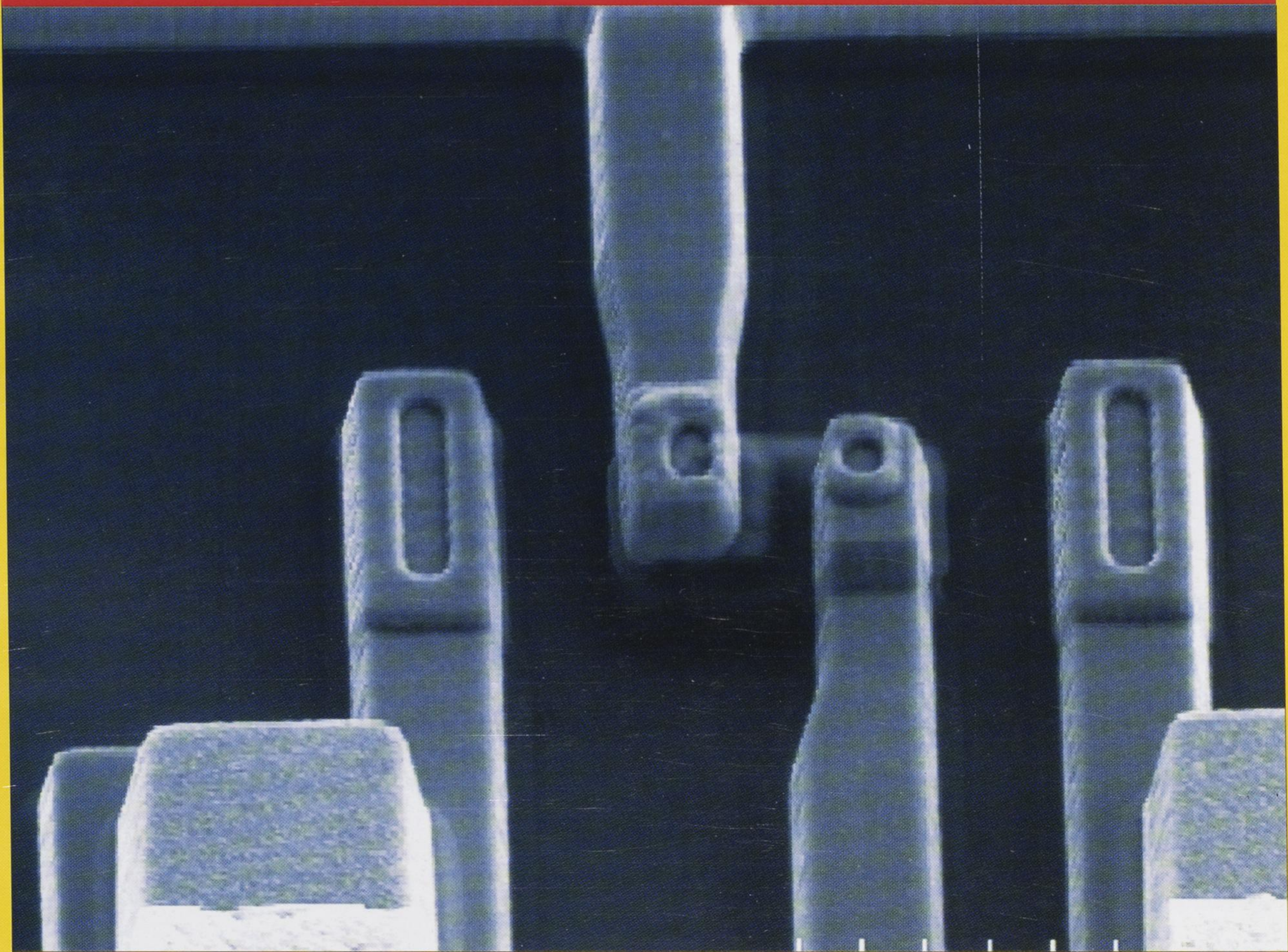


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April 2002 Volume 8 Number 3

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GaAs ICs **TriQuint, Xindium, InGaP** **HBTs and the handset market**

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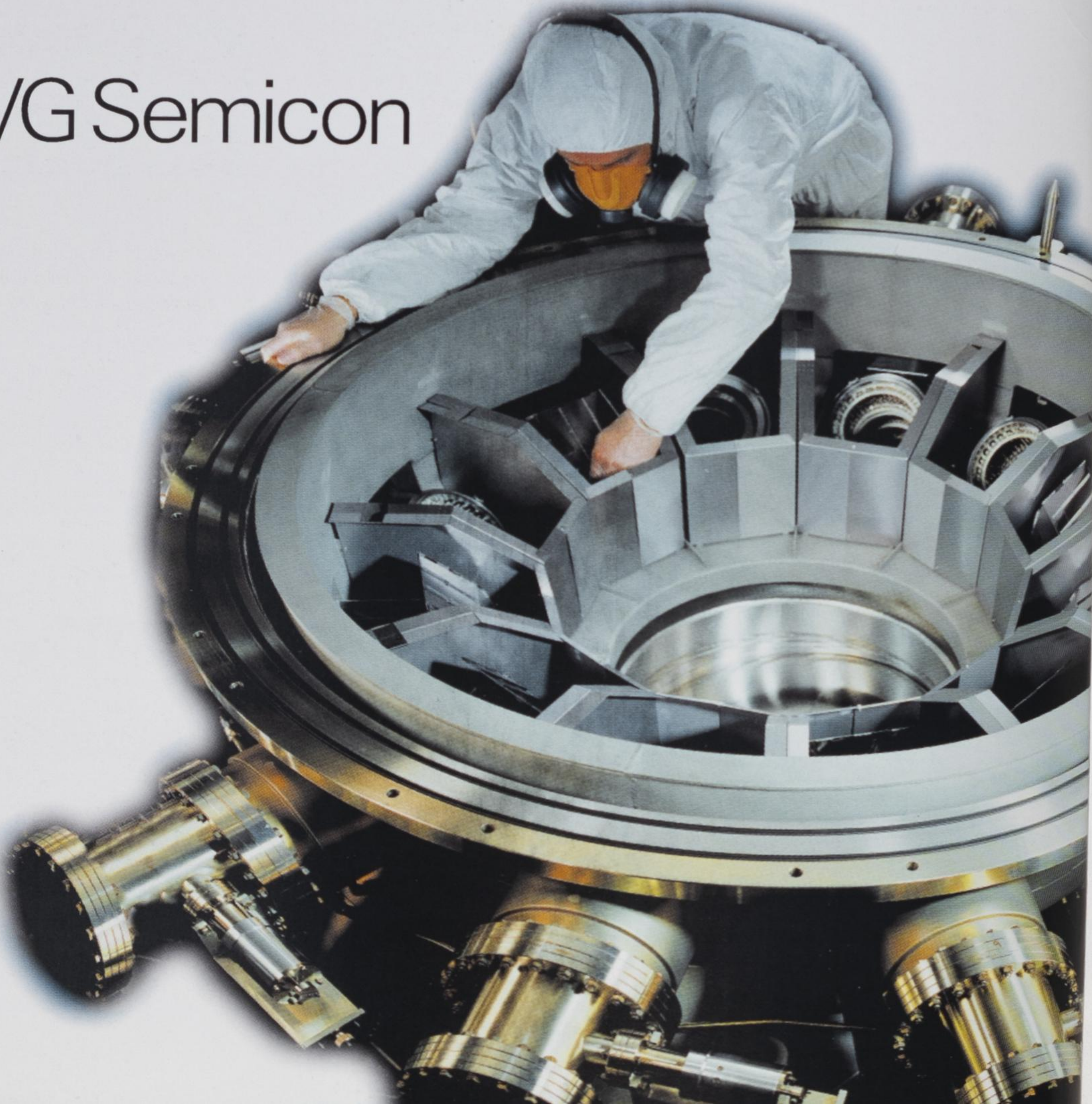
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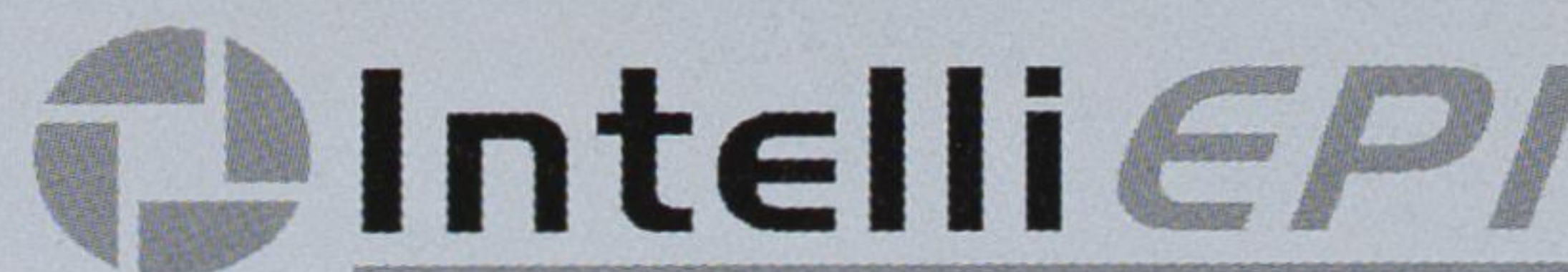
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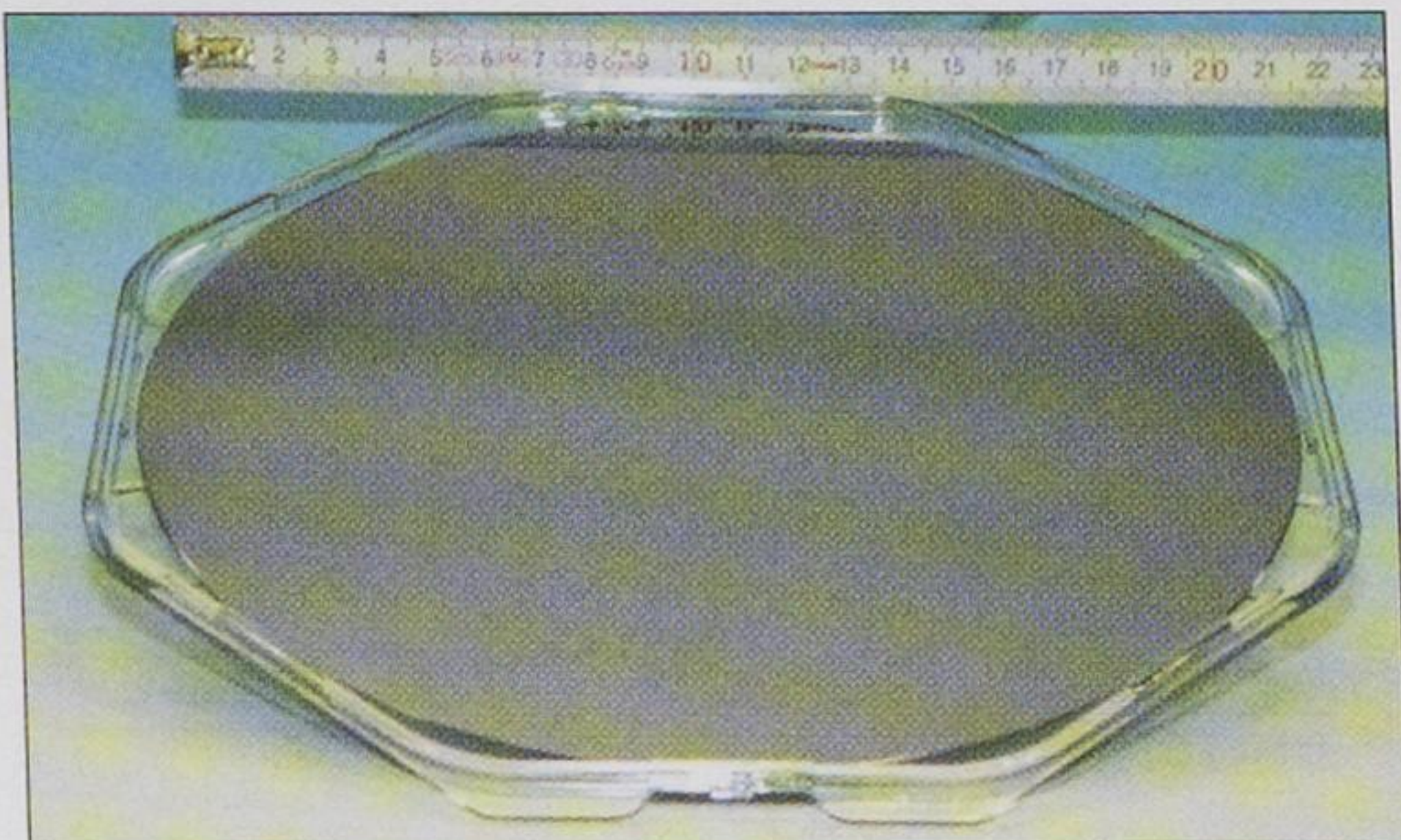
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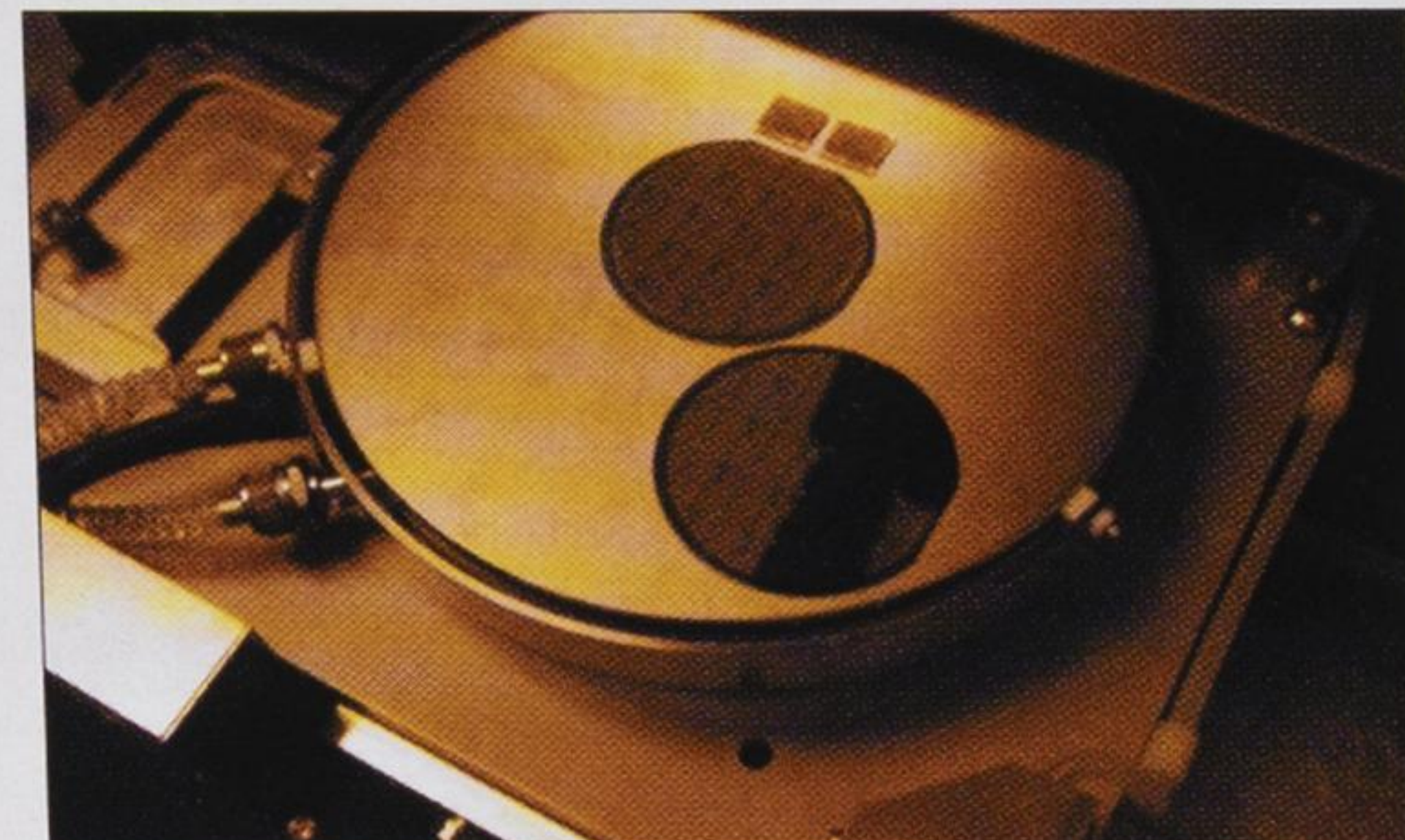
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White LEDs are now being considered for use in automobile headlamps **p15**



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Richard Dixon explores the advances in VCSEL arrays and long-wavelength lasers presented at Photonics West.

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TriQuint has virtually completed the conversion of its fab in Oregon to 6 inch wafers and also has a 6 inch fab in Texas ready for the market upswing, writes Tim Whitaker.

63 New technologies spur growth in wireless handset markets

The wireless handset market is poised to recover from its slump in 2001 as subscribers buy handsets with new features and services, writes Tim Whitaker.

67 Xindium uses InP expertise to make commercial 40 Gbit/s ICs

Xindium Technologies is using research results published by the University of Illinois at Urbana-Champaign to build high-speed, low-power indium phosphide ICs, writes Tim Whitaker.

69 The advance of GaAs/InGaP HBTs gathers momentum

The popularity of InGaP HBTs is growing and MOCVD seems to have cornered the InGaP HBT epiwafer market. Jon Newey looks at the reasons for this and asks MBE companies why they think they can get a bigger slice of the InGaP pie.

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On the cover: InGaP HBTs are replacing GaAs/AlGaAs HBTs in many applications (cover picture courtesy of WIN Semiconductors) – see page 69.

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New Blu-ray Disc optical recording format exploits blue-violet lasers

Nine leading consumer electronics manufacturers have jointly established the basic specifications of a next-generation high-capacity optical-disc video-recording format called "Blu-ray Disc". The new format enables the recording, rewriting and playback of up to 27 Gb of data on a single-sided, single-layer 12 cm CD/DVD-sized disc using a 405 nm blue-violet laser.

The companies that established the basic specifications of the Blu-ray Disc are Hitachi, LG, Matsushita, Pioneer, Philips, Samsung, Sharp, Sony and Thomson. Several of the companies such as Pioneer, Sony and Philips have already demonstrated prototype Blu-ray players using violet lasers. Toshiba, which is not part of the agreement, has also demonstrated a similar player.

In addition to actively promoting the new format throughout the industry, the nine companies will begin licensing as soon as specifications are completed. Licensing is expected to start around spring 2002, and Blu-ray players could go on sale at the start of 2003.

Current DVD players use 650 nm red lasers, while CD players use 780 nm diodes. A number of competing formats for record-

able DVD players have been introduced, like DVD-RAM, DVD-RW and DVD+RW; the Blu-ray agreement is likely to render these obsolete. The use of a 405 nm laser, in combination with a 0.85 numerical aperture (NA) field lens and other features, leads to a sig-

Blu-ray can record more than 2 hours of digital high-definition video and over 13 hours of standard TV signals.

nificant reduction in beam-spot size on the surface of the disc. This boosts the recording capacity compared with conventional DVD players, which can record 4.7 Gb of data on a single-sided disc.

With a capacity of 27 Gb, Blu-ray can record more than 2 hours of digital high-definition video and more than 13 hours of standard TV broadcasting. 50 Gb double-layer discs are also under development. High-speed data transfer at a rate of 36 Mbit/s is also possible, sufficient to record high-definition TV.

It will not be possible to play Blu-ray discs

with existing DVD and CD players, because they do not contain 405 nm lasers. Blu-ray drives will need to contain 780, 650 and 405 nm lasers in order to be compatible with CD and DVD discs. Chris Buma, program manager for A/V disc recording at Philips, says the power requirements for the 405 nm lasers are quite low compared with current DVD formats. "The required powers are 5.2 mW for writing and 0.3 mW for reading."

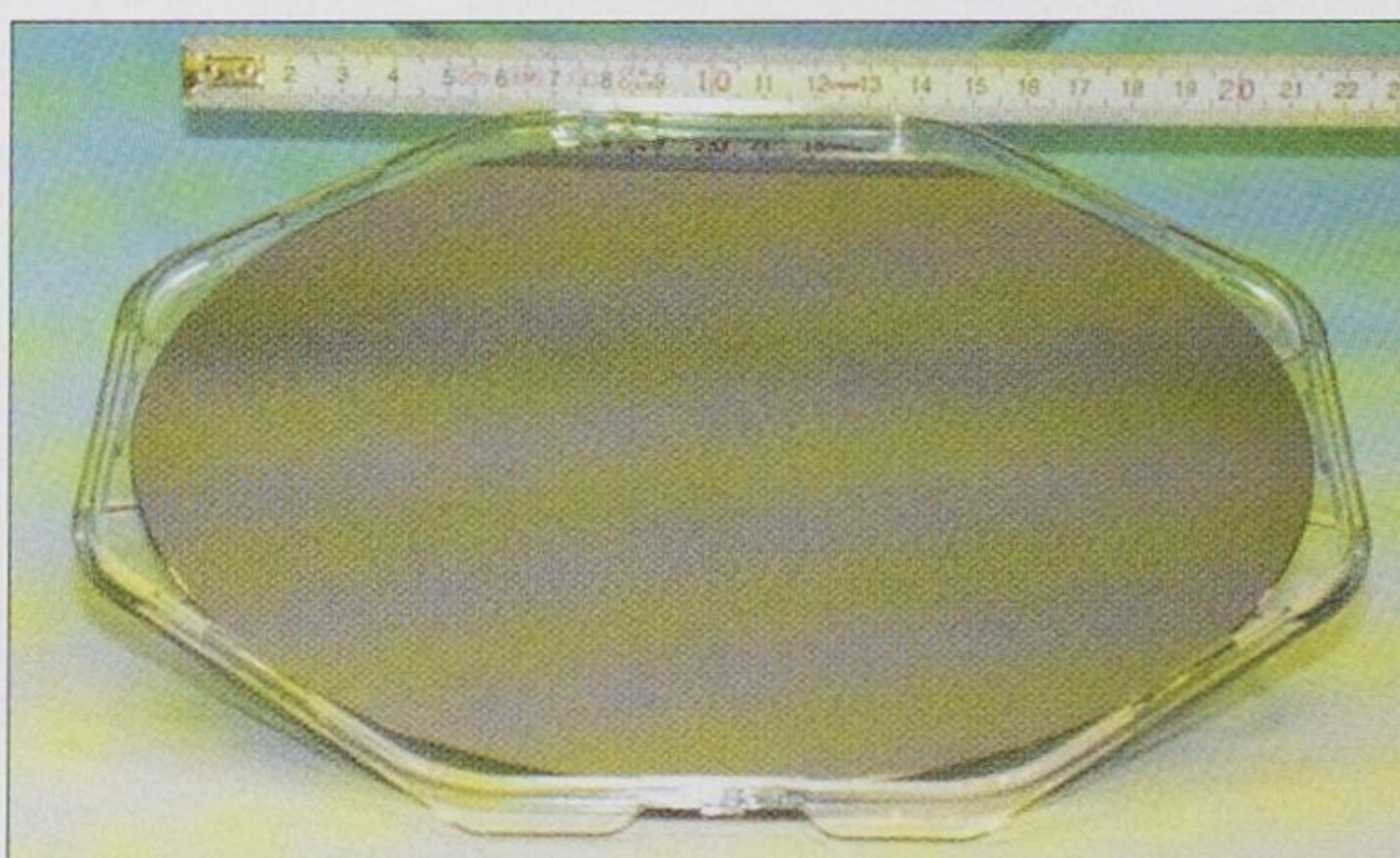
At present, the only commercial source of blue-violet lasers is Nichia, although Cree and Toyoda Gosei are both making progress in this area. On February 26, Cree announced that its blue laser had reached a projected lifetime of 10,000 hours (see p21), more than 4 years after Nichia passed the same milestone.

As this issue was going to press, Sanyo Electric announced that it had developed a 405 nm laser on a GaN substrate. This enables a vertical chip structure, simplifying the device-fabrication procedure and reducing the chip size compared with InGaN-on-sapphire devices. The company has also used ion implantation to achieve current confinement and significantly reduce the threshold and operating currents.

Freiberger makes 200 mm GaAs wafers with VGF

Freiberger Compound Materials of Freiberg, Germany, has succeeded in producing the first 200 mm (8 inch) diameter GaAs wafers from vertical gradient freeze (VGF) crystals. While these first wafers were produced under R&D conditions, Freiberger will continue to enhance and optimize the processes used so that they are production-worthy when the market begins to move to this diameter.

Freiberger is an established manufacturer of GaAs substrates using the liquid-encapsulated Czochralski (LEC) crystal growth method, and has also developed its own VGF growth technology. The company says that LEC is a more economical production process, while VGF wafers feature different



Freiberger has produced 8 inch GaAs wafers from a crystal grown by VGF.

characteristics, such as a lower etch-pit density, which can be an advantage in certain applications. The VGF process is in full pro-

duction for 100 and 150 mm wafers, and the firm claims to be the only GaAs wafer producer offering both LEC and VGF.

In August 2000, Freiberger presented the world's first 200 mm GaAs wafers obtained from LEC-grown crystals. The VGF-grown 200 mm wafers were fabricated as part of a project funded by the German government.

Future applications for semi-insulating GaAs will benefit from the larger 200 mm wafer diameter because increased wafer size is the key to higher production efficiency and cost savings in semiconductor fabs. In addition, 200 mm GaAs wafers will allow fabs to use state-of-the-art processing equipment designed for 200 mm silicon processing.

Compound semiconductor news is updated daily at www.compoundsemiconductor.net

AXT opens Ga extraction plant in China

AXT has significantly expanded its operations in China and has taken steps to ensure a guaranteed supply of both raw gallium and polycrystalline InP material. In addition to announcing that it owns 51% of a gallium extraction facility in China that can produce 20 tons of unrefined gallium per year, AXT has also developed a proprietary process in China to manufacture high volumes of InP polycrystalline material, the key ingredient in the manufacture of InP substrates.

"Expansion in China is a key component of our plans," said Morris Young, AXT's president and CEO. "Our China operation is the cornerstone of our growth strategy. Our presence in China brings us closer to many of our customers and sources of raw materials, and improves our efficiency, competitiveness and control over production costs."

AXT has already transferred a large segment of its wafer-manufacturing activities to its facility in Beijing. "We have already qualified our China-produced substrates with a majority of our customers, and have scheduled qualification with a number of others," added Young. "The production and investment steps we are announcing today constitute the next implementation phase in our long-term China strategy. We expect our presence in China to continue to enhance our competitiveness as the industry recovers."

Gallium extraction

AXT announced that it is a 51% owner of Beijing Ji-Ya Semiconductor Material Company Ltd, a gallium-extraction facility located in Shan Xi, China. The facility, which began production in late 2001, is capable of providing approximately 20 tons of gallium annually, enough to meet most of AXT's peak-period needs. AXT and its partners developed the proprietary process used to extract gallium from aluminum ore during the past eighteen months. Beijing Ji-Ya is likely to be one of the lowest-cost producers of 99.99% pure gallium in the world, and third-party processors will refine the gallium to 7N (99.99999%) purity. Gallium is the most expensive raw material in a GaAs substrate.

"This investment provides us with a secure source of gallium," said Young. "During early 2001, our production was nearly affected by a lack of this critical raw material and we were forced to pay high prices for some of the gallium we purchased. With our new investment,

AXT's recent quarterly revenues

Division	Revenue (\$million)			Sequential change (%)
	Q4 2000	Q3 2001	Q4 2001	
Substrates	36.4	20.5	11.5	-44
Optoelectronics	1.8	2.3	3.9	+70
total	38.2	22.8	15.4	-32

AXT owns 51% of an extraction facility in China that produces 20 tons of Ga a year.

the likelihood of future supply problems is significantly reduced and we are better protected from price fluctuations." AXT has the right of first refusal on materials produced by Beijing Ji-Ya.

InP polycrystalline material

Since early 2001, AXT has been developing its own process in China to manufacture high volumes of InP polycrystalline material. While both indium and phosphorus are in adequate supply, there have been shortages of the polycrystalline material, which is the critical ingredient in the manufacture of InP substrates. After success with a pilot project, manufacturing efforts were transferred to Nanjing Jinmei Gallium Ltd, a Nanjing company of which AXT owns 88%. Current production capacity is around 4 tons per year.

"Developing our own polycrystalline process assures AXT of an adequate supply of this important material and gives us tighter control of our raw material purity," added Young. "Our Nanjing facility already meets all of our needs and can increase its production rate to meet our requirements during periods of higher demand."

Revenue continues to fall

AXT's revenue slumped significantly in the fourth quarter of 2001. At \$15.4 million, the company's total revenue was down 32% compared with \$22.8 million in the third quarter of 2001, and down 60% compared with \$38.2 million in the fourth quarter of 2000. Revenue for the substrate division, which represents 75% of total revenue, fell sharply while the optoelectronics division grew by 70% sequentially (see table).

In the year ended December 31, 2001, total revenue grew by 3.6% to \$119.5 million.

Substrate revenue fell by 4% to \$108.8 million compared with 2000, while optoelectronics revenue grew by 32% to \$10.7 million.

Outlook for 2002

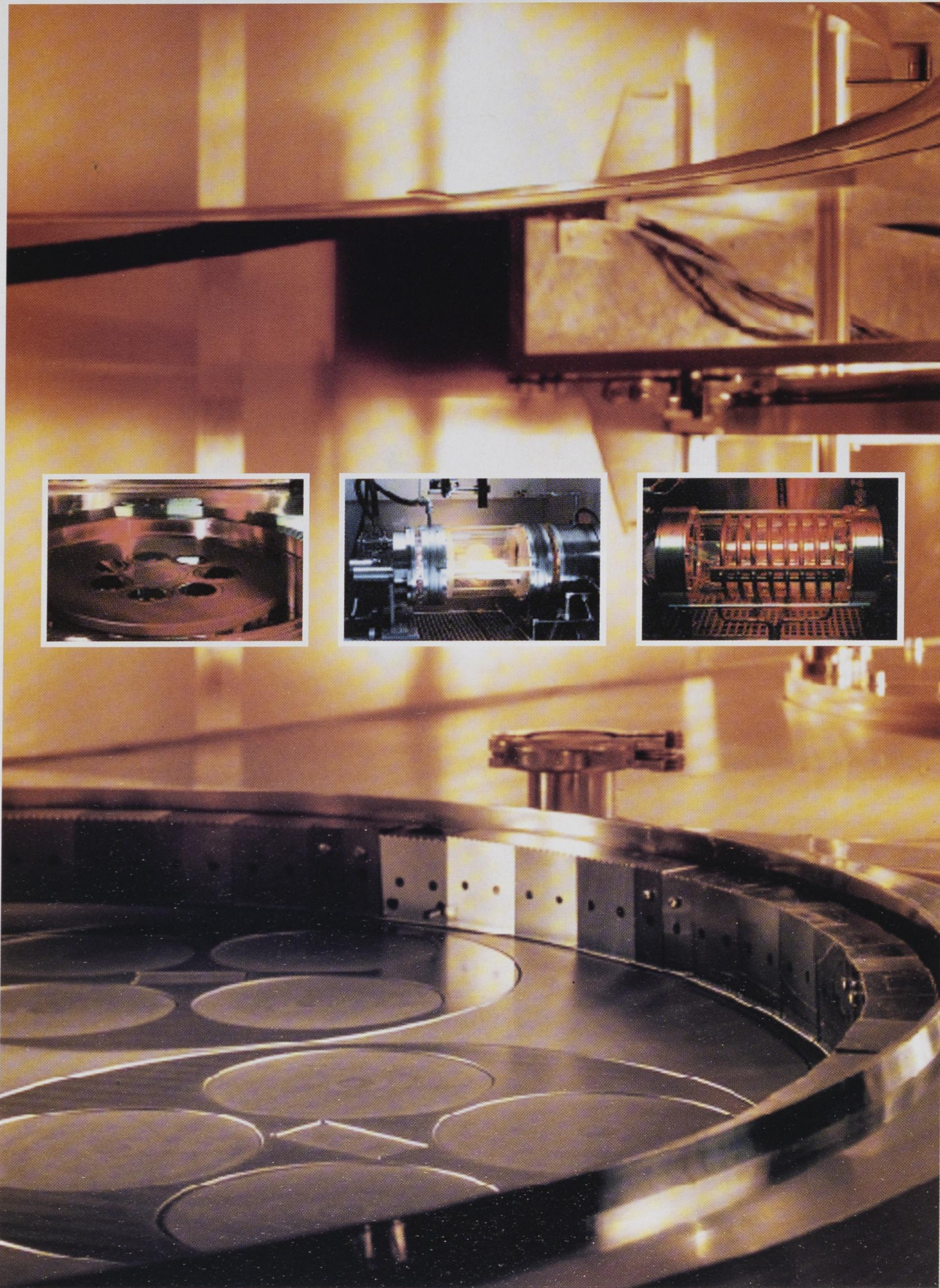
AXT experienced what were referred to as "challenging" business conditions in the fourth quarter of 2001, but Young says the company continues to take important steps to strengthen its position further as a leading supplier of compound semiconductor substrates. "We were pleased to see that during the fourth quarter, one of the world's leading providers of cellular handsets introduced a wafer quality specification for its 6 inch HBT and PHEMT device production that specifies VGF-type characteristics," said Young. "We believe this specification effectively narrows the market in favor of AXT. We believe our VGF GaAs and InP substrates continue to offer superior features for manufacturers of electronic and optoelectronic devices."

AXT's LED business is also showing positive signs. "We are running our LED operations around the clock to meet robust demand for our full range of LED products in the signage, backlighting and consumer-device markets," continued Young. "We have made significant advances in brightness over the last year and believe that we have abundant opportunity to grow our revenue and market share in the future."

While the industry continues to be affected by excess inventory issues in the near term, Young says that early signs of recovery are being seen in certain segments of AXT's business. "We believe that our leadership position in large-diameter GaAs and InP substrates, the rapid growth in our LED business and our progress in VCSEL technology position us well for growth as conditions improve."

AXT anticipates that revenue in the first quarter will be flat or show growth of up to 5% compared with the fourth quarter. An increase in sales of LED products is anticipated, while substrate revenue is expected to be approximately flat.

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Emcore buys Tecstar's applied solar division

Emcore has bought Tecstar's applied solar division for \$21 million. The deal gives Emcore the necessary facilities for all aspects of solar-panel manufacturing, from epitaxy and solar-cell fabrication to panel assembly.

At present, Emcore manufactures solar cells at its Photovoltaics division in Albuquerque, New Mexico, which has multiple MOCVD systems. The company claims to produce the most efficient radiation-hard solar cells in the world, with a beginning-of-life efficiency of 27.5%. Solar-panel arrays are critical sub-assemblies in satellite manufacturing, and higher solar-cell efficiency enables a satellite to generate more power for a given panel area. The deal will reduce the number of major compound semiconductor solar-cell manufacturers to two, namely Emcore and Spectrolab, a Boeing company.

For more than 40 years Tecstar has provided fully integrated solar panels that have powered many well known space programs

including the NASA Mars Pathfinder (see *Compound Semiconductor* October 2001, p23). Tecstar's record with major solar-panel integrators will be an important asset to Emcore in its quest to increase its presence in the satellite communications sector.

"Emcore has the most advanced solar-cell technology available today," said Reuben Richards, its president and CEO. "By acquiring Tecstar, we are combining our industry-leading technology with Tecstar's proven flight heritage to offer manufacturers an integrated solution to meet all of their satellite power needs from a single source." Emcore's multi-junction solar-cell technology will be used on approximately 10 satellite launches over the next three years. The company is currently qualifying its advanced solar cells with Tecstar's proven solar-panel processes for low-Earth and geostationary orbits.

The acquisition, which was completed in mid-March, was first announced in early

February as part of Tecstar's attempt to stave off bankruptcy. The company had filed a Chapter 11 motion in the Bankruptcy Court, which effectively allows companies time to reorganize while keeping creditors at bay. The proceeds from the Emcore transaction and the disposal or reorganization of Tecstar's remaining assets will go to Tecstar's creditors.

Tecstar had built up a large MOCVD manufacturing capacity at its facility in City of Industry, California. Emcore says that Tecstar's numerous multiwafer MOCVD systems, all made by Aixtron, are not part of the purchase agreement and will remain as assets of Tecstar to be sold separately. Emcore will take over the City of Industry site, which will continue to construct solar panels.

Earl Fuller, VP of Emcore's Photovoltaic division, added, "The experience and industry knowledge of Tecstar's talented employees will be a tremendous contribution to our satellite communications programs."

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RFMD finds new markets for MMICs

RF Micro Devices has begun shipping PA modules and LNAs to a top European handset OEM. Expected to reach the multimillion-dollar level this calendar year, the shipments include triple-band GSM power amplifier modules qualified for GPRS applications up to Class 12. RFMD will also ship GaAs HBT dual-band LNAs, which have an added bypass switch and are intended as front-end receivers

in 950 MHz GSM and DCS1800/PCS1900 applications. The LNA order marks RFMD's first volume shipment of a small-signal device for GSM applications, and underlines the company's strategy of expanding its overall IC footprint in wireless handsets while continuing to gain market share in power amplifiers, said president and CEO David Norbury. RFMD has also accessed a new market by

securing an order from Palm for GaAs HBT power amplifier MMICs. The products will be used in the new Palm i705 handheld personal digital assistant (PDA) to enable wireless connectivity for email access and Web browsing. "This win is significant as it further diversifies our customer base, increases our PA market share and extends our reach into the handheld market," said Norbury.

Alenia wins Teledesic contract

Italian satellite manufacturer Alenia Spazio SpA has been contracted to build the first two satellites for Teledesic's global broadband Internet-in-the-Sky satellite communications network. The Teledesic constellation will eventually consist of 30 medium-Earth-orbit (MEO) satellites, and offer broadband Internet services using Ka-band communications. Alenia Spazio beat Lockheed Martin for the contract, and has a long history of satellite manufacturing, having built 72 satellites for the Globalstar program along with the first geostationary Ka-band satellite, Italsat F1.

Several years ago, Teledesic's plan was to launch 288 low-Earth-orbit (LEO) satellites and to start delivering broadband services by 2002. However, the failure of the Iridium and Globalstar networks forced a rethink. "Teledesic initially opted for a LEO satellite system, which requires many more satellites than a MEO architecture," said Teledesic's strategic marketing manager, Roger Nyhus. "However, we found that with an MEO constellation we could provide the same level of service with fewer satellites at a much reduced cost." The first 12 satellites are expected to cost less than \$1 billion, and will offer continuous commercial service in several areas of the world. The remaining 18 satellites will enable full global coverage.

The Teledesic satellites are likely to employ



ALENIA SPAZIO

Alenia Spazio built 72 satellites at a rate of one per week for the Globalstar program.

GaAs RFICs operating in the Ka-band, as well as high-efficiency compound semiconductor solar cells. Also, Teledesic customers will each require a ground terminal to communicate with the satellite network, and these are likely to utilize high-frequency GaAs MMIC power amplifiers.

Conexant scores CDMA design wins

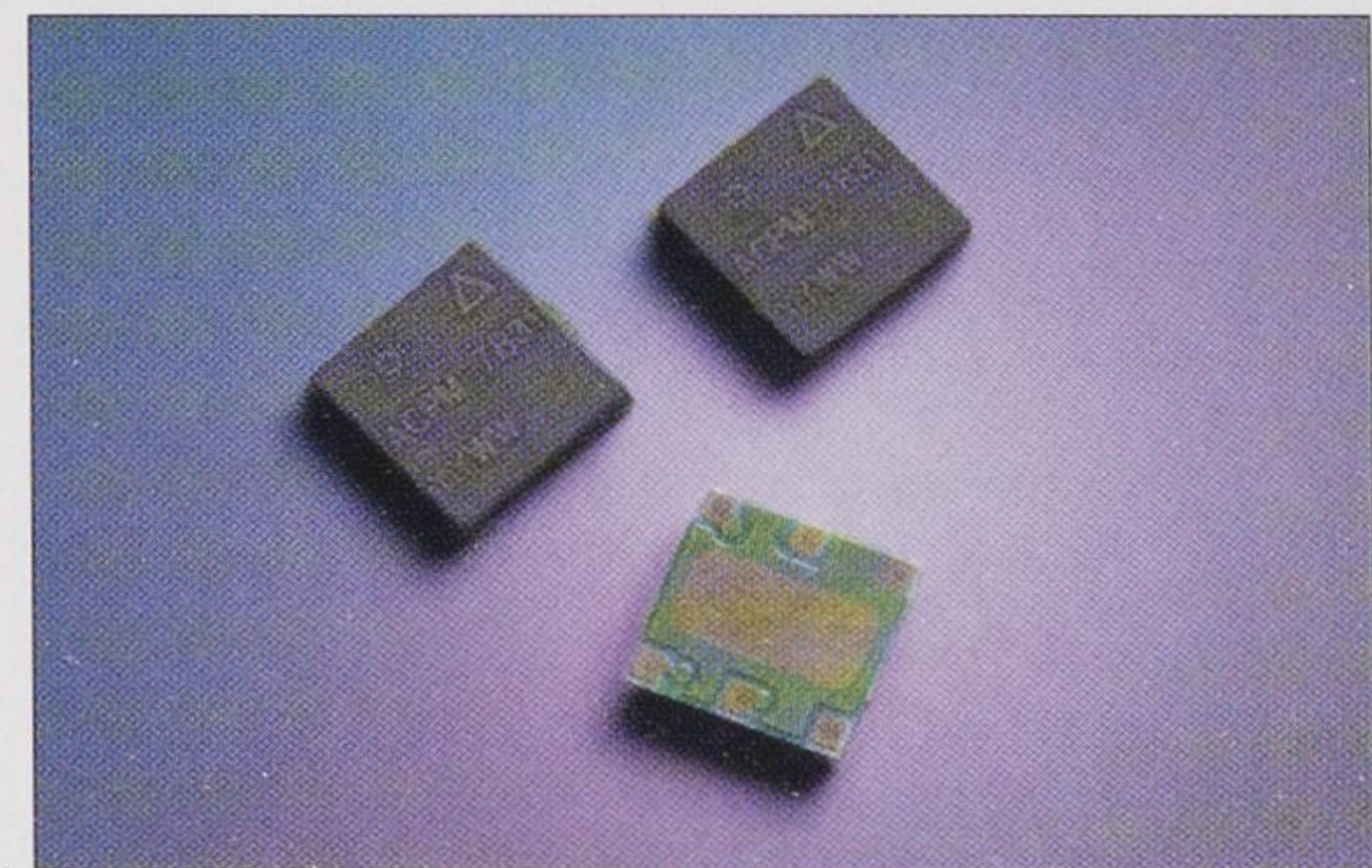
Conexant has announced multiple design wins for its PA modules from Chinese handset manufacturers. The orders come from 7 out of the 10 manufacturers approved by the Chinese government for China United Communications Corporation's recently launched

nationwide CDMA cellular network. Among the companies placing contracts are Haier Group Co Ltd, TCL Holdings Co Ltd, ZTE Corporation, Kejian Group and Lanchao Group. Conexant will supply modules that employ its 50 GHz AlGaAs/GaAs or InGaP/GaAs HBT power amplifiers. The new network will support approximately 15 million subscribers by the end of 2002, growing to 50 million subscribers by 2005.

Agilent and Tropian demonstrate new 2.5G transmitters

Tropian Inc (Cupertino, CA) and Agilent have demonstrated a complete 2.5G transmitter solution for GSM/GPRS/EDGE handsets. The new transmitter is intended for multi-band multimode GSM, EDGE and TDMA handsets. The transmitter features Agilent's enhancement-mode (E-mode) PHEMT power amplifier modules and Tropian's polar-loop modulator circuit technology. Tropian's circuit applies amplitude and phase modulation in separate paths, which the company says eliminates linear circuitry and its associated problems. This architecture enables multi-mode capability in both base stations and handsets, with backward and forward compatibility with analog and digital voice, and 2.5G and 3G high-speed wireless services.

"By joining with Tropian, we were able to combine best-of-class technologies that will enable handset manufacturers to extend battery life, reduce part count and size, and sup-



AGILENT

Agilent's E-mode PHEMT modules are used with Tropian's novel modulator circuit.

port multiple modulation formats within a single transmitter," said Bryan Ingram, business unit manager for Agilent's Wireless Semiconductor Division.

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Maxwell
TECHNOLOGIES

Conexant forms SiGe foundry

In the latest in a series of steps to reorganize the company into separate units, Conexant is to form a new specialty foundry company with Carlyle Group, a private equity firm. The as yet unnamed foundry will manufacture wafers for wireless and fiber-optic communication applications using a range of silicon processes including SiGe BiCMOS and analog and mixed-signal CMOS. Carlyle will hold 55% of the equity of the new company and Conexant will own the remainder. Carlyle will pay Conexant \$20 million and also contribute \$30 million in cash to the new venture.

Conexant will supply several specialty processes to the venture, together with manufacturing equipment at its Newport Beach, CA wafer fabrication facility, which has a

capacity of 20,000 8 inch wafer starts per month. The company has a 0.35 μ m SiGe BiCMOS process that delivers operating frequencies up to 70 GHz, and is also developing 160 and 200 GHz SiGe processes.

Conexant's three business units will be served by the new company under long-term supply contracts. This includes the wireless business which, with the GaAs wafer fab in Newbury Park, CA, is to spin off and merge with Alpha Industries (see *Compound Semiconductor* Jan/Feb 2002, p3). The other two business units support broadband access and Internet infrastructure markets. Known as Mindspeed, the latter business unit is also likely to be separated into an independent company in the future.

RFMD unveils tri-band chipset

RF Micro Devices has introduced a highly integrated transceiver with triple-band 950/1850/1950 MHz GSM operation that can also receive GPRS and EDGE data. The Polaris "Total Radio" RF transceiver provides a lower-cost baseband interface with fewer components, reduced power drain and lower cost of materials.

RFMD says the new chipset has only 20 parts compared with around 50 in a typical radio architecture. The Polaris includes a front-end receiver with three SiGe BiCMOS LNAs for the separate bands. The chipset also contains an RFMD GaAs HBT PA module, which employs an integrated closed-loop power controller and delivers 35 dBm for GSM and 32 dBm in DCS/PCS modes. The company has also integrated VCOs, associated loop filters and many of the power supply bypass capacitors.

The RF6001 transceiver uses a very low intermediate frequency (VLIF) architecture that dispenses with SAW filters used to change the signal into a much lower frequency surface acoustic wave suitable for baseband pro-

cessing. The chipset is now sampling, with production set for the fourth quarter, and a quad-band GSM version due later this year.

RFMD is not alone in producing complete radio chipsets, and some companies supply direct conversion GSM/GPRS transceiver chipsets that also eliminate IF parts, but typically feature more complex circuits and higher power consumption. "RFMD's VLIF approach eliminates problems that are common with direct conversion designs, such as the presence of local oscillator signals that fall exactly on the receiver input frequency," said Paul Brey, applications engineering manager for the GSM/GPRS/EDGE product line at RFMD. "With VLIF, DC products created in the mixer fall just outside of the IF band. This makes implementation in a real production phone much easier and less risky than with traditional direct conversion approaches, while offering all of the benefits. In addition, using cost-effective SiGe technology for the RF front-end provides excellent receiver sensitivity and virtually eliminates external matching components."

Cadence and Agilent make RF design deal

Two suppliers of RF design software, Cadence Design Systems and Agilent Technologies, have announced a partnership to develop integrated solutions that will accel-

erate the design of ICs for wireless and fiber-optic applications. The companies will jointly develop a more integrated design flow for large-scale RF and mixed-signal ICs. This new design system should shorten the time required for product development, reduce design costs and enable companies to focus on innovative products.



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Blue LED market gains new suppliers

By Richard Dixon

Two new suppliers have joined the handful of companies that currently manufacture GaN-based LEDs. Oriol is a two-year-old Silicon Valley start-up that has the capacity to manufacture 17 million devices per month, while Tekcore has begun sampling blue and green LEDs from its new plant in Taiwan.

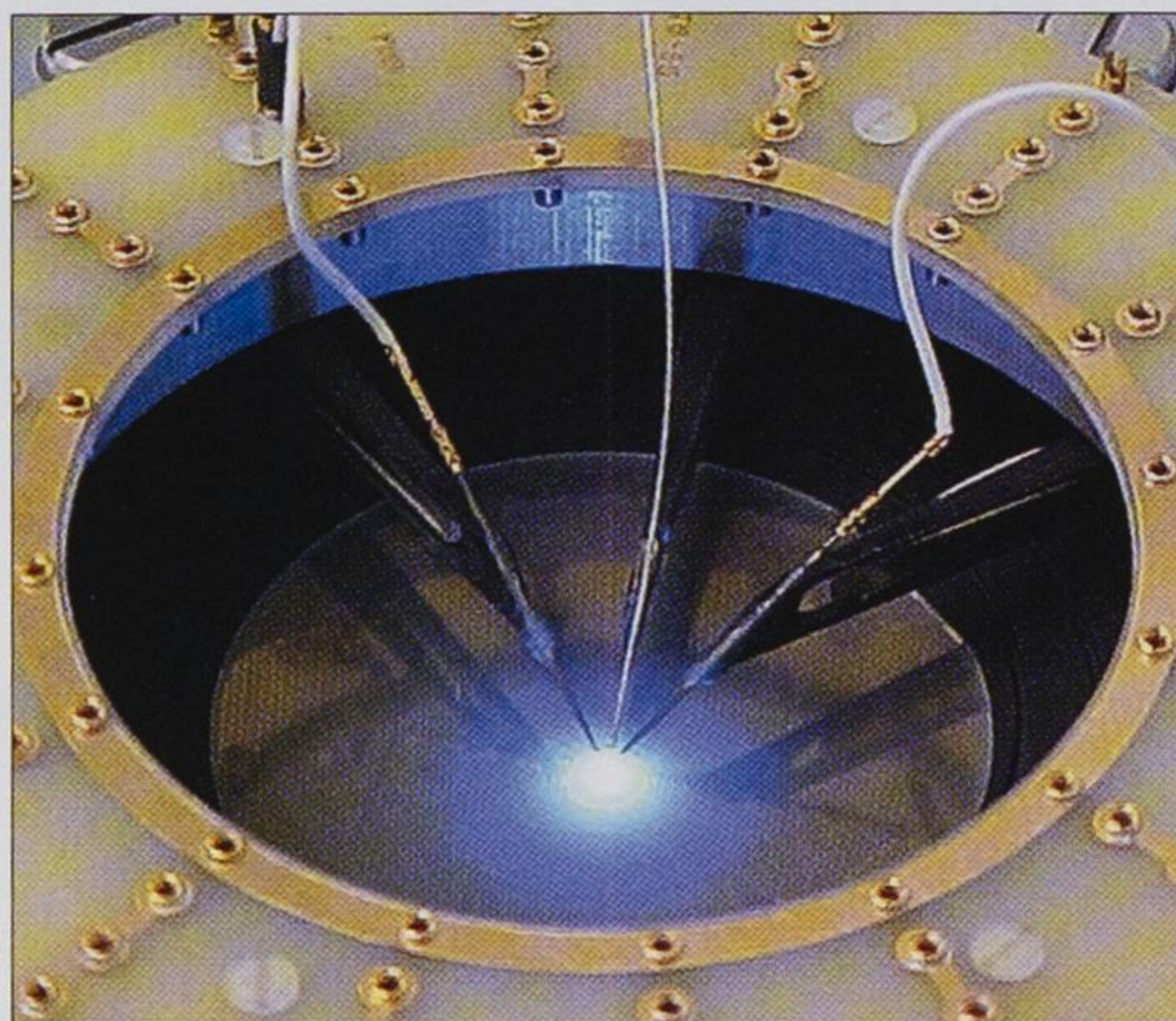
Oriol launches Gigabright LEDs

Oriol's first products are blue InGaN-based LEDs operating at 445 and 475 nm. These "Gigabright" devices are available as chips and lamps, and deliver up to 5 candela in 5 mm packages with a 15° viewing angle. A white LED with a 25° viewing angle delivers around 2.6 candela, and green (505 and 525 nm) emitters will be introduced soon. All devices operate at 20 mA with a forward voltage of 3.3 V.

"Since the current competition can only typically offer 3.5 candela ratings in production, these metrics firmly place Oriol in a brightness leadership position within the extremely competitive high-brightness LED arena," claims Oriol's president Burt Lancaster. "In addition, some LED die makers have been developing products that require special handling, while Oriol die can be packaged using traditional die-mount equipment and processes."

The new LEDs have a standard die size of $350 \times 350 \mu\text{m}^2$ and other sizes are planned, including larger chips with high lumen output for use in specialty lighting applications. The devices feature patent-pending designs that include metal layers which function as reflectors or current-spreading regions.

"Oriol has taken several approaches that will enable us to reduce costs and still a make profit," says marketing manager Tom Jory. "One of these is a concentrated effort to improve yields and obtain more die from a wafer. We achieve this in a number of ways, includ-



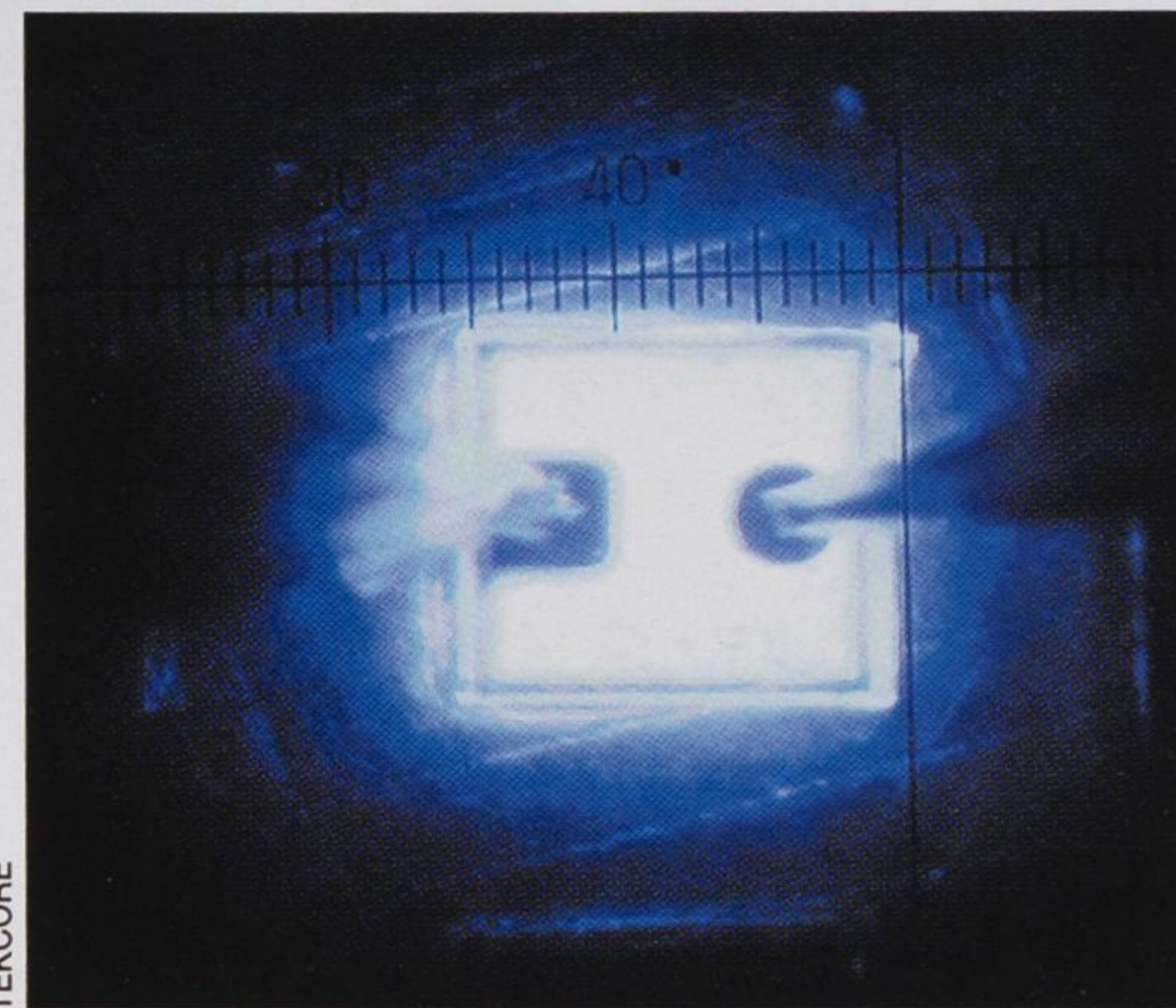
Oriol took less than two years to develop its first InGaN LEDs: 3.1 cd blue devices and white LEDs rated at 5.1 cd.

ing reducing material losses during dicing."

Oriol has a 1200 sq. ft device processing facility in Santa Clara, CA, and grows its device epiwafers by MOCVD on 2 inch sapphire substrates. Additional epiwafers are purchased from US and Taiwanese vendors. The company's estimated chip production capacity is currently 17 million units per month, and it plans to triple its capacity by early 2003 when it moves into a new facility being built in Lodi, CA. The eventual goal is a six-fold expansion of chip production. Oriol does not manufacture lamps in-house, but relies on Asian packaging houses.

Taiwan's answer

Recent start-up Tekcore Co Ltd has joined a growing list of Taiwanese companies attempting to commercialize GaN-based LEDs. Tekcore fabricates GaN-on-sapphire chips using in-house growth and processing facilities. Founded in late 2000, the company's product development ramp has been steep. After moving to its new facilities in March 2001, Tekcore finished the installation of its



Tekcore, a new Taiwanese LED chip supplier, produces blue LED die with a luminous efficiency of up to 6 lm/W.

MOCVD systems in June and started producing chips in October.

The first products are 470 nm blue and 505 and 525 nm green LEDs. These have been available in production quantities for sampling to potential customers since December 2001, says Tekcore. The devices operate with a forward voltage of 3.3 V at 20 mA, and deliver a radiant output power of ~6 mW after packaging. The luminous efficiency is 6 lm/W.

Tekcore employs 47 people at its 2800 m² (~30,000 sq. ft) facility in Nantou. It has two 6 x 2 inch production MOCVD machines, and another high-volume system is on order for the summer. The company's current capacity is 600 wafers per month.

"We expect to reach 1200 wafers per month by the end of this year, and 2200 wafers per month in 2003," says the company's president Nithi Nithipalan. "Our next products will be UV LEDs in the 370 to 390 nm range. We are currently in the development stage and expect to sample these devices by the fourth quarter of 2002. We are also planning to embark on the development of blue laser diodes."

Rohm gives \$2.5 M to research center

Rohm is to donate \$2.5 million to the Solid State Lighting and Display Center (SSLDC) at the University of California, Santa Barbara. Headed by blue LED and laser pioneer Shuji Nakamura, the center's five-year objective is the development of a white LED that is longer lasting and uses less energy than conventional

fluorescent lamps. Rohm's contribution will support research into GaN-based devices that are brighter than current blue LEDs.

The SSLDC has previously received donations from Mitsubishi Chemical and also from Cree, which in September 2000 pledged \$1.2 million towards the endowment of the Cree Chair to support GaN materials and device research. Shuji Nakamura was named as the inaugural recipient of the Cree Chair 12 months later.

**Our report
from the
Strategies in Light
2002 conference
begins on
page 51**

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Nichia's large-area LED boosts power

In the past year, Cree has made very rapid brightness enhancements to its LED chips (see p18) and appears to have overtaken Nichia, which had been the brightness leader since the nitride LED market took off. But Nichia announced at the Strategies In Light meeting in early February that it is planning to increase the brightness of its devices by 50% in 2002, and is targeting a threefold increase by 2004. "Given that this is the first time that Nichia has publicly discussed its roadmap, we believe Nichia is paying closer attention to Cree and realizes it needs to catch up," said Hans Mosesmann of Prudential. "Brightness and cost are the two driving factors in this market, and Cree is currently the brightness and cost leader. Given Nichia's new initiative it is clear that the industry as a whole will benefit because both companies will be pushing each other to innovate at a higher level."

One recent development from Nichia is a new ultra-thin surface-mount white LED that achieves a luminous intensity ~50% higher than the company's current products. The increased brightness results from efficiency gains made by improving the InGaN-on-sapphire chip design and the phosphor, says the company. Higher output is offered without an increase in size or power consumption.

Target markets include the backlighting of full-color LCD screens used in mobile phones, personal digital assistants, handheld video cameras and digital cameras. Nichia estimates that around 60 million handsets, mainly for sale in Japan, now have color LCD screens. The first samples of Nichia's NSCW215 series are side-view surface-mount LEDs with thicknesses of 0.8 or 1.0 mm. The output is 600 mcd. Engineering samples are available this quarter with volume production expected in the second quarter of the year.

Tenfold increase for large-area chips

At the beginning of March, Nichia joined rival LED makers LumiLeds, Cree and AXT by announcing the development of large-area InGaN LEDs for illumination applications. Nichia's new chips have an area of $1 \times 1 \text{ mm}^2$, allowing the devices to be driven at 350 mA and at powers of 2 W – up to 10 times the power of its current devices. Under these conditions, packaged LEDs have exhibited luminous flux values of 23 lm for white, 7 lm for blue, 28 lm for blue-green and 20 lm for green.

Emphasis has also been placed on manufacturability, and the new devices are housed in heat- and UV-resistant surface-mount packages that can be installed using standard auto-

mated assembly methods, including solder reflow. "Assembly manufacturers need components that are easy to install," said Noboru Tazaki, managing director and general manager of the company's Optoelectronics Products Division. "Nichia's high-power LEDs represent advanced technology, but more importantly the parts can be mounted with automated assembly equipment."

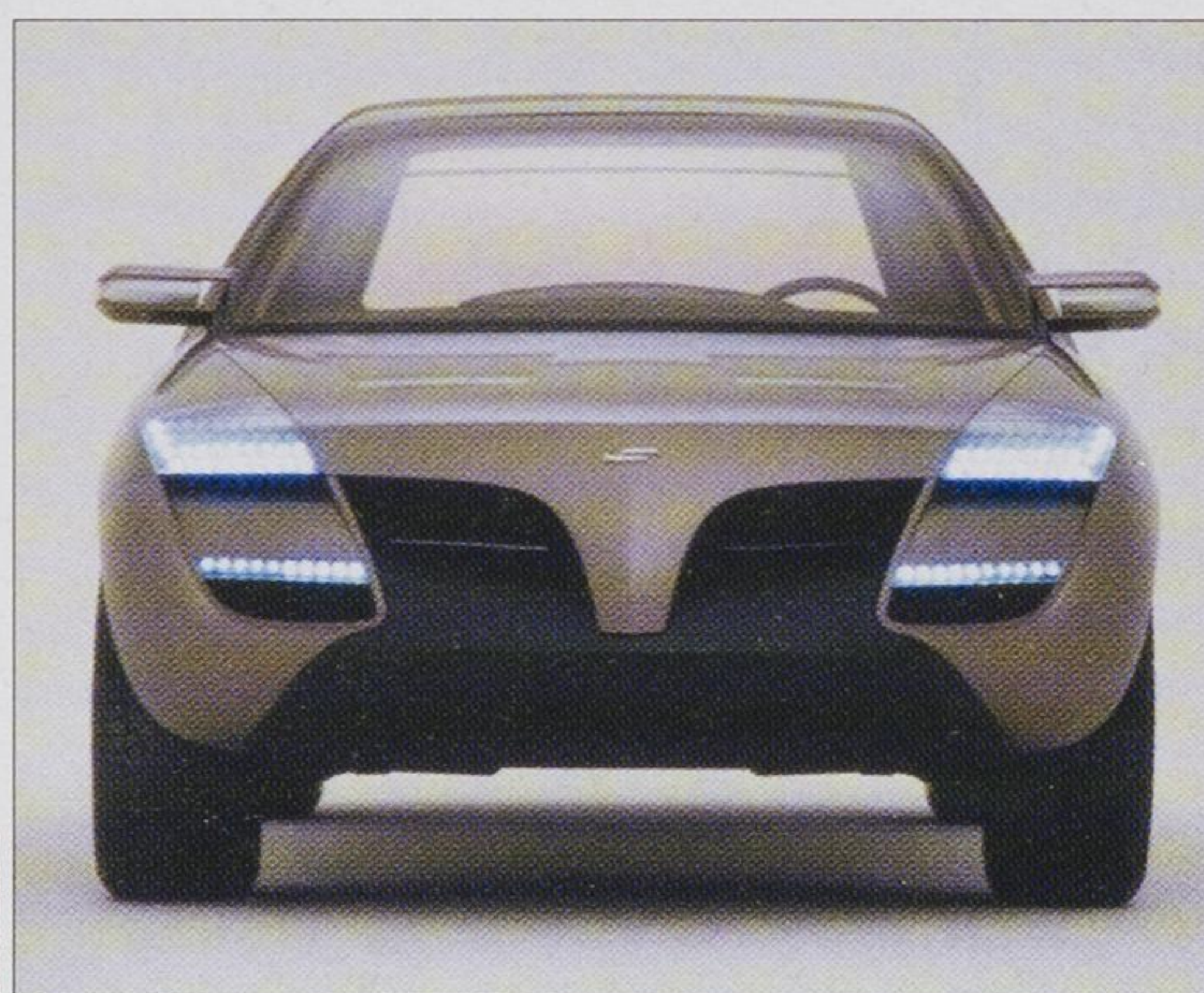
Nichia has developed two packages to house its new devices. The NSCx180F contains no plastics or organic resins and features a thermal resistance of 15°C/W . The resulting InGaN LED produces almost 100 mW of UV emission at 380 nm, at a current of 500 mA. In comparison, Cree's 405 nm device offers 250 mW. The package has dimensions of $10 \times 10 \times 2.3 \text{ mm}^3$, and an estimated lifetime of 100,000 hours.

The second package is rated at 8°C/W and dissipates more heat using an integrated copper heat sink. Featuring a resin optic lens, the NSCx190D suits channel letter displays, traffic signals and other specialty lighting applications. Measuring $11.2 \times 7.2 \times 6 \text{ mm}^3$ the package has an estimated lifetime of 50,000 hours. Engineering samples of the new LEDs will be available in the second quarter of the year.

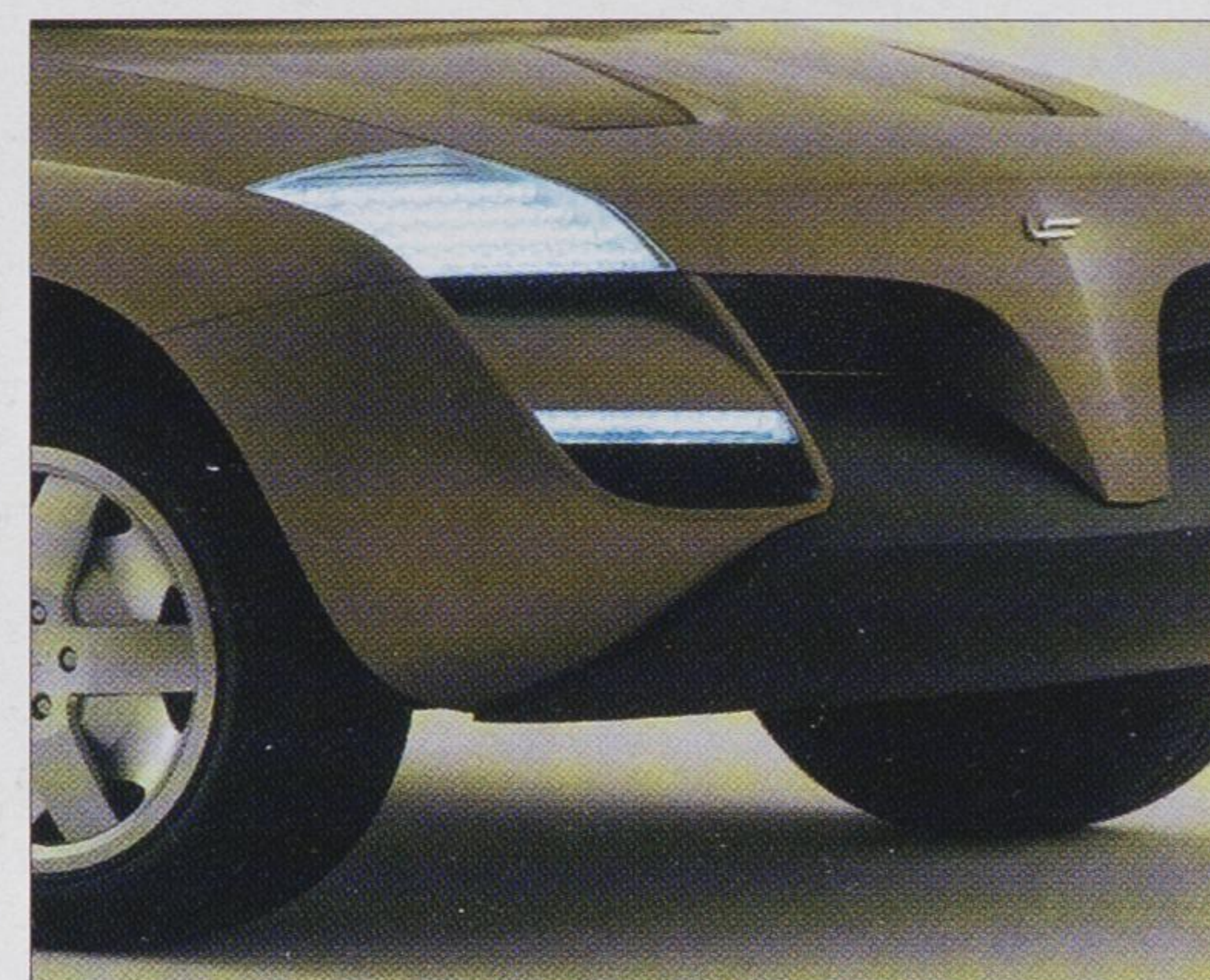
Car makers demonstrate white LED headlights

For several years, high-brightness LEDs have been used in both interior and exterior applications in automobiles, notably for red center high-mounted stop lights (CHMSLs). However, white LEDs have not been used in headlights due to the difficulty of creating a powerful enough beam. Headlights need ~1000 lm for low beam operation, and considerably more for high-beam illumination.

But at the Detroit Auto Show in January, Ford unveiled its Mighty F-350 Tonka concept truck which used a cluster of white LEDs as the headlights. Similarly, the Fioravanti Yak concept car, unveiled at the Geneva Motor Show in Switzerland, employed white Luxeon LEDs supplied by LumiLeds in a specially designed headlight cluster. The new headlamp clusters employ 36 Luxeon Star LEDs in an optical system controlled by software to produce different beam patterns. A single Luxeon LED delivers more than 50 lm of white emission – or as much as 20 times the power out-



The Fioravanti Yak concept car employs 36 Luxeon devices in the main headlamp cluster. The small footprint of the lamps provides the designer with a great deal of freedom.



put of conventional white LEDs.

"Fioravanti's use of Luxeon technology in their concept vehicle's headlamp is a milestone in the ongoing transition from conventional lighting solutions to LED-based light sources," said Mark Swoboda, LumiLeds'

VP of marketing. "It demonstrates that high-power LEDs are increasing their penetration in the market-place as the technology improves, giving designers the ability to incorporate smaller, longer-lasting and more energy-efficient light sources."

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Cree issues warning on Q1 2002 targets

On March 12 Cree warned that product delays and lower demand for LEDs will affect its financial targets for the March quarter. The company now expects to report revenue of \$32–34 million and to break even before taking a one-time charge of \$60–77 million for reduced goodwill associated with its UltraRF products. Analysts had been expecting Cree's results to be roughly similar to the December quarter, when the company reported profits of \$5.8 million on revenue of \$41 million.

Cree's CEO Chuck Swoboda predicted that revenues will increase by around 5% in the next quarter, as the LED business picks up again and the company receives more revenue from contract research. In the meantime, results are being hurt by the need to "manage the rotation" of Cree's LED business from larger- to smaller-volume customers. It seems that Osram, Cree's largest customer, is delaying some of its orders with Cree. There have

Cree's revenues

Quarter	Revenue (\$million)
March 2002	33.0
December 2001	41.0
September 2001	43.1
June 2001	44.7
March 2001	53.4

The March 2002 figure is an estimate.

also been reports from other sources that prices of blue LEDs are falling rapidly, having declined by as much as 33% during the last six months. Also Cree's recently purchased UltraRF division will be several months late ramping up production of its latest generation of LDMOS products, causing a revenue shortfall of around \$4 million.

The news sparked off a day of downgrades and heavy selling. UBS Warburg cut its price target on Cree shares from \$32 to \$15. Stock plunged from \$16.25 to \$12.40 at the opening bell on March 13, but closed at \$14.39. More than 12 million shares changed hands, which is five times Cree's normal trading volume.

This new disappointment follows a major sell-off in January when Cree management issued an earlier downward revision of their forecast (see *Compound Semiconductor* March 2002, p65). Shares dropped from \$31 to \$16 after that announcement but then stabilized until this new release.

Cree unveils power chips

Cree has made its first foray into large-area LEDs for specialty lighting applications, with the unveiling of its new X-Bright 900 Power Chip InGaN-on-SiC LEDs. These are 470 nm blue and 405 nm UV devices that employ the company's X-Bright design, but also have a die size of $900 \times 900 \mu\text{m}^2$. This is significantly larger than the $300 \times 300 \mu\text{m}^2$ chip typical for the industry, and allows much higher drive currents to be employed.

The company has recently made several design changes in order to improve photon extraction, culminating in the X-Bright series of LEDs which use a combination of chip shaping and flip-chip bonding onto a reflector, allowing more light to escape in the forward direction (see *Compound Semiconductor* December 2001, p9).

Cree's newest devices were unveiled at the recent Strategies In Light conference, held February 6–8 in San Francisco, CA. The new chip is driven at a current of 350 mA, which is more than 10 times higher than the drive currents used in industry-standard 5 mm lamps. Biased with a forward voltage of 4.0 V, the output power of the UV device is 250 mW – an order of magnitude brighter than Cree's standard X-Bright chips. The 470 nm X-Bright 900 blue emitter provides a brightness

of 150 mW at 350 mA, while Cree's standard X-Bright 470 nm LED is rated at 16 mW for a drive current of 20 mA. The company is currently sampling the new devices and expects production to commence shortly.

"This is a tremendous milestone for Cree and for the industry," said president and CEO Chuck Swoboda. "We believe that our power chip sets a new standard for commercially available power chips in the market. Since these chips deliver more than 10 times the light output of our standard X-Bright chips, we expect these high-power LED devices to enable a new range of lighting applications."

New green 505 and 525 nm LEDs

Cree has also recently announced several new green LEDs, including a 525 nm Megabright device and 505 and 525 nm X-Bright LEDs. The new LEDs are intended for full-color indoor and outdoor displays, advertising panels, traffic signals and consumer products. The X-Bright 505 nm LED exhibits a typical brightness of 11 mW, while the 525 nm emitter is rated at 9 mW. The Megabright device produces 7 mW and joins the company's 8 mW Megabright 505 nm LED. All the chips are nominally driven at 30 mA and have a forward voltage of 3.6 V.

Toyoda Gosei to ship white LEDs

Toyoda Gosei has received its first orders to manufacture white LEDs. According to the Japanese newspaper *Nihon Keizai Shimbun*, the company will start producing about 10 million units per month after April, mainly for use in cellular phones with color LCD screens.

Around 12% of phones shipped worldwide in 2001 had full-color displays, and almost all the handsets shipped in Japan in 2002 will have color screens. In a market currently dominated by Nichia, Toyoda Gosei says its aim is to "grab a considerable share" by offering competitively priced devices. First-year sales of ¥10 billion (~\$75 million) are being targeted, increasing to ¥40 billion (~\$300 million) in fiscal 2004.

The orders are also significant as the company may see lower sales of blue devices. According to the article, Toyoda Gosei's main LED business for blue and green devices reached sales of ¥17.7 billion (~\$132 million) last March. However, the slowdown in cell-

phone sales and the shift from monochromatic to full-color LCDs has meant demand for blue LEDs has declined. The company's LED sales are thus expected to fall slightly to ¥17 billion (~\$126 million) this financial year, which ends in March 2002.

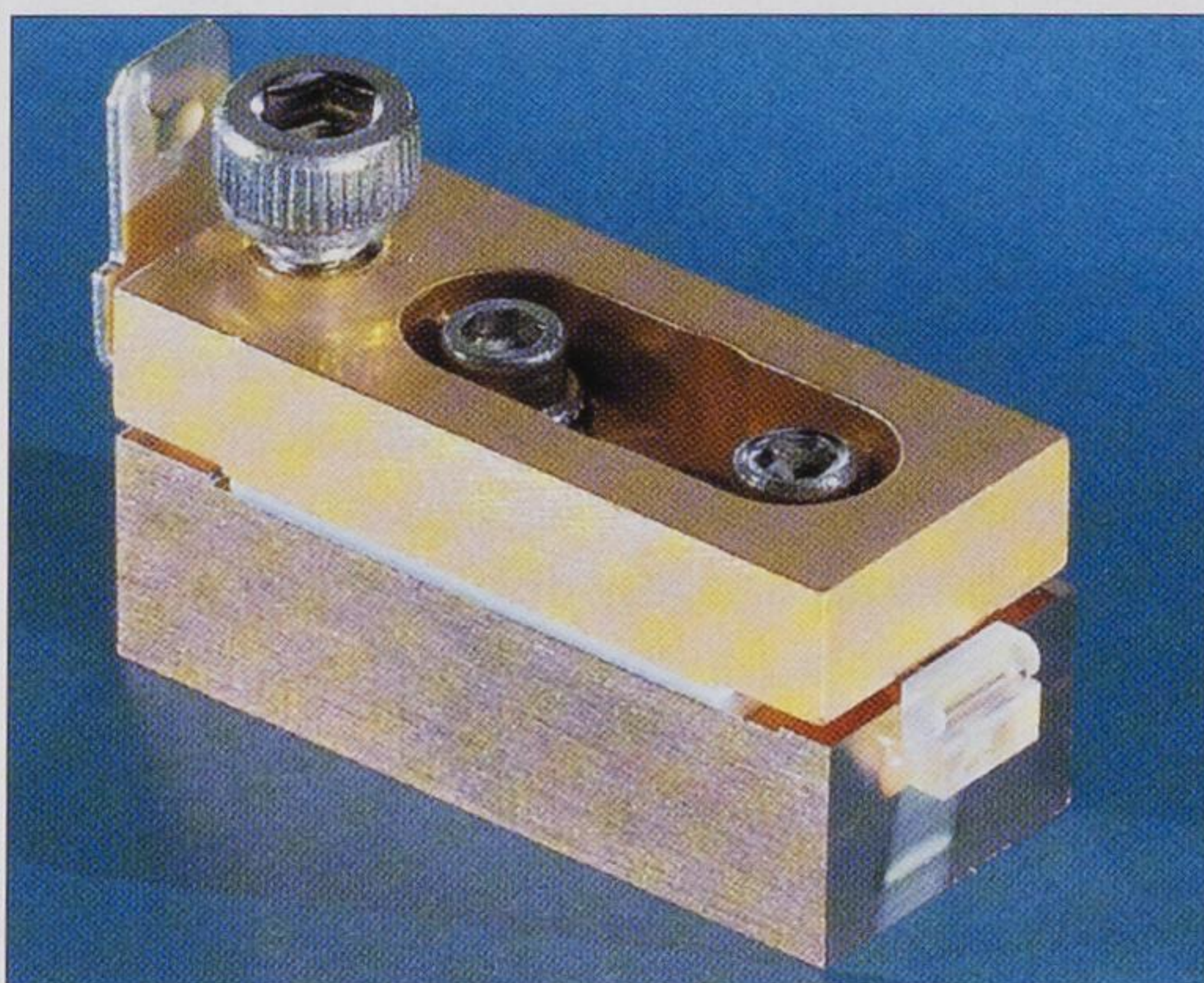
● On February 28, 2002, Tokyo District Court rendered judgments in two patent infringement lawsuits filed by Nichia against Toyoda Gosei, in both cases finding that Toyoda had not infringed on the patents in question. Patent no. 2,735,057 refers to a structure with an n-type InGaN cladding layer, but the court found that the corresponding layer in Toyoda Gosei's product is a GaN layer. Patent no. 2,770,720 refers to a transparent electrode for making an ohmic contact, containing Au alloy, and an electrode for bonding, containing Au and not containing Al or Cr to prevent an ohmic contact with said electrode. The infringement case was rejected because Toyoda Gosei's product contains Al.

New diode laser solders telecom fibers

Coherent has developed a fiber-coupled high-power laser diode array for welding gold metallized fibers to gold-plated substrates. At present this is performed using complex solid-state laser techniques. The need for precision alignment of 125 μm diameter optical fibers places stringent demands on the accuracy of the soldering system, and as Tony Hoult, Coherent's applications manager, told the *Optics.org* website, "Using solid-state lasers is a hard process to control. You need precise beam placement as three spots are used in the welding process. Accurate fiber alignment is hard to achieve and so people have started to look at diode laser soldering."

Damage limitation

The high thermal conductivity of an AuSn solder, along with its 280 °C melting point, mean that a careful balance between the laser's power density and exposure time is required in order to avoid heat damage to the fiber. Coherent's laser diode array consists of 19 emitters, each capable of 5 W output



Coherent's new 7 W, 808 nm diode laser is packaged in an industry standard conduction-cooled 10.5 x 25 mm² package.

power at 800 nm. The light is coupled into an 800 μm diameter fiber and delivers 40 W output power. For an 800 μm diameter spot at the soldering surface, the power density is 6 kW/cm². This enables a defect-free 500 μm AuSn solder joint to be formed in 2 seconds without damage to the fiber.

New diode boosts power

Coherent has also introduced a diode laser with a CW output power of 7 W. The new 808 nm device joins the company's existing range of aluminum-free InGaAsP/InGaP near-infrared lasers in the 790–813 nm range. According to Coherent, the new emitter is intended as a direct thermal source for material processing and medical and industrial markets, and also as a pump source for Nd: YAG solid-state lasers. Operating at less than 2 V and with a drive current of 8 A, the diode has a single broad-area emitter design with a stripe width of 500 μm , and it is mounted in an industry-standard 10.5 x 25 mm² conduction-cooled package. The spectral width is typically less than 2.5 nm FWHM, with a beam divergence of 35° by 10°.

"Our new diode provides the highest CW optical power that is commercially available from a 500 μm broad-area single-emitter device," said product line manager Michael Atchley. "This will allow our customers to upgrade the performance of their products without having to sacrifice size or reliability."



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QC lasers hit room temperature

A team from the University of Neuchatel and the Swiss Federal Institute of Technology has reported the first CW operation at room temperature for a quantum cascade laser (QCL). Operating at 19 °C, the new device had single-mode emission at 9.1 μm with an output power of 17 mW. At 39 °C the output power was 3 mW. The laser structure was grown by MBE on an InP substrate and contained 35 repeats of a region consisting of an n-doped injector layer and four undoped InGaAs/InAlAs QWs.

The demonstration of CW operation at room temperature brings QCLs closer to commercial viability as sources for chemical sensing and free-space laser communications. Another benefit is the ability to tailor the emission across a wide range of wavelengths in the infrared region by adjusting the thickness of the QWs in the active region rather than their composition. At present the laser has a lifetime of a few hours, although the group believe that further improvements to the epilayer quality and design will improve lifetime and raise the operating temperature to as high

as 100 °C. Alpes Lasers in Switzerland plans to commercialize the device and aims to have a product on the market in mid 2002.

Lucent Technologies' Bell Labs is another organization that is currently developing QCLs. Bell Labs' VP of physical research, Federico Capasso, spoke to *Opto & Laser Europe* magazine, a sister publication of *Compound Semiconductor*. "Room temperature, portable QCL-based sensor systems for detecting chemicals at concentrations of as little as 10–50 parts per billion will reach the market soon," said Capasso. He believes that sensor systems containing QCLs will be available by the end of 2002. Capasso also said that the flexibility to engineer QCLs emitting at a wide range of wavelengths could see them extend to emission at 70 or 80 μm , and even to emit multiple wavelengths from a single device. QCLs can also be modulated at high speeds. Combined with the ability to tailor emission within the infrared to correspond to atmospheric absorption minima, they become ideal as free-space data communication sources.

Red laser spot size reduced to 80 nm

A joint effort involving Japan's National Institute of Advanced Industrial Science and Technology, together with TDK and Sharp, has resulted in the development of a novel lithography technique that uses 635 nm semiconductor lasers. The method uses heat from the laser to create a pattern with features as small as 80 nm on a photoresist film. The ability to define such small features lies in the use of a substrate structure that absorbs heat efficiently, minimizing the area over which heating occurs. The researchers used an optical disc as the substrate and rotated it under the laser beam. By changing rotation speed and the optical power of the beam, the heat can be restricted to a much smaller area than the optical spot size (~1 μm), creating dots with diameters down to 80 nm and line widths of 110 nm. The technique could give a 20 fold increase in the volume of data stored on conventional DVDs, and could provide major cost savings over the expensive short-wavelength lithography systems currently used to define features of around 100 nm.

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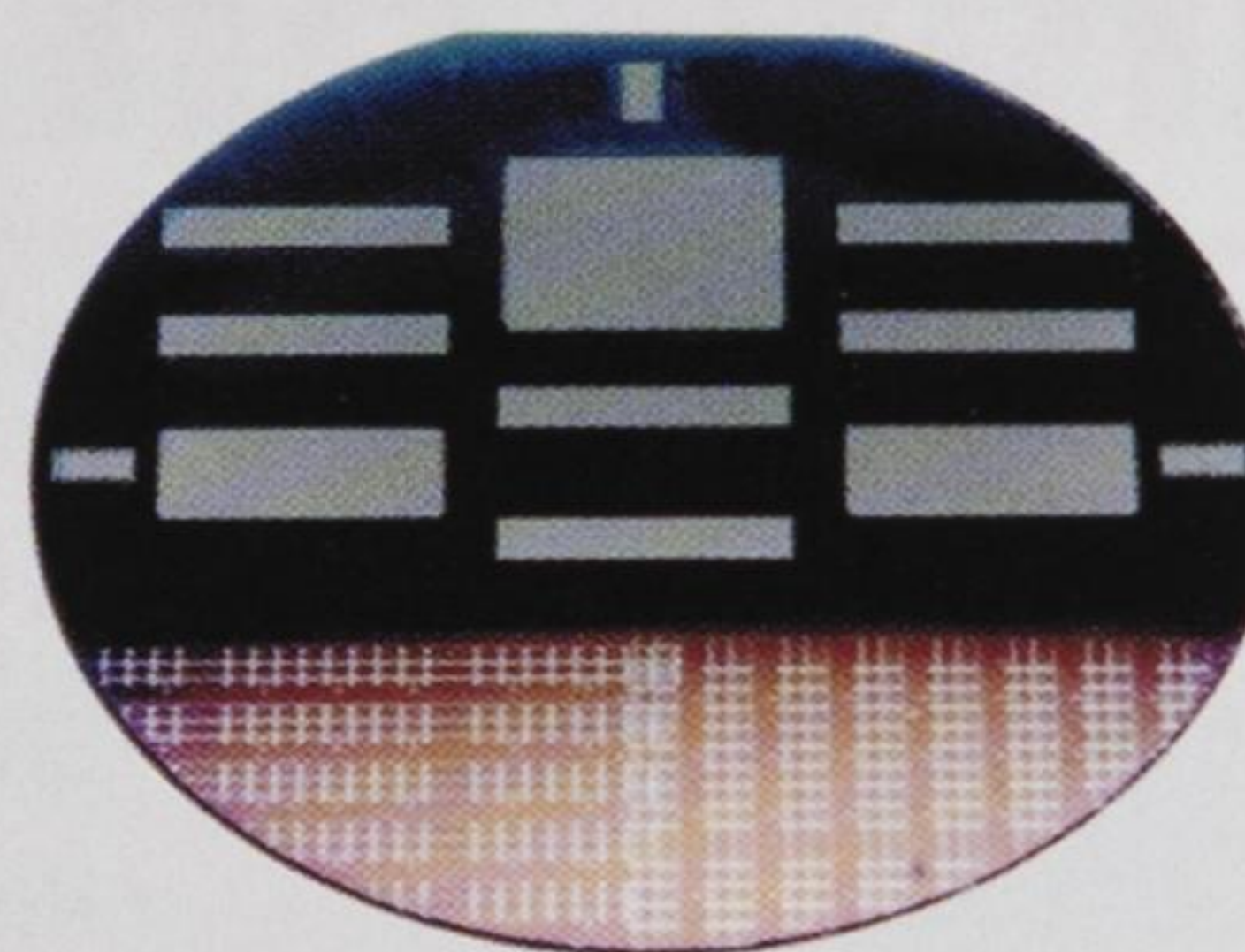
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Cree's violet laser lifetime exceeds 10,000 hours

Cree has announced that its 3 mW violet 405 nm laser diodes exhibit a projected lifetime at room temperature of more than 10,000 hours. Cree and a number of other companies are currently developing blue lasers, but at present Nichia is the sole commercial supplier of blue and violet GaN lasers, having introduced violet lasers in 1999 and blue devices in 2001. However, Cree now appears to be accelerating its development program, having announced a lifetime of 1000 hours for its InGaN-on-SiC devices just three months ago (*Compound Semiconductor* December 2001, p3). The company says that evaluation of its lasers is currently underway at major manufacturers of DVD players.

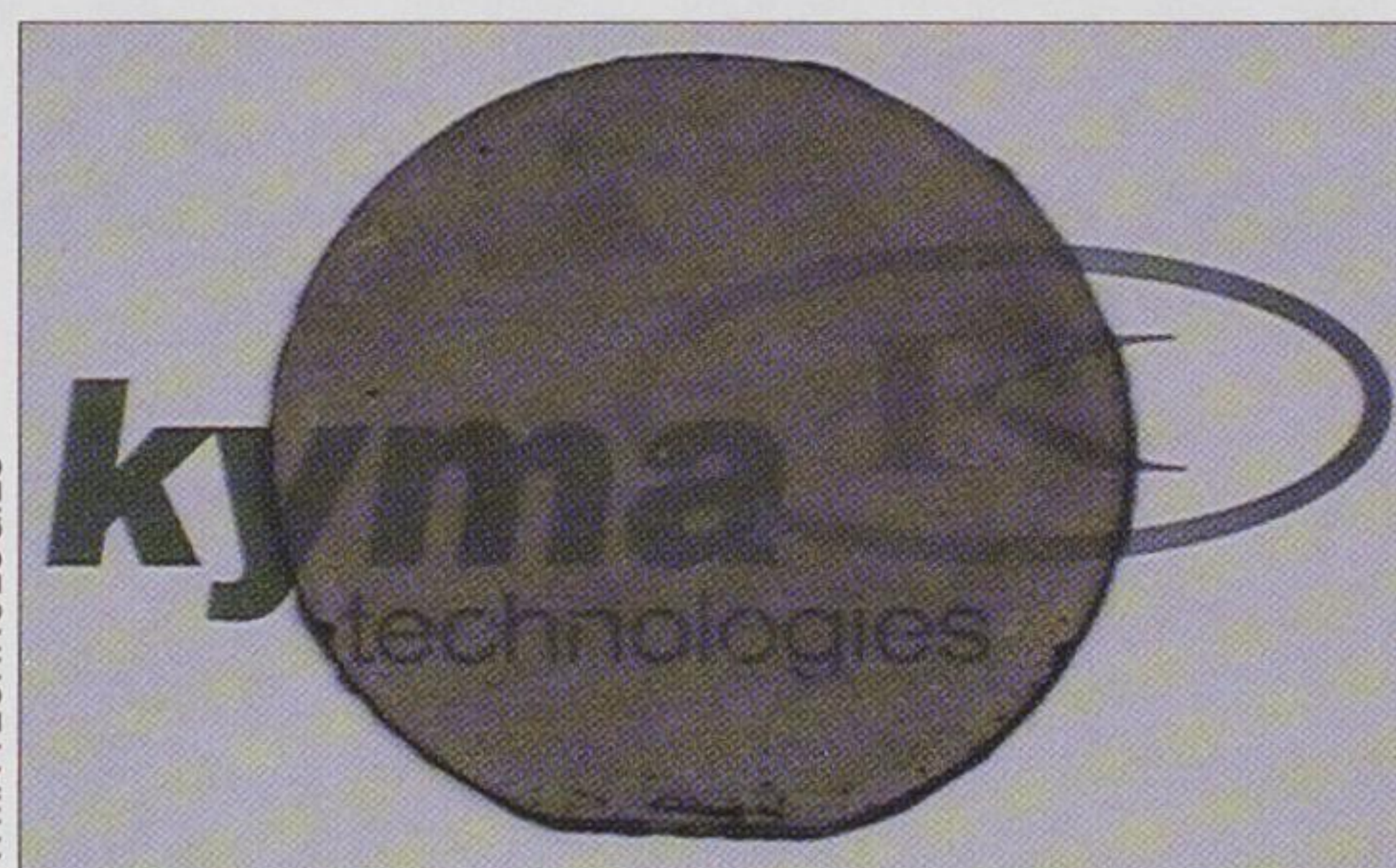
Cree believes that the blue laser diode it is

developing will meet the standards recently set out for the optical disc format that will succeed DVD. The new format has been agreed by nine companies and will be known as the Blu-ray Disc. The Blu-ray system will employ a 405 nm laser diode to record up to 27 GB of data on a CD/DVD-size disc (see p3). "This is one of the most significant achievements in the history of the company," said Chuck Swoboda, Cree's president and CEO. "We have accelerated our blue laser diode development and continue to target a product launch by the end of June 2002. We believe these diodes will meet the uniform standards being formulated, and look forward to participating in the exciting new optical disc applications under development."

Kyma ships 2 inch GaN wafers

Kyma Technologies has delivered single-crystal 2 inch GaN substrates to a manufacturer of microelectronics and optoelectronics devices. The new substrates are free-standing n-type GaN wafers with a thickness of 500 µm, and exhibit a usable area of more than 90%, says Kyma. The substrates are manufactured using a proprietary high-transport rate PVD process and should be available commercially by the end of the second quarter. The company is keeping the exact details of the process under wraps, but says that multiple GaN wafers are obtained from a 2 inch diameter boule.

GaN is the ideal material to replace the sapphire and SiC substrates that are currently used to grow GaN epitaxial layers. The absence of thermal and lattice mismatch reduces stress and defect densities, and the conducting nature of the material simplifies contacting procedures and device processing. Kyma



Kyma's GaN growth process enables 500 µm thick free-standing GaN substrates to be cut from a 2 inch diameter boule.

produces both GaN and AlN wafers up to 2 inches in diameter. The company is currently involved in quality assessments with several companies, and has been developing solar-blind UV detectors with Emcore (see *Compound Semiconductor* November 2000, p13).

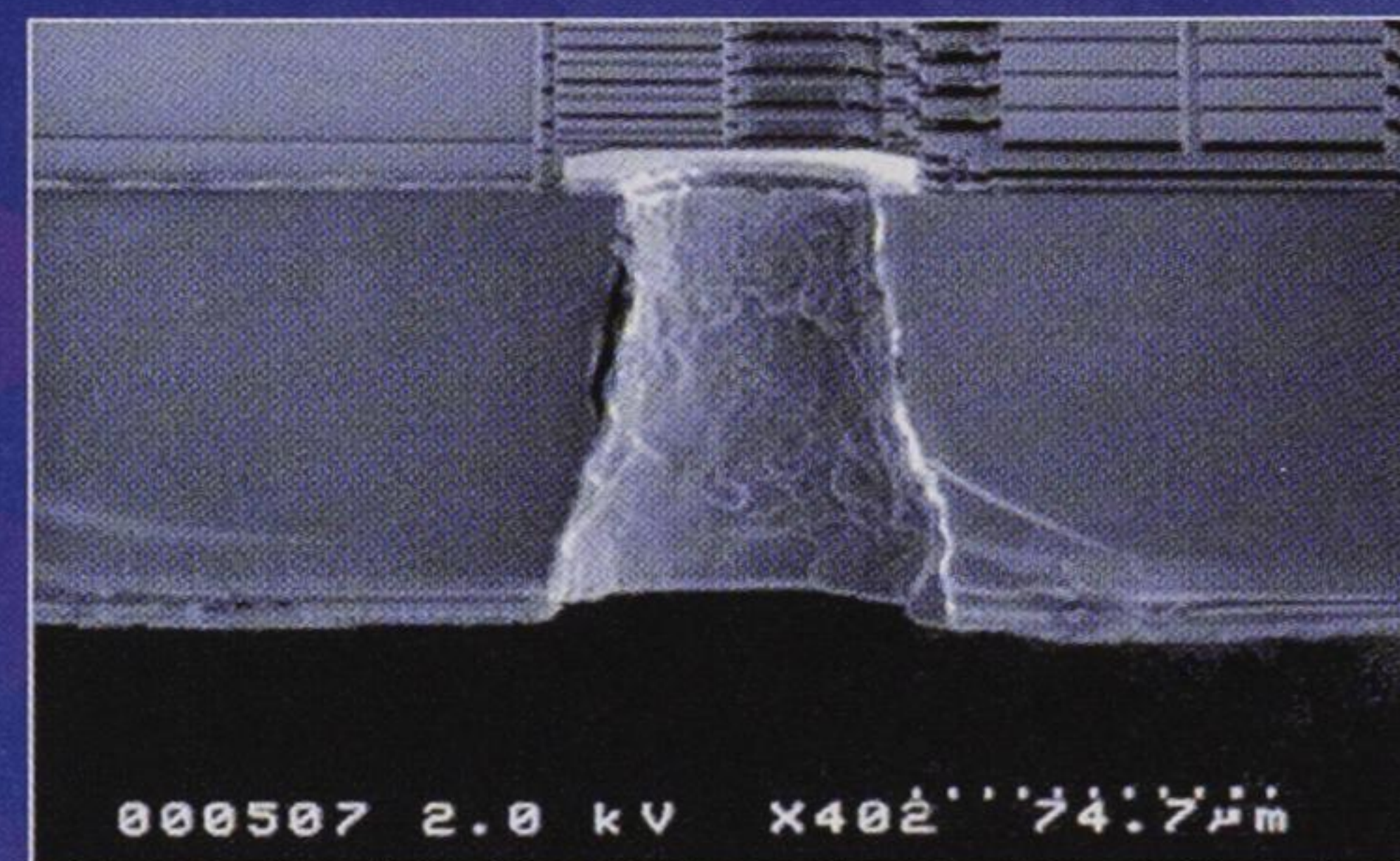
Cermet gets 50 mm substrate order

Cermet, a manufacturer of ZnO and GaN substrates, has received a production order for 50 mm diameter substrates from a top-tier US device maker. Cermet says that its substrates have defect densities comparable to more mature semiconductor substrates like GaAs.

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Finisar purchases active component capability for metro modules

By Richard Dixon

Finisar, a supplier of optical transceiver modules and network performance test systems located in Sunnyvale, CA, has reorganized its component subsidiaries, Sensors Unlimited and Demeter Technologies, into a single marketing entity called Sensors-Demeter Components Group. Sensors Unlimited, based in Princeton, NJ, makes high-speed photoreceivers as well as InGaAs-based near-IR cameras, while Demeter's facility in El Monte, CA, manufactures a range of lasers for fiber-optic communications. On February 7, Finisar also announced the acquisition of AIFOTec, a German manufacturer with proprietary optical module assembly and test technology.

Finisar goes vertical

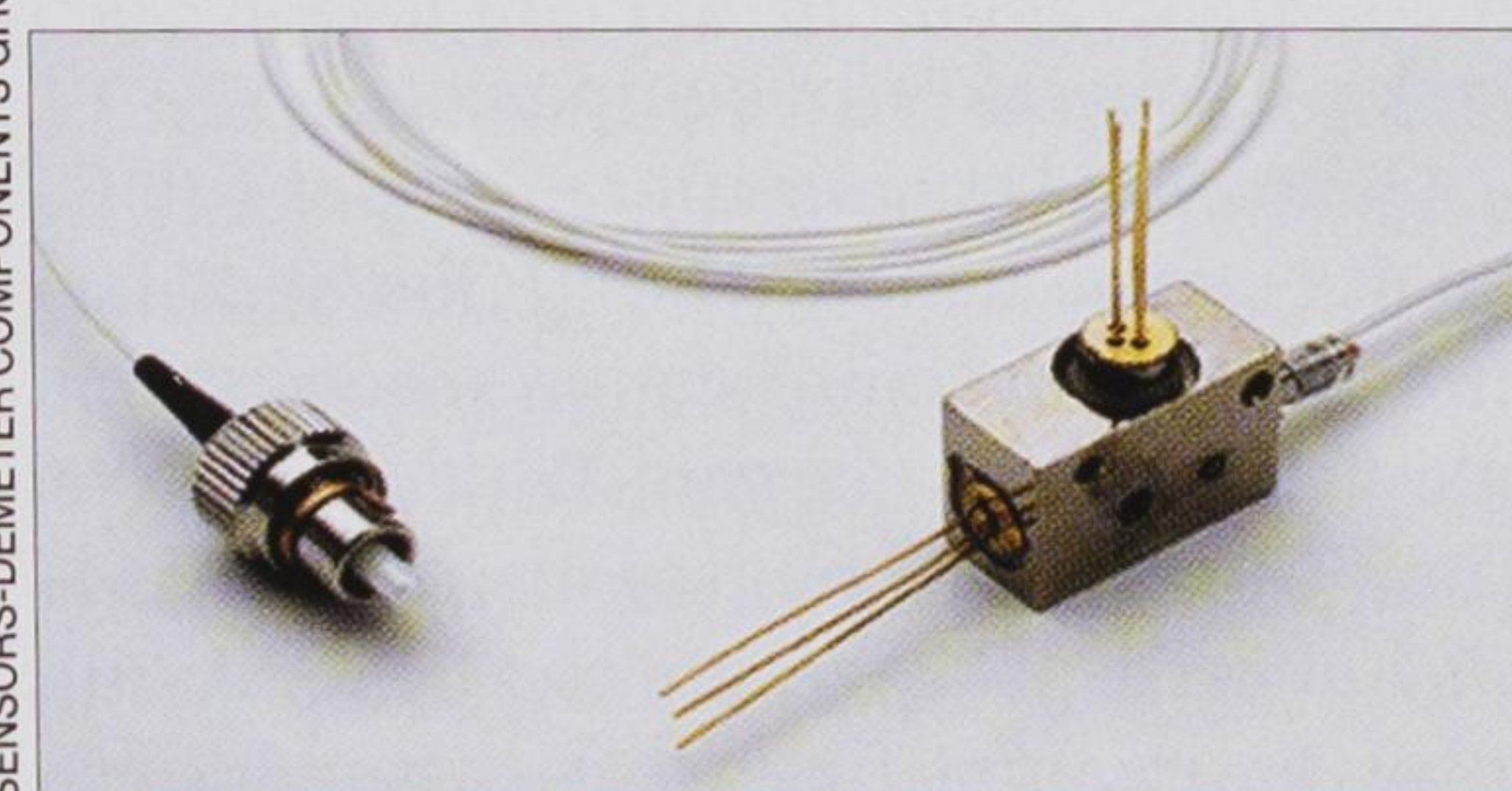
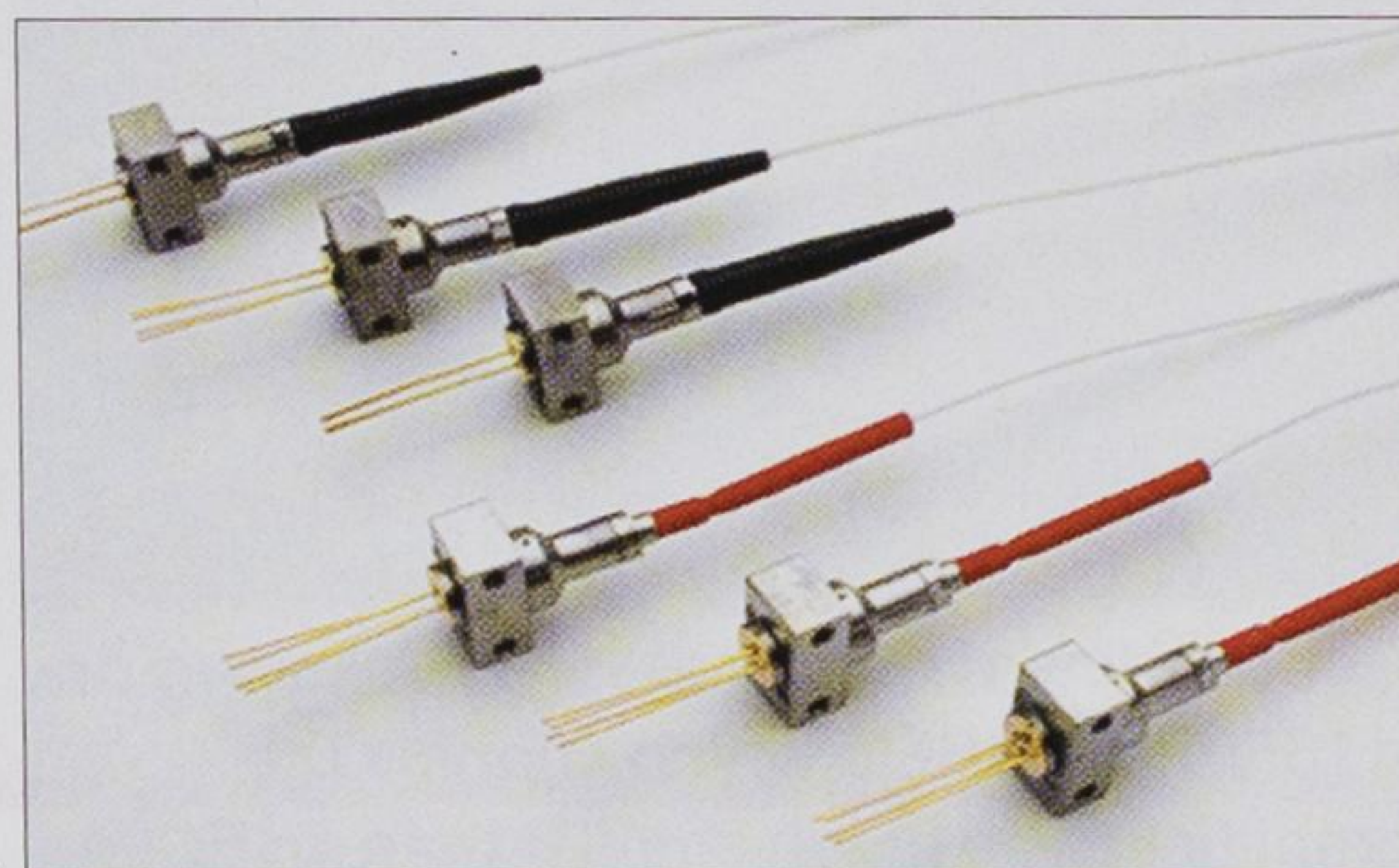
Finisar's optical modules are targeted at several markets, including Gigabit Ethernet local-area networks, Fibre Channel storage-area networks and metro markets. The company is a leading supplier of CWDM optical transceivers for the metro market, which it says provides a lower cost solution than DWDM technology. Since acquiring Sensors Unlimited in August 2000 and Demeter in November of the same year, Finisar now has the capability to manufacture the key laser and photodetector components that go into the transceivers.

According to Bill Woodrow, sales and marketing director for the new Sensors-Demeter group, Finisar is now unique as an optical sub-system module supplier. "Finisar has the two important actives that are required in a transceiver, and is therefore a vertically integrated sub-systems company," says Woodrow.

Despite being part of Finisar, the Sensors-Demeter group will continue to supply the merchant transceiver market. "Customer confidentiality will be maintained using a marketing firewall between Sensors-Demeter Components Group and Finisar," says Woodrow. "That way, both companies can supply components to Finisar directly, but are also free to supply the merchant market."

Demeter adds lasers to the mix

Demeter was founded by two ex-AXT employees in August 2000 and is housed in a vertically integrated 25,000 sq. ft facility in



Sensors-Demeter Components Group makes a range of lasers and receivers (top) and a 1310 nm active coupler module (bottom).

El Monte. The company uses MOCVD to fabricate ridge-waveguide Fabry-Perot and DFB lasers with InAlGaAs QW structures (see *Compound Semiconductor* September 2001, p47). Processing and packaging are done in small quantities on-site, with high-volume packaging taking place at Finisar's facility in Malaysia. Processed lasers are available as chips or as uncooled optical modules with a TO-56 flat-window cap package. Outputs range up to 5 mW in CW mode, and 1310 nm emitters can be directly modulated at data rates up to 2.5 Gbit/s; similar 10 Gbit/s versions with in-built cooling will also be available in the near future. Demeter also produces module-level products, including wavelength combiners and pigtailed active couplers (see figure). Bi-directional modules combine 1310 and 1550 nm wavelengths into a single unit and target fiber-to-the-home applications.

APDs and beyond

The first products to be released under the Sensors-Demeter name are InGaAs APDs intended for use in 2.5 and 10 Gbit/s receivers. Operating at 1550 nm and from a 3.3 V supply, the 10 Gbit/s APDs provide a responsivity of 7 A/W and a sensitivity of -22 dBm. The new diodes are manufactured by Sensors

Unlimited, which also makes InGaAs near-infrared cameras, focal-plane arrays and network monitoring equipment.

"APDs offer additional amplification compared with *pin* diodes, and provide anywhere between 6 and 10 dB of extra sensitivity when compared with *pin*/pre-amp combinations," says Sensor's president and CEO, Greg Olsen. "The extra link budget allows the number of metro network connections to be increased." Available on a sub-mount or in small TO-46 cans, the new detectors are as reliable as *pin* diodes, says Olsen. Packaged versions are sold with an integrated transimpedance amplifier on board.

"We currently outsource our epiwafer requirements, and will be starting in-house epitaxial growth at the R&D level very soon," adds Olsen. "The primary reason for this is to develop 40 Gbit/s receivers for next-generation optical networks, in addition to working on integrating TIAs onto the InP substrate to further reduce costs."

Automated packaging

The acquisition of ailing Munich-based AIFOTec for \$2.3 million included capital equipment, inventory and intellectual property, and primarily provides Finisar with additional automated module manufacturing technology. AIFOTec has developed a proprietary hybrid integration method for producing fiber grating laser arrays designed for CWDM or DWDM applications. The company employs a silicon wafer as the sub-assembly, with v-grooves etched to secure fibers for attachment to lasers. Flip-chip bonding is subsequently used to mount the active components (see *Compound Semiconductor* November 2001, p41). Finisar will retain the company's 30 employees, and will use AIFOTec to strengthen its European sales and marketing presence under the new name of Finisar Europe GmbH.

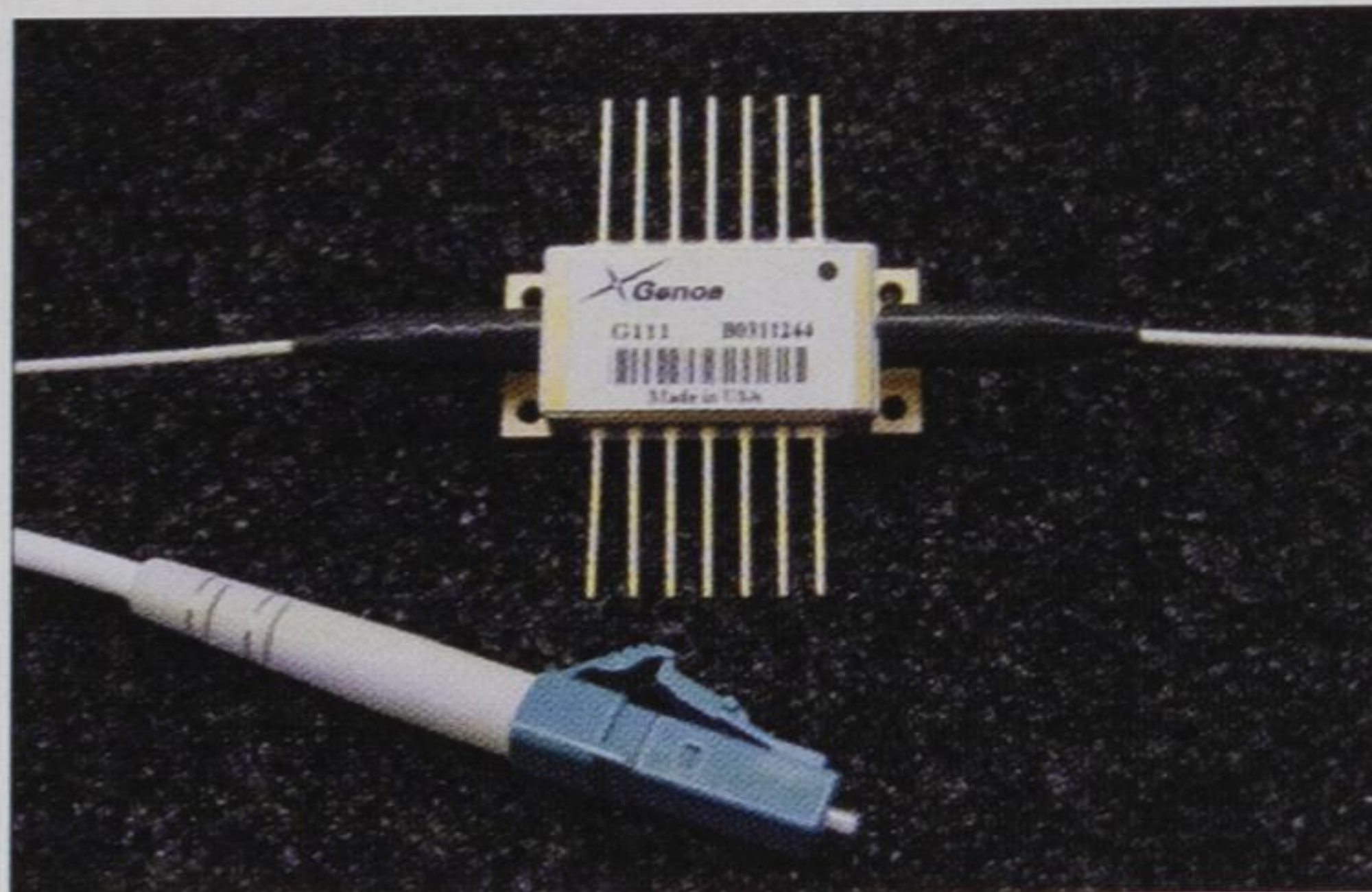
"We believe that the technologies and processes developed for telecom applications at AIFOTec can be readily applied to products for datacom and metro access applications," explained Jerry Rawls, Finisar's president and CEO. "AIFOTec will enable us to produce optical products with higher levels of performance and lower manufacturing costs."

Genoa ships new LOAs

Genoa, a manufacturer of optical amplifiers with facilities in Fremont, California, and Eindhoven in the Netherlands, has begun commercial shipments of its new linear optical amplifier (LOA). Making its debut at OFC last year, Genoa's amplifier uses a 1550 nm InP-based VCSEL and is the first chip-based amplifier for use in optical networks.

The company's device uses the active region of a VCSEL to provide a waveguide for the signal as it passes through the device (see *Compound Semiconductor* May 2001, p49). The VCSEL pumps an excess of photons into the gain medium, amplifying all wavelengths in the same way as an EDFA amplifies optical signals in a WDM network. However, the LOA is significantly smaller than an EDFA.

"Our pre-production activity was unusually strong, in spite of the recent correction in the network market," said president and CEO Rick Gold. "LOAs have been sampled by companies that range from telecommunications giants to aggressive start-ups hoping



Genoa's linear optical amplifier is based on a 1550 nm VCSEL, which enables the amplifier to be much smaller than an EDFA.

to skip a generation of equipment."

Genoa's G111 amplifier provides full C-band coverage at more than 40 Gbit/s and features a flat gain amplification spectrum that alleviates the need for gain-flattening filters. The VCSEL chip is housed in a standard 14-pin butterfly package and can be used with receiver preamplifiers, loss-less modules, inline and tributary amplifiers, and transmitter boost stages.

EpiWorks raises detector standards

EpiWorks, an epiwafer manufacturer based in Champaign-Urbana, IL, is producing InP/InGaAs *pin* photodetector epiwafers up to 4 inches in diameter. Mesa diodes fabricated from the company's epiwafers and employing a 2 μ m i-layer typically operate with less than 100 pA of leakage current at a 5 V reverse bias. The company says that this is an order of magnitude improvement over the current industry standard.

"The limitations of *pin* photodetector performance are determined by the epitaxial wafer technology," said Epiworks' director of R&D Nada El-Zein. "Our technology provides two distinct benefits: first, our ultra-pure material allows our customers to achieve very low dark current, and second, our EpiDetector process provides excellent resistance characteristics for high-speed applications."

"We have also developed a unique capability to monitor the quality of our production with full-wafer, quick-lot diode fabrication," added Dave Ahmari, executive VP of business development. "This allows us to continually monitor and improve our material quality by directly studying the diode characteristics."

Agility wins funding, makes deal in Japan

Tunable laser manufacturer Agility Communications has closed an additional \$27 million of series C funding, bringing the total received to more than \$200 million since it was formed in 1998. Investors include General Bank, Nissho Electronics, Siemens Venture Capital, London Pacific Assurance and Mitsubishi International.

"We now have additional financing options and are well positioned to ride out the downturn while continuing to build our company and ramp our widely tunable lasers into high production," said Ron Nelson, Agility's president and CEO. Agility's tunable lasers are now sampling to more than 40 customers.

Agility has also sealed a strategic deal with one of its investors, Nissho Electronics, to distribute the company's widely tunable sampled-grating DBR lasers in Japan. The deal enhances Nissho's aim to be a key provider to the Japanese market of new technologies for optical networking that will help to meet the rising demand for bandwidth.



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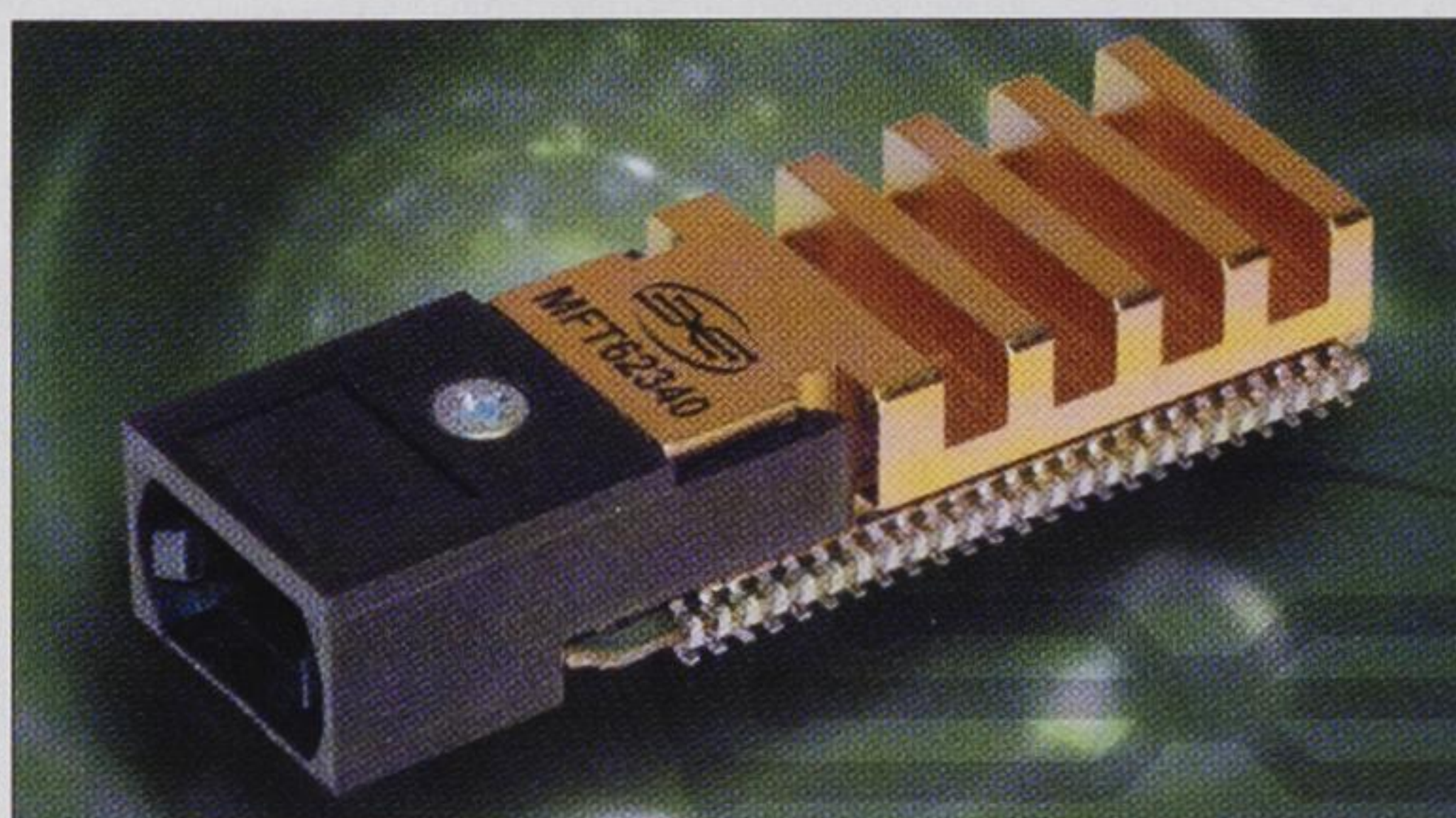


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Picolight and Zarlink launch optical modules

Picolight and Zarlink have launched new parallel optical modules. Picolight has expanded its Magnus family with a 10 Gbit/s 12-channel transponder, while Zarlink's new 12-channel parallel optical transceiver module is designed for low-cost very-short-reach (VSR) optical interconnects.

Picolight's Magnus VSR4-1 transponder adds to the 32 Gbit/s 12-channel design that went into production in August 2001. It employs 850 nm VCSELs and dissipates under



Zarlink's 12-channel transceiver provides an aggregate data rate of 30 Gbit/s.

5 W. The module supports the latest standards for VSR 300 m links. Currently sampling, the module will enter volume production in the second quarter of 2002.

Zarlink's transmitter and receiver operate from 155 Mbit/s to 2.5 Gbit/s per channel for a maximum aggregate bandwidth of 30 Gbit/s. The new module uses 850 nm oxide-confined VCSELs and *pin* diode receivers, and is available in production volumes. A four-channel 10 Gbit/s transceiver is due in mid-2002.

Thales to spin off its interconnects lab

French defense contractor Thales is to spin off the optical interconnects lab in its Research and Technology Division. The new company, as yet unnamed, will concentrate on commercializing its parallel optical interconnect modules for very-short-reach (VSR) appli-

cations such as intra-cabinet communications. Called D-light, the modules use 850 nm VCSELs and *pin* diodes and the product range will include four-, eight- and twelve-channel transmit and receive modules operating at 2.5 Gbit/s per channel.

Production of the VCSELs and *pin* diodes will be subcontracted with the design, packaging and assembly of the modules' components being done by the new company.

Volume production is expected to begin in early 2003.

Thales will take a share in the new company and discussions with other possible stakeholders are ongoing. Thales is likely to remain a major customer for the products of the spin-off because optical interconnects are integrated into many of Thales' products for the defense, aerospace and information technology markets.

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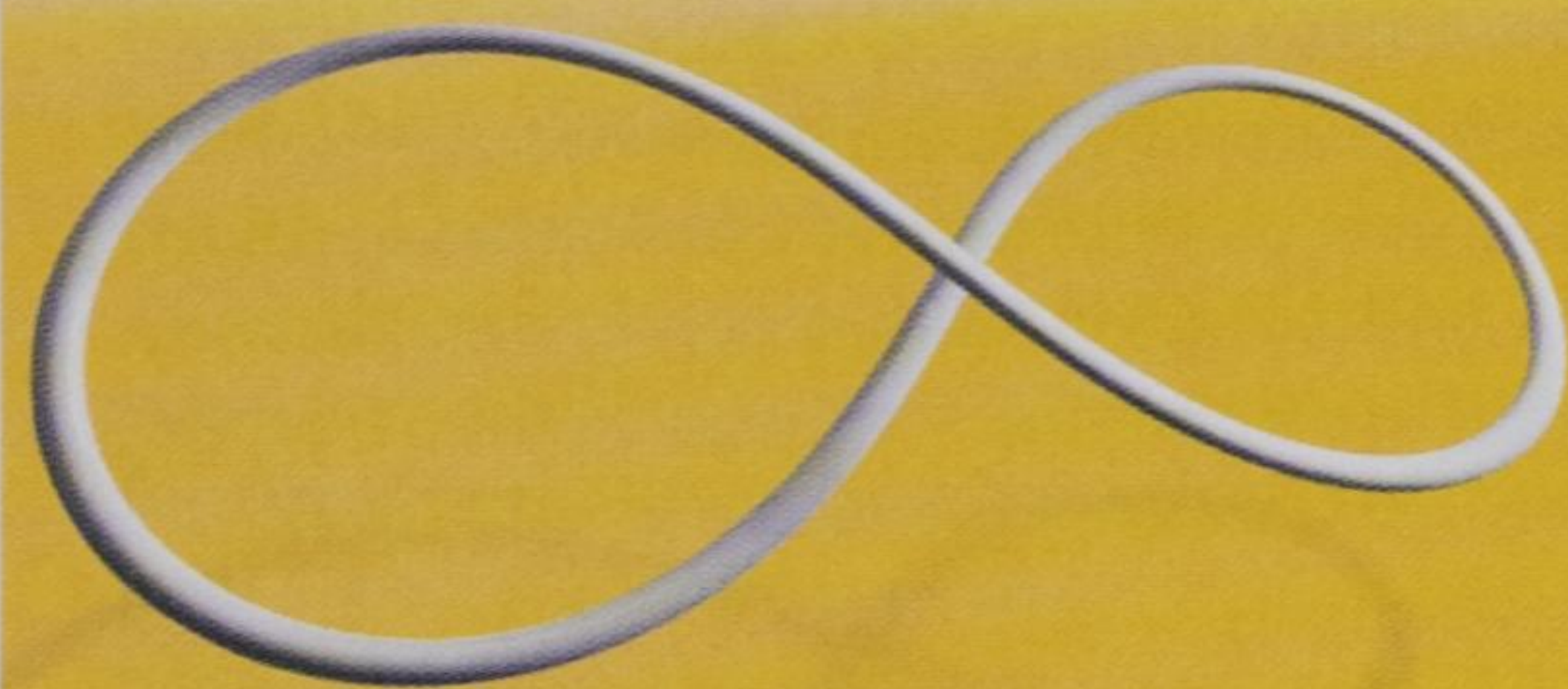
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CyOptics and Kamelian open new InP processing facilities

CyOptics and Kamelian have opened new wafer-fabrication facilities for manufacturing InP-based components for optical networks. CyOptics has invested more than \$10 million on constructing and equipping a site at Yokneam in Israel, which will produce packaged chips and hybrid InP-based components. These will include modulators, lasers and detectors that operate at data rates of up to 40 Gbit/s.

The fab consists of 11,000 sq. ft of class-100 and class-1000 cleanrooms and the equipment includes an 8 × 3 inch MOCVD reactor. The new facility is the first production-level InP fab in Israel.

The company's first InP wafer-processing and characterization facility came online in January 2000. The new plant was constructed in just six months and will enable increases of 125% in monthly wafer production and a subsequent 130% in packaging.

"This leading-edge InP facility greatly enhances our ability to provide next-generation products which are essential for lowering optical system costs," commented CEO John Pilitsis. "CyOptics' investment reflects our commitment to provide our customers with the most cost-effective high-

performance products based on our foundation of manufacturing excellence."

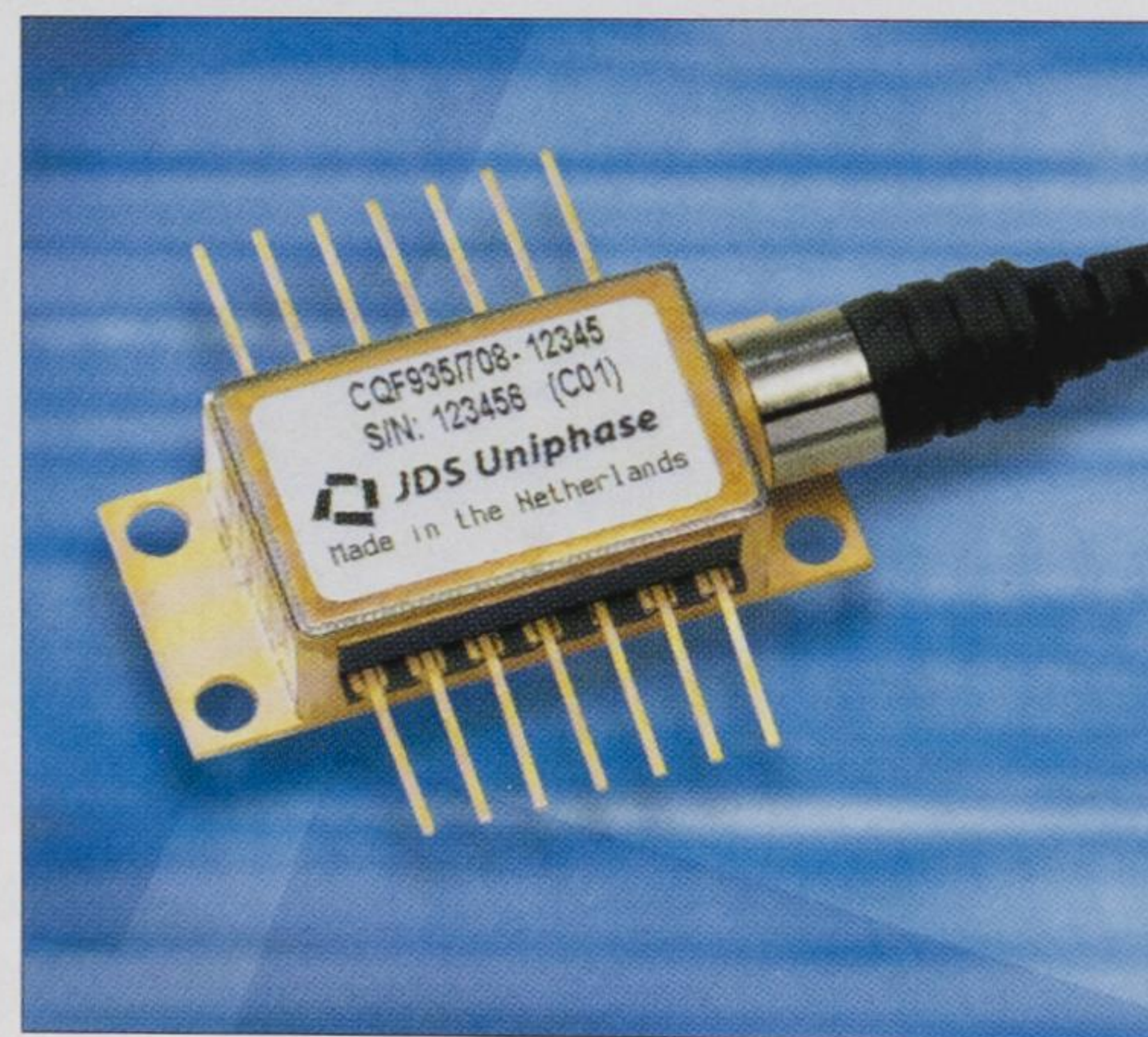
Kamelian passes another milestone

Kamelian, a manufacturer of InP-based semiconductor optical amplifiers (SOAs), officially opened its manufacturing facility in Oxford, UK, on February 8. The 20,000 sq. ft facility cost £9 million (\$12.7 million) to construct and equip. The new facility can handle the entire manufacturing process from epitaxial growth and device processing through to the packaging and testing of the company's SOA products.

The first devices now sampling to customers are discrete optical preamplifiers and power boosters, with more complex subsystems in development. These subsystems will see Kamelian's SOAs coupled with other optical components using the company's proprietary hybrid integration technology (see *Compound Semiconductor* April 2001, p41).

"This formal opening represents a significant milestone for us," said Kamelian's CEO Paul Kay. "It is a great tribute to the team at Kamelian that we have so quickly established a world-leading semiconductor facility and are now gearing up for full production."

JDSU unveils new DFB lasers



JDSU's new high-power lasers will be used as DWDM sources in CATV networks.

JDS Uniphase (JDSU) has unveiled a new family of high-power CW lasers for DWDM metro and long-haul architectures and the emerging market for wavelength-specific

components in CATV networks. The new lasers are available with 40 and 50 mW output powers, and the 40 mW version is available with internal wavelength monitoring if this is required.

High-power lasers can be used to compensate for the increased losses in high-speed long-haul networks. In addition, JDSU says it is targeting CATV networks that now use high-power lasers as sources for DWDM, in which specific wavelengths are allocated to particular services.

The new sources typically feature a maximum relative intensity noise of -160 dB/Hz, 1 MHz linewidth and sidemode suppression ratios of 45 dB. For the 40 mW internal wavelength-monitored device, the thermal stability is 0.0001 nm/°C. All lasers are available at ITU 50 GHz for the C- and L-bands, and are provided with built-in thermoelectric coolers and polarization-maintaining fiber.

Companies join together and forge multi-source agreements

A number of companies have been involved in new multi-source agreements (MSAs). Agere, Alcatel and Nortel are collaborating on compact EDFAs for metro edge and ultra-long-haul applications. The new agreement establishes a standard specifying uniformity in package outlines, pin function definitions and optical and electrical characteristics.

Meanwhile, Alcatel, CyOptics and Oki Electric are to enter into an MSA for 40 Gbit/s InP electroabsorption modulators. These are

expected to compete with lithium niobate modulators by delivering a smaller footprint and lower power consumption. The first phase of the MSA covers pin-out and footprint standardization and will be completed by the end of the year.

Gore has announced that it is joining Picolight and Emcore in their recent MSA for the manufacture and supply of connectorized 12-channel parallel optical modules (see *Compound Semiconductor* March 2002, p20).

TriQuint teams up with Picosecond

Picosecond Pulse Labs and TriQuint have collaborated on the development of a lithium niobate modulator driver module targeting 40 Gbit/s networks. The driver module incor-

porates a 43 Gbit/s GaAs MMIC chipset developed for optical networking applications by TriQuint. The new module is SONET/SDH compatible with non-return-to-zero data rates up to 43 Gbit/s. At 43 Gbit/s the driver operates with 7 V eye amplitude (V_{amp}) output drive, with an output amplitude adjustment range of 6 dB with 1.5 ps RMS of jitter.

In brief...

CyOptics launches zero-insertion-loss modulator

CyOptics has released a zero-insertion-loss InP external electroabsorption modulator with up to 10 dBm of output power. Intended for 10 Gbit/s metro and long-haul applications, the EAM2010 gives low chirp when operated with a singlemode laser resulting in the low dispersion losses necessary for 80–125 km uncompensated links. The module includes integrated power monitoring and control functions.

Modulight and CyOptics gain ISO certification

Modulight and CyOptics have recently received ISO 9001:2000 certification for their plants in Finland, and in the US and Israel, respectively.



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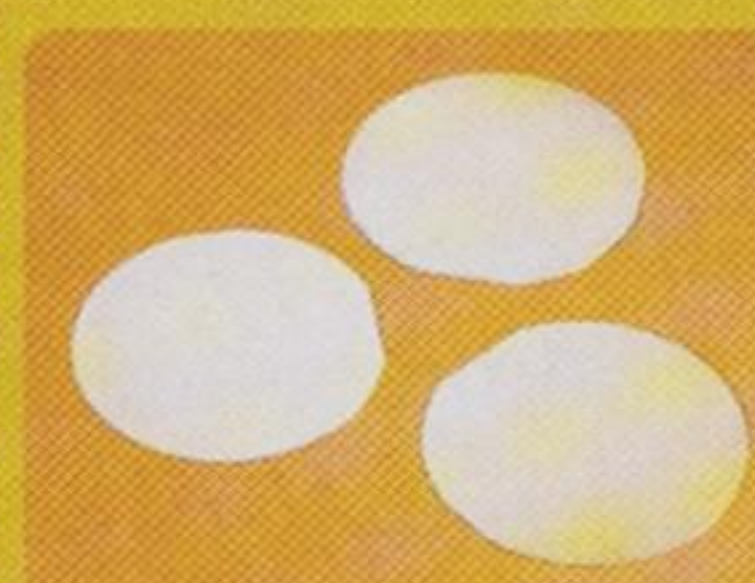
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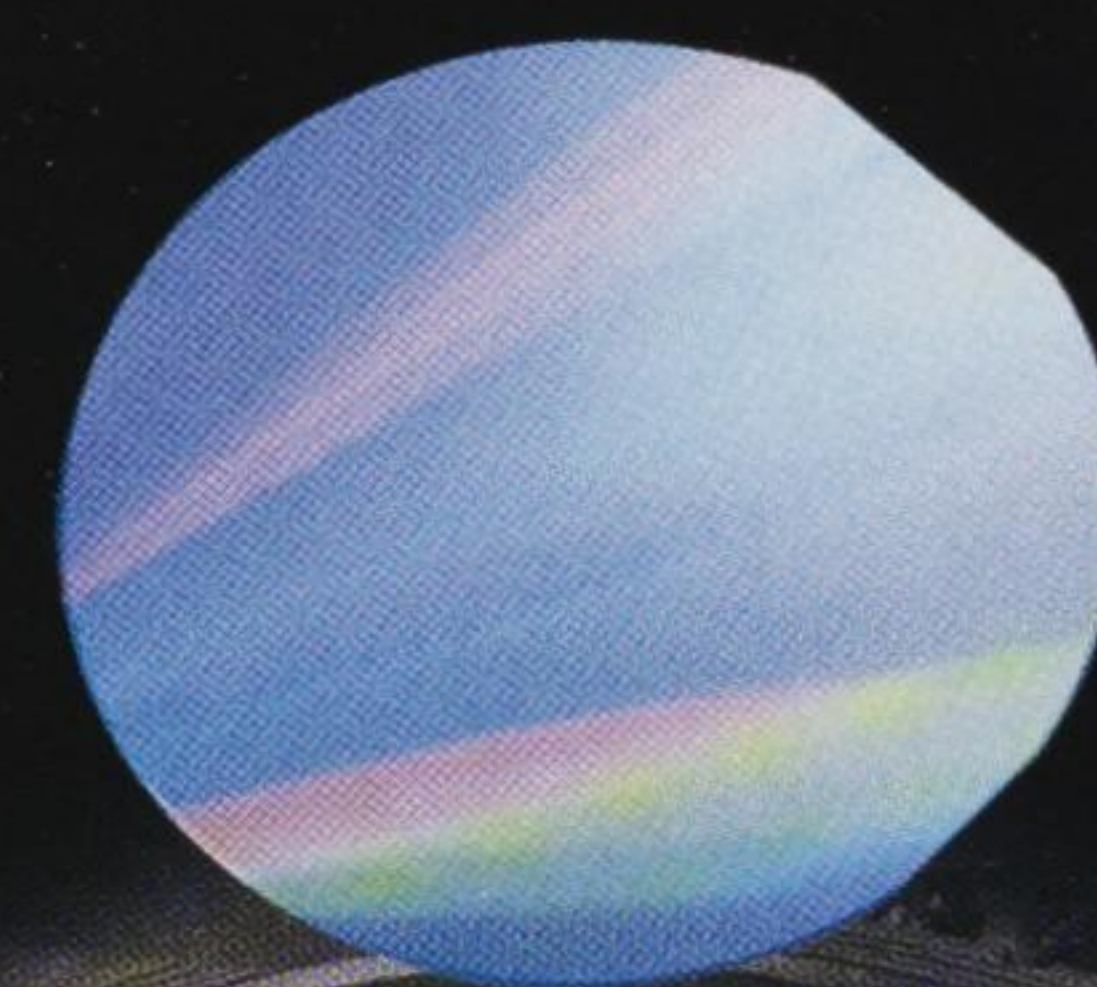
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Inphi proposes 40 Gbit/s standard

By Tim Whitaker

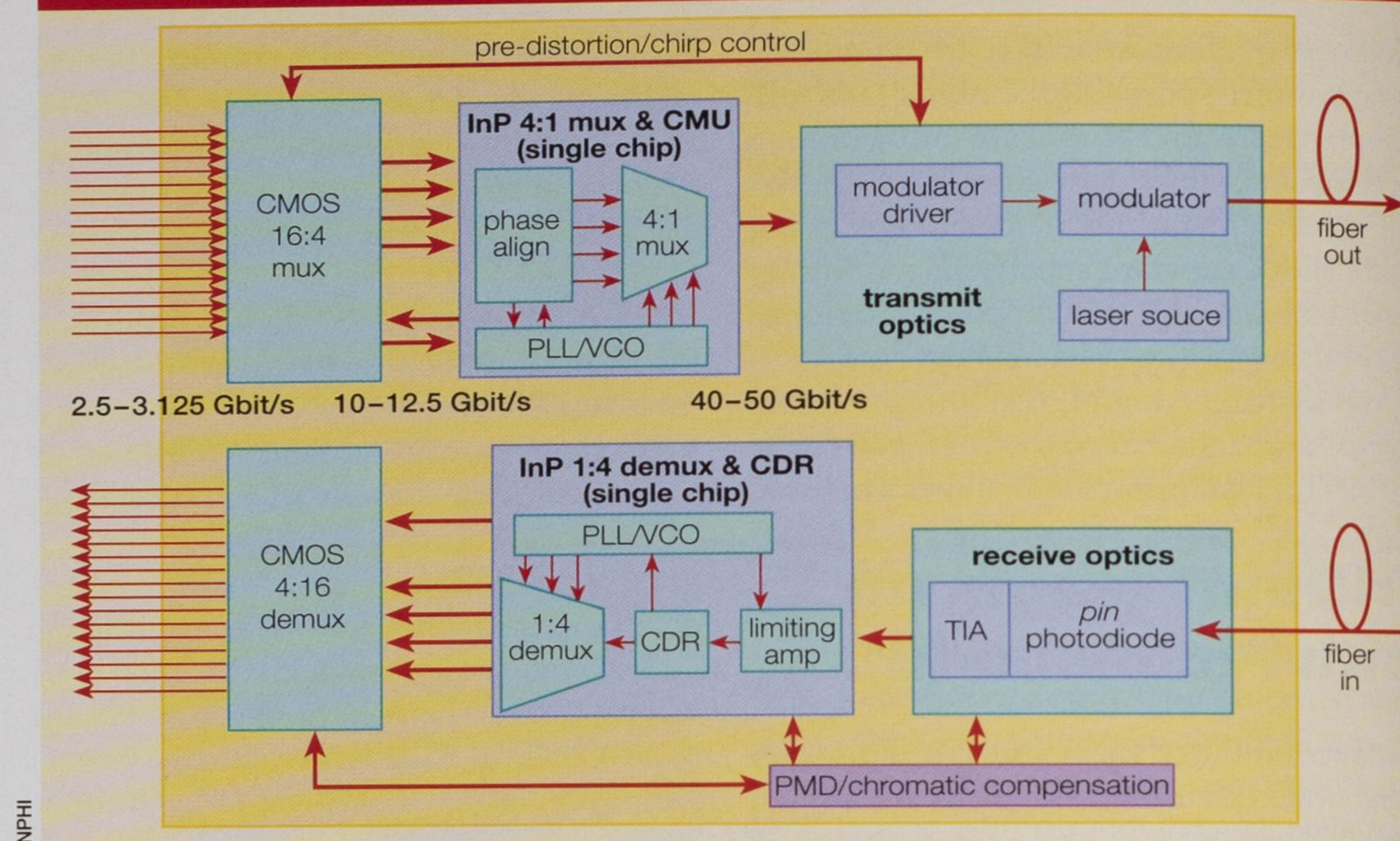
Inphi, a fabless designer of high-speed ICs, has joined with Broadcom to develop a low-power, feature-rich OC-768 (40 Gbit/s) architecture. Currently under consideration by the Optical Internetworking Forum (OIF), the architecture combines the high speed and low power of InP with the high gate count and low cost of CMOS. It is designed to enable long-haul equipment suppliers to build 43–50 Gbit/s linecards and allow module manufacturers to develop cost-competitive solutions for short-reach and metro applications at 40 Gbit/s.

“OC-768 is a very cost-effective way for carriers to meet the demand for bandwidth, but they can’t deploy such systems until they have all the components,” says Inphi’s director of marketing Gary Franzosa. “Industry standards are key to the future of OC-768. A 40 Gbit/s transponder multi-source agreement was announced at ECOC last October, and an SFI-5 interface standard was presented to the OIF late last year. The missing piece is an architectural standard.”

The proposed architecture uses CMOS to implement functions up to 10 Gbit/s, while InP is used for the parts that operate at 40–50 Gbit/s and interface with the physical layer functions (see figure). InP technology enables robust OC-768 fiber-optic links by ensuring that the physical layer electronics meet stringent performance criteria. For example, InP technology provides sufficient gain to drive the optical modulator and enables rise and fall times of 8 ps with very low jitter (< 1 ps rms). Inphi has already introduced modulator drivers with this level of performance. CMOS 16:4 mux and 4:16 demux ICs interface with the 16-bit data bus operating at 2.5–3.125 Gbit/s. “The combination of CMOS and InP is the perfect match in terms of density, power consumption and speed,” says Gopal Raghavan, co-founder and CTO of Inphi.

Inphi has introduced a number of ICs for 40 Gbit/s networks, including mux and demux ICs, modulator drivers and TIAs. The ICs are mainly InP HBT parts fabricated for Inphi by Global Communication Semiconductors, although other processes are used. “The modulator drivers are all manufactured in a GaAs PHEMT process today,” says Franzosa. At present, GaAs PHEMTs are a more suitable production process. “Eventually modulator drivers will be fabricated using an InP DHBT process,” adds Franzosa.

Proposed architecture for OC-768 transceivers



The 40 Gbit/s architecture proposed by Inphi and Broadcom combines the high speed and low power of InP with the high gate count and low cost of CMOS.

Inphi demonstrates 80 Gbit/s ICs

In January Inphi demonstrated a 1:4 demultiplexer in InP running at a data rate of > 80 Gbit/s. The IC was based on a half-rate architecture and dissipated 1.3 W of power. In a half-rate design the clock driver samples the incoming signal on both the rising and falling edge of the clock. By contrast, in a full-rate design, the signal is sampled on only one clock edge, either rising or falling but not both. With half-rate architectures it is possible to use lower speed parts, for example a 20 GHz clock can give a 40 GHz rate. However, a half-rate clock is much less robust and not often deployed. “With a half-rate architecture you have to be able to clearly detect both edges, and if there is any skew or delay you

can miss one of the edges,” says Franzosa.

In October 2001 Inphi announced packaged mux and demux prototypes based on a full-rate architecture operating at speeds of > 50 Gbit/s with a power consumption of < 900 mW. Recent results for SiGe ICs revealed a speed of 56 Gbit/s for a half-rate architecture. Although Inphi’s half-rate demux operates at a much higher speed than the SiGe circuits, it dissipates the same amount of power. At 40 Gbit/s, the SiGe half-rate circuits dissipated about three times as much power as the Inphi demux. “We have now demonstrated the fastest half-rate and full-rate InP parts for applications at speeds of 40 Gbit/s and higher,” says Raghavan.

Inphi’s 4320 and 4020 mux ICs operate at 43 and 40 Gbit/s, respectively. The parts consist of a 4:1 mux and integrated VCO with a phase-locked loop (PLL) and output buffer. Power dissipation is < 2.5 W, and the parts have a very fast rise and fall time of 8 ps. Operation at 43 Gbit/s allows forward error correction (FEC), while 40 Gbit/s parts are suitable for metro and short-reach applications where FEC is not required. The 4321 and 4021 parts are 1:4 demux ICs with clock and

data recovery, a VCO and PLL, and a limiting amplifier on the front end. In mid February Inphi announced a series of GaAs-based modulator drivers. The products provide a 4–8 V differential, and Inphi is sampling to a number of tier-one and other manufacturers. The 4310DZ part operates at 43 Gbit/s with a power consumption of < 4 W. The 2010DZ is suitable for 13 Gbit/s return-to-zero and 20 Gbit/s non-return-to-zero networks, and has a control function to keep the eye open.

Japanese wafer makers suffer drop in shipments

In the six months from April to September 2001, shipments of compound semiconductor wafers from Japanese manufacturers totaled ¥23,147 million (\$179 million), a fall of 29% compared with the preceding six months. Shipments are now similar to those in 1997 and 1998, after a high point of ¥33,308 million in April–September 2000.

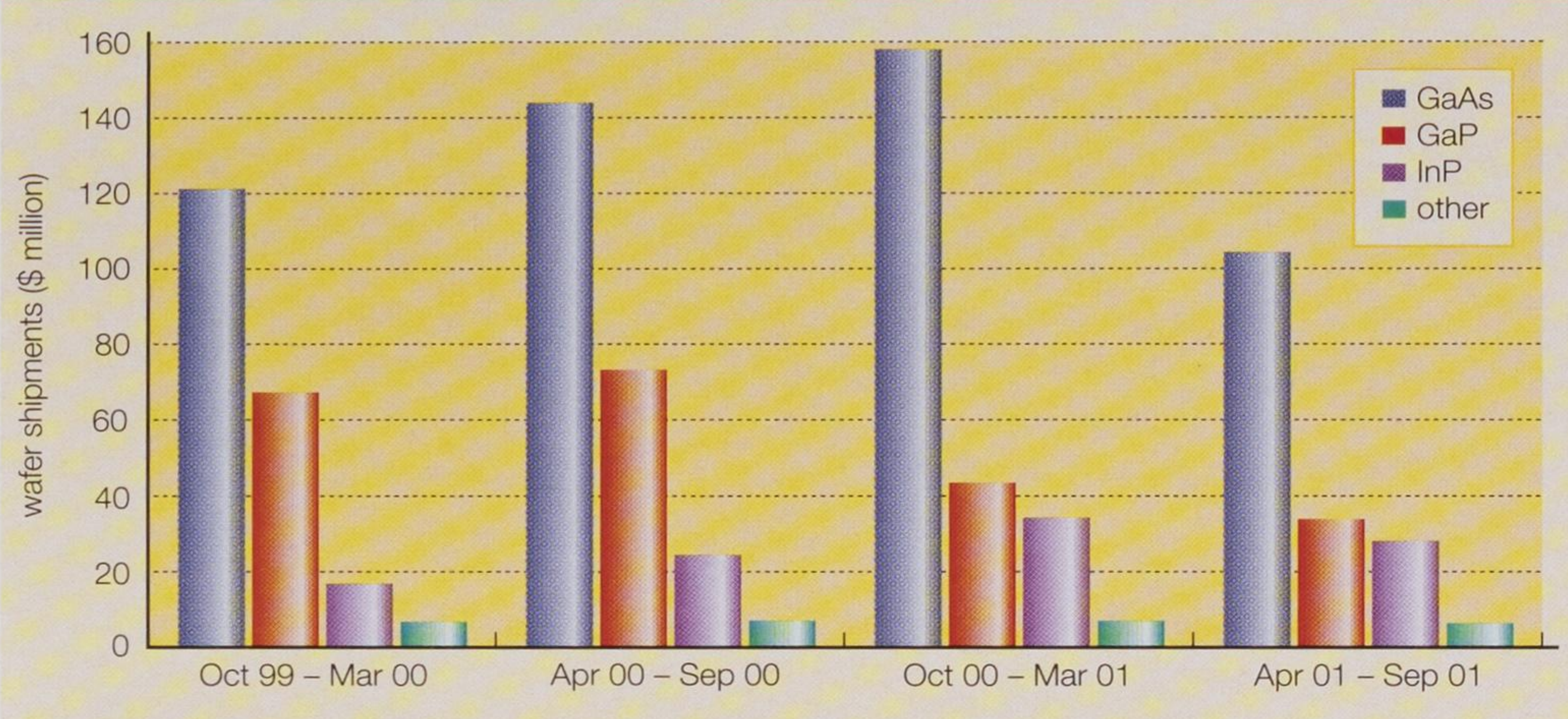
The data are collected from the nine wafer suppliers who make up the Japanese Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS).

Wafer shipments had a compound annual

growth rate of 21% from 1998 to 2000. GaAs and InP shipments were hit by last year's slowdown in the communications markets, and by price erosion and reduced demand in markets such as those for CD and DVD lasers. Shipments of GaP wafers, used mainly as substrates for low- and medium-brightness LEDs, had already started to decline in 2000 due to price erosion and loss of market share.

Just over half of GaAs shipments and a larger proportion of InP wafers are used by domestic device makers in Japan, while almost two-thirds of GaP wafers are exported.

Japanese wafer shipments



Shipments of GaAs wafers fell by 34% in April–September 2001 compared with the previous six months. GaP wafer shipments fell by 22%, while InP shipments fell by 18%.

Mitsubishi's flip-chip bonding improves 40 Gbit/s components

Mitsubishi Electric has developed two new components, a modulator and a photodiode, for 40 Gbit/s networks. Performance improvements have been achieved through novel device structures and by using flip-chip bonding to eliminate bond wires.

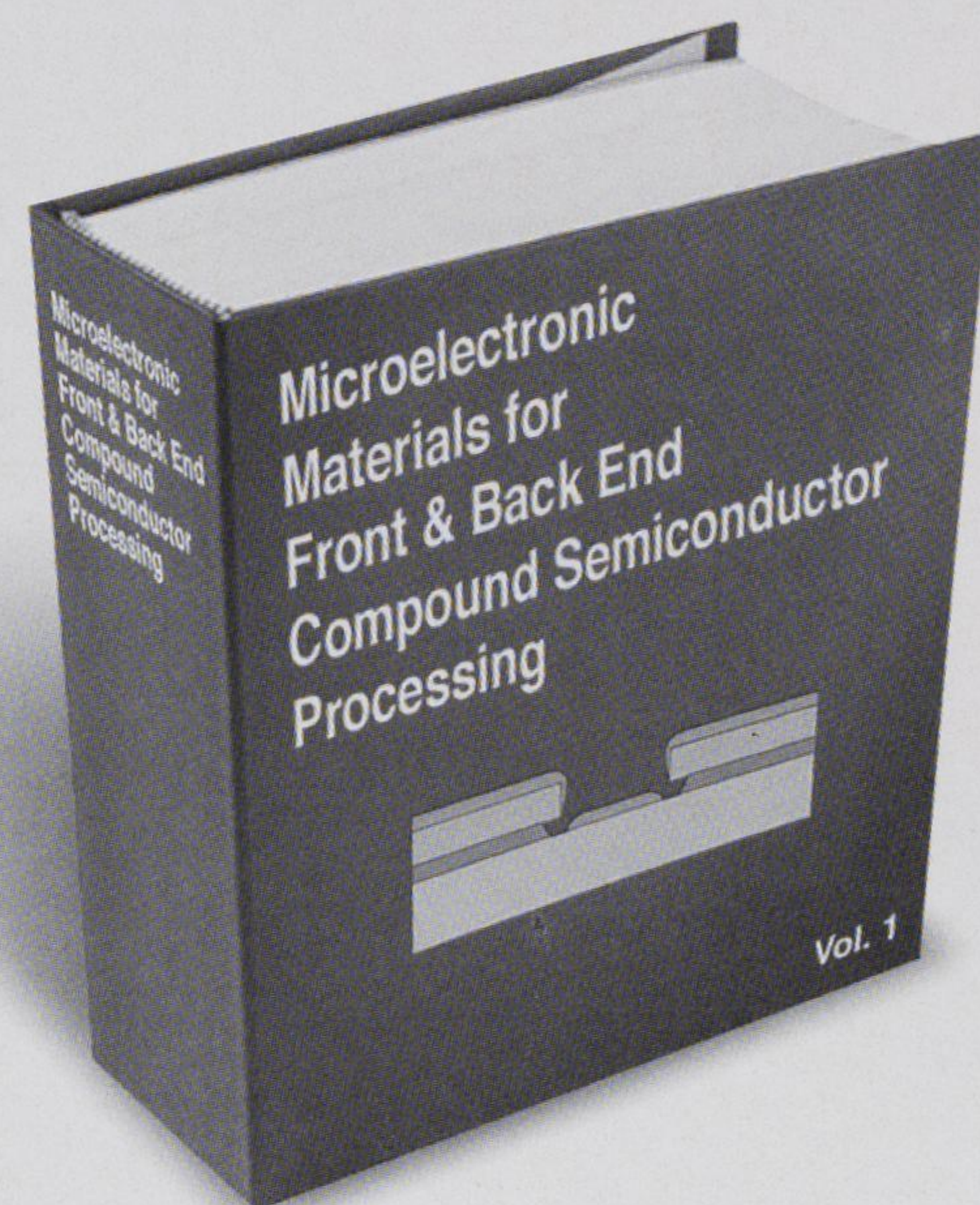
"The key components of high-speed optical systems are a modulator to convert electrical signals to optical signals and a photodiode to reverse the process. These components determine the upper speed limit," said Tatsuo Hatta, head researcher at Mitsubishi Electric's Information Technology R&D Center. "Until now, this limit has been low due to the para-

sitic capacitance of the various components. Inductance between the wires inside the package also reduces the performance."

The InP-based modulator is fabricated on a semi-insulating Fe-doped InP substrate, enabling a 20% reduction in parasitic capacitance. In order to remove the inductance from bond wires, the modulator is flip-chip bonded directly onto a ceramic microwave circuit.

The photodiode is a waveguide-type detector with a large area to reduce parasitic capacitance to less than 0.1 pF. The device is directly mounted on a pre-amp IC using Au flip-chip bonding, the first time this has been achieved.

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EV Group expands Austrian facilities

EV Group has now completed its second expansion within a year. Construction work on the second phase of enlarging its Austrian manufacturing headquarters began back in March 2001. The expanded site is located at Schaerding and is intended to provide the company with significantly more production floor space and cleanroom facilities, as well as additional application and process qualification laboratory space.

EV Group operates four subsidiaries worldwide, supplying bond and mask aligners, wafer bonders, photoresist coating systems and cleaners. The systems are used in a range of processes and applications, including MEMS,



EV Group's recently expanded facilities in Austria will create more production capacity for processing equipment.

compound semiconductor materials, LED production, wafer-level packaging and flip-chip bumping. The expansion has created over 100 new jobs in R&D, manufacturing and customer support at the Austrian location.

"Through our enhanced network, we can provide our customers with full support capabilities, regardless of location," said the company's CEO Peter Podesser. "We have also strengthened our US organization by doubling the number of staff and improving our Rhode Island and Arizona facilities. In the Asia-Pacific region, we have increased the customer support capabilities in Japan, Taiwan and Singapore."

TFS licenses Heatpulse products

Total Fab Solutions (TFS) of Tempe, AZ has licensed the manual Heatpulse rapid thermal processing (RTP) product lines from Mattson Technology. The license means that TFS is now the sole supplier of parts, servicing and new tool sales for the Heatpulse 610 product line, and will also support the older generation 410, 310 and 210 products.

"The licensing agreement of the Heatpulse RTA 610/410/310/210 product lines is a win-win situation for both TFS and Mattson Technology," says Wayne Morrow, strategic business manager with Total Fab Solutions. "It allows each company to concentrate on

their core competencies, while still continuing to support the installed base and provide solutions for future customers."

The tools are used for R&D and for the small-scale production of silicon and compound semiconductor devices. "The Heatpulse 610 is predominantly used for ohmic alloying and for implant annealing of InP-, GaAs- and GaN-based materials," explains Morrow. "With an installed base of more than 600 tools, I believe that the Heatpulse X10 products have been used to develop more III-V processes than any other research-level RTP system."

Air Products wins gas supply deal

Air Products and Chemicals has secured a gas management contract at DenseLight Semiconductors' new InP device fabrication plant in Singapore. DenseLight recently announced a range of InP-based products, including direct-modulated DFB lasers, gain chips and superluminescent diodes. Air Products supplied all of the plant's gas cabinets, valve manifold boxes and racks at DenseLight's 50,000 sq. ft facility, while Kinetic Systems (a joint venture partner with Air Products) provided complete installation, hook-up and commissioning of high-purity gas piping and abatement systems. Air Products is also supplying DenseLight with arsine, phosphine, ammonia, boron trichloride, hydrogen chloride and other specialty gases.

Evans Analytical opens east coast lab

Evans Analytical Group has announced plans to open a new laboratory in the Boston area. Slated to begin offering services in July 2002, the Massachusetts-based site will be called Evans Northeast, and is the seventh facility in the company's growing independent analytical services group, and the second site on the east coast. The lab will initially be equipped with a quadrupole secondary ion mass spectrometer (SIMS), a magnetic sector SIMS system and a total reflection X-ray fluorescence tool. There are also plans to add additional equipment as the laboratory expands. Evans Analytical has four laboratories in the US, in California, New Jersey, Minnesota and Texas, in addition to facilities in Taiwan and the UK.

JMAR gets X-ray funding from DARPA

JMAR Research (San Diego, CA) has received up to \$34.5 million from DARPA for further development of its X-ray lithography system. The aim is to develop a point source that produces 1 nm feature definition, which will enable next-generation high-frequency GaAs and GaN MMICs for use in electronic warfare arrays and forward-looking military radar.

Equipment sales

- The **Russian Federal Nuclear Center** (Chelyabinsk, Russia) has acquired an **Aixtron AIX 2400G3 HT** reactor for the manufacture of GaN-based high-brightness blue LEDs. The system has a capacity of 11 × 2 inch or 5 × 3 inch wafers, and according to Aixtron is the first MOCVD system in Russia capable of volume production.
- **SUSS MicroTec** has received its first Lithography Cluster order from a major optoelectronic device manufacturer. The cluster tool, consisting of a coater, a developer, and exposure and alignment cells, is suitable for manufacturing products such as MMICs, lasers, LEDs and infrared sensors.
- **Yale University** (New Haven, CT) has ordered an **Aixtron AIX 200/4 RF-S** MOCVD system and entered into a joint R&D contract to develop GaN optoelectronic devices and structures.

Gas purification revisited

By Tim Whitaker

In our December 2001 issue (p51) we published an article entitled "Gas purifiers earn their place in MOCVD material growth" in which we described the different technologies available for gas purification. In response to comments received about this article, we would like to clarify some of the issues involved in gas purification.

Palladium membrane purifiers, or Pd-cells, have been in use for many years and are currently the most common technology for hydrogen purification. In contact with a heated Pd membrane, hydrogen molecules dissociate into protons and electrons that diffuse across the membrane, while larger contaminant molecules are left behind. The nature of the purification process employed by Pd-cells means they have a limitless capacity to remove contaminants. However, some users report that Pd-cells can fail by a number of routes, as described in the article.

A number of alternatives to Pd-cell technology have emerged in recent years, and advocates of these new technologies argue that they offer superior performance to traditional Pd-cells. One such alternative is the nickel/titania "catalytic" hydrogen purifier, manufactured by Aeronex. Others, as described in the article, include getter and resin purifiers.

Nickel/titania purifiers

Nickel/titania purifiers can operate with hydrogen from either high-pressure gas or low-pressure liquid sources, and can remove contaminants to less than one part-per-billion (ppb). The technology is termed "catalytic" although it is not, strictly speaking, a catalytic process; this is because the media were used as catalysts for other purposes before being applied to purification.

Nickel/titania purifiers consist of two major components. The first part is nickel dispersed on high-surface-area silica. The nickel is activated (made ready to absorb contaminants) under high temperature. During purification the nickel initially binds with H₂ forming a nickel hydride. This reacts further to remove O₂, CO, CO₂, hydrocarbons, volatile metals and sulfur.

The second part of the purifier contains a titania-based material, which is placed downstream of the nickel. During high-temperature activation, the titania is reduced from an eight-coordinate to a four-coordinate state. Contam-

inants are removed by chemisorption and physical adsorption. The major purpose of the titania is to increase the purifier's efficiency and capacity (lifespan) for absorbing water.

This purification technology is pressure insensitive and operates at ambient temperature. Moreover, since the reactions to remove contaminants are reversible at elevated temperature (> 200 °C), the nickel/titania purifier media can be regenerated *in situ*. This is accomplished by heating the purifier while purging with H₂. To provide a continuous supply of purified H₂, two purifier canisters can be employed in parallel with associated plumbing and controls. While one purifier canister is online and purifying H₂, the second purifier canister is regenerating or waiting to go online.

Aeronex believes that the nickel/titania purifier technology offers a number of advantages over Pd-cell technology, such as robustness and reliability.

Pd-cells

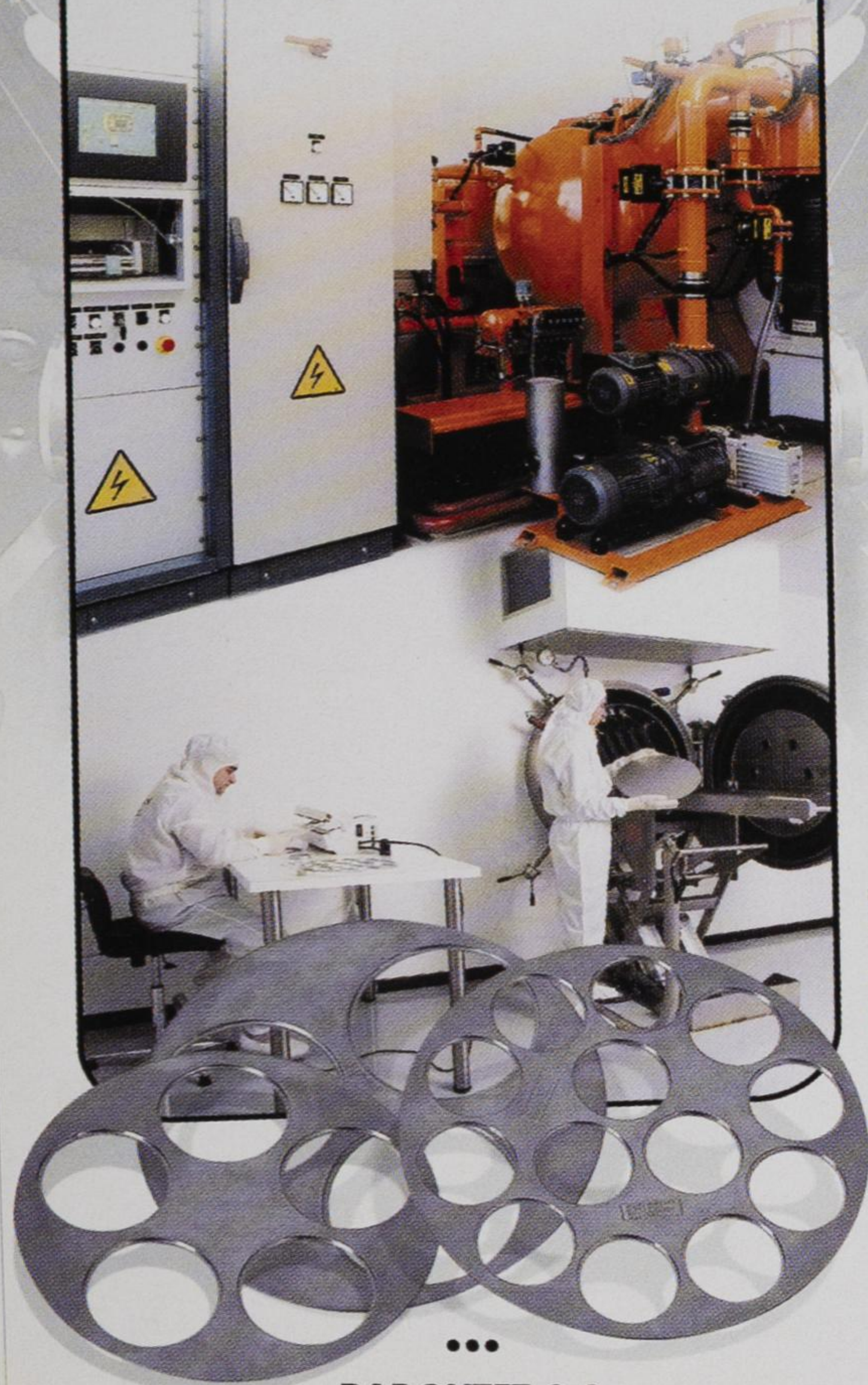
Manufacturers of Pd-cells have commented that, while not perfect, Pd-cell technology is still the "workhorse" for hydrogen purification in the compound semiconductor industry. One manufacturer claimed that alternative technologies have not withstood the test of time. Also, in our article we stated that Pd-cell throughput could be varied from 1 to 1000 liters/hour. In fact, the purifiers manufactured by Johnson Matthey range from 5 to 1200 liters/minute.

The inside-out Pd-cell design, presented in the article as a new technology, has actually been commercialized for quite some time. However, this design is not the preferred approach since the ultrapure hydrogen is on the outside of the membrane where it is in contact with numerous heated surfaces, which may lead to the generation of particulates in the ultrapure gas stream. Also, the Pd tube is attached at both ends, restricting its ability to expand and contract as it heats and cools. Manufacturers of conventional outside-in Pd-cells have stated that tube crushing as a result of tube imperfection, cited in our article as a drawback of such designs, has never occurred in more than 30 years of experience.

If you have comments on this or any other article in Compound Semiconductor, please contact the editor (tim.whitaker@iop.org).

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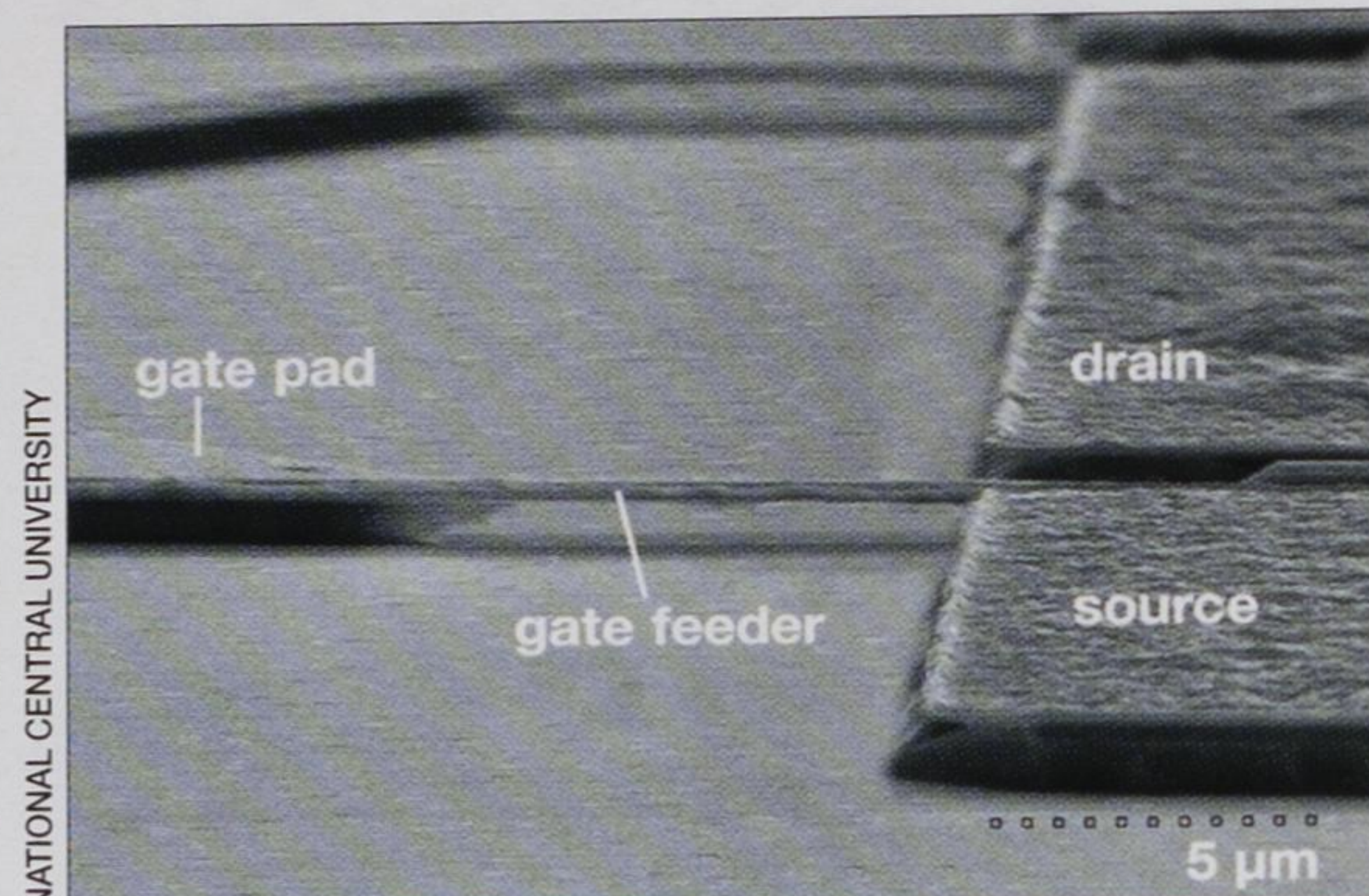
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Air-bridge gate HFET structure provides improved device linearity

Device linearity is an important issue for microwave power amplifier applications, especially in modern digital communication systems. A group from the National Central University in Taiwan has proposed a simple and effective way to fabricate AlGaAs/InGaAs HFETs with improved linearity (*Elec. Dev. Lett.* 2002 **23(1)** 1). The group found that by applying a second mesa etch after the final gate deposition, the gate feeder formed an air-bridge without contacting the mesa edges. Standard HFETs were fabricated alongside the modified HFETs (MHFETs) in order to make performance comparisons.

The air-bridged gate reduced the gate leakage current by an order of magnitude compared with the standard gate HFET, and therefore improved the device linearity. The MHFET showed an increase in



An SEM image of the MHFET device showing the air-bridge gate feeder linking the gate pad to the gate.

turn-on voltage to 1.05 V from 0.95 V for the HFET, and the breakdown voltage for the MHFET was higher at 10.2 V, compared with 8.2 V for the HFET. The lower gate leakage current and higher turn-on voltage also gave the MHFET higher maximum transconductance and I_{ds} values of 240 mS/mm and 835 mA/mm, respectively, compared with 226 mS/mm and 750 mA/mm for the standard HFET.

For devices with a 1 μ m gate length and a drain-source voltage of 3 V, f_t and f_{max} values were 13 and 32 GHz, respectively for the MHFET, and 10.5 and 28 GHz, respectively for the HFET. This improvement in RF per-

formance was the result of a reduction in parasitic capacitance, obtained using the air-bridge gate structure. The parasitic feedback capacitance values were 0.15 pF/mm for the MHFET and 0.21 pF/mm for the HFET.

Doped spin-on silica promotes variable QWI

One of the primary requirements for the monolithic integration of optoelectronic devices is the capability to selectively engineer the band gap of the semiconductor heterostructure across the wafer. To achieve this, the postgrowth technique of quantum-well intermixing (QWI) has been found to be a useful and straightforward method. Impurity-free vacancy disordering (IFVD) is one of the QWI techniques of great interest because it is suitable for a number of device applications (see *Compound Semiconductor* September 2001, p63). SiO_2 is the most commonly used capping layer to promote intermixing by IFVD, however, to achieve device integration it is also essential to have a capping material that can inhibit intermixing in order to realize area selectivity in IFVD.

Commercial spin-on glass (SOG) has recently been introduced to form SiO_2 layers to promote IFVD because it is simple and inexpensive. A group from the Australian National University and the University of New South Wales has reported using SOG solutions doped with P or Ga and an undoped SOG solution to mix a GaAs/AlGaAs QW structure (*Appl. Phys. Lett.* 2002 **80(7)** 1171). By varying the SOG baking temperature (100–400 $^{\circ}\text{C}$) and the sample annealing temperature (800–925 $^{\circ}\text{C}$), P-doped SOG films created a similar amount of intermixing as the undoped SOG films. However, for all the samples encapsulated with Ga-doped SOG layers, significant suppression of intermixing was observed under all the baking/annealing conditions. In addition, the Ga-doped SOG film did not show problems such as cracking during processing or difficulties in removal after annealing. This makes it an ideal capping layer for the prevention of intermixing, and it can be used in combination with other intermixing promoting layers for device integration.

Super high-gain low-noise PHEMTs fabricated

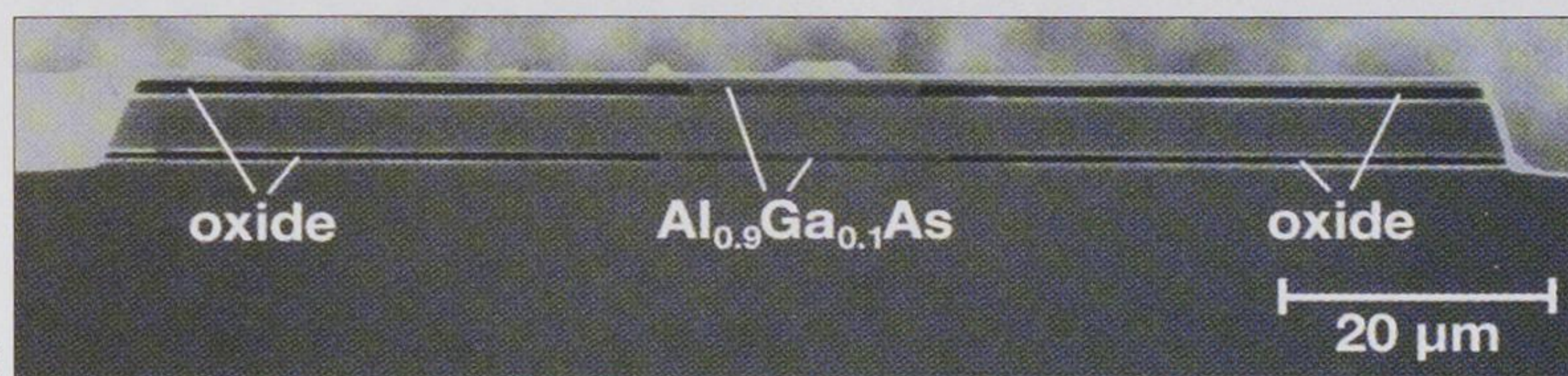
A group from Transcom and the National Cheng-Kung University in Taiwan have published results of a high-gain low-noise InGaP/InGaAs/GaAs PHEMT (*Electron Dev. Lett.* 2002 **23(2)** 70). The device structures were grown by MOCVD on 4 inch semi-insulating GaAs substrates. The Hall mobilities at room temperature and 77 K were 5170 cm^2/Vs and 18,700 cm^2/Vs , respectively, corresponding to 2DEG densities of $2.14 \times 10^{12}/\text{cm}^2$ and $1.98 \times 10^{12}/\text{cm}^2$.

The devices were processed using a conventional optical lithography technique. Etching of the InGaP for the mesa was achieved using an $\text{HCl}/\text{H}_3\text{PO}_4$ (3:1) solution, and the Au/Ge/Ni was evaporated to form the source and drain ohmic contacts, which were then annealed for 20 seconds at 420 $^{\circ}\text{C}$. To form the InGaP gate, the $\text{HF}/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ solution was used to selectively remove the GaAs cap layer. Ti/Pt/Au was then deposited for the Schottky gate by lift-off.

The fabricated PHEMTs with $0.25 \times 160 \mu\text{m}^2$ and $0.25 \times 300 \mu\text{m}^2$ gate dimensions showed a saturation drain current of 304 mA/mm and 330 mA/mm, respectively, and extrinsic transconductance of 320 mS/mm and 302 mS/mm, respectively, at 0 V_{gs} , 2 V_{ds} . Noise figures for 160 μm and 300 μm gate-width devices at 12 GHz were 0.46 dB with a 13 dB associated gain, and 0.49 dB with a 12.85 dB associated gain, respectively. With such high gain and low noise, the drain-to-gate breakdown voltage can be over 11 V. A highly selective recess wet etching process enabled the standard deviation in the threshold voltage across a 4 inch wafer to be 22 mV for 160 μm gate-width devices.

To probe the thermal stability of the noise performance, the devices were stressed at high temperatures for 12 hours. Small NF_{min} variations and associated power gain during high-temperature stress indicate very good thermal stability for the fabricated InGaP gated PHEMTs.

Wet oxidation provides high-temperature QCLs



An SEM cross section of the QCL. The oxide-defined current aperture is clearly visible in the upper and lower AlGaAs cladding layers.

Quantum cascade lasers (QCLs) show considerable promise for a wide range of mid-IR applications. However, their threshold current densities are intrinsically high ($\sim 1 \text{ kAcm}^{-2}$) due to rapid non-radiative intersubband scattering by longitudinal optical phonon emission. Such high-current densities demand careful attention to device fabrication and thermal management. Steer *et al.* at the University of Sheffield, UK have addressed this by developing broad-ridge (width $\sim 100 \mu\text{m}$) GaAs-based QCLs with $20 \mu\text{m}$ wide current apertures defined by selective wet oxidation of the upper and lower $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ optical cladding layers (*Elec. Lett.* 2002 **38**(2) 75). Measurements of the optical and electrical characteristics of the devices, which display laser emission at a wavelength of $9.35 \mu\text{m}$, reveal similar threshold currents and far field patterns to those obtained from conventional $20 \mu\text{m}$ wide ridge lasers. The key advantage of broad-area lasers is that the active core is surrounded by semiconductor material of relatively high thermal conductivity, greatly aiding heat removal from the active region compared with conventional devices. This is demonstrated by measurements which show a significantly decreased dependence of threshold current on repetition rate for pulsed operation, compared with conventional ridge QCLs.

Back-barrier PHEMTs aid carrier confinement

PHEMTs consisting of an InGaP top-barrier layer and an InGaAs channel have advantages over the more traditional AlGaAs/InGaAs system, including better $1/f$ noise figures and high etch selectivity between GaAs and InGaP when forming the gate recess. However, the difference in conduction band energies of InGaP and AlGaAs is smaller than the AlGaAs/InGaAs system, resulting in lower channel carrier density. A group from the National Chiao Tung University in Taiwan, GCS and the University of California, Los Angeles has reported improving on the InGaP/InGaAs/GaAs system by adding an AlGaAs back-barrier layer between the GaAs substrate and InGaAs channel (*Jpn. J. Appl. Phys.* 2001 **40** (Pt. 1, 12) 6761).

The AlGaAs layer improves the PHEMT performance as it provides an additional high-barrier heterojunction behind the channel, which improves carrier confinement and mobility within the channel. Large ($100 \times 200 \mu\text{m}^2$) PHEMTs gave peak values for carrier mobility of 5032 and $4137 \text{ cm}^2/\text{Vs}$ for devices with and without the AlGaAs back-barrier, respectively. Compared with the InGaP/InGaAs/GaAs PHEMT the new structure gave a 1.3 times lower source resistance. For $0.3 \times 80 \mu\text{m}^2$ devices, lower knee voltage and higher transconductance and f_t and f_{max} values were observed in the devices with the AlGaAs back-barrier.

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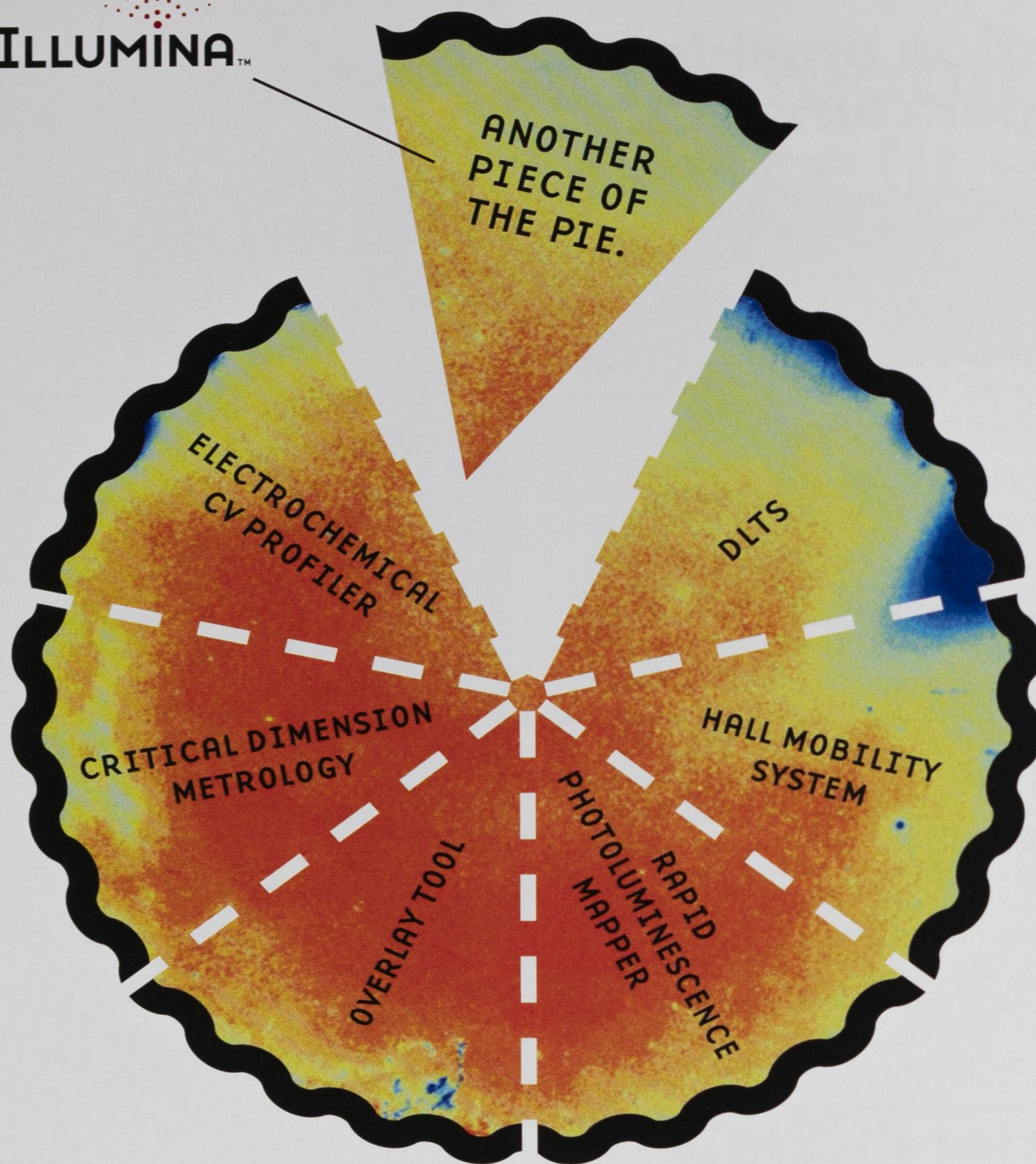
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Infineon looks towards a silicon vision of the future

According to results presented at a recent conference, Infineon Technologies has developed circuits using CMOS and SiGe processes that could remove the need for III-V devices.



The frequency quadrupler had a bandwidth of 3 dB in the 24–45 GHz frequency range, representing a new record for SiGe.

Infineon Technologies sees a future in which III-V devices have largely been replaced by high-performance Si-based devices. Infineon believes that its latest SiGe bipolar process can support most of the applications currently being implemented in GaAs or InP. Furthermore, those applications currently being met by production SiGe processes can now be implemented in Infineon's newest 0.12 μm CMOS process.

In essence, Infineon is mapping out a future in which Si-based devices are pushed up the high-frequency application food chain, squeezing GaAs and InP into the extreme high-frequency regime where commercial applications and markets are essentially nonexistent. At this year's IEEE Solid State Circuits Conference (February 3–7 in San Francisco), Infineon presented results from both their SiGe and CMOS processes in support of this vision of the future.

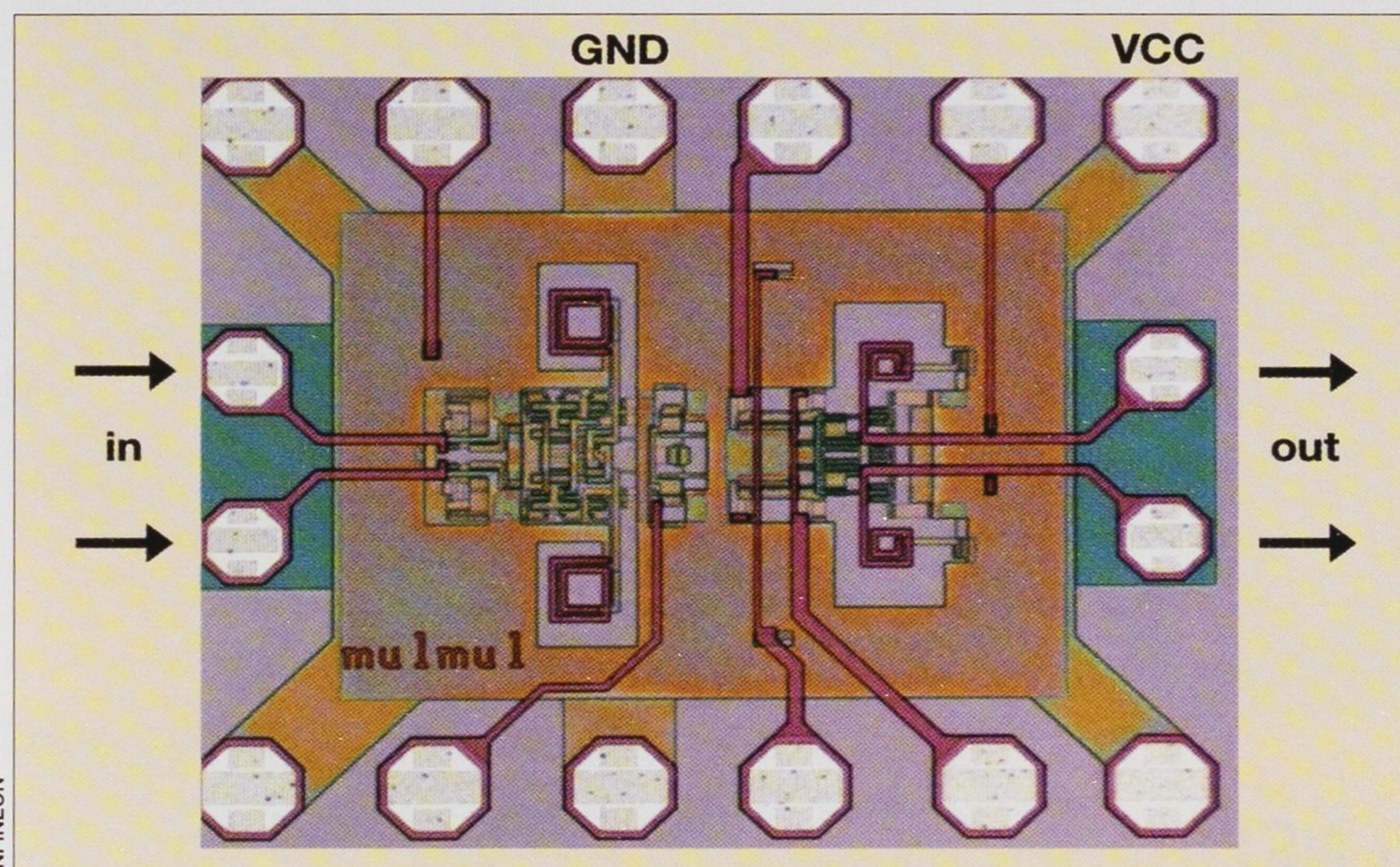
CMOS sets records

While many of the advanced CMOS processes that have recently been unveiled show excellent RF performance, this improvement is often achieved through the implementation of non-standard CMOS approaches. These include the use of high-resistivity substrates, thickened

top layer metal, buried and epitaxial layers, and even SOI substrates. Infineon's 0.12 μm process is implemented using a standard CMOS approach in conjunction with a six-layer copper metallization scheme. The resulting NMOS devices exhibit f_t and f_{max} values of 100 and 60 GHz, respectively; these RF characteristics are not only comparable to advanced SiGe production processes, but even to some basic GaAs production processes.

This CMOS process was used to fabricate a high-speed frequency divider (Knapp *et al.*). Current high-speed CMOS frequency dividers (used for frequency synthesis as well as for clock and data recovery applications) typically exhibit a maximum operating frequency of 10 GHz, and often utilize dynamic circuits or injection-locked oscillators that limit their operational frequency range. Infineon's approach relies on current-mode logic (CML) and differential signals. This allows for a wider range of operating frequency (down to DC) and a reduction in internal voltage swing, which in turn improves operating speed. Also, the differential signals provide sufficient noise margins for operation with small voltage swings – for this device, operating from a 1.5 V power supply, the internal voltage swing was only $2 \times 550 \text{ mV}_{\text{p-p}}$. Consisting of a master-slave D-type flip-flop and an output buffer, the circuit performed up to a maximum frequency of 25.4 GHz (roughly twice that of the best previously reported value for CMOS devices) and down to a frequency of 1 GHz (below this, performance is degraded by the limited slew rate of the sinusoidal input signals). Relying on the same logic approach, a multiplexer was also fabricated. Again using a 1.5 V supply, the multiplexer operated up to a data rate of 25 Gbit/s, showing an eye opening of 330 mV, and consumed 29.4 mA.

The same CMOS process was used to fabricate a VCO operating at 51.6 GHz, with a tuning range of 1.4 GHz, and a phase noise of -85 dBc/Hz at 1 MHz offset. Requiring a 1 V power supply, the VCO consumed a record-setting 1 mW (only one-tenth the power of other CMOS VCOs operating at this frequency). The windings for the inductor coil were fabricated from the fourth, fifth and sixth layer of the six layers of copper metallization, with careful design obtaining the best compromise between winding series resistance and winding parasitic capacitance to the substrate (Tiebout *et al.*).



Infineon's 24–45 GHz frequency quadrupler, which has a bandwidth of 3 dB. The chip, implemented in a 0.4 μm SiGe bipolar process, measures $0.55 \times 0.45 \text{ mm}^2$.

The high-speed frequency divider performed up to a maximum frequency of 25.4 GHz, roughly twice that of the best previously reported value for CMOS devices.

SiGe for high frequencies

For applications that require higher performance than can be delivered by its CMOS process, Infineon plans to use its 0.4 μm SiGe bipolar process. This exhibits f_t and f_{max} values of 106 and 145 GHz, respectively, and a CML gate delay of 6.5 ps, and is implemented with four metallization layers.

High-frequency applications under development include local multipoint distribution systems (LMDS) operating at 28 and 38 GHz, and the European microwave video distribution system (MVDS) operating at 42 GHz. One method of accessing the frequency ranges required for these applications is to use frequency multipliers to convert lower frequencies to the desired higher frequency range (Hackl *et al.*). To that end, a frequency quadrupler (based on generating harmonics with a non-linear element and filtering out the desired band) capable of converting 10 GHz signals directly to LMDS and MVDS bands was implemented in Infineon's SiGe process (see figure, p37). The resulting quadrupler had a bandwidth of 3 dB in the 24–45 GHz frequency range, representing a new record for SiGe. The device also exhibited a maximum gain of 7.3 dB at 44 GHz, while utilizing a 5 V power supply and running at 84 mA. As an example for MVDS applications, a 10.5 GHz input signal was quadrupled to 42 GHz, while the fundamental, second- and third-order harmonics were suppressed at the 42 GHz target frequency by more than 22 dB.

Not just performance

These devices clearly demonstrate that III-V devices face performance competition not only from SiGe bipolar processes but even from CMOS. Typically man-

ufacturers using Si-based processes stress the performance capabilities of their circuits, giving detailed examples of how they compare to III-V devices while barely mentioning the costs, simply stating that Si devices are intrinsically cheaper than III-V devices. This may not be as clear-cut as Si manufacturers state, even though substrate costs are certainly cheaper in the case of Si. For the type of small analog circuits described here, the actual substrate cost per die is often only a small fraction of the chip cost regardless of substrate type (this argument would of course not be true for large circuits such as DSPs or microprocessors). In addition, these manufacturers claim to be using standard CMOS and bipolar processes, implying that this translates to low cost. These standard processes are in fact quite sophisticated, often requiring significantly more mask layers than a GaAs HBT process (and certainly many more than a MESFET or PHEMT process). So while it is becoming clearer that compound semiconductors face stiff competition in the performance arena for many commercial applications, cost must still be considered, and cost competition may be every bit as fierce as performance competition. ●

Further reading

H Knapp *et al.* 2002 "25 GHz Static Frequency Divider and 25 Gbit/s Multiplexer in 0.12 μm CMOS" 2002 *IEEE Solid State Circuits Conference* (San Francisco).

M Tiebout *et al.* 2002 "A 1 V, 1 mW, 51 GHz Fully Integrated VCO in Standard CMOS" *ibid.*

S Hackl *et al.* 2002 "45 GHz SiGe Active Frequency Multiplier" *ibid.*

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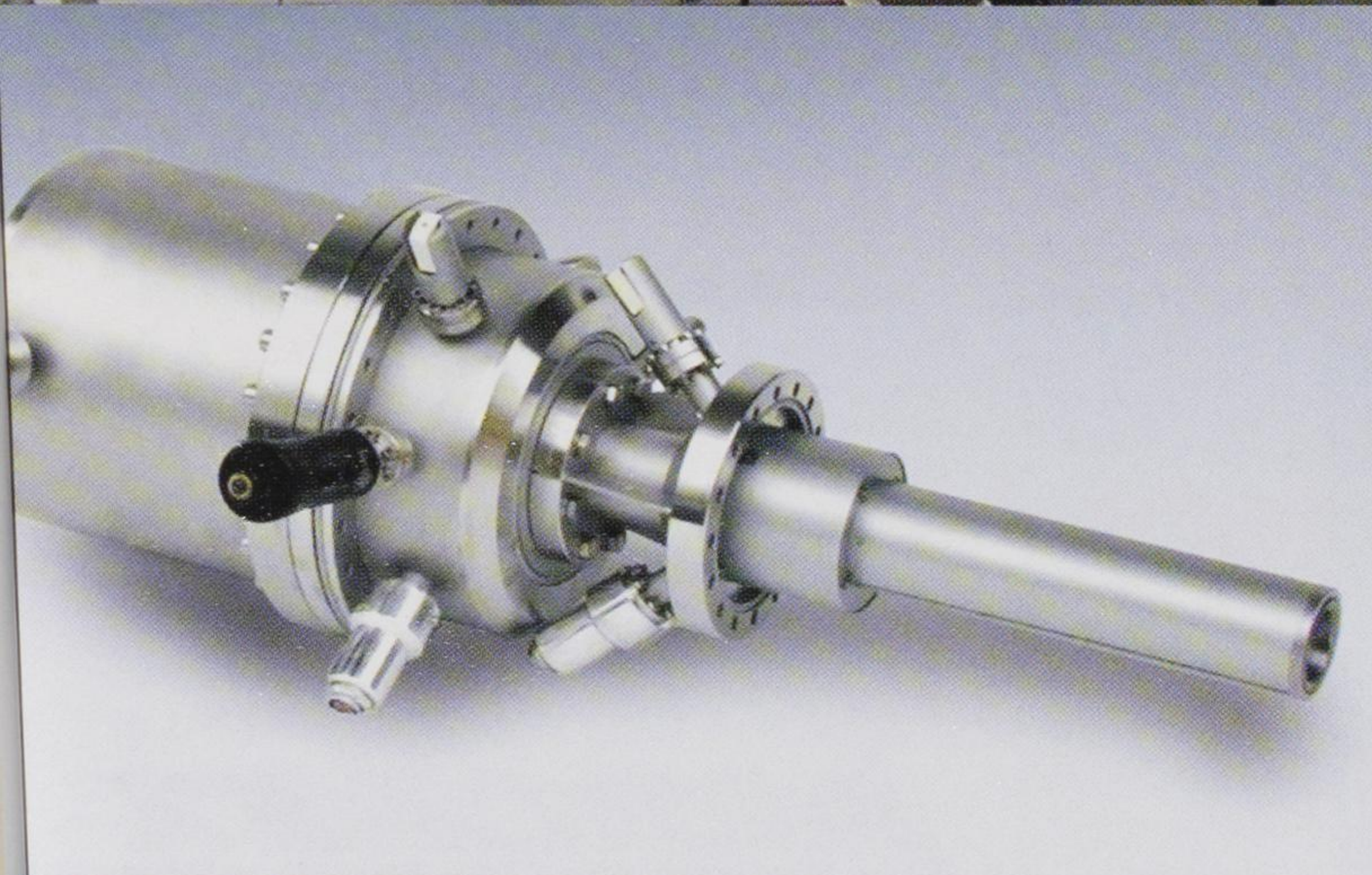
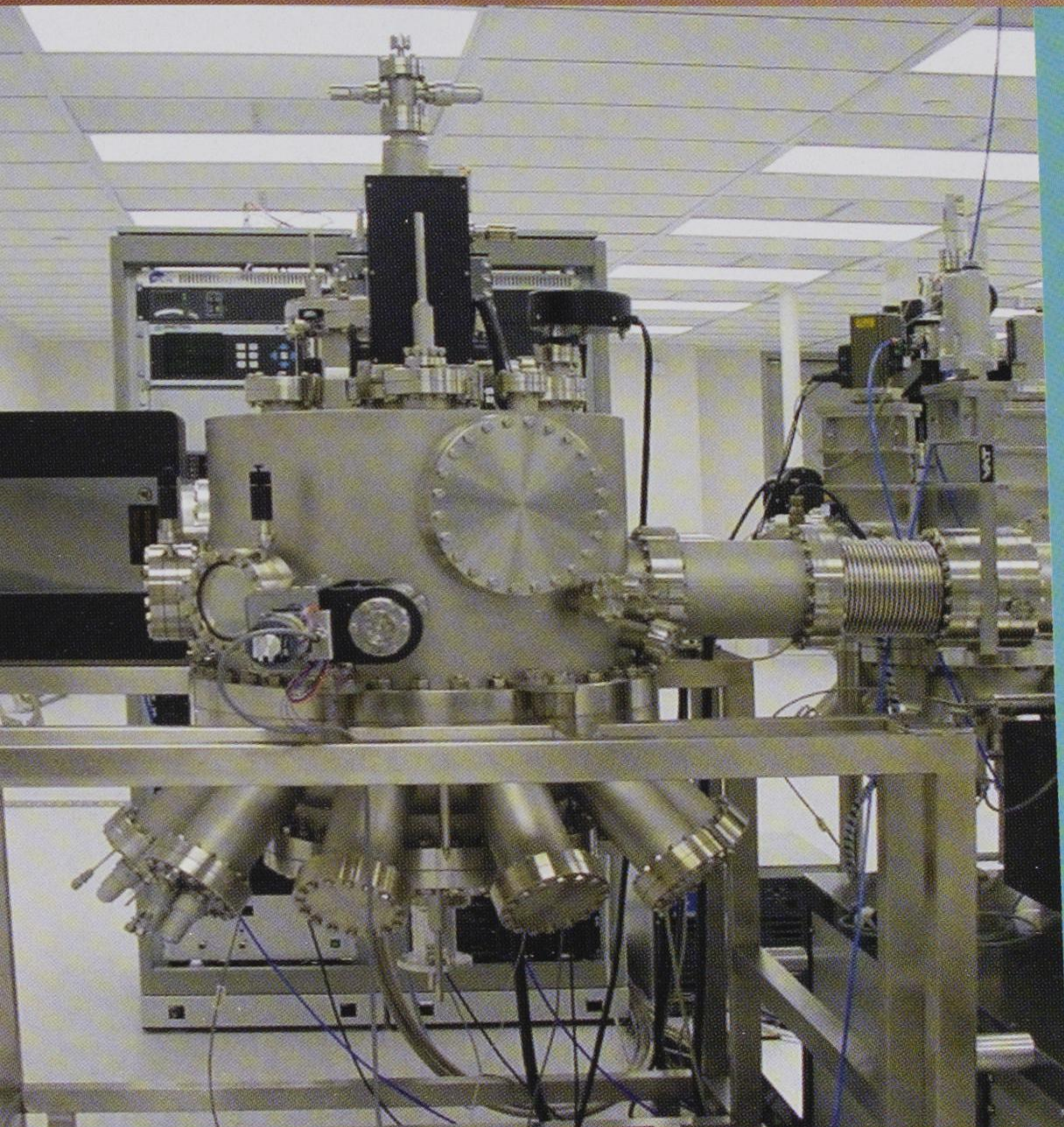
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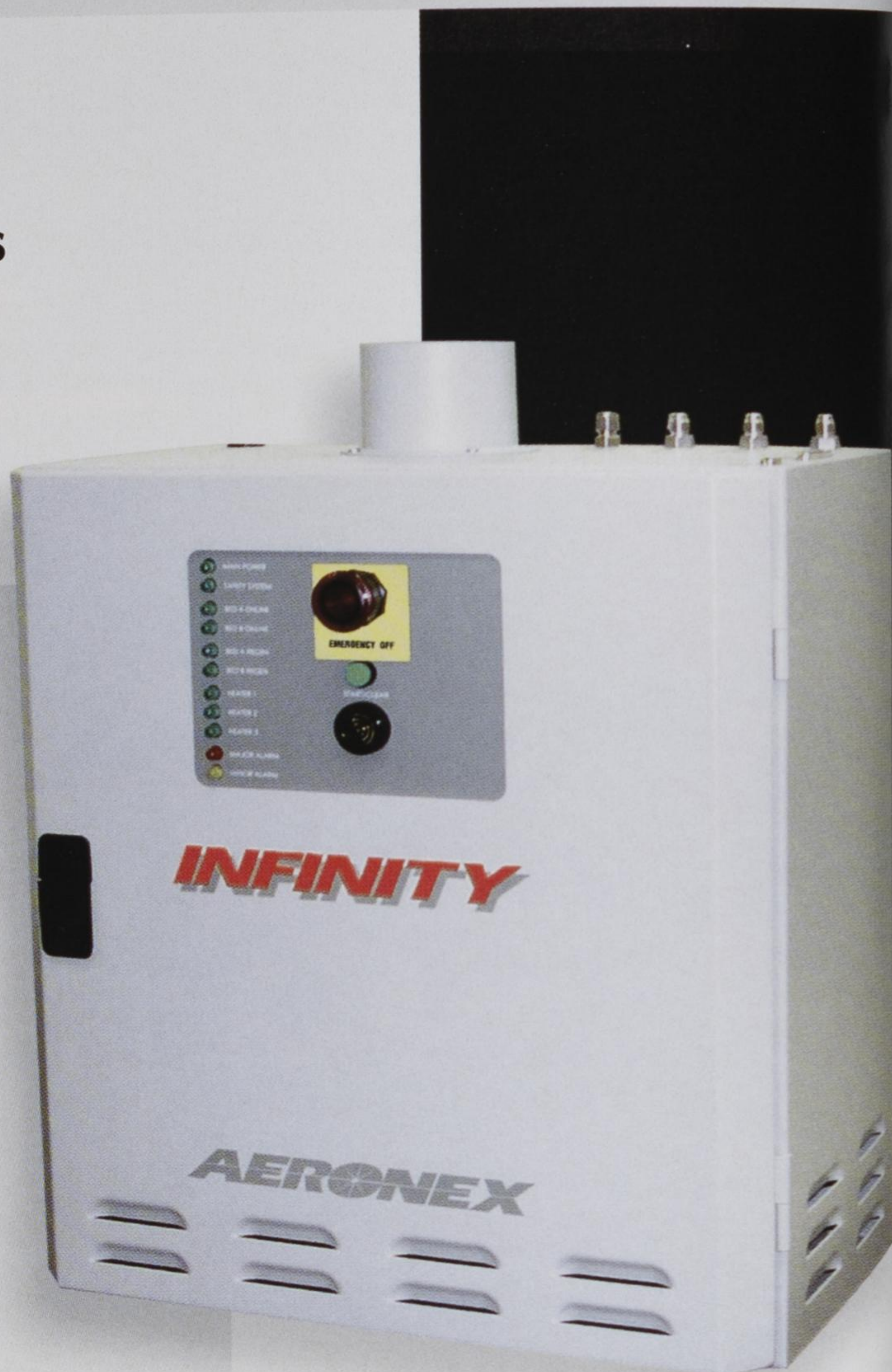
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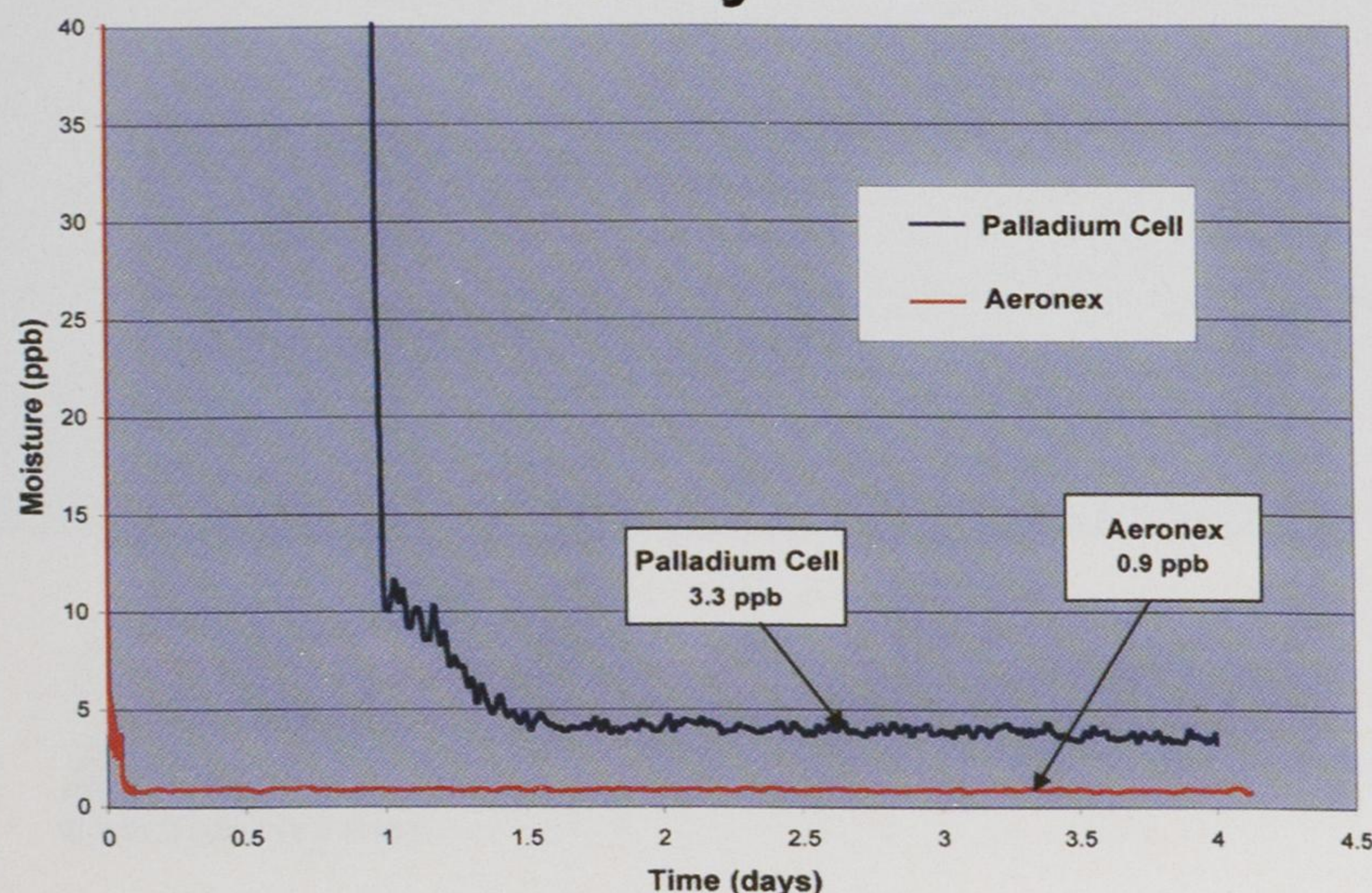
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Korea is the new compound semiconductor boom region

Once dominated by large industrial conglomerates, the compound semiconductor industry in Korea now has many much smaller start-ups, write **Tim Whitaker** and **Bridget Adams**.

Korea is rapidly emerging as a compound semiconductor powerhouse. From relatively humble beginnings in government and industrial research labs, Korea's compound semiconductor industry now includes a large number of start-up companies making a broad range of products. A lot of activity is focused on InP-based lasers and GaAs-based VCSELs for fiber-optic applications, and there are also a number of epi-wafer foundries, several companies selling high-brightness LEDs, and one of the world's first 6 inch GaAs foundries.

Much of the early compound semiconductor work in Korea was performed at the Korea Advanced Institute of Science and Technology (KAIST). "In the early 1980s, the only person in Korea who had an MOCVD system for GaAs growth was Y S Kwon, a professor at KAIST," says Y H Lee, also of KAIST. "Several companies attempted to do some R&D on compound semiconductors, but in terms of making money the industrial effort was not particularly successful." However, adds Lee, the last few years have seen many success stories, with companies such as LG, Knowledge*on and Samsung starting to make a profit from devices such as LEDs, and lasers for CD and DVD players.

Korea is now in the process of breaking out of its traditional mould, which has seen the business landscape dominated by slow-moving industrial conglomerates or *chaebol*. "Historically, three of the largest *chaebol* – Samsung, LG and Hyundai – worked on compound semiconductors, but Hyundai closed down all their activities in this area in 1998 due to the Asian financial crisis," explains Holger Juergensen of Aixtron. "Today, there are several businesses related to LG and Samsung that work on compound semiconductors, as well as a number of new start-up companies."

Korea has one of the world's highest usage of cellphones and the Internet, and these domestic markets are fertile testing grounds for



Samsung, a giant Korean conglomerate, is one of the world's leading manufacturers of mobile handsets. Various subsidiaries of the company make fiber-optic components and PA modules, while SAIT has developed nitride-based LEDs and lasers.

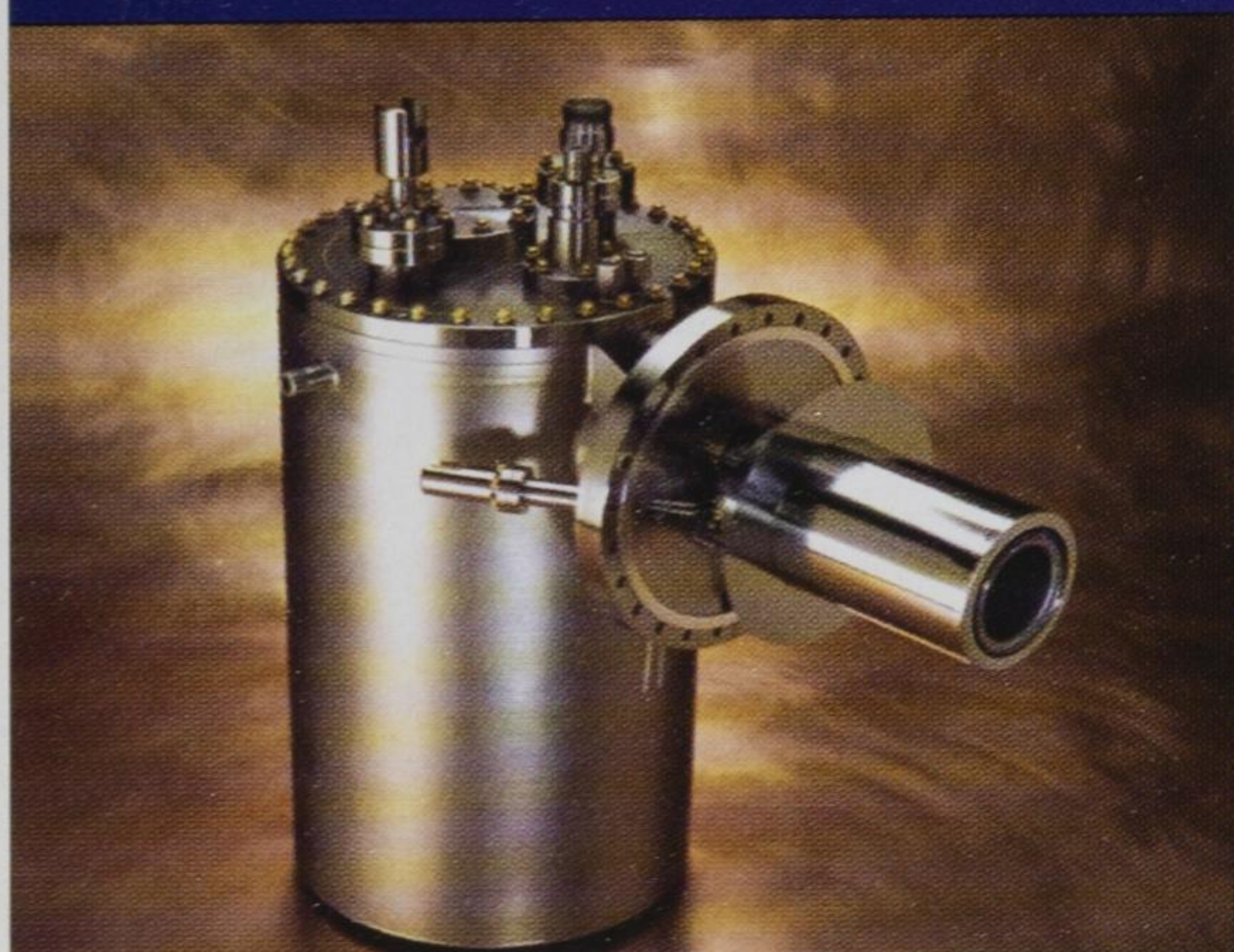
new technologies. Not surprisingly, many start-ups have been established to produce components for the communications industry. With several world-class university and other research labs specializing in optoelectronics, there is a good supply of both ideas and engineers. Capital is harder to come by in the present uncertain climate, but is available as venture capital and also in the form of investment from, or joint ventures with, the established *chaebol*. "In this sense Korea is a hybrid between Japan and the US," says Emcore's Tom Miehe. "As in Japan, many people work for large corporations, but there is also the scope to spin-off small companies or invest in start-ups."

"There were at least 10 start-up companies founded in Korea in 2000–2001," says Euijoon Yoon, CEO of one such company, Nanotron Technologies. "Many were set up by researchers from Samsung and LG, or by university professors. The compound semiconductor industry is blooming in Korea."

However, Korea has not escaped the industry downturn; equipment manufacturers report successful years in 1999 and 2000, but fewer sales last year. "From my point of view the market for compound semiconductor equipment was not so good in 2001," says James Park, president of Hanvac, a Korean company that manufactures MOCVD systems for the domestic and foreign markets. "But I think that the equipment market will improve towards the end of this year, and the market for devices should become much better."

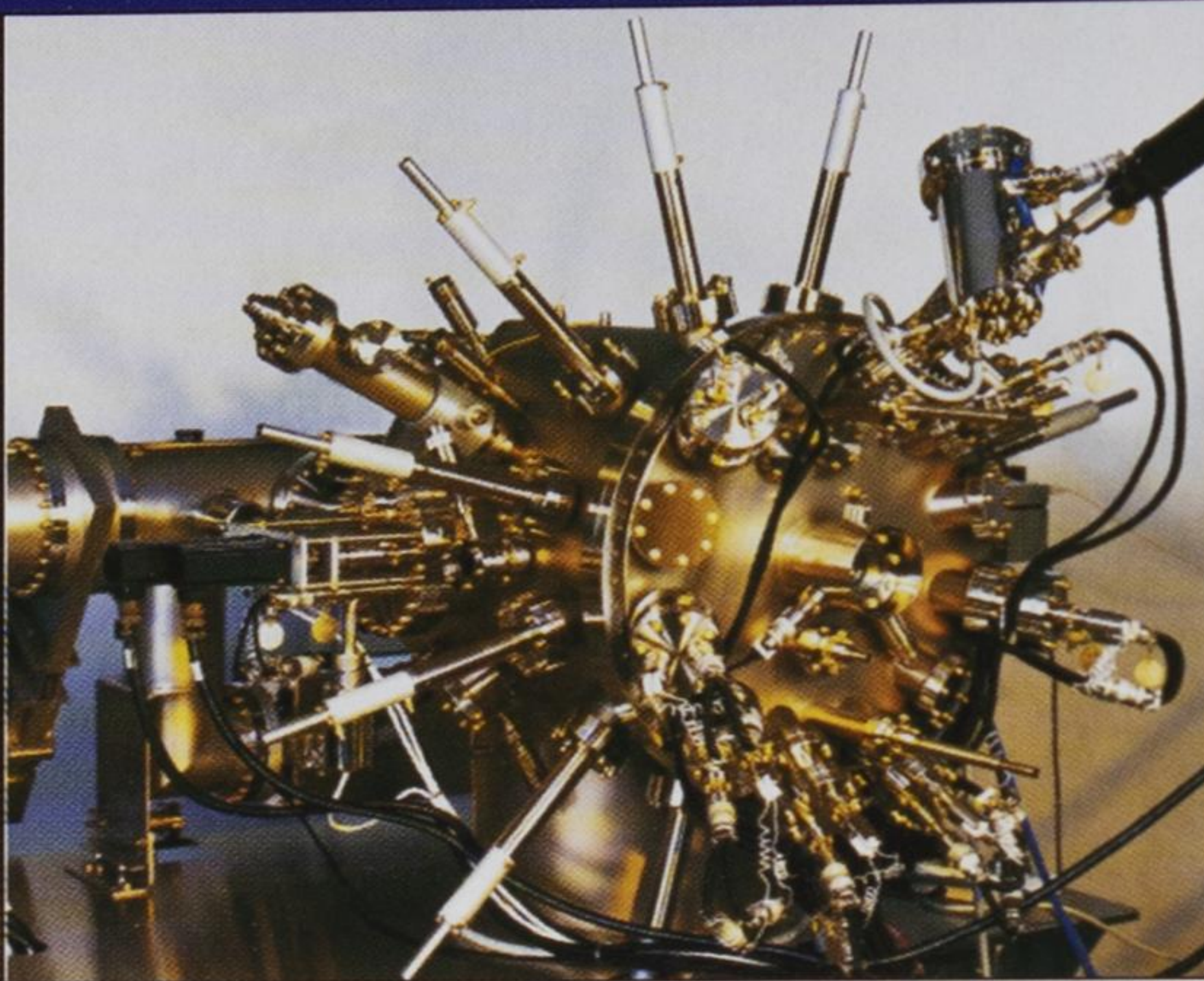
In contrast to Taiwan, where the focus on low-cost manufacturing has led to a pre-eminent position in several segments of the LED market, Korean companies have somewhat different agendas. "Korean companies tend to look at leading-edge technologies rather than addressing very low cost markets," says Tom Miehe. As described on the following pages, Korean companies are looking at VCSELs, nitride-based LEDs and a range of other compound semiconductor devices.

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Samsung focuses on fiber-optics, CD/DVD lasers and nitride-based emitters

Samsung Electronics

established a fiber-optics division in 1983 and began the R&D of optoelectronic components in 1990. It developed 780 nm VCSELs for CD optical heads in 1995, and has since developed many devices for fiber-optic applications.

In 2000, the company formed an optoelectronics division and commenced mass production of optical components and subsystems at a new 100,000 sq. ft plant in Suwon. Facilities include MOCVD and MBE epitaxial growth systems, a 2 inch wafer-processing line, automated high-throughput assembly and low-cost plastic packaging capabilities. Among the many products offered by Samsung are: 1550 nm electro-absorption modulated laser modules at 2.5 and 10 Gbit/s, 2.5 Gbit/s directly modulated DFB lasers,

10 Gbit/s *pin* receiver modules incorporating TIAs, VCSEL-based transceivers, and 1550 nm semiconductor optical amplifiers.

Samsung has also been active in applying VCSELs to digital multimedia devices for home networking, graphic interfaces and optical disc drives (see *Compound Semiconductor* Sept/Oct 2000, p71).

Samsung Electro-Mechanics (SEM)

manufactures a range of red (635 and 650 nm) and infrared (780 nm) laser diodes housed in small TO-18 packages, with built-in photodiodes for optical power monitoring. Low-power visible lasers are used for DVD, DVD-ROM, laser pointers and measuring instruments, low-power IR lasers are used for CD and CD-ROM players, while higher power lasers are used

in magneto-optical storage, MiniDisc systems, and CD-RW and DVD-RAM players. SEM also manufactures infrared LEDs for remote control, opto-interrupter and optical communication applications, as well as visible LED chips for signal lamps, display panels and indicators. SEM also sells power amplifier modules incorporating die from suppliers such as TriQuint.

Samsung Advanced Institute of Technology (SAIT)

has been involved in the development of nitride-based LEDs and lasers for several years. In early 1999, the company reported the development of blue and green LEDs (see *Compound Semiconductor* Jan/Feb 1999, p18) and subsequently demonstrated room-temperature, CW violet laser diodes (see *Compound*

Semiconductor August 2000, p24). Yongjo Park, manager of the compound semiconductor laboratory at SAIT, reports that improvements to the lasers have recently been made. "We were successful in the fabrication of a high-power violet laser with a lifetime of 8.6 hours at 50 °C in an automatic power-controlled mode at 30 mW power," he says. The devices were grown on epitaxial lateral overgrowth GaN substrates with a low dislocation density of $10^6/\text{cm}^2$. "The fabrication procedure was similar to that for the previous low-power (3 mW) laser, except for further optimization of the growth parameters for the active layer," adds Park. He also reports that SAIT is working to improve the quality of GaN substrates for the growth of high-power violet lasers, but further details are not yet available.

Epiwafer foundries

Epiplus An epiwafer manufacturer located in Gyeonggi-Do, Epiplus was set up in May 2000 using capital supplied by institutional investors. A second round of funding came at the end of the same year. At the same time, Epiplus was selected as a lead manager in an epiwafer technology development program sponsored by the Korean Ministry of Commerce, Industry and Energy. The company moved to its new building in early 2001 and started commercial production of epiwafers in the second half of the year. Epiplus now manufactures a product range including 4 and 6 inch InGaP/GaAs and AlGaAs/GaAs HBT epiwafers, and blue and green GaN-based LED epiwafers.

EpiValley Located in Kyung-gi-Do, a suburb of Seoul, EpiValley was founded in December 1999 and currently has 26 employees. According to Joongseo Park, general director, the company manufactures a wide range of epiwafers. "We have five MOCVD systems and a monthly capacity of around 1000 wafers," says Park. "Our products include epiwafers for AlGaAs/GaAs VCSELs, InGaP/GaAs HBTs,

AlInGaN-based LEDs and HEMTs, as well as 650, 780 and 808 nm laser diodes." EpiValley also sells custom-designed epiwafers based on GaAs, InP and AlInGaN materials.

Nanotron Technologies Nanotron was founded in May 2000 by Euijoon Yoon, an associate professor at Seoul National University (SNU), together with some of his students from the School of Materials Science and Engineering. Yoon has worked on MOCVD growth of III-V epilayers since joining SNU in 1992, and now runs three MOCVD growth systems, each dedicated to a different materials system (GaAs, InP and GaN). The machines are part of the Inter-university Semiconductor Research Center (ISRC) at SNU, which has other III-V research facilities and operates a CMOS fabrication line. "ISRC agreed to provide Nanotron with full access to its III-V facilities and also an office space," says Yoon. "The company is also part of the SNU Technology Incubation Center."

At present, Nanotron's primary products are epiwafers. "I have received orders from research institutes and universities in Korea," says Yoon. "However, as our name implies,

we are also working on the fabrication of optical devices based on quantum dots." Last year, Nanotron Technologies was awarded Technology Business Incubation funding from the Korean Ministry of Commerce, Industry and Energy for the development of quantum-dot optical devices.

PROWTech PROWTech has focused on the R&D and mass production of optoelectronic device epiwafers for more than 10 years. "Our company produces infrared LED epiwafers by LPE technology using home-made GaAs ingots," says Jiny Jang. "All our equipment for growing these epiwafers is also home-made."

Furthermore, PROWTech has extended its product range to include VCSEL and *pin* photodiode epiwafers in the 780–980 nm range. These products, targeted at optical communications applications, are grown by MOCVD. Jang says that PROWTech plans to double its production capacity in 2002.

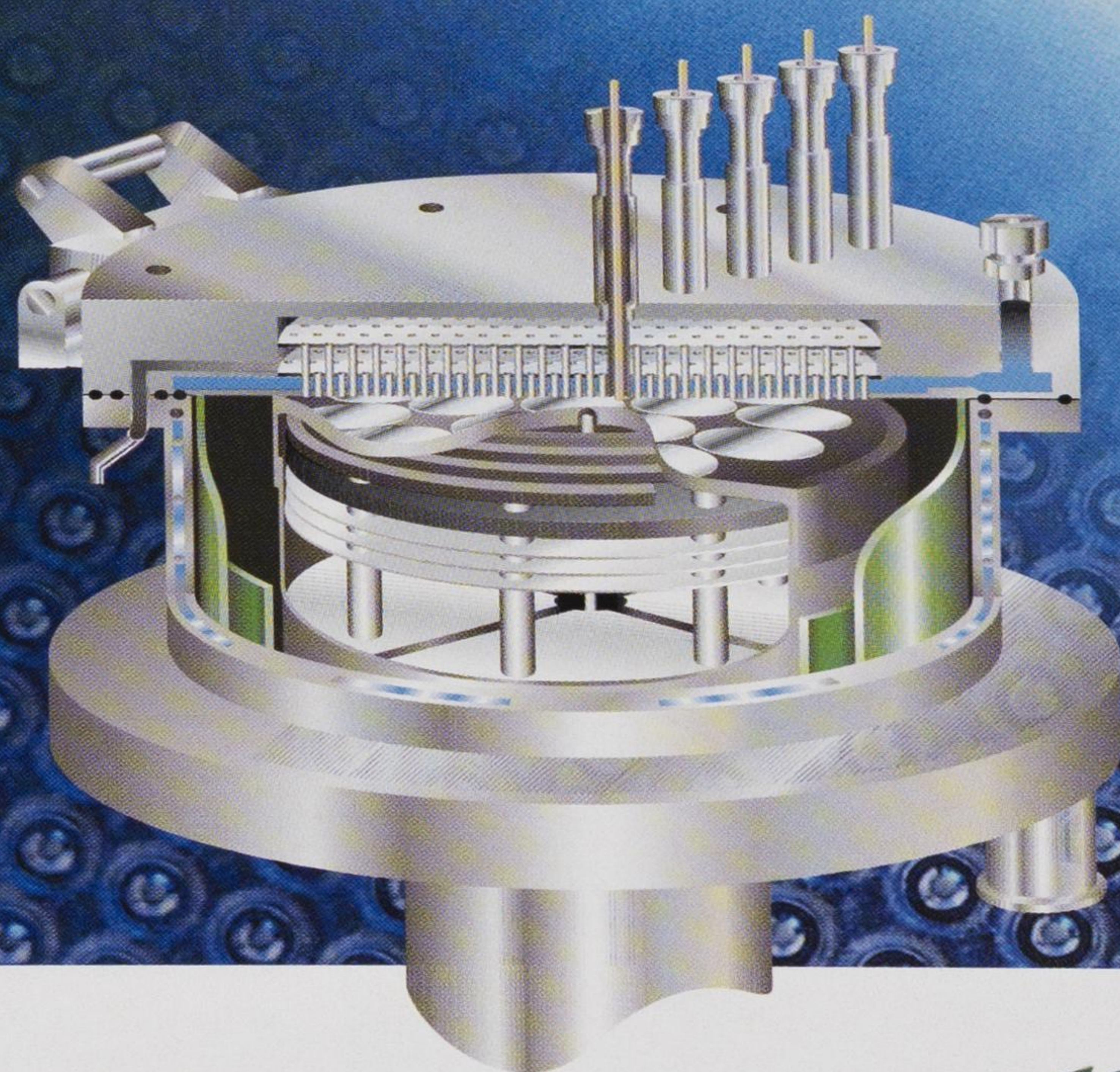
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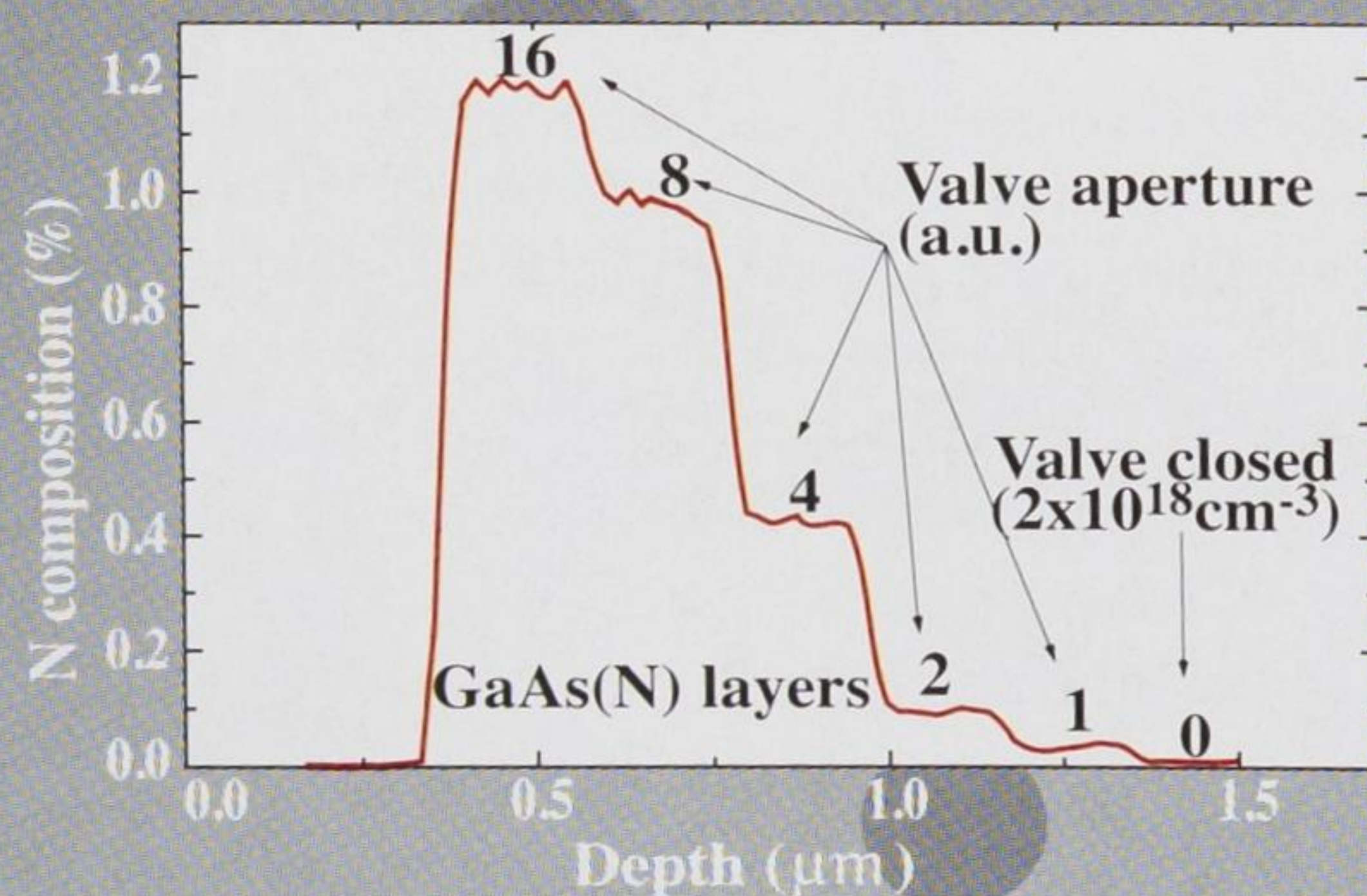
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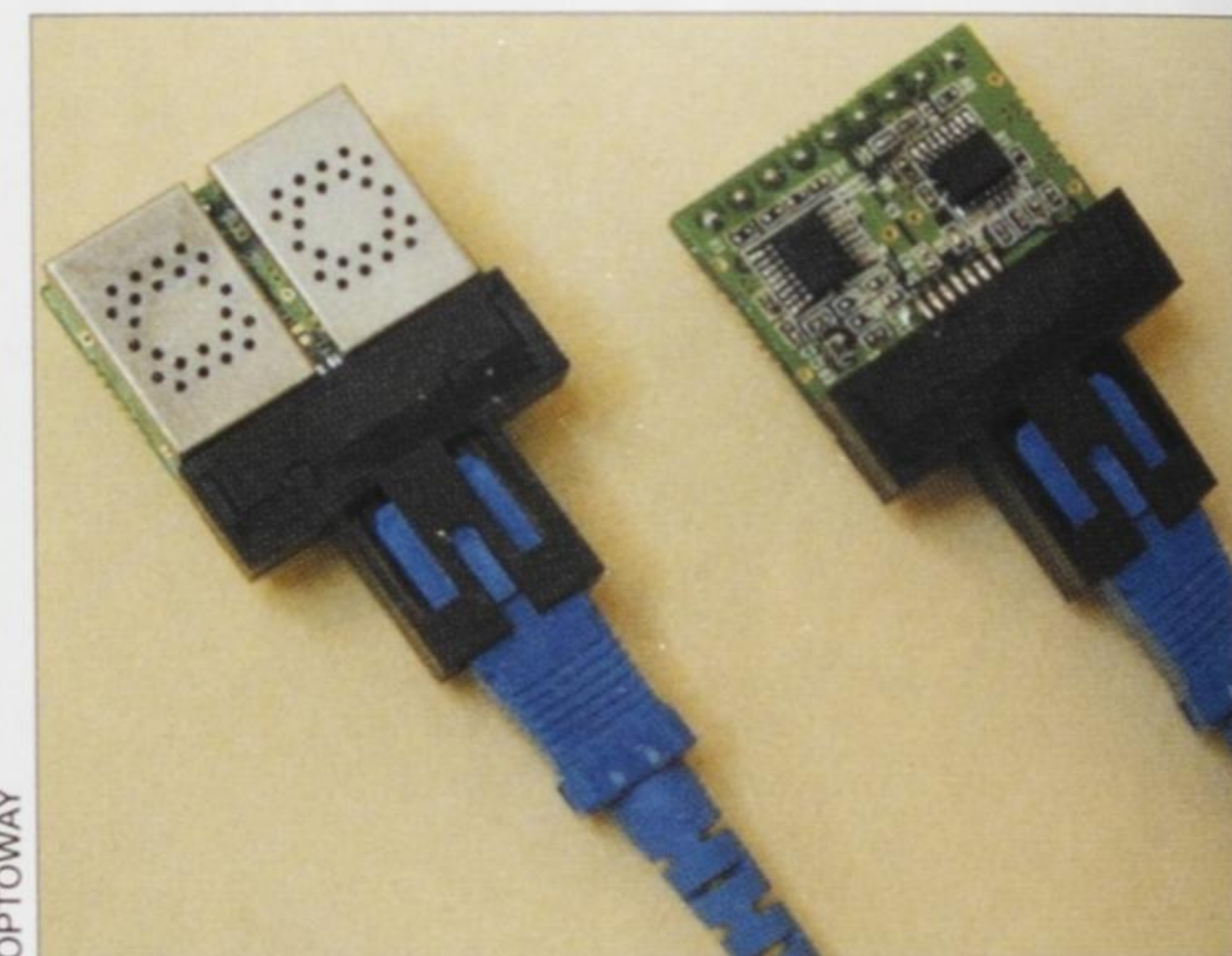
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former name of the company. These are AlGaAs/GaAs infrared LEDs operating in the 700–880 nm range. The company has produced IR LEDs for over 10 years and claims to be the world's leading manufacturer by volume. Knowledge*on also makes 850 nm GaAs-based VCSELs. More recently, the company completed Korea's first and only 6 inch GaAs wafer foundry. Pilot operation began in the fall of 2001, and commercial operation was scheduled to start at the end of the year with an initial capacity of 3000 wafers per month. Products include InGaP HBTs and MMICs for wireless (CDMA, GSM, DCS, 3G etc) and fiber-optic (40 Gbit/s) communication applications.

High Quality Technology (HiQTech) Based in Ochang and founded in April 1999, HiQTech opened a new 50,000 sq. ft factory with 7500 sq. ft of cleanroom space in August last year. The company has a number of vertical gradient freeze (VGF) furnaces for the fabrication of Si-doped and undoped GaAs wafers up to 4 inches in diameter. HiQTech works in close collaboration with Sung Kyun Kwan University (SKKU) in Suwon, and has research programs which aim to improve product quality and develop new products. A new VGF method for GaAs bulk crystal growth has been developed, which results in material quality that is claimed to be comparable to that produced by other companies. According to company president Young-Duck Yoon, HiQTech is aiming to produce 3 inch GaAs wafers at a volume of 10,000 per month from the first quarter of 2002. The company plans to extend its facilities to achieve a monthly output of 30,000 wafers, with diameters from 2 to 4 inches, by the third quarter of 2002. Products currently in R&D include semi-insulating 6 inch GaAs wafers, 3 and 4 inch InP and GaP wafers, 3 inch sapphire substrates, p-type GaN wafers, and several other types of compound semiconductor wafers.

NeoSemiTech Another new wafer producer is NeoSemiTech, which invested \$5 million in a new plant in Incheon that was set up in March 2000. Members of senior management gained silicon wafer manufacturing experience working for LG, and NeoSemiTech has developed analogous mass-production methods for compound semiconductor wafers. Myung Hwan Oh, CEO and president of NeoSemiTech, says the company is now at the initial stage of growing ingots on a pilot scale using two crystal growth methods, Czochralski



This 155 Mbit/s VCSEL-based bi-directional transceiver, manufactured by Optoway, is one of a large number of fiber-optic components manufactured in Korea.

and Bridgman, for wafer sizes between 2 and 6 inches. The maximum wafer production capacity will be 30,000 wafers per month, and estimated revenues in 2004 are \$50 million. The company hopes to expand its product line with InP wafers by 2003, and GaN and SiC wafers by 2005.

Fiber-optic components

Opto*on Established in August 2000 and based in Taejon, Opto*on supplies optical chips and modules with data rates from 155 Mbit/s to 2.5 Gbit/s. The company's roots are in the Electronics and Telecommunications Research Institute (ETRI), also located in Taejon. Opto*on has expertise in InP-based material growth and material processing technology, and supplies components including InGaAsP/InP MQW lasers. The company is currently preparing a mass-production line, expected to be operational during 2002, and has vertically integrated manufacturing capabilities covering epitaxial growth, chip processing and module packaging. Its target markets are access, metro and Ethernet applications.

Opticis Founded in December 1999, Opticis designs and manufactures high-performance, low-cost VCSEL-based data transmission modules. As high-speed digital interfaces prevail in the PC industry, the connectivity issue becomes more critical, since the traditional copper cable connector struggles over distances greater than several meters. According to one of the company's founders, Hyun-Kuk Shin, Opticis has translated the major PC interfaces such as DVI (Digital Visual Interface), USB (Universal Serial Bus) and IEEE 1394 (FireWire) into optical link modules using VCSEL technology. "These modules can support much longer link distance than copper

cable connectors,” says Shin. “For example, DVI optical extension modules can link PCs and digital display devices up to 500 m apart.” Opticis has also developed multi-gigabit VCSEL transceivers for data communications, including SC and SFF connection styles. Shin says that Opticis has devoted its efforts to making its solutions price-competitive through innovative low-cost packaging and VCSEL manufacturing. The company manufactures both VCSELs and *pin* photodiodes, and sells chips to some key customers. Using an index-guided 850 nm VCSEL structure, Opticis has realized low power consumption and simplified packaging. In addition, to implement bi-directional circuits for DVI or USB optical extension modules, Shin says that Opticis has invented a way to automatically control the direction of the data signal without using a microprocessor. The company is targeting short-haul (i.e. less than 1 km) datacom and consumer markets, and opened a sales office in North America in April 2001.

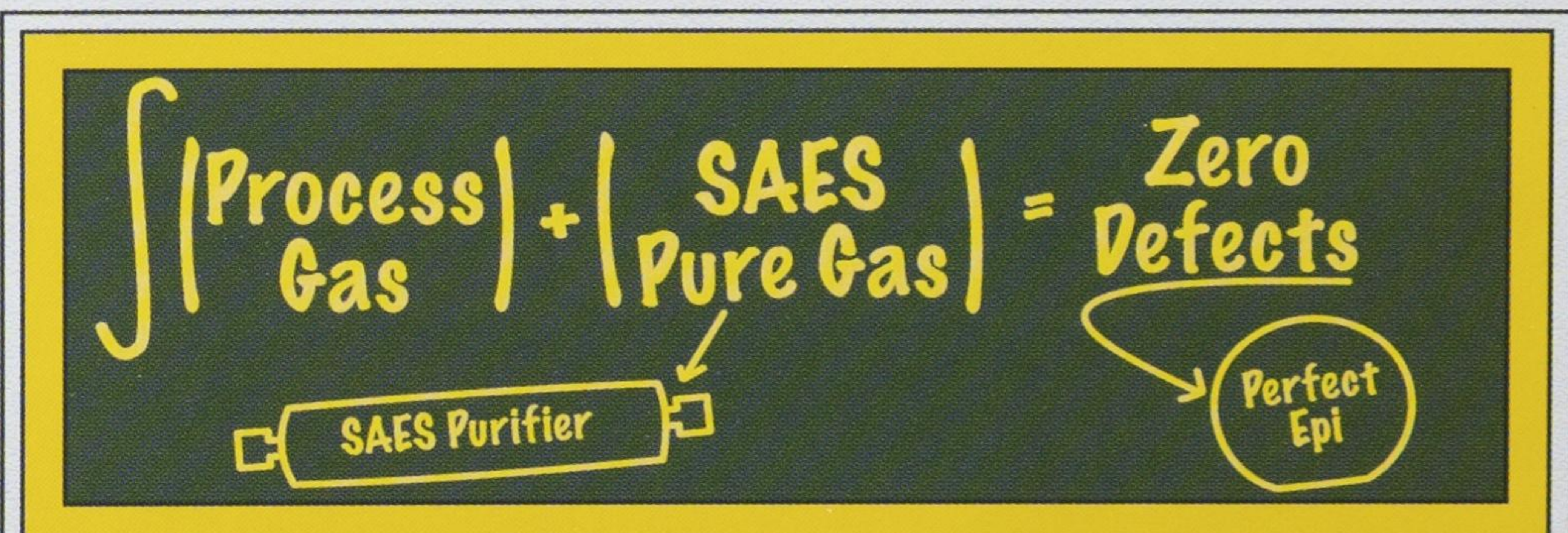
Optowell Backed with venture capital funding, Optowell is based in the Semiconductor Physics Research Center of Chonbuk National University, Chonju. The company was established in May 2000, and received first-round funding of more than \$3 million in June 2001. Optowell specializes in the design, MOCVD epitaxial growth and chip fabrication of GaAs-based VCSELs. The company aims to supply VCSEL epiwafers, chips and arrays to module manufacturers, and its products are based on R&D work at Chonbuk National University over a 10 year period. Optowell supplies 3 inch AlGaAs/GaAs VCSEL epiwafers, suitable for oxidation or ion-implantation processes, along with VCSEL chips and 1D and 2D VCSEL arrays. The lasers operate at speeds of up to 2.5 Gbit/s and at a wavelength of 850 nm; both single and multimode lasers are available, along with custom-designed units. Optowell also has the technology to produce 780–980 nm VCSELs, while devices operating in the 1300 nm range have been successfully beta-tested.

Optoway Founded in March 2000, Optoway specializes in the development and manufacturing of VCSELs. The company is located at the Science and Industrial Complex in the Daeduck Venture Valley area of Korea, and has a 15,300 sq. ft facility for device fabrication, test and packaging. With 50 employees, Optoway produces 780–860 nm VCSELs, *pin* photodiodes and UV detectors in chip form

and in various types of package (e.g. TO-46 metal cans and SC-type optical sub-assemblies). The production of VCSELs and PDs started in May 2001, and in subsequent months the company started to produce blue LEDs and UV detector chips. An R&D center was opened in Seoul in September 2001 for transceiver development, which has already yielded new products. “Recently, we finished development of a 155 Mbit/s VCSEL-based bi-directional transceiver,” says sales manager Ho-Young Shin. “This incorporates dual-wavelength VCSELs and is assembled with fully passive alignment and injection molding, which is a proprietary technology of the US company PhotonAge Inc.” Shin believes that the transceiver, which should be ready for mass production in March, will be a reliable and lower cost solution for volume markets such as fiber-to-the-home, fiber-on-the-desktop, storage-area networks and Gigabit Ethernet.

Vichel Located in Seoul and dating back to February 2001, Vichel sells 850 nm VCSEL transceiver modules and is also developing next-generation optical chips. According to

CEO Sang Kyu Kang, the company buys devices from external suppliers, but is in the process of building a chip fabrication line, which will be ready in summer 2002. The company’s development program includes long-wavelength, high-power VCSELs, which are expected to be sampled around the first half of 2003, followed later in the year by an optical IC for high-capacity switching and a tunable VCSEL. Vichel is also working on 1310 nm GaAs-based VCSELs with InGaAsN active layers, and has developed a new epitaxy method that allows fine control of the nitrogen concentration. The company has designed and patented a chip structure that allows the single transverse mode to be maintained regardless of the power or the surface-emitting area, unlike conventional devices or those using external cavities. The company’s variable-wavelength VCSEL is tuned using the electro-optic effect, and will eventually be combined with a switch IC to allow optical wavelength switching. Kang says that Vichel has received investments totaling about \$1 million, most of which has been spent in order to develop mass-pro-



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LG Elite The LG Electronics Institute of Technology (LG Elite) was founded in 1987 and has developed a wide range of optoelectronic devices, including AlGaAs-based lasers for CD and MiniDisc players and AlInGaP-based red lasers, which are used in LG's DVD players. InGaAsP/InP telecom lasers developed at LG Elite are being commercialized by LG Cable spin-off Neoptek (see below). The research center has also developed blue, green and white GaN-based LEDs, including devices grown on GaN substrates. Recently, LG Elite produced a violet laser operating at 403 nm at room temperature, with a threshold current of 80 mA at an operating voltage of 5 V. The device features a 700-pair n-GaN/undoped GaN superlattice above the sapphire substrate. The lab is also developing high-power GaAs-based lasers including 15 W arrays. On the RF side, LG Elite designs and manufactures GaAs HBT MMICs on a 4 inch line and is developing 6–18 GHz switch and power modules, and AlGaIn/GaN HFETs for base-station power amplifiers.

LG Innotek The optical device business of LG Innotek, founded in 1995, fabricates a range of laser diodes and LEDs in a 18,000 sq. ft class 100 cleanroom. Automated packaging takes place in a 36,000 sq. ft facility. Lasers with wavelengths in the 635–810 nm range, such as 150 mW, 808 nm devices for diode-pumped solid-state lasers, are grown by MOCVD. The company also manufactures blue surface-mount LEDs, and H B Shin, general manager of the optical devices sales division, reports a tremendous growth in demand for these products from the Korean mobile-phone market.

Neoptek A spin-off from LG Cable based in Kyungki-di, Neoptek is a new company with a long history. Basic research on the Neoptek range of transmitter, receiver and transceiver products began in 1980 within the LG Group. In order to serve the fast-growing fiber-optic market, Neoptek was established in 2001, and now has over 80 employees. LG Group companies retain around 60% of the equity in Neoptek, the other 40% being held by management

and employees. The company expects overseas investment in the near future. Neoptek concentrates on the development of components for subscriber-level metro, access and datacom systems. The company develops and produces both chips and passive components, and packages these into modules. Products include 1310 and 1550 nm InGaAsP MQW diodes with Fabry-Perot or DFB structures, and 2.5 Gbit/s DFB lasers and tunable lasers are also being developed.

Part of Neoptek's focus has been to grow its export business; until last year Neoptek's predecessor had sold only into Korea. As most Korean and Chinese telecom companies use only 5 V systems, Neoptek has invested in the development of 3.3 V components for export, and has also concentrated on quality assurance. The company has ramped up production from under 10,000 units per month in January 2001 to nearly 70,000 units per month by December 2001. This represents an annual sales volume of around \$30 million, now mostly for export.

duction capabilities for optical transceiver modules, and the company is seeking about \$10 million from overseas.

XL Photonics Established in November 1999, XL Photonics produces transmitter and receiver modules for WDM and SONET/SDH applications, including 2.5 Gbit/s directly modulated FP or DFB laser modules, and 2.5 Gbit/s *pin* PDs and avalanche PDs. Although the company has the technology for both chip fabrication and module packaging, it does not have its own fab. However, this is about to change, as director of marketing Suk Doo Yoon explains:

“As it is becoming very difficult or almost impossible to procure chips at reasonable prices, we decided to establish our own fab. The building is currently under construction and we have already placed equipment orders.” The fab is scheduled for completion at the end of March 2002. “After going through a test period, we estimate that we will be capable of mass-producing *pin* PD chips in July 2002,” says Yoon. XL Photonics expects to produce 2.5 and 10 Gbit/s APD chips and FP lasers by September of this year, and will probably execute an expansion program in 2003 that will include the introduction of DFB lasers. ●

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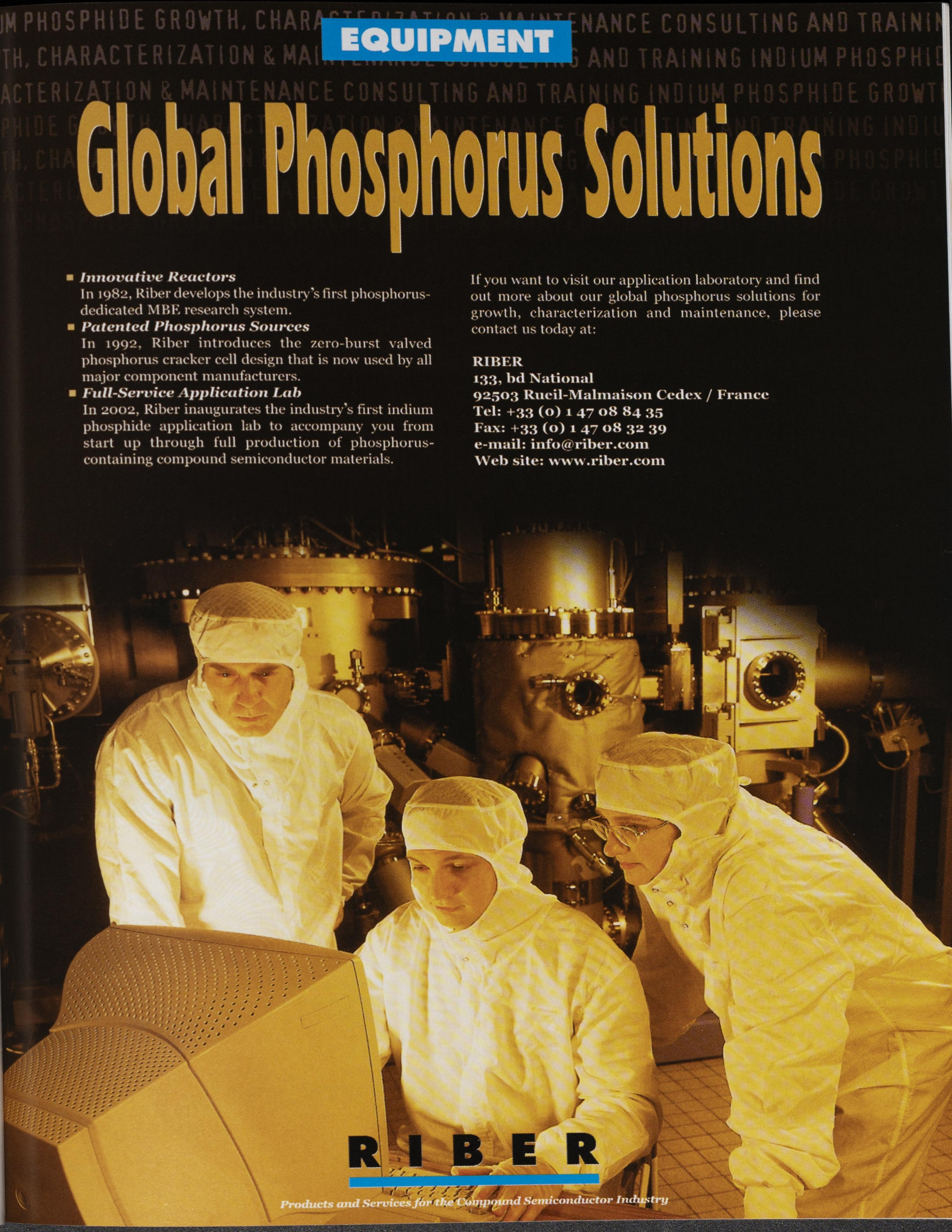
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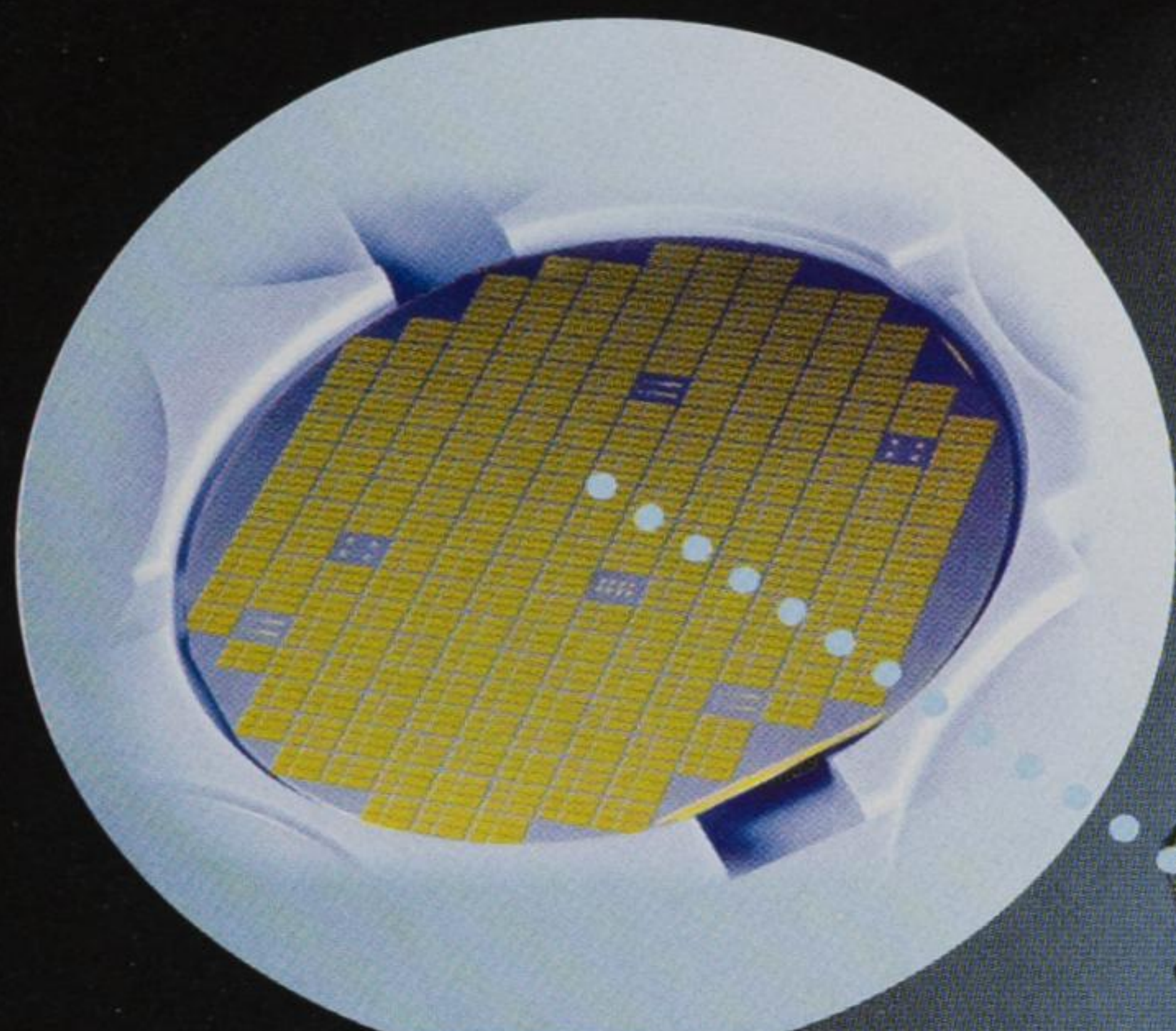


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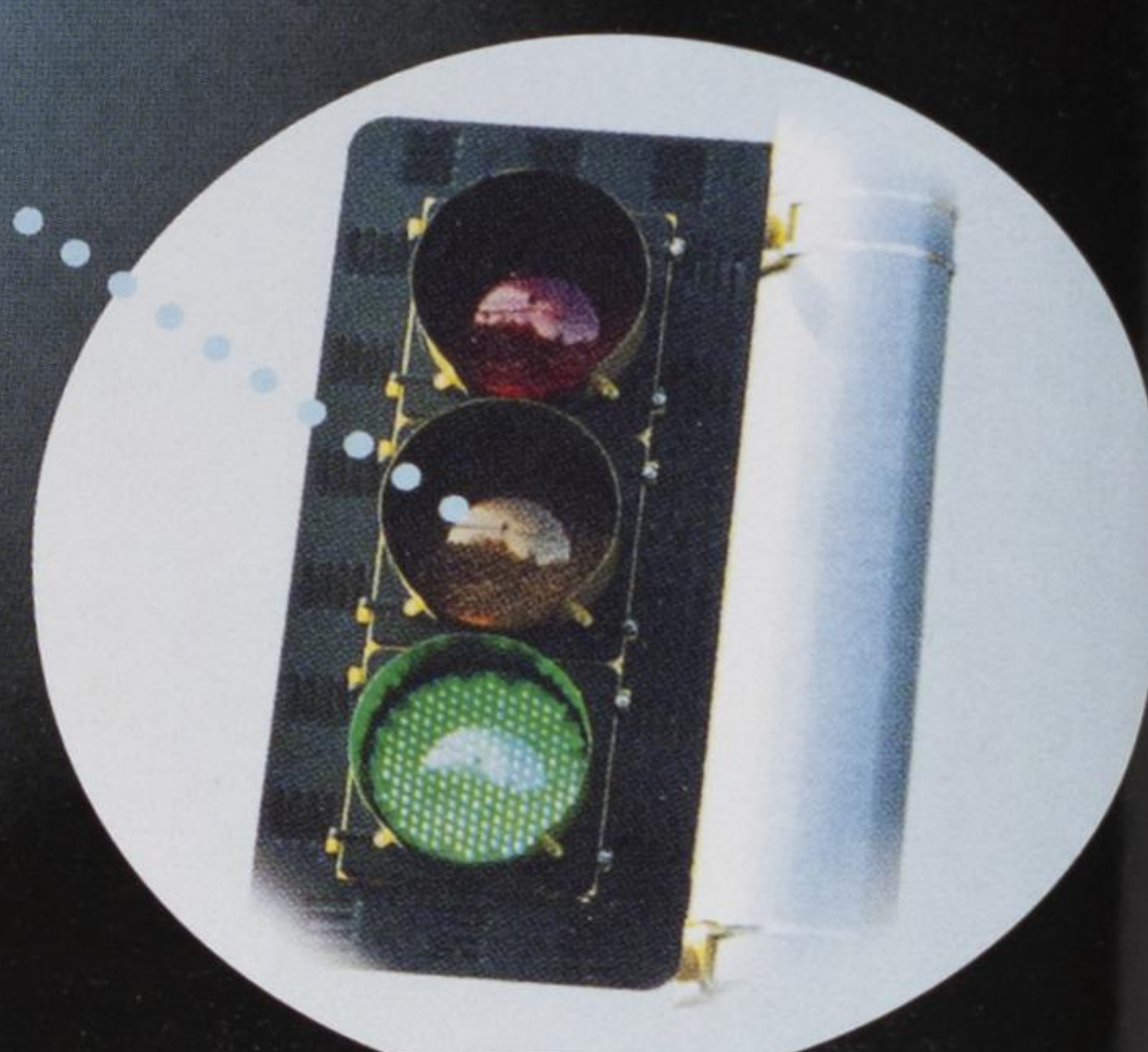
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HIGH-BRIGHTNESS LEDs

High-brightness LED market to grow after flat year in 2001

Driven by automotive and backlighting applications, the market for high-brightness LEDs looks set to grow by about 10% in 2002. **Richard Dixon** reports from the Strategies in Light conference.

As with most industries in the technology sector, high-brightness (HB) LEDs were not spared last year's economic downturn. However, the HB-LED industry fared much better than either the fiber-optics or microelectronics sectors, experiencing a flat year in 2001 that saw total revenues of around \$1.2 billion (figure 1). This compares with a market growth rate of around 46% between 1999 and 2000. Bob Steele of Strategies Unlimited predicts that 2002 will see a modest recovery for these devices, and a return to "normal" trends by 2003. Steele made the comments during his market overview of the high-brightness LED industry, which opened the recent Strategies in Light 2002 conference.

Better times ahead

Despite a flat 2001, Steele estimates that the HB-LED market will grow by around 15% in 2002, and by 20–30% thereafter. This is a healthy growth rate, although it is well below the CAGR of 47% for the five years up to 2000. Further ahead, the market is now projected to reach \$3 billion by 2006, which compares with last year's forecast of \$3.25 billion by 2005.

LED unit sales increased throughout 2001, but this was offset by a drop in average selling prices, resulting in zero revenue growth. While recession woes were the root cause for the lack of growth, the declining value of the Japanese yen (down by around 11%) had an additional effect to the tune of approximately \$80 million in lost revenue, because Japan supplies over half the HB-LEDs worldwide.

Steele notes that providing the economy picks up, recovery is assured because the factors that underpinned the excellent growth in pre-2001 LED markets remain essentially unchanged. "The market was flat in 2001, but that was really in the midst of a high-tech downturn that took semiconductors down 31% and components for use in fiber-optics down by as much as 45%," says Steele. "In this light, flat was a good performance, and to sustain

High-brightness LED market

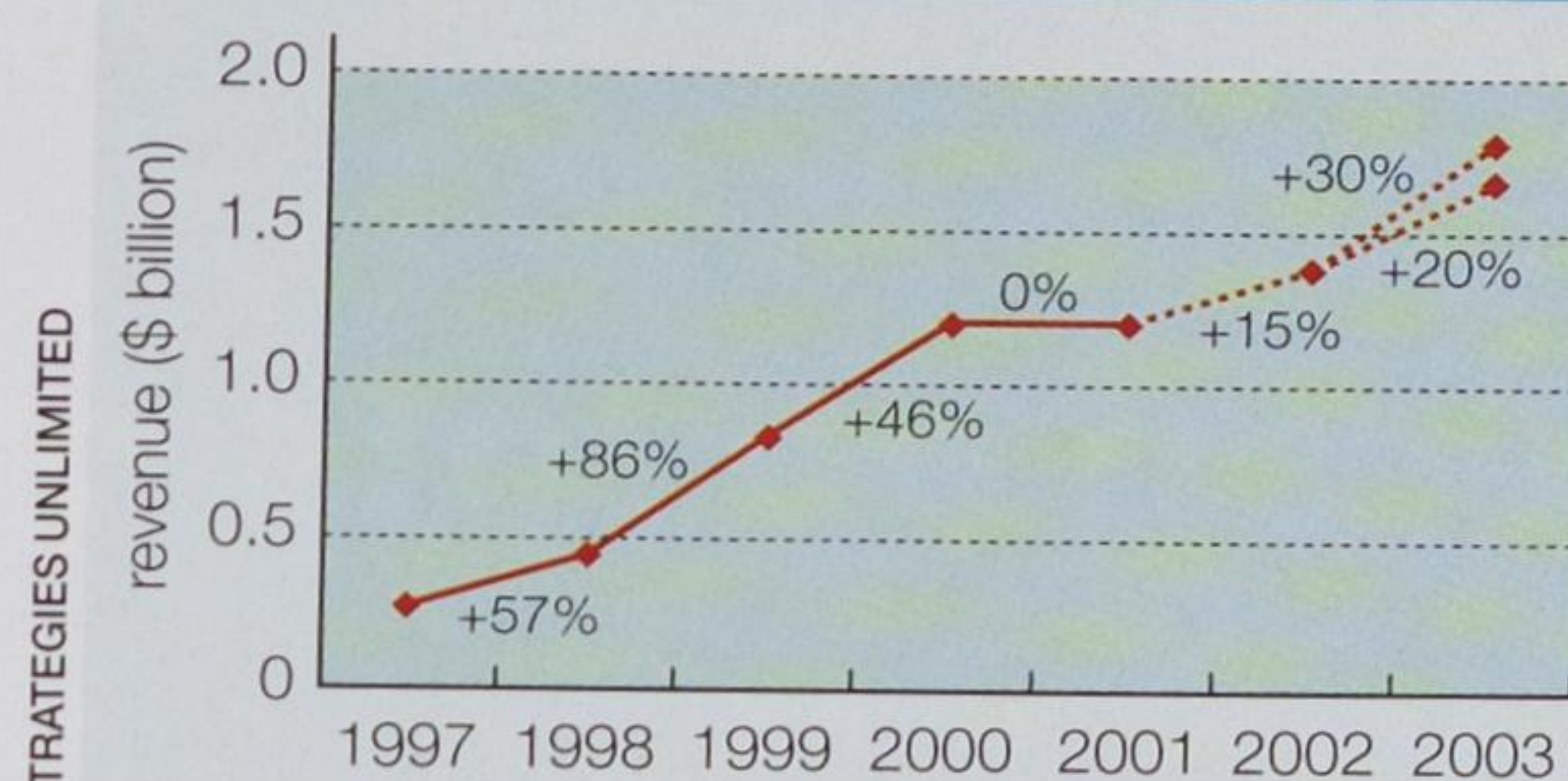


Fig. 1. After five years of rapid growth, the market for HB-LEDs was flat in 2001. Recovery is expected during 2002, with a growth rate of 20–30% expected in 2003.

HB-LEDs in 2001 by application

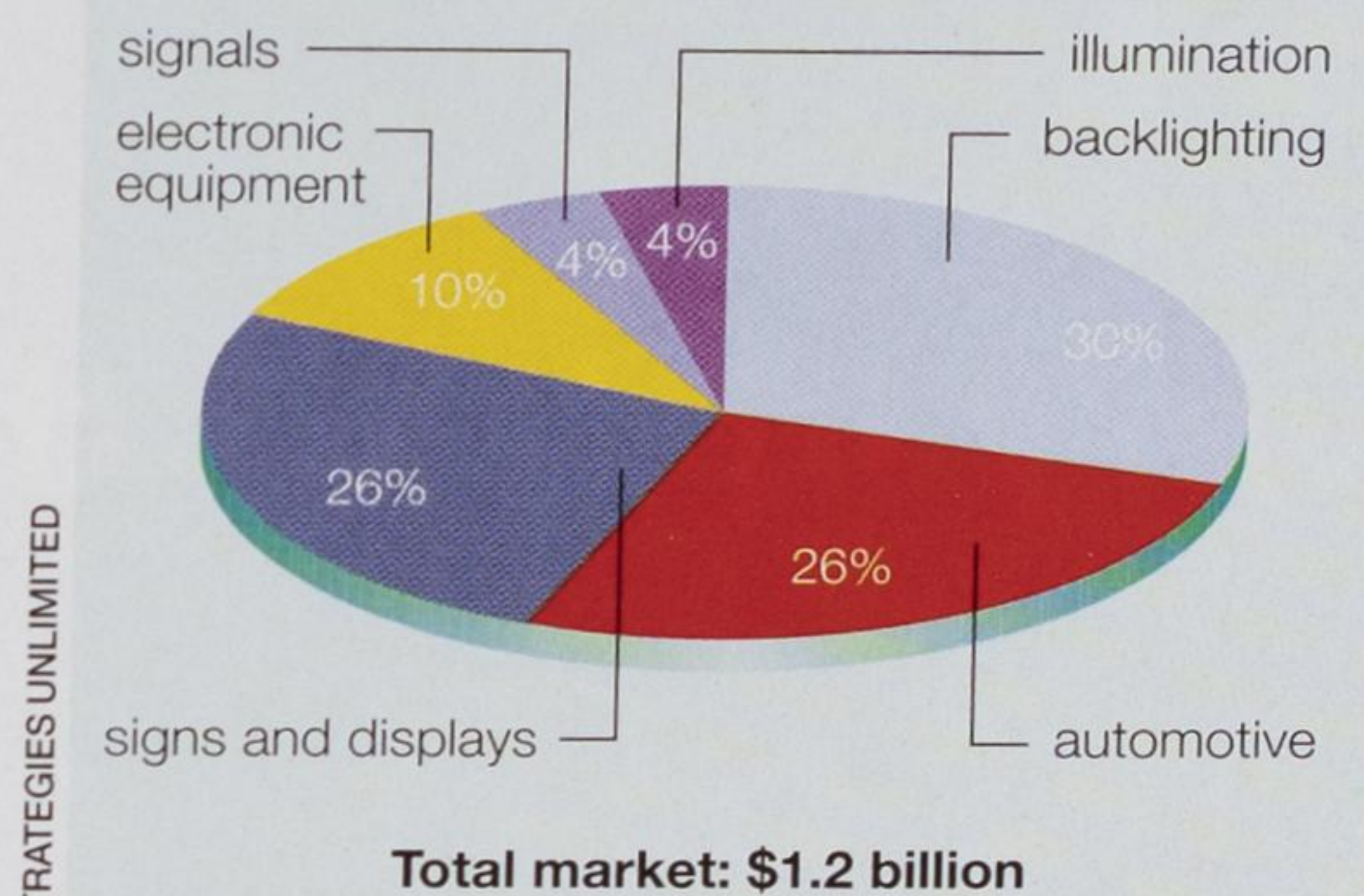


Fig. 2. LEDs for backlights, traffic signals and automotive applications made considerable market gains in 2001, while electronic equipment indicators and full-color displays suffered from the bad economic climate.

the market overall was a very positive result."

"What I observed is that none of the fundamental driving forces for growth in HB-LEDs have changed at all," continues Steele. "Last year we had a situation where some areas just slowed down." For example, sales of cell phones declined, but sales of white LEDs for use in cell-phone display backlights increased their penetration into this application, and so unit volumes increased.

Steele's report on the HB-LED market was

based on a forecast for InGaN-, AlGaAs- and AlInGaP-based devices supplied as standard packaged lamps, surface-mount LEDs or in high-flux packaged devices. For the analysis, Steele chose devices with typical outputs exceeding several hundred mcd, which is much higher than required for standard indicator applications.

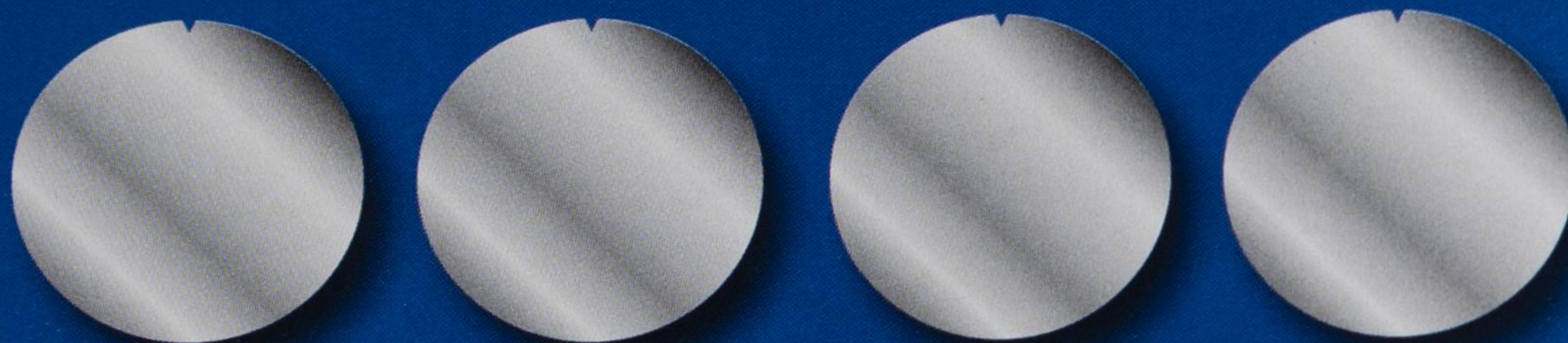
Winners and losers

HB-LEDs continue to penetrate existing markets and find their way into new applications. Major market sectors include signs that employ monochromatic displays for moving messages and highway information; full-color displays for large video screens; LEDs for interior and exterior lighting applications in cars, trucks and buses; and traffic signals. Other areas are backlights for LCD displays in mobile phones, PDAs and digital cameras, as well as illumination applications such as machine vision and architectural and specialty lighting. The electronic equipment sector includes indicator lamps in industrial and consumer items, such as Sony's PlayStation 2 which uses blue LEDs.

Overall, there was a large variation in the growth rates for these different applications last year. Some areas continued to grow nicely, says Steele, particularly traffic signals and interior automotive lighting (figure 2). Traffic signals grew the fastest at a rate in excess of 100%, although this market is still only 4% of the total. HB-LEDs continue to penetrate automotive applications, a market which grew by 18% year-on-year and now accounts for 26% of the total. The biggest market for HB-LEDs is now backlighting, which grew 11% compared with 2000 and now makes up 30% of the total, up from a 27% share in 2000.

Automotive Automotive applications are already one of the largest markets for HB-LEDs (approximately \$310 million in 2001), and there is still considerable potential for

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growth. Compared with conventional incandescent lighting, LEDs allow new styling options, reduced assembly and rework costs, and offer high reliability. Generally the market can be split into interior and exterior applications.

One of the first HB-LED applications was in exterior center high-mounted stop lamps. Around 40% of the world's cars now feature these lights, which offer greater safety because they are brighter and turn on faster than incandescents. North American car makers lag behind their European competitors, such as VW, BMW, Mercedes and Audi, who have used LEDs in dashboard and interior lighting for some time, and are also beginning to leverage the use of LEDs in their vehicles as a marketing or branding ploy. In the US, some high-end cars such as the Lincoln Navigator use LEDs in the interior, and the entire tail-light section of GM's Cadillac DeVille employs Agilent's transparent-substrate AlInGaP LEDs.

The main LED suppliers for European cars are Osram Opto Semiconductors and Cree. In the interior, Steele says there will be continued penetration in Europe's already well established market, and large growth in Japan, albeit from a small market base. This market now represents \$240 million and has been growing at 64% per year since 1997. By comparison, the automotive exterior LED market is smaller at around \$85 million, and grew at 25% per year in the last five years.

Traffic signals The number of LED traffic signals in use worldwide, which was under 400,000 units in 2000, increased dramatically during 2001 to around 1 million units. This equates to 4% of the total traffic-signal market. Red and green signals are now seen in approximately equal numbers, while yellow traffic signals using AlInGaP LEDs are more rare. This is because the time period that the ball is on is much less than 50%, and the pay-back time for replacing incandescent bulbs with more expensive LEDs is therefore much longer. The growth is being driven by rapid pay backs in energy consumption and maintenance costs, and this market is mainly in North America at present.

Mobile-phone displays Full-color displays in mobile-phone handsets require white LED backlights. The fraction of phones with this type of display almost doubled in 2001, rising from 6.9% to 12.6% during a year in which overall handset shipments fell slightly (figure 3). Most of this market is currently in Japan. Handset makers offering color displays in-

Mobile-phone handset displays

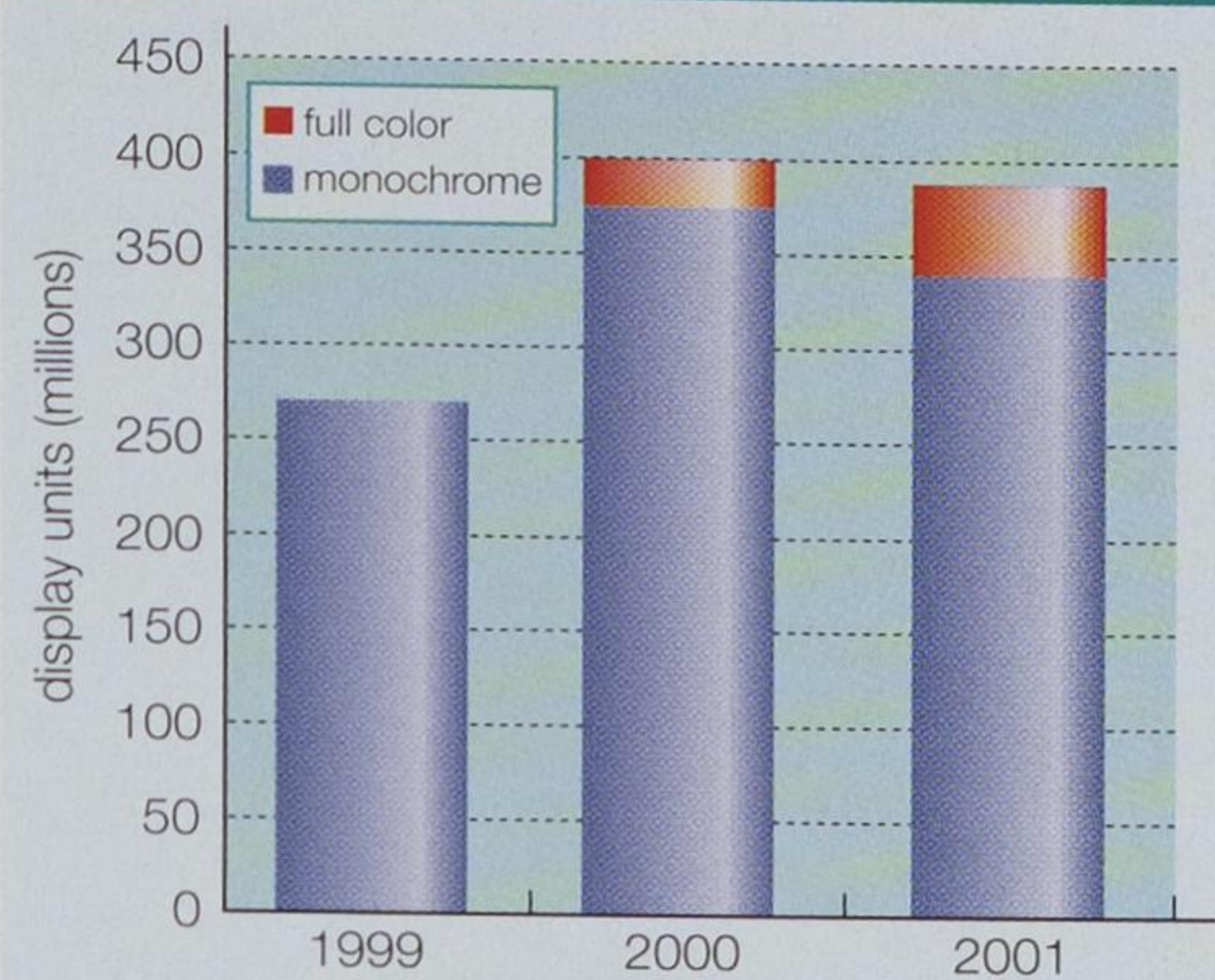


Fig. 3. Full-color displays, requiring white LED backlights, doubled their penetration into the handset display market to 12.6% last year, mainly in Japanese phones.

HB-LEDs in 2001 by device type

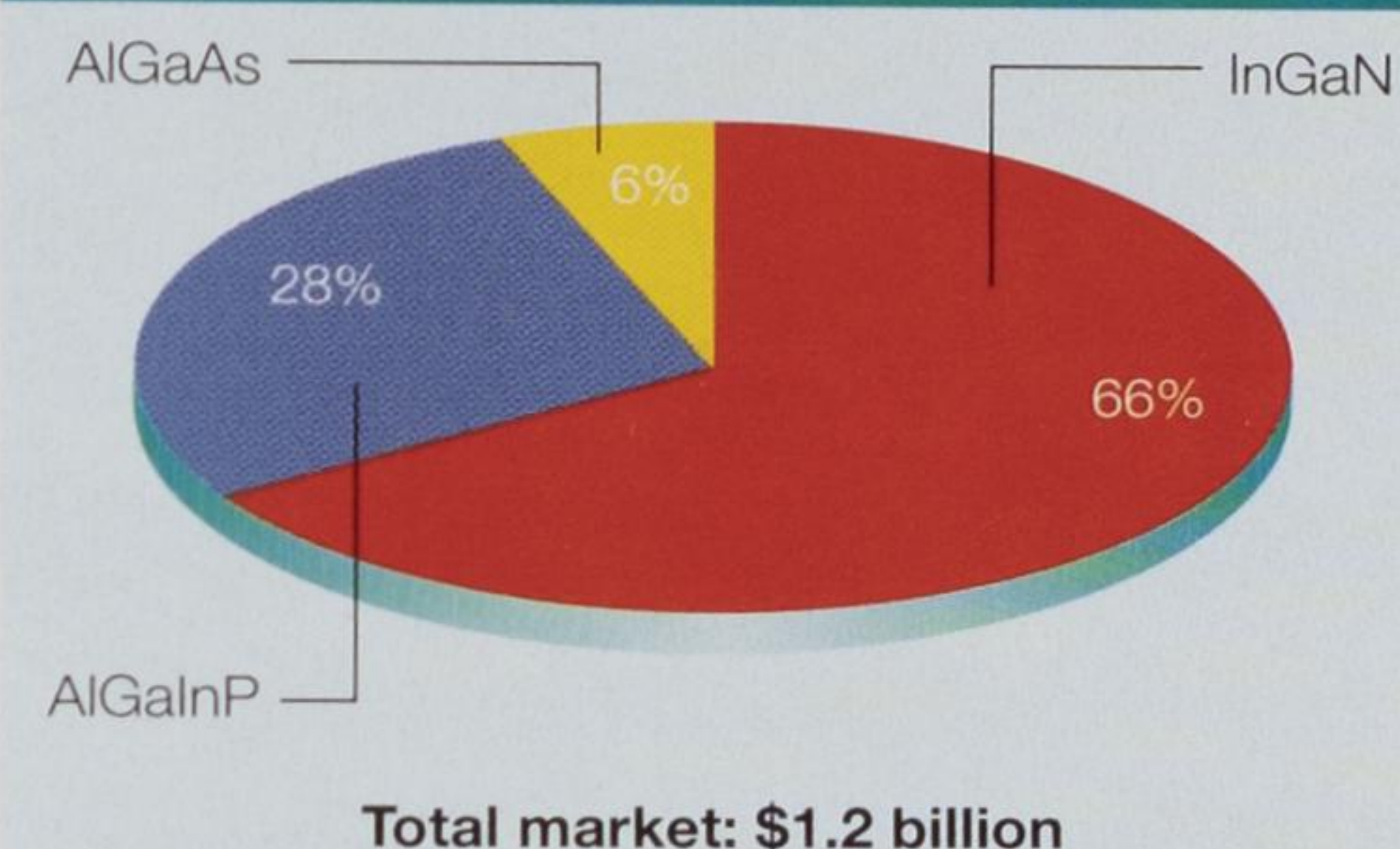


Fig. 4. InGaN LEDs dominated the market in 2001 and experienced a 10% growth in revenues, whereas AlGaAs revenues fell.

clude Sanyo in the US, while Nokia expected to introduce its new 7650 color-screen model in Europe in the second quarter of 2002. New applications are also likely to emerge for color screens in PDAs and digital cameras.

Displays and electronic equipment Some markets, such as outdoor displays and electronic equipment, slowed markedly in 2001, largely because of the weak economy. Displays in particular were affected by the reduction in advertising revenue resulting from the depressed economy in the US. The outdoor-displays market, which is dominated by sales to sports venues, was down 19% from \$250 million to just over \$200 million. The electronic equipment sector, which includes LED indicator lights, dropped by 23%, largely due to the overall weakness in sales of such equipment. However, monochromatic signs used in transportation and messaging grew last year, largely buoyed by public funding schemes, says Steele.

"For large full-color signs, which are very

capital intensive, there just wasn't the rate of spending and investment in the economy that would support those applications," says Steele. "In terms of square meters employed, the market was about flat as far as we could tell, but the LED value that went into the displays was down due to falling prices. This did not reflect any perception of the quality or performance of LEDs for these applications, rather that the end markets were not being supported by the economy."

Average selling prices and materials

There was also a large variation in the market growth for the different types of HB-LEDs, i.e. AlGaAs (red), AlInGaP (yellow-red) and InGaN (blue-green and white). "The number of units were up overall, but the market stayed flat due to falling prices, which fell faster last year than in previous years," says Steele. "Part of that was due to the fact that when the market slows, supply and demand takes over and companies tend to cut prices. Thus the revenues were lower despite higher unit penetration in many cases."

"As an example, GaN LEDs have suffered gradual annual price decreases of only 10% in recent years, but were 20% cheaper than previous years in 2001," says Steele. "Part of that was due to the weak yen, and the fact that a huge fraction of GaN LEDs comes from Japan, which naturally has an impact on prices. However, there are other factors, such as Cree continuing to lower the costs of its GaN chips."

Sales of InGaN LEDs accounted for about two-thirds of the total market, or \$800 million, in 2001 (figure 4). In the last five years, shipments of InGaN LEDs have increased by 14 times, while revenues have grown by a factor of five. Growth was more modest in 2001, with 10% revenue growth in 2001 compared with 45% in 2000.

The market for AlInGaP LEDs in 2001 was around \$340 million, while AlGaAs LEDs lost market share and had revenues of around \$75 million. "What generally happens is that for a given product the prices are lower from year to year," says Steele. "For the new products coming in, you might pay the price that corresponds to the older product which has lower performance. Therefore, each year you get more lumens for your dollar."

Strategies in Light 2002 (February 7-8) was organized by Strategies Unlimited, a market analysis company based in Mountain View, CA. Tel. +1 650 941 3438, Web www.strategies-u.com.

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VCSELS continue to push back technological barriers

VCSELS are still developing quickly despite the challenges of manufacturing large arrays and the reliability of the materials used in long-wavelength lasers for optical networking, as **Richard Dixon** discovered at the recent Photonics West conference in San Jose, California.

The large number of presentations that made up the VCSEL sessions held during this year's Photonics West event (January 20–25) testified to the continued high interest in 850 nm lasers for short-reach (i.e. less than 500 m) communications links.

Papers on 1310 and 1550 nm VCSELS also generated great interest. Long-wavelength devices are eagerly anticipated as cost-effective replacement sources for edge emitters. These devices are slated for 10–40 km optical links in high-growth areas at the edge of the network, including metro access and enterprise communications.

Manufacturing

In his invited talk, Honeywell's Jim Tatum suggested doing away with proprietary packaging in favor of standardized packages. This should enable VCSEL makers to move on to the next step of automated assembly and manufacturing. The standardization of packaging will enable the vendors of automated manufacturing tools to design products specifically for VCSEL producers if the market is large enough. Currently, each manufacturer has its own package, and the number of variations may be slowing market development.

Tatum also considered replacements for the traditional TO-46 can, which still features leads that can reflect power during 2.5 GHz operation. Controlled-impedance ceramic packages could be the answer owing to their essentially flat impedance response up to 12 GHz, which would be adequate for 10 Gbit/s applications. Tatum said he would also like to see an industry consensus on a 10 Gbit/s integrated VCSEL/TIA/pin photo-detector package.

Flip-chip arrays

B Schneider of ULM Photonics stressed the importance of flip-chip bonding to large-scale VCSEL array manufacturing (see figure 1). Flip-chip processing is seen as vital to the

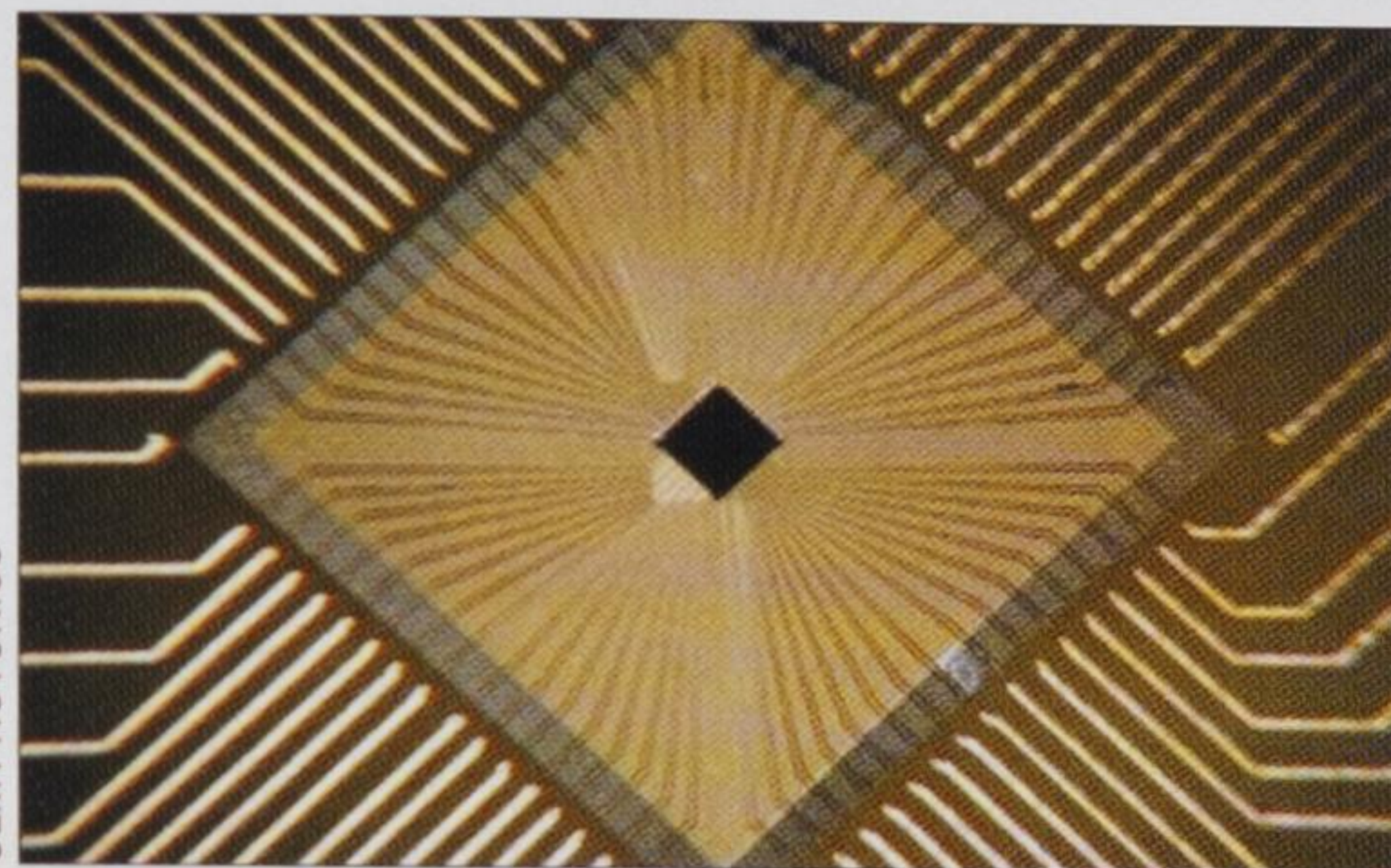


Fig. 1. ULM Photonics' 8 × 8 VCSEL array is shown on a sub-mount. The array uses flip-chip bonding to attach 10 Gbit/s devices for an aggregate data rate of 640 Gbit/s and total power dissipation of less than 1 W.

manufacture of large arrays: it simplifies assembly and test, and eliminates complicated wire-bonding and bond-pad schemes. ULM's 850 nm VCSELS employ a coplanar waveguide structure that allows all the contacts to be placed on the top, while bottom emission requires removal of the GaAs substrate.

The company's devices exhibit a series resistance of 70 Ω at 4 mA, and provide an output power of 2 mW. The threshold current is typically 1 mA, and even after substrate removal thermal resistance is only 2.6 K/mW.

Large-scale arrays undergoing accelerated aging at 160 °C and 7 mA drive current typically fail at around 1350 hours, which extrapolates to more than 10 million hours at room temperature. Schneider concluded by saying that singlemode operation at 10 Gbit/s is still desirable, and that processing and reliability issues still remain the main challenges for VCSELS to overcome.

Long-wavelength VCSELS

Long-wavelength VCSELS have developed more slowly than their shorter-wavelength 850 nm cousins as a result of fundamental materials issues. Mirror structures with high reflectivity can be grown on GaAs, but 1300 nm active regions are difficult to grow

in this material system. However, good InP-based long-wavelength active regions can be grown, but at the expense of good mirrors.

One way around this is to use wafer bonding to fuse the different materials that give the desired emission wavelength and high-reflectivity mirrors. Alternatively, quaternary alloys such as InGaAsN can be used in the active region to overcome the problems of lattice matching GaAs-based mirrors to InP.

J Klem of Sandia National Laboratories discussed advances in 1300 nm VCSELS based on InGaAsN with nitrogen contents up to 1.5%. Sandia's devices are grown by MBE on 3 inch GaAs substrates. Several new oxide-confined monolithic VCSEL designs were also described. These incorporated compositionally graded mirror interfaces and doping profiles, which reduce the operating voltage to 4.3 V. Adding nitrogen allows the indium content to be increased in the InGaAs QWs, although too much indium causes strain relaxation and limits the number of QWs that can be introduced. Sandia has thus opted for 34% indium in InGaAsN wells that are 6 nm thick.

One scheme discussed employed a monolithically grown GaAs tunnel junction and two n-type DBRs that are designed to reduce free-carrier absorption losses. This led to output powers of 2 mW at room temperature for large-aperture devices. A second design with a smaller aperture operated at a much lower voltage of 2.7 V. This device has a threshold current of 1.1 mA and demonstrated 0.68 mW of CW output power. The slope efficiency was reported to be 0.24 W/A.

T Miyamoto of the Tokyo Institute of Technology also discussed the fabrication of GaInAsN/GaAs VCSELS for telecom applications. Miyamoto described a process that involved growing the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ /GaAs DBRs (35 pairs on the bottom and 24 on top) by MOCVD, and depositing the three QWs separating the mirrors using CBE. Apertures of $9 \mu\text{m}^2$ were formed using oxi-

dation at 450 °C and devices exhibited 1 mW in CW mode at a wavelength of 1185 nm. The threshold current was 2.6 kA/cm², and the maximum pulsed power output was 4 mW for a slope efficiency of 0.22 W/A.

Miyamoto's colleague T Kondo described 1160 nm VCSELs based on an active region with three strained In_{0.36}Ga_{0.64}As quantum wells. Using an aperture size of 9 μm², these devices achieved a threshold current of 3 mA and current density of 3 kA/cm². The output power was 2 mW and slope efficiency was 0.3 W/A at 25 °C. The dependence of current on temperature was nearly constant up to 70 °C, which led Kondo to suggest that the devices could be used as uncooled sources in LAN applications.

Cielo ships a range of long-wavelength VCSELs that can be driven at up to 10 Gbit/s in eight- and twelve-channel arrays, while its singlemode devices give up to 1 mW output power. Lance Thomson gave an update on Cielo's latest 1300 nm device, which now offers 1 mW at temperatures up to 90 °C with a wavelength drift of 0.08 nm/°C. VCSELs operating at a current density of 35 kA/cm² and at 90 °C have functioned reliably for 1550 hours, he added.

Emcore's long-wavelength VCSELs

Hong Hou gave an overview of Emcore's 1300 nm singlemode VCSEL, which is intended for telecom applications. The device features an In_{0.34}Ga_{0.66}As_{0.99}N_{0.01} QW active region surrounded by high-index GaAs/AlAs DBR mirrors (39 pairs on the bottom and 25 pairs on top).

A device with a wavelength of 1275 nm has been designed with an 8 μm aperture, and provides a threshold current of 3 kA/cm². The singlemode output is 0.4 mW, and more than 1 mW in multimode operation. The company's target is 0.7 mW for 2 km optical links.

Hou explained that higher-power singlemode devices still remain a major challenge, and that currently only around 60% of the optical power is coupled into a singlemode fiber with optics. In addition, the series resistance in the long-wavelength emitter needs to be reduced from its current level of 100 Ω to 30 Ω demonstrated by the company's 850 nm products. Emcore is also working to remove the wavelength's dependence on temperature.

Developments in 10 Gbit/s VCSELs

Swiss VCSEL specialist Avalon Photonics is manufacturing singlemode VCSELs for absorption spectroscopy applications, and



Fig. 2. An optical micrograph showing part of UEC's VCSEL array. Two lasers with 10 μm apertures that have been formed by oxide confinement are visible. The VCSELs are spaced at 250 μm intervals.

developing 1 × 4 and 1 × 12 arrays using multimode fiber at rates of up to 3.125 Gbit/s (see *Compound Semiconductor* May 2001, p70).

John Humphries described Avalon's new 10 Gbit/s devices, which consist of small (4 μm) apertures designed to lower parasitic resistance and reduce power consumption at these high modulation rates. Humphries noted that reducing the dimensions of the oxide region could lower the series resistance from 100 Ω to around 40 Ω.

Avalon is targeting 10 Gigabit Ethernet applications, in addition to cable television and remote antenna addressing for mobile-phone systems. The last two applications use analog modulation schemes that require low noise, high linearity and fast modulation, and may benefit from Avalon's VCSELs, which feature a low relative intensity noise (RIN) of -130 dB/Hz at 10 GHz.

Emcore's Hou gave a paper on the company's VCSEL arrays, which together with single devices constitute a capacity of 1.5 million VCSELs per month. The company's roadmap includes 4 × 8 and 4 × 12 arrays, in addition to 32 × 32 arrays at 2.5 and 3.3 Gbit/s. VCSELs capable of 10 Gbit/s performance are also under development. Their mesa structure reduces series resistance, which is currently 60 Ω. The power output is 1 mW. Initial results of accelerated reliability studies (at 70 °C and 6 mA) for 10 Gbit/s 1 × 12 arrays led to lifetimes of 4 × 10⁵ hours.

S Chiou reviewed United Epitaxy Company's (UEC's) recent VCSEL activities. Development began in October 2000, and GaAs-based VCSELs that operate in the 780–850 nm range were first announced last June (see *Compound Semiconductor* June 2001, p15). These devices are available as epi-wafers on 3 inch GaAs substrates, or as chips. Red 650 nm devices are also being developed.

UEC now has a third facility at an industry park in Tainan, Taiwan and has a total of 30 MOCVD reactors, including five dedicated to nitride-based materials. By June this year, the company plans to offer 10 Gbit/s 850 nm single VCSELs and 4 × 2.5 Gbit/s arrays.

UEC's arrays contain VCSELs with 10 μm apertures placed at 250 μm intervals (figure 2). The measured series resistance is 35 Ω, and the devices deliver 2 mW of multimode output power at 5 mA for a forward voltage of 1.8 V. To date, these devices have operated at 5 mW for 1000 hours at 70 °C. In contrast with the multimode devices, UEC's singlemode 850 nm VCSELs have a relatively high series resistance of 75 Ω and an output of 1.5 mW at 5 mA. The threshold current lies at 1.5 mA and the singlemode suppression ratio is 40 dB.

AXT develops 10 Gbit/s VCSELs

One area of focus at AXT has been singlemode 850 nm VCSELs, which resulted in 3.125 Gbit/s devices last year (see *Compound Semiconductor* June 2001, p13). Other areas of development include all-important steps to automate packaging processes and to improve optical coupling to the fiber.

B Liang described new 10 Gbit/s multimode VCSELs that achieve 3 mW over the 5–75 °C range. AXT is currently sampling these devices, which deliver 12.5 GHz of bandwidth and feature a threshold current of 1.5 mA.

Reliability studies show failure rates (taken at the 0.1% level and using a 10 mA drive current) that extrapolate to lifetimes of 10⁵ hours at 85 °C. The company is also working on large-area (8 × 8) arrays and singlemode devices for encoder and printing applications. Singlemode VCSELs have so far achieved 0.5 mW output at 3 mA, and a 0.25 W/A slope efficiency at 25 °C.

Zarlink looks to large apertures

Zarlink has commercialized 12 × 2.5 Gbit/s arrays and is developing 850 nm selectively oxidized designs for 10 Gbit/s operation. According to Thomas Aggerstam, the modulation characteristics of the company's VCSELs have been substantially improved by moving to InGaAs QWs, which exhibit better gain characteristics than GaAs QWs.

Grown by MOCVD, Zarlink's devices have both contacts on the top of the structure (figure 3), and are grown on semi-insulating GaAs substrates. The Bragg mirrors have alternating quarter-wavelength high- and low-index layers of AlGaAs. A high aluminum content layer above the active region and top

p-DBR is oxidized to form the aperture.

The active region contains a one wavelength thick AlGaAs/InGaAs MQW, and the top DBR is implanted to reduce the capacitance of the thin oxide layer. A benzocyclobutene insulator is also used to reduce parasitic capacitance from the bond pads.

Two aperture sizes were characterized: a 6 μm device achieved 4 mW and a bandwidth of 16.5 GHz, while the larger 12 μm emitter exhibited 18 mW at 13.6 GHz. Tests over 300 m fiber resulted in power losses of 0.5 dB, although no reliability data were available.

Reliability issues

T Lowes of Gore Photonics discussed the long-term testing of the VCSELS used in its commercially available 1.25 Gbit/s nLighten modules. Up to 1500 devices have been analyzed to date. According to Lowes, current-voltage curves stay the same over 9000 hours, although the threshold currents increase as the devices age. Gore's VCSELS exhibit lifetimes that exceed the requirements of most systems, with eventual failure occur-

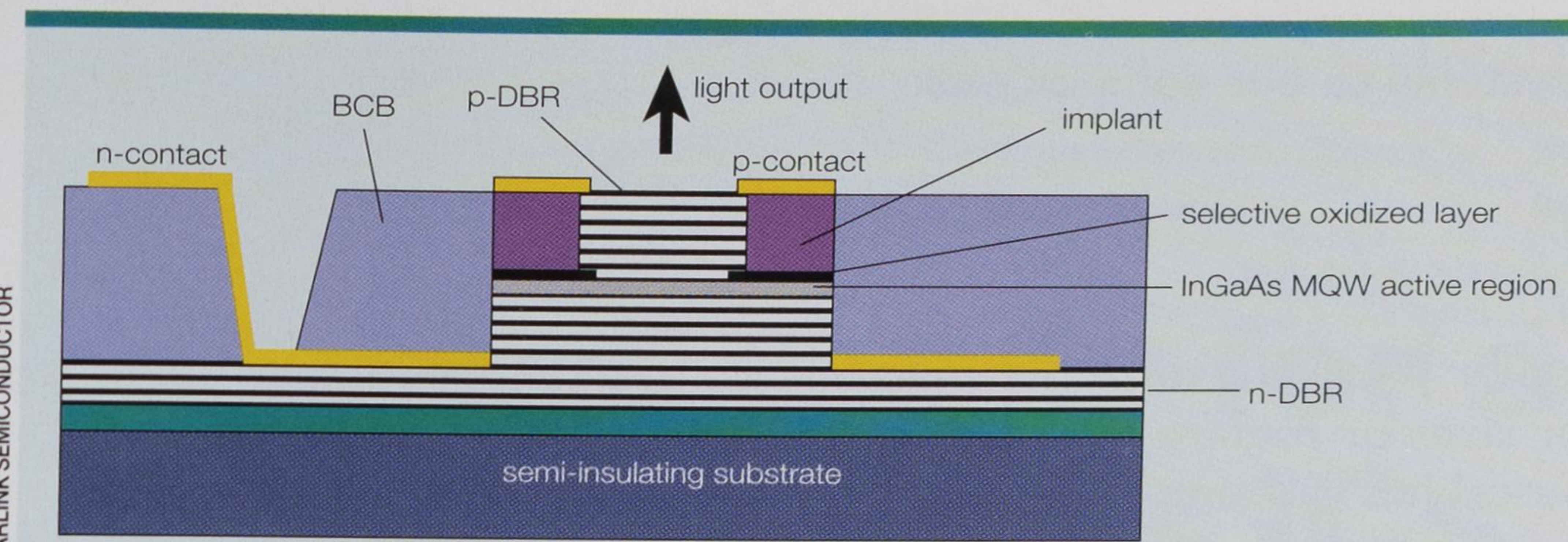


Fig. 3. Schematic showing the VCSEL structure developed by Zarlink. The top DBR has been implanted to reduce the capacitance of the thin oxide layer, while the addition of a benzocyclobutene (BCB) insulator reduces parasitic capacitance from the bond pads.

ring in the mirror regions.

Agilent's R Herrick noted that VCSELS in real situations can be affected by the modules' self-heating. This can increase the device-junction temperature by up to 20 °C. He also questioned the use of mean-time-to-failure (MTTF) data without failure distributions. Actual failure could occur two or three times more quickly than using data for only 1% of

the MTTF specifications would predict.

Herrick gave an example of VCSELS in an air-conditioned room, which can experience a case temperature of ~50 °C, which has led to a lifetime of around 32 years under certain operating conditions. Where rooms or modules lack adequate cooling, case temperatures can soar to 90 °C and cause the MTTF to drop to as low as four years.

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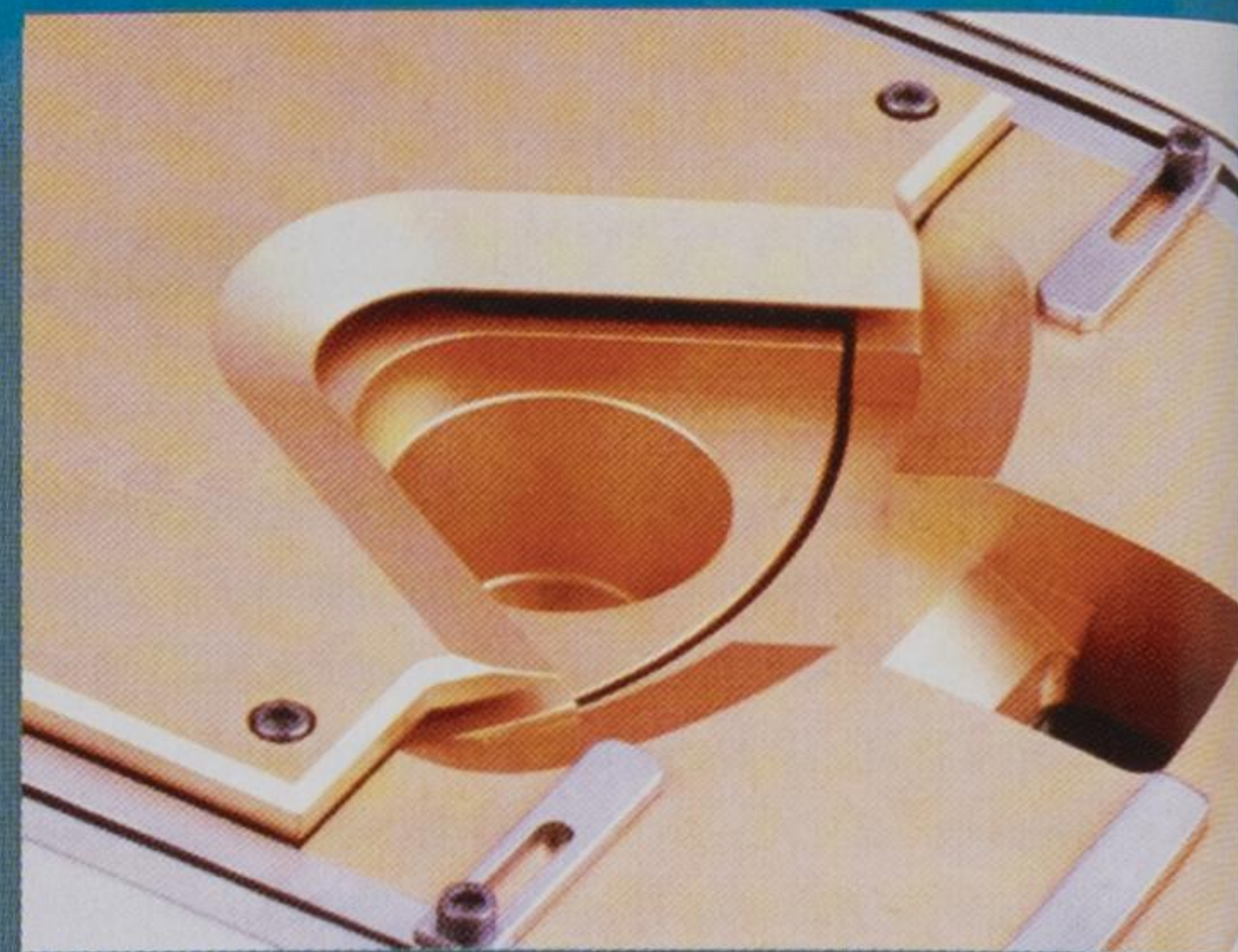
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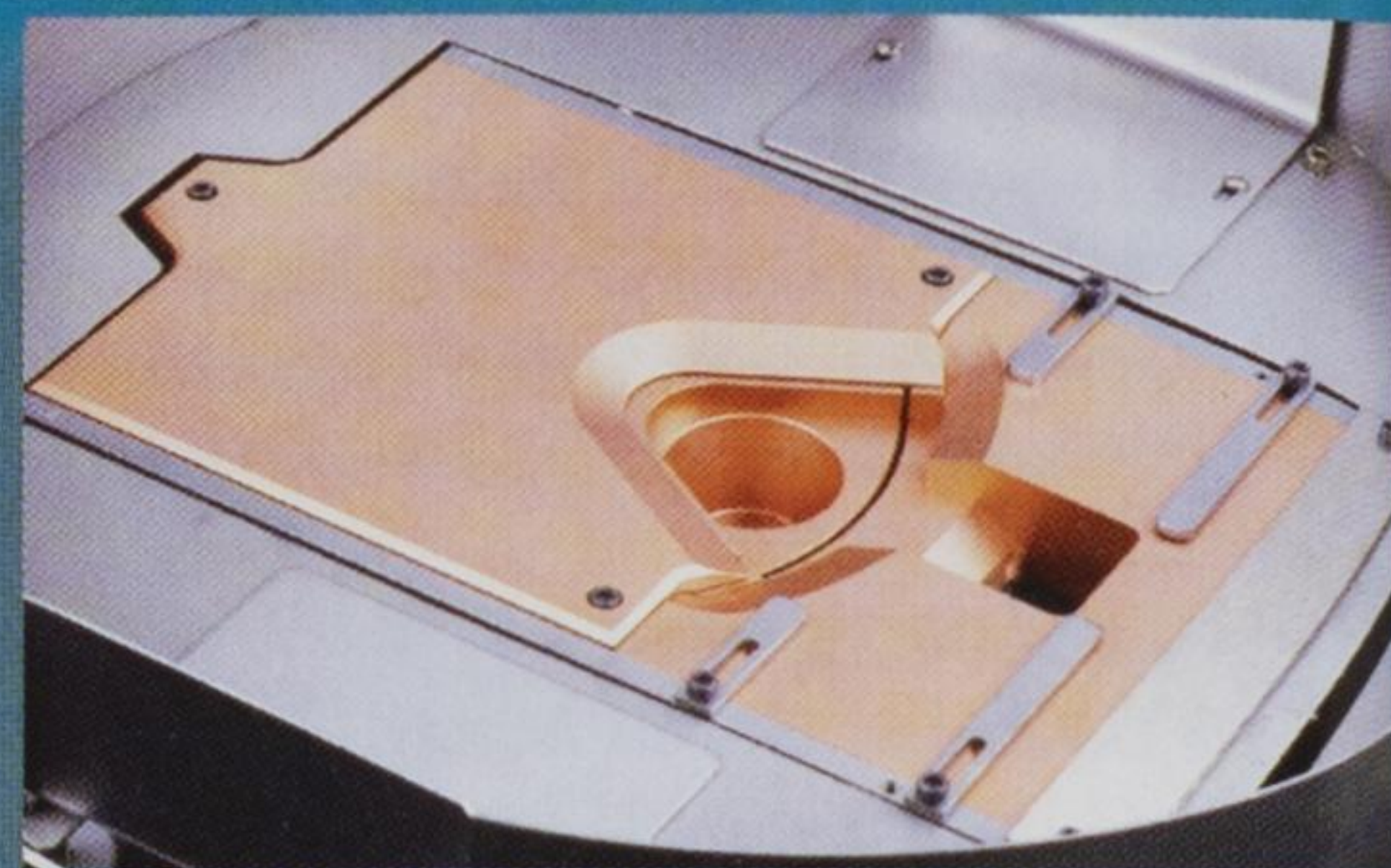
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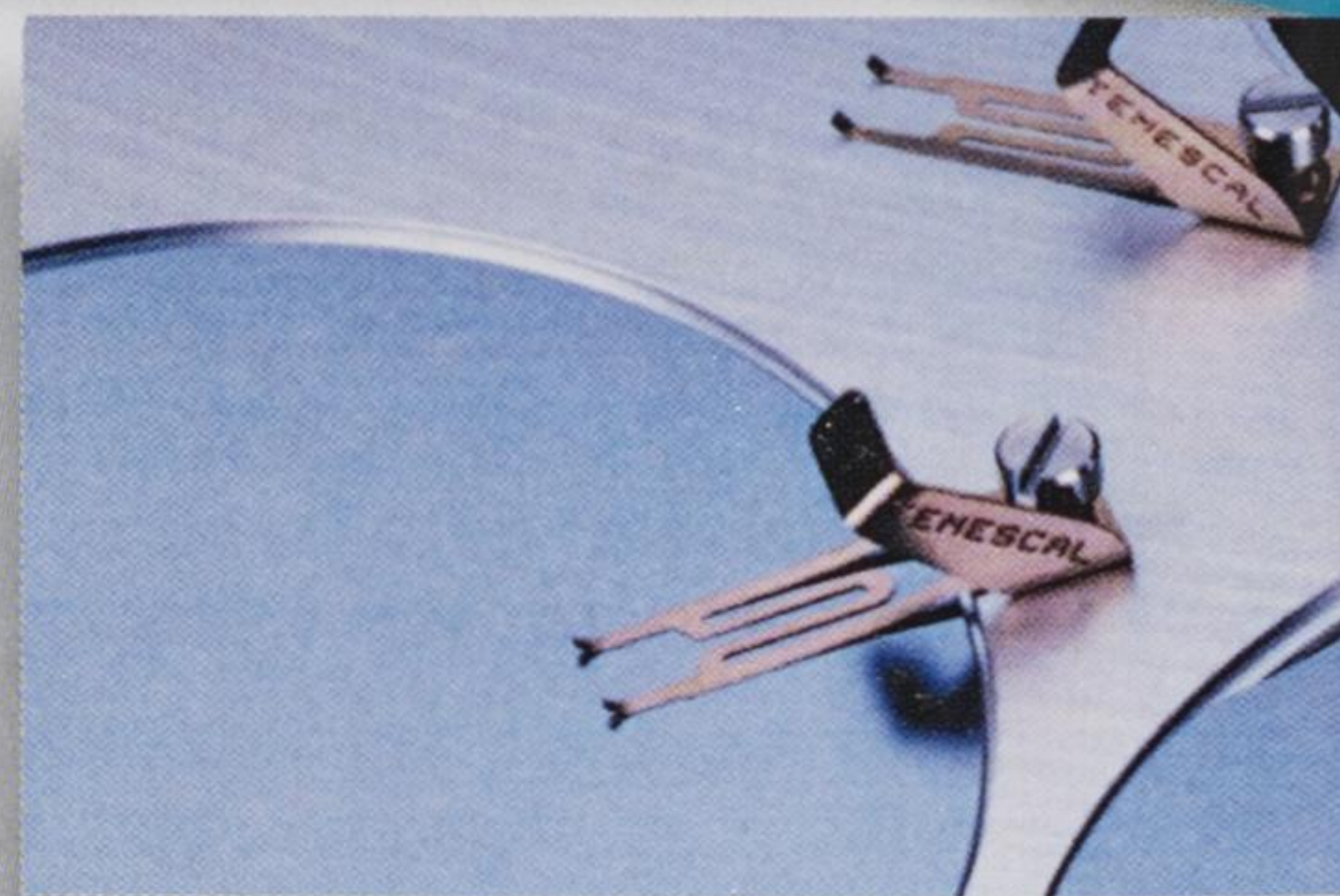
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TriQuint fabs stand ready for a surge in demand for GaAs ICs

TriQuint has virtually completed the conversion of its fab in Oregon to 6 inch wafers, and also has a 6 inch wafer fab in Texas standing ready for the market upswing, writes **Tim Whitaker**.

Two years ago, TriQuint, like many other GaAs manufacturers, was expanding rapidly to meet the explosive market demand for GaAs ICs. In the early part of 2000, the company expanded its wafer fabrication facilities in Hillsboro, Oregon, and began to convert its processes at that site to 6 inch operation. However, industry conditions meant that the conversion did not happen as quickly as had been anticipated.

"We were ready to convert completely to 6 inch wafers by the end of 2001," said Rob Christ, TriQuint's foundry marketing director. "However, like everyone else in the industry we had a lot of 4 inch wafer inventory to burn through."

The conversion to 6 inch manufacturing at Hillsboro is now well advanced. "All our processes except those requiring backside vias are now qualified on 6 inch wafers," continued Christ. "This includes our MESFET, HBT and passives processes."

Another aspect of TriQuint's capacity expansion was revealed in May 2000, when the company announced plans to purchase a DRAM fabrication plant in Richardson, Texas from Micron Technology, a deal that was completed in September of that year (see *Compound Semiconductor* July 2000, p6). Around half of the 48,000 sq. ft facility was set aside for the relocation of TriQuint's Texas operation, which is currently housed in leased space on the Texas Instruments campus in Dallas. The other half of the fab contains 6 inch lines to duplicate the high-volume processes in Hillsboro.

In the company's conference call in early February, president and CEO Steve Sharp stated that utilization at TriQuint's fabs is currently in the 20-30% range. Sharp also stated

Revenue by application

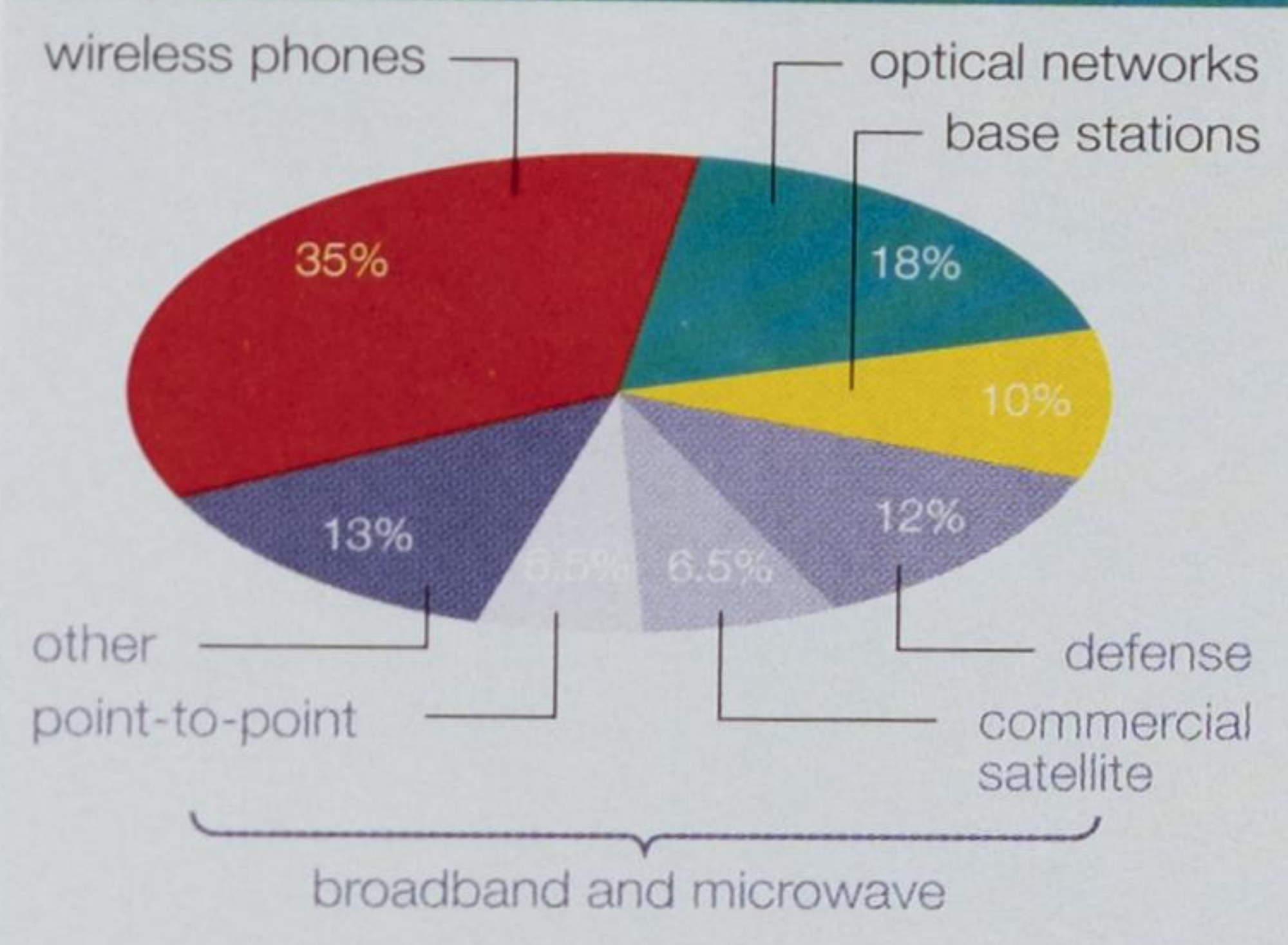


Fig. 1. Wireless communications (handsets, base stations and point-to-point) made up more than half of TriQuint's revenue in 2001, while the defense and commercial satellite business almost doubled in size last year.

"All our processes except those requiring backside vias have now been qualified on 6 inch wafers."

that yields at the Oregon fab reached 90% for the last quarter of 2001 and improved for the fifth year in a row.

TriQuint Texas will complete its move from the TI North building in Dallas by June. The operation will continue to use 4 inch wafers for its high-frequency processes, which include 0.25 and 0.15 μm PHEMT processes, along with VPIN, HFET and research processes. Several of the processes developed in the Texas operation are being moved to 6 inch lines in Hillsboro. "These include our InGaP HBT and 0.5 μm PHEMT processes. These processes are added to our 0.5 μm

MESFET [D and E/D], and our new low-cost four-layer metal [total 9.5 μm gold] passives process," said Christ. He added that TriQuint has investigated InP-based ICs and metamorphic HEMTs at its central research labs in Texas, but has yet to move any of these technologies into production.

Financial results

TriQuint's full-year revenues for 2001 were \$335 million, down 37% from the record \$460.6 million recorded in 2000. During the company's conference call, Sharp gave several reasons for the decline. These included the decline in sales of wireless phones and optical networking products, reduced demand for base stations as phone companies cut back on capital spending, and the overall unfavorable economy. Among the bright spots were that sales of RF filters nearly tripled over 2000, while the commercial satellite and defense business more than doubled from 2000 and now accounts for nearly 20% of the company's revenues (figure 1).

In the wireless-phone business, which accounted for 35% of TriQuint's total revenue in 2001, the fourth quarter of 2001 was essentially flat, with strength in RF SAW filters being offset by a decline in wireless GaAs products. The company's products are in a number of new phones including Nokia's 8265. "2002 should be an exciting year, with most of the major handset OEMs predicting a recovery in handset unit shipments in the second half of the year," said Sharp. "Many new models will be introduced and many will have our products." TriQuint sees modules and GSM as two key areas for development. "Our focus for 2002 will include more modules, an entry in GSM phones and broaden-

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ing our application base within the mobile phone," he explained.

In fiber-optic network applications, TriQuint saw reduced orders from two major customers, Lucent and Nortel. To help alignment with new and different technologies in the optical networking market, the company made a strategic relationship with Network Elements, also located in Oregon. The deal should help both companies with product development, and around 20 TriQuint employees will transfer to Network Elements to work on new products and applications.

TriQuint serves a broad base of companies, and had 34 customers in 2001 that generated more than \$1 million in revenue. Nokia accounted for 15% of sales and was the only customer to account for more than 10% of TriQuint's revenue.

InGaP HBT foundry deal with Philips

In mid-February, TriQuint Semiconductor and Philips Semiconductors formed a strategic partnership that guarantees Philips controlled access to TriQuint's InGaP HBT processing facilities, and provides for joint development of future advanced process technologies. Philips Semiconductors is a leading supplier of power amplifier and front-end modules for the mobile-phone industry, employing a mix of technologies including its own silicon RF processes. Philips believes that TriQuint's InGaP HBT technology will enhance this portfolio to produce the highly linear, highly efficient devices required in RF power amplifiers for high-data-rate 2.5G and 3G systems such as EDGE and UMTS.

"Today's mobile-phone manufacturers increasingly look to modules as a way of simplifying their design and production process and guaranteeing RF performance," said Thierry Laurent, senior VP of mobile communications at Philips Semiconductors. "In a module you have the opportunity to mix a range of technologies in order to offer customers the very best price:performance ratio. We believe that InGaP HBT is the best technology with which to implement components such as the output stage of linear and highly efficient PA modules and front-end modules."

TriQuint will also benefit from the partnership. "Philips' strong RF market presence offers us increased manufacturing volumes starting with our current, second-generation InGaP HBT process," said Bruce Fournier, VP and general manager of foundry services at TriQuint. "Additionally, their success in mobile wireless applications provides market-

Revenue by division

	2000	2001
Texas (MMICs)	18%	30%
Sawtek	35%	28%
Wireless Communication	24%	22%
Foundry Services	13%	12%
Telecom and Computing	10%	8%

Last year TriQuint's Texas (MMICs) division and Sawtek accounted for more than half of the company's total revenue of \$335 million.

"We are getting very clear signals that GaAs-based HBTs are becoming ever more in demand for GSM applications."

driven insight for advanced technology development in the area of InGaP HBT and beyond. With advanced technology and world-class manufacturing efficiency, we expect this partnership to be a very competitive force in the GSM and CDMA markets."

Both partners will sell their own products in the market. Early collaboration has already resulted in a new W-CDMA PA module (Philips' BGY402, sampling now) and PA and front-end modules for GSM phones. TriQuint is currently shipping PA products into the CDMA market and offers this InGaP HBT process, as well as other GaAs processes, to the market through its open foundry.

TriQuint's second-generation HBT process, manufactured on 6 inch wafers at the Hillsboro facility, contains a number of improvements on the previous iteration. "We have added three-layer gold metallization, with 6.5 μm total thickness, for improved heat spreading, resulting in about 15% smaller dice," explained Christ. "We've also added high-value capacitors [1200 pF/mm²] and NiCr resistors."

TriQuint and Philips have been working together for more than five years and the future development of advanced processes will focus on consumer applications for mobile communication markets.

Modules and GSM are key areas

Like other GaAs IC suppliers in the mobile handset market, TriQuint now has a strong focus on modules. In fact, it is now virtually impossible to sell a power amplifier for a mobile phone unless it is in module form.

"Modules are gaining more and more acceptance in the phone market, so you really have to be making modules or selling die to be in this business for the long term," said Christ. Some modules are very simple, with 50 Ω inputs and outputs. However, one of the reasons that TriQuint acquired Sawtek (see *Compound Semiconductor* June 2001, p4) was to be able to integrate more functions such as SAW filters and switches into higher value-added modules.

TriQuint will also be looking to gain more design wins in GSM-based platforms. CDMA accounted for 48% of TriQuint's 2001 sales for mobile phones and base stations, with TDMA at 36% and GSM at only 9% of the total. "While TriQuint has had some involvement with GSM power amplifiers, the company's main strength has traditionally been in receivers," said Christ. A lot of the parts for mobile phones shipped by TriQuint are LNA downconvert mixers, and the company has a major contract with Nokia to supply these parts for US TDMA handsets. "GSM receivers use highly integrated silicon parts, so we haven't seen a big market for GaAs ICs there," he added.

However, TriQuint is now addressing the GSM power amplifier market. This is an area where low cost has been more important than ultimate performance, and a significant proportion of GSM power amplifiers are silicon LDMOS modules supplied by Hitachi. However, as 2.5G technologies such as GPRS and EDGE gain acceptance, efficiency will become much more important. "GPRS has a high duty cycle, which rapidly drains the battery, making high efficiency a crucial feature," Christ continued. "We are getting very clear signals that GaAs HBTs are becoming ever more in demand for GSM." Even Hitachi has recognized the need to adopt GaAs HBT technology through its recent agreement with RF Micro Devices (see *Compound Semiconductor* December 2001, p7).

PAs for VSAT ground terminals

TriQuint's Texas operation, which manufactures high-frequency MMICs for a variety of applications, accounted for 30% of the company's total revenue in 2001 (see table). The division recently introduced a new high-power transmit amplifier operating in the 27–32 GHz band for satellite ground terminal and millimeter-wave digital-radio applications. The TGA4501 power amplifier MMIC is manufactured at TriQuint Texas with a mature high-yield 0.25 μm power PHEMT

GaAs ICs

technology and has a four-gain-stage architecture and a nominal output power of 34.5 dBm, with a gain of 20 dB.

Emerging broadband satellite networks will provide wideband, high-speed communications for Internet and multimedia applications in North America and Europe in 2003 and beyond. Various networks, which typically use 20 GHz downlinks and 30 GHz uplinks, are in different stages of development; Teledesic recently announced plans to build the first two spacecraft for its multi-satellite system (see p9). To communicate with such satellite networks, customers will require a high-power ground terminal. The TGA4501 is ideally suited for use as a high-power transmission amplifier in such applications, and also in digital radios that require high linear power.

Owing to the power and linearity performance available from this single-chip solution, subsystem integrators can replace multi-chip modules and decrease product complexity and cost. "Typical specifications require a minimum power level for the uplink

"We'll move to a 6 inch line when market demand is there, but at present we can't say when that would be."

so that it can operate in all conditions and cope with temperature variations and different levels of attenuation," said Larry Mowatt, director of TriQuint's Satellite Communications business unit. "Previously, this level of power has been obtained by combining multiple chips inside a module, while this new product offers a single-chip solution."

TriQuint's power PHEMT process produces high-frequency device performance comparable to that normally associated with 0.15 μm gate length devices while providing high device yields from a mature production process. "The 0.25 μm process has been in production since the early 1990s and is very mature," said Mowatt. "One change for this application is the use of a 50 μm substrate,

which provides a very compact profile for the chip, and helps us meet the desired price point. With our 0.25 μm process, we can achieve the output power and gain performance that often requires the use of a 0.15 μm gate in competing processes."

The process uses 4 inch wafers and will continue to do so even after it is transferred to the new facility in Richardson. "We'll move to a 6 inch line when market demand is there, but at present we can't say when that would be," he continued. "We would not want to move to a new facility and also change wafer size, so we've always envisaged the move as a two-stage procedure."

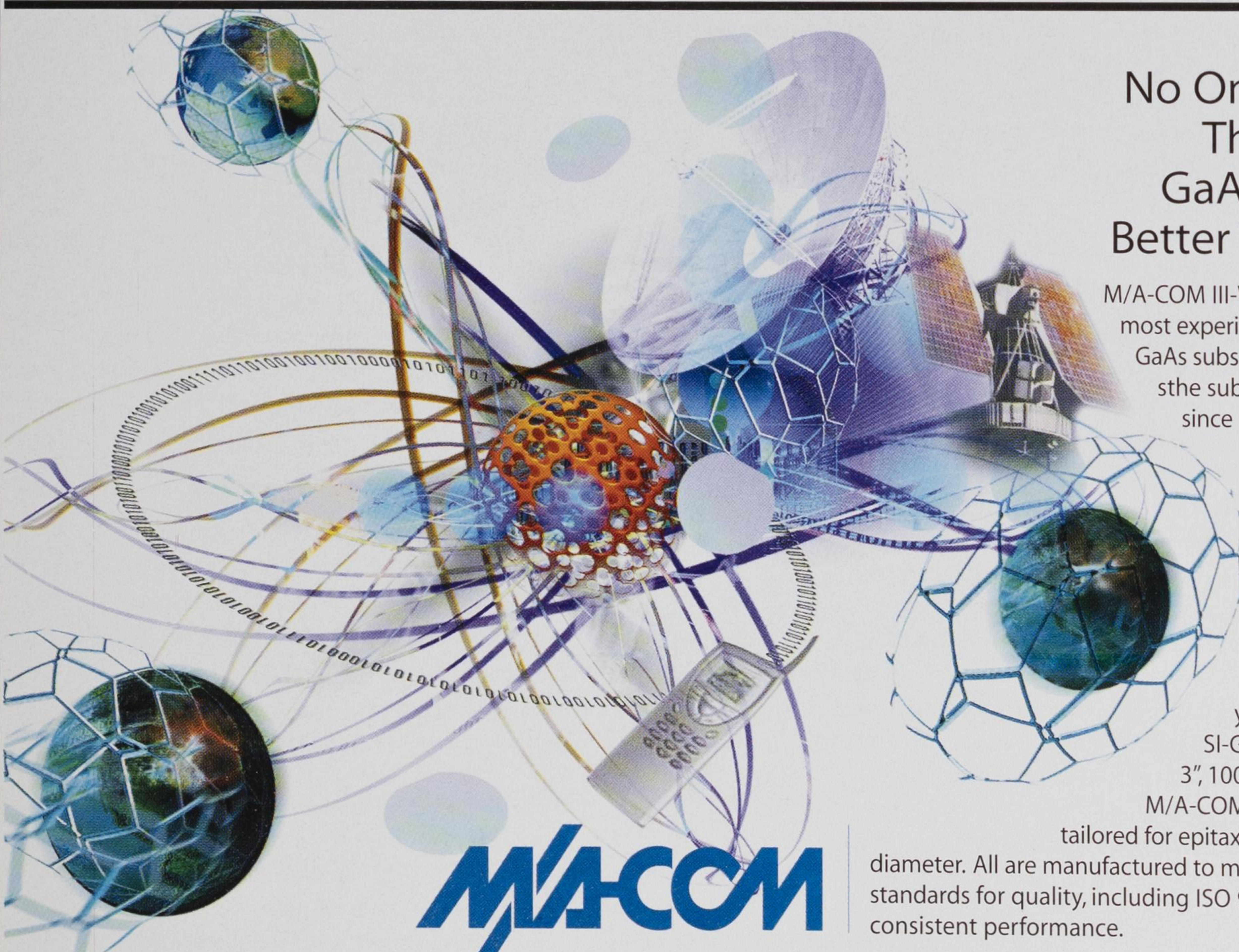
TriQuint says that the TGA4501 has been designed into several Ka-Band VSAT ground-terminal and millimeter-wave radio products by leading systems and subsystems manufacturers. The MMIC is offered as a $4.29 \times 3.02 \times 0.05 \text{ mm}^3$ chip with gold-plated bond pads and backside metallization. It is currently shipping in pre-production volumes, with an expected ramp-up to full volume production in the second half of 2002. ●

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New technologies spur growth in wireless handset markets

The wireless handset industry is poised to recover from its slump in 2001 as subscribers buy replacement handsets with new features and services, writes **Tim Whitaker**.

Global handset sales

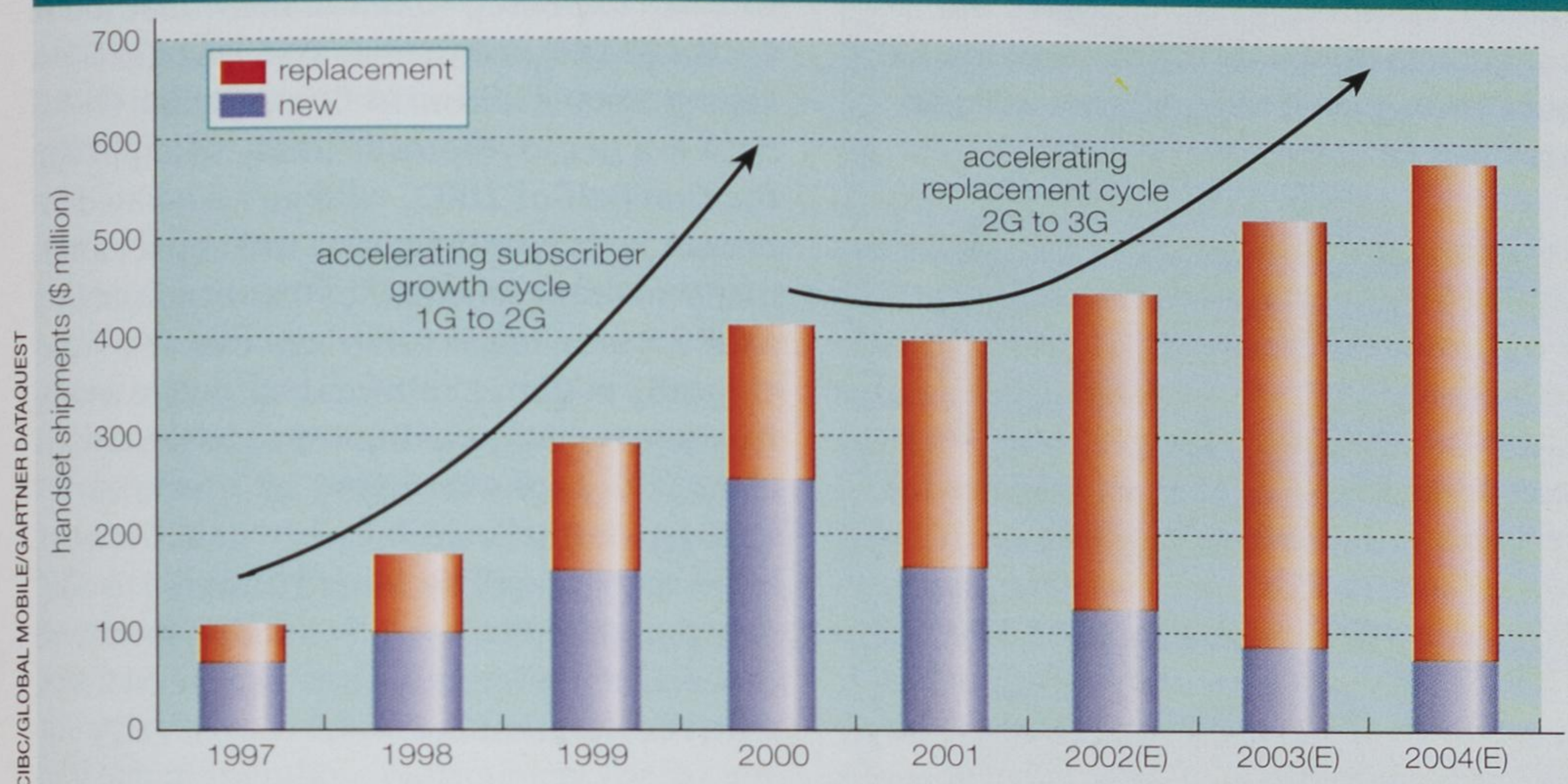


Fig. 1. Rapid growth in the years up to 2000 was driven by accelerating subscriber growth for 2G handsets. Shipments fell in 2001, due to an inventory overload, but growth is expected to return in 2002 as 2.5G and 3G networks are deployed. The largest contributing factor to future handset growth is replacement handsets for existing subscribers.

In 2001 wireless handset shipments fell for the first time in the industry's history. A number of factors conspired to cause this drop; weak economies in most countries, stale and uninspired product offerings from handset manufacturers, reduced or terminated handset subsidies, and a much slower-than-expected migration to next-generation 2.5G and 3G services. The impact for suppliers of GaAs ICs was severe, since the handset manufacturers had stockpiled a large inventory of components to meet the projected demand.

According to analyst research reports on the wireless market by CIBC World Markets, most of the effects that caused problems in 2001 will be mitigated, if not eliminated, in 2002. The industry is expected to see a 14.4% compound annual growth rate (CAGR) from 2001 to 2004. The main growth driver will be existing subscribers acquiring replacement handsets to gain new features and services, such as color screens and data capability.

Handset sales

Recent figures show that total handset shipments during 2001 were 399.6 million units. This represents a 3.2% year-on-year decline compared with the 413 million units shipped in 2000 (see figure 1).

For 2002 CIBC anticipates a return to positive unit growth of 15%, and predicts shipments of around 447 million units, within a range of 440–460 million units. Both Nokia and Motorola agree broadly with these estimates; Motorola has forecast shipments in the 420–460 million range, while Nokia's 2002 forecast is in the 420–440 million range.

CIBC believes that the handset market should retain double-digit growth through to 2004, reaching an estimated 584 million units. The largest contributing factor to future handset growth is existing subscriber handset replacements. 2001 was the first year in which replacements handset sales exceeded sales to new subscribers, and this trend is set

Subscriber forecast

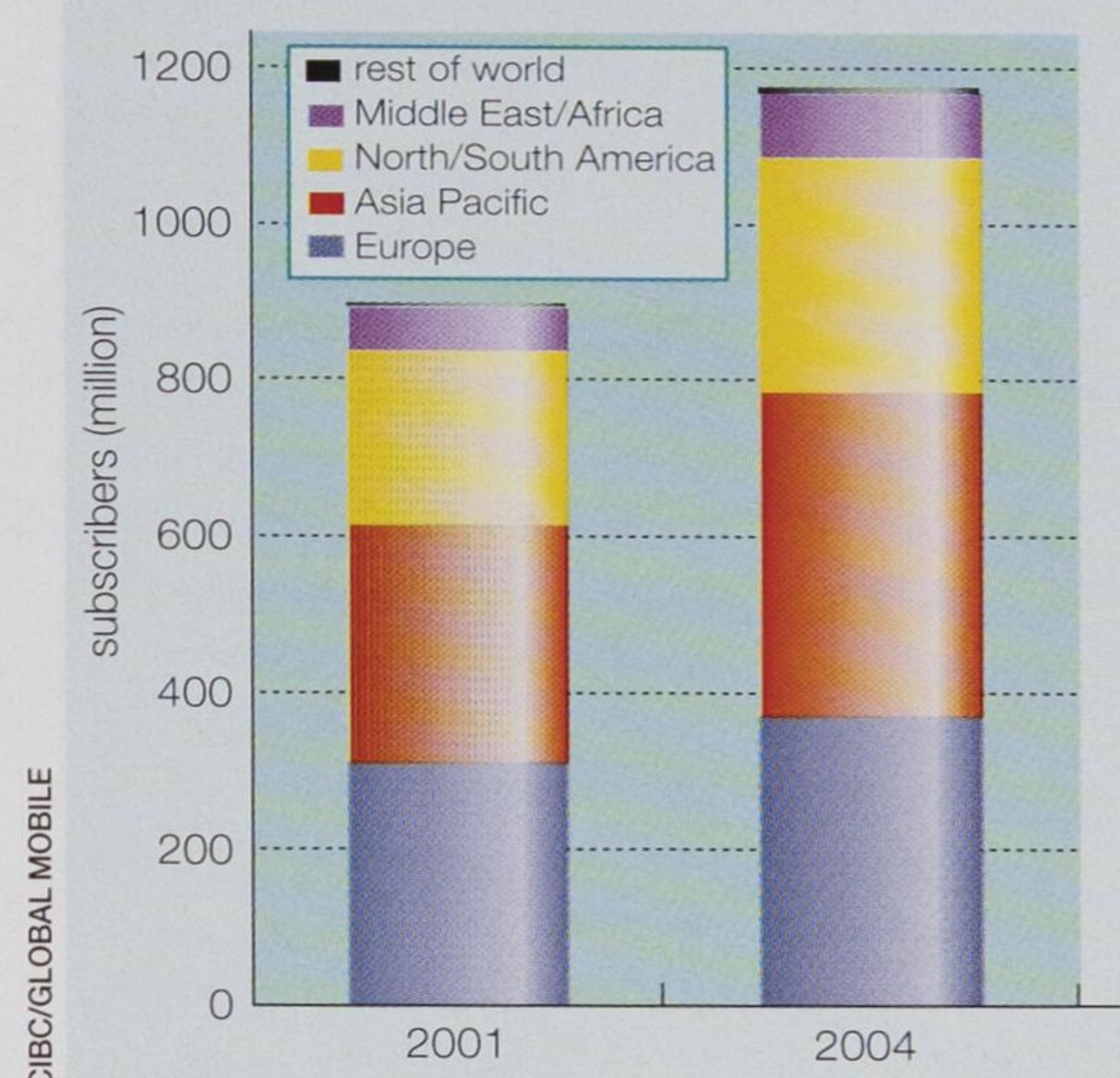


Fig. 2. Wireless subscriber numbers will reach about 1.18 billion in 2004, and Asia Pacific and the Americas will both see CAGRs exceeding 10%.

to continue. Over the 2001–2004 period the CAGR for replacement purchases is forecast to be 31.8%, while the CAGR for new subscriber handset purchases will be –23.5%.

Subscribers

At the end of 2001 there were just less than 900 million mobile subscribers worldwide, with approximately 34% of these in both Europe and Asia Pacific, and 25% in North and South America (figure 2). CIBC predicts that total subscriber numbers will reach 1.18 billion by 2004, of which 415 million will be in the Asia Pacific region and 372 million in Europe.

A penetration of around 70% is sufficient to saturate most markets, and with the overall penetration figure in Europe possibly exceeding 70%, limited growth is expected in this continent. However, Europe could see a strong replacement market with GPRS through 2004. In Asia Pacific the overall penetration reached only 9% in 2001 and strong growth is expected.



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GaAs ICs

Forecast by technology

Technology	Number of handset shipments (thousands)		CAGR 2001 to 2004
	2001	2004	
AMPS	7754	4622	-15.8%
GSM	238,950	168,161	-11.1%
GPRS	10,000	218,748	179.7%
TDMA	41,393	2278	-62%
CDMA	68,709	1191	-74.1%
1XRTT	3300	143,717	251.8%
W-CDMA	20	28,988	1032%
PDC	18,451	14,472	-7.8%
Total	388,577	582,177	14.4%

Table 1. GSM/GPRS technologies will continue to dominate the handset market, but CDMA-based technologies will gain a great deal of the market share.

Japan is still dominated by PDC, which has around 51 million subscribers, compared with 9 million CDMA subscribers. Initial subscribers for NTT's FOMA 3G service totaled 11,000 at the end of October 2001. With the exception of this service, all Internet-based services in Japan are available on 2G networks, such as PDC and cdmaOne, and with 2G and 2.5G handsets. As W-CDMA and 1XRTT services gain momentum in 2002, subscribers will upgrade their older 2G Internet-enabled handsets to higher speed versions with expanded multimedia capabilities. While just over half the handsets sold in Japan in 2001 had full-color displays, virtually all those sold in 2002 will be color, which has important implications for the high-brightness LEDs used as backlights in these displays.

China represents the largest single opportunity for both wireless infrastructure and wireless subscriber growth. At the end of 2000 China had 85.4 million subscribers and a penetration of 6.8%. The number of subscribers reached more than 140 million by the end of 2001, and could top 200 million by 2004. However, if CIBC's more aggressive forecast proves to be correct, this will result in an additional 97 million new subscribers, which also means the same number of shipments of new handsets.

Technology

GSM continued to dominate handset shipments in 2001, accounting for 239 million units. Around 69 million CDMA handsets and 41 million TDMA handsets were shipped last year (see table 1). GSM and GSM/GPRS phones are expected to represent the majority of handset shipments through to

2004, while CDMA will continue to gain market share based on strong growth in Asia Pacific and the Americas.

Data will be an important technology catalyst, driving an increased rate of replacement phone purchases and various technology transitions. The first platforms that will show the potential of data, will be GPRS and cdma2000 1XRTT. Around 10 million GPRS handsets and slightly more than three million cdma2000 handsets were shipped in 2001, while around 70 million 2.5G (GPRS and 1XRTT) handsets could ship in 2002.

The vast majority of current GSM operators are expected to make the transition to GPRS (2.5G) and then to W-CDMA (3G). A strong acceleration in commercial GPRS network deployments is likely to happen in the first half of 2002, with an associated increase in subscribers and in handset shipments in the second half of the year. Enabling a GPRS network is relatively easy, and usually only requires minimal hardware modifications to the existing GSM base stations along with a software upgrade. In contrast, W-CDMA requires an entirely new network buildout, and will be initially limited to densely populated regions. 3G deployment will proceed at a relatively slow pace until 2003, with acceleration in 2004.

Replacement handset market

For the first time in the mobile-phone industry, new subscribers are no longer driving the demand for wireless handsets. Instead, existing subscribers are replacing their handsets for a variety of reasons. These include replacing lost, stolen or damaged handsets, acquiring a new handset design that is smaller, lighter or has a full-color display, or even moving location, which could require a new service operator. The most compelling reason is to obtain new features such as multimode or multiband capability, Internet access, or enhanced SMS capability.

Data-capable handsets are already available, and have strong penetration in Japan. The rest of the world is likely to follow suit, although it will take until 2004 before 2.5G and 3G data-capable handset shipments overtake 2G voice handsets (see figure 3). Data-capable handsets will experience a CAGR in excess of 200% in the 2001–2004 period.

Infrastructure

Spending on wireless infrastructure seems likely to remain weak in the early part of 2002. However, recovery is likely to commence

CIBC/GLOBAL MOBILE/GARTNER DATAQUEST

Handset shipments by generation

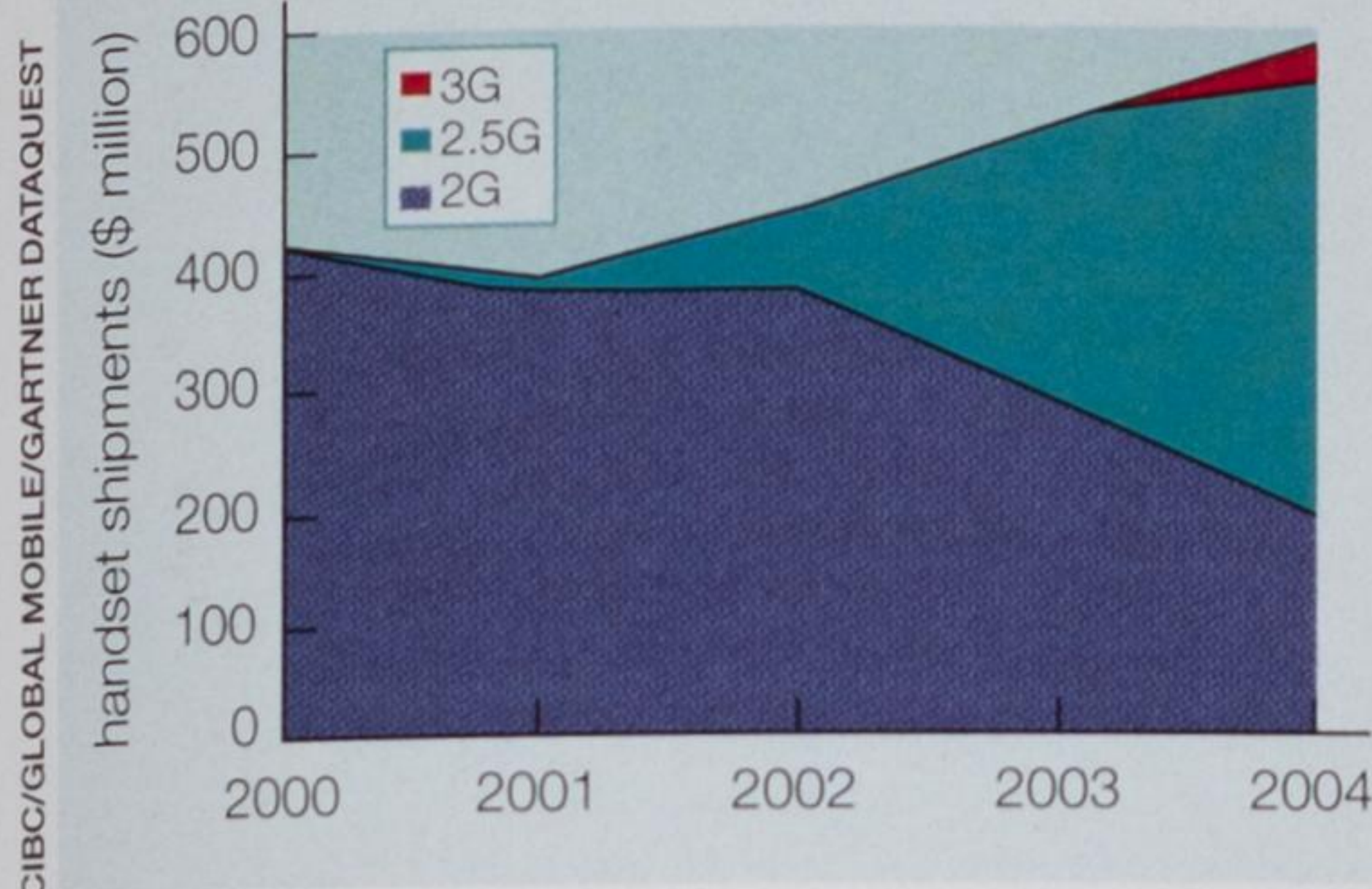


Fig. 3. 2.5G handsets (GPRS and 1XRTT) are expected to make their mark in 2002, and ramp steadily after that. 3G technologies will experience a slower ramp, reaching 5% of the total market by 2004, compared with 62% for 2.5G handsets.

towards the second half of the year, driven by the need to address the quality of service and the reliability of existing networks. Future spending will be driven by the build-out of 3G networks. Announced infrastructure contracts totaled \$6.4 billion in the fourth quarter of 2001, which is down from the peak of \$11.4 billion in the second quarter of 2001, but this is still at a very high level on a historical basis. There is a long lag time of 12 to 24 months between the contract announcements and actual spending, particularly for 3G networks. 3G announcements dropped rapidly towards the end of 2001, due to the fact that by that stage most operators had already announced their intentions.

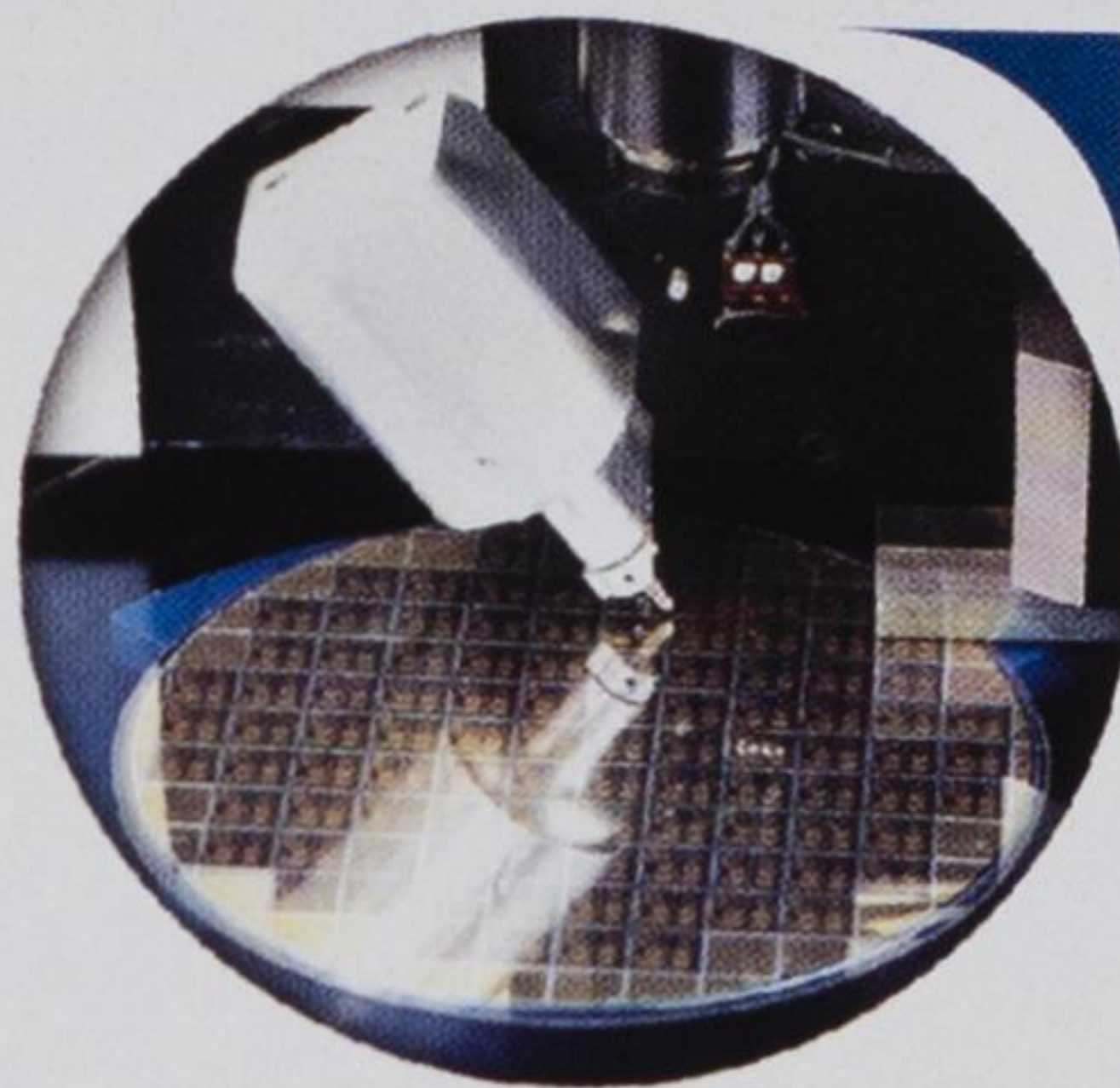
Component vendors

If handset shipments pick up to the extent that CIBC has predicted, then GaAs IC vendors should see strong growth exceeding 15% during 2002. CIBC points towards companies such as Alpha, Celeritek, RFMD and TriQuint as being particularly good prospects for growth, since these should all benefit from recent design wins on new platforms at top-tier vendors. Many new platforms are more complex multiband and multimode phones that require additional GaAs content per phone. The merger of Alpha and Conexant's wireless businesses will create the world's largest supplier of GaAs semiconductors, with an unrivaled breadth and depth of products, and further consolidation may also occur before long.

For more information on CIBC World Markets' equity research on wireless technology, contact Earl Lum at earl.lum@us.cibc.com.

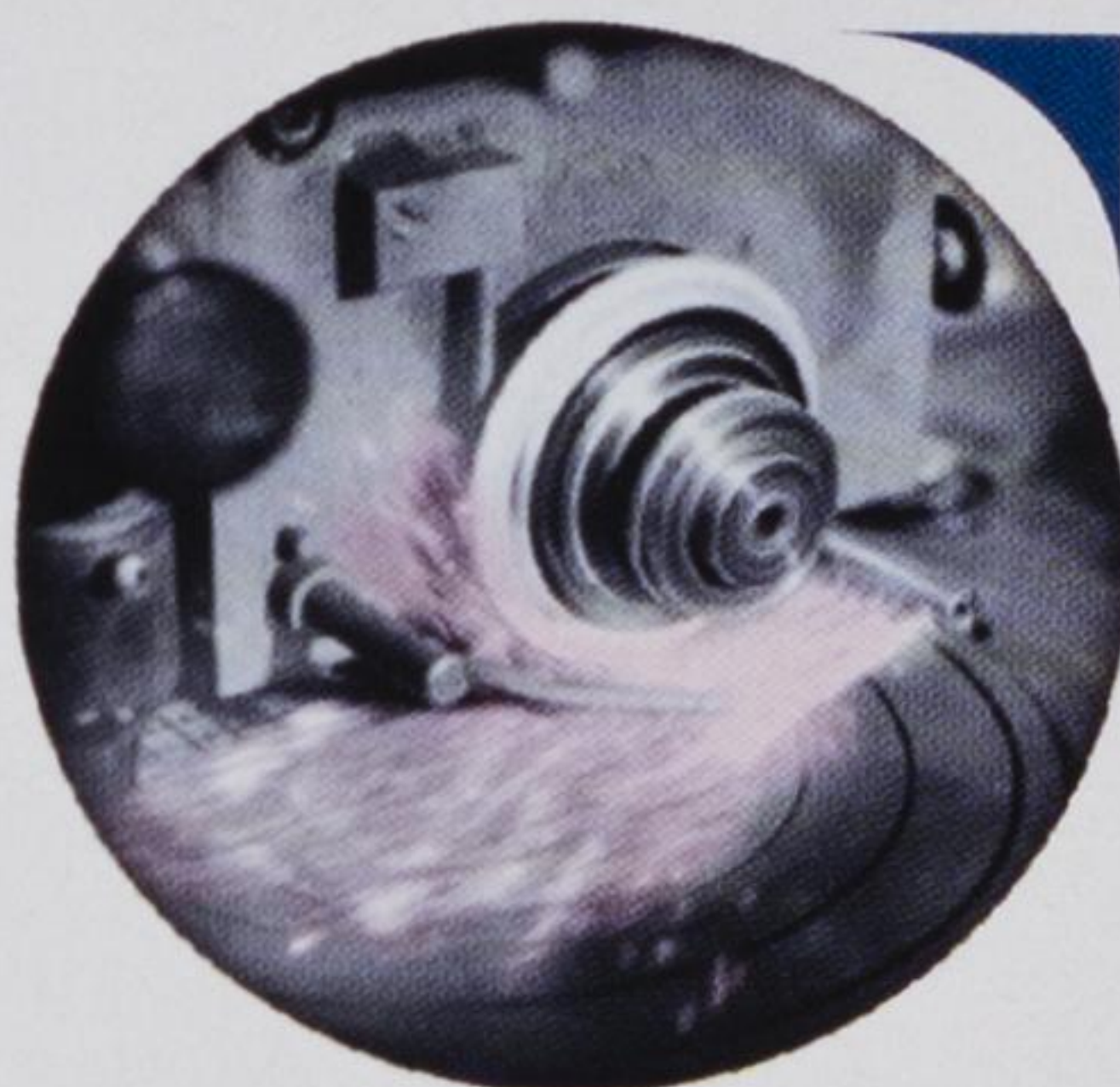
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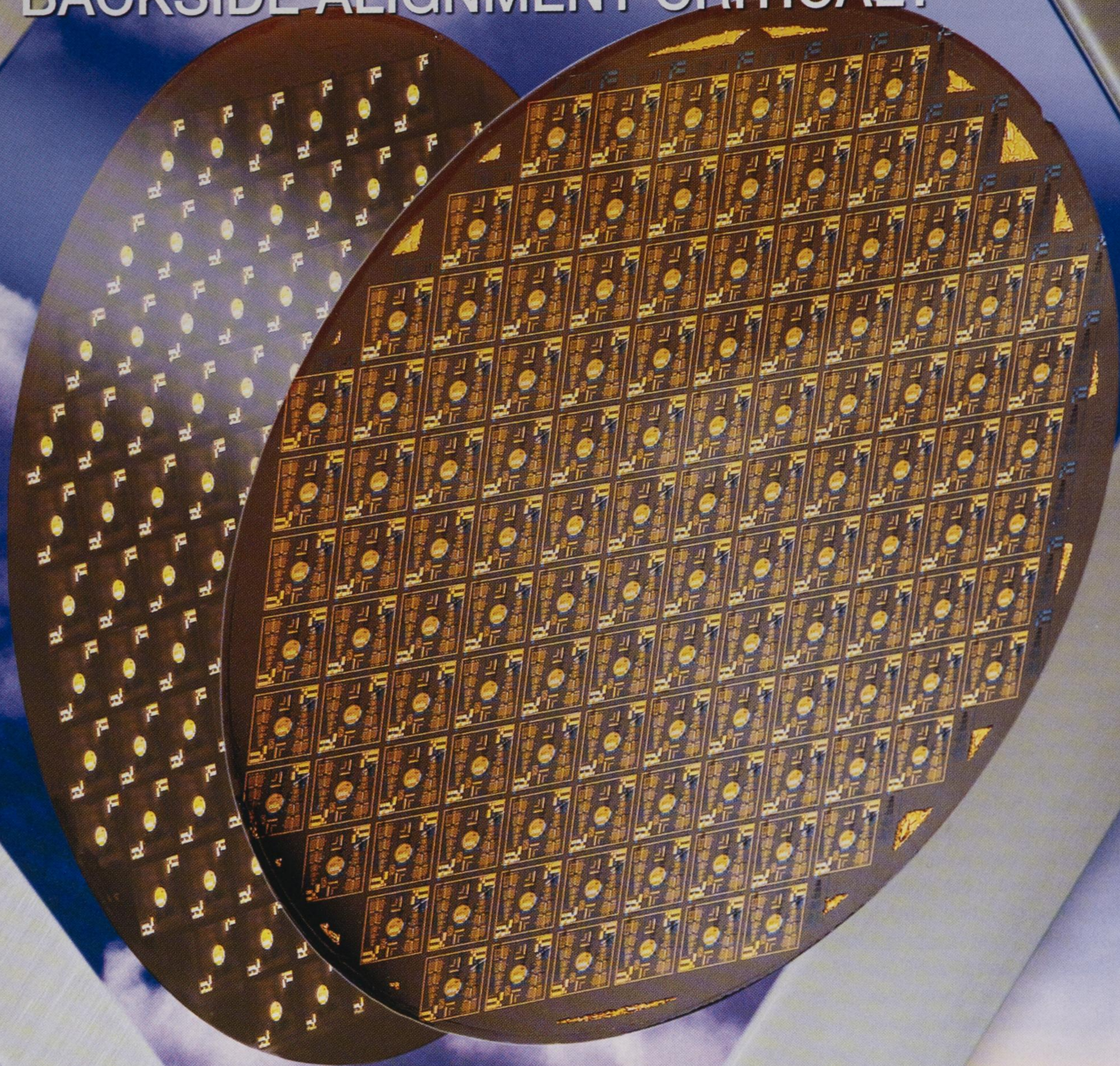
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Xindium uses InP expertise to make commercial 40 Gbit/s ICs

Xindium Technologies is using research results published by the University of Illinois at Urbana-Champaign to build high-speed, low-power indium phosphide ICs, writes **Tim Whitaker**.

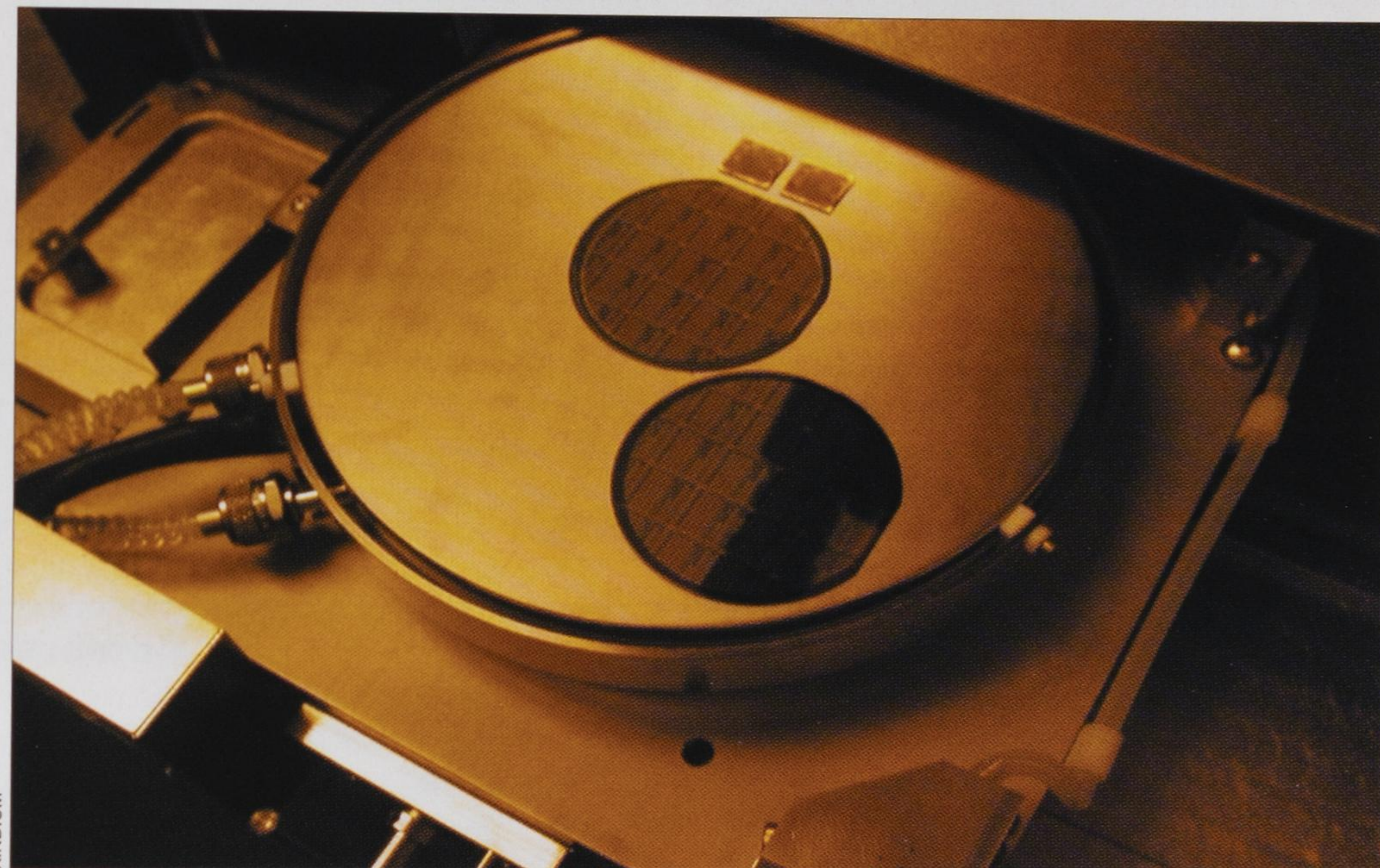
Xindium Technologies, a year-old spin-off from the University of Illinois at Urbana-Champaign (UIUC), is developing high-speed InP-based components for both optical and wireless networks. The company plans to build a pilot line for design verification and rapid prototyping, and will ultimately license its processes and designs to foundries for high-volume manufacturing.

Xindium's capabilities, which include the design and fabrication of optoelectronic ICs using InP and related materials, build on 20 years of research experience at UIUC with InP and GaAs devices for optical and wireless applications. Xindium will maintain a strong research collaboration with the Microelectronics Laboratory at UIUC, which has a long history of successful III-V optical and wireless device and circuit research. The company's first targeted products will be a >40 GHz *pin* detector, an integrated *pin* detector and HBT-based TIA, and a customer-specified TIA integrated with a post-amplifier.

Company background

Xindium was founded in February 2001 by three UIUC professors, Milton Feng, José Schutt-Ainé and Ilesanmi Adesida, and is headed by president and CEO Cindana Turkatte. One of the company's first actions was to secure an intellectual-property agreement with the university allowing Xindium to expand on UIUC's technology. "The agreement allows Xindium to use published research results developed at UIUC and to create commercial products," said Turkatte.

The company was incorporated in March 2001 with \$5 million in series A funding from Vantage Point Venture Partners. Xindium has a use-of-facilities agreement with UIUC, which enables the company to carry out design verifications and fabricate initial working prototypes in the Microelectronics Lab. After filing three patents on the epitaxial recipe, the InP HBT process and methods to



Using results from research carried out at the University of Illinois at Urbana-Champaign, Xindium is fabricating 40 Gbit/s InP-based ICs including *pin* diodes integrated with TIAs.

ensure signal integrity in its circuits, Xindium has already migrated to product development.

During 2002, Xindium plans to secure series B funding, which will allow the building of a pilot line. This is necessary because although UIUC does not have restrictions on commercial activities (unlike some other universities, which can't sell commercial samples), it will not be possible to get ISO qualification for the current facility. "The Xindium pilot line will be an adjunct to the UIUC Microelectronics Lab, rather than a separate fab," said Turkatte. "It will contain all the critical elements that require ISO qualification." As well as building qualified production devices for customers, the pilot line will allow Xindium to assemble a reference model that can be licensed to foundries. Xindium has already been approached by at least two foundries interested in licensing the company's technology.

Integrated products

Like some of its competitors, Xindium is convinced that InP is vital for 40 Gbit/s systems. At present, companies are building 40 Gbit/s transceivers using separate components, but will be looking for integration, starting with the *pin* detector and the TIA. Further integration will have to wait until the InP manufacturing industry matures. A TIA with a post-amp and AGC function requires about 50 transistors, or 100 for differential output, while a CDR and demux IC requires approximately 1000 transistors. "InP is not yet ready for the production of such complex ICs with high yield," explained Turkatte, "but next year it will be."

At this year's GaAs Mantech conference, Xindium and UIUC will describe an InP SHBT process with f_t and f_{max} values of 160 and 250 GHz respectively, which is being used for current products.

GaAs ICs

Meeting customer requirements

Xindium's strategy for generating revenue recognizes the need to wait until customers are ready for InP ICs. The company expects strong revenue growth beginning in 2004, and in the meantime will proceed with a low-expense burn-rate and a flexible production strategy. "We're working with customers now on the design-in cycle, which can take six to eighteen months," said Turkatte. "Along with establishing a prototyping and manufacturing capability, this will allow us to provide the right product when the customer is ready to start buying in volume." Several years ago, when the market was growing very rapidly, customers were forced to select from whatever products the suppliers chose to build. Now the market is returning to proper engineering fundamentals, and working in response to customer requirements. Xindium offers a menu-type specification for its ICs rather than a fully custom approach, which keeps costs under control. The company is able to simulate circuits fully as they operate under all environmental conditions. After the

customer signs off the software model, Xindium is able to carry out rapid prototyping. The company is seeking to agree test methods for 40 Gbit/s parts, which it hopes to publish, and is also collaborating with customers and competing suppliers on next-generation RF connector standards to reduce losses and improve performance.

Extensive expertise

The unique expertise at Xindium, built up through many years at UIUC, combines an understanding of the InP epitaxial layer structures with high-speed optoelectronic circuit design and skills in RF engineering and testing. "The key to building circuits with excellent signal integrity at high speeds is to understand how the circuit performance and design relates to the epitaxial structure," said Turkatte. "This takes a foundation of many years of experience, and is also protected by our intellectual property, making it very difficult for competitors to enter the market."

Xindium does not plan to grow production epiwafers, since there are commercial epi-

wafer foundries capable of growing the InP-based structures. "One of the first things we did this time last year was to start to qualify epiwafer vendors," said Turkatte. "Two suppliers have been qualified, and both MBE and MOCVD techniques are being used."

Xindium's first two products, the *pin*-TIA and the customer-specified TIA, will be available in wafer or chip-on-carrier form. Future receiver products will include a VCO and a demux IC with CDR, as well as 10 and 40 Gbit/s ICs with higher levels of integration. On the transmitter side the company has plans to introduce modulator post-amplifiers, laser-driver amplifiers and 4:1 mux ICs. The company will also look to address wireless applications when new (3G and beyond) services are introduced and when the manufacturing infrastructure for InP-based ICs is sufficiently advanced.

Turkatte feels that Xindium's manufacturing and marketing strategy and its access to the Microelectronics Lab at UIUC provide a distinct advantage over other companies seeking to enter the InP IC market. ●

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The advance of GaAs/InGaP HBTs gathers momentum

The popularity of InGaP HBTs is growing and MOCVD seems to have cornered the market for InGaP HBT epiwafers. **Jon Newey** looks at the reasons for its success so far and speaks to various MBE companies to find out why they think they can win themselves a bigger slice of the InGaP pie.

The GaAs/AlGaAs HBT has been one of the great compound semiconductor success stories. One of the main reasons has been the existence of a high-volume commercial application to drive the technology, namely power amplification in wireless communications. The HBT has successfully met the demand for reliability, high efficiency and good linearity.

The vertical dimensions of the transistor layers determine the DC and RF properties of HBTs, so the epitaxial process used to form the device layers plays a crucial role. Devices such as PHEMTs are also grown epitaxially, but because these are laid out laterally the gate dimensions defined by lithography are a crucial factor in performance. The vertical nature of the HBT structure means that device performance is less constrained by the lithography steps during processing. When an HBT manufacturing facility receives a supply of epiwafers, the vertical transistor structures are already in place. The manufacturing process involves defining and connecting individual transistors into a circuit (figure 1). The manufacturer can benefit from the relatively relaxed design rules on defining and connecting the individual transistors, compared with those needed to define the gate features in FET-type devices.

The move to InGaP emitters

The first GaAs-based HBTs to be commercialized had AlGaAs emitter layers, but the majority of development and new HBT production programs are now focusing on devices with an InGaP emitter layer (figure 2, p70). In the future it looks like the GaAs/InGaP HBT will supersede the GaAs/AlGaAs HBT in many applications. There are a number of reasons why using an InGaP emitter might improve the performance of HBTs. InGaP provides a larger difference in valence band energies between the base and the emit-

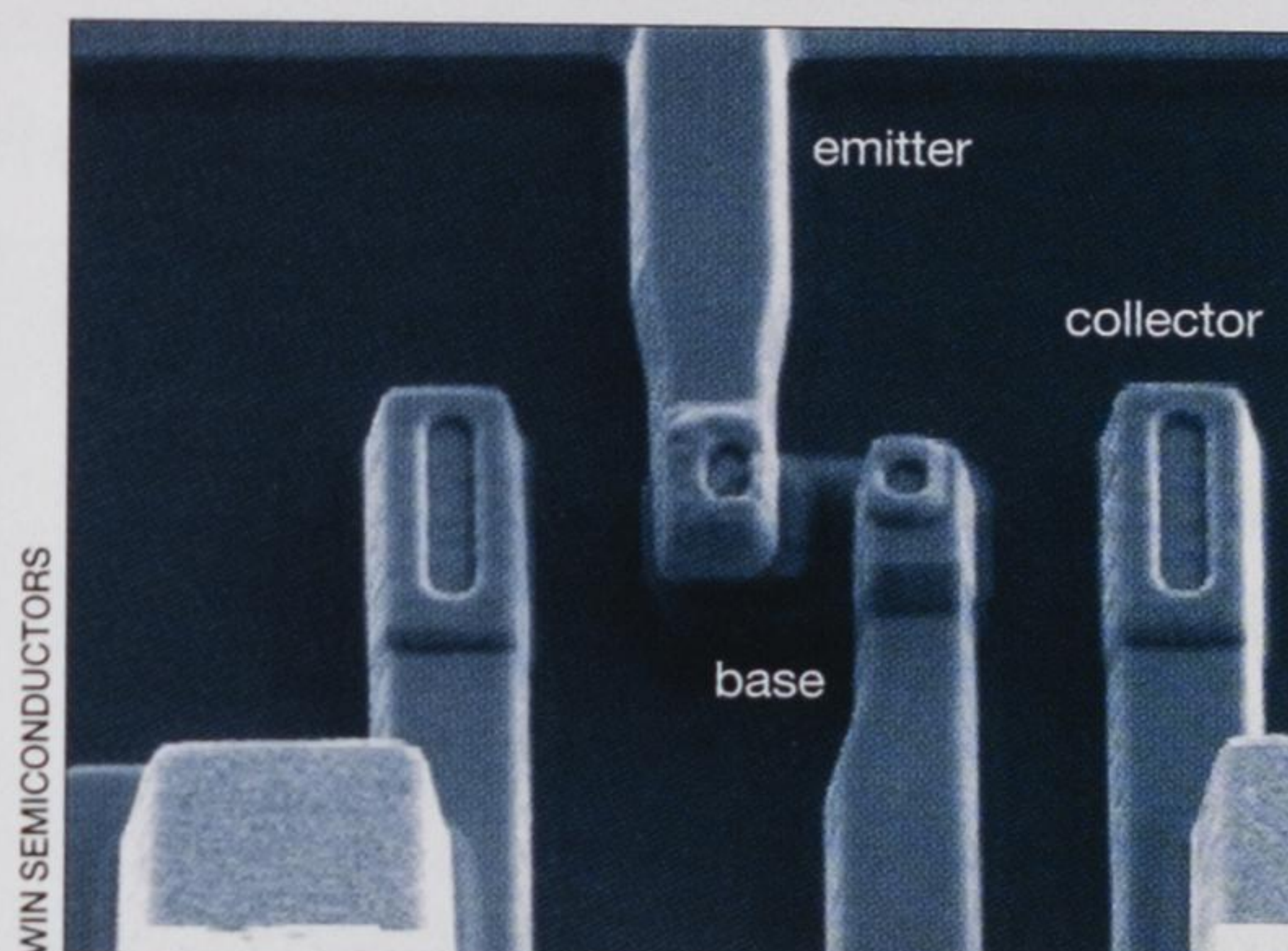


Fig. 1. An SEM image of the InGaP HBT manufactured by WIN Semiconductors.

ter. Secondly, the high etch selectivity between InGaP and GaAs makes device processing easier. Finally, oxygen incorporation into AlGaAs emitters is thought to give rise to recombination centers, which reduces a device's reliability. InGaP is less reactive to oxygen so higher current gain and reliability can be achieved.

While the side-by-side comparison of InGaP and AlGaAs emitter structures may well show some differences in factors like reliability, it is not clear that users exercise the reliability already available from an AlGaAs structure. The improvements of going to InGaP for an application such as a cell-phone PA may well be insignificant. As Kopin's Dave Davito pointed out, "Whether the device lasts 10^6 or 5×10^6 hours is really irrelevant as nobody is ever going to see that. Our customers tell us they need to offer an InGaP HBT in their product portfolio because their competitors have one too. That is at least partially driving the shift to InGaP."

The MBE-grown GaAs/AlGaAs HBTs initially developed by TRW use the highly mobile element Be as the p-type base dopant. This dopant needs to be kept to such a level that diffusion into surrounding layers does not occur and affect device performance. A high

p-type doping in the base layer is necessary to achieve good RF characteristics and the industry seems to have standardized on a carbon-doping level of 4×10^{19} atoms/cm³ for InGaP HBTs. Be doping levels are typically 1×10^{19} atoms/cm³. The flexibility that the additional RF performance from higher base doping brings to designers will be another factor driving the uptake of InGaP HBTs.

Challenges to epi

In order to exploit the benefits of HBTs fully, manufacturers need epiwafers with good uniformity of layer thickness, doping and crystal quality, both across the wafer and from wafer to wafer. Without this, transistor parameters such as turn-on voltage, base resistivity and breakdown voltage will not be reproducible irrespective of the processing steps taken to define and connect the HBTs.

The move to InGaP has highlighted a number of problems that growers have had to tackle. Arsenic is easily incorporated into InGaP to form InGaAsP which has a lower bandgap energy and etch selectivity. A lattice-mismatched InGaAsP layer may be unintentionally formed at the GaAs/InGaP interface, introducing defects at the interface. The electrical properties of InGaP change with its crystal structure and composition, so good control of the In and Ga composition is needed to prevent defects being introduced. In_{0.51}Ga_{0.49}P is required for lattice matching to GaAs.

Another critical step is the growth of a highly n-type InGaAs non-alloy emitter contact layer. This layer is lattice mismatched to the GaAs emitter contact below and care must be taken to reduce surface roughness for high In content layers. Carefully optimizing the growth parameters results in surface roughness of about 1 nm for In_{0.6}Ga_{0.4}As layers.

Hydrogen in MOCVD can cause a number of problems in the base layer. The gas passivates the carbon dopant and causes an initial

GaAs ICs

instability in the current gain of the device. This transient instability is often referred to as "the burn-in effect".

MOCVD gets a head start

A search through the marketing literature of the world's epiwafer vendors will reveal that the growth of InGaP HBT epiwafers is largely the territory of MOCVD. The reasons for this are varied and are founded on historical and political grounds as much as economic and technical ones. When AlGaAs HBTs first became commercially available MBE was the dominant technique used to grow them, but the pendulum has swung to MOCVD with the advent of InGaP emitter HBTs.

Phosphorus had an obstacle to overcome before it could be routinely and safely used as a solid source in MBE. The safest form of phosphorus, red phosphorus, does not give stable results from a normal MBE effusion cell. White phosphorus is the more reactive relation of red, and while it is possible to get more stable effusion from this material its reactivity makes it difficult to handle safely.

The two main types of phosphorus sources now available are valved phosphorus compound cells in which P_2 is extracted from a GaP source, and valved cracker cells. The valved cracker cell has a three-stage design. The first stage converts red phosphorus to white, the second then effuses the white P_4 and the third cracks the P_4 into P_2 which is incorporated into the growing film. Excess P_2 condenses as red P_4 on the reactor's cryopanel making it safer to handle during maintenance.

While MBE phosphorus sources were being developed and refined, MOCVD growers were able to use gas-phase phosphorus precursors so the epitaxy of phosphide materials by MOCVD became established well before MBE. As Veeco-Applied Epi's Tom Bird explained, "People were taught to use MOCVD in universities. Once they graduated and left to work in industry they purchased MOCVD systems and did not consider MBE until the technology to handle phosphorus effectively became available."

The economics of epitaxy

With companies such as Riber, Thermo VG Semicon and Veeco-Applied Epi offering large multiwafer systems, MBE has established itself as a production technology in recent years making it economically competitive with multiwafer MOCVD systems. Gather together representatives of the companies selling MOCVD or MBE platforms

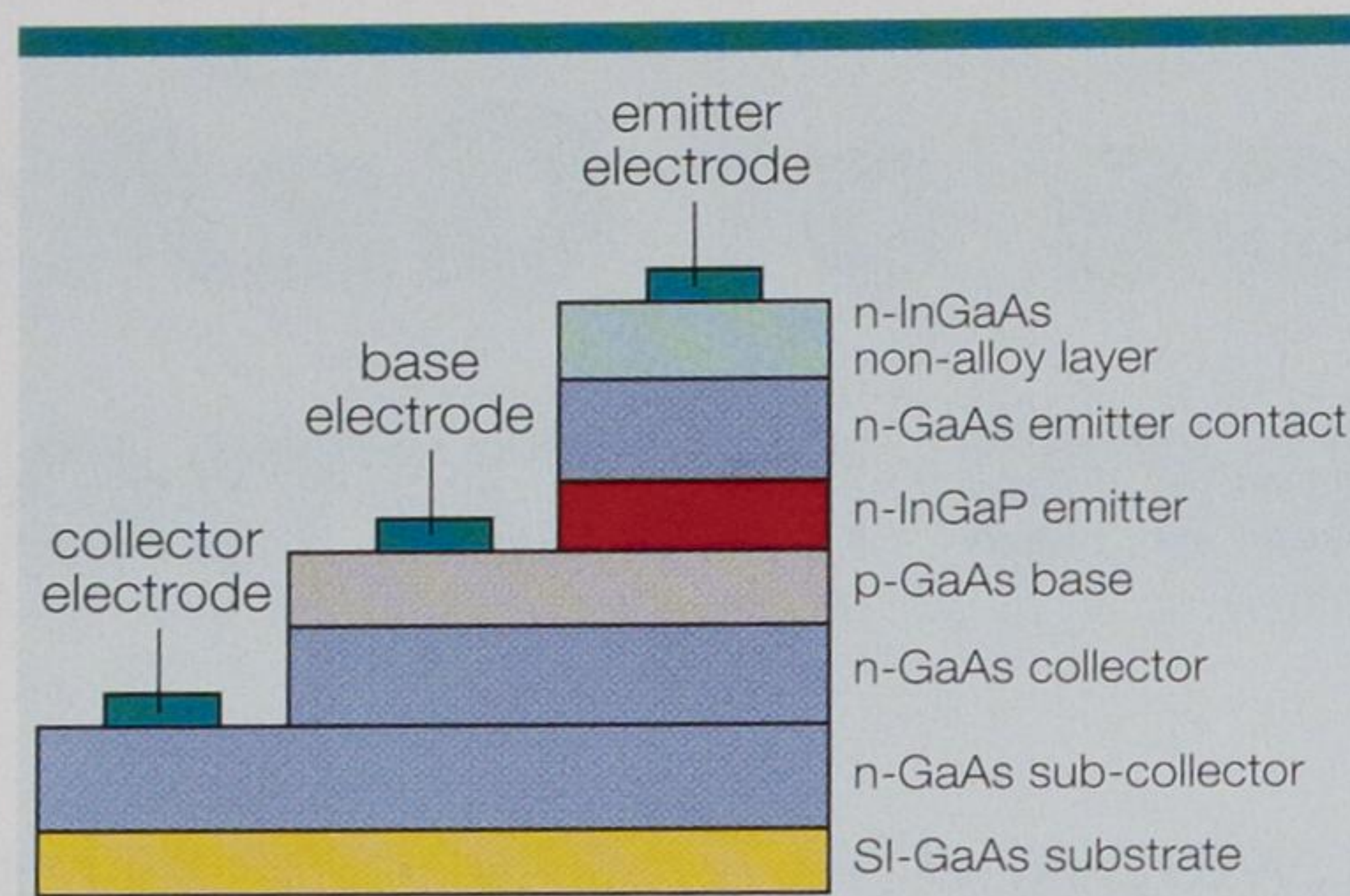


Fig. 2. A typical InGaP HBT structure. Carbon is used as the p-type base doping and 4×10^{19} atoms/cm³ is the industry standard. Emitter and base-layer thicknesses are in the region of 700 Å.

RFMD is evaluating both MOVPE- and MBE-grown material, suggesting that the choice is not clear cut.

and they will each offer good reasons why the overall costs of buying and running their systems in a production environment are the same if not less than with the competing technique.

Anybody starting to grow InGaP HBT epiwafers (and many other types of epiwafers) can take the relatively easy route of approaching a MOCVD reactor vendor such as Aixtron or Emcore and purchase a turnkey system to grow the structure of interest. "If you wanted to get into InGaP HBT epiwafer production quickly and with minimal effort, buying a reactor and the necessary process know-how is certainly an option," said Paul Cooke, a product manager in Emcore's electronic materials division. This has not been the case for those purchasing MBE reactors, however in October 2001 epiwafer vendor Picogiga announced that it would license the MBE process it had developed and commercialized for InGaP HBTs.

MBE sees opportunity at 6 inch

Picogiga sees the migration of HBT production to 6 inch wafer fabs as one of the opportunities for MBE to gain on MOCVD's larger market share. As new 6 inch fabs come online, new processes can be towards the front of the queue for qualification.

"MOCVD is very well established, but customers today have a strong desire to differentiate themselves from their competitors," said Picogiga's CEO Linh Nuyen. "We believe that MBE offers a significant performance advan-

tage with better reliability, no burn-in, lower haze and superior surface characteristics."

The possibility of surface haze arises when growing the lattice-mismatched InGaAs emitter contact layer. Epiwafer vendor IQE has significant experience with both MBE and MOCVD. Steve Bland, a research manager at IQE, says that the company has seen no evidence of any significant difference in surface roughness between MOCVD- and MBE-grown InGaP HBT epiwafers.

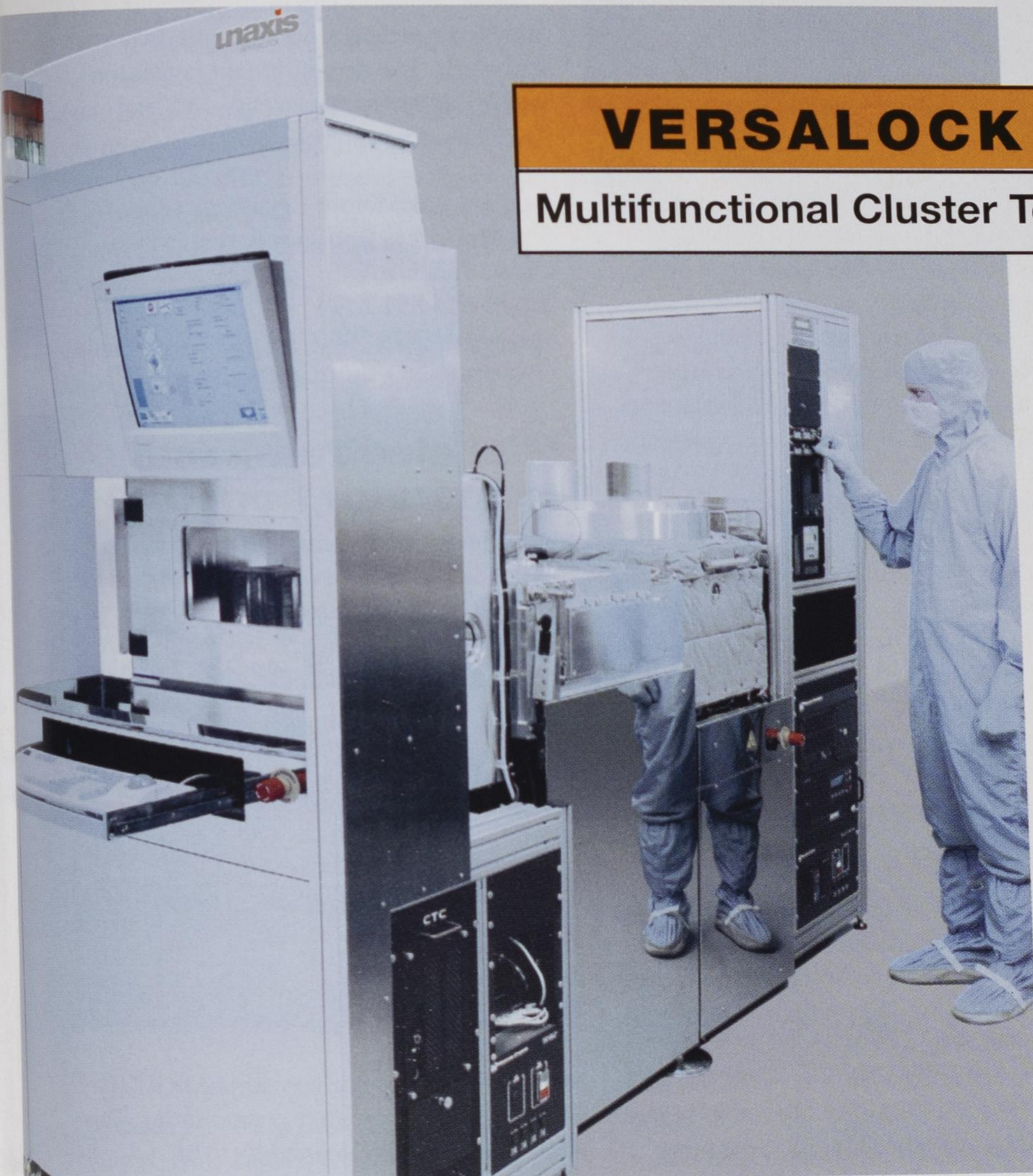
Where the InGaP HBT structure itself is concerned, those choosing the MBE route will cite other advantages often described as inherent to MBE processes including cross-wafer uniformity of composition, layer thickness and crystal quality. Apart from residual gas in the vacuum chamber, hydrogen is not a factor in the MBE process and there is no chance of hydrogen incorporation into the base leading to the burn-in effect.

Conversely, hydrogen is everywhere in the MOCVD process, but Kopin's Davito thinks MOCVD growers have this problem under control. "The elimination of hydrogen has been touted as the definitive step to be taken to solve all the issues with HBTs," he said. Suppliers of MOCVD epiwafers now offer "transient- or hydrogen-free" material with a maximum variation in current gain of below 5%. This has been achieved through optimized growth processes and *in situ* annealing. "Annealing the MOVPE material tends to reduce the maximum current gain achievable," explained IQE's Bland. "Interestingly, the hydrogen-free material produced by this route exhibits a current gain that is similar to the material grown by MBE." As Emcore's Cooke pointed out, "An MOCVD grower who does not have hydrogen under control will not be in the HBT business very long."

Future directions

It is an interesting time for the HBT. The introduction of an InGaP HBT process in GaAs/AlGaAs HBT pioneer RFMD's new 6 inch fab will be watched closely (see *Compound Semiconductor* March 2001, p3). RFMD's GaAs/AlGaAs HBT production has relied upon an in-house MBE capability for its epiwafers. The company has yet to decide on whether to utilize its MBE resource for InGaP HBTs and is evaluating external sources of MOVPE- and MBE-grown material. That the company is evaluating both types suggests that the choice is not clear cut and either method can produce material of the necessary quality for acceptable costs.

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making IT possible

Diamond-coated wires achieve crystal slicing

Crystal Systems has introduced a new slicing technology for crystals and wafers. Using the company's Fixed Abrasive Slicing Technology (FAST), the system employs a blade-pack of multiple wires coated with diamond particles.

The FAST unit operates at rotation speeds up to 5000 rpm, achieves a high surface speed and has a minimum contact length with the wires. This increases the pressure between the diamond particles and the sample, improving the cutting effectiveness. The results are high wafer-cutting accuracy and low kerf-loss and damage. The system is suited to substrates such as silicon and SiC, in addition to the sapphire wafers that are used in LED and laser diode manufacturing.

Contact Kurt Schmid, Crystal Systems, 27 Congress Street, Salem, MA 01970, USA
Tel. +1 978 745 0088
Fax +1 978 744 5059
Web www.crystalsystems.com

Cercis launches new 1310/1550 nm testers

Cercis has unveiled new laser test light sources. The 520D35 series consists of dual-wavelength (1310 and 1550 nm) test meters for single-mode fibers or components with up to -10 dBm output. Standard modulation rates up to 2 kHz are possible, and the optical output of each light source is tested to NIST standards. AC and battery operation modes are supported.

Contact Karen Kinsman, Cercis Inc, 108 West Franklin Avenue, Pennington, NJ 08534, USA
Tel. +1 609 737 5120
Fax +1 609 737 5122
Web www.cercis.com

Ultra Tec's AR coating aids backside analysis

Ultra Tec has introduced a new bench-top coating unit that adds an anti-reflective (AR) film to backside-thinned packages and wafer-level components prior to testing. A spin-on layer of polymer is applied to the surfaces of back-thinned and polished samples using standard selected area



preparation equipment. This improves the image contrast by up to 60% and the transmitted photon efficiency up to 30%, says the company.

The ARC-lite AR coating system is suitable as a preparation for backside emission and other thermal measurements of GaAs ICs and devices including telecom lasers. The process takes place at room temperature in less than one minute.

Contact Tim Hazeldine, Ultra Tec Manufacturing Inc, 1025 E Chestnut Ave, Santa Ana, CA 92701, USA
Tel. +1 714 542 0608
Fax +1 714 542 0627
Email info@ultratecusa.com

Cleaning station for MOCVD reactor traps

IEM Technologies' new cleaning station allows the potentially hazardous task of cleaning MOCVD reactor traps to be carried out on-site. This improves safety, as well as increasing throughput, reducing waste and lowering costs, says IEM.

The Centurion comprises an oxidation step and cleaning station integrated into a fume cabinet. This is connected to a scrubbing system that removes and contains any toxic and hazardous substances. The design prevents discharge to drain off any toxic effluent, and the scrubber prevents harmful emissions from entering the atmosphere.

Contact Peter Vernon, IEM Technologies Ltd, Unit 6, Fothergill House, Colley Lane Industrial Estate, Bridgwater, Somerset, TA6 5JJ, UK
Tel. +44 1278 420555
Fax +44 1278 420666
Email IEMuk1@aol.com

Lake Shore unveils temperature monitor

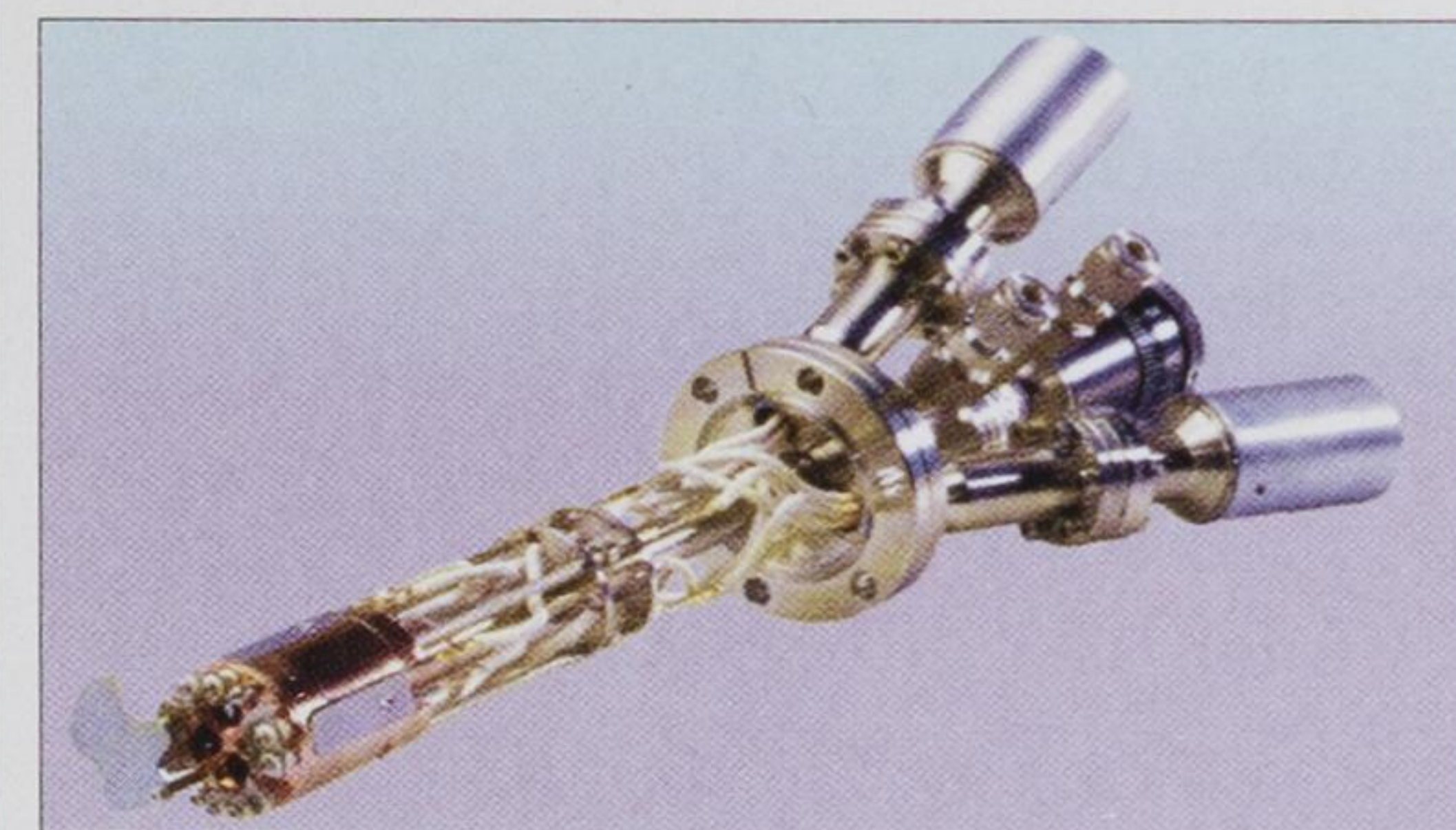
Lake Shore Cryotronics has introduced a new temperature-monitoring system. The model 211 is a single-input instrument designed for cryogenic or high-temperature operation, and aims to support both diode and resistance temperature sensors.

Measurements can be displayed in K, °C, and °F for temperature, in addition to volts and ohms. The measurement ranges for voltage and current cover 0-10 V and 4-20 mA, respectively.

Contact Lake Shore Cryotronics Inc, 575 McCorkle Boulevard, Westerville, OH 43082, USA
Tel. +1 614 891 2244
Fax +1 614 818 1600
Web www.lakeshore.com

Mini electron-beam evaporator from OAR

Oxford Applied Research has launched a mini electron-beam evaporator designed for low-contamination and sub-monolayer deposition of thin films. Evaporation from up to four different ports containing either rod or



bulk materials is possible with the EGCO4, which is equipped with flux monitoring. This allows the detection sensitivity to be amplified, and also the removal of energetic and damaging ions from the beam, says OAR. Designed for UHV chambers employing a standard NW35CF flange, applications include catalysis, small-scale MBE growth, semiconductor doping and contact metalization.

Contact Steve Rothstein, Oxford Applied Research USA Inc, One Gateway Center, Suite 2600, Newark, NJ 07102, USA
Tel. +1 866 669 4627 (toll-free in the US)
Fax +1 973 622 3423
Web www.oaresearch.com

SmartProbe speeds plasma characterization

According to Scientific Systems, plasma-based processes account for 25% of chip manufacturing problems. The company has therefore upgraded its Langmuir probe in order to speed the characterization of plasma processes used to etch semiconductors, deposit thin films or modify surfaces.

The new version is called the SmartProbe and measures density, uniformity and electron temperature distribution. It can now be triggered to measure pulsed plasmas at 100 kHz, compared with just 18 kHz in its previous form. The unit also features an RS232 connection to allow portability via a laptop.

Contact Roisin Cheshire, Scientific Systems Ltd, Unit 3, Howth Junction Business Park, Kilbarrack, Dublin 5, Ireland

Tel. +353 1 816 7526

Fax +353 1 839 5133

Email rcheshire@scisys.com

Web www.scisys.com

Low-speed saw from Allied High Tech

Allied High Tech Products has released its latest precision low-speed saw. The TechCut 4 incorporates a gravity-feed design featuring 1.0 µm cross-indexing resolution, a 3–6 inch blade range, a large work platform and variable speed control from 10–500 rpm. In addition, the new saw features a rotation cutting attachment, integration with machine controls, and a retractable dressing stick.

Contact Kim Dermit, Allied High Tech Products Inc, 2376 East Pacifica Place, Rancho Dominguez, CA 90220, USA

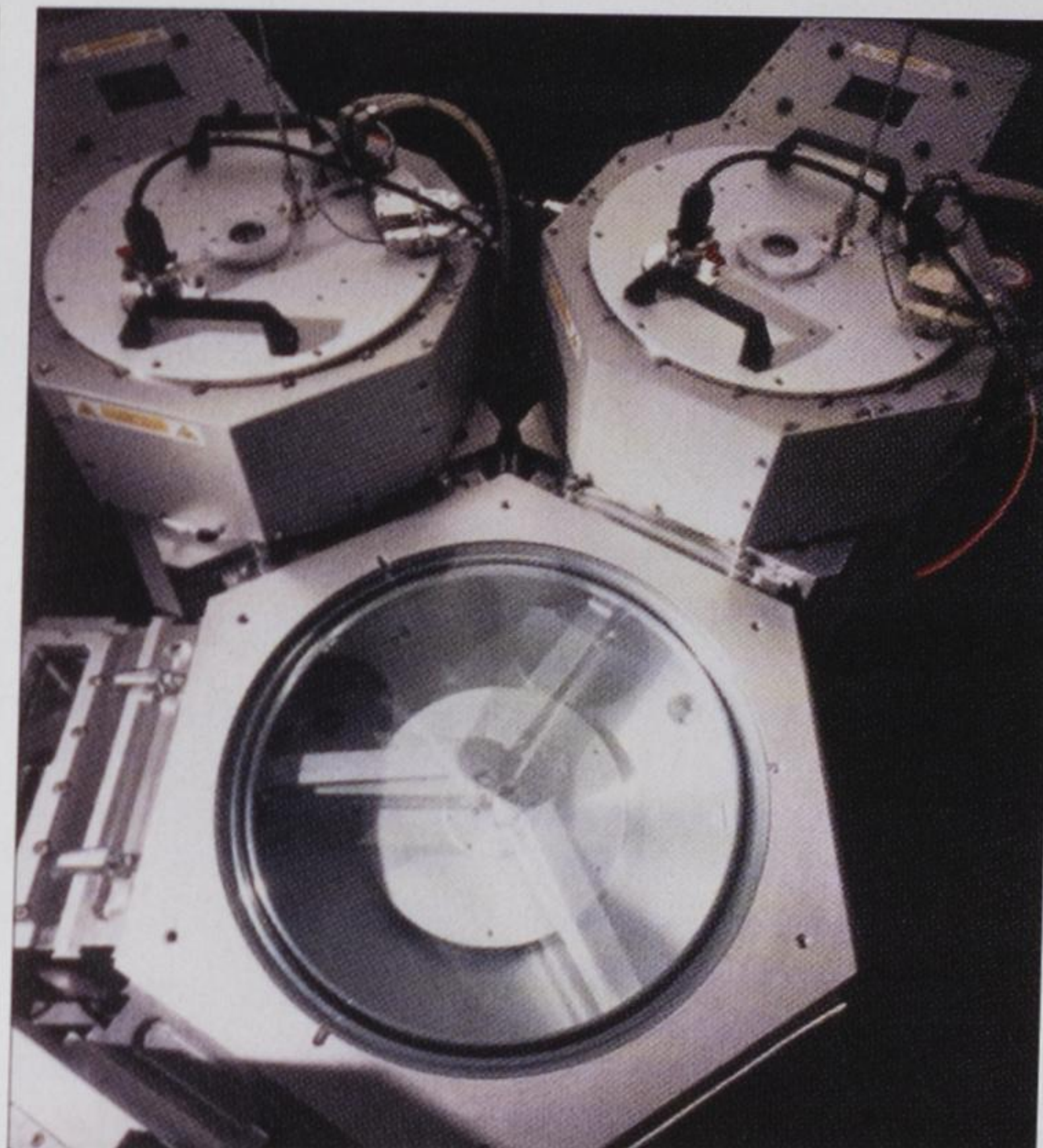
Tel. +1 310 635 2466

Fax +1 310 762 6808

Email kwdermit@alliedhightech.com

Cluster platform for plasma processing

STS supplies a range of plasma processes for GaAs, InP, GaN and GaP material systems used in the manufacture of ICs, lasers, VCSELs, LEDs, lenses, waveguides and photonic devices. The company's new Asset system features an inductively coupled plasma (ICP)



processing tool in a cluster tool platform.

The cluster consists of a central six-port core that can be configured for as many as two Brooks vacuum cassette handlers and four ICP (or a combination of ICP, CVD, RIE and AOE) sources.

In addition, the company says that its system also addresses some of the problems faced by GaAs MMIC manufacturers, such as fragile wafers sticking to clamp ring assemblies. A clamp applies pressure evenly to the wafer edge and at the lowest pressure required to achieve a good seal against the helium backside cooling pressure.

Contact Carolyn Short, STS plc, Imperial Park, Newport NP10 8UJ, UK

Tel. +44 1633 652 400

Fax +44 1633 652 405

Email carolyn_short@stsystems.co.uk

Maxwell unveils single-rack RF and DC tester

Maxwell Technologies has released a single-rack RF and DC version of its Automated Accelerated Reliability Test Systems (AARTS) product line. The new rack offers the same features as the larger channel unit and is intended for accelerated aging characterization tests on discrete transistors, MMICs, hybrid microwave ICs and RF/microwave module assemblies.

The AARTS family supports 4, 8, 16, and 32 channels of capacity with full RF, DC, and temperature stress capabilities, in addition to 24, 48, and 96 channels of DC test capability. Various modulation signals, such as CDMA, inter-modulation characterization testing, and multi-tone RF

input signals, are also supported, and the system can be equipped with a parametric analyzer for I-V characterization.

Contact Fred Puglisi, Maxwell Technologies, 9244 Balboa Avenue, San Diego, CA 92123, USA

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Fax +1 858 503 3301

Email fpuglisi@maxwell.com

New book explores reflow soldering

New applications for reflow soldering and higher production volumes involving fewer defects and new lead-free solders, create challenges for electronics assembly.

A new book by the VP of technology for the Indium Corporation of America, Ning-Cheng Lee, examines such issues for reflow soldering processes. *Reflow Soldering Processes and Troubleshooting: SMT, BGA, CSP and Flip Chip Technologies* covers advanced component technologies, materials, alloys and fluxes, application methods and processing recipes.

Contact Leo Devine, Indium Corporation, 34 Robinson Road, Clinton, NY 13323, USA

Tel. +1 315 853 4900

Fax +1 315 853 1000

Email devine@indium.com

Hercules lithography system from EV Group

An automated system designed to perform photoresist coating, photolithography and wafer developing has been released by EV Group. The Hercules is intended for MEMS and compound semiconductor device production (e.g. GaAs circuits, LEDs and laser diodes), as well as for wafer-level packaging.

The wafers are handled by a robotic cassette-to-cassette system between spin-coat, bake, chill, align/expose and develop stations. Both 2 and 3 inch InP wafers and GaAs wafers up to 6 inches in diameter can be accommodated. Very thin wafers mounted on carriers can also be safely moved through the stations using the robot handling system.

Contact Rose Gismondi, EV Group, 1210 Pontiac Avenue, Cranston, RI 02920, USA

Tel. +1 401 784 0008

Fax +1 401 784 9933

Email r.gismondi@evgroup.com

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Aixtron's sales show the value of LEDs and Asia

Wondering about the status of the compound semiconductor industry? **Marie Meyer** explains why Aixtron's 2001 financial results provide some valuable insights into the current picture.



If you are looking for a stock to serve as an indicator of trends in the compound semiconductor industry, you could do worse than follow Aixtron.

Aixtron is the largest supplier of epitaxy equipment, and epitaxy is the enabling technology for virtually all of the compound semiconductor devices in high-volume production today. Aixtron is active in all of the important geographic regions, and unlike most of the device manufacturers, Aixtron participates in all of the major application areas for compound semiconductors. Slightly more than 40% of its 2001 revenues came from the LED market, with the remainder divided between

communications and consumer-related products. Also, Aixtron is virtually a "pure play" in the compound semiconductor field. Although it is developing new CVD systems for silicon, organic LEDs and other types of electronic materials, at present almost all of its revenues come from the compound semiconductor industry.

One argument against using Aixtron in this role is that, as a manufacturer of capital equipment, its results tend to trail the fluctuations of the market as a whole. In contrast, manufacturers of consumables (such as epi-wafers and substrates) respond almost immediately to shifts in the demand curve. This was illustrated last fall when Aixtron reported that sales had more than doubled in the third quarter compared with the same period a year ago; in contrast, AXT and Kopin saw their sales drop by 31% and 48% respectively.

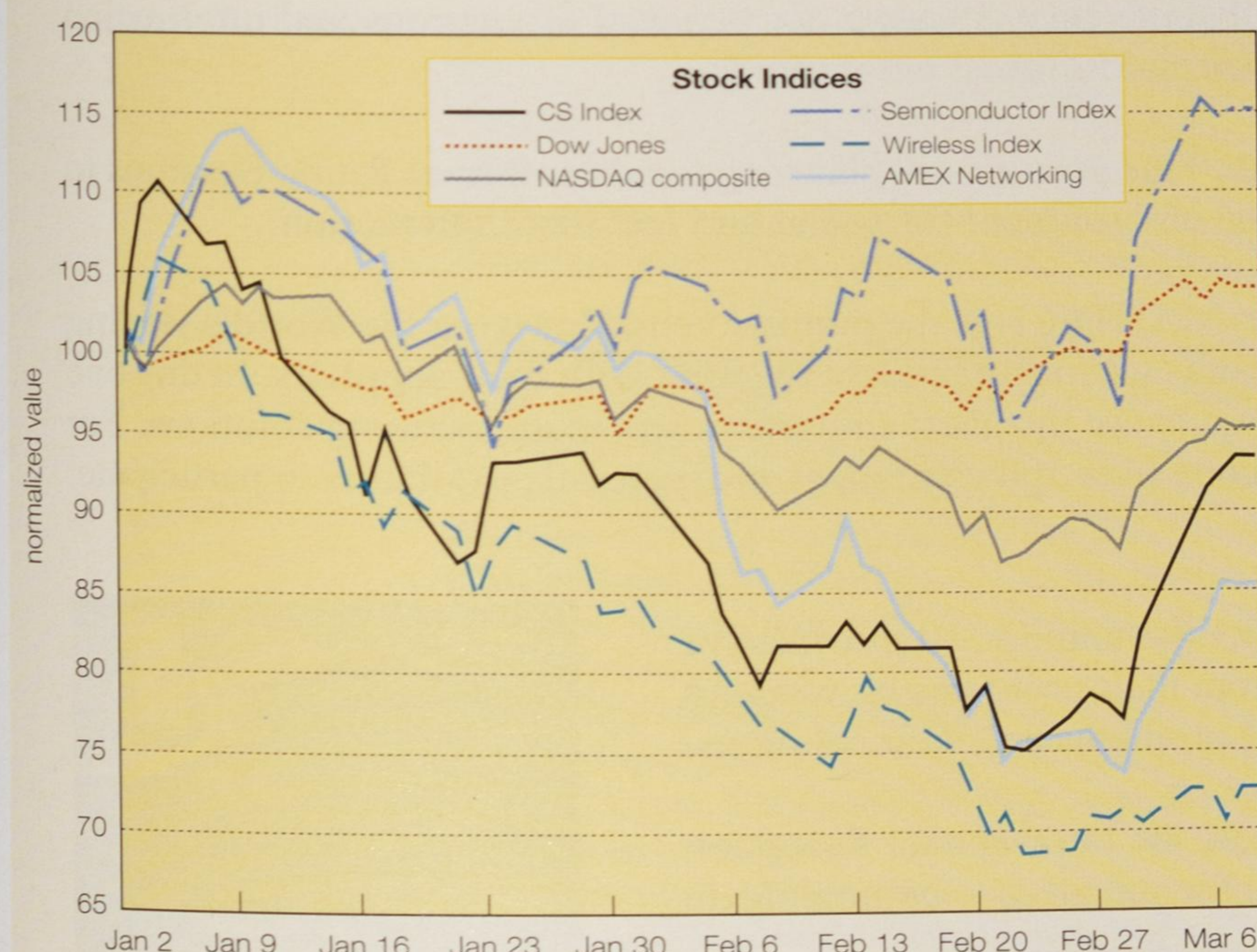
With this in mind Aixtron's rival Emcore also deserves consideration for "industry bellwether" status, because it sells both MOCVD reactors and epi-wafers. But it should be noted that Emcore is still ramping up its materials businesses, and the attendant R&D spending and vagaries of new-product launches make the company's bottom-line results a bit unpredictable. Another candidate is IQE, a materials company that serves a broader range of application areas than AXT or Kopin. Its 2001 year-end results, to be announced on March 20, will meet with great interest.

Aixtron results for the last five years (€ million)

	1997	1998	1999	2000	2001
sales	39.68	55.61	84.66	157.90	240.10
operating income	6.56	11.21	17.09	32.90	24.20
net income	2.25	5.68	10.38	18.49	33.60
earnings per share*	0.027	0.098	0.172	0.290	0.520

*=including extraordinary items

Industry indices



Aixtron's 2001 results

With all this in mind, what lessons can be learned from Aixtron's 2001 results, which were announced on March 8? First, things are not quite as bad as they seem. Despite the general economic malaise, Aixtron posted revenues of €59.5 m (\$53.5 m), which is just a 4% decline in sales compared with the third quarter.

Second, the outlook for next year is not as dire as it once appeared. Aixtron is forecasting 2002 revenues of €210 m, down 13% from 2001 results. Granted, this is the first decline in six years. However, the fact that the company is not predicting a bigger drop in revenue is reassuring. And its management seems quite confident of their ability to meet their target. In a presentation to analysts and members of the press on March 8 in Frankfurt, the company stated that it already has €133 m of new orders on its books for delivery in 2002.

Aixtron's top-line performance appears to be related



2002 International Conference on Compound Semiconductor Manufacturing Technology

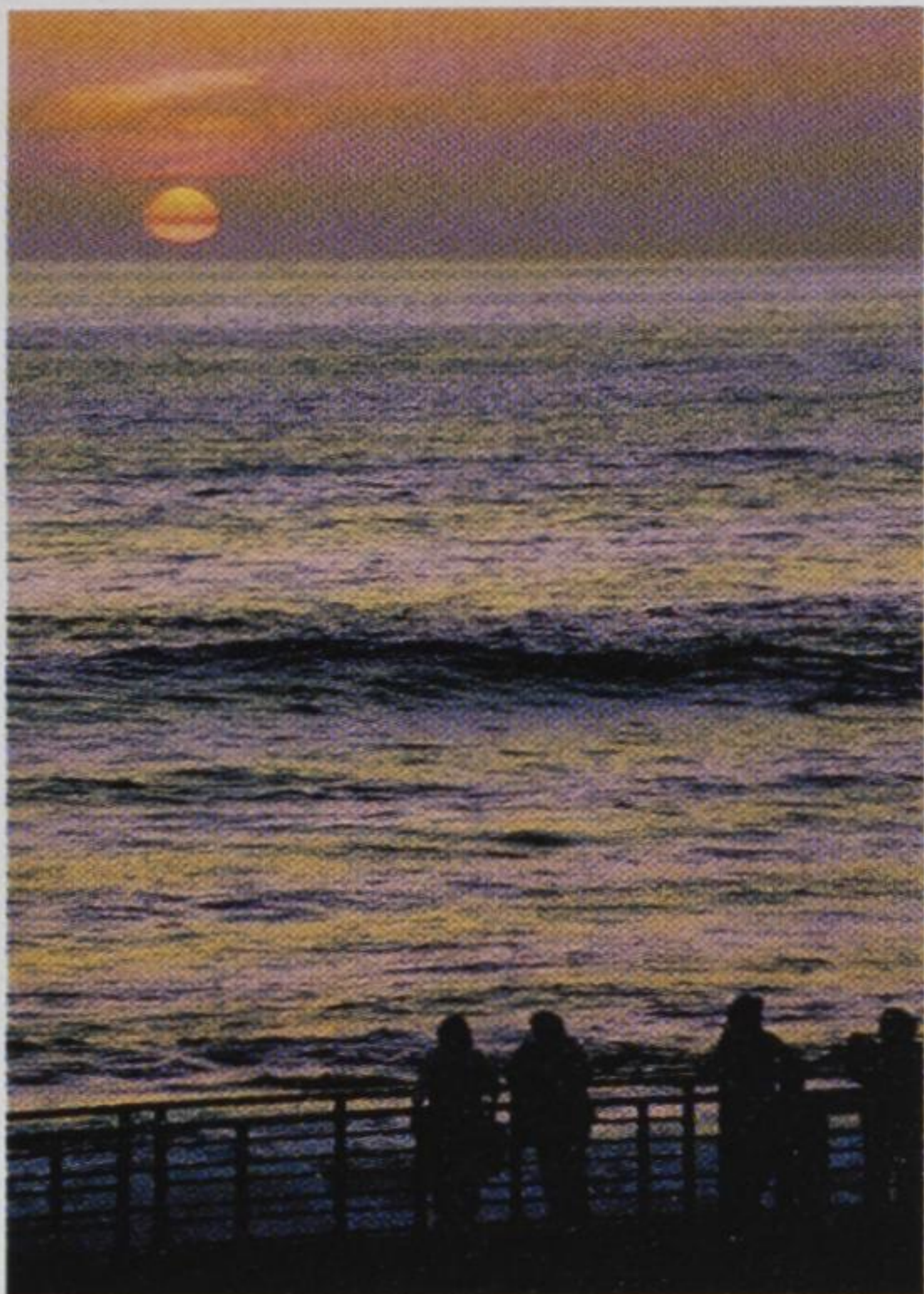
April 8-11, 2002

Sheraton San Diego Hotel & Marina, San Diego, CA, USA

Web address: www.GaAsMANTECH.org

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❑ **Technical Sessions:** over 60 papers addressing manufacturing, processing, reliability, device technologies, optical devices, materials (GaAs, InP, GaN) and packaging. The plenary session includes talks by leading technologists from around the world. Edgar Martinez from DARPA will provide an “Overview of Emerging Compound Semiconductor Technologies.” Additionally, future business trends and new paradigms in the industry will be discussed.

❑ **Workshop:** To meet the rapid demand, GaAs MANTECH will again sponsor an intensive four-topic workshop led by industry experts on April 8th, the day before the main conference. Workshop topics include:

- InP Technology
- Semiconductor Band Gap Engineering
- Fundamentals and Modeling of III-V MOVPE
- Telecom Basics: The Role of Compound Semiconductors

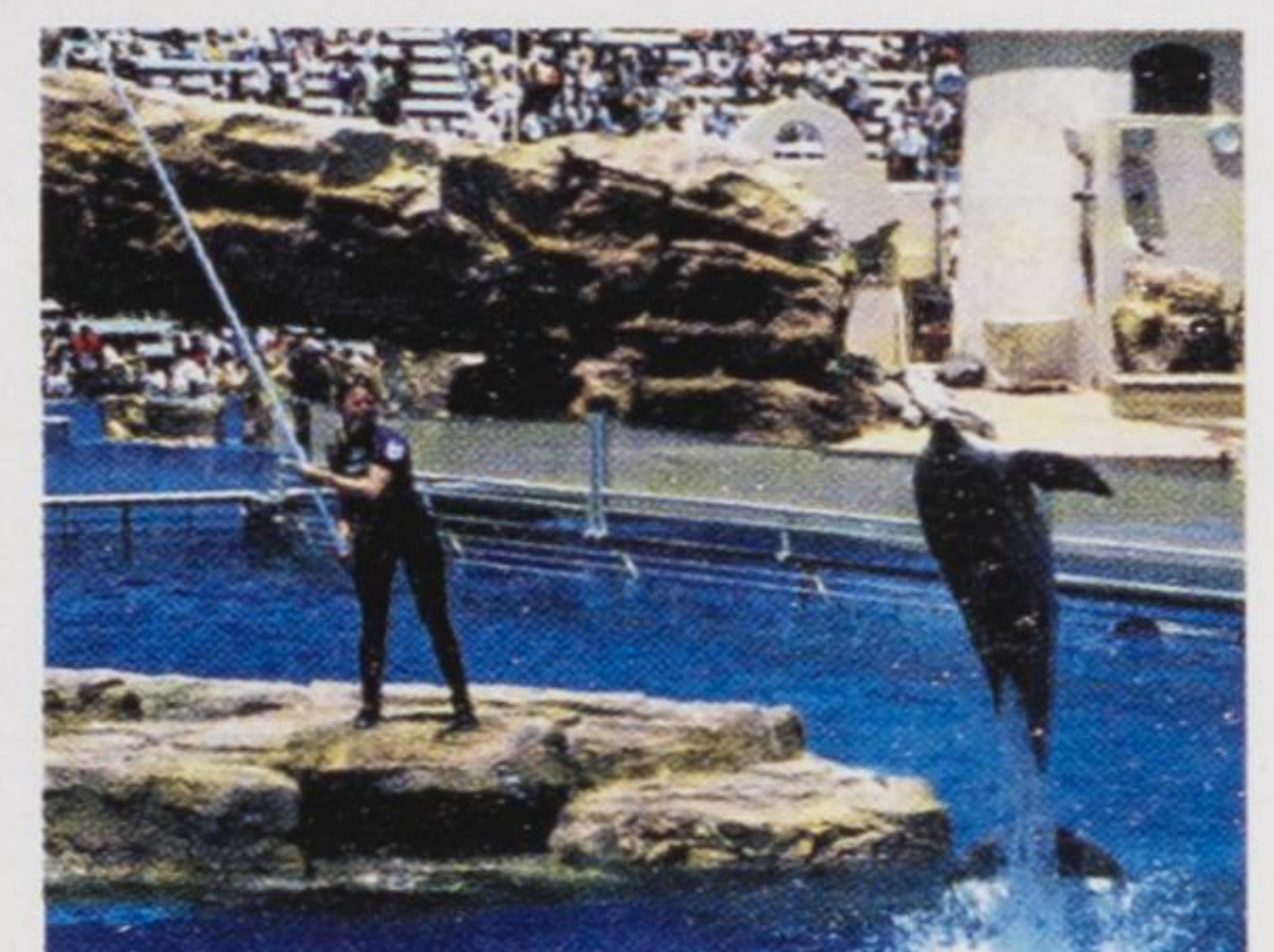
❑ **Interactive Forum:** This popular session provides an excellent and informal opportunity for all conference attendees for personal discussions and information exchange in an open and informal environment.

❑ **Rump Sessions:** This year we are planning to add informal Rump Sessions to further enhance the environment for social and technical interaction.

❑ **Exhibits:** GaAs MANTECH is the premier venue bringing the World’s leading compound semiconductor manufacturers together with their suppliers. In this one location you will get to see the latest equipment and manufacturing solutions. For 2002 we are expecting over 100 equipment and materials exhibitors to participate.

❑ **Ugly Picture Contest:** This is a very popular, entertaining and informative contest. It gives everyone a chance to benefit from their problems by winning a prize for the worst examples of manufacturing problems and their solutions.

❑ **Social events,** including the Exhibits Reception, the International Reception and the Awards Luncheon provide opportunities for attendees to communicate with international colleagues and develop business contacts.



****For registration and advanced program, please visit us at www.GaAsMANTECH.org**

Aixtron's ups and downs appear to be related to total demand, not just shifts in MOCVD equipment market shares.

Market overview

Company	Symbol	Closing price on March 8	52-week low-high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	20.30	13.0625-41.4500	897.8 m	N/A
Anadigics	ANAD	13.84	9.4000-25.3800	420.1 m	N/A
Celeritek	CLTK	10.59	8.9500-16.9100	128.9 m	N/A
Conexant	CNXT	13.25	6.5700-18.1100	3.387 bn	N/A
Endwave	ENWV	0.82	0.6000-3.2969	29.4 m	N/A
Multilink	MLTC	2.69	1.8800-18.4000	184.3 m	N/A
RF Microdevices	RFMD	21.83	8.7500-37.5000	3.653 bn	N/A
Sirenza Microdevices	SMDI	6.45	2.9800-17.0000	190.0 m	N/A
TriQuint	TQNT	12.24	8.9000-32.7300	1.594 bn	N/A
Vitesse	VTSS	9.76	6.6500-45.0000	1.954 bn	N/A
Opto companies					
Agilent	A	36.09	18.0000-41.1800	16.746 bn	N/A
Agere	AGRa	4.35	3.1000-9.5000	7.115 bn	N/A
Alcatel Optronics	ALAO	6.31	4.0400-37.2500	104.1 m	N/A
Coherent	COHR	35.46	25.0500-45.5500	1.016 bn	47.06
Cree	CREE	18.80	12.2100-36.6500	1.365 bn	N/A
JDS Uniphase	JDSU	6.37	4.7400-29.5000	9.624 bn	N/A
Stratos Lightwave	STLW	4.57	3.1800-14.2500	292.9 m	N/A
Uniroyal Technology	UTCI	0.45	0.2699-10.1100	12.6 m	N/A
Semiconductor materials and equipment companies					
ATMI	ATMI	32.00	14.5000-32.7300	971.5 m	N/A
AXT	AXTI	10.98	8.5500-41.6500	245.5 m	N/A
Emcore	EMKR	9.48	7.5900-44.1300	346.8 m	N/A
Kopin	KOPN	10.62	4.0000-19.0500	726.7 m	N/A
Tegal	TGAL	1.36	1.0000-3.4500	19.5 m	N/A
Trikon	TRKN	15.40	6.9600-16.7200	197.4 m	17.16
Veeco	VECO	31.65	19.9000-57.5000	909.6 m	54.84
European companies (currency data in €)					
Aixtron	AIXG.F	21.05	13.50-59.85	1.35 bn	43.5
Bede	BED.L	2.98	1.95-3.56	86.3 m	N/A
Bookham	BHM.L	2.09	1.22-25.14	296.1 m	N/A
Filtronic	FTC.L	7.03	1.38-8.62	518.0 m	N/A
IQE	IQE.L	2.17	1.40-4.56	355.0 m	99.83
Picogiga	PGIG.LN	5.22	2.60-34.00	33.73 m	N/A
Riber	RIBE.LN	3.87	2.51-23.00	72.44 m	25.86
ST Systems	SRTS.L	2.60	1.63-4.15	81.46 m	20.33

*Market capitalization = # shares × current share price.; **Price/Earnings ratio = current share price ÷ (income for the last four quarters ÷ # shares).

to total demand, as opposed to shifts in MOCVD equipment market shares. Its management says that the Aixtron group (which includes Epigress and Thomas Swan) captured 58% of the market in 2001, virtually the same result as the previous year. Emcore commanded some 30% of the market; the remainder was served by Nippon Sanso, Nissin Electric and "home-made" systems.

The final message from the press conference is the growing importance of the Asian market. Shipments to Taiwan, Japan, Korea and China grew by €55 m in 2002, an increase of 83%. Asia now accounts for half of Aixtron's sales. Sales to the North American market were sluggish in contrast, increasing just 7%.

Aixtron also announced that it would implement a

new organizational structure. Equipment manufacturing will be divided into two business units: Compound Semiconductor Equipment (CSE) and Semiconductor Equipment (SE). The latter will include all of Aixtron's initiatives outside of compound semiconductors, including SiGe and OLEDs. The CSE unit will be run by Paul Hyland, who is currently managing the Thomas Swan operation in the UK. Aixtron's top executives, Holger Juergensen and Kim Schindelbauer, will also be changing jobs. Both will move up from their current positions as members of the Executive Board to a new Chairman's Committee within the company's Supervisory Board. They will advise the Executive Board on mid- to long-term strategic decisions, such as technology, future products and potential acquisitions.

8-11 April

GaAs Mantech

San Diego, CA, USA

Web: www.gaasmantech.com

16-18 April

Semicon Europa

Munich, Germany

Web: www.semi.org/web/wexpositions.nsf

22-25 April

Optronix 2002 World Forum

London, UK

Web: www.optronix2002.com

12-16 May

Indium Phosphide and

Related Materials (IPRM)

Stockholm, Sweden

Web: www.congrex.com/iprm2002

14-16 May

Opto 2002

Erfurt, Germany

Web: www.sensorfairs.de/opto2002

15-17 May

Wireless Design Conference

London, UK

Web: www.wdc-optoconference.com

19-24 May

CLEO/QELS

Long Beach, CA, USA

Web: www.cleo-online.org/

20-24 May

29th IEEE Photovoltaics Specialists Conference (PVSC)

New Orleans, LA, USA

Web: www.ewh.ieee.org/soc/pvsc/

3-5 June

LightFair

San Francisco, CA, USA

Web: www.lightfair.com

3-7 June

IEEE MTT-S International Microwave Symposium

Seattle, WA, USA

Web: www.ims2002.org

3-7 June

International Conference on MOVPE

Berlin, Germany

Web: www.icmovpe-2002.de

10-14 June

Int'l Conference on Electronic Materials (IUMRS-ICEM 2002)

Xi'an, China

Web: www.c-mrs.org.cn/icem2002/

17-21 June

European MRS meeting

Strasbourg, France

Web: www-emrs.c-strasbourg.fr/

24-26 June

Device Research Conference

Santa Barbara, CA, USA

Web: www.tms.org/Meetings/Specialty/DRC/z2002/DRC-2002-home

26-28 June

Electronic Materials Conference

Santa Barbara, CA, USA

Web: www.tms.org/Meetings/Specialty/EMC02/EMC02

11-13 November

Compound Semiconductor Manufacturing Expo (CS-MAX)

San Jose, CA, USA

Web: www.cs-max.com

For links to event websites, visit the Calendar section of our website at www.compoundsemiconductor.net.

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