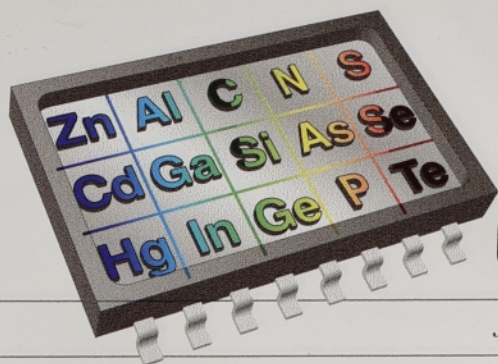




COMPOUND SEMICONDUCTOR

January 2000

Volume 6 Number 1

Things to Watch

Components for Fiber Optics
3G Wireless • High Brightness LEDs
Silicon Germanium • Pump Lasers
Broadband Microwave • Optical Networking
Silicon Carbide ICs • DVD
InP Microelectronics

January 11, 2000

Benjamin John Whitaker

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Length 20.5 inches

Proud Parents Tim & Jane



Also in this Issue:

- New Colors from GaN
- Blue VCSELs
- THz Communications
- GaAs IC Report



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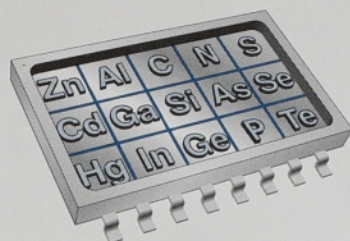
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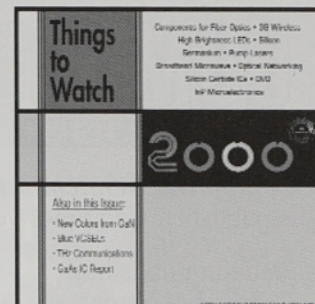
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COVER STORY – THINGS TO WATCH IN 2000

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The "2000" logo is a collage consisting of multi-color rare earth (RE)-doped GaN electroluminescent devices (ELDs) from the Nanoelectronics Laboratory of the University of Cincinnati (UC). Green emission is from GaN:Er ELDs, red from GaN:Eu, yellow from GaN co-doped with Er+Eu and blue from GaN:Tm. Five working GaN:RE ELDs make up the shape of the "UC" logo. This work is described in detail on page 48.

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COMPOUND SEMICONDUCTOR

Compound Semiconductor
is published nine times yearly by

Franklin Publishing
163 Cabot Street
Beverly, MA 01915 USA
TEL [1] 978 927 9994
FAX [1] 978 927 9893
Individual annual subscription
price: \$90 U.S., \$115 foreign.
Library rate: \$300 U.S. and foreign.

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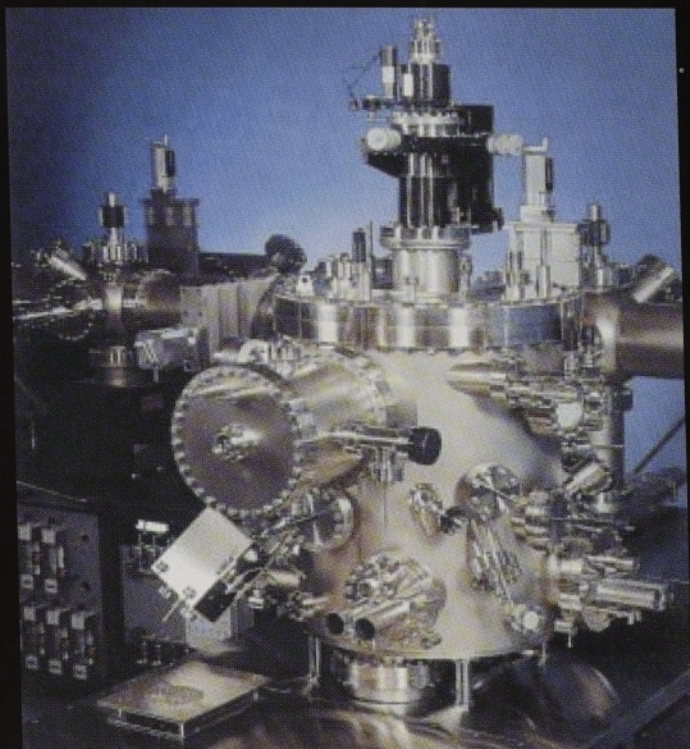
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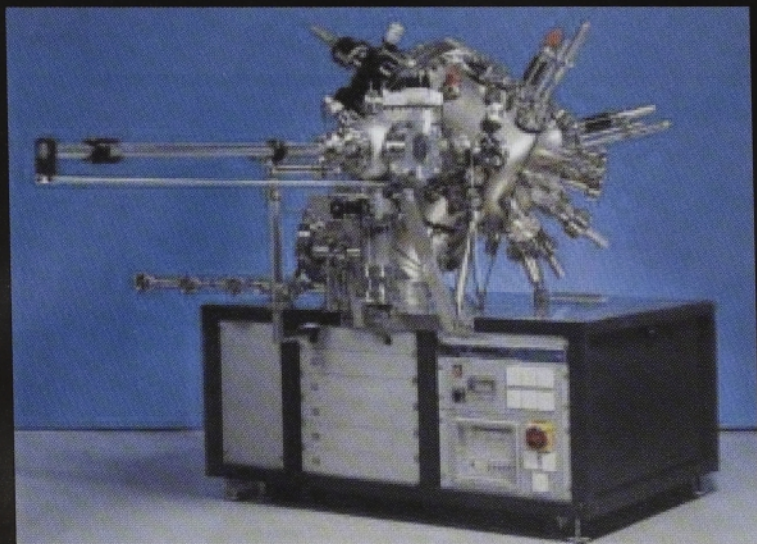
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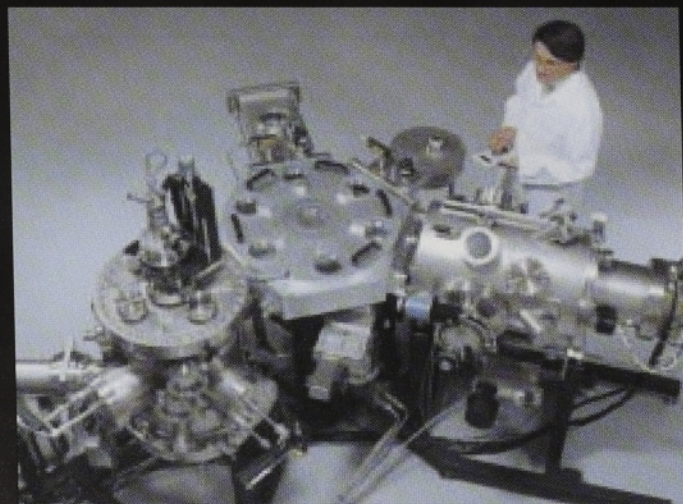
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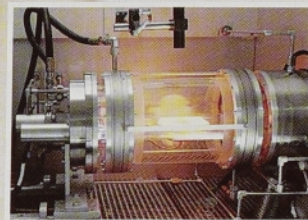
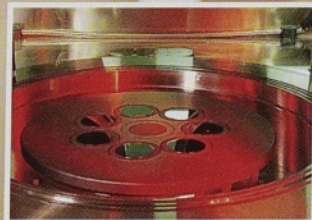
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Internet Match-Making in the Telecom Industry

Three months is a long time in the telecommunications industry. The world's fiber optic equipment makers are all working furiously to assemble all the pieces they will need to address the opportunities presented by the explosive growth of the Internet (see box). And so while *Compound Semiconductor* was on its winter hiatus, a backlog of reports on deals amongst fiber optic equipment makers emerged. The following is a brief summary. For more forward-looking coverage of fiber optics see our Cover Story, beginning on page 65.

JDSU Uniphase + E-Tek Dynamics

JDS Uniphase became the world's largest producer of telecom optoelectronics in January when it agreed to buy E-Tek Dynamics Inc., for \$15 billion. E-Tek is a major producer of passive optical components. The two companies combined will have revenues of approximately \$1.3 billion, or roughly 30% of the estimated \$4.5 billion global market for telecom optical components and modules. Lucent, with approximately \$1 billion in telecom optoelectronic sales, is in second place. By most estimates, Corning (see below), Furukawa and Alcatel (see page 8) round out the top five.

This move is just the latest in a string of acquisitions for JDS Uniphase. And as this issue went to press, shares in SDL, Inc. were soaring on rumors that they would be the next company to join the fold. However, many analysts say this would be one acquisition too far, given SDL's currently very high valuation.

Nortel + Qtera

On December 15 Nortel Networks announced that it was acquiring Qtera Corporation for \$3.25 billion. Qtera is the leading developer of ultra-long-reach optical networking systems which hold the promise of sending optical signals as far as 4000 kilometers without electrical regeneration.

"The surge in Internet usage and eBusiness makes the delivery of the high-performance, all-optical Internet essential," said John Roth, president and chief executive officer, Nortel Networks. "The addition of Qtera's capabilities enhances Nortel Networks' ability to deliver to customers the greatest capacity, the highest speed and, now, the longest reach Optical Internet solutions in the market."

Nortel reports that Qtera's approach has been successfully trialed by Qwest Communications, one of Nortel's major customers.

The deal is an extremely lucrative one for Qtera, which is headquartered in Boca Raton, Florida. It has just 170 employees, few customers, and very little in the way of revenues. Upon completion of the acquisition, Qtera will become a wholly owned subsidiary of Nortel Networks.

Corning + Lasertron

In November Corning Inc. (Corning, NY) scooped up Oak Industries Inc. (Waltham, MA) in a stock deal worth approximate-

ly \$1.8 billion. The star in the portfolio of companies owned by Oak is Lasertron Inc., a manufacturer of telecom lasers, especially pump lasers for EDFAs (erbium-doped fiber amplifiers). The deal is expected to close during the first quarter of 2000.

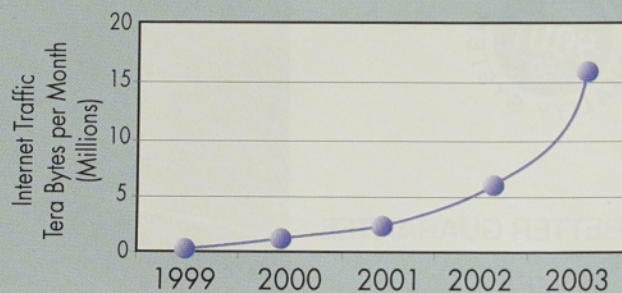
Lasertron is one of the few companies in the pump laser field with both internal laser chip making capability and packaging expertise. They also recently expanded manufacturing capacity for DFB transmission lasers.

Corning is one of the leading suppliers of optical fiber. They are also a major supplier of EDFAs, which in the past they have built using pump modules supplied by Lasertron, as well as SDL and others.

Cisco Systems + Pirelli Optical Systems

And finally, in late December Cisco Systems announced that it would acquire the optical systems business of Pirelli S.p.A. of Milan, Italy. This represents Cisco's first move into the DWDM market. As part of the deal, Cisco will invest \$100 million in Pirelli's optical components and submarine transmission system business. Cisco will receive 10% ownership of that unit. Pirelli was the first vendor to offer 10 Gb/s transmission systems with open interfaces that allow the equipment to interoperate with other vendor's systems. According to Cisco, Pirelli's DWDM business doubled in 1999, and the company believes that it can maintain that pace. Cisco executives have noted that they do not plan to maintain a sole, captive supply of optical components.

Internet Traffic Report

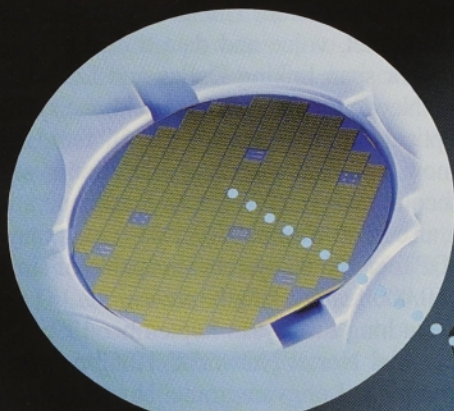


Source: RHK

Internet traffic in North America has reached 350,000 terabytes per month and is forecast to rise sharply, according to a new study released by telecom market research firm RHK in late January. The firm says "Internet traffic continues to soar to dramatic new levels, driving the need for new, denser equipment solutions in a still evolving service provider network architecture." RHK indicates that data traffic has now surpassed the amount of voice traffic on the nation's telephone system.

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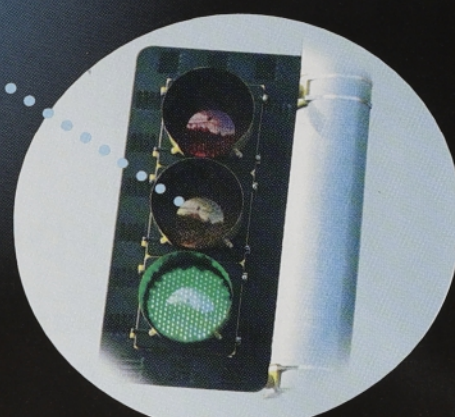
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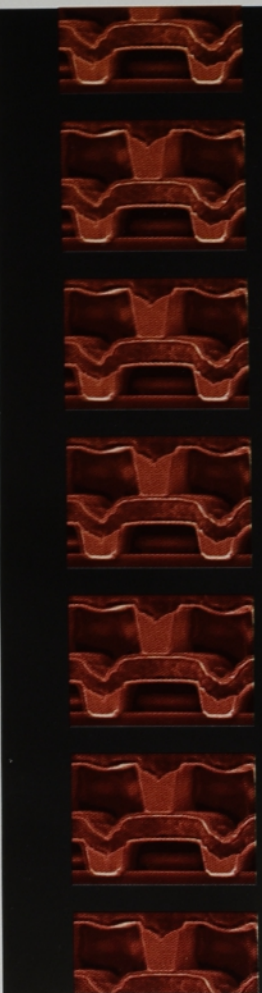
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Nortel and MCI Make First Demo of Terabit Internet

On January 18 Nortel and MCI WorldCom announced they successfully completed the industry's first live commercial trial of a terabit per second Internet transmission. The late-December trial was staged carrying live Internet, voice and data traffic on MCI WorldCom's existing network span linking Dallas and Longview, Texas and relied on Nortel Networks' OPTera LH backbone system and the OPTera 1600G optical amplification system. OPTera LH is commercially available now, and the optical amplification system will be available in the second quarter 2000. The system, operating on a 10 Gbps platform, uses 160 channel DWDM. Operating at maximum capacity, the OPTera 1600G system is capable of simultaneously transmitting 360,000 feature-length movies.

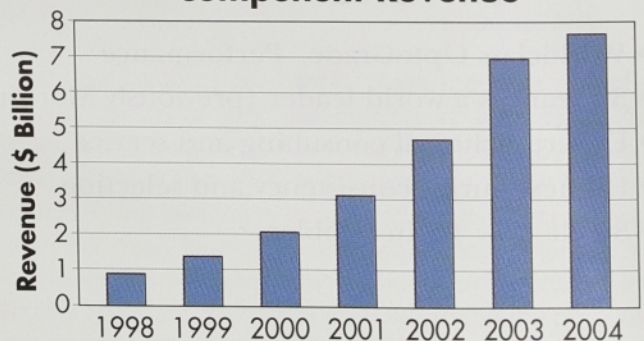
MCI and Nortel have a long history. In September 1995 MCI was first to commercially trial Nortel Networks' 10 Gbps system (OC-192) on the same Dallas to Longview route. Nortel claims to have 90% of the market for 10 Gbps SONET/SDH systems.

RHK Names Top DWDM Suppliers

Nortel Networks is the top supplier of DWDM and SONET/SDH optical equipment, according to figures recently released by the market research firm of Ryan Hankin Kent (RHK). Nortel's shares of these markets were 32% and 26% respectively. RHK also said that Alcatel was the number one systems vendor in the global telecommunications transport market, which comprises submarine networks and other long-haul optical transmission systems. Alcatel holds a 21% share in the overall market, as well as 37% share of the submarine networks segment and a 37% share of the digital cross-connect systems segment. "Alcatel has successfully penetrated all global markets," says Stephane Teral, Director, European Transport with RHK. "Considering their strong position in submarine systems, Alcatel is the global leader in terms of DWDM market share when you consider the global market encompassing both terrestrial and sub-sea applications."

RHK reports the market for key terrestrial DWDM optical components grew to \$1.4 billion in 1999. They predict an annualized growth rate of 50% through 2003, reaching \$7.0 billion.

Key Terrestrial DWDM Optical Component Revenue



Source: RHK

Lucent Active in 980-nm Pump Laser Modules

Tyco Submarine Systems Ltd. has given Lucent Technologies a major order for high-power laser modules for use in EDFAs in Tyco's submarine cables. Lucent says the modules are a new design that provides up to 120 mW, compared to 75 to 85 mW in previous models. The deal could be worth as much as \$100 million over the next 18 months. It follows upon a December, 1998 order for 980nm pump modules that is expected to be worth up to \$150 million.

"Our latest undersea components and our expertise in the development and manufacture of laser modules enable us to meet Tyco's high-reliability and certification requirements," said Dan DiLeo, president of the optoelectronics components business of Lucent's Microelectronics Group. "We're already planning next-generation components to operate at even higher power levels delivering even more bandwidth in the coming year."

Tyco is one of the leaders in the submarine fiber optic cable business, having already completed 85 undersea fiber optic networks, with more than 350,000 kilometers of fiber optic cable connecting over 100 countries.

Ortel to Supply Low Cost Chips

In other news, Lucent has given an exclusive contract to Ortel Corp. (Alhambra, CA) for the purchase of uncooled 980 nm pump laser chips for use in Lucent's next-generation EDFA modules designed for metropolitan area networks.

Ortel had previously attempted a vertically integrated approach to the 980nm market - making their own chips, doing their own packaging, and controlling their own distribution. However, the company decided to exit this business in late 1998 due to disappointing results. The new arrangement is intended to add more value, as it will leverage Ortel's chip-making capacity with Lucent's packaging and distribution expertise.

According to an Ortel spokesperson, the new product offering is targeted at emerging metro applications that don't have high power requirements. Because they are uncooled, the lasers will be less expensive, as they will not require a thermoelectric cooler or external grating for stabilization. They will also consume less power and have a smaller footprint.

"This alliance enables Ortel and Lucent to combine both companies' proven abilities in laser design and automated packaging to develop an innovative uncooled 980 nm laser solution for metro EDFA modules," says Steve Rizzzone, chairman, president and CEO of Ortel.

"This supplier relationship will allow us to lower the costs of EDFA modules in the metro market," says Anders Olsson, VP of the Optoelectronics business unit in Lucent's Microelectronics Group. "Since these modules can operate over a wide temperature range, on-board coolers are not needed, resulting in significant savings in power consumption and system costs. As a result, we see the cost of 980 nm pump lasers dropping to commodity levels in the next six months."

Furukawa Establishes FITELE

Furukawa Electric Co., Ltd. of Japan has announced the formation of FITELE Technologies, Inc., a wholly owned company headquartered in Clinton, NJ. The company says that it expects to emerge as one of the top 3 suppliers of optoelectronic components within 24 months.

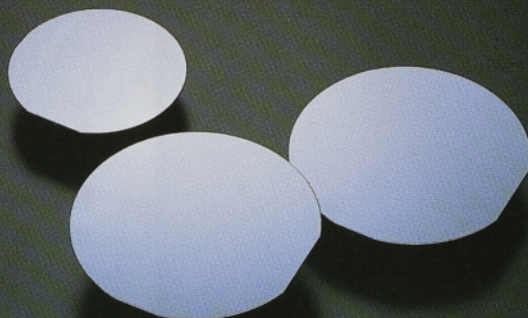
Furukawa Electric is an established manufacturer of 1480 nm pump lasers. The company will also provide "integrated custom solutions in passive devices for DWDM optical networking systems and optical amplifiers, and will emphasize a product roadmap based on tunability and MEMS technology."

FITELE Technologies, supported by over 1,000 Furukawa scientists, engineers and product developers, will concentrate on marketing, regional product development, sales, and manufacturing to aggressively participate in the large and rapidly growing North American market of fiber optics and optoelectronics products.

The newly appointed CEO of FITELE Technologies is John Pilitsis, the former COO of Lucent Technologies and Chairman of the Optoelectronics Industry Development Association.

In other news, JDS Uniphase and Furukawa announced in November that the two companies would continue to collaborate with each other on future developments of optoelectronic and manufacturing technologies for rapidly developing fiber optic markets. Furukawa also reaffirmed its intention not to compete with JDS Uniphase on future products.

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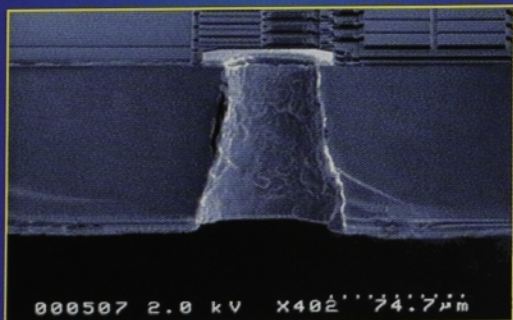
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NITRIDE NEWS

Nakamura Moves to UCSB

Shuji Nakamura, the man largely responsible for the pre-eminent position of Nichia Chemical Industries in the field of GaN-based LEDs and lasers, has chosen a future in academia. Dr. Nakamura has accepted an appointment to the faculty of the College of Engineering at the University of California at Santa Barbara (UCSB), and will take up the position in February. Nakamura has conducted research in GaN-based materials and devices at Nichia since 1979, and headed the company's R&D Department since 1993.

"I am very grateful to Nichia for the superb research opportunities they have provided me," says Nakamura. "But I felt that I had come to a crossroads in my life. There is a spectrum of orientation for research that ranges, let us say, from the purely commercial to the purely academic. I decided that an academic context would now be better for my work."

"Nakamura has achieved remarkable creative feats with the new semiconductors based on gallium nitrides," says UCSB Chancellor Henry Yang. "What a pleasure it is for UCSB to welcome such a world-class researcher to Santa Barbara."

Nakamura, aged 45, grew up on the southern island of Shikoku, Japan, and received his degrees from the University of Tokushima, Japan. He holds 80 Japanese and ten U.S. patents and has authored more than 150 scientific papers and two books.

Cree Expands, Receives LED Orders

Cree Inc. has commenced facility construction to expand its manufacturing capacity for high brightness LED products by an additional 125,000 sq. ft. This will increase the square footage of the company's production facilities by 45%, and should be completed towards the end of 2000.

In the last few months, Cree received several new orders for LEDs, primarily from Taiwanese customers, valued at \$22 million. These orders target new and emerging applications including cellular phones and other consumer products. "Cellular phone markets provide some of the fastest growing new opportunities for our products and continue to expand the breadth of our customer and application base, particularly in Taiwan," says Chuck Swoboda, Cree's president and COO. At the end of December, Cree announced the receipt of further LED orders totaling \$14 million from customers in several Asian countries.

Cree Shrugs Off Nichia Patent Infringement Allegation

According to Cree, one of the distributors of its LED products in Japan, Sumitomo Corp., has been named in a lawsuit brought by Nichia Corp. Nichia holds a large number of patents in the field of GaN-based LEDs and lasers, and is involved in an ongoing series of lawsuits with Toyoda Gosei [see CS 5(4), p. 6]. The suit against Sumitomo, filed in Tokyo District Court, alleges infringement of a patent issued to Nichia in Japan and seeks an injunction that, if granted, would preclude Sumitomo from selling Cree's older, standard brightness blue LED product in Japan. Cree's management believes the infringement allegation is without merit and that the lawsuit is motivated by competitive factors. Cree is assisting Sumitomo in defending the case in accordance with the terms of the parties' distributorship agreement.

Asked to comment on the situation, Chuck Swoboda, Cree's President and COO, said, "While no one can predict the outcome of any litigation matter, Cree is confident that its products do not infringe the patent in questions, and believes the court should find accordingly. We are defending the matter vigorously."

Pioneer and Rohm Initiate Blue-Violet Laser Development Partnership

Pioneer Corporation (Tokyo, Japan) and Rohm Co. Ltd. (Kyoto, Japan) have announced a partnership agreement to develop GaN-based blue-violet semiconductor lasers for next generation optical storage systems. By combining Pioneer's expertise in optical disk technology and GaN-based laser fabrication with Rohm's experience in the mass production of laser diodes, the two companies plan to produce commercial products within two years.

Pioneer has been at the forefront of DVD development, and recently exhibited a rewritable DVD-RW recorder at the 1999 Japan Electronics Show. In the near future, it is expected that services such as multi-channel digital broadcasting will create a strong demand for new optical disc systems with a large recording capacity that exceeds the current DVD format. For example, home server systems that are capable of recording and reproducing two hours of high definition signal information will be required.

Blue Lasers for Next-Generation DVD

In order to fulfil these increased data storage needs, Pioneer has been working on a new recording/playback method for the ideal optical disc system, as well as developing new technologies for signal processing and data coding. A short-wavelength laser light source has been under development at its Corporate R&D Laboratories since 1992, under the guidance of Dr. Akasaki of Meijo University.

The wavelength of laser light used in an optical storage system largely determines the size of the laser spot on the disk, which in turn determines the storage capacity. While CD systems use 780 nm lasers and today's DVD players use 650 nm sources, the next generation of DVD players will use blue-violet lasers at wavelengths close to 400 nm.

In June 1998, Pioneer successfully demonstrated pulsed operation of an InGa_N-based laser at room temperature. The device structure, grown by low-pressure MOCVD on a (11 $\bar{2}$ 0) (a-face) sapphire substrate, contained a MQW active region with 10 undoped In_{0.15}Ga_{0.85}N wells and Si-doped In_{0.03}Ga_{0.97}N barriers.

Mirror facets were formed by cleaving the substrate along the (1 $\bar{1}$ 02) (r-face) direction, and the typical cavity length was 500 μ m. Since then, Pioneer made progress in lowering the threshold current and operation voltage by improving the micro-fabrication process and optimizing the structure, and as a result demonstrated CW laser operation in 1999.

Rohm Brings Mass Production Experience

Rohm was the first company to commence mass production of semiconductor laser structures grown by MBE. In 1997, Rohm established the world's largest mass production line for red semiconductor lasers, with a capacity of 1 million units per month. These 650 nm lasers, designed for operation in current DVD players, have a maximum output power of 7 mW, a maximum operating temperature of 70°C and a MTTF (mean time to failure) of 10,000 hours at 60°C and 5 mW. Furthermore, Rohm has developed basic technologies for manufacturing blue LEDs and is also developing blue lasers using materials other than GaN.

Pioneer and Rohm intend to combine their technological knowledge in order to "make further improvements in crystal growth technology, device structure and production processes to obtain a practical output level and life length."

450 nm Lasers Announced by Nichia

While violet lasers emitting in the 390-420 nm range have been demonstrated by a number of groups, longer wavelengths are difficult to achieve in InGa_N-based devices. This is because the threshold current density increases dramatically as the In mole fraction of the InGa_N well layers increases. Nichia has now demonstrated* the first real blue InGa_N-based lasers at 450 nm, a wavelength required for full color laser displays. The devices had an estimated lifetime of 200 hours under room temperature CW operation at an output power of 5 mW. The lowest threshold current density was obtained with a single InGa_N QW active layer, and the In mole fraction required to achieve operation at 450 nm was 30%. [*S. Nakamura et al, Appl. Phys. Lett. 1999, 76(1), p. 22]

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Implant Sciences to Develop Blue Laser Using Ion Implantation

Implant Sciences Corporation (Wakefield, MA) was recently awarded a \$750,000 contract from the U.S. Army to develop a nitride-based, single-mode blue laser diode. The contract is the second phase of a two-part BMD-sponsored program, and follows directly from the company's development of a GaN blue LED with an ion-implanted base.

A feature of the ion implantation technology developed by Implant Sciences during the first phase was the attainment of a high acceptor concentration in the diode p-type region. This was achieved through the use of an AlN capping layer to prevent GaN decomposition and contamination during implantation by Mg^+ . Also, Mg was co-implanted with P, which helps the Mg species to move to electrically active sites.

The company now wants to implement the processes developed for the LED, and the specially designed end-station, into a fabrication technology for laser diodes. The emphasis will be on using ion implantation to form AlGaIn waveguides and low resistivity ohmic contacts to p-type GaN.

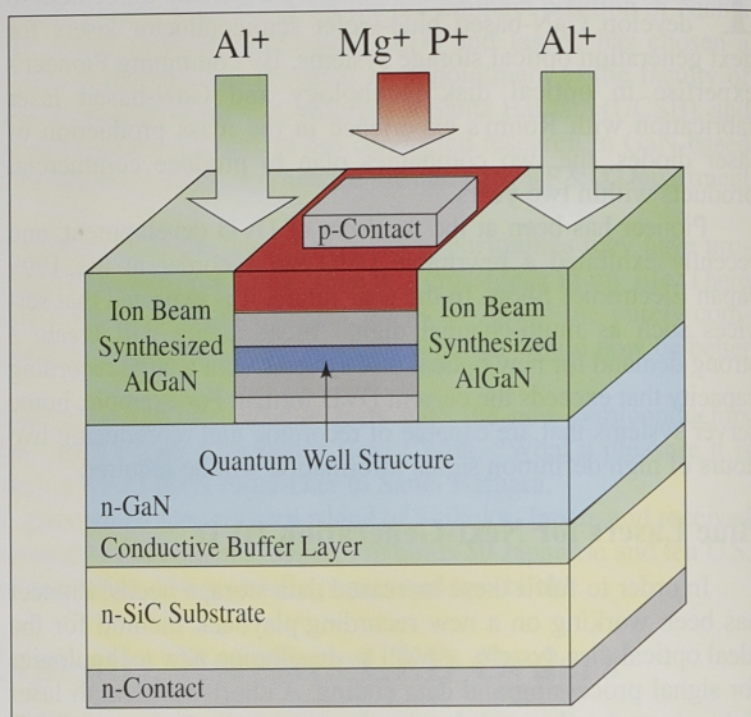
The "Cycling Implant" Process

"To develop a GaN laser diode, one of the issues will be achieving the high dose implantation required with low levels of radiation damage," says Dr. Leonid Krasnobaev, Implant Sciences' principal research scientist. Implantation causes stoichiometry changes, particularly in materials such as InP, SiC or GaN, which consist of elements with greatly differing atomic masses. Large displacements of the host material atoms and results in insufficient numbers of the right species being locally available to correct the stoichiometry during annealing and recrystallization.

To prevent these effects, the company has developed a process it calls "cycling implant", which results in high quality material with a final dose of up to $10^{18}/cm^2$. The key is the use of a series of low-dose ion implantation steps, typically around $10^{13} cm^{-2}$, each followed by a rapid thermal anneal at temperatures in the 600-1200°C range. To attain the required doping concentrations in GaN, this cycle is usually repeated around a hundred times. At these low implant doses, asserts Krasnobaev, the stoichiometry of the crystal does not change as drastically compared to high dose implantation. As a result, he says, the cycling implant process leaves the implanted crystal almost without defects, and no further heat treatment is required to activate the dopants.

Ion-Implanted Waveguides for GaN Blue Lasers

The same approach is being employed in the development of an ion-implanted waveguide for a single-mode laser. In the structure shown in the figure, Al will be implanted into GaN to synthesize an AlGaIn waveguide. To produce material with a low refractive index and low levels of radiation damage, a cycling implant with a total dose of 10^{17} - $10^{18}/cm^2$ is required.



Conceptual diagram showing how Al^+ , Mg^+ and P^+ ions can be implanted into an epitaxial structure and patterned to define a single-mode laser. Implant Sciences says the implantation damage is controlled by a "cycling implant" process using low implant doses (10^{12} - $10^{13}/cm^2$) followed by rapid thermal annealing. The required carrier concentration is achieved by repeated cycling of the process.

"The doping level produced by ion implantation in GaN is now comparable to that produced during film growth, and is beginning to be competitive with other doping processes," says Krasnobaev. Contrary to doping during film growth, ion implantation using either a mask or photoresist patterning now allows both n- and p-type planar doping. This offers new possibilities for GaN-based device design and fabrication, he adds.

Uniroyal Doubles Reactor Capacity

Citing a very strong market demand for high brightness LEDs, Uniroyal Technology Corporation is doubling its capacity for blue and green devices by purchasing two additional Emcore D180 reactors. "We are doubling our reactor capacity based on strong market growth expectations and the exceptional interest we are receiving from customers for our high brightness capabilities," says Howard Curd, Chairman and CEO of Uniroyal Technology Corp. The additional reactors are expected to be ready for commercial production by June 2000. Uniroyal's Tampa facility will produce high brightness blue and green LEDs as well as red, orange and yellow colors.

Nitres Develops AlGaN/GaN HEMTs with Record Power Performance

Nitres, Inc has recently developed high performance AlGaN/GaN HEMTs, remarkably advancing the state-of-the-art of GaN-based microwave power technology [1]. The devices were grown by metal-organic-chemical-vapor deposition on semi-insulating SiC substrates. The epi-layers consisted of an insulating GaN buffer and a modulation-doped AlGaN layer to supply charge for the 2-dimensional gas as well as to offer a Schottky-gate barrier.

The gate lengths were 0.5-0.6 μm defined by optical stepper lithography. Small-signal current-gain and power-gain cutoff frequencies were measured as 30 GHz and 100 GHz respectively for the 0.5- μm gate devices at a drain voltage of 30 V. These superior gain properties at such a high bias voltage are in agreement with the high electron velocity predicted for this material system. Figure 1 shows the on-wafer measurement results of large signal characterization of a 100-mm-wide device. A power density of 9.1 W/mm was achieved along with 47% power added efficiency (PAE). This power density level is the highest for a field effect transistor (FET) to date and is 9-times greater than GaAs-based FETs in the same frequency band. When optimized for efficiency, an excellent PAE and power density combination of 60% and 6.5 W/mm was also achieved.

Large-periphery devices were also fabricated and flip-chip bonded on to AlN carriers for thermal management. A 2-mm-wide device generated an output power of 9.8 W at 8.2 GHz with 44% PAE as seen in Figure 2. This represents a much improved scaling effort than before since with 2-mm gate periphery, this device outperformed previously reported 3-mm gate periphery AlGaN/GaN HEMTs [2] in all aspects including output power, PAE and operation frequency.

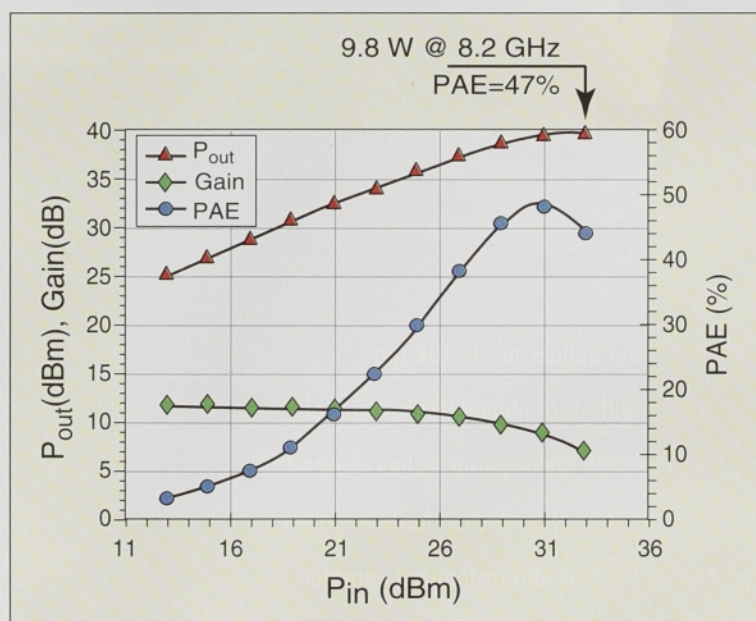


Figure 2. Power performance of 2-mm-wide AlGaN/GaN HEMTs, showing an output power of 9.8 W with 44 % PAE at 8.2 GHz.

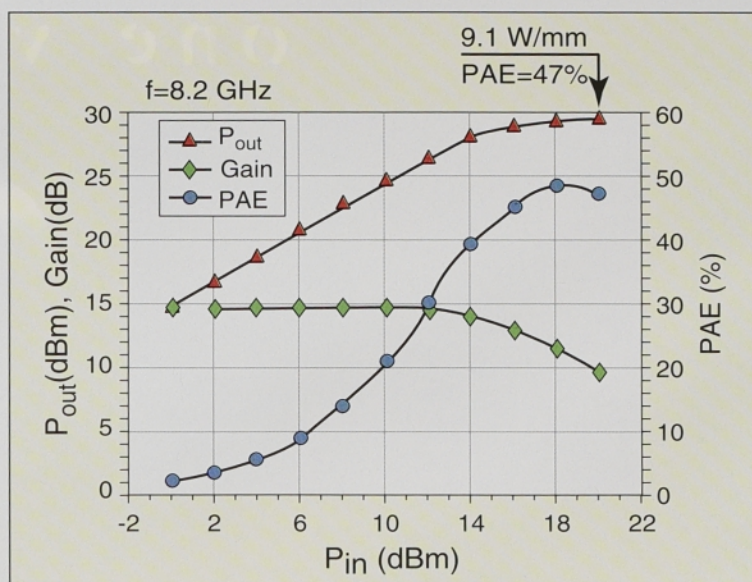


Figure 1. Power performance at 8.2 GHz showing a record power density of 9.1 W/mm with a PAE of 47%.

Further work at Nitres resulted in an amplifier IC demonstration employing a 4-mm-wide device and delivering 14.1 W output power at 8 GHz with 25% PAE, which sets the highest power level for a GaN-based FET or amplifier at X band to date (Figure 3).

GaN device

and IC technology

will target both

military and com-

mercial applica-

tions. The former

include radars

(ship-board, air-

board and ground)

and high perfor-

mance space elec-

tronics; and the lat-

ter include base

station transmitters,

C-band Satcom, Ku-K band VSAT and broadband satellites,

LMDS and digital radio. Initially, GaN will be a replacement tech-

nology and vie to take markets from existing technologies includ-

ing high power microwave tubes. Ultimately, the compact size of

GaN-based transistors will lead to lower cost products. This will

increase system efficiency, reduce system costs, and will expand

the market applications.

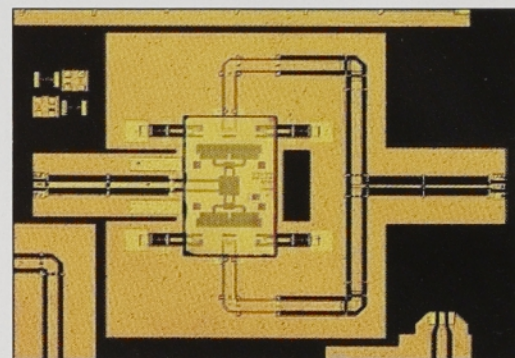


Figure 3. Photograph of Nitres' 14.1 W amplifier.

[1] Y.-F. Wu et al, "High Al-Content AlGaIn/GaN HEMTs On SiC Substrates with Very-high Power Performance", *IEDM Technical Digest*, pp. 925-927, Dec. 5-8, 1999.

[2] S.T. Sheppard et al, "High Power Microwave GaN/AlGaIn HEMTs on Silicon Carbide", *IEEE Electron Device Lett.*, Vol. 20, No. 4, pp. 161-164, April 1999.



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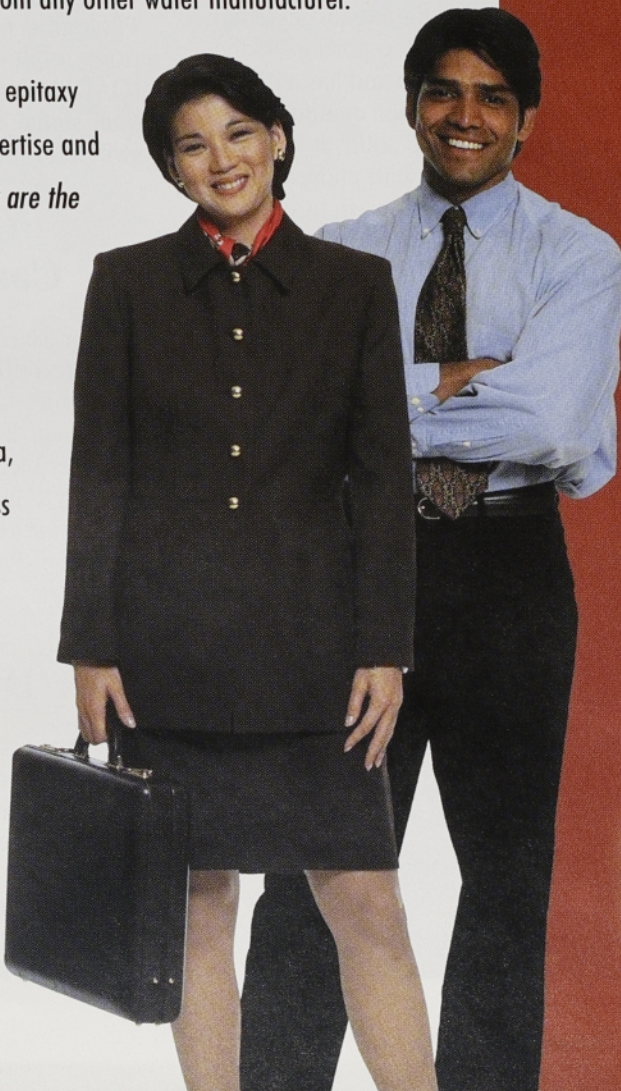
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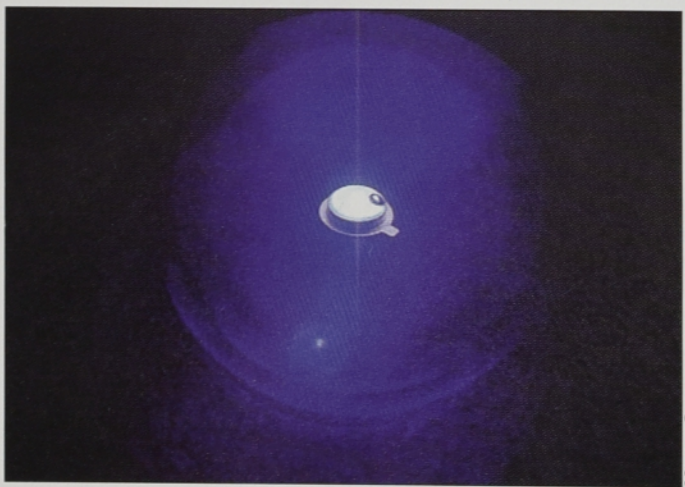
Citizen Doubles LED Production Capacity

Citizen Electronics, one of world's largest LED manufacturers, aims to double its production capacity from the current level of 200 million units per month by March 2000. The company will invest more than 2.5 billion yen (\$23.8 mil) to double the combined output capacity of its subsidiaries in Fukushima Prefecture, Japan and the Chinese province of Guangdong. The expansion targets the growing demand for LEDs in wireless handsets – Citizen describes this market as “extremely buoyant” and states that the number of LED chips consumed by a cellular phone exceeds 10. In 1999, Strategies Unlimited ranked Citizen as the 10th largest manufacturer of visible LEDs worldwide [see CS 5(3), p. 10].

Nitres Develops Record High Efficiency InGaN LED

Nitres Inc. (Westlake Village, CA) reports that it has developed a near-UV/violet InGaN LED with 20% quantum efficiency (QE) - see Figure. This is the highest external QE ever reported for an LED in the UV-to-blue portion of the wavelength spectrum. The LED emits at 405 nm and has a power output of 12 mW at a drive current of 20 mA. High quantum efficiency is critical to making energy-efficient solid state light bulbs, using UV and near-UV LEDs together with phosphors or other wavelength conversion materials. The Nitres light emitter has overall (wall plug) efficiency of 12%.

“This technology has the potential to revolutionize the lighting industry by enabling solid state light bulbs with high efficiency and lifetimes of 5-10 years,” says Fred Blum, Nitres’ CEO. “Such solid state bulbs potentially will have efficiencies which are 2-3 times greater than incandescent bulbs.” Nitres is working on light emitters operating below 400 nm; at these wavelengths, the light emitter better matches typical phosphor absorption bands.



Nitres Inc.

EG&G Becomes PerkinElmer

EG&G, Inc., a global, diversified technology company that manufactures a wide range of optoelectronic components, recently began operating under its new name of PerkinElmer, Inc. During the course of 1999, EG&G sold its Technical Services division, and this group retained the EG&G name. When the company subsequently acquired the Instruments division of PerkinElmer, it gained a new name as well.

PerkinElmer Optoelectronics, headquartered in Santa Clara, CA, is one of four businesses within the company. Within this business, a unit was recently formed to focus on products for telecommunications applications, particularly APDs, PIN photodiodes and other detector products. Wafer fabrication and assembly is carried out at the Vaudrueil, Quebec facility in Canada, with high volume packaging undertaken at the company's facility in Manila, Philippines. Some activities from the company's plant in St. Louis, MO will be transferred to Vaudrueil. The PerkinElmer telecom unit expects sales in 2000 to exceed \$50 million.

The company recently took a 13% equity stake in Montreal-based Bragg Photonics, Inc., a producer of fiber optic components utilizing fiber-grating technology. Bragg Photonics' products serve a rich variety of photonic applications including DWDM, optical add-drop multiplexing (OADM), laser wavelength stabilization, dispersion compensation, signal equalization in EDFAs and optical cross connect switches (OXC's).

Commercial Quantum Cascade Lasers from Alpes

For the first time, mid-infrared quantum cascade (QC) lasers are available on the commercial market. The manufacturer, Alpes Lasers (Neuchâtel, Switzerland), is a spin-off company from the University of Neuchâtel formed by a group of engineers including Jerome Faist, one of the developers of the original QC laser at Bell Labs. One of the first products is a “plug and play” starter kit designed for technology evaluation, containing a Fabry-Perot QC laser in the 9.8-10 μ m range.

Matsushita Licenses DVD Laser Technology

Matsushita has obtained from Competitive Technologies (Fairfield, CT) a non-exclusive license to use its high power laser diode technology. Based on impurity-induced layer disordering of lasers, the technology was invented at the University of Illinois at Urbana-Champaign, and provides the ability to increase the performance and durability of high-powered lasers used in high-power optical storage devices such as DVD drives.

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Boston Laser Acquires Polaroid's Laser Diode Division

Boston Laser Inc. (BLI), a new company specializing in high-brightness, high-power laser diode systems, was formed earlier this year by the acquisition of Polaroid's Laser Diode Division. Polaroid has been a leader in the design and manufacture of high power laser diodes since 1986 [see CS 4(7), p. 23].

BLI's products use various optical techniques to combine the power from individual laser diodes, in order to achieve high brightness, power and reliability. Every laser diode in BLI systems is selected for performance and reliability (unlike low-cost, laser bar systems).

BLI has formed a number of strategic alliances with industry leaders to offer high power laser diodes and laser power supplies, as well as high brightness, high power fiber-coupled lasers, fiber-coupled laser systems, and connectorized laser diode systems. Other product lines will include low-noise, frequency-doubled, diode-pumped, solid-state lasers, and high power fiber lasers and Raman amplifiers for telecom applications.

Spire Sells Optoelectronics Business to Methode

Spire Corporation (Bedford, MA) has agreed to sell substantially all the assets of its optoelectronics business segment to Methode Electronics, Inc. (Chicago, IL) for \$12.95 million in cash. "The transfer of Spire's optoelectronics business to Methode positions that business well for commercializing the technologies it has developed," says Roger Little, President of Spire. "At the same time, it allows Spire to strengthen its financial position and to pursue more aggressively its solar and biomedical businesses." Methode manufactures component devices for OEMs in a number of industries. One of its current product lines is VCSEL-based communications data links, which could tie in well with Spire's VCSEL manufacturing capabilities.

Laser Diode Acquires Nortel's Short Wavelength Laser Business

Laser Diode Inc. (Edison, NJ) has acquired Nortel Network's short wavelength laser division. The business will be transferred from Nortel's factory in Paignton, UK in three phases, over the next few months. The division produces 850-, 905- and 1550-nm pulsed semiconductor lasers, for a variety of measuring applications as well as fiber-optic instrumentation.

"Our company has produced pulsed lasers throughout out thirty-year history," says Maurice Murphy, President of Laser Diode, Inc. "While these products were first used in military applications, such as missile fuses, many new industrial and telecommunication applications have been developed over the past decade. We will continue to supply and develop our traditional 'home grown' products as well as the excellent new products coming from the acquisition." Nortel Networks completed this transaction in order to concentrate on its core businesses.

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Hughes Sells Satellite Systems Operations, including Spectrolab, to Boeing

Hughes Electronics is to sell its satellite systems businesses to Boeing in an all-cash transaction valued at \$3.75 billion. Included in the acquisition are Hughes Space and Communications Company, the world's leading manufacturer of communication satellites; Hughes Electron Dynamics, a leading supplier of electronic components for satellites; and Spectrolab, a premier provider of solar cells and panels for satellites.

The move will enable Hughes, a unit of General Motors, to focus on its high-growth entertainment, information and business communications services businesses including DIRECTV, PanAmSat and Hughes Network Systems. The acquisition of Hughes' satellite business, coupled with Boeing's already strong large-scale systems integration capabilities, will enable Boeing to offer unparalleled integrated space, air and terrestrial information and communications systems to its customers. As a result of the transaction, Hughes will become one of Boeing's largest customers for satellites.

Hughes Focuses on Communications Services

Hughes will retain its units in the communications services industry, namely DIRECTV, PanAmSat and Hughes Network Systems. DIRECTV is the world's largest direct-to-home provider of digital entertainment programming, with more than 9

million subscribers worldwide.

PanAmSat Corp., 81% owned by Hughes, is the world's largest commercial operator of communications satellites and has a customer base that includes the world's premier entertainment, communications and Internet companies. PanAmSat recently launched the largest commercial communications satellite, Galaxy XI, a Hughes HS 702 model with 40 Ku-band and 24 C-band transponders and end-of-life power of more than 10 kW. To achieve higher power and longer life, the solar array of the HS 702 carries angled reflector panels along both sides of the solar wings, forming a shallow trough that concentrates more of the sun's rays onto the solar cells. The dual-junction solar cells, manufactured by Spectrolab, are able to convert nearly one-quarter of the sun's rays into spacecraft power.

Hughes Network Systems (HNS) provides enterprise satellite-based private communications networks. Its DirecPC business, offering high-speed broadband Internet service, will launch a joint service with AOL later this year. HNS will also introduce Spaceway, a two-way, interactive broadband service offering high-speed data communications, beginning in 2002. HNS also recently announced that it would discontinue its terrestrial mobile cellular and narrowband local loop product lines in order to focus on its leading broadband point-to-multipoint (LMDS) product line.

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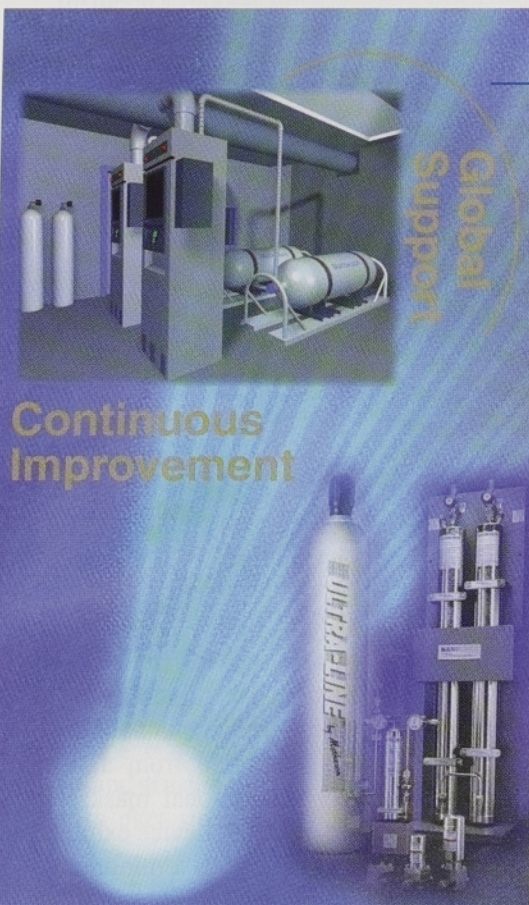
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Tecstar to Sell LEDs

Tecstar, one of the leading manufacturers of compound semiconductor solar cells, is leveraging its huge MOCVD production capacity in order to introduce a new product line - epitaxial wafers for high brightness LEDs and related optoelectronics devices. While solar power will remain a core product focus for Tecstar, similarity between the epitaxial growth and processing methods for LEDs and solar cells works to assure the success of both product lines, says the company.

The company's MOCVD production plant powered the commercial satellite constellation revolution - the Iridium, OrbComm and Globalstar "constellations" all employed Tecstar's high efficiency solar cells. Tecstar's Applied Solar Division (ASD) will now be available to support manufacturers of high and ultra-high brightness LED devices and lamps. "The formation of our new Optoelectronic Products Organization will allow Tecstar to take advantage of our existing facilities and competencies to drive the continued growth of our company," said David Van Buren, president and CEO.

Tecstar says that it is establishing large epitaxial wafer supply partnerships with several of the leading optoelectronic device developers and manufacturers, and expects to announce initial partnership agreements in the first quarter of 2000.

Emcore Receives Export License for Solar Cells

Emcure has received an export license from the U.S. State Department permitting it to export up to 300,000 high-efficiency solar cells for panel assembly in Japan. The panels will then be shipped back to the U.S. While initial shipments had been made under previous export licenses, the present license enables Emcore to meet the demands of its long-term supply agreement with Space Systems Loral. Emcore also entered into a technical assistance agreement with Loral and Mitsubishi Electric Corporation.

Emcore started shipping cells in December 1999, with the majority of shipments scheduled for the quarter ending March 31, 2000. Initial shipments will be of dual-junction GaInP₂/GaAs/Ge solar cells, with triple-junction devices shipped later in the period. "We are very happy that we have received our export license from the State Department," commented Reuben Richards, Emcore's President and CEO. "Our photovoltaic division has the production capability and technical expertise to meet Loral's product delivery schedule. From December 1999 to March 31, 2000, we expect to recognize approximately \$7 million in revenue from solar cell shipments."

In related news, Emcore also announced that its PhotoVoltaics facility in Albuquerque has achieved ISO-9001 certification, less than one year since it opened.

SILICON UPDATE

The Other IEDM

ROBERT A. METZGER

Every December brings us the International Electron Devices Meeting (IEDM). Certainly of great interest for the compound semiconductor community, this venue is used to present some of the best GaAs and InP-based results of the year, and the 1999 meeting was certainly no exception [see CS 5(9) p. 50]. However, it should be remembered that the IEDM is primarily a silicon device conference - actually *the* silicon device conference. If you want to get a glimpse of where silicon is going, and just how quickly it may be closing in on your compound semiconductor-based technology (or possibly even passing it), this is a conference you need to pay attention to.

SiGe

As with previous years, the IEDM has been the meeting in which many companies unveil the latest twists in their SiGe technology - this has been especially true of **IBM's** effort. This year, IBM discussed its latest SiGe technology, one aimed specifically at RF and microwave applications. Its new HBT uses a self-

aligned 0.18 μ m emitter, and has been integrated with IBM's copper interconnect technology. The device delivers an f_t and f_{max} of 90 GHz (measured at $V_{CB} = 0.5$ V), along with a minimum noise figure of 0.4 dB with a BV_{CEO} product of 2.7 V (a higher breakdown version with a BV_{CEO} of 5.5 V is available, in which this enhancement has been traded off against a reduced f_t of 25 GHz).

This latest version of IBM's SiGe technology nearly doubles the RF performance of SiGe devices currently in production, and out-performs just about any commercial GaAs-based RF devices.

Lucent Technologies also used this IEDM meeting to unveil its SiGe BiCMOS technology (see *Things to Watch* in this issue). In an effort to reduce production costs, the sub-collector of the device uses a high energy implant rather than epitaxial growth.

Its SiGe BiCMOS process has evolved from a 0.25 μ m CMOS process, and requires only 4 additional mask steps to implement the bipolar portion. The resulting device exhibits an f_t and f_{max} of 52 and 70 GHz respectively, with a minimum noise figure of 0.5 dB and a BV_{CEO} of 4.0 V. As a demonstration of the



technology's abilities, Lucent has fabricated 4:1 multiplexer and 1:4 demultiplexer circuits exhibiting 10 Gbit/s operation.

Straight Silicon

There is, of course, more to advanced silicon than simply the addition of germanium to the base of a BJT. While a 6.7 ps gate delay is very impressive, this performance does not come for free - added processing complexity and CVD growth are required. Attempting to push conventional Si BJT technology as hard as possible, and using only ion implantation, researchers at **Infineon Technologies** in Munich (Germany) reported on an

IBM's SiGe technology nearly doubles the RF performance of SiGe devices currently in production, and out-performs just about any commercial GaAs-based RF devices.

implanted bipolar technology using 0.2 μm emitters, which demonstrated an f_t and f_{max} of 52 and 65 GHz, respectively, and with a BV_{CEO} of 2.7 GHz - near SiGe performance without the added complexity of using germanium.

Infineon's bipolar devices were used to fabricate an ECL ring oscillator with a minimum gate delay of 12 ps, in addition to the fabrication of a dynamic 2:1 frequency divider operating as fast as 52 GHz - a record for silicon, and only 20 GHz slower than the best that even high speed InP-based HBTs have been able to obtain.

Pushing conventional silicon structures such as the above can produce devices which can compete with both SiGe- and III-V-based structures. But how about beyond such conventional structures? Silicon research groups are now combining silicon on insulator (SOI) technologies, with novel dual-gate structures in which the channel of a MOSFET can be electrically controlled from both the top and bottom of the channel. This approach reduces short channel effects, which is of critical importance if device performance is to be enhanced through the tried and trusted silicon paradigm of pushing to ever smaller ($< 0.1 \mu\text{m}$) gate lengths.

One such approach is that offered by

researchers from the **University of California at Berkeley** with a device called the FinFET. The FinFET consists of a vertical silicon fin, formed from the starting 50 nm thick silicon layer on an insulating SOI substrate by a combination of E-beam lithography and sacrificial oxide growth and removal. The resulting fins have a thickness of only 15-30 nm. A gate oxide of 2.5 nm is grown on the sides of the fins, and the gate material consists of 200 nm of in-situ doped SiGe (60% Ge, which results in a much lower gate resistance - a very important consideration when using such narrow gate lengths). The resulting PMOS FinFET with a 45 nm gate length showed an effective I_{dsat} of 820 $\mu\text{A}/\mu\text{m}$ (equivalent to a

very respectable 820 mA/mm) for a $V_d = V_g = 1.2 \text{ V}$.

And for those who wish to get a glimpse of the ultimate FET-based circuit, one which operates through the transport of a single electron, NTT discussed just such a device based on SETs (single electron transistors). Using a technique which they call V-PADOX (vertical patterning dependent oxidation), NTT exploits the variation in pattern-dependent silicon oxidation rates in order to form single-electron islands, and the tunnel barriers between them.

As in the case of the Berkeley effort, an SOI type substrate is used in which the starting epitaxial Si is patterned so that a thin region of silicon is sandwiched between two thicker layers. As a result of this initial geometry, during the oxidation process to form the SET, a pair of SETs aligned in parallel is created, which in turn can be connected in series to form an inverter. Input-output transfer with a gain larger than unity was demonstrated for this circuit at temperatures as high as 27 K.

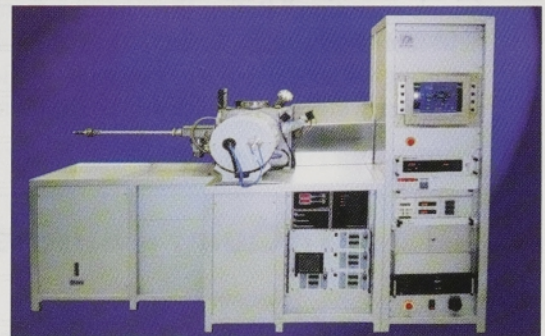
This certainly does not represent a process which is ready to be inserted in the RF front-end of a cell phone, but clearly demonstrates that silicon-based devices still have many generations to go before hitting the final wall and having to cede territory to compound semiconductors.

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TriQuint Expands its Oregon Fab, Plans 6-inch Conversion

TriQuint Semiconductor, Inc. has revealed plans to enlarge its wafer fabrication facility in Hillsboro, Oregon by increasing the current clean room area by around 35%. Once the \$6 million expansion is complete, the company will convert the fabrication facility to 6-inch wafer manufacturing.

"Demand continues to be very strong for our products, driven by the substantial increase in worldwide communications applications," says Steven Sharp, TriQuint's President and CEO. "Our Hillsboro site was designed to allow timely expansion of our manufacturing capacity to support the rapid growth of our markets and customers, and this project is part of our long-term growth strategy."

In December 1997, TriQuint completed the transfer of all its operations to a new 32-acre corporate campus in Hillsboro, comprising a 160,000 sq. ft. facility with a 16,000 sq. ft. wafer fabrication clean room. The additional clean room floor space will be used to increase TriQuint's production capacity for 4-inch wafers. The facility expansion is expected to be complete in the second quarter of 2000, at which point TriQuint will begin to convert the facility to 6-inch (150-mm) wafer manufacturing.

"When we moved to the new facility, all the newly purchased capital equipment was fitted with the capability to handle 6-inch wafers," explains Rob Hamilton, TriQuint's director of strategic marketing communications. "Some pieces brought from the old fab may need updating, but all the new equipment is capable of 6-inch operation." Rather than starting from scratch and building new fabrication lines, conversion from 4-inch to 6-inch manufacturing will consist of steps such as verification of processes on the larger wafers and evaluation of different suppliers.

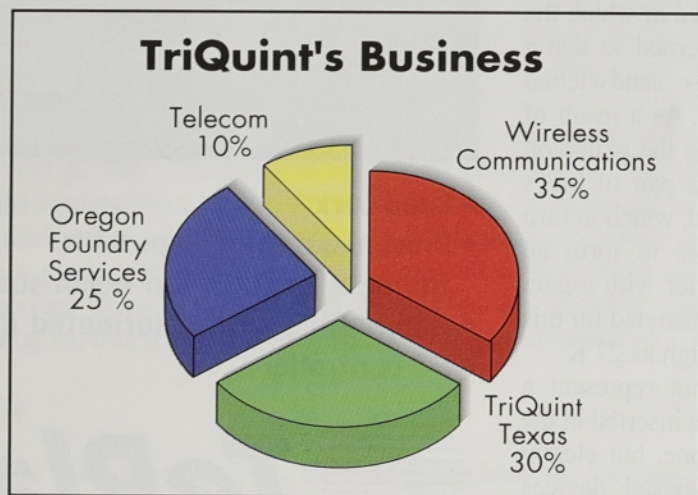
TriQuint's target is to have the fab fully converted to 6-inch operation by the middle of 2001. At this stage, the company expects that the Oregon wafer fabrication facility will be capable of supporting revenues of approximately \$450 million per year. This will represent a three-fold increase compared to the company's estimated total revenue of \$160 million for 1999.

Processes in Oregon and Texas

At present, TriQuint's Oregon facility is devoted to GaAs MESFET production, and runs several different MESFET processes. However, the company has a second fab in Dallas, Texas that runs the full range of GaAs processes, including MESFET, PHEMT, HFET and HBT. TriQuint Texas is the former MMIC business of Texas Instruments that TriQuint purchased from Raytheon TI Systems in January 1998. "One of the particularly attractive aspects of the acquisition of the old TI GaAs group was that they already had several advanced processes in place or in late stages of under development, including PHEMT and HBT," says Rob Hamilton. "Although MESFET technology will still be the primary focus at the Oregon facility, at the appropriate point, we are considering the introduction of HBT and PHEMT processes in Hillsboro at that site. The wireless group Texas operation is already implementing designs in our Texas operation from our wireless group in Oregon using these processes, targeting wireless applications up to about 5 GHz."

While TriQuint needs HBT and PHEMT processes in order to challenge for certain slots, particularly handset power amplifiers, the company is confident in the capabilities of their MESFET technology. "We don't have many handset power amplifier slots at present, since most have gone to HBTs," acknowledges Rob Hamilton. "However, most of the major cell phone manufacturers are using our devices in the receiver path. We feel confident that MESFET technology will remain an appropriate technology for converters and receiver path devices for the RF portion of handsets. At higher frequencies, and whenever there is more than a minimal power level, MESFET technology provides both a cost-effective and a high performance solution." TriQuint's wireless communications division is targeting the 2.4 GHz industrial, scientific and medical (ISM) band, wireless local loop (WLL) and microwave multipoint distribution systems as well as cellular handsets and base stations.

An important factor in favor of MESFETs is that a large number of passive devices – inductors, capacitors, precise resistors – can be realized on-chip using MESFET technology. "When you take into account biasing, matching and inter-stage passive devices, MESFET is a very cost-effective technology for an IC," says Rob Hamilton.



Foundry services comprise around one third of revenues from TriQuint Texas, so that over a third of TriQuint's total business is foundry related.

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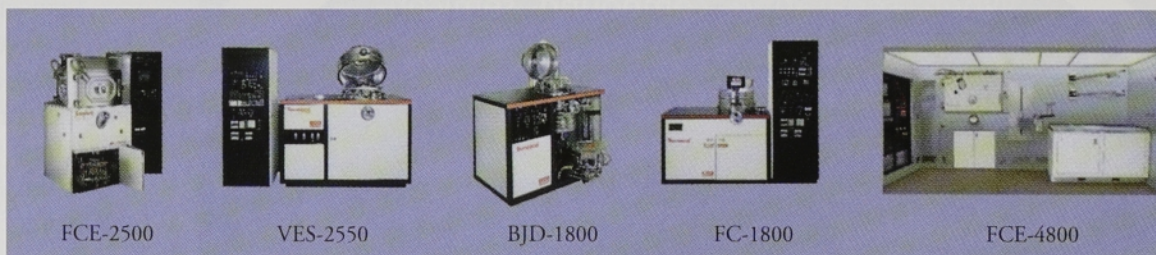
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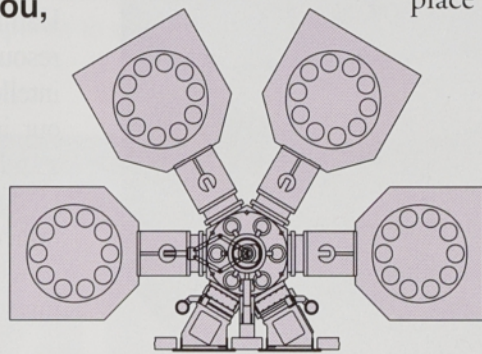
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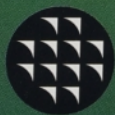


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GaAs ICs - NEWS

TriQuint also manufactures transmission and switching devices for telecom applications up to 10 Gb/s, including laser and modulator drive ICs and crosspoint switches. The latter are large ICs and their yield will benefit directly from the conversion to 6-inch manufacturing. The company is also developing next generation 40 Gb/s components using MESFET and PHEMT processes.

Like many other GaAs manufacturers, TriQuint is evaluating the performance, cost and other pros and cons of SiGe technology, and does not rule out accessing a SiGe process at some point in the future. "We will use whatever makes sense from a product and a requirement standpoint," says Rob Hamilton.

Foundry Services, Design Partnerships

During the course of 1999, TriQuint announced partnerships with several design houses to provide custom ICs using TriQuint's foundry processes. "Quite often, potential customers of our foundry division do not have internal RFIC design resources," explains Rob Hamilton. "TriQuint doesn't offer these resources, mainly in order to protect everyone's intellectual property including our own. Also, our in-house expertise is devoted to designing standard products within our other divisions." Under the new partnership agreements, customers can be directed to external design houses with which TriQuint has an established working relationship.

TriQuint's GaAs foundry operation, one of the largest in the world, comprises over a third of the company's business. As well as the foundry business in Oregon, around one third of the revenues from TriQuint Texas come from foundry services (see Chart). "Rather than just being an attempt to fill our excess capacity, the foundry division has dedicated wafer starts every week and is a very important aspect of our business," says Rob Hamilton.

Qualcomm Sells Handset Business to Kyocera

Kyocera, a Japanese manufacturer of KCDMA wireless handsets, has acquired Qualcomm's terrestrial-based CDMA phone business, including its phone inventory and manufacturing equipment. Kyocera estimates that it will produce around 16 million handsets, including CDMA, in the year ending March 31, 2001.

Anadigics Expands 6-inch Operation

Anadigics has announced plans to expand its 6-inch manufacturing operation in Warren, NJ. The \$10 million development will add further class 10 cleanroom space and equipment to the company's existing facility, which runs InGaP HBT, PHEMT and MESFET processes. Scheduled for completion by the end of the first half in 2000, the expanded facilities will approximately double current production capability.

"The wireless and broadband communications markets are growing at a tremendous pace," observes Bami Bastani, president and CEO of Anadigics. "This manufacturing expansion plan provides the necessary capacity to serve our customers and is consistent with our 2000 year-end projected growth rates in these markets."

Anadigics recently announced the shipment of its first 3 V InGaP HBT PA samples to major wireless handset manufacturers.

One Million Tuner ICs Shipped to Motorola

During 1999, Anadigics shipped more than 1 million GaAs QAM tuner ICs for implementation in Motorola's cable modem products. Anadigics' RF tuning chipset performs the functions of a double-conversion CATV tuner. Due to its linearity and noise figure, the chipset offers a bit-error-rate superior to discrete sin-

gle or double conversion solutions over a wide dynamic range. "Since this chipset is implemented in GaAs, it offers a better noise figure and much lower distortion than other available solutions," explains Ron Michels, VP of cable & broadcast products at Anadigics. "Motorola is now working with us in the development and evaluation of our next generation of cable tuner products."

In other news, Anadigics has been granted a second US patent for its single-chip power amplifier architecture. The patent integrates a negative voltage generator, enabling a one-chip PA solution for use in wireless handsets. The company has also announced the opening of a new design center in Newbury Park, California.

GCS Earns ISO 9002 Certification

Global Communication Semiconductors (GCS) has achieved ISO 9002 certification, the first "pure play" GaAs foundry to earn this award. GCS (Torrance, CA) offers InGaP and AlGaAs HBT foundry services, VCSEL and PIN diodes for the fiber communication market, and SAW filters for handset applications. The company also plans to offer PHEMT foundry services in the first quarter of 2000.

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TRW and RFMD Expand Strategic Relationship

TRW and RF Micro Devices have expanded their strategic relationship through several agreements that license RFMD to use TRW's patented GaAs HBT technology. RFMD will manufacture products for commercial coaxial and other non-fiber wire applications, including the broadband wired market. Products serving this fast growing market include CATV distribution amplifiers, cable modems, digital television converters and television tuners, both analog and digital. RFMD recently formed a fifth product line to focus on the broadband cable communications sectors.

"The agreements underscore the strong, ongoing relationship between TRW and RFMD," says Timothy Hannemann, executive VP and general manager of the TRW Space & Electronics Group. "Together, we have successfully penetrated the wireless telecommunications market, and we are just as optimistic about these new products for wired telecommunications." TRW also

agreed to retain ownership of at least 10% of current outstanding RFMD stock until at least May 1, 2001. Since January 1999, TRW has reduced its ownership in RFMD to approximately 20%, raising proceeds to pay off debt incurred to finance its acquisition of LucasVarity. TRW's GaAs HBT technology is currently responsible for almost 90% of RFMD's revenues.

First SiGe Product from RFMD

RFMD has introduced its first component manufactured using IBM's SiGe HBT process. The product is a complete receiver front-end combining an LNA and mixer for dual-mode CDMA/FM cellular applications at 900 MHz. This process is the sixth that RFMD has access to, including its own GaAs HBT process, as well as silicon CMOS, BiCMOS and BJT, and GaAs MESFET.

Celeritek, EiC Introduce InGaP HBTs

Celeritek recently announced a new production-ready InGaP HBT process, and subsequently launched its first HBT product – a power amplifier module that is less than half the size of comparable solutions. The product integrates 14 supporting components, and has been specifically developed to meet the continuing requirements for small, low-cost, high capacity wireless voice and data applications.

The HBT process adds to the company's existing MESFET and PHEMT GaAs technologies. "Adding HBT to our process capability is a natural progression for Celeritek," says Tamer Hussein, President and CEO, "especially now that we have a

proprietary single supply HBT technology that will satisfy our customers' ongoing demand for linear efficiency."

In other news, Celeritek has opened a design center in Lincoln, England, for the design and development of transceivers for millimeter-wave radios.

EiC it will commence with volume delivery of gain blocks, designed and processed using InGaP/GaAs HBT technology at its 4-inch fab in Fremont, CA. The company has previously offered a number of products based on its AlGaAs/GaAs HBT process.

Alpha and Ericsson Sign MCM Development Contract

Alpha Industries has entered into a contract with Ericsson to develop multi-chip modules (MCMs) for leading-edge digital wireless telephone standards, including EDGE and other future highly linear applications. The modules will help this new third generation (3G) standard achieve extremely high data transmission rates while remaining compatible with today's digital standards.

Mark Comerford of Alpha's wireless semiconductor operation stated, "Alpha is developing multi-chip modules for high-volume wireless applications, integrating RF ICs and other components into a single package. This combination of complex functions into a single device allows higher performance, smaller circuit boards and easier manufacturing.

"The development contract with Ericsson is a significant milestone in Alpha's entry into the multi-chip module business. It demonstrates that Alpha's relationship with Ericsson is expand-

ing into important new areas. Ericsson is now Alpha's second largest customer, and we aim to grow our business with them even further."

Alpha Upgrades Fab For 6-Inch Conversion

Alpha has significantly increased its manufacturing capacity with the addition of a new high throughput i-line stepper. The stepper, a PAS 5500/100 manufactured by ASML, is part of the equipment that Alpha is adding in order to double its capacity by the summer of 2000. "After that, we plan to more than double our capacity yet again by converting from four to six inch GaAs wafers," says Bruce Nonemaker, Alpha's VP of Operations. "With this equipment fully operational, more than 90% of our manufacturing capacity is 6-inch compatible."



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Kopin Receives Major HBT Production Order From Mitsubishi, Buys 8 Reactors

Kopin Corporation has announced the volume manufacture of GaAs HBT transistor wafers for Mitsubishi Electric PAs used in GSM digital wireless handsets.

Dr. John C.C. Fan, Kopin's president and CEO said; "We have collaborated with Mitsubishi over the past several years in the development of a high-quality HBT process for Mitsubishi's GSM products." Kopin already supplies its GaAs HBT transistor components for digital handsets incorporating the CDMA standard, and recently announced that it is quadrupling its HBT capacity for completion by the end of the first quarter of 2000. "Given the existing strength in our HBT business, our facility will reach full capacity in 2000," added Dr. Fan.

In more news, Kopin has acquired eight Aixtron production systems (5 x 4-inch and 5 x 6-inch or 8 x 4 inch), also for GaAs HBTs, to be delivered in calendar year 2000. This will bring the total number installed by the end of 2000 to sixteen, including eight multiple 4-inch HBT systems and eight multiple 6-inch HBT systems. This increases Kopin's 4-inch HBT transistor capacity to more than 300,000 wafers per year and its 6-inch capability to 120,000 wafers per year.

Epitronics to Supply Raytheon with InGaP HBT Epiwafers

Epitronics has been selected by Raytheon RF Components as its primary supplier of InGaP emitter HBT epitaxial wafers. Epitronics' Dr. Timothy Murray said; "The fast-growing wireless communications markets are demanding smaller, more capable, highly reliable components. We've worked with several companies from initial research to commercial ramp up. Raytheon is one of the first to publicly announce the availability of parts based on these advanced technologies."

Oerlikon-Buhrle Acquires Plasma-Therm

Oerlikon-Buhrle Holding (OBH), a Zurich-based diversified conglomerate that owns Balzers Plasma Systems, has announced a definitive agreement to acquire Plasma-Therm for around \$150 million. The deal is expected to be completed by early February 2000.

This reinforces OBH's recent streamlining into a high-technology business, it says. "The offer for Plasma-Therm is in line with OBH's strategy to strengthen its position in the semiconductor equipment industry," said Willy Kissling, OBH's chairman and CEO. "The acquisition is an important step in attaining the size and strength needed to successfully operate in this rapidly growing field in the long-term."

MOCVD Reactor Sales

Swedish company **Acreo AB** has bought an **Emcore** D-180 MOCVD reactor for the growth of QWIPs. The company has opted for a 4-inch platform to accommodate the relatively large chip sizes associated with QWIP arrays. **Uniroyal Technology Corporation** (UTC) has also purchased two additional D180 reactors (see Nitride News).

The **University of Magdeburg** has purchased an **Aixtron** AIX 200/4RF-S MOCVD system with in situ reflectometry for the growth AlGaIn-based structures for detectors and electronics applications. The **Ecole Polytechnique Fédérale de Lausanne** (Switzerland) has also ordered an AIX 200 MOCVD reactor for the growth of GaAs and InP-based low dimensional quantum nanostructures. **Arima Optoelectronics Corporation** has recently ordered several AIX 2400G3 HT reactors for the production of GaN-based LEDs and an AIX 2600G3 for mass production of AlGaInP LEDs and HBTs.

MBE Reactor Sales

VG Semicon has received an order valued at approximately \$4 million for several of its V100 MBE systems from **RFMD**. Scheduled to be shipped in mid-2000, these systems will increase RFMD's capacity for GaAs wafers used in devices for wireless communications.

Riber has received an order from Taiwan-based **Procomp Informatics** for two of its MBE 6000 (4 x 6 inch and 9 x 4 inch) production MBE systems. This brings the total number of orders for this system to 10.

IQE Invests in More MBE Production Reactors

IQE has announced orders for six new multi-wafer MBE production systems. The order, which includes an option on two further machines, is for a combination of **VG Semicon** (V100 and V150) and **Riber** production systems, scheduled to be delivered over the next 12 months.

IQE's CEO Tom Hierl commented that most of the leading component manufacturers have announced their plans to move to six inch manufacturing, starting the 1st Quarter of 2000, and new entrants to the marketplace are starting directly with six inch manufacturing. "The manufacturing efficiencies obtained by using six inch wafers are such that we believe all of the major manufacturers will have to move to this platform to remain competitive," he said.

IQE says it has completed its first production orders for 4 inch wafers using the multiwafer VG 150 MBE system currently in operation, and has also received its first volume order for six inch wafers.

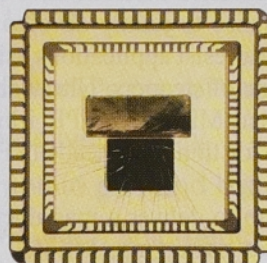
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Tegal Receives Plasma Etcher orders from RFMD, Taiwan

Tegal has received more orders for its 901G diode plasma etcher, used to etch GaAs devices used in wireless communication products. These include a repeat order from RFMD and a follow-on order for three systems from a Taiwanese telecom chip producer.

TePla Announces Takeover

TePla, a German manufacturer of microwave plasma surface treatment sources, circuit boards and laser-based measuring instruments, has announced its intent to acquire Plasma-finish GmbH, a plasma surface finishing concern also based in Germany (Schwedt). Kirchheim-based TePla's plasma treatment is used to improve surface adhesive properties, remove photore-sist marks from wafers, and clean wafer boats or chips prior to processing.

Ultratech Stepper and ShinEtsu MicroSi Announce Alliance

Ultratech Stepper and ShinEtsu MicroSi have formed a non-exclusive strategic alliance to jointly develop processes for thick film and specialty photoresist applications using Ultratech's 1X and reduction (XLS) line of steppers. Ultratech will evaluate the performance of ShinEtsu MicroSi's SIPR i-line, g-line and broadband resist materials for thin film heads (TFH), microma-chining and bump processing.

The two companies aim to deliver a manufacturing process that includes semiconductor packaging, MEMS, GaAs wafers, high energy implants and RF devices. "Having access to ShinEtsu's impressive range of resist products allows us to further refine the working process of our most advanced tools, including the new i-line and deep UV XLS reduction steppers and the new broadband 1X bump stepper," said Ultratech's president and COO, Daniel Berry.

Sputtering System for Compound Semiconductor and SAW Devices

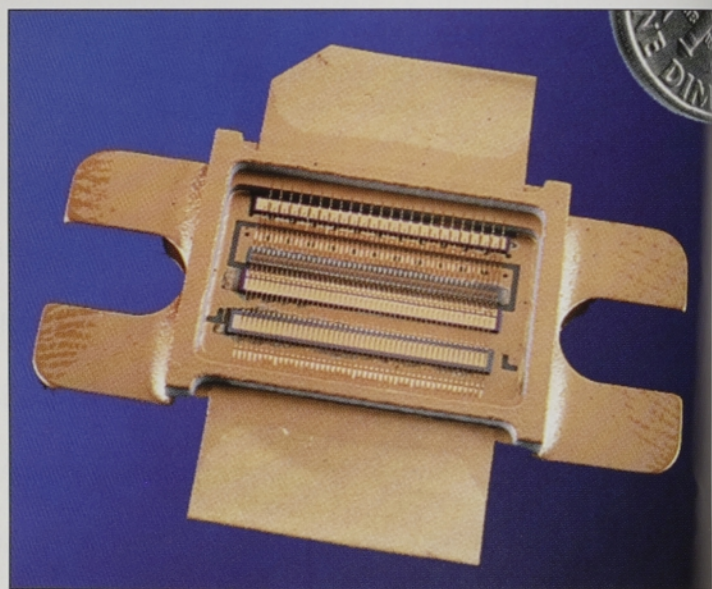
Ulvac Technologies has unveiled a new cluster-type sputtering system for compound semiconductor and SAW devices. The SME-200 has been designed specifically to supply films for production processes that include gate electrode, capacitor, and resistance on compound semiconductors, and electrode layer on SAW (surface acoustic wave) devices. Able to accommodate 3-8 inch wafers, the SME-200 can be configured as either a sputtering-, plasma- or heating chamber.

Northrop Grumman Buys Reactor for SiGe Power Transistors

Northrop Grumman has taken delivery of an ASM America reactor for the epitaxial growth of SiGe HBT structures on Si substrates. The E2000 reactor is used to make power MMICs for the world's first SiGe airport surveillance radar, based on a common-base class C device operated in pulsed mode at 2.7-2.9 GHz with a minimum output of 180 W.

"Our development of SiGe microwave transistors has allowed us to increase the power and efficiency of our solid-state transmitters using fewer components, resulting in smaller and more reliable radar designs," said Northrop Grumman's Kelly Overman.

SiGe transistors are employed in the final two stages of the transmitter chain, as the driver device and the output devices on the PA module, used in the preamplifier panels and the output panels of the transmitter. GaAs devices are typically not available at such high power levels for reasons of heat conduction (SiGe is 3.3 times more heat conducting than GaAs). In addition, says the company, as relatively large devices are required, SiGe improves yield and lowers the cost.



In Brief...

Freiberger Compound Materials GmbH has announced ISO 14001 approval for its environmental management system. The GaAs substrate supplier also holds the ISO 9001 approval.

Picogiga recently signed sales representation agreements with **Mi-Net Technologies** in the UK and **Marketech International Corp.** in Taiwan to develop sales in these two regions.

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1999 GaAs IC Symposium

Monterey, CA
October 17-20, 1999

TIM WHITAKER

In the plenary session of the 1999 GaAs IC Symposium, **George Bechtel of Strategies Unlimited** predicted that the total market for GaAs ICs, valued at \$1.9 billion in 1999, will grow at a compound annual growth rate of over 20% in the next 4 years. The market is expected to reach \$4.0 billion in 2003 (see Figure 1). Analog applications comprised 79% of the market in 1999, but digital applications, driven by high-speed fiber-optic communications and computer markets will have a slightly higher growth rate. The fastest annual growth rates, possibly in excess of 50%, are likely to be observed in the satellite and automotive radar markets.

Wireless telephony, which accounted for 70% of the 1998 GaAs IC market, will continue to be the single largest application over the next five years. Cellular and PCS handset production is likely to exceed 500 million units in 2003, compared to 240 million units in 1999. GaAs IC chip usage in this market will reach \$2.2 billion. GaAs ICs (power amplifiers, low noise amplifiers

and switches) have captured a dominant position in the RF front-end of most mobile handsets, and emerging 3G applications will require even higher performance. Bechtel noted the growing role of silicon and SiGe in the RF and microwave market (See *Things to Watch*.) The improved performance of silicon-based technologies – both silicon BJTs and CMOS now have f_{max} values similar to those of GaAs MESFETs – will confine GaAs to the RF front end.

While the level of integration of analog GaAs ICs will remain low, with no “single-chip radios”, a number of multi-chip modules containing mixed device types have been developed for RF front-ends. New silicon technologies are enabling the production of complete RF front-ends operating up to 2.5 GHz.

According to Bechtel, the usage of epitaxial device technologies is growing rapidly. In 1998, around 65% of GaAs ICs (by revenue) were fabricated by ion-implantation. The remainder were epitaxial devices; HBTs, epitaxial MESFETs and PHEMTs accounted for 17%, 10% and 8% of the total revenue respectively. HBTs captured over 50% of the sockets for handset applications.

Is Ion Implantation Dead or Dying?

A spirited panel session discussed the future of ion implantation and the challenges posed by epitaxial technologies. **Steve Mahon of TriQuint** noted that ion implantation still dominates the GaAs industry, and predicted that MESFET technology will continue to be widely used for at least the next five years. Epitaxial technologies win on smaller die size and prosper where device attributes match system needs, a prime example being HBT power amplifiers for wireless handsets. Ion implantation is very cost-competitive, especially when inductors, capacitors and other passives are taken into account, and also allows for LSI and VLSI digital functions.

Stating that epi would be likely to capture almost all markets when it was able to match the die cost of ion implantation, **Mark Wilson of Motorola** provided a cost model to compare the two. He estimated that epi could match the die cost of ion implantation when the cost of a 4-inch epiwafer falls below about \$450, or when 6-inch epiwafers are available for about \$800. Unless these targets can be met by epiwafer vendors, said Wilson, more fabs are likely to rely on their internal epi capability.

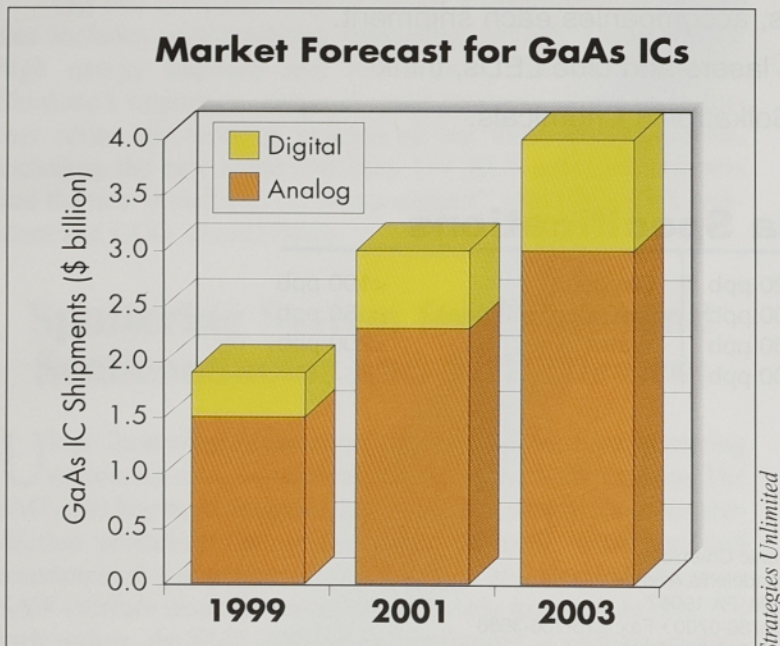
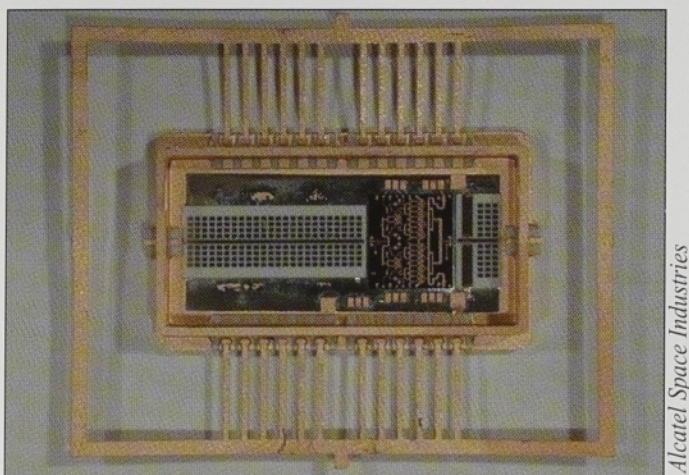


Figure 1. Market forecast for GaAs ICs over the next few years. Wireless handsets alone will account for \$2.2 billion of analog IC shipments, while around half of all digital shipments will be for telecommunications applications.

	Monthly shipments of 4-inch equivalent GaAs wafers	Proportion of epiwafers shipped
1997 (Worldwide)	33,000	26%
1999 (Worldwide)	49,000	44%
(Japan only)	18,500	51%
2002 (Worldwide)	81,000	52%

Sumitomo Electric

Figure 2. Shipments of 4-inch equivalent GaAs wafers, and percentage of epiwafers.



Alcatel Space Industries

Figure 3. An 8W C-band amplifier for space applications, consisting of a two-stage PHEMT-based MMIC in a Cu-W microwave package.

Masamichi Yokogawa of Sumitomo Electric estimated that epiwafers accounted for over half of all GaAs wafers consumed in Japan in 1999 (see figure 2). PDC phones for the Japanese wireless market are currently using PHEMT-based PAs and ion implanted switches, while next-generation handsets (W-CDMA or IMT 2000) will utilize InGaP HBTs. Yokogawa also spoke about the relationship between epiwafer vendors and device manufacturers. Epi is a value-added product containing significant intellectual property, and fabs are becoming increasingly reliant on their epi vendors. Many fabs work with only one supplier of particular types of epiwafer, and are seeking strategic relationships to secure the supply. These relationships are desired by epi vendors to offset the huge risk of moving to 6-inch wafers.

Application-Driven Device Technology

On behalf of Vitesse Semiconductor, the perennial advocate of MESFET technology, Ira Deyhimy emphasized that customers do not buy technology, they buy the most cost-effective products that satisfy their requirements (p. 29). MESFET technology provides the most cost-effective solution in the present market, although 0.18 μm CMOS will encroach at OC-48 (2.5 Gb/s) and lower data rates. GaAs and bipolar SiGe are candidates at OC-192 (10 Gb/s), and Vitesse plans to introduce a new process (H-GaAs-V) during 2000 to focus on 10 Gb/s applications.

Power Amplifiers

NEC described a wideband CDMA (W-CDMA) handset power amplifier operating at 1.95 GHz with a record PAE value of 54.4% and 25.5 dBm output power, fabricated using a double-doped heterojunction FET (p. 295). These values were increased to 57.4% and 26.2 dBm by the use of a MMIC predistorter. The PA also realized the W-CDMA adjacent channel leakage power ratio (APCR) requirement of -40 dBc at 5.0 MHz offset with a channel width of 4.096 MHz).

High efficiency and low distortion power are a vital requirement in communication satellites. Characteristics such as high gain, linearity and high output power make PHEMTs a very attractive choice for microwave power amplifiers. A paper from Alcatel CIT and Alcatel Space Industries described a C-band MMIC amplifier with an output power of 8 W (39 dBm) at 2 dB of gain compression, a linear gain of 27 dB and an associated PAE of 42% in the 3.5-4.4 GHz frequency range (p. 77). A two-stage MMIC amplifier was fabricated using TriQuint Texas' 0.25- μm PHEMT process, and was brazed onto a Cu-W package (see Figure 3). Comprehensive modeling was performed, resulting in an exact non-linear model of the PHEMT device and optimization of the amplifier's matching network.

Wide bandwidth amplifiers are key components in phased-array radars and instrumentation, and must operate over a decade bandwidth with high PAE. Simple lumped broadband amplifiers have gain-bandwidth products limited by the f_T value. A paper from the University of California at Santa Barbara (p. 81) described such an amplifier with an alternative f_T -doubler topology resulting in 12 dB gain and a bandwidth of up to 33% of f_T . The 0.2-6 GHz power amplifiers were fabricated using a GaAs MESFET process (TriQuint Texas) with an f_T of 18 GHz, and demonstrated over 23 dBm (200 mW) of output power and more than 25% PAE. The same circuit topologies will be used to implement efficient broadband high power GaN-based microwave amplifiers.

Communication Transmitters and Receivers

Ka-band (26-40 GHz) broadband transmitters with several Watts of output power are required for LMDS, wireless LANs, personal communications network links and satellite communication systems. Researchers from NEC's Kansai Research Labs reported a 28 GHz power amplifier module with 4.5 W output power under CW operation. The amplifier comprised four fully matched MMICs fabricated using a 0.35 μm gate-length, double-heterojunction AlGaAs/InGaAs/GaAs FET. The amplifier also delivered 3 W in the 26.5-28.5 GHz range.

A 42 GHz MMIC chipset for the front-end transceiver for a multipoint video distribution system (MVDS) was described by United Monolithic Semiconductors (p. 109). The chipset comprised four MMICs fabricated on a 0.25 μm PHEMT process. These were a local oscillator, a receiver MMIC incorporating an LNA and a downconverter mixer, an upconverter MMIC, including a mixer and a driver amplifier; and a power amplifier MMIC.

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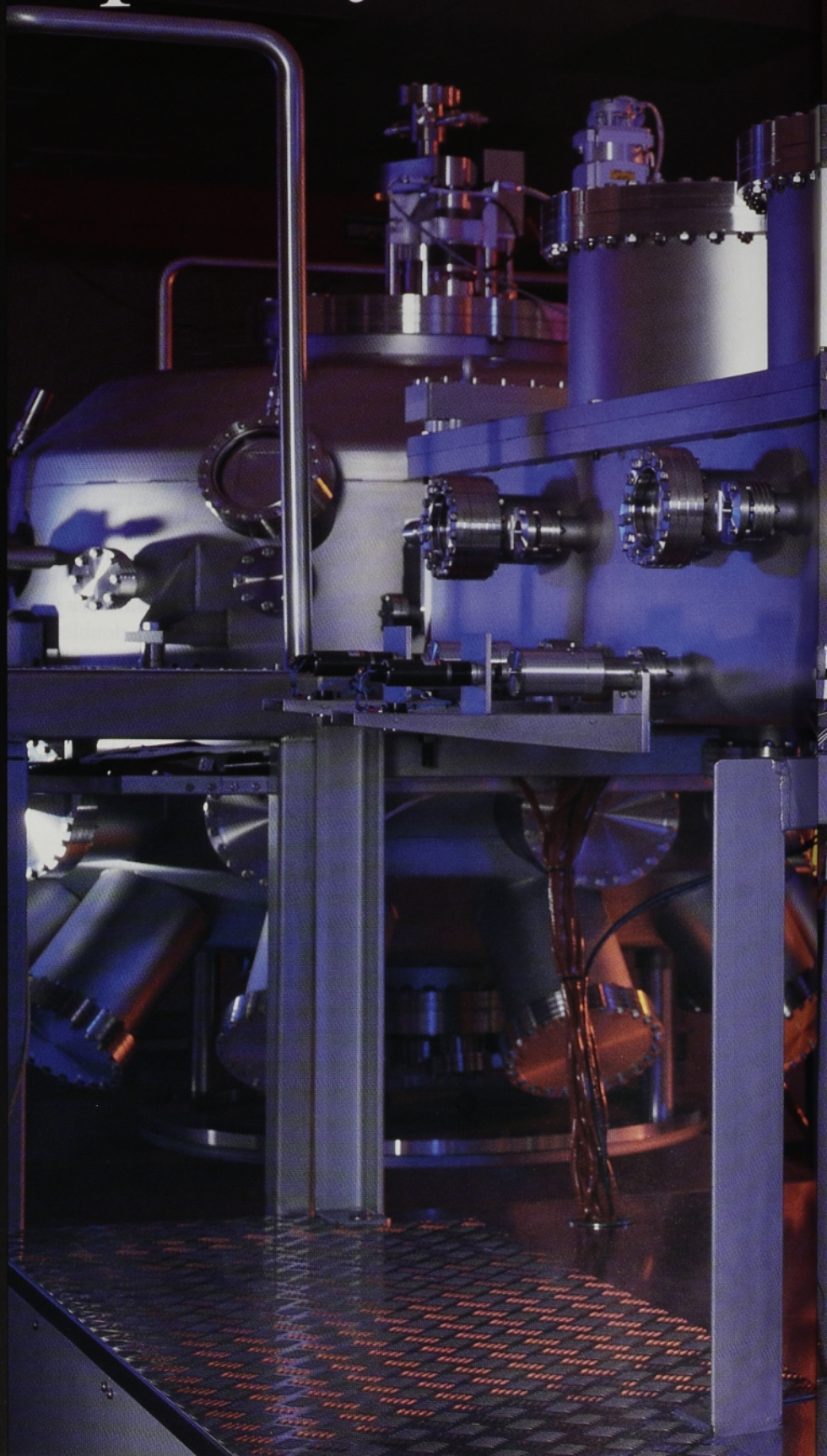
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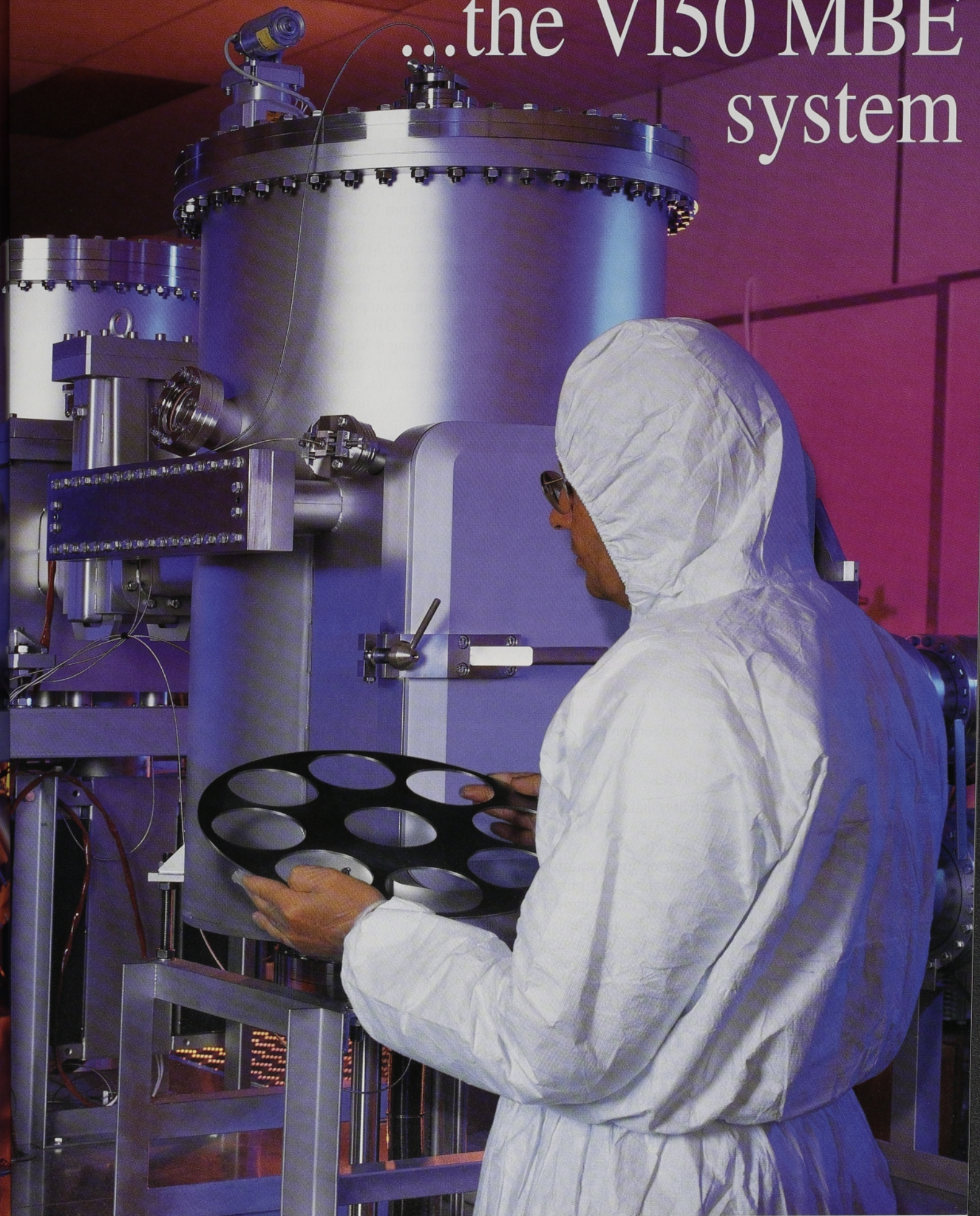
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Lucent Technologies described a 5.2 GHz transmitter MMIC for wireless local area network (WLAN) applications capable of sending highly efficient modulation schemes such as QAM (quadrature amplitude modulation), that are suitable for multimedia networking applications. The MMIC, consisting of an upconversion mixer and two-stage amplifier, was designed into the TriQuint Texas 0.6- μ m gate length GaAs MESFET process. The gain and 1 dB compression point were 14 dB and +11 dBm respectively.

Optical Communications and OEICs

Gigabit Ethernet is one of the fastest growing markets in the local area network (LAN) field. The IEEE 802.3z standard describes physical layer transmission at 1.25 Gb/s up to 550 m with multimode fiber at a wavelength of 850 nm. As cost is a major factor in this market, monolithically integrated detectors and amplifiers are essential. Separate papers from **Anadigics** and Taiwan's **Industrial Technology Research Institute** (ITRI) described the integration of metal-semiconductor-metal (MSM) photodetectors with MESFET-based transimpedance amplifiers (p. 91, p. 95).

Low cost, compact and reliable systems operating at 10 Gb/s are now in demand for optical communication systems. NEC reported a transmitter module containing a built-in modulator driver IC, and a receiver module with a built-in preamplifier IC (p. 287). Both ICs were fabricated in a 0.3 μ m gate AlGaAs/InGaAs HJFET (PHEMT) process. The power consumption of the driver IC has to be low to prevent the temperature of the modulator from rising, as this causes the wavelength to shift. The transmitter module contained an electroabsorption modulator integrated with a DFB laser, a monitor photodiode, a thermoelectric cooler and the driver IC. The receiver module contained a planar superlattice APD, a thermistor and the preamplifier IC. The modules measured 12x20x8 mm³ and 18x22x8 mm³ respectively.

Millimeter-Wave Applications

In an invited paper, Keiichi Ohata of **NEC's Kansai Research Labs** described mm-wave GaAs IC interconnect and packaging technology trends in Japan (p. 105). As certain applications for mm-wave MMICs reach or approach mass production, high performance, low cost packaging that is highly reliable and allows high productivity becomes increasingly important. Several technologies have been investigated in Japan; these include ceramic-base packages up to W-band, flip-chip bonding and packaging for low cost and high productivity assembly, and 3D MCM technology.

Although oscillators operating at millimeter-wave frequencies are commonly fabricated using HEMT technology, their phase noise performance is limited by 1/f noise in the transistors, while HBTs have an inherently lower phase noise than HEMTs. **Teratec Corp.** reported a 146.7 GHz oscillator fabricated using InGaP/InGaAs HBTs, which is believed to be the highest frequency fundamental mode oscillator for a bipolar technology (p. 237). The InGaP emitter layer ensures reliability and the graded

InGaAs base layer realizes high-speed performance. Teratec is an R&D consortium under the control of Japan Key Technology Center, with in-house processes including epitaxy and photolithography. GaAs-based devices and circuits are under development for internal purposes at present, with a view to commercialization in the future.

77 GHz MMICs for automotive radar sensors were described by both the **Fraunhofer Institute** (p.207) and **Hitachi** with **Eaton VORAD** (p. 211). Both groups used GaAs PHEMT technologies. Fraunhofer IAF described a compact coplanar transceiver MMIC measuring 1.75 x 1.75 mm², using space-saving 0.15- μ m dual-gate PHEMTs. The MMIC allows the bidirectional operation of a single T/R antenna and achieves a maximum output power of 10 dBm and a conversion loss of 1.5 dB at 77 GHz. The paper from Hitachi described a T/R module containing 4 MMICs (VCO, PA and two receivers) housed in a single-cavity structure for low cost manufacturing that has a dielectric interconnecting sheet and a filtering lid to avoid undesirable interference between the Tx and Rx ports. A microstrip-patch planar antenna was incorporated to form a single-body transceiver/ antenna unit.

Metamorphic HEMTs

Following a review of metamorphic HEMT technology by Alain Cappy of IEMN [see CS 5(8), p. 40], two papers from **Raytheon RF Components** described recent device results. The first (p. 221) described low noise devices with a 0.61 dB minimum noise figure and 11.8 dB associated gain at 26 GHz, and amplifiers with less than 1.8 dB noise figure with gain greater than 24 dB in the 27-32 GHz range. The In content of the InGaAs channel in these devices was 60%.

Raytheon also reported a 32% In channel MHEMT that exhibited an output power density of 650 mW/mm at 35 GHz with a drain bias of 6 V (p. 225). This was stated to be the highest biasing of an MHEMT to date, making this device suitable for mm-wave power applications. The device exhibited comparable power to a GaAs PHEMT but with higher gain (6.2 dB) and improved f_T (97 GHz).

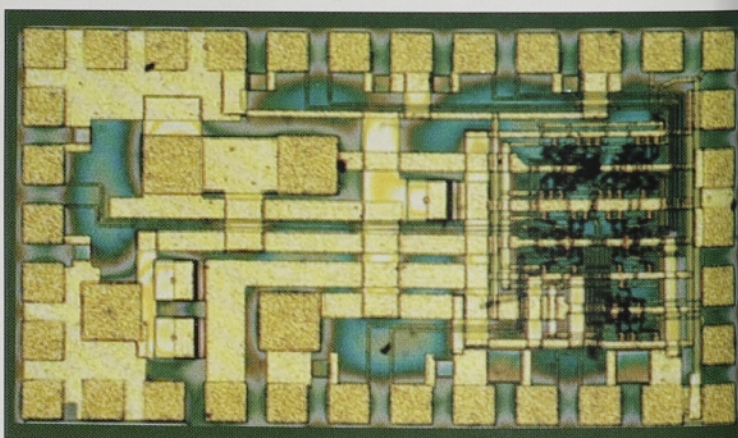


Figure 4. Die photo of the monolithic electronic 4:1 multiplexer (MUX) core fabricated by Lucent Technologies. The total die size is 1.0 x 1.8 mm² but the main limitation on size is the package frame, as is evident from the photo.

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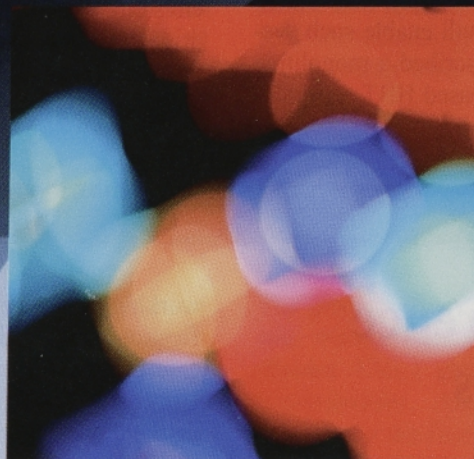
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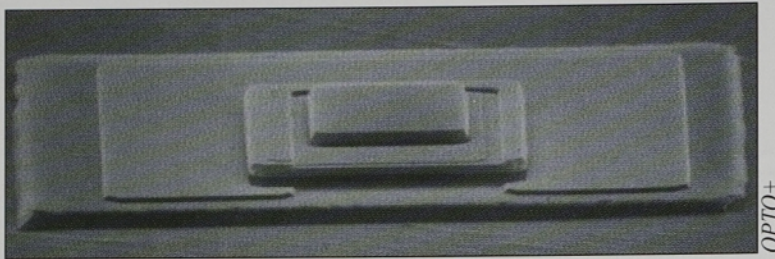


Figure 5. SEM micrograph of an InGaAs/InP double heterojunction HBT fabricated by OPTO+ for use in 40 Gb/s optical communications systems.

InP Devices for Fiber-Optic Applications...

At the panel session on the future of InP ("InP Commercial Devices...When?"), it was clear that InP technology will soon impact a number of commercial markets, including optical transmission systems and millimeter-wave transceivers (See *Things To Watch* section).

A number of system providers are developing or trialing 40 Gb/s fiber-optic transmission links, and InP is a candidate technology for some of the high speed ICs that will enable such systems. J.P. Mattia of **Lucent Technologies** described a monolithic electronic 50 Gb/s 4:1 MUX core in an InP-based HBT technolo-

gy (p. 189). This is believed to be the fastest rate achieved in a monolithic 4:1 MUX to date, although 80 Gb/s has been achieved for a 2:1 selector. This device is capable of accommodating 4 channels of data at 10 Gb/s, with sufficient system margins to allow for error correction. The multiplexers were fabricated using HRL Labs' InP HBT technology (see Figure 4).

A 68 GHz 2:1 frequency divider with measured input sensitivity less than 6 dBm from 53-68 GHz was reported by **TRW** (p. 193). This is believed to be the fastest digital frequency divider reported in any semiconductor technology. For more details, see CS 5(9), p. 50.

A monolithic integrated transimpedance amplifier (TIA) for a 40 Gbit/s receiver was demonstrated by **Ruhr University**, working with **Siemens AG**, **HRL Labs** and the **University of Rosenheim** (p. 99). The TIA was realized on a single chip using an InP-HBT technology.

OPTO+, a joint France Telecom and Alcatel CIT laboratory for optoelectronics research, described an InP DHBT self-aligned process with f_T and f_{max} of 130 GHz and 150 GHz respectively (p. 185). The device is shown in Figure 5. Several 40 Gb/s circuits, including 2:1 and 4:1 multiplexers and a 2:1 MUX-driver, have already been fabricated, characterized and assessed in system experiments. The 2:1 multiplexer was used in a 40 Gb/s electronic time division multiplexing (ETDM) system demon-

CONFERENCE

International Conference on II-VI Compounds

Kyoto, Japan
November 1-5, 1999

ANDREAS WAAG

Physikalisches Institut, Universitaet Wuerzburg

The 1999 International Conference on II-VI Compounds was held from November 1st to 5th in the beautiful city of Kyoto, Japan. Prof. Fujita from Kyoto University as the chairman of the organizing committee and Prof. Taguchi from Yamaguchi University as chairman of the program committee brought together more than 300 participants from 19 countries.

Blue Laser Diodes

In the introductory talk of the conference, S. Itoh (Sony) summarized the achievements of his group, which is leading the field of blue laser diode research using II-VI compounds. With a lifetime of 500 hours (CW at RT), ZnSe-based laser diodes are not yet seriously considered for commercialization. The groups

working on laser diodes are now mostly focussing on the identification of degradation mechanisms. Experimental results indicate that both the unstable nitrogen acceptor (K. Ando, Tottori Univ., W. Faschinger, Univ. Wuerzburg) as well as the large strain in the ZnCdSe quantum wells are the main driving forces for degradation.

In view of these difficulties, new approaches have been reported, including the demonstration of the first II-VI laser diode based on a CdSe quantum dot active region (S. Ivanov, Ioffe Institute, St.Petersburg). Lattice matched BeTe-ZnSe LEDs (G. Reuscher, Univ. Wuerzburg) and ZnMgSeTe materials (M. Tamargo, New York) were also described. The development of lattice matched active regions as well as alternative p-type doping procedures (co-doping, modulation doping etc.) seem to be key issues for further improving the performance of ZnSe-based laser diodes.

Magnetic Materials

Magnetic nanostructures also played an important role throughout the conference. D. Ferrand *et al.* reported ferromagnetic behavior of p-type ZnMnTe. Similar to GaMnAs, the free holes are mediating a ferromagnetic coupling between Mn spins, which is antiferromagnetic otherwise. Kuroda (Univ. Tsukuba) and the Furdyna group (Notre Dame, USA) reported on the growth and investigation of semimagnetic quantum dots. The giant g-factor of semimagnetic II-VI materials makes them very interesting for the investigation of exchange interaction in

strator within the European ACTS/HIGHWAY project. 40 Gb/s transmission over 46 km standard fiber loops (from Stuttgart to Ludwigsburg, Germany) was performed with a bit-error-rate (BER) of 10^{-13} .

...and Mm-wave Power

TRW described the first InP HBT power amplifier chip results at K-band (p. 73). A fully monolithic 21 GHz power MMIC was demonstrated, which achieved 62.8% PAE with 10 dB gain and 20 dBm output power. A higher power MIC at 18.5 GHz achieved 25 dBm output power with 40% PAE at 1 dB compression under class AB operation. Both amplifiers were operated under low DC power with collector current densities below 35 kA/cm² and a collector-emitter voltage of less than 3.3 V.

Sanders, a Lockheed Martin Company, reported an InP HEMT-based power amplifier with the best combination of output power and efficiency at V-band for any solid state amplifier (p. 145). A single-stage amplifier with 600 μ m cell periphery demonstrated 224 mW of output power at the peak power-added efficiency of 43% with 7.5 dB power gain at 60 GHz. The MMICs were realized using a double heterojunction InGaAs/InAlAs/InP HEMT structure with a 0.1 μ m T-gate.

In the following paper, TRW described a single chip InP

HEMT amplifier module operating at 62 GHz with 1 W output power and 21% PAE and 15 dB associated gain (p. 149).

Enhancement-mode FETs

The use of enhancement-mode FETs or HBTs in wireless handsets eliminates the need for a drain switch and a negative voltage generator IC, and reduces cost, size and current drain. **Motorola** has developed a true enhancement-mode (E-mode) heterostructure insulated-gate FET (HIGFET) device that is suitable for both digital and analog PAs and shows promise for use in small signal applications (p. 123). The device has a high Schottky turn-on voltage ($V_{TO} = +1.8$ V at 1 mA/mm) compared to pseudo E-mode PHEMTs. Also, the threshold voltage (V_{TH}) is controlled by the epitaxial material, rather than by the recess etch as in PHEMTs. Less than 1% degradation of I_{dmax} and V_{TH} was demonstrated after 2,000 hours at 250°C.

An E-mode 0.8 μ m gate PHEMT process was described by **Alpha Industries** (p. 127). A 2-mm E-PHEMT demonstrated 35 mW/mm with 71% PAE at 1.5 V and 0.9 GHz, which is believed to be the best result to date for any single supply technology. The E-PHEMT technology offers advantages compared to HBTs, including a shorter time to grow the epitaxial layer, fewer processing steps, high efficiency and the ability to integrate PAs with switches.

CONFERENCE

reduced dimensions. In a late news contribution, A. Waag *et al* (Univ. Wuerzburg) reported on the first efficient electrical injection of spin polarized carriers into non-magnetic GaAs, using BeMnZnSe as a spin filter [for details see Nature 1999, vol. 402, p. 787]. In general, magnetic II-VI semiconductors in connection with spin electronics is believed to be an important area in the future.

Zinc Oxide

Despite the lack of convincing data on reliable p-type doping of ZnO, activities on the growth and characterization of this material are increasing. Material of surprisingly good structural quality can meanwhile be grown. The Yao group (Sendai/Tsukuba) as well as Kawasaki *et al.* (Tokyo Institute of Technology) reported a well-developed ZnO MBE technology. Yamamoto introduced theoretical considerations on the co-doping method as a means to get p-type ZnO. From the experimental side, Aoki (Shizuoka Univ.) reported on the p-type laser doping of ZnO with phosphorous. It will be interesting to see whether ZnO-based optoelectronic devices can be realized in the future.

Excitonic Phenomena

Due to a strong Coulomb interaction, the II-VI materials serve as model systems for investigating excitonic phenomena.

The physics of excitons in quantum-confined heterostructures was widely represented in this conference. Arto Nurmikko (Brown Univ.) gave a plenary talk on exciton-polaritons in microcavities. Andre (Grenoble) and Neukirch (Berkley) reported on the fine structure of excitonic states in quantum dots.

Particular progress has been made on the observation of single quantum dots, as described by Woggon (Dortmund), Puls (Berlin) and Bacher (Wuerzburg). Research on positively- and negatively-charged excitons in ZnSe- and CdTe-based QWs [Yakovlev (Wuerzburg), Vanelle (Toulouse), Homburg (Bremen), Kossacki (Lausanne), and Wagner (Chemnitz)] as well as on spin dynamics of excitons [Henneberger (Berlin), Kalt (Karlsruhe), and Akimoto (Tsukuba)] are two more examples of the present activities.

Conclusions

There have been many more interesting contributions that have not been mentioned. Indeed, this conference was a bridge between the "old" and "new" II-VI physics, as Prof. Fujita said in the opening session. Dominated by the blue laser in the early 90's, the II-VI community is now diversifying and heading into new areas: magnetic materials, exciton physics, quantum dots, new materials. But in view of the difficulties for GaN concerning the fabrication of laser diodes with wavelengths above 450 nm, the "laser area" is still very attractive, both from an applied as well as research point of view.

Femtosecond Optoelectronic Devices for Telecommunications with Terabits-per-second Data Rates and Beyond

OSAMU WADA*

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Since its installation in the early 1980s, optical-communication technology has developed very rapidly, and the current commercial optical-communication systems run at a bit rate of 10 Gbps, as is shown in Figure 1. However, as can also be noted from the illustration, there is no sign that the volume of information to be transmitted/processed will saturate; rather, it is expected to increase continuously, as evidenced by the explosive expansion in the use of the internet, and also of mobile phones and computers. Thus, the throughput of the current communication systems is insufficient to support the information volume required by a future multimedia-based society.

Requirements for Femtosecond Devices

It is anticipated that the communications and signal-processing systems will have to fulfill, circa 2010, a throughput of 5-100 Tbps or even higher [1]. Such an increase in system performance of more than 500-fold cannot be achieved simply by modifications to the existing systems, and substantial improvements in both the devices and systems are crucial for success.

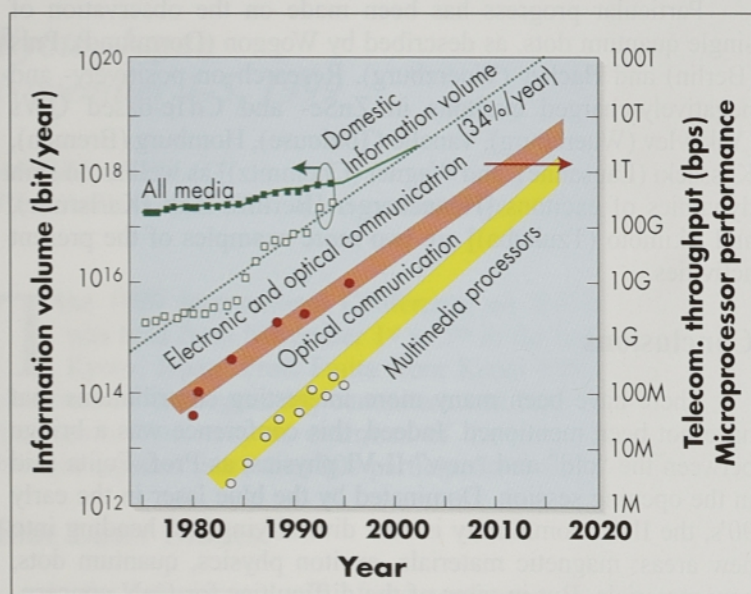


Figure 1. In Japan, trends in domestic information transmission volume and throughput of trunk line optical communication systems shows no signs of saturation – rather, continuous explosive expansion will be fueled by the internet and increasing use of mobile phones and computers.

The wavelength-division multiplexing (WDM) technique, in which the data are multiplexed into many different wavelengths, can improve the overall throughput, and can still maintain the operating bit rate to a moderate degree. Although WDM systems are being energetically developed worldwide, this technique will become impractical when too many wavelength channels are used, which is due to the limited amount of flexibility in their management.

Another important approach is the use of optical time-division multiplexing (OTDM), which is based on ultra-fast, all-optical devices. OTDM will be able to break the speed limit set by existing devices, and realize an ultra-high throughput once the necessary device technology is established.

The feasibility of ultra-fast transmission and processing throughput in the range of 100 Gbps to 1 Tbps has been demonstrated in laboratories by employing primarily optical fiber-based

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Monolithic passively mode-locked semiconductor laser diode (PML-LD)

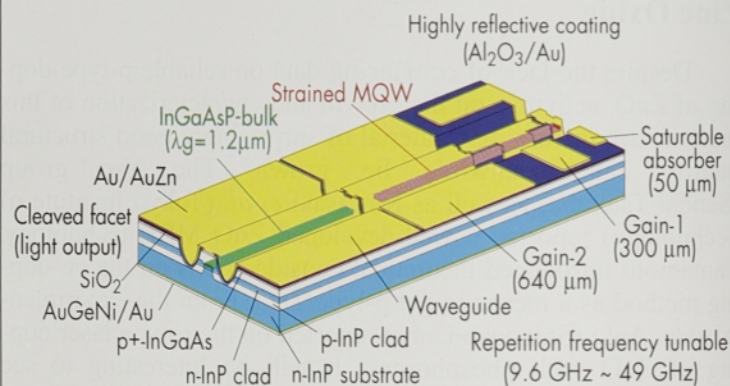


Figure 2. The structure of a monolithic InGaAsP/InP mode-locked laser manufactured by the Oki group at FESTA. Consisting of a saturable absorber, two gain sections and a passive waveguide section, this device has generated ps pulses in the 10-50 GHz range, and even up to 200 GHz using multiplexing. A pulse exhibiting 500 fs FWHM duration has been generated with this technique [4].

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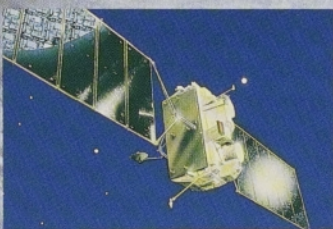
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devices [2]. However, to establish practical OTDM systems, compact, reliable and cost-effective femtosecond optoelectronic devices should be developed on the basis of compound semiconductor technology, and in particular, InP-based materials.

Among the many different devices required for Tbps OTDM systems, the key devices needing development using this technology are femtosecond laser light sources and all-optical switches, which operate in the sub-picosecond (ps) and femtosecond (fs) time domain. Thus, in this article we describe several ultra-fast InP-based devices being developed at FESTA (The Femtosecond Technology Research Association) under a Japanese MITI project known as 'Femtosecond Technology'. This project began in 1995 as a ten-year program, aiming to develop novel principles for ultra-fast devices in the first six years, followed by their corresponding device technologies by 2004 [3]. Although some of early results have already been published [1, 8], more recent topics are introduced here.

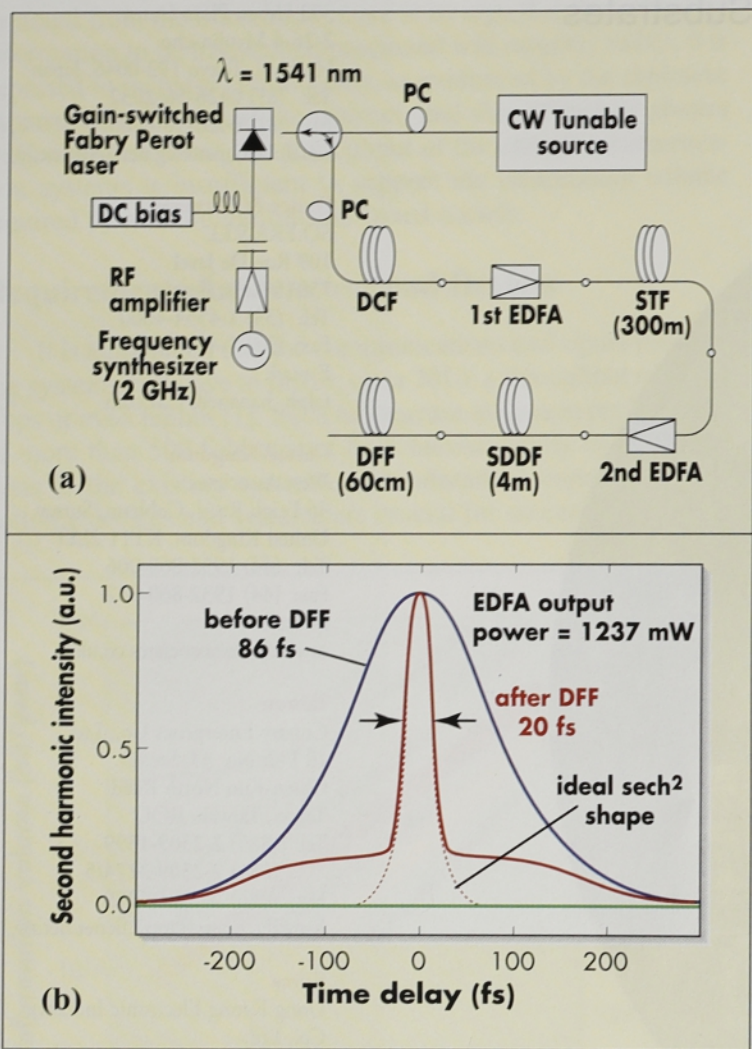


Figure 3. a) Block diagram of FESTA's femtosecond light source showing the incorporation of a multi-stage fiber compressor (PC = polarization controller, DCF = dispersion compensating fiber, STF = single mode transmission fiber, SDDF = staircase-like dispersion decreasing fiber, DFF = dispersion-flattened fiber). b) auto-correlation trace of a pulse output from the femtosecond light source shown in part a, which achieves a record short pulse width of 20 fs (after ref. 5).

Femtosecond Laser Sources

The monolithic semiconductor laser's ability to generate transform-limited pulses at extremely high repetition rate, a result of the very wide gain bandwidth and the extremely short round trip time in the laser cavities, is very advantageous. Of the potential candidates for generating high-repetition-rate pulses, mode-locked lasers have been most extensively studied.

An InGaAsP/InP monolithic laser consisting of a saturable absorber, two gain sections and a passive waveguide section (as shown in Figure 2) has been fabricated by the Oki group at FESTA using the MOCVD technique [4]. This laser has generated ps pulses at a repetition frequency of 10-50 GHz, and even up to around 200 GHz using the multiplexing technique. Using this laser, a serial combination of two fibers with different group velocity dispersion and dispersion slope with optimized lengths has exhibited an excellent chirp compensation characteristic. Starting from a mode-locked laser pulse with a 13.6 ps duration and 5 nm spectral width, an almost transform-limited pulse exhibiting 500 fs FWHM duration has been generated with this technique [4].

More recently, the world's shortest pulse using a semiconductor laser has been generated at FESTA Laboratories by further optimizing this multi-stage fiber compressor technique [5]. Figure 3a shows the block diagram of a four-stage compressor consisting of a standard single-mode transmission fiber (STF) for 3rd order soliton compression, an erbium-doped fiber amplifier (EDFA) for soliton narrowing, a staircase-like dispersion decreasing fiber (SDDF) for adiabatic compression, and a dispersion-flattened fiber (DFF) for higher-order soliton compression. Starting from a gain-switched 7.5 ps laser pulse at a wavelength of $1.55 \mu\text{m}$, a record for short pulse width of 20 fs (corresponding to only four optical cycles!) has been achieved at the output of the DFF, as is shown in Figure 3b.

In view of making such devices sufficiently compact for practical applications, a technology that enables the group velocity dispersion (GVD) control within semiconductor materials is

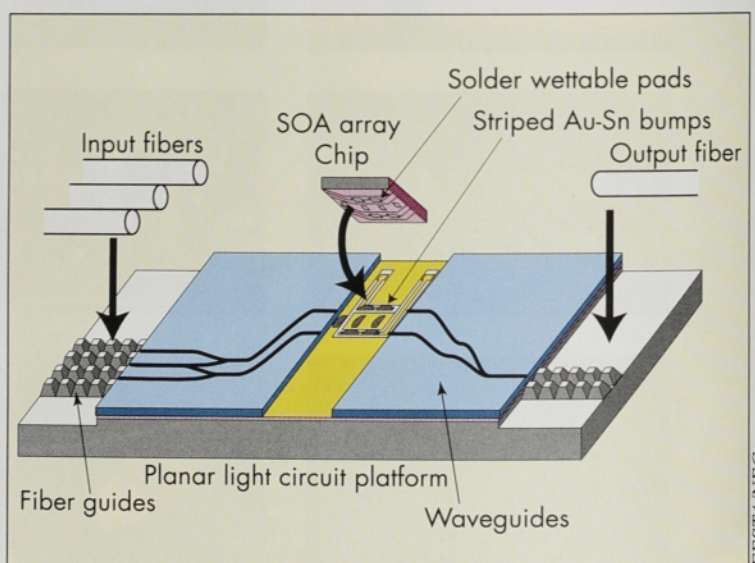


Figure 4. NEC group's integrated symmetric Mach-Zehnder semiconductor optical amplifier (SOA) all-optical switch module (after ref. 7).

challenging, but also extremely important. A pulse compressor based on a coupled-semiconductor-waveguide structure with a giant GVD has been proposed by the Hitachi group [6] at FESTA, and recently, the pulse compression from 2.2 ps down to 510 fs has been successfully demonstrated in an InGaAsP/InP device with dimensions of only 5 mm. Such semiconductor-based dispersion control contributes greatly to the development of compact monolithic femtosecond lasers and other waveguide devices.

Femtosecond All-Optical Switches

All-optical switches feature an ultra-fast response time, a high repetition rate, low switching energy, a high extinction ratio, and low insertion loss. In previous semiconductor optical modulator-based switching devices, the response speed has been limited by the carrier recombination lifetime, which is in the nanosecond timeframe. How this problem can be overcome is a central issue in the development of the switch, and there are a number of different approaches being pursued to produce ultra-fast all-optical switches. One is to develop new device structures that, while enabling ultra-fast operation, don't rely on the material properties. In this vein, optical interferometer structures have been proposed for push-pull operation, enabling ultra-fast gating that is not limited by the carrier lifetime.

Figure 4 shows the structure of FESTA NEC group's all-optical switch module, fabricated from an InGaAsP/InP semiconductor optical amplifier (SOA) array chip and planar light-wave circuits using a self-alignment hybrid packaging technique [7]. Very recently, demultiplexing of the world's highest bit-rate signals from 160 Gbps to 10 Gbps has been demonstrated using just such a symmetric Mach-Zehnder interferometer switch, indicating promising performance for ultrahigh bit-rate systems.

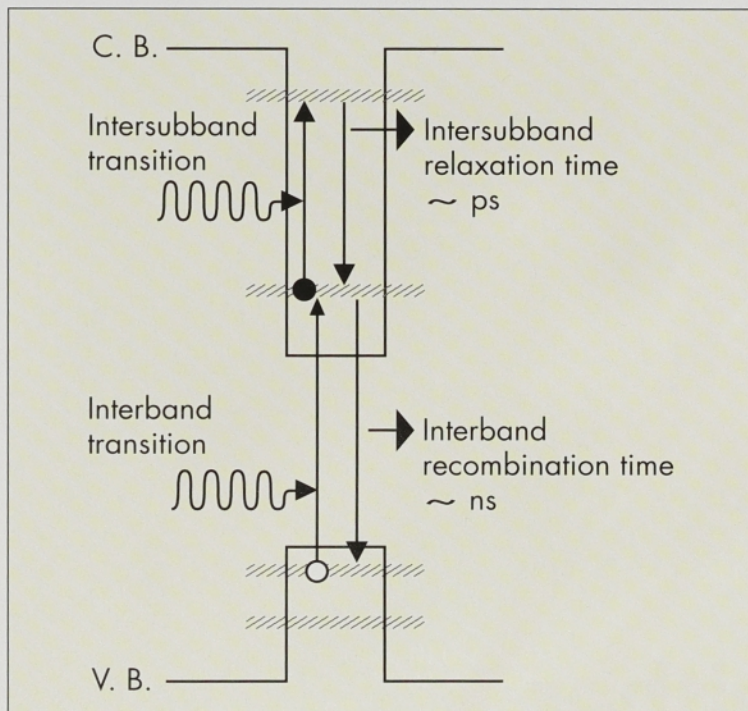


Figure 5. Schematic showing the interband and intersubband transitions in a single quantum well.

Intersubband Transition All-Optical Switches

Another important approach for developing ultra-fast optical switches is to introduce concepts based on ultra-fast physics, which so far have not been employed in devices. These include the intersubband transition (ISBT), spin relaxation, and four-wave mixing, for example [8].

To take one example, we can consider the ISBT in a single quantum well (QW). In conventional semiconductor optoelectronic devices, the interband transition (IBT) is the transition mechanism, and therefore the response time is determined by the carrier recombination lifetime (see Figure 5). In contrast, the ISBT within the conduction band can exhibit an ultra-fast response time, in addition to a large optical non-linearity. Using this approach, the operation wavelength can be widely tuned by designing the quantum well structure and by the choice of heterojunction materials. However, so far there have been no studies on ISBT switching at communication wavelengths.

At FESTA we have proposed coupled-double (C-DQW) [9], and -triple (C-TQW) quantum well structures [10] based on the InGaAs/AlAsSb system lattice-matched to InP as ISBT-based switch structures for the 1.55 and 1.3 μm wavelengths. The key concept of the coupled-quantum well structure is the split of quantized electron states, which allows the ISBT energy to be increased sufficiently to reach the communication wavelengths. The switching dynamics in single QW, C-DQW and C-TQW devices have been analyzed numerically, and the results are summarized in Figure 6. Ultra-fast responses, with FWHM down to 300 fs, can be designed by optimizing the coupled QW structure.

Our recent experiments have shown very strong ISBT absorption, down to 2 μm in an InGaAs/AlAsSb SQW structure grown by MBE, and also the first observation of ISBT absorption saturation at 2.3 μm [11]. Also, the GaN/AlGaN material system, which has a larger conduction band discontinuity, is being developed by the Toshiba group at FESTA for high-per-

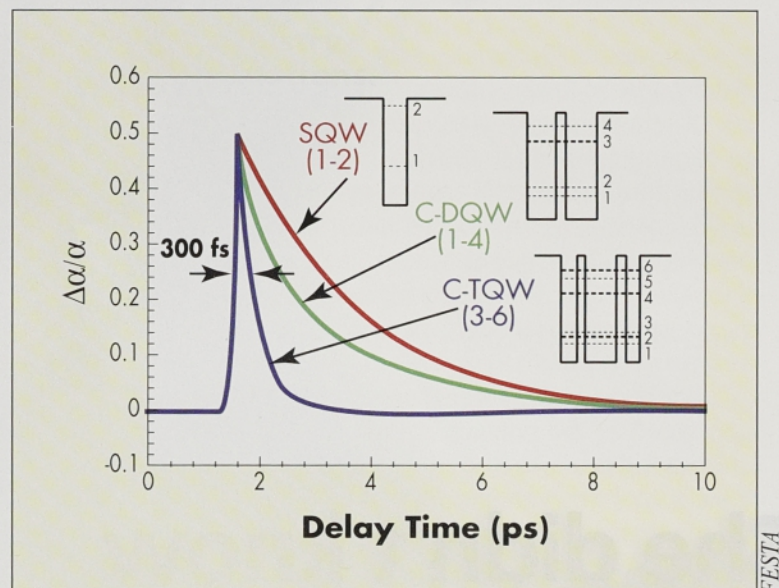


Figure 6. A comparison of the transient responses from intersubband absorption evaluated for InGaAs/AlAsSb single QW-, coupled-double QW- and coupled-triple QW- structures at 1.55 μm (after ref. 10).

formance ISBT switches. An extremely fast response time of 80 fs has been predicted, and also ISBT absorption has been demonstrated at 3 μm in MOCVD-grown quantum wells [12]. This ongoing work emphasizes the promise of the intersubband transition in compact, all-optical switches operating at Tbps data rates.

Conclusions

Development of compound semiconductor-based femtosecond optoelectronic devices is key for constructing optical transmission and signal processing systems to meet the future information throughput requirements of greater than 1 Tbps. Generation, as well as switching, of ultra-short optical pulses in the sub-ps and shorter range have already been demonstrated in a variety of InP-based devices. Further improvements towards higher repetition rates, lower timing jitter and reduced power consumption must follow, leading to the production of useful, practical ultra-fast devices that support future optical systems.

A part of this work was performed under the management of the Femtosecond Technology Research Association (FESTA) and supported by the New Energy and Industrial Technology Development Association (NEDO).

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

Lasers and LEDs for Printing

TIM WHITAKER

Laser printers remain one of the largest markets for semiconductor lasers, despite the arrival of low cost alternatives in the form of desktop inkjet printers. The market for laser diodes in the 750-980 nm wavelength range for printing applications was an estimated 12.6 million units in 1999, equivalent to around \$43 million. In terms of units shipped, this is the third largest market for lasers after optical storage (CD, DVD etc), and laser pointers. "Almost all printers with a throughput of 8-40 pages per minute use single 780 nm lasers," says Patrick Maeda, a Principal Engineer at Xerox's Palo Alto Research Center (PARC). "These devices are leveraged from the huge market for 780 nm diodes for CD players."

Several manufacturers, including Xerox, use other system configurations, including shorter wavelength diodes and print-heads with two monolithically integrated lasers. "Some of the newer machines now use shorter wavelength red laser diodes, which provide improved spot resolution," says Maeda. "For high

resolution systems with medium or high print volumes [40-65 or 90-180 pages per minute respectively], Xerox uses visible lasers in a dual-spot configuration, with two monolithically integrated devices. Also, some of the print engines manufactured by Fuji Xerox use dual-spot infrared diodes."

Shorter Wavelength

In the same way that shorter wavelength lasers increase the capacity of optical storage systems, replacing IR diodes with visible lasers provides higher resolution in printing applications. "With a diffraction-limited laser scanner, the spot size is determined by the numerical aperture of the beam and by the laser wavelength," says Patrick Maeda. "The numerical aperture is determined largely by the optics and the size of the polygon mirror. Blue lasers have roughly half the wavelength of their IR counterparts, so that with the same numerical aperture you get about half the spot size."

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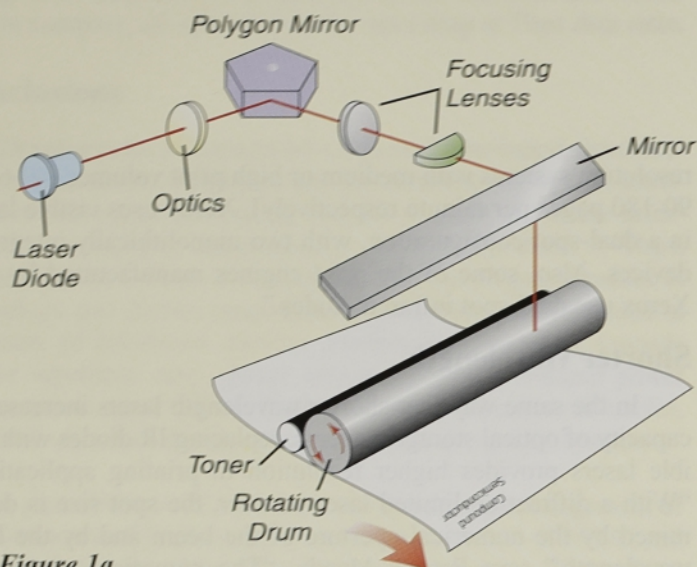


Figure 1a.
A typical laser printer

The normal configuration for a desktop laser printer is shown in Figure 1a. The laser diode is directly or externally modulated, and the light beam is reflected from a facet of the polygonal mirror rotated by a scanner motor, and refracted through a lens to scan the beam across a rotating cylindrical drum. The drum is coated with a photosensitive material - today most photoreceptors are organic and are based on phthalocyanine derivatives. The laser writes a pattern of electrostatic charge that equates to the latent image. Toner particles are attracted to the electrostatic charge pattern as the drum passes through the toner tray. The toner

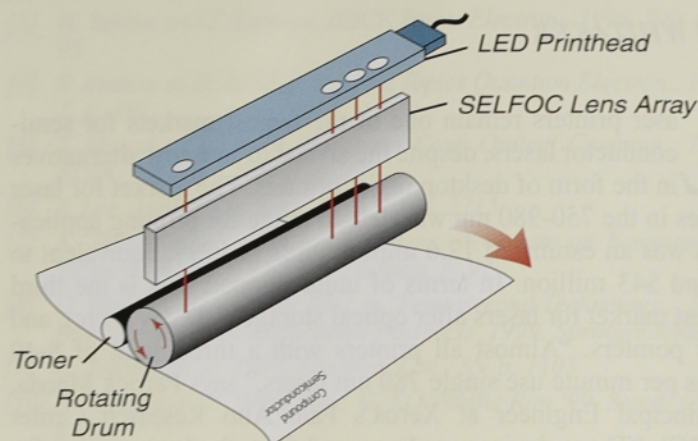


Figure 1b.
An LED printer

particles are transferred to the paper electrostatically and fused by compression or heat to create the printed page.

In an LED printer (Figure 1b), a linear printhead containing several thousand LEDs pulse-flashes across the entire page width to write each line. The SELFOC lens array contains a number of index-graded rods. The optical configuration is much simpler than for a laser printer, leading to improved reliability and other advantages. Lower brightness, higher power consumption and lower printing speed are disadvantages at present.

The desire for smaller spot sizes and higher resolution is driving a move towards shorter wavelength emission, and a number of printers already use visible (red) lasers. Xerox PARC has an ongoing program to develop InGaN-based lasers for printing applications, and several months ago reported a device operating in CW mode at room temperature, with a lifetime exceeding one hour [see *CS 5(4)*, p. 16].

Dual-Beam Systems

For higher print speeds, system limitations such as the rotation speed of the polygon mirror become important. One way around this is to use two or more lasers in parallel to write multiple scan lines simultaneously. This requires that individual scanned laser spots must be positioned very precisely relative to one another, and monolithic arrays are the most practical solution.

Using two beams instead of one, it is possible to deliver twice as much information to the recording medium (the photoreceptor on the drum in this case). "This additional bandwidth

can be used to increase the print speed or scanning resolution, or a combination of both," says Maeda. "It also allows us to introduce more sophisticated image processing." For an equivalent optical system and drum rotation speed, dots can be spaced more closely using two lasers, and a greater number of lines can be addressed in a given distance on the drum.

"In some low volume printers, the scanning resolution was doubled to 1200 spi [spots per inch] by halving the rotation speed of the drum and writing twice as many lines over the same distance," says Maeda. "For higher print volumes, it is necessary to increase the rotation speed. Virtually all Xerox printers with a resolution of 600 spi or higher and offering print output volumes of 40 pages per minute or higher use a dual-spot laser system."

One example of a dual-spot laser system was described in a previous publication¹. The lasers were independently addressable GaInP diodes operating at 675 nm. The MOCVD-grown laser structures included a single compressively strained InGaP quantum well surrounded by AlGaP waveguide layers, with AlInP

¹ R. Geels et al, *Elec. Lett.*, 1992, 28(15), p. 1460

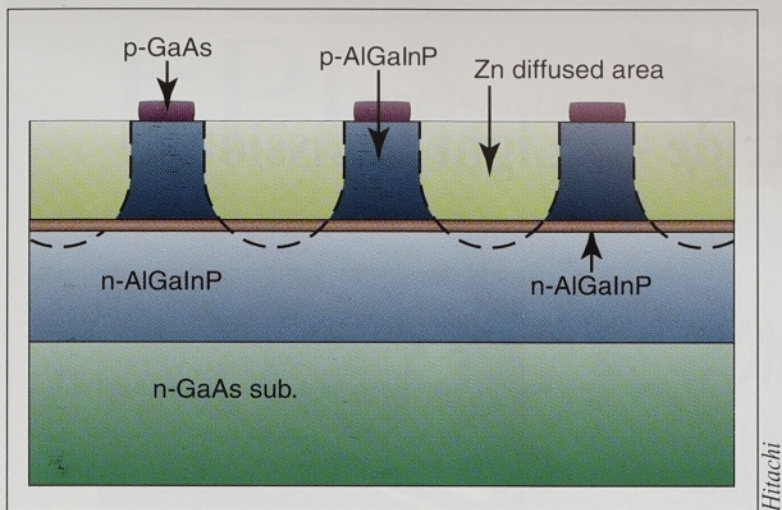


Figure 2. Cross-section of GaInP/AlGaInP laser diode array, fabricated by a self-aligned Zn diffusion process.

cladding layers. The dual-spot diodes were fabricated by etching and regrowth to obtain buried 5 μm -wide waveguides with a 50 μm center-to-center spacing. Singlemode output powers of 30 mW per emitter were obtained with less than 0.3% crosstalk.

At the 1999 Photonics West meeting, researchers from Hitachi² described a method to fabricate arrays of 630 nm laser diodes using a Zn diffusion process to isolate the active elements. The device (see Figure) contained a MQW region with GaInP tensile strained layers and AlGaInP barrier layers. After the p-type GaAs cap was patterned into stripes, Zn diffusion was carried out. This formed a quantum well intermixed region with a PL peak wavelength of 595-600 nm, some 25-30 nm shorter than the wavelength of the laser stripe, which provided waveguiding. The high resistivity of the Zn-diffused region was also effective in isolating the laser elements.

LED Printers

As an alternative to laser printers, several companies now manufacture machines with printheads containing several thousand LEDs. The LEDs are positioned to span the entire print width (see box), resulting in a much simpler optical configuration with no moving parts. This offers advantages in areas such as reliability, asynchronous operation, and form factor for small tandem color printers.

First generation LED printers contain printheads with several thousand LEDs precision-mounted and wire-bonded to a substrate, resulting in a relatively expensive system with a high dissipative power. For printers where water cooling of the printhead cannot be employed, the LEDs must be driven at lower exposure levels which results in lower print speeds.

There are other reasons why laser printers are typically faster than LED printers at present. One factor is that lasers are several orders of magnitude brighter than LEDs. Another is that the optical system throughput can be two to eight times higher for a scanning optical system relative to a Selfoc lens array. "These factors partly explain why a watercooled 7200-spot LED printhead pro-

vides roughly the same amount of light exposure as a dual-spot laser printhead," says Patrick Maeda. "Even though there are limits to polygon rotational speeds, more beams can be added to the laser to increase print speeds beyond where they exist today."

The print speed of LED printers is directly related to the LED light output, and the resolution is related to the spacing between the devices. Oki Electric has made good progress in improving both these areas, and has developed a process to fabricate monolithic arrays of AlGaAs LEDs with a pitch of 21.2 μm , using a controlled solid phase Zn diffusion technique to form the individual emitters [see CS 5(4), p. 38]. The process has enabled Oki to introduce 1200 dpi printers that incorporate print heads containing a number of such arrays, with a total of 15,360 LEDs. Importantly, the process also results in much lower power consumption and higher brightness compared to earlier versions using GaAsP as the active layer material in the LEDs.

Xerox uses LED technology in its engineering printer, which has a long print width of 36 inches and is used to produce blueprints and other large format engineering documents. The form factor of an LED print head lends itself to this type of arrangement. For a laser printer, it would be necessary to build a system to scan over the whole print width. The optics scale accordingly, and would be at least two times larger than for a standard page size printer. Xerox has also investigated the use of VCSELs for printing applications, and has fabricated monolithic arrays containing many thousands of independently addressable elements with a pitch of 3 μm [see CS 4(2), p. 26]. The aim is to produce a single chip array, and to use a projection lens to magnify the output across the full print width.

Color Printing

In some configurations, the LED approach also lends itself to single pass color printing. "In most color printers there is one print head and one photoreceptor," explains Maeda. "The drum rotates four times, one for each of the four standard process colors. This reduces the machine's productivity by a factor of four compared to black and white printing." However, it is possible to introduce four photoreceptors and four imagers in tandem, which allows the printing process to be completed in a single pass through the machine. Single pass, full color printing has been implemented using either laser or LED printheads in tandem. "The LED printhead form factor is, in general, more rectangular than that of a laser printhead," says Maeda. "It is larger in width, smaller in depth, similar in height and can be placed much closer to the photoreceptor. So for a small desktop single pass color printer, the LED printhead is preferred. For larger systems however, this form factor difference may not be as critical."

It seems clear that printing technology, at both the device and system level, needs to keep pace with ongoing requirements for higher print volumes and higher resolution. Patrick Maeda envisages more use of dual-spot and multi-spot lasers, and the continued development of shorter wavelength devices. He also sees more use of LEDs in tandem color printers, particularly with the development of high brightness AlGaAs LED arrays.

² S. Nakatsuka and S. Saito, *Proc. SPIE 1999*, 3628, p. 196

Rare Earth Doped Gallium Nitride — Light Emission from Ultraviolet to Infrared

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The lanthanide elements, commonly known as the “rare earths” (RE), have been an increasingly important ingredient in a variety of photonic applications [1], ranging from solid-state lasers to color displays to optical fiber telecommunications. RE elements have a partially filled inner ($4f^n$) shell shielded from its surroundings by completely filled outer ($5s^2$ and $5p^6$) orbitals. This results in optical emission of very sharp lines at wavelengths from the UV to the IR, which are relatively independent of the host material and are determined by the energy of the transition between $4f$ states of the RE. While the host material has a weak influence on the emission wavelength, it does have a very strong effect on the radiative transition probability. In general, doping of conventional semiconductors (Si, GaAs, etc.) with REs has suffered from limited solubility and severe temperature quenching, which has made the room temperature operation impractical.

Emission Peaks

In this paper we briefly review the recent breakthroughs made with the incorporation of trivalent rare earth (RE^{3+}) elements into GaN films and resulting light emitting devices. GaN is a wide bandgap semiconductor that is intensely investigated [2] for optical and electronic applications. Er^{3+} doping of GaN has been shown to produce strong near-IR $1.5\ \mu m$ emission suitable for fiber optic telecommunications from the lowest excited state. At Cincinnati, we have obtained for the first time photoemission from higher excited RE states in GaN covering the entire visible spectrum: light emission in the green (from Er at 537/558 nm) [3,4,5], red (Pr at 650 nm, Eu at 621 nm) [6,7], and blue (Tm at 477 nm) [8]. Emission in the near-infrared (IR) is also obtained at 801 nm from Tm [8], at 1000 and 1540 nm from Er [5], and at 956, 1303 and 1914 nm from Pr [6].

The rare earths were introduced during growth of the GaN layer by MBE on either sapphire or Si substrates. Figure 1 shows emission spectra from electroluminescent devices (ELD) for GaN doped with Tm, Er, Pr and Eu. Also shown in Figure 1 is the intrinsic GaN emission in the ultraviolet part of the spectrum at ~ 365 nm. The primary visible colors emitted by GaN ELDs doped with these individual REs are very “pure” and match very well the CIE coordinates adopted by the National Television System Committee (NTSC).

In addition to the pure colors, mixed colors have been obtained by co-doping GaN films with a combination of REs. As seen on the cover of this issue and discussed in more detail below, GaN:RE ELDs have been developed which emit in a variety of pure and mixed colors. In general, emission from GaN:RE is surprisingly strong, being observable with the naked eye at room temperature. Significant signal reduction with temperature is generally not observed until well above room temperature. Thus, rare-earth-doping of GaN represents an interesting alternative to semiconductor alloying (GaN/InN/AlN) for visible light emis-

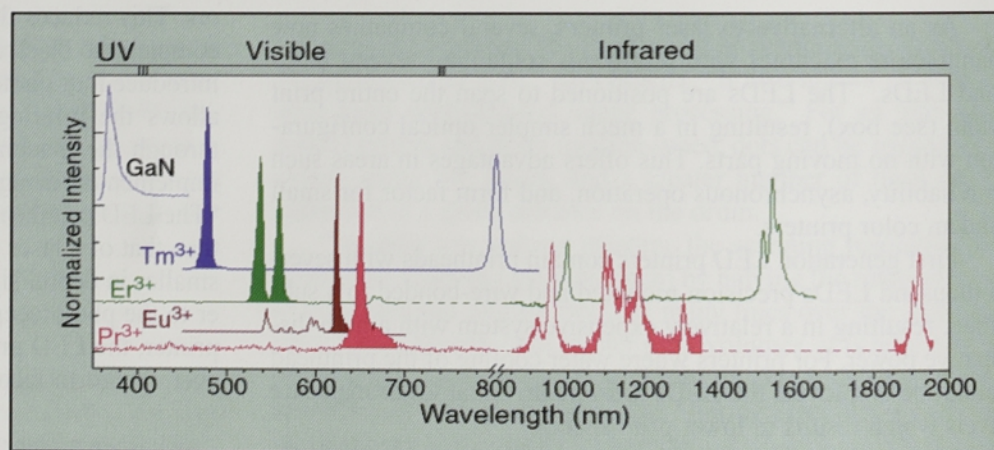


Figure 1. The emission spectrum of several different RE-doped GaN films from visible to IR wavelengths. All spectra are normalized to their own highest value and are not readily comparable to each other in intensity. The color of the GaN:Tm emission is blue, GaN:Er is in the green, and both GaN:Eu and GaN:Pr emit in the red. For the visible region, all spectra were taken from working ELDs. In the IR region, the GaN:Tm and the GaN:Er spectra are from working EL devices while the GaN:Pr is from PL data.

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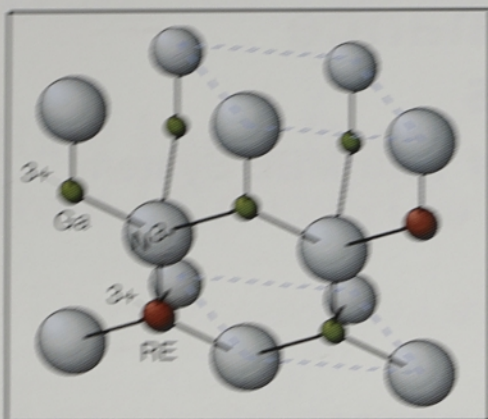


Figure 2. Preliminary model of the GaN:RE crystal structure. The Er-N bond has been measured to be 2.17 Å, versus a Ga-N bond length of 1.95 Å.

sion applications and has the additional attractive aspect of strong IR emission for telecommunications and other applications. The use of Si as the substrate material for GaN:RE ELDs is another clear advantage of this technology.

Rare Earth Incorporation

Theoretically, RE intra- $4f^n$ atomic transitions are parity forbidden by the Laporte selection rule. RE ions incorporated into a partially ionic solid frequently substitutionally occupy the cation site. In the cation site an uneven ligand crystal field relaxes the selection rule and increases the probability of intra- $4f^n$ transitions [9]. These $4f-4f$ transitions, however, are still not fully allowed, resulting in excited state lifetimes of $\sim 10^{-3}$ s for RE-doped systems. In wurtzitic GaN, which has a significant component of ionic bonding, the RE^{3+} ions have strong optical activity levels, since they are generally substitutionally located on the Ga sublattice where the lack of inversion symmetry produces strong ligand fields thereby increasing the $4f-4f$ transition probability. These substitutional RE dopants are therefore likely to be the optically active RE centers observed in GaN:RE.

A preliminary model of the GaN:RE crystal structure is shown in Figure 2. A strongly bonded GaN lattice, in conjunction with substitutional incorporation [10] allows unusually high RE doping concentrations (up to at least ~ 1 at. %) with no quenching or saturation of the optical signal. By comparison, the use of

RE^{3+} -doped II-VI semiconductors as emitters and phosphors suffers from a more weakly bonded lattice, and substitutional location of the RE^{3+} ions on the $2+$ cation sites, which generates electrically-active defects due to lack of charge neutrality.

RBS channeling analysis [11] confirms that a great majority ($\sim 90\%$) of the Er ions occupy substitutional sites on the Ga sublattice even at relatively high concentrations of >0.1 at.%. The Er-N bond has been measured by EXAFS analysis [12] to be 2.17 Å, versus a Ga-N bond length of 1.95 Å. This unusually short Er-nearest neighbor bond length in GaN is thought to be due to two major factors: (a) the low 4-fold coordination, compared for example to a 12-fold coordination in $ErSi_2$; (b) a more polar bond for the Er-N than for Ga-N (due to electronegativity differences), which helps to energetically compensate for the Ga - Er size mismatch.

Light emission from GaN:RE has been demonstrated via photoluminescence (PL), cathodoluminescence (CL), and electroluminescence (EL). The dominant mechanisms for excitation and subsequent relaxation of RE dopants in GaN

are depicted in Figure 3. In PL electron-hole pairs are generated by above band-gap photon absorption, carrier generation is provided by a high energy electron beam in CL, and in EL carrier injection occurs by the application of bias voltage to electrical contacts on the GaN layer.

Low Voltage ELD

The form of EL that the GaN:RE ELDs utilize involves impact excitation of RE dopants. In order for hot carrier excitation to occur, a high electric field is applied across the GaN layer. Green light emission from GaN:Er ELDs has been observed at an applied bias as low as 5 V. This indicates that the minimum field strength required for GaN:RE ELDs is an order of magnitude lower than the 1-2 MV/cm required for II-VI:RE based ELDs. In Figure 4, a low voltage GaN:Er ELD is shown emitting green light at a bias of 7.5 V, along with a corresponding graph of current and light intensity vs. applied voltage. The device consists of an Er-doped GaN layer grown by MBE on an n^+ Si substrate and a top-side circular ("ring contact") transparent bias electrode of In-Sn oxide (ITO). The combination of

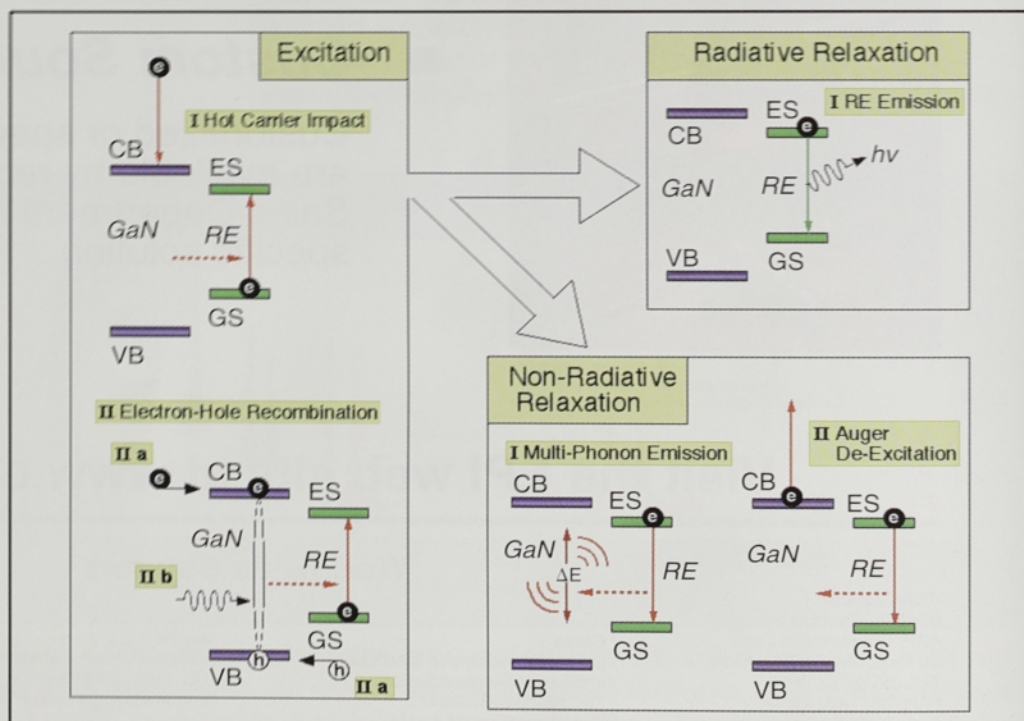


Figure 3. The dominant mechanisms for excitation and subsequent relaxation of RE dopants in GaN. Shown schematically in the diagrams are the conduction band (CB) and valence band (VB) edges of GaN and the ground state (GS) and excited state (ES) for RE transitions.

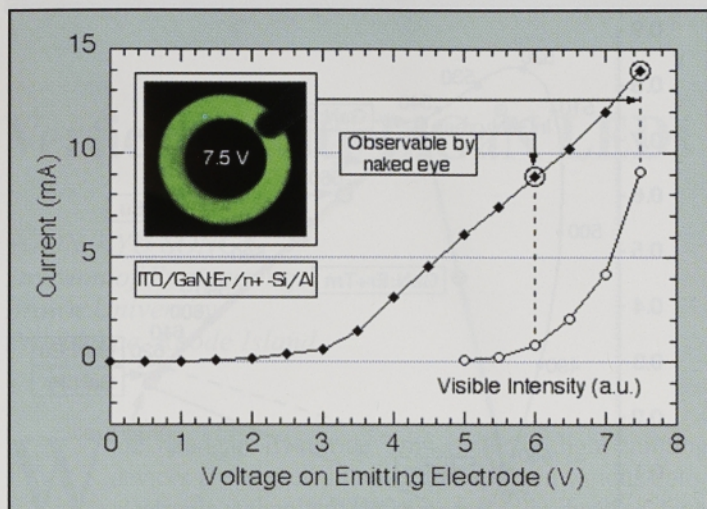


Figure 4. GaN:Er ELD current and EL intensity as a function of voltage on emitting electrode. A thin (~300 nm) GaN layer and n^+ Si substrate are used to obtain low-voltage optical turn-on at 6V. The inset is a photograph of green emission under the ITO bias electrode at 7.5 V.

this very simple device structure with the use of Si substrate indicates the potential of this technology for low-cost displays and for integration with Si technology for drive and control circuitry.

1.5 μm Operation

A second major application of RE-doped GaN is in the area of fiber optic telecommunications, which has seen explosive growth in terms of both new network installation and network bandwidth. Fiber optic signals carry near-IR wavelengths, primarily 1.5 μm and secondarily 1.3 μm , which are the wavelengths of minimum loss and minimum dispersion in silica fibers.

Fiber optic sources and amplifiers have been developed using Er^{3+} and Pr^{3+} doped in a variety of glasses. Semiconductor-based equivalents that could take advantage of semiconductor technology for miniaturization and operation, have suffered from low solubility and thermal quenching. Extensive research has been carried out on Er-doped Si (for reviews see Coffa et al. [13] and Fitzgerald and Kimmerling [14]). The IR radiation is nearly completely quenched at temperatures around 200 K. The addition of a significant oxygen concentration has also been shown to improve the Er temperature quenching in silicon [15,16] but at the expense of a more complicated process and degraded electrical properties. An increasing semiconductor bandgap has also been shown to reduce temperature quenching [17]. GaP, which has a larger bandgap than Si, still exhibits [18] a reduction in EL intensity at 300 K compared to low temperature values.

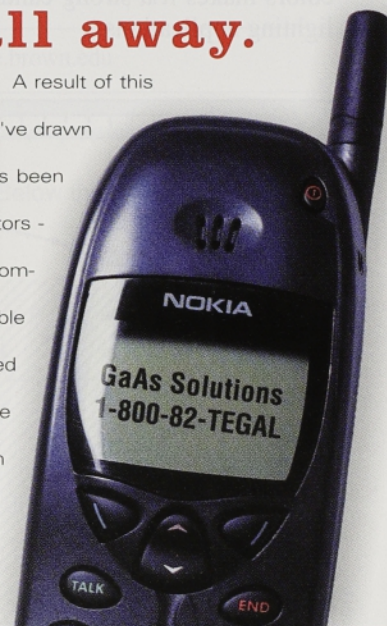
In Er-doped GaN, the thermal quenching is for all practical purposes, no longer a problem. Figure 5 shows the temperature

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dependence of the 1.5 μm electroluminescence of a GaN:Er ELD. Notice that the EL intensity actually peaks at around 375 K. A practical operating temperature range for these devices would be from 275 K to 410 K, representing a maximum $\pm 5\%$ deviation in signal intensity. This is important especially when considering the temperature quenching of the IR light emission in other semiconductor hosts. We therefore conclude that GaN has a significant advantage as a host for erbium compared to GaAs, GaP and Si, which have been extensively studied for Er-based light emitting applications. In the case of GaN:Er, it appears that devices could be developed for semiconductor light sources and amplifiers of 1.5 μm signals.

Pure and Mixed Colors

The versatility of the GaN:RE technology is illustrated using the CIE chromaticity diagram shown in Figure 6. The triangle in the diagram connects the three primary visible colors emitted by the GaN doped with Tm (blue), Er (green), and Eu and Pr (red). The coordinates of this triangle match very well the standard primary colors of the NTSC. In addition to primary colors, mixed colors or hues can be obtained by incorporating multiple REs into the GaN layer, whose combined emission is perceived by the eye as a range of colors depending on the relative intensities of the constituents. Examples of mixed colors shown in Figure 6 are a combination of Er and Tm yielding the cyan color and Er and Eu producing orange and yellow colors. The ability of RE-doped GaN technology to cover the visible color spectrum with both primary and mixed colors makes it a strong candidate for a variety of display and lighting applications.

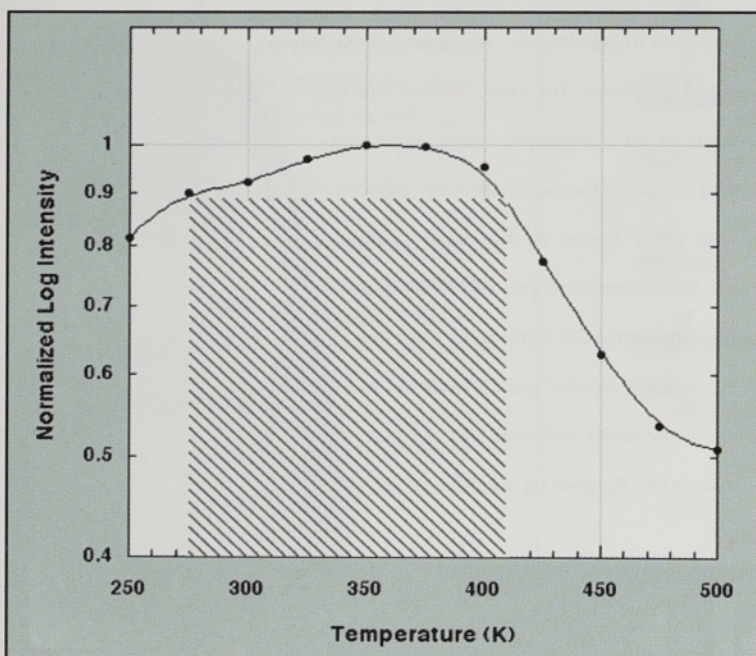


Figure 5. Temperature dependence of the 1.5 μm electroluminescence of a GaN:Er ELD. The shaded region indicates the useful operating temperature range, corresponding to a maximum $\pm 5\%$ change in signal intensity.

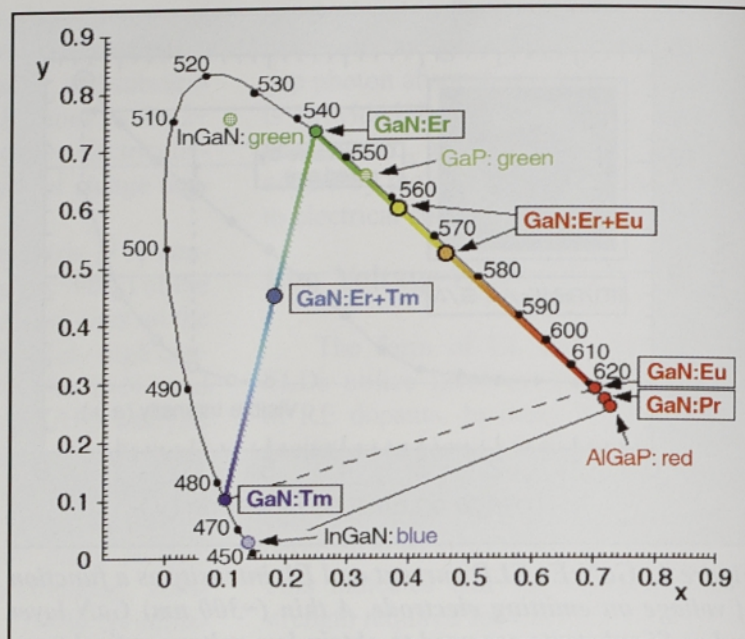


Figure 6. CIE x-y chromaticity diagram showing the location of pure color emission from GaN ELDs doped with Tm (blue), Er (green), Eu (red) and Pr (red) and of mixed color emission using GaN:Er+Tm (cyan) and yellow and orange emission from the GaN:Er+Eu ELD. Also shown are the coordinates of other commercial LEDs.

The authors are pleased to acknowledge the support of this work by BMDO/ARO and the contributions of their many collaborators at other institutions.

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Vertical Cavity InGaN LEDs and Lasers

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Wide bandgap III-nitride semiconductor light-emitting devices are expected to play a key role in various optoelectronic technologies such as full color displays, high performance color copying/printing, and high density optical storage.

In the past few years, high efficiency (~10%) bright blue and green LEDs based on InGaN quantum well heterostructures have been produced and sold in their millions by leading manufacturers such as Nichia, Hewlett-Packard (now Agilent) and Cree. Furthermore, progress with GaN-based diode lasers has led to their commercial availability from Nichia early this year [1].

Together with this remarkable commercial success, other scientific advances in nitride materials and devices suggest a further broadening of the base of this emerging technology, for which potential applications abound. Thus, in spite of several technical, device-related challenges, optimism is warranted. Given this, it is natural for nitride researchers to look at vertical cavity light emitters, such as resonant cavity LEDs (RCLEDs) and vertical cavity surface emitting lasers (VCSELs), as candi-

dates for enlarging the range of applications for wide bandgap semiconductor optoelectronic devices.

VCSELs and RCLEDs

VCSELs have gained in importance in recent years for applications where the beam quality, prospects for high density arrays, and ability to be integrated into microelectronics are at a premium. Whether for highly-parallel optical interconnects, optical disk heads, or printers and scanners, the vertical cavity configuration offers many distinct advantages. In the case of RCLEDs, the quasi-beam-like directionality of the spontaneous emission and enhancements to the radiative recombination can be useful for a broad range of display applications.

The near-term technological prospects for blue, green and near-ultraviolet VCSELs and RCLEDs are difficult to gauge in the present, incipient research stages. For example, it is unclear

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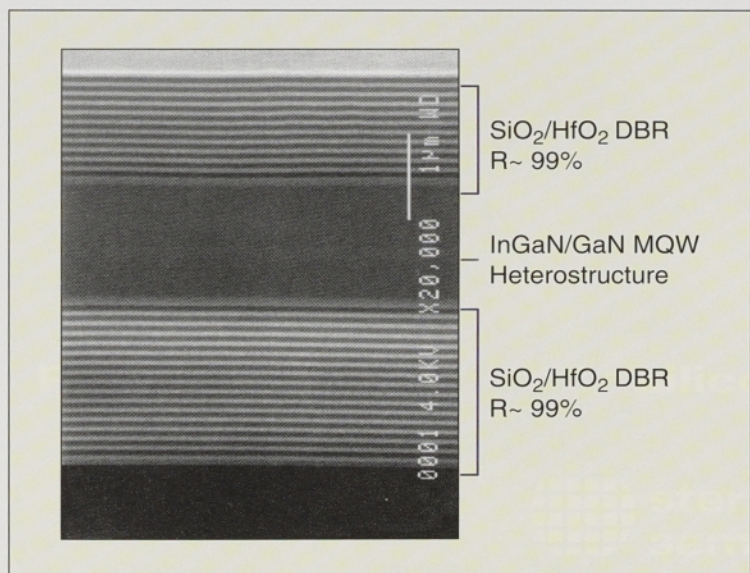


Figure 1. SEM cross-sectional image of an InGaN MQW vertical cavity structure containing dielectric distributed Bragg reflectors (DBRs). The sapphire and GaN are separated by a UV laser, which allows the deposition of a second HfO₂/SiO₂ multilayer dielectric stack to complete the vertical cavity structure.

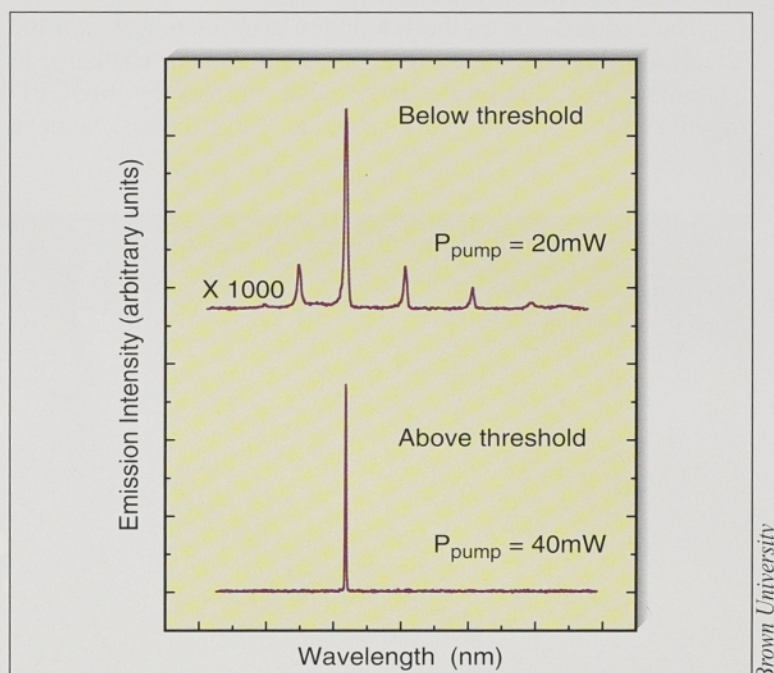


Figure 2. Top: spontaneous emission spectrum of the InGaN MQW VCSEL shown in Figure 1 below threshold ($P_{th} = 32$ mW) and bottom: stimulated emission spectrum above threshold under quasi-CW pumping conditions at $T = 258$ K.

which combination of epitaxial growth and device design/processing schemes might result in a technologically viable VCSEL. However, there are ample reasons to suggest that microcavity emitters based on wide bandgap semiconductors could offer opportunities both in terms of basic physics and device performance. These features originate from the strong light-matter coupling fundamental to low dimensional wide bandgap semiconductor microcavities, and may boost the operational characteristics of nitride-based VCSELs and RCLEDs in future.

Challenges Facing Nitride Vertical Cavity Devices

The current challenges facing efforts to realize blue and violet RCLEDs and VCSELs in the AlGaInN material system have many similarities with those encountered earlier with the conventional III-V compounds. On one hand, the nitride p - n junction heterostructures have produced both excellent LEDs and strikingly robust diode lasers; on the other, the formation of a reasonably high-quality vertical cavity is much more challenging in the nitride compounds than in the non-nitride III-V semiconductors. In addition, the relatively low lateral conductivity of p -type materials in the current nitride compounds is another serious obstacle, challenging the design of any vertical cavity device injection scheme that aims for electrical efficiency.

The Optical Resonator: Choosing Distributed Bragg Reflectors

There are two approaches for microcavity fabrication, one based on in-situ, as-grown GaN/AlGaIn multilayer distributed Bragg reflectors (DBRs), and the other on dielectric DBRs. Hybrid schemes also have considerable merit and recent experiments have shown some promise.

The contrast due to the low index of refraction within the AlGaIn alloy system makes it at first sight a major challenge to create low loss, high-reflectivity DBR mirrors by MOCVD growth directly on a sapphire substrate. Nevertheless, Someya

and co-workers [2] have incorporated a 43-period MOCVD grown GaN/Al_{0.34}Ga_{0.66}N DBR mirror ($R \sim 0.98$) grown on sapphire into a hybrid vertical cavity structure in which the second mirror comprises a 15 period ZrO₂/SiO₂ dielectric DBR ($R = 0.995$). The active medium in the resonator consists of a 2.5 λ thick InGaIn quantum well heterostructure (housing 26 wells).

Upon high-excitation pulsed-pumping with a low repetition rate UV laser, the authors, as well as Krestnikov et al [3], observe stimulated emission from the structure and attribute this to vertical cavity lasing. The threshold for the onset of stimulated emission was very high, however, typically ~ 10 mJ/cm² in terms of the incident pulse energy density.

High-Q Cavity with Dielectric DBRs

The creation of an all-dielectric DBR resonator of relatively high quality has been recently demonstrated by Song et al [4, 5]. The fabrication involves the separation of a quantum well heterostructure from its sapphire substrate and its subsequent integration with high reflectivity, low loss HfO₂/SiO₂ dielectric mirrors.

The process involves the initial flip-chip mounting of the nitride substrate onto an artificial host substrate (by various wafer bonding and related approaches) and the release of the sapphire substrate through exposure of the structure to a single pulse of UV excimer laser radiation ($\lambda = 308$ nm). The UV laser radiation is absorbed selectively near the GaN/sapphire interface and, once a critical pulse energy density is exceeded, leads to the physical separation of the sapphire over a macroscopic area. This is due to forces that are presumed to originate from rapid thermal decomposition of the GaN [6,7]. Finally, a second HfO₂/SiO₂ multilayer dielectric stack can be deposited to complete a vertical cavity structure, as shown in the cross-sectional electron micrograph of Figure 1.



Figure 3. Color photograph of the violet beam emerging from an MQW InGaIn VCSEL cavity, showing a narrow radiation angle of approximately 5°.

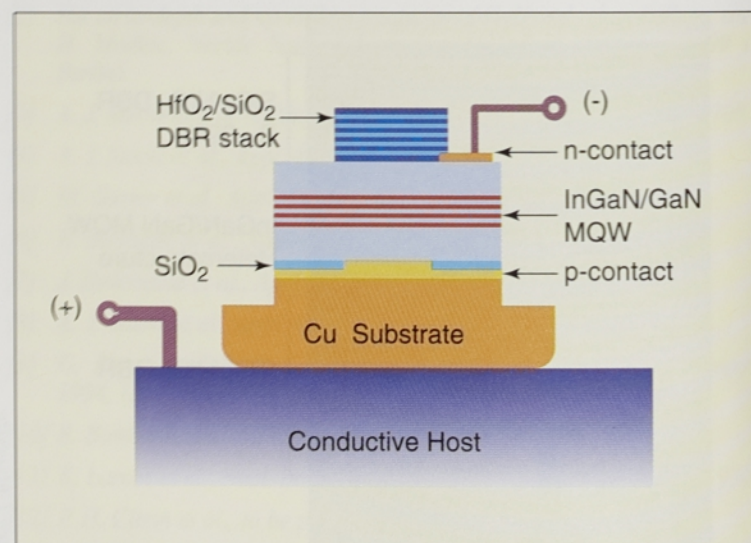


Figure 4. Schematic illustration of the vertical injection LED, incorporating a SiO₂/HfO₂ dielectric mirror stack. The sapphire substrate and InGaIn/GaN/AlGaIn QW heterostructure are separated by excimer laser irradiation, and followed by the deposition of a high reflectivity dielectric DBR on the n -side of the device. The p -side uses the natural reflectivity of the contact metals (typically up to $R \sim 0.6$) to define the vertical cavity.

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Quasi-Continuous Wave Optically Pumped VCSELs

These “all-dielectric” mirror structures have led to the demonstration of an optically-pumped VCSEL in structures that, in initial experiments, shows a cavity Q-factor approaching 1000. Figure 2 (upper trace) shows the emission spectrum at $T = 258$ K from one such structure under quasi-continuous wave (cw) optical pumping [5]. The modes are well defined and exhibit a linewidth of approximately 0.5 nm.

Under optical pumping at relatively modest levels of quasi-cw excitation with the third harmonic of a mode-locked Nd:YAG laser (average power ~ 40 mW), strong stimulated emission has been measured from these structures (lower trace) at frequencies corresponding to the modal positions. This includes a well-defined threshold at 32 mW and the clear observation of linearly-polarized far field emission with the radiation angle of 5° , as shown in Figure 3.

In-Plane vs. Vertical Cavity Lasing

In our experience, it has been very difficult to obtain “true” vertical cavity lasing in InGaN/GaN/AlGaIn heterostructures, the reason being that such VCSEL operation has to compete strongly with in-plane lasing. The latter occurs readily through the formation of “accidental” optical resonators defined by cracks induced by strained AlGaIn layers.

This competition between in-plane and true perpendicular vertical cavity lasing will be an important issue in the further development of nitride-based VCSELs. Nitride-based heterostructures contain extended defects, such as the cracks that develop along a principal crystalline axis in the case of AlGaIn once the Al composition exceeds around 10%.

In their recent work on surface mode lasing from a 2λ thick low-Q resonator with closely stacked ultra-thin InGaIn quantum dots in a GaN matrix, Krestnikov et al [3] noted that optical pumping conditions need to be sufficiently extreme in order that the in-plane lasing saturates. If this is the case, the implication is that the lasing threshold for a true VCSEL might be prohibitively high, especially for the resonator scheme requiring AlGaIn DBR mirrors. Hence, considerable effort is still required to improve the material homogeneity of VCSELs at the blue and near ultraviolet wavelengths (it is noted that the data shown in Figures 2 and 3 were obtained on crack-free material grown by special techniques).

Vertical Cavity InGaIn LEDs

So far we have mentioned the first promising efforts but also highlighted the challenges facing the realization of an electrically-injected vertical cavity nitride-based device. To this end, we have fabricated a demonstration device that may constitute an approach to the creation of a resonant cavity LED [8]. The method is again based on the separation of the sapphire substrate from the InGaIn/GaN/AlGaIn quantum well structure by excimer laser irradiation, and the deposition of a highly reflective dielectric DBR on the n-side of the device.

A schematic diagram of the structure is shown in Figure 4. The p-side uses the natural reflectivity of the contact metals (typically up to $R \sim 0.6$) to define the vertical cavity. The optical aperture defined by this construction was typically about $20\ \mu\text{m}$ in diameter.

Figure 5 shows the spectral and electrical characteristics of this type of vertical cavity LED. The devices have been operated in continuous mode up to a current density of $1\ \text{kA}/\text{cm}^2$ (Figure 5, right), demonstrating both a well-defined vertical cavity modal structure (Figure 5, left) and their robustness as rudimentary RCLEDs.

Electrical Transport Issues – Low p-Type Conductivity

The current-voltage characteristics of devices such as shown in Figure 4 highlight a difficult challenge facing the realization of realistic RCLEDs, and especially blue VCSELs. The bias voltage at which significant forward current injection ($\sim 1\ \text{kA}/\text{cm}^2$) occurs for this device with a particularly thick ($\sim 2\ \mu\text{m}$) p-type GaN layer is a few volts higher than that of a device with a conventional structure. This phenomenon is associated with the rather low resistivity of p-GaN and its alloys. The hole mobility in p-GaN is of the order of $10\ \text{cm}^2/\text{Vsec}$, while the maximum reported free hole concentration is $p < 1 \times 10^{18}\ \text{cm}^{-3}$. Thus, in the case of vertical cavity structures that employ dielectric DBRs (or as-grown

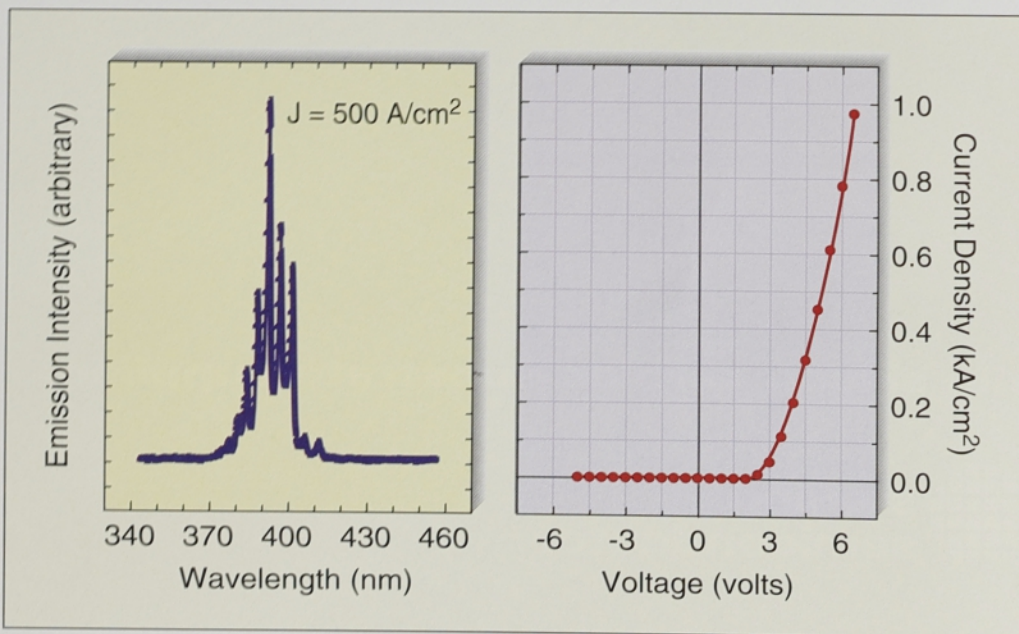


Figure 5. Left: emission spectrum of a vertical cavity LED at room temperature under CW injection displaying well-defined cavity modes; right: current density-voltage characteristics of the device in the high injection regime at room temperature demonstrating cw operation up to $1\ \text{kA}/\text{cm}^2$.

AlGaIn DBRs with a high Al fraction), the injection of holes requires an enhancement scheme that will allow the holes to reach the optically active region below the DBR.

In the case of a standard *p*-type GaN current spreading layer, the lateral conductivity is not sufficient to compete with vertical transport until the device area approaches approximately 1 μm . Such a small optical aperture in turn implies prohibitive transverse modal losses for a VCSEL.

AlGaIn/GaN Superlattices for Lateral Transport

Some progress has been recently made in reducing the lateral resistivity of GaN by employing a concept that is related to modulation doping in conventional III-V semiconductors. Kozodoy et al have achieved high *p*-type conductivity in Mg-doped AlGaIn/GaN superlattices. Effective hole concentrations exceeding $2.5 \times 10^{18} \text{ cm}^{-3}$ have been achieved, and a lateral resistivity as low as $0.2 \Omega \text{ cm}$ has been realized [9].

In the case of nitride-based heterostructures, dielectric polarization and piezoelectric contributions significantly modulate the band edge energies that can be exploited in these modulation-doped schemes. While the value of the lateral resistivity reported by these authors is still about one order of magnitude less than required for a practical VCSEL, the "bandstructure engineering"

approach suggests that further improvements may be possible, in particular, by optimizing the superlattice structure with specific nitride compounds.

Acknowledgements

This work was supported by the National Science Foundation. I would like to acknowledge with gratitude Arto Nurmikko at Brown University, Rick Schneider and our collaborators at Agilent Technologies, whose work has been featured in this article and in the reference list.

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Applied Optoelectronics Fabricates IR Photodetectors on Wafer-Bonded Substrates

Applied Optoelectronics Inc., (AOI; Sugar Land and Houston, TX) in collaboration with Dr. Gail Brown and co-workers at the Air Force Research Laboratory (AFRL; Wright-Patterson AFB, Ohio), has fabricated new long-wavelength infrared photodetectors using MBE-grown InAs/InGaSb type-II superlattices. When operated as photoconductors at cryogenic temperatures (10 K), these detectors exhibited cutoff wavelengths from 10 to over 21 microns. The device structures were grown on a revolutionary bonded substrate, the use of which improves the device photoresponse by a factor of six compared to a control sample utilizing a standard GaSb substrate (see Figure 1). The GaAs-based bonded substrate allows transmission of far infrared radiation, which is a great improvement over conventional lattice-matched substrates such as GaSb.

AOI has also developed a number of unique mid-IR laser structures, including the first laser grown on a compliant substrate. In this case, the compliant substrate allows the type-II laser structure to be optically pumped by a 980 nm laser diode array with the epitaxial side of the mid-IR laser soldered to a copper heat sink, for more efficient removal of waste heat from the active region. Using this approach, an optically-pumped 4.6 μm wavelength laser was fabricated that produced more than 200 mW peak power in 500 μs pulses at a repetition rate of 500 Hz. This power level was achieved at 80 K operating temperature,

and the laser operated with reduced power output to more than 200 K.

The company has also demonstrated the first dual wavelength laser based on a type-II interband cascade (IC) configuration. Two peaks were observed at 4.482 and 4.568 μm under pulsed operation. At 110 K, the devices demonstrated a peak output power of 150 mW per facet with a pulse length of 5 μs and a frequency of 1 kHz. The threshold current density was 119 A/cm², and the average external quantum efficiency (EQE) was 278% with an output power of 150 mW per facet for a 0.4-mm long device.

Growth of Type-II Superlattice Photodetectors on Compliant Substrates

Type II InAs/InGaSb superlattices (SLs) are alternatives to HgCdTe alloys or GaAs-based quantum well infrared photodetectors (QWIPs) for infrared detector arrays. The bandgap of these SLs can be continuously adjusted by changing the thickness and composition of the layers to cover the mid- to very long-wavelength IR spectrum. Infrared photodetectors operating in the 3-25 μm region are in demand for a number of applications. These include focal plane arrays for military applications (e.g. missile seekers), night vision, surveillance for home and business safety, inspection of semiconductor ICs and chips, industrial monitoring and inspection, and R&D.

One factor limiting the development of InAs/InGaSb SL arrays has been the GaSb substrates used for lattice-matched growth. These are conductive, limited to 2-inch diameter and are highly absorbing at IR wavelengths in excess of 5 μm . Normally, IR detector arrays are fabricated by bonding the detector epi side down onto a silicon readout chip [see CS 5(7), p. 50]. This means that the substrate has to be transparent at the wavelength of interest, or that it has to be thinned substantially to a thickness less than 20 μm .

The IR transmission of both GaAs and silicon substrates is much higher than GaSb, for the same wafer thickness. However, because of the large lattice mismatch between GaAs and the InAs/InGaSb SL, the quality of SLs grown on GaAs substrates with thick GaSb buffer layers has always been low.

The alternative pursued by AOI and the AFRL is to use compliant substrates. These are substrates having a thin, mechanically flexible top layer that is able to deform in order to accommodate the lattice mismatch between the substrate and the epilayer(s). In this case, the compliant substrate consists of a 120 Å In_{0.53}Ga_{0.47}As compliant layer loosely bonded to a GaAs sub-

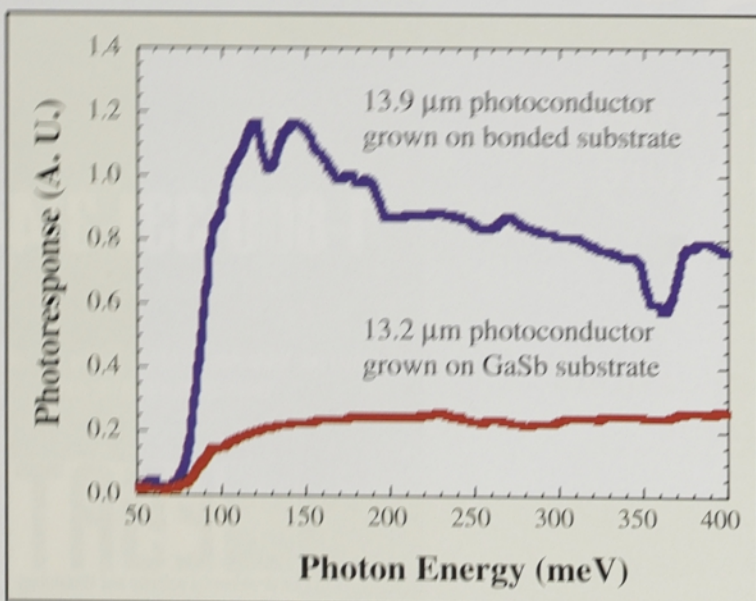


Figure 1. Performance comparison of InAs/InGaSb type-II superlattice photodetectors grown on AOI bonded substrates (blue) and standard GaSb substrates (red). Note the factor of six improvement near the cutoff energy (13.9 μm).

strate. This is fabricated in a three-step process (see Figure 2), beginning with MBE growth of the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layer on an InP substrate. Then, the epilayer side was bonded to a GaAs wafer using a stainless steel fixture to press the wafers together, after which the wafer sandwich was annealed at 300°C for 3 hours in a nitrogen-purged furnace. Finally, the InP substrate was selectively etched away using HCl.

The device layers, also grown by MBE, consisted of a 0.5 μm GaSb buffer, followed by a 100-period InAs/ $\text{In}_{0.23}\text{Ga}_{0.77}\text{Sb}$ superlattice. The periods were between 56 Å and 72 Å thick, depending on the design, and the InAs layers were typically designed to be at least twice as thick as the InGaSb layers. The photoresponse of the SL grown on the compliant substrate was compared to that of a similar structure grown on GaSb, as shown in Figure 1. Since the detectors were operated as photoconductors, the devices grown on the semi-insulating compliant substrates show improved photoresponse when compared with the same samples grown on p-type GaSb substrates. The devices were all grown on 2-inch substrates, which had an RMS surface roughness of ~ 7 Å for the GaSb substrate compared to 8-40 Å for the structures grown on compliant substrates as measured by atomic force microscopy. Cross-sectional TEM studies were also performed on superlattice test structures grown on the compliant substrates. These studies indicated no threading dislocations in the samples grown on compliant substrates.

The compliant substrate fulfills two important needs for future devices: the electrical isolation of the SL detector from the substrate, to prevent electrical crosstalk between pixels in an array, and a semiconductor-transparent substrate for backside illumination. Current efforts are aimed at creating detector arrays that can be integrated with readout circuitry utilizing standard epi-side down bonding techniques.

About Applied Optoelectronics

Applied Optoelectronics Inc. (AOI) was established in February 1997, and currently has 13 full-time staff members. Based in Sugar Land and Houston, Texas, the company develops and manufactures a range of optoelectronic products, and is in the process of building a new 15,000 sq. ft. manufacturing facility in Sugar Land to support both R&D and production.

AOI manufactures a variety of wafer-bonded 2-inch diameter substrates for epitaxial growth. These are used internally, for MBE growth of long-wavelength photodetectors and optically pumped mid-IR lasers, and are also available commercially. In the second quarter of 2000, the company plans to introduce a standard line of mid-IR optically pumped laser subsystems having quasi-CW output powers above 100 mW. These lasers will be liquid nitrogen cooled, but can also be operated with thermoelectric cooling, with lower output power. The thermoelectric cooling will be an option available after the liquid nitrogen standard package production is under way.

Single element long wavelength photodetectors will also be offered in the second or third quarter of 2000. These will have cutoff wavelengths greater than 5 μm and will utilize liquid

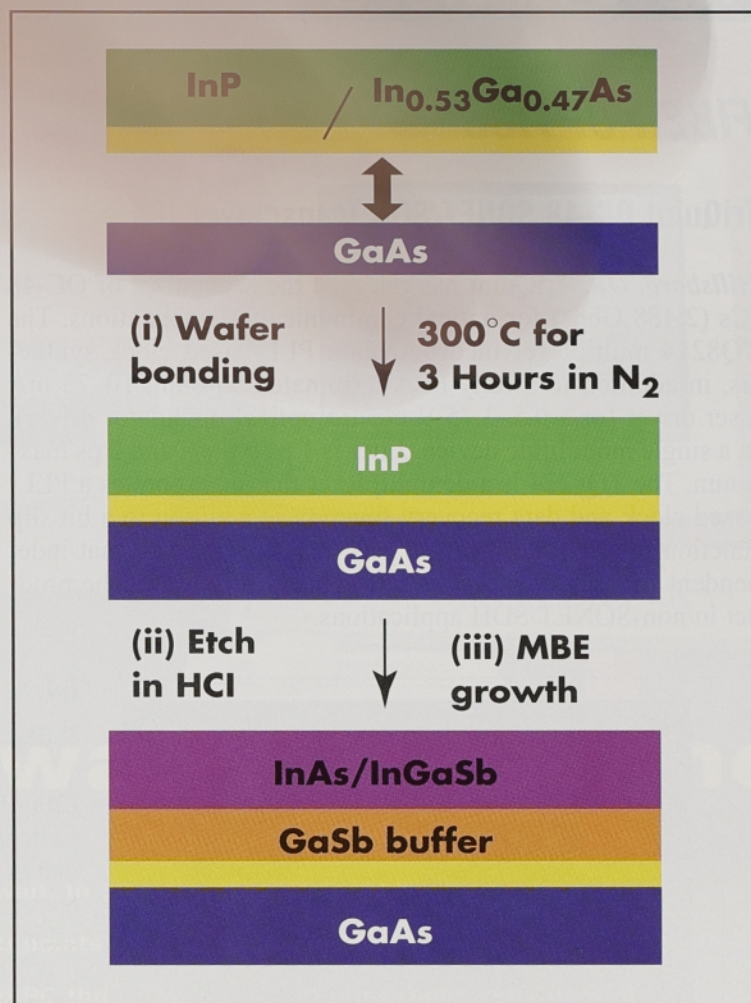


Figure 2. Schematic showing compliant substrate fabrication. (i) An InP substrate with a thin $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layer is bonded to a GaAs substrate and annealed at 300 °C under nitrogen. (ii) The InP is removed by selective etching to form a compliant substrate. (iii) A GaSb buffer and InAs/InGaSb superlattice are grown by MBE on the compliant substrate.

nitrogen cooling. Cutoff wavelengths greater than 19 μm have been demonstrated, using liquid helium cooling, and will be offered in prototype quantities during 2000. Electrically pumped, type-II quantum well mid-IR lasers in liquid nitrogen- and thermoelectric-cooled packages are also under development - current prototypes operate with CW output powers of >50 mW per facet at 80 K.

Much of AOI's R&D work is contract research funded by government agencies including the US Air Force, the National Science Foundation, and the Ballistic Missile Defense Organization. The various projects are aimed at increasing the output power and operating temperature of mid-IR lasers, improving the detectivity of long-wavelength photodetectors, and examining new techniques for creating alternative substrates for epi growth. In addition, the company plans to expand its range of laser wavelengths into the near infrared, for telecom and datacom applications, and both edge-emitters and VCSELs are currently under development.

FIBER-OPTICS

TriQuint OC-48 SONET/SDH Transceiver ICs

Hillsboro, OR. TriQuint has released the second set of OC-48 ICs (2.488 Gbps) for optical communication applications. The TQ8214 multiplexer incorporates a PLL-based clock synthesis, in addition to a fully back-terminated 50-ohm, 10–75 mA laser driver (or a 0.5–3.75 V electro-optical modulator driver), in a single monolithic device. Jitter is 1 ps typical and 2 ps maximum. The TQ8224 is a demultiplexer that incorporates a PLL-based clock and data recovery function in addition to a bit slip function to align the received bits into words for format-independent framing of received data. This allows use of the product in non-SONET/SDH applications.

Conexant High Speed Crosspoint Switch

Newport Beach, CA. The digital crosspoint-switching matrix is the most common architecture for handling terabits of Internet traffic and other high-volume communications requirements. Conexant Systems has added a new single-chip digital fiber-optic crosspoint-switch to support 2.5 Gbps OC-48 networks, while providing an easy upgrade path to 10 Gbps systems. The CXS1610 is a differential high-isolation crosspoint switch that uses 16×16 matrix density and has the capacity for up to 200 Gbps data throughput. The CXS1610 adds only 2.5 ps of single-channel RMS jitter, and is manufactured using Conexant's GaAs HBT process.

64 × 65 Crosspoint Switch and Quad OC-48 Retimer from Vitesse

Camarillo, CA. Vitesse has introduced a new family of OC-48 crosspoint switches including the industry's largest. The VSC836 is a 64×65 switch that is suitable for DWDM switch core systems and has the capability to operate at 2.7 Gb/s for forward error correction systems. It is priced at \$765 each for quantities of 1000.

Vitesse also introduced the VSC8124, the industry's first quad OC-48 retimer, offering a 4-channel data retiming capability.

Lucent New EDFA Doubles Bandwidth

Breinigsville, PA. Lucent Technologies Microelectronics Group has introduced a high-power, flat-gain EDFA module that operates at an extended wavelength transmission window of optical fibers - referred to as L-band. Until now, EDFAs could only operate sufficiently in the C-band (1530–1565 nm). The L-band window will allow system manufacturers to double the bandwidth capacity of DWDM systems, says Lucent.

Operating at a output power of 25 dBm, the new EDFA has a gain flatness of less than 0.8 dB over the 1570–1610 nm window. Samples are available now and full production is expected in early 2000.

Lucent also recently announced that it has begun volume production of a 40 Gb/s lithium niobate electro-optic modulator.

10 Gb/s ICs from Oki

Sunnyvale, CA. Oki Semiconductor has three new ICs for receiver and transmitter applications (10 Gbps): a 2V limiting amplifier (KGL4217) reduces total power dissipation (0.25 W), while the 16:1 mux (KGL4221) and 1:16 demux (KGL4222) operate at 12.5 GHz. The latter are manufactured using Oki's 0.2 μm gate length GaAs MESFET process.

New Devices from Ortel

Los Angeles, CA. Ortel has unveiled the model 2650A photodiode featuring very high linearity and very low capacitance over a 1 GHz bandwidth for use in AM-VSB CATV, QAM 64/256, PON, FTTC and FTTH receivers. It also announced the Medalion Transmitter, which is capable of launching 18 dBm of optical power into long-distance fiberoptic link at 1550 nm, while also unveiling its highest power 1310 nm linear forward path laser to date for CATV. The Mercury laser module combines 31 mW output power with superior distortion performance over an enhanced operating temperature range of -40 to 85° C.

Anadigics Data Tuner for Broadband Cable

Warren, NJ. Anadigics has introduced a low power, high performance, integrated data tuner. Using both GaAs and Si to provide the upconverter, SAW filter, downconverter, and dual synthesizer functions in a double conversion data tuner, it is designed specifically to support the latest 256 quadrature amplitude modulation (QAM) digital formats.

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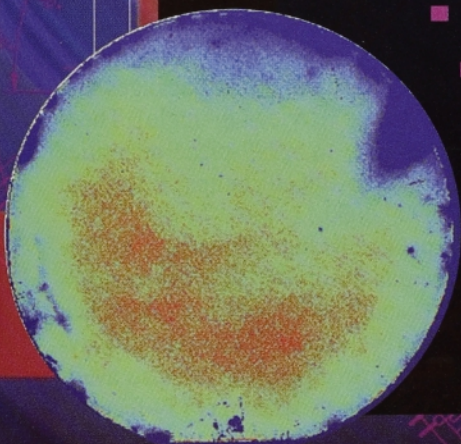


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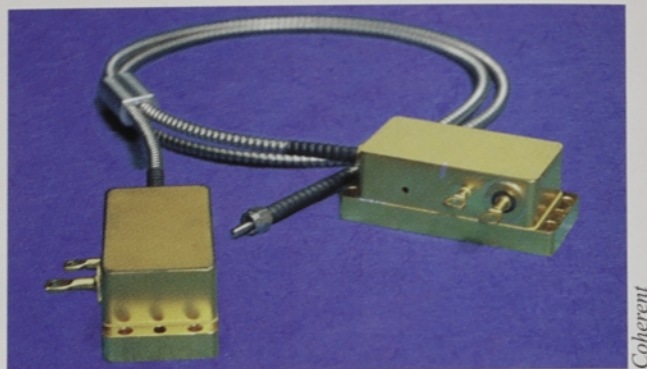
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OPTO DEVICES

Coherent 60 W CW Fiber-Array Package

Santa Clara, CA. Coherent Semiconductor Group has announced a 60 W CW, multi-head fiber-array package operating from 780-840 nm. Based on proprietary aluminum-free active area (AAA) technology, the device delivers CW output power through a 1200 μm diameter 38-fiber bundle with a beam divergence of <0.16 NA, FWHM. Coherent also offers multi-head FAP bars in wavelengths ranging from 940-980 nm, suited to integration into Yb-doped solid-state laser pumps and telecommunications applications.



Coherent

Vishay Optocoupler Family

Malvern, PA. Vishay Intertechnology has announced six new optocoupler devices offering designers a choice of single-, dual-, and quad-channel options. The K815P (single), K825P (dual), K845P (quad), TCED1100 (single), TCED2100 (dual), and TCED4100 (quad) feature a GaAs IRED coupled with a photodarlington transistor output.

Combining a high current transfer ratio of 600% with a very low input current, these isolation devices are suited to signal transfer systems, pulse-dial circuits, ring detector circuits, and loop monitor circuits.

Toshiba Surface Mount LEDs

Irvine, CA. Toshiba America Electronic Components has announced a line of AlInGaP-based surface mount device (SMD) LEDs. Designed for automotive interiors (backlighting, switch illumination, third brake lights and turn signals), the 1100 and 1102 series both consist of eleven clear and diffused lens diodes offering up to 0.65 cd in the wavelength range 562-636 nm (true green to red). The diffused lens is offered in a 2.8 mm diameter lens and the clear lens is offered in a flat-top type.

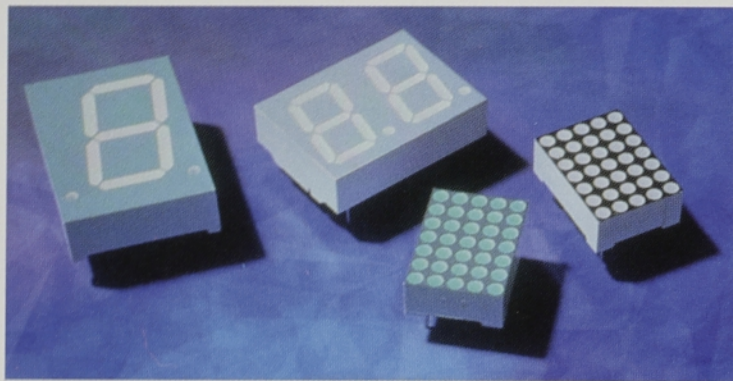
Infrared Data Transceiver from Rohm

Kyoto, Japan. Rohm Co. Ltd. has developed a super-mini infrared communication module (RPM870-H7) for low power data transceiver functions between devices such as computers, cell phones, PDAs and digital cameras. The device supports transmission rates of 2.4-115.2 kbps at distances up to 20 cm.

AlInGaP Lamps, 7-Segment and 5 × 7 Dot-matrix Displays from Agilent

Palo Alto, CA. Agilent has introduced a series of cost-competitive red and amber AlInGaP LED lamps in 5 mm packages that provide up to 6 cd of intensity (at an 8° viewing angle). These new products cost only \$0.14 in one to 9,999-piece quantities compared to \$0.29 for its previous AlInGaP lamps. Pricing in quantities from 50,000 to 499,999 is \$0.12.

The company has also expanded its line of displays: its new 7-segment displays feature decimal point and offer viewing distances up to 10 meters (33 feet) and 7 meters (23 feet), each at a 50° viewing angle. 5×7 dot-matrix displays capable of displaying a full range of alpha and numeric characters are also available, and are visible at distances of up to 12 meters (39 feet).



Agilent

WIRELESS

Watkins-Johnson GaAs FETs for 3.5 GHz/5.8 GHz

Milpitas, CA. Watkins-Johnson has introduced new GaAs FETs packaged in 3×3 Ball Grid Array (BGA) packages. The AP3 features an IP3 output of 39 dBm and a P1dB of +22dBm from 0.1-6.0 GHz. The AP4 features an IP3 output of 40 dBm and a P1dB of +27 (0.1- 6.0 GHz).

Conexant 900 MHz and 2.4 GHz Chipsets

Newport Beach, CA. Conexant Systems, Inc. has introduced a chipset family for DSS cordless phones. Consisting of a 900 MHz or 2.4 GHz transceiver, a RF power amplifier and a base-band device, these chipsets are priced at \$25 in quantities of 100,000.

TURN UP THE VOLUME

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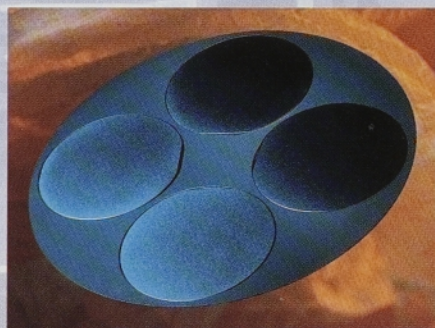
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R I B E R

Products and Services for the Compound Semiconductor Industry

Ultra-Small MMIC Switch from Sanyo

Tokyo, Japan. Sanyo's new ultraminiature GaAs MMIC switch for mobile phone handsets and terminals offers the industry's smallest package for this class of device. The SPM3203 is supplied in an MCP6 package measuring $2.0 \times 2.1 \times 0.9$ mm³ and offers an insertion loss of 0.55 dB and 21 dB isolation.

Alpha's PHEMT Switches Require No Negative Voltage

Woburn, MA. Alpha Industries has introduced a new range of GaAs PHEMT RFIC switches for high-power, high-linearity wireless communication applications that require no negative voltage connection. The AS190-73 and AS191-73 are both SPDT (single pole double throw) type, and the AS166-300 and AS189-300 quadruple throw type (SP4T). Each requires a low positive voltage of between 0 and 2.75 V and can operate up to 4 W.

Anadigics 3 V Tri-mode dual band PA driver

Warren, NJ. Anadigics has introduced two new 3 V RFICs for wireless handsets. The AWD5101S4 is a dual-band driver PA supporting PCS and cellular TDMA and AMPS. The AWT4502S4 is a transmit PA for PCS TDMA that delivers +28.5 dBm minimum output power.

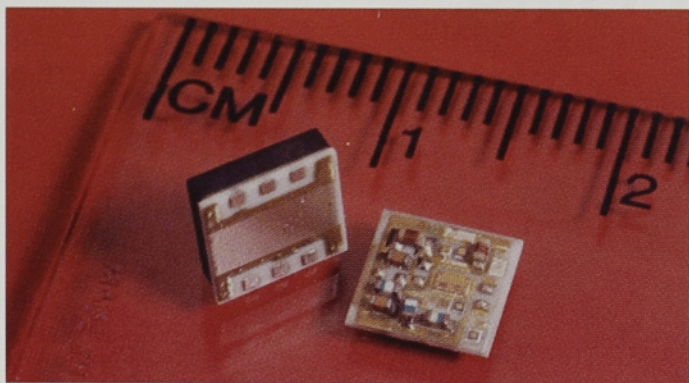
New M/A-COM Switches

Lowell, MA. M/A-COM has unveiled three new GaAs switches. The SW-425 MMIC SPDT is a new 3 W cellular T/R and antenna changeover switch covering the DC-3.0 GHz range designed for portable phones and data radios as an internal/external antenna select switch. Two new GaAs SPDT switches, the SW-437 and SW-442, offer positive/negative control voltages (2.5–8.0 V) and low insertion loss. All are intended for high-linearity CDMA, TDMA, GSM and W-CDMA applications.

New GaAs HBT Devices from RFMD

Greensboro, NC. RF Micro Devices has announced several new devices made with its GaAs HBT process and operating at 3 V: the RF2153 works from a single power supply and is a high-power, high-efficiency 1900 MHz CDMA/TDMA/PACS linear PA delivering 29 dB of linear output power and 30 dB of linear gain. The RF2459 is a downconverter for the 1500-2500 MHz band, and the RF2365 is a LNA for digital cellular applications, operating with a 1.6 dB noise figure at 1850 MHz and 1.75 dB NF at 2450 MHz.

The RF2351 broadband linear amplifier is suitable for use in CDMA or TDMA systems in the PCS (1710–1910 MHz) band. The device can operate on a 3-6 V power supply, and at 3.5 V, delivers +16 dBm OP1dB, 21dB of gain and a NF of 2.5 dB.



Celeritek

InGaP HBT CDMA PA from Celeritek

Santa Clara, CA. Celeritek, Inc. has announced the CHP1232-PM, an InGaP HBT 3-stage PA module developed for PCS CDMA handsets and infrastructure systems, WCDMA 3G handsets and wireless local loop (WLL) subscriber units in the 1.85-1.91 GHz frequency range. Typical features include single positive supply 3.2 V operation, 30 dB gain, 35% linear PAE, and +28 dBm output power (IS-98 CDMA mode).

TriQuint Introduces Two TDMA Receiver ICs

Hillsboro, OR. TriQuint has announced the TQ5122, a cellular frequency band receiver, and the TQ5622, a PCS frequency band receiver; these designed for use in IS-136, TDMA, or equivalent wireless handsets. Both devices include an LNA, mixer, LO Buffer, and IF buffer amplifier and operate from a single 2.8 V power supply. Conversion gain is 18.5 dB for the 5122 and 17.5 dB for the 5622. Both have an Input Intercept point, IIP3, of greater than -9 dBm and NF of 2.8 dB.

Mitsubishi's 3.4-3.6 GHz and 1.85-1.9 GHz GaAs FETs

Sunnyvale, CA. Mitsubishi Electronics America has announced the sample availability of a family of GaAs FETs for C-band WLL PAs that operate in the 3.4- to 3.6-GHz frequency band. The devices offer typical P1dB power outputs ranging from 4–30 W, respectively. The IM3 distortion for the family is typically -45 dBc at power outputs ranging from +25 dBm to +34.5 dBm.

The FA01384In is a high-efficiency three-stage GaAs FET RF amplifier module for 1.85–1.91 GHz (PCS CDMA cellular phones). It features idle drain current of 85 mA, PAE of 37% and 3.2 V operating voltage.

As usual, the New Year presents an opportunity to look forward and highlight some of the technologies and applications that are expected to have a major impact on our industry. Ten of these are presented in the following sections.

It is clear that we have now entered the Communications Age. Driven by continued Internet growth, deployment of fiber-optic systems continues unabated, and fiber gets closer and closer to the home and office. In turn the demand for photonic components (lasers, amplifiers, detectors) is increasing at an exponential rate and further technological advances are required to help achieve the goal of all-optical networking [see Sections 1, 5 and 7]. In addition, a very obvious theme in the telecommunications industry is the large number of acquisitions, as manufacturers such as JDS Uniphase seek to offer the broadest possible range of components. Only the lack of suitable acquisition targets is likely to stop this particular trend.

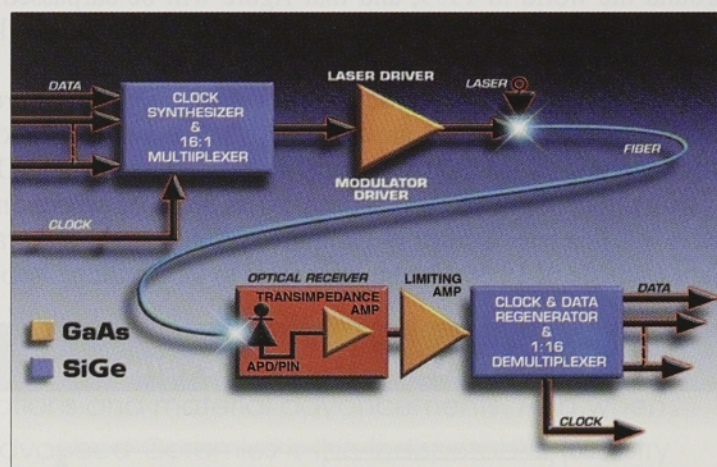


Wireless will continue to be the major application for GaAs, spurred on by the arrival of new 3G formats [see Section 2]. At higher frequencies, broadband communications and sensor applications will also provide growing markets [see Section 6]. But GaAs won't have the field to itself – SiGe is already making inroads into high-speed fiber-optic applications and certain components of wireless handsets [see Section 4]. GaAs manufacturers now recognize that different technologies are suited to different applications, and are developing or accessing a broad portfolio of processes, including silicon and SiGe technologies. Looking slightly further afield, both silicon carbide and indium phosphide ICs will soon be challenging for many high power and high frequency applications in the commercial market [see Sections 8 and 10].

Things to Watch



Several other optoelectronic fields are likely to experience continued success, including VCSELs for data communications and high power lasers for a variety of applications in the medical, printing and materials processing industries. High brightness LEDs are now in widespread use in automobiles and outdoor displays, and are beginning to challenge other niche lighting markets [see Section 3]. In the field of optical data storage, it appears that DVD is finally going to "make it big", creating a demand for millions of visible laser diodes and driving further development of violet lasers [see Section 9].



Things to Watch in 2000

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Components for Fiber Optics

MARIE MEYER

You may have missed it, but some time last year, the Computer Age ended, and the Communications Age began. This according to George Gilder, a technology analyst well known for sweeping pronouncements. His thesis is that "PCs remain important, but peripheral" as they are replaced by bandwidth as the paradigm of the economy. Communications capacity replaces computer power as the driving force of technological advance.

Many of us in the compound semiconductor industry have been enamored with wireless communications for quite some time. Now it is the turn of "wired" communications to take center stage. The outlook for growth in this area is simply astounding. According to Tom Hausken of Strategies Unlimited, capital investment in telecommunications by U.S. carriers is outpacing the world's GDP (gross domestic product) by ~5:1. KMI Corp. estimates that more than 60 million km of fiber was installed around the world in 1999, and that figure will be surpassed in each of the next five years, peaking at more than 105 million km in 2004 (enough for 137 round-trips to the moon!).

The number of fiber optic components consumed will grow even more rapidly. Gone are the days when a communications link consisted of one transmitter and receiver. In today's DWDM systems, four, eight or even sixteen lasers are used where once there was just one. Strategies Unlimited recently revised upward their estimate of 1999 telecom laser sales to \$2.2 billion. Robert

Things to Watch

2000 #1

Market for Telecom Active Components (\$ Million)

Component	1995	2000	2005	2015	2025
Transmitters	1,175	3,180	9,150	81,900	289,000
Receivers	390	1,060	3,050	22,300	55,800
Optical Amplifiers	390	2,050	4,330	14,100	38,300
	1955	6290	16,530	118,300	383,100

Source: ElectroniCast

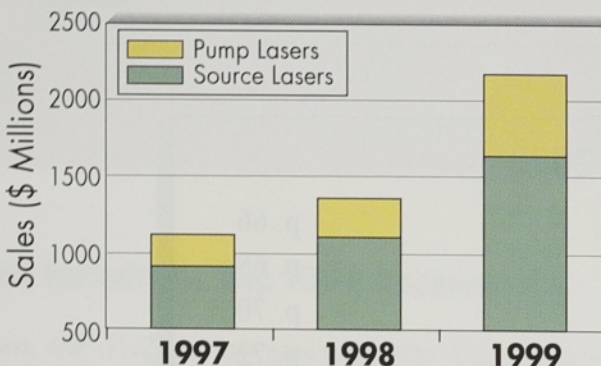
Nolan of Communications Industry Researchers (CIR) explains, "because there is more demand for bandwidth generally, fiber is being pushed closer into the access market and to buildings and even, in a few instances, to residences. The number of fiber optic components increases exponentially the more localized these systems become. This is a trend that will continue to pay major dividends to the fiber optic component industry for many years to come."

The market for active telecom components (transmitters, receivers and optical amplifiers) will exceed \$6 billion this year, according to Jeff Montgomery of ElectroniCast Corporation. These calculations are based on the value of complete functional units, e.g. a complete packaged unit consisting of laser and photodiode plus the electronic ICs and other components. He believes that that III-V components account for slightly less than half of the total value. In a recent long-term forecast, he predicted that active components will enjoy a CAGR of around 18% over the next 25 years, roughly double the growth rate for fiber optic cable.

North American suppliers have a commanding lead in the optical components market. The two largest players in the industry, JDS Uniphase and Lucent, are headquartered in the U.S., followed closely by Nortel, which is Canadian. Yet JDSU and Nortel both have extensive manufacturing operations in Europe.

CIR estimates that North American manufacturers held a 54% share of the worldwide market for components in 1999. No

Telecom Laser Diode Revenue



Selected Growth Rates

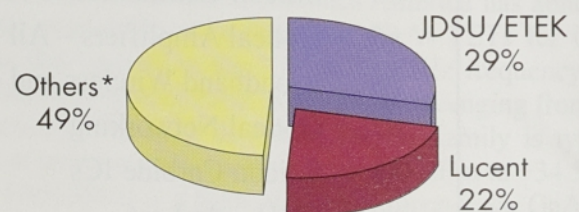
World GDP	3.2%
Telecom Revenue	6.6%
Telecom Capital Investment*	15.8%
Telecom Laser Sales	37%

* U.S. carriers only

Source: Strategies Unlimited

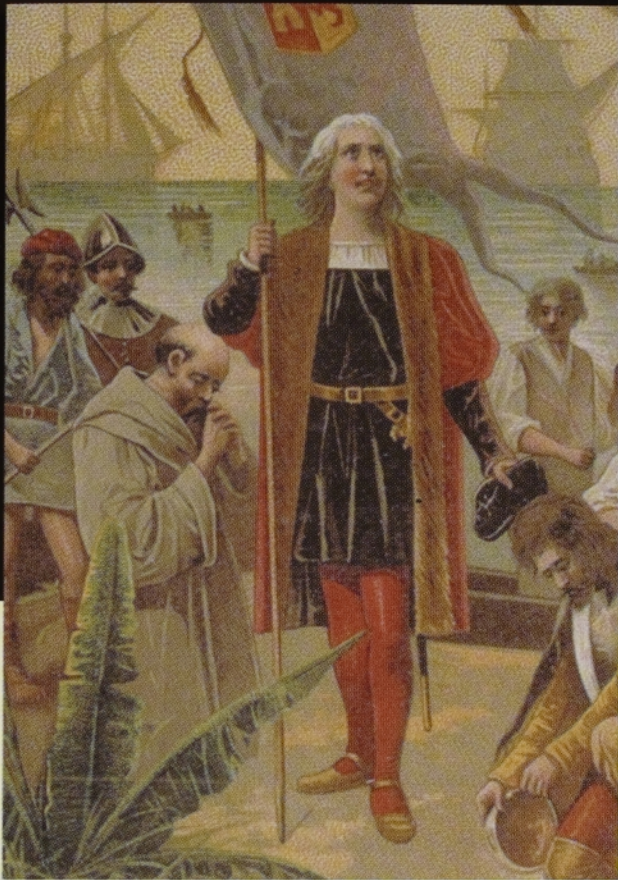
Optical Components & Modules, 1999

(Total = \$4.5 Billion)



* Including Nortel, Corning, Furukawa & Alcatel

Source: CIBC World Markets



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dramatic changes to this picture are predicted in the foreseeable future. CIR's Robert Nolan attributes North America's predominance to the continued strength of the economy. It also has benefited greatly from being the first to deregulate its telecommunications industry. As Nolan puts it, "competitors come into a marketplace looking to provide infrastructure to compete effectively against the incumbent carrier. Nothing beats fiber for providing bandwidth fast in a way which competitors can grow rapidly - so competitors to the entrenched monopoly almost invariably will deploy fiber optics. This, in turn, often causes a reaction by the incumbent carrier to install and upgrade its own fiber facilities so that it can be more competitive."

All of which helps to explain why Japanese suppliers - despite their fabulous resources - are not making a bigger impact in this market. They are being hampered by their own communications industry, which remains one of the most heavily regulated in the developed

world. But once these shackles are finally thrown off - and it seems inevitable that they will be - it should spark another boom in this already remarkable field.

World Shares of Component Market

Supplier Origin	1999	2003
North America	54%	45%
Western Europe	19%	19%
Japan	9%	11%
Korea	4%	6%
Other Asia	8%	11%
ROW	6%	8%

Source: CIR

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3G and Wireless

Things to Watch 2000#2

MARIE MEYER

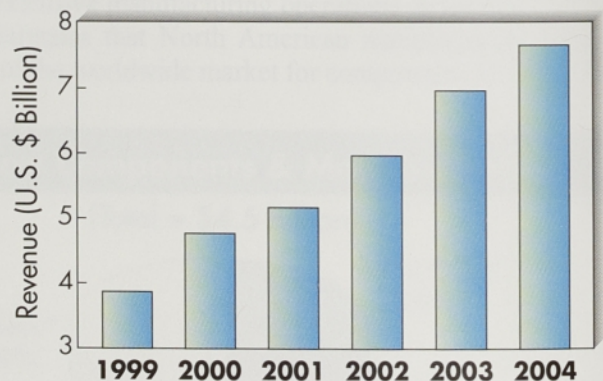
The wireless industry is growing so fast that even the insiders are having trouble keeping up. Witness the announcement made on December 3 by Nokia, wherein the world's largest mobile phone manufacturer made a significant upward revision in its estimate of global mobile subscriber growth. There are believed to be more than 450 million subscribers worldwide at the present time. Nokia had previously predicted that the 1 billion subscriber mark would be reached in 2003. But recent trends led the company to move that target date up to the end of 2002. In other words, the number of mobile phones users will double in the next two years.

CDMA & GaAs

Wireless has been a godsend for manufacturers of RF semiconductors. According to a new study by Strategies Unlimited, the worldwide market for RF semiconductor devices in mobile telephones reached \$3.9 billion in 1999, and will nearly double, reaching \$7.7 billion, by 2004. Strategies Unlimited says that GaAs chips comprised 33% of the market in 1999.

While silicon and silicon germanium technologies are improving all the time, there are changes afoot in the wireless industry that are extremely favorable to

RF Semiconductors for Mobile Phones



Source: Strategies Unlimited

Figure 1. The market for RF semiconductors for use in mobile phones.

GaAs. The first is the growth in popularity of CDMA. It is the fastest growing cell phone standard, and the CDMA Development Group reports that there are now 50 million CDMA subscribers worldwide. And a recently released report from Micrologic Research says that CDMA phone shipments grew a whopping 166% in 1999, to 42 million units. In comparison, 125 million GSM phones were shipped, which was a 42% increase over the previous year. Micrologic predicts that by 2004, 40% of all mobile phones sales will be CDMA.

CDMA uses direct sequence spread spectrum technology to provide more conversations for a given bandwidth. It requires very linear transmission to prevent spectral regrowth as well as high DC to RF conversion efficiency at low power levels. Overall, the performance specification of the power amplifier is critical in a CDMA phone - which is very good news for GaAs.

3G Cellular & GaAs

Another trend favoring the use of GaAs is the introduction of 3G cellular services. Old-fashioned analog phones such as AMPS are considered first-generation (1G) technologies. Second generation (2G) is the collective term for all of the the digital cellular standards currently in use, including GSM, CDMA, Japan's Personal Digital Cellular (PDC), etc. 2G systems were designed for voice, although they now also transport a limited amount of low-speed data communication. Third-generation (3G) cellular systems will begin to appear this year. They are the first mobile phones designed for high bandwidth functions such as transmitting not just voice signals but also data and even video at speeds of up to two megabits per second.

Like 2G systems, 3G cellular will persist with multiple air interfaces: the 3G standard is in fact a family of standards, to ensure backward compatibility. For example, there will be

UWC-136, which will be compatible with TDMA, and there will be CDMA2000, which will be compatible with today's CDMA. But, most excitingly, there will also be a variant called UMTS/WCDMA, which will be compatible with GSM, currently the most common standard world-wide.

The first commercial 3G cellular system is scheduled to begin service in March 2001 in Japan.

3G will place strict requirements on the performance of the RF portion for the phone. This is especially true with regard to the handset power amplifier - and possibly the base station amplifier as well. According to Sanjiv Shah, Marketing Manager for Raytheon RF Components, "with 3G, GaAs will be the technology of necessity. Right now, the main technologies for mobile phone power amplifiers are silicon, GaAs MESFET, GaAs pHEMT and GaAs HBT. Silicon today accounts for 50% of PA market. GaAs will account for a much greater share in the next few years with the increased implementation of CDMA and 3G around the world. With 3G with its increased channel bandwidth, increased linearity, and also need for longer talk times for handsets, the 2 suitable technologies are GaAs pHEMT and GaAs HBT. The other technologies will not cut it!"

Mobile Phones Sales

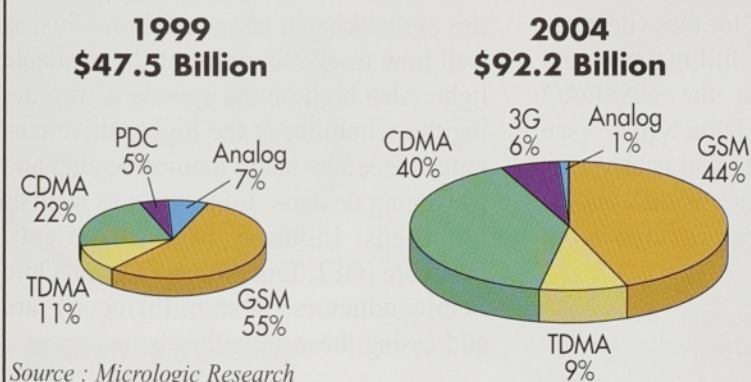


Figure 2. Revenues from shipments of terminals for several cellular technologies. The GSM terminal market is the largest at present, although Micrologic Research believes that by the year 2003 revenues from CDMA terminal sales will almost equal those from GSM.



Intelligent Epitaxy Technology, Inc.

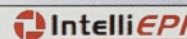
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High Brightness LEDs

RICHARD DIXON

Things to Watch
2000 #3

High brightness LEDs continue to be star performers. According to Strategies Unlimited's Robert Steele, markets for AlInGaP red and amber and InGaN blue and green emitters continue to outstrip forecasts - 1999 saw sales of high brightness (HB) LEDs top \$600 million, up from \$440 the previous year.

The LED market has for a long time been a commodity one - low brightness LEDs are cheap and found everywhere as indicator devices in a host of appliances and instruments. Of the total \$9 billion market for compound semiconductors, LEDs account for 33%. Which, at prices ranging from \$0.50-1.00 for high brightness LEDs and less than \$0.10 for conventional low-brightness versions, amounts to a lot of LEDs.

As the brightness of these emitters has increased, new applications have become possible. Several car manufacturers have decided that the value added by these devices, both aesthetically and in

terms of reliability, is worth the extra investment compared to a simple bulb. Blue and now white LEDs supplied by the likes of Infineon and Cree are employed in the dashboard as backlighting or as interior lighting in both the Volkswagen and Audi models.

On the outside of the car, high brightness LEDs have been in use for some time in center mounted brake lights, and more recently, tail lamps clusters. The 'cold light' and long life span of these sources considerably frees car designers - they no longer have to design bulky lighting compartments to house lamps that require heat protection or room for maintenance. Agilent now supplies the red and orange HB LEDs for the taillight module on the new 2000 Cadillac. The cluster contains 72 LEDs in total, including 16 for the tail-light function, 52 for braking and 4 for the side marker light.

More and more message and full video LED signs are also emerging in public places and at entertainment arenas, such as at football stadiums in America. Requiring LEDs that retain their high brightness in adverse conditions (such as caused by high humidity and large temperature changes), these large screens provide volume markets for these devices. Recently, a high-profile full message and video sign opened for the NASDAQ building in New York's Time Square (see Figure). At 8-stories high and nearly a $\frac{1}{4}$ of an acre in area, it is the world's largest full color display - it also contains more than 18,000,000 LEDs.

General Illumination

Recently, there has been a lot of speculation about white LEDs for general illumination. Currently valued at \$10 billion worldwide, this represents a huge potential future market for LEDs.

The emission of white light is most

commonly formed by the re-emission of a broad luminescence from a YAG phosphor, which is excited by a blue LED. The performance of these devices has the potential to far outstrip incandescent bulbs, and eventually challenge fluorescent lighting.

However, so far their use has been confined to specialist applications such as theatre and architectural lighting. These applications make use of the LED emission's directed nature (i.e. the high brightness is achieved at relatively low viewing angles of 10-20°) and longevity. LEDs also allow lighting to be placed where excessive heat would be detrimental or would otherwise make the changing of fixtures difficult.

But while LED devices are making headway in these niche applications, the consensus is that solid-state lighting for general illumination is still 5-10 years away. At present, white LEDs deliver 10-15 lm/W, equivalent to an incandescent bulb. But a number of chips would be required in an overhead fixture to provide enough brightness for broad area illumination, making them too expensive.

Thus, to get more light out, LEDs need to be driven harder. Many laboratories are looking at ways to achieve this, as well how to extract more of the available light. Also high on the agenda is improving the reliability at the higher drive currents needed by using innovative chip and packaging designs. Joint ventures such as LumiLeds Lighting (Philips/Agilent), GELcore (GEL/Emcore) and Osram Opto Semiconductors (Osram/Infineon) are addressing these and other issues.

Chip Developments

LumiLeds has scaled up its LED chips to make 'power' or high-flux LEDs: 1 x 1 mm² AlInGaN blue devices with 10x the junction area of conventional



The new 8-story high NASDAQ information and advertisement screen, made by Canadian company Smart Vision, contains over 18 million HB LEDs.

0.35 x 0.35 mm² LEDs. At drive currents up to 1 A - 30x the current used to life-time test its standard product - the reliability of these large area chips is comparable to standard 5 mm AlInGaP devices, says the company. LumiLeds has demonstrated a green traffic light engine containing just 12 of these high-flux LEDs (this compares to with more than 100 needed at present). It has also developed an LED module that drives a fiber system. Looking rather like a light saber from the Star Wars movie, LumiLeds says this could find use as contour lighting on buildings.

LumiLeds also produces AlInGaP power LEDs. The company employs a transparent GaP substrate in a 'truncated inverted pyramid' (TIPLD) configuration. This design has enabled external quantum efficiencies of 55% for red devices (~ 650 nm) and a brightness of more than 100 lm/W for its 610 nm orange AlInGaP LEDs at 100 mA (see research review). This exceeds even fluorescent lighting, which typically exhibits a brightness of around 70 lm/W.

Packaging Issues

As an integral part of the LED, packaging is crucial to reliability and performance. In the case of white LEDs, phosphors also determine color and performance.

Nadarajah Narendran, director of research at the Lighting Research Center of Rensselaer Polytechnic Institute (Troy, NY), says that many of the standard 5 mm white LED products currently available under-perform in reliability terms.

"The general perception given to the lighting industry is that these lamps are capable of operating for 100,000 hours. Although LEDs can produce light for a very long time, at present their useful life for general lighting applications is much shorter," he says. "Our research indicates that the light output of these 5 mm white LEDs depreciates to 50% of its initial value within 10,000 hours."

Narendran adds that excessive light loss is probably due to degrading phosphor and reduced light transmission by the epoxy surrounding the LED chip.

"Presently, the LED device manufacturers are working on alternate packaging concepts to improve overall performance," he says.

But there may be other ways to achieve bright solid-state sources. Gentex (Zeeland, MI) recently announced a package that reportedly increases the brightness LEDs by up to 10x. Much interest surrounds a package containing four white LEDs that could increase the intensity and make these devices much more cost effective in future.

For proprietary reasons, details of the package are being kept under wraps at present. However, Gentex says it purchases standard LEDs and makes high brightness white sources through additive color mixing of blue/green and amber LEDs. The company says it envisages applications that include automobile license plate illuminators, architectural lamps and interior aircraft lighting.

Whether this will speed the lighting revolution remains to be seen. But with so many potential applications, the future for HB LEDs looks very bright indeed.

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Silicon Germanium

RICHARD DIXON

In the next 5 years, SiGe ICs for wireless and optical communications will capture around 10% of a burgeoning \$19 billion communications market, according to a recent report by George Bechtel of Strategies Unlimited.¹

Bechtel says markets for SiGe ICs will grow from \$30 million in 1999 to \$450 million by 2002. "This steep ramp-up will be driven by the use of SiGe in optical communications and wireless handsets," he says. "In handsets, SiGe will allow a higher degree of integration."

By 2005, he says, around \$1 billion of this \$1.8 billion communications market will be for mixed signal and digital ICs for digital transceivers in wireless and optical communications. \$800 million will be for analog RFIC shipments.

Wireless Communications

So where will SiGe be used? In wireless handset applications, GaAs is predominantly used as analog RF front-end transmitters (PAs/switches) and receivers (low noise amplifiers or LNAs). These functions require a combination of low noise, low power consumption and high power added efficiency (PAE) to improve reception and talk times. Particularly for digital phones operating at 1800/1900 MHz where linearity is critical, GaAs is the material of choice.

Where SiGe will share the market with GaAs is for LNAs, IFs (intermediate frequency chips), mixers and VCOs, components that are found in the front-end receiver portion. This is largely because of SiGe's excellent noise figures (now less than 1 dB) and the ability to integrate the LNA and IF/mixer chips onto one or at most just two ICs. This increases the

amount of Si integration back down the chain to the digital processing chips used in the base band.

SiGe's opponents say its inability to meet the higher linearity and efficiency requirements of the newer digital standards is a major limitation. But analog phones, which use the 800/900 MHz frequency bands, have no such linearity requirement, and Si RF devices are almost exclusively used in analog handsets. Analog handsets still amount to more than half of the cell phones currently in use.

Happily for GaAs, the use of digital handsets is on the rise; the new 3G Internet standard, which includes CDMA, GSM, TDMA and DECT, will also demand this format.

Raytheon's marketing manager for handset products, Sanjiv Shah, says that for digital phones, the critical parameters for PAs are linearity and efficiency. "SiGe has a place in the RF portion of phones," says Shah, "but in the transmit chain, the jury is still out as to whether SiGe will be suitable for the PA function."

According to Shah, questions remain as to whether SiGe can meet the linearity requirements, provide the required efficiency, and more importantly, whether it exhibits sufficient breakdown voltage to operate reliably. "Most phones now operate at 3-3.5 V," says Shah. "For safe operation, you need 2-3 times this value for the breakdown voltage, which in current SiGe devices is still marginal." At present, SiGe devices exhibit breakdown voltages of 5-7 V.

Things to Watch

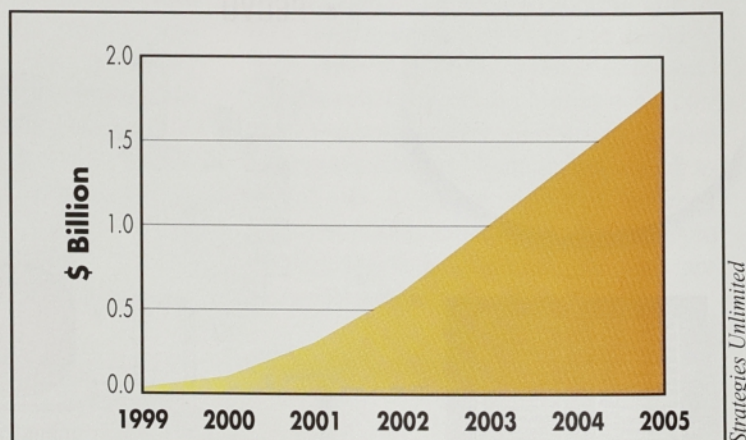
2000#4

Infineon

A company with its own SiGe process is **Infineon**. Its new 'B7HF/C' SiGe HBTs are capable of cut-off frequencies (f_T) of 75 GHz. This is in addition to Infineon's GaAs MESFET and PHEMT activities, and a 25 GHz Si BiCMOS process. With this range at its disposal, the company's philosophy on component choice, particularly for wireless handsets, is interesting.

Bernd-Ulrich Klepser, senior manager in Infineon's RF ICs business unit, recently described the company's first dual band SiGe LNAs and PLLs for mobile communications. "SiGe is the successor of our present B6HFC Si BiCMOS technology," says Klepser. "The B7HFC process produces both fast SiGe transistors and high-quality passive components. We believe there will be a strong trend to replace handset components with SiGe ICs."

Infineon's first commercially available SiGe LNAs feature minimum noise figures as low as 0.8 dB at 1800 MHz. This compares with 0.5 and 0.3 dB for its GaAs MESFET and PHEMT processes at 2 GHz, respectively.



Markets for SiGe are on a very steep ramp-up – from \$30 million to a \$1.8 billion industry by 2005, driven by markets for wireless and optical communications.

¹ *Silicon Germanium 1999*. Contact: Strategies Unlimited; tel: +1 650 941 3438.

According to Klepser, SiGe will form the basis of future highly-integrated RFICs for GSM and CDMA mobile applications. "SiGe will replace our highly-integrated Si BiCMOS cellular and cordless transceivers," he says.

However, Klepser says that SiGe will not replace Infineon's GaAs PAs for GSM, at least in the near future. Where GaAs will feel the competition is in components for LNA and other receiver functions. "SiGe offers GaAs-like noise performance at low cost. And LNAs are key building blocks for future highly-integrated SiGe BiCMOS transceivers," he says.

Optical Communications

In fiber optic communications for 2.5 Gbps and 10 Gbps optical links, SiGe is increasingly being employed in clock and data regeneration, demultiplexing/multiplexing, and overhead framing and processing. And at lower data rates, i.e. 155 and 622 Mbps, Si BiCMOS and Si CMOS are already replacing GaAs.

Lucent Technologies manufactures components for network transport and wireless communication ICs using both GaAs and Si. The company recently announced a 0.25 μm SiGe process and says it is targeting 10 Gbps SONET/SDH applications, usually the domain of more expensive GaAs technology.

Mike Woomer, marketing manager in Lucent's Microelectronic Group, says that while SiGe is still being assessed for the pre-amplifier stages (usually the domain of GaAs), it is being taken very seriously for components such as the baseband (or limiting) amplifier, demux/mux and clock and data recovery functions (see Figure).

Developed at Bell Labs, the new 0.25 μm process features bipolar npn transistors with cutoff frequencies (f_T) of more than 70 GHz. The first products are expected to ship in the second quarter of 2000.

Mike Iannuzzi, a technical manager at Lucent Microelectronics, sees many advantages with SiGe. In addition to an integration advantage, he says, it also consumes less power. "The lower power requirement results from the lithography process used in SiGe or SiGe BiCMOS," says Iannuzzi. "In comparison to GaAs lithography, the devices are a lot smaller, use less current, and hence less power."

However, he adds that the transmitter usually requires the direct modulation of Mach-Zehnder and electroabsorption lasers, and these require high breakdown voltages to drive them. "Typically, GaAs is used because it is capable of driving the large output changes required." Thus, for the moment Lucent is still using its GaAs technology for front end functions,

including the receiver. "It's still too early to say if SiGe will be able to achieve the same sensitivity as equivalent GaAs components," says Iannuzzi.

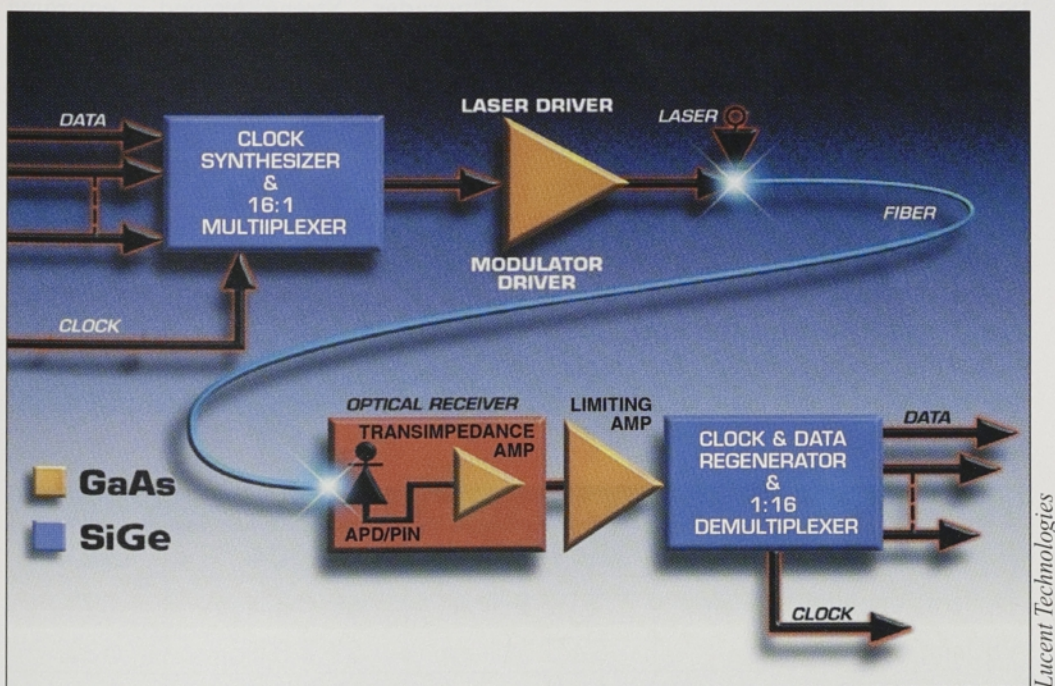
For next generation 40 Gbps systems, Lucent is also evaluating SiGe for the driver amplifier in the transmitter, and InP for the transmitter. At these data rates, Iannuzzi says SiGe will be implemented in a 0.16 μm SiGe BiCMOS process technology, to be launched sometime in 2001. "Our general strategy will be to make as many of the components in our optical communications modules from SiGe," he says.

Prospects for GaAs

Many GaAs companies seem to have accepted that SiGe is suited for certain applications, and a number have signed agreements with the two main SiGe foundries, **TEMIC** and **IBM**, to develop SiGe products. **M/A-COM** is using TEMIC's process and is in the early stages of product development. And working with IBM's process, **Alcatel** has recently introduced a 10 Gbps SiGe SONET transceiver. Another GaAs company in the IBM stable is **RF Micro Devices**, which has just unveiled its first SiGe product [see page 26].

So should the GaAs industry be worried? According to George Bechtel, SiGe shows promise as improved performance replacements for Si in the PA function, but will not compete with GaAs for PAs or optical switches. "I still believe that GaAs will maintain the larger share of the PA market," says Bechtel, "particularly as GaAs manufacturers progress to 6-inch wafers and component prices drop." Raytheon's Sanjiv Shah agrees. "The PA will be dominated by GaAs-HBTs and enhancement mode-PHEMTs," he says.

But SiGe will increasingly challenge GaAs for receive functions, and also looks set to replace Si BiCMOS in both front-end transmit and receive analog functions. "For the receiver, and up to driver amps in the transmit side, SiGe will be a player," Shah predicts. "How successful it will be is a matter of how competitive the pricing is, and the competition will come from silicon and silicon BiCMOS." Shah sums it up: "In the end," he says, "it's all about price."



Lucent's next generation 10 Gbps system for SONET/SDH applications showing the GaAs and SiGe components. The company says it aims to replace as many parts as possible with SiGe.

Optical Amplifiers – All Pumped Up

MARIE MEYER

It could be argued that the one component that keeps the Internet alive is the 980nm laser diode. Without this device, which is the key component for Er-doped fiber amplifiers (EDFAs), the Internet would have collapsed under its own weight long ago. Instead, thanks to optical amplification and WDM, telecom network capacities are keeping pace with the doubling of Internet traffic every 6-12 months.

James Jungjohann of CIBC World Markets recently predicted that the optical amplifier market could reach \$9.6 billion by 2004, from \$1.3 billion in 1999. Accordingly, the demand for 980nm and 1480nm pump lasers is at unprecedented levels. He believes that the total markets for 980nm and 1480nm pump modules could grow from the current levels of \$272 million and \$109 million, respectively, to over \$2.7 billion and \$1.7 billion in 2004. See Figure 1.

Factors Driving Growth

Jungjohann identifies eight key factors driving the growth of optical amplifiers:

1) Higher Channel Counts.

Channel or wavelength counts have risen since the first WDM system was put into service by Sprint in 1996. That system, which was manufactured by Ciena, had 16 channels; today, the state-of-the-art is 80 channels or more. Each increase in the number of channels requires at least a proportional increase in the optical power of the system.

2) Faster Transmission Speeds. The transition to higher speed 10 Gbps (OC-192) technologies and ultimately 40 Gbps (OC-768) deployments requires more power. Each increase in speed shortens the signal – the OC-768 signal is only 25% as long as the OC-192 signal. Because there are fewer photons per bit,

for a given detector to generate the same electrical signal, that signal must be four times more powerful.

3) Multiple Pump Lasers. Figure 1 predicts a higher growth rate for the lasers than for the amplifier modules. Part of the reason is that several pump lasers may reside inside one optical amplifier. By 2004, the number of pumps per high-powered amplifier is expected to more than double to eight. The allocation will be roughly even between 980nm and 1480nm lasers, with a slight edge for the 1480nm units. This may be a practical limit, because amplifier design gets too complex with more than eight pumps. Therefore, the trend would be toward higher power chips.

4) Tighter Amplifier Spacings. A typical long-haul DWDM network uses one amplifier every 100 km. But this is likely to change. Greater power demands and higher speeds, i.e., dispersion limits will tighten amplifier spacings, meaning the market will require even more amplifiers.

5) Higher Powered Modules. Added EDFA functionality for DWDM introduces large internal losses that must be compensated by more costly, higher power pumps and/or additional pump stages. These internal losses stem directly from higher channel counts and transmission speeds; EDFAs must incorporate gain flattening for more wavelengths and dispersion compensation for higher speeds, both of which drain signal power.

6) Metro Applications. When metro applications begin, they will include power-draining wavelength add/drop functions. Therefore, the use of amplifiers or smaller “amplers” in metro applications should increase. For example, the long-haul WDM market uses amplification primarily to make up for absorption losses; short-haul WDM will depend on optical amplifiers to make up losses from routing (handling) light in metro environments.

7) Huge Undersea Opportunities. Undersea amplifiers will see very high growth rates as fiber networks circle the globe. Here, 980nm pumps continue to take share from the incumbent 1480nm in EDFA design as the 980s’ higher output power attracts undersea WDM system designers focused on extending the reach of the network. 980nm pumps function as the enabling technology behind undersea WDM and eventually all undersea EDFA business may head to 980nm.

8) Ramping Cable Network Upgrades. Strong demand is emerging for EDFAs used in conjunction with high power 1550nm source lasers in cable television networks. Today, cable makes up less than 10% of the total market, but this percentage will grow significantly as newer architectures utilizing WDM and emphasizing 2-way transmission begin pushing the EDFA further down into the system.

In summary, more amplifiers per kilometer, more pumps per EDFA and

Module and Pump Laser Diode Sales			
	1999	2004	CAGR
Optical Amplifier Modules	\$1.3 Billion	\$9.6 Billion	49%
980nm Laser Diodes	\$272 Million	\$2.7 Billion	58%
1480nm Laser Diodes	\$109 Million	\$1.7 Billion	74%

James Jungjohann, CIBC World Markets

Figure 1. The market for optical amplifiers and 980nm and 1480nm laser diodes.

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more market applications are creating a dramatic surge in pump laser unit demand - such that it is outpacing current capacity. In response, both 980nm and 1480nm pump laser manufacturers are redesigning their chips for higher power and doubling/tripling capacity.

Who Does What: 980nm

Several large OEMs produce optical amplifiers including Corning, Lucent, JDS Uniphase, Nortel, Alcatel, and Pirelli. The pump laser module(s) account for approximately 30% of cost of a typical EDFA - see Figure 2. As mentioned previously, both 980nm and 1480nm lasers are used. The 980nm lasers are manufactured almost exclusively in the U.S. and Europe; Japanese companies dominate 1480nm production. Japanese EDFA designs tend to have the highest 1480nm content, whereas the rest of the world employs more 980nm pumps.

JDS Uniphase and SDL are the dominant manufacturers of 980nm diode lasers with approximately 60% and 30% of the market, respectively, according to Jungjohann.

The barriers to entry in 980nm pump laser manufacturing are very high, higher than for any other optical component. Perhaps the most significant hurdle is the thousands of hours of both laboratory and field test data both SDL and JDSU have logged proving their lasers meet network operators' stringent terrestrial and undersea requirements. The companies' resultant FIT (failure in time) scores, near 100, show their lasers will not fail in 100-plus years continuous use.

A second key barrier to entry is power requirements. As WDM system OEMs move to higher channel count systems, they continuously demand higher powered pump lasers. The fact that power and reliability are inversely related makes for a very steep learning curve. Thus the other manufacturers, most notably Lasertron (recently acquired by Corning), Furukawa, Spectracom (acquired by ADC in 1999) and others are continually playing catch-up. But if/when a market for devices with less demanding specifications opens up, this may create opportunity for the second-tier suppliers.

Who Does What: The Niche for 1480nm Lasers

While many of the big market trends favor the producers of 980nm lasers, there is still a substantial market for 1480nm lasers. Its larger effective pumping power makes 1480nm the preferred wavelength in the booster (second) stage of an amplifier since noise generation can be accommodated by providing an adequate signal power input. In general, the choice of pump wavelength in the booster is determined by power output (measured in dBm) per dollar; this metric currently favors 1480nm lasers. Also, the decline of the Yen in 1999 gave Japanese producers of 1480nm pumps a pricing advantage.

There are more participants in the 1480nm chip market, with over ten suppliers actively vying for market share. Again, production is dominated by a few large players. Jungjohann believes Furukawa currently holds about 40% of the market for 1480nm pumps, Sumitomo about 20% and JDSU and Alcatel about 15% each. Anritsu, Fujitsu and others share the remainder.

The Changing Market, Part I: 20,000 Megabits Under the Sea

The introduction of 980nm pump laser technology into submarine networks created a major market shift in 1999. It could be said that undersea sales are growing like kelp!

Previously, 1480nm lasers were the only choice for submarine EDFAs. They were more noisy than their 980nm counterparts, but the early generations of submarine networks, typically eight-channel, 2.5 Gbps systems, could tolerate it, and the 1480nm

laser was considered to be much more reliable than the 980nm laser. But now submarine designers are moving to 16 OC-192 channels (and in Alcatel's case, 32 channels), which makes the improved noise performance of the 980nm pump lasers indispensable. Fortunately, key suppliers of 980nm pumps can now meet the 100-year MTTF (mean time to failure) specification that is required for the undersea market.

The first was JDSU. Working with Lucent, they announced the first submarine-qualified 980nm pump laser module in December, 1998. It is being deployed by Tyco Submarine Systems, which is considered to be the second largest undersea systems provider. Then in 1999 SDL announced that it had been qualified to supply 980nm pumps to Alcatel. With over a third of the market, Alcatel is the largest undersea fiberoptic system provider. KDD is also known to be rolling out 980nm-pumped submarine systems.

The undersea opportunity for 980nm lasers is huge. They have the opportunity to supplant the once-exclusive 1480nm lasers, because of their higher associated bandwidth (power), proven reliability and low noise features. One possible scenario is a rapid, across-the-board conversion from 1480nm-only systems to amplifier designs utilizing both 1480nm and 980nm pumps, much like what happened in terrestrial systems. But it is also possible that 980nm pumps eventually push 1480nm pumps out of undersea EDFA design completely.

Jungjohann believes that the market

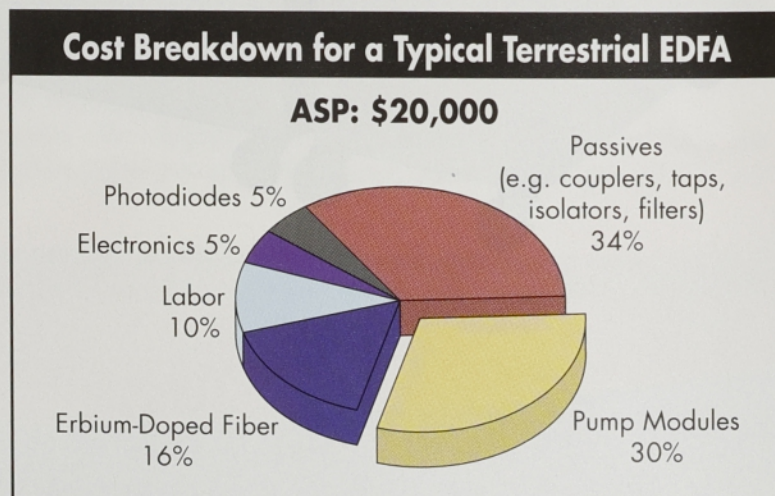


Figure 2. Cost breakdown for a typical EDFA.

Undersea Fiberoptic Cable Deployment: 1988-2003

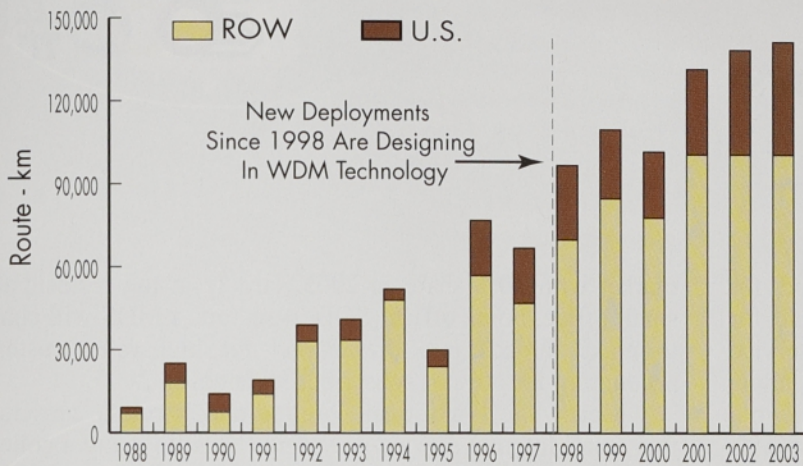


Figure 3. Deployment of submarine fiber optic cable.

for undersea components could soon rival the terrestrial market in value, as submarine components can command up to 3X higher average selling price compared to components for terrestrial use. The dynamism of the submarine market has taken many observers by surprise, and it now appears that the combined 980nm/1480nm pump laser undersea market could be much larger than estimates made just a year ago. JDSU and SDL currently account for virtually 100% of the undersea 980nm chip market, and Jungjohan says this is likely to continue, given their extremely reliable, high powered products.

The Changing Market, Part II: Coming Soon to a Cable Near You

CIBC believes optical amplification will play a large role in metro architectures, although there are other analysts that would disagree. Estimates of the metro market's potential size vary - some say it is just a fraction of the long-haul market, some say it is 2X bigger, or even more. Thus far, the high technology cost of WDM has hampered its acceptance in metro applications. This puts pressure on systems OEMs like Lucent, Ciena and Nortel to introduce a price-competitive product for the local loop. Component suppliers

in turn have felt compelled to develop lower cost technologies. A new, low-cost optical amplifier, known as an "amplet," is expected in 2000 with an initial price tag around \$5,000.

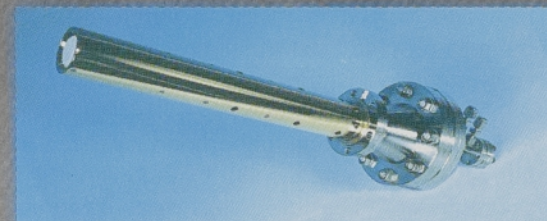
In addition to metro WDM, there should also be applications for amplets in the CATV industry as it changes its infrastructure to allow two-way communications over the cable network. Led by AT&T, CATV suppliers are integrating WDM into their HFC architecture. As a part of this new design, expect to begin seeing lower cost EDFAs pushed deeper into the network. The further down the amplet is pushed, the greater the demand, as the number of lower powered EDFAs needed for amplification grows.

The fiber amplifier market is in a very dynamic phase. When one steps back and looks at the overall picture, it is amazing to think what an enormous impact a tiny compound semiconductor device the size of a grain of sand can have on the world's ability to communicate. Over the next five years, 980nm and 1480nm laser diodes will play a pivotal role in establishing the next generation of communications networks.

The data in this article originally appeared in a research note "Pumped Upon the Optical Amplifier Market" by James Jungjohann of CIBC World Markets, and is used here by permission.

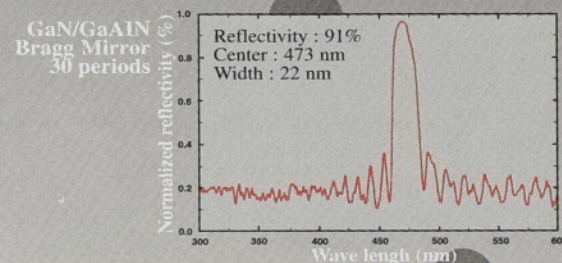
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Broadband Wireless and Millimeter-wave Sensors

TIM WHITAKER

The microwave communications industry is poised for another round of growth, as a result of the demand for broadband capabilities in the local loop. Many service providers will soon invest in wireless systems that will allow them to provide "last mile" connectivity to their customers in a cost-effective fashion, says Andy Fuertes, Senior Analyst with Allied Business Intelligence (ABI). "The arrival of broadband technologies to the neighborhood has been delayed by problematic rollouts, raising the value of the wireless broadband market," says Fuertes. "The limitations of conventional wired broadband technologies have become evident - line congestion and slow deployments of DSL and cable modems have proven to be constant hurdles faced by many service providers."

As a result, service providers are turning to wireless technologies. These include LMDS (local multipoint distribution system), MMDS (multichannel multipoint distribution system), and PCS (personal communication system) systems operating in the various ISM bands (900 MHz, 2.4, 5.1 and 5.8 GHz). These technologies are expected to gain over 9 million broadband subscribers by 2005, according to a new report from ABI [1].

"These wireless systems will be used to provide fiber and high-speed copper equivalents to otherwise under-served customers," says Fuertes. MMDS, including the 3.4-3.7 GHz worldwide standard for fixed wireless access, is expected to lead the

market with 70% share in 2005, largely in the residential and small office, home office (SOHO) sectors. LMDS will continue to make inroads into the market for high-value customers, accounting for 60% of subscriber revenues in 2005.

Meanwhile, traditional wireline and wireless carriers will join small Internet service providers (ISPs) in using a collection of (largely unlicensed) bands and technologies to address dark spots in their coverage areas. Due to its generous spectrum allocation, the 5.8 GHz band is receiving the most attention for unlicensed broadband local loops. Systems operating in this band are expected to account for close to half a million subscribers in 2005.

Total shipments of customer premise equipment for high-speed wireless technologies are expected to reach 3.6 million units in 2005, according to the report's findings.

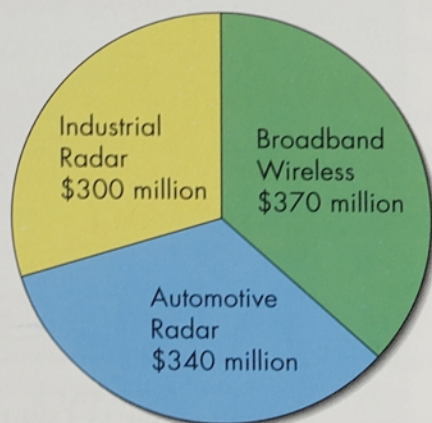
Emerging Business Opportunities for Millimeter-wave Modules

The availability of commercial microwave and millimeter-wave modules is a key growth factor for a number of innovative products, says Patric Heide of Siemens AG Corporate Technology. These include broadband millimeter-wave communications, automotive distance warning systems and industrial sensors. "These markets are going to generate more than \$1 billion in the near future," says Heide. (See Figure for details.) "Success in these cost-sensitive volume markets depends strongly on the ability of suppliers and system integrators to find novel technical solutions that are attractive in terms of production simplicity." The key, explains Heide, is to move away from military-oriented manufacturing and develop commercial, high-volume production techniques.

Siemens has already developed millimeter-wave modules for fully automated production, targeting applications such as broadband communications (18, 23, 26, 38, 58-64 GHz etc), automotive radar for adaptive cruise control (77 GHz) and radar for industrial sensing applications (24 GHz). Patric Heide will describe these activities in detail in the next issue of *Compound Semiconductor* magazine.

Commercial Millimeter-Wave Equipment

Worldwide Revenues in 2003



Forecast for millimeter-wave equipment sales in 2003, compiled from market studies by Frost & Sullivan, ABI and Strategies Unlimited. Data courtesy of Patric Heide, Siemens AG Corporate Technology.

[1] "LMDS, MMDS and ISM 2000: Global Markets and Trends for Fixed Wireless Broadband" is available from Allied Business Intelligence. TEL: [1] 516 624 3113, WEB: www.alliedworld.com.

Andy Fuertes will present a talk entitled "Broadband Applications for Microwave Technologies in the Local Loop" at the Key Conference, March 13-14, 2000 in Key West.



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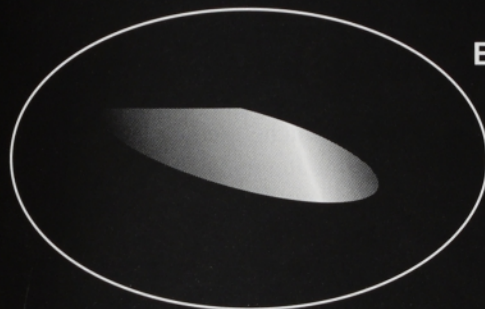
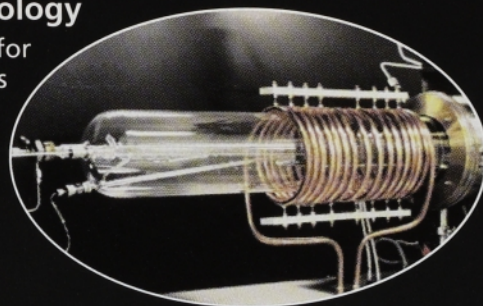
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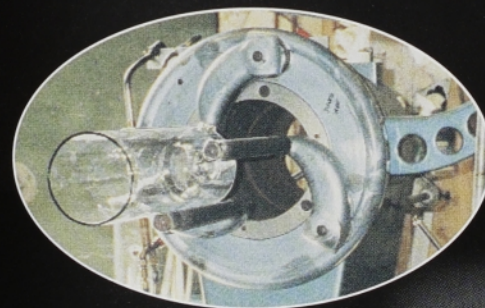


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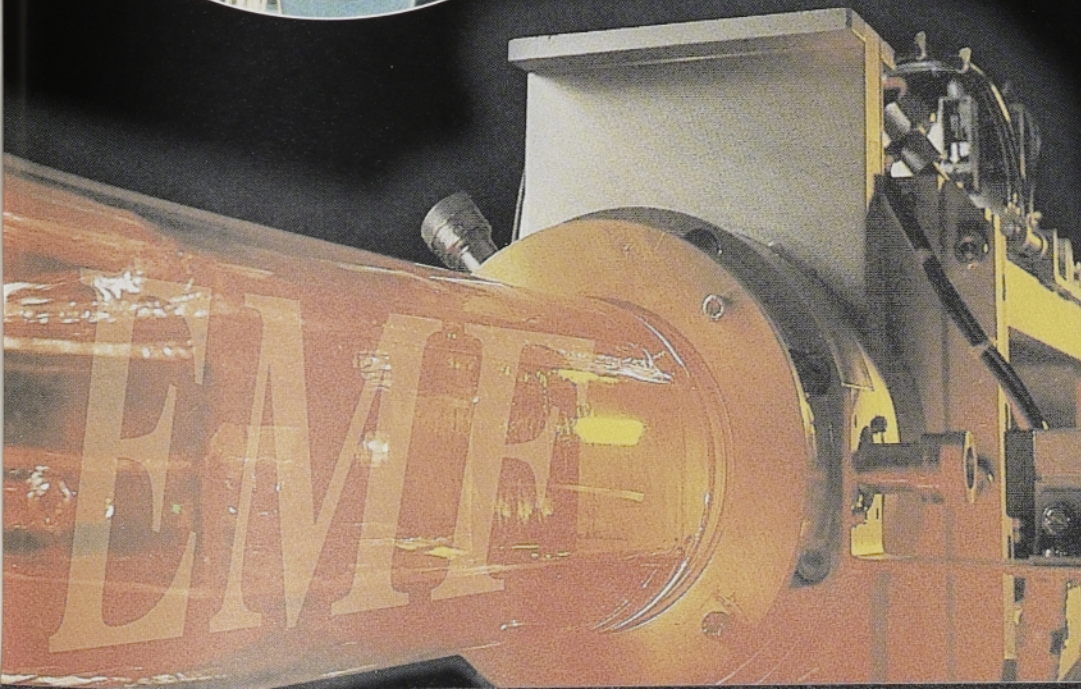
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Optical Networking

TAM WATKINS

 Things to Watch
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At present, the main market for WDM systems is in long-haul transmission. Most systems are effectively point-to-point links carrying multiple wavelengths. These have the capability to route one or more wavelengths around local networks along the main trunk line, using passive optical add-drop multiplexers (OADMs) (see Figure 1a).

The single pipe is now beginning to turn into a mesh network with a larger amount of switching and routing functionality (see Figure 1b). These features will be increasingly in demand as WDM penetrates the short-haul metro and access markets. The ultimate goal will be to create networks such as the one in Figure 1b that can switch and route multiple wavelengths to multiple destinations without the need to convert the optical signals back into electronic form. To reach that goal, some new technologies will be required.

Optical Switches

Switching in optical networks currently requires optical-electrical-optical conversion. The signal is detected, processed, and re-transmitted, using photodetectors (PDs), high-speed ICs (including large electronic crosspoint switches) and modulated lasers, respectively. Often, EDFAs are placed before or after the switch to act as a pre-amplifier or a booster amplifier.

Future all-optical networks will require switches that operate without opto-electronic conversion. While these will eliminate PDs, ICs and lasers from the switch, they will introduce lossy

processes that necessitate the use of additional amplification. "This represents a near term application for low noise, local amplification at reduced cost," says Toby Strite of JDS Uniphase Switzerland. "Amplifier manufacturers are very excited by the additional market for mountains of low performance amplifiers and pump lasers to locally compensate small losses as they occur."

These low cost amplifiers – known in industry jargon as *amplers* – are likely to be EDFAs with lower performance specs than the ones used in long-haul links. "In metro applications, amplifiers will sit on the outputs of switches and OADM's to counterbalance signal losses," says Jim Jungjohann of CIBC World Markets. "Pumping power will likely be provided by a single low-cost, lower power 980 nm pump laser. These pump modules are expected to sell for less than \$500, compared to the \$2,200 price tag for higher-powered modules."

One way to reduce the cost of EDFAs is to eliminate the cooler that controls the temperature of the pump laser and limits its wavelength drift. Uncooled, low power (~40 mW) lasers are already available at 1480 nm, while manufacturers are now introducing different wavelength stabilization techniques for uncooled 980 nm pumps.

In addition to being attractive to local telephone service providers, the *amplifier* should also appeal to CATV suppliers. CATV is undergoing a massive transformation; for example, AT&T has embraced WDM as the key to its HFC architecture as it works to offer two-way communications over the cable network. Wherever there is WDM, there is a demand for amplification, and low cost *amplifiers* are likely to offer the best solution for these short-haul CATV applications.

Semiconductor Optical Amplifiers

Semiconductor optical amplifiers (SOAs) have the same basic structure as laser diodes – light is amplified by stimulated emission during its passage through the gain medium – and these components may find applications in metro and access networks. "The jury is still out on the use of semiconductor optical amplifiers," says Gerlas van den Hoven, product manager for SOAs at JDS Uniphase Netherlands. "Although no systems have been deployed that use large quantities of SOAs to date, there are a number of applications that look attractive." These include using SOAs as pre-amplifiers just in front of detectors – in this case, the low power output of SOAs compared to EDFAs is less important than in other situations.

Van den Hoven says that SOAs have been used in demonstrations of 8-channel transmission at 20 Gb/s over limited distances (up to 200 km) at 1550 nm. These devices are also useful

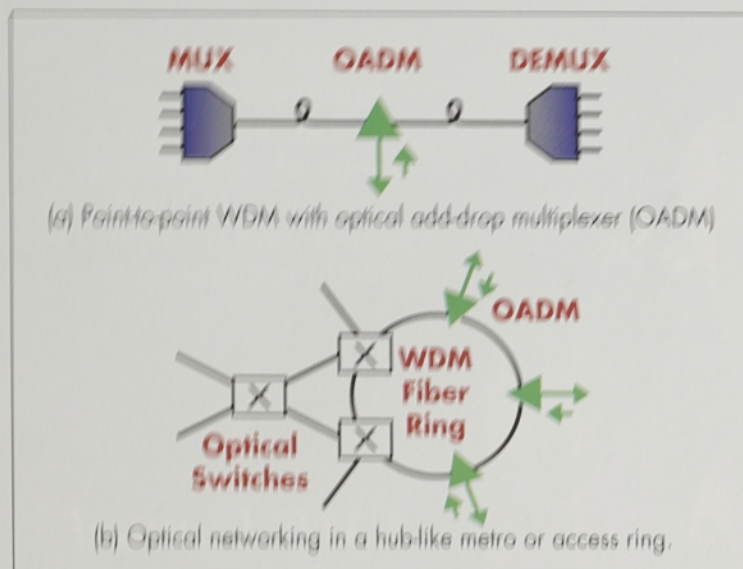


Figure 1. WDM systems are evolving from (a) point-to-point links with add/drop functionality to (b) networks with large amounts of switching and routing functionality.

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in 1310 nm systems, a wavelength at which EDFAs cannot operate. Short haul systems at 1310 nm that previously had no need for amplifiers may now require them to enable more channels or higher data rates, and to compensate for losses incurred by optical switching and routing.

One very attractive feature of SOAs is their compactness. "While EDFAs contain Er-doped fiber and one or more pump lasers, as well as couplers and isolators, SOAs are single components in compact butterfly packages," explains Gerlas van den Hoven. "Also, SOAs are based on the same InP technology used to fabricate DFB lasers, which is rapidly becoming a high volume commodity technology."

The cost of SOAs in high volume is expected to be roughly 1.5-times the cost of regular DFB lasers, mainly because SOAs have two fiber couplings.

Wavelength Conversion and Optical Regeneration

One area in which SOAs will almost certainly be used is in wavelength conversion, according to Jong-Ryeol Kim of Samsung. "WDM technology uses multiple wavelengths to transmit independent data on each wavelength channel," he says. "Wavelength converters are necessary to avoid wavelength contention in such systems. They can also be applied to other functional devices, such as optical demultiplexers, regenerators and so on. Because of these wide applications, wavelength converters are expected to be the most prominent application of SOAs." Another potential application is in high-speed optical matrix switches that use many monolithically integrated SOAs as gate elements.

The wavelength converter switches the optical signal from one carrier wavelength to another. Obviously, this can be done by opto-electronic conversion, using a laser at a different wavelength to re-transmit the regenerated optical signal [see Figure 2a].

The same function can be achieved using two SOAs in a Mach-Zehnder interferometer (MZI) configuration, as shown in Figure 2b. Light from a laser source is split into two paths containing SOAs. The incoming optical signal (λ_{in}) enters one of the SOAs, inducing a relative phase shift that saturates the gain. When the light is recombined, constructive or destructive interference will occur depending on the phase difference between the two paths. The result is an optical signal at the new wavelength (λ_{out}).

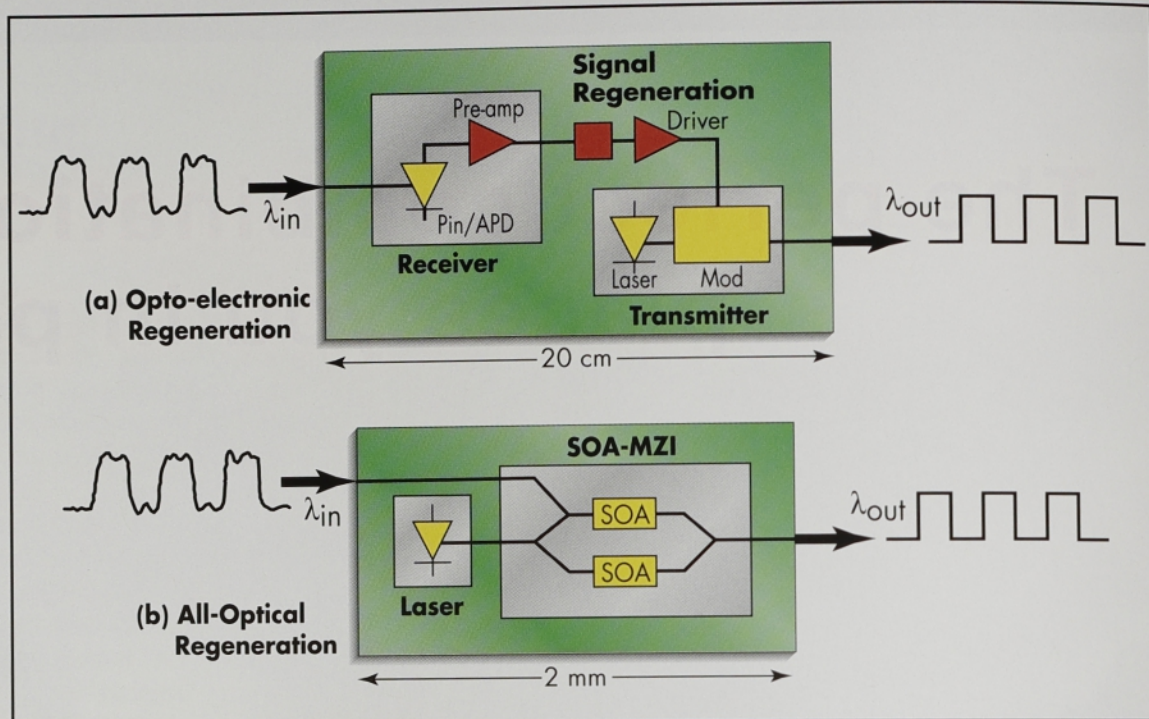


Figure 2. (a) A "conventional" opto-electronic signal regenerator in which the signal is retimed and reshaped in electronic form. (b) An all-optical regenerator with two semiconductor optical amplifiers (SOAs) in a Mach-Zehnder interferometer (MZI) configuration.

The ultimate aim is to achieve all-optical regeneration – using components such as the one shown in Figure 2a to amplify, retime and reshape optical signals without the need for opto-electronic conversion.

Long Haul Optical Networks

As a first step towards all-optical networks, several companies are seeking to greatly increase the distance traveled by optical signals before regeneration is necessary. In terrestrial systems, this is around 600 km at present, while in submarine systems the distance can be up to 6,000 km. These very expensive undersea systems use sophisticated modulation techniques to shape the signal in such a way that the pulse shape periodically regenerates itself as it passes along the fiber. Broadly speaking, the techniques are similar to those used in soliton transmission (see below), and are now being applied to terrestrial systems by companies such as Qtera (Boca Raton, Florida) and Corvis (Columbia, MD).

Qtera - recently acquired by Nortel Networks for \$3.25 billion [see page 6] - has developed an optical transport platform that transmits bundles of 10 Gb/s signals using DWDM over a distance of 4,000 km without regeneration. The technology may eventually supersede the current generation of 10 Gb/s DWDM platforms, a market dominated by Nortel. Because regeneration occurs less frequently, this technology uses fewer photodiodes, ICs and modulated lasers than current systems. But a great deal of amplification will still be required to compensate for optical loss in the system. For ultra-long-haul transmission, this will result in an increasing demand for high performance EDFAs.

Solitons

After several decades of R&D work, soliton DWDM transmission systems are about to reach the commercial market. Algety Telecom (Lannion, France) – a spin-off from France Telecom's CNET – aims to combine the high channel density and bandwidth utilization of DWDM with the speed per channel advantages of solitons. Soliton technology decreases the data signal's sensitivity to losses, and with it the need for amplification and regeneration stations.

So what is a soliton? In simple terms, it is a pulse with a special shape that is periodically regenerated as the pulse travels along the fiber. All optical signals experience pulse dispersion in optical fiber, which causes pulses containing a range of wave-

lengths to spread out as they travel. A competing effect is self-phase modulation, which spreads the pulse out over a range of wavelengths. Essentially, the two effects cancel each other out and the pulse returns to its original form. Attenuation weakens the pulse but optical amplifiers restore its power.

In the 1970s, soliton transmission was regarded as the technology of choice for optical systems operating at up to 100 Gb/s, but the commercialization was delayed by the emergence of WDM in the mid-eighties.

Jérôme Faul, VP of Marketing, says that Algety is focusing on systems and software. The company will not manufacture photonic components (lasers, modulators, amplifiers), which are not significantly different from those in "traditional" systems.

Silicon Carbide ICs

TIM WHITAKER

Silicon carbide is obviously not a new material, but commercial electronic devices fabricated in SiC are rare. However, this technology is currently generating a huge amount of interest right now, if the attendance at the recent International Conference on SiC and Related Materials (ICSCRM '99) is anything to go by. Over 650 people showed up, including many representatives of companies who appear to be moving closer to producing commercial SiC devices for high frequency, high power and high temperature applications.

Commercial SiC Devices from Cree

Cree is leading the way as far as commercialization of SiC devices is concerned. The company announced its first commercial SiC RF power transistor in the middle of 1999. According to Ray Pengelly, Cree's general manager of Microwave and RF Products, there will be a family of RF and microwave power transistors introduced on a regular schedule during 2000 to complement the 10-watt device that has been introduced to date. "The target applications are infrastructure needs above 2 GHz and, where appropriate, below 2 GHz," says Pengelly. "These include multichannel multipoint distribution systems (MMDS), wireless local loop (WLL), radar, weather control radar, and some medical applications."

"SiC will compete head on with GaAs MESFET technology," explains Ray Pengelly. "The intention is to take a portion of the infrastructure market away from MESFETs. Because of the ability of SiC technology to allow a re-think of the thermal characteristics and operating conditions of the transistors, it will allow smaller sub-systems to be realized and/or higher case temperatures to be achieved."

At ICSCRM '99, Kansai Electric of Japan and Cree announced a SiC bipolar *pin* diode with a new record high breakdown voltage of 6.2 kV. The device has a low forward voltage of

4.7 V at 100 A/cm² and exceeds the practical trade-off limit (blocking voltage and forward voltage) of commercially available Si pin diodes for the first time.

Northrop Grumman's Plans

Northrop Grumman has been involved in the development of SiC microwave devices for more than a decade. The primary focus has been the Static Induction Transistor (SIT) which is well suited for high peak power applications. "This high peak power, along with SiC's unique thermal properties has allowed us to target these devices for use in radar applications thereby providing higher power density, lower weight, smaller volume and reduced cost," says a Northrop Grumman spokesperson. "These devices have been demonstrated in several prototype radar systems and are now entering pilot production."

The company expects that improved material quality, larger wafer size and device yield improvements should lead to large volume production of these devices in the next few years. Like most microwave devices, SiC commercialization will be primarily driven by the booming telecommunications industry, continues the spokesperson. "As the technology matures, SiC will surely play a key role in the radar, telecommunication and electric power utility industries."

Activities in Japan

A study comparing wide bandgap semiconductor technology in the U.S. and Japan was recently released by ITRI – the International Technology Research Institute based at Loyola College in Maryland*. The report found that optoelectronics and high frequency electronics are seen as the main applications for GaN technology in Japan. SiC is the main focus for high power electronics, while high temperature electronics is not considered

Things to Watch

2000 #8

a major field. Japan enjoys a lead in GaN technology for light emitters but is generally behind the U.S. in SiC device development. Several Japanese companies are developing SiC devices for power applications, including Denso, Fuji Electric, Kansai Electric, Hitachi, Matsushita and Toshiba. Others, such as NEC and Sony, are developing GaN devices for high frequency satellite and communication base station applications.

Progress on SiC in Europe

ITRI's report on wide bandgap semiconductor R&D in the U.S. and Europe was previewed during the 1999 Fall MRS meeting [1]. Companies developing SiC technology include Siemens and DaimlerChrysler in Germany, Thomson-CSF in France, and ABB, IMC and Ericsson in Sweden. The ITRI panel visited ABB and Siemens, and stated that these two companies see SiC as the technology of choice for high power switching electronics.

Infineon's Power Semiconductor Group in collaboration with Siemens Corporate Technology reported performance and reliability measurements of packaged SiC Schottky diodes at ICSCRM '99. The long-term stability of these diodes was demonstrated under high thermal and electrical stress, showing that the

chosen packaging and passivation scheme is highly stable. Siemens/Infineon appears to be poised to enter full production of SiC rectifier diodes – according to the ITRI panel, Siemens is already shipping 600 V, 5 A samples to customers.

ABB is “developing a production process for high voltage SiC diodes” according to the ITRI panel. At ICSCRM '99, a paper from ABB's Corporate Research labs described the fabrication of a high power module combining silicon IGBT switch chips and large area SiC diodes. These modules, rated for 2500 V and 150 A, are operated in application circuits for high voltage DC (HVDC) transmission, such as HVDC lighting. Regarding commercialization, it was stated in the ITRI report that “progress

in defect understanding and crystal perfection is needed to open industrial manufacturing.”

At DaimlerChrysler unipolar SiC Schottky diodes are under development for use in power converters. These are

expected to find applications in traction, auxiliary and generator converters for electric cars, such as hybrid cars and fuel cell vehicles. For example, traction converters for electric cars require devices operating at 600 V and 400 A.

Several ongoing European programs are supporting the development of SiC technology. These include TELSIC (Telecommunication by SiC), a project involving both Thomson-CSF and Ericsson, and JESICA (Joint European SiC Activity), which seeks to establish a commercial European source for high quality SiC substrates.

What about Nitrides?

Although nitride-based devices and ICs have yet to reach the commercial market, their time will come. Ray Pengelly states that Cree is aggressively working on the development of GaN-based MMICs and that commercialization will happen “in the near future”.

“GaN-based devices and ICs are currently at the developmental stage, and have shown very high promise for all frequencies of interest up to K-band,” says Bernd Keller of Nitres. Some of Nitres' recent results are described on page 13.

“GaN technology will target both military and commercial applications,” continues Keller. “The former include radar systems (ship-board, air-board and ground) and high performance space electronics; and the latter include base station transmitters, C-band satcom, Ku-K band VSAT and broadband satellites, LMDS and digital radio. Initially, GaN will be a replacement technology and vie to take markets from existing technologies including high power microwave tubes. “Ultimately, the compact size of GaN-based transistors will lead to lower cost products,” says Keller. “This will increase system efficiency, reduce system costs, and expand the market applications.”

* For information on ITRI's reports on wide bandgap semiconductor technology, visit <http://itri.loyola.edu>.

Ray Pengelly and Bernd Keller will speak on the subject of wide bandgap devices for wireless communications at the Key Conference, March 13-14, 2000 in Key West.

“Improved material quality, larger wafer size and device yield improvements should lead to large volume production of these devices in the next few years.”

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DVD – At Last

TIM WHITAKER

It seems that 2000 is going to be the year in which the long awaited surge in sales of DVD players and drives finally begins. DVDs offer a much greater data storage capacity than CDs, partly due to the differing laser wavelengths used - 650 nm for DVD, 780 nm for CD. However, several factors, including the continued absence of a common format for rewritable DVD, have delayed the take-off of DVD until now.

Consumers are beginning to take advantage of features offered with DVD movies, such as subtitles, high quality audio tracks and a choice of wide screen or letterbox format. According to two recent reports from Cahners In-Stat Group [*] estimates that around 13.5 million DVD-video players will ship in 2000, although other estimates are almost twice that amount. As more movie titles become available on DVD, this market should grow at a CAGR of around 19% between 2000 and 2003 [see Figure].

"Many manufacturers have jumped on the DVD bandwagon, which resulted in the price declines that have driven sales growth," says Michelle Abraham, senior analyst with In-Stat. "In

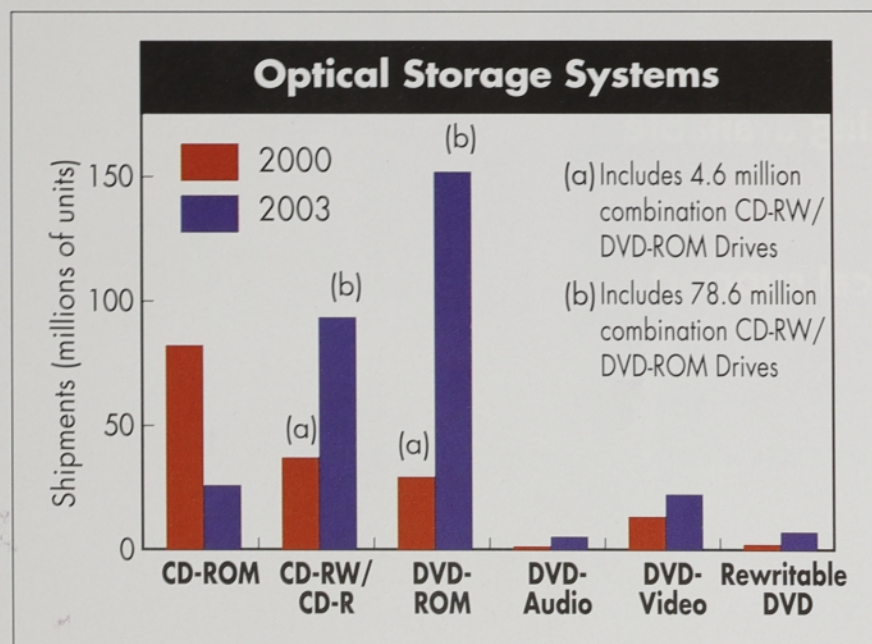
2000, players will reach the sub-\$150 price level which will contribute to continued growth." Abraham added that DVD-audio will also help propel DVD player sales due to its multichannel sound capability. However, it could be argued that CDs offer more than enough audio storage capacity for most users.

It was originally assumed that the personal computer industry would take advantage of the capabilities of DVD-ROM and install these drives into PCs instead of CD-ROM drives. Although many OEMs are now doing just that, the DVD drive market is still not meeting original expectations. CD-ROM drives will continue to outship DVD-ROM drives until 2002, but 2000 will see the start of the long-awaited significant decline in CD-ROM drive shipments.

Combination Drives and Compatibility

A major issue for DVD is to ensure back-compatibility with existing formats – in other words, to ensure that DVD players can read all types of CDs. While current DVD players can read CD-audio disks with a 650 nm laser, they can't necessarily read CD-recordable (CD-R) disks because the disk's surface has a different reflectivity. Philips sells a DVD player with a dual-laser (650 nm and 780 nm) optical head for CD-R compatibility. Many DVD-ROM drives also incorporate two lasers, although it is possible to read CD-RW (rewritable CD) disks with a 650 nm laser.

With rewritable DVD players and drives, another major issue is that several different formats are in existence, each backed by a group of leading manufacturers. Naturally, this has prevented extensive adoption of any of these formats, and in the meantime CD-RW has emerged as a very popular alternative. Not least this is because a CD-RW disc costs about 2 dollars and stores 650 MB, while other removable storage media cost seven to nine dollars for high-capacity floppy disks with about four to five times less capacity than CD-RW discs.



Predicted unit shipments of CD and DVD players and drives in the next few years. During this period, DVD-ROM will supercede CD-ROM in new PCs, and the home DVD-video player market will grow steadily. Drives combining CD-RW and DVD-ROM will prove extremely popular during this period, while rewritable DVD technologies will grow slowly. Many types of DVD drive contain both 650 nm and 780 nm lasers to ensure compatibility with all disk formats. Data courtesy of Michelle Abraham, Cahners In-Stat Group.

* "DVD Markets and Opportunities in the Living Room" and "CD Still Ahead of DVD in the PC" are available from Cahners In-Stat Group. Contact: Christina Hecht, TEL [1] 480 483 4443, EMAIL checht@cahnersinstat.com.

The popularity of CD-RW drives is having an impact as PC OEMs choose between incorporating a CD-RW or DVD-ROM drive into their PC models. "Rather than make that choice, PC OEMs are eager for combination CD-RW/DVD-ROM drives," says In-Stat's Michelle Abraham. "Once combination drives reach \$100, they will account for 25% of the total CD/DVD drive market."

The number of these CD-RW/DVD-ROM combination drives is expected to increase from around 4.6 million in 2000 to 78.6 million in 2003. A model currently available from Toshiba contains an optical head incorporating a high power 780 nm laser for writing CD-RW/-R and a low power 650 nm laser for reading DVD discs.

DVD-RAM from Panasonic

One of the several rewritable DVD technologies under development is DVD-RAM. Drives with a capacity of 4.7 GB per side are already being shipped by Panasonic and Hitachi. The Panasonic model features a fast, random access at a transfer rate of 22.16 Mbit/s, and more than 100,000 write/rewrite cycles can be performed. Two lasers are employed to allow all CD formats to be read.

Existing DVD-ROM drives can't read the new DVD-RAM media. However, new DVD-ROM drives that can read this media are already on the market, according to Andy Marken of Marken Communications, representing Panasonic Industrial Co. "From an OEM perspective, Apple is clearly leading the pack in offering the DVD-RAM in their upper G4 systems," says Marken. "These will migrate down into the other G4 systems later this year. Also, all iMacs ship with DVD-ROM drives that read DVD-RAM media."

Panasonic reports that demand for DVD-RAM drives grew from 120,000 units in 1998 to nearly 600,000 units in 1999, of which Panasonic had a 60-65% share. An estimate of 2.5 million units has been put forward for 2000, although Cahners In-Stat predicts a figure of around 1.2 million units for all rewritable DVD drives. The slow development of this market is emphasized by the sales prediction made in 1997 that shipments of DVD-RAM drives would reach 9 million units by 2000.

Other Formats - DVD+/-RW

Other formats are having mixed fortunes. Hewlett-Packard and Sony are shelving plans to introduce a 3 GB drive in the DVD+RW format; instead, they will introduce a 4.7 GB version later this year by which time more DVD-ROM drives capable of reading DVD+RW media will be on the market.

In November 1999, Pioneer introduced the industry's first consumer-use DVD Recorder for the Japanese domestic market. This player uses Pioneer's re-recordable DVD-RW disc media that can be rewritten about 1000 times. The price is around \$3,000, and at present there is only one media manufacturer.

Obviously, it will be a while before home DVD recorders replace video tape recorders. "High prices, format wars, and copy protection issues will keep DVD-Video recorders out of the mainstream for several years," says Michelle Abraham.

4.7 GB of storage capacity is equivalent to:

- 4,700 full-color pictures (640 x 480, 24 bit/pixel)
- 210 minutes of compressed MPEG-2 DSS satellite-quality video
- 120 minutes of compressed MPEG-2 theater-quality video
- >7 hours of CD-quality audio
- >400,000 documents, or 8 four-drawer filing cabinets

Next Generation DVD

Several companies have demonstrated prototype high-density DVD systems that use violet lasers, supplied by Nichia, to increase the data storage capacity to around 15 GB per side. Matsushita has used a second harmonic generation blue laser to demonstrate the feasibility of high-density recording, while at the same time developing a violet diode laser for the same purpose. Pioneer recently showed a prototype system with a capacity of 27.4 GB, and has entered into an agreement with Rohm to develop and commercialize blue laser technology [see page 11]. Despite this activity, the commercialization of such systems will undoubtedly wait until the current generation of DVDs is clearly established as the predominant optical storage technology.



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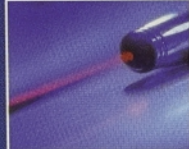
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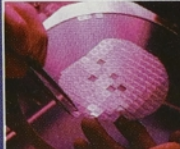
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Indium Phosphide Microelectronics

TIM WHITAKER

Will this be the year that indium phosphide ICs enter commercial high-speed fiber-optic and high frequency wireless applications? Perhaps not. But the consensus of experts in the field is that the technology is maturing rapidly. TRW, NTT and HRL Labs all intend to introduce products within a 1-2 year time frame, and in terms of commercialization, it's definitely a question of "when", not "if".

Commercialization Soon

"Our InP foundry capability is operational," says Dwight Streit, Director of Telecom Products at TRW. "We are beginning to work with specific customers on product development, and we expect that initial InP products will be inserted into commercial applications over the next 18 to 24 months." Streit notes that InP ICs will be initially used for both digital applications, such as OC-768 (40 Gb/s) fiber-optic systems, and for RF applications such as high frequency transceivers. He adds that there are several other applications that TRW is investigating with partners that are in their early assessment phase now.

In addition to TRW, several other companies discussed their plans for InP at a panel session at last October's GaAs IC Symposium. NTT is strongly focused on the use of InP HEMTs for 40 Gb/s optical communications [see CS 5(8), p. 31]. According to NTT's Yasuro Yamane, the company plans to commercialize this technology by introducing InP HEMT ICs as engineering samples by March 2001, and as commercial samples by March 2002.

Marko Sokolich states that HRL Labs has already shipped commercial products utilizing InP HEMTs. "They are currently shipped only in small quantities for frequencies above 60 GHz,"

"Questions concerning cost, yield, reliability and overall manufacturability of InP ICs are the same questions that were asked of GaAs some ten years ago. The short answer is yes, these problems can be overcome."

he says. "Large volume shipments in excess of 1 million units are still 2-3 years out." In some cases, the performance enhancement provided by InP ICs (above 30 GHz) leads to much higher yields and smaller chips, and will offer a cost advantage over GaAs. InP ICs may also provide a lower cost at the system level...for example chips that have added margins in transmission rates or enhanced gain or reduced noise figure in high frequency amplifiers. "In this case the chips will command a premium based on system cost reduction and could sell for significantly more than the GaAs they replace," says Sokolich. An analogous price premium is enjoyed by GaAs HBT power amplifiers in wireless handsets.

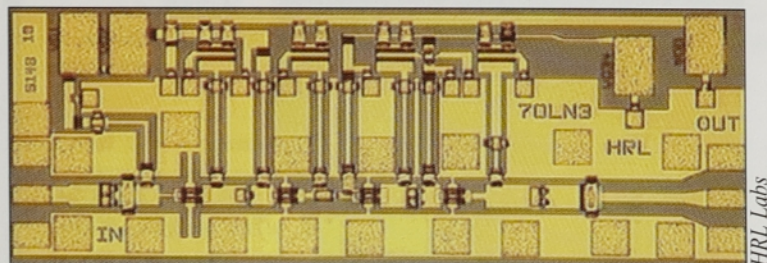
Sokolich sees many applications for InP ICs. "Although SiGe may be capable of some 40 Gb/s transmit/receive circuit applications, InP HBT ICs have significantly higher margins (moderate scale circuits at 50 Gb/s have been demonstrated as well as small scale 80 Gb/s circuits). Anything that requires high breakdown (at above 30 GHz) such as laser drivers will probably be made with III-V semiconductors...

probably InP DHBTs. Applications at above 60 GHz – including last mile or wireless LAN components, automotive radar and passive imaging – are also prime targets for InP ICs."

In contrast, Sanders, a Lockheed Martin company, has no plan to commercialize InP ICs. "This is due to the high cost of the technology," explains Pane Chao. "Instead, we propose to use GaAs-based metamorphic HEMTs using 6-inch wafers." Metamorphic HEMT technology provides performance approaching that of InP HEMTs while benefiting from certain advantages – including size, cost and mature process technologies – associated with the use of GaAs substrates. Pane Chao adds that today's InP technology is good in applications where absolute performance is required and cost is no object.

Is InP Manufacturable?

Indium phosphide clearly offers enhanced performance compared to existing technologies, but there are a number of frequently quoted disadvantages and potential problems that could



A four-stage W-band low noise amplifier fabricated using InP HEMTs.

Additional information supplied by Andrew Johnson. Dwight Streit will present a talk entitled "How Cost-Efficient InP Changes the Telecommunication Industry's Competitive Landscape" at the Key Conference, March 13-14, 2000 in Key West.

hold up its commercialization. These include cost, yield, reliability and the size and fragility of InP substrates.

"No one has demonstrated good reliability with power InP ICs, although low noise InP IC technology has been space-flight-qualified by companies such as Sanders," says Pane Chao. "However, to Sanders, the biggest problem of commercializing InP technology is that it is limited to 3-inch wafer size. While 4-inch may be available in the future, GaAs-based MHEMT technologies can do 6-inch - a significant cost disadvantage for InP."

"There is no fundamental reason for the long-term cost of InP substrates to exceed the cost of GaAs substrates."

The question of whether problems concerning cost, yield, reliability and overall manufacturability of InP ICs can be overcome is exactly the same question that was asked of GaAs some ten years ago, says Dwight Streit. "At TRW, we see no intrinsic barrier to achieving the same production capability with InP that exists with GaAs," he says. "We have already demonstrated outstanding yield and reliability with our existing InP production line. Cost goes down as volume goes up. The short answer is yes, these problems can be overcome."

"In this initial stage, performance and reliability are more important than cost," says Yasuro Yamane of NTT. "The market

size will eventually determine the cost, and we can overcome yield and reliability problems."

At the GaAs IC Symposium panel session, substrate manufacturers were quick to point out that prices for InP substrates will fall rapidly as demand rises, and that fragility is not a major problem - points that Marko Sokolich agrees with. "There is no fundamental reason for the long-term cost of InP substrates to exceed the cost of GaAs substrates," says Sokolich. "3-inch InP wafers are no more fragile than 3-inch GaAs - I have managed a 100 wafer/week GaAs fab as well as a lower volume InP fab effort and noted no significant difference in breakage." He adds that HBT and HEMT functional yield should be comparable to GaAs in the long run.

Another interesting point made by Marko Sokolich is that packaging advances in the next 10 years will make the discussions about the superiority of different material systems - Si, GaAs, InP or whatever - entirely obsolete! "The best material for the problem at hand will be chosen for each component of even the least costly system," he says. "I envision InP, GaAs, SiGe and CMOS coexisting on the same low-cost 'chip'."

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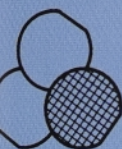
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ABSTRACT DUE DATE: 10 December 1999

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Wide Bandgap Materials

New Approaches to Epitaxial Lateral Overgrowth

• Lateral overgrowth from trenches (LOFT) is described. A GaN layer with a high threading dislocation density is grown, trenches are etched, and the bottoms of the trenches and the tops of the mesas are coated with SiO₂. GaN regrowth occurs from the trench sidewalls only. Threading dislocations are reduced from $8 \times 10^9/\text{cm}^2$ in the original film to $6 \times 10^7/\text{cm}^2$ in the regrown layer. Residual dislocations extended from the trench sidewalls or were generated where two growth fronts merged.

[Y. Chen et al, **Hewlett-Packard**, Appl. Phys. Lett. 1999, 75(14), p. 2062]

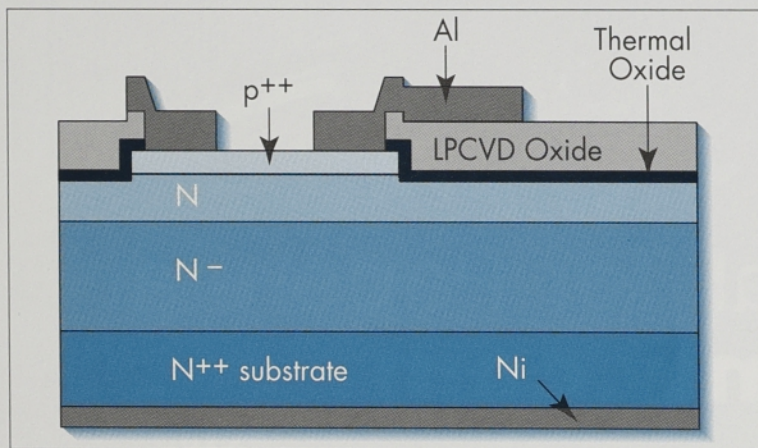
• Single step epitaxial lateral overgrowth (ELO) of GaN on SiC and sapphire substrates patterned with silicon nitride is described. A high temperature AlGaIn nucleation layer is critical; this provides a template for GaN ELO in the mask openings, but does not deposit on top of the mask features. Stripes in the $\langle 1100 \rangle$ direction produced truncated trapezoidal structures that eventually coalesced into a planar surface. As with conventional ELO, GaN grown above the mask had a high threading dislocation density ($\sim 10^9/\text{cm}^2$) while in the ELO regions over the mask features the density was less than $10^5/\text{cm}^2$.

[J. Smart et al, **Cornell University**, Appl. Phys. Lett. 1999, 75(24), p. 3820]

SiC and Diamond UV Photodetectors

• A 4H-SiC visible-blind reach-through avalanche photodiode (RAPD) with a peak responsivity of 738 A/W at 320 nm was reported. The device structure (see Figure) contains an n-type multiplication layer and an n- photon absorption layer. The visible-blind rejection ratio (peak responsivity divided by responsivity at 400 nm) was about 2500 at 93.9 V reverse bias. The fall time of 4 ns was the fastest ever reported for visible-blind UV photodetectors, and the devices operated at temperatures up to 257°C.

[Feng Yan et al, **Rutgers University and Sensors Unlimited**, Proc. ICSCRM '99: Elec. Lett., 1999, 35(11), p. 929]



Cross-section of the 4H-SiC RAPD

• A metal-semiconductor-metal (MSM) UV photodetector fabricated from a thick polycrystalline diamond film grown by plasma-assisted CVD is reported. The device operated up to 300 °C with a peak responsivity at ~ 225 nm. By stacking this device with a SiC UV photodetector exhibiting a maximum photore-sponse at a longer wavelength (330 nm), it may be possible to fabricate a device with high sensitivity across the entire 200-400 nm range.

[S. Salvatori et al, **Universita degli Studi Roma TRE, Italy**; Elec. Lett., 1999, 35(20), p. 1768]

Single-spot Nitride Lasers

A far-field pattern with a single spot is a critical feature of nitride laser diodes for high-density optical storage applications. Multiple spots are often seen due to optical leakage from the waveguide layer. Growing a thick, crack-free AlGaIn layer on GaN to suppress this leakage proves difficult due to lattice mismatch. Here, laser structures (grown by MOVPE on sapphire with a low-temperature buffer layer) incorporate a 3- μm thick n-Al_{0.03}Ga_{0.97}N contact layer instead of the conventional n-GaN contact layer. The subsequent 1- μm thick n-Al_{0.06}Ga_{0.94}N cladding layer has a tensile strain of only 0.07%. The improvement in optical confinement results in a single spot in the far-field pattern.

[T. Takeuchi et al, **Meijo University and Hewlett-Packard, Japan**; Appl. Phys. Lett., 1999, 75(19), p. 2960]

780 nm VCSELs with 3.4 mW Output Power

Oxide-confined 780 nm VCSELs are reported with a single-mode power of 3.4 mW, the highest value ever obtained at this wavelength. The AlGaAs-based MOCVD-grown structures had an oxide aperture of 3.5 μm while the size of the aperture in the upper metal contact was 4 μm , to suppress the higher order mode.

[N. Ueki et al., **Fuji Xerox**, IEEE Photonics Tech. Lett., 1999, 11(12), p. 1539]

High Power 730 nm AlGaAs Laser

High power operation of 730 nm AlGaAs lasers grown by MOCVD is reported. The devices demonstrated 1000 hours of reliable operation (average degradation rate of 5.4%) at a power of 1.0 W at room temperature for devices with a 100- μm emission aperture and 500 μm cavity length.

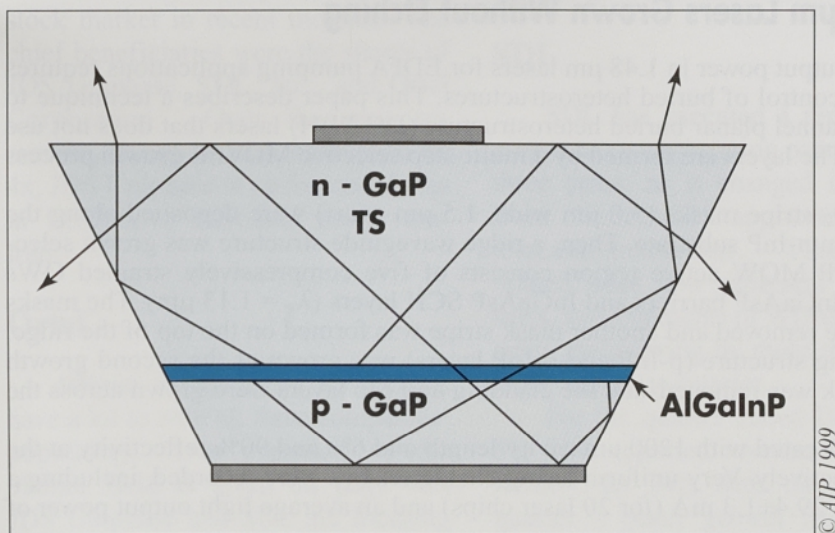
[R. Singh et al, **Polaroid**, Appl. Phys. Lett., 1999, 75(14), p. 2002]

Optoelectronic Devices

100 lm/W AlGaInP LEDs

Light extraction efficiency of AlGaInP LED chips is substantially improved by using a truncated-inverted-pyramid geometry (see Figure) to decrease the mean photon path-length within the crystal. Record performance for visible LEDs is achieved: peak efficiencies exceed 100 mW/lm at 100 mA and 300 K for orange emitters (610 nm), with a peak luminous flux of 60 lumens (350 mA, 300 K).

[M. Krames et al, **Agilent Technologies**, Appl. Phys. Lett., 1999, 75(16), p. 2365]



Schematic diagram showing means by which photons are redirected by internal reflection.

High Power 9.7 μ m AlGaAs QC Laser

An AlGaAs-based unipolar quantum cascade laser operating at a wavelength of 9.7 μ m and a temperature of 77 K. Peak output powers exceeded 1 W per facet, which has never previously been achieved for QC lasers at this wavelength. The threshold current density was 4.9 kA/cm² at 77 K with a slope efficiency of 240 mW/A, and the maximum operating temperature was 190 K.

[H. Page et al, **Thomson-CSF**, Elec. Lett., 1999, 35(21), p. 1848]

52 GHz Bandwidth Photoreceiver OEIC

This paper reports the monolithic integration of a 1.55 μ m InGaAs pin photodiode and a HEMT-based distributed amplifier, resulting in a photoreceiver OEIC with an optical/electrical (O/E) conversion factor of 105 V/W and a 3 dB-down bandwidth of 52 GHz. The device layers were grown by a single step MOVPE process on InP. The photodiode has a multimode waveguide structure, which provides high coupling efficiency without degrading the bandwidth.

[K. Takahata et al, **NTT Photonics Labs**, Elec. Lett., 1999, 35(19), p. 1639]

1.3 μ m Lasers Operating at 10 Gbit/s at 70°C

Reliable uncooled lasers operating at 1.3 μ m are attractive sources for low cost, high-speed data links, such as local area networks operating at up to 10 Gbit/s. High temperature direct modulation and transmission at 10 Gbit/s has been demonstrated at 1.3 μ m for the first time. The laser was a seven QW InGaAsP ridge waveguide device with a small signal -3 dB bandwidth of >10 GHz. Uncooled direct modulation at a data rate of 10 Gbit/s was achieved with an extinction ratio of >8 dB up to 70°C. Transmission over 2.2 km of singlemode fiber was demonstrated, with a total power penalty of 2.5 dB at an error rate of 10⁻⁹.

[A. Massara et al, **University of Bristol**, Hewlett Packard and Aston University (UK), Elec. Lett., 1999, 35(19), p. 1646]

198 W Laser Diode Array

A record high CW output power of 198 W is reported for a single monolithic laser diode array at 940 nm. This wavelength is required for pumping Yb:YAG solid state lasers. The InGaAs/AlGaAs lasers were grown by MOCVD on GaAs. The 1-cm wide array had a total emitting aperture of 4800 μ m, was bonded to a water-cooled copper heatsink and was operated at 240 A with a junction temperature of 100°C. This array had an extrapolated lifetime of 1-4x10⁴ hours at 60 W CW and 31°C. An array with a 2850 μ m emitter aperture demonstrated a record electrical-to-optical power conversion efficiency of 62%.

[X. He et al, **Opto Power**, Elec. Lett., 1999, 35(20), p. 1739]

RT operation of a Type-II Interband Laser at 3.3 μ m

Pulsed operation at room temperature of an electrically pumped interband mid-IR laser above 3 μ m is reported for the first time. The devices emitting at 3.30 μ m employed a type-II 'W' quantum well design with a broadened waveguide. The spectral width at 300 K was 12 nm and the peak output power was 2 mW/facet. The characteristic temperature for the range 100-280 K was 48 K. The MBE-grown devices had active regions containing either 5 or 10 wells of InAs/In_{0.25}Ga_{0.75}Sb/InAs/AlGaAsSb in each period.

[H. Lee et al, **Sarnoff Corp., Naval Research Labs and Sensors Unlimited**, Elec. Lett., 1999, 35(20), p. 1743]

High Power, 1.3 μm GaInNAs CW Lasers

• 1.29 μm GaInNAs/GaAs lasers with a threshold current of 680 A/cm² and a maximum output power of 2.4 W for CW operation at room temperature have been demonstrated. These values are a significant improvement over previously published results. The laser, grown by RF-plasma MBE, had an active region consisting of three 6 nm GaInNAs QWs separated by 20 nm barriers, within a 300 nm undoped GaAs cavity.

For broad area lasers ($W = 100 \mu\text{m}$, $L = 1120 \mu\text{m}$), the slope efficiency at 10°C was 0.59 W/A and an output power of 4 W was recorded for pulsed operation. The maximum CW power was 2.4 W at about 7 A. For narrow stripe-width lasers ($W = 3.5 \mu\text{m}$, $L = 350 \mu\text{m}$), a threshold current of 21 mA and a slope efficiency of 0.25 W/A were recorded at RT. Lasing operation was maintained at 100°C. The T_0 value was 110 K for a 700- μm long device, while values around 70 K are typical for 1.3 μm InGaAsP-based lasers.

[A. Egorov et al, **Ioffe Institute and Infineon Technologies**, Elec. Lett., 1999, 35(19), p. 1643]

• A lifetime of 1,000 hours was demonstrated for a 1.3- μm GaInNAs laser grown by GSMBE. The device had a characteristic temperature of 214 K in the 20-80°C range. Under auto-current-control conditions with a current of 130 mA and an output power of 1.7 mW, no degradation was observed and the threshold current density decreased by 14% (3.7 kA/cm² to 3.2 kA/cm²). Likewise, degradation was not observed under auto-power-control conditions at 50°C and 1.0 mW.

[M. Kondow et al, **Hitachi**, Jpn. J. Appl. Phys., 1999, Vol. 38, Part 2 (12A), p. L1355]

• 1.3 μm GaInNAs/GaAs double quantum-well ridge stripe lasers grown by MOCVD are reported. A threshold current density of 1.0 kA/cm² was measured at 20°C and the characteristic temperature (T_0) was 148 K at 20-80°C.

[Sato and Satoh, **Ricoh**, IEEE Photonics Tech. Lett., 1999, 11(12), p. 1560]

RT Operation of 1.3 μm Quantum Dot Lasers

• Room temperature CW operation of a 1.3 μm InGaAs/GaAs quantum dot laser with a single layer active region. The threshold current was 4.1 mA for a stripe width of 9 μm , and the threshold current density was 45 A/cm² with an output power of approximately 150 mW.

[G. Park et al, **University of Texas at Austin**, Appl. Phys. Lett., 1999, 75(21), p. 3267]

• CW operation at 17°C of a quantum dot laser in the 1.26-1.28 μm wavelength range. The active layer contains three planes of InAs QDs covered by thin InGaAs layers, to prevent gain saturation. The threshold current density was 90-105 A/cm² for a 200- μm stripe width and the output power was 2.7 W.

[A. Zhukov et al, **Ioffe Institute and T.U. Berlin**, IEEE Photonics Tech. Lett., 1999, 11(11), p. 1345]

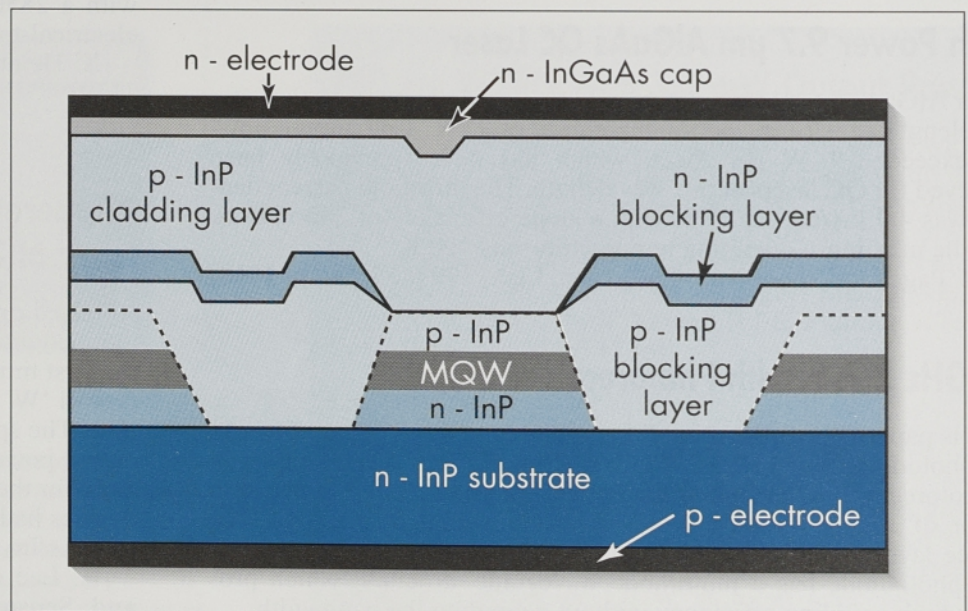
260 mW, 1.48 μm Lasers Grown Without Etching

Achieving high output power in 1.48 μm lasers for EDFA pumping applications requires precise dimension control of buried heterostructures. This paper describes a technique to fabricate double channel planar buried heterostructure (DC-PBH) lasers that does not use etching processes. The layers are formed by a multi-step selective MOVPE growth process (see figure).

Initially, two SiO₂ stripe masks (5.0 μm wide, 1.5 μm apart) were deposited along the [011] direction of an n-InP substrate. Then, a ridge waveguide structure was grown selectively. The InGaAsP MQW active region consists of five compressively strained QWs ($l_g = 1.2 \mu\text{m}$) with InGaAsP barriers and InGaAsP SCH layers ($\lambda_g = 1.13 \mu\text{m}$). The masks in the channels were removed and another mask stripe was formed on the top of the ridge. The current blocking structure (p-InP and n-InP layers) was grown as the second growth step. The ridge mask was removed, and the cladding and cap layers were grown across the whole structure.

Devices were fabricated with 1200 μm cavity length and 6% and 90% reflectivity at the front and rear respectively. Very uniform lasing characteristics were recorded, including a threshold current of 29.4 ± 1.3 mA (for 20 laser chips) and an average light output power of 262 ± 1.4 mW at 1 A.

[Y. Sasaki et al, **NEC**, IEEE Photonics Tech. Lett., 1999, 11(10), p. 1211]



The ridge waveguide structure was grown selectively up to the dashed line. A mask was then deposited on top of the ridge to allow selective growth of the current blocking layers. Finally, the cladding and cap layers were grown across the whole structure.

Red Hot Optoelectronics

MARIE MEYER

There is much discussion in this issue's news section and cover story about the strengths of the fiber optic industry. All of this excitement was also clearly visible in the stock market in recent months. The chief beneficiaries were the shares of JDS Uniphase, SDL, Inc., and Ortel Corporation. Over the past six months, shares in SDL have risen by 4x, JDS Uniphase is up 5x, and shares in Ortel have increased nearly ten-fold.

Ortel

980nm pump lasers for EDFAs have a lot to do with all three companies' popularity. (An overview of the 980nm field is given on page 76.) JDS Uniphase and SDL are focusing on high power Fabry Perot (FP) lasers. JDS Uniphase recently added new capacity for packaging their own chips, whereas SDL supplies them in chip form only. Ortel, on the other hand, is focusing on low cost, low power, uncooled distributed feed back (DFB) pump lasers, and recently landed a contract to supply chips for Lucent's new EDFAs for metro applications (see page 9). At this time, it appears that Ortel has this niche all to itself. But it should be noted that there are some skeptics who doubt that the metro WDM market will expand in the near-term.

This contract may serve as an endorsement for Ortel's new management and strategic focus. "We believe this is a very strong validation that Ortel is successfully transitioning into higher growth opportunities in telecom markets as opposed to their traditional CATV focus," said James Jungjohann of CIBC World Markets.

"Lucent is a profile win and offers renewed credibility to Ortel." It is possible that this contract may lead to other opportunities with Lucent, such as 10 Gbps transmitters and receivers.

SDL

SDL has executed a remarkable corporate re-engineering over the past three years, as it changed its focus from industrial applications to telecommunications. Fiber optic related sales now represent 75% of sales, and shipments of WDM components are growing by more than 40% from quarter-to-quarter.

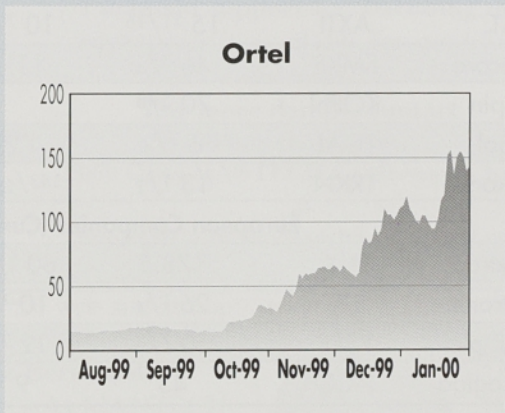
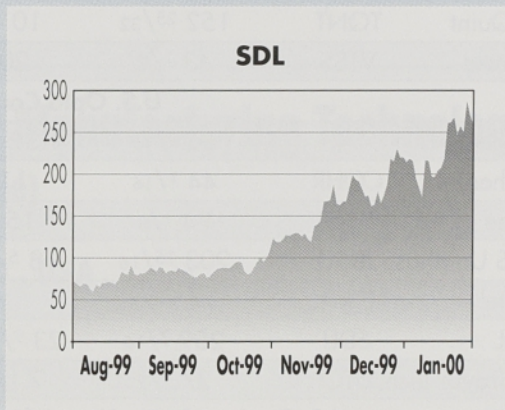
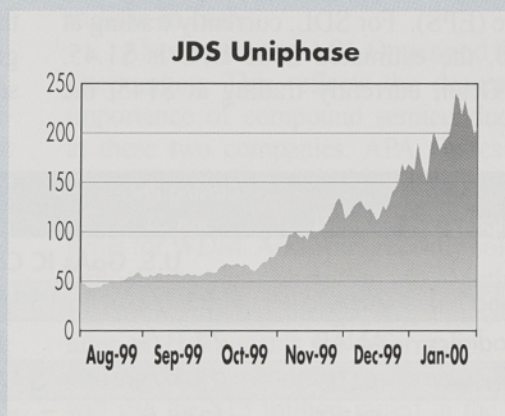
For the quarter ended December 31, SDL reported revenue of \$58.7 million, up 24% over the previous quarter - better growth than either Ortel or JDS Uniphase. Alcatel is SDL's largest customer; both Corning and JDS Uniphase also account for more than 10% of the company's sales. Income for the quarter was a record \$12.0 million, an increase of 282% compared to the fourth quarter of 1998, and up 45% from the preceding quarter.

JDS Uniphase

Following an aggressive mergers and acquisitions strategy, JDS Uniphase has become the largest supplier of fiber optic components (see page 6). In this market, captive suppliers, like Lucent and Nortel, account for about one-half of component output. So one wonders who is left to be acquired among the other merchant (independent) suppliers who account for the other half.

Rumours are rife that the next target will be either SDL or Ortel. SDL

Opto Enthusiasm Share Prices - Last Six Months



shares soared more than 15% to a new high of \$287 on January 27 as the story was circulated that a deal would be struck over the weekend. The companies themselves did not comment, and the following day brought a massive market-wide correction, caused by fears of an interest rate hike. This seems to have squelched the speculation for now. But for how long?

Superficially, it seems inevitable that both SDL and Ortel will be added to the JDS Uniphase fold. But there are also some indications to the contrary. Both SDL and Ortel have a share price that is very high compared to their earnings per share (EPS). For SDL, currently trading at \$260, the estimated 2000 EPS is \$1.45. For Ortel, currently trading at \$145, the

estimated 2000 EPS is \$0.10. Add in the fact that acquisitions usually come at a premium over the current share price, and it may be hard to demonstrate how the deal would improve JDS Uniphase's bottom line. There is also the fact that a JDS Uniphase/SDL combination may run afoul of antitrust concerns. This does not appear to be a concern in the case of Ortel.

It seems that all three companies have latched onto the best growth opportunity in the communications industry. Their share prices may never soar again as they have in the past six months. However, the recent market correction notwithstanding, they are all three likely to enjoy impressive growth in the future - whether together or separate.

The Compound Semiconductor Portfolio Expands

In this issue we introduce the new list of companies that are tracked in the Compound Semiconductor Portfolio. As before, our only criteria for inclusion is that the company receive a significant portion of its revenues from compound semiconductor-related activities.

Agilent Technologies

The first new addition is Agilent Technologies, the company that was spun-out of Hewlett-Packard last year. Agilent conducted its IPO on November 18, 1999, raising \$2 billion for approximately 16% of its equity. This was the largest IPO in the history of Silicon Valley. Hewlett-Packard still owns the remainder of the company, and will distribute the Agilent shares to Hewlett-Packard shareholders in the second half of this year.

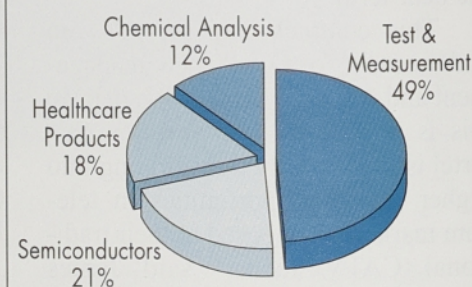
Agilent has four main product areas - see chart, below. Their Semiconductor Products Division, which had revenues of \$1.72 billion in 1999, is one of the leading manufacturers of compound semiconductor devices. Strategies Unlimited believes them to be the largest optoelectronic components manufacturers in the world. Agilent is widely recognized as an innovator in LED technology, and Strategies Unlimited reports that they are the largest manufacturer of visible LEDs in the world, with more than 15% of the market. They are also a major manufacturer of fiber optic communications components. For the datacom field, they

Company	Symbol	Closing Price Jan 31	52 Week Low-High	Market Cap*	P/E Ratio**
U.S. GaAs IC Companies					
Alpha Ind.	AHAA	83 3/4	13 1/2 - 100 1/8	1.636B	65.79
Anadigics	ANAD	77 11/16	13 - 85	1.412B	N/A
Celeritek	CLTK	23 15/16	3 5/8 - 30 3/4	178.5M	N/A
Conexant	CNXT	84 1/2	7 13/16 - 90 1/4	16.472B	144.17
RFMD	RFMD	81	15 7/16 - 95	6.429B	143.06
TriQuint	TQNT	152 25/32	10 5/16 - 163	2.826B	147.25
Vitesse	VTSS	43 1/2	20 3/8 - 58	6.830B	91.62
U.S. Opto Companies					
Agilent	A	66 3/16	39 13/16 - 80	29.917B	50.42
Coherent	COHR	44 1/16	11 5/8 - 62	1.085B	92.19
Cree	CREE	94 1/8	15 1/8 - 112	2.777B	197.06
JDS Uniphase	JDSU	203 15/16	18 5/8 - 248 1/2	58.494B	N/A
Ortel	ORTL	143 5/8	6 - 171	1.788B	N/A
SDL	SDLI	259 3/16	23 9/16 - 288 1/2	9.167B	403.36
Uniroyal Tech.	UTCI	27 1/2	7 1/4 - 30 1/2	326.7M	68.30
U.S. Semiconductor Materials & Equipment Companies					
ATMI	ATMI	34 3/4	16 7/8 - 38 3/16	910.5M	106.87
AXT	AXTI	15 11/16	10 7/8 - 36 3/16	293.7M	33.47
Emcore	EMKR	46 3/4	11 1/4 - 64 5/8	634.2M	N/A
Kopin	KOPN	70 3/8	6 - 83	2.105B	N/A
Tegal	TGAL	6 1/4	2 - 13 1/2	67.4M	N/A
Trikon	TRKN	13 1/2	153/256 - 15 25/64	127.0M	N/A
European Companies (Currency Data in Euros)					
Aixtron	AIX	178.5	60 3/4 - 178 1/2	2.75B	277
Filtronic	FTC	26 1/4	10 1/2 - 34 5/8	2.1B	72.56
IQE plc	IQEP	50 7/8	12 1/2 - 51 3/8	694M	>100
Picogiga	PICO	43	9 15/16 - 49	67.8M	48

*Market Capitalization = # shares x current share price

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

Agilent Technologies 1999 Revenues - \$8.3 Billion



manufacture a variety of VCSEL and LED-based transceivers. In the telecom area, Agilent has an important manufacturing operation in the United Kingdom. Known as the Fiber Optic Component Operation, it was acquired in 1993 from British Telecom. It includes an InP laser diode manufacturing facility in Ipswich, England. And although we classified them as an "opto" company in our table (see left), Agilent also has a prominent Wireless Semiconductor Division that manufactures GaAs RFICs & MMICs.

Filtronic

Our newest European member is Filtronic plc., which is based in Bradford, England. The company is well known as a manufacturer of microwave components and subsystems. In August 1998 they acquired Litton's Solid State Division, based in Santa Clara, CA. It is now known as Filtronic Solid State (FSS). Their operations include a GaAs/InP fab specializing in 0.25 micron InGaAs PHEMT MMICs for applications up to 40 GHz.

Filtronic is currently in the process of building a new 6-inch GaAs fab at Newton Aycliffe, County Durham, England. The fab will occupy a 310,000

sq. ft. facility that was originally built by Fujitsu for silicon DRAM manufacturing. Filtronic intends to utilize the materials technology and design expertise developed at FSS to establish volume GaAs PHEMT fabrication at the Newton Aycliffe facility. The new fab will support a high volume merchant GaAs ICs business as well as captive chip making for integrated modules that Filtronic is developing for the mobile handset market. When the new fab is completed it will likely be one of the largest GaAs fabs in the world.

Tegal & Trikon

We have also added two new semiconductor equipment companies to the list. The first is Tegal, a manufacturer of plasma etch systems. The company does not disclose the details of its revenue mix according to process technology. However, they do say that GaAs is now "as important as silicon" for their sales to the semiconductor industry. The company was formed in December 1989 via the spin-off of the former Tegal division of Motorola.

The other new equipment company is Trikon. They are traded as a U.S. company, but their operations are based in

Wales. This makes Wales the second-most well represented country in the Portfolio, after the U.S., because it is also home to IQE! Trikon manufacturers systems for CVD, sputtering, and etch applications. They indicate that the GaAs industry currently accounts for around 25% of their revenues.

APA Optics, Plasma-Therm & Spire

There are also three companies that are leaving the Portfolio. The first is Plasma-Therm, which was recently acquired by Oerlikon-Bührle (Balzers' parent company) for approximately \$150 million in cash.

Also leaving are APA Optics and Spire Corporation. This reflects the decreasing importance of compound semiconductors at these two companies. APA Optics has changed its focus from wide bandgap semiconductor development to passive components for WDM. And Spire recently sold its Optoelectronics operation to Methode Electronics, Inc. (Chicago, IL), a manufacturer of components for information processing and networking equipment. Spire will use the \$13 million raised in the sale for investment in its photovoltaics equipment and biomedical operations.

2000 International Conference on Gallium Arsenide Manufacturing Technology

(2000 GaAs MANTECH Conference)

May 1-4, 2000

Omni Shoreham Hotel, Washington, D.C., USA

<http://www.gaasmantech.org>

In its 15th year serving the compound semiconductor community, the 2000 GaAs MANTECH Conference will address "*Compound Semiconductor Manufacturing into the New Millenium*" with sessions including manufacturing, processing, test & reliability, device technologies, materials and packaging as well as a look at technology and business trends in the industry.

Our host city will be Washington, D.C., where we will again sponsor a Workshop on the day before the conference covering topics ranging from HBT reliability and failure analysis techniques to DOE and SPC basics.

Conference sessions will cover the following areas:

**MANUFACTURING
PROCESSING
TEST & RELIABILITY
DEVICE TECHNOLOGIES
MATERIALS
PACKAGING
COMPETING TECHNOLOGIES
The FUTURE** - business outlook, trends, new paradigms.

Attention Students!

Financial support for attending the conference is available for qualified students.

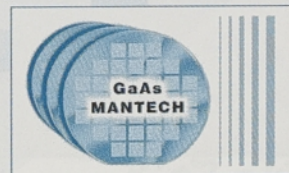
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