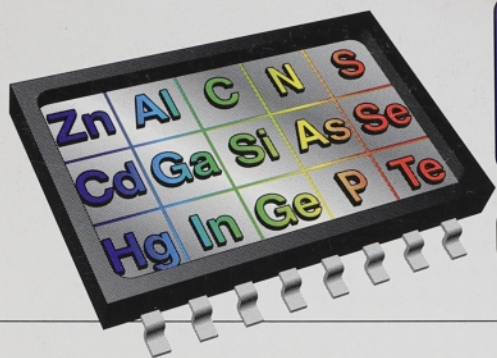




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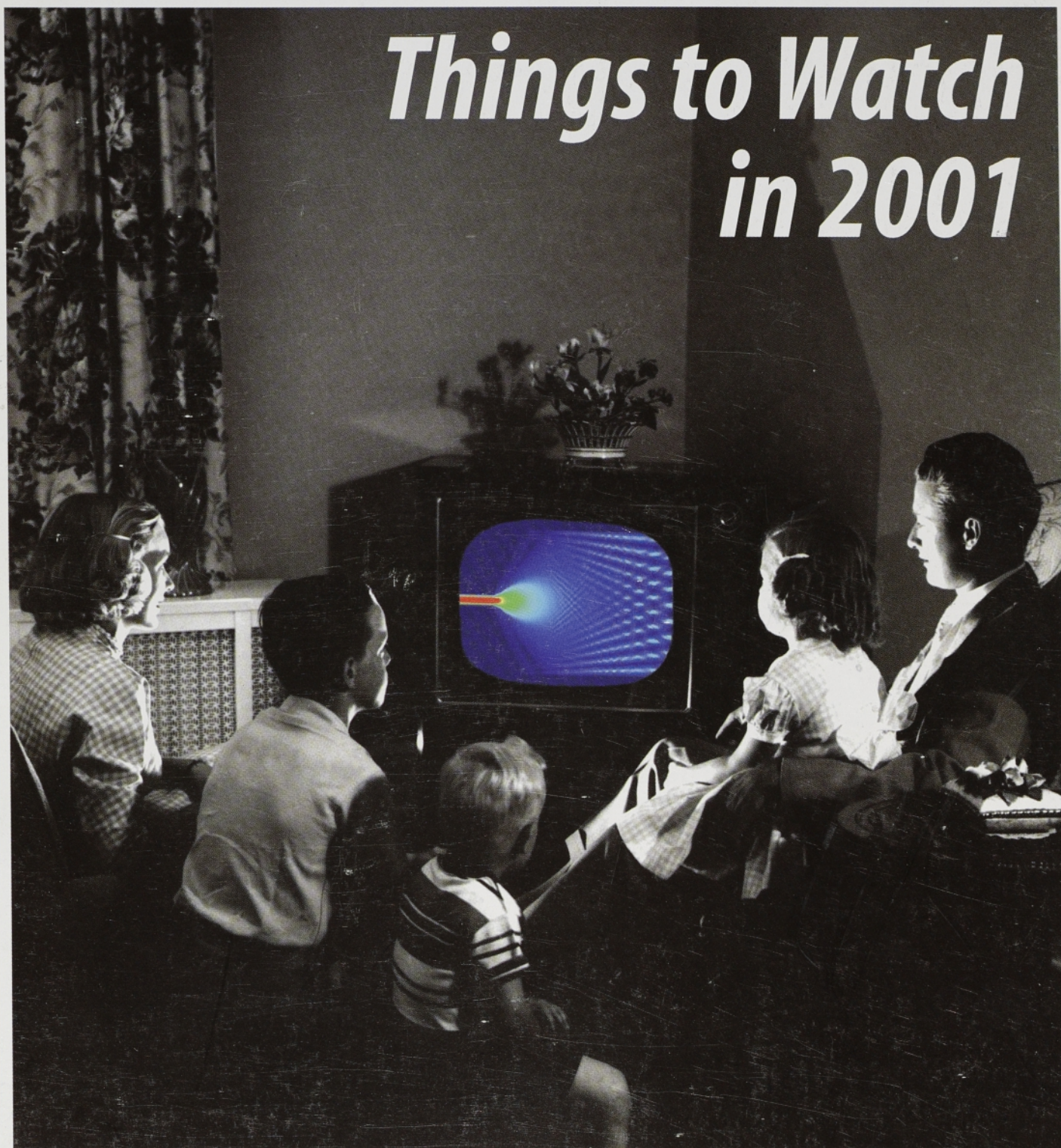
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Will develop testing and screening procedures for optoelectronic products for telecommunications market. Analyze test data for laser diode products and perform failure mode analysis. Specify requirements for test, burn-in, and life-test equipment.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

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

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

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

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

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

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

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

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

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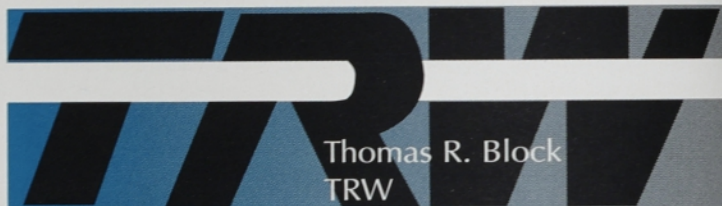
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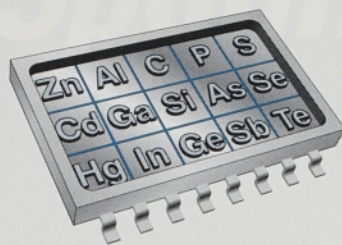
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*Things to Watch
in 2001*

Twelve technologies come under scrutiny in our annual Things to Watch feature. The TV is screening the latest InP integration scheme. Coverage begins on page 45.

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The Fraunhofer Institute for Applied Solid State Physics is a leading German institute for compound semiconductor research.

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NEC Divests Optical and Microwave Operations

NEC is to divest its optical semiconductor operations together with its microwave compound semiconductor and silicon activities into a new company, to be formed in October 2001. NEC identifies these devices as key enablers of broadband and mobile networking equipment—the move is aimed at reinforcing NEC's position as global leader in this area while maximizing the overall corporate value of the NEC Group, says the company.

The new spin-off is expected to generate first year sales of ¥120 billion (\$1.02 billion) and will employ around 500 people. NEC will exercise 100% ownership and intends to take the as-yet unnamed company to an initial public offering within two years.

Device R&D will be located at a facility within the NEC Kansai plant in western Japan and at Tsukuba City, Ibaraki Prefecture. NEC says this will allow the new company to achieve a highly integrated research, development and production organization, and believes this will treble sales of optical and microwave devices from ¥100 billion (\$852 million) in fiscal year 2000 to ¥300 billion (\$2.55 billion) by 2005.

NEC is one of the world's largest manufacturers for optical networking components, including 2.5 and 10 Gb/s laser diodes

and InGaAs detectors for WDM applications, in addition to GaAs-based microwave RFICs used in wireless handsets and a range of other applications. According to Japan's Nihon Keizai Shimbun newspaper, sales of NEC's optical and microwave chips for high-speed communications currently account for around 9% of the world market.

NEC says it will also consider additional investment in California Eastern Laboratories (CEL), a company based in Santa Clara, California that represents NEC in the North American market. The new semiconductor firm will also select foundry partners in Japan and Taiwan and investigate opportunities with optical semiconductor companies.

NEC Develops SiGe RF Transistor

In more news, NEC has begun shipping samples of a high-performance SiGe PA for use in W-CDMA cell phones and multimedia devices. The chip achieves a noise factor of 0.9 dB and a power gain of 14.5 dB, 60% higher than conventional silicon transistors. The sample price is 27 cents, and the company will launch production at 2.5 million units per month in April, ramping to 30 million units per month by the end of 2001.

NTT Electronics Builds WDM Device Plant

NTT Electronics has constructed a manufacturing plant in Naka, Ibaraki Prefecture for WDM devices at a cost of ¥14 billion (\$12 million). With a total floor space of 20,000 m² (~215,000 sq.ft.), the plant will produce WDM devices, semiconductor lasers and other components for supply to major communications equipment makers including Lucent Technologies. One of the largest of its kind, the factory expands the company's WDM device production capacity by 300–400%. NTT Electronics is 86% owned by the NTT group and posted sales of ¥28.3 billion (\$240 million) in the year ended March 2000.

Manufacturers Boost Compound Semiconductor Output

Japanese compound semiconductor makers plan to boost output in response to rising demand from manufacturers of optical communications equipment, cellular phones and DVD players, according to industry sources. **Showa Denko KK** has provided more details of its recently announced ¥3 billion (\$25.6 million) investment to more than triple capacity of InP substrates and epiwafers at its plant in Chichibu, Saitama Prefecture [see

CS 6(7), p. 37]. The company says it will build a production facility for InP wafers at the plant and is targeting a monthly output capacity of 2,200 units by the end of 2001.

Anritsu says it plans to triple output capacity of semiconductor laser parts for fiber-optic communications equipment by fiscal year 2003. The company, which currently turns out 10,000 units a month, aims to meet rising demand from networking manufacturers for WDM systems.

Matsushita Reduces Gate Leakage in GaN Devices

Matsushita (Kyoto, Japan) has developed a wafer insulating technology for GaN that reduces the gate leakage current by a factor of one hundred compared to the level attained when separating devices by dry etching. The technology allows a selected area on a wafer surface to be heated to 900°C in an oxygen atmosphere. This creates an oxidized 6-μm-thick insulating layer between devices, and results in a leakage current between the devices of only 65 pA—six orders of magnitude smaller than the level of conventional systems when a voltage of 30 V is applied. At 400 V, the leakage current reaches just 1 μA. The technology will pave the way for the development of small, high-output cell phone base station PAs, says Matsushita.

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PlayStation 2 Ships 11 million Units

Sony's new PlayStation 2 gaming console shipped 4 million units in Japan in 2000, and cumulative global sales are expected to reach 11 million units by the end of March. The console features a DVD player, meaning that PlayStation 2 has made a significant contribution to the DVD laser market. The original PlayStation, which shipped 76 million units worldwide, was a CD-ROM-based system. Another interesting feature of the PlayStation 2 is that it features nitride-based LED indicator lights manufactured by Cree.



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Japan Aviation's Touch Panel Halves LED Requirements

Japan Aviation Electronics Industry of Tokyo has developed an LED touch panel that requires half the usual number of LEDs and photodetectors. This development leads to simplified drive circuitry and makes the panel more compact, in addition to reducing the manufacturing costs by about 30%. In a typical optical-based touch panel, LEDs are located all around the periphery of the panel, with photodetectors placed directly opposite each LED. When a finger touches the panel, light is blocked from a particular LED, and this information is used to determine its position on the screen. With the new design, a reflective plate is placed opposite the LEDs to bounce the light back to the photodetectors, which are located on either side of each LED. This setup requires only half the number of optical devices, which only need to be located on two sides of the panel, instead of all four. So far the company has used the technology to develop a reflective optical touch panel with a screen size equal to a 6.5 inch LCD, and has plans to market the device for car navigation systems.

Northrop Grumman to Acquire Litton Industries

Northrop Grumman will acquire Litton Industries in a transaction valued at approximately \$5.1 billion. Litton is a leading supplier of advanced electronics and information systems, and is the premier designer and builder of non-nuclear surface warships. Northrop Grumman provides systems integration, information technology and defense electronics—the two companies each employ in the region of 40,000 staff.

Northrop Grumman operates a GaAs foundry activity at its Advanced Technology Center in Baltimore, MD and has also developed SiC microwave devices for radar systems. Litton's Airtron subsidiary is a leading supplier of semi-insulating GaAs substrates and also supplies SiC wafers. However, we don't believe that compound semiconductor-related activities were a major factor in the acquisition.

Osram Enhances Brightness of Blue InGaN LEDs

Osram Opto Semiconductors (Regensburg, Germany) has unveiled a new chip designed to enhance the out-coupling of light from its blue GaN/InGaN LEDs.

Known as ATON, the chip achieves twice the brightness of Osram's standard device and attains a level of 5 mW at 20 mA in 5 mm lamps. Osram introduced the new chip to market early in 2000. Since production began in August/September, the company says it has improved brightness levels to 8 mW. Osram has also licensed the new technology to Cree, which transferred the technology to its operations between June and September.

The new process is based on a patent-pending technology that improves the external light extraction by optimizing the geometry of the chip. The inclined facets avoid total internal reflection, compensating for the higher refractive index of SiC as compared to sapphire substrate materials [see CS 6(8), p. 81].

According to Volker Härle, who heads up InGaN development, the light extraction is improved as a result of an increase in the overlap of incident rays with the out-coupling cone through the inclined substrate facets, which results in

a drastic increase of the sideward light extraction. The side emission of the ATON chip efficiently illuminates the reflector of Osram's standard packages (see Figure 2). Härle says this leads to an almost doubling of brightness for the same current and no epitaxial changes, and is applicable for all of the company's visible GaN/InGaN chips. "ATON is also compatible with Osram Opto Semiconductors' standard mounting and packing technology," he says.

The new design has also been optimized for mechanical stability and features new packaging adhesives and improved thermal and electrical resistance. In addition, light extraction analysis has been applied to the chip using simulation tools such as ray-tracing techniques.

"Osram Opto Semiconductors' new ATON technology allows the compensation of the disadvantages of SiC substrates compared to sapphire," Härle continues. "Therefore, the new process enables us to close the brightness gap of the InGaN

LEDs to other competitor devices based on sapphire."

Things to Watch: High Brightness LEDs for Lighting

Beginning on page 50, we describe a number of the issues facing the LED lighting industry as it works towards the long-term goal of capturing a significant part of the general illumination market. We discuss the requirements of the lighting industry, the issues involved with creating white light using LEDs, and the specific challenges faced by manufacturers of both AlInGaP- and InGaN-based LEDs.

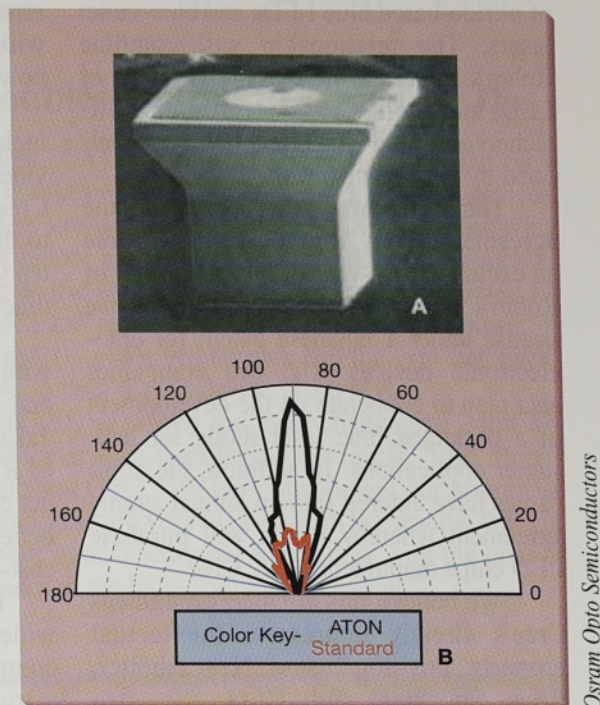


Figure 1. (A) Osram's ATON chip consists of angled facets that increase the light extraction efficiency by reducing total internal reflections; (B) comparison of the far field characteristics for standard and ATON chips in a 5 mm lamp.

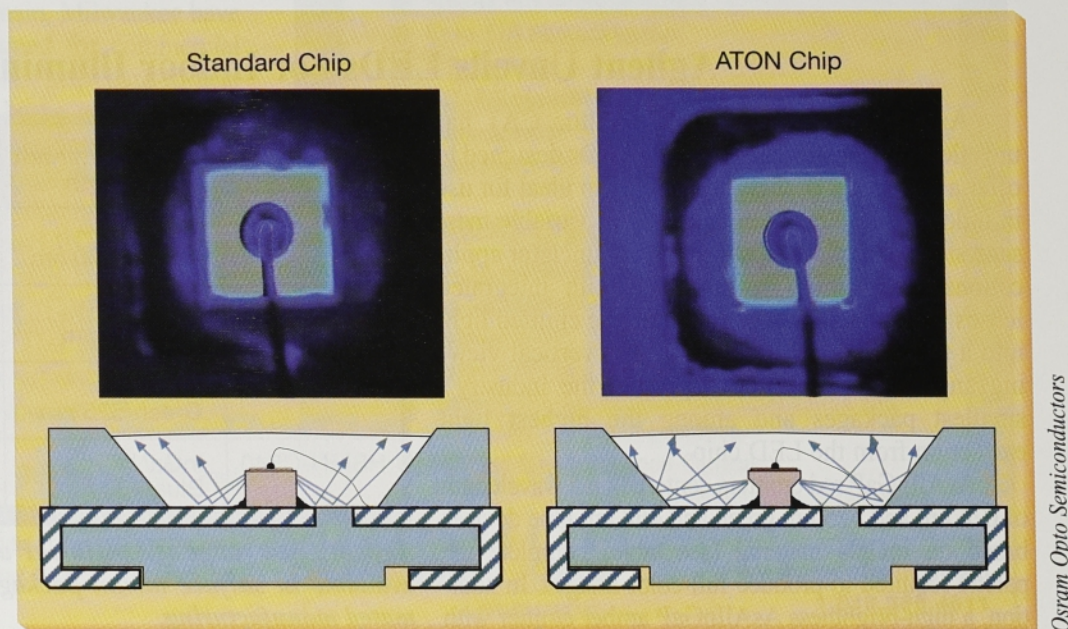


Figure 2. Comparison of the illumination of the standard device and an ATON chip.

Cree and Rohm Form Blue LED and Laser Alliance

In mid-December, Cree (Durham, NC, USA) and Rohm Co., Ltd. (Kyoto, Japan) announced an alliance in the field of nitride-based blue LEDs and blue-violet lasers. The relationship will combine Rohm's expertise in mass-production of LEDs and lasers, Cree's world-leading SiC technology, and GaN technology developed by both companies.

There are three main aspects to the agreement: firstly, Rohm has granted Cree an exclusive five-year license to several of Rohm's U.S. patents and a non-exclusive license under a Japanese patent for optoelectronic devices. The two companies also plan to cooperate on the development of a packaged blue laser diode for consumer applications. In addition, the companies have entered into an annual supply agreement whereby Rohm will purchase LED chips manufactured by Cree.

"We believe this alliance strengthens Cree's already impressive intellectual property position," said Neal Hunter, Cree chairman and CEO. "It also launches yet another new phase in Cree's laser diode development efforts. As a result of this alliance, Cree could potentially reduce the time to market of a commercially viable laser device. Given Rohm's packaging experience and market leadership in optoelectronics, the alliance

may be particularly beneficial to Cree's laser diode plans in the consumer arena for DVD type applications." Cree recently reported a blue InGaN-on-SiC laser diode with a lifetime of around 100 hours at a power level of 1–3 mW.

"Although the alliance does not include joint LED development, it provides yet another customer relationship for Cree's LED chip product line, comparable to those we have established over the past ten years with other LED component manufacturers in Japan," added Hunter.

"Cree has made tremendous advances with their SiC technology and GaN LED and laser diode devices," said Hidemi Takasu, director and member of the board of Rohm. "Combined with Rohm's product capabilities and market knowledge, we believe we are well positioned to introduce cost-effective products."

Rohm is one of the top 10 worldwide manufacturers of optoelectronic components, but does not currently offer nitride-based devices, despite having developed GaN technology. This is believed to be due to the ongoing patent dispute in Japan between Nichia and Toyoda Gosei. According to an article that appeared in Japan's Nikkei Industrial Daily newspaper, Hidemi Takasu commented on Rohm's decision to enter

the market at this time. "With global development competition growing more severe, we simply didn't want to wait for a decision in the domestic lawsuit," he said. Takasu also stated that Rohm and Cree are in active discussions to ensure that their manufacturing methods do not infringe on Nichia's patents.

Rohm Sues Nichia

At the same time as the Rohm-Cree alliance was announced, Rohm filed a lawsuit against Nichia to protect the patents that were licensed to Cree. Rohm stated that it has filed patent infringement lawsuits against Nichia and Nichia America Corporation in the U.S. International Trade Commission (ITC) and the U.S. District Court for the Eastern District of Pennsylvania. In its complaints, Rohm alleged that Nichia is infringing its U.S. Patents 6,084,899 and 6,115,399 by manufacturing and selling certain GaN-based LED products. The district court lawsuit seeks damages and injunction against infringement. The subject of the patents is a structure that allows high-brightness devices by lowering the operating voltage in light emitters such as GaN-based blue LEDs and GaN-based blue-violet semiconductor lasers.

Agilent Unveils LEDs For Indoor Illuminated Signs

Agilent Technologies (Palo Alto, CA) has unveiled a series of surface-mount LEDs designed to offer a wide field of view, making them ideal for use in indoor full-color illuminated signs, variable message signs and related display and annunciator applications. The lamps are equipped with integrated lenses and reflectors to concentrate the emitted light into a typical 100° horizontal by 40° vertical viewing angle. These emitters represent the industry's smallest packages and among the highest light extraction from the LED chip.

AsAlInGaP red emitters centered on a wavelength of 626 nm and 525 nm green and 468 nm blue devices based on InGaN material (see table) complete the palette required to produce full-color images. In addition, a high-brightness AsAlInGaP amber emitter with

Part Number	Color/Dominant Wavelength	Luminous Intensity Iv (mcd)	Price (5,000,000 pc.)
HSMA-C540	AsAlInGaP Amber/590 nm	160 typ.	\$0.13
HSMC-C540	AsAlInGaP Red/626 nm	210 typ.	\$0.13
HSMM-C540	InGaN Green/525 nm	230 typ.	\$0.58
HSMN-C540	InGaN Blue/468 nm	55 typ.	\$0.58

Agilent's new range of AsAlInGaP and InGaN LEDs for indoor signage are available in surface mount packages and designed for high speed automated manufacturing.

a wavelength centered on 590 nm produces a color preferred for single-color variable message signs. All patterns are optically matched.

Agilent's surface-mount LEDs are designed for high-speed automated manufacturing technology. The 2.0 mm × 1.25 mm package matches an industry standard size

for many chip capacitors, making it compatible with available automated pick-and-place equipment. The package is also compatible with infrared and convective reflow soldering processes used in automated assembly, and is available on 8 mm tape on 180 mm (7-inch) diameter reels containing 3,000 units.

More Patent News

At the end of November, **Nichia** won a second ruling against **Toyoda Gosei** in the long-running dispute over nitride-based LEDs. Toyoda Gosei has apparently already stopped manufacturing and selling the disputed products, and filed an appeal against the ruling on the same day.

On December 21, **Nichia** filed counterclaims for patent infringement and trade secret theft against **North Carolina State University (NCSU)**, **Cree Inc.**, and **Shuji Nakamura**. The claims were filed in the U.S. District Court for the Eastern District of North Carolina, and include the U.S. Patents 5,306,662, 5,578,839, 5,747,832 and 5,767,581. The patents and trade secrets cover methods of manufacturing and designs for GaN-based LEDs, laser diodes and electronic devices.

Shuji Nakamura, who was largely responsible for the development of commercial nitride-based LEDs and lasers while employed at Nichia, is now a professor at the University of California at Santa Barbara and a part-time employee of Cree. The inclusion of Nakamura in the new lawsuit indicates Nichia's belief that Nakamura may have leaked trade secrets to Cree. This latest lawsuit comes in retaliation to an action brought by Cree and NCSU in September against Nichia over a patent covering lateral overgrowth technology [see CS 6(7), p.19].

LEDs Aid Healing Process

Doctors at the Medical College of Wisconsin, Milwaukee have discovered that LEDs, originally designed for commercial plant growth research in space by NASA, help hard-to-heal wounds, such as diabetic skin ulcers, serious burns, and severe oral sores caused by chemotherapy and radiation. The project includes laboratory and human trials, approved by the U.S. Food and Drug Administration and funded by a NASA SBIR contract.

"The near-infrared light emitted by these LEDs seems to be perfect for increasing energy inside cells," said Harry Whelan, professor of pediatric neurology and director of hyperbaric medicine at the Medical College of Wisconsin. "This means whether you're on Earth in a hospital, working in a submarine under the sea or on your way to Mars inside a spaceship, LEDs boost energy to the cells and accelerate healing."

The wound-healing device is a small, 3.5 inch × 4.5 inch portable flat array of LEDs, which can be applied directly to the patient's cheek, for about one minute per day. The red light penetrates to the inside of the mouth, promoting wound healing and prevent further sores.

AXT Doubles Output of Green LEDs

AXT (Fremont, CA) has introduced green LEDs that have twice the output power of the company's existing devices. The new emitters are designed to compete in rapidly growing high brightness indoor and outdoor display applications such as video displays, traffic signals and commercial signs. Based on AlInGa_N, the 525 nm green LED has a typical output power of 1.5 mW at 20 mA (D-grade brightness), and the expected packaged lamp power output for the device is 3.0 mW.

"The green LED is among the most challenging AlInGa_N devices to produce at such high brightness levels," said Morris Young, president and CEO. "We have quadrupled our brightness in only six months and are very pleased with the results. We will continue to invest in advancing our technology with the goal of becoming a leader in the high-brightness segment."

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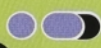
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Injection Molding Gives Global Light Industries an Edge

TIM WHITAKER

Global Light Industries GmbH, a German manufacturer of high brightness LEDs, is tapping into a growing demand for customer-specific LED solutions. One of the reasons for its growing success is the use of an injection molding technique to encapsulate its own LED chips. Global Light manufactures high brightness LEDs across the full visible range, using nitride-based devices for the blue and green emitters and AlInGaP technology for longer wavelengths.

Global Light has around 65 staff and is located in a new technology park at Kamp-Lintfort, Germany, about 80 km north of Cologne. The company's manufacturing facility, which has been operational for over two years, comprises a class 1000 clean room with a number of multi-wafer MOCVD growth reactors. All the LED manufacturing steps, including epitaxy, chip fabrication and packaging, are co-located at this site, a distinctive advantage in the LED industry where most other companies send chips offshore to be packaged. Largely, this is because conventional epoxy-dip packaging of LEDs is a tedious, massively parallel process that is highly labor-intensive.

In contrast, Global Light uses a much faster injection molding technique. The mounted chip is placed in a mold into which polymer is injected to encapsulate the device. "As far as we are aware, this process is unique to us within the LED industry," says Markus Kamp, Global Light's Manager of R&D. The entire procedure of die bonding, wire bonding, injection molding, testing and selection takes less than 15 minutes, and the most time-consuming part is

waiting for the solder to dry during the die bond step.

Injection molding allows fabrication of (almost) all conceivable LED shapes, including integrated optical functions such as Fresnel lenses or parabolic reflectors, as shown in the top figure. This is not possible with conventional epoxy-dip techniques (where the LED must be retractable from the form), and provides a great deal of flexibility in terms of features such as viewing angle, as well as precise dimensional tolerances over an extended temperature range. "At present, most of Global Light's products are still conventionally shaped LEDs, but we can produce any shape required," says Markus Kamp. "Display manufacturers and other customers are now starting to realize that these options are becoming available for the first time." The nature of the encapsulating polymer can also be varied according to customer requirements, for example to provide particular protection against UV light or salt water.

Global Light's main market is in LEDs for displays and signage, ranging from large, full-color outdoor displays to small, single-color information signs. As well as supplying customized products, Global Light also provides advice and assistance covering aspects such as the best way to handle and drive the devices.

"Global Light's strategy is to offer versatility and flexibility," says Kamp. "Our in-house epitaxial capabilities in both nitride and AlInGaP-based materials allow us to supply customer-specific colors or wavelengths, while the injection molding process lets us vary performance parameters such as viewing angle."

The entire procedure of die bonding, wire bonding, injection molding, testing and selection takes less than 15 minutes.



(top) Global Light's injection molding encapsulation process allows LEDs to be fabricated with unconventional shapes, as shown for this AlInGaP LED. (bottom) A conventionally shaped blue InGaP-based LED.

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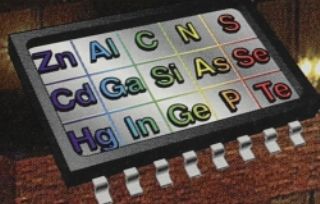
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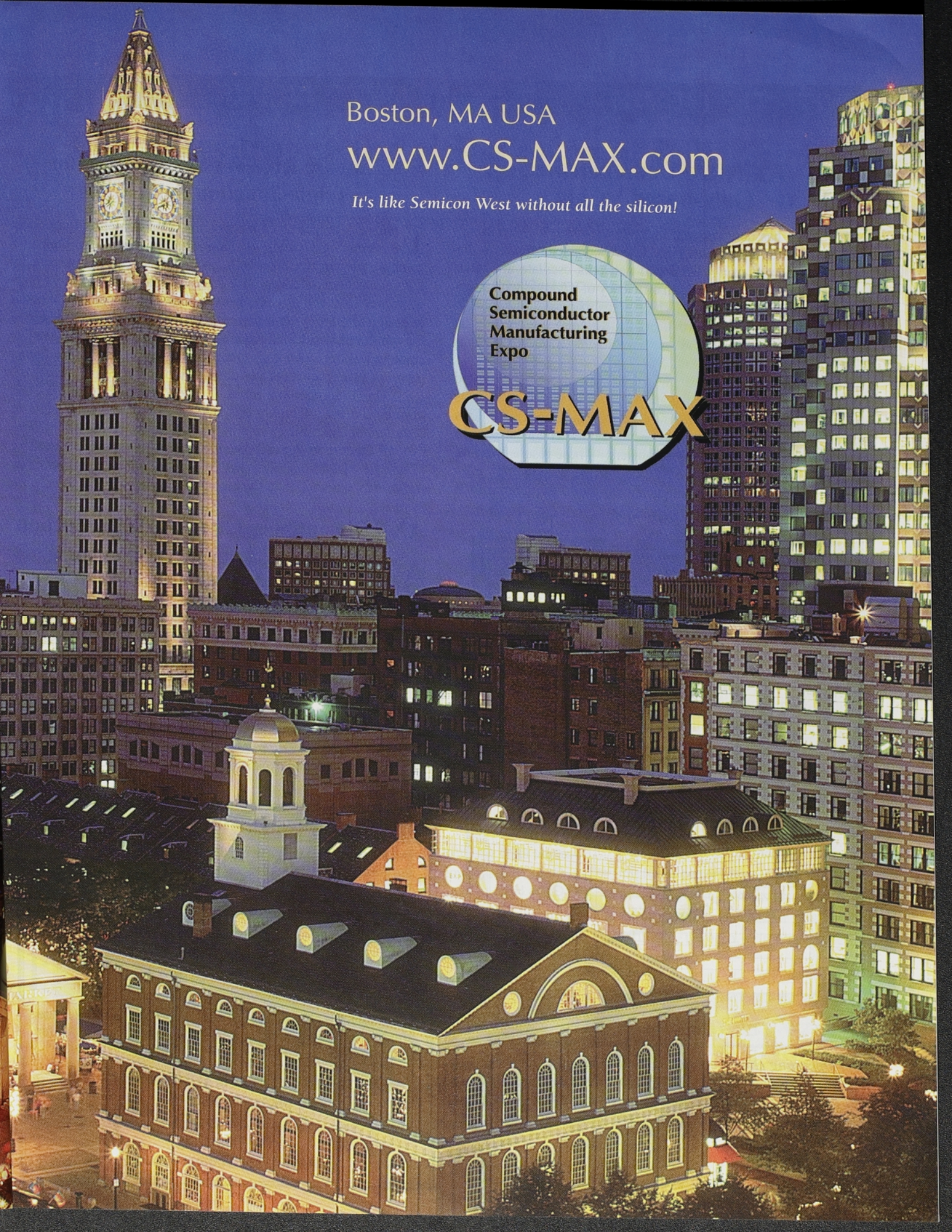
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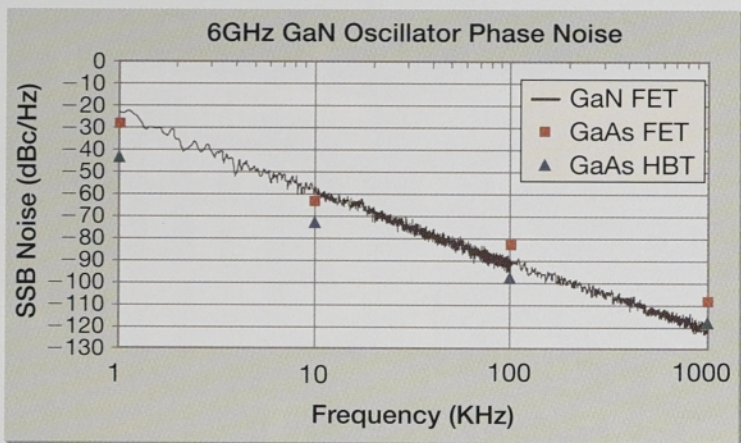
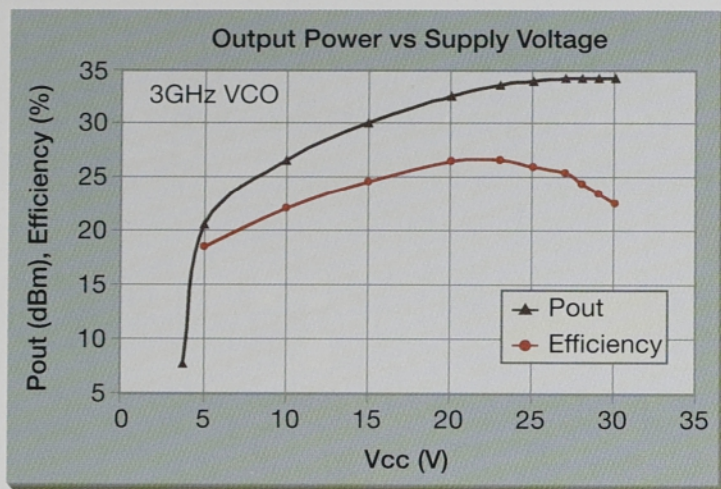
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RF Nitro Demonstrates GaN-based VCOs

RF Nitro has demonstrated the industry's first high efficiency multi-Watt AlGaIn/GaN HEMT VCOs. Varactor-tuned oscillators implemented using distributed networks oscillate at 3 GHz with a output power of 2.7 W, an efficiency of 27% and with a supply voltage range of 3.5–30 V. The nominal bandwidth tuning was 6%. Based in Charlotte, North Carolina, RF Nitro was recently set up to manufacture microwave and millimeter wave components based on GaAs and GaN [see CS 6(7), p. 17]

Separate designs for single side-band noise of GaN-based VCOs were phase noise tested at 6 GHz along with GaAs VCOs based on FET and HBT designs (see figure). GaN FET VCOs were found to be comparable to the phase noise characteristics of VCOs built using GaAs FET amplifiers. "These results indicate high power AlGaIn/GaN-based VCOs may be used as high efficiency sources for radio communications," said Joseph Smart, VP of Advanced Technology.



(top) Operating characteristics of GaN VCOs tested at 3 GHz, and phase noise behavior at 6 GHz compared to GaAs HBTs and FETs as a function of frequency. (bottom) GaN exhibits comparable phase noise performance to these devices.

Emcore Receives \$12M Order for Triple-Junction Solar Cells

Emcore has received an additional \$12 million order from Space Systems/Loral (SS/L) of Palo Alto, California for high efficiency, triple-junction solar cells, used to provide power in space for communications satellites. "We selected Emcore's innovative high-efficiency solar cell products because their technology will allow us to design satellite systems that offer increased power over the life of the spacecraft," said John Klineberg, president of SS/L. "In satellite communications, solar cells are extremely significant, since higher solar-cell efficiency translates directly into enhanced performance."

"This is another in a series of orders that highlights the trend towards the use of highly efficient multi-junction solar cells in commercial and military satellite applications," added Hong Hou, CTO of Emcore's solar cell division in Albuquerque, New Mexico. "These new triple-junction solar cells provide 71% more power at end-of-life, on-orbit, than the highest efficiency silicon cells."

AXT Discontinues Laser Diode Production

AXT will stop production of laser diodes in 2001 in order to focus on core businesses, namely substrates, LEDs and VCSELs. In 1999, AXT acquired Lyte Optronics and the subsidiary Apollo Photonics business, which was at one time one of the world's leading producers of visible laser diodes. "Over the past year, we have experienced tremendous growth in our GaAs and InP substrate businesses, successfully launched our new high-brightness blue, green and cyan LED products, and introduced VCSEL wafers and chips," said Morris Young, president and CEO. "We are very encouraged by the market demand for our products, and believe that by focusing our efforts in these core areas, we can most effectively utilize our resources for continued expansion."

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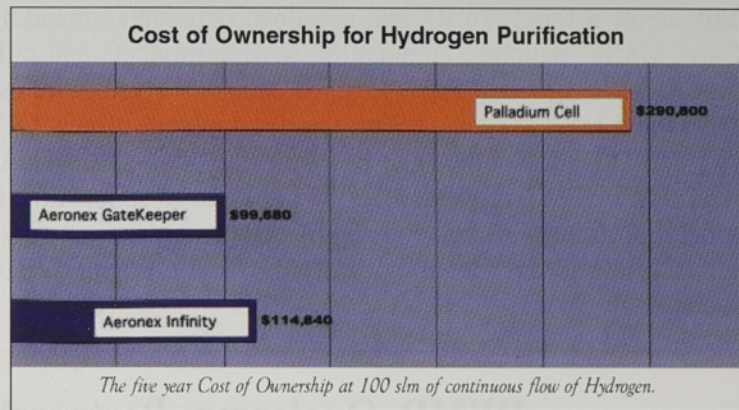
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this patented technology handles **high flows** at a **very low pressure drop**. The purifier requires no power and is unaffected by intermittent power failures that can cause cracking of palladium cells. The inorganic media is hydrocarbon free, so system upsets won't result in expensive tool repair or chamber clean up.

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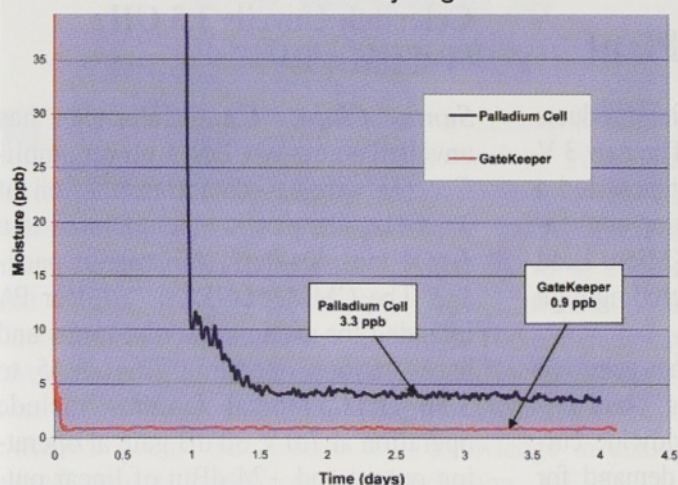
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Alpha Wins Orders From Cisco, Siemens

Alpha Industries has begun shipping production volumes of its GaAs MMICs and RF semiconductors for broadband Internet access under a new global sourcing alliance with a leading network provider, believed to be Cisco Systems. Alpha will supply a family of RF and broadband products, including GaAs MMIC switches, attenuators, passive products and millimeter-wave devices for use in broadband fixed wireless access and LAN systems. "With the development of new OC-192 and OC-768 components based on our high-speed GaAs HBT and PHEMT processes, Alpha is poised to support next-generation fiber-optic systems, high-speed enterprise networks and last-mile access technologies," said Lj Ristic, Alpha's VP of Technology.

In more news, Alpha has begun shipping GaAs ICs for Siemens' newest dual-band GSM wireless handsets for the European market, and expects full production to begin by June 2001. Siemens, the world's fourth-largest handset manufacturer, emerged as one of the fastest-growing mobile phone companies in the third quarter of 2000. Dave Fryklund, general manager of Alpha's IC Business Unit, said that the Siemens contract underscores the company's strategy to expand its relationship with key OEM handset customers. "We expect our involvement with Siemens and the other market-leading handset manufacturers to increase as we continue to offer improved performance in our GaAs control ICs, and as we introduce the first switch-filter solutions this quarter based on our new Alpha Integration Platform [see CS 6(9), p. 32]."

RFMD, Qualcomm Partnership Unveils New PA Modules

RF Micro Devices and Qualcomm CDMA Technologies (QCT) have developed a series of highly integrated PA modules, the second set of products to come from the partnership between the two companies. Based on a RFMD's GaAs HBT process, "the new PA3300 PA module continues QCT's commitment to develop CDMA RF products that enable manufacturers to develop more sophisticated yet cost-effective wireless handsets," said QCT's marketing and product manager, Johan Lodenius.

"By teaming together from the concept stage through development, we were able to create a highly integrated and innovative PA module optimized to support and complement Qualcomm's total CDMA solution," said RFMD's Jerry Neal.

The new PA module forms part of a highly integrated CDMA chipset solution. The total package size of the 13-pin land grid array (LGA) package is $6 \times 7.5 \text{ mm}^2$, and features integrated bias control and compensation for consistent performance of gain, quiescent current and Adjacent Channel Power Rejection (ACPR). The US cellular module delivers 28 dBm linear output power with 28 dB gain from a 3.2 V supply. Sample shipments for cellular and PCS are available now, with Korean PCS and JCDMA samples expected to follow in the first quarter of 2001, and an IMT band version expected to sample in the second quarter of 2001.

Filtronic Launches First Products From New Plant

Filtronic Compound Semiconductors has launched the first commercial products manufactured at its facility at Newton Aycliffe (County Durham, UK). The new 3 V products comprise of a low loss SPDT microwave and SPQT MMIC switches, and a high isolation SPDT MMIC switch, and are targeting handsets and base station applications. Filtronic says these switches will initially be available in 4×4 MLF (Micro Lead Frame) type packages, and will satisfy all GSM operation requirements, including high isolation and large signal operation.

"The Newton Aycliffe facility has come a long way in a short time and has achieved production status readiness as indicated by these and other new products," said Filtronic's Christopher Snowden. "With the number of mobile handsets worldwide currently estimated to be over 600 million and increasing rapidly, we see demand for microwave switches within handsets and base stations increasing commensurately."

New Products

W-CDMA PAs from RFMD

Greensboro, NC. RF Micro Devices has introduced three new GaAs HBT linear variable gain amplifiers. Two amplifiers, the RF2381 and RF2377 TX, are part of a complete single-mode W-CDMA chipset solution previously announced in February 2000. Operating from a single 2.7–3.3 V power supply, all three amplifiers feature a 50 dB linear gain control range, high linearity, high gain and a low noise figure. Manufactured using GaAs HBT process technology, these components are offered in six-lead plastic SOT packages (SOT23-6).

Celeritek Unveils 3.5 GHz W-CDMA PA

Santa Clara, CA. Celeritek has unveiled a new W-CDMA power amplifier for wireless data transmission at 3.5 GHz. The part is manufactured in a $4 \times 4 \text{ mm}$, leadless chip carrier package. The CMM3566-LC is a linear PA intended for use in subscriber units and base stations operating from 3.45 to 3.50 GHz. Typical features include operation at 7.0 V, 30 dB gain at operating output and +24 dBm of linear output power (W-CDMA).

Fujitsu Expands GaAs MMIC PA Line

San Jose, CA. Fujitsu Compound Semiconductor, Inc. is introducing four new millimeter-wave, high power MMIC amplifiers manufactured with a 0.25 μm PHEMT process. Covering the 17.5 to 31.5 GHz frequency band with output power ranging between 26 and 31 dBm, these new devices are designed for point-to-point or point-to-multipoint radio link and Local Multipoint Distribution System (LMDS) applications.

Stanford Microdevices Unveils 3G Base Station Components

Sunnyvale, CA. Stanford Microdevices, a fabless GaAs manufacturer, has unveiled a new line of GaAs and SiGe transceiver ICs and multichip modules for 3G wireless base station applications, including modulator, mixer, amplifier, transmitter and receiver functions. Production volumes are targeted for mid-2001. "For Stanford Microdevices, this new line represents an initial step into products featuring higher levels of functionality and integration for the fast-growing mobile arena," said Gary Gianatasio, VP and general manager of mobile wireless infrastructure products.

Samsung Employs Infineon's New Mixers

Infineon's new linear GaAs down-conversion mixer ICs will be employed in the next generation of cell phones and modem-enabled PDAs manufactured by Samsung Electronics Company. The new mixers combine excellent linearity with low noise figures and low power consumption, in addition to reduced distortion for improved data transfer rates. "We chose Infineon because of their vast experience with RF technology and linear down-converters, their established leadership in GaAs process technology, and their ability to meet our high volume requirements," said Dales Sohn, of Samsung's corporate planning team.

\$15M Investment for Hittite Microwave

Hittite Microwave Corporation, a fabless MMIC house based in Chelmsford, MA, has received \$15 million in funding from venture capital company Summit Partners of Boston. Hittite's high volume MMIC production includes around 150 GaAs MMICs covering the DC to 40 GHz range, and consists of switches, mixers, sensors, attenuators, amplifiers, frequency multipliers and ASICs. The company says the investment will allow continued growth, including the expansion of its design and manufacturing capabilities. Hittite has extensive device and system level knowledge in analog and mixed signal MMIC design, including MESFET, HBT, PHEMT, and BiCMOS IC fabrication processes.

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

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

Stated HPMO Business Manager Barry Cottrell,

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

The dedicated Deer Park HPMO production facility includes state-of-the art distributed control system (DCS) processing large-scale stainless steel reactors, and cylinder loading facilities. Systems will employ Akzo Nobel proprietary, ether-free synthetic protocols insuring industry leading purity and consistency well known to Akzo Nobel customers. The new scale of operation, to be commissioned during 2001, will support projected industry growth through 2006.

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

About Akzo Nobel High Purity Metalorganics

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

About Akzo Nobel

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

Internet: <http://www.akzonobel.com>

More New Companies Join the Ranks of Fiber-Optic Component Manufacturers

Qusion Technologies Opens 33,000 Sq.Ft. Manufacturing Facility

Qusion Technologies, a telecom component manufacturer founded in late 1999, has opened a 33,000 sq.ft. facility in South Brunswick, NJ. The new facility will enable the company to realize its long term aim of manufacturing complete telecommunications modules by monolithically integrating optical components, including lasers, modulators and detectors, onto a single chip.

"Qusion's mission is the full integration of all optical components for modules operating at 40 Gb/s and higher, although initially we will be manufacturing modulators and optical switches," says CEO Fred Rappaport. "We expect to demonstrate the first fully integrated transceiver modules by the end of 2001."

The company's new production facility includes a 4,000 sq.ft. class 1000 clean room, in addition to a class 100 clean room space for photolithography. Expected to house 50 employees by the end of 2001, the South Brunswick facility will be equipped with an MOCVD reactor system, and the first InP and InGaAs devices are expected by mid-2001.

"We believe that separate parts of the industry for optical components and electronic components will not exist in future," added Igor Trofimov, chief technology officer. "If photonic integration using InP is successful, the telecom industry will merge both parts into a single branch of the industry."

T-Networks Receives \$29M in First Round Financing

T-Networks (Allentown, PA), a company founded in July 2000 to develop and manufacture 40 Gb/s transceiver modules, has raised \$29 million in its first round of funding. The company will manufacture components and subsystems at its vertically integrated facility, which is currently undergoing an expansion to add 48,000 sq.ft. of space to the existing 6,000 sq.ft. building.

"Our goal is to make a telecom transmitter containing lasers, photodetectors, ICs and packaging, in a user-friendly interface for operation at 40 Gb/s and higher," said CTO and co-founder Aaron Bond. "To do this we're bringing together expertise and experience in several key areas—epitaxial growth, design and fabrication of high speed RFICs and RF photonic chips, and high volume packaging of optoelectronics devices."

Optillion Receives Second-Round Investment of \$53M

Optillion, a fiber-optics transceiver company based in Stockholm, Sweden, has received \$53 million in a second round of equity financing. Founded in December 1999, the company

says its first products will be transceivers for 10 Gigabit Ethernet data communications. Optillion expects the financial injection to enable it to accelerate transceiver development, build a manufacturing plant and open US offices. Slated to be on-line in mid-2001, the new manufacturing operation in Stockholm will be used to manufacture chips and package transceivers.

Kamelian Receives \$20M Development Boost

Kamelian, a developer and manufacturer of fiber-optic components and modules based in Glasgow, UK, has received \$20M to finance a major expansion program. The company plans to build a dedicated manufacturing facility near Oxford, UK, and will also expand its Glasgow R&D facilities. Kamelian specializes in the design and fabrication of integrated optical chips, and low volume prototype manufacturing is currently being performed by an optoelectronics foundry located at the same site. The first products are expected during 2001.

"Kamelian's powerful technology platform combines its expertise in designing and manufacturing active optical components that have optical switching and amplification capabilities, with key know-how in the hybrid integration of these active [chips] with [passive devices] that perform static wavelength routing functions," said CEO Paul May. "This combination provides us with a range of products that perform such dynamic optical functions as switching, wavelength conversion and signal regeneration."

Cielo Demonstrates 2.5 Gb/s SONET Link Using 1.3 μ m VCSELs

Cielo Communications (Broomfield, CO) has demonstrated OC-48 (2.5 Gb/s) error-free data transmission over 20 km of single-mode fiber using a 1.3 μ m VCSEL. Developed jointly with Sandia National Laboratories [see CS 6(5), p. 67], the short reach transmitter was tested for SONET compliance and achieved a bit error rate (BER) of $< 10^{-12}$. The transceiver link consisted of a packaged VCSEL transmitter and laser driver, and a PIN photodiode receiver with transimpedance- and post-amplifiers, in addition to commercially available ICs and proprietary optical packaging.

Long wavelength VCSELs are being sought for telecommunication optical transmitters because of the advantages offered over existing edge-emitting lasers, which include

[cont. on page 20]

[cont. from page 19]

faster modulation speeds, easier testing capability, smaller size, lower power consumption and device costs.

"Based on its inherent technical advantages, the 1.3 μm VCSEL will obsolete the majority of 1.3 μm edge-emitting lasers used in telecommunications today," claims Bob Mayer, Cielo's VP of marketing. "Our achievement is a major milestone in demonstrating the capability of the 1.3 μm VCSEL to deliver the performance required in SONET applications. The optical power, wavelength and spectral purity have been the major hurdles for 1.3 μm VCSEL technology, and we are excited about our optical transmitter since it exceeds these OC-48 short reach requirements with considerable margin."

Alfalight Receives \$28 M Funding for 980 nm Pump Lasers

Alfalight, a 2-year old high-power diode laser company based in Madison, WI, has secured \$28 million in second round venture funding. The investment round was led by Advanced Technology Ventures, and included original investors who provided \$6.1 million in funding just 7 months ago. Alfalight manufactures high power, single-mode 980 nm lasers for optical communications applications and 980 nm aluminum-free multi-mode lasers, primarily for the metro amplifier market. These technologies are based on IP exclusively licensed from the Wisconsin Alumni Research Foundation. Alfalight will use part of the capital to complete a 20,000 sq.ft. building in Madison. The company also recently opened a 15,000 sq.ft. packaging facility near Montreal, Canada.

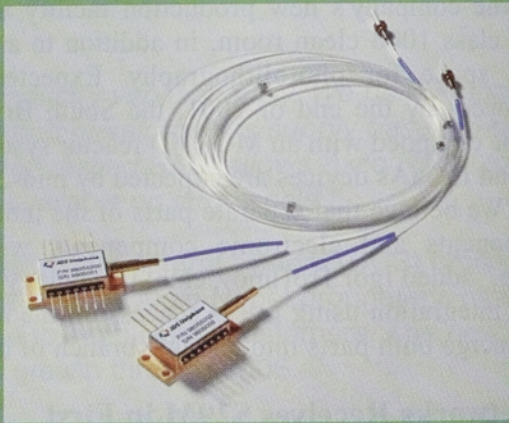
SDL to Supply Multi-mode Pump Lasers to IPG Photonics

SDL (San Jose, CA) is to provide high volumes of multi-mode pump lasers to IPG Photonics (Sturbridge, MA) for various cladding-pumped fiber products. The contract will run through the end of 2002, with expected revenues totaling \$66.7 million. Multi-mode pump lasers employ a broad emitting aperture to allow operation at power levels as high as several watts, and are used as cooled or uncooled optical pump sources for active, cladding-pumped fibers. SDL's 6380 multi-mode pump laser and other multi-mode pump lasers will be employed in IPG Photonics' industrial fiber

PL980S 5000 Series 980 nm Pump Module from JDS Uniphase

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lasers, Raman fiber lasers, and various optical amplifier products. These pumps will also be used in IPG Photonics' new generation of low-cost metro amplifiers for use in the emerging metro access networks.

Universities Get \$25 Million Gifts to Launch Photonics Centers

A former CEO of E-TEK Dynamics is to donate \$25 million to both Duke University and Stanford University to establish new centers for advanced photonics. "We want to help create at Duke and Stanford the world's finest centers for photonics, which we hope will coalesce universities, industry and government to enable the full attainment of the potential of optics," said Michael Fitzpatrick. He sees a critical shortage of trained photonics engineers as endangering progress in the industry, and hopes to address this shortfall by creating centers of research excellence to "attract great students and great faculty with great labs, advanced curricula and industry internships".

"It is very important that we continue the basic research in universities," said David Miller, who will head up the new photonics Institute in Stanford. "With the rapid growth of markets and the short development cycles of photonic products, industry has less time to do research. It is also very important that we train the next generation of photonics professionals with the broad skills needed by industry."

The Key Conference Compound Semiconductors in Communications

Confirmed Speakers*

- Market Trends in Active Optical Components
John Lively, Senior Analyst Optical Components, RHK
- The Optical Component Market—A Wall Street Perspective
Jim Jungjohan, Managing Director Photonics Research, CIBC World Markets
- The Status of the World-Wide GaAs Industry
Stephen Entwistle, Program Director, Strategy Analytics
- The Outlook for Compound Semiconductors: Explosive Growth Continues
Dale Pfau, Managing Director, Equity Research, CIBC World Markets
- The Role of Compound Semiconductors in IP Networks & Their Status in Japan
Yoshiyasu Kanno, General Manager, Fujitsu Quantum Devices

Presented By:



World Markets

- The Engineering Shortage and Other Issues from the Perspective of a Fabless Company
Steve Richeson, CEO, RF Solutions
- Panel Discussion on III-V Substrates: Quality & Availability
With representatives of AXT, Freiberger, Hitachi Cable, Sumitomo Electric and Wafer Technology
- High Volume, High Frequency GaAs MMICs: The Practical Solution to the Access Bottleneck
Doug Lockie, Executive VP, Endwave Corporation
- Evolution of Optical Networking Components
Ira Deyhimy, VP of Strategy & Business Development, Vitesse Semiconductor
- OEICs: Commercialization at Last!
Michael Lebby, President & CEO, Ignis Optics, Inc. (previously with Intel Capital)

Surface Emitting Lasers: A Key Technology for Revolutionizing Photonics

Manufacturing

Malcolm Thompson, CEO, Novalux

Pushing the Envelope in High Bit-rate Fiber Optic Receivers

Mark Itzler, VP and CTO, JDS Uniphase Epitaxx

GaN ICs for Wireless AND Wired Communications

Lester Eastman, Cornell University

Heterogeneous Optoelectronic Integration: Can III-Vs and Silicon Co-Exist in the Same Package?

Elias Towe, University of Virginia (previously Program Manager, Optoelectronics, DARPA)

The Engine for High-Speed Optical Communications

Andrew Carter, VP Strategic Technologies, Marconi Caswell UK

Markets and Applications for High Frequency GaAs and InP ICs

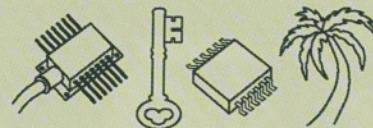
Albert Lawrence, Director Wireless Telecom Products, TRW Ventures

Unstable VCSEL: Enabling Wavelength-on-Demand in Metro Networks

Connie Chang Hasnain, CTO, Bandwidth9 and UC Berkeley

Subject to change. See website for final program.

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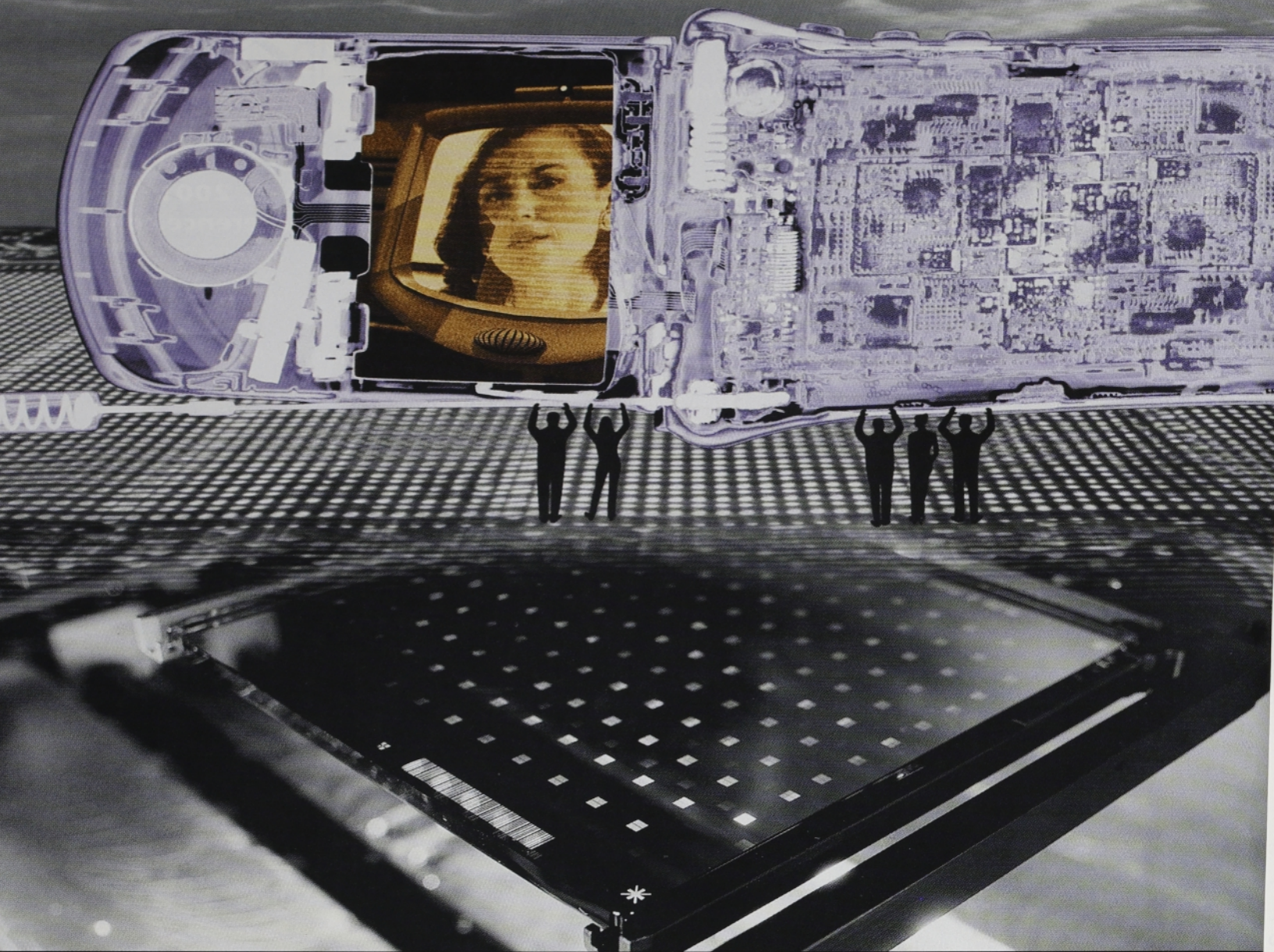
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Optical Amplifiers in Huge Demand—Raman to the Fore

The worldwide optical amplifier market for telecommunications is set to grow from over \$3 billion in 2000 to \$7.3 billion in 2004, representing a CAGR of 22%, according to Strategies Unlimited. Close to half of the 2004 market will be for Raman amplifiers, which are increasing in demand for emerging ultra-long-haul and 40 Gb/s networks. While EDFAs will continue to thrive in a variety of applications, the emergence of Raman amplification will lead to a substantial change in the design of EDFAs, as well as the mix of pump laser products needed to drive the amplifiers. New, lower-cost technologies will also emerge; these include erbium-doped waveguide amplifiers (EDWAs), where a substrate is doped instead of a fiber, and semiconductor optical amplifiers (SOAs). Low cost EDFAs also promise to compete strongly.

The report also notes that nearly \$1.6 billion worth of lasers were manufactured in 2000 to pump the optical amplifiers. Almost all pump lasers are semiconductor lasers, but

fiber lasers (which are themselves pumped by diode lasers) are also used for EDFA and Raman applications. Like the optical amplifier business, the pump laser market is also very dynamic, with many new suppliers poised to take market share from established players.

CIBC World Markets has also issued a bullish forecast for Raman, estimating that the Raman amplifier market could rise from \$245 million in 2000 to \$4.8 billion in 2005. The driving forces are the need to move to more cost-effective networks utilizing higher channel counts, higher transmission speeds and longer distances. Raman amplifiers are complementary to EDFAs, and can reduce the overall cost of network amplification by 40% or more compared to networks that are wholly dependent on EDFAs. In turn, this will create a huge market for pump lasers operating at or near 1480 nm. Unit sales are forecast to increase from 60,000 in 2000 to over 2.1 million in 2005, which equates to a \$2.3 billion market.

Formal Opening for Former Epitaxx Expansion

On December 19, 2000, JDS Uniphase opened its new facilities in West Trenton, NJ, in a ceremony attended by Christie Whitman, Governor of New Jersey, and Josef Straus, CEO and Co-Chairman of JDS Uniphase. The former Epitaxx facility, which manufactures fiber-optic detectors and receivers, has been expanded significantly.

"JDS Uniphase is continually striving to increase manufacturing output to meet customer demand," said Josef Straus. "The opening of these new and expanded facilities is a vital step towards achieving that goal."

Before JDS Uniphase purchased Epitaxx in November 1999, the company occupied a 42,000 sq.ft. facility and employed about 200 staff. Now, the total space available to the West Trenton Division at two separate sites is some 196,000 sq.ft. and there are close to 1000 staff. Wafer fabrication and optical sub-assembly manufacturing takes place at the original building, which has been extended by 26,000 sq.ft. Module assembly takes place in a 29,000 sq.ft. space in a new building, which also contains almost 50,000 sq.ft. of clean room space that is currently been fitted out.

InGaAs Detectors for OSI Fibercomm

OSI Fibercomm, the recently formed subsidiary of OSI Systems, has received an initial order of \$2 million from a manufacturer of long-haul fiber optic equipment for the development, engineering and production of InGaAs monitor arrays for WDM applications. The order is set to ship over the next twelve months.

"We are excited by the acceptance of OSI Fibercomm's products by the major long-haul equipment manufacturers," added Steven Cuffel, OSI Fibercomm's VP of sales and marketing. "We have also started shipping production quantities of InGaAs photodiodes at the rate of 10,000 units per month for use in the telecommunications market."

Founded in 2000, OSI Fibercomm designs and manufactures InGaAs and silicon photodiodes for use in fiber-optic modules and subsystems at its fab in Hawthorne, CA. The company out sources InGaAs growth to a European epitaxial vendor.

Sensors Unlimited Expands Princeton Facility

Sensors Unlimited has opened its newly expanded facilities in Princeton, NJ for the design and manufacture of InGaAs photodiode arrays for monitoring fiber-optic networks. The company, now part of Finisar, currently has over 35,000 sq.ft. of space, including a class 1,000/100 cleanroom for device processing and testing of detectors and lasers. Facilities include photolithography, dielectric deposition, thermal and e-beam metal deposition, p-contact diffusion and annealing, chip dicing and automatic probing. Test facilities include infrared detector testing and automated characterization of lasers with wavelengths from 0.65 to 5 mm.

"The cleanroom has tripled in size to over 5,000 sq.ft. and includes increased use of automation of the company's operations, which speeds the fabrication process," said John Sudol, VP of operations. "In addition, we can now produce larger size wafers, which yields more linear arrays per wafer and exponentially increases our production output."

Akzo Nobel Invests in High Purity Metalorganics

In December, Akzo Nobel announced substantial investment in its production, distribution and service capabilities at its Deer Park, Texas complex in response to the rapidly growing demand for high purity metalorganic (HPMO) source materials.

"We believe that for this industry to reach its full growth potential, it must be underpinned by a strong metalorganics supply base," says HPMO Business Manager Barry Cottrell. "Investment in manufacturing facilities, coupled with a streamlined organization and increased R&D, allows Akzo Nobel to respond to this challenge by making the highest purity metalorganic sources available on large scale."

The dedicated Deer Park HPMO production facility includes state-of-the-art distributed control system (DCS) processing, large-scale stainless steel reactors, and cylinder loading facilities. Systems will employ proprietary, ether-free synthetic processes ensuring industry leading purity and consistency. The expanded operation, to be commissioned during 2001, will support projected industry growth through 2006.

Accent Optical Technologies Receives \$15.9M Investment

Accent Optical Technologies (Bend, OR), formed recently from the buy-out of Bio-Rad's Semiconductor Division, has received a second round of funding from investors totaling \$15.9 million. Accent says the proceeds will be used to finance the development of the optoelectronic research and development center in Hemel Hempstead, England, and to expand facilities in Korea, Taiwan and Japan. In addition, the funds will also be used as working capital and to retire debt.

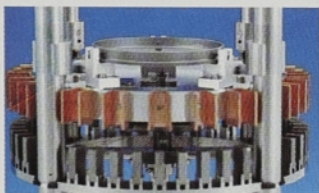
Global Communications Technology Orders Tegal Etch System

Tegal (Petaluma, CA) has received an order from Taiwan-based Global Communications Technology for a 901G diode plasma etch system. The system is configured for nitride applications and will be used to produce GaAs devices for the telecommunications market. Scheduled for installation February 2001, the 900G series is scalable from 3- to 6-inch wafers and includes an automated cassette-to-cassette etch system for GaAs substrates. Global Communications Technology operates a 6-inch GaAs wafer fab in Hsin Chu, where it manufactures HBTs, PHEMTs, digital ICs and optoelectronic devices [see Things to Watch, this issue].

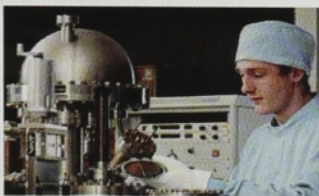


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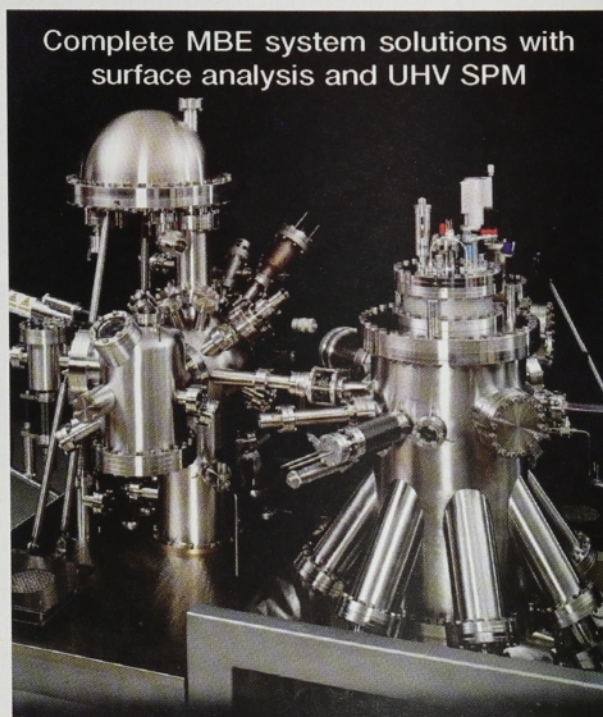
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Anadigics Buys Trikon Metallization System

Anadigics has placed an order for Trikon's Sigma λ P APVD system, to be used for both front and backside metallization schemes at Anadigics' 6-inch manufacturing facility in Warren, NJ. Developed for high-volume Si production with a capacity for more than 3,000 wafers per week, the Sigma λ P system has been modified to meet the demands of GaAs production. The metallization system will also be shipped with Trikon's cold electrostatic chuck for low-temperature, low damage lift-off metallization.

Reactor Sales

Intelligent Epitaxy Technology (IntelliEPI) has ordered three **Riber** MBE systems, including an MBE6000 system (4 × 6-inch) and two MBE7000 production MBE systems (7 × 6-inch), for delivery in 2001. IntelliEPI has installed an MBE6000 reactor at its Richardson, Texas facility, the first of the four reactors bought as part of its recently announced expansion program [see CS 6(8), p. 39].

Qusion Technologies, a recent start-up based in Princeton, NJ (see Fiber-Optics News), has ordered an AIX 2400G3 MOCVD system from **Aixtron** for growth of InP-based laser materials and other modules for fiber optic systems. In addition, Aixtron has sold an AIX 2400G3 reactor to **Opto Speed**, a group with subsidiaries in Switzerland, Germany and Italy that has decided to increase its epitaxial production capacity for InP-based lasers, detectors and other optoelectronic devices used in 10 Gb/s product families.

Kopin Announces C-Doped InP HBT Epiwafers

Kopin (Taunton, MA) is manufacturing C-doped InP HBT epiwafers up to 4-inch in diameter in its production MOCVD systems. "Our proprietary and patent-pending process overcomes previous difficulties to incorporate sufficient quantities of carbon into InP HBTs, especially by MOCVD," said John Fan, Kopin's president and CEO. "Although Be-doped InP HBTs have been grown by MBE, C-doped HBTs are preferable because carbon is a more stable dopant."

"We have achieved active carbon doping levels exceeding $1 \times 10^{19} / \text{cm}^3$, a critical threshold for many circuit applications, and are steadily increasing the doping level for even higher speed circuits," added Roger Welser, Kopin's director of transistor technology. "The transistor characteristics of large area InP HBTs grown and fabricated at Kopin are excellent, suggesting very high material quality is obtained by our MOCVD process."

JMAR Awards Contract to SAL for X-Ray Lithography Stepper

JMAR Technologies has awarded a contract to SAL (South Burlington, VT) worth more than \$1.0 million to construct an X-ray lithography system. The XRS 2000 NanoPulsar™ system will be powered by JMAR's PXS-125 laser plasma X-ray source. In addition, the system will include a collimator developed by X-Ray Optical Systems (Albany, NY) to direct the X-rays onto the mask/wafer target.

"The completed NanoPulsar system is expected to achieve better than 130 nm resolution," said John Carosella, president of JMAR's NanoLight division. "JMAR and SAL are targeting markets such as the high speed GaAs semiconductor devices used in advanced telecommunications, which require critical dimensions ranging from 130 nm to 70 nm."

Rodel Introduces Polishing Pad

Rodel (Chiba, Japan) has introduced a new polishing pad for GaAs, InP and Si wafers. The SPM3100 is an advanced poromeric pad that reduces break-in times and allows production wafers to be polished immediately after installation. While physical property variation is a common problem for poromeric pads coated on traditional felt substrates, the new pad's pore structure is grown directly on Mylar to reduce such variation. This provides the necessary balance between pad compressibility and hardness, providing low levels of scratching, light point defects and haze, while maintaining the wafer's geometry, says the company.

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The 2000 International Electron Devices Meeting

ROBERT A. METZGER

The International Electron Devices Meeting (IEDM), held last year in San Francisco from December 10–13, 2000, is the premier venue for both researchers and manufacturers to report their latest device results. While compound semiconductors represent only a small fraction of the work presented, other technologies based on widely differing materials such as silicon and organics are also of great relevance to the III-V community. These other technologies represent potential competition for compound semiconductors in the marketplace, but also potential opportunities for collaboration and synergy, in addition to access to applications that compound semiconductor devices alone would not be capable of.

Electronic Devices

HEMTs

In the quest for ever higher operating frequencies, Lai and coworkers from TRW reported on the first G-Band (140–220 GHz) amplifiers. Using InGaAs/InAlAs/InP PHEMT technology featuring In content greater than 70% in the channel region, gate lengths of 70 nm and a backside process to reduce substrate thickness to 50 μm , f_t values in excess of 300 GHz were achieved (see Figure 1).

These amplifiers showed 7–8 dB of gain per stage at 200 GHz operation, while a three stage single-ended microstrip MMIC amplifier gave 10–12 dB gain and a NF of 5.1 dB at 151 GHz. Parts fabricated using this technology included a three-stage amplifier showing 14 dB of gain with less than 7 dB of noise from 170–190 GHz, and a six-stage amplifier covering the frequency range of 160–215 GHz with 20 dB average gain, and a NF of

8 dB at 170 GHz, making these the highest frequency gain amplifiers reported to date. These high frequency devices will offer higher bandwidth, reduced aperture and instrument size, and narrower beam widths for radar and remote sensing applications.

Other HEMT highlights include work performed by Gassler and coworkers from the University of Ulm on metamorphic InP-based HEMTs grown on GaAs substrates, with a graded AlInAs buffer to transition between the GaAs and InP lattice constant. These devices feature a composite channel comprised of a 5 nm InGaAs layer with an In content of 43%, coupled with an undoped 5 nm InP subchannel and a 10 nm InP donor layer doped $2 \times 10^{18}/\text{cm}^3$. The introduction of this InP subchannel improves device performance due to the reduction of impact ionization in InP as compared to InGaAs. The resulting device exhibited f_t and f_{max} values of 188 and 300 GHz respectively, along with an I_{DSmax} of 625 mA/mm and a transconductance of 850 mS/mm for 20 nm gate length devices—values quite comparable to InP-based HEMTs grown on more expensive InP substrates.

Power HBTs

In the area of III-V HBTs for power applications, both double heterostructure GaAs- and InP-based HBTs have found a wide range of uses in commercial and military applications. However, both these material systems suffer from a bandgap spike produced at the interface between the narrow bandgap base and

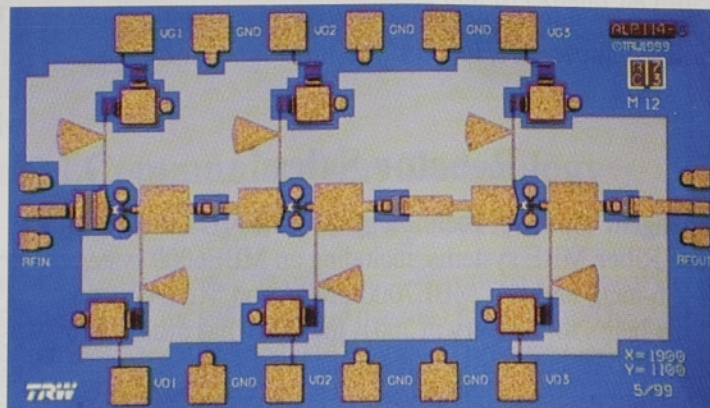


Figure 1. Photograph of an InP 3-stage single-ended HEMT LNA for operation in the range 165–190 GHz (Lai et al.).

wide bandgap collector junction, which must be reduced through bandgap grading or spacer approaches in order to optimize current transport.

Dvorak and coworkers from Simon Fraser University report on another double heterostructure HBT approach using an abrupt InP/GaAsSb/InP structure, in which the staggered bandgap lineup between GaAsSb and InP eliminates the junction interface bandgap spike (see Figure 2). These MOCVD-grown devices used a 20–25 nm strained GaAs_{0.6}Sb_{0.4} base layer, carbon doped at a level of $8\text{--}10 \times 10^{19}/\text{cm}^3$. The resulting HBTs exhibited an f_t value of 250 GHz and f_{max} value greater than 200 GHz, and BV_{CEO} greater than 6 V. This represents the highest reported f_t for any kind of DHBT produced with conventional processing approaches.

Wide Bandgap Materials

While GaAs- and InP-based devices continue to see improvements in operating frequencies, rapid improvements in power capabilities are being demonstrated in the wide bandgap GaN material system. Wu and coworkers from Cree Lighting achieved a new power record for

pulsed operation of a AlGaIn/GaN HEMT amplifier grown on SiC (see Figure 3). Using 0.5–0.6 μm gate lengths, these devices showed f_t and f_{max} values of 25–30 and 60–100 GHz, respectively, operating at a current density of 1–1.3 A/mm and exhibiting a breakdown of 70–80 V. The devices were flip-chip bonded to AlN, onto which all MIM capacitors, metal resistors and airbridge interconnects were fabricated. This approach improves the amplifiers' thermal and electrical characteristics. With an 8 mm gate periphery and operating under a 5% duty cycle at 6 GHz, the device delivered a power density of 6.4 W/mm for a total power of 50 W. Such performance is 6–10 times higher than that achieved by GaAs-based devices of the same size.

GaN-based HEMTs show greatly enhanced power densities as compared to GaAs-based devices, but these higher power levels increase the demands on device isolation since drain voltages may be 20 times higher. Masato and coworkers from **Mat-sushita Electronics** reported on a selective thermal oxidation process by using a Si mask over the active device area (which is oxidized to form SiO_2 and subsequently etched away), while a Ga_2O_3 layer is formed in the desired isolation regions. The resulting leakage current between devices as compared to those formed by conventional mesa isolation was reduced by 5 orders of magnitude for devices operating at drain voltages of 120 V.

In other work modifying the surface properties of GaN devices, Lee and coworkers from **Daimler Chrysler** and the **Korea Institute of Science and Technology** demonstrated that surface passivation with SiN improved HEMT output power from 0.59 W/mm to 1.45 W/mm. This improvement is attributed to the passivation of surface states, which act as a current limiter in the gate-drain region of the device.

Also paying close attention to the surface behavior of GaN devices, Chumbes and coworkers from **Cornell** reported on using a PECVD Si_3N_4 process, which had initially been developed to improve RF performance through surface passivation. The Si_3N_4 is used as the insulator material in a

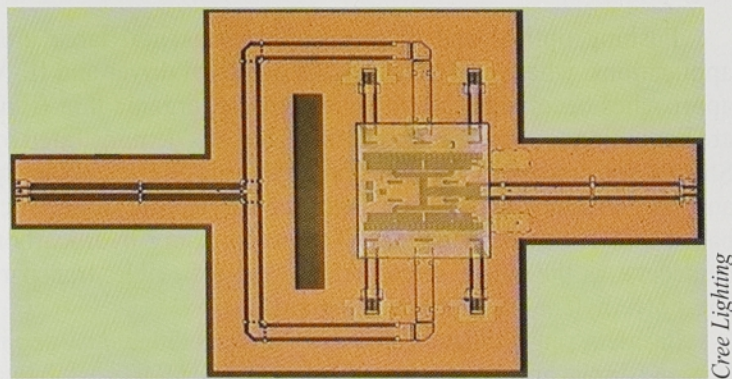


Figure 3. Flip-chip IC amplifier based on AlGaIn/GaN HEMT with an 8 mm periphery. Operating under a 5% duty cycle at 6 GHz, the device delivered a total power of 50 W (Wu et al).

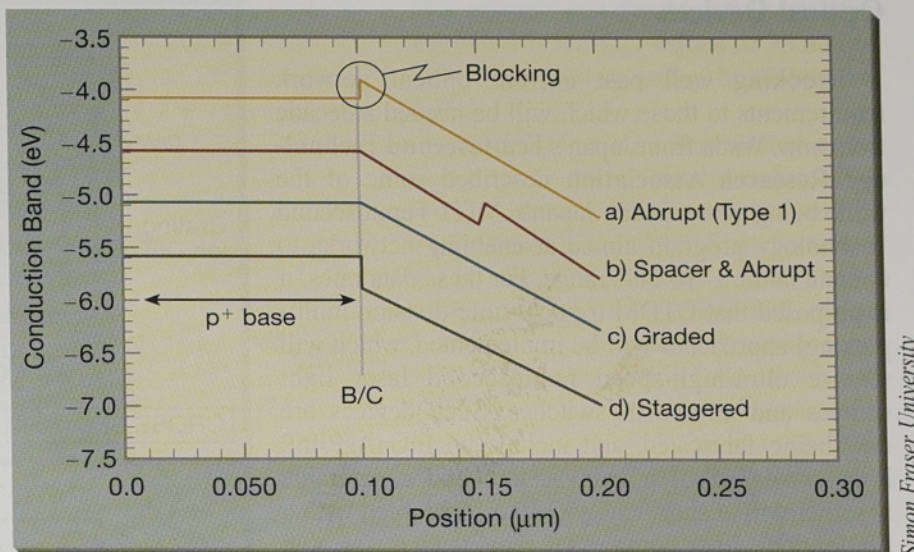
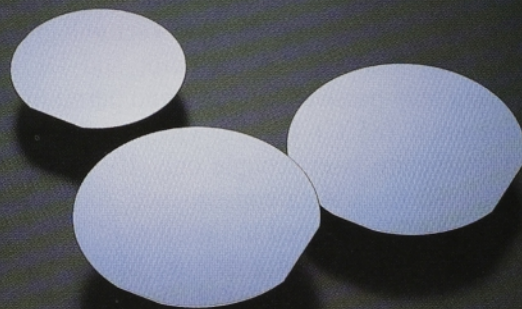


Figure 2. Conduction band diagrams illustrating various approaches used to overcome collector current blocking at the B/C junction in DHBTs. Also shown is the staggered line up B/C junction for InP/GaAsSb/InP DHBTs.

AlGaIn/GaN MISFET. These devices delivered 750 mA/mm with peak transconductances of 110 mS/mm, and with a 28 V bias generated 4.2 W/mm and 36% PAE at 4 GHz operation.

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Optical Devices

Looking well past current optical network requirements to those which will be needed a decade from now, Wada from Japan's **Femtosecond Technology Research Association** described some of the work being done under Japan's MITI Femtosecond Technology program aimed at enabling networks to operate in the 1–10 Tb/s range. For these data rates, it is proposed that OTDM (optical time-division multiplexing) approaches will be implemented, which will require ultra-high-speed femtosecond laser light sources and all-optical switches. Such devices are now being fabricated, and include an InGaAsP/InP laser consisting of a gain section and a saturable absorber with a short cavity (170 μm) coupled with a single-mode fiber compressor. This device was able to successfully generate a pulse train with a width of only 390 fs and a repetition rate of 500 GHz, making it suitable for OTDM applications.

Other OTDM compatible components described included a Mach-Zehnder all-optical switch comprised of an InGaAsP/InP semiconductor optical amplifier array and planar lightwave circuits. Such a device has been used to demultiplex a 168 Gb/s signal down to 10.5 Gb/s—the highest demultiplexed data rate reported to date.

At the other end of the spectrum, focusing not on ultimate performance, but on manufacturability, Klotzkin and coworkers from **Lucent Technologies** described directly-modulated Fabry-Perot and DFB lasers requiring only passive alignment and permitting high temperature operation (85°C) for 2.5 Gb/s applications. Typical buried heterostructure lasers couple only 10–15% of their light into a flat cleaved fiber. As a consequence, such lasers must be packaged and carefully aligned to the fiber to improve coupling efficiency. Klotzkin described a 1.3 μm MQW InGaAsP laser with a narrow far field distribution (which couples more light into

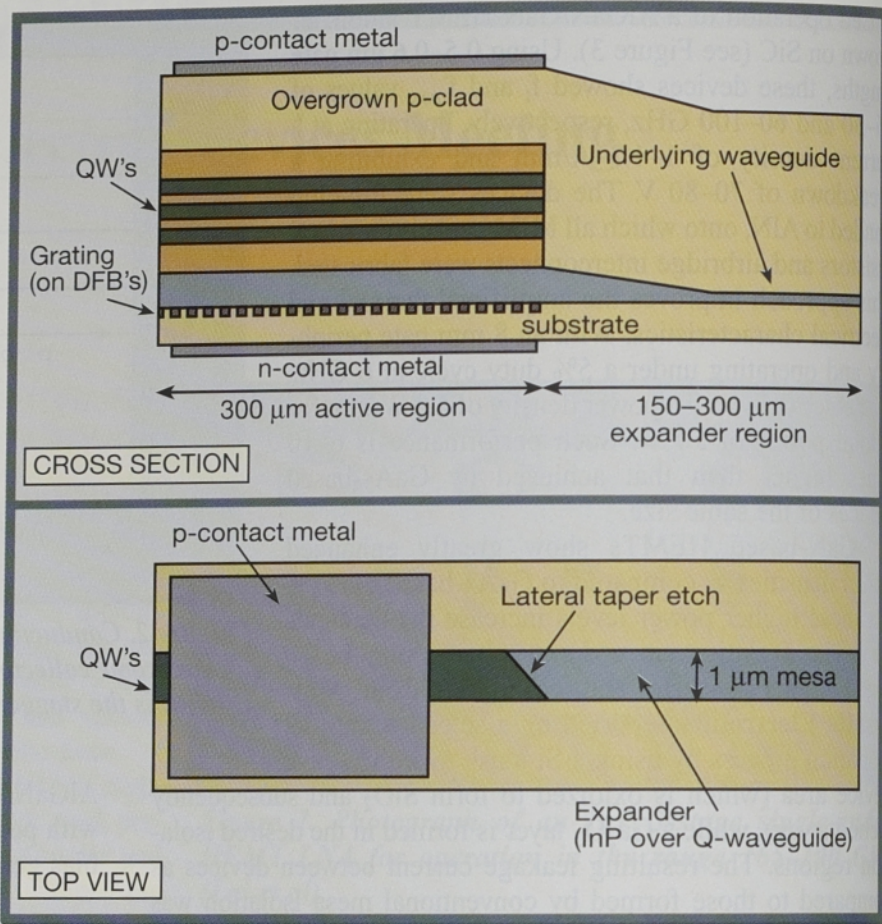


Figure 4. Cross-section and top view of the spot size converted laser, which allows an unpackaged, uncooled laser to couple 45% of its light into the fiber at a data rate of 2.5 Gb/s (Klotzkin et al).

a passively aligned fiber), in which the laser is divided into two sections—the active region with a small 1 μm spot size (which delivers good laser performance) coupled with a mode expander to increase the spot size to 4 μm , which improves its coupling efficiency to the fiber (see Figure 4). Using such an approach, the unpackaged laser passively coupled 45% of its light to the fiber at 2.5 Gb/s operation in an uncooled state.

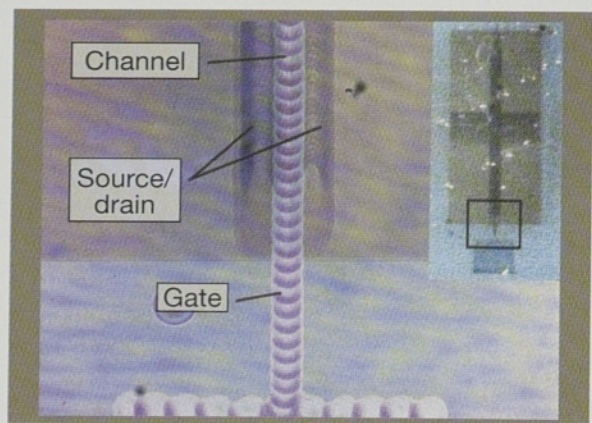


Figure 5. Photo showing an ink-jet printed TFT with a channel length of 5 μm (inset shows completed device). The gate electrode is well aligned with the channel. Applications could include large scale applications requiring kHz-range frequencies of operation (Kawase et al).

Organic Devices

Pushing optical and display applications into large area applications, where cost becomes the principal driver and III-V approaches become prohibitively expensive, organic thin films are beginning to show their potential. This was demonstrated by Sheraw and coworkers from the **Pennsylvania State University** and the **Sarnoff Corporation**, with the fabrication of organic based thin film transistor (OTFT) circuits using hydrocarbon pentacene as the active semiconductor on a flexible, transparent, polyethylene naphthalate substrate.

Inverters, ring oscillators, frequency dividers differential amplifiers and display pixel arrays were fabricated with OTFTs exhibiting mobilities of 1 $\text{cm}^2/\text{V}\cdot\text{s}$. The resulting ring oscillators exhibited propagation delays of less than 40 $\mu\text{sec}/\text{stage}$, and below 50 μsec at bias levels of 8 V—the fastest organic circuits reported on flexible substrates to date.

The ultimate in inexpensive transistor fabrication was reported by Kawase and coworkers from the **University of Cambridge**, who reported all-polymer transistors fabricated by ink-jet printing. With 5 μm gate lengths, the printed transistors showed a mobility of $0.02 \text{ cm}^2/\text{V}\cdot\text{s}$ and on/off ratios exceeding 1×10^5 (see Figure 5). These devices are certainly not ready to compete with InP-based HEMTs, which exhibit mobilities above $10,000 \text{ cm}^2/\text{V}\cdot\text{s}$, but for large-scale kHz-range applications, this may become a very important technology.

Silicon

While economics and performance criteria will not find OTFTs and III-V-based devices competing for any current applications, the same thing can not be said of III-V and Si devices, especially as Si-based device performance continues to penetrate into regimes once believed to be the exclusive domain of III-V devices.

Washio and coworkers from **Hitachi** reported on their SiGe HBT/CMOS on SOI process, which is suitable for both microwave and high speed digital applications. Using a 30 nm SiGe base, in which the Ge content ranges from 5 to 12.5%, two different versions of HBTs were produced. A high speed process with a breakdown voltage of 2.5V exhibited f_t and f_{max} values of 76 and 180 GHz, respectively. This is the highest reported f_{max} for Si technology. A higher voltage version with a breakdown of 3.9V exhibited an f_t and f_{max} of 47 and 125 GHz, respectively.

Not only do these characteristics make these devices well suited for many RF applications (although the relatively low breakdown may limit their insertion in power amplifier sockets), these devices were also used in the fabrication of a differential ECL ring oscillator which showed a minimum gate delay of only 6.7 ps.

While not as spectacular as the Hitachi results, an impressive RF SiGe BiCMOS process was reported by Hashimoto and coworkers from **NEC**.

This process was capable of devices that exhibited f_t and f_{max} values of 73 and 61 GHz, respectively and a breakdown of 2.6 V.

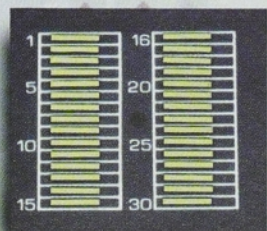
SiGe HBTs are often viewed as the major Si-based competitor for III-V devices, but remarkable progress has also been reported for CMOS performance. Momiyama and coworkers from Fujitsu reported on an RF NMOS/SOI 80 nm gate length process operating with a gate voltage of 0.65 V and a source drain voltage of 1.5 V. These devices exhibited f_t and f_{max} values of 140 and 60 GHz, respectively—RF characteristics better than that reported by the Hitachi SiGe HBTs, and on par with most III-V results.

And while sub 50 nm gate lengths had been the exclusive regime of high performance GaAs and InP HEMTs, Chau and coworkers from **Intel** reported on a 30 nm gatelength CMOS process, with NMOS and PMOS gate delays of 1.0 and 1.7 ps, and outstanding g_m NMOS and PMOS values of 1200 mS/mm and 640 mS/mm, respectively.

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Compound Semiconductor Research at the Fraunhofer IAF

Recently celebrating its 50th anniversary, the Fraunhofer Society is Germany's leading organization of institutes for applied research. The Fraunhofer Institute for Applied Solid State Physics focuses on the investigation of compound semiconductor materials and devices.

RICHARD DIXON



The Fraunhofer Institute für Angewandte Festkörperphysik (IAF, or Institute for Applied Solid State Physics) is one of 47 German research institutes of the Fraunhofer Society, a body that recently celebrated its 50th anniversary. To commemorate the event, IAF's innovative research—in particular, its LEDs—are now depicted on a postage stamp.

In addition to LED research, the Fraunhofer IAF is one of Europe's leading centers engaged in applied R&D of compound semiconductor materials, devices and ICs. Based in Freiburg in the south of Germany, IAF designs, demonstrates and undertakes small volume production of MMICs,

mixed signal/digital circuits and optoelectronic devices based on GaAs, InP, antimonides and group III-nitrides.

Among the Institute's stated goals is the development of devices and circuits to meet the requirements of its customer base, which includes the German Ministry of Defense, and its industrial partners. This association with the defense industry, which provides 60% of IAF's \$15 million in funding and operating costs, contrasts with the majority of other Fraunhofer Institutes. The German Federal Ministry of Education and Research supplies a further 17%, with the remaining 23% supplied by industrial contracts.

Around 160 scientists and engineers (total staff 210) are employed in 86,000 sq.ft. of offices and laboratory space, which includes 8,600 sq.ft. of clean rooms for device and circuit processing and epitaxy. Fraunhofer IAF recently installed a 6 × 2-inch production MOCVD system for the growth of III-nitrides used to manufacture UV LEDs, laser diodes and FETs. The institute also recently formed EpiNova, a commercial enterprise founded by a small group from its Epitaxy Division [CS 6(5), p. 25]. EpiNova rents laboratory and office space at Fraunhofer IAF, and specializes in the design and MBE growth of customized MESFETs and PHEMTs in small and medium quantities, using substrates sizes up to 6-inch.

The formation of EpiNova is just an extension of the more commercial prac-

tices recently instituted by the Fraunhofer IAF, says marketing manager Roland Diehl. "The emphasis has now shifted from predominantly institution-funded research to contract research supported by revenue obtained from R&D contracts with the industrial sector and public authorities," he says. "In addition, research has been reorganized under new business units, all of which has helped speed up technology transfer and innovation in 'hot' markets."

Diehl believes that by capitalizing on its strength in component development, which includes prototype and small-volume production, Fraunhofer IAF can target markets such as wireless communications, optical telecommunications and interconnects, as well as high-speed data processing, LEDs, IR lasers and detectors, and high-power diode lasers. Some of the institute's recent achievements in these and other fields are presented below.

HEMTs for Wireless Communications

Research into HEMTs is undertaken by the Institute's Devices and High Frequency Circuits division, which employs GaAs HEMT technology to realize MMICs PAs covering the 1–60 GHz range for cell phones and communication networks, WLANs, wireless broadcast transmitter systems, commercial LMDS

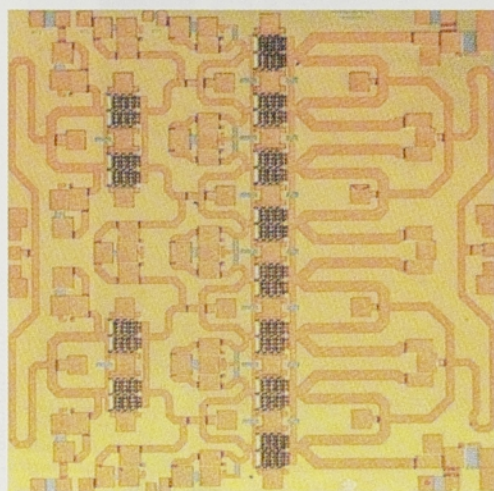


Figure 1. Power HEMTs operating at 2 GHz offer 1.6 W/mm of saturated output power density and a PAE of 66%.

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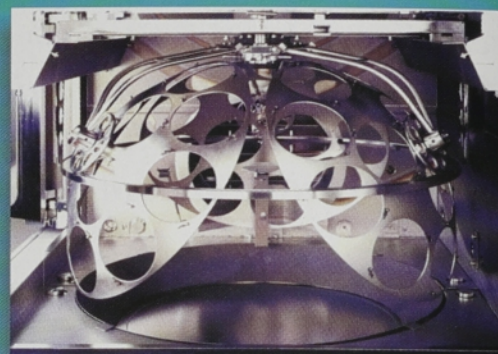
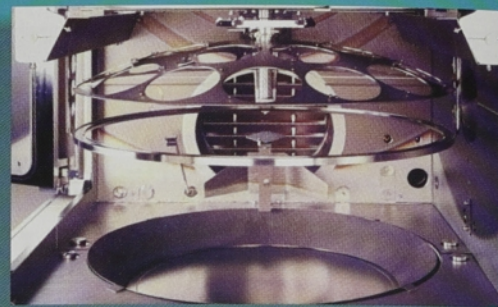
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and satellite cross-links. The design route involves the use of compact coplanar devices and circuits for power applications with gate lengths of 0.5 μm , 0.3 μm or 0.15 μm . Device simulation at Fraunhofer IAF has led to PHEMTs employing a double recess and asymmetrically placed gate that achieve a breakdown voltage of 24 V. These devices have a small signal gain of 22 dB at 2 GHz, and more than 1.6 W/mm of saturated output power density and power added efficiency (PAE) of 66% (see Figure 1).

Metamorphic HEMTs

The Institute works also closely with companies such as Infineon, UMS and Alcatel on MHEMT processes. Axel Hülsmann, who heads up the III-V Technology Division, says MHEMTs grown on 6-inch GaAs wafers offer cost advantages for high volume production compared to InP HEMTs. "It is hard to directly compare cost structures as 4-inch InP wafers still have no realistic market price," says Hülsmann. "While MHEMTs require a 1 μm thick metamorphic buffer that adds to the production costs, the [6-inch] wafer area is more than twice that of a 4-inch wafer, and circuits employing GaAs MHEMTs are currently cheaper to produce." Although he notes that this balance may change when 4-inch

InP wafers become available in sufficient quality, price and quantity.

Hülsmann adds that for power applications, GaAs-based MHEMTs also allow more freedom when choosing the lattice constant. "InP substrates offer better thermal conductivity compared to GaAs, lowering the channel temperature for a given power dissipation. But as innovative mounting techniques enter production, such as flip-chip with thermal bumps at the source islands, the improved thermal conductivity afforded by InP assumes less importance," he says.

IAF's MHEMT designs are based on a quaternary $\text{Al}_x\text{Ga}_{1-x-y}\text{In}_y\text{As}$ buffer with a linear grading of the group III-components (see Figure 2), which maintains a two-dimensional growth mode in thick (~1mm) buffer layers. A buffer thickness of 1 μm has a sufficiently small composition gradient to obtain a continuous two-dimensional growth mode and results in good material properties for electrical devices, says Hülsmann. MHEMTs with a 0.15 μm gate length on such buffer layers have exhibited 13.5 dB of gain at 94 GHz, with an f_{max} values up to 450 GHz.

40 Gb/s Optical Data Transmission

Multiplexer Modules

As part of KomNet, a project funded by the German Federal Ministry of Education and Research, Fraunhofer IAF develops a variety of high bit rate circuits for 40 Gb/s optical telecommunication systems. These include multiplexers, modulator drivers, limiting amplifiers, frequency dividers, VCOs, data and clock recovery circuits and demultiplexers. The institute has also recently begun offering packaged ICs and modules, for example, a 2:1 multiplexer module is now offered for operation at 40 Gb/s, realized using an enhancement-depletion PHEMT technology with a gate length of 0.2 μm (Figure 3). The multiplexer module multiplexes two 20 Gb/s signals into one 40 Gb/s signal at the transmitter side of optical network.

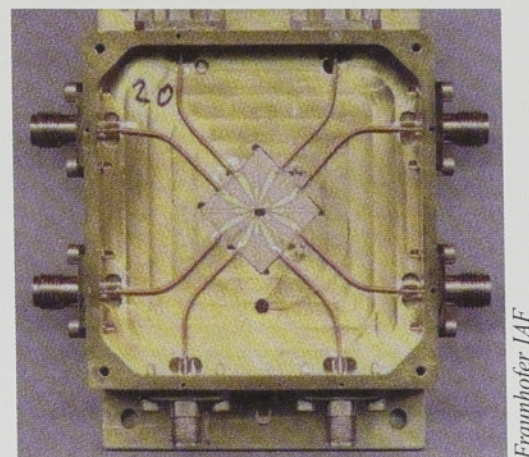


Figure 3. 2:1 multiplexer module for 40 Gb/s data transmission (module size: $6 \times 8 \text{ cm}^2$).

Hybrid Integrated Photoreceivers

Fraunhofer IAF's work on photoreceivers includes multi-mode waveguide photodiodes. These devices use a separate confinement heterostructure in which the optical waveguide is no longer formed by the photodiode absorption layer but by a second cladding layer. This allows the optical waveguide width to be chosen independently of the absorption layer width, eliminating the problem of poor bandwidth that occurs with conventional surface illuminated photodiodes, which require a thick absorption layer and thus suffer from carrier transit time limitations.

Multimode waveguide photodiodes are designed to be flip-chip mounted on a front end amplifier. These are grown by MBE and based on a 0.15 μm gate length AlGaAs/InGaAs/GaAs process. Using this approach, a 3 dB bandwidth at 41 GHz has been obtained for a photodiode operating at a wavelength of 1.55 μm .

Low-Noise QWIPs

IAF has patented a novel low noise QWIP for use in infrared cameras operating in the 8–12 μm regime. The device optimizes the potential distributions in a four-zone structure (Figure 4), which are realized using MBE-grown layers of GaAs, AlGaAs and AlAs. In the Fraunhofer IAF design, the photoexcited carriers traverse a barrier layer (drift zone) and are captured by a narrow QW

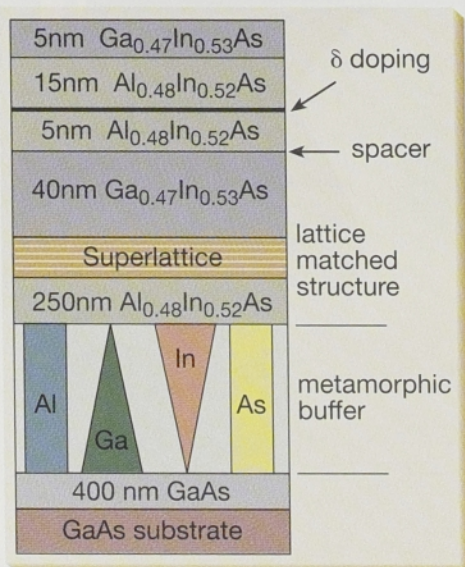


Figure 2. Schematic diagram showing the linearly graded buffer scheme employed to grow metamorphic HEMTs on GaAs substrates.

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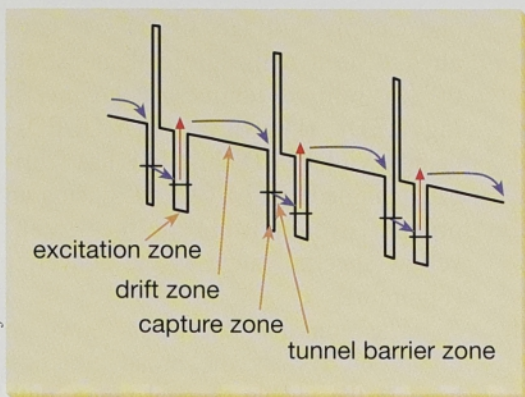


Figure 4a. Schematic showing the potential distribution and transport mechanism for low noise QWIPs.

(capture zone) from where they are transferred across a tunnel barrier (tunneling zone) into the excitation zone of the adjacent period.

The responsivity of such a low-noise QWIP under applied bias reveals that a significant photocurrent exists at zero bias, which allows the detector to be operated without a dark current. This small photocurrent gain allows the use of about 4 times higher doping densities compared to conventional QWIPs, increasing the internal quantum efficiency to about 40%. In addition, the amount of noise is considerably reduced as a consequence of the suppression of recombination noise.

Fraunhofer IAF's industrial partner, AEG Infrarot Module (AIM) of Heilbronn/Germany has fabricated a low-noise QWIP prototype camera based on IAF's QWIP focal plane arrays with 256×256 pixels, which it says shows great promise for high-performance thermal imaging for use in both military and civilian applications, including medical imaging and environmental monitoring. A low-noise version of the 640×512 focal plane array has also been realized. Excellent temperature resolutions of less than 7 and 13 mK have been achieved in IR cameras with 256×256 and 640×512 QWIP arrays, respectively.

High-Power Diode Lasers

High power diode lasers are being developed by a joint venture of Fraunhofer IAF with the Fraunhofer Institute

for Laser Technology (ILT) in Aachen. ILT is responsible for the micro-channel copper heat sinks and the mounting and testing of the devices, which are available commercially in small quantities. According to Michael Mikulla of the Optoelectronics Division, the direct application of high-power diode lasers to material processing applications such as welding, cutting or surface treatment is becoming more attractive. "The main applications for diodes include direct material processing, for example medical treatment with single arrays, up to and including welding of metal sheets with stacked arrays," he says.

The Institute recently transferred its epitaxial growth and fabrication of high power diode lasers to a 3-inch wafer process, resulting in a higher yield and up to eighty $2 \text{ mm} \times 10 \text{ mm}$ chips per wafer compared to around twenty on a 2-inch wafer. Devices are grown by MBE with a single InGaAs QW constituting the active region. The emission wavelength is adjustable between 880 nm and 1060 nm by varying the indium content. The quantum well is embedded in an 880 nm thick AlGaAs core region with a low Al-content, and the optical waveguide is formed using AlGaAs cladding layers with a higher Al-content.

Single Broad Area Lasers and Arrays

As part of the joint venture, IAF and ILT have mounted single broad area emitters (980 nm) p-side down on copper C-mounts. These devices emit a maximum output power of 9.2 W for a drive current of 10 A, and 50°C lifetime tests have shown that under a constant power condition of 1.5 W, devices are very stable for more than 3000 hours, with no sudden COMD-related failure. If a 20% current increase over the lifetime is chosen, the life expectancy extrapolates to at least 20,000 hours, and 50,000 hours at room temperature.

Broad area 980 nm arrays with a stripe widths up to 1 cm are also produced. These are mounted p-side down on micro-channel heat sinks at the ILT. A novel method of high power testing,



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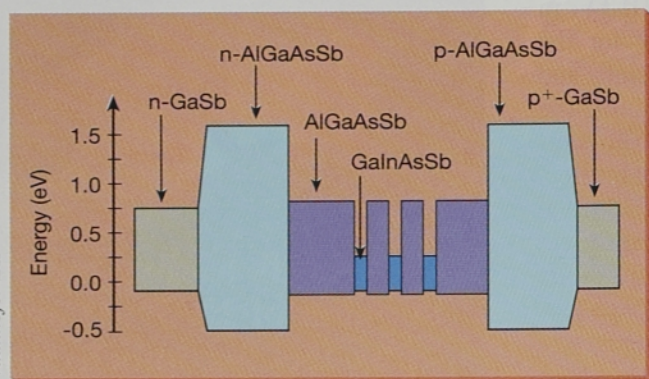


Figure 5. Band edge profile of a triple-QW large optical cavity laser structure.

allowing drive currents as high as 360 A, has been used to measure the CW output power. According to Mikulla, an output power of 267 W has been achieved at 330 A drive current. "To the best of our knowledge, this sets a record for a single 1 cm laser bar operating at 980 nm," he says. So far, lifetime testing has validated the performance of the devices for up to 5,000 hours when operated at 60 W of CW output power.

Long-Wavelength Lasers

Current research at the Fraunhofer Institute on infrared diode lasers is based on both GaInAsSb/AlGaAsSb and GaInAsP systems. The aim is to develop diode lasers for room temperature CW operation at wavelengths beyond 2 μm , with the primary focus on spectroscopic and sensing applications, as well as for materials processing.

GaInAsSb/AlGaAsSb Lasers

GaInAsSb/AlGaAsSb type-I QW lasers are grown by solid-source MBE on n-type substrates and processed into ridge waveguide lasers. Figure 5 shows the band edge profile of a triple-QW large optical cavity laser structure, which contains an active region with three compressively strained 10 nm wide $\text{Ga}_{0.70}\text{In}_{0.30}\text{As}_{0.06}\text{Sb}_{0.94}$ QWs separated by 20 nm thick $\text{Al}_{0.28}\text{Ga}_{0.72}\text{As}_{0.02}\text{Sb}_{0.98}$ barriers and sandwiched between 400 nm thick $\text{Al}_{0.28}\text{Ga}_{0.72}\text{As}_{0.02}\text{Sb}_{0.98}$ separate confinement layers.

High efficiency, low-loss type I diode lasers emitting in the 1.8 to 2.3 μm

wavelength range were achieved with an excellent power conversion efficiency of up to 28% at 1.94 μm , demonstrating the potential for high power operation, particularly when mounted p-side down to improve thermal management. IAF is currently working to extend the wavelength and power range, and has recently achieved optically pumped laser emission at 3.65 μm based on an InAs/GaSb type II mid-infrared laser.

GaInAsP Lasers

While GaInAsP lasers are widely used for fiber optic telecommunications at 1.3 and 1.55 μm , at IAF this material system is also being examined to extend the long wavelength limit out to 2 μm for use in gas sensing, among other applications. Long wavelength lasers for this application are grown on InP substrates by MOCVD, using two compressively strained 12 nm wide $\text{Ga}_{0.25}\text{In}_{0.75}\text{As}$ QWs for the active regions. IAF has fabricated ridge waveguide diodes (32 $\mu\text{m} \times 1760 \mu\text{m}$) that showed CW emission up to 2.09 μm at a heat sink temperature of 330 K. With these GaInAsP-based devices, tunable diode laser absorption spectroscopy (TDLAS) for the detection of CO_2 at 2.004 μm has been demonstrated.

AlGaInN-Based Violet LEDs

LED research at Fraunhofer concentrates on the development of advanced luminescence converting white LEDs that require efficient violet and UV-emitting LED chips based on AlGaInN. The emission of these LED chips is then converted into blue, green and red secondary emission with a phosphor, adding up to white light with a high color rendering index. AlGaInN-based LEDs are fabricated on 2-inch sapphire substrates using low-pressure MOCVD. For an emission wavelength of 420 nm, encapsulated LEDs emitting up to 3 mW at a current of 20 mA

and supply voltage of 3.7 V have already been realized. To demonstrate the feasibility of luminescence-converting LEDs (known as LUCOLEDs) using a violet LED chip, IAF has fabricated single band LUCOLEDs using an organic dye emitting in the green-yellow spectral range as the converter (Figure 6).

The emission spectrum shown in Figure 6b reveals the broad emission band in the visible spectral range, with only a small primary emission from the short violet chip, which indicates that a large fraction of the pump light is absorbed in the converter. Further work is being directed towards even shorter wavelength LEDs (370 to 410 nm) to optimize the efficiency of conversion, and their integration into LUCOLEDs employing inorganic phosphors for three-band (red-green-blue) conversion.

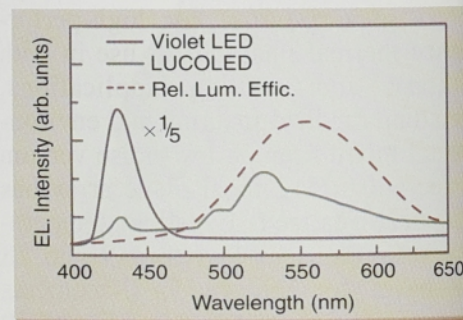
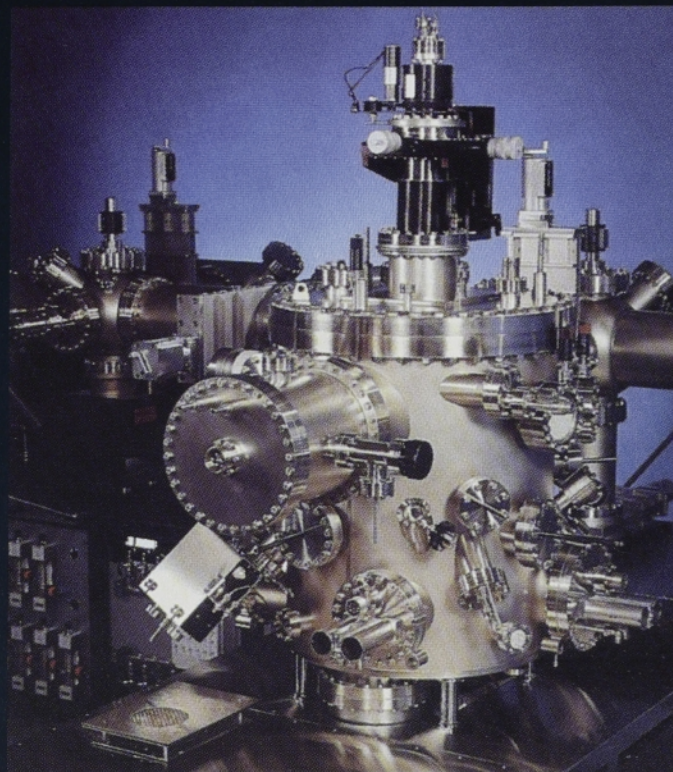


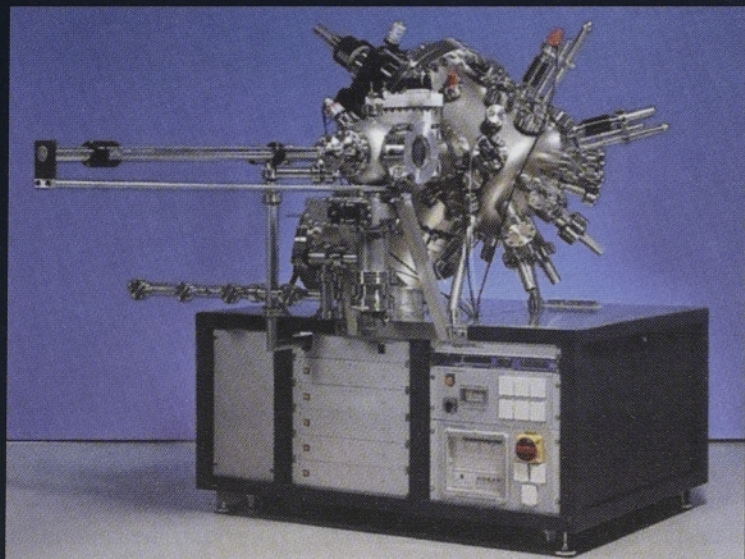
Figure 6. a) Luminescence converting AlGaInN violet LED chip fabricated at the IAF; b) Electroluminescence spectra of single LED and luminescence-converting LED based on violet chip, indicating that a large fraction of the pump light is absorbed in the converter. (Dashed line shows eye responsivity).

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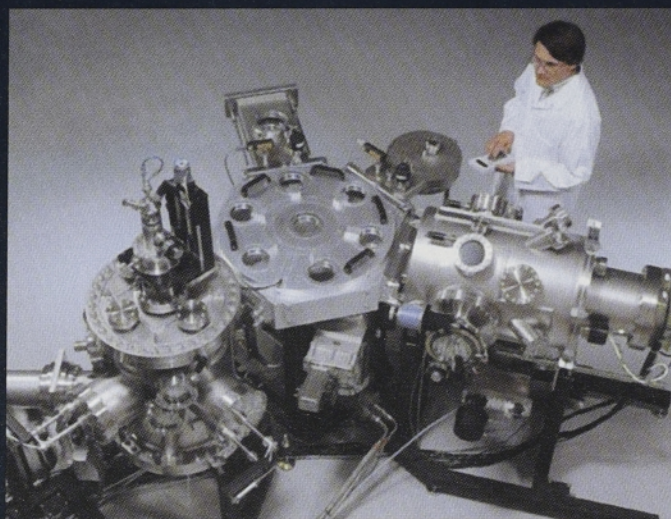
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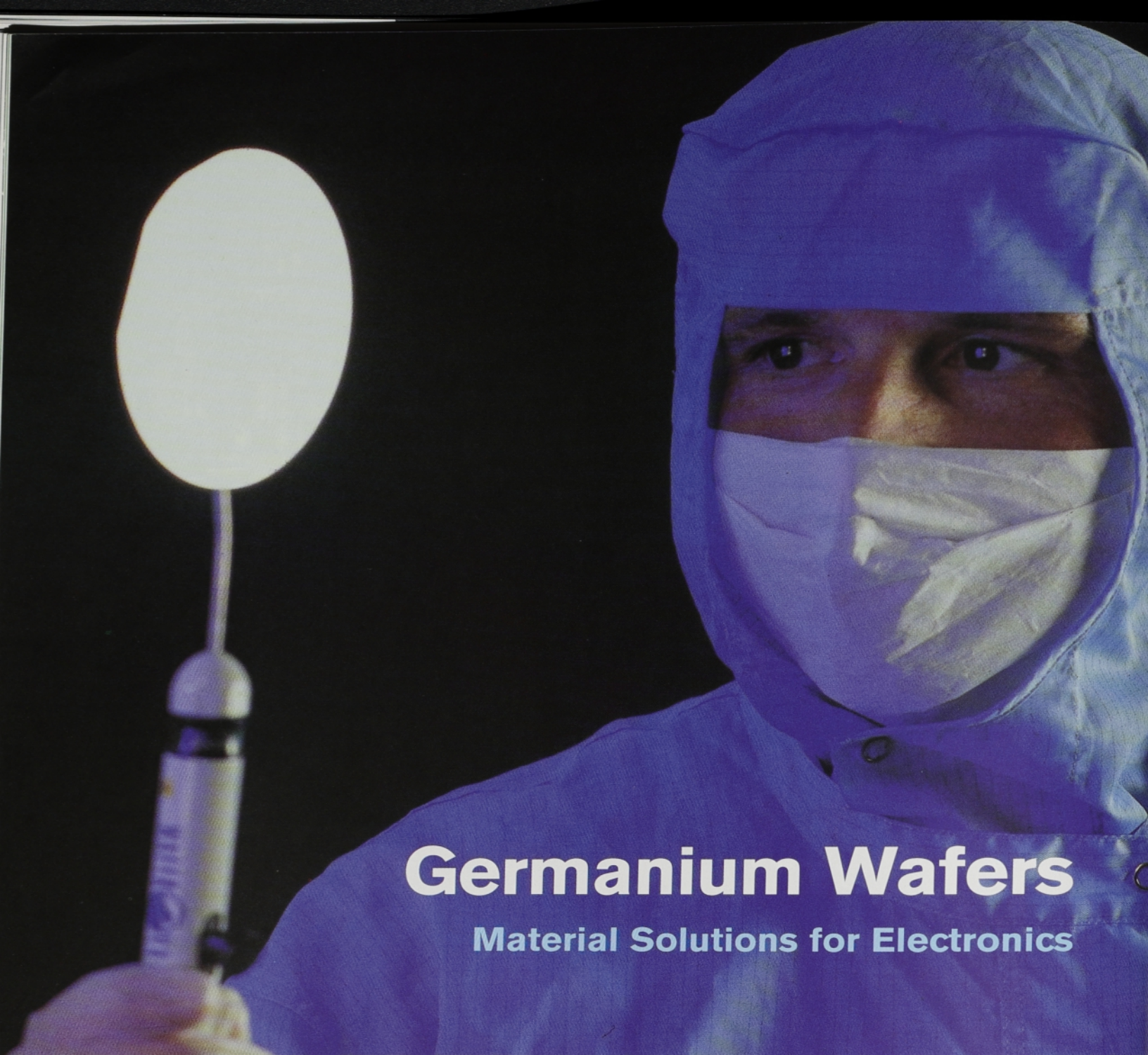
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Major Push Needed for US Nitride Effort

RICHARD DIXON

If there was one clear message to emerge from the recent Wide Bandgap Electronics Technology Workshop*, it was that over the next five years a major investment is needed to push the US wide bandgap materials effort from the laboratory into systems for military and commercial applications. So say the policy makers and resource sponsors, wide bandgap (WBG) materials researchers, devices and system designers who convened in Columbia last December. But who will pay?

Material of the Future

Wide bandgap materials such as SiC and GaN exhibit many highly desirable properties: the combination of the large band gap, high breakdown voltage (up to 150 V), good transport properties and ability to form high quality heterostructures in AlGaIn/GaN make WBG materials ideal candidates for high power, high temperature applications. It is this robust nature (i.e. temperature resistant/radiation hard) that has the military so fired up, particularly for high power amplifiers, which they believe are vital to enabling systems that maintain a competitive edge in a future theatre of war.

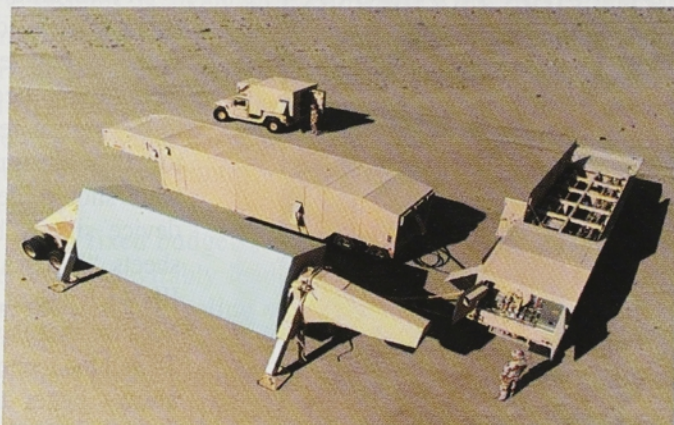
The defense industry wants WBG devices for new high power, more compact systems for electronic warfare, missile seeking and higher power radar systems. Radars should have increased range and functionality for no increase in radar footprint, a point which is very important for warships. Similarly, very low noise robust GaN-based LNAs will help combat the effects of stray signals and jamming in communications, and nitride-based sensors could be used by ground forces to detect chemical or biological attack. In its wish list, the airforce would like high bandwidth down-links on its unmanned aeronautical vehicles (UAVs) used for reconnaissance missions.

But if WBG materials are not to remain a future technology, a coordinated R&D effort will be needed of similar magnitude to the GaAs MIMIC (Microwave and Millimeter Wave Monolithic IC) program set up in 1987 to develop GaAs technology. Over the 8 years it ran, this \$530 million program was responsible for much of today's GaAs IC manufacturing infrastructure.

According to John Zolper, Program Officer for high power devices in the Electronics Division of the Office of Naval Research (ONR), an additional investment of approximately \$50 million per year over 5 years is needed to establish a manufacturing base for WBG microwave materials, devices, and circuits

for specific applications. This sum is less than was previously invested by the DoD through DARPA (Defense Advanced Research Projects Agency) under the GaAs MIMIC program.

"We think we can live with a lower level of funding [than the MIMIC program] because we can leverage the expertise established in those earlier programs in areas such as materials characterization, electromagnetic design, and processing," says Zolper. "The investment is needed because the technologies that we have now, such as GaAs MMICs, can no longer meet the increasing system requirements. If you look at it from the perspective of a new destroyer, which costs \$1–2 billion, or a new aircraft carrier, which is even more expensive, investing now in certain key technologies is justifiable for these new platforms. Such platforms have a service life of 30 to 50 years, so the technology investment made



The defense industry requires WBG devices for new systems for electronic warfare, missile seeking and high power solid-state radar.

* University of South Carolina, Columbia, SC. December 4–6, 2000.

today will pay dividends for many years. It is the system pull that establishes the technology investment."

Still Too Immature?

In fact, defense platforms such as the US Navy's DD21 destroyers are now entering the planning stages for service in 2012, and if WBG technology is going to make it into new military system architectures, designers will need to be convinced that this technology is the best solution over the next five years. But is GaN and SiC ready? Most participants agreed that many problems still remain to be solved at both materials and device level before WBG devices find their way into systems. Not least is how these new materials, which have much higher power densities, will be thermally managed and packaged in new system architectures.

According to HRL's Dave Grider, at the system level technology needs to be "transparent" to the designer, who should decide on a GaN MMIC device simply by checking specification sheets. "When a system designer looks at a III-V RF circuit, he expects to see a MMIC because that is what he can buy in GaAs. To sell the technology to system users, it is always better to sell the device performance rather than what it's made of."

At the device level, reliability and yield still need to be understood. Materials issues such as epitaxial layer uniformity and reproducibility also need considerable investigation. Phenomena that limit RF performance, such as gain compression and gate lag—an effect caused by traps found on the surface and in the highly defective GaN material that delay the response between the gate bias and current in the channel of a FET—need to be correlated with material defects and resolved.

Substrates

Many of these aspects are intimately tied in with substrates, the lack of which

for GaN is viewed as one of the most serious obstacles to the commercialization of wide bandgap microelectronic devices. Currently GaN is grown on semi-insulating SiC wafers up to 2-inch in diameter. And while some progress is being made with free-standing GaN substrates grown by HVPE or PVD, a GaN substrate of sufficient diameter appears some years off. By comparison, the GaAs industry now achieves economies of scale with 4- and 6-inch substrates.

Litton Airtron's Tom Anderson believes the current drive for large diameter wide bandgap materials is for compatibility with existing 3- and 4-inch device fabrication lines, rather than reduced costs. "Improvements in material quality and cost are normally associated with an increase in substrate diameter," says Anderson. "The opposite is actually true, and initially it is always more expensive per unit area to produce a large diameter crystal and much harder to produce lower

densities of defects with the scaled-up diameter. The commercial driver for larger diameters is lower per-die cost and higher per-wafer device yield. Lower device costs expand the market and economies of scale drive down the substrate cost."

SiC substrate research also suffers from the lack of commercial "pull" from the optoelectronics device manufacturers to develop larger wafer diameters. For FETs, SiC is the ideal substrate material because of its excellent thermal conductivity helps to dissipate heat. By contrast, LEDs are small area, commodity devices, and also seem to be miraculously insensitive to large numbers of defects (~10¹⁰ dislocations per cm² caused by lattice mismatch. Hence, for optoelectronics inexpensive sapphirine substrates suffice in most cases.

Some believed that electronic grade SiC is also just far too expensive at present. TRW's Mike Wojtowicz noted that cost, quality and availability of substrates are factors that could seriously impede

Wide bandgap microwave devices promise enabling performance, but need a critical push to realize the same success in real systems.

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commercialization. Even a 4-inch InP wafer is only 20% of the cost of a 2-inch SiC substrate, he said. Tom Anderson was able to underline this with a sobering thought: the price per inch² for 6-inch GaAs is currently \$14–17, compared to \$800 for semi-insulating 2-inch SiC.

Commercial Drivers

In the commercial sector, the excitement is tempered by the lack of an obvious big market, such as exists for GaAs for wireless handsets or nitride-based high brightness LEDs, which face little competition from other materials. In comparison, wide bandgap materials face stiff competition from existing GaAs and Si devices for RF applications. Some in-roads are being made for SiC devices, which are more mature than GaN, and market opportunities already exist in electric power switching in utility grid systems and control of power in the electrical subsystems of emerging automobile, ship and aircraft technologies. SiC is now also competing with Si for microwave power generation above handset frequencies up to around 7 GHz.

Progress is also being made with GaN devices by companies such as Cree and HRL (see table), although most speakers were quick to point out that these results represented demonstrations, and that much work needs to be done on reliability and reproducibility. However, TRW's Mike Wojtowicz said GaN technology was "just too good to pass up". TRW is currently working with a defense contractor on developing a reliable GaN process for LNAs and PAs, he said.

ONR's John Zolper added that WBG technology is primarily a DoD unique technology at present, but as with GaAs, the commercial applications will come later. "Although the commercial driver is not there at the moment, I'm optimistic that this will come as [the technology] stabilizes," he says. "The size of program required is such that it needs to be a tri-service initiative, and we are actively making our case within the navy and in tri-service committees. In addition, various companies have their own efforts and we would look to leverage and share costs in any potential effort." But as Raytheon's Tom Kazior notes: "If there was a glaring commercial application for this technology we could probably figure out other sources of money to fund a commercial venture."

Push Comes to Shove

If large investment from the industrial sector is not forthcoming, support for WBG research must fall on the shoulders of the government, which in the near term is the main customer. However, DARPA is currently unable to give substance to plans it may have for WBG research funding past 2001.

"DARPA and other agencies in the government are currently in the process of identifying their funding priorities for the fiscal year starting in October 2001," says DARPA's Edgar Martinez. "With the current investment situation in this area, it will be very

Comparison of State-of-the-Art
RF Power Performance for RF HPAs

Technology	Company	Freq (GHz)	Pout (W)	PAE (%)	Gate Width (mm)	Power Density (W/mm)
GaAs PHEMT (CW) ¹	NEC	12	15.8	36	25.2	0.63
GaN HFET (Pulsed) ²	Cree	10	50	28	12	4.17
GaN HFET (CW) ³	*Nitres	8	14.4	25	4	3.60
GaN HFET (CW) ⁴	HRL	9	22.9	37	4	5.73

1 NEC, Private communication

2 Wide Bandgap Electronics Workshop, December 4-6, 2000, Columbia, SC
MMIC SSPA with a total GaN HFET gate periphery of 12-mm

3 International Electron Device Meeting, Washington D.C., Dec. 5-8 1999
MIC SSPA combining 4 discrete GaN HFETs, 1-mm each

4 Wide Bandgap Electronics Workshop, December 4-6, 2000, Columbia, SC
MIC SSPA combining 4 discrete GaN HFETs, 1-mm each

*Now Cree Lighting Company

Recent demonstrations of the performance of GaN and GaAs microwave devices show the potential for much higher power operation from smaller device areas in GaN (data presented by Dave Grider, HRL).

difficult for this technology to be successfully transferred to industry, where the production of critical components for military systems is likely to take place. If we are successful in demonstrating the potential of this technology minimizing the current technical risks, and establishing an industrial base on which affordable and dependable components can be manufactured on a regular basis, then it will be the job of the DoD services and defense contractors to insert the technology in military systems."

With fixed budgets, any increases in defense spending in one sector inevitably leads to cuts in others areas. Nevertheless, the general feeling was that WBG technology is important enough to warrant serious lobbying efforts to raise awareness at Government level. While the situation could ease with a new White House administration eager to spend more on defense, another funding route that was also being openly touted was the congressional "plus up". Plus ups are where Senators lobby for extra money to be set aside for projects at state level, and while this would bring much needed dollars to WBG research, it is criticized by some for diluting other projects and for by-passing the DoD—potentially leading to an uncoordinated allocation of funds and also endangering the usual competition processes.

The point on which everyone did agree was that additional dollars will need to be invested soon if wide bandgap microwave materials and devices are to reach maturity in the next 5 to 7 years, and to meet system insertion targets for new military platforms. The wireless industry has adopted GaAs largely because of its enabling performance and because many manufacturing issues had been ironed out in the MIMIC program. While wide bandgap microwave devices certainly promise enabling performance, they also need a critical push to realize the same success in real systems and in the commercial sector.

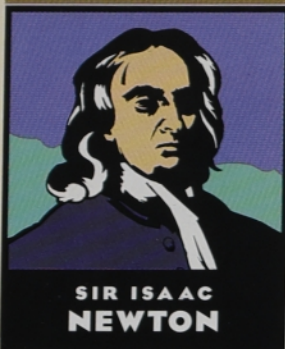
1688 John Worgan opens his shop for the sale of mathematical instruments.

1703 The first telescopic level is created for Sir Isaac Newton.

1714 A mechanical model of the solar system, called an "orrery" after the Earl of Orrery for whom it was created, is shown to His Majesty George I.

1795 The equatorial telescope is created for the Armagh Observatory.

1809 Edward Troughton refines the dividing engine, an important contribution to the development of precision astronomical instruments.



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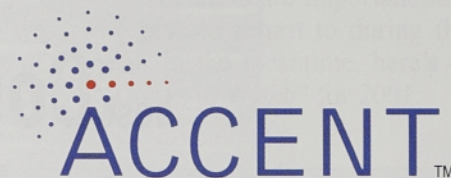
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Things to Watch in 2001

Things to Watch
2001

Our annual list of Things to Watch covers a wide range of issues related to compound semiconductors, starting with an investigation of the effect of the recent stock market turmoil on the demand for GaAs ICs and fiber-optic components. Although LEDs are not expected to penetrate the general lighting market for many years, such applications present many near-term challenges. In the GaAs industry, we take a look at the extensive activity in Taiwan, which is intimately linked to a rise in the number of foundries. We also investigate the current shortage of GaAs wafers, and the growing popularity of enhancement-mode HEMTs.

Several topics related to fiber-optic components are discussed. Indium phosphide is one of the platforms that will be used to facilitate the integration of optical and electronic functions, a focus for all the leading companies in the industry. The continued proliferation of 10 Gb/s networks and standards, such as 10 Gigabit Ethernet, is intertwined with a growing demand for VCSEL transceivers. Looking further ahead, terrestrial concentrator systems using GaAs solar cells could open up a whole new market for compound semiconductors.

40 Gb/s components and optical amplifiers—the market for these latter components is discussed on page 23 of this issue.

In the LED field, patent lawsuits continue to fly between the major nitride-based LED manufacturers and, as described on page 8, Rohm has now joined the fray. Meanwhile, the prices of these products looks set to fall, which will help the penetration of new markets.

In our HEMTs vs. HBTs article, we touch on the subject of the continued shift of power amplifier products for handsets from RFICs to highly integrated modules.

All these are important subjects that we plan to return to during the coming year. In the meantime, here's our list of "Things to Watch" for 2001:

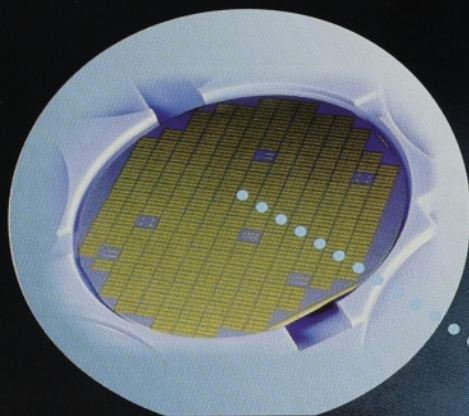
What Else is Going On?

Plenty. Among the other topics we could have included are the emergence of fiber-optic devices such as tunable lasers,

- | | |
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| 2 High Brightness LEDs for Lighting | p. 50 |
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| 4 Convergence of Optics and Electronics | p. 60 |
| 5 Indium Phosphide Planar Integrated Optics Comes of Age | |
| Contributed by Jens Noeckel, Tom Pierson and Jane Zucker of Nanovation Technologies | p. 61 |
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| Contributed by Dale Murray of ElectroniCast | |
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| Contributed by Sarah Kurtz and Robert McConnell of the National Renewable Energy Laboratory | |
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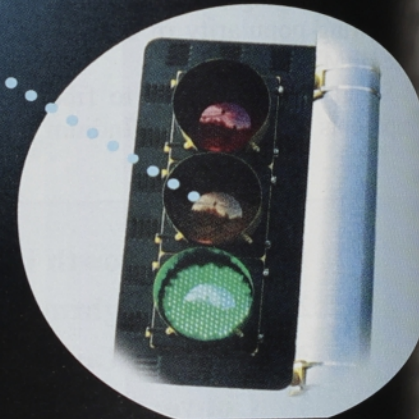
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More Growth in Communications

MARIE MEYER

Things to Watch
2001

#1

There has been a great deal of turmoil in the telecommunications industry over the past several months. On the wireless side, the major handset manufacturers have indicated that growth is slowing. On the wired side, it is becoming increasingly obvious that many communications service providers are saddled with more debt than they can cope with. There have already been a few bankruptcies, and more companies are expected to exit the market in the coming year.

What does all this mean for manufacturers of GaAs ICs and fiber optic components? We spoke with several market and financial analysts to get their assessment of the year ahead. The consensus response was that opportunities still abound for compound semiconductors in communications. And while there are clearly some issues that need working out, this sector is still poised to produce growth rates that would be the envy of many other industries.

John Lau, who covers compound semiconductor stocks for WIT SoundView, believes that we are still in the initial stages of a multiyear high growth cycle for compound semiconductors, largely because increasing demand for bandwidth at higher data rates favors III-V devices. When asked if he is standing by this prediction in light of the aforementioned turmoil in the telecom industry, he said "Absolutely! This talk of a slowdown is all relative. Compound semiconductors still have great prospects."

Echoing the sentiment, Alex Gauna, VP of Equity Research at Banc of America Securities, said "It is true that 2001 will not be the boom year that 2000 was. Last year we had a confluence of economic conditions and technology

advances that made a market that we are not likely to see again anytime soon. Still, the outlook for compound semiconductors this year is very good."

After two years of phenomenal growth, GaAs will lose some momentum in 2001. However, growth of 25–30% is expected.

Wireless Trends

Nokia and Motorola have stated that 405–410 handsets were sold in 2000, below previous expectations. Motorola's preliminary forecast, tempered by some more recent input from analysts, indicates that 2001 sales could be as high as 575 million units or as low as 505 million units.

It is clear that we are talking here about "decline" on a very relative scale, but it will nonetheless impact the GaAs industry. After two years of phenomenal growth, GaAs will lose some momentum in 2001. However, growth of 25–30% is expected. George Bechtel of Strategies Unlimited expects sales of GaAs ICs to reach \$3.8 billion in 2001, up 26% [see Figure 1]. This is only disappointing when compared to the >40% growth rate recorded in 2000.

By way of contrast, John Lau recommends a look at the computer industry. "Unit volumes for PCs are projected to increase by 15%, while ASPs [average selling prices] decline approximately 15%, projecting flat revenue growth for many PC box suppliers in 2001," he said. Contrast that with the communications industry. "Even if you

take the pessimistic end of 2001 handset forecasts, 505 to 525 million handsets, that is still up 25% over 2000."

However, the outlook is not completely rosy. Hans Mosesman of Prudential Securities says "Manufacturers have to dig themselves out of an inventory issue in the first six months of this year." In 2000, as handset forecasts were continuously escalating, many manufacturers began "increasing inventory when they shouldn't have," says Mosesman. "Now that we all know that demand was in fact not that great, it has been somewhat shocking how quickly things have changed—we sort of fell off a cliff in late November." It will take time to use up all this extra inventory in the pipeline.

Wired Trends

The big story in the fiber-optic networking industry is cutbacks in capital expenditure by the telecom carriers.

Figure 1. Worldwide Sales of GaAs ICs

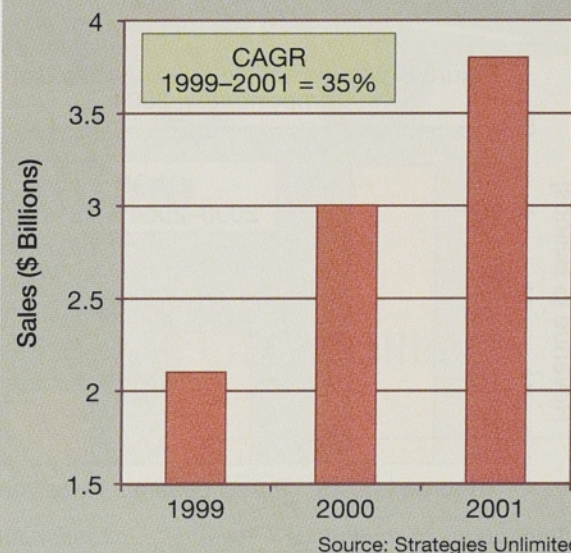
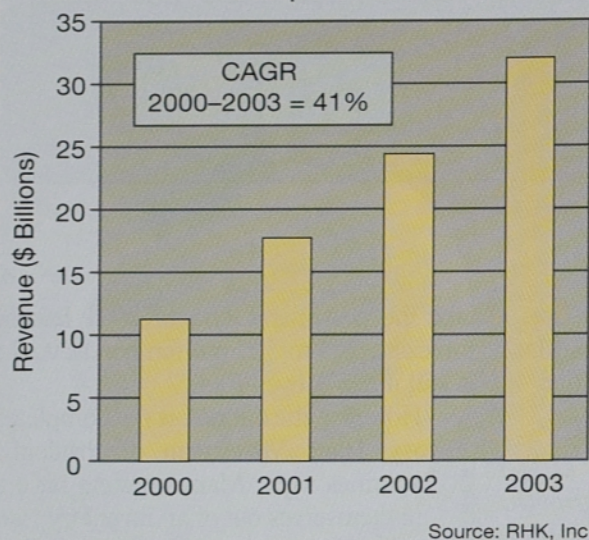


Figure 2. Worldwide Telecom Optical Component Market



However, once again, it must be noted that the decreases are relative. RHK predicts that capital expenditures by service providers will grow from \$306 billion in 2000 to \$370 billion in 2001, a 21% increase. John Lively of RHK notes that it is difficult to know which of the dozen or so technologies that are used in networking are going to be most affected. "However, it is our belief that optical technologies, especially new, more advanced optical technologies, are going to suffer the least, if at all, because they are the key toward moving to lower cost-per-bit," says Lively. "Ultimately, that is what the carriers need to

Uniphase for Deutsche Banc Alex Brown, believes that this phenomenon is

In March 2000 RHK forecast that the worldwide telecom optical component market would reach \$23 billion in 2003. More recent data from RHK indicates that the figure will be more than \$30 billion. A growth rate in excess of 50% is expected in 2001, with shipments of DWDM components nearly doubling in comparison to 2000.

already visible in the supply of passive components. The key indicator is lead times for delivery, which have dropped significantly. "Lead times for passives were in the eight weeks range and we believe they have come down to the four to five weeks range in recent weeks," says Srikanth. But he notes that lead times are not easing in the active components segment, especially for 980nm pump lasers and high-speed modulators. RHK believes that the growth rate for active components will outstrip passive components by 10-15% over the next

several years, with source lasers, pump lasers and detectors all growing by more than 40% per year between now and 2004 [see Figure 3].

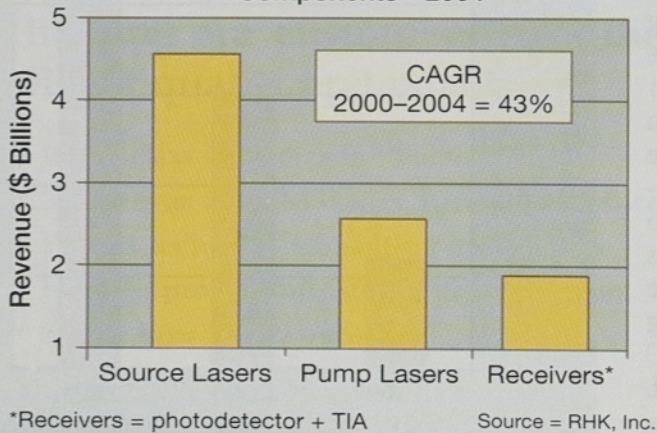
Wall Street Trends

Despite the strengths of the compound semiconductor industry, share prices in this sector continue to languish. Fiber optic component suppliers are down 60% from their historic highs, and the GaAs IC companies are down more than 66%. Should we worry? This turn of events will certainly make some aspects of operations more difficult at those companies. For example, it may be necessary to increase salaries, as employees sour on being compensated in stock options. Obviously, this means there is less money left over for growth-producing activities, such as product development and capacity expansion. Acquisitions financed by issuing shares also become more difficult. However, it should not be seen as a sign that the industry is in decline. "Don't interpret stock market volatility as an indicator of revenue and earnings volatility in a field such as this," cautions Alex Gauna. He, like all of the other analysts we spoke with, remains very bullish on the entire sector.

Hans Mosesman sums up the outlook by saying "compound semiconductors are one of the areas in technology stocks and are going to continue to be one of the most compelling areas for investors."

Both in the stock market and in the real world, we should all try to stay focused on the big picture in 2001. "It would be foolish to think that the market would perfectly follow a trend line without any deviations here and there," says John Lively. "Markets just don't behave that way in the real world." Perhaps we can consider these forecasts as something like a picture postcard of our destination, rather than detailed driving instructions. So don't be surprised to hear that there are a few detours along the way.

Figure 3. Market for Selected Active Optical Components—2004

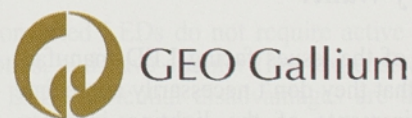


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High Brightness LEDs for Lighting

TIM WHITAKER

Things to Watch
2001

#2

High brightness LEDs continue to make inroads into various markets, including displays, signage, traffic signals, backlights for cell phones and automotive dashboards, and exterior automotive lighting. While there has also been penetration of various niche lighting markets, the "Holy Grail" of replacing existing (incandescent, fluorescent etc.) technologies for general illumination remains in the distant future.

A U.S. effort to seek federal funding for an industry-wide development program has been gaining momentum recently. A similar effort, entitled "The Light for the 21st Century", is already under way in Japan. In the U.S., the Optoelectronics Industry Development Association (OIDA) and the Department of Energy (DOE) recently organized two workshops, the first to examine the technical issues, roadblocks and challenges facing the LED community [1], and a similar workshop to examine the potential of organic LEDs (OLEDs). This article reports only on the LED workshop.

As described in the Agilent/Sandia white paper [see CS 6(2), p.32], the potential benefits of solid state lighting (SSL) are enormous. By 2025, it is estimated that SSL could decrease by 50% the global amount of electricity used for lighting, and reduce total global electricity consumption by 10%. This would result in savings totaling around \$100 billion per year, as well as environmentally significant reductions in the levels of carbon dioxide emission from power generation.

These savings assume a 50% market penetration by SSL, which in turn requires light sources capable of operating at a luminous efficacy of 200 lm/W. There are many hurdles to overcome before this daunting level of performance can be achieved, both for AlInGaP and InGaN devices (see page 53) and in using these devices to make white light sources.

What Does the Lighting Industry Want?

One of the issues facing LED manufacturers is that they don't necessarily appreciate the requirements of the lighting industry. While excited by the potential energy savings,

controllability and other attributes of LEDs, the lighting industry also expects that LEDs will have the same properties as existing light sources in terms of features such as distribution, flux density and color quality. At the OIDA workshop, Steve Johnson, head of the lighting research group at Lawrence Berkeley National Laboratory, discussed some of the most important attributes of light sources:

1. **Distribution.** Light distribution in a uniform, controllable, efficient manner is perhaps the primary concern of the lighting industry. Although LEDs are in theory an extremely good point source, the spatial and power distribution of light from packaged LEDs is not well defined by the manufacturers' specifications. Also, the color of white LEDs can shift from the center of the device to the sides, due to the color mixing that occurs to create white.
2. **Light output/flux density.** The lighting industry works with the total luminous output of a lighting system. A 100 W incandescent bulb provides 1700 lumens, while the best LED gives about 60 lumens. Methods to combine many LEDs to get the desired aggregate output, and the effect this has on light distribution, also need to be considered.
3. **Color rendering index** (for white light). Color rendering refers to how a color appears when illuminated by different light sources, compared to the color under natural day-

Color Rendering Index (R_a) Requirements		Performance of Solid State Lighting	
Application	R_a	Technology	R_a
Indoor/retail	90+	Phosphor-converted LEDs:	
Indoor office/home	80	Blue LED + yellow phosphor	60+
Indoor work area	60	Blue LED + green and red phosphors	90+
Outdoor pedestrian area	60+	Multi-chip LEDs:	
Outdoor general illumination	40-	RGB (610 nm + 540 nm + 470 nm)	80+
		Blue + yellow (500 nm + 595 nm)	40

Table 1. Color rendering index (R_a) requirements for various applications, along with the potential color rendering performance of different solid-state lighting technologies. These figures show the poor performance of multi-chip LEDs using only 2 devices, or of PC-LEDs combining a blue LED and yellow phosphor. Courtesy of Mike Pashley, Philips Research.

[1] OIDA Workshop on LEDs for Solid State Lighting, October 26-27, 2000, Albuquerque, NM

light. A source is assigned a color rendering index value R_a between 1 and 100 by comparing the appearance of various colors under illumination by the source in question and by various standards. As shown in Table 1, the application-specific requirements for R_a vary a great deal—for example, R_a must exceed 80 for general illumination. The table also shows the potential performance of various LED lighting technologies.

4. **Controllability.** The potential for fully controllable LED light sources is very exciting for the lighting industry. The ability to vary the source intensity or switch a lamp on and off without affecting the lifetime is very attractive. Also, combinations of different colored LEDs allow any color to be produced.
5. **Color temperature**—see footnote [2]. Fluorescent lamps are sold with different (fixed) color temperatures for different applications, and LED light sources will need to replicate this. There is at present a huge difference in the acceptable variations of color accuracy in fluorescent lamps, and the color variations found in white LEDs.
6. **Lifetime.** LED light sources offer very long lifetimes, with the potential to reduce replacement and maintenance costs and therefore overall operating costs.
6. **Cost.** Although low cost is obviously of paramount importance in the lighting industry, many of the other requirements, such as long lifetime and high efficiency, also have a large cost element.
8. **Efficacy (lumens/watt).** The potential to greatly increase the efficiency of LEDs could lead to considerable savings in electricity usage, which of course lowers the overall cost of operation.

Challenges for Solid State Lighting

There are two main approaches to achieving white light using LEDs. One is to combine the output from two or more LEDs of different colors (the multi-chip LED approach), the second is to use a phosphor or other material to down-convert the emission from a blue or UV LED (the phosphor converted

Challenge	Requirements
More lumens (higher light output)	Improved device efficiency (more lm/W) Larger, shaped die Improved high power packages
More lumen-hours (longer lifetime)	Improved die reliability Improved thermal management Eliminate thermal and photo-degradation of encapsulant Improved lifetime at high drive current
More lumens/dollar (cost-effective illumination)	10X reduction in die cost Reduced package cost/die

Table 2. Some of the many challenges faced by the solid state lighting. Others include color control, industry standardization of illumination sockets, and the need for high volume, low cost automated manufacturing.

or PC-LED approach). These methods have many pros and cons, and are both likely to remain in use for several years.

Ensuring color quality and control is essential to all applications, and can prove difficult with either white LED approach. Color accuracy in PC-LEDs is strongly affected by the emission wavelength and other parameters of the blue pump LED, as well as by the amount and distribution of the phosphor around the LED chip. Flux variations in any of the components of a multi-chip LED can shift the color accuracy, and because two different material systems are currently involved (AlInGaP and InGaP) there is unlikely to be a uniform, predictable degradation of LED properties over time. Active control is therefore required in multi-chip LEDs to maintain the color accuracy.

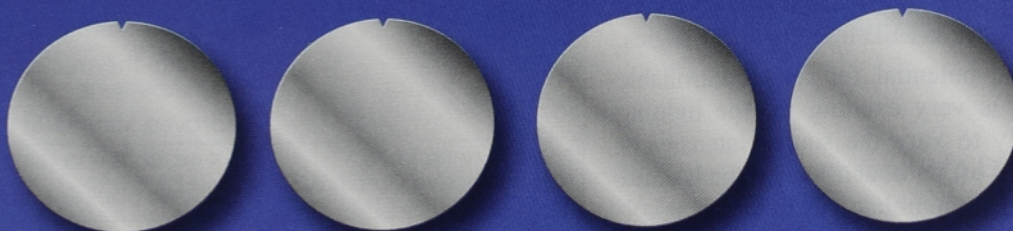
“The color accuracy of PC-LEDs is fixed by the manufacturing process, so this step is critical,” notes Mike Pashley of Philips Research. “RGB multi-chip LEDs can theoretically be adjusted to give the correct white point; the challenge is to do that cost-effectively.”

An example of the difficulty of achieving good color quality with multi-chip LEDs was given by Mike Krames of LumiLeds Lighting, who described a multi-chip LED combining 460, 530 and 630 nm devices. The combination potentially offers high efficiency but has a poor color rendering index. A better CRI value can be achieved using 460, 550 and 610 nm LEDs, but this introduces further problems. Using a 610 nm AlInGaP LED causes both the color temperature and wavelength to vary with temperature, while both the efficiency and color stability with drive current of the InGaP green LED suffer at wavelengths above 540 nm.

Phosphor-converted LEDs do not require active control or color-mixing optics, and have simpler (less expensive) fabrication than RGB LEDs. Potential disadvantages are the lack of available converter materials and the inherently lower efficiency. “Conversion efficiency is still a problem with PC-LEDs—the power conversion efficiency from blue to white is about 0.58 for a single phosphor,” says Mike Krames.

[2] Any color of light can be expressed by its chromaticity coordinate x, y on the CIE 1391 chromaticity diagram. The boundaries of the diagram (the so-called Spectrum Locus) represent monochromatic colors. The Planckian Locus traces the chromaticity coordinates of a blackbody radiator at temperatures in the 1000–20,000K range. Color Temperature refers to any point on the Planckian Locus. A typical incandescent lamp has a color temperature of around 2850K, and the typical color of daylight is 6500K—most white lamps fall between these color temperatures. Any shift of color temperature along the Planckian Locus is usually acceptable depending on the application; shifts away from the Planckian Locus are often unacceptable.

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	2000	2003	2005	2007
Source efficiency (lm/W)	19	30	60	120
Color Rendering Index	40	60	80	90
Reliability* (Kilo-hours)	5	10	50	100
Luminous output	2	100	500	1000
Cost (\$/kilo-lumen)	>100	100	50	20

* Time to degradation of 50% of sample devices.

Table 3. White LED Target Specifications

As shown in Table 1, the combination of a blue LED and a yellow YAG phosphor does not give a sufficiently high CRI value for indoor lighting applications. Other combinations, such as blue LEDs with green and red phosphors, have also been investigated. Fluorescent lamps use a tri-color phosphor optimized for white point and color rendering, which is excited at 254 nm.

One potentially optimal solution for white LEDs is to use a three-color phosphor and a UV LED. Since the LED does not contribute to the visible light output, the white point is independent of the LED characteristics. "Future solid-state lighting is likely to combine high quantum efficiency UV LEDs plus an optimized three-color phosphor plus low-cost packaging," says Steve DenBaars of Cree Lighting. His company has reported excellent results for short wavelength LEDs, namely 28% QE for 405 nm InGaN LEDs, compared to 17% for 520 nm devices. However, a great deal of work is necessary to create phosphors that can absorb at violet/near-UV wavelengths and provide the correct emission characteristics.

According to Mike Pashley, while PC-LEDs in particular provide a low profile light source, many LEDs operating at 30 lm/W are required to get the desired total lumen output, meaning that the

total area of the LED light source can be large. Even so, because the chip size is very small, collimation and beam-shaping optics can be positioned close to the source, allowing easy control of the light to generate complex light distributions. "LEDs have the potential to illuminate a designated area with much greater efficiency than existing sources," says Mike Pashley. "A good example is street lighting, where low pressure sodium lamps throw light everywhere in a very inefficient manner."

The Next Steps

One of the main aims of the OIDA Workshop was to reach an industry-wide consensus on the targets and challenges for solid-state lighting, some of which are listed in Table 2. Based on the target of eventually achieving 200 lm/W sources, a tentative roadmap of parameters for white LEDs was put forward at the OIDA workshop [see Table 3]. These numbers reflect expectation of general trends and have not yet been accepted by OIDA or DOE.

OIDA's intention is to generate a framework that will assist in forming partnerships between industry, government, academic institutions and national laboratories to accelerate the effort for achieving commercial solid state lighting. The process will also assist industry in strategic business and technology planning, identify opportunities for government-industry collaboration, and highlight issues that are more suited for research programs in national labs and academic research programs. Specific recommendations will be given to both industry and the Department of Energy to advocate the need for a major industry-government cooperation to put the U.S. into a leading position in solid state lighting. The stakes include (i) substantial energy savings, (ii) reduced carbon dioxide pollution and (iii) the creation of a new U.S. lighting industry.

Challenges for AlInGaP- and InGaN-based LEDs

In any potential market for high brightness LEDs, from traffic signals to white lighting for general illumination, there remains a great deal of work to be done to increase market penetration of LED technology. *Compound Semiconductor* spoke to Frank Steranka, R&D Manager at LumiLeds Lighting, who outlined some of the challenges raised at the recent OIDA Workshop.

A general feature of LED-based lighting applications is that wider market acceptance requires brighter devices at lower cost. Competing technologies, such as incandescent bulbs, provide a large number of lumens per dollar, and LEDs will eventually have to offer competitive cost-performance figures. "For red or amber devices, penetration of markets such as automotive is largely determined by the cost benefit of LED technology," says Frank Steranka. "There are certainly other advantages to using LEDs, but a lot of auto companies look only at the bottom line."

"In general, the more LEDs start to penetrate the lighting market as a whole, the less the unique features of LEDs are going to count, and the more the cost of the solution compared to competing technologies becomes important."

"In general, the more LEDs start to penetrate the lighting market as a whole, the less the unique features of LEDs are going to count, and the more the cost of the solution compared to competing technologies becomes important."

The driving forces are a little different for nitride-based LEDs, where energy savings are an important factor in a larger fraction of the market. "For AlInGaP, energy savings are important for traffic signals, but much less so for other red lighting markets such as signage or automotive," says Frank Steranka. "For nitrides, cost is important but it can be somewhat offset by energy savings, especially in general lighting applications—when lights are on a lot of the time, energy usage quickly adds up."

The general target for high brightness LEDs is therefore to increase the number of lumens per dollar, using techniques such as increasing the internal quantum efficiency, improving the

extraction of photons, and reducing manufacturing costs by raising yields and improving epitaxial growth.

AlInGaP LEDs

One target for AlInGaP LEDs is to improve the internal quantum efficiency, particularly at shorter wavelengths, where reduced conduction band offsets result in poor carrier confinement. Bandgap engineering of the device structure could result in significant improvements in both performance and temperature sensitivity. A number of techniques have been employed in AlInGaP semiconductor lasers to try to improve confinement of the carriers in the light-generating region, but these have not been widely employed to date in LEDs. "These require tight control over the growth process, and are possible approaches for the future as the quality of production-scale MOCVD reactors improves," notes Frank Steranka.

There is also a need to be able to operate the devices at higher current densities. "The more current you can drive through one of these LEDs while maintaining high reliability and efficiency, the more lumens you get out: the cost is roughly the same so the lumens per dollar rises." However, operation at very high current densities generates heat and causes the efficiency to fall. Bandgap engineering can make devices less sensitive to temperature, and improved heat sinking also helps by getting the heat out more effectively. The development of low thermal-resistance packaging has been a major focus at LumiLeds.

Another key area for AlInGaP LEDs is light extraction. LumiLeds' truncated-inverted-pyramid chip structure has proved successful in extracting over 50% of the photons generated, and results in improvements in lumens per dollar. However, further gains are possible. For example, the use of higher index encapsulants could also potentially increase light extraction. AlInGaP LEDs have an index of refraction approaching 3.5, compared to 1.5 for standard epoxy encapsulants. For such a large refractive index step, there is a small critical angle and a lot of light gets reflected back into the chip. The challenge is to raise the index of refraction of the encapsulant without reducing its transparency or adding cost.

Considering LumiLeds' wafer-bonded transparent substrate approach, it may be that the introduction of an "epi-ready" transparent substrate (e.g. a GaP substrate with a high quality GaP-to-AlInGaP graded layer) could reduce manufacturing costs. "On the other hand, the wafer bonding process is fairly well understood, so huge savings are not necessarily going to arise," says Steranka. "Larger wafer sizes might help: if 4-inch GaP wafers were available, we would consider switching [from 3-inch] and that would likely help reduce the cost."

Nitride Devices

Probably the biggest target for nitride devices is to develop improved or new substrate materials to replace sapphire and enable

the growth of lower defect density material. Many alternatives including bulk GaN, AlN and ZnO, are being considered. Commercially available MOCVD reactors also require improvement—problems relate both to the design of reactors and the lack of fundamental understanding of the nitride growth processes.

"I think everybody would agree that the key to getting low cost nitride devices is improved yield," says Frank Steranka. "One major route to achieve this would be to improve the MOCVD epitaxy process, allowing deposition of InGaN layers with more uniform composition."

Yet another key issue is the efficiency of nitride devices at high current densities. "Today's devices fall in efficiency as the current density is increased," says Steranka. "Eliminating this problem could also result in significant improvements in lumens per dollar."

White lighting requires the development of improved phosphors to better

match the LED emission characteristics. The two main approaches are combining blue LEDs and yellow phosphors, or combining UV LEDs and three-color (red, green, blue) phosphors. The OIDA meeting suggested that it could take about 5 years of work to develop the latter type of phosphor.

The blue LED + yellow phosphor approach requires further improvements in efficiency. It is difficult to control the color temperature of the white light, partly due to variations in the emission of the blue LEDs, partly due to the manufacturing control required to ensure the right amount of phosphor around the chips. Also the color rendering index needs to be improved if this approach is going to be used in a bigger fraction of the indoor illumination market.

At shorter wavelengths, performance appears to be more sensitive to defect density. Gains in performance and lifetime in short wavelength blue lasers have come about as a result of reduced defect density, using ELOG and then ELOG on GaN. Defect density seems to be a bigger issue for short wavelength violet/UV emitters than for longer wavelength devices.

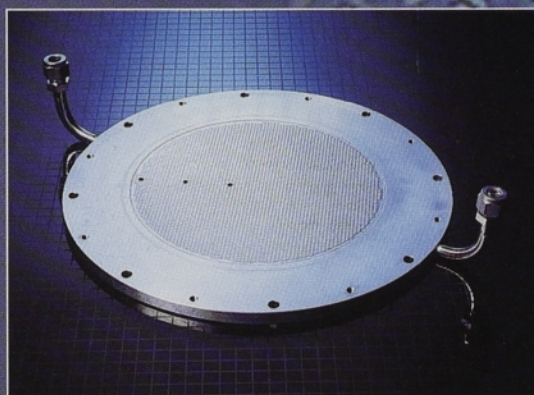
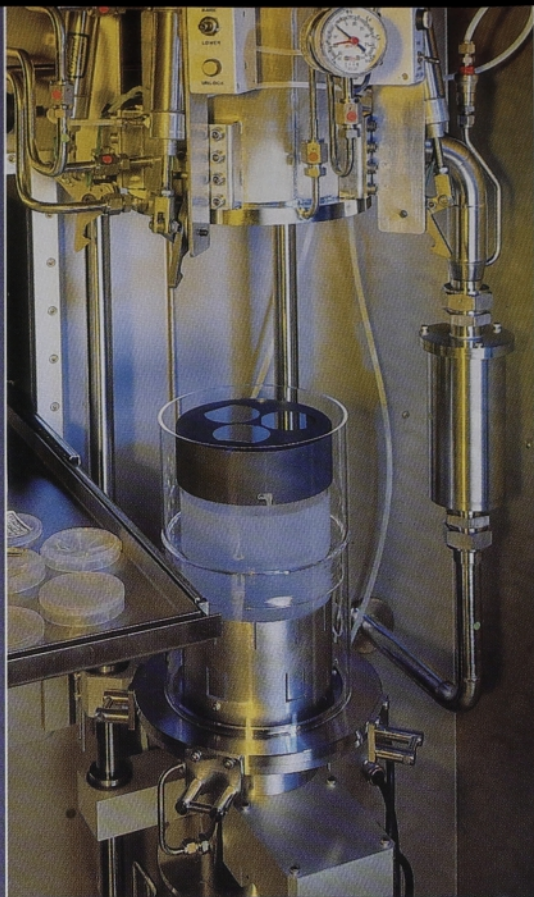
A lot of the packaging materials commonly used for LEDs are not suitable for UV emitters. "LumiLeds uses a silicon encapsulant, which has fewer issues in the deep blue to UV range. This is why we have been able to demonstrate long-term stability from our white high-power LEDs," says Frank Steranka. "However, other encapsulants that won't degrade or yellow, or won't absorb UV light at all, are also desirable for other types of devices."

For nitride devices, light extraction is less of a problem since the sapphire substrate is reasonably transparent. "LumiLeds recently introduced a flip-chip structure [see CS 6(9), p. 19] which does a pretty good job of enabling the photons to escape," says Frank Steranka. "Most of the focus for nitrides in the future will be on the development of alternate substrate materials, further improvements in the MOCVD epitaxy process, and improvements in high-current density efficiency. The resulting improvements in luminous flux and yield will drive the improvements in lumens per dollar that are required for solid state lighting to become a reality."

"Most of the focus for nitrides in the future will be on the development of alternate substrate materials, further improvements in the MOCVD epitaxy process, and improvements in high-current density efficiency."

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GaAs in Taiwan

TIM WHITAKER

It's no secret that there's an awful lot of building going on in Taiwan, with new GaAs foundries and epiwafer vendors seemingly springing up all over the place. The exact number of fabs is something of a mystery, and seems to change depending on who you ask, and when you ask.

Over the past year, the situation in Taiwan was characterized by investors with large amounts of capital viewing GaAs as an excellent investment opportunity. In some cases, these investors had little or no knowledge of the GaAs industry but were attracted by sky-high market projections and the success of silicon foundries such as TSMC and UMC. With the recent changes in market conditions (either real or perceived), there has been some retrenching by investors, who are being more careful about where they spend their money, with the result that some projects will be delayed or may not get off the ground at all. For the

worldwide GaAs industry, this is probably not such a bad thing, since it reduces the threat of an over-capacity situation in the market, which would drive prices through the floor. It also may somewhat reduce the pressure being felt by GaAs substrate suppliers (see page 77).

The failure or delay of some of these plans is not surprising when one also considers that there are only a finite number of groups that fully understand complex process technologies like HBTs. Although such processes have matured considerably, it remains relatively easy to get initial results and much more difficult to ramp up to high volume production.

Nevertheless, many projects remain on track, aided in no small part by the Taiwanese government, which is aggressively supporting compound semiconductor technologies, according to John Lau of WIT SoundView. "Taiwan's government has targeted compound semiconductors as the next generation technology needed for advanced communication chips," says Lau, who attended the grand opening of the new WIN Semiconductors fab in late December, an event marked by speeches from the Vice President of Taiwan and several ministers of state. "The government has invested indirectly in both WIN and Compound Semiconductor Manufacturing Corp. (CSMC)," he says. "Both these companies are following the highly successful foundry model developed within the silicon industry by companies such as TSMC and UMC."

New GaAs Foundries

WIN and CSMC join Hexawave and Advanced Wireless Semiconductor Co. (AWSC) on the list of GaAs fabs in Taiwan, and these will soon be joined by Global Communication Technology (GCT), which is eventually planning to build two fabs (see box). Two other ventures are moving forward rapidly:

- **G-Advanced Semiconductor Manufacturing Co.** (GASMC) held a ground-breaking ceremony for its new 6-inch GaAs fab in July of last year. The first phase of construction at the Koos Lungtan Industrial Park is expected to be completed by April 2001. GASMC, founded by Uni-President Enterprises, Compal and Bao-Chen Group, will start trial production of 6-inch GaAs MMIC wafers in the fourth quarter of 2001.
- Epiwafer producer **Procomp Informatics** has set up a joint venture with **Acer Communications and Multimedia** to build a 6-inch GaAs foundry. One of the foundry's

Things to Watch
2001

#3



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largest customers will be Mitsubishi Electric, while Celeritek has also invested in the new company, known as **Suntek Compound Semiconductor Co. Ltd.**

An interesting point to consider is why these new companies are all offering foundry services. One reason is undoubtedly the optimism generated by the huge success of TSMC and UMC; also, as Ron-Ting Huang of GCT points out, there is a lack of experienced design teams in Taiwan. Another issue is the difficulty faced by new, small companies in trying to gain design wins with large manufacturers of products such as handsets—the new companies may not have the critical mass to be credible to the major handset suppliers.

UMC's chairman, John Hsuan, has expressed reservations about Taiwan's GaAs industry, pointing out that there aren't enough fabless design houses to stimulate process development at the foundries. He believes that if the foundries receive orders only from integrated device manufacturers (IDMs), their business will be "merely a manufacturing business—it would not require continual improvement in technological expertise." Hsuan went so far as to predict that only one GaAs foundry company would survive in Taiwan.

Epiwafer Vendors

Predictably, along with the new foundry activity in Taiwan there are also a growing number of companies providing GaAs epiwafer services. The list includes Procomp Informatics, VPEC and UEC [see CS 6(7), p.28], as well as new players such as South Epitaxy Co. [see CS 6(7), p.31]. ATMI recently announced that it would expand its Epitaxial Services business into Taiwan and the Asia-Pacific region, although it does not have plans to establish a GaAs epiwafer production facility in Taiwan at present. Among the new epiwafer ventures are the following:

- The world's largest HBT epiwafer supplier, **Kopin**, is in the process of setting up an overseas subsidiary in Hsinchu to bring it closer to the local Taiwanese market. Several 6-inch production MOCVD systems are being installed in a leased facility, and production is expected to begin in mid- to late 2001.
- **Hitachi Cable** has spent 1.7 billion yen (US\$14.5 million) to acquire a 51% stake in **Giga Epitaxy Technology Corp.**, a company which is building a facility to manufacture GaAs-based epiwafers. The 10,000 m² plant, which is located in Yangmei, Taoyuan County, is expected to become operational in the third quarter of 2001. Giga Epitaxy will initially produce an equivalent of 2,000 4-inch wafers a month, and within five years the capacity is expected to grow to 10,000 wafers/month. The company will focus on the production of 4- and 6-inch HBT epiwafers grown by MOVPE. Hitachi Cable's plant in Japan is currently capable

Global Communication Technology

Global Communication Technology Corp. (GCT) is close to completing its first 6-inch GaAs foundry in Hsinchu, Taiwan, and is already planning a second fab. *Compound Semiconductor* spoke to GCT's President, Ron-Ting Huang, a former vice president of Global Communication Semiconductors (GCS).

- CS. When will the GCT fab be finished? When will you start trial, and volume, production?
- GCT. GCT's 6-inch GaAs fab, which is equipped with a class 1 clean room, will be completed in January 2001. Equipment installation and qualification will follow right away, and we expect these procedures to be completed in March. Process qualification will be started in Q2. Trial production will commence in Q3 and mass production will begin in Q4, 2001.
- CS. What will be the capacity of the new fab?
- GCT. The capacity of Fab I will be 5,000 6-inch wafers per month by the end of 2001.
- CS. How are plans for GCT's second fab coming along?
- GCT. Construction of the second fab will begin in Q1, 2002 and is expected to be completed in Q1, 2003. The maximum capacity of Fab II will be 15,000 6-inch wafers per month.
- CS. What's the relationship between GCS and GCT?
- GCT. GCT is a completely independent company, and eventually we plan to become publicly traded in either Taiwan or the USA. We expect that GCT and GCS will become a second source for each other.
- CS. Who are GCT's main shareholders?
- GCT. First International Computer (FIC), VIA and Central Investment Holdings each own 12.67% of GCT.
- CS. What are the main reasons to establish GCT in Taiwan?
- GCT. Manufacturing costs are much lower in Taiwan than in the USA.
- CS. Why are new foundries appearing in Taiwan, and not integrated device manufacturers (IDMs)?
- GCT. TSMC and UMC in Taiwan have demonstrated a very successful model for Si foundry services. Hopefully, GCT can demonstrate the same successful model for GaAs. Taiwan still suffers from a lack of good RF design teams, so it makes more sense to start as a foundry.
- CS. Where will most of GCT's business come from?
- GCT. We expect a 50:50 split between fabless design houses and IDMs.
- CS. What factors will make existing IDMs outsource to foundries?
- GCT. The main factors are cost reduction and flexibility.

of producing 8,000 wafers a month; the firm plans to triple epiwafer capacity at that plant by June 2001.

- One of Taiwan's largest silicon foundries, **UMC**, has provided 40% of the capital to fund **Epitech**, which plans to make 6-inch InGaP and InP HBT epiwafers. Construction of the company's facility in Tainan began in September 2000, and trial production is expected to begin in February 2001. By 2004, Epitech is targeting a production volume of 150,000 6-inch HBT wafers per year (12,500/month) as well as 24,000 4-inch VCSEL epiwafers.

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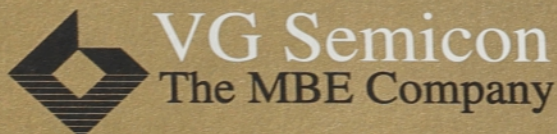
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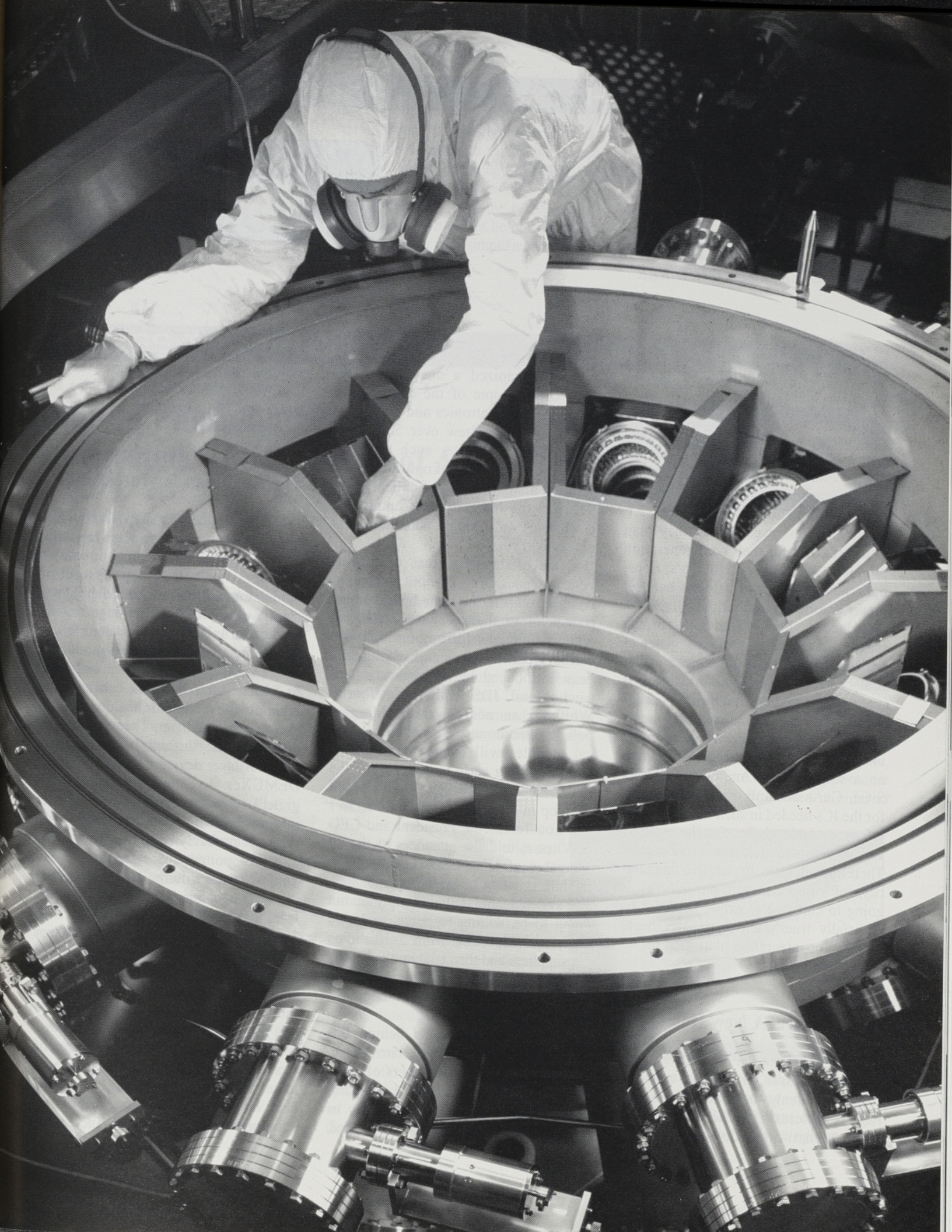
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Convergence of Optics and Electronics

MARIE MEYER & TIM WHITAKER

Things to Watch
2001

#4

Last year, we chose InP Microelectronics as one of our "Things to Watch", and there was certainly a great deal of activity in this field. TRW announced that construction of its new 4-inch InP production facility was complete—volume shipments of InP chips are expected in the second half of 2001. Furthermore, both Vitesse and RF Micro Devices revealed that they plan to use InP ICs for their next generation products, focusing on 40 Gb/s fiber-optic components and wireless handset power amplifiers respectively.

One of the hottest topics in the industry at present is the convergence of optical components and communication ICs. There are several possible levels of integration, ranging from the co-packaging of electrical and optical components in modules right through to monolithic integration of different types of devices on a single wafer. And while CMOS, SiGe, GaAs and InP are all contenders for the ICs needed in such modules, only InP is a viable choice for the emitters and detectors at telecom wavelengths. Therefore, despite its relative immaturity, InP's importance in our industry is going to continue to grow. This will be especially true when companies begin looking for integration platforms for 40 Gb/s components.

Convergence: A New Hot Topic

While integration has been a popular research topic for 15 years or more, it has suddenly become a topic of intense interest in the commercial realm. That was demonstrated in

December when the investment firm JP Morgan organized a one-day conference on the topic of the convergence between optoelectronics and communications ICs that drew over 500 attendees! Several topics such as next generation packaging of optics and ICs, contract manufacturing of optical products and the integration of optics and electronics on a single substrate were discussed.

One of the first areas of convergence is packaging of optical components and ICs in the same box to create transponders that perform send and receive functions for any optical port. These types of product have already been introduced by suppliers such as Lucent and JDS Uniphase. Charlie Whilhoit, an analyst at JP Morgan, believes that commercial 40 Gb/s optical modules will emerge towards the end of 2001 or early in 2002, while the real momentum for these products will develop in the second half of 2002.

Lou Tomasetta, President and CEO of Vitesse, told the attendees at the JP Morgan conference that "at 40 Gb/s, the module is going to be the component". The system manufacturers simply are not going to be willing to purchase 15–20 different components from 5–10 different suppliers and then take on the task of assembling it all. Instead, Tomasetta said, they want to buy "a box with an optical fiber coming out the end."

What are the drivers behind this trend? The first is cost. In the current system there are too many layers of overhead—there is the component company, the module assembly company, one or two other contract manufacturers, and,

ultimately, the system company itself. In addition, more highly integrated modules would produce savings in size and power, and can also deliver improvement in performance.

The Roadmap for Integration

What is the roadmap for integration? Tomasetta says the place to start is detectors and amplifiers integrated together. Next is electroabsorption modulators with high voltage drivers, a classic example of something that can be done in InP but can't be done if you are using a lithium niobate modulator or are making your drivers from GaAs or SiGe. "After that you can begin to integrate the modulator, the driver and a wave guide amplifier. Then you can do the detectors, the amplifiers and the physical layer devices, the MUXes and DEMUXes. Eventually, you can integrate a transceiver and sooner or later integrate even a transponder, with the laser probably being the most difficult component to integrate," said Tomasetta. He said the goal is to reduce the cost of a module from its current level of \$5,000–\$10,000 to less than \$1,000. "I know a lot of people say that is not possible, but with high volume integration on four, six or eight inch wafers, you would be amazed at what kind of cost reductions you can get once you invest in doing the integration."

Whilhoit predicts that a number of strategic partnerships or mergers will arise, cutting across the boundaries between traditional electronic and optical component manufacturers. Increasing

investment is also likely to be targeted towards companies that focus on packaging, modules and integrated components, rather than those producing stand-alone devices.

All of this may sound as though there is a juggernaut gathering steam in the communications industry. Nevertheless,

don't be surprised if you hear some contrary opinions. "Typically the most prevalent technical argument against integration is that the best technology is needed for each component and customers are not willing to trade off any performance," explains Tomasetta. But he notes that this is generally an over-simplification. There

may be some very-high end applications where this argument is true—for example, a very long single reach cable with no amplifiers in the middle. However, for the high-volume, short-distance applications, the system companies will be happy to trade performance for the many benefits of greater integration.

THINGS TO WATCH

Indium Phosphide Planar Integrated Optics Comes of Age

JENS NOECKEL, TOM PIERSON and JANE ZUCKER
Nanovation Technologies

Things to Watch
2001

#5

Integrated optics had its start in the sixties, when scientists observed that light could be guided and steered by thin films. The first big commercial success of integrated optics occurred in the next decade, with the development of low-loss optical fiber. This invention was responsible for a giant leap in capacity in the mid-eighties when fiber cables started to replace copper cables in the telecom network.

Planar lightwave circuits (PLCs), where flat layers (rather than the cylindrical core found in fibers) guide light, stayed on the sidelines. Although capable of higher optical signal processing functions beyond mere transport, PLCs did not find a mass market. More expensive than electronic alternatives, they were confined mostly to niche markets and laboratory applications during the beginning of the fiber-optic revolution.

In the last decade, however, the explosive growth in Internet traffic has brought a bandwidth boom, and a critical need to manage huge volumes of information. Now the time has come for wavelength-division multiplexed (WDM) photonics, where many color-coded sig-

nals co-propagate in the same medium. WDM has caused a second giant leap in communications capacity. Planar integrated optics components, with their ultra-fast capability for routing and processing of optical signals, have finally been pressed into service. Demand for many optical components now exceeds supply.

Indium Phosphide: Adapting Form to Function

PLCs can serve many roles in fiber-optic networks: splitting and combining of signals, sorting of different wavelengths, modulation, switching between space channels, monitoring, filtering, amplifying, and grooming (i.e., the reshaping and retiming of optical signals). Many materials can be used for passive functions such as filtering and splitting. However, for the generation and detection of light in the 1200–1600 nm fiber-optic region of the spectrum, the current material of choice is indium phosphide (InP).

Unlike sophisticated modern silicon ICs, state-of-the-art indium phosphide photonic integrated circuits are still in their infancy, with several orders of magnitude less complexity. Nevertheless, indium phosphide PLC manufacturers must develop a similar set of standard micro-fabrication, mass production, and packaging techniques. Smaller, faster, cheaper and more functional photonic integrated circuits are needed in order to

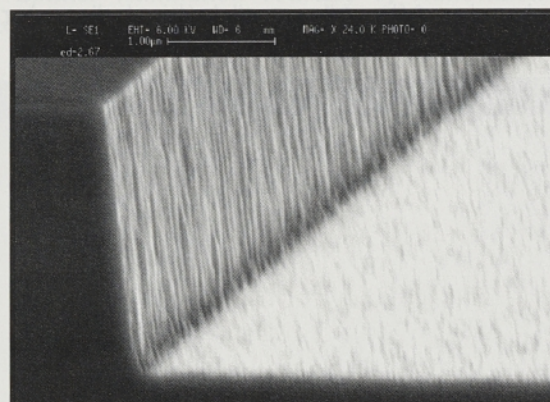
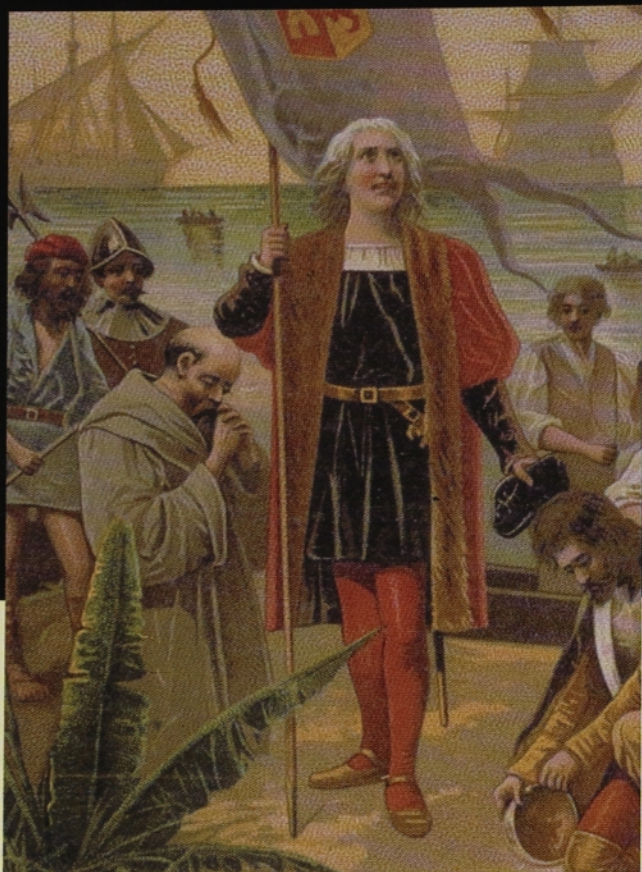


Figure 1. Scanning electron micrograph of an InP waveguide etched using conventional chlorine-based ICP RIE displays edge roughness on the sidewall and substrate floor.



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Some of the challenges to material science are already apparent with the simplest possible circuit, a straight rib waveguide. Figure 1 shows a typical result of inductively coupled plasma reactive ion etching (ICP RIE) of indium phosphide using a chlorine-based process chemistry. ICP RIE is a dry etching technique in which an electric field causes energetic ions to strike the surface of a semiconductor substrate at an angle perpendicular to the substrate surface. Although "dry" ion etching is much more directional than wet chemical etching, the level of surface roughness shown can cause unacceptable scattering loss and a high variability in device parameters.

Sharp Splits, Smooth Curves

One of the keys to high-quality mass production is standardization of fundamental components. A basic building block for indium phosphide photonic circuits is the multimode interference (MMI) coupler. MMI couplers (such as that shown in Figure 2) are used in interferometric modulators and wavelength filters. MMIs are also employed in power splitters, like the 1 X 8 depicted in Figure 3. The fact that indium phosphide circuits are able to confine light very tightly proves advantageous for the operation characteristics of MMI devices. Numerical simulations based on the Time/Frequency Domain Simulator for Photonic Devices (TFDS) [1], which takes into account both reflection and scattering effects, demonstrate that sharply defined, vertical sidewalls are essential for accurate spectral response and power splitting in MMI structures. To develop a fast, highly controllable ICP RIE method yielding deep, vertical sidewalls and smooth morphology, it is necessary to move beyond simple etch chemistries.

Chemistry is Key

Process engineers control the quality and speed of ICP RIE by varying conditions such as ion flux, ion energy, gas flow, temperature and pressure, and especially the gas composition. For

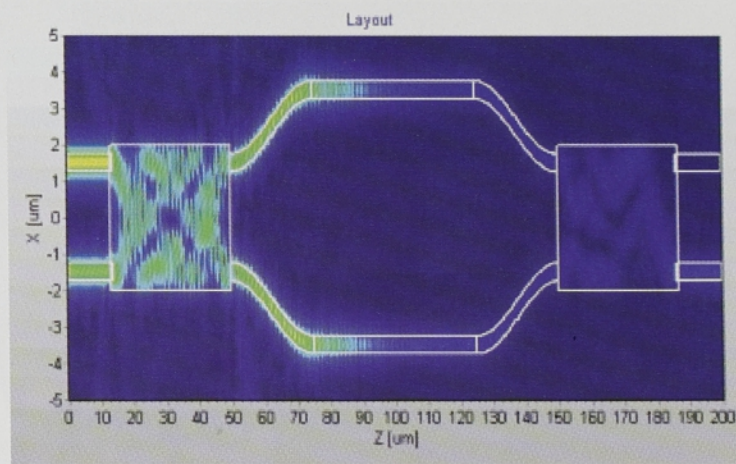


Figure 2. Optical intensity pattern within an electroabsorption modulator, relying on two multimode interference couplers (rectangular boxes) to split and recombine a light wave fed in at the top left. A voltage applied to the two arms in the center determines which path the light takes. Calculated via Apollo Photonics' Time/Frequency Domain Simulator For Photonic Devices (courtesy of Apollo Photonics).

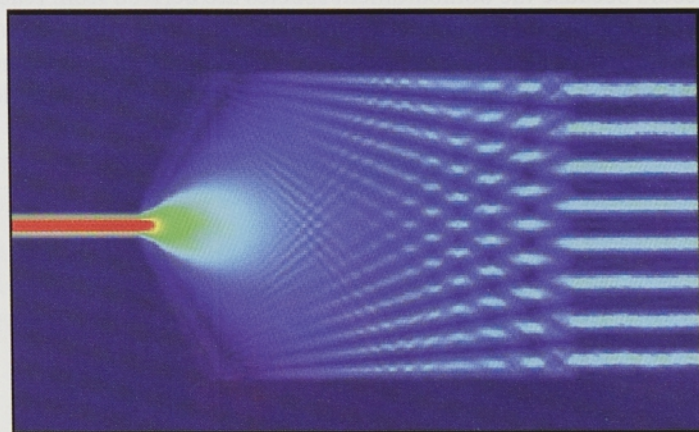


Figure 3. Optical Intensity Pattern within a 1X8 Multimode Interference Splitter (simulation courtesy of Nanovation Technologies).

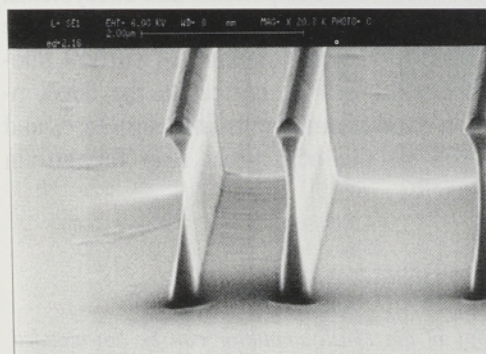


Figure 4a. Scanning electron micrograph of InP slabs displays an undercut profile, characteristic of an etch process that is dominated by chemical rather than physical mechanisms.

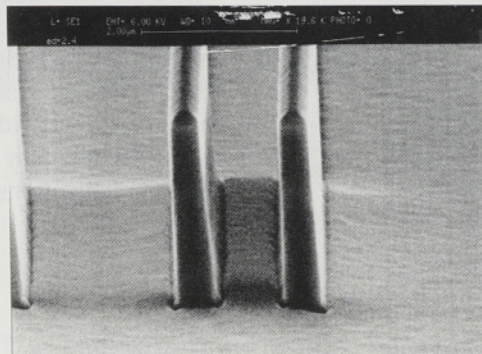


Figure 4b. As the flow of etchant gases is tuned toward a less dominant chemical attack, the etch profile becomes slightly overcut and lateral attack of the slab sidewalls is suppressed.

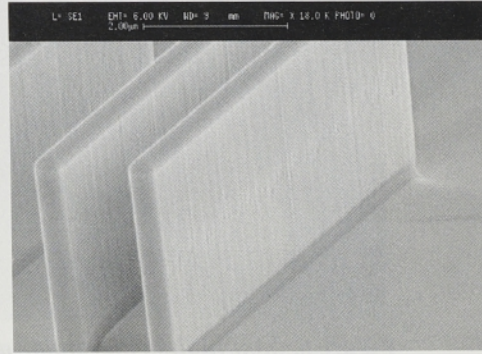


Figure 4c. Optimization of the process chemistry yields a highly vertical etch profile with ultra-smooth surface morphologies. The InP slabs shown above are 0.4- μ m-wide and etched 3- μ m-deep at a rate of 1 μ m/min.

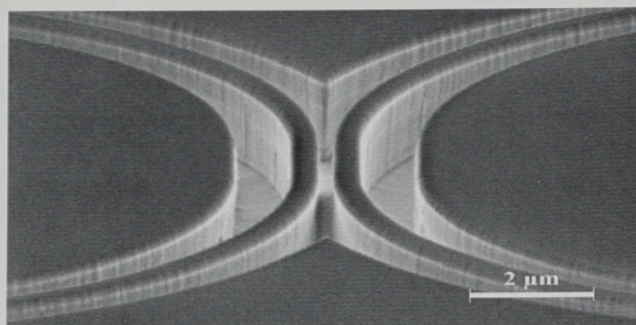


Figure 5. Deeply-etched directional indium phosphide coupler structure produced at Nanovation Technologies. The minimum separation between waveguides is 0.25 μm.

example, fast etching of indium phosphide—several microns per minute—has been achieved with mix of chlorine gas and argon gas [2]. High-speed etching is a necessity for high-throughput production. However, the requirements of smooth surfaces or straight sidewalls might call for quite different recipes.

The quest for the perfect profile involves a balancing act between physical and chemical effects [3]. Chemical etching occurs because the bombardment species are derived from reactive gases and thereby undergo chemical reactions with the target substrate. During chlorine-based ICP RIE of InP, chlorine ions react with indium and phosphorus atoms to form volatile

products that are removed from the semiconductor surface. The differing reaction rates of the InCl_x and PCl_x can translate to different removal rates of the substrate atoms and result in rough-etched surface morphologies as shown in Figure 1.

On the other hand, physical effects include brute-force sputtering, wherein high-energy ions impact the semiconductor surface and physically eject target atoms from the surface. Physical sputtering also aids in the removal of etchant by-products. Clean up mechanisms during ICP RIE, both physical and chemical, are important. If by-products are allowed to accumulate near the sample, they can slow down the etching rate, form their own masking layer, and cause irreproducible results.

The series of photos in Figure 4 shows how the balance between physical and chemical etching affects waveguide quality. Figure 4 shows a series of 0.4-μm-wide InP slabs after ICP RIE. In Figure 4a, the hourglass profile is representative of an aggressive chemical-etch component. Lateral attack of the slab sidewalls results in undercutting of the silicon dioxide etch mask. By contrast, Figure 4b shows InP slabs etched in a process containing a less prominent chemical component resulting in an overcut profile. By optimizing the mixture of process gases the engineer can tailor the etch profile to satisfy desired properties. For photonic structures, the desired properties include high verticality and smooth-etched surfaces. Figure 4c shows a pair of InP slabs RIE etched in a chlorine-based process under optimized process conditions. The etch rate achieved for this process is a respectable one-micron-per-minute.

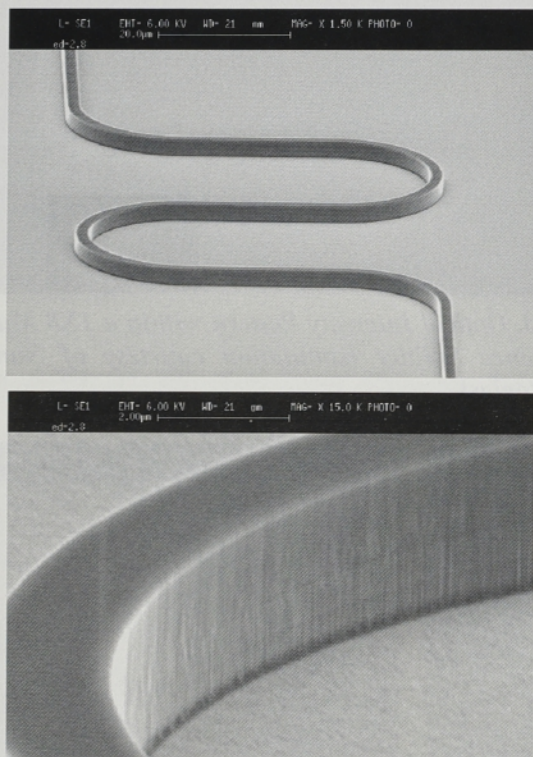


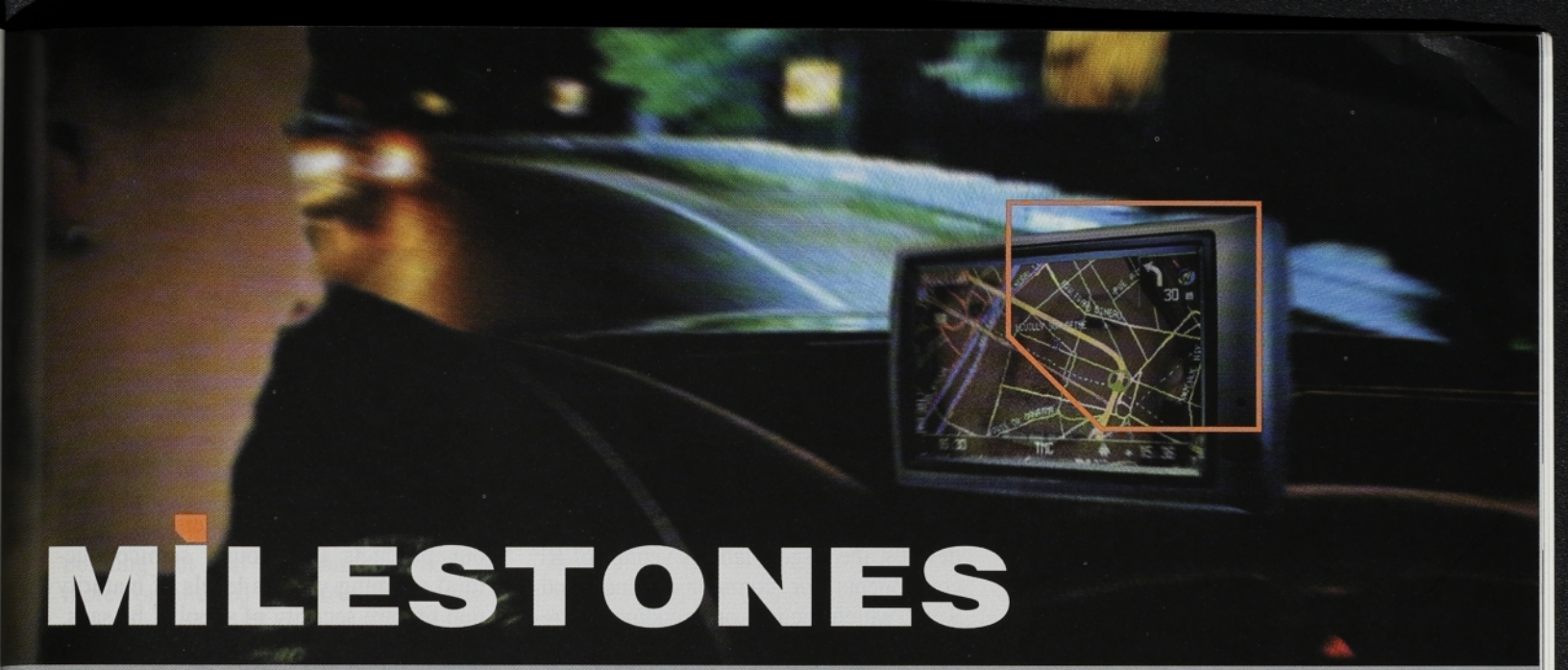
Figure 6. (top) Indium phosphide meandering waveguide structure produced at Nanovation Technologies by e-beam lithography and inductively coupled plasma reactive ion etching process. (bottom) Magnified view of the etched waveguide surface.

Advanced Nanostructures Meet Their Market

In recent years, progress in dry etching has made entirely new types of semiconductor materials and devices a reality. These include photonic-bandgap crystals, micro-electromechanical structures (MEMS), ultra-narrow gap directional couplers (Figure 5) and extremely tight radius bends (Figure 6). However, such feats of fabrication are no longer regarded as laboratory curiosities or “gee-whiz” demonstrations. With the growth in the number of WDM channels and the extension of fiber-optic networks closer to the home, there is intense pressure to develop cost-effective, mass-produced PLC components and subsystems. Ultra-precise processes such as the ones discussed here are already being incorporated in the manufacture of current integrated circuits. Nanostructures will be critical to the development of the next decade’s communications infrastructure, and will certainly play a role in the next great leap forward in telecommunications capacity.

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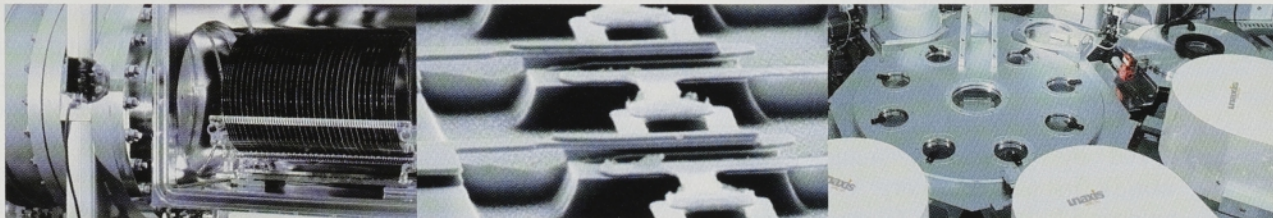
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GaAs Foundries

TIM WHITAKER

Things to Watch
2001

#6

Foundries are not new to the GaAs industry—just ask TriQuint, TRW, OMMIC (formerly Philips Limeil) and a number of other manufacturers that fabricate device wafers according to their customers' proprietary designs. However, while these fabs also have in-house designers, a number of new companies are emerging which are positioned as "pure-play" foundries. These fabs have no designers, and their entire business is to fabricate customer-specific devices and ICs.

The first such "pure-play" foundry in the GaAs industry was Global Communication Semiconductors (GCS) of Torrance, CA. Another GaAs foundry based in California, Network Device Inc. (NDI), was purchased by Alpha. Not surprisingly, most of the other new foundry activity is taking place in Taiwan. The foundry model has been adopted extremely successfully in the silicon industry, especially in Taiwan, resulting in the formation of manufacturing giants such as Taiwan Semiconductor Manufacturing Company (TSMC) and UMC.

The first Taiwanese GaAs foundry, Advanced Wireless Semiconductor Company (AWSC), commenced operations at the end of 1999, and has since been followed by WIN Semiconductor, the world's first 6-inch foundry. As described on page 57 of this issue, Global Communication Technology (GCT) has also built a 6-inch GaAs foundry and there are several more in the pipeline.

Who Uses Foundry Services?

Broadly speaking, there are two types of foundry customer; design houses that don't have a fab, and existing GaAs manufacturers (also referred to as IDMs, or integrated device manufacturers) that need to outsource production for a variety of reasons.

The growing list of fabless GaAs companies includes Stanford Micro-devices, the largest fabless vendor of RF components for communications; End-wave, which focuses on broadband wireless systems; and Multilink, a fiber-optic IC manufacturer [for a profile of these three companies, see CS 6(8), p.55]. A new entrant to the field is RF Solutions—see box.

According to Owen Wu, President of GCS, around 40% of his company's business comes from fabless companies, with the remainder coming from IDMs. "Both groups using foundries will increase in the future, however the percentages will remain roughly the same i.e. 40–50% for fabless, 50–60% for IDMs," he says.

There are three main reasons why IDMs use foundry services, says Owen Wu. "Many GaAs manufacturers want to offer their customers a second source for their products," he says. "Secondly, some manufacturers don't have enough capacity and have to use foundries to cover the overflow. Also, foundries can offer access to new or alternative technologies that the IDMs don't have."

Fujitsu Outsources Production

Earlier this year, Fujitsu Quantum Devices, ranked by some as the largest GaAs manufacturer in the world, announced that it would outsource up to 35% of its total production by 2002 [see CS 6(6), p.31]. The company is planning to use foundries to produce some of its RF and microwave GaAs products, while at the same time expanding its internal production capacity.

Gene Brannock, Executive VP of Fujitsu Compound Semiconductor Inc. (a member of the family of Fujitsu subsidiaries in the US), explained the reasoning behind this decision. "Fujitsu is now exploring the use of foundry ser-

vices, and outsourcing in general, because we see the markets served by our products (compound semiconductors) reaching various levels of maturity that require security of supply," he says.

"This security of supply takes several forms. We require flexibility in rapidly changing market segments, such as Light-wave Optics, and we also need to ensure adequate supply from multiple sources in larger scale market segments, namely Cellular Terminals. Further, we need access to state-of-the-art performance in emerging and high reliability market segments, such as Space and Cellular Base Stations.

"It is not practical to envision a single manufacturing entity managing these diverse disciplines well. Hence, Fujitsu is focusing on maintaining its core competency and utilizing the appropriate manufacturing core competencies, whether these are internal or external."

Why Use Foundries?

Of course, there are many arguments both for and against the use of foundries. For fabless companies, the most obvious advantage of using foundries is that there is no need to build a fab. There is a lower capital investment, a lower technology risk and a greater degree of process flexibility. Building a fab can involve a commitment to technology up to two years in advance. A fabless model provides shared economies of scale and there is no cost to exit, while a fab must be filled.

However, there are certainly drawbacks to being fabless, the main one being slow turnaround time related to the difficulty of securing priority in over-subscribed fabs. Speaking at the 2000 GaAs IC Symposium, Larry Wang of EiC described how his company was initially fabless. "We ran into problems with securing commitment and delivery from

foundries," he says. "Our customers were concerned about the supply volumes that we could guarantee. In the end, we decided that we had to go ahead and build a fab." EiC's fab commenced production in early 1998.

With the prospect of lots of new foundry capacity in the industry, the current climate seems much healthier for fabless vendors. In fact, the foundries will require more fabless design houses to keep them in business. It is also worth pointing out that the foundry model is more complicated for GaAs than for silicon. Most silicon foundry work involves digital VLSI, with simple on/off gates,

large die sizes, 8-inch (or larger) wafers, mature processes and designs that are easily ported from one foundry to another. A lot of GaAs foundry work involves analog ICs that depend on transistor characteristics, which are in turn closely related to process parameters, especially for HEMTs (the properties of HBTs are more closely tied to the epitaxial layer structure). This reduces the level of portability between foundries, and can lead to specialization. Nevertheless, the demand for foundry services looks set to rise, and both foundries and fabless companies will play an increasingly important role in the GaAs industry.

A Fabless View—RF Solutions

A number of companies in the GaAs industry are focusing their efforts on design and utilizing foundry services for their manufacturing needs. *Compound Semiconductor* spoke with Steve Richeson, CEO of RF Solutions, a fabless design company based in Atlanta, Georgia.

"Four years ago, fab capacity was the main constraint for GaAs ICs in the wireless industry," says Steve Richeson. "Starting about 18 months ago, fab capacity has increased rapidly, and the primary constraint is now the availability of designers." RF Solutions has about 35 employees and has grown out of Georgia Tech, which creates more RFIC designers than almost anywhere else. "It takes longer to make an IC designer than it does to make a fab," says Richeson. "We think that design will continue to be the primary constraint in the industry for the next six years."

To compete with established GaAs manufacturers, RF Solutions has to differentiate itself, either in terms of market focus or by designing more efficiently. "Product designers at GaAs fabs have established channels to market and can push their designs out to the fab and make money," says Richeson. "Their focus is to innovate rapidly, whereas we have to be extremely efficient with our designs. When you have your own fab you're less concerned with that."

RF Solutions' target market is transceivers for wireless broadband devices operating at 2–6 GHz, focusing on high levels of integration, with lots of different functions on a single chip. Volume production in these markets is too far in the future to attract a great deal of interest from the incumbent GaAs manufacturers, says Richeson. "There aren't many public companies that can rationalize spending \$14 million this year on below-the-line costs to develop MCMs for broadband wireless, which is what we're doing. The incumbents watch companies like us then snap them up as the market gains traction—that's how R&D is done these days."

The landscape of the wireless GaAs industry is also changing. "We're selling highly integrated RF modules to companies that make wireless networking equipment," says Steve Richeson. "In a couple of years there won't be any more wireless equipment companies that buy RF components and make wireless devices, only networking companies that buy RF blocks."

Richeson is confident that gaining access to foundries will not prove to be a stumbling block. "With all the new fabs and capacity expansions, we don't see a constraint on the supply side," he says. "Also, we've taken steps in building our Board of Directors to establish relationships with various fabs, to make sure we don't get left out."

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10 Gigabit/Second Communication Systems

Things to Watch
2001

#7

TIM WHITAKER

Optical links operating at 10 Gb/s are now well established in long-haul telecommunications backbones, and operators are looking towards next generation 40 Gb/s systems. At the same time, new standards and lower cost products are being developed that lead to proliferation of 10 Gb/s in metropolitan area networks (MANs), local area networks (LANs) and very short reach (VSR) links. The driver, as always, is the huge demand for bandwidth. Two major areas of work are the development of a standard for 10 Gigabit Ethernet, and the introduction of a SONET standard for VSR optics.

Very Short Reach (VSR) Optics

Current 10 Gb/s (OC-192) SONET and SDH standard optical interfaces are designed for transmission distances of 2 km or more, resulting in excessively high component costs when used for the very short distance requirements such as intra-office applications. Typically, the need is to connect co-located elements of a communications network, such as switches, routers, optical cross-connects and DWDM transport gear. The 10 Gb/s very short reach (VSR) interface is being promoted within the Optical Internetworking Forum (OIF) as a way to speed deployment of OC-192 links while lowering overall connectivity costs [see CS 6(3), p.52].

Recently, Cisco Systems and Ciena, two of the world's leading optical network providers, demonstrated the first successful interoperability test of 10 Gb/s VSR optics using Cisco's Internet routers and Ciena's optical core switching system. The transmitters contained 12-element arrays of 850 nm VCSELs, each operating at 1.25 Gb/s and transmitting in parallel over 300 m of multi-mode ribbon fiber.

"This successful interoperability test represents an impor-

tant milestone for service provider networks moving to 10 Gb/s core IP infrastructures," said Tony Bates of Cisco. "With VSR optics, service providers can deploy a low-cost, standards-based 10 Gb/s optics solution months ahead of other proposed technologies."

Several VCSEL manufacturers, including Agilent, Emcore, Honeywell, Infineon, Gore and Mitel, have developed parallel VCSEL arrays for VSR links, while both Vitesse and Conexant have announced ICs for these applications.

VSR optics looks set to become an important market for VCSELs. In a recent market forecast, ElectroniCast predicted that SONET VSR would account for 26% of the total VCSEL transceiver market in 2004, equivalent to \$884 million [see page 78]. In comparison, another major market for VCSELs, Ethernet, is expected to grow from \$86.5 million in 1999 to \$952 million in 2004.

"We feel that the majority of the 10 Gb/s datacom market for VCSELs is going to be for short distance computer room interconnects, and that the market will be split between parallel and

PMD Interface (Optical Transceiver)	Laser Technology	Fiber Type	Minimum Distance	Major Applications
850 nm serial	1 × 10 Gb/s VCSEL	Multi-mode	65m	Connecting switches, routers within equipment rooms in central offices or points-of-presence (POPs)
1310 nm wide WDM	4 × 2.5 Gb/s uncooled DFB lasers or VCSELs	Installed Multi-mode	300m	LAN backbones within/ between buildings, around campuses Links from 10 GbE networks to SONET/SDH WAN networks
		Single-mode	10km	LAN/MAN backbones connecting geographically separate buildings, remote servers
1310 nm serial	DFB lasers or VCSELs	Single-mode	10km	
1550 nm serial	Cooled DFB lasers	Single-mode	40km	MAN/WAN backbones

Figure 1. Four physical media dependent (PMD) interfaces, otherwise known as optical transceiver technologies, have been ratified to support 10 GbE. The PMD sublayer is the part of the physical layer that transmits and receives optical signals. The different PMDs support a wide variety of applications in local area networks (LANs), metropolitan area networks (MANs), and wide area networks (WANs).

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serial solutions,” says Jim Tatum, Honeywell’s VCSEL Technology Manager. “In addition to our parallel array product, Honeywell has developed a VCSEL for 10 Gb/s datacom—we are currently sampling this product to key customers, and are in the package definition stage.”

10 Gigabit Ethernet

The various Ethernet iterations (Ethernet at 10 Mb/s, Fast Ethernet at 100 Mb/s, Gigabit Ethernet at 1 Gb/s) have been widely adopted in local area networks (LANs), and now the industry is developing a new standard at 10 Gb/s. 10 Gigabit Ethernet (10 GbE) is designed as the natural evolution of Ethernet to both higher speed networking and greater distances. As well as a 10X speed increase, 10 GbE has a specification for long-haul (40+ km) transmission which can be used for building metropolitan area networks (MANs). The new standard will also include an option to allow 10 GbE to be transported across existing OC-192 SONET infrastructures.

Standards and Product Development

Since March 2000, about 75 companies have been discussing and defining the industry standard for 10 GbE as part of the IEEE 802.3ae Task Force. The objectives for this group include defining physical layer specifications for various link distances. Picolight, a VCSEL-based transceiver manufacturer located in Boulder, CO, was one of founding members of the 10 GbE activity. “We are editing the portion of the standard that addresses Fiber Physical Layer i.e. the types and specifications of laser-based transmit and receive circuits that implement a ‘standards compliant fiber link,’” says Picolight’s CEO, Stan Swirhun.

In November 2000, a group of four optical transceiver technologies, otherwise known as physical media dependent (PMD) interfaces, were ratified for the 10 GbE standard [see Figure 1]. “Picolight was largely responsible for championing the serial 10 Gb/s VCSEL implementation,” claims Stan Swirhun. “The industry as a whole believes this will be the volume leader, probably accounting for at least 50% of units sold. Essentially this is a recognition that many 10 GbE links will be short distances from switch to switch, router to router, in locations such as points-of-presence (POPs) where there is a high switching density.”

The 10 GbE standard is expected to be ratified in early 2002, but as usual, there will be a few companies who will “jump the gun”, explains Stan Swirhun. “A few communications circuits companies will have initial products out before then, and a very few optoelectronics companies—Picolight is one of them—will have 10 GbE transceivers in customers’ hands before the standard closes.”

According to the Dell’Oro Group, shipments will ramp slowly in 2001/2 then take off in 2003 [see Figure 2]. Picolight thinks these estimates are on the conservative side and that the market could reach 100K units during 2002. Figure 3 also shows that the number of Gigabit Ethernet ports will increase from 4.2 million in 2000 to over 32 million in 2004. These unit volumes

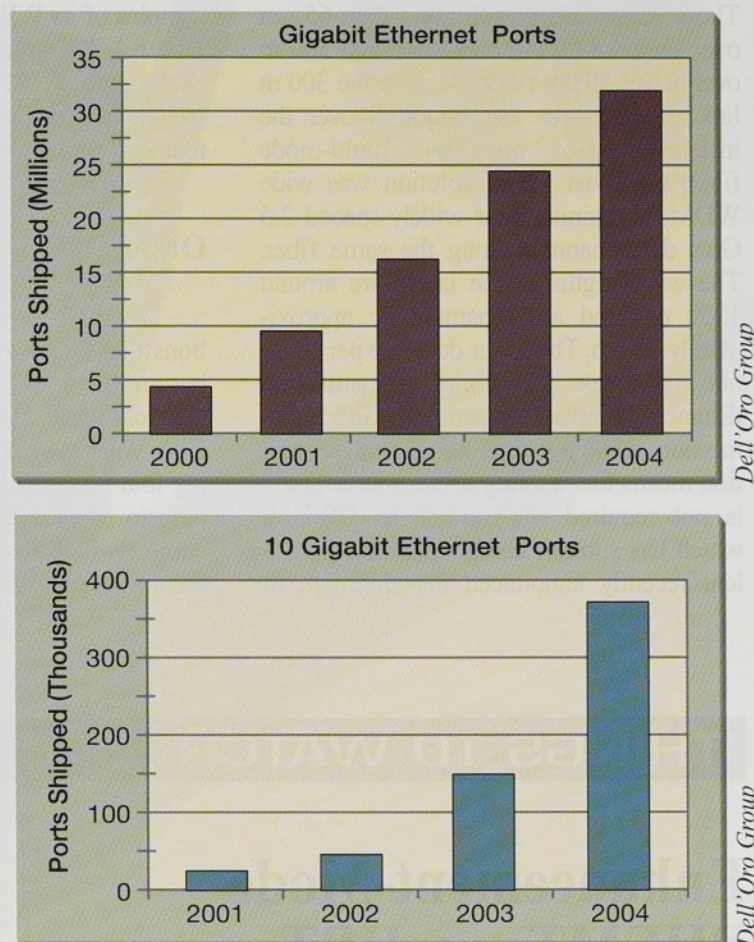


Figure 2. Market forecasts for Gigabit Ethernet and 10 Gigabit Ethernet, courtesy of the Dell’Oro Group. At least 90% of the Gigabit Ethernet market is for short reach applications using 850 nm VCSEL-based transmitters. Other sources suggest that 50% or more of the 10 GbE ports shipped will contain 10 Gb/s serial 850 nm VCSEL transceivers.

are considerably larger than the number of lasers that will be required for any other communications application.

PMD Interface Technologies

Altogether, some 20 PMD candidates were initially put forward for consideration. As shown in Table 2, 1310 nm and 1550 nm serial interfaces were selected for the longer reach, single-mode applications, but the objectives for multi-mode fiber proved more difficult to resolve.

Due to dispersion in multi-mode fiber, the transmission distance decreases very significantly when the data rate increases [see CS 6(5), p. 57], and standard multi-mode fiber can only support link distances of less than 100 m at 10 Gb/s (depending on the exact fiber type). However, the use of specialty fiber enables link distances of several hundred meters or more.

For the shortest reach application, 10 Gb/s serial 850 nm VCSELs transceivers were selected as the lowest cost solution.

These transceivers reach more than 65 μm over standard 50 μm core fiber and 300 m over newer 50 μm fiber. Because the 300 m link distance was also required over the installed base of "worst-case" multi-mode fiber, the most viable solution was wide WDM, combining four widely-spaced 2.5 Gb/s data channels along the same fiber. The wavelengths of the lasers are around 1300 nm and are separated by approximately 25 nm. The lower data rate per channel translates into higher transmission distances compared to serial 10 Gb/s transmission, while the large wavelength separation means that cooling of the source lasers is not required (in contrast to DWDM, which has sub-nm channel spacings). Agilent recently announced the shipment of

samples of its WDM transceiver [see CS 6(8), p.17]. Four uncooled DFB lasers, each operating at 3.125 Gb/s, are mounted side by side on a ceramic submount and aligned to a low-cost silicon waveguide combiner.

Other 10 Gb/s Activities

There are a number of 10 Gb/s solutions that didn't make the cut for 10 GbE, but are likely to find other markets. Blaze Network Products (Dublin, CA) has a 10 Gb/s WDM transceiver product containing four 850 nm VCSELs, and is also planning to introduce a 1310 nm version. The company recently received \$40 million in a second round of financing.

Meanwhile, Alvesta (Sunnyvale, CA) is promoting its 4-channel parallel solution, again using 850 nm VCSELs. The transmitter and receiver are integrated into the same small package, unlike 12-channel parallel products in which the transmitter and receiver are in separate modules. The VCSELs transmit at 2.5–3.125 Gb/s over 4 separate fibers.

Finally, there is work underway to define a standard for next generation 10 Gb/s Fibre Channel systems, for use in storage area networks (SANs). The required physical layer devices are likely to be very similar to those used in 10 GbE. ElectroniCast estimates that the market for VCSEL transceivers used in Fibre Channel could reach \$782 million by 2004.

THINGS TO WATCH

Enhancement-Mode PHEMTs vs. HBTs

RICHARD DIXON

HBTs have recently established themselves as the technology of choice for the PA function in handsets, largely due to excellent power performance and linearity for CDMA and new W-CDMA applications. And while new players such as Alpha, Anadigics, Raytheon and Celeritek are joining established manufacturers such as RF Micro Devices and Conexant in volume production of these devices, companies such as Motorola and Agilent have recently introduced enhancement-mode (E-mode) PHEMTs products that could challenge the HBT for sales of handset PAs.

The Single Supply Voltage Issue

The GaAs HBT has effectively replaced the MESFET for the power amplifier functions in wireless handsets. An important reason for its popularity with system designers is the single positive supply voltage. The HBT features a near zero leakage current in the off-state, which has allowed handset manufacturers to eliminate the negative voltage supply and the switch needed to turn off the drain current. This leads to battery power savings and increases the amount of usable board space, and reduces the overall cost of the phone.

Things to Watch
2001

#8

In contrast, MESFETs and PHEMTs require an additional negative voltage supply to isolate the appreciable leakage current (several mA) that would otherwise place a drain on the battery when the phone is in the standby mode. But with the E-HFETs and E-HEMTs recently introduced by Motorola and Agilent, the drain currents are now low enough (i.e. in the μA range) to eliminate the negative supply voltage and the need for a MOS drain switch. And with the playing field now level, both technologies can compete for the PA function.

Horses for Courses

So could HBTs be in for more competition from E-mode PHEMTs in future? According to Earl Lum, market analyst for CIBC World Markets, E-PHEMT devices will become very important for control functions such as switches and modulators, but the jury is still out regarding the PA function.

"In general, we are seeing more modules being employed in handsets, which favors HBTs for the PA," says Lum. "Modules are certainly the direction the industry will be taking in future. If the application is CDMA, the chances are that HBTs will dominate because of the better linearity. However, in the

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case of GSM, the market will be split between E-PHEMTs and HBTs. For the W-CDMA applications that are now coming on-line, where more stringent demands are placed on linearity for data transfer, HBTs will dominate. E-PHEMTs do however show some advantages in terms of improved efficiency, and traditional FET manufacturers will probably develop these devices in parallel with their HBT efforts."

Lum adds that last year saw several companies undergoing a design and product introduction phase, and 2001 will likely see companies consolidating production orders of HBTs, with InGaP replacing AlGaAs as the emitter structure. "This year we will see a critical mass for production of HBTs, with companies such as Celeritek, Anadigics, Raytheon and Alpha ramping up their production," he says.

Best of Both Worlds

Motorola has recently qualified its E-HFET process, and is also working on a HBT process. The company's new E-HFET features a hetero-insulating gate that allows a high turn-on voltage [CS 6(9), p. 28]. "The insulating gate allows us to apply a bias of up to +1.8 V on the gate," says Motorola's Mark Wilson. "This means we can set the threshold voltage up as high as +0.5 V, which is enough to achieve the necessary off-state leakage characteristic to achieve a truly-off device. Hence, we can eliminate the Si MOS switch required to shut off the drain current in the same way as a HBT device."

Comparing both technologies, Wilson believes that the issue of die sizes, which is often quoted as a reason to favor HBTs over PHEMTs, is more complicated than at first sight. "An E-PHEMT will occupy more area than a HBT on the wafer, and if you only take into account the active area of the transistor, HBTs are smaller by a significant amount. However, in an HBT, you still need to provide ballasting to prevent problems with thermal runaway. In addition, passives and bond pads take up roughly the same area in both technologies."

Taking this into account, he says, the E-PHEMT ends up being around 20–30% larger. "However, the cost of an HBT epi-

wafer is around 20% higher than for the E-PHEMT, and the processing involves 1–2 more mask layers, which tends to offset the gains made in die yield," he says.

So if there is no big cost differentiation, what about the performance? Wilson says some applications are well suited to E-PHEMTs, such as PAs for GSM applications, which benefit from the excellent PAE performance (>60%). This is because the PA does not need to be backed off to improve the linearity, and can thus be driven hard.

The E-mode device is also inherently more robust and reliable. "As you back off the current density in the HBT transistor to give you more reliability, you have to increase the die size. This means you start to lose some of the benefits you might have gained through the die size of an HBT."

According to Sanjiv Shah, director of product management, **Raytheon** is moving ahead aggressively with InGaP HBT technology, in both existing processes and with the development of next generation processes, and the company expects significant product announcements to be made early this year. "We have evaluated E-mode PHEMTs, and concluded that these devices tend towards better linearity and PAE," says Shah. "However, working against this is the die cost per square mm, and most importantly, the leakage current, which is an issue for most manufacturers."

Shah says that in terms of performance, HBTs are making improvements all the time and that the technology gap between the two types of devices is now insignificant. "At the end of the day, people have made their bets with the choice of technology, and are moving ahead with these [choices]," he says. "That said, Raytheon is developing an E-PHEMT process, although not for handset applications."

Infineon is also forging ahead with its new GaAs HBT process, which is designed for volume production of PAs for Bluetooth applications and handset PA modules. "HBTs currently dominate the handset business because of the smaller die size and the superior linearity, which is important for highly linear PAs and modules used in next generation W-CDMA phones," says Markus Behet, product manager for GaAs projects and wireless projects at Infineon. "Nevertheless, stud-

ies have shown that E-PHEMTs can offer higher PAE, and are well suited to saturated-mode PAs for GSM applications. The E-PHEMT technology also exhibits good thermal stability, and is not subjected to reliability issues known for HBTs," he says.

RF Micro Devices is the world's leading supplier of GaAs HBTs. In a recent panel discussion (GaAs IC Symposium, Seattle October 2000), a spokesman for the company said that HBTs were the preferred technology as a result of their very low leakage current in the off-state, and because most HEMTs needed a drain switch as a result of an appreciable residual drain current. In addition, in a HBT the control of the turn-on voltage is set by the material bandgap, not by the recess etch of layer thickness. In a HEMT, the turn-on voltage variation can be as much as a ± 30 mV for a epilayer thickness variation of several monolayers.

Agilent recently unveiled its own single supply voltage E-PHEMT device, which it touts as demonstrating superior PAE performance to both current and newer generation InGaP HBTs for CDMA, DCS and GSM applications [see CS 6(8), p. 19]. The company claims its new device should also increase the CDMA phone battery life by up to 15%. "Direct comparisons [between HBTs and E-PHEMTs] are difficult," says Dave Wu of Agilent's Wireless Semiconductor Group. "When you design a PA for a system there are many other design constraints, and you have to meet all the specifications. This includes system and internal circuit specifications, but also the ability to supply product in high volume. That said, we do see that the E-PHEMT device has a raw performance advantage over the HBT, and our initial evaluations for CDMA and W-CDMA PAs have revealed very good linearity from these devices."

Alpha also subscribes to the ideal model of having both technologies on board. "In my opinion, it is beneficial to have both HBT and E-PHEMT technologies as part of our available process portfolio," says engineering manager Gene Tkachenko. "While the HBT is preferred in many wireless phones as a result of the single supply operation and smaller die

size, E-PHEMT devices have higher PAE, and the performance gap over HBT widens as the supply voltage is reduced from 3.2 to 2.4 V, and below. Both technologies have pluses and minuses that have to be carefully weighed when making a decision as to which technology platform to use for a specific PA design. In the case of HBTs, the device performance is traded-off to achieve a thermally robust design and ensure device stability, reliability and ruggedness. In the E-PHEMT device, the main trade-off is between electrical performance and process reproducibility.

"Ultimately, it comes down to providing a solution at the lowest possible cost," Tkachenko concludes. "The majority of today's cellular phone PA solutions are designed to be in the form of a module and the PA chip cost is only a fraction of the overall module cost. Thus, design and price considerations dealing with other parts of the module such as the Si controller chip are becoming increasingly important."

A clear Winner?

"It is difficult to judge which of these technologies will win the race," concludes Infineon's Markus Behet. "Clearly, right now the HBT is the dominant technology, mainly because of its maturity. But my feeling is that the E-PHEMT device will capture a share of the market once the technology is stable and more companies jump on the train. In future, there will be a market for both technologies, taking advantage of their respective strengths."

Mark Wilson says that Motorola's strategy is to have both technologies. "If you are pushing the AlGaAs HBT hard there could be some questions about reliability, especially for base station applications, but it's also important to remember the handset has a relatively short life. However, the newer InGaP HBTs are more reliable and manufacturable than the original AlGaAs HBTs, and that's certainly the approach we have taken with our HBT development. We look forward to evaluating the manufacturing economics of these two technologies over the next year," he says.

CIBC's Earl Lum believes that PA modules may also be a deciding factor in future. "This year it will be very important which company comes out with the best PA module. In general, we are seeing that handset makers are favoring modules, and the company that supplies these will have an edge in terms of design wins."

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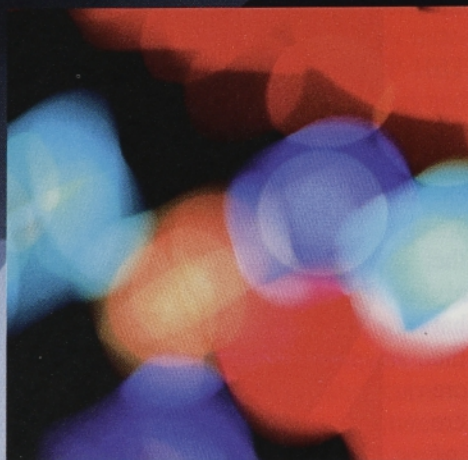
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The Supply Chain 1: Wafer Shortages

MARIE MEYER

Things to Watch
2001

#9

A sure sign of growing pains within the compound semiconductor industry is the fact that there are not enough III-V substrates to go around. The problem begins with the supply of gallium. While there is still plenty of it in the earth's crust, there is simply not enough capacity for extracting gallium from ore. At least two, possibly more, major new plants are said to be in the works, but the industry has been waiting for months now for confirmation. In the meantime, prices continue to rise. The spot market price for 99.9999% ("6N") pure gallium, which is most commonly used in bulk crystal growth, is now more than \$1,500 per kilogram, an increase of 125% in one year.

In turn, the substrate manufacturers are being squeezed between the gallium shortage and skyrocketing demand for GaAs wafers. It seems that no one correctly predicted how quickly 6" GaAs would catch on. The supply problem is most acute at the smaller companies and the newer entrants to the market. Buyers at some facilities made no attempt to conceal the fact that they feel as if they are at the mercy of their suppliers. "Suppliers are able to ask whatever price is required as well as ask for down payments to guarantee capacity," one source complained.

The picture is different for the more established players. Representatives of the largest fabs that we spoke to indicated that because of the length of their relationships with their GaAs suppliers, as well as their formidable clout, they were able to guarantee themselves a supply of wafers at a price that they thought was fair to both parties. Apparently, the fabs are making some concessions on price in light of the escalating cost of gallium. In return, the wafer manufacturers appear to be working furiously to

assure customers that the long-term problem is being addressed. A manager at one of the biggest US GaAs fabs told us "We are working closely with vendors on quality and delivery issues and there does seem to

These supply problems undoubtedly result from the fact that the huge upsurge in demand for compound semiconductors caught everyone—suppliers and fabs alike—by surprise. Therefore, it is difficult to envision any remedy other than patience.

be hope toward the latter part of 2001, but from now to then, the supply will be thin."

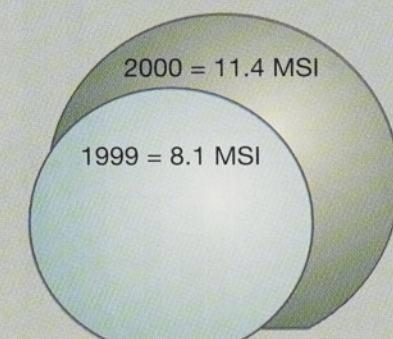
We also spoke with a major manufacturer of LEDs, who had this to say: "Like most companies, we've made arrangements with our key suppliers to support our requirements, but it does limit our flexibility to respond to changes in market demand. We have confidence in our suppliers that they will continue to be able to support us. They are also responding to the worldwide shortage by bring new capacity on line, but it is not expected to be available till 2002. 2001 will be a tough year."

There may also be issues looming in the InP area. A manager at a major epiwafer producer had this to say: "Despite the recent boom in the sales of reactors for long wavelength [InP-based] laser applications, the substrate suppliers' response has been nil. When I contact them, I'm told that GaAs expansion is the number one issue and by October 2001 the situation should change as far as capacity is concerned. In terms of InP I'm told that they are only just now beginning to consider an expansion of capacity." The supply of semi-insulating InP also needs to be improved,

as TRW, RFMD and Vitesse have all announced plans for commercial production of InP ICs. In fact, Vitesse has already begun running a few sample InP wafers through one of their 4" lines at their Camarillo, CA fab. A Vitesse representative said that quality of the wafers seen so far could be described as "reasonable", but as was the case with GaAs several years, the wafers were also noticeably inconsistent.

These supply problems undoubtedly result from the fact that the huge upsurge in demand for compound semiconductors caught everyone—suppliers and fabs alike—by surprise. Therefore, it is difficult to envision any remedy other than patience. Perhaps some sort of compound semiconductor industry association should be formed in hopes of averting future crises. But for now, we will all have to rely upon the gallium suppliers and wafer manufacturers to fix the situation on their own. While we don't want to be overly dramatic, it should be noted that this is a very big responsibility.

Consumption of Semi-Insulating
GaAs Wafers
Annual Growth = 41%



MSI = Million square inches

Source: Strategies Unlimited

Explosive Market Growth for VCSELs

DALE MURRAY*
ElectroniCast Corporation

The VCSEL-based transceiver market took hold in 1999 with consumption of \$262 million, more than three times that of 1998. Fueled by the recent success of Gigabit Ethernet and Fibre Channel, this explosive growth will continue, supported by a number of all-new applications, reaching \$3.4 billion in 2004 and continuing on to \$14.1 billion in 2009, as noted in Figure 1. The drivers for this dynamic growth are:

1. Rapid advancement of datacom standards:
Explosive growth of Gigabit Ethernet, followed soon by 10 Gigabit Ethernet.
Continued aggressive growth of Fibre Channel, migrating to 2 Gb/s Fibre Channel, and on to 10 Gb/s.
2. Penetration of telecom:
Low cost solutions for Very Short Reach SONET at 10 Gb/s.
3. New opportunities:
Serial and array links within Infiniband switch fabrics.
Deployment of intra-system array-VCSEL interconnects.

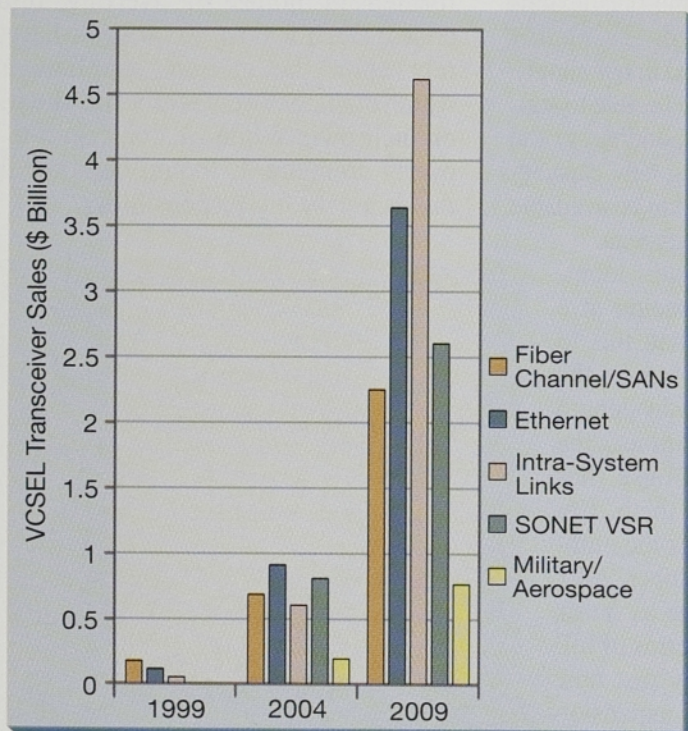


Figure 1. VCSEL transceiver market forecast.

Things to Watch
2001 #10

The dynamic ramp of the VCSEL transceiver market has stretched the development and production capabilities of the traditional transceiver vendors and has provided opportunities for new vendors in the market. But margins are already thin on commodity versions and price erosion will continue. New markets, faster speeds, and wider links mean new opportunities for innovation, market differentiation and margin recovery. Manufacturers of network equipment are ready to go, and demand for VCSEL transceivers will exceed supply for 12–24 months. The winning transceiver vendors will be those that appreciate the concept of time-to-volume rather than time-to-market.

Emergence of VCSELs

In the late 1980's, U.S. military weapon system planners foresaw a far future need for many-orders-of-magnitude greater data transport than was feasible at that time; to be accomplished in very little physical space and being rugged enough for operation in severe environments. It appeared that the capabilities of diode edge-emitting lasers could not be pushed up enough to meet the need. Transporting the data via a large number of parallel high data-rate channels appeared to be a candidate solution, but fabrication, cost and other factors made edge-emitters an unattractive option.

VCSELs looked more attractive, especially in array format, provided that they could be brought to commercial production. Accordingly, over the past ten years, the U.S. government (mainly the Defense Advanced Research Projects Agency, DARPA) has spent approximately \$200 million on contracts to industry, university and other laboratories to advance VCSELs to commercial availability. Within the contacts, much of this funding was matched by the industrial laboratories. There also were numerous large and small independently funded VCSEL projects, in North America, Europe and Japan, to move this technology along. Altogether, worldwide, roughly \$500 million has been spent in this field over the past ten years.

VCSEL lasers can be modulated at very high speed and perform very efficient power conversion. This means low power consumption for transmit modules. The well-confined circular output beam of a VCSEL allows efficient coupling

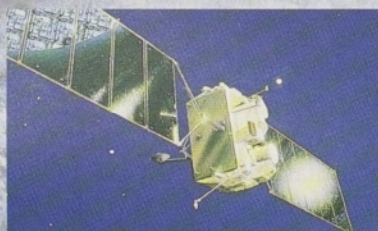
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into an optical fiber. This leads to relatively coarse alignment requirements within the optical subassembly. Surface emission allows for low-cost "LED-style" packaging schemes. Also, because VCSEL geometry and manufacturing tolerances are based simply on lithography, they are ideally suited to fabrication in arrays.

The required data rates of short-reach data transport have been multiplying dramatically, especially since 1996, leading to a strong commercial demand pull for low cost, relatively low power, medium/high data rate lasers. The VCSEL has emerged as the strongest candidate for this task.

Non-communication applications for VCSELs (such as laser printers, laser sensing and storage) have now emerged as well. VCSEL vendors are rapidly expanding capacity—Honeywell alone is shipping hundreds of thousands of VCSELs per week. There is strong investor interest in supporting this expansion, and the inundation of funds is supporting renewed efforts at expanding VCSEL technology. Current VCSEL diode development (for communication applications) includes new materials, processes and structures, new device designs, and of course, faster speeds. These efforts are depicted in Figure 2.

High-speed Datacom

The growth of Gigabit Ethernet has been explosive and will be followed soon by 10 Gigabit Ethernet. We will see continued

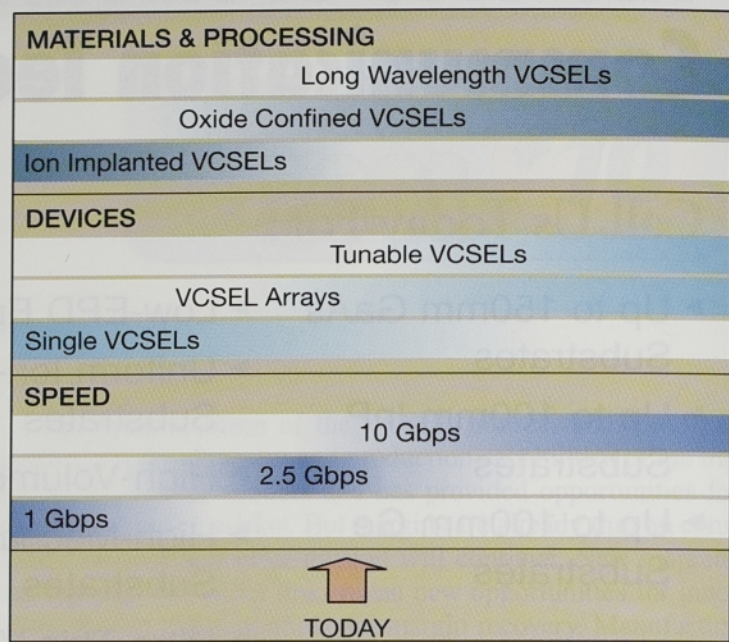


Figure 2. Development of VCSELs for communication applications.

aggressive growth of Fibre Channel, migrating to 2 Gb/s Fibre Channel, and on to 10 Gb/s. After an intense standards battle, a serial VCSEL transceiver was chosen as one of four acceptable solutions for 10 Gigabit Ethernet. In the Fibre Channel committee, three of five accepted solutions use 850 nm VCSEL transceivers. Included are Coarse WDM (CWDM) VCSEL transceivers, a new approach that avoids 10 Gb/s line rates and more expensive electronics. In each of these two markets, multi-mode short reach solutions dominate and by 2004, these two applications alone will grow almost eight-fold over 1999.

VCSELs in Telecom

The extremely rapid growth of networking and Internet access has been fueling extraordinary growth of aggregation switches, very high speed routers, high capacity DWDM transmission equipment, larger digital cross connects, and now optical cross-connects for optical networking. These developments are serving the expansion of the Internet backbone with most equipment being installed in telephone central offices and Points of Presence (POPs), forming the core network.

As routers grow to terabit scale, and cross-connects and transport systems manage OC-192 traffic, these systems need to be interconnected at 10 Gb/s to minimize the large number of interconnections. However, with all this equipment within one facility, link distances are short, the majority less than 100 meters. SONET compliant optical links are optimized for much longer reaches and cost as much as \$15,000.

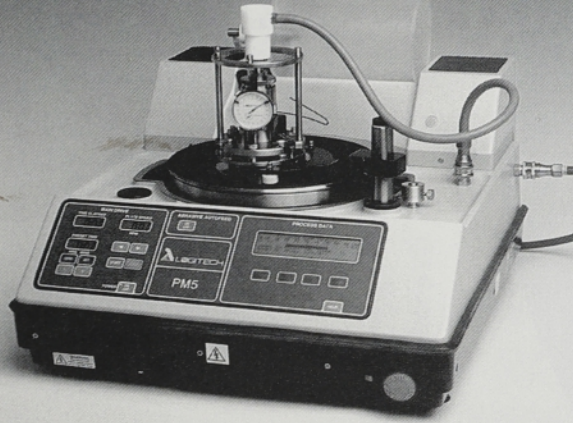
Low cost solutions for Very Short Reach (VSR) SONET at 10 Gb/s are being defined with a target of \$500 per interface. VCSEL-based parallel optical interconnects are considered the leading solution. New "converter ASICs" interface existing array VCSEL transmitters and receivers to SONET hardware. Deployment is

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about to begin and take-up will be rapid. By dividing bandwidth across multiple fibers, a Very Short Reach OC-768 array VCSEL link will by 2003 provide low-cost 40 Gb/s transport up to a few hundred meters.

Optical Interconnects

High performance systems of all types are evolving rapidly. Internal backplane speeds are escalating, pushing the fundamental limits of copper. Highly scalable, carrier-class systems are beginning to consume multiple equipment racks, placing heavy emphasis on redundant interconnections between complex switch fabrics and I/O line cards. In contrast to standards-based interconnects such as Gigabit Ethernet and SONET, optical array interconnects are now mostly a collection of proprietary intra-system interconnects based on array VCSEL links. The term "optical backplane" can mean the optical analog to a traditional electrical backplane, or it can mean the use of

array optical interconnects to create a new architecture, not previously possible. They are seeing rapid production deployment in terabit routers, digital cross connects, and optical cross connects.

Emerging Applications

The now-pervasive PCI bus has been in use for almost a decade. It is found in almost every type and size of system and is still evolving. But the increasing use of ever-faster CPUs, larger databases, and faster networks is now outstripping the capability of the PCI bus. PCI is a shared architecture where all devices compete for bandwidth. In the networking domain, shared hubs have evolved into full bandwidth switches using a point-to-point architecture. In the same way, Infiniband is intended to replace the PCI bus with a high-bandwidth switched network topology. It is a network approach to I/O, effectively creating "a switch inside the server" using a packet protocol.

Why Use VCSEL-Based Transceivers?

Performance

VCSEL lasers can be modulated at very high speed, especially as compared to LEDs that are used in low data rate local area networks (LANs). Today, the majority of VCSEL transceiver applications are at 1 Gb/s and are moving to 2.5 Gb/s. Prototype VCSEL modules are emerging for 10 Gb/s data rates. Because of the high reflectivity of the mirror stacks, and the excellent confinement of the current path, VCSELs perform very efficient power conversion (the record is 57% but typical is 6–25%). This means low power consumption for transmit modules. Drive currents of oxide confined VCSELs are around 250 mA. As speeds and densities increase, low power consumption is critical in today's high performance communication equipment.

Reliability

VCSELs have been shown to have lifetimes from 1–10 million hours (100 years). This is far higher than the lifetimes of CD lasers, which had been used prior to 1999. It is important to note that this reliability can be achieved without hermetic packaging.

Ease of Transceiver Manufacturing

The well-confined circular output beam of a VCSEL allows an efficient coupling of power into an optical fiber. This leads to relatively coarse alignment requirements within the optical subassembly. Surface emission allows for low-cost "LED-style" packaging schemes. In some cases, such packaging can include passive alignment of the VCSEL within the assembly. Non-hermetic packaging allows for VCSELs bonded to lead frames or flex circuits and imaged through molded plastic optics, eliminating the requirement of sealed metal TO cans.

Because VCSEL geometry and manufacturing tolerances are based simply on lithography, they are ideally suited to fabricate in arrays. Today, 1D arrays of 12 VCSELs are common with reasonable yields. Eventually, 2D arrays will evolve into high-yield production. Reduction of input power also leads to simplified packaging and thermal management. It also reduces the EMI (electromagnetic interference) shielding challenges of transceiver packaging.

Cost

Standard microelectronics style processing is used to produce VCSEL diodes. Because they emit from the surface, each VCSEL on a wafer can be probe-tested before dicing and packaging, so yield issues can be caught before subassemblies are produced. In 1D arrays, VCSELs can be much higher yield than edge-emitting laser arrays. As noted above, VCSELs offer numerous advantages for transceiver packaging, all of which lead to lower cost transceiver modules.

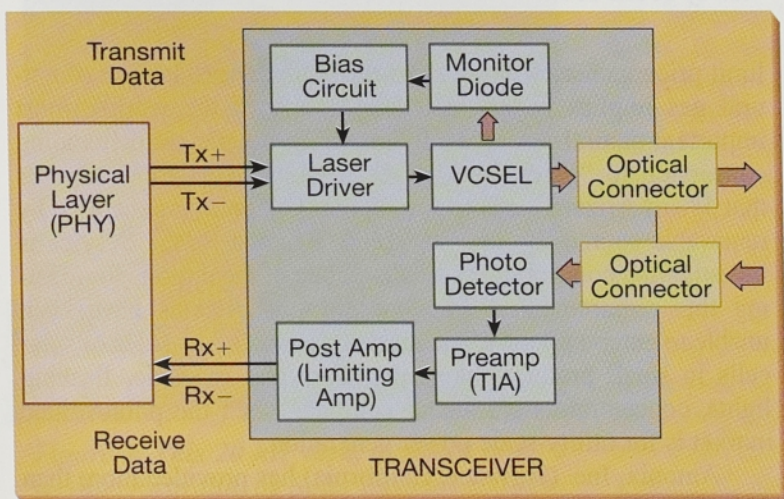


Figure 3. Block diagram of a typical VCSEL transceiver interfaced to the "physical layer" (PHY) of a communication link. In terms used by standards committees, a transceiver is part of the Physical Media Dependent (PMD) portion of a standardized link.

Compound Semiconductor Solar Cells for Electric Power Generation

SARAH KURTZ and ROBERT McCONNELL
National Renewable Energy Laboratory
Golden, CO, USA

Recent headlines reporting sky-high natural gas prices and the possibility of \$3/gallon for gasoline in the U.S. in the not-so-distant future have led many of us to add "energy prices" to our list of "things to watch." What might not be obvious is that the rising cost of energy could result in a new and, potentially, large market for compound semiconductors: solar cells for terrestrial applications. *Compound Semiconductor* magazine has already reported the success of GaInP/GaAs/Ge solar cells for satellites [1]. These solar cells have a higher efficiency than any other commercially available solar cell, and if they now enter the terrestrial solar cell market, the potential sales growth is even greater.

Energy Generation Using Photovoltaics

For decades, scientists have been projecting that solar cells (photovoltaic devices) will help to meet our world's electricity needs, but the cost of their electricity still exceeds that of conventional electricity. Nevertheless, the photovoltaic industry has been growing at a healthy rate. U.S. production was 77 MW in 1999, up 50% from 1998, but still too small to help reduce fossil fuel usage: The U.S. power industry is adding about 25,000 MW of new electricity generating capacity this year. One approach to reducing cost and rapidly increasing solar-electricity generation is to use cheap lenses or mirrors to focus light onto small solar cells. With this approach, expensive cells are cost effective if they have very high efficiency. In volume production, systems using GaAs-based solar cells in reflective dishes are estimated to be able to generate electricity at a cost of 7 to 15 cents/kWhr for a plant located in Albuquerque [2]. This is only a little greater than today's low electricity prices (average of 4–9 cents/kWhr in the U.S.), and these may increase; during recent shortages the selling price of electricity has spiked to more than \$1/kWhr in California. Solar cells provide the highest output when the sun is shining most brightly, often close to the times of peak demand.

Because it burns cleaner and generates less greenhouse gas than coal, natural gas is being used in almost all of the new electricity generation facilities. Increased demand for natural gas has quintupled its price in the past year. The natural gas industry projects that billions of dollars of investment will be required to meet the increasing demand. Although increased supply will

Things to Watch
2001

11



Arizona Public Service

Figure 1. This 70 kW MegaModule has been operating at the Arizona Public Service Solar Test and Research (STAR) Facility in Tempe, Arizona since September, 2000. Amonix constructed the system using Amonix silicon concentrator cells and Fresnel lenses which concentrate the light by a factor of about 250.

limit price increases in the short term, higher production of natural gas implies faster depletion of one of the world's most important natural resources. Increasingly, people are demanding conversion to "green" energy. In Arizona, legislation requires that 1% of Arizona's electricity (about 75 MW) be generated by renewable sources by the year 2005. Arizona Public Service is investigating concentrator systems as one of the options for meeting this requirement. While concentrator systems have been unable to enter a photovoltaic market dominated by sales of solar cells in small products like calculators and roadside, flashing lights, concentrators can better compete when the photovoltaic market is for utility-scale power generation.

Amonix, Inc. (Torrance, California) has provided more than 200 kW of concentrator systems for Arizona Public Service installations (see Figure 1), and are continuing to ship 10 kW/week, with production booked for the next year. This represents the first time that a concentrator company has started a continuous production line. Solar Systems (Hawthorn, Australia) is

also starting a production line installing 52 of their 24 kW dishes (see Figure 2) in Australia. Other companies, including Entech (Keller, Texas) and SunPower (Sunnyvale, California), are also marketing concentrator products.

Opportunities for GaAs-Based Concentrator Systems

The growing market for the silicon-based concentrator products raises the question of when compound semiconductor solar cells might also be used in similar systems. Spectrolab recently reported a terrestrial concentrator cell efficiency of 32% for their GaInP/GaAs/Ge cell [3]. The company estimates cell costs [4] that are consistent with the projected electricity cost of 7–15 cents/kWhr [2]. JX Crystals and Tecstar are developing a stacked GaInP/GaAs over GaSb concentrator cell [5]. New multijunction concepts may eventually increase the concentrator cell efficiency to over 40%, increasing the advantage of compound semiconductor cells over silicon cells, which are currently ~26% and may never pass 30% in efficiency.

Silicon concentrator cells are likely to be cheaper than III-V cells in terms of

\$/cm². However, if the GaAs-based cells are used at higher concentration, a smaller area is needed, and so they might be cheaper when priced by \$/watt. This trade off is complex because, for example, increasing the concentration ratio may increase the cost of the optics and support structure. Factors that might cause one to switch from Si to III-V cells are decreasing costs of III-V cells, improvement of III-V cell efficiencies, or if higher concentration systems become practical. The biggest advantage of the III-V cells is their high efficiency, which reduces the system cost/watt.

While compound semiconductor space solar cells need only minor modifications to make them suitable for concentrator systems, the development of a high-performance, reliable concentrator system will take both time and a large investment. Concentrating Technologies (Huntsville, AL) has been addressing this issue by developing a 2 kW dish concentrator system for Arizona Public Service using dense arrays from Spectrolab (GaInP/GaAs/Ge—see Figure 3) and Amonix (silicon). The National Renewable Energy Laboratory (NREL) is also funding Concentrating Technologies to fabricate and install a 2 kW prototype dish system in Golden for off-grid applications. In addition, NREL is funding Amonix and Spectrolab to make improvements in their close-packed array designs and United Innovations for development of a unique cavity-based concentrating PV concept. Solar Systems Australia has completed the development of its production Dish PV concentrator system. This includes optical matching of the dish and PV receiver as well as a fully modular close-packed receiver capable of delivering 24 kW at 500 suns. Control and data acquisition are integrated so that the dish delivers optimum light flux to the PV receiver and produces maximum output at all times.

Another indication of growing industry maturity is the recent devel-



Figure 3. Dense array of GaInP/GaAs/Ge (triple-junction) solar cells made by Spectrolab. This ~20 × 20 cm² array will generate about 2.5 kW DC when Concentrating Technologies integrates it into a dish concentrator system, operating at ~ 250 suns.

opment of an IEEE qualification test standard by the concentrator industry and utility representatives.

The combination of rising demand for energy, increasing concern for the environment, and the likelihood that fossil fuels are not inexhaustible, implies that energy prices will eventually rise. Further development and economies of scale will reduce the price of concentrators. The convergence of these two trends implies that an opportunity for renewables, and, specifically, compound semiconductor concentrator cells, is something to be watching for.

Acknowledgment

We thank D. Friedman and numerous others at NREL and at the companies mentioned above for their help with this article.

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Figure 2. This 20 kW dish, installed in Fosterville, Australia, by Solar Systems is a prototype of the 24 kW systems that will soon be installed elsewhere in Australia. The receiver uses silicon concentrator cells made by SunPower and has an area that is 1/500 of the dish area.

The Supply Chain 2: Metalorganic Sources

TIM WHITAKER

As source materials for MOCVD growth, metalorganic precursors support a very large portion of the compound semiconductor industry. But these materials are very difficult to manufacture in large quantities at the high purity levels required for epitaxial growth. As the industry matures, suppliers are moving towards larger production volumes and batch sizes along with higher levels of automation, resulting in higher quality and consistency and economies of scale. Although considerable improvements have been made, it seems there is still a way to go.

"We believe that for the compound semiconductor industry to reach its full growth potential, it must be underpinned by a strong metalorganics supply base," says Akzo Nobel's Business Manager for high purity metalorganics, Barry Cottrell. "The industry will never break into areas such as LED-based lighting unless the entire supply chain improves. When we make projec-

tions about how many tons of metalorganics might be required, it is questionable whether the current methods of manufacturing are capable of supporting these volumes."

Supply Capacity

It appears that all the vendors are scaling up to produce larger batch sizes and increase capacity, or have already done so. "Currently, we are equipped to handle projected capacity requirements for the next 2-3 years," says Epichem's Ravi Kanjolia. "However, we are already looking at the demand for 2004 and beyond." Rohm & Haas and EMF have also expanded, while Akzo Nobel recently announced that it will invest heavily to enhance its production capabilities at its complex in Deer Park, Texas, providing sufficient capacity to satisfy projected requirements through 2006 [see page 24].

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Source Purity

Is there still a pressing need to improve the purity of metal-organic sources? For some materials and for certain devices, the answer is yes. But trying to directly link the quality of metal-organic sources to the performance of the final device is fraught with difficulties, partly due to the lack of accurate analytical techniques (see below) and also because there are so many variables in an MOCVD system. "If you improve one thing, it often reveals weaknesses in another," says Rodney Moss of Agilent's Fiber-Optic Components division. "Impurities can come from source gases (arsine and phosphine), metalorganics or carrier gases, or they can be related to the integrity of the growth system itself."

In terms of source quality, Akzo Nobel believes that one of its key strengths is its ability to manufacture TMAI—the other suppliers buy and purify TMAI. "The easiest way to purify something is not to introduce any impurities in the first place," says Barry Cottrell. "Purification is expensive, and the limits of purification techniques are being reached."

Consistency

As the industry matures, it is coming to terms with one of the issues—the lack of consistency between batches. "As we move towards a true production-oriented business, the main issue is consistency," agrees Mike Timmons of Rohm & Haas. "Metalorganic sources are not yet commodity items—TMGa is the closest to being a commodity, while TMIn and TMAI are much more difficult to produce consistently well. The industry is still working with batch processes, so there is batch-to-batch variation, and also relatively low levels of automation: that's something we're working to improve right now."

According to Ravi Kanjolia, Epichem is placing great emphasis on process control and consistency for production. "All our plants for the core products (TMGa, TMIn, TMAI, TEGa, DMZn, DEZn and Mg alkyls) are automated and run by PLC-based computer controls," he says. "The critical process parameters are all recorded throughout the manufacturing stages. When our material has been qualified for device production, we don't want to surprise the customer with either poor or better quality." Customers need to be informed of any changes to the manufacturing process, and the new source material goes to the customer's research group for qualification, rather than being used in production.

Larger Batch Sizes

"The keys to consistency are process automation and scale up to produce larger batch sizes; these are two reasons for our facility expansion," says Barry Cottrell. Akzo Nobel's approach will be to make large batches and reserve them for specific customers once the material has been qualified.

Epichem is promoting a system that automatically refills bubblers from large batches of material stored at the customer site. The EpiFill system consists of a cabinet that stores two 20-kg batches of TMGa, which are connected to fixed bubblers on up to 8 different MOCVD systems. When one of the bubblers

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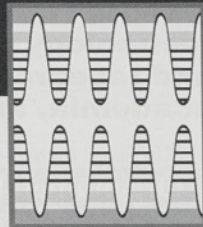
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THINGS TO WATCH

reaches a low level it is automatically refilled from the central supply. Epichem says this reduces the downtime necessary to evacuate, purge and change the bubbler, to leak test afterwards and to carry out qualification runs.

Delivery Methods for Solid Sources

Obtaining consistent delivery from solid sources, notably TMIn, has proved to be an ongoing problem, and several solutions have been suggested. Epichem has focused on solution sources, in which the material is suspended in a solvent that also acts as an oxygen getter. Rohm & Haas has introduced the Uni-Flo cylinder which contains a metal sintered filter rather than a conventional dip tube. "None of the proposed alternatives solve all the problems of solid source delivery," says Mike Timmons. "Each one has a range of parameters where it operates most efficiently."

Characterization

An ongoing problem in the metalorganics industry is the absence of reliable methods of analytical characterization. "It is not possible to compare material from different vendors based on a certificate of analysis," says Mike Timmons. "All vendors have different methods of preparing analytical samples. The ability to detect impurities is a function of how you prepare the sample and what equipment you use, and there's a great deal of intellectual property involved."

Rohm & Haas has invested heavily in film growth qualification of sources, and provides electronic data from material grown using its sources, particularly TMIn. Other vendors, notably Mochem, also use this approach. Unfortunately, it is not possible to replicate the exact growth conditions and device structures used by each customer. So what is the usefulness of the film growth data? "It indicates potential—that the potential performance of the source is sufficient that the customer may want to go ahead and qualify it for production," says Mike Timmons.

The problem still remains that growers don't have a way to compare materials from different suppliers without carrying out their own growth testing. This means that customers are more likely to stick with their existing supplier—at least until they get a bad batch of material.

Other Issues

As MOCVD systems become more and more commonplace, they are no longer necessarily operated by trained engineers. Metalorganics are highly dangerous chemicals, and safety is an issue. Another is price—to satisfy the demands of the compound semiconductor industry in the coming years, prices will have to fall as these products become closer to being commodity items.

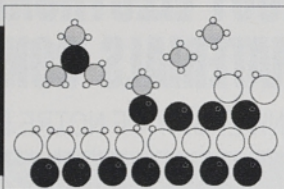
On the issue of price, it is worth pointing out that one of the starting materials for making TMGa is GaCl₃, which is turn made from elemental gallium, the same material that is causing all sorts of problems in the GaAs substrate business . . .

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Agere Poised for Impressive Debut

MARIE MEYER

Who is the world leader in sales of communications semiconductors? According to Lucent, it is the company they are about to spin-off, Agere Systems. On a pro-forma basis Agere notched \$4.7 billion in sales in 2000, and while this company may be only a few weeks old, it already employs 16,500 people worldwide.

Agere is one of the few companies in the world to combine top-notch optoelectronics and IC manufacturing. Around 25% of sales in 2000 were derived from optoelectronics. This equates to around \$1.2 billion, which makes Agere one of the top three manufacturers in this area, rivaling Nortel and JDS Uniphase. The company grew its sales 27% last year, driven by the optoelectronics segment, which posted an 82% increase in sales. More than 75% of sales last year were to companies other than Lucent. All of Agere's IC fabs are dedicated to silicon, but they do purchase GaAs parts from Vitesse and TriQuint, among others.

Lucent is proposing to sell roughly 20% of Agere to the public in an IPO in March. Jim Jungjohann, who follows the photonics sector for CIBC World Markets, has done a "back of the envelope" calculation that values Agere at \$50.3 billion. His formula is based on the assumption that the opto unit grows 50% and the IC business grows 15% next year, producing total revenue of \$6.3 billion. Looking at Agere's "peer group" in the stock market, he says it could be assumed that the opto business should be valued at around 18 times 2001 revenue, while the IC group should be valued at 6 times 2001 revenue. However, Jungjohann thinks that some adjustments are needed, to account for an increased debt burden and lower profitability due to higher R&D expenditures stemming from

loss of access to Bell Labs. He is also factoring in a 15% "IPO discount" to reach a final valuation of around eight times forecasted 2001 revenue.

Interestingly, this figure represents 75% of Lucent's current market valuation of about \$65 billion. Jungjohann believes that Lucent will receive as much as \$10 billion in the offering, making it one of the largest IPOs ever. He believes that the new company is likely to be one of the top players in the optoelectronics marketplace.

In addition to Lucent, Agere's other top customers include Nortel and Cisco.

Their top ten customers accounted for 52% of revenues in 2000. Lucent has given Agere a three year purchase agreement obligating it to purchase at least \$1 billion worth of components from Agere annually. Jungjohann predicts that Lucent's preeminent position on Agere's customer list will diminish after the IPO, when Agere will have a better opportunity to improve relationships with Lucent's rivals.

Agere's management have indicated that they will focus their efforts on the three areas of their business that have the

Company	Symbol	Closing Price Jan 12	52 Week Low - High	Market Cap*	P/E Ratio**
GaAs IC Companies					
Alpha	AHAA	35 15/16	22 3/8 - 78 1/4	1.544B	42.77
Anadigics	ANAD	17 7/8	13 5/16 - 112 1/8	534.6M	22.47
Celeritek	CLTK	17 1/4	15 5/16 - 85 1/4	204.3M	34.8
Conexant	CNXT	19 15/16	12 5/8 - 132 1/2	4.837B	N/A
Endwave	ENWV	3 13/32	2 1/2 - 20 5/8	116.2M	N/A
RF Microdevices	RFMD	24 7/8	12 1/16 - 92 1/4	4.035B	76.29
Stanford Microdevices	SMDI	38	13 3/4 - 60 1/4	1.001B	N/A
TriQuint	TQNT	43 1/4	21 - 67 3/4	3.393B	56.25
Vitesse	VTSS	58 1/16	35 5/8 - 115 11/16	10.482B	81.25
Opto Companies					
Agilent	A	56 1/8	38 1/16 - 162	25.480B	35.31
Alcatel Optronics	ALAO	51	38 1/8 - 71 3/4	841.5M	41.45
Coherent	COHR	37 1/8	25 - 107 3/8	1.014B	14.54
Cree	CREE	32 3/16	27 3/4 - 101	2.299B	55.46
JDS Uniphase	JDSU	50 3/16	37 - 153 7/16	48.257B	N/A
SDL	SDLI	181	94 3/4 - 460 1/2	15.824B	167.87
Uniroyal Tech.	UTCI	8 1/16	5 1/4 - 36 7/16	205.2M	N/A
Semiconductor Materials & Equipment Companies					
ATMI	ATMI	23 5/8	14 3/8 - 60 3/4	713.5M	19.01
AXT	AXTI	42 3/16	14 1/2 - 49 9/16	926.6M	100.15
Emcore	EMKR	50 7/16	19 5/16 - 86 1/2	1.716B	N/A
Kopin	KOPN	13 3/16	8 3/4 - 49 7/8	836.5M	74.22
Tegal	TGAL	2 13/16	15/16 - 91 1/16	35.1M	N/A
Trikon	TRKN	11 1/2	8 1/2 - 28 9/16	134.3M	10.33
European Shares (Currency Data in Euros)					
Aixtron	AIX	101.51	67 - 175	3.234B	168
Filtron	FTC	6.4	2.12 - 36	470.24M	N/A
IQE	IQE	2.77	2.56 - 12.18	451.01M	190
Picogiga	PICO NM	28.2	9.25 - 36.5	182M	65
Riber	RIBER	17.36	9 - 38.5	365M	N/A

*Market Capitalization = # shares × current share price

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

best growth prospects—namely, optical components, ICs for network communications, and wireless local area networking products. The company predicts a compound annual growth rate from 1999 to 2003 in these three areas of 36.6%, 26.0% and 31.4%, respectively

Agere's opto portfolio is primarily made up of active components, including lasers, modulators, amplifiers, and transceivers. The company recently added more passive components, such as filters and silicon waveguides.

The majority of Agere's products in the high-speed long-haul transport area

operate at 2.5 or 10 gigabits per second. The company says it has 40 gigabits per second modulators and receivers being sampled by customers. In addition to the long-haul market, Agere is also offering optoelectronic components for the submarine, metropolitan, cable television (CATV), and data communication markets. A list of products offered for the different applications is shown in the Table.

The remaining 75% of Agere's business is ICs for communications and computing. In the communications area, Agere is producing ICs for both the wireless and fiber optic communications.

When Lucent was spun off from AT&T in 1996, one of the things it took with it was the prestigious Bell Laboratories. As part of this latest spin-off, 275 research engineers will be transferred to Agere. They will join 2,800 other development engineers and scientists, also previously part of Bell Laboratories, who are already part of Agere. An as-yet undisclosed intellectual property portfolio is also being transferred from Bell Laboratories to the new company. Nevertheless, Agere will need to increase its R&D investment in order to make up for the loss of total access to Bell Labs. On a proforma basis, Agere's R&D expenditures were \$827 million in 2000, up 21% over the previous year and up more than 75% since 1998. The company is projecting R&D expenditures of \$1.2 billion in 2001.

Commenting on the prospects for Agere, Jungjohann noted that they lag their key competitor JDS Uniphase somewhat in product depth and breadth, particularly in passive optical components. However, he said, "we believe the company has an important competitive offering in its early move to marry its ICs with optoelectronics. The company's first product from this union, transponders, appear to successfully position Agere in the attractive subsystem market." He says this market is seeing "robust growth" as Nortel, Lucent and other system companies outsource an ever greater percentage of this type of equipment.

John Young, the former CEO of Hewlett-Packard, will be Chairman of Agere, and John Dickson, CEO of Lucent Microelectronics, will be the President and CEO of the newly independent company.

Dan DiLeo will change from President of Lucent Microelectronics to head of the Agere Optoelectronics Group, and Sohail Khan will continue on as the head of the IC group.

Agere Product Line		
Product	Speed	Network Application
Lasers		
EM (electroabsorptive modulated) laser	2.5 & 10 Gb/s	high-speed transport, metro
DM (directly modulated) laser	2.5 Gb/s [1]	high-speed transport, metro, CATV
Uncooled lasers	155 Mb/s–10 Gb/s	metro
Source lasers [2]	—	high-speed transport
Pump lasers	—	submarine, high-speed transport, metro
Analog DFB lasers	Up to 1 GHz	metro, CATV
Modulators		
Lithium niobate modulators	10 Gb/s [3]	high-speed transport, metro
Lithium niobate polarization controllers	10 Gb/s & 40 Gb/s [4]	high-speed transport
Amplifiers		
Er doped fiber amplifiers	—	high-speed transport, metro
Transmitters		
Cooled laser transmitters – DWDM	2.5 Gb/s [1]	high-speed transport, metro
Cooled laser transmitters – CATV	110 NTSC Channels	CATV
Uncooled laser transmitters	2.5 Gb/s [1]	Metro
Tunable laser transmitters [5]	2.5 Gb/s	high-speed transport
Receivers		
PIN Receivers	2.5 & 10 Gb/s [3]	high-speed transport, metro, CATV
APD Receivers	2.5 Gb/s [1]	high-speed transport, metro
Transceivers		
Transceiver modules	155 Mb/s to 2.5 Gb/s	metro, CATV, data communication
Transponder [6] modules	2.5 Gb/s [1]	high-speed transport, metro
Passive Devices		
Si waveguide multiplexors/demultiplexors [7]	—	high-speed transport
Passive optical filters	—	all
MEMs Devices [8]		
Dynamic gain equalizers	—	high-speed transport, metro
Optical cross connects	—	high-speed transport, metro

Notes

[1] 10 Gb/s product is being sampled by some customers but further design and manufacturing development is required before it will be available for sale in commercial quantities.

[2] For externally modulated transmissions.

[3] 40 Gb/s product is being sampled by some customers but further design and manufacturing process development is required before it will be available for sale in commercial quantities.

[4] Both are being sampled by customers and are ready for manufacture in commercial quantities.

[5] Can be tuned to one of 10 adjacent channels for DWDM systems. A recently introduced 20 channel CW tunable source laser module is being sampled by some customers but further design and manufacturing process development is required before it will be available for sale in commercial quantities.

[6] Integrated modules that, like transceivers, contain both a transmitter and receiver and also include a variety of ICs such as MUX/DEMUXes.

[7] Up to 40 channels.

[8] Devices are being sampled by some customers but further design and manufacturing process development is required before they will be available for sale in commercial quantities.

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