss Federal Institute of Technology, Zurich, Switzerland.
For contributions to the development of microwave semiconductor devices and circuits.

David Paul Bour, Xerox Palo Alto Research Center, Palo Alto, CA.
For contributions to the development, material growth, and understanding of semiconductor quantum-well lasers.

Leonard J. Brillson, Ohio State University, Columbus, OH.
For contributions to the understanding and control of semiconductor interfaces and electrical contacts by atomic-scale techniques.

Dennis Glenn Deppe, University of Texas, Austin, Austin, TX.
For developments in novel optoelectronic materials and devices that have led to new low power and microcavity semiconductor lasers, including dielectrically-apertured and oxide-confined vertical-cavity surface-emitting lasers.

Emmanuel Benoit M. Desurvire, Alcatel-CIT, Marcoussis, France.
For contributions to the fundamental understanding, modeling, designing and early system applications of Erbium-doped Fiber Amplifiers.

Robert Michael Kolbas, North Carolina State University, Raleigh, NC.

For contributions to understanding and development of quantum well heterostructure lasers and light emitters.

Lawrence Ernest Larson, University of California, San Diego, La Jolla, CA.
For contributions to development and applications of high-speed integrated circuits and devices.

Chien-Ping Lee, National Chiao Tung University, Hsin Chu, Taiwan.
For contributions to optoelectronic integrated circuits and compound semiconductor devices and technology.

John Haig Marsh, University of Glasgow, Glasgow, Scotland.
For contributions to development of integrated optics based on semiconductor quantum well devices.

Yi-Ching Pao, Filtronic Solid State, Inc., Santa Clara, CA.
For contributions to the development and manufacturing of molecular beam epitaxial based microwave and millimeter-wave devices and integrated circuits.

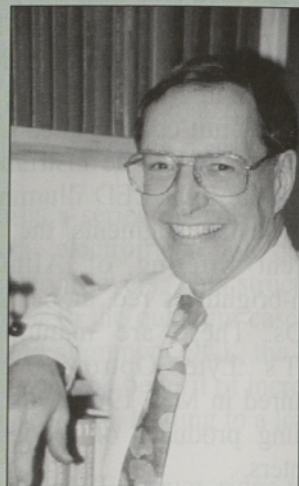
David L. Pulfrey, University of British Columbia, Vancouver, British Columbia, Canada.
For contributions to the modeling of heterojunction bipolar semiconductor devices.

Eric Fred Schubert, Boston University, Boston, MA.
For contributions to semiconductor doping and resonant-cavity devices.

Naoki Yokoyama, Fujitsu Laboratories, Ltd., Atsugi, Japan.
For contributions to the development of self-aligned gallium arsenide MESFET integrated circuits.

James Harris to Receive Liebmann Award from IEEE

James Harris, Jr. of Stanford University will receive the 2000 Morris Liebmann Memorial Award from the IEEE for his contributions to technology enabling the



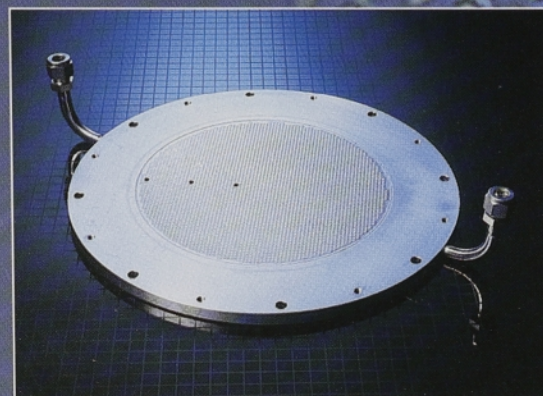
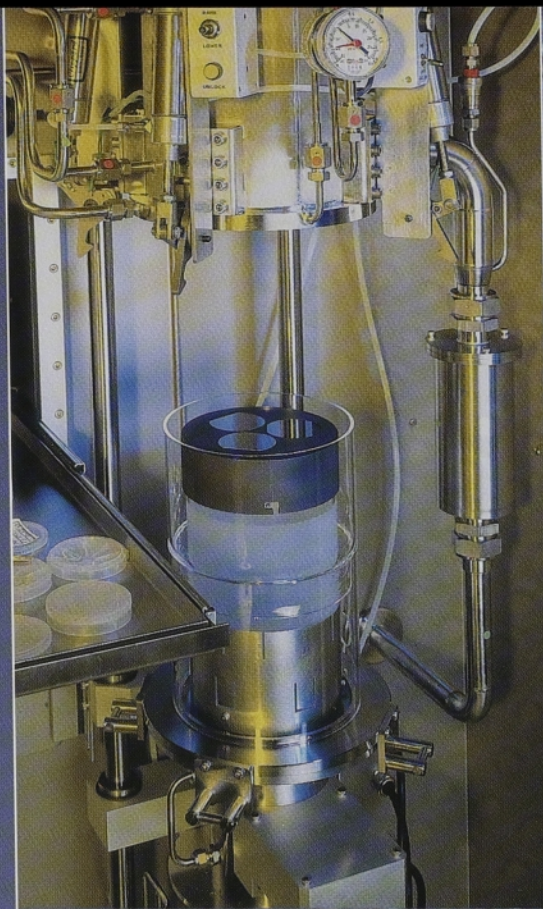
commercialization of GaAs devices and circuits. Harris is a Professor of Electrical Engineering, Applied Physics and Materials Science at Stanford.

Harris pioneered several key compound semiconductor technologies. In the early 1970's he worked at the Rockwell International Science Center in Thousand Oaks, CA and initiated much of that company's work on III-V compound semiconductors. He developed the first successful n-type ion implantation in GaAs, and, working with Roland Ware (then at Metals Research, currently with M/A-COM), he grew the first 3 LEC GaAs boule. This convinced Rockwell management that it was possible to move GaAs technology from small, irregularly shaped Bridgemen substrates to 2" and 3" circular substrates, thus enabling GaAs processing to become more "Si like". These successes were the basis for the first GaAs IC pilot line at Rockwell and his implant process has been widely adopted for direct implant of high speed GaAs ICs.

In 1973 Harris initiated work on MBE growth of GaAs and led the group at Rockwell that produced the first successful GaAs HBT. In 1982 Dr. Harris moved to Stanford University, where he established a large and very successful graduate program.

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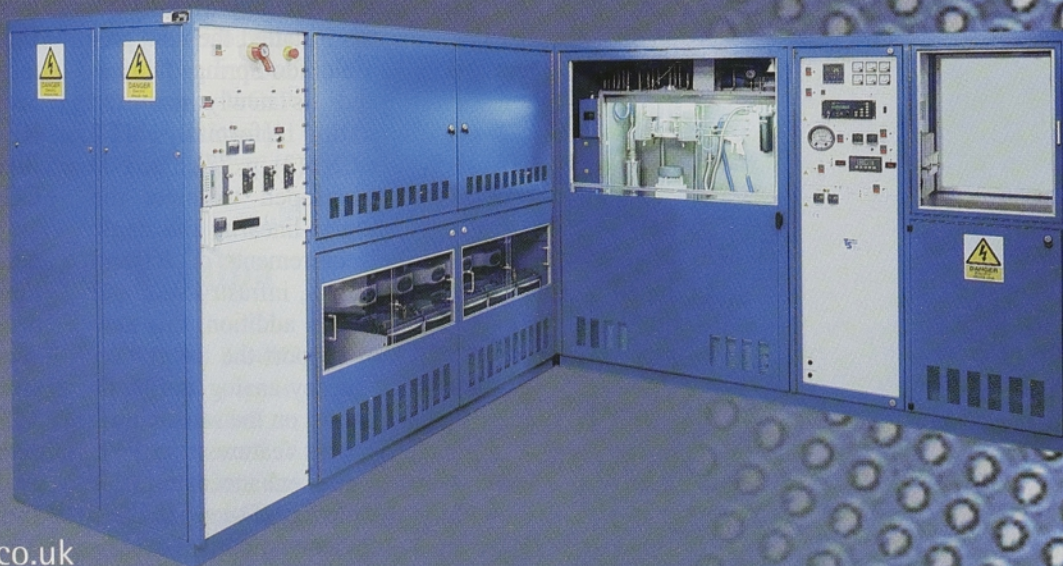
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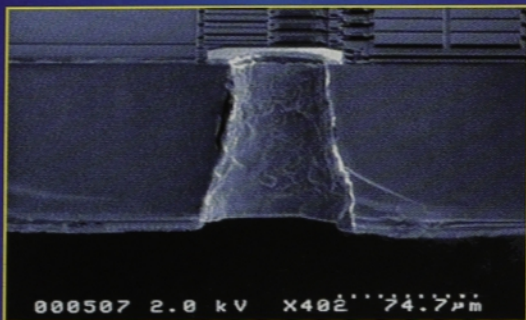
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GaAs ICs - NEWS

Alpha Announces New Contracts with its Two Largest Customers

Alpha Industries recently announced that it is shipping record quantities of GaAs RFIC switches and power amplifiers under new contracts with its two largest customers, both major handset manufacturers. The company is shipping GaAs switches and PAs to the largest U.S. wireless handset manufacturer, believed to be Motorola. In addition, the company has gained new contracts for GaAs switches and discrete semiconductors with a major European handset manufacturer, believed to be Ericsson. As a result, Alpha says it expects to double its business with Ericsson this year.

Alpha reports that its business with Motorola is growing rapidly. "The new contract...provides us with an increase of 40% in market share for the RFIC switches that our customer uses in its wireless handsets," says Chris Conlin, Alpha's director of worldwide sales. "We are shipping increasing volumes of our GaAs power amplifiers into their fastest-selling handsets. Alpha has semiconductors in

virtually all handsets manufactured by our customer, and in most cases, we are the primary supplier.

"We are shipping more than 20 different types of GaAs RFIC switches, a significant percentage of which were developed in the last year," Conlin continues. "Our newest generation of ultra-high efficiency PHEMT switches is shipping in volume, and is being incorporated into the newest phones, which are capable of enhanced data and Internet access." Conlin added that the increased efficiency and competitive price of RFIC switches has resulted in more handset OEMs converting to GaAs IC switch technology.

Alpha's increased market share with Ericsson centers on multiple supply agreements for shipments of its GaAs RFIC switches and discrete semiconductors. "We have established ourselves as a critical supplier of these strategic GaAs semiconductor products and expect to double our sales volume with this customer this year," said president and COO David Aldrich.

M/A-COM's New Enhancement/ Depletion Process

A new GaAs-based enhancement/depletion (E/D) mode process has been unveiled by M/A-COM. The company has installed the new process at both its Colorado Springs fabrication facility and its newly acquired Roanoke operation [formally ITT GaAsTEK - see CS 6(2), p. 77]. The E/D process was developed to meet the increasingly stringent linearity and single supply voltage requirements of 2G and 3G wireless handsets, infrastructure and WLAN products. In addition, this new process will also support the integration of both high-frequency analog and high-speed digital circuitry on the same chip.

The E/D process features two FET device types - one enhancement (E-) mode and one depletion (D-) mode FET. The E-mode device supports on-chip gain mode switching and removes the

negative voltage supply requirement, while the D-mode FET is used for RF switching, mixing and amplification. Cellular phone transceivers developed using this process offer more than 50% lower current consumption for equivalent RF performance compared to the latest SiGe BiCMOS products, says M/A-COM.

The key figures of merit for this process include an Ft value of 25 GHz and Fmin of 0.3 dB, with an associated gain of 16 dB at 2 GHz. For frequency converters requiring optimum linearity and minimum current, the E/D process achieves an IP3 efficiency of 7.5, more than twice that of the best SiGe technology currently available, says the company. Two new products (see page 58) represent the first of several standard PCS/cellular band converters planned for this year.

Microsemi Acquires Infinesse, Plans GaAs HBT Fab

Microsemi Corp. has acquired the HBT business products group of Infinesse Corp. for \$6 million and over 300,000 Microsemi shares. The move is the latest in a series of acquisitions by Microsemi aimed at establishing the company as a major wireless and broadband communications supplier. Infinesse is a fabless product design and development house based in Los Angeles with extensive expertise in the design of RF and HBT-related products using the GaAs, InGaP and SiGe material systems. The Infinesse group includes a number of ex-TRW employees. Among Infinesse's previous customers is Alpha Industries - Infinesse designed HBTs that were initially fabricated for Alpha by NDI [see CS 5(3), p. 4].

Microsemi supplies RF/microwave, power management, transient suppression and power conditioning semiconductor devices. For the latter product category, Microsemi has an alliance with Sterling Semiconductor to develop SiC-based devices [see CS (5)8, p. 16]. The Infinesse acquisition is part of Microsemi's strategy to expand its product offerings in the wireless, broadband, and analog and mixed signal IC sectors. The company previously acquired the RF products group of SGS Thompson, Linfinity Microelectronics Inc. and Narda Microwave Semiconductor.

Microsemi plans to develop and produce a full set of single-function packaged devices and multi-function multi-chip modules (MCMs) with advanced power management techniques designed to improve RF amplifier linearity and efficiency.

Infinesse already has GaAs HBT products in design for 3G applications; these will be co-developed with other Microsemi groups and will address CDMA and W-CDMA applications at cellular, PCS and 3G frequencies. Also under development will be Bluetooth (2.4 GHz) and LAN/Data (5.7 GHz) ICs.

Infinesse currently uses foundry services to handle its immediate production needs. "As part of Microsemi, we will expand these resources by allocating a portion [around 25%] of our existing [Si] device fabrication capability to [GaAs-based] HBT products," said a Microsemi's Manuel Lynch. "We believe that without the advent of next generation, high-frequency InGaP HBT amplifiers, users will not be able to access the anticipated multimedia data streams in wireless broadband communication networks."

First GaAs HBT PAs from Toshiba

Toshiba has introduced its first RF GaAs HBT MMIC power amplifier to the US market. The TG2013F is applicable to 1.9 GHz PCS and CDMA systems, and offers an output power of 29 dBm (single 3.6 V power supply), gain of 24 dB and efficiency of 30%. The TG2013F is housed in a thin, flat 20-pin package (5.3 mm x 6.4 mm) designed for handsets. Sampling now, full production quantities will be available in the second quarter of 2000.



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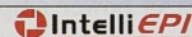
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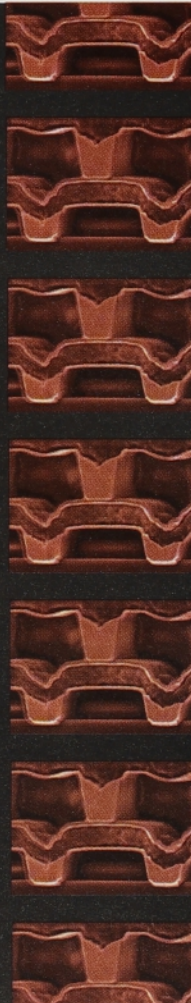
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Anadigics Ships Multi-band PAs for Ericsson's TDMA Handsets

Anadigics is now shipping production volumes of multi-band power amplifiers for use in Ericsson's T18d dual-band wireless phones, which feature digital fax/data and full graphic display capabilities. This Ericsson phone is the third T-class platform to employ Anadigics' patented multi-band technology, which enables operation in D-AMPS 900 MHz and TDMA 1900 MHz bands using one power amplifier.

Celeritek Receives Orders for LMDS Downconverters, CDMA PAs

Celeritek has reported \$6.4 million in repeat orders for GaAs power amplifiers for use in CDMA applications. These orders come hard on the heels of an \$8.5 million contract from the same US handset manufacturer [see CS 6(2), p. 77], and are expected to ship in the first half of the year.

"The additional orders represent follow-on business from a previously announced major US handset manufacturer and are for 3.0 V CDMA power amplifiers packaged in leadless chip carrier packages," says President and CEO Tamer Hussein. "These amplifiers will be used in CDMA handsets targeted for high volume, data-enabled, consumer applications."

In more news, Celeritek has received a \$2.6 million order for 28 GHz low noise downconverters. Expected to ship this year, the follow-on order is from a major full service provider of 28 GHz Local Multipoint Distribution Services (LMDS) for the provision of broadband fixed wireless point-to-multipoint communications.

Celeritek's Frank Sasselli said; "The market for multipoint is beginning to be accepted and adopted by the service providers. We believe the leaders are proving that wireless broadband data systems work, and now we're seeing the first signs of production rollouts. The order activity in this segment is very encouraging."

ISO-9001 Certification For EiC's GaAs HBT Fab

EiC has received ISO-9001 certification for its Fremont, California-based 4-inch GaAs HBT wafer fab line, design team and production test functions. After 8 months of internal and third party auditing, EiC passed the final audit and gained recommendation for certification as of December 1999.

EiC specializes in the development of RFIC components, including broadband amplifiers, driver amplifiers, LNA with down converters and up converters. Also manufactured are gain blocks for the 0-3 GHz spectrum, and PAs in the 800-950 MHz band and the PCS band.

RFMD Announces Orders from Groupe Sagem

RF Micro Devices has received production orders for GSM and DCS/PCS power amplifiers from Groupe Sagem, a French manufacturer of GSM mobile phones. Groupe Sagem's customers include the UK's Vodafone, Germany's D2 Mannesmann Mobilfunk and the French companies SFR, Bouygues Telecom and France Telecom.

Motorola Selects Anadigics Amplifier for CATV Communications Link

Motorola has selected Anadigics' GaAs reverse amplifier for use in its CentriQ 1000 Communications Gateway product, delivering voice, data, and video to the home via an external CATV system. "Our communication gateway required a reverse amplifier that met requirements and was robust enough to stand up to the demanding requirements of the overall system, which is the primary gateway and network control for home delivery of IP telephony and data over the CATV network," remarks Motorola's Marc Kauffman.

Anadigics' ARA1400I consists of an integrated reverse amplifier, precision step attenuator, and RF switching capability. Delivering up to 33 dB gain at 5 V operation, the device provides low distortion and output noise power performance, while meeting all MCNS/DOCSIS standards developed by the cable industry. The precision attenuator varies gain in 4 dB steps over a range of 56 dB.

Science Fiction or Fact? - #2

- From the book "*Manifold: Time*", by Stephen Baxter, published by Ballantine Books, January 2000.

"It took the squid only days to build their cephalopod *Mayflower*. They sent their robots to work leveling the floor of a small crater. Over the crater they built a roughly spherical cage of unprocessed asteroid nickel-iron. Then they began to manufacture the skin of the bubble ship that would take them to Jupiter's orbit. It was simple enough: modified firefly robots crawled over the floor of the crater, spraying charged molecules onto a substrate, like spray painting a car, until a skin of the right thickness and precision of manufacture down to the molecular scale was built up."

"It was a manufacturing process called molecular beam epitaxy that had been piloted on Earth decades before. But nobody had succeeded in developing it to the pitch of sophistication the squid had reached."

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Solkatronic Expands Specialty Gas Production

Solkatronic Chemicals, a business unit of Air Products and Chemicals, has completed several capacity extensions of electronic specialty gases at its two manufacturing facilities. Solkatronic carried out the product ramp-ups during the last quarter of 1999. Capacity at the company's Morrisville (PA) facility for ammonia products, which include its Blue Ammonia proprietary product for GaN processes used in the production of blue lasers and LEDs, has been doubled. Additionally, Solkatronic has doubled the arsine capacity at its Catoosa (OK) production facility.

Trikon Receives System Orders from TriQuint, Major Communications Company

Trikon Technologies (Newport, Wales) has revealed that a major North American communications company, believed to be Nortel Networks (Ottawa, Canada), has ordered eight plasma etch and CVD systems for a broad range of processes for the manufacture of InP optoelectronic devices. Nigel Wheeler, president and CEO, said: "This order was for a combination of MØRI and ICP technologies on the Omega single chamber platform for plasma etching of InP and dielectric layers, and for Delta single chamber plasma CVD systems depositing a range of dielectric materials."

In more news, Trikon has also received additional Sigma PVD and MØRI plasma etch cluster tool orders from TriQuint Semiconductor (Hillsboro, OR) for use in the company's 6-inch GaAs wafer line.

Emcore Increases GaInP HBT and PHEMT Capacity

Emcure's Electronic Materials Division (E²M) has completed the first phase of an expansion at its Somerset, New Jersey fabrication facility. This is in response to increased demand for its GaInP HBT and pHEMT products used in wireless and fiber optic communication devices. The additional 2,000 sq. ft. of fabrication space will accommodate up to six additional Emcore production reactors and allow expansion of the division's characterization capabilities. The first phase nearly doubles production capacity for 4- and 6-inch wafers.

"Recent orders for both pHEMT and HBT epitaxial materials for wireless applications have resulted in a 300% increase in E²M's six month backlog since the beginning of FY2000," said Reuben Richards, president and CEO. The company says it has also launched a second phase of expansion that will again double production capacity for these products.

EPI Files Patent Infringement Lawsuit Against Riber

EPI MBE Products Group (St. Paul, MN) has filed a patent infringement lawsuit, naming Riber Inc. (Edison, NJ) and Riber's parent company, Riber S.A. (Cedex, France) as defendants. The suit, filed in January, alleges infringement of EPI's exclusively licensed U.S. Patent 5,156,815, which relates to effusion sources for MBE systems.

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Reactor Sales

DCA (Finland) has received its first multiwafer production MBE system orders from Applied Optoelectronics, located in Sugar Land (TX). A 3 x 2-inch system will be delivered in September and is intended for the growth of InP devices. A second reactor will be used to grow Sb-based mid-IR devices [see CS 6(1), p. 58 and page 12].

Mitsubishi Electric Company (Itami, Japan) has placed an order for an Aixtron AIX 2400G3 reactor equipped with an automatic wafer handler, designed for the mass production of lasers.

EPI MBE Products Group has orders for two of its GEN2000 multiwafer production MBE systems from Filtronic Compound Semiconductors Ltd. The company is a subsidiary of Filtronic plc that manufactures microwave and millimeter wave RF components and sub-systems from its GaAs semiconductor facilities in County Durham (UK).

MBE Technology will buy two Riber 6000 multi-wafer reactors. The first system will be delivered in April and the second later in October, with an option on a third in early 2001.

TriQuint Orders Mattson PECVD Systems

TriQuint has placed a follow-on order for several plasma-enhanced CVD systems from Mattson Technology (Freemont, CA). Installation of multiple Aspen II systems is expected to begin at TriQuint's newly-expanded facility in Hillsboro (OR) in April.

KDF Sputtering Systems Contract

A major fiber optic communications supplier, believed to be JDS Uniphase (San Jose, CA), has ordered several of KDF's in-line sputtering (634GT) and in-line batch sputtering systems (654 NTX). These PVD tools shipped in March.

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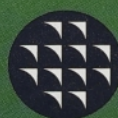


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The Market for Compound Semiconductors in Telecommunications Networks

TOM HAUSKEN
Strategies Unlimited*

*Presented at the Key Conference
on Compound Semiconductors
Key West, Florida
March 13-14, 2000*

The compound semiconductor industry is poised between two of the world's most important industries—semiconductors and telecommunications. Worldwide sales of semiconductors exceeded \$144 billion in 1999. While silicon is, obviously, the dominant semiconductor material, compound semiconductors have conclusively established their own niche in the last 5–10 years. Compound semiconductor sales reached \$10.98 billion in 1999, equivalent to approximately 7.5% of total semiconductor sales. As shown in Figure 1, compound semiconductor sales doubled from 1994 to 1999. Moreover, the pace of growth has quickened in the last two years. In 2000, total compound semiconductor revenues are expected to increase to approximately \$13.6 billion, representing a growth of 24%.

Compound semiconductor sales can be broken down into two main segments, as shown in Figure 2—an optoelectronics segment, with \$8.53 billion in sales in 1999, and an electronics segment with \$2.45 billion in 1999 sales. Telecom modules account for the largest segment of optoelectronics sales. This sector includes not only the chips used in the modules, but also the packaging. Visible LEDs comprise a segment that is almost as large as the telecom module segment in terms of revenue;

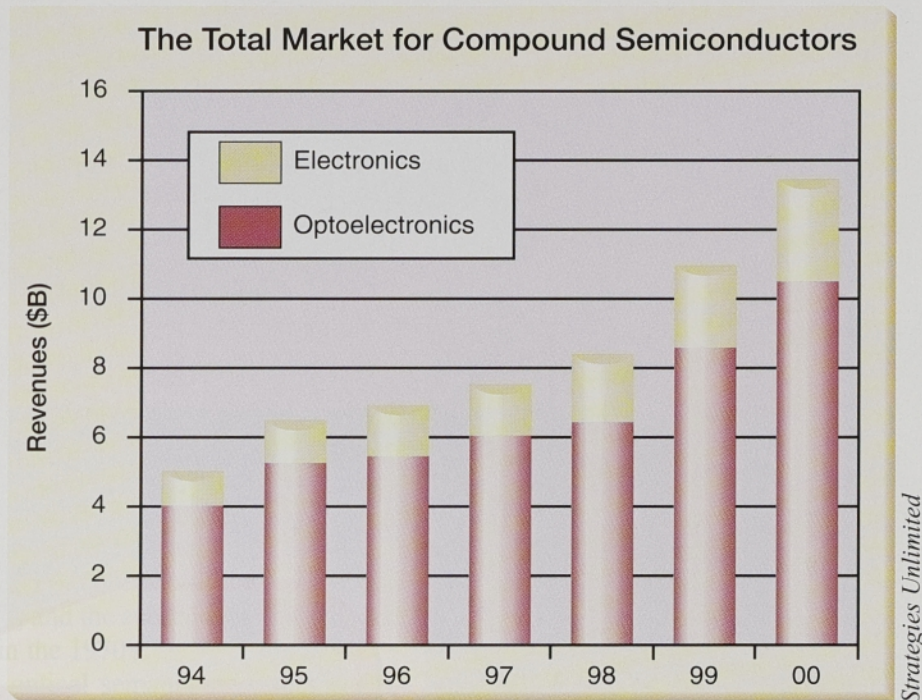


Figure 1. The total market for compound semiconductors is expected to reach \$13.6 billion in 2000, representing a CAGR of 24%.

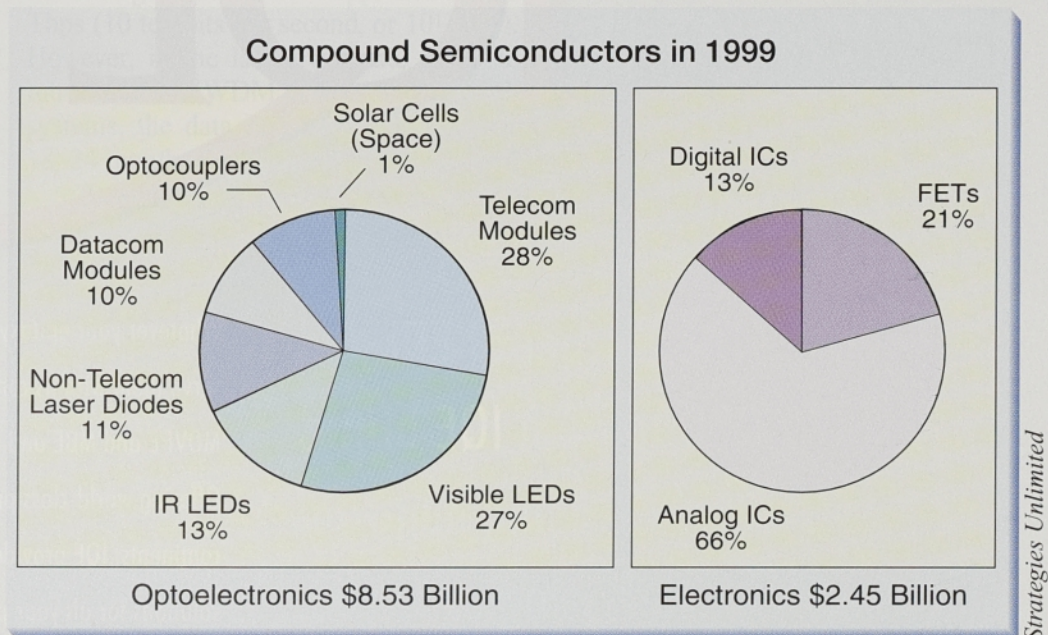


Figure 2. Optoelectronic segments made up around 78% of the compound semiconductor market in 1999.

*Strategies Unlimited is a market research firm specializing in compound semiconductor and related components, based in Mountain View, CA. Web site: <http://www.strategies-u.com>.



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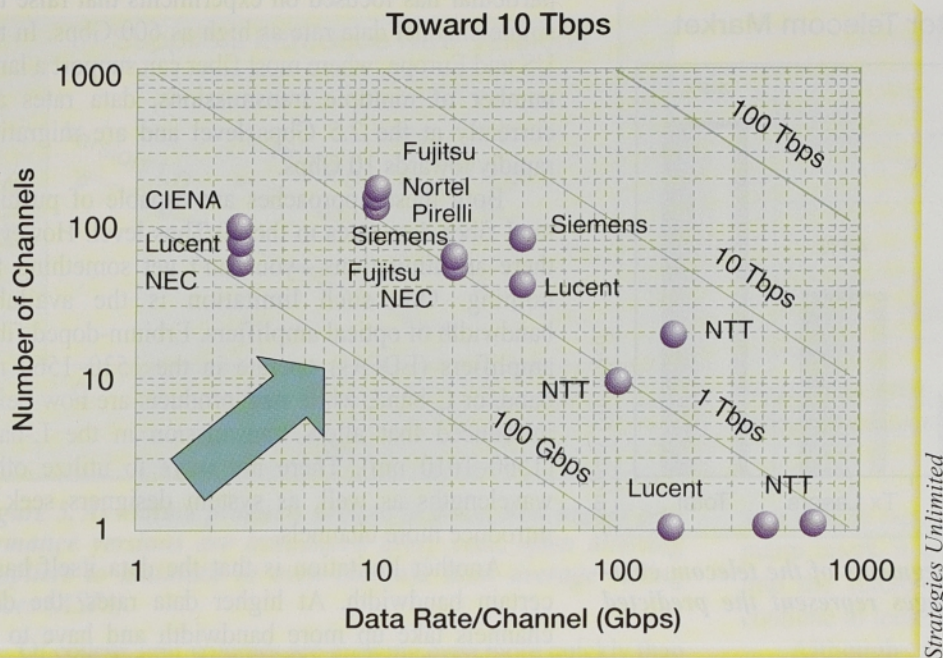


Figure 3. By increasing both the number of wavelength channels and the data rate per channel, fiber-optic networks are moving towards the 10 terabit per second (10 Tbps) level.

however, visible LEDs represent a much larger unit volume, due to their significantly smaller unit cost. On the electronics side, most of the revenues are generated by analog ICs, driven by the rapidly growing wireless sector, with the remaining demand shared between digital ICs and discrete FETs.

In 1999, almost half of all compound semiconductor revenues were derived from communication applications. This percentage has been rapidly increasing in recent years, and it is expected to continue improving. By briefly examining how this market evolved, we can gain insights into its future directions.

Internet Driving Growth

Many consider that commercial optical communications date back to the late 1970's to early 1980's. In fact, the roots of this technology can be traced back nearly 200 years earlier, to an optical semaphore system developed in France, which was able to send message over 1000 km in only 20 minutes, using 100 repeating stations. Soon after that, the telegraph was developed, and the first transatlantic telegraph links were established in the mid 1800's. In the later part of the 19th century,

the radio and the telephone were developed; coaxial cable was laid across the Atlantic in the 1950's, then came the introduction of communication satellites in the 1960's, and the subsequent introduction of fiber in the 1970's.

The optical semaphore system had a data rate of less than 0.01 bps (bits per second). Over the last two centuries, the data rate has doubled about every 4.5 years on average, and is now approaching 10 Tbps (10 terabits per second, or 10^{13} bps). However, in the last few years, with the introduction of WDM in fiber transmission systems, the data rate has doubled every 18–24 months.

A common perception is that the major focus of competition and growth has been in so-called "last mile" products, which enable access to the network. However, the primary growth up to now has actually been in the core infrastructure, or backbone, which serves both the wireless and the wire line market. This growth has been driven in large part by increased demand from the Internet.

Internet traffic has been growing at 100% per year for the past few years, and it will overtake voice traffic on the network within the next one or two years. And while there is ample infrastructure capacity to handle current traffic, carriers



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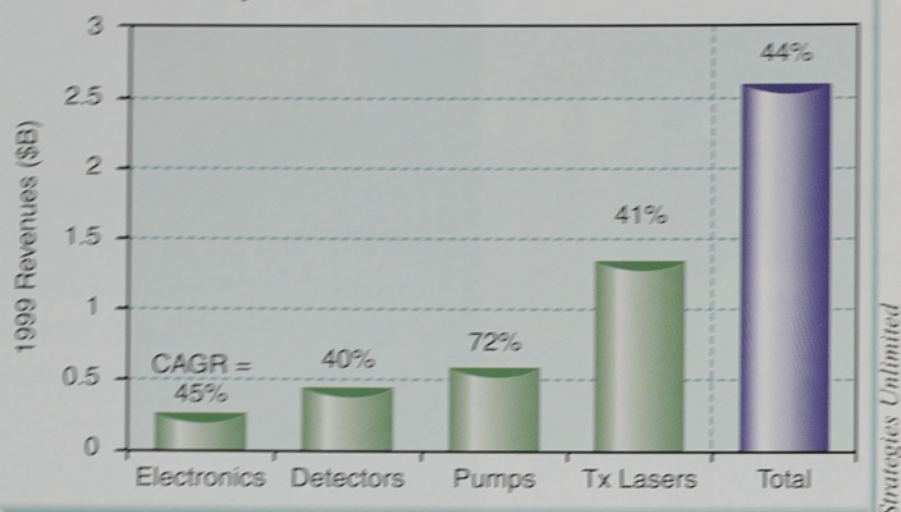


Figure 4. 1999 revenues from the different segments of the telecom compound semiconductor market. The percentages represent the predicted growth rates in 2000.

are making huge investments aimed at increasing capacity as they look at the huge potential demand 3–10 years from now. Current network revenues are at \$800 billion and growing at a CAGR of 8–9%, while capital expenditures in the building of new network infrastructure is \$160 billion and growing at a CAGR of 8.6%. The percentage of capital expenditure to revenue in the telecommunications sector is 20%, which is one of the highest ratios in the world economy.

Obviously, there is a large mismatch in the ratios: telecom revenues are growing at only a 8–9% CAGR, while the growth on Internet traffic is approaching a CAGR of 100%. Thus the industry is faced with the challenge of growing capacity at a very fast rate while enjoying very little revenue growth. This in turn explains why there is such tremendous interest in the introduction of new optoelectronic technologies, as it is only through innovation in this area that future cost targets can be met.

Data Rates and Technology

The advent of wavelength division multiplexing (WDM) technology has had a profound impact on the telecommunications infrastructure. For the first time, WDM allows a large number of information channels to share a single fiber, with each channel transported by a different wavelength. Even with the success of WDM, fiber capacity demands are such that carriers are also looking for ways to increase the data rate per channel using time division multiplexing (TDM) techniques, in combination with WDM. Figure 3 illustrates the multiplicative nature of total data rates when the large number of channels enabled by WDM are combined with higher TDM data rates.

Total data transmission rates are approaching 10 Tbps, and different pathways exist for reaching these higher rates. In Japan, for example, a large amount of installed fiber is suited for higher data rates but not for high channel counts. Therefore, NTT in

particular has focused on experiments that raise the single channel data rate as high as 600 Gbps. In the US and Europe, where most fiber can support a large number of multiple transmissions, data rates are currently at the 2.5 Gbps level and are migrating rapidly towards 10 Gbps.

Both these approaches are capable of pushing total fiber data rates to the 10 Tbps level. However, there are limitations—you can't get something for nothing. One such limitation is the available bandwidth of optical amplifiers. Erbium-doped fiber amplifiers (EDFAs) operate in the 1530–1560 nm band, or C-band, while new products are now being introduced that allow transmission in the L-band (1560–1610 nm). There are ways to utilize other wavelengths as well, as system designers seek to introduce more channels.

Another limitation is that the data itself has a certain bandwidth. At higher data rates, the data channels take up more bandwidth and have to be spaced further apart. Moving from 2.5 Gbps to 10 Gbps provides a four-fold increase in data rate for approximately double the cost, but unfortunately the channel spacing limitation may allow only half the number of channels.

Transmission distance is another issue—as data rates increase, the “reach” of the data drops. For a four-fold increase in data rate, the signal has to be regenerated perhaps twice as often—which adds considerably to the system cost.

Therefore, the optimum data rate and number of carrier wavelengths is highly dependent on the physical infrastructure of the optical network being utilized. However, regardless of which combination of approaches is used to increase the total network capacity, all will require significant investment in optoelectronic infrastructure.

Future Prospects

The compound semiconductor industry will reap major benefits from investment to increase fiber-optic capacity. For 1999, sales of compound semiconductors into the optical telecom market were valued at \$2.6 billion. As shown in Figure 4, demand for each type of compound semiconductor used in fiber optics (source lasers, pump lasers, detectors, and electronics) is growing at more than 40% per year. This in turn puts tremendous pressure on the semiconductor companies to increase both the size and the sophistication of their operations. It is apparent that those suppliers who can reduce their packaging costs and increase their levels of automation will gain market share. The products themselves are becoming more sophisticated as well. For example, we are starting to see more electronics placed within the optoelectronic package. Therefore a laser transceiver is no longer just a laser, detector and thermoelectric cooler, but now may also include laser drivers, clock circuits, multiplexers and demultiplexers. Also, at the same time, the lasers themselves are becoming more sophisticated, and often have monolithically-integrated modulators.

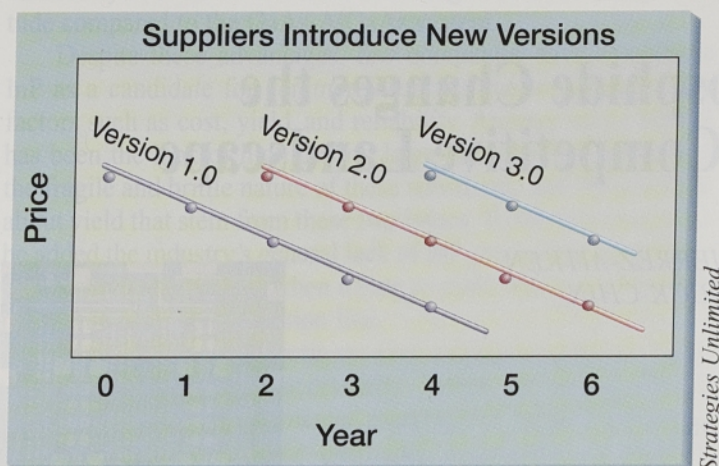


Figure 5. As mature products decline in price, new higher performance versions are introduced every year, often allowing suppliers to maintain or even increase their average selling prices (ASPs).

Of course, unit volumes are growing even more quickly than revenues. But while "price erosion" and lower ASPs (average selling prices) are frequently mentioned, these concepts illustrate only part of the picture. It is true that prices for individual products tend to decline—but the semiconductor suppliers are not standing still. As they introduce better and more sophisticated products, they can maintain or even raise their ASPs, as is illustrated in Figure 5. This in turn helps to maintain the tremendous revenue growth that we are now seeing.

How much longer can this go on? Obviously, it would be difficult to sustain a >40% growth rate over a period of several years. Nevertheless, it is also clear that the growth rate for this

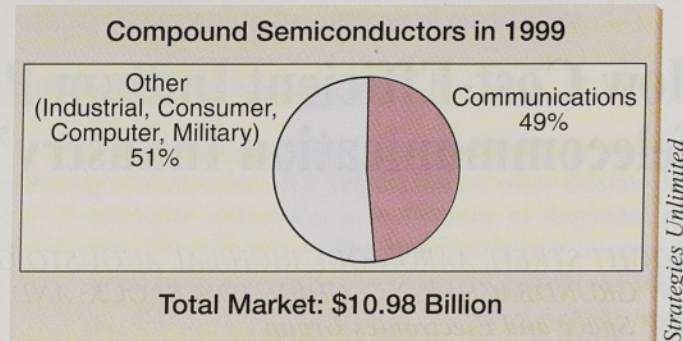


Figure 6. In 1999, almost 50% of compound semiconductors were utilized in communications (wireless or wireline) applications.

year will, in fact, be even higher—for some components, such as pump lasers, it will exceed 70%. While it is not clear how far into the future this boom can be maintained, the prospects continue to look very good.

Although this article has focused on fiber optic communications, wireless communications are also of great importance to the compound semiconductor industry. When the revenues from fiber optics and wireless are added together, we see that communications now account for almost half of all compound semiconductor sales—see Figure 6. It has been said that we are standing on the verge of the "Communications Age"—a time when communications capacity replaces computer power as the driving force of technological advancement. It could also be said that compound semiconductors are helping to enable the Communications Age and are also poised to benefit handsomely from it.

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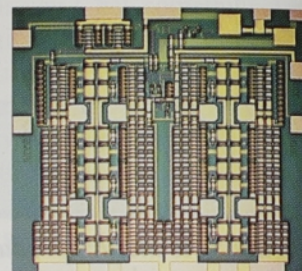
TRW Space and Electronics Group

Redondo Beach, CA

Presented at the Key Conference on Compound Semiconductors

Key West, Florida

March 13-14, 2000



When TRW unveiled plans to produce GaAs HBTs for the commercial marketplace in 1993, the announcement was met with great skepticism. The conventional wisdom of the time held that the HBT was not sufficiently reliable or manufacturable to be transferred from the research lab to high volume production. Worse yet, TRW planned to grow the device layers by MBE, and intended to use beryllium rather than carbon to dope the base layer.

However, in the intervening years, TRW's GaAs HBT has emerged as the technology of choice in a large number of commercial telecommunications applications. TRW expanded its GaAs HBT production line to satisfy the emerging commercial HBT requirements. In addition, TRW licensed its HBT process to RF Micro Devices, a fabless design house which subsequently built its own HBT fabrication facility and now commands an estimated 19% share of the worldwide GaAs MMIC market for wireless applications [1]. Within the last two years, most of the major GaAs device manufacturers have announced their own GaAs-based HBT processes and devices. What had been revolutionary

in 1993 is now a prominent commercial technology supporting rapidly growing product lines.

TRW is now poised to once again offer the commercial marketplace a new device technology, one that has the potential to far outperform GaAs-based HBTs. For more than a decade now, it has been generally recognized that the highest performance three terminal devices – including both HBTs and HEMTs – are those which utilize the InP-based material system, which includes alloys of InGaAs and InAlAs that can be grown lattice matched to InP. InGaAs exhibits a higher electron velocity than GaAs, leading to higher f_t values for both HEMTs and HBTs. For those applications in which large electric fields are required, InP can be used in place of InGaAs both in the collectors of HBTs as well as within the channel regions of HEMTs to achieve high breakdown performance. A further advantage of these alloys is that the broad spectrum of materials properties found within the InP-InGaAs-

[1] "GaAs Device Markets", Stephen Entwistle, Strategy Analytics, presented at the Key Conference 2000. To be published in CS 6(4).

Comparison of HBT Technologies

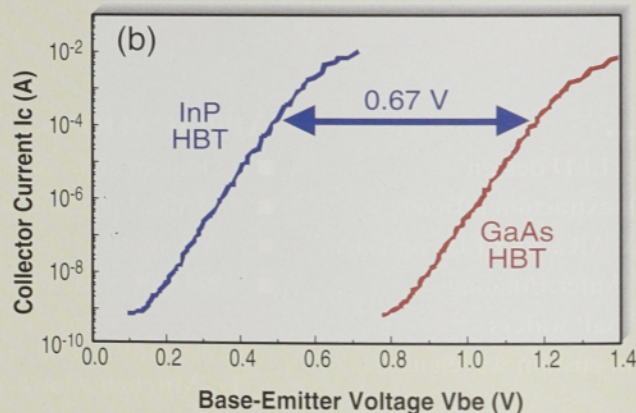
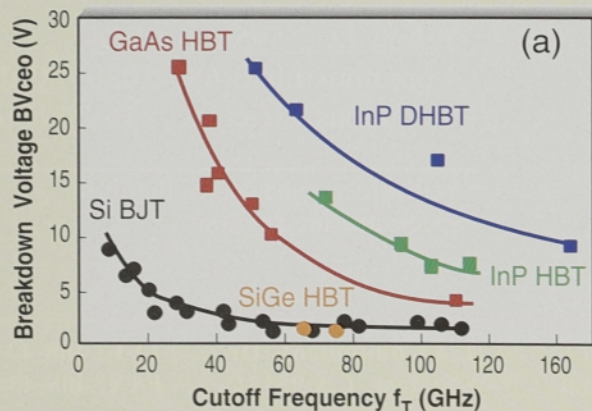


Figure 1. Compared to other HBT technologies, InP HBTs exhibit (a) superior breakdown at high frequencies and (b) significantly lower turn-on voltage.

InAlAs system offers a much wider range of device design latitude compared to the GaAs-AlGaAs system.

Despite these advantages, few companies have considered InP as a candidate for commercialization due to concerns over factors such as cost, yield, and reliability. Another major barrier has been the lack of high quality large-diameter InP substrates, the fragile and brittle nature of these substrates, and the concerns about yield that stem from these two issues. To these factors must be added the industry's general lack of InP processing experience - an asset that is critical when trying to make the move from the research lab to the production line.

However, these problems are very similar in nature to those that were solved - very successfully - when introducing TRW's GaAs HBTs into the commercial marketplace some 7 years ago. Lessons learned from that particular experience are directly applicable to the commercialization of InP circuits. TRW's current InP HBT process is very similar to its advanced 1 μm GaAs HBT process. Although there are specific alloy differences which impact growth and etching, a great deal of the process flow in the advanced GaAs HBT process has been transferred directly to the InP HBT process.

In TRW's experience, high quality 3-inch InP substrates are readily available, and high quality 4-inch InP substrates are in development. This fact, coupled with the extensive process development and epitaxial growth experience with the InAlAs-InGaAs-InP material system that can be found at TRW, leads us

to believe that InP HBTs and InP HEMTs are now poised to make the transition into the commercial marketplace.

A Disruptive Technology

Systems utilizing InP-based HBT and HEMT devices have operating characteristics that outperform all other existing telecom technologies and enable a wide range of important new applications. There is also a large technical barrier to entry for InP due to the complex nature of InP epitaxial growth and MMIC processing. These factors combine to create a scenario where high performance products enabled by a new generation of InP devices will disrupt existing product lines utilizing GaAs- or Si-based technologies.

Figure 1a illustrates the superior breakdown and high-frequency performance of InP HBTs compared to silicon BJTs, SiGe HBTs and GaAs HBTs. The InP HBT utilizes an InGaAs collector, while the DHBT uses a wide bandgap InP collector that further enhances breakdown characteristics [2]. In addition, InP-based HBTs exhibit significantly lower turn-on voltage compared to GaAs HBTs, as shown in Figure 1b. This is a conse-

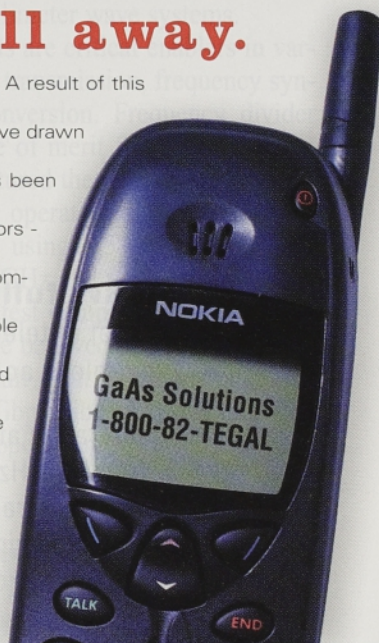
[2] The double heterojunction bipolar transistor (DHBT) has an n-type InP collector, a p⁺ InGaAs base and an n⁺ InAlAs emitter. The standard InP HBT structure has an n-type InGaAs collector, a p⁺ GaInAs base and an n⁺ InAlAs emitter and thus contains only a single heterojunction.

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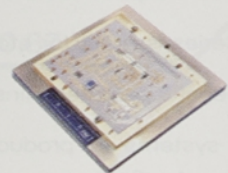
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InP DHBT Record Power Performance

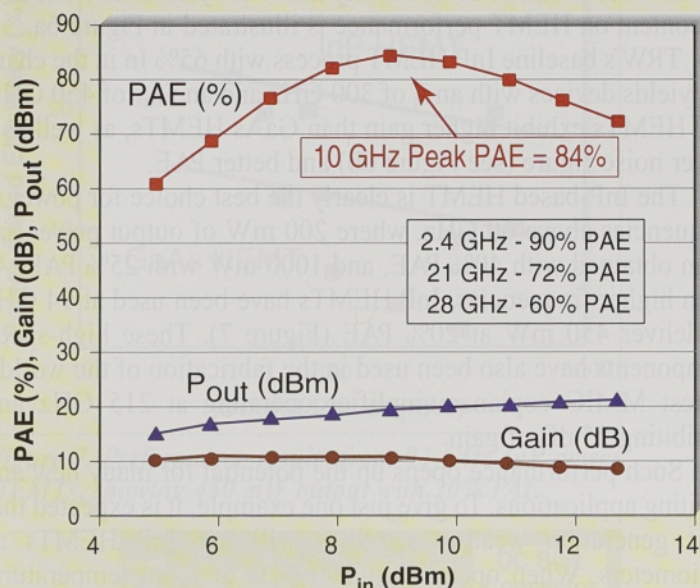


Figure 2. InP DHBTs have demonstrated record power performance up to Ka-band.

quence of the small 0.78 eV bandgap of the InGaAs base material in an InP HBT, compared to the larger 1.42 eV bandgap of the GaAs base in a GaAs HBT. This low turn-on voltage characteristic allows for better power-added efficiency and lower operating voltage, which in turn allows the use of smaller, lighter batteries. This is of critical importance for any battery-operated device such as a cell phone. InP HBTs also exhibit excellent noise and linearity performance compared to GaAs HBTs, and show superior low-current gain uniformity. In addition, the use of InP substrates allows for the monolithic integration of HBTs or HEMTs with optoelectronic devices such as LEDs, lasers, and photodiodes that are fabricated on InP and operate in the 1.3-1.55 μm region.

Setting Device Performance Records

InP-based HBTs and HEMTs have established a number of device performance records. As shown in Figure 2, InP DHBTs have demonstrated excellent power performance in several important frequency bands, including 90% PAE at 2.4 GHz, and 60% PAE at 28 GHz. Compared to GaAs HEMTs, InP HBTs operate at much higher power densities and offer excellent linearity, making this the superior technology for power applications at these frequencies. Also, the use of InP HBTs rather than GaAs HEMTs can result in substantial reductions in size and cost.

While GaAs HBTs have been widely utilized as power amplifiers in many system applications, Figure 3 illustrates that InP-based HBTs offer clearly superior performance at high current densities. Again, the InP HBT is clearly the device of choice for microwave power applications. TRW has also found that InP

f_T vs. Current Density

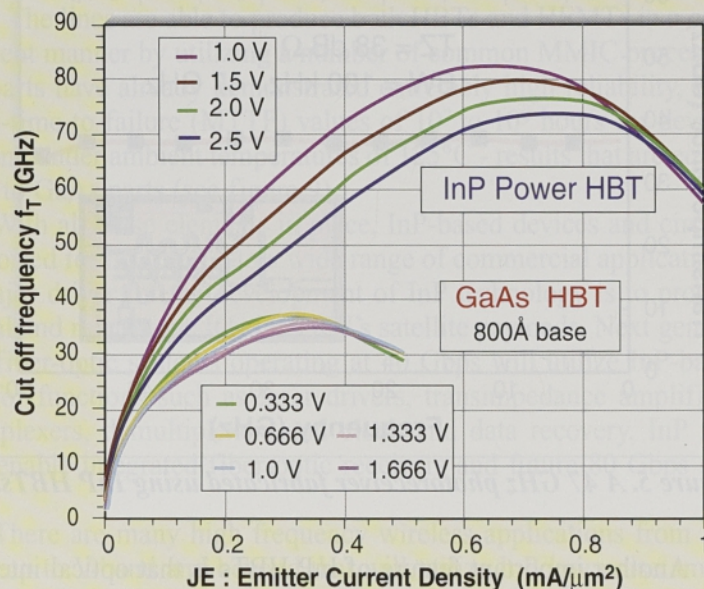


Figure 3. A comparison of cutoff frequency and current density for InP and GaAs HBTs clearly demonstrates the superiority of InP for power applications.

HBTs provide superior linearity performance compared to other devices, and as such have been used in the fabrication of high intercept amplifiers operating up to 44 GHz. Voltage-controlled oscillators operating over the 20-95 GHz range have also been fabricated, enabling their use in millimeter wave systems.

High-speed digital logic circuits are critical enablers in varied applications such as fiber-optic transmission, frequency synthesizers, and analog-to-digital conversion. Frequency divider performance is a recognized figure of merit for digital IC processes, and TRW recently manufactured the world's fastest digital IC – a static frequency divider operating at 80.1 GHz (see Figure 4). The IC was fabricated using $1.5 \mu\text{m} \times 4 \mu\text{m}$ InP DHBTs, which exhibited f_t of 180 GHz and f_{max} of 280 GHz. It should be noted that this result is test equipment limited – the actual operating characteristics were believed to be even higher! Nevertheless, this performance result clearly demonstrates that these devices would support 40 Gbps fiber applications, and show strong potential for 80 Gbps operation.

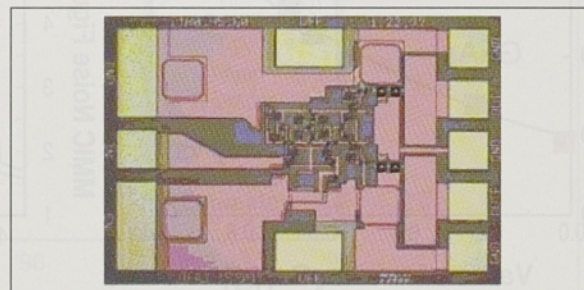


Figure 4. The world's fastest digital circuit – a static frequency divider operating at 80.1 GHz.

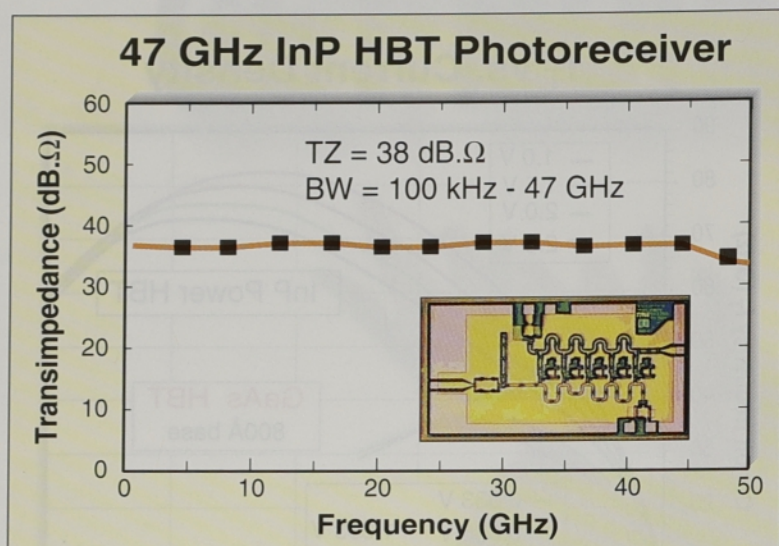


Figure 5. A 47 GHz photoreceiver fabricated using InP HBTs.

Another important feature of InP HBTs is that optical integration is easily facilitated during processing. This can be achieved through the monolithic integration of a Schottky diode using the large bandgap material of the HBT's collector. Alternatively, it is possible to fabricate a p-i-n diode in which the i region of the diode is fabricated from the lightly doped HBT collector. Such p-i-n devices have been used to produce a 47 GHz bandwidth photoreceiver, exhibiting 0.6 A/W responsivity (see Figure 5). Such devices, when monolithically integrated with high speed InP HBTs or HEMTs, will greatly enhance the performance of high-speed fiber optic systems.

InP HEMTs

Despite the excellent high frequency characteristics of InP HBTs, there are many distinct advantages to using InP HEMTs in applications requiring very high frequency or very low noise operation. While pseudomorphic GaAs HEMTs are limited to around 20-30% InAs mole fraction in the InGaAs channel, growing the HEMT structure on an InP substrate allows InGaAs with

up to 65% InAs to be used in the channel. This translates into superior performance that has made the InP-based HEMT the fastest three terminal device in any material system. The effect of In content on HEMT performance is illustrated in Figure 6a.

TRW's baseline InP HEMT process with 65% In in the channel yields devices with an f_t of 300 GHz and an f_{max} of 450 GHz. InP HEMTs exhibit higher gain than GaAs HEMTs, as well as a lower noise figure (see Figure 6b) and better PAE.

The InP-based HEMT is clearly the best choice for power at frequencies above 60 GHz, where 200 mW of output power has been obtained with 40% PAE, and 1000 mW with 25% PAE. At even higher frequencies, InP HEMTs have been used at 94 GHz to deliver 450 mW at 20% PAE (Figure 7). These high-speed components have also been used in the fabrication of the world's fastest MMIC coplanar amplifier operating at 215 GHz and exhibiting 15 dB of gain.

Such performance opens up the potential for many new and exciting applications. To give just one example, it is expected that next generation weather satellites will use InP HEMTs as radiometers. When operated at 100 GHz at room temperature, these devices exhibit a gain of 25 dB and a noise figure (NF) of 3.0 dB. When cooled to 20 K, the gain increases to 32 dB and the noise is reduced to 0.4 dB (see Figure 8). This level of performance will allow weather satellites to null out the effect of signal interference from water in the atmosphere, permitting the measurement of wind velocity as a function of depth in the atmosphere. Such data can be used in sophisticated 3D weather models to better predict the behavior of hurricanes.

Production and Commercial Applications

Regardless of InP's superior performance, a cost effective manufacturing process is required to allow this technology to compete effectively in the marketplace. TRW's approach has been to model the InP process on its proven, high volume GaAs HBT process, and has transferred many process steps directly to its InP line.

InP faces many of the same issues that were successfully addressed for GaAs seven years ago, including substrate supply, epitaxy, yield and backside processes. As noted previously, the availability, cost and reproducibility of InP substrates is improving rapidly. For its epitaxial requirements, TRW has established a reproducible InP MBE production process. The existing TRW InP process line now exhibits yields equivalent to those of GaAs HBT processes. In addition, backside processes for thinning InP substrates and fabricating vias, both of which are critical to maximize device performance, are already in place.

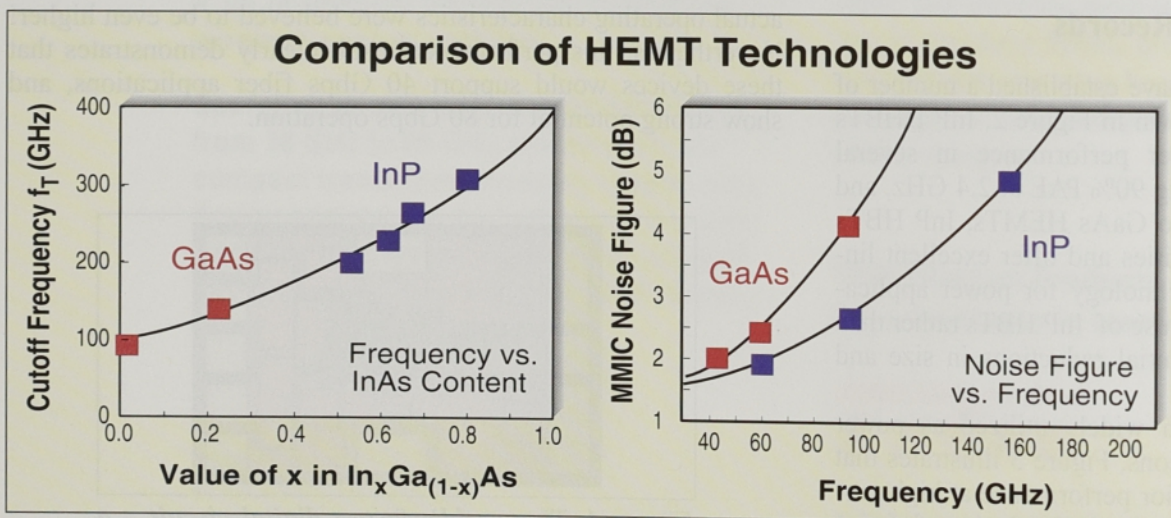


Figure 6. InP HEMTs outperform GaAs PHEMTs in terms of cutoff frequency and noise figure.

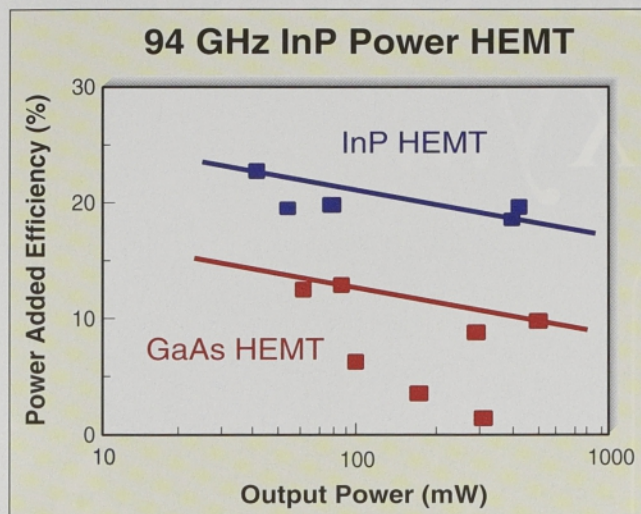


Figure 7. Performance results from 94 GHz InP power HEMTs, showing 450 mW output with 20% PAE.

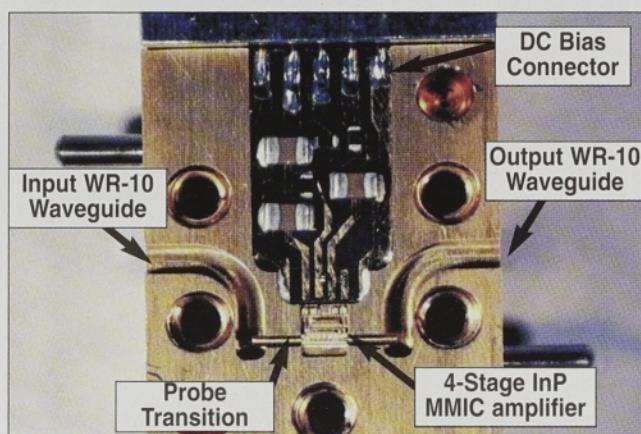


Figure 8. Photo of a 100 GHz, 4-stage InP HEMT low noise amplifier demonstrating 32 dB gain and <0.4 dB noise figure at 20 K.

The result is a high volume, cost-efficient InP production line. TRW has an established, space-qualified 3-inch InP process and is also developing a 4-inch process for commercial and space applications. The lines are able to produce both HBTs and HEMTs in a cost-efficient manner by utilizing a number of common MMIC processes. InP parts have already demonstrated extremely high reliability, with mean-time-to-failure (MTTF) values of 10^7 to 10^9 hours for devices running under ambient temperatures of 125°C - results that are equivalent to GaAs parts (see figure 9).

With all these elements in place, InP-based devices and circuits are poised for insertion into a wide range of commercial applications. A major driver for the development of InP technology is to provide digital and microwave ICs for TRW's satellite payloads. Next generation fiber-optic systems operating at 40 Gbps will utilize InP-based ICs for functions such as laser drivers, transimpedance amplifiers, multiplexers, demultiplexers and clock and data recovery. InP will also enable integrated fiber-optic receivers and future 80 Gbps systems.

There are many high frequency wireless applications from Ku-band up to V-band and beyond that will utilize InP low noise amplifiers, VCOs and power amplifiers. These include technologies for "last mile" broadband access, such as LMDS, and other emerging product lines such as 60 GHz picocells and 94 GHz wireless links. New telecom standards, such as wideband CDMA and Bluetooth, along with a wide range of 3G phones, are all expected to greatly benefit from InP's superior device characteristics.

In two years' time, the industry will have a completely different view of InP compared to the present. The technology will have transitioned from R&D projects and military driven programs into the commercial sector, where its impact has the potential to radically alter the competitive landscape.

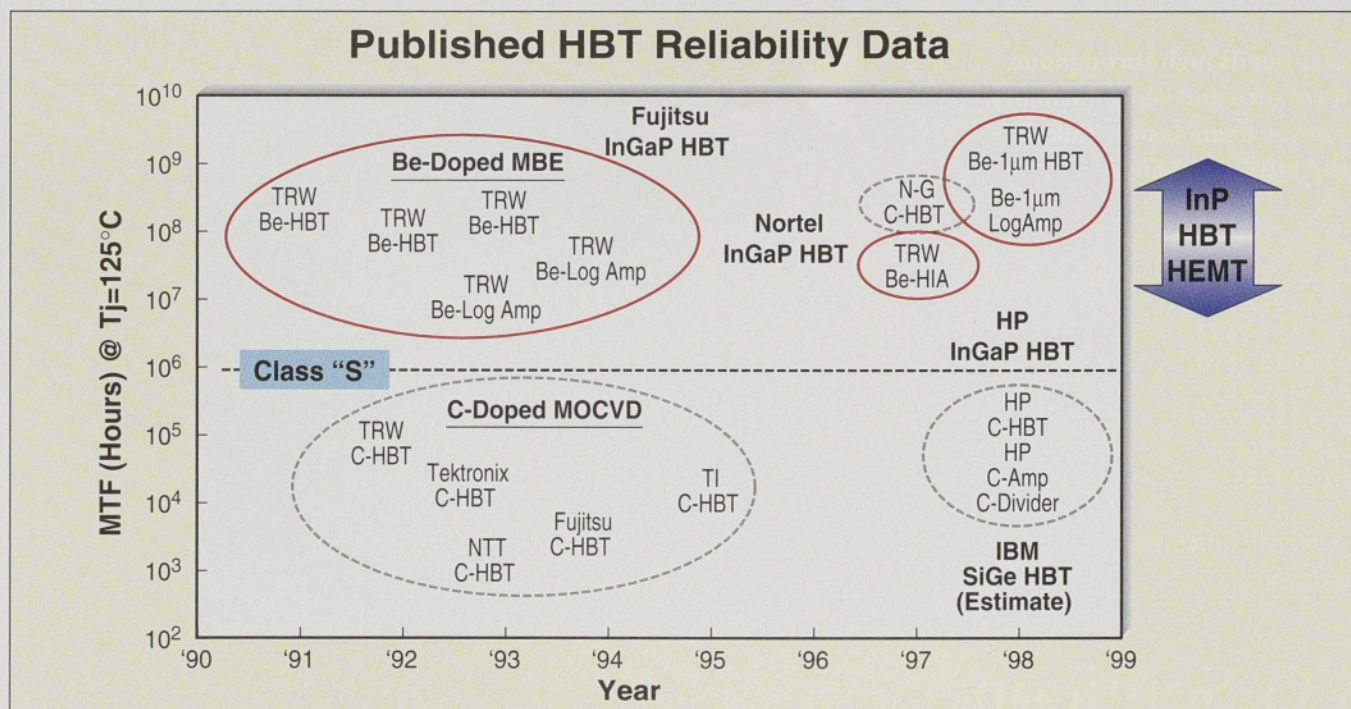


Figure 9. Published reliability data for HBTs. Class "S" represents the level necessary for space qualification.

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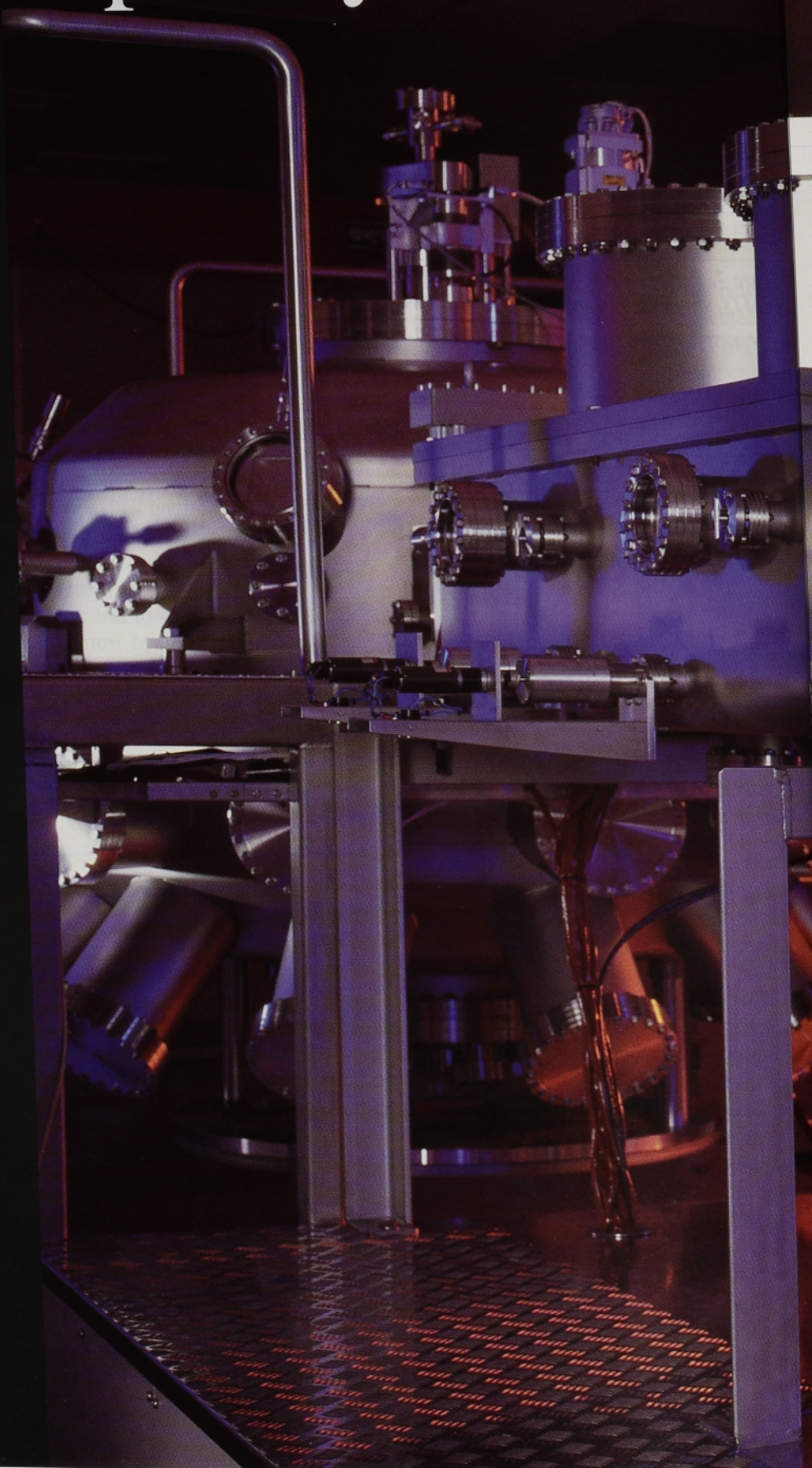
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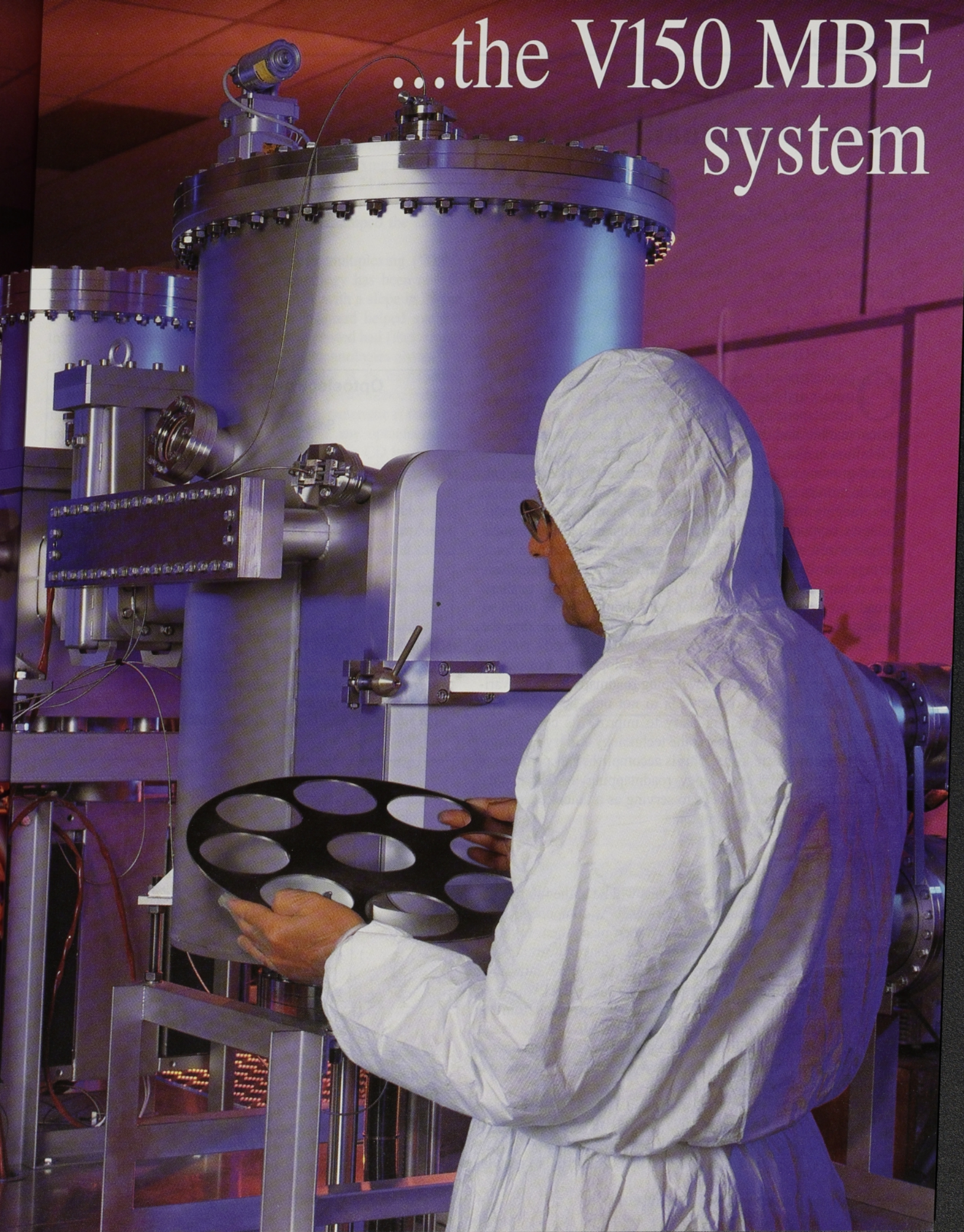
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Future Opportunities for Optoelectronic Components

ARPAD BERGH

President, Optoelectronics Industry Development Association
Washington, DC

Presented at the Key Conference on Compound Semiconductors
Key West, Florida
March 13-14, 2000

Optoelectronics can be viewed as the meeting place of electronics and optics, where electrons and photons are used simultaneously. Anchored firmly between a \$12 billion optics market and the \$150 billion electronics market, the \$50 billion market for optoelectronic components is probably the fastest growing of these three areas. It is important to realize that optoelectronics is not an industry, but consists of many technologies, ranging from lasers to image sensors, with all these technologies supporting a whole variety of industries. These can be characterized within four broad categories: communications, storage, displays and imaging, each of which represent multibillion dollar markets as shown in Figure 1. In addition to these broad categories, LEDs and solar cells should also be noted as important optoelectronics markets, much smaller in size than the other four categories, but growing quickly.

The Optoelectronics Industry Development Association (OIDA) is in the process of developing roadmaps for these various segments. OIDA's objective is to not only help the North American optoelectronics industry to improve its competitiveness, but in general to promote the technology and try to enlarge the optoelectronics industry. This is accomplished in a number of ways, ranging from technology roadmapping to carrying out optoelectronic market surveys to serving as a voice for industry to the government in Washington.

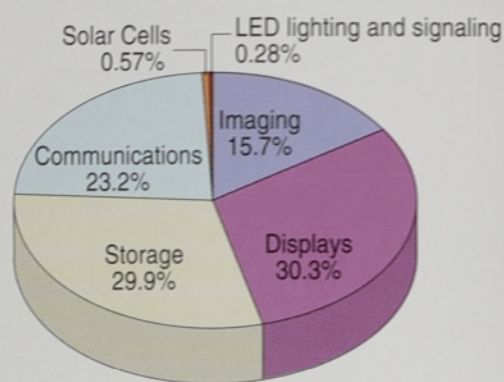
Projections

When trying to see where markets will be in the future, technologists usually project the performance of components up to ten to twenty years in the future and then place them in today's markets. But this is a flawed methodology, usually leading to big surprises when demand comes much faster than anticipated. Instead, we should try to determine what the market will be ten years from now for the devices we will have ten years from now.

At first this may sound like a daunting task, because most of the things that we will have ten to twenty years from now are already here. Usually it takes twenty years for a new technology to become an overnight success.

The Internet is a perfect example of this phenomenon. Although first developed in 1975, the Internet did not really take off in any commercial sense until 1995. Since then, its growth has been explosive - and it is the catalyst for the future growth of

Optoelectronic Industries 1998



Total Market Value: \$140.6 billion
North America Estimate: \$42.8 billion

Figure 1. The four main industries that utilize optoelectronic components - communication, storage, displays and imaging - each represent multibillion-dollar markets.

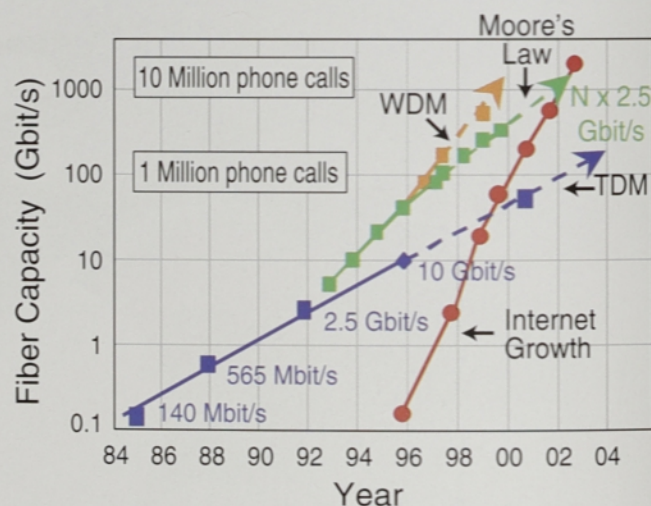


Figure 2. WDM technology is now allowing fiber capacity to grow faster than Moore's Law (which states that the number of transistors per square inch doubles every 18 months). If the fiber network had remained dependent solely on TDM technology, Internet demand would quickly have swamped the existing fiber capacity.

optoelectronics. The ability of the Internet to drive the optoelectronics marketplace has already made itself felt. As shown in Figure 2, the fiber capacity required to handle Internet traffic is doubling every 3-12 months. When Internet growth began to take off around five years ago, time division multiplexing (TDM) was only able to double transmission capacity every 24 months. If the fiber network had remained dependent solely on TDM technology, Internet demand would quickly have swamped the existing fiber capacity.

But fortunately, wavelength division multiplexing (WDM) techniques came into play. WDM technology has been able to double fiber capacity every 10-15 months, with a slope in Figure 2 much closer to that of Internet growth, and helped avoid a tremendous bottleneck which would have existed had fiber capacity been constrained by reliance on TDM technologies alone.

Thus one characteristic of our industry is its tremendous growth rate as exemplified by improved performance and an increase in capacity. The other important characteristic is the continuous, relentless decrease of cost. Almost any optoelectronic component, whether it is something as basic as a CD laser or as sophisticated as a high cost fiber amplifier, will have an experience curve which exhibits a 75% slope in cost. This is shown in Figure 3. Costs drop with increasing volume of production while performance improves. This recipe has fueled the explosive growth of the silicon IC industry and is doing the same to the optoelectronics communication market.

In making predictions of where optoelectronics technologies

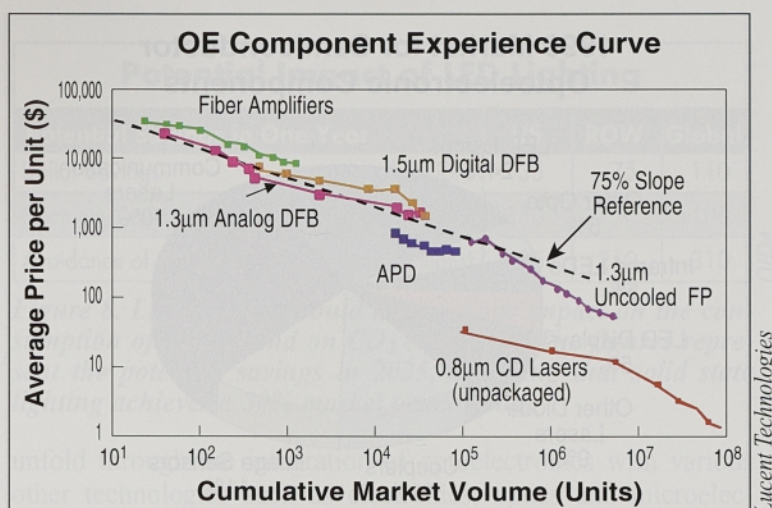


Figure 3. The cost of almost any optoelectronic component decreases at a rate of 75% as the market volume increases.

are heading, it is not only important to keep in mind how the silicon IC industry has evolved, but to also realize that a major paradigm shift is occurring in the telecommunications industry. The location of the intelligence in the network is shifting. Formerly, intelligence was located in a central office. But today it has spread outward, distributed throughout the network, and the form of communication has shifted from analog audio to digital multimedia, with the added complexity of mobility thrown into the mix.

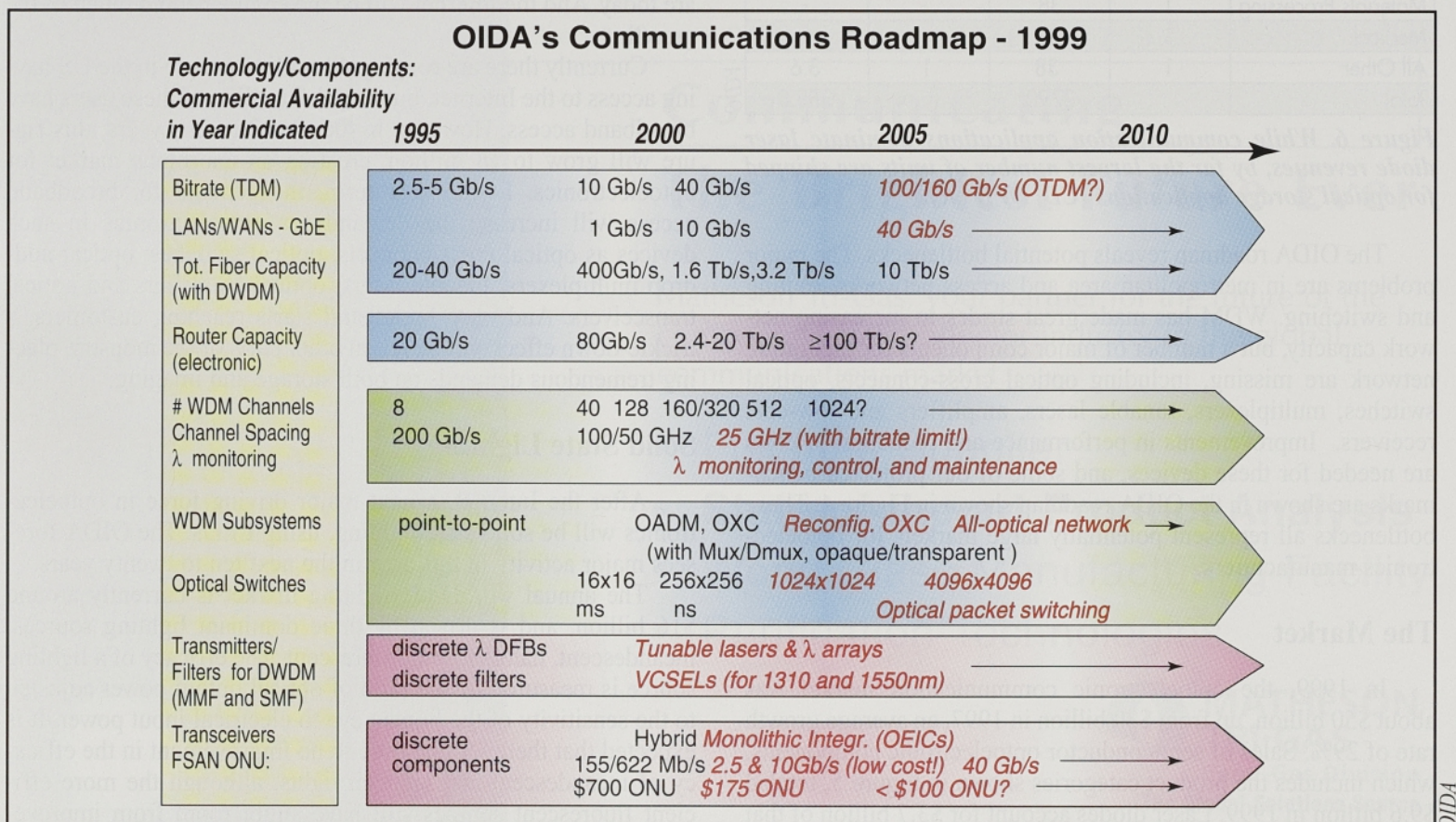


Figure 4. OIDA's roadmap for the commercial introduction of optoelectronic components in the communications industry. Red italics indicates that major industry efforts are required to achieve commercialization.

1999 Market for Semiconductor Optoelectronic Components

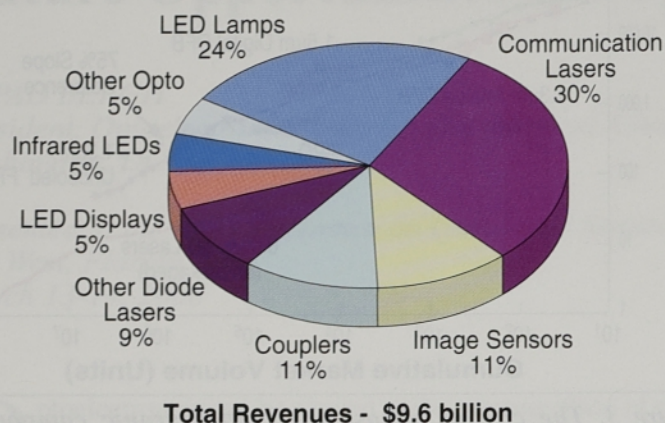


Figure 5. OIDA estimates that the total market for semiconductor optoelectronic components reached \$9.6 billion in 1999.

Laser Diode Markets

Application	Laser Revenues		Unit Sales of Lasers	
	Market share (%)	Revenue (\$ million)	Market Share (%)	Unit Sales (million)
Communication	71	2691	2	7.2
Storage	22	834	84	300.7
Image Recording	2	76	3	10.7
Laser Pointers	2	76	10	35.8
Materials Processing	1	38	-	-
Medical	1	38	-	-
All Other	1	38	1	3.6
Total		3790		358.0

Figure 6. While communication applications dominate laser diode revenues, by far the largest number of units are shipped for optical storage applications (CD, DVD etc).

The OIDA roadmap reveals potential bottlenecks. The major problems are in metropolitan area and access networks, routing and switching. WDM has made great strides in increasing network capacity, but a number of major components for this future network are missing, including optical cross-connects, optical switches, multiplexers, tunable lasers, amplifiers and low-cost receivers. Improvements in performance and reduction in costs are needed for these devices, and some of our projected benchmarks are shown in the OIDA roadmap shown in Figure 4. These bottlenecks all represent potentially large markets for optoelectronics manufacturers.

The Market

In 1999, the optoelectronic communication market was about \$50 billion, up from \$30 billion in 1997, an average growth rate of 29%. Sales of semiconductor optoelectronic components, which includes the product categories shown in Figure 5, totaled \$9.6 billion in 1999. Laser diodes account for \$3.7 billion of that market. Over 70% of laser diode revenues are directly tied to communications, as shown in Figure 6. While this makes com-

munications a dominant force in terms of laser diode revenues, in terms of the number of devices sold, the story is quite different. Laser diode unit sales amounted to 358 million in 1999, of which only 2% were for communication, with the majority being used for optical disk applications. This situation arises because high-end communication lasers are priced around \$1000, while low-end storage lasers cost as little as \$1. The resulting average price of a semiconductor laser is around \$9.

While 358 million units may sound impressive, it is insignificant as compared to the 50 billion LEDs produced annually. However, with an average cost much less than that of a laser diode (approximately \$0.06 each), the total LED market is around \$3.2 billion. As mentioned earlier, relentless decreases in cost are a characteristic of our industry. Bear in mind that the silicon IC industry generates impressive annual revenues of \$150 billion by fabricating transistors that have a unit cost on the order of one-millionth of a cent.

Another way of looking at the economics of optoelectronics is in terms of "real estate". The \$3.7 billion in revenues generated by semiconductor laser sales can be produced using substrate areas measured in hundreds of square meters, while the \$3.2 billion generated by the less expensive LEDs require in excess of 5,000 m² of substrate material. However, as shown in Figure 7, the silicon industry needs 40,000,000 m² of substrate to generate its \$150 billion in revenues.

Optoelectronics are at the very beginning of a growth era. It is doubtful that compound semiconductors will ever catch up with silicon, but they will certainly come much closer than they are today. And the Internet will be the engine behind much of the growth.

Currently there are roughly 40 million people in the US having access to the Internet, but only 1.7 million of these users have broadband access. However, in the next 2 to 2½ years, this figure will grow to 18 million, creating an enormous market for optoelectronics. In the near term, the demand for broadband access will increase the demand for optoelectronics in such devices as optical cross-connects, optical switches, optical add-drop multiplexers, tunable lasers, optical amplifiers and optical transceivers. And once broadband starts reaching customers, a trickle-down effect will be felt in other parts of the industry, placing tremendous demands on both storage and imaging.

Solid State Lighting

After the Internet, a next major driving force in optoelectronics will be solid state lighting, using LEDs. The OIDA foresees major activity in this area in the next ten to twenty years.

The annual worldwide lighting market is currently around \$16 billion, and is driven by three dominant lighting sources: incandescent, halogen, and fluorescent. The efficacy of a lighting source is measured by the ratio of optical output power adjusted to the sensitivity of the human eye to electrical input power. It is expected that there will be little to no improvement in the efficacy of incandescent and halogen lights, although the more efficient fluorescent sources still have slight room from improvement. But with solid state LED-based lighting, we can easily anticipate a light source with an efficacy which is 2X better than

Comparison of Semiconductor Markets			
Component	Revenue (\$ B)	No. of chips per year	Semiconductor area (m ²)
Semiconductor Lasers	3.7	360 Million	100*
LEDs	3.2	50 Billion	5,000*
Silicon ICs	150	285 Billion	40,000,000

Figure 7. A comparison of the substrate "real estate" required to generate the total market revenue of three different semiconductor markets. Clearly, the laser diodes generate far greater value per unit substrate area than LEDs or silicon ICs. [*Approximate area assuming 100% yield].

the best fluorescent sources, and 10X to 15X better than halogen or incandescent lights. Tremendous savings in energy costs will result - perhaps as much as 50% [see Figure 8]. As a result, it is possible that we would not have to build any new power plants in the next 30 years.

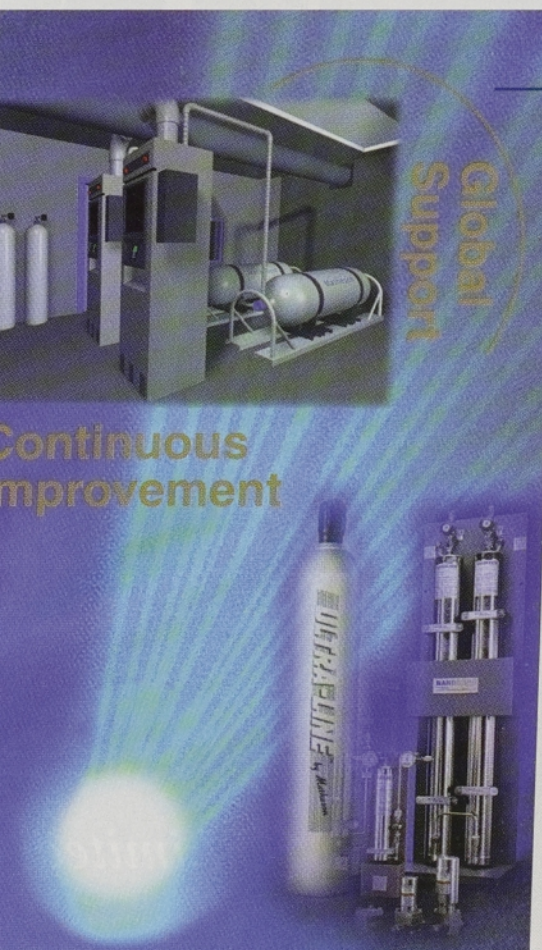
Further down the road, the OIDA sees the possibility of a fundamental paradigm shift, in that many new opportunities

Potential Impact of LED Lighting				
Potential Savings in One Year		US	ROW	Global
Dollar Savings	\$ Billions	35	75	110
Electricity Savings	TeraWatt Hours	350	750	1100
Avoidance of CO ₂ Emissions	Tons (Millions)	95	210	310

Figure 8. LED lighting could have a huge impact on the consumption of energy and on CO₂ emissions. The figures represent the potential savings in 2025, assuming that solid state lighting achieves a 50% market penetration.

unfold through the integration of optoelectronics with various other technologies such as electronics, optics and microelectromechanical systems (MEMS). It is quite conceivable that most of the devices that we produce in optoelectronics can be mounted on silicon. And that really is a paradigm shift in all the market segments, including even the simplest one, in lighting, opening the door to what might be called "smart lighting".

But while these tantalizing prospects are still somewhere in the future, the Internet is here with us today. Broadband access will grow explosively over the next five to ten years, and it will be the primary driving force for optoelectronics components.



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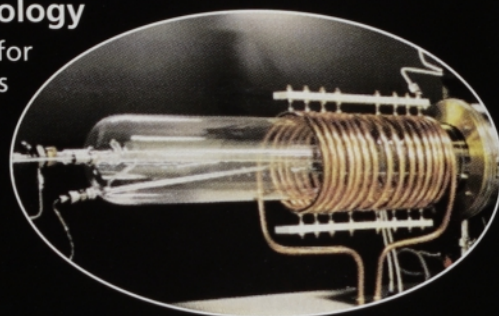
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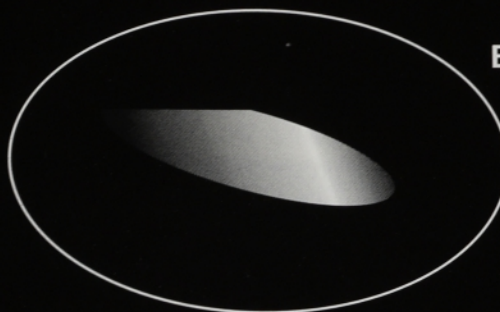
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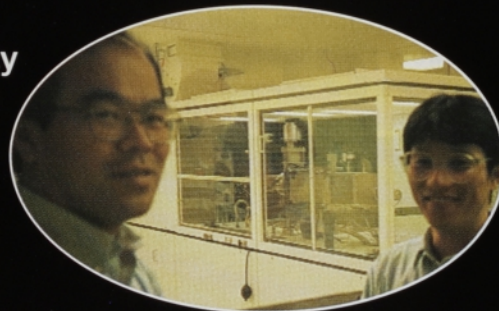
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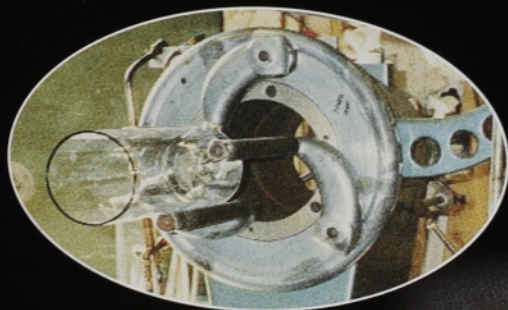
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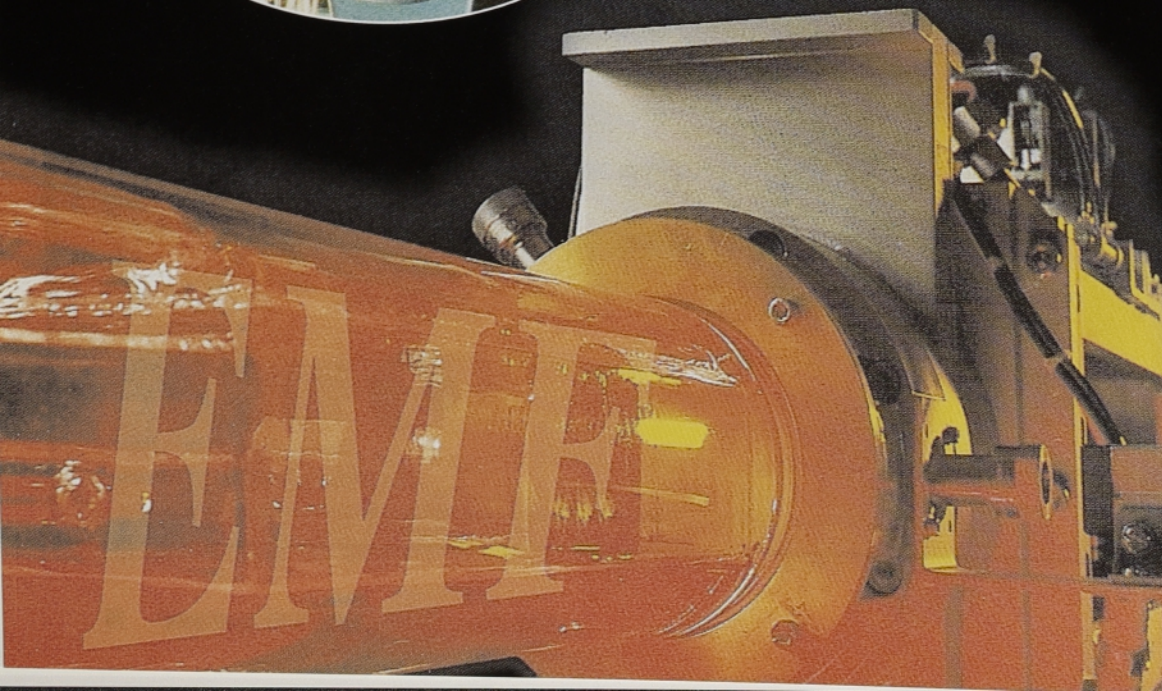
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GaAs Optoelectronic Integrated Circuits for Datacommunications

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*Presented at the Key Conference on Compound Semiconductors
Key West, Florida
March 13-14, 2000*

The recent explosive growth in the Gigabit Ethernet datacommunications market has been driven by the rapid proliferation of local area networks (LANs) in the business community. As network traffic has increased, the LAN component of the network, which often runs at 10 Mbps when operating in the Ethernet mode, or 100 Mbps in the Fast Ethernet mode, has become a major bottleneck to overall network speed. As a result, Gigabit Ethernet has been developed for high speed 1.25 Gbps communications, increasing network speed by a factor of 10-100 over the earlier standards.

A block diagram for a typical Gigabit Ethernet transceiver system is shown in Figure 1. The system front end requires a photodiode for receiving the optical input, a laser or LED for transmitting an optical output, and analog ICs consisting of a low noise transimpedance amplifier (TIA) and high gain post-amplifier on the receiver side, along with a driver circuit to operate the output laser/LED. The back end of the transceiver is comprised of digital ICs that handle the data using Serializer/Deserializer (SerDes) and Encoder/Decoder circuits. The transceivers used in the local area interface cards in LAN applications also have many applications in switches, routers and hubs.

GaAs has long been the semiconductor of choice for optical devices due to its direct bandgap, which allows for efficient generation of photons by LEDs or laser diodes, as well as in the conversion of photons into electron-hole pairs needed for detectors. Its 1.42 eV bandgap allows for efficient operation and emission at 850 nm, which is the most commonly used wavelength for short-distance communications applications. Also, the high speed electronic capabilities of GaAs, whether implemented through the use of MESFETs, PHEMTs or HBTs, should enable greater levels of integration than would be possible in any other

Gigabit Ethernet Datacommunications

- 1.25 Gbps transmission rates at 850 nm wavelength up to 550 m
- IEEE 802.3z standard

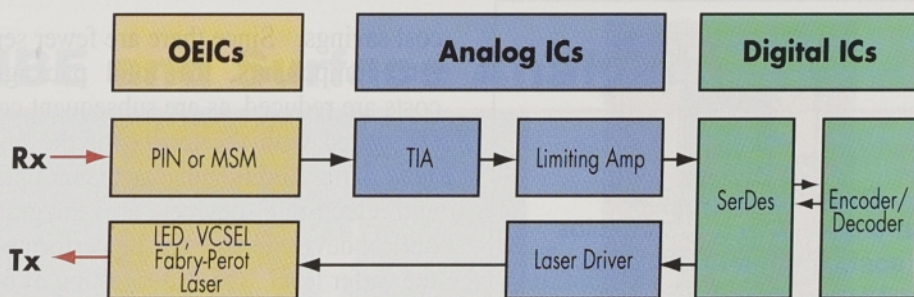


Figure 1. Block diagram of a typical Gigabit Ethernet transceiver.

material system. This feature is just now being exploited, and it opens up exciting prospects. Because Gigabit Ethernet systems demand both high bandwidth analog capabilities as well as high-speed digital capabilities, significant transceiver performance improvements can be had by the direct integration of optical and electronic components within the transceiver.

Performance and Cost

A major advantage derived from integrating the optical and electronic functions into a single die is the elimination of the additional capacitances that would be introduced from the bond wires connecting different die. In addition, matching circuitry and buffering elements that are typically required between die can be eliminated. An example of this integration approach is schematically shown in Figure 2 for the case of a MESFET-based transimpedance amplifier (TIA) monolithically integrated with a metal-semiconductor-metal (MSM) detector. A microphotograph

OEIC Monolithic Integration

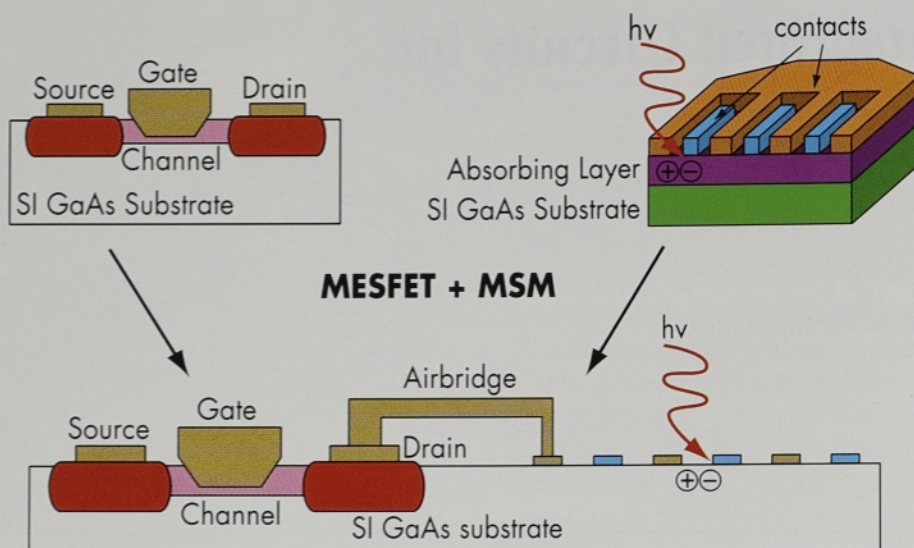


Figure 2. An example of the use of monolithic integration to form an optoelectronic integrated circuit (OEIC). A lateral electronic device, in this case a GaAs MESFET, is integrated with a metal-semiconductor-metal (MSM) photodiode on a semi-insulating GaAs substrate.

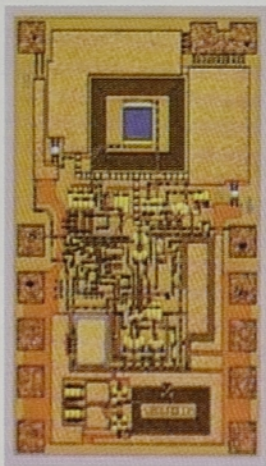


Figure 3. Photograph of an 850 nm OEIC consisting of a MESFET-based transimpedance amplifier (TIA) and a metal-semiconductor-metal (MSM) photodetector. The MSM-TIA has a bandwidth of 1200 MHz, a responsivity of 1300 V/W and dissipates 120 mW of power.

of the MSM-TIA integrated transceiver is shown in Figure 3. Additional integration paths exist in the transmit portion of the transceiver, combining VCSELs and laser drivers on one GaAs IC.

While performance improvement is very important, optoelectronic monolithic integration can also result in significant

cost savings. Since there are fewer separate components, the total packaging costs are reduced, as are subsequent costs associated with the testing of the packaged parts. Additionally, as planar optical and electronic devices are integrated, optical device testing can be performed at the wafer level. On-wafer testing of optical devices can reduce the cost by automating the test process and eliminating the need for costly packaging prior to test. On-wafer testing has allowed for low-cost, high throughput MSM-TIA and VCSEL production, using techniques similar to those employed in high volume electronic semiconductor manufacturing. This approach has resulted in the production of Gigabit Ethernet transceivers with prices below \$100.

The market potential for Gigabit Ethernet transceivers is substantial - as shown in Figure 4, it may approach \$450 million by 2003. But Figure 4 also assumes that substantial price reductions can be accomplished. It is anticipated that further component integration will allow full on-wafer transceiver functionality testing, which in turn will further reduce testing and packaging costs, helping to continue to drive down the cost of the transceivers.

Circuitry

Thus far, integration of commercially available Gigabit Ethernet transceivers has been limited to the front end. It has taken the form of horizontal integration of an MSM photodiode with a transimpedance amplifier, operating at 850 nm and 1.25 Gbps, as shown in Figure 3. Power supply requirements for Gigabit Ethernet have migrated down to the 3.3 V level in order to reduce power consumption. As a consequence, the low voltage power supplies used typically do not supply sufficient voltage to operate the depletion mode circuits used in the analog portion of the transceiver. To overcome this problem, a GaAs-based DC-DC negative voltage converter capable of generating up to 4 volts is included in the transceiver to drive the analog circuitry. This converter is designed with an oscillator frequency in the 4-10 GHz range, which is well out of the Gigabit Ethernet band, thereby reducing interference. At the same time this also allows the use of smaller on-chip capacitors which in turn reduce die size.

Future Prospects and Challenges

Improvements in transceiver performance and the further lowering of cost will come about as GaAs IC fabrication migrates from MESFET-based devices to higher performance PHEMTs or HBTs. In addition, the transition from 4" to 6" GaAs substrates will help lower the cost per die, as well as permitting the fabrication of larger circuits and higher levels of integration. As performance is increased and costs drop, we expect to see Gigabit Ethernet usage move quickly from the system level and into the desktop regime.

While currently limited to horizontal integration, the use of vertical integration of front ends will permit the fabrication of more compact circuits that will enable the fabrication of transceiver arrays and small-form-factor packages. In addition, we expect to see networks moving toward longer wavelengths, making them more compatible with long distance fiber-based telephone transmission systems operating at 1310 nm. Such a wavelength will require more sophisticated epitaxial capabilities, requiring a bandgap smaller than

that of GaAs. This can be achieved by using either strained InGaAs (In>35%) layers in photodiodes grown on GaAs substrates, or fabricating the transceiver on InP substrates, which will permit the growth of alloys with bandgaps compatible with 1310 nm operation. We believe this migration to InP-based Gigabit transceivers will represent a substantial manufacturing challenge.

While many of these improvements will address cost issues, they will also result in performance improvements, which is of critical importance. Demand for Gigabit Ethernet products has already been pushed into the 2.5 Gbps regime with upward of 40% of demand already at this higher data rate. And we expect that commercial 10 Gbps Gigabit Ethernet applications will appear in the not-too-distant future. Thus it appears that another high volume market is emerging for GaAs circuits.

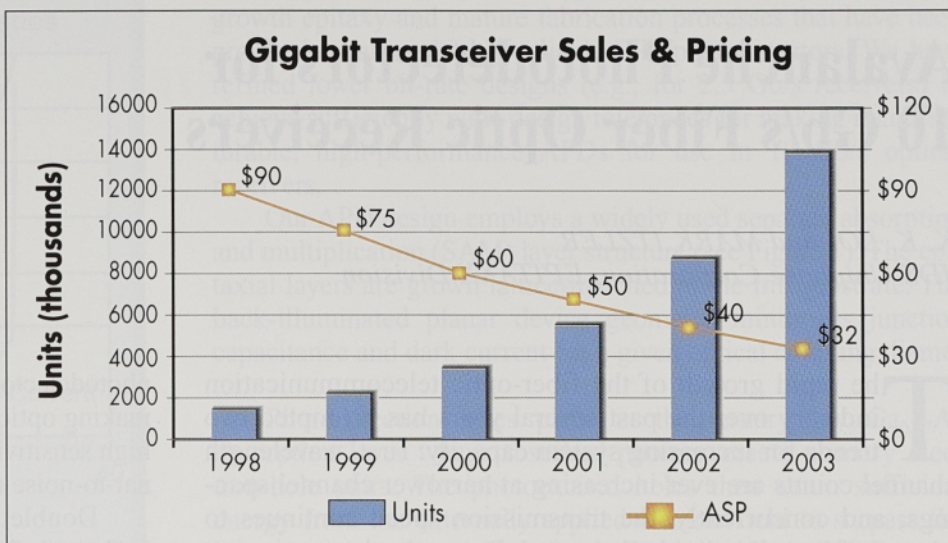


Figure 4. Gigabit Ethernet transceiver market volume forecast, together with the predicted trend for average selling price (ASP). Component integration will allow full on-wafer transceiver functionality testing, which in turn will further reduce testing and packaging costs, helping to continue to drive down the cost of the transceivers.



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Avalanche Photodetectors for 10 Gb/s Fiber Optic Receivers

K. K. LOI and MARK ITZLER

JDS Uniphase Corporation, EPITAXX Division

The rapid growth of the fiber-optic telecommunication industry over the past several years has prompted two trends for increasing system capacity: first, wavelength channel counts are ever increasing at narrower channel spacings; and concurrently, the transmission speed continues to increase for each individual channel. Presently, the continuing demand for bandwidth by both end users and optical network providers poses an imminent need for widespread deployment of dense wavelength division multiplexed (DWDM) fiber links operating at standard OC-192/STM-64 data rate. The successful deployment of each new generation of DWDM transmission systems is directly tied to the availability of suitable optoelectronic components. Component manufacturers are coping with this enormous market opportunity by quickly introducing advanced products with performance tailored to the specific needs of 10 Gb/s applications.

The digital optical receiver is an indispensable component in fiber-optic telecommunication links since it enables conversion of data from the optical to the electrical domain. High-capacity transmission systems supporting data rates of 10 Gb/s and higher impose stringent requirements on receiver performance parameters such as sensitivity, bandwidth, transimpedance, group delay, return loss, and overload power. High-responsivity, low-noise

photodetectors are pivotal in making optical receivers with high sensitivity and good signal-to-noise ratio (SNR).

Double heterostructure InGaAs/InP positive-intrinsic-negative (PIN) photodiodes are commonly used in 10 Gb/s receiver modules. The photocurrent of a PIN detector is primarily governed by its inherent quantum efficiency, and at best, each incident photon can generate a single electron-hole pair to contribute to the total photocurrent.

Avalanche photodetectors (APDs) provide an elegant solution to circumvent the quantum limitation of the PIN detector. An avalanche multiplication region with high electric field intensity is incorporated in the APD layer structure, where injected primary charge carriers accelerate and generate additional electron-hole pairs through impact ionization. The average number of electron-hole pairs resulting from each absorbed photon is referred to as the multiplication gain M , and the total photocurrent of an APD is larger by a factor of M than that of a PIN diode with comparable absorption properties. Although the statistical variation of the avalanche process inevitably introduces stochastic

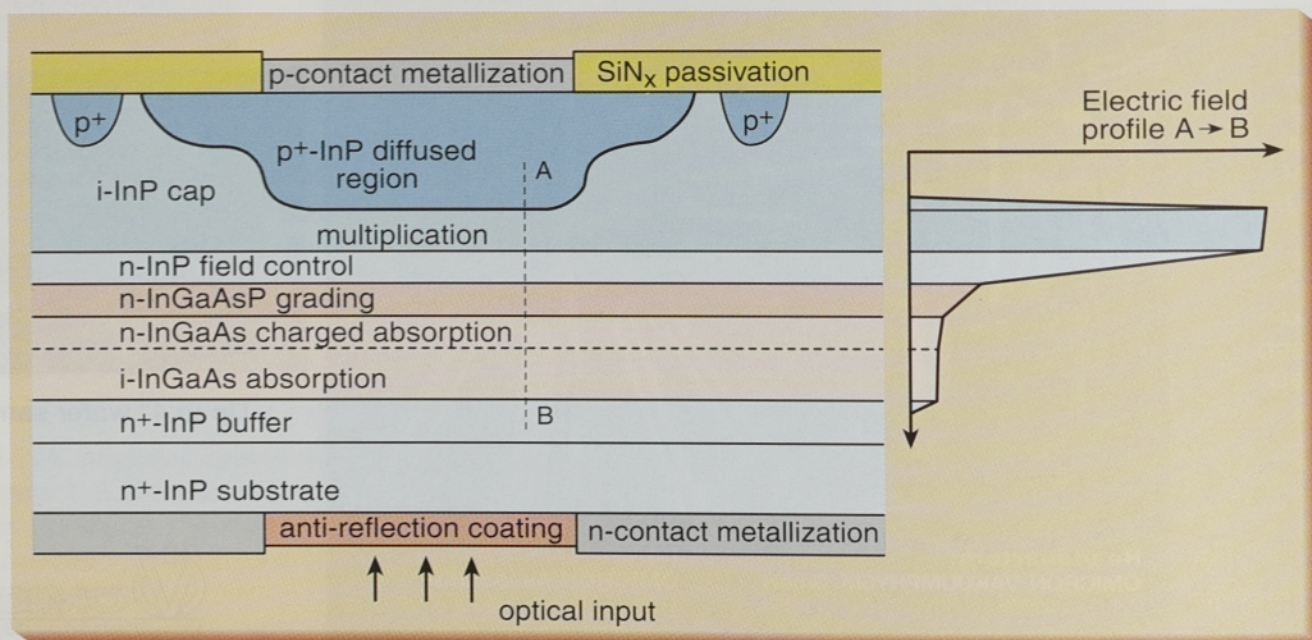
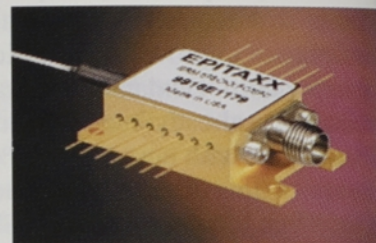


Figure 1. Passivated planar avalanche photodiode structure and electric field profile. A doped field control layer maintains high electric field in the multiplication layer and low field in the absorption layer.

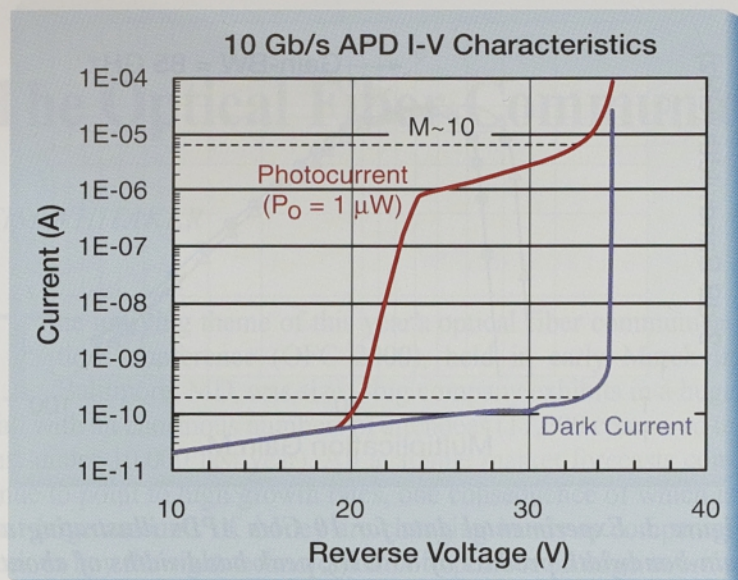


Figure 2. Experimentally measured APD photocurrent (with 1 μW illumination at 1550 nm) and dark current as a function of reverse voltage bias. Dashed lines indicate photocurrent and dark current values for an operating bias corresponding to a gain of 10.

tic gain fluctuations, the noise resulting from these gain variations will be irrelevant as long as it is not the dominant noise source. At high frequencies, increased pre-amplifier noise is unavoidable, and this amplifier noise will dominate the APD noise for at least modest APD gains (e.g., gains less than 15). Therefore, in a well-designed high-frequency optical receiver, the internal gain of the APD can provide a substantial improvement in signal-to-noise ratio (SNR), and consequently optical sensitivity, relative to canonical PIN photodiode-based receivers. APDs provide optimum performance when the APD noise is comparable to the amplifier noise, and for InP-based APDs this occurs for gains ranging from 10 to 15. The associated improvement in receiver sensitivity can be as large as 10 dB, depending on design and bit rate.

APD Device Design

High-reliability 10 Gb/s InP-based APDs are challenging to design and fabricate reproducibly. Specifically, APDs have historically been plagued by the difficulty in controlling premature avalanche breakdown at the edge of the device where electric fields tend to be enhanced by p-n junction curvature effects. Edge breakdown is detrimental since it can result in a highly non-uniform gain profile across the active region. Advanced technologies such as second-step epitaxial regrowth, mesa etching, superlattice structures, ion implantation, resonant cavities, and the combination of Zn and Cd diffusions have been investigated by various researchers and optoelectronic component suppliers in developing high bit-rate APDs for use at telecommunications wavelengths from 1300 to 1620 nm.

Recently, we have made substantial progress in the development of planar InGaAs/InP APDs suitable for high bit-rate appli-

cations [1]. Our design strategy has pursued the use of single-growth epitaxy and mature fabrication processes that have been proven in making highly reliable PIN photodetectors. We have refined lower bit-rate designs (e.g., for 2.5 Gb/s receivers) to achieve sufficiently wide design tolerances for making manufacturable, high-performance APDs for use in 10 Gb/s optical receivers.

Our APD design employs a widely used separate absorption and multiplication (SAM) layer structure (see Figure 1). The epitaxial layers are grown lattice-matched to the InP substrate. The back-illuminated planar device geometry minimizes junction capacitance and dark current for a given optical coupling diameter.

Photodetection takes place in the ternary $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ absorption layer where absorbed photons create primary electron-hole pairs. The photoexcited holes then attain sufficient energy from the externally applied electric field to surpass the heterojunction potential barriers and traverse the bulk InP multiplication region. Moderately doped InGaAsP grading layers are embedded between the InGaAs absorption and InP field control layers to avoid hole pile-up which would otherwise occur at the ungraded InGaAs/InP heterointerface. An appropriate amount of integrated charge is incorporated in the InP field control layer to support a sufficiently high electric field in the InP multiplication region for generating avalanche gain and also to maintain a low field in the InGaAs absorption region to avoid deleterious tunneling effects.

The p-n junction is formed by closed-ampoule Zn diffusions through a patterned SiN_x passivation layer. This standard Zn diffusion process is identical to that already used in making high-reliability PIN diodes. The recessed junction profile is shaped using a two-stage Zn dopant diffusion technique. The multiplication width is wider at the device periphery, yielding a higher breakdown voltage compared to that of the central thinner multiplication region. In order to further reduce surface field intensity at the edge of the device, an annular floating guard ring is introduced surrounding the device periphery. This shaped junction profile coupled with the simultaneously diffused floating guard rings effectively controls edge breakdown. The front-side annealed AuZn p-contact metal also functions as a partial reflector which increases the quantum efficiency to yield at least 0.7 A/W responsivity at unity gain.

Performance and Reliability Characteristics

High-quality single-growth epitaxial material, well-established fabrication processes and wide design tolerances contribute to good consistency of performance over the radius of two-inch wafers. Total dark currents are on the order of 1 nA for an operating gain $M \sim 10$, capacitances are about 0.2 pF, and breakdown voltages vary by less than ± 1.5 V over the inner 40 mm diameter of the wafer.

[1] M. A. Itzler, K. K. Loi, S. McCoy, N. Codd, and N. Komaba, *Proc. 25th OFC 2000*, Vol. 4, p. 126–128, paper FG5(2000); M. A. Itzler, K. K. Loi, S. McCoy, N. Codd, and N. Komaba, *Proc. 12th LEOS '99*, Vol. 2, p. 748–749, paper ThK0005 (1999).

Figure 2 displays the dependence of APD photocurrent (with 1 μ W illumination at 1550 nm) and dark current on reverse voltage bias. The multiplication gain M is related to measured photocurrent I by the expression $M=I/(R_1 P_0)$, where R_1 is the responsivity at $M=1$ and P_0 is the incident optical power. The data in Figure 2 were obtained from an APD with $R_1 = 0.7$ A/W. Photocurrent measurements indicate typical gain values of 50 when operated at a bias that gives 100 nA of dark current. Occasional devices reach a maximum gain in excess of 200. Two-dimensional gain contours exhibit reasonably small gain fluctuations of less than $\pm 5\%$ across a 22 μ m effective coupling diameter even beyond typical operating gains. This good gain uniformity combined with the ability to reach high gains provides direct evidence of good edge breakdown control.

Figure 3 illustrates the experimentally measured electrical bandwidth of two typical devices as a function of gain. Peak 3-dB bandwidths reach 10 GHz. There is an inherent trade-off between high gain-bandwidth product (G-BW) and turn-on of high bandwidth at low gain. The right-hand curve in Figure 3 exhibits a G-BW of 95 GHz and attains high bandwidths for $M \geq 4$. The left-hand curve shows a lower G-BW of 85 GHz accompanied by a lower turn-on gain of $M \sim 3$. It is desirable to achieve high bandwidth turn-on at lower gain because this renders a larger dynamic range by accommodating a wider optical input power range within the saturation limit of the pre-amplifier.

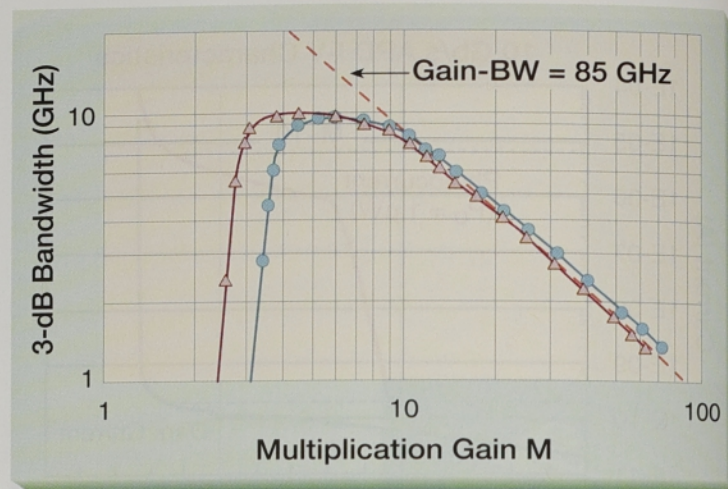


Figure 3. Experimental data for 10 Gb/s APDs illustrating a gain-bandwidth product of 85 GHz, peak bandwidths of about 10 GHz, and high bandwidths at gains as low as $M \sim 3$. At low gains, bandwidth is limited by incomplete depletion of the active absorption region. At moderate gains, bandwidth is independent of gain and limited by the carrier transit time or RC effects. At high gains, speed is limited by the avalanche multiplication time, imposing a constant gain-bandwidth product.

Reliability performance has been studied using hermetically sealed devices burned in at 200, 225 and 250°C. Cumulative failures at different temperatures exhibit similar slopes, and an activation energy of at least 1.4 eV is estimated. These lifetime results indicate that these 10 Gb/s APDs have reliabilities comparable to simple PIN photodiodes with failure rates well below 1 FIT

(failure in time per 10^9 hours) at 40°C operating temperature. Furthermore, this reliability performance is also consistent with similarly designed 2.5 Gb/s APDs, which exhibit a mean lifetime of 10,000 hours when burned in at 200°C.

Finally, 10 Gb/s hybrid integrated receiver modules have been assembled using these high-performance APDs together with various pre-amplifier ICs (e.g., GaAs HEMT and SiGe HBT transimpedance amplifiers). A dynamic range of at least 23 dB has been experimentally obtained, which is attributed to the APD's capability of achieving high bandwidth (≥ 8 GHz) over a wide range of gain ($3 \leq M \leq 10$). Bit-error-rate (BER) measurements performed with a pseudo random bit sequence of $2^{31} - 1$ NRZ signals reveal a back-to-back sensitivity of better than -27 dBm at 10^{-10} BER. This represents a significant sensitivity improvement of at least 5 to 6 dB over similar receivers based on PIN photodiodes.

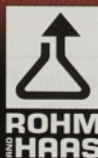
The impact of enhanced receiver sensitivity and dynamic range grows in importance as the complexity and channel density of WDM systems increase. The relatively inexpensive increase in optical link power budget afforded by the use of APD-based receivers gives system designers greater flexibility, and the development of these important building blocks for next generation fiber optic networks has been enabled by the recent availability of high-performance commercial 10 Gb/s APDs.

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The Optical Fiber Communications Conference (OFC 2000)

TIM WHITAKER

The unifying theme of this year's optical fiber communications conference (OFC 2000), held in early March in Baltimore, MD, was size – big company exhibits in a huge hall with an enormous numbers of attendees (17,000 compared to just under 10,000 last year). All available market forecasts continue to point to high growth rates, one consequence of which is that large amounts of money are changing hands as companies seek to buy the right technology mix to provide an edge in critical areas such as optical networking. A number of stands had signs saying "A JDS Uniphase company" while at least two independent conference exhibitors (Xros and CoreTek) will shortly become part of Nortel Networks (see page 8).

In terms of technology, a number of trends were evident. The 10 Gb/s market is accelerating very rapidly, with many vendors introducing source lasers, detectors and ICs (see page 55).

Additionally, suppliers are addressing ways to bring 10 Gb/s transmission from the long-haul market into metro applications by introducing lower cost transceivers, and are even using VCSEL technology to develop 10 Gb/s links for distances as short as 300 m. The widespread introduction of 40 Gb/s transmission systems is still at least two years away, but product development is well underway.

The move towards all-optical networks [see CS 6(1), p. 80] is creating a huge level of interest. The biggest buzz at OFC was created by Agilent's optical switching technology, reflecting the huge potential of this market. Nortel's recent acquisitions of Qtera, Xros and CoreTek were all motivated by the need to acquire valuable optical networking technologies.

These areas, along with other critical components including tunable lasers, VCSELs, and 980 nm pump lasers, are discussed below.

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Tunable Lasers

Tunable lasers that can operate at any one of a wide range of transmission wavelengths are in great demand to reduce the number of separate parts that make up a DWDM system. As well as inventory reduction, tunable sources may also be in demand for sparing, optical add-drop multiplexers, and fast packet switching. Tunable laser specialist **Altitud AB** was exhibiting both its grating coupler sampled reflector (GCSR) laser [see CS 5(6), p. 32] and a tunable DBR chip. **JDS Uniphase** was also showing its 3-section DBR tunable laser while **CoreTek**, which has a tunable VCSEL product, was one of two companies purchased by Nortel after OFC.

Alcatel launched a broadband CW tunable laser module in an industry standard butterfly package, covering 32 channels with 50 GHz spacing with an output power of 10 mW. It is a two-section DBR laser with a buried ridge structure. According to Alcatel, the device will cut DWDM system spare parts costs by a factor of 10.

Lucent Technologies announced a 10-channel tunable transmitter for both short- and long-haul 2.5 Gb/s optical networking systems. The C489 transmitter packs a highly integrated single-chip 1.5- μ m DBR laser, booster amplifier, photodetector, and electroabsorption modulator. It also features built-in patented LambdaLock spectral stabilization which "locks" the laser emission to any of ten adjacent 50 GHz channels, providing stability better than 20 pm.

Nortel Adds Automation, 10 Gb/s Parts

Nortel Networks is targeting substantial growth in its optoelectronics business this year assisted by a \$660 million investment, much of which will be used to add to the company's components capabilities. A key theme is automation – Nortel is automating its components manufacturing end-to-end, as part of its on-going strategy to increase optical component production, especially for 10 Gb/s parts.

"We are experiencing strong global market pull for 10 Gb/s DWDM components," says John Pittman, managing director of Nortel Networks' optoelectronics division. "In today's market, process automation innovations are just as important as new product technologies." Nortel fabricates ICs and optoelectronic chips at its facilities in Ottawa, Canada and packages these into modules in Paignton, UK. Key areas of automation at the Paignton facility are chip test, precision optical alignment, package lidding, silicon board population and wire bonding.

At OFC, Nortel announced several innovative optoelectronic modules targeted at 10 Gb/s applications, including a tunable laser module containing a GaAs modulator, an integrated laser-modulator with built-in wavelength stabilization and VOA, and an APD-preamp module.

Nortel and **Marconi** demonstrated a 10 Gb/s tunable laser module combining Nortel's tunable laser, an Etalon wavelength locker, and Marconi's GaAs modulator. The tunable emitter offers 20 channels on a 50 GHz grid, and is based on a 3-section DFB laser [see CS 5(6), p. 30]. Marconi also exhibited its own tunable laser source.

40 Gb/s Transmission

A number of companies were demonstrating systems and components for the next generation of long haul networks. **Alcatel** demonstrated a 40 Gb/s system featuring 16 channels with 200 GHz spacing. **Corning Lasertron** and **Picometrix**, a privately held developer of ultrafast products, announced the availability of prototype samples a new 40 Gb/s InGaAs pin photodetector.

Hitachi showed a prototype 40 Gb/s transmission system fabricated using SiGe ICs, and has also built a similar system using InGaAs/InP HBT-based ICs. The transmitter had two 20 Gb/s input channels and consisted of a 2:1 MUX IC, a flip-flop IC and a modulator driver IC, together with a modulator and CW laser.

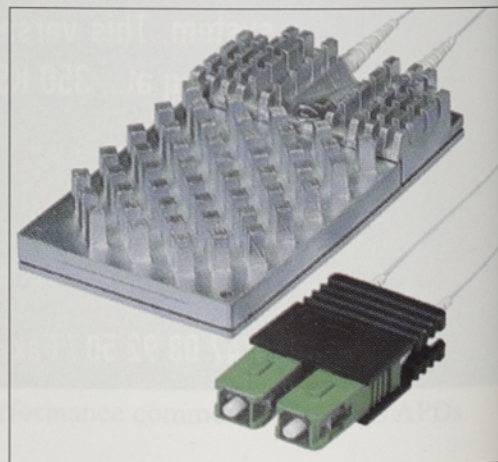
Marconi Technologies were showcasing a range of 40 Gb/s products, including tunable lasers, GaAs modulators, and receiver modules combining photodiodes and 40 GHz travelling wave GaAs MMIC amplifiers. **CyOptics** unveiled its InP-based pulse generating laser and electroabsorption modulator products [see CS 6(2), p. 10].

10 Gb/s Transceivers

As 10 Gb/s systems become more widely deployed in short reach metro networks, system providers are seeking lower cost compact transceivers incorporating multiple components. **Alcatel**, **Lucent** and **Hitachi** announced a multisource agreement for 10 Gb/s transceivers incorporating serializer/deserializer (SERDES) functionality. The agreement specifies a small package, common footprint, a wide range of 10 Gb/s optical characteristics and common electrical interfaces at 622 Mb/s. Several standards were specified from short reach/intra-office links of less than 2 km to long haul links up to 80 km in length.

Toshiba launched a range of 10 Gb/s receiver, transmitter and transceiver modules, while **Mitsubishi Electronics** launched 2.5 Gb/s transmitter and receiver modules for metro applications in the 15-60 km range, utilizing uncooled DFB lasers and APD detectors.

Infineon announced what was described as the industry's smallest 10 Gb/s



transponder, designed to link high-end routers to metro networks over distances up to 10 km. The transponder contains a directly modulated, uncooled DFB laser and utilizes SiGe ICs to achieve a low power consumption of only 6 W. The absence of a thermoelectric cooler results in a package size of only 3 x 1.6 x 0.6 inches (75 x 42 x 15 mm – see photo).

Amplifiers

To increase the penetration of fiber in the metro and short reach markets, lower cost amplification is required. Fortunately, the power requirements of amplifiers in such networks are much lower than in long haul systems.

Alcatel announced a compact optical amplifier measuring 70 x 95 x 12.5 mm, designed for use in single-channel branches of metro systems, pre-amplifiers for 10 Gb/s systems, and for loss compensation in optical cross-connects and other optical networking elements. The amplifier, which uses customized 980 nm pumps, provides either 10 or 15 dBm (10 or 31 mW) output power.

E-TEK Dynamics launched what was described as the industry's first EDFA designed specifically for the metro market. The module offers low noise (5 dB) and high gain (20 dB) in the 1530-1560 nm window. The output power is only 10 mW, although higher power is available. The module contains a single 980 nm pump laser and measures 99 x 61 x 3 mm.

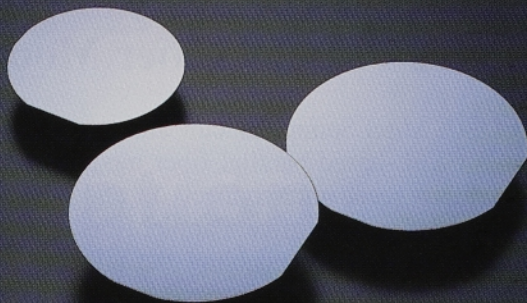
980 nm Pump Lasers

Announcements regarding 980 nm pump lasers and modules at OFC were characterized by the emergence of new vendors and a general increase in output power.

ADC Telecommunications announced the availability of its high-power 980-nm pump laser diode and module. These products, ADC's first active optical components, were enabled by the acquisition of Spectracom in June 1999 [see CS 5(6), p. 6]. The company manufactures both laser chips and modules at its facility in White Bear Lake, MN. The 980 nm pump laser products comply with the required Bellcore GR-468-CORE reliability testing protocol, with initial results that exceed industry requirements. ADC utilizes a unique patent-pending epitaxial mirror on facet (EMOF™) technology that virtually eliminates catastrophic optical mirror damage (COMD). Additionally, the EMOF process allows ADC to batch process their 980 nm laser diodes, thus greatly increasing production throughput and capacity.

Corning Lasertron launched a new generation of 980 nm pump laser modules capable of producing up to 300 mW of fiber-coupled power. The company has also begun volume production of its OptiLock™ wavelength-stabilized pump laser, offering 90-200 mW of power. The modules incorporate Bragg grating stabilization to provide a fixed, narrowband, stable spectrum over a wide range of operating powers and temperatures. "We are extremely pleased to be shipping our new OptiLock pump in volume to several long haul and metropolitan system manufacturers," says David Nislick, VP of marketing.

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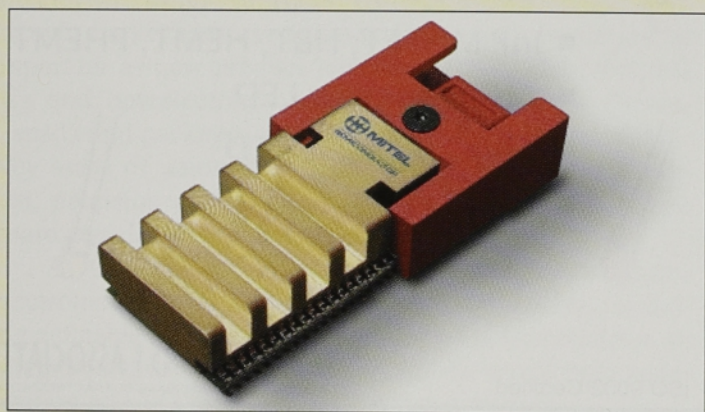
At OFC, Mitel Semiconductor announced its 623-family of VCSEL-based parallel fiber modules for short- and medium-reach interconnects in and between network equipment in the central office. Parallel fiber modules improve channel cost and density, enabling the all-fiber architectures that will displace the current interconnect scheme made up of conventional copper and single-channel fiber optic links.

The new modules are transmitters and receivers with 4, 8 or 12 channels, capable of operating at 2.5 Gb/s per channel, which provide 10, 20 or 30 Gb/s respectively over a distance of up to 300 m. VCSEL arrays for the transmitter contain 4 devices in a linear configuration - for a 12-channel transmitter, three such arrays are mounted side-by-side. "We need only consider uniformity and yield for a four-channel chip, rather than for a monolithic 12-channel chip as used by our competitors," explains Olof Svenonius, product line manager for parallel fiber modules at Mitel Semiconductor. "This gives significant advantages in overall cost and link performance - we can offer a tighter optical power specification and hence higher minimum launched optical power. We also get the flexibility to build 4, 8, and 12-channel parts using the same building blocks."

"The VCSELs for the 2.5 Gbps products use the proven ion-implanted technology," adds Olof Svenonius. "However, oxide-confined VCSELs will be required for higher bit rates and Mitel is therefore actively pursuing developments in this area."

Manufacturability is an important feature of the modules, which incorporate Mitel's patented Smart OSA technology. This significantly improves fiber coupling, as well as simplifying the assembly of optical interconnects. The 623-family is designed to fit existing, fully automated assembly lines. "Our vision is to make modules that are as easy as ICs for customers to work with," says Olof Svenonius. "We have removed the need for manual assembly steps and the specialty equipment required for high-performance fiber optics, which means further cost reductions and faster time to market."

Mitel is collaborating with other manufacturers to create a range of complementary products, including serializer/deserializer (SERDES) ICs from AMCC, and fiber connectivity systems from Tyco Electronics and US Conec.



Mitel Semiconductor

Coherent has delivered the first prototypes of its optically pumped semiconductor (OPS) device, which produces 500 mW of fiber-coupled power at 980 nm in a non-telecom-qualified package. The device consists of a VCSEL-like structure in which the cavity is formed by the rear DBR mirror and an external front mirror [see CS 5(3), p. 35]. Coherent has successfully reduced the package size to be consistent with current EDFA pumps and is now focusing on producing a telecom-qualified package.

E-TEK Dynamics introduced a 220 mW pump laser module, which has been qualified at 100°C for 50 hours. Current lifetime data exceeds 5,500 hours.

JDS Uniphase introduced a new 980 nm pump module incorporating the current high-reliability G05 series laser chip to achieve optical output powers in excess of 250 mW. Output powers of 350 mW are expected in the second half of 2000, by inclusion of the new G06 series laser chip in the module. The company states that proven high-reliability assembly technology enables high-coupling efficiency and stable optical output power, and allows the design to be utilized in submarine as well as terrestrial telecommunications systems.

Mitsubishi Electronics announced a 250 mW pump laser capable of operating at up to 70°C. The device has an optimized ridge waveguide structure, and employs a window structure that widens the bandgap to reduce the power absorption of the active layer at the facet. As a result, the power limit is limited by thermal saturation rather than by COMD. The device has operated reliably at a high output power level for over 10,000 hours. Samples will be available in April with volume production commencing in the third quarter of 2000.

SDL announced a new generation of 980 nm pump modules providing up to 300 mW of output power. The SDLO 2700 series utilizes SDL's new 6540 chip that has operated at over 500 mW, in combination with an advanced fiber-coupled package with reduced dimensions that has greatly improved thermal performance. The new 6540 chip is specifically designed to operate with SDL's patented fiber Bragg grating. The modules are available now in sample quantities, and production quantities are expected in the second half of 2000.

VCSELs

A number of VCSEL-based products were on display at OFC. Both **Emcore's** **MODE** division and **Honeywell Microswitch** were showing 850 nm VCSELs with oxide-confined structures, operating at 2.5 Gb/s. Emcore stated that the new devices offer higher speeds, lower threshold current and greater uniformity than its previous generation of ion-implanted devices. The new devices are available as bare die or can be built into TO-cans or optical sub-assemblies.

Infineon was demonstrating the latest 2.5 Gb/s per channel version of its 12-channel parallel optical link (PAROLI™) module, featuring 12-device arrays of oxide-confined VCSELs in the transmitter.

Targeting similar applications in parallel data links, **Anadigics** announced a 12-channel MSM (metal semiconducting)

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10 Gb/s Very Short Reach (OC-192 VSR) Fiber-Optic Links

Data traffic continues to grow at an explosive pace, and leading Internet service providers report bandwidth on their backbones is doubling every 6-9 months. One consequence of this growth is that service providers are demanding low-cost, standard interfaces for interconnecting equipment within the central office or Point-of-Presence (POP). Links that interconnect core routers, or that connect these routers to the optical transport network terminals, are now being installed with a capacity of 10 Gb/s. All this equipment is typically located in the same building, so most of these links are less than 400 meters; one service provider said that 75% of its intraoffice interconnects are less than 100 m long.

However, the only standardized 10 Gb/s interfaces are SONET/SDH serial interfaces designed for wide-area networking and long-haul systems, which have extremely high component costs. To address this problem, a group of components suppliers and system vendors are developing an OC-192 parallel optical interface based on the use of VCSEL technology (see Figure 1). As shown in Figure 2, the cost of these parallel links will remain significantly lower than serial links, until the next-generation short-reach OC-192 serial interface is developed and defined.

The very short reach (VSR) OC-192 parallel optical interface is being promoted within the Optical Internetworking Forum (OIF) by a group of 15 companies. At OFC, **Cisco Systems** was demonstrating a system employing VCSEL arrays manufactured by **Gore**, together with a converter IC developed by **Conexant**. Other companies involved in the OIF proposal include **Infineon**, another supplier of VCSEL-based parallel optical modules; **Vitesse**, another manufacturer of converter ICs; and **Ciena**, which was showing products (router-to-router and router-to-network connections) incorporating OC-192 VSR technology at OFC.

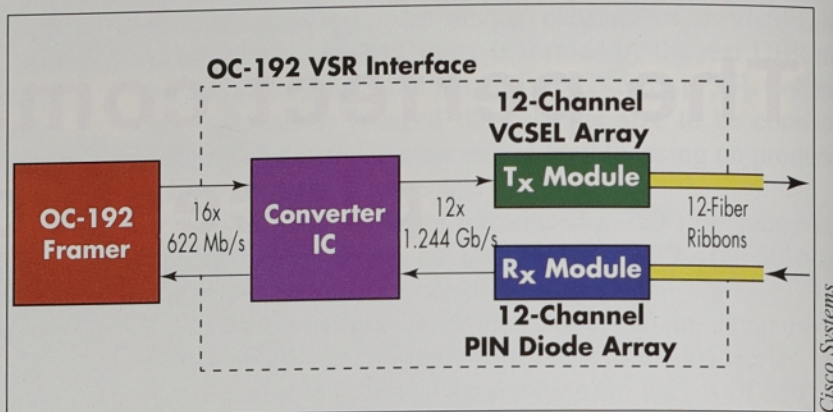


Figure 1. Functional block diagram for the OC-192 VSR interface. The optical source is a VCSEL array providing 12 data channels at 1.25 Gb/s, which are transmitted at 850 nm over a 12-fiber parallel ribbon. The receiver contains a 12-detector array. Also required is a converter IC which converts between the standard interface from an OC-192 framer (16 channels x 622 Mb/s) and the 12-channel x 1.25 Gb/s format required for transmission over the parallel fiber links.

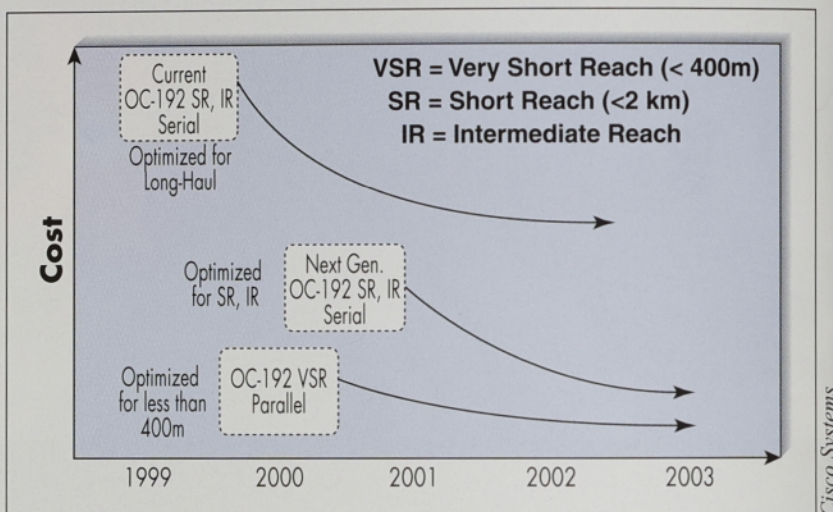


Figure 2. Cost trends for OC-192 interface technologies.

ductor metal) photodetector array for use in 850 nm applications up to 3.125 Gb/s.

Gore demonstrated a working prototype of its nLighten™ module incorporating 12-channel VCSEL arrays delivering up to 1.5 Gb/s per channel. This product was utilized in Cisco's very short reach (VSR) 10 Gb/s system demonstrator (see box).

Gore also presented the first public demonstration of its 1310 nm single mode VCSEL operating at 2.5 Gb/s over a distance of 25 km. The laser, fabricated using innovative wafer bonding techniques [see CS 5(3), p. 26], features a narrow spectral width and low beam divergence for improved optical coupling, as well as stable performance characteristics over temperature.

New Focus (Santa Clara, CA) introduced VCSEL-based transceivers for 10 Gb/s serial links. The products use 850 nm

VCSELs purchased from external vendors and are targeted at very short reach (<300 m) and central office interconnect applications, as well as 10 Gigabit Ethernet.

Optical Networking

Qtera, the developer of ultra-long-haul photonic networking systems purchased by **Nortel Networks** for \$3.25 billion, announced its long-awaited first product. ULTRA is a 10 Gb/s backbone that supports transmission over a distance of 4000 km without optoelectronic regeneration [see CS 6(1), p. 82]. At OFC, Qtera demonstrated 10 Gb/s transmission of 56 DWDM channels over a distance of 3600 km. Today's long-haul 10 Gb/s systems require opto-electronic regeneration every 600 km. The Qtera

technology promises dramatically reduced capital and operating costs, simplified network architectures, rapid wavelength provisioning and tremendously greater bandwidth compared to today's optical networks. Qtera and **GTE Internetworking** (a unit of GTE, one of the world's largest telecommunications companies) announced field trials of a Qtera system on GTE's Atlanta to Washington D.C. route. The system will carry multiple 10 Gb/s channels over 1550 km without opto-electronic regeneration.

Agilent Technologies' paper value rose by an incredible \$12 billion following the company's announcement of its new optical switching technology based on reliable inkjet and planar lightwave circuit (PLC) technologies. The photonic switching platform includes a 32 x 32 port photonic switch and a dual 16 x 32 port photonic switch, and several industry leaders are already integrating the platform into carrier-class network elements. The switches re-direct light without the help of mirrors or any other moving parts. It is composed of a vertical and horizontal array of permanently aligned waveguides, and light is transmitted across a horizontal path from the input to output port. When a switch command is issued, a bubble is created at the intersection of the appropriate waveguides and the light is reflected down a vertical path to the switched port. This bubble is formed using the same reliable technology now used in inkjet printers.

Profile – Multiplex Inc.

Multiplex is a vertically integrated manufacturer of photonic components based in South Plainfield, NJ. Founded in 1998, the company has 15,000 sq. ft. of manufacturing space, including facilities for MOCVD growth, device processing, module packaging and testing. Further expansion to add an extra 20,000 sq. ft. is currently underway. Products include high power 980 nm pump laser modules, electroabsorption modulator lasers (EMLs) and high speed photoreceivers.

At OFC, Multiplex exhibited 980 nm pump laser chip-on-submount products offering up to 280 mW kink-free output power. The InGaAs/AlGaAs MQW laser is mounted on a SiC submount. The company states that burn-in is performed at a temperature of 100°C, ensuring high reliability. Multiplex has developed a proprietary facet passivation coating, the MX5, which effectively protects the laser facets from catastrophic optical damage (COD). A 980 nm pump module with fiber Bragg grating stabilization is also available, offering up to 220 mW.

Multiplex was also showing 2.5- and 10-Gb/s integrated electroabsorption modulator and DFB lasers (EMLs) and optical receiver modules for operation up to 12.5 Gb/s, incorporating a PIN diode, a low noise TIA and a limiting amplifier. The company is developing a 10 Gb/s tunable EML, consisting of a 3-section DBR laser with gain, phase and Bragg regions, plus an integrated electroabsorption modulator.



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A wide range of new products were announced at the Optical Fiber Communication Conference (OFC 2000). For more news from this show, see page 47.

FIBER-OPTIC ICs

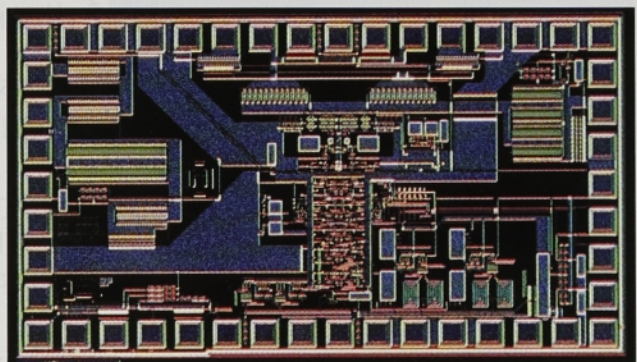
• **Applied Micro Circuits Corp. (AMCC)** introduced the YUKON (S4803), the industry's first single chip OC-48 SONET/SDH framer/mapper with integrated clock recovery (CDR) and clock synthesis (CSU). The company claims that this silicon-based IC offers an unequaled level of integration, a 65% reduction in board real estate compared to existing solutions, reduced design complexity and a significant decrease in power and cost.

• **Conexant** launched a family of 2.5 Gb/s ICs including a transimpedance amplifier (TIA), a programmable laser driver and a high-gain limiting amplifier fabricated using a Si BiCMOS process, together with a laser or modulator driver GaAs HBT-based IC. Several weeks before the conference, Conexant announced a family of OC-192 ICs based on GaAs HBT and SiGe processes [see CS 6(2), p. 72].

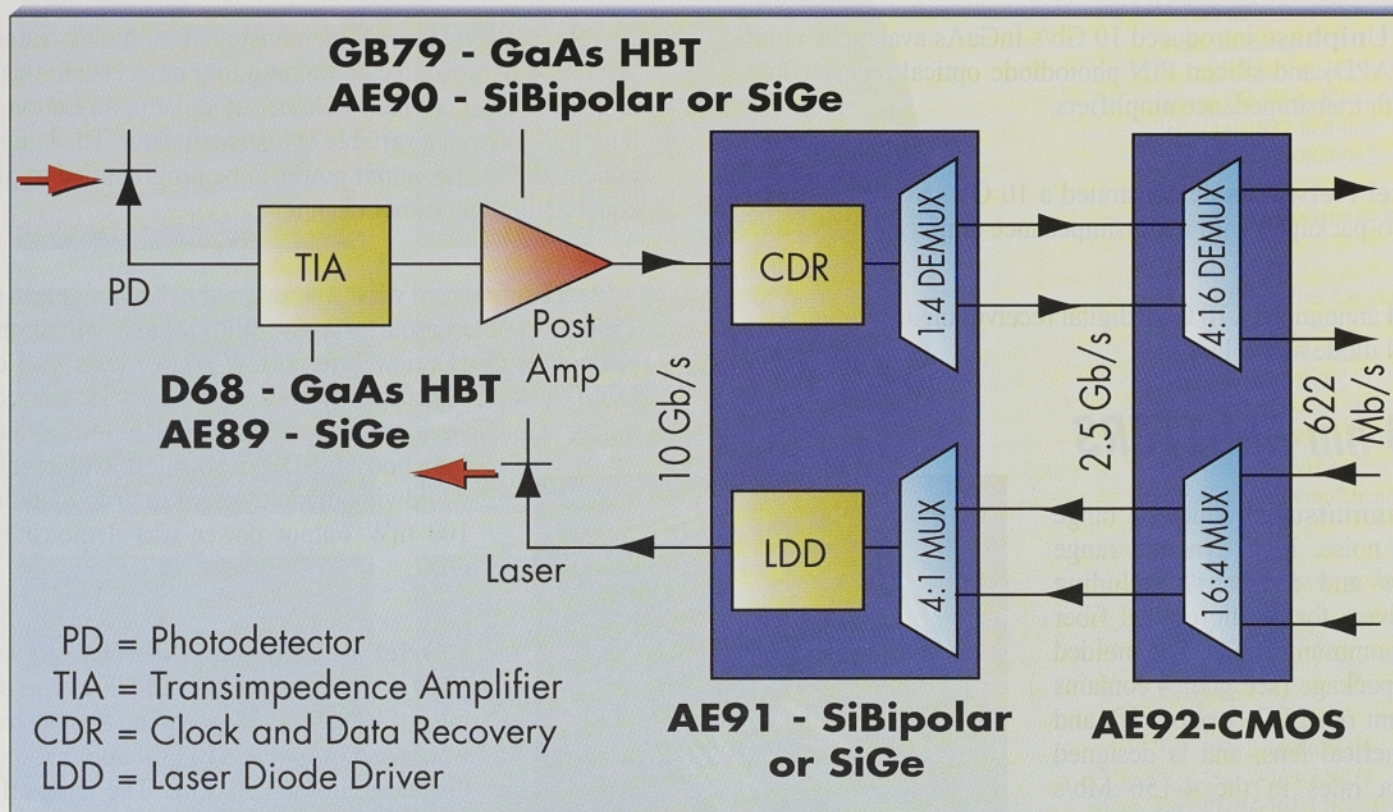
• **Infineon** was offering a complete range of interface ICs, from 100 Mb/s to 10 Gb/s, all fabricated using in-house silicon BiCMOS or SiGe processes.

• **Philips Semiconductors** introduced a range of Si BiCMOS transimpedance amplifiers (TIAs) for 155 Mb/s, 622 Mb/s, 1.2 Gb/s and 2.5 Gb/s applications.

• **Vitesse** introduced ICs comprising a complete line card for OC-192 SONET/SDH systems. The new 10 Gb/s ICs were a laser driver (see photo), a 16:1 mux with clock multiplication unit (CMU), a 1:16 demux with clock data recovery (CDR), and a transport-terminating receiver. The laser driver, mux and demux are GaAs MESFET-based ICs while the transport-terminating receiver is fabricated using a 0.25 μ m CMOS process. For details on Vitesse's technology strategy for 40 Gb/s ICs, see page 7.



Vitesse

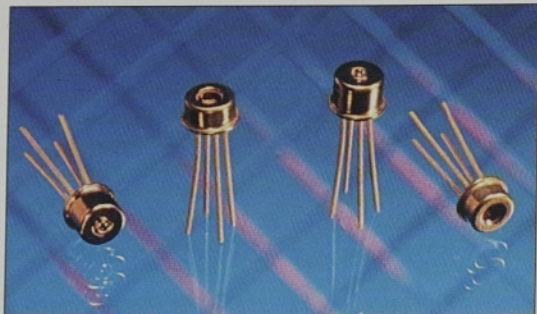


Summary of Nortel Networks' current portfolio of fiber-optic ICs

RECEIVERS

• **Anadigics** introduced the world's first high-speed integrated fiber optic datacom receivers with patented automatic data control. The new products combine a 2.5 Gb/s detector together with a PHEMT-based pre-amplifier and are designed for operation at

850 nm and 1300 nm, for applications such as 2X Fibre Channel and the emerging 2.5 Gb/s Infini-band fiber optic networks.



Anadigics

• **Corning Lasertron** announced the availability of samples of their 10 Gb/s PIN-based receiver.

• **Discovery Semiconductors** introduced the DSC R405, a balanced photoreceiver with 15 GHz bandwidth. The device offers a typical responsivity of 120 V/W with 12 dB gain.

• **Ericsson Microelectronics** released an optical receiver front-end module for WDM applications up to 3 Gb/s. The PGR 20312 combines an avalanche photodiode (APD) and a wideband linear GaAs MMIC pre-amplifier in a 14-pin butterfly package. A version with a PIN diode receiver is also available.

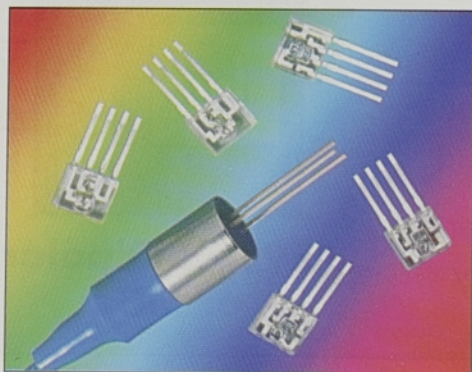
• **JDS Uniphase** introduced 10 Gb/s InGaAs avalanche photodiode (APD) and silicon PIN photodiode optical receiver modules with transimpedance amplifiers.

• **Nortel Networks** demonstrated a 10 Gb/s avalanche photodiode co-packaged with a transimpedance amplifier.

• **Ortel** announced a 10 Gb/s digital receiver incorporating a planar PIN diode and a TIA.

650 nm EMITTERS

• **Hamamatsu** introduced a range of low noise, high dynamic range emitters and receivers, including transceivers for plastic optical fiber (POF) communications. The molded plastic package (see photo) contains a 650 nm red LED, a photo IC, and non-spherical lens, and is designed for data rates in the 4-156 Mb/s range.



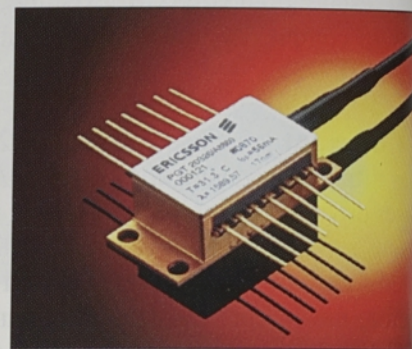
Hamamatsu

SOURCE LASERS

• **Alcatel** released a 40 mW strained layer MQW laser chip for operation with an external modulator, together with a 20 mW laser module for 2.5 Gb/s direct modulation applications. The company also announced an integrated laser-modulator for 2.5 Gb/s systems operating in the L-band (1570-1610 nm).

• **Corning Lasertron** introduced a second generation 2.5 Gb/s directly modulated DFB laser module for metro and access networks with up to 10 mW output power across C- and L-bands (1528-1605 nm).

• **Ericsson Microelectronics** announced an L-band DFB laser monolithically integrated with an electroabsorption modulator for 2.5 Gb/s transmission over distances of up to 480 km.



• **JDS Uniphase** introduced a 10 Gb/s electroabsorption modulated laser (EML) for single channel applications in short- and intermediate-reach systems.

• **Nortel Networks** demonstrated a highly integrated laser/modulator source combining four devices into one module: a CW laser, a Mach-Zehnder modulator, an Etalon wavelength locker and a variable optical attenuator. The latter component allows the output power to be programmed to provide equalization with other channels.

• **Ortel** announced what was claimed to be the highest power 1550 nm DWDM source laser. "With 80 mW minimum output power, Ortel's new Inferno CW source laser will enable OEMs to add functionality to their product by overcoming higher signal losses, and in some cases will eliminate the need for a booster EDFA," says Jeff Rittichier, VP of worldwide marketing. An Inferno module with 100 mW output power was demonstrated at OFC.

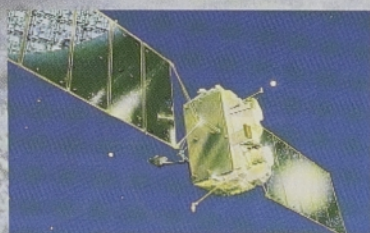
• **Ortel** also introduced the Daytona laser, a 1310 nm directly modulated DFB laser operating at 10 Gb/s and designed for metro networks and drop-side DWDM applications over distances up to 50 km. The cost-effective Daytona has an output power of 4 mW.

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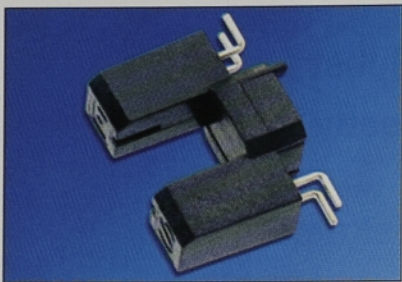
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OPTO DEVICES

Osram SMT Reflective Sensors

Regensburg, Germany. Osram Opto Semiconductors has unveiled a new family of surface mount (SMT) reflective sensors employing its TOPLED technology. These are available in transistor output versions (SFH9201, 9202) and diode output (SFH 9220), in addition to 660 nm red emitter (SFH 9260) and Schmitt trigger (SFH9240/41). Working at an optimum spacing of between 1 and 5 mm, these flat, epoxy encapsulated sensors are useful for monitoring position, motion, speed and rotation in various applications including printers, faxes, video-recorders and diskette drives.



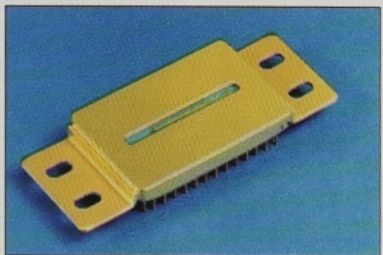
Osram Opto

Fiber-Coupled Laser Diode from Coherent

Santa Clara, CA. Coherent Semiconductor Group has introduced the 'F-Package' System - a microprocessor-controlled, large-core optical-fiber laser diode system operating in the wavelength range from 650-980 nm. The integrated module eliminates the need for external thermal management and plugs directly into standard wall sockets. A 0.5 m fiber couples the single-stripe laser diode, which delivers 0.2-2.5 W depending on configuration. Including all drive and TEC electronics, the module weighs just 4.0 kg. Diodes are interchangeable to allow different wavelengths for applications as diverse as soldering, epoxy curing, medical therapeutics, graphic arts and pumping solid-state laser media.

DWDM Wavelength Monitor from Sensors Unlimited

Princeton, NJ. Sensors Unlimited has introduced a 512-pixel InGaAs photodiode array designed for spectral monitoring in DWDM systems with 25 GHz and 50 GHz channel spacings. The LY Series contains a linear InGaAs array with 512 pixels on a 25- μ m pitch, in combination with a low noise CMOS multiplexer.



Sensors Unlimited

WIRELESS

Enhancement/Depletion Mode Devices from M/A-COM

Lowell, MA. M/A-COM has introduced the first products based on its new enhancement/depletion mode (E/D) process (see page 16). The MD59-0021 is a fully integrated LNA/ downconverter IC with LNA, RFA, downconverter floating FET mixer, IFA and LO buffer. Key attributes include a low noise figure, high input intercept point and optional control of LNA IP3. The MD59-0022 is a fully integrated upconverter/driver featuring an IFA, upconverter mixer, 2 stage driver and LO buffer. Both products are designed for digital PCS applications and operate on a single 2.7 V supply.

Anadigics PHEMT Switches with Integrated Decoder

Warren, NJ. Anadigics has unveiled a new line of GaAs integrated SP4T (single pole, quadruple throw) antenna switches with internal decoders. These 3 V PHEMT switches simplify digital and analog multi-mode, multi-band cellular handset designs by integrating logic control and RF band and mode selection. The new switches include the AWS5509S17 tri-band SP4T switch for GSM, DCS, and PCS operation and the AWS5510S20 dual-band SP4T switch for AMPS/TDMA 800 and AMPS 1900 handsets.

In addition to reducing component count and eliminating interconnects, these single supply switches exhibit a low insertion loss (0.4 dB typical for the AWS5510S20), high isolation (better than 20 dB between all ports), and low harmonics (better than -65 dBc). The devices feature +2.7 V, DC CMOS-compatible control and have no negative voltage requirements.

TriQuint CDMA Tri-Mode Receiver Chipset

Hillsboro, OR. TriQuint Semiconductor has released a set of four RFIC receive chain ICs. Housed in SOT23-8 packages, these chipsets will allow handset designers true tri-mode CDMA (IS-95 standard) operation, in addition to applications at similar wavelengths for pagers, WLAN, or base station equipment.

Operating with single 3 V supplies, the chipset consists of two LNAs and two down-convert mixers (each in cellular or PCS frequencies). The TQ3131 and TQ5131 are LNAs operating in the 869-894 MHz range with typical gain and noise figures of 13 and 1.4 dB. The TQ3631 and TQ5631 are 1930-1990 MHz downconverters that typically supply a gain of 15.0, noise figure of 5.7 dB and IP3 input of +1.0 dBm.

RFMD Introduces 3 V LNA, Linear PA

Greensboro, NC. RFMD has developed a LNA with a high dynamic range designed for CDMA, TDMA PCS and W-CDMA/CDMA2000 applications. Manufactured with RFMD's GaAs HBT process, the RF2364 functions as a front-end device, with the ability to set the bias current externally. Featuring a single 3 V supply, 19 dB of gain and a low noise and high intercept point, the LNA includes a power down feature that can be used to completely turn off the device.

The company's new RF2162 linear amplifier IC, targeting 3 V handheld systems, is designed for use as the final RF amplifier in dual-mode CDMA/AMPS digital cellular equipment. This GaAs HBT-based device features a 50 ohm input, 29 dBm linear output power, 29 dB linear gain and 35% linear efficiency.



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Midwave-Infrared Semiconductor Lasers

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Naval Research Laboratory

While III-V semiconductor lasers emitting in the midwave-infrared (mid-IR) region of the electromagnetic spectrum, defined here as wavelengths between 3 μm and 5 μm , are immature compared to their near-IR counterparts, they are nonetheless advancing at a rapid pace. This is being driven in part by the race to develop a convenient (i.e. portable and non-cryogenic) laser source for chemical sensing. Most chemicals in gas phase have "signature" mid-IR absorption lines that are spectroscopically narrow and orders of magnitude stronger than the overtone features in the near-IR. Once inexpensive mid-IR diode lasers displaying the required levels of performance finally become available, we may expect them to find use in a wide variety of contexts such as atmospheric pollution monitoring, leak detection, chemical process control, auto-exhaust monitoring, drug detection, and military-base clean-up. Other potential applications include range finding, IR illumination, IR countermeasures, and laser surgery.

A key requirement for most of the envisioned mid-IR systems is continuous-wave (cw) emission. In order to take full advantage of the inherent compactness of diode lasers, practicality excludes the use of cryogenic liquids or heavy closed-cycle refrigerators. Ambient-temperature operation is therefore ideal, although thermoelectric cooling (with a device temperature of at least ≈ 240 K) would be feasible in many of the planned scenarios. While 1–10 mW of cw output power is adequate for most chemical sensing systems, other applications will need 100–500 mW or more. Spectroscopic detection will also require wavelength purity, i.e., lasing in a single optical mode, and the ability either to tune the lasing wavelength or to provide several fixed frequency sources with excellent stability.

Lead Salt and Quantum Cascade Lasers

The oldest mid-IR diode technology, and for years the only one to be commercially available, is the lead

salt laser. These IV-VI devices have operated up to 333 K in pulsed mode [1], and their maximum cw temperature of 225 K is the highest for any electrically injected mid-IR laser [2]. However, since the lead salts are more susceptible to damage and have lower thermal conductivities than III-V materials, cw output

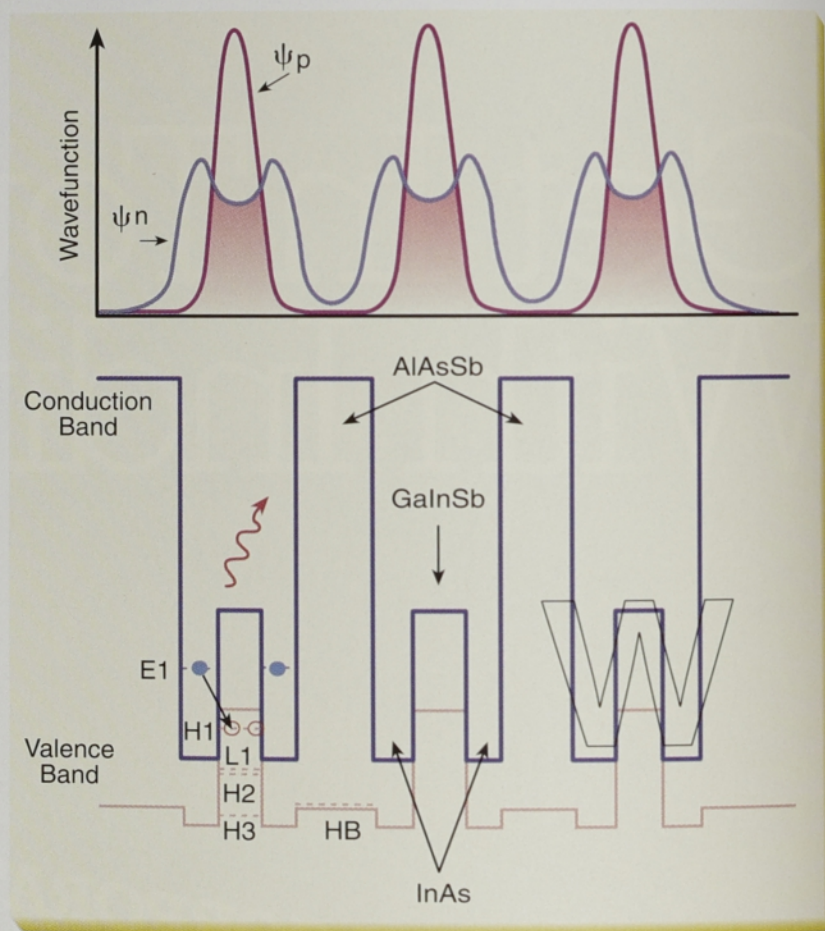


Figure 1. Conduction and valence band profiles, energy levels, and wavefunctions for the three periods of an InAs/GaInSb/InAs/AlAsSb "W" laser. The electron and hole subbands are marked as follows: E1 – first conduction subband, H1, H2, H3 – first, second, and third heavy-hole subbands associated with the GaInSb well, L1 – first light-hole subband, HB – heavy-hole subband associated with the barrier layer.

powers are typically ≤ 1 mW even for 77 K operation. Under pulsed optical pumping, IV-VI vertical-cavity surface-emitting lasers (VCSELs) have quite recently operated up to 289 K at $\lambda = 4.5$ μm [3].

InGaAs/InAlAs/InP and GaAs/AlGaAs quantum cascade lasers (QCLs), which employ conduction intersubband rather than interband radiative transitions to achieve gain, are now under intense development as chemical sensing sources [4]. Achievements include ambient-temperature pulsed operation over a wavelength range of 4.6–12 μm [5], and single-mode output with excellent side-mode suppression and up to 100 mW of power (at 80 K) when distributed-feedback devices are fabricated [6]. However, to date the highest cw operating temperature has been 175 K [7]. Extending beyond that to the thermoelectric cooler range will be challenging, due to significant heat-dissipation requirements associated with relatively high threshold current densities in conjunction with operating voltages corresponding to at least the photon energy times the number of cascaded periods.

Type-I and Type-II Interband Lasers

Interband III-V lasers having InAsSb or GaInAsSb bulk or quantum well (QW) active regions with type-I band alignments and spatially direct optical transitions bear the greatest similarity

to the highly successful near-IR diodes. However, the small energy gap substantially boosts the rate of non-radiative Auger recombination, and the most convenient barrier materials often provide inadequate electrical confinement. The result is a rapid increase of the lasing threshold with temperature, which has thus far prevented pulsed operation above 255 K [8]. Cw lasing has been achieved up to 175 K at $\lambda \approx 3.5$ μm , which decreases rapidly with increasing wavelength. Cw output powers have been as high as ≈ 200 mW at 80 K [9, 10].

Antimonide QW structures with a type-II band alignment and spatially indirect optical transitions offer much greater opportunities for custom-tailoring of the electronic states through wavefunction engineering. This leads, for example, to nearly an order of magnitude suppression of the Auger recombination rate [11], accompanied by a similar reduction of the high-temperature lasing thresholds. Preliminary type-II superlattice lasers developed at HRL quickly achieved parity with the type-I devices in terms of maximum operating temperatures for both pulsed (255 K) and cw (180 K) operation [12].

Type-II "W" Lasers

The mid-IR laser development at NRL has concentrated on a more advanced type-II design known as the "W" QW laser [13], which has four layers in each period of the active region

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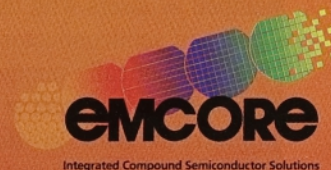
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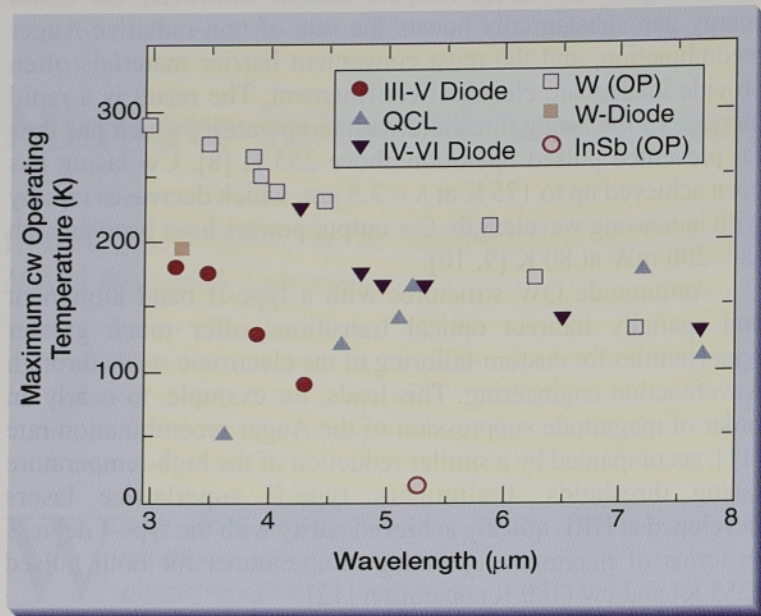


Figure 2. Maximum cw operating temperatures as a function of wavelength in the 3–8 μm range for optically pumped W, W-QW diode, III-V diode, quantum cascade, and IV-VI diode lasers.

(e.g., InAs/GaInSb/InAs/AlAsSb) and takes its name from the shape of the conduction band profile. Figure 1 illustrates that the GaInSb hole QW is bounded by two InAs electron QWs, which are in turn surrounded by AlAsSb barriers. Despite the type-II alignment, the wavefunction overlap (and hence the gain) is significantly enhanced by the second electron well in each period. Other advantages include a two-dimensional density of states for both electrons and holes (due to the high AlAsSb barriers), excellent carrier confinement, and the suppression of Auger recombination mentioned above.

The simplest way to inject electrons and holes to achieve a population inversion for lasing is to pump optically, with a shorter-wavelength laser. Optically-pumped W lasers emitting beyond 4 μm have operated up to 360 K (limited by the maximum dewar temperature) in pulsed mode, and were the first semiconductor mid-IR lasers to achieve cw operation nearly to room temperature (to 290 K) [14]. In fact, cw lasing was achieved at wavelengths as long as $\lambda = 7.1 \mu\text{m}$, which is more than 2 μm beyond any earlier interband III-V device. That demonstration was aided by a novel mounting approach called the diamond pressure bond (DPB) [14], in which the bare epitaxial side of the cleaved semiconductor wafer is mechanically pressed against a diamond heat sink.

Figure 2 compares maximum cw operating temperatures vs. wavelength for a series of optically-pumped and electrically-pumped W lasers with the best results for all of the other major classes of semiconductor mid-IR lasers. At $\lambda = 3.2 \mu\text{m}$, a DPB-mounted optically-pumped W laser produced 540 mW of cw output power per facet at 78 K, which for that temperature is the highest to date in the mid-IR. Other recent work has demonstrated significant improvements in the threshold, internal

loss, and power conversion efficiency using the optical pumping injection cavity (OPIC) approach [15], in which the active region is placed inside an etalon cavity for the pump beam.

Electrically Pumped W-QW Lasers

Electrically pumped mid-IR lasers will ultimately be much more attractive for chemical sensing and other applications because of their potential for extreme compactness, low power consumption, and low cost. One promising approach is the interband cascade laser (ICL), in which multiple photons are generated by each injected electron as in the quantum cascade laser. Because the lasing transition takes place between the conduction and valence bands rather than conduction subbands, the short phonon relaxation lifetime and resulting high current threshold of the QCL are eliminated. High external quantum efficiencies [16,17], pulsed output powers of up to 4 W (at 80 K), and pulsed operation nearly to room temperature (to 286 K, using a W active region) [18] have been achieved. However, growth of the ICL is quite demanding, since numerous periods with many layers in each period must be grown. For the near term, the much simpler W-quantum-well diode [19,20] may be advantageous except in applications where very high output powers are required.

Figure 3 illustrates schematically the conduction and valence band profiles for the W-QW diode laser developed by the team of NRL, Sarnoff Corporation, and Sensors Unlimited, Inc. While injected electrons easily tunnel from one QW period to the next to uniformly populate all the wells, hole transport is known to be

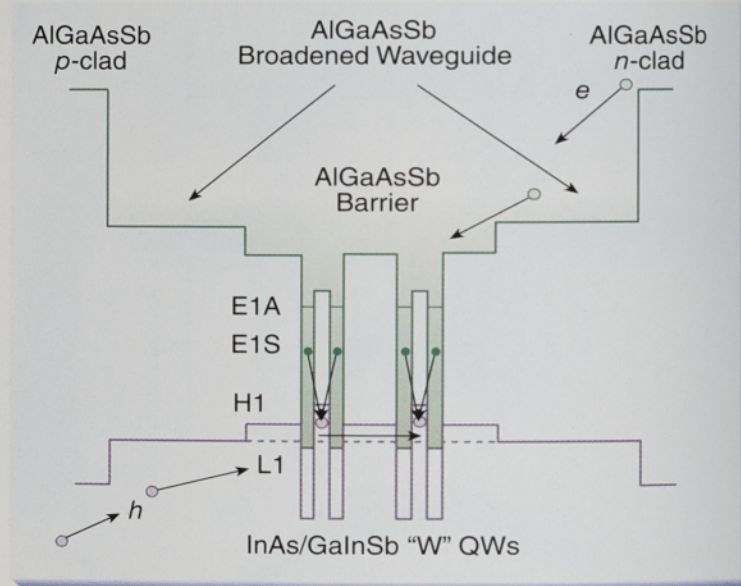


Figure 3. Schematic of the W-QW diode laser with a broadened waveguide. While only two four-constituent periods of the W active region are shown, the tested devices contained either 5 or 10 periods. The electron and hole subbands are marked as follows: E1S and E1A – lower conduction subbands with symmetric and antisymmetric wavefunction profiles, respectively; H1 and L1 – first heavy-hole and light-hole subbands, respectively.

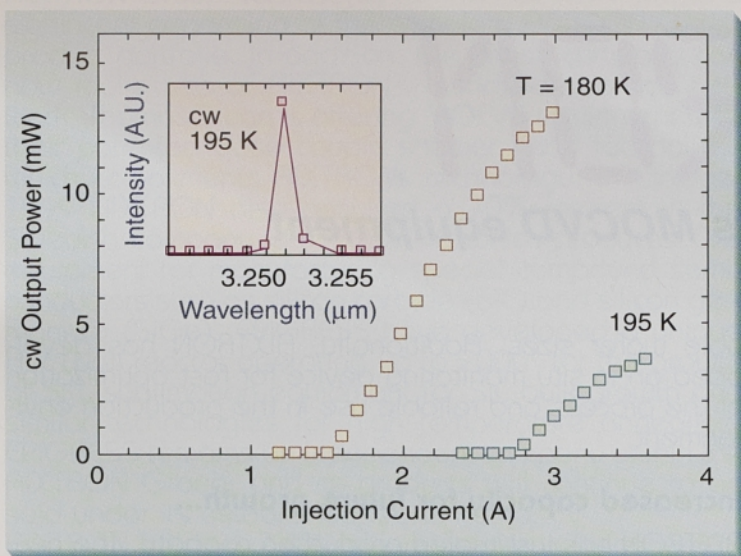


Figure 4. *Cw output power vs. injected current at heat sink temperatures of 180 K and 195 K, for a W-QW diode laser with 5 active periods. The cw spectrum at 195 K, taken at a resolution of 1 nm and an injection current of 3.5 A, is shown as the inset. The cavity length is 2 mm and the stripe is 100 μm wide.*

problematic in type-II QW lasers with large valence band offsets because of the very low tunneling rates for heavy holes. To reduce the valence quantum confinement, the diode structure shown in Figure 3 employs specially designed quaternary AlGaAsSb barriers rather than the AlAsSb barriers used in optically pumped lasers. This raises the L1 subband to within ≈ 100 meV of H1, and allows thermally excited light holes to provide the needed tunneling transport and assure that all of the QWs become populated by injected holes.

Another key design element is the insertion of relatively thick undoped AlGaAsSb separate confinement layers on each side of the active region. By increasing the mode overlap with the waveguide core, this "broadened waveguide" maximizes the optical confinement factor in the active region while minimizing free-carrier absorption losses in the doped cladding layers. Sarnoff recently studied analogous broadened-waveguide lasers with type-I QW active regions that achieved 300 K cw operation at wavelengths as long as 2.7 μm [21].

Pulsed Room Temperature Laser Operation Beyond 3 μm

In pulsed mode, a device with 10 active W-QW periods operated to 310 K at $\lambda = 3.27$ μm [20]. This represents the first room-temperature lasing of any electrically-pumped interband III-V laser at a wavelength longer than 3 μm , a goal that has been pursued by the mid-IR diode community for over three decades. Similar devices with 5 W-QWs operated to 280 K.

The cw performance was superior for the 5-QW structures owing to their lower thresholds associated with the smaller number of periods. The cw lasing threshold was 63 A/cm² at 78 K and increased to 1.4 kA/cm² at $T_{\text{max}} = 195$ K. While the

maximum cw output power of 140 mW at liquid-nitrogen temperature was slightly smaller than the best previous results in the 200–225 mW range, the degradation with increasing temperature was much slower. At 180 K, the highest cw operating temperature for any previous interband or intersubband III-V mid-IR diode laser (see Figure 2), the output power for one W-QW device was still 20 mW. High-temperature cw light-current characteristics for another diode are shown in Figure 4. The inset illustrates that the spectral linewidth was instrument-limited at $T = 195$ K for a current of 3.5 A, where the output power was 3 mW.

At present, these preliminary W-QW diodes are far from optimized. For example, the diode turn-on voltage of 1.5 V at 78 K was several times the design value and the differential resistance (>1 Ω) was also too high. Simulations project that once the thresholds are reduced in structures with fewer active QWs and lower loss, thermoelectrically cooled and even ambient-temperature cw operation should become feasible.

We have attempted to convey in this brief overview that convenient and efficient non-cryogenic mid-IR diodes suitable for use in chemical sensing and many other applications may now be on the horizon.

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...keeping up pace with its MOCVD equipment

AIXTRON is the world's leading manufacturer focusing exclusively on MOVPE and MOCVD equipment for compound semiconductors and ferroelectric or high-dielectric materials. AIXTRON's product range includes production and R&D equipment for p-HEMTs, HBTs, UHB-LEDs (incl. blue and green), laser diodes and space solar cells. Headquartered in Aachen, Germany, AIXTRON has a subsidiary in Chicago and an international service, sales and distribution network with key locations including Los Angeles, Taiwan, Japan, Korea, and China. Since the founding of the company in 1983, AIXTRON has installed over 350 systems world-wide. The most recent development highlights of AIXTRON are captured below...

The technology lead in 6" equipment...

1999 has seen increased purchases of multiwafer 6" equipment, with a technology shift from MBE towards MOCVD due to the fact that today's MOCVD equipment has higher throughput (with 5 x 6" wafers capacity) at lower cost. AIXTRON has a vast backlog of the 5 x 6" AIX 2600G3 systems for HBT/pHEMT, from Kopin, EPI/IFE, Epitronics and others, with Kopin taking delivery of one reactor per month.

The technology lead in III-Nitride equipment...

The same reactor platform is in use by many well known LED companies for the production or development of its blue and green LED products. Manufacturers are increasingly switching from 2-inch wafers to the larger 3-inch wafers. Thanks to AIXTRON's flexible single platform concept, users can fit it to take all avail-

able wafer sizes. Additionally, AIXTRON has developed an in situ monitoring device for fast optimization of the process and reliable use in the production environment.

Increased capacity for future growth...

AIXTRON has just tripled production capacity. The new additional factory for the final assembly of MOCVD equipment concludes the first of three construction phases on a total area of 10,000 m². The expansion allows AIXTRON to manufacture an additional 210 units of equipment per year.

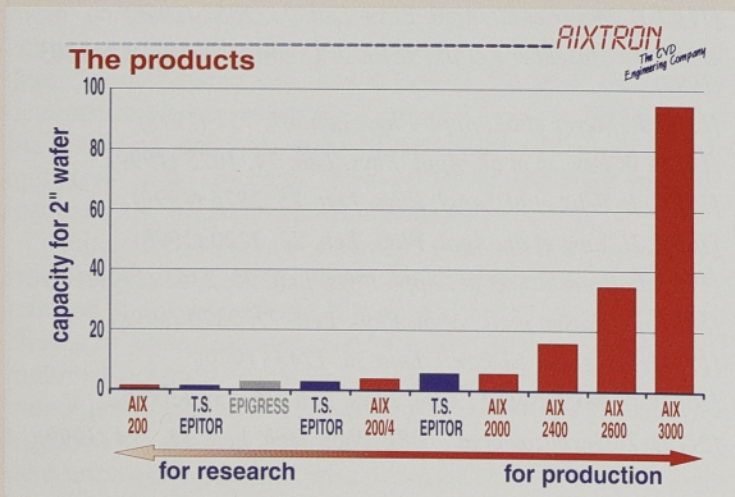
The benefit to the customer is clear: by optimizing the production process and reducing throughput times the delivery times can be drastically reduced from currently 6-8 months to 4-5 months.

1999 Financials confirm strong, profitable growth surpassing all expectations...

That AIXTRON is a rapidly and profitably growing company has been further reflected in the positive financial statement figures for 1999 where revenues rose by 53% to EUR 84.7 million and Group earnings by 92% to EUR 10.4 million. Before goodwill amortization, Group earnings rose by 107% to EUR 11.2 million. AIXTRON achieved a return on sales of 12.3%, (13.2% before goodwill amortization). At the end of the year, AIXTRON's market capitalization amounted to EUR 2.16 billion. Earnings per share amounted to EUR 0.69, or EUR 0.74 before goodwill amortization. AIXTRON's share price climbed from EUR 52.2 to EUR 139.8 – an increase of more than 160%. Since February 1999, AIXTRON shares have also been included in the SEMIndex. Following the resolution of the Annual Shareholders Meeting in May 1999, AIXTRON's share capital was converted to Euros in June 1999 and increased to EUR 15 million in order to round off the resulting fractions. This corresponded to a 1:3 share split and was designed to improve the liquidity of AIXTRON's shares and facilitate new investment or additional purchases. In line with another resolution, AIXTRON increased again its share capital by 3% in November 1999. As a result, the number of AIXTRON shares rose to 450,000.

The Industry Partner with broad portfolio...

The acquisition in September 1999 of Thomas Swan Scientific Equipment Ltd. which is now run as an independent MOCVD equipment manufacturer, within the



AIXTRON Group, represents for the AIXTRON Group a significant expansion of the complete AIXTRON Group product portfolio. In addition, the British company can now make use of AIXTRON's worldwide service network. Thomas Swan is offering MOCVD equipment with their patented close couple shower head technology which compliments AIXTRON's technology. In October 1999 AIXTRON also acquired a 70% interest in the Swedish company EPIGRESS AB which produces CVD equipment for manufacturing special compound semiconductors such as silicon carbide (SiC) and silicon germanium (SiGe). EPIGRESS have developed a unique Hot Wall reactor operating up to 2000° for the growth of SiC, sublimation equipment for SiC bulk growth and similar technologies for high temperature annealing. EPIGRESS remains an independent company within the AIXTRON Group, and its products will continue to be sold under its established brand name.

AIXTRON holds a 7.4% minority stake acquirement of J.I.P.ELEC, France. J.I.P.ELEC offers a unique vaporizer technology as required for the fabrication of oxides.

The AIXTRON pure play policy allows intense customer services...

The acquisition of the two pure equipment suppliers, Thomas Swan Scientific Equipment Ltd., UK, and EPIGRESS AB, Sweden (70%) reinforces the AIXTRON Group's pure play strategy. The AIXTRON Group's pool of current and potential customers has increased substantially thanks to its British subsidiary and its vertical reactor technology. The amalgamation of EPIGRESS's and AIXTRON's technical expertise in the area of CVD equipment for silicon carbide chips will make a key contribution to further expanding the company's leading position on the global market for special compound semiconductors, too. Both companies are pure equipment suppliers and concentrate on their core competency – the development and manufacture of MOCVD equipment. EPIGRESS's equipment allows the AIXTRON Group to further expand its product range, and the acquisition is expected to bring additional synergies in the areas of research & development as well as service and logistics. Focused on the further develop-

ment of SiC production equipment and the creation of custom solutions, EPIGRESS too is a pure equipment manufacturer.

Commitment to the Future: Strengthened Focus on R&D...

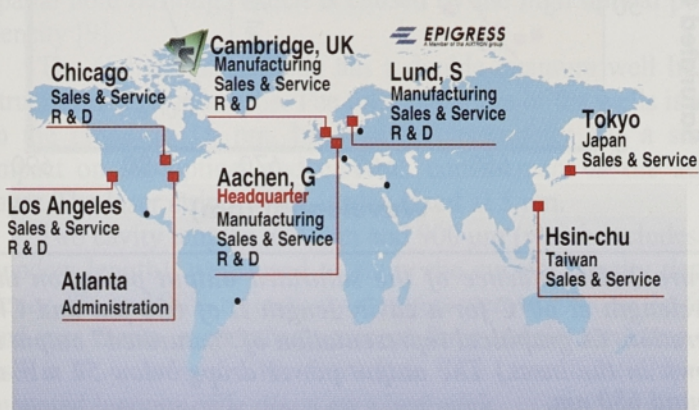
AIXTRON is participating in a large number of national and international projects together with research institutes and industrial partners. AIXTRON is currently coordinating a national project on Nanotechnology. The scope of the project is the improved MOCVD control of blue/green Quantum Dot based lasers. AIXTRON is also participating in many large EU financed projects, for example the HECTOR project aiming at the fabrication of Multilayered Oxides for Silicon Memories.

AIXTRON is focusing on further improvement of the productivity and cost-effectiveness of its processes and equipment, as well as on increasing their flexibility and expanding the range of applications for which they are suited. Last year AIXTRON invested roughly 7% of revenues in application-oriented Research & Development. The focus is on translating material synthesis procedures that have been well-researched and mastered in the laboratory into industrial-strength production processes.

Countless Opportunities in a global market environment...

As the leading supplier of MOCVD equipment and with a global market share of over 50%, which is steadily increasing, AIXTRON provides the key technology needed to manufacture compound semiconductors. The superior process efficiency of AIXTRON's equipment enables users to produce compound semiconductor chips well over 30 percent cheaper than with other manufacturers' equipment. AIXTRON is also a leader when it comes to customer satisfaction: The well-known market research institute VLSI Research Inc. USA, asked 37,000 people from the manufacturing industry and business to rate their suppliers' equipment and customer service. In 1999, AIXTRON took part in this global study for only the second time and was awarded second place. With such a successful history and with such exciting future prospects, AIXTRON has proven itself time and time again as being the no. 1 company offering dynamic and challenging career opportunities for today's and tomorrow's specialists.

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100 mW CW Operation of 650-685 nm Red Lasers for DVD

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At present there is great interest in the commercialization of compound semiconductor-based laser diodes as light sources for DVD systems due to the greater storage capacity of this format compared to CDs. This is in part due to the shorter wavelength of the lasers employed (around 650 nm) compared to those for CD players (780 nm). In addition, "writable" formats are required for DVD-R, DVD-RAM, DVD-RW and high-density MO (magneto-optical) drives. Reliable, high-power red laser diodes with a fundamental spatial mode and an emission wavelength in the 630-690 nm range are therefore very desirable for these high-density and recordable optical data storage systems.

Currently, rewritable DVD systems use medium power laser diodes with a maximum pulse power rating of around 50 mW. But to focus a higher optical power onto the disk, the system

requires a complicated optical pickup with a beam shaping function, which needs a prism with accurate alignment technology. Higher power laser diodes, e.g. up to 100 mW and beyond, are therefore very promising, not only to eliminate the beam shaping function, but also to increase the recording speed.

Window-Mirror Waveguide Design

In order to increase the output power of DVD lasers and at the same time retain reliability, it is necessary to increase the threshold for catastrophic optical mirror damage - the COD level

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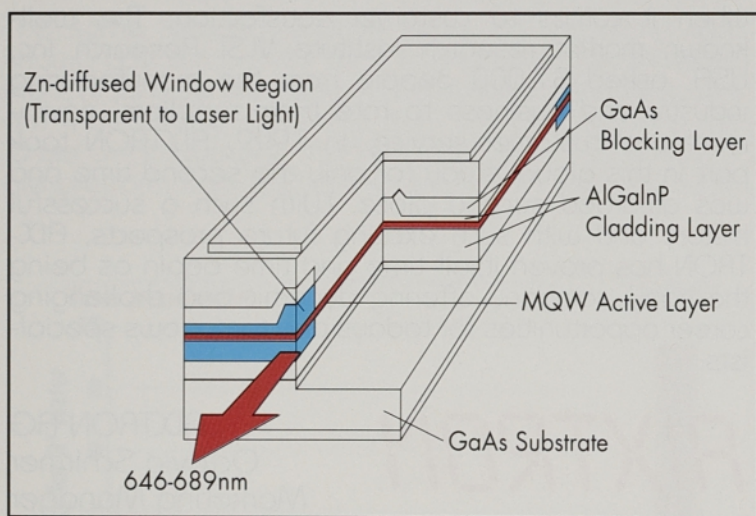


Figure 1. Schematic diagram showing the window-mirror structure employed in red laser diodes manufactured in the 646-689 nm range. For the active regions, the TQW 650 nm laser employs 5 nm wells, and the DQW 680 nm laser 8 nm wells. Zn diffusion is used to disorder a 20 μ m region at the facets to make a window for the laser light, effectively reducing optical absorption and damage.

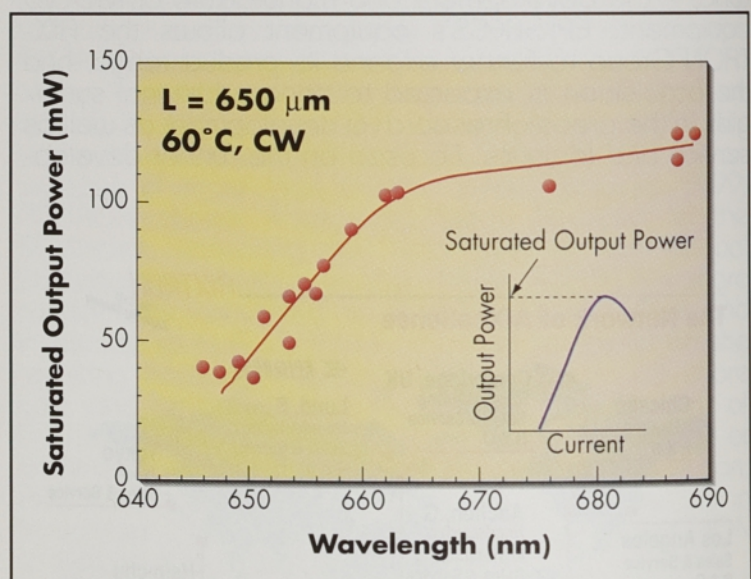


Figure 2. Dependence of the saturated output power on the wavelength at 60°C for a cavity length L of 650 μ m and CW operation. (A graphical representation of "saturated" output is shown in the inset.) The output power drops below 50 mW at around 650 nm.

- and also the saturated output power level at elevated temperatures. We have previously reported improvement in the COD limit using a waveguide design for lower optical power density [1] and also window mirror structures [2-5].

In this earlier work we employed a solid-state, zinc-diffused approach to achieve a "window-mirror-structure" in AlInGaP red laser diodes, and noted improvements in both high-power operation and reliability [6-9]. In this instance, the diffused region reduces mirror damage by limiting the amount of optical absorption at the mirror face. We have since succeeded in realizing mass production of these "window-mirror" laser diodes [10].

Having achieved these gains with the COD limit, we have turned our attention to the improvement of the saturated output power. This characteristic is a function of the carrier overflow from quantum well active layers in InGaP/AlInGaP-based red laser diodes. A reduction in the operating wavelength of red lasers is achieved by increasing the bandgap of the QW active region. In turn this leads to less effective carrier confinement, a problem exacerbated at high temperatures. In particular, we have examined the dependencies of the maximum output power on both the wavelength and the laser cavity length (L) in the wavelength range 646-689 nm. The result is reliable 100 mW CW (continuous wave) operation of 659 nm red laser diodes, and 120 mW CW operation of red-emitting lasers at 687 nm.

Device Structures

Figure 1 shows a schematic illustration of the 646-689 nm red laser diode structure formed with a window-mirror. In order to prevent catastrophic optical mirror damage, the window-mirror structure is formed by disordering the quantum well with zinc diffusion supplied by a solid source. The window-mirror regions are 20 μm long, with a current blocking layer at each mirror facet which acts to suppress optical absorption and the surface recombination of the injected electrons. The active area consists of $(\text{Al}_{0.7}\text{Ga}_{0.3})_{0.5}\text{In}_{0.5}\text{P}$ cladding layers, $(\text{Al}_{0.5}\text{Ga}_{0.5})_{0.5}\text{In}_{0.5}\text{P}$ guide layers and $\text{Ga}_x\text{In}_{1-x}\text{P}$ ($x = 0.38 - 0.51$) quantum well layers. The output wavelength is tuned using the well thickness and the Ga content.

For all diodes, we employ a large compressively-strained GaInP QW to maintain the conduction band offset. For the 650 nm laser diode, a triple quantum well structure with 5 nm wells is employed. This device structure represents an optimized trade-off between electron overflow and kink generation due to spatial hole burning, which is caused by the high optical power density [9].

The 685 nm laser diode has a double quantum well InGaP structure with 8 nm wells. The total thickness of the wells is kept in the range 15-16 nm, because this parameter has a strong impact on the optical and electron confinement in the active layer. The laser stripe width is also fixed at 5 μm .

Two cavity lengths, 650 μm and 900 μm (which includes the window length), were used to study the current density dependence. 8% and 90% reflectivity coatings were applied to the front and rear facets, respectively, except for a special structure that uses a 3% coating for the front face. The laser diode chip was mounted junction-side down on a heat-sink.

Laser Performance

Saturation Output Power vs. Wavelength

We have investigated the dependence of the saturation output power on the wavelength at high temperature (60°C) and under CW operation. Figure 2 shows the relationship between the saturated output power (see inset for a graphical representation of saturated output power) and the wavelength for 650 μm laser diodes. A saturated output power of 124 mW is obtained at 687 nm, which gradually decreases at a rate of 0.6 mW/nm as the wavelength shortens to 662 nm. From 662 to 646 nm, the saturated output power rapidly decreases at the much higher rate of 4.5 mW/nm, which is thought to be due to electron overflow. This suggests that it is much more difficult to realize high-temperature, high-power operation in the wavelength range 645-660 nm.

Saturation Output Power vs. Cavity Length

The cavity length has a strong impact on the temperature characteristics and the maximum (saturated) output power. We have tested the dependence of the saturated output power at 60°C on the cavity length for both 659 and 687 nm laser diodes under CW operation. The saturated output power of the 659 nm device is increased from 90 to 121 mW as a result of the extension of the cavity length from 650 to 900 μm . Similarly, the output of the 687 nm diode is increased from 124 to 165 mW due to the extension of the cavity length (see Figure 3).

In order to assess the relationship between the saturated output power and the current density, the dependence of the threshold current density (J_{th}) and the operating current density (J_{op}) on the cavity length at 60°C was also investigated. Extending the diode cavity length from 650 μm to 900 μm reduces the threshold current density by 19% and 16% at the 659 and 687 nm wavelengths, respectively.

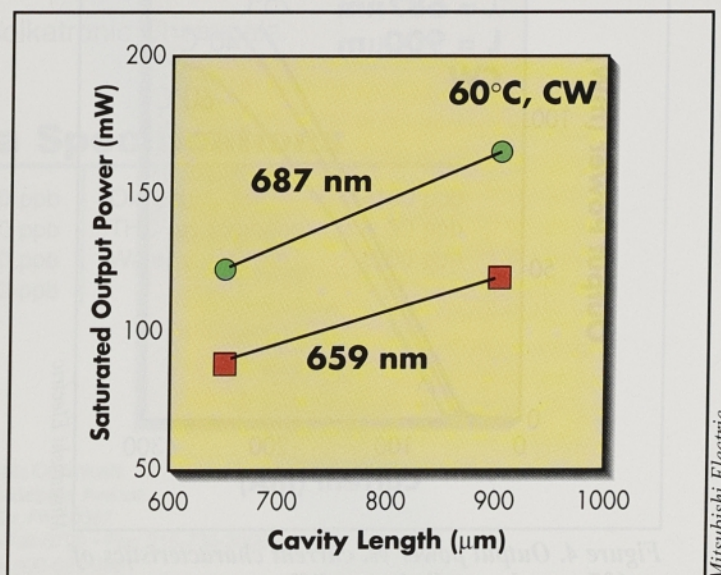


Figure 3. Data showing the strong dependence of the saturated output power (for high temperature and CW operation) on the cavity length for laser diodes at two wavelengths.

In addition, at 60°C, the current density for 50 mW operation is reduced by 17% for the 659 nm emitting diode, and by 16% at the 687 nm wavelength. These results prove that the extension of the laser cavity length is effective in reducing the current density at high-power and temperature, which is a result of the improved electron confinement in the longer cavity.

Further studies have also revealed that the operating current density strongly influences the output power for all wavelengths examined. To maintain >100 mW operation at 60°C, the current density should be kept below 4 kA/cm².

100 mW CW Diode Operation

659 nm Laser Diodes

The light output power versus current (P-I) of the 900 μ m cavity length laser diode emitting at 659 nm were determined for two temperatures – 25°C and 60°C. Relatively linear P-I characteristics are obtained up to 100 mW, even at the higher temperature. Far-field-patterns reveal Gaussian-like beam patterns ($\Theta_{//} = 9^\circ$ and $\Theta_{\perp} = 22^\circ$ to the junction plane) up to 100 mW without marked changes. This testifies to stable transverse-mode operation.

To test the reliability, these 659 nm diodes were aged at 60°C under CW operating conditions at an output power of 100 mW. Reliable 1000 hour operation has been realized at this temperature for the first time.

687 nm Laser Diodes

The higher output power operation of the 687 nm laser diode was also tested, as shown in Figure 4. A 3% reflectivity coating was applied to the front facet to obtain the sufficiently high kink

level for the operating output power. P-I characteristics for this device, operated at both 25° and 40°C, reveal kink-free operation up to 130 mW, with saturation beginning of the 60°C sample. Again, Gaussian-like far-field-patterns ($\Theta_{//} = 10.2^\circ$ and $\Theta_{\perp} = 21.6^\circ$) confirm the fundamental-transverse-mode operation.

CW aging tests were also performed for the 687 nm laser diodes (40°C, 120 mW), and these diode lasers have been operating for over 1800 hours without a noticeable increase in the operating current. To the best of our knowledge, this represents the best high-power reliability operation among fundamental, transverse-mode red laser diodes.

Conclusions

We have investigated the dependence of the saturation output power on the wavelength and the cavity length of InGaP/AlInGaP-based red laser diodes in the wavelength range 646-689 nm. The saturated output power decreases very significantly at wavelengths shorter than 660 nm. This indicates difficulties for high-power and high-temperature operation of 650 nm laser diodes. The extension of the cavity length from 650 to 900 μ m is one of the ways to raise the saturated output power. This results in a reduction of the operating current density for both high-power and high-temperature operation. (Performance improvements from further extension of the cavity length could be limited by the package sizes required by manufacturers.)

These improvements have led to the realization of the first 1000-hour, 100 mW CW operation of red-emitting 659 nm laser diodes. In addition, the 900 μ m cavity length 687 nm diodes with the larger bandgap offset have shown reliable 120 mW CW operation for 1800 hours at 40°C.

To the best of our knowledge, these aging results represent the highest power operation among fundamental-transverse-mode red laser diodes, making these devices very suitable for high density- and high-speed optical recording systems. At present, there is no plan to mass produce 100 mW lasers, although a pulsed 70 mW version for 4.7 Gb storage capacity DVD-RAM is planned for the second quarter of 2000 to add to the pulsed 60 mW versions.

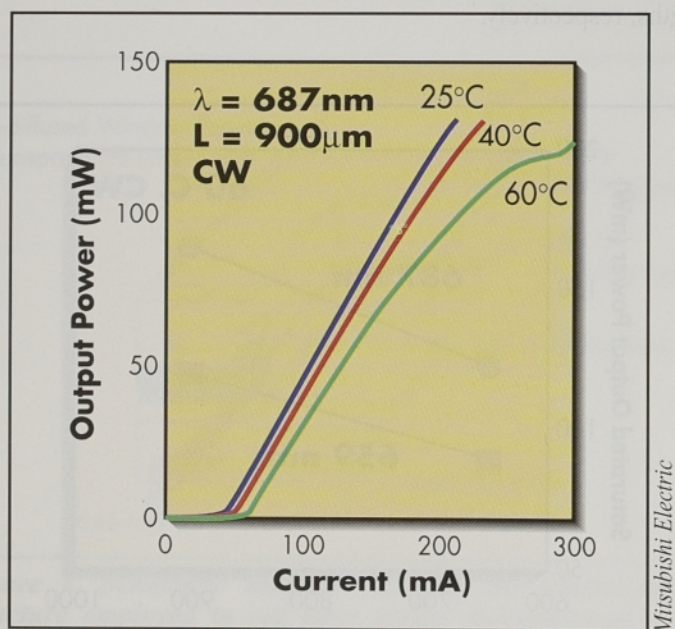


Figure 4. Output power vs. current characteristics of a 687 nm laser diode at different temperatures, revealing data free of inflexions up to 130 mW at the lower temperatures, and the beginning of saturation for the 60°C sample at this power level.

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Blue Lasers and LEDs - ISBLLED 2000

ISBLLED, held in Berlin recently, is one of the major forums for research into short wavelength lasers, photodetectors and LEDs.

RICHARD DIXON

More than 150 delegates made the trip to Zeuthen in Berlin for this year's ISBLLED 2000 conference (March 6-10), the third in this series of international symposia on blue lasers and LEDs. The scope is inevitably broader than the title suggests - 40 talks and 42 posters encompass research and device developments in the UV to green wavelengths.

The commercial driving force of course remains the nitrides for blue lasers and LEDs, which find use in lighting, display and optical storage applications. In the UV region, GaN is employed as solar blind detectors and also efficient white light phosphor drivers. Meanwhile, laser diodes and LEDs based on II-VI materials still garner support for the green region of the spectrum.

Some key themes emerged from the meeting. These included templates and substrates for the improved growth of GaN, and the understanding of the epitaxy of high In- and Al-content GaN layers for green lasers and UV photodetectors, respectively. In addition, piezoelectric field effects continue to be of concern to III-nitride researchers, as is the continuing issue of reliability in II-VI lasers diodes and LEDs. Some of the highlights are presented below.

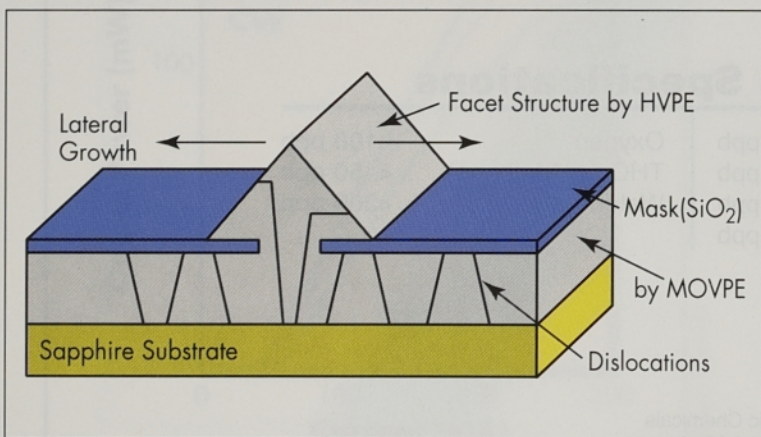


Figure 1. The FIELO (facet-initiated epitaxial overgrowth) technique uses a SiO₂ mask to initially filter threading dislocations originating in the GaN/sapphire. An area of reduced dislocation density is formed at these {1-101} facets, coalescing after 30 mins of HVPE growth. The dislocation density of the GaN layer is reduced by an order to 10⁷ cm⁻².

Developments in GaN LEDs

The proceedings opened with a talk from **Osram Opto Semiconductors**. Regensburg-based Osram Opto is the alliance of Infineon and Osram. V. Härle began by outlining recent improvements in Osram's LEDs, which are grown on SiC substrates. They also employ licensed conducting buffer (CB) technology from Cree to accommodate the SiC and GaN device regions. He also described the processing steps that led to the company's TOPLED white LEDs, a small profile device very popular in the auto industry. These LEDs now exhibit efficiencies around 14-15 lm/W. Increasing the output of these LEDs is now high on the agenda of manufacturers targeting the lighting industry. Osram is no exception - it now produces a super bright chip operating at 460 nm capable of 17 mW (1.1 lm) at a forward bias of 3.7 V.

Härle sees room for improvement, particularly as Osram has not yet experimented with flip chip technologies (flipping the chip and mounting substrate side up allows more of the light to escape).

Osram has remained relatively quiet about its laser research. Last September, however, it announced a violet InGaN laser diode (LD), the first to be developed in Europe [see CS 5(7), p. 12]. While the violet laser was the feature of a poster session, Härle commented that the company's blue LDs were still 1-2 years away from commercialization.

M. Mizuta outlined the CW operation of NEC's InGaN MQW layers grown on FIELO (facet-initiated epitaxial lateral overgrowth) GaN substrates (see Figure 1). FIELO substrates offer reduced dislocation density surfaces for growth, says Mizuta. Currently, HVPE growth can be achieved up to 600 µm thick on 2-inch sapphire wafers, and scaling up is possible.

Using these substrates, violet InGaN lasers containing 3 QW's can be run CW at power levels up to 40 mW in a single transverse mode. NEC's recent HVPE epitaxial layer overgrowth (ELOG) GaN lasers featured threshold current density and threshold voltage of >10 kA/cm² and 10 V, respectively [see CS 5(4), p. 16]. These new devices exhibit reduced threshold current densities of 5.4 kA/cm² and turn-on voltages of 7.5 V. Unfortunately, reliability data was not available.

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D. Bour (now with LumiLeds Lighting) presented Xerox's latest InGa_N MQW blue LDs, which are intended for use in arrays for xerography. The shorter wavelength allowed by blue diodes leads to a smaller spot size and greater depth of focus, enabling higher resolution. According to Bour, heat dissipation is a critical factor under CW operation, as the current density is presently very high (i.e. several kA/cm²).

Ridge waveguide lasers grown on sapphire substrates have been investigated by Xerox. The GaN/InGa_N MQW active regions contained four or five x 3 nm In_{0.1}Ga_{0.9}N QWs and Al_{0.08}Ga_{0.92}N cladding layers. Efforts have been made to improve recent lifetime results of around 1 hour by using optimized ridge widths for the laser and reflective mirror coatings formed by chemically-assisted ion beam etching (CAIBE). Additionally, thinning the sapphire substrate to less than 100 μm and mounting on a copper heat sink has also been found to be beneficial. The lowest CW threshold current achieved in this manner was 60 mA (10 kA/cm²) for a 2 μm x 300 μm stripe.

While the device demonstrated 1 hour of life, more recent, 2 μm x 400 μm stripe devices, which use ELOG substrates and no front mirror coatings, have now been continuously operated at 400 nm for around 15 hours. Some gains in the threshold voltage, which is 1-2 V above Nichia's lasers, could still be made using superlattice p-cladding layers, says Bour.

Materials for UV Photodetectors

Although Commercial UV photodetectors are predominantly based on Si, GaN photoconductive devices are now available for missile detection, flame sensing and solar UV monitoring. They are also suitable for high-density optical storage and next-generation white LEDs. Other wide bandgap materials, such as ZnSe and related alloys, also remain attractive for these applications.

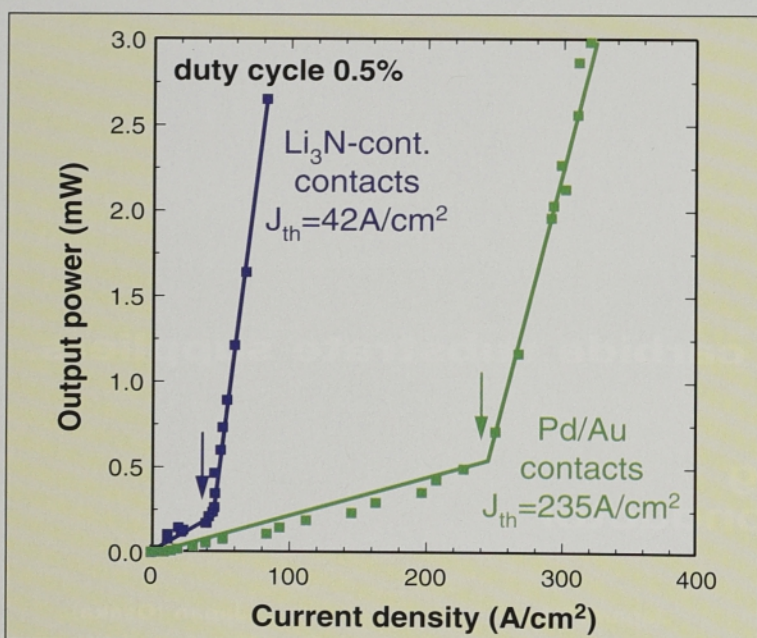


Figure 2. TUB's Li₃N contacts have been used to reduce the threshold current density of ZnCd(S)Se SQW-based II-VI lasers to 42 A/cm² – the lowest values for II-VI lasers to date.

GaN

GaN-based devices suffer when Al is incorporated to achieve cut-off wavelengths below the bandgap wavelength of GaN (~360 nm). AlGa_N devices usually exhibit poor optical quality, and these structures also suffer from a high piezoelectric strain due to the large lattice mismatch. This results in deterioration of the emission efficiency as a result of the spatially-induced indirect transition.

Harris et al from the University of Tokyo have attempted to incorporate Al up to 80% in GaN alloys. At these concentrations, a GaN QW surrounded with one monolayer-thick AlGa_N barriers can achieve photoluminescence at a wavelength as short as 247 nm (5.03 eV). Despite the effects caused by the high piezoelectric fields in these ultra-thin layers, Harris concludes that the recombination lifetimes (~0.5 ns) in these high Al content AlGa_N layers is encouraging for future device applications.

ZnMgBeSe

Considerable interest exists in ZnMgBeSe photodiodes, which can be grown lattice matched to GaAs with a direct bandgap ranging from 2.75 – 3.5 eV. These Be-containing chalcogenides are also known to feature strong covalent bonding, and thus can resist defect generation and propagation.

However, according to F. Vigué and colleagues at France's CRHEA/CNRS research center, so far ZnMgBeSe photodiodes have not been forthcoming because of p-type doping issues, but reliable n-type doping has now allowed them to attempt Schottky barrier photodetectors.

Initial experiments with ZnSe devices have shown promise [see page 80 for more details], and increasing the Mg and Be contents in ZnMgBeSe alloys allows the cut-off wavelength to be gradually tuned towards the UV. A ZnMgBeSe Schottky layer, lattice matched to GaAs, featured reduced dark current levels, and these results have been repeated in devices with bandgaps up to 3 eV.

Developments in II-VI Lasers and LEDs

As M. Strassburg of the Technische Universität Berlin (TUB) points out, II-VI semiconductors such as ZnSe are still promising for laser diodes operating in the blue-green to green spectral range. However, a severe reliability problem still exists – the best devices (i.e. Sony's ZnSe-based lasers) currently hover around the 400 hour mark.

Hence the interest in TUB's novel contact designs that considerably lower the current density, and could lead to longer lasting lasers. The new electrode-contact structure consists of a thin lithium nitride layer between the Pd/Au electrode and ZnSe/ZnTe MQW contact. The contact was applied to several different double heterojunction SCH lasers with ZnCdSe and ZnCdSSe SQW active regions, in each case leading to a reduction in the current density and operating voltage. Typically, values of ~42 A/cm² are observed for a laser with a 20 μm wide stripe using the processed lithium nitride layer (Figure 2). These are the lowest values reported for II-VI lasers to date.

Threshold voltages were also reduced by ~30% to 5.5 V. Strassburg notes that aging performance is improved due to the

reduced heat generated in the device. Stripe lasers, room temperature-aged under CW conditions at 1 mW, have typically been able to achieve up to 10 hours of operation, compared to minutes for lasers prepared with conventional *p*-type contacts. However, possible detrimental effects caused by self-compensation of the lithium ion on the lifetime are unclear at present.

A. Waag of the **University of Würzburg** presented some unconventional beryllium-based II-VI light emitters. BeTe is a wide bandgap material relatively closely lattice matched to GaAs and ZnTe (mismatch = 0.5%). And MBE can be used to produce high-quality BeTe-ZnSe heterostructures on GaAs.

One of the promising device types described consisted of a *p*+-BeTe/*n*+-ZnSe Esaki tunneling junction – a reverse injection device that uses a tunneling junction to inject holes. This is made possible by the high *p*-type doping available to BeTe. By reverse biasing such a junction, electrons are injected from the *n*-ZnSe layer into the *p*-BeTe layer via interband tunneling, and the electric current can be converted into a hole current.

Waag says test structures have already demonstrated good current voltage performance: current densities of 1 kA/cm² at 4 V. Moreover, devices with this active region are unstrained, allowing them a substantially longer lifetime than LEDs containing strained active regions, such as ZnCdSe.

Pure green LEDs based on ZnTe have also been demonstrated by the **Japan Energy Corporation**. ZnTe is of interest because of a room temperature band gap of 2.26 eV and direct optical transition, but suffers from self-compensation effects, in particular with *n*-type dopants. This has so far limited the formation of *p*-*n* junctions. Oda and colleagues report the first operation of such a device, which was grown on VGF, *p*-type ZnTe substrates.

Aluminum was used as the *n*-type dopant, and, following a simple thermal diffusion process for Al into the *p*-ZnTe to produce the junction, green EL was observed at room temperature.

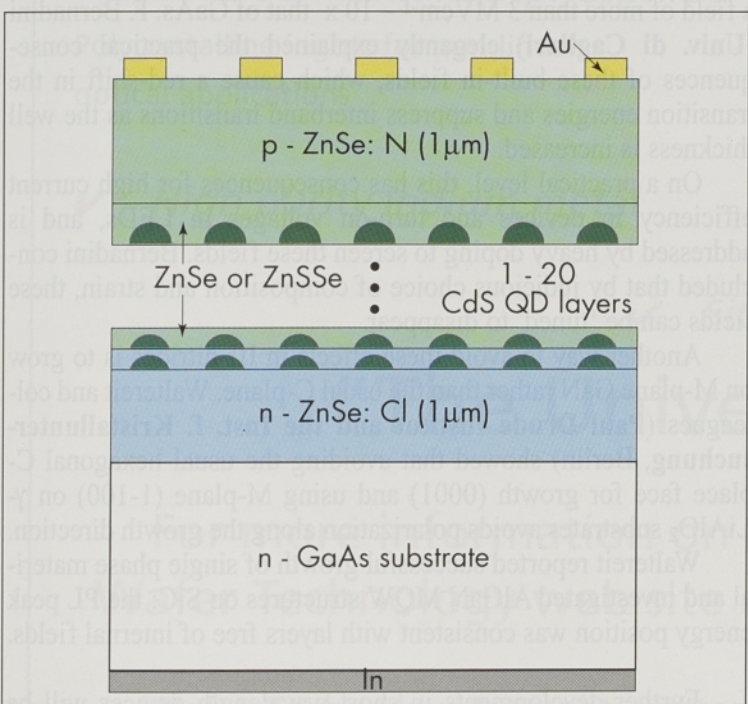


Figure 3. Schematic of MBE-grown CdS quantum dots embedded in up to 20 layers of ZnSe or ZnS.

At a current of 20 mA, 550 nm emission was sustained for more than 1,000 hours, demonstrating the potential of this material system for future green light emitters.

ZnO is similarly regarded as a promising photonic material in the UV range, owing to a wide direct bandgap of 3.37 eV and extremely large exciton binding energy. Progress to date has included optically pumped excitonic lasing at room temperature on sapphire substrates. Ko and co-workers from **Tohoku University** in Japan reported on the growth of ZnO on GaN, which results in the low lattice mismatch (1.8%) and the same wurtzite lattice structure.

To avoid the heterovalent problem associated with the II-VI/III-V interface, Ko's group has employed various Zn pre-growth treatments and low temperature ZnO buffers. High quality material and high electron concentrations (Ga: 1.9×10^{20} cm⁻³) are possible, which bodes well for future devices.

Kobayashi [now Waseda Univ.] and co-workers from **Chiba University** demonstrated novel MBE-grown LEDs based on CdS stacked and embedded in the *pn* junctions (see Figure 3) of ZnSe or ZnS active layers. Both blue and intense green EL emission was observed at room temperature from these devices (see Figure 4), which are grown on GaAs substrates. Essentially, the CdS QDs occupy a volume of only a few monolayers on the ZnSe and ZnS surfaces and do not initiate the defects that would lead to device degradation. The size and composition of the dots determines the emission wavelength.

Cubic GaN

Y. Taniyasu, also from **Chiba University**, reported LEDs based on cubic InGaN/GaN DH structures. The growth of high quality cubic (zincblende) III-nitrides on GaAs (001) substrates could provide an alternative approach for fabricating future low cost UV visible LEDs and laser diodes. While the technology is in the early stages, the main advantages are expected to be the reduced dislocation content, a result of the closer matching of the c-GaN layers and GaAs substrates; but also, the availability of high quality, inexpensive sources of GaAs wafers up to 6-inch in diameter.

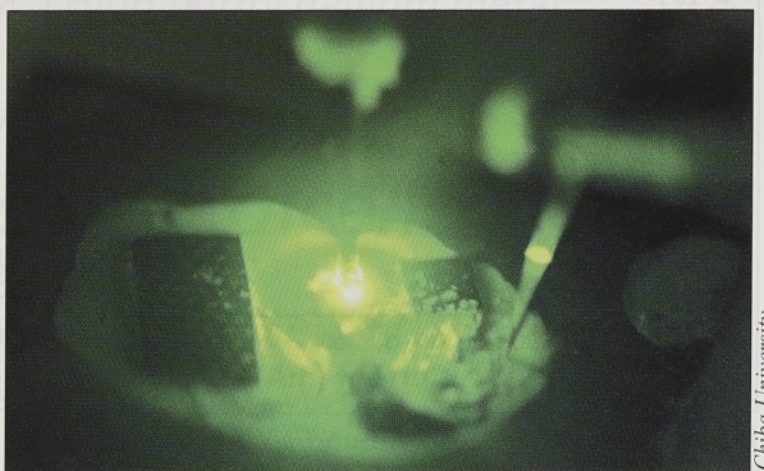


Figure 4. Intense green EL observed at room temperature from ZnSe/CdS quantum dots stacked and embedded in the *p*-*n* junction of ZnSe or ZnS layers.

Taniyasu and colleagues grew a cubic $\text{In}_{0.07}\text{Ga}_{0.93}\text{N}$ active layer double heterostructure LED, sandwiched between asymmetric GaN barriers and AlGaIn waveguides. EL studies reveal violet-blue emission centered at 430 nm at currents exceeding 5 mA. A turn-on voltage of 4.9 V, while higher than that of hexagonal GaN, is thought to be due to the increased surface roughening during growth, and the formation of stacking faults and hexagonal domains.

Templates and Quasi-Substrates

Typically, the low leakage properties of AlGaIn FETs, the dark current and wavelength cut-off characteristics of solar blind photodetectors, and the reverse bias leakage current of p-n diodes and LEDs are strongly affected by the density of threading misfit dislocations. These originate from the large substrate mismatch between GaN and sapphire or SiC. Monica Hansen from UCSB neatly demonstrated how the performance of InGaIn MQW laser diodes can be improved using different types of GaN template layers.

GaN templates on sapphire, fully-coalesced laterally epitaxially overgrown (LEO) GaN on sapphire, and initial results of GaN on SiC using conducting buffers (similar to those pioneered by Cree) were assessed. Lasers grown on LEO structures enable a 50% reduction in the threshold current density (from 10 to 4.8 kA/cm^2) compared to planar GaN on sapphire. The internal quantum efficiency could also be improved from 3% to 22% using LEO GaN templates. However, for lasers grown on sapphire substrates, CW operation is not yet possible due to high turn-on voltages (12–15 V).

Lasers grown on SiC benefit from reduced device heating, and also higher Al compositions can be grown as a result of the lower mismatch between the SiC substrate compared to sapphire (~4% compared to ~13%). Hansen described UCSB's first

attempts to use conducting buffers as templates for simple diode structures. These devices employ an AlGaIn:Si layer with up to 20% Al content prior to growing the GaN layers. So far, a reduction in the resistance of 23 to 2 Ω has been achieved. GaN/SiC-based laser diodes are currently in preparation.

M. Kamp's group (University of Ulm) is concerned by the limitations set on GaN devices by heteroepitaxial substrates. The Ulm team has investigated different substrates for LED fabrication. Thin GaN layers deposited on SiC, as well as thick GaN layers grown on sapphire, were reported. Both templates, which are grown using HVPE, are suitable for subsequent quasi-homoepitaxial growth. The performance of LEDs grown and fabricated on these templates was compared with similar structures on sapphire. SiC out-performed sapphire due to its thermal conductivity advantage (Figure 5). Additionally, it benefits from a vertical device design and the ability to cleave lasers mirrors, which leads to simplified processing and lower production costs. However, as H.Y.A. Chung of the University of Ulm noted, the total GaN thickness on SiC should be kept below 5 μm to avoid cracking.

Single crystal GaN substrates feature similar advantages, says Kamp, plus very low dislocation densities (10^4 cm^{-2}), and allow LEDs to withstand CW current densities beyond 3 kA/cm^2 . This permits devices to be driven much harder.

C. Miskys of the Technical University Munich also reported that large areas (up to 5 cm diameter) of high quality (dislocation density $2 \times 10^7 \text{ cm}^{-2}$) GaN. This is obtained using the laser lift-off technique. A pulsed laser is used to locally induce lift-off without bowing of the subsequent free-standing HVPE GaN [see CS 5(4), p. 20 for more details of this technique].

Piezoelectric Effects

Spontaneous polarization and piezoelectric fields are considerable in the wurtzite materials such as GaN, which possesses a field of more than 3 MVcm^{-1} – 10 x that of GaAs. F. Bernadini (Univ. di Cagliari) elegantly explained the practical consequences of these built-in fields, which cause a red-shift in the transition energies and suppress interband transitions as the well thickness is increased.

On a practical level, this has consequences for high current efficiency in devices and turn-on voltages in LEDs, and is addressed by heavy doping to screen these fields. Bernadini concluded that by judicious choice of composition and strain, these fields can be 'tuned' to disappear.

Another way to avoid these effects in III-nitrides is to grow on M-plane GaN rather than the usual C-plane. Waltereit and colleagues (Paul Drude Institut and the Inst. f. Kristalluntersuchung, Berlin) showed that avoiding the usual hexagonal C-plane face for growth (0001) and using M-plane (1-100) on $\gamma\text{-LiAlO}_2$ substrates avoids polarization along the growth direction.

Waltereit reported successful growth of single phase material and investigated AlGaIn MQW structures on SiC: the PL peak energy position was consistent with layers free of internal fields.

Further developments in short wavelength devices will be presented in two years' time, when the event will be held in Cordoba, Spain.

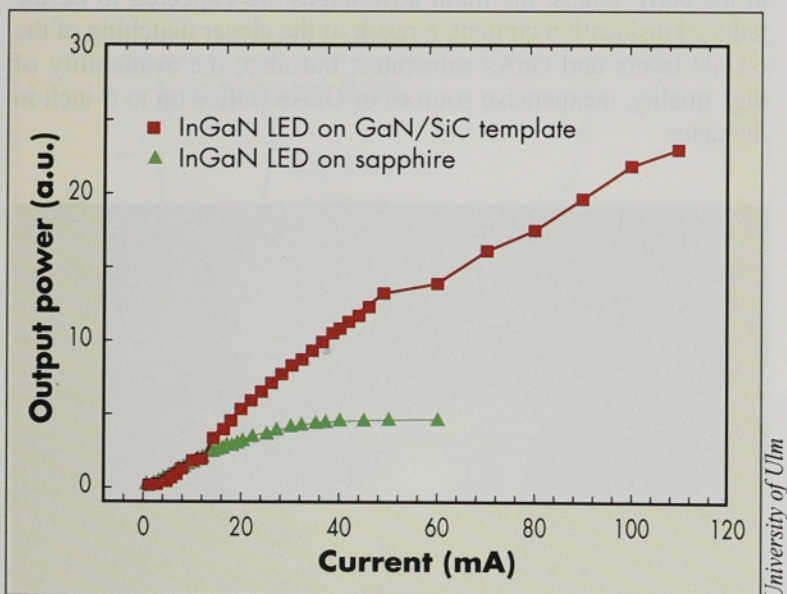


Figure 5. Output power of InGaIn/GaN LEDs on GaN/SiC quasi-substrates and sapphire at room temperature. At higher current densities the LED on GaN/SiC templates reveals almost no saturation due to ohmic heating, resulting in 2–3 x higher output power.



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Silicon Carbide High Temperature Gas Sensors

SUSAN SAVAGE

ACREO AB, Kista, Sweden¹

ANITA LLOYD SPETZ

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As environmental issues become more widely debated and regulated, the requirement to detect and control unwanted emissions becomes more urgent. Gas sensors that can be used at high temperatures and in aggressive environments have the potential to improve our environment through the control of industrial and car emissions, and also provide the capability for in-line monitoring of production processes. Silicon carbide is an ideal material from which to produce these sensors. Its wide bandgap permits its use at temperatures up to 1000°C, while its high electric field strength permits a very fast response time. Also, silicon carbide is very hard and chemically inert, which permits its use in aggressive atmospheres.

Sensor Function

An electronic device based on silicon carbide can function as a sensor by the application of a catalytic metal on a thin insulating layer to its surface. The catalytic metal can be for example platinum, iridium, palladium, or combinations of these. Metal oxides can also be used on devices where the catalytic material does not need to conduct large currents.

Thick homogeneous catalytic metals can be used to directly detect hydrogen or hydrogen-containing molecules such as hydrocarbons. The molecule dissociates on the surface of the metal, and the resulting hydrogen ions diffuse through the metal in the order of nano- to microseconds to the insulator surface [see Figure 1]. This creates a polarized layer on the surface of the insulating layer, which in its turn causes a change in the number of mobile carriers in the device, and hence a change in the device's electrical characteristic. For example, a change can be detected in the flat-band voltage of a capacitor or in the I-V characteristic of a Schottky diode. Figure 2 shows the measured I-V curves of a Schottky diode in two different atmospheres that contain propane and oxygen respectively. It is seen that the curve is shifted to lower voltages in the case of the propane-containing atmosphere. The gas response can thus be measured as a voltage shift at a constant current level.

Molecules such as O₂, NO_x and CO, when in the presence of hydrogen-containing molecules, can be indirectly detected by thick catalytic

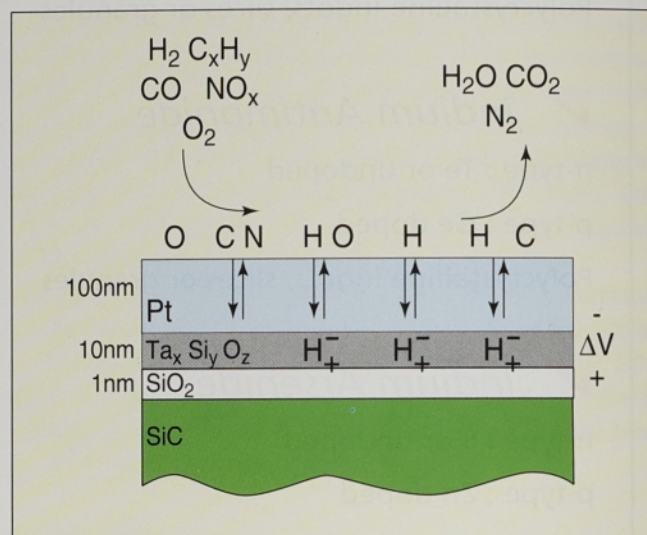


Figure 1. Detection of gases with catalytic metals.

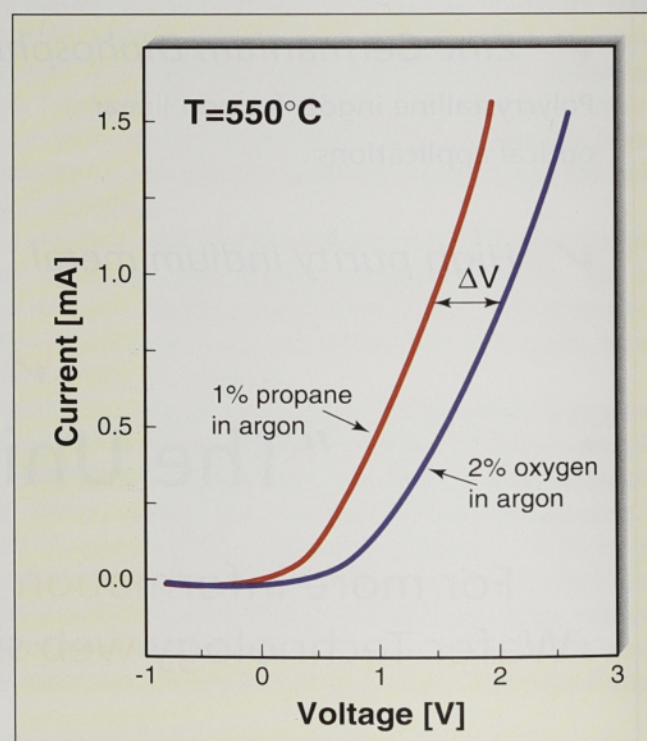


Figure 2. I-V characteristics of a Schottky diode sensor in two different atmospheres.

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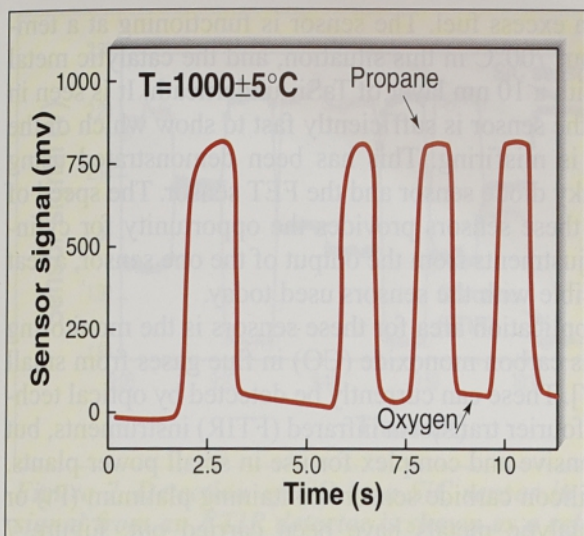


Figure 3. Response of a capacitor sensor at 1000°C to pulses of 0.5% propane/argon in 0.7% oxygen/argon.

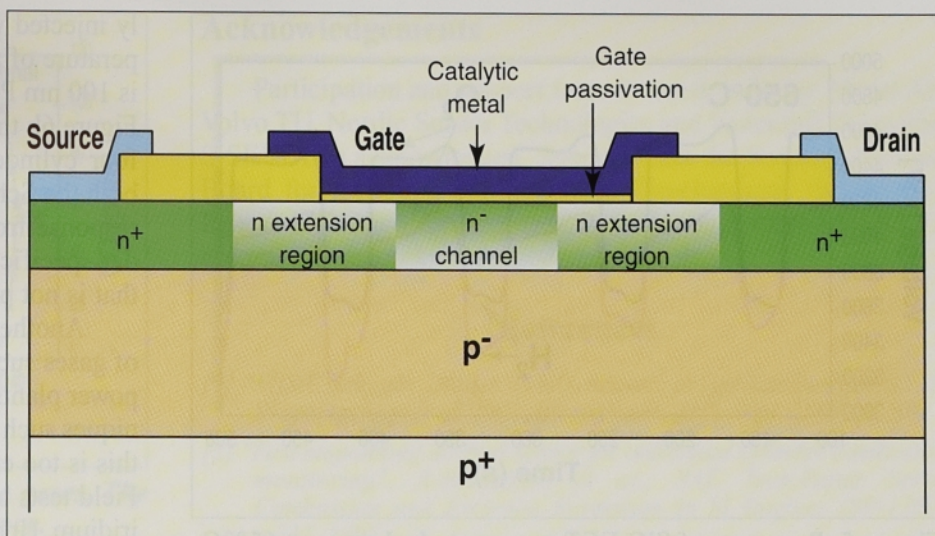


Figure 4. Cross-section of silicon carbide FET.

metals through their chemical reactions on the surface of the metal, which in turn influences the concentration of polarized species at the metal insulator interface. For example, oxygen will consume hydrogen atoms on the surface of the metal, which lowers the hydrogen content at the interface and so causes a reduction in the sensor response to hydrogen. CO will consume oxygen atoms and so cause the hydrogen response to increase. NO can either consume or release oxygen, depending upon the temperature and the type of catalytic metal.

Thin films or thick porous metal films can be used to directly detect non-hydrogen-containing molecules, as well as those that do contain hydrogen. Charged or polarized gas species which sit on the oxide surface exposed in the metal cracks and holes or on the metal at the borders of the cracks cause a change in the number of mobile carriers in the device and so permit detection of the gas. It has been observed that a thin film and a porous film of the same metal will detect the same gases, but at different concentrations, thus providing the opportunity to sense gases in different concentration ranges.

The sensitivity and selectivity of the sensor response to different gases is very much dependent upon the metal composition and the operating temperature [1]. For example, the maximum sensitivity of Schottky diode sensors to 250 ppm NO_x in 1%O₂/N₂ shifted by about 40°C when the catalytic metal composition was changed from 50 nm Pt to 50 nm Pt + 8 nm Ir. Also, the selectivity between NO and O₂ was greatly enhanced by increasing the working temperature of a Schottky diode sensor from 200°C to 300°C. This means that there is the possibility to tailor the sensor for each specific application by choosing with care the catalytic metal composition, the metal structure (for example porous or non-porous), and the operating temperature.

Sensor Devices

Use of these sensors at high temperatures requires the existence of an electronic device that will function in a stable manner at the highest required temperature. The silicon carbide material

itself has the potential to function electrically up to 1000°C, but an electronic device made in this material can break down prematurely if there are weaknesses in the device design. Therefore, the development of a suitable electronic device is essential in order that the sensors can be used to their full capability.

The simplest electronic devices are capacitors and Schottky diodes, and silicon carbide sensors based on these devices have been under development by S-SENCE for several years [1-3,5-8]. The capacitor sensors have demonstrated gas-sensitivity up to a temperature of 1000°C [see Figure 3] for a limited time [3]. However, both these devices have disadvantages. Capacitors require complicated surrounding circuitry in order to measure the gas response, and Schottky diodes require the use of extremely thin insulating layers under the catalytic metal which can lead to instabilities and degradation of the device characteristic at high temperatures.

During the past two years, a gas sensor based on a silicon carbide field-effect transistor (FET) has been under development in a co-operative effort between S-SENCE and ACREO. The silicon carbide FET was designed and processed by ACREO [4] for stability at the highest temperatures, and functioned as a gas sensor by the application of one of the catalytic metals previously developed by S-SENCE. The device design is shown in Figure 4. A voltage applied between the source and drain contacts causes a current to flow through the channel region. The catalytic metal is placed over the channel region. The presence of gas molecules in the atmosphere causes the concentration of mobile carriers in the channel to change in the manner described earlier in this article, which shifts the characteristic in a similar way to that shown in Figure 2. In order to promote high-temperature stability, medium-doped extension regions to the source and drain regions were included in the design, as shown in Figure 4. This promotes an improvement in the quality of the gate passivation that overlaps these regions and so improves the stability of the device.

The first batch of FETs has successfully demonstrated gas-sensitivity to hydrocarbons [4,5]. The gas response of two different FET sensors at 650°C to hydrogen pulses injected into an

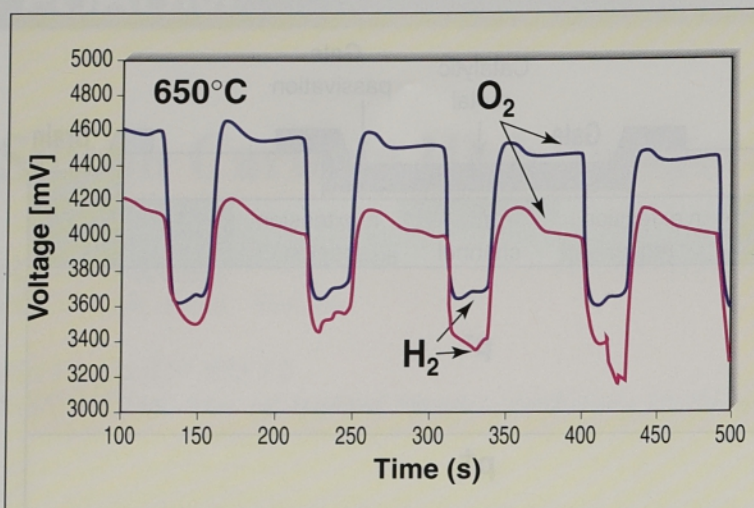


Figure 5. Response of SiC FET sensors to hydrogen at 650°C.

oxygen-containing atmosphere is shown in Figure 5. These devices were operated for more than 17 hours at 600°C without failure. However, their lifetime decreased rapidly with increasing temperature, and at 775°C they operated for only 10 minutes before failure occurred. Severe degradation of the metal surface was observed after failure at the highest temperatures, and it was concluded that catalytic etching by the hydrogen/oxygen atmosphere was the main failure mechanism at these temperatures. However, other measurements showed that the device itself was not entirely stable at temperatures over 500°C, and so a second batch with an improved design has been processed. This is presently being evaluated and initial results indicate good gas response with improved stability. It is therefore anticipated that silicon carbide gas sensors that perform in a stable manner at the highest temperatures will be a reality within the near future.

Sensor Applications

The sensors produced by S-SENCE and ACREO have been tested in a variety of applications, both in simulated environments in the laboratory and in real environments in the field. One application for these sensors is cylinder-specific monitoring of hydrocarbons in the exhaust gases of automobile engines [6]. In field tests, the silicon carbide sensor is placed in the exhaust system, at the point where the four outlet pipes from the cylinders join together [see Figure 6a]. A typical measurement cycle is shown in Figure 6b, where one of the cylinders has been deliberately

ly injected with excess fuel. The sensor is functioning at a temperature of about 700°C in this situation, and the catalytic metal is 100 nm Pt with a 10 nm layer of TaSi_x underneath. It is seen in Figure 6b that the sensor is sufficiently fast to show which of the four cylinders is misfiring. This has been demonstrated using both the Schottky diode sensor and the FET sensor. The speed of response from these sensors provides the opportunity for cylinder-specific adjustments from the output of the one sensor, a feat that is not possible with the sensors used today.

Another application area for these sensors is the monitoring of gases such as carbon monoxide (CO) in flue gases from small power plants [7]. These can currently be detected by optical techniques such as fourier transform infrared (FTIR) instruments, but this is too expensive and complex for use in small power plants. Field tests of silicon carbide sensors containing platinum (Pt) or iridium (Ir) catalytic metals have been carried out. Figure 7 shows a typical measurement of the Pt sensor response at 265°C to flue gases from a small combustion plant of 25 kW into which four different gases have been injected together in a pulsed manner. Measurements were also made simultaneously with an FTIR instrument as a reference. It is seen that the silicon carbide sensor followed the CO concentration as measured by the FTIR instrument very closely, even though the other gases (O₂, NO and SO₂) also varied in concentration. The iridium sensor also followed the CO concentration, but was found to be less selective than the Pt sensor.

The selective catalytic reduction of NO in diesel exhausts is carried out by the injection of ammonia [8]. Therefore, the presence of an ammonia sensor in the system is highly desirable. Recent results obtained from silicon carbide sensors have shown that a thick porous Pt film and a thin Pt film have different dynamic ranges for the ammonia response [9].

These results point towards the possibility of using arrays of sensors with different catalytic metals, different metal structures (for example, porous or non-porous) and different operation temperatures in a high temperature electronic nose to identify several components in, for example, flue gases. The production of an

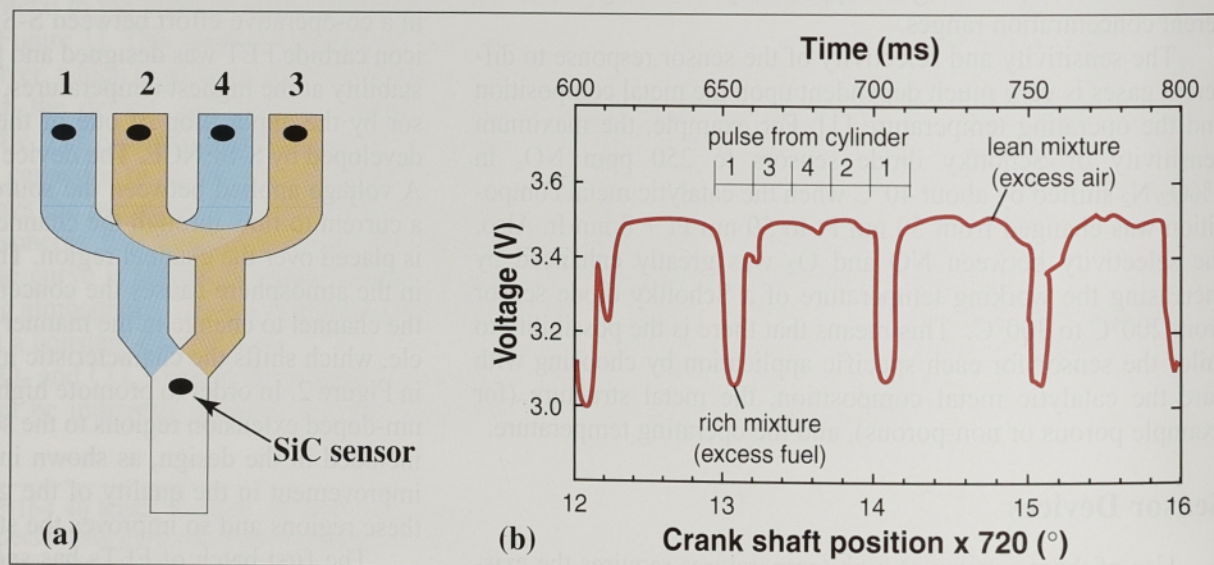


Figure 6. Testing of a SiC hydrocarbon sensor in the exhaust system of an automobile engine, showing (a) position at which SiC sensor is placed in exhaust system (b) response of SiC sensor when one cylinder is injected with excess fuel.

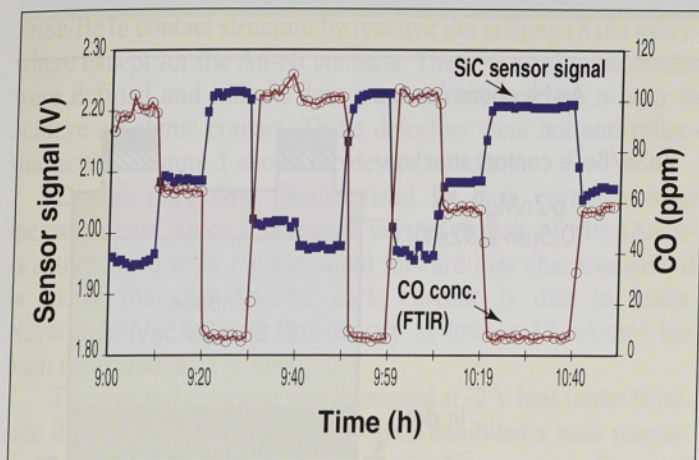


Figure 7. Detection of CO by a SiC sensor in flue gases. The signal from an FTIR detector is shown as a reference.

electronic nose based on silicon carbide sensors is also of great interest for in-line production monitoring or other situations where the detection of several gases is required at high temperatures or in aggressive environments.

Summary

The development and field-testing of hardy high-temperature sensors based on silicon carbide devices has to date shown promising results in several application areas. As the need to take care of the environment becomes more urgent, these small and relatively cheap sensors could be used to increase the monitoring of gases, or to replace or complement larger and more expensive sensors used today. The silicon carbide sensors are sensitive to a wide range of gases, and so provide the opportunity to produce electronic noses that directly sense gases where only an indirect method (for example, the lack of another gas) is possible today.

Acknowledgements

Participation and support from Swedish industry, Mecel AB, Volvo TU, Nordic Sensor Technologies and Vattenfall TU, within S-SENCE is acknowledged. Support from the Swedish National Board for Industrial and Technical Development, the Swedish Research Council for Engineering Sciences and the SSF-SiCEP program is also acknowledged.

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Zn(Mg)BeSe p-i-n Photodiodes

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UV photodetectors have a number of important applications such as in-situ combustion monitoring, UV astronomy, air quality analyzing, or personal UV exposure dosimetry [1,2]. Light detection in that range is currently performed with conventional semiconductors such as Si or GaAs, which, however require the use of various filters. With a 2.7 eV bandgap, ZnSe seems to be much more suited for this purpose. More precisely, considerable interest exists in the ZnMgBeSe quaternary alloy, which can be grown lattice matched onto GaAs substrates with a band gap ranging from 2.75 to more than 4 eV.

Samples were grown by solid source MBE on semi-insulating GaAs (001) substrates. An n-doped ZnBeSe layer was followed by an intrinsic layer with the same Be content. Both layers have a room temperature bandgap of 2.75 eV. A p-doped ZnMgBeSe layer was subsequently grown, on top of which a ZnSe/BeTe superlattice was deposited in order to achieve an

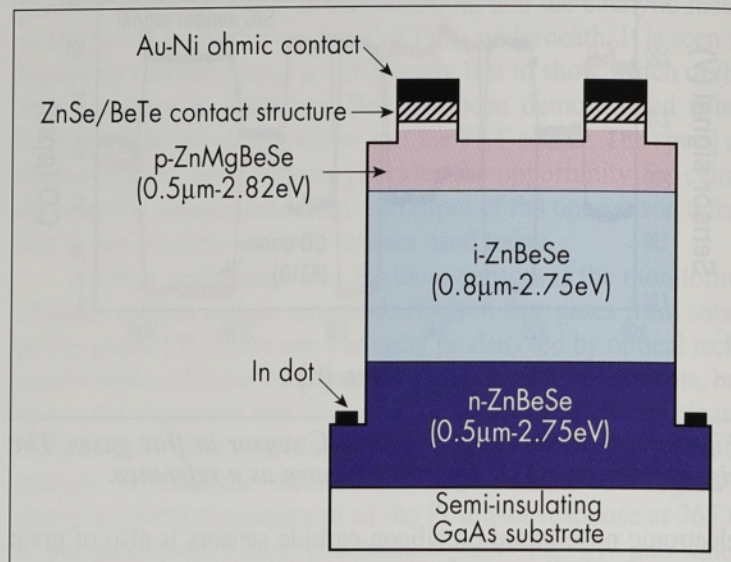


Figure 1. Schematic representation of the device structure.

ohmic contact [3]. In-situ p-type doping was performed with a nitrogen RF plasma source. The room temperature bandgap of the quaternary alloy was fixed at 2.82 eV, a value slightly larger than the intrinsic layer bandgap in order to reduce losses by surface recombination. All layers were grown lattice matched to GaAs.

Device processing consisted of the deposition of an Au-Ni ohmic contact on the top of the structure and the removal of the



**She didn't know
the temperature either**

ZnSe/BeTe contact structure by reactive ion etching (RIE) everywhere except for the Au-Ni contacts. Then $\sim 5 \text{ mm}^2$ mesa diodes were defined and indium dots were soldered on the n-layer to achieve an ohmic contact. These detectors were not anti-reflection coated. Figure 1 shows the device structure.

Diodes were first characterized by dark current-voltage measurements. Since a saturation current density of $\sim 10 \text{ pA/cm}^2$ is extrapolated from the measured forward bias characteristic, it is likely that the reverse dark current is due to leaks. Nevertheless, a dark current density as low as 12 nA/cm^2 has been measured at -2 V bias.

The spectral response was measured at -2 V bias under front-side illumination. The p-i-n photodiode exhibited a peak responsivity of 0.17 A/W at 450 nm [Figure 2], corresponding to a quantum efficiency of 47%. Since we can estimate that roughly 30% of the incident light is lost by reflection on the surface, an efficiency higher than 70% should be realizable with the application of an anti-reflection coating to these devices.

The long wavelength cutoff is sharp with a rejection ratio of four orders of magnitude. This result is attributed to the high crystalline quality and the low impurity concentration of the material. Indeed, since ZnSe is a wide band gap material, defects and impurities might easily introduce energy levels within the gap which would act as generation-recombination centers, enhancing the long wavelength responsivity and decreasing the responsivity at short wavelengths. Such effects have been minimized thanks to the growth of a non-relaxed heterostructure of high crystalline quality.

These promising results, as well as the possibility of tuning

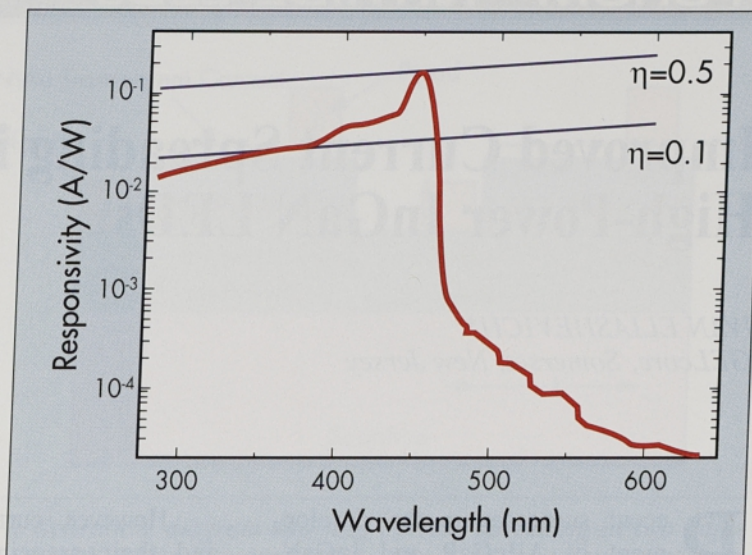


Figure 2. Spectral response of a typical photodiode under -2 V bias.

the ZnMgBeSe bandgap to more than 3.5 eV , offer a very interesting way to achieve efficient UV photodetectors.

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Improved Current Spreading in High-Power InGaN LEDs

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Recent successes in the development of AlInGaP and InGaN-based LEDs has enabled the commercialization of emitters with external quantum efficiencies in excess of 15% covering the whole visible spectrum. The luminous efficiency of the best commercially available LEDs now surpasses that of incandescent lamps and is approaching the output of fluorescent sources.

However, the total optical power emitted from a single LED lamp is currently limited to less than 100 mW. This limitation creates a major hurdle on the road to making LEDs for conventional lighting and other applications. Indeed, further increases in the LED efficiency will require better light extraction through innovative chip and package design.

A chip that can operate at high currents is also a requirement. A simple estimate shows that an ideal LED with close to 100% electrical-to-optical power conversion efficiency would only emit about 30 lm at the standard operating current of 20 mA - a miniscule amount of light compared to the regular 1000 lm from an incandescent bulb.

While there is room for an increase in the operating current of standard 0.3-0.4 mm sized chips, current-dependent degradation mechanisms such as defect propagation and dopant diffusion apparently limit this operating current value to 70 mA or less. Given the cost penalty associated with a module that contains a large number of small chips, the current tendency towards increasing both the chip size and current density is likely to continue, and in fact accelerate, in future.

However, current-crowding effects, and their associated negative consequences for light output and reliability, limit the performance of traditionally designed chips (Figure 1). This is because the collection or crowding of the current in a localized area of the device causes a decrease in light generation efficiency due to high electrical carrier density and local heating. Current dependent degradation also intensifies, resulting in still lower efficiency and higher local current leakage. This leads to a run-away effect that causes the accelerated device degradation.

Similar effects caused by current-crowding near a wire-bonded contact pad are also revealed in a number of commercial LEDs at operating current levels that exceed the specified limit. Moreover, such effects appear after extended periods of operation even at moderate current levels.

This article highlights current-spreading and reliability issues related to the InGaN chip size and operating current density. It also seeks to outline a framework for quantitative analysis of the problem, and proposes solutions for next-generation LEDs.

LEDs with a Lateral Current Path

GaN-based LED structures grown on insulating sapphire substrates require both *n*-type and *p*-type ohmic contacts to be applied to the same side of the epitaxial wafer. Access to the *n*-type layers (the bottom side of the *p-n* junction) is provided by etching a mesa structure through

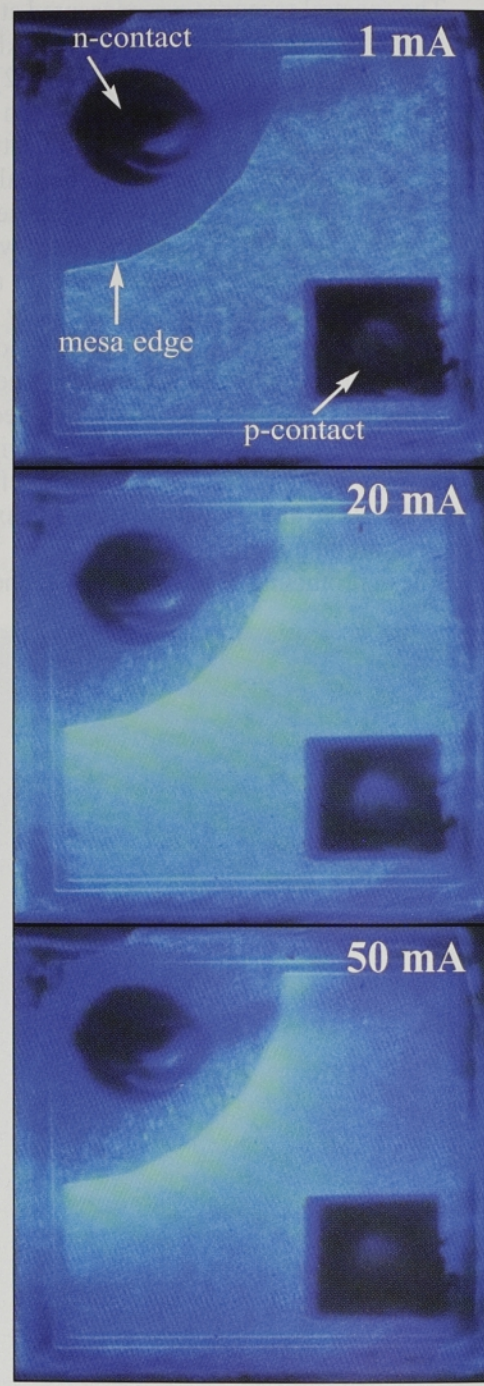


Figure 1. Current crowding [bright contrast] in InGaN LEDs at high drive currents. The traditional (i.e. 0.3 mm) chip design does not allow the high-current operation required for low-cost lighting applications.

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the top p -type layers and p - n junction into the n -type material. The n -type ohmic contact can be subsequently formed on the exposed n -GaN surface, while a p -type contact is made to the mesa top surface.

P -type GaN typically exhibits a very high resistivity; hence, a thin transparent Ni/Au metal layer is deposited on top of the mesa to spread the current across the device. As a result of this contact geometry, a structure with a lateral current path is formed. A cross-section of the LED structure showing two adjacent devices on a wafer is shown in Figure 2.

The current spreads uniformly across the device when the total voltage drop is the same along any possible current path independent of l (the length of the current path through the n -type layer). The total current path between p - and n -wire-bonded pads is L (refer to Figure 2), which scales with the chip size. In this instance, the total voltage drop across the diode consists of three major parts:

- a voltage drop across the transparent metal layer (V_P) proportional to the lateral resistivity of the layer, the current density, and $(l-L)$;
- a voltage drop across the p - n junction (V_J), which exhibits a weak dependence on the current density once the diode is turned on; and
- a voltage drop across the n -type GaN layer (V_N) proportional to the lateral resistivity of the layer, current density, and l .

Current density dependent contributions resulting from the vertical resistance of the ohmic contacts and p -type GaN layer do not fundamentally change this analysis and may usually be ignored. For a given current density, the total voltage drop is independent of l when the maximum possible contribution from both the transparent metal layer and n -type GaN layer are much smaller than the voltage drop across the p - n junction (i.e. current uniformity condition). This maximum possible contribution is a product of the distance between the pads L and the resistivity of the corresponding layer.

For a larger chip size, the lower resistivity of the transparent metal and n -type GaN is required to keep the current spreading uniform. The current uniformity condition also becomes more stringent for higher current densities, since V_P and V_N increase with current much faster than V_J . A high operating temperature may also enhance current crowding by reducing V_J and causing a decrease in carrier mobility.

In the case where the transparent Ni/Au metal layer may be considered to be a perfect current spreader with negligible contribution to the total resistance, only the n -GaN resistance significantly affects current spreading. If the n -GaN conductivity is insufficient to

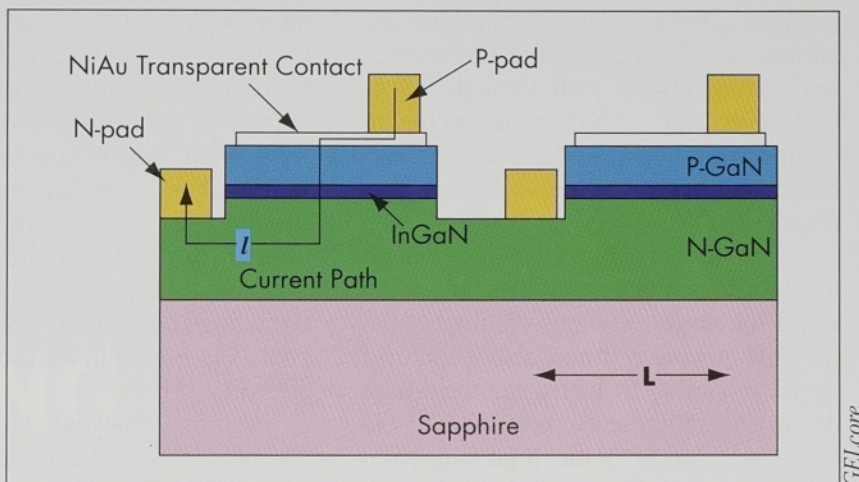


Figure 2. Schematic diagram showing current spreading in two adjacent LEDs with a lateral current path. The light emission is uniform when the voltage drops across all the possible current paths are equivalent. The difference in voltage drops between various current paths may become significant when the chip is operated at high current density or high temperature. The risk of current crowding also increases with larger chip size.

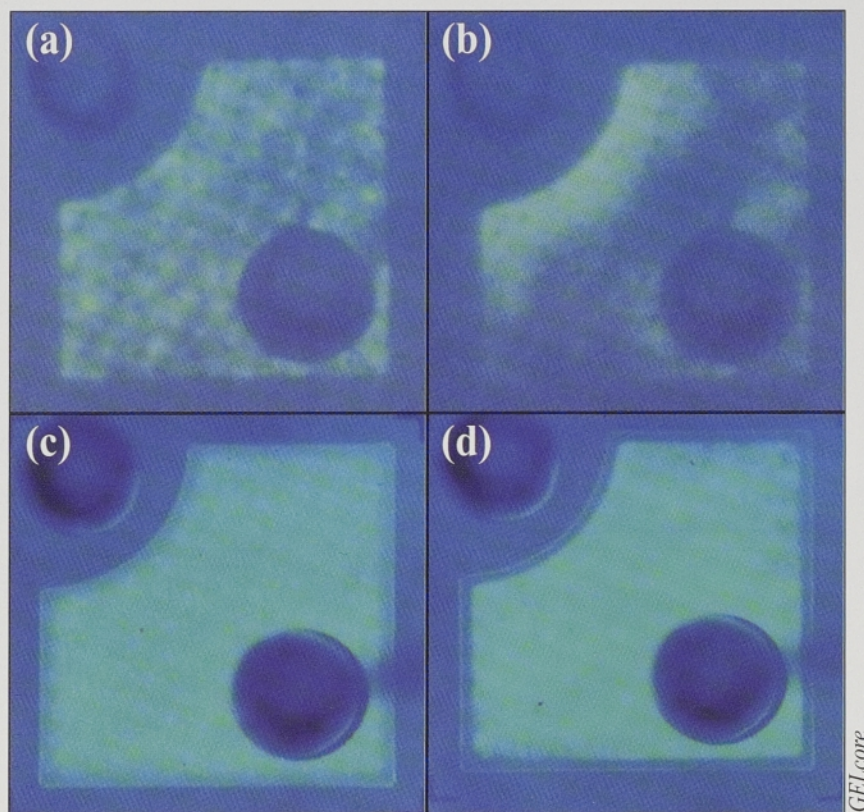


Figure 3. Current crowding effects can be reduced by increasing the conductivity of the n -GaN layer. Parts (a) and (b) show the device before and after aging at 30 mA and 55°C for 1000 hours using a n -GaN layer doped to $7 \times 10^{17} \text{ cm}^{-3}$. Current crowding is clearly visible. A theoretical model has revealed that using n -GaN doping levels above $1 \times 10^{18} \text{ cm}^{-3}$, the voltage drop across all possible current paths is equivalent, resulting in uniform current spreading. This is experimentally corroborated for an LED with n -GaN doping of $1.5 \times 10^{18} \text{ cm}^{-3}$, tested at 20 mA and room temperature before (c) and after 1000 hours of aging at 30 mA and 55°C (d).

meet the current uniformity condition, the current crowds into the area corresponding to the shortest path through the n -GaN layer, and the light emission region is limited to the edge of the mesa immediately adjacent to the n -contact pad (Figure 1).

Current crowding is undesirable in most LED structures. It may adversely affect the uniformity and stability of the far-field emission. It may also jeopardize device reliability by increasing the rate of defect generation and propagation in the localized region with high injection current density. Current leakage through the p - n junction, which is often associated with defects, would cause an irreversible local decrease of the total voltage drop. This in turn would create a preferred channel at the low as well as high temperature and injection current density.

The development of current crowding during aging at 55°C for 1000 hours is shown in Figure 3 (a and b). A possible solution, involving an increased doping level of the n -GaN layer is shown in the images in parts c and d. Higher doping leads to improved conductivity layers and hence better reliability.

The assumption of perfect current spreading by the Ni/Au metal layer is only valid for relatively thick, high Au content layer contacts. On the other hand, a thin

layer with a low Au concentration is preferred to achieve a better contact transparency and improve the light output. In general, while a thinner, more transparent Ni/Au contact is desirable, insufficient transparent contact conductivity leads to current crowding around the p -pad rather than n -pad. Otherwise, the mechanism of current crowding caused by the transparent contact is similar to the process described above for n -GaN.

Current crowding around the pads has been observed for LED chips using contact layouts similar to that originally introduced by Nichia. The chips discussed in this part of the article were commercially available samples manufactured in Japan and Taiwan, as well as early prototypes made at Emcore. (Figure 3).

New Contact Designs

A chip design with a ring n -contact and central p -pad placement (designed by Emcore) is shown in Figure 4b. This design has the current path distance L effectively reduced by approximately a factor of 2 compared to the traditional chip shown in Figure 4a. This relaxes the current uniformity condition for both the transparent contact and n -GaN. No cur-

rent crowding around any contact pads has been observed up to 130 mA for the chips with the improved design. This is also the case after the Ni/Au layer was thinned down in order to exhibit a resistivity of $\sim 40 \Omega\text{cm}$, i.e. up by a factor of 4 from the original value.

Aging tests were performed for LEDs with thin Ni/Au transparent contacts, ring n -contacts and central p -pad at the temperature of 55°C and an injection current of 30 mA. No current crowding was observed during aging.

High-Power Chip Designs

The improved chip design with the ring n -contact and central p -pad was also used at GELcore to fabricate large size LEDs with side dimension up to 0.7 mm, i.e. 4 times the area of a standard chip. These large devices were operated at a drive current of 300 mA for up to 200 hours without exhibiting current crowding effects.

In future, even higher current levels may be possible with more advanced chip designs employing the same concept of reduced current path distance described here (e.g. the interdigitated contact bars that have been recently proposed by LumiLeds Lighting).

The light output from a large chip operated at 300 mA now reaches the level required for some niche lighting applications such as small flashlights and task lights. A combination of low power consumption, directional light emission pattern, light weight, ruggedness, and reliability are among the advantages that make LEDs particularly attractive for these applications.

Conclusions

Overcoming the problem of current crowding is a prerequisite if larger InGaN LED chips are to be commercialized. An optimized large chip design enables cheaper, more powerful and reliable LED light sources. These are beginning to penetrate the lighting market as replacements for miniature and sub-miniature incandescent bulbs used in niche applications.

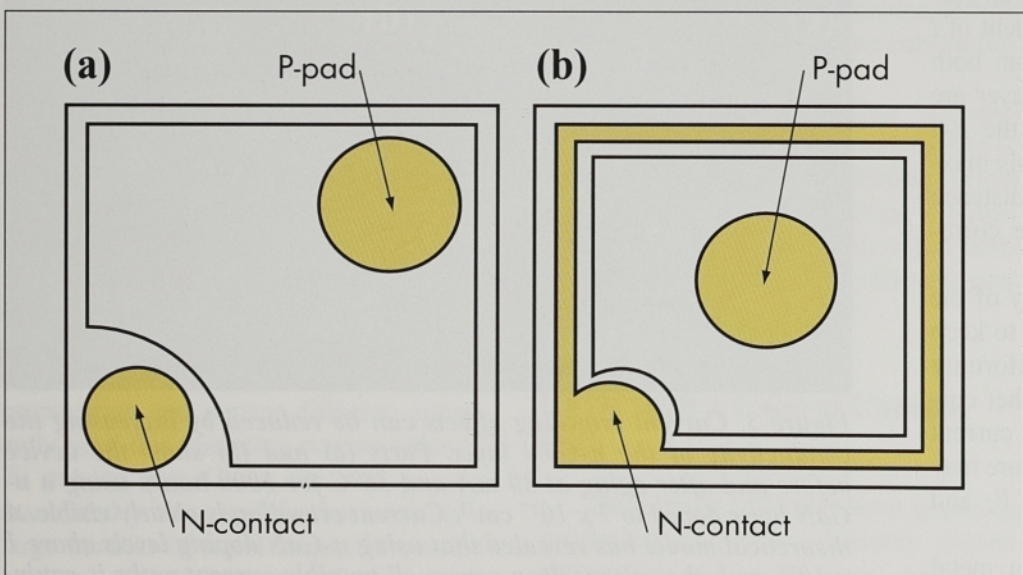
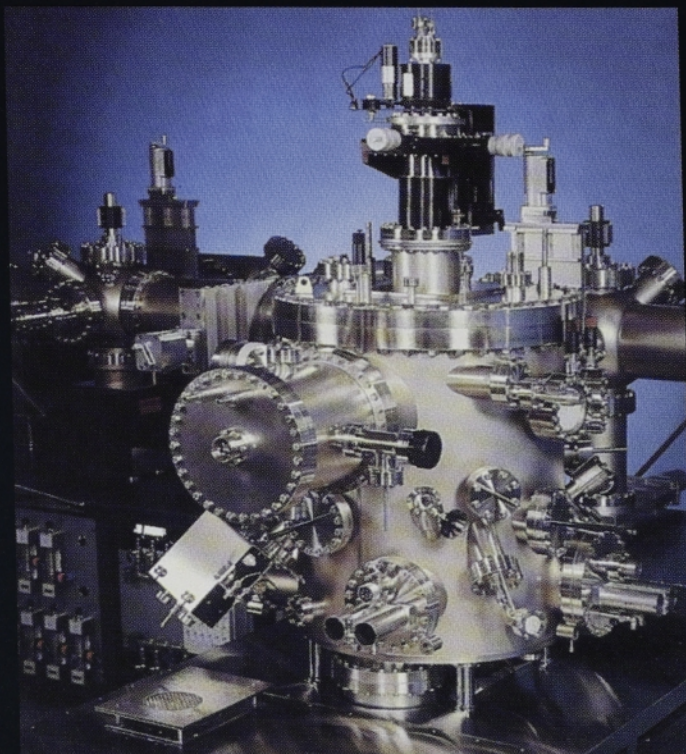


Figure 4. Improvements in current spreading in LEDs with a lateral current path: (a) shows the standard contact used in tests described here, and (b) a new ring n -contact that reduces the current path distance through both the n -GaN and transparent contact, preventing current crowding during high-power operation.

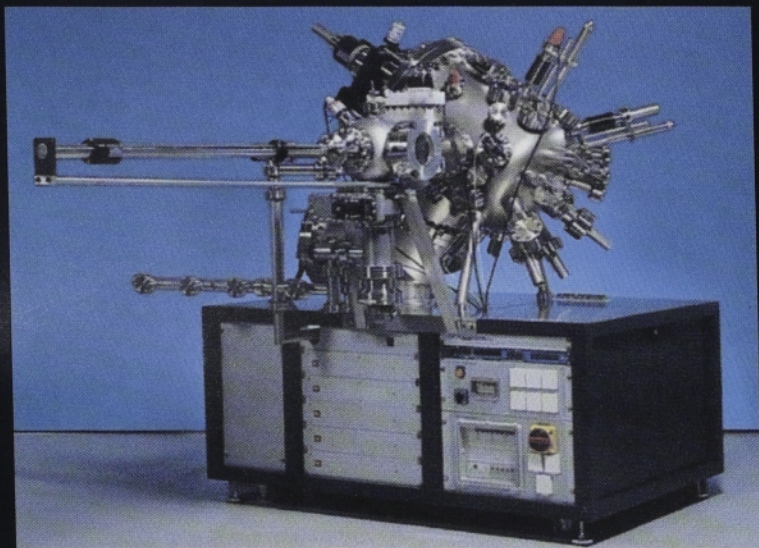
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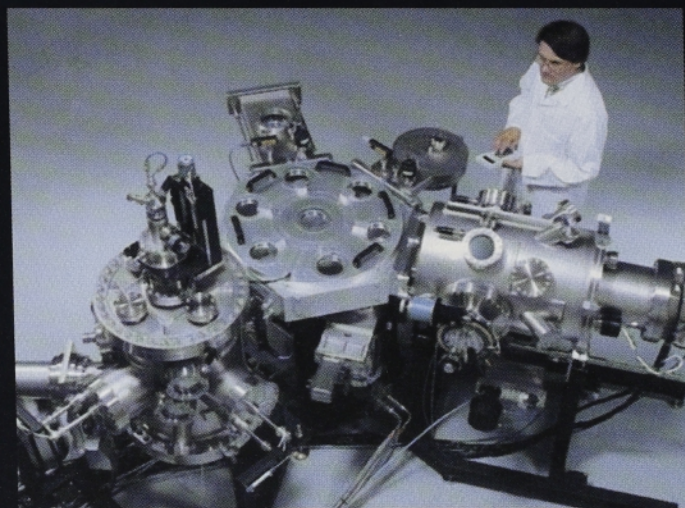
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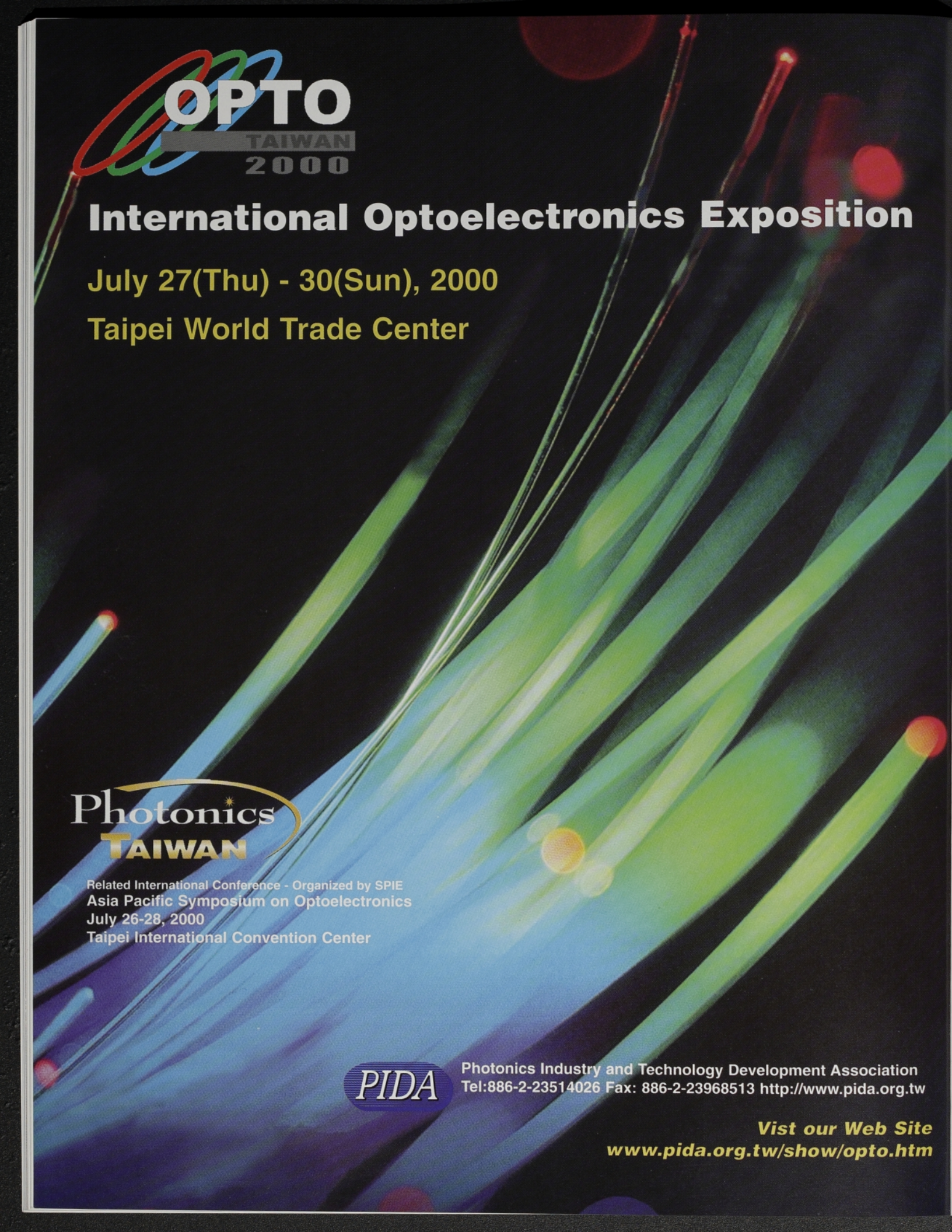
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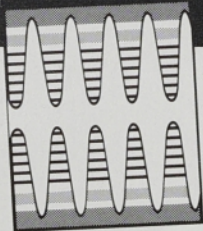
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Sounding a Bearish Note

MARIE MEYER

For many people, the term “semiconductor” is synonymous with “computer chip”. But in the last few years communications applications have displaced computers as the most exciting area in the semiconductor industry. This

has been a great benefit for manufacturers of compound semiconductors. Still, it comes as somewhat of a surprise to learn just how well the top companies are doing. As an example, on March, 30, I drew up a list of the top 30 semiconduc-

tor companies traded in the U.S. markets, and then ranked them by their market capitalization (number of shares multiplied by share price). All companies selling discrete transistors and transistor based ICs were included, including the “fabless”

ones. Opto semiconductor companies were excluded, as were semiconductor equipment companies, like Applied Materials.

Given that the GaAs market is more than 50 times smaller than the Silicon market, it is quite impressive that two GaAs companies cracked the Top 20. Vitesse, with a market cap of \$14.6 billion, is #14 on this “transistor list”, RF Micro Devices, with a market cap of \$10.4 billion, is #19. They outranked such well-known companies as National Semiconductor (#20), AMD (#21), and Cypress Semiconductor (#23). Another “GaAs company”, Conexant, ranked #15, but is probably less surprising, as they also have a thriving silicon business.

When the top two opto semiconductor companies are added to the list, things get really

Name	Market Cap* (\$B)	Market Cap Rank	12 Month Revenue (\$M)	Market Cap/Revenue Ratio	Ratio Rank	Products
Intel	\$424	1	\$29,400	14	10	microprocessors
Texas Inst.	\$133	2	\$9,470	14	9	digital signal processors
Taiwan Semi.Mfg. Co.	\$83	3	\$1,650	50	19	dedicated IC foundry
JDS Uniphase	\$83	4	\$673	123	25	fiber optic components
ST Microelectronics	\$50	5	\$5,060	10	8	broad semiconductor portfolio
Broadcom	\$44	6	\$518	85	21	broadband transceiver chips (fabless)
Micron	\$33	7	\$4,920	7	3	DRAM and other memory products
Analog Devices	\$27	8	\$1,640	17	11	analog & mixed signal chips
Xilinx	\$25	9	\$901	27	15	PLDs (fabless)
PMC-Sierra	\$24	10	\$263	92	22	ATM & SONET chipsets (fabless)
LSI Logic	\$20	11	\$2,090	9	7	broadband chip sets
Linear Technology	\$18	12	\$580	30	16	linear circuits
Maxim	\$17	13	\$688	25	14	wide range of analog semiconductors
AMCC	\$16	14	\$145	112	23	Si & SiGe high speed ICs
Altera	\$15	15	\$837	18	13	PLDs (fabless)
Vitesse	\$15	16	\$310	47	18	GaAs high speed ICs
Conexant	\$14	17	\$1,660	9	6	broad semiconductor portfolio
SDL	\$14	18	\$187	72	20	fiber optic components
Chartered Semi. Mfg.	\$12	19	\$694	17	12	dedicated IC foundry
Atmel	\$11	20	\$1,330	8	5	memory & logic chips
RF Micro Devices	\$10	21	\$261	40	17	GaAs HBT power amps
National Semi.	\$10	22	\$2,020	5	2	broad semiconductor portfolio
AMD	\$9	23	\$2,860	3	1	microprocessor & memory chips
Globespan	\$6	24	\$56	113	24	DSL ICs (fabless)
Cypress	\$5	25	\$706	7	4	digital & mixed signal ICs & RAM

*Market Capitalization = # shares x current price

ATM = Asynchronous Transfer Mode
 DSL = Digital Subscriber Line
 PLD = Programmable Logic Devices
 RAM = Random Access Memory

interesting. See Table. If JDS Uniphase was classified as a semiconductor company, instead of a fiber optic components manufacturer, it would be # 4 on the list; SDL would rank 18th.

If you follow the stock markets closely, you probably know that something more important was happening on March 30: there was a big down-turn in technology stocks, and semiconductor companies in particular were hammered. There was a mixed rally on the 31st, but as this issue went to press the overall outlook was still not clear.

As a result of the turmoil, many investors are now asking whether tech stocks are overvalued. The time-honored tool for comparing stock valuations is the price/earnings ratio - the current price of a share divided by the company's earnings per share. But this measure has fallen into disuse with regard to "New Economy" stocks, largely because of the fact that many of these companies do not have any earnings!

A new ratio has come into vogue - divide the company's market cap by its revenues for the past twelve months. This is the number that is set out in the fifth column of the table on the previous page. JDSU has the highest market cap/revenue ratio of all the stocks in the table; SDL has the 6th highest, and Vitesse and RFMD are the 8th and 9th highest. And if this metric were to be applied to all of the stocks in the compound semiconductor portfolio, companies with even higher ratios would emerge.

Does this mean that compound semiconductor stocks have become too expensive? Unfortunately, there is no easy answer to this question. It is obvious that investors are paying a premium for these stocks. But then again, in many cases their prospects for growth out-strip those of more conventional semiconductor companies. With one exception, all of the large semiconductor companies with high market cap/revenue ratios are focused on communications markets, often to the total exclusion of the computing market.

And since compound semiconductors are the fastest growing segment of this fast growing area, it can certainly be argued that the leaders in this field deserve their very high valuations.

If we are indeed entering a period of prolonged turbulence or even bearishness in the stock market, the most likely impact will be a "flight to quality" as far as the compound semiconductor stocks are concerned. Until now, almost all have fared equally well - the "rising tide lifts all boats" philosophy. In the future, it seems likely that investors made skittish by the big correction of late March will be more selective in their choices.

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Company	Symbol	Last	52 Week Low-High	Market Cap*	P/E Ratio**
U.S. GaAs IC Companies					
Alpha Ind.	AHAA	95	17 5/8 - 156 1/2	1.889B	78.2
Anadigics	ANAD	66	10 5/8 - 112 1/8	1.799B	684.38
Celeritek	CLTK	63 1/4	3 5/8 - 85 1/4	484.7M	N/A
Conexant	CNXT	71	11 5/8 - 132 1/2	14.383B	118.75
RFMD	RFMD	134 3/8	19 - 184 1/2	10.724B	240.74
TriQuint	TQNT	73 1/2	6 1/8 - 135 1/2	2.781B	108.86
Vitesse	VTSS	96 1/4	20 3/8 - 115 11/16	15.151B	197.87
U.S. Opto Companies					
Agilent	A	104	39 13/16 - 162	47.008B	71.92
Coherent	COHR	52	11 5/8 - 107 3/8	1.291B	98.66
Cree	CREE	112 7/8	18 5/8 - 202	3.724B	208.47
JDS Uniphase	JDSU	120 9/16	12 13/16 - 153 3/8	85.870B	N/A
Ortel	ORTL	187 11/16	6 - 229 1/8	2.400B	N/A
SDL	SDLI	212 7/8	18 15/16 - 244 3/4	15.486B	516.89
Uniroyal Tech.	UTCI	47	7 1/4 - 72 7/8	581.5M	80
U.S. Semiconductor Materials & Equipment Companies					
ATMI	ATMI	47 3/4	18 1/4 - 60 3/4	1.411B	121.62
AXT	AXTI	32 3/8	10 7/8 - 49 9/16	606.2M	1006.25
Emcore	EMKR	115 1/16	11 1/4 - 173	1.778B	N/A
Kopin	KOPN	68 3/4	6 - 99 3/4	2.056B	2283.33
Tegal	TGAL	6 5/8	2 - 13 1/2	73.6M	N/A
Trikon	TRKN	14 1/4	1 - 17 1/4	134.0M	N/A
European Companies (Currency Data in Euros)					
Aixtron	AIX	229	60 - 281 3/4	3.575B	365
Filtronic	FTC	30.121	25 1/8 - 37	2.1B	77
IQE	IQE	?	?	?	?
Picogiga	PICO	90 3/8	9 1/2 - 128	142M	143

*Market Capitalization = # shares x current share price

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

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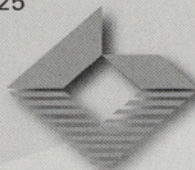
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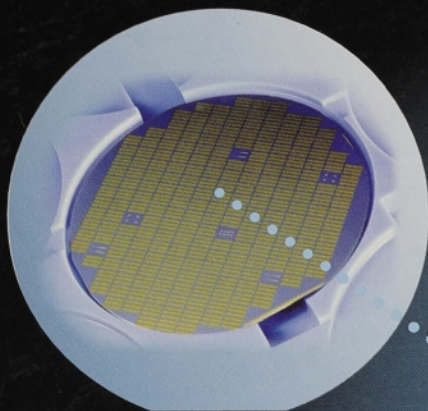
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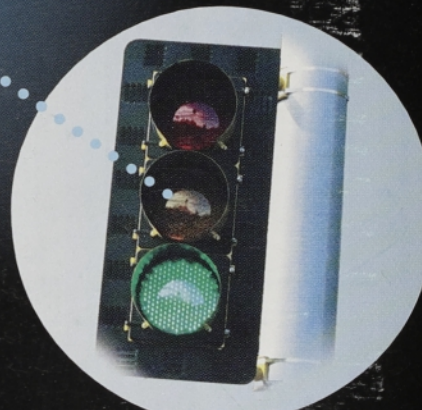
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