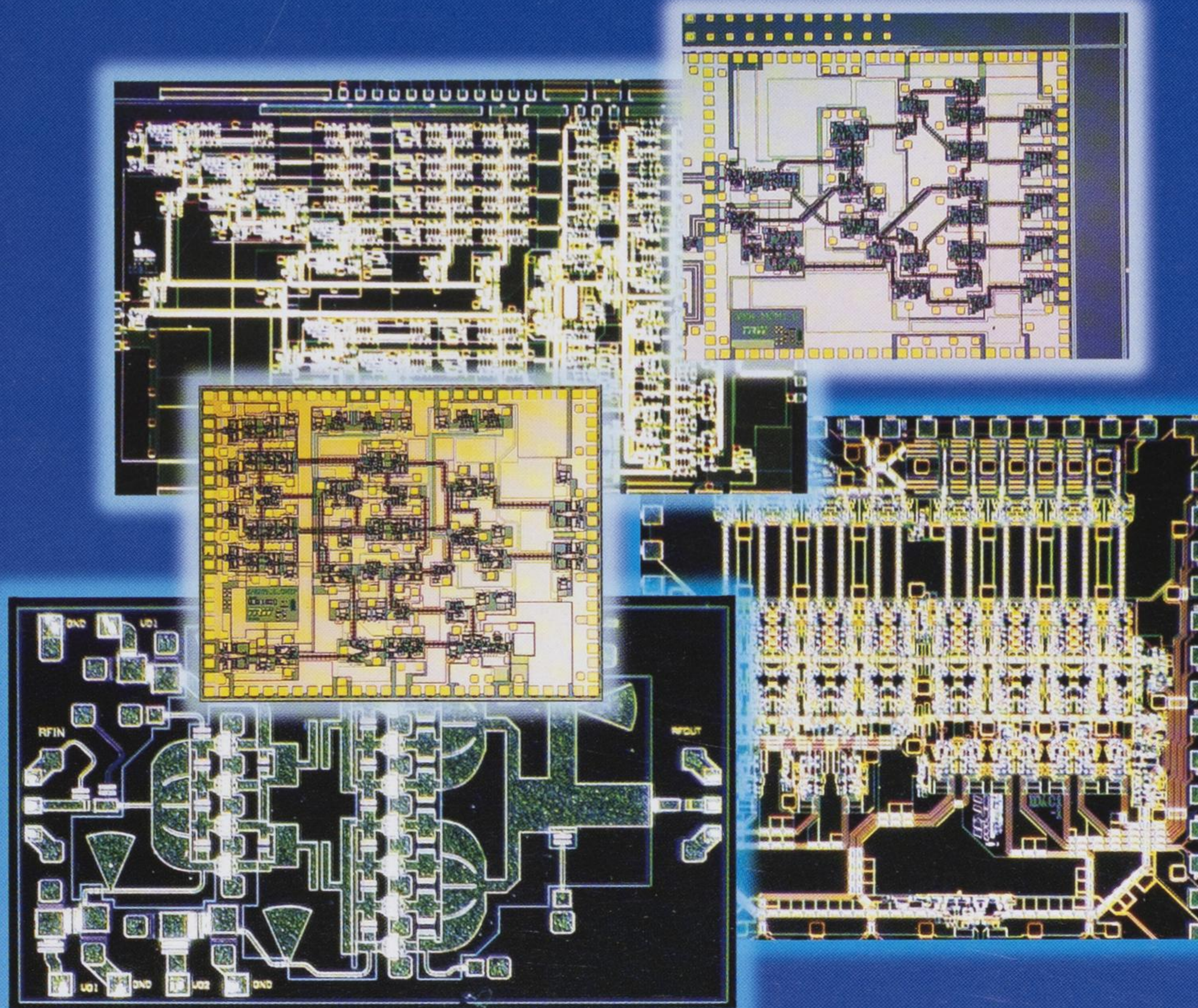


COMPOUND SEMICONDUCTOR

May 2002 Volume 8 Number 4

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INDIUM PHOSPHIDE **Production of InP substrates** **and ICs gathers momentum**

ALSO INSIDE

**New technologies
abound at OFC**

**Showa Denko
shows 6 inch InP**

**VCSEL testing
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from the lab



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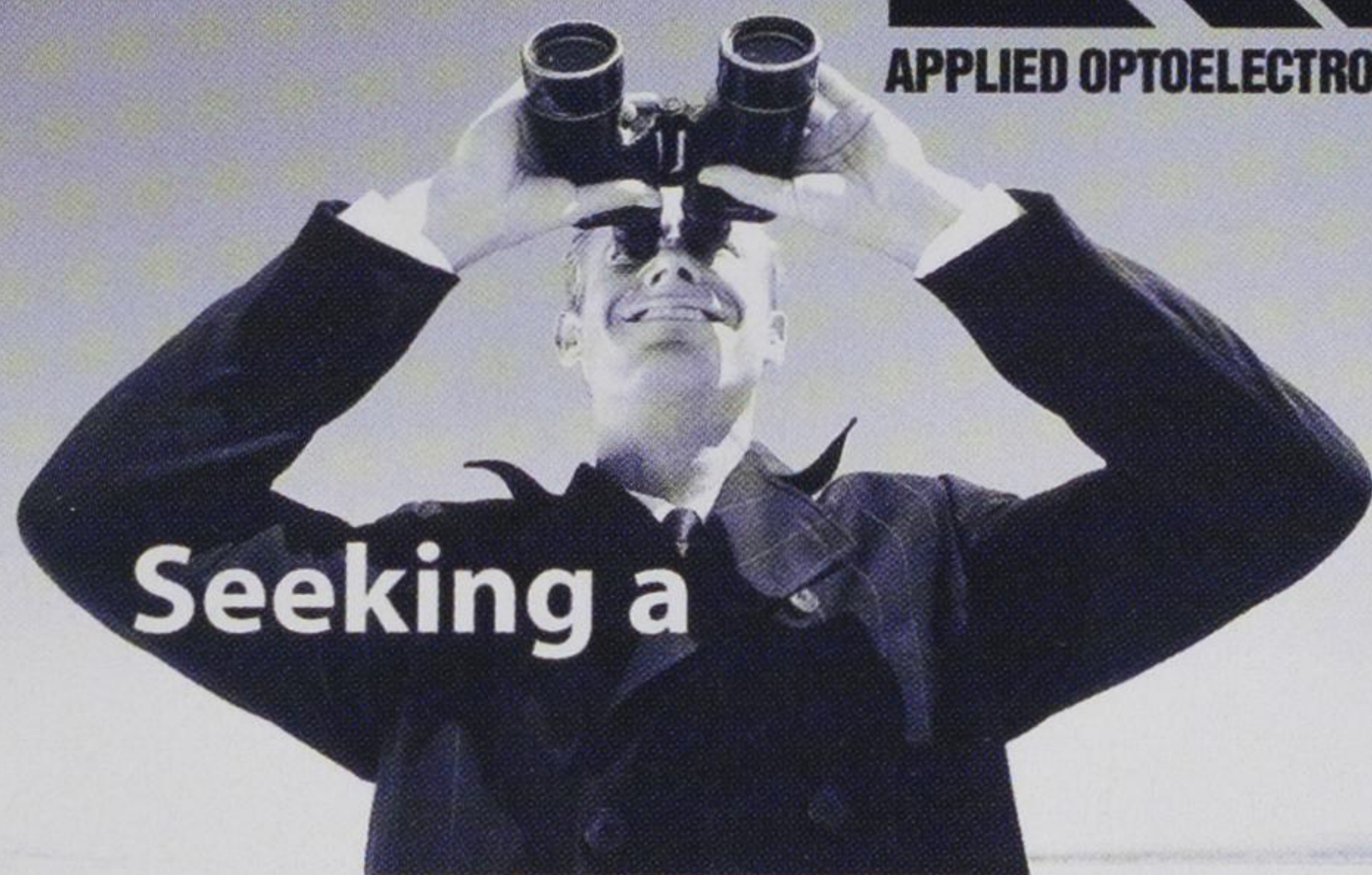
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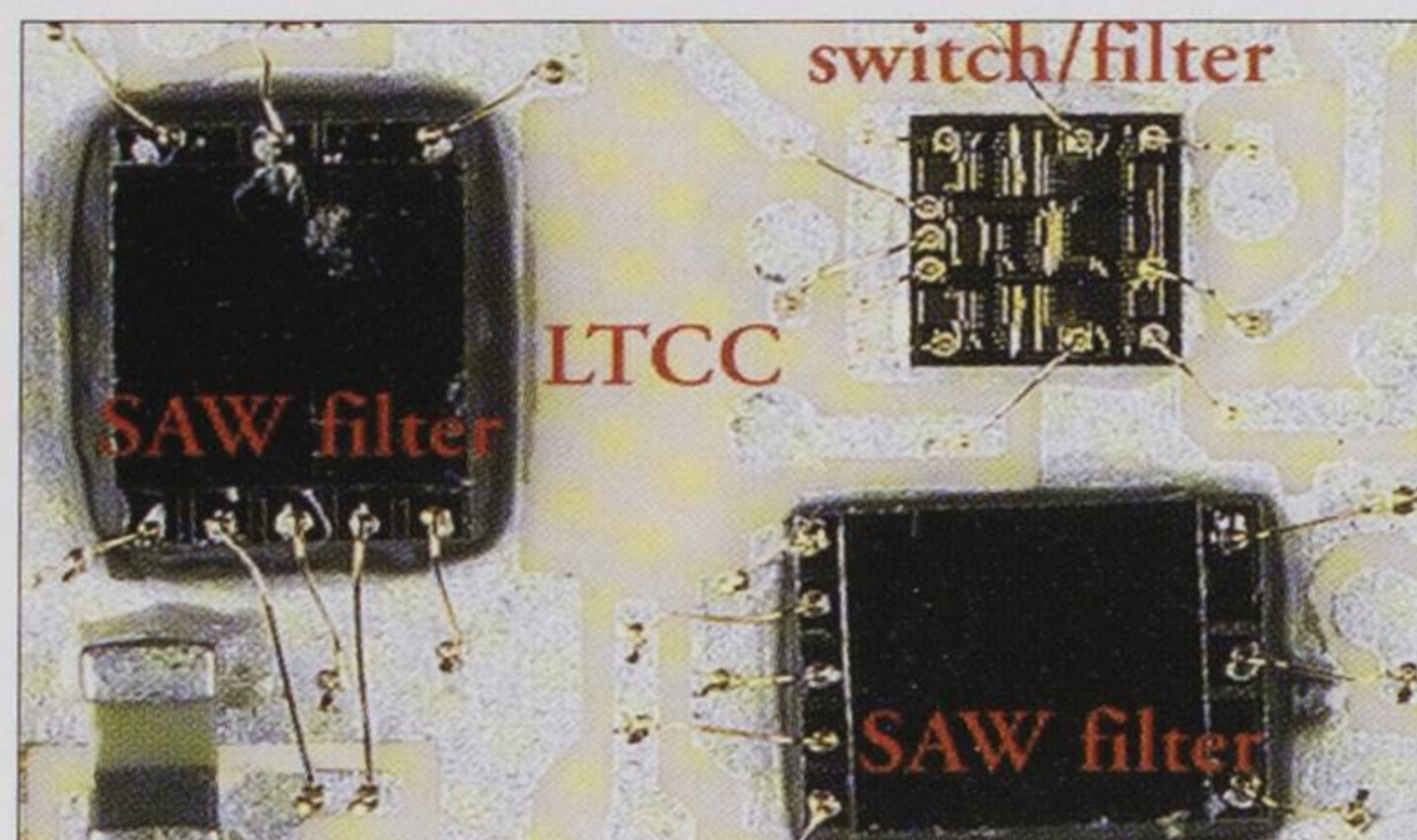
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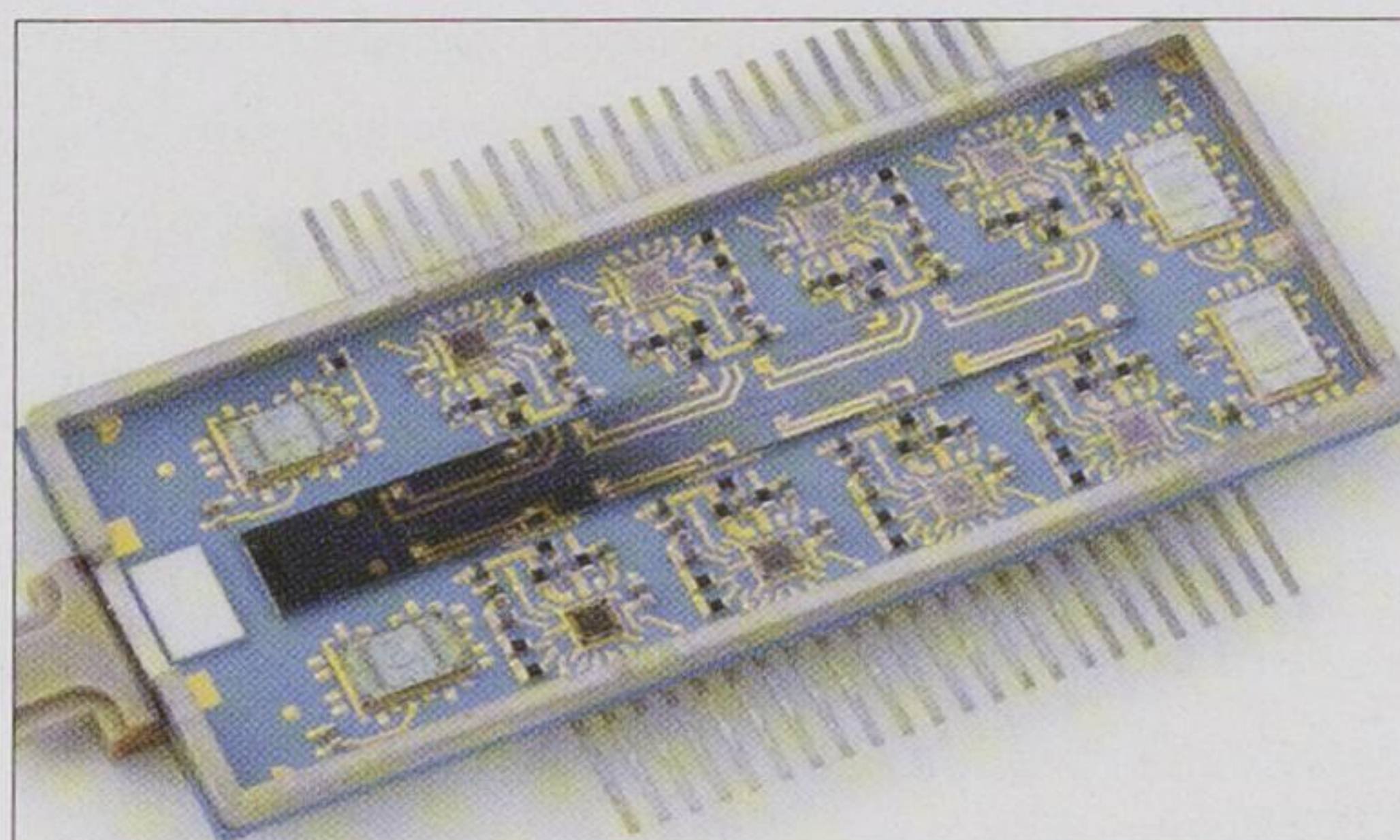
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COMPOUND SEMICONDUCTOR

MAY 2002 VOLUME 8 NUMBER 4



To help its module activities, Alpha has acquired LTCC manufacturer Aimta **p6**



Bookham Technology unveiled an eight-channel hybrid transmitter at OFC **p23**



Velocium discusses key factors in transferring InP HBTs from the lab to the fab **p41**

NEWS

- 3** **Headline News:** Bubbles of enthusiasm enliven Optical Fiber Communication conference... Showa Denko samples 6 inch InP wafers
- 6** **GaAs News:** Alpha buys more module technology... Sirenza acquires 12% stake in GCS
- 9** **LED News:** PARC and Crystal IS demonstrate UV LEDs on AlN... AXT supplies LEDs to Agilent
- 10** **Nitride News:** Sanyo Electric develops InGaN laser on GaN using ion implantation... Nakamura wins \$16 million to develop bulk GaN
- 13** **Fiber News:** Opto Speed raises funds... AOI moves into telecom lasers
- 15** **Materials & Equipment:** IQE and CST sign wafer foundry agreements

FEATURES

- 21** **Silicon Update**
FinFET process pushes gate lengths below 50 nm.
- 23** **Device makers fight it out to share in the 10 Gbit/s action**
Despite a lack of customers, there is a lot of activity at the component level of the fiber-optic market. Tim Whitaker and Richard Dixon report from March's OFC conference.
- 29** **Essient Photonics brings new thinking to optical modulation technology**
- 30** **QPI unveils lasers with circular beams**
- 32** **Nova Crystals takes InGaAs-on-silicon avalanche photodiodes to the market**

49 HB-LEDs continue progress towards solid-state lighting

High-brightness LEDs continue to penetrate a range of markets, says Richard Dixon in the second of two reports from the Strategies in Light conference.

55 VCSEL testing cuts lead times

Scott Jennato, Joe Jablonski and Don Feuerstein look at a new approach to VCSEL testing that should increase wafer yields, and reduce manufacturing costs and time to market.

COVER STORY: INDIUM PHOSPHIDE

35 Indium phosphide ICs in strong demand for 40 Gbit/s networks

Backed by growing market interest and the availability of 4 inch substrates and epiwafers, several IC manufacturers are now developing products for 40 Gbit/s networks, writes Tim Whitaker.

41 The path to InP production

Companies aiming to transfer indium phosphide technology from the lab to the fab can learn a great deal from the GaAs industry, writes Velocium's Dwight Streit.

45 Substrate makers tackle the growing challenges of InP

As demand increases for high-speed indium phosphide ICs in fiber-optic networks, wafer manufacturers must strive to keep pace. Rebecca Pool discovers some of the issues involved in supplying high-quality InP substrates grown using different techniques.

DEPARTMENTS

- Index 2** **Research Review 17**
- Product Showcase 58** **Portfolio 59**
- Advertising Index 62** **Calendar 62**

On the cover: indium phosphide ICs are now in demand for high-speed fiber-optic applications (picture courtesy of Velocium, a TRW company) – see page 41.

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Organization Index

ADC	28	MetroPhotonics	24
Agere	13, 19, 23, 61	Microsemi	50
Agilent	9, 26, 50, 61	Mitsui Chemical	26
Agility	24, 28	MRSI	58
Aimta	6	Multilink	38, 61
Aixtron	16, 61	NEC	13
Albany Nanotech	16	NEL	35
Alcatel Optronics	13, 26, 61	Newport	58
Alpha Industries	6, 35, 61	Nichia	17, 50
Alvesta	25	Nikko Materials	46
Amberwave	15	Nitronex	50
Anadigics	6, 61	NMRC (Ireland)	19
Applied Optoelectronics	13	Nortel Networks	13, 26, 28, 45
ATMI	61	Northwestern Univ.	17
Avalon Photonics	25	Nova Crystals	16, 23, 32
Axcel Photonics	26	OEpic	24
AXT	9, 47, 61	OIDA	50
Bede	59	Opto Speed	13, 38
Bookham Technology	23, 26, 61	Osram Opto Semiconductors	49
Celeritek	61	Oxford Applied Research	58
Centellax	25	Oxford Inst. Plasma Tech.	15
Cielo	25	Palomar Technologies	15
Ciena	3	PARC	9
Coherent	61	Pelk Design Group	53
Conexant	61	Picogiga	61
Corning Lasertron	26	Picolight	13
Cree	9, 11, 50, 61	PRI Automation	16
Crystal IS	9	Quantum Devices	28
CS Clean Systems	16	Quantum Photonics	16
CST	15	RF Micro Devices	6, 61
DA-LightCom	26	RHK	3
Dialight	50	Riber	59
Eblana Photonics	23	Rockwell Scientific	11
Emcore	11, 16, 61	Sanyo	10
Endwave	61	Schefenacker Research	49
Ericsson Microelectronics	16	Shenzhen University	15
Essient Photonics	23, 29	Showa Denko	4
Fiberspace	26	Sirenza Microdevices	6, 61
Filtronic	61	Stella Vista America	49
Flextronics	3	Stratos Lightwave	61
Fraunhofer IAF	16	Sumitomo Electric	13, 46
Fujitsu Quantum Devices	13	Surface Technology Systems	58, 61
Furukawa	26	Suss Microtec	55, 58
Galleos Lighting Design	53	Tegal	61
GCS	6, 35	ThreeFive Photonics	24
Global Light	50	T-Networks	13
Hitachi	35	Tokyo Inst. of Tech	18
Honeywell	25	Tokyo Science Univ.	11
HRL Labs	35	Trikon	61
Infineon	13, 26	TriQuint	61
Intel	3, 13	Uniroyal Technology	61
Iolon	15, 28	United Epitaxy Co.	16
IPAG	38	Univ. of Ca Santa Barbara	11, 17
IQE	15, 59	Univ. of Ca. Berkeley	21
iTerra Communications	25	Univ. of Ca. LA	16
Japan Energy	46	Univ. of Tsukuba	11
JDS Uniphase	13, 26, 61	Veeco	61
Kamelian	13	Velocium	35, 41
Kopin	61	Vitesse	35, 61
Lucent	26	Wafer Technology	47
LumiLeds Lighting	9, 50	WorldCom	3
Luxtron	58	Xindium Technologies	24
M/A-COM	46		
Max Planck Inst.	17		

Bubbles of enthusiasm enliven Optical Fiber Communication conference

By Tim Whitaker

Many of the 32,000 people who attended the recent Optical Fiber Communication (OFC) conference, held on March 17–22 in Anaheim, CA, no doubt hoped to discover when the current downturn will end. Most if not all went away disappointed. Component vendors, analysts, market researchers and even the service providers perched on top of the food chain were unable to answer the questions of when and how quickly growth will return to this previously vibrant industry.

However, everyone seems confident that growth will be back at some point and companies have different strategies for riding out the current slump. Many have restructured to make their manufacturing operations leaner, and there is a trend towards automation and outsourcing. There continues to be a great deal of new product development and technical innovation, and some companies spoke of the downturn as a positive opportunity to refine their product offerings in time for the upswing.

While there were 6000 fewer attendees than last year, the number of companies in the exhibit rose from just less than 1000 to 1200. Although venture capital is more scarce, new companies continue to appear. Cash conservation is key: start-ups were keen to stress that they had several million dollars in the bank and were spending slowly to see them through to better times, when someone would actually buy their product. Nevertheless with so many companies at all levels of the industry more consolidation and bankruptcies are inevitable.

Managing through cycles

As a prelude to OFC, an executive forum entitled Managing Through Cycles was held to discuss strategies for working through the downturn and into the recovery period. In his introduction John Ryan, chief analyst at RHK, set the scene perfectly. “In 1999–2000 everyone spent money like drunken sailors,” he said. “Now we’re in the hangover period.”

Ryan predicted that it will take at least one more year for the industry to pick up. “After a slow start, recovery will be in full swing by mid-2003 throughout the value chain. Growth will occur before then in certain sectors.” Others seemed less certain of the timing for recovery, but are sure that it will happen

sooner or later. Bandwidth demand remains and Internet traffic is still growing at slightly more than 100% a year, although this is significantly down from the 160% growth in 2000. Global penetration of the Internet is still small, and new applications – such as wireless data, streaming data and interactive gaming – are emerging rapidly.

“The bottom line is that we are planning for recovery,” said Steve Jackson, director of network architecture and standards at WorldCom, a leading US carrier. “We’re looking at optical technology for next-generation networks, but at the same time legacy networks also have to be managed.”

Service providers have already slashed their capital expenditure (capex) costs, and there is little indication of when this spending

“In 1999 and 2000 everyone spent money like drunken sailors. Now we’re in the hangover period.”

will return and filter down through the food chain. However, a key message was the need for component vendors and system suppliers to help carriers reduce their operating expenditure (opex). Rather than installing new fiber, carriers are looking to utilize their existing infrastructure to provide new services, so need ways to increase flexibility and functionality and to control and manage bandwidth. As the network vendors – companies like Cisco, Ciena, Nortel and Lucent – concentrate on tasks such as network management, they are passing responsibility for the hardware further down the chain. Module and subsystem vendors such as JDS Uniphase, Agere and Alcatel are seeking to incorporate more and more functionality into their products while reducing cost, footprint and power consumption. In turn, this creates opportunities at the component level for products such as low-cost amplifiers, uncooled and tunable lasers and long-wavelength VCSELs, and products with more integration at the chip or module level.

According to Mark Christensen of Intel Capital, companies must continue to invest in R&D even when cutting expenditure every-

where else. Steve Alexander, CTO of Ciena, agreed that development must continue. “At present, no-one is buying products,” he said. “We need to make sure we have the correct products ready for when recovery occurs.”

A series of future challenges from the service-provider perspective were put forward by Jackson. “Service providers will require next-generation fiber, bit rates as high as 320 Gbit/s, 160–240 wavelengths and an ultra-long-reach of 6000 km.”

Outsourcing

Several of the panel spoke about the importance of outsourcing in order to reduce manufacturing costs. “In the past, technology was king, capital was freely available and companies focused on building the best possible components using their own manufacturing resources,” said Christensen. “Now the customer is king, capital is scarce and modules and outsourcing are much more important.”

It seems likely that some companies built fabs when they shouldn’t have. “Companies have no business being in manufacturing unless they’re a manufacturing company,” said Christensen, who added that the Far East should be part of everyone’s plans, since the region is a big market and is also developing infrastructure for low-cost but highly sophisticated manufacturing.

According to Ron Keith, general manager of Flextronics Photonics, the race to install capacity has been replaced by the need to provide the best price:performance ratio and this should favor outsourcing. “No industry competes on capacity for long,” said Keith. “If you can’t eat it then it’s subject to economic cycles.” People are building customized equipment and doing things their own way, which is bad for the industry at large. “Everyone is convinced they have the best manufacturing technology and they want to protect their intellectual property rather than introduce standards,” explained Keith.

Several of the speakers agreed that bankruptcies and consolidation must occur at all levels of the industry. Steve Alexander, CTO of Ciena, put it bluntly: “There can’t be hundreds of suppliers in this industry.”

● Next year’s OFC will be held in Atlanta, GA on March 23–28.

Japan's Showa Denko samples 6 inch InP wafers

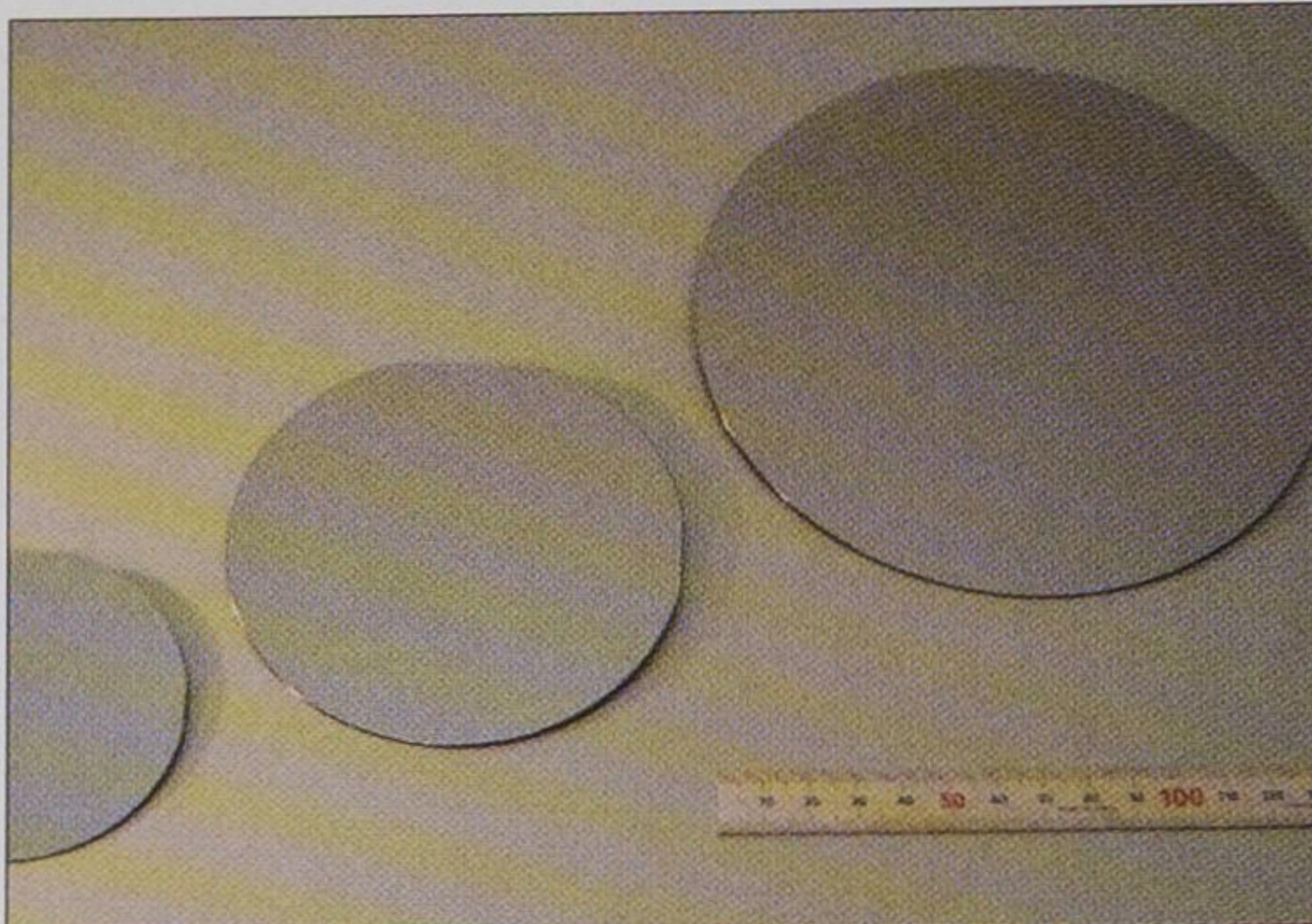
By Rebecca Pool

Japanese wafer manufacturer Showa Denko has developed the world's first 6 inch InP wafer. Showa Denko is already shipping sample quantities and plans to start volume production later this year.

The company makes the 6 inch wafers using a proprietary hot-wall liquid encapsulated Czochralski (LEC) method. According to Takayuki Sato, marketing manager of compound semiconductor materials, growing 6 inch wafers in this way has posed some fabrication problems.

"There are more difficulties in growing 6 inch boules than 4 inch boules and it is very important to maintain thermal stability during crystal growth," he said. "We are continuing to adjust the growth conditions to improve the crystal quality and have achieved dislocation densities of $1 \times 10^5/\text{cm}^2$." This is comparable to the dislocation density of wafers currently available.

Showa Denko hopes that its latest wafer



SHOWA DENKO

Japan-based Showa Denko has added 6 inch InP wafers to its product portfolio.

"While wafer demand will be relatively small over the next two years, we expect growth in the future."

will become the material of choice for photo-diodes in 40 Gbit/s fiber-optic communica-

tion systems and believes that by 2005 the wafer will constitute up to 10% of its total InP wafer and epiwafer sales.

"Some of our customers have already asked us to provide them with 6 inch wafers," said Sato. "While we suppose that the volume of wafer demand will be relatively small over the next two years, we expect growth in the future," he added.

Sato also believes that chip makers' need to upgrade their equipment from 4 to 6 inch wafers will not hamper demand as many device manufacturers, particularly in the US and Taiwan, already have 6 inch fabrication lines for GaAs devices.

"We have a plan to start volume production by the end of the third quarter of 2002," Sato concluded. "Production capacity will be approximately 500 wafers per month, and because we have a compatible process between 6 and 4 inch [wafers] we will be able to adjust the volume of our production according to the customer's demand."

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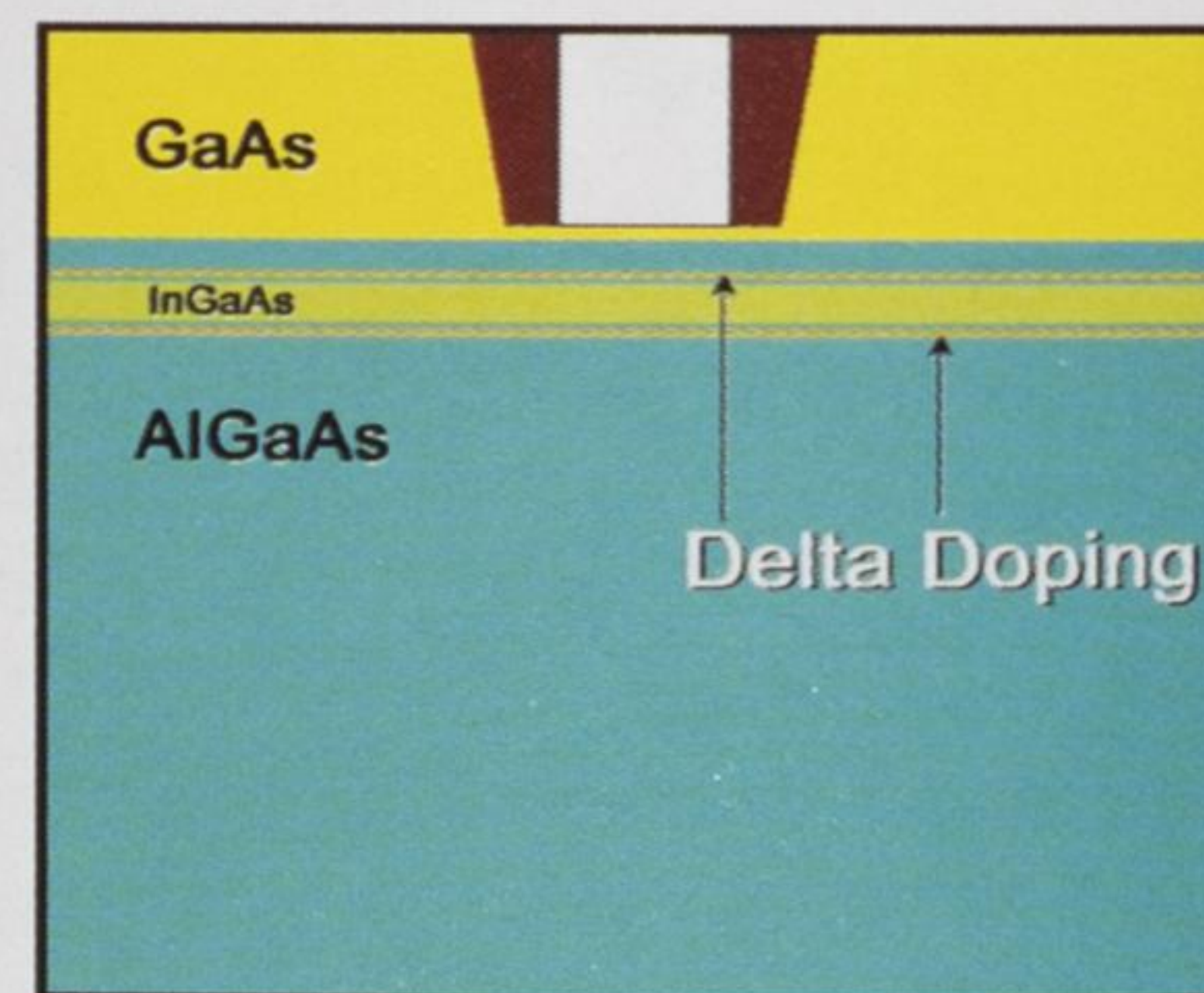
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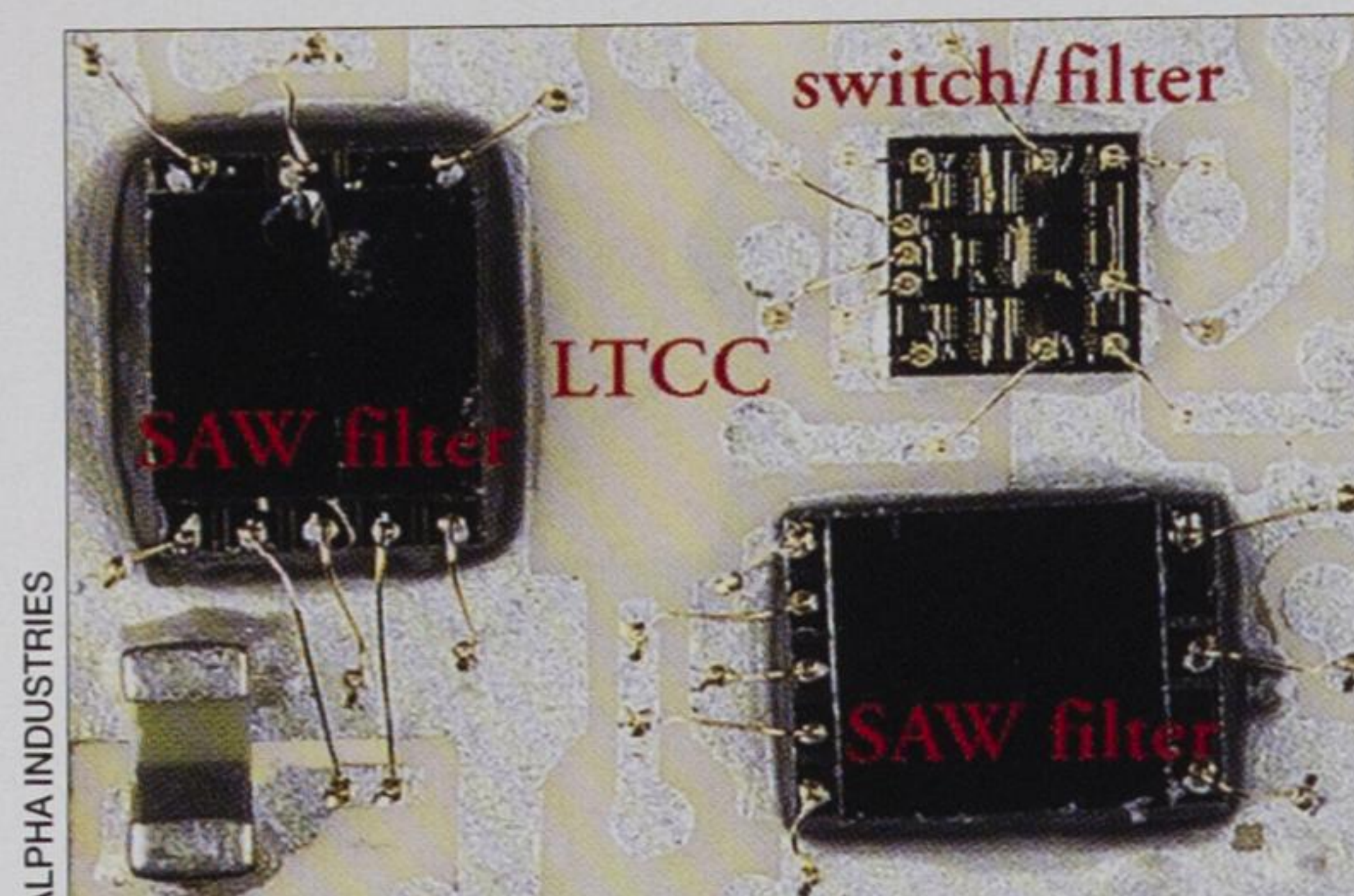
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Alpha buys more module technology

Alpha Industries has acquired Aimta of Fremont, CA for \$7 million in cash. Aimta develops low-temperature co-fired ceramics (LTCC) used to make GaAs switches for wireless handsets, and the acquisition gives Alpha intellectual property, design and prototype engineering capabilities. In addition, the company has dedicated LTCC manufacturing capacity at a facility in Taiwan operated by Integrated Module Technology, the company that formed Aimta. Alpha expects the transaction to conclude shortly.

This is the latest in a series of deals to consolidate Alpha's RF front-end technology roadmap. Last year the firm unveiled a multi-chip module integration platform for RF applications up to 3 GHz, and made an alliance with SAW filter manufacturer EPCOS to co-develop switch/filter modules (see *Compound Semiconductor* August 2001, p9).

Alpha's CTO Lj Ristic says LTCC enables passive components such as capacitors, inductors and resistors to be integrated using a multi-layer approach. Individual passive components are placed on separate ceramic



LTCC enables smaller SAW filters and GaAs PHEMT switch-filter modules to be made, leading to higher-frequency operation.

layers using conductive metal layers, and each ceramic layer is also punched through to allow interconnection between layers. These layers are subsequently aligned and laminated under heat and pressure, creating a monolithic substrate with as many as 20 levels.

Ristic says this enables significant size reductions and higher-frequency operation than conventional PCBs, and is very efficient for making GaAs switch-filter modules, in

addition to power amplifier modules and wireless LAN devices.

"Major wireless handset OEMs recognize the emergence of LTCC as an important advance in multi-chip module integration," said Ristic. "LTCC represents an enabling technology for high-performance RF modules that are smaller, less expensive and have a lower part-count than modules using competing technologies. LTCC also reduces design lead times, enhances functionality and shortens time-to-market for new handsets."

Design wins

Alpha says the technology is already driving new design wins. These orders include a module that combines a GaAs switch and filter designed into a mobile platform serving as a CDMA wireless handset and GPS receiver.

In addition, Alpha has qualification orders from an established OEM for GaAs/LTCC switch-filter modules used in 802.11a and 802.11b WLAN chipsets. This product is scheduled to enter volume production in the second half of the year.

Sirenza acquires 12% stake in GCS

Global Communication Semiconductors (GCS) has raised \$10 million in funding from Sirenza Microdevices and KLM Capital Group, taking the total GCS has raised since January to \$27.5 million (see *Compound Semiconductor* March 2002, p17).

Sirenza (formerly Stanford Microdevices), which contributed \$7.5 million to the latest funding round, is a fabless IC supplier. GCS is one of Sirenza's principal wafer fabrication partners, supplying products including InGaP and InP HBT wafers. The purchase of GCS

stock gives Sirenza a 12% stake in the company and a seat on the board of directors.

"This investment supports our fabless operating model," said Robert Van Buskirk, Sirenza's president and CEO. "We believe it will strengthen our supply chain and help maintain our price:performance leadership across a broad spectrum of products for both wireless and broadband wireline markets."

● Sirenza recently upgraded its 1994 ISO 9000 certification to the new, more rigorous ISO 9001:2000 standard.

Anadigics awarded patent for converter

Anadigics has received a patent for a DC-DC converter, a circuit that changes the voltage of a DC power supply typically used to step-up or step-down voltage. US patent no. 6,314,008 was awarded for a design that delivers a very low incidence of spurious signals from a single power supply for front-end amplifiers. These amplifiers have applications in cable-television systems and other broadband RF receivers.

Amplifiers using depletion-mode devices such as FETs require a bias voltage to turn the

devices off (non-conducting) from the normal on (conducting) state. According to Anadigics, if a depletion-mode device requires a negative bias supply, but the main circuit power supply is positive, the negative bias potential must be generated from the positive potential. The company's patented circuit avoids this by generating a plurality of output DC voltage levels with the opposite polarity of the DC control voltage. In addition, the device converts the DC control voltage to an output voltage functioning as a DC-DC converter.

RFMD, Alpha ship handset PA modules

RF Micro Devices has begun production shipments of two GaAs HBT PA modules to a leading handset manufacturer for use in CDMA 1X handsets for the North American market. Shipments are expected to reach a multimillion-dollar level this calendar year.

"This OEM has consistently been one of our top customers, and we are pleased to expand our long-standing relationship to include power amplifiers for a major CDMA 1X handset platform," said president and CEO David Norbury.

Meanwhile, Alpha has announced that its quad-band InGaP HBT power amplifier module has been designed into two next-generation mobile phones scheduled to be introduced in 2002 by a top-tier wireless handset OEM. Alpha's 137-501 module effectively eliminates the need for more than two-dozen matching components, and will be integrated into dual-band GPRS-compatible handsets that are expected to be introduced in the US, Europe and Asia later this year. The module can be used to power quad-band handsets as well as dual- and tri-band phones.



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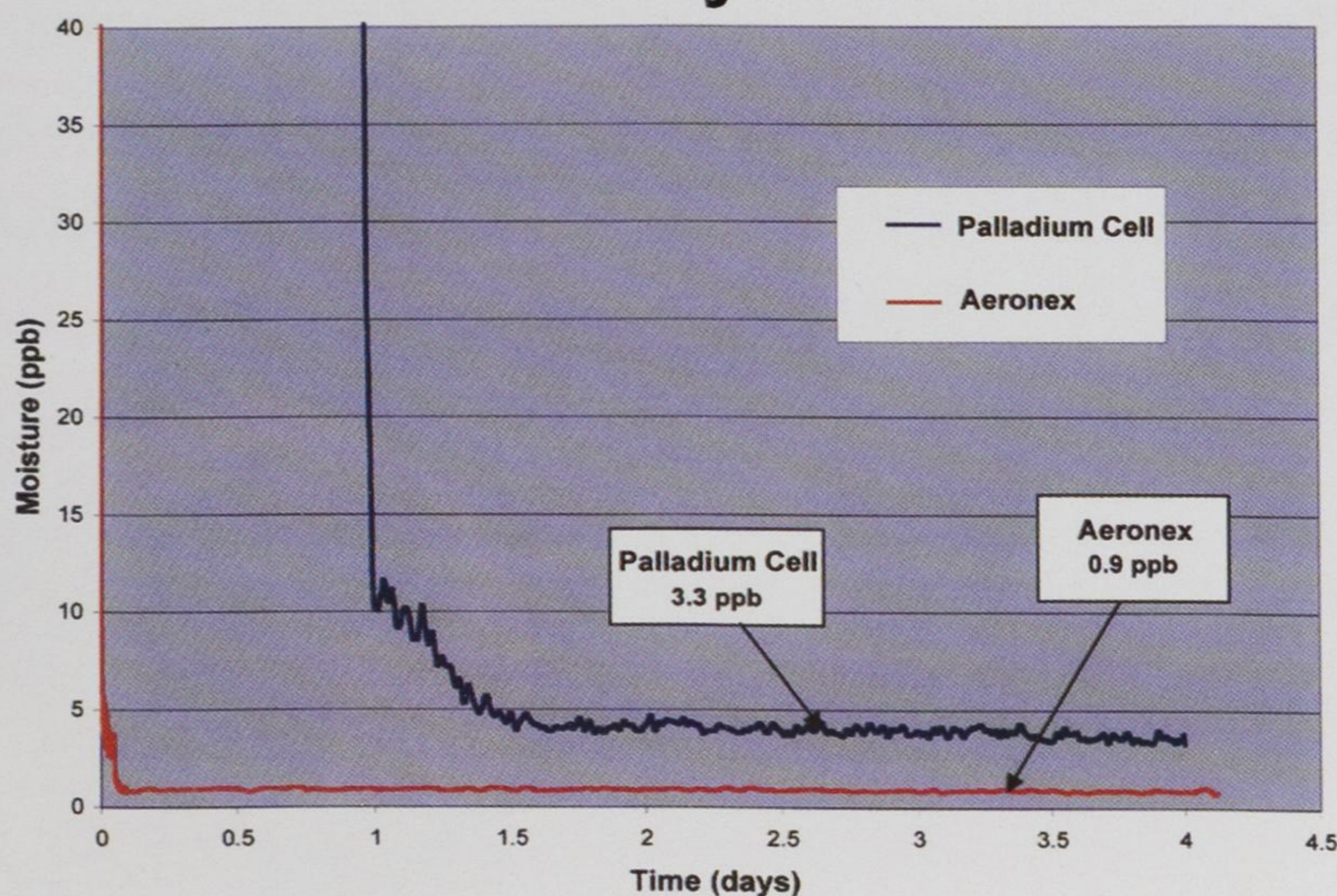
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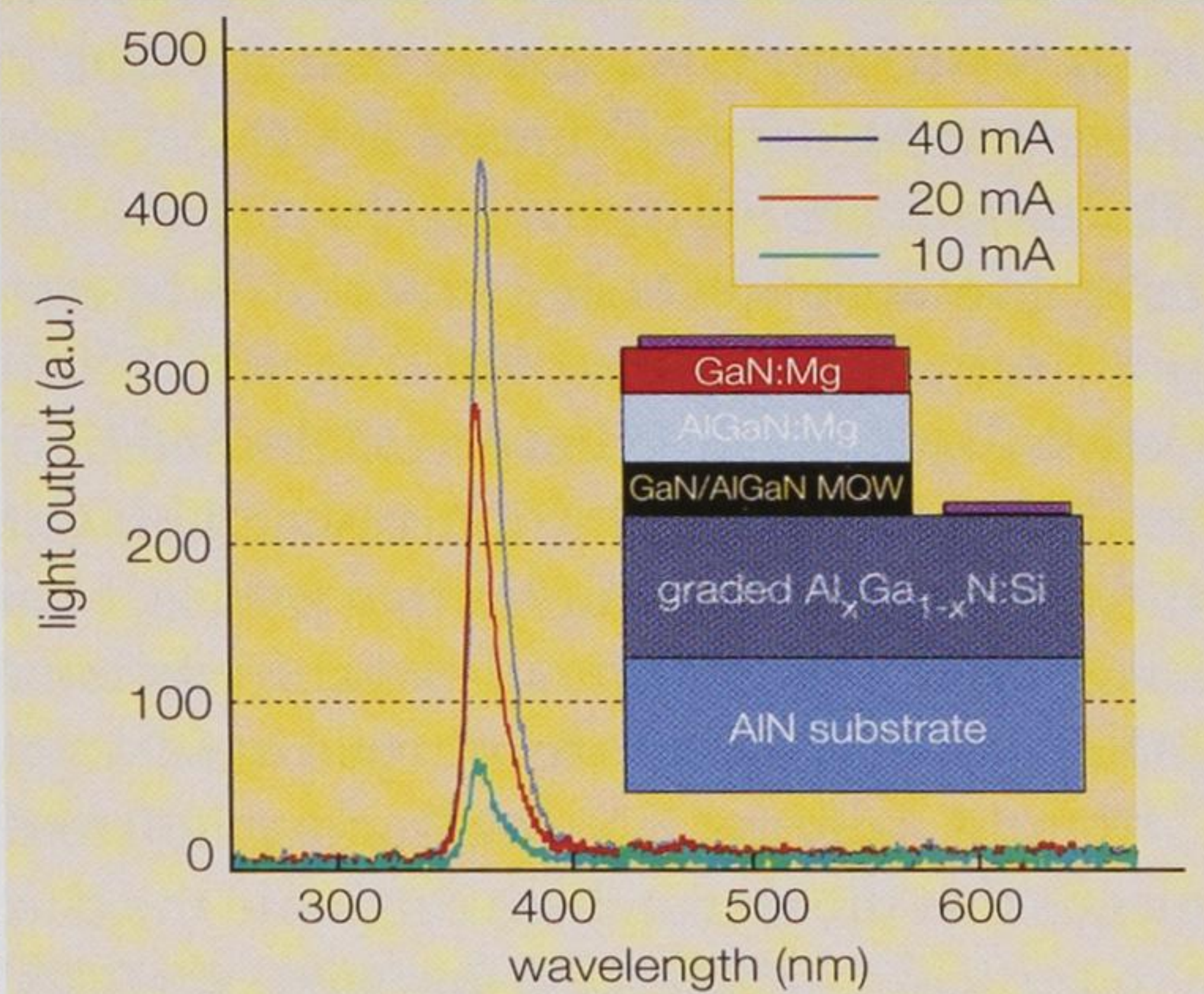
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PARC and Crystal IS demonstrate UV LEDs grown on AlN substrates

Researchers at Palo Alto Research Center (PARC), a subsidiary of Xerox, and Crystal IS, a substrate supplier, have demonstrated what they claim is the first UV LED grown on a single-crystal AlN substrate. The 100 μm device has a top p-contact, a lateral n-contact and incorporates a GaN/AlGaIn MQW active region (see figure). Light is extracted through the bottom of the transparent AlN substrate. The emission wavelength is close to 360 nm, making the device suitable as a source for phosphor excitation, water purification, or as a compact analytical device for the biotechnology and pharmaceutical markets.

AlN has a high thermal conductivity of approximately 320 W/m.K, which is almost double that of GaN and 10 times that of sapphire, the most common substrate used for the growth of GaN-based LEDs. This provides better heat dissipation during high-power operation. Other advantages of AlN are that the difference in thermal expansion between AlN and GaN from 1000 °C to room temperature is negligible, and the lattice mismatch is also much smaller than that between

Ultraviolet LED on AlN



PARC and Crystal IS have developed the first UV LED on AlN. The device operates at 360 nm and is grown on a single-crystal (0-112) aluminum nitride substrate with a Si-doped graded AlGaIn layer.

GaN or AlGaIn and sapphire. This becomes increasingly important for devices that have AlGaIn active layers with high Al concentrations, which is required for deep-UV LEDs

with emission wavelengths below 300 nm.

Crystal IS supplies AlN single-crystal substrates from 0.5 inch diameter boules. Supported by BDMO funding and operating from a leased space at Rensselaer Polytechnic Institute, the company has plans for 2 inch wafers sometime in 2002. At present, substrates are cut and treated using chemical-mechanical polishing and have dislocation densities of less than $10^3/\text{cm}^2$, at least six orders of magnitude less than typical GaN layers on sapphire. According to PARC's Michael Kneissl, the growth technique used reduces the RMS roughness of the surface from 0.83 to 0.38 nm prior to deposition of a graded AlGaIn:Si buffer.

"There are a number of issues relating to the device fabrication, as well as growth, that have to be optimized to make a high-output device," explained Kneissl. "At the moment the drive voltage is quite high because p-type doping at this high aluminum content is hard to achieve. The contact resistance is also not ideal due to the transition layer and the etching down to make a contact to this layer."

AXT supplies LEDs to Agilent

AXT has signed a deal to supply InGaIn LEDs to Agilent Technologies, even though Agilent also manufactures such devices. AXT will supply InGaIn LEDs to Agilent's Malaysian manufacturing arm for use in cellular-phone backlights and other applications.

"Agilent has an internal supply of InGaIn devices, including a supply from LumiLeds, but in order to meet the growing customer demand for high-quality InGaIn LEDs for the mobile-phone market, we are also outsour-

cing InGaIn chips from a few select vendors," said Soo-Ghee Lee, Agilent Optoelectronic business unit manager. Cree is also known to sell InGaIn chips to Agilent.

"Agilent packages its ChipLED devices and also tests the final product, adhering to the company's high-quality standards," continued Lee. "Stringent specifications are in place to ensure that the LEDs receive the required quality, and customers are fully supported by Agilent."

Cree reports first-quarter revenue fall

On April 11 Cree announced that its revenue for the March 2002 quarter was \$33.4 million. This represents a sequential fall of 19% compared with the \$41.2 million recorded in the quarter ended December 23, 2001. One year ago Cree reported revenue of \$53.4 million for the first quarter of 2001. The company had

a net loss of \$68 million, or 94 cents a share, for the March 2002 quarter. However, the results included a one-time pre-tax charge of \$82.5 million related to the downsizing of Cree's UltraRF business. Excluding these charges, the company recorded a net income of \$320,000. Looking forward, Cree has predicted a 5% sequential revenue increase in the current quarter and also reported order bookings for 70% of the expected revenue for its LED business.

LumiLeds provides LEDs for displays

LumiLeds Lighting has entered into a strategic relationship with Mitsubishi Electric to supply liquid-crystal display (LCD) modules employing high-brightness LEDs. Mitsubishi will use LumiLed's Luxeon high-flux LEDs in a new thin-film transistor LCD design that provides higher brightness. The monitors are expected to deliver improved color fidelity and longer life than current LCD screens using cold cathode fluorescent lamps.

The first monitors are due to appear by the end of 2002, and one of the initial applications, which is currently under development by Mitsubishi's Advanced Display subsidiary, will be a large high-resolution display for desktop publishing.

"Our customers have expressed a strong interest in our Luxeon LCD modules, and we believe that the technology will eventually replace cold cathode fluorescent lamps in most monitors on the market," said Eishi Gofuku of Mitsubishi's LCD division.

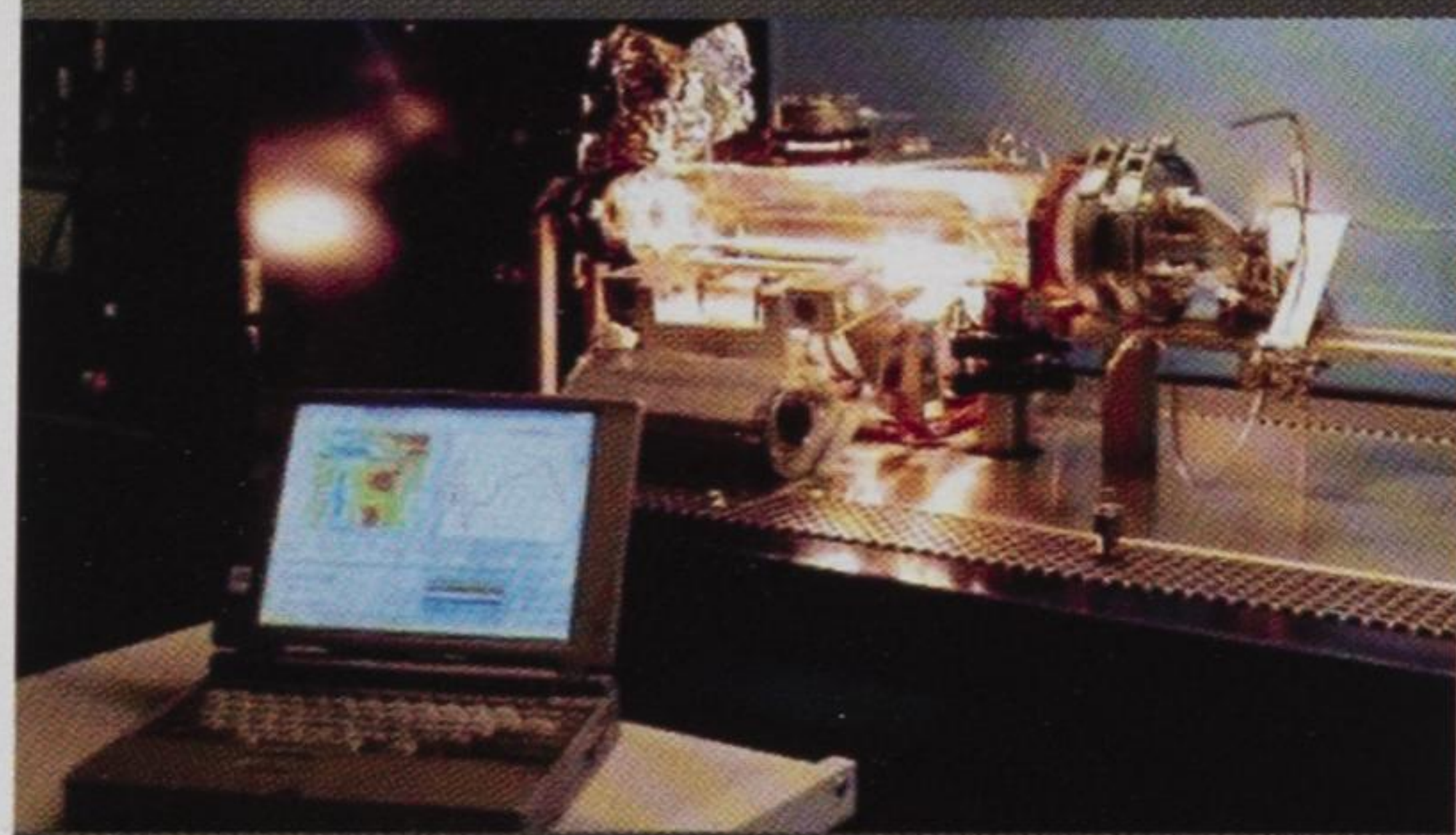
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Sanyo Electric develops InGaN laser diode on GaN

By Rebecca Pool

Sanyo Electric of Japan has developed an InGaN 405 nm laser diode that it plans to mass-produce for advanced DVD systems. The diodes are built on a GaN substrate and have an output power of 5 mW and an operating lifetime of at least 2000 hours. While Sanyo Electric would not reveal the details of its GaN substrate production, researchers told *Compound Semiconductor* that the laser has a structure which differs from conventional InGaN-on-sapphire devices in two main ways.

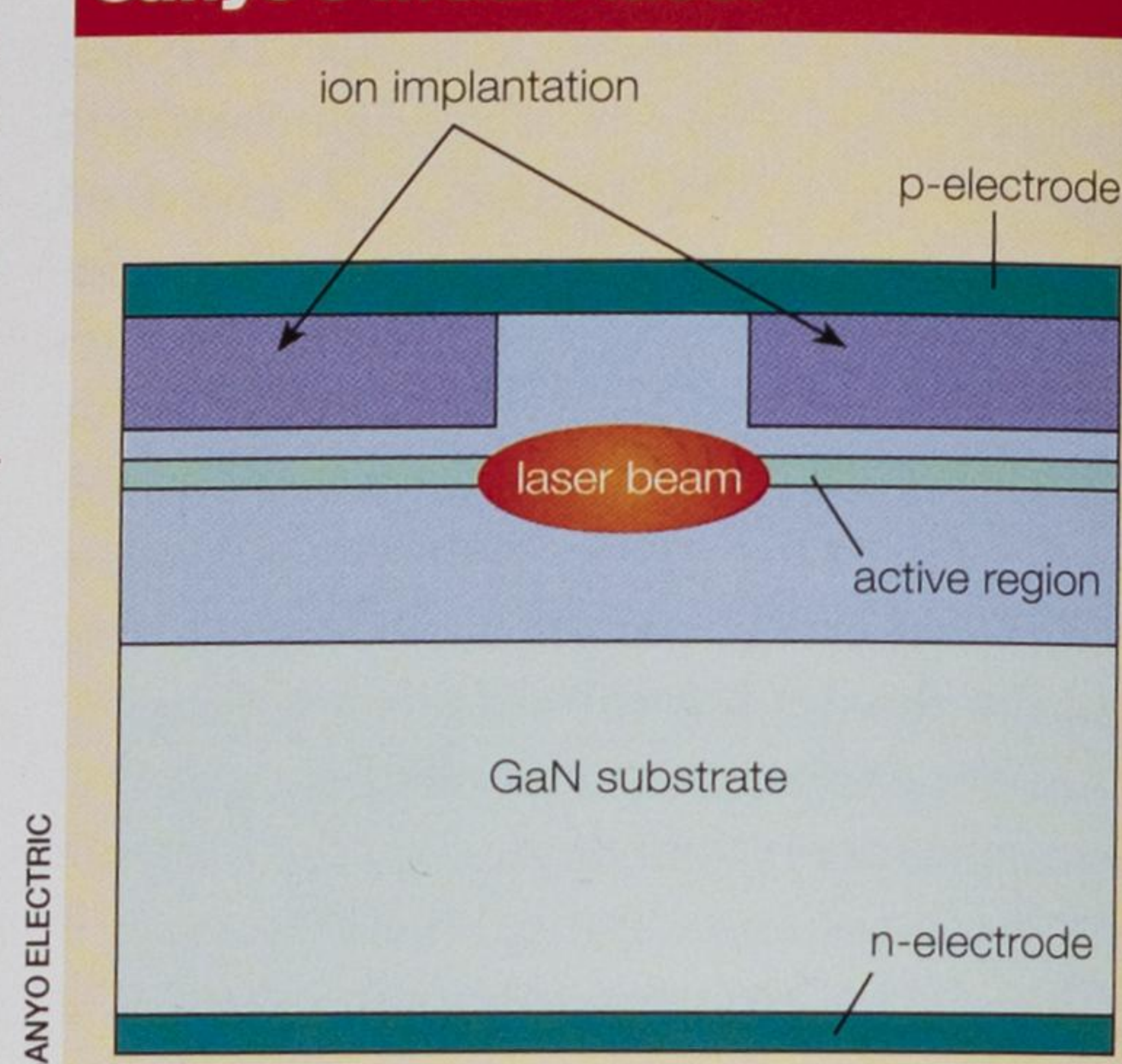
Firstly, using a GaN conducting substrate means that the researchers can build the chip as a vertical structure with the electrodes sited at the top and bottom of the device. Secondly, ion implantation in the p-type cladding layer provides optical and current confinement, helping to stabilize the laser and reduce noise.

Device fabrication

To make the device, Sanyo Electric researcher Minoru Sawada and colleagues deposited the epitaxial layers as a vertical stack on the GaN substrate, carried out the ion implantation step and then added the electrodes (see figure). According to Sawada, this vertical top and bottom electrode arrangement makes chip production simpler and less costly, because his team can sidestep the initial etching stage of InGaN-on-sapphire chip production that is necessary to allow electrode fabrication on the n-type cladding layer. He also says that the vertical structure lends itself to the mass production of these laser diodes more easily, and reduces the chip size by up to half compared with conventional chips.

Blue laser diodes typically suffer from beam instabilities that generate noise and lead to high operating currents. To combat this, the researchers implanted a so-called "stable beam structure" into the device's p-type cladding layer. According to the team, implanted ions in this region stabilize the laser in both vertical and lateral directions

Sanyo's InGaN laser



Sanyo Electric's new laser diode is based on a vertical stack structure with top and bottom electrodes. Ion implantation in the p-type layer improves laser-beam stability and results in low noise and a low operating current.

within the diode. This step also removes the need for a second etch to produce a ridge in the p-type layer that would otherwise help stabilize the laser.

Although reluctant to reveal more details of the ion implantation process, Sawada said: "By optimizing the ion implantation conditions, we introduce a refractive index difference in the lateral direction of a laser diode. We can use this to obtain both current and optical confinement within the diode, and in this way achieve a stable laser beam."

Next-generation DVDs

Sanyo Electric is already a leading manufacturer of 780 nm AlGaAs lasers for CD players and 650 nm AlInGaP lasers for DVD drivers. The electronics giant now plans to target next-generation large-capacity optical disc systems, and will start selling its InGaN laser diodes at volume production levels by April next year.

**Compound semiconductor news
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Emcore, Rockwell advance GaN HEMTs

Emcore is to supply GaN HEMT epiwafers to Rockwell Scientific, as part of a joint development agreement between the companies. Rockwell Scientific will provide feedback to Emcore on material-device correlation, as well as device behavior.

"The GaN market is rapidly expanding and this partnership with Rockwell Scientific will help us to provide effective GaN-based products," said Emcore's VP of sales and marketing, Tom Mieke. "Having our materials thoroughly road-tested by Rockwell also ensures that our high-volume production facilities will be fully optimized."

GaN devices offer extremely high temperature operation at high power levels and also have good linearities, which makes them ideal as power amplifiers in wireless base stations. The use of GaN-based HEMT amplifiers as compact devices that can handle high powers is also being explored for military applications.

Rockwell senior scientist Karim Boutros believes that GaN HEMTs are vital in developing robust microwave device applications. "Partnering with Emcore means that we can make fundamental material and device advances that will drive GaN-based power amplifiers into military and commercial systems," he added.

Cree gets millions to target anthrax

As part of its continuing fight against terrorism, the US government has awarded LED maker Cree \$14.5 million to develop 280 to 340 nm LEDs and laser diodes for systems that detect biological agents such as anthrax. Cree's potential new devices will also find use in tactical communications.

The award comes from the US Army Research Laboratory (ARL) and, supported by DARPA, forms part of a four-year contract totaling \$26.5 million. Cree's CEO Chuck Swoboda says the company is looking forward to using its technologies in new applications. "We are excited to embark on research where LEDs and laser diodes could be integrated into critical applications that will protect our armed forces and US citizens," he said. "We believe this funding will enable us to expand the opportunities for our products beyond traditional LED and laser applications."

Nakamura wins ERATO award

Blue laser diode inventor Shuji Nakamura has won a \$16 million (¥1.7 billion) grant to develop bulk GaN and perfect the deposition of thin-film GaN. The five-year exploratory research for advanced technology (ERATO) grant comes from the Japan Science and Technology Corporation (JST) and will fund work at the University of California at Santa Barbara where Nakamura is director of the Center for Solid State Lighting and Displays.

"The ERATO award is more like a gift than a standard research grant as I can determine exactly how to use it," said Nakamura. "It is a wonderful, creative way of supporting research and I am deeply honored that JST has selected me as the focus for their support."

Getting to grips with GaN

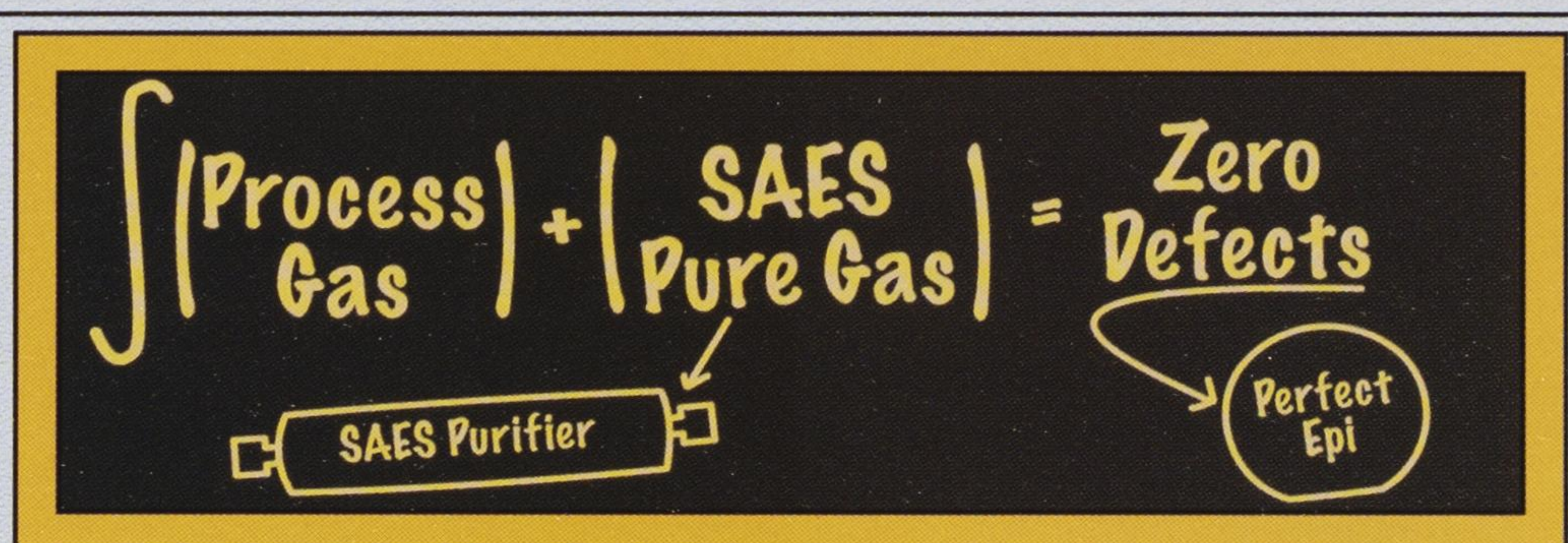
GaN is notoriously hard to fabricate in bulk form, and is typically deposited as a thin film on sapphire, silicon or silicon carbide. But during heteroepitaxial growth, defect-free layers of GaN are very difficult to obtain be-

cause of lattice mismatches at the substrate/GaN interface.

Nakamura intends to solve the fabrication problems by first building a high-pressure, high-temperature vessel to make "nearly perfect" bulk crystals. He will also develop technologies to deposit high-quality GaN on heterogeneous substrates.

Nakamura then plans to explore the defects that develop within GaN during crystal and thin-film growth and examine how these defects influence device performance. By doing this he hopes to improve GaN growth, a development that is crucial to the widespread commercial use of devices such as blue LEDs and laser diodes, as well as GaN-based HEMTs.

While working on this project, Nakamura's UCSB team will join forces with Japanese researchers. Nakamura has chosen the Tokyo Science University and Tsubuka University as partners, because he believes that they are two of the world's best gallium nitride research facilities.



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Opto Speed raises funds

Opto Speed, a Swiss manufacturer of InP-based optoelectronic components, has secured \$17.5 million in second-round funding from venture-capital company The Carlyle Group. Since the company was founded in 1995 as a spin-out from ETH Zurich, Opto Speed has successfully developed InGaAs

photodetectors, semiconductor optical amplifiers, Fabry-Perot and DFB lasers, and *pin* photodiodes. The additional funding means that Opto Speed can expand its manufacturing capacity in Switzerland and Germany, and will also enable the company to open a US sales and marketing office.

New multi-source agreements

Alcatel Optronics, Kamelian and JDS Uniphase have announced a multi-source agreement (MSA) that defines mechanical and performance specifications for semiconductor optical amplifiers (SOAs). The mechanical interface covered by the MSA has the same configuration for pin functions as the industry standard for pump lasers. This makes it easier for manufacturers to integrate SOAs into their products for applications such as amplification, regeneration, wavelength conversion and switching. For pre-amplification applications, Class A SOAs will feature a noise figure of less than 9 dB, gain greater than 20 dB and minimum output power of 5 dBm. For booster applications, Class B SOAs will have a noise figure of less than 12 dB, gain greater than 15 dB and minimum output power of 8 dBm.

Intel, Picolight and Infineon have established a MSA to define a smaller, more cost-effective form factor for 10 Gbit/s fiber-optic

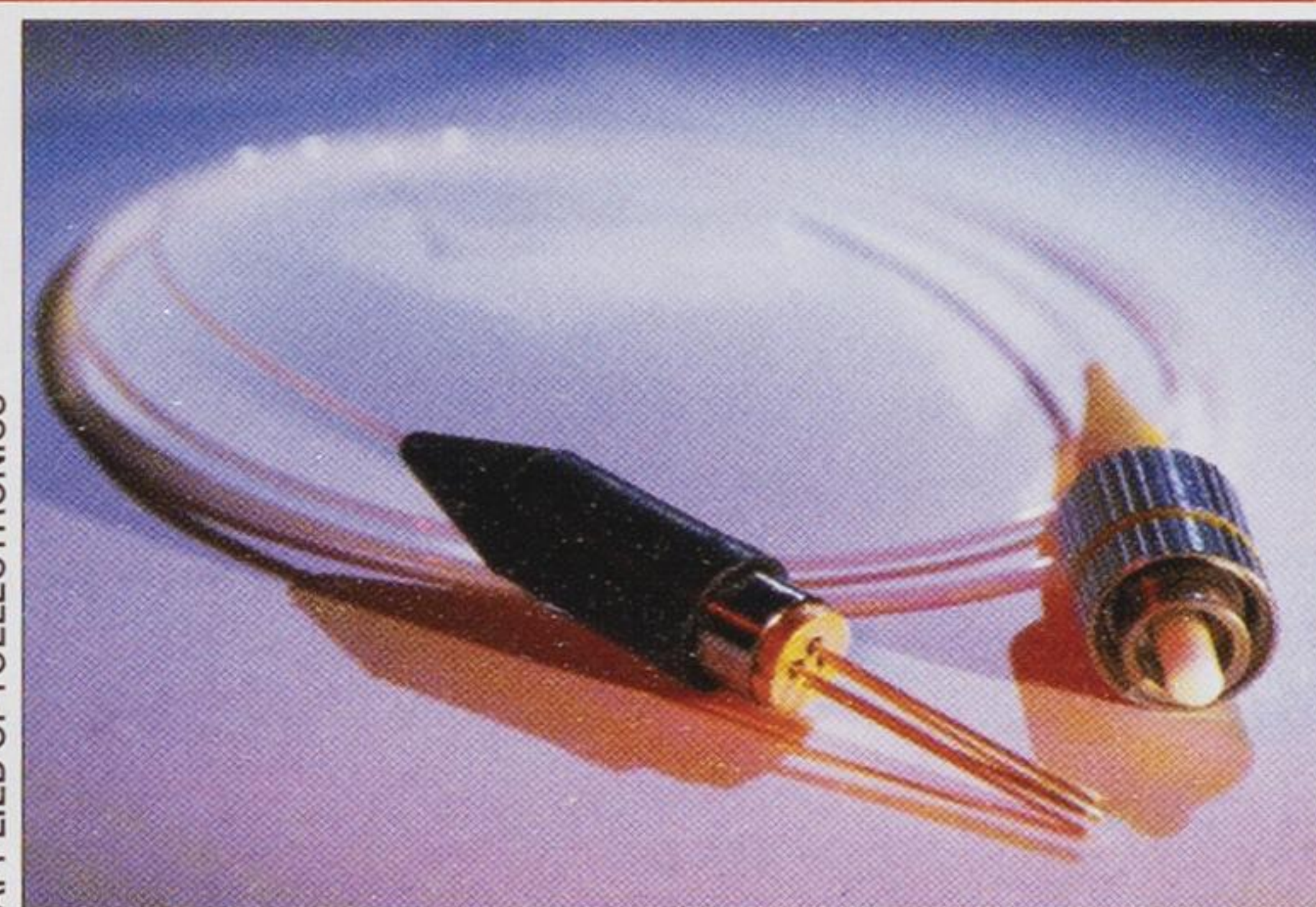
modules optimized for enterprise, SAN and switching center applications. Named XPAK, the new format increases component density with 20 devices to be installed on a single 17 inch PCB, in addition to defining improved power efficiency and integration requirements for 10 Gbit/s links up to 10 km. This will allow 10 Gigabit Ethernet and Fibre Channel deployment to move from aggregated uplink applications to high-volume server-to-switch and storage-to-switch links.

Sumitomo Electric has entered into three MSAs with different partners. The first is with Fujitsu Quantum Devices and covers electroabsorption modulators integrated with DFB lasers and driver ICs. The second MSA with Nortel Networks lays out the specifications for Mach-Zehnder optical modulators integrated with DFB lasers. The final MSA is with NEC Compound Semiconductor Devices and covers *pin* detector- and APD-TIA receiver modules.

AOI makes move into telecom lasers

Best known for quantum cascade lasers and long-wavelength VCSELs, Applied Optoelectronics (AOI) has unveiled two new 1310 nm uncooled DFB laser modules in standard coaxial packages. The DFB-1xxx-CX-2-3.2 operates at 3.2 Gbit/s and is available at four separate wavelengths in order to address the coarse WDM 10 Gigabit Ethernet standard. The second laser, the DFB-1310-CX-2-2.5, is designed for 2.5 Gbit/s metro networks and intermediate reach applications.

"We're very excited to be one of the first laser manufacturers to produce a high-performance laser module specifically designed for 10 Gigabit Ethernet," said Stefan Murry, AOI's marketing director. "Equipment designers need cost-effective lasers that meet rising



AOI has recently introduced a new range of uncooled 1310 nm DFB laser modules.

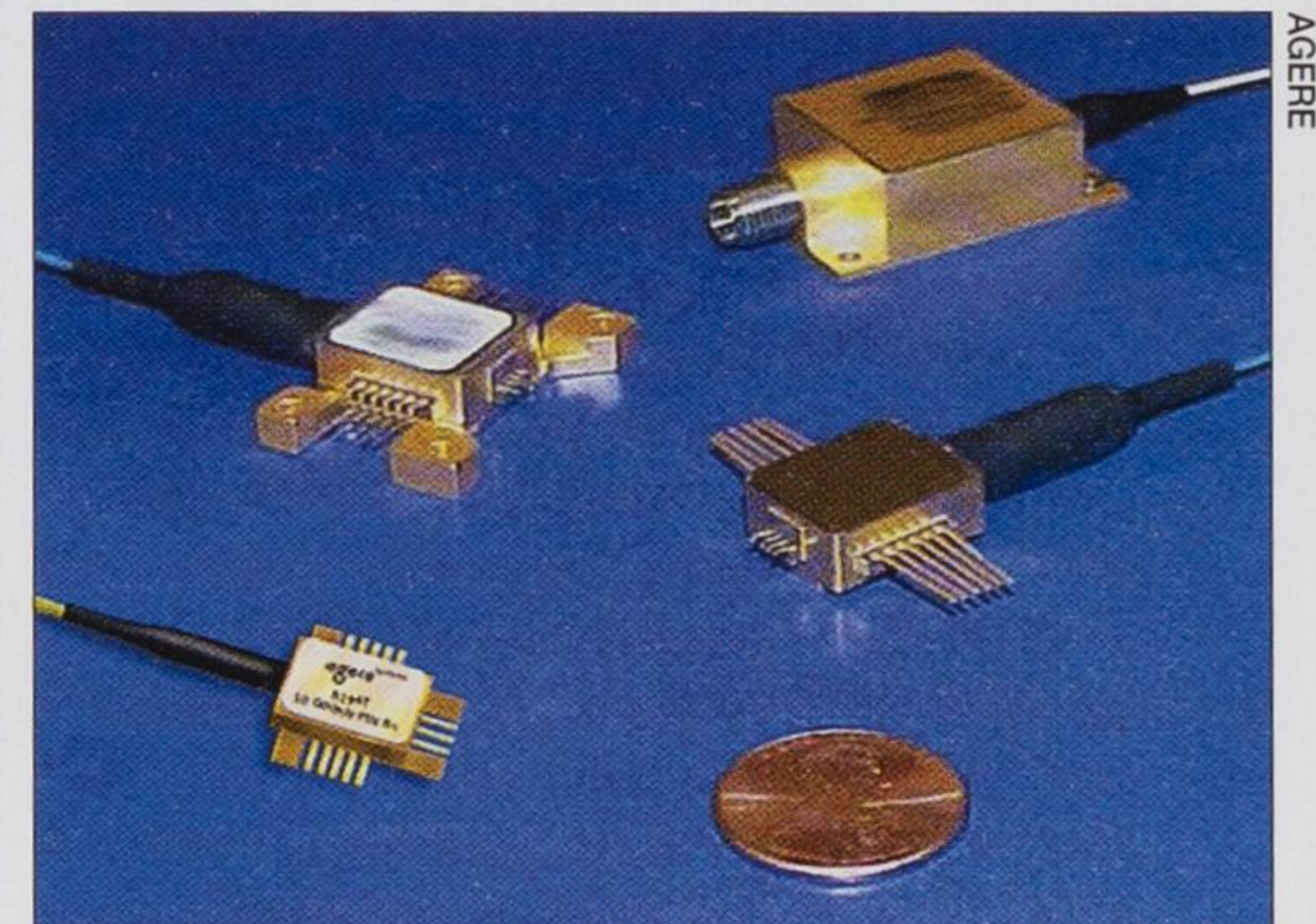
performance standards and our new lasers meet these challenges."

In addition to the two digital transmitter lasers, the company will offer a version designed for analog transmission over the 50 to 860 MHz frequency range, which is used to transmit cable television signals.

Common standard agreed for receivers

Agere and Nortel have agreed a common format to establish standards for surface-mount 10 Gbit/s *pin* and APD receivers, which will be developed and marketed by the companies independently. The standard specifies 17-pin butterfly-type surface-mount packaging for small-form-factor ($8 \times 10.7 \times 3.3 \text{ mm}^3$) devices mounted directly onto a PCB. Initial offerings are expected to include 1R-type receivers, which combine a photodetector and a transimpedance amplifier (preamplifier).

In compliance with this multi-source agreement, Agere has announced the first 10 Gbit/s

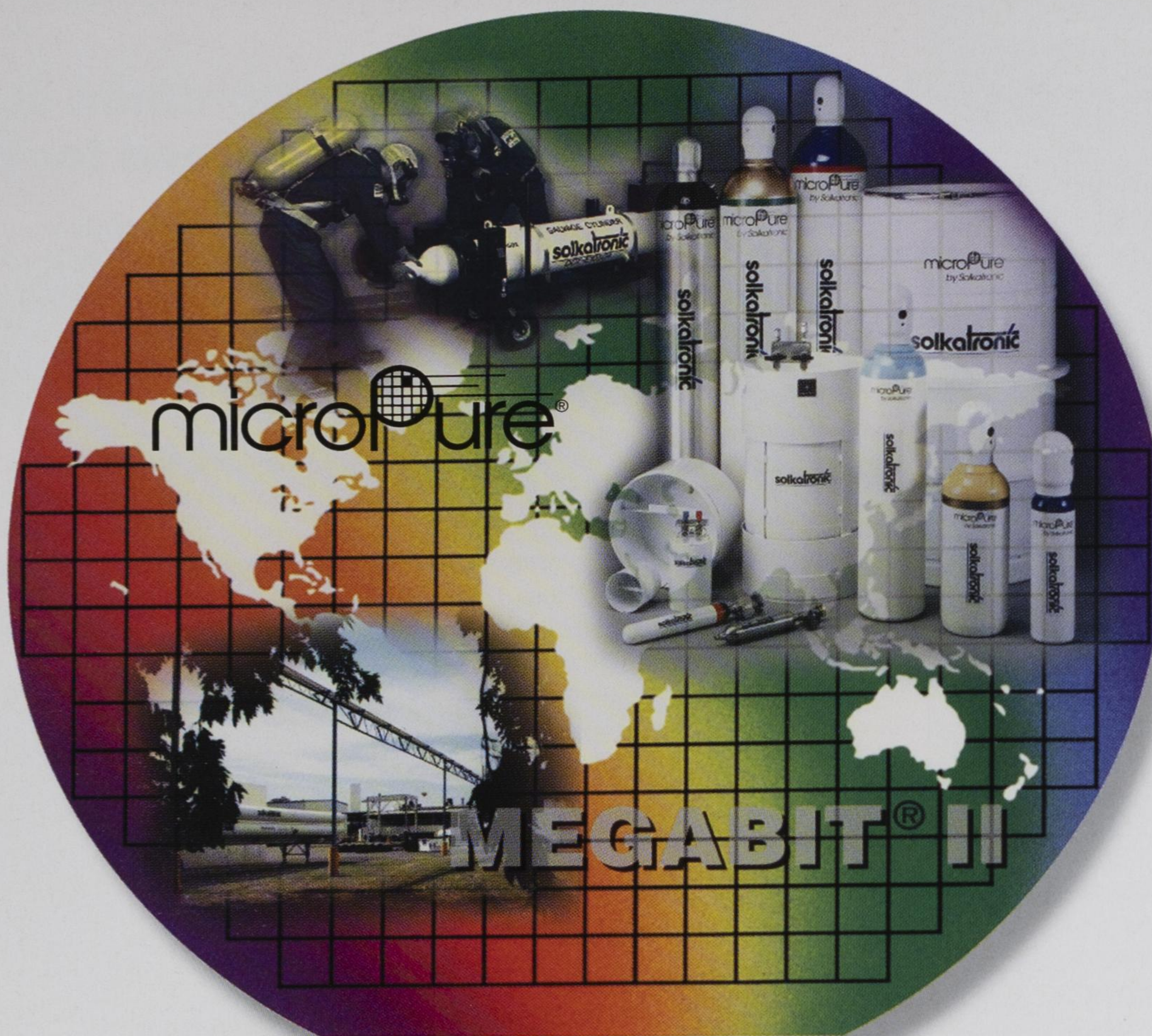


A range of 10 Gbit/s receivers from Agere.

surface-mount optical receivers, which can be mounted directly onto the surface of a line card without coring a hole through the board, saving real estate and manufacturing time. The RA194W APD receiver delivers -26 dBm sensitivity and -2 dBm overload, while the R194T *pin* receiver is optimized for a high-gain differential output transimpedance amplifier with power dissipation of 0.15 W. Production quantities are expected in the third calendar quarter of 2002.

T-Networks wins modulator orders

T-Networks of Allentown, PA has announced design wins for its InP electroabsorption optical modulators from unnamed optical equipment manufacturers. The modulators will be incorporated into products for 10 Gbit/s long-reach, 10 Gbit/s DWDM and 40 Gbit/s 2 km applications. The design wins represent a major milestone for the company founded in July 2000, and will lead to volume production later this year.



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IQE and CST sign wafer foundry agreement

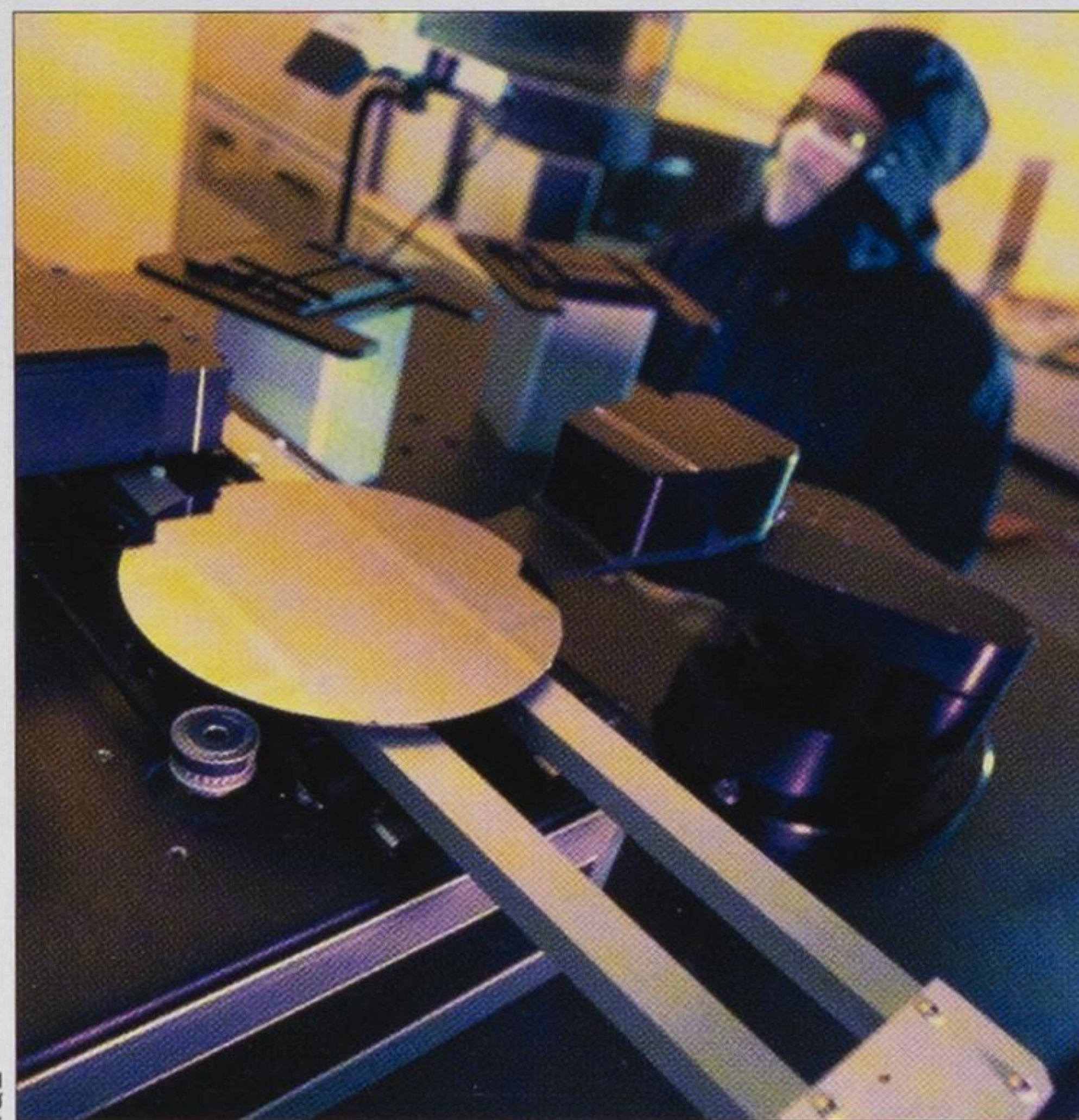
Epiwafer supplier IQE and optoelectronic foundry Compound Semiconductor Technologies (CST) have formed a strategic partnership to provide combined epitaxial growth and wafer fabrication services. The new partnership will offer full growth and processing of optoelectronic devices such as DFB and buried heterostructure lasers, 980 nm pump lasers and photonic ICs.

As part of the deal, IQE will employ CST's device-level feedback to provide its customers with shorter process development and qualification times, and device-level testing. IQE and CST have also agreed to market each other's complementary capabilities for optoelectronic products.

"We have been working with IQE for some time now to provide epitaxial processes for device manufacturing, whilst also maintaining a tight loop for information feedback between both companies to achieve the best results and to develop the processes," says CST's CEO Neil Martin. "We have now formalized this relationship and are creating the proper outsourcing supply chain based on the way the optoelectronic component market is developing."

Companies such as IQE provide the base epitaxial material, but devices now frequently require additional layers of post-processing epitaxial growth. A closer relationship with the customer in the development of such devices is therefore essential.

"There is also an increasing trend toward outsourcing," adds Martin. "This partnership offers a significant opportunity for companies to consider how they bring their products to market." CST already has a basic epitaxial



IQE and CST will offer epitaxial growth and device processing and test services.

capability, particularly for the MBE growth of GaAs-based devices. However, the majority of wafers currently processed by CST are InP-based epiwafers, so the link-up with IQE is appropriate in order to provide a supply channel for such products.

IQE joins with AmberWave

In more news, IQE Silicon Compounds, a subsidiary of IQE that supplies silicon-based epitaxial wafers and services, is to partner with AmberWave Systems to develop a high-volume epiwafer production capability for AmberWave's strained silicon technology. Known as ϵ MOS, AmberWave's technology offers improved CMOS circuit performance and will initially target microprocessor ICs, with digital, wireless and optoelectronic applications anticipated later.

Equipment sales

● **Shenzhen University** of the Guangdong Province in China has purchased two Plasmalab 80Plus systems from **Oxford Instruments Plasma Technology** (Yatton, UK). Intended for reactive ion etching and plasma-enhanced CVD, the systems

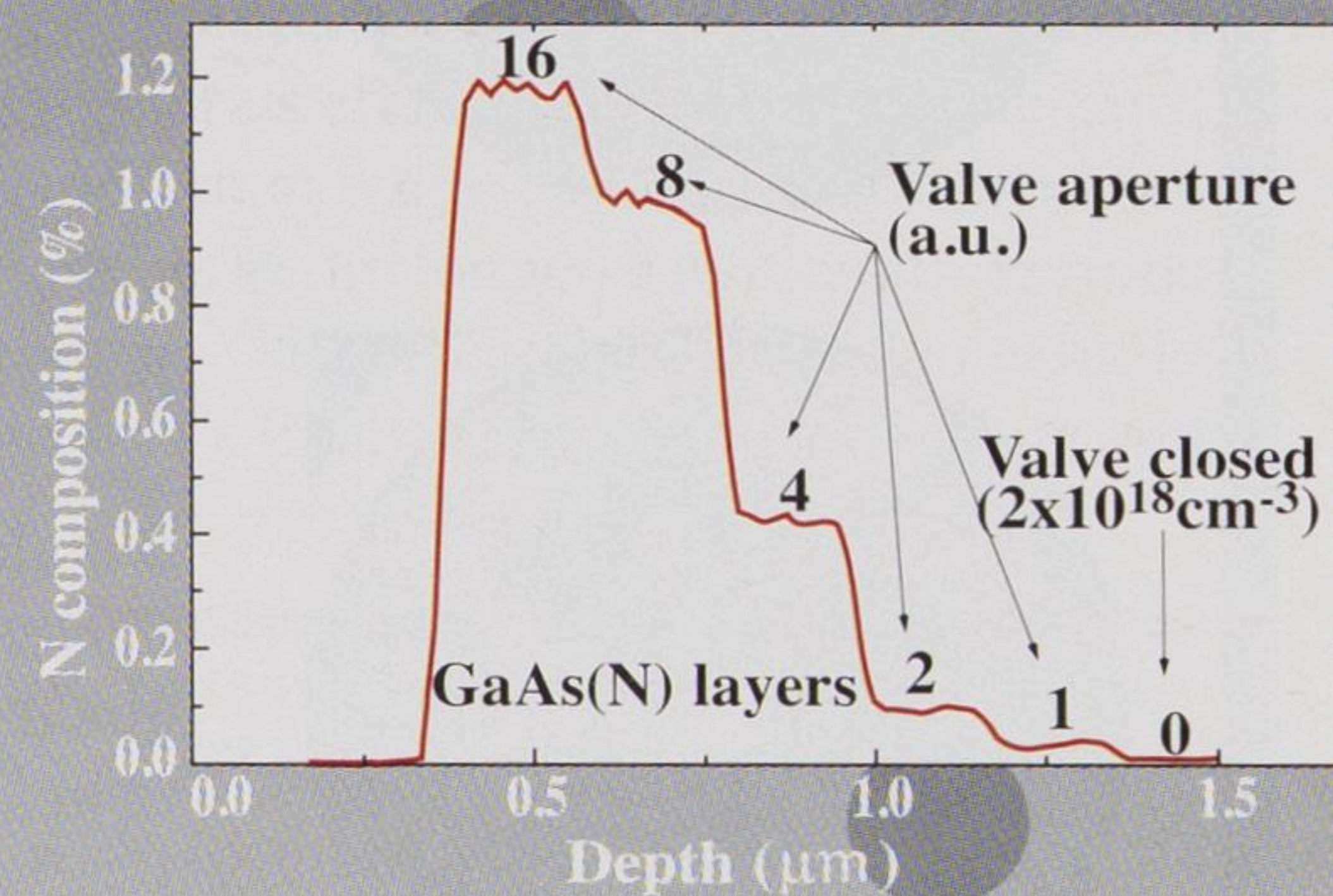
will be used for GaN-based blue LED processing at the university's Institute of Optoelectronics.

● **Iolon** has recently purchased two 3500-II assembly automation systems from **Palomar Technologies** to improve

the yield and streamline the production of its external cavity tunable lasers. The systems position and attach micro-optical components to a ceramic substrate, eliminating the variability that is typically present in manual assembly.

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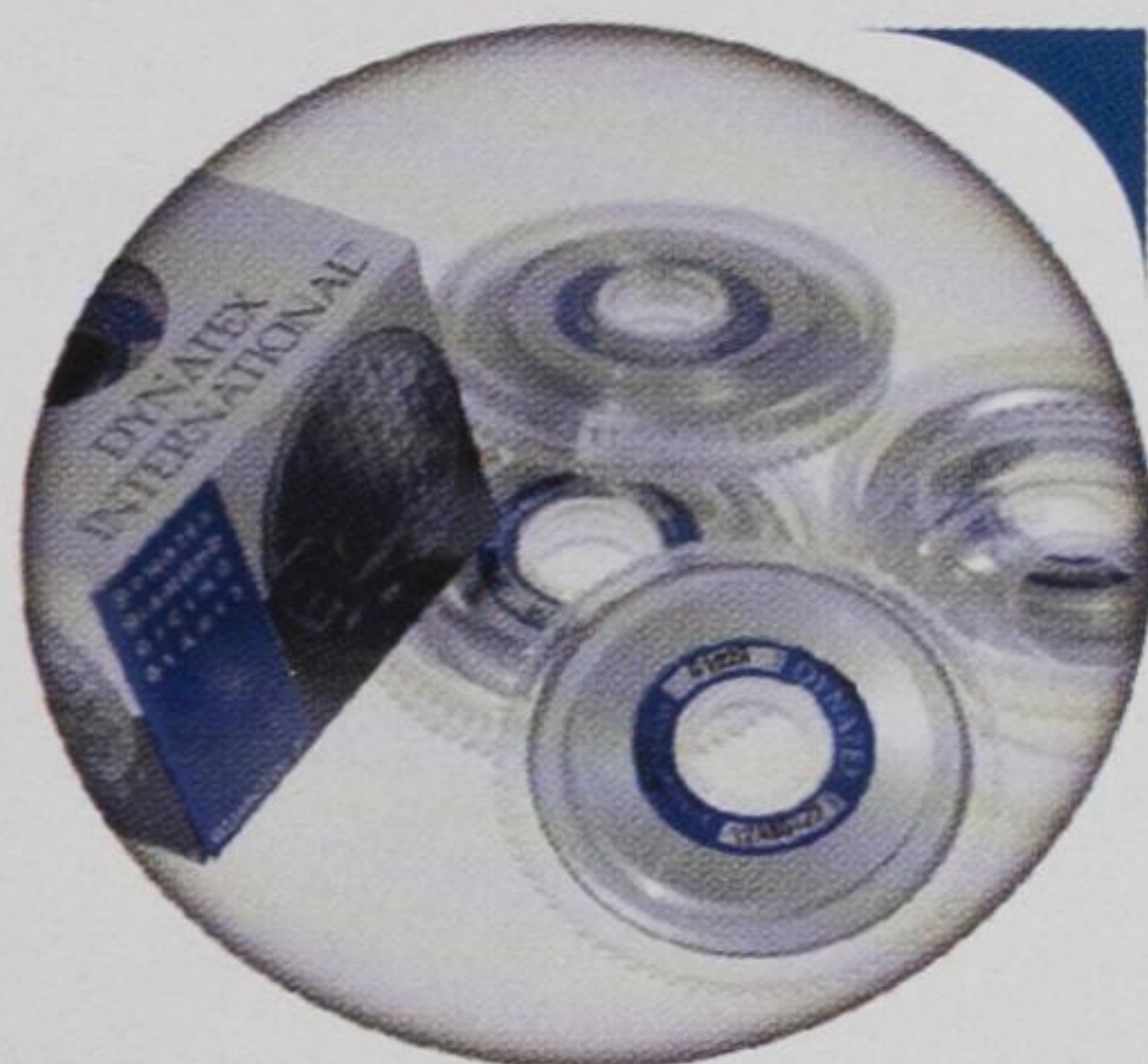
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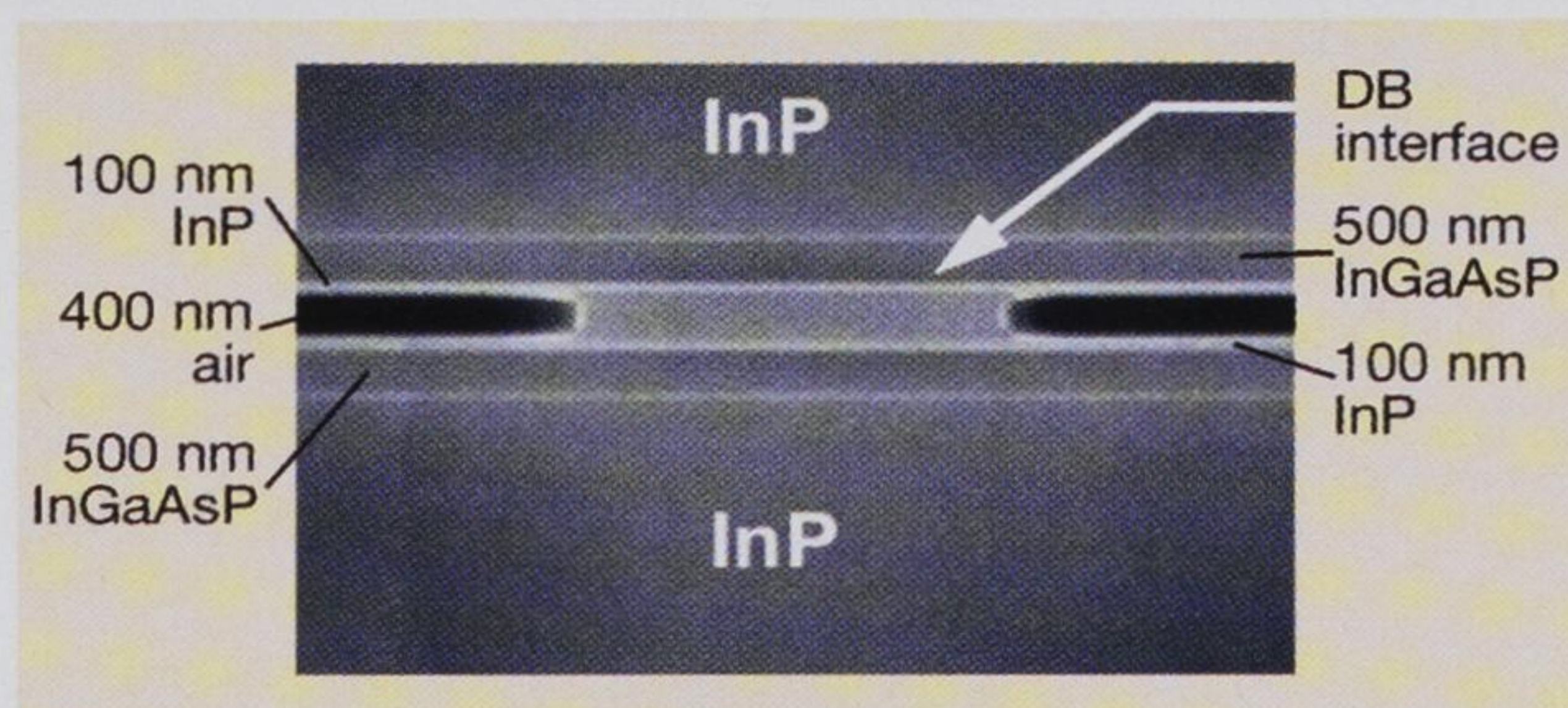
More equipment sales

- **Ericsson Microelectronics** has taken delivery of a waste-gas purification system from **CS Clean Systems**. The Cleansorb CS195SC single-column dry bed absorber will be used with an Aixtron 200 reactor to produce InGaAsP-based optoelectronic devices.
- Laser-diode manufacturer **Quantum Photonics Inc** has selected a factory management software suite from **PRI Automation** of Billerica, MA. PRI's Promis Manufacturing Execution System (MES) enables real-time control of critical processes and workflow on the manufacturing floor, and allows companies to define, control and optimize manufacturing processes to produce maximum yield.
- **Nova Crystals** (San Jose, CA) has purchased two **Emcore** Discovery LDM (laser diode machine) production tools. The company will use the reactors to support the manufacturing and development of high-speed long-wavelength lasers and InGaAs-on-Si avalanche photodiodes.
- The **Fraunhofer Institute for Applied Solid-State Physics** (Freiburg, Germany) has purchased an additional **Aixtron** AIX 200/4RF-S reactor for the development of nitride-based high-brightness blue and UV LEDs, as well as violet lasers.
- The **University of California, Los Angeles** (UCLA) has acquired an **Emcore** Discovery 125 MOCVD research and production reactor to grow compound semiconductors and to launch a new program in optoelectronic ICs.
- **Albany NanoTech** of Albany State University of New York has also acquired an **Emcore** Discovery 125 MOCVD machine. The tool will be used to support research into GaN and related III-nitride materials. The company has an R&D, prototyping and technology deployment resource center with cleanroom facilities.
- **United Epitaxy Company** (Hsinchu, Taiwan) has ordered an **Aixtron** AIX 2600G3HT MOCVD reactor with a capacity of up to 24 × 2 inch or 8 × 4 inch wafers for the manufacture of high-brightness LEDs.

InP wafer bonding for 3D structures

Wafer bonding allows the integration of lattice mismatched materials without introducing threading dislocations. It also enables the fabrication of three-dimensional structures that are difficult to form epitaxially. N Jinn-Phillipp and colleagues at the Max Plank Institut in Germany and the University of California, Santa Barbara have used an InP wafer bonding technique to fabricate a vertical coupler for separated input and output waveguides (*Appl. Phys. Lett.* 2002 **80**(8) 1346). The coupler demonstrated a uniform and very short coupling length of 62 μm and a small excess optical loss of 1.1 dB/cm at 1.55 μm due to the bonding process.

The group investigated the interface structure of directly bonded InP wafers by cross-sectional TEM. In most regions the interface is almost perfect, with lattice planes crossing the interface without dis-



SEM image of the vertical coupler formed by direct bonding.

tortion. Between the well-bonded regions small inclusions associated with dislocations are observed at the interface. The dislocations were found to accommodate the tilt misorientation between the two wafers without introducing extra misfit along the interface, and the small inclusions of a few nanometers in size were identified as indium. The formation of these In inclusions is due to the elevated temperature employed for direct bonding (630 °C), and was identified as the cause of excess optical loss in the vertical coupler. The group expects to reduce the density of dislocations further by using wafers without any miscut. They also suggest that the excess optical loss due to the formation of the inclusions may be eliminated by using lower temperature and a phosphor atmosphere for direct bonding.

Nichia team develops phosphor-free white LEDs

Today's commercial white LEDs typically comprise a blue LED with a YAG phosphor to produce white light. However, problems with phosphors have driven researchers to develop phosphor-free monolithic white LEDs, although so far such devices have suffered from low emission efficiencies. Motokazu Yamada and colleagues at Nichia have developed white LEDs with multi-color emitting MQW active layers, which they claim have high luminous efficiencies (*Jpn. J. Appl. Phys.* 2002 **41** (Pt. 2, 3A) L246).

The monolithic LED structure was grown by MOCVD onto a 2 inch sapphire substrate. The MQW active layer comprised an InGaN QW, with GaN and AlGaIn barriers, and was sandwiched between n-type and p-type GaN layers. By changing the In content within an LED's active layer, the researchers were able to tailor its emission wavelength. From 370–600 nm the LED had at least 5% external quantum efficiency, with a peak of 21% at 415 nm. "[From this we realized] that it is possible to make high efficiency white LEDs without phosphor by stacking several InGaN quantum wells with different compositions," said Yamada.

The researchers went on to make two white LEDs with different active layers that emitted two or three colors. The active layer of the first contained yellow and blue light-emitting QWs, while the second consisted of red, green and blue light-emitting QWs. At room temperature and with a 20 mA forward current, the first device had an average color rendering and luminous efficiency of 42.7 and 11.04 lm/W, respectively. The second LED showed an average color rendering and luminous efficiency of 80.2 and 7.94 lm/W, respectively.

Despite the first LED's better luminous efficiency the researchers say it is unsuitable for practical use because of its low color rendering. For general illumination, a color rendering of 80 is required. In contrast the color rendering of the second LED is suitable for general lighting systems, but has a luminous efficiency that is only one-third of the value needed for commercial white LEDs. "This is because of low luminescent efficiencies at the longer wavelength regions in the active layer," said Yamada. The researchers now plan to build on the efficiency of the second LED by improving its yellow and red QW efficiencies.

Sensitive GaInAs/InP QWIPs grown on silicon

Quantum-well infrared photodetectors (QWIPs) are of interest for many commercial, industrial and military applications. At present most QWIPs are grown on GaAs and InP substrates, and complicated fabrication processes are used to hybridize the QWIP focal plane array with the silicon-based read-out integrated circuit (ROIC). QWIPs grown directly on Si substrates make monolithic integration with the Si-based ROIC possible. However, the major obstacle to this is the large lattice mismatch between Si and III-V material, which creates a high density of threading dislocation in the epitaxial layer.

A number of growth techniques have been utilized to grow GaAs and InP on Si. A team at Northwestern University, Illinois has published work on an *in situ* thermal annealing technique that reduces the

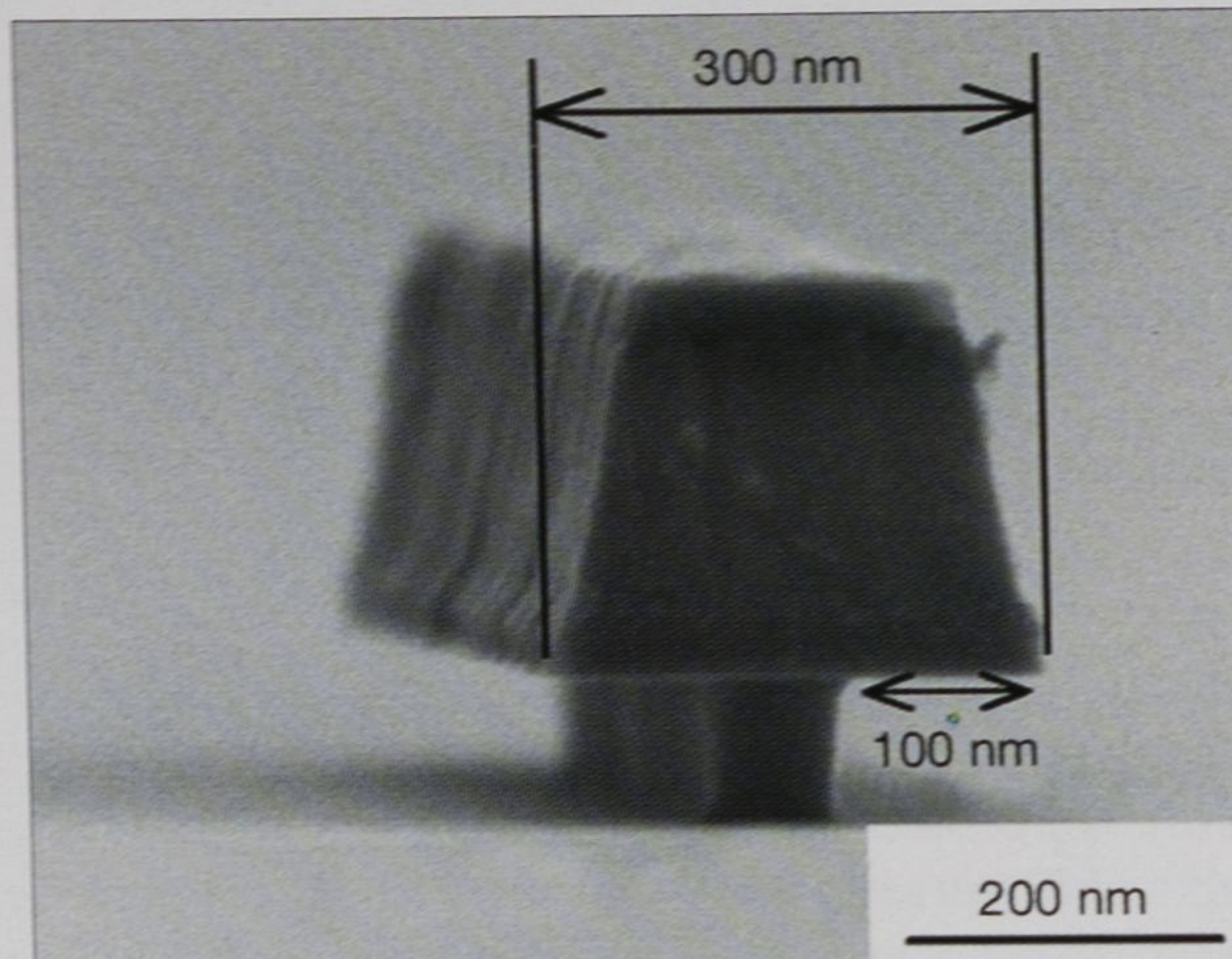
dislocation density in a 6 μm epitaxial InP buffer grown on a GaAs-coated Si substrate by LP-MOCVD (*Phot. Tech. Lett.* 2000 **14**(3) 372). The annealing process was performed between room temperature and 550 °C for every 1 μm InP growth. Twenty periods of a GaInAs/InP QWIP structure were grown on top of the thick InP buffer.

The performance of a QWIP-on-Si device was compared with that of a QWIP-on-InP. The large dark current of the QWIP-on-Si was due to the presence of threading dislocations, and a small blue-shift was observed in the spectral response curve for the QWIP-on-Si relative to that of the QWIP-on-InP. A record high detectivity of $2.3 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$ was achieved for the reported QWIP-on-Si detector and, compared with the GaAs/AlGaAs QWIP-on-Si, the GaInAs/InP QWIP-on-Si showed much better detector performance. A comparison of QWIP-on-Si detectors with different InP buffer thicknesses indicates that there is an optimum thickness for the InP buffer layer on Si that gives the best detector performance.

Combination etch produces 0.1 μm emitter HBTs

Reduction of the emitter size in an HBT decreases extrinsic base-collector capacitance, giving improved high-speed operation with low power dissipation. InP/GaInAs DHBTs with 0.1 μm wide InP emitters along the (010) direction have been fabricated by researchers at the Tokyo Institute of Technology in Japan (*Jpn. J. Appl. Phys.* 2002 **41** (Pt. 2, 2A) L121). Such HBTs have the narrowest emitters reported to date. Size reduction of an emitter formed along the (010) direction is difficult because wet etching readily undercuts the emitter layer. However, undercutting of the InP collector layer can be used to reduce the base-collector capacitance of an HBT.

The group reported the development of an etch process that minimized emitter undercut, yet gave precise control of the collector undercut. A CH_4/H_2 reactive ion etch (RIE) was used to etch the InP emitter layer, and the RIE etch was stopped with 10 nm of the InP emitter layer remaining. The emitter etch was com-



The combination of two HCl-based wet etches suppressed undercutting of the emitter to 100 nm and gave a smooth base-layer surface. The etches gave a 0.1 μm emitter with vertical sidewalls.

pleted by wet chemical etching to reduce possible damage to the surface caused by the RIE.

A vertical emitter sidewall was necessary because during the base electrode deposition metal would also form on the emitter facet if it was tilted, and so the emitter and base would not be electrically isolated. A combination of two kinds of HCl-based solutions gave a vertical emitter sidewall and a smooth base layer surface (see figure). A self-alignment process was used to fabricate the base metal, and a wet-etched-undercut air-bridge structure was introduced to obtain wiring for the fine emitter electrode. A high current gain of 51 was successfully obtained at a collector current density of 50 kA/cm^2 when the emitter width was 0.1 μm . The evaluated surface recombina-

tion current of the emitter periphery region was lower than the previously reported values, and current amplification was confirmed even when the collector current was less than 1 μA .

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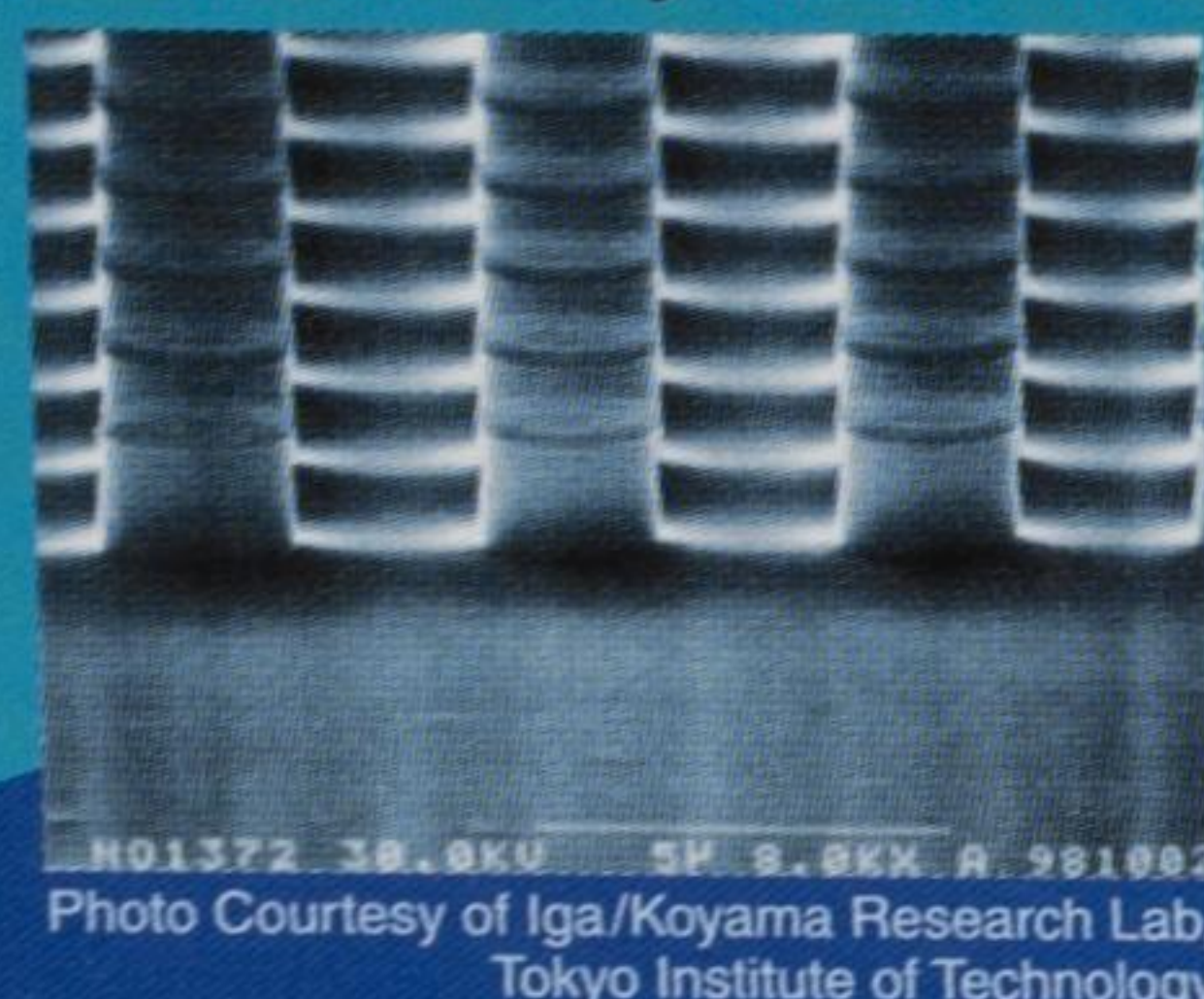
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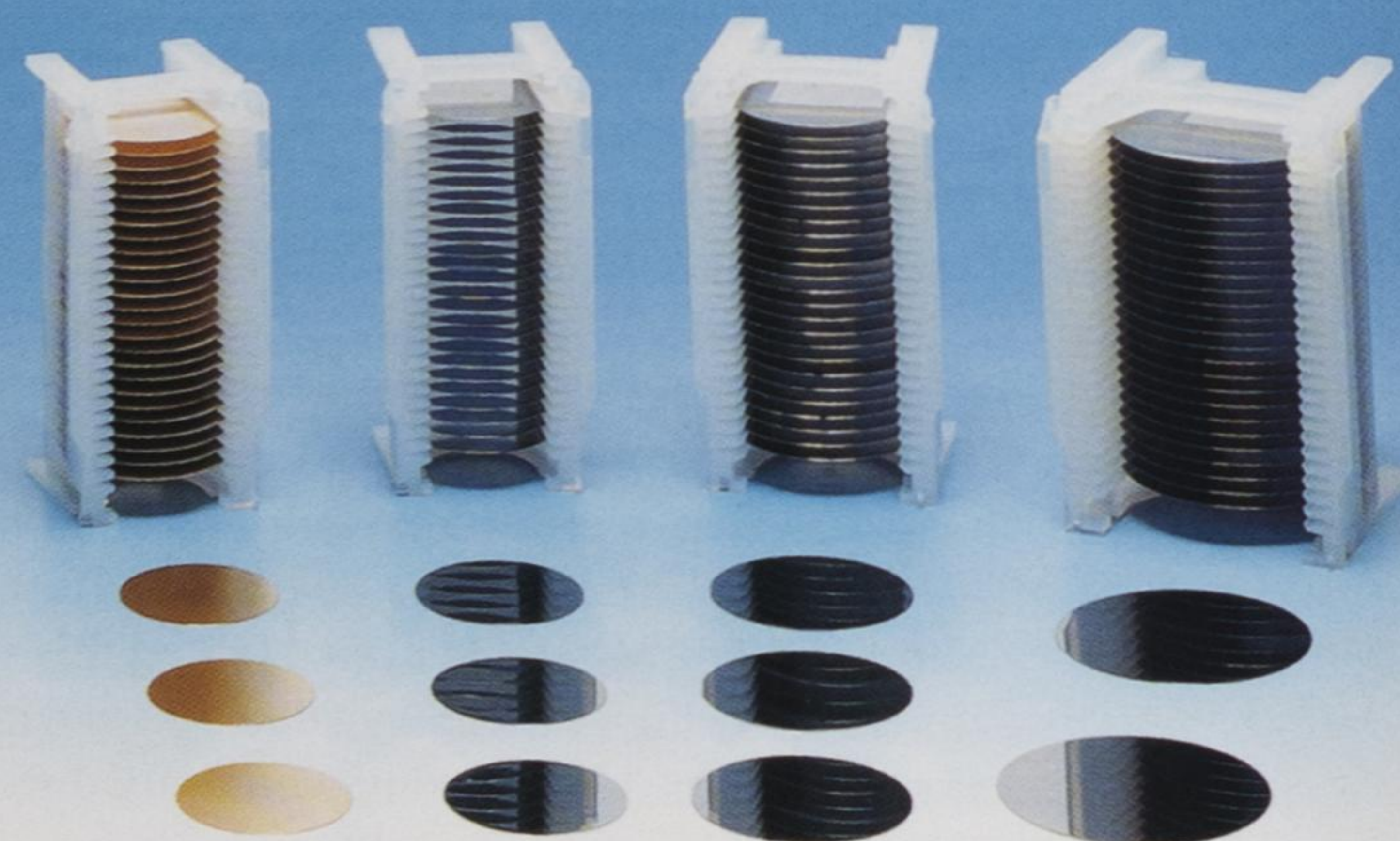


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Red VCSELs set new temperature record

Red VCSELs generally have poor temperature characteristics due to leakage currents caused by low band offsets and poor thermal conductivity of the constituent AlInGaP materials. For a given red VCSEL design there is a maximum temperature for the junction at which lasing can be obtained. Once that design has been adopted, improved thermal performance comes from the management of additional temperature rises due to current injection.

Researchers at the National Microelectronics Research Centre in Cork, Ireland have used selective oxidation of AlGaAs to control the spatial mode (*Elec. Lett.* 2002 **38**(5) 222). For optimal lateral heat removal, a 4 μm current aperture was used. The devices lased in CW mode at up to 80 °C, a record for this material. This performance comes with a trade-off between maximizing the operational temperature and the room-temperature power, which is a function of the aperture size.

The devices had a number of other near ideal properties. At room temperature the threshold current was only 200 μA , and the output power was close to 1 mW. The emission had a predominantly single-mode spectrum at 668 nm, with a side-mode suppression ratio greater than 20 dB at all temperatures. The wavelength variation with temperature was 0.043 nm/°C. These devices are expected to be used both in plastic optical fiber-based data communications and in hand-held beam scanners where the low power consumption permits extended battery operation compared with edge-emitting lasers, which have much higher operating currents.

Agere team fabricate tandem EA modulator

A group from Agere systems has published details of an InP-based tandem electroabsorption modulator (TEAM) for 40 Gbit/s optical communications (*Phot. Tech. Lett.* 2002 **14**(1) 27). The device monolithically integrates two MQW modulators, a semiconductor optical amplifier (SOA) and spot size converters (SSCs) on the input and output. The two modulators provide pulse generation and data encoding for return-to-zero (RZ) modulation (see *Compound Semiconductor* March 2002, p50). Without the pulse-generating modulator operating, the TEAM can be used in non-return-to-zero mode (NRZ). The integrated SOA reduced the effect of any optical losses, while the SSCs improved optical coupling efficiency to the fibers.

The device was fabricated using four low-pressure MOVPE growth steps. First the MQW active regions of the two modulators and SOA were grown by selective-area epitaxy. The SSCs were connected to the modulators by etching the active region and selectively growing into the etched region. The SSC waveguides were then buried under a semi-insulating InP cladding layer and an InGaAs contact layer. Deep-ridge mesas were then formed by the reactive ion etching of trenches into which semi-insulating InP was grown.

Devices with 600 μm long SOAs had up to 8.5 dB fiber-to-fiber gain with 150 mA SOA drive current and 0 dBm input power. For devices with an 80 μm long modulator and optimized for low junction capacitance, a bandwidth of 57 GHz was estimated. The TEAM demonstrated 40 Gbit/s operation for RZ and NRZ operation with the SOA driven at 80 mA and the data encoder running at 2.5 V_{p-p}.



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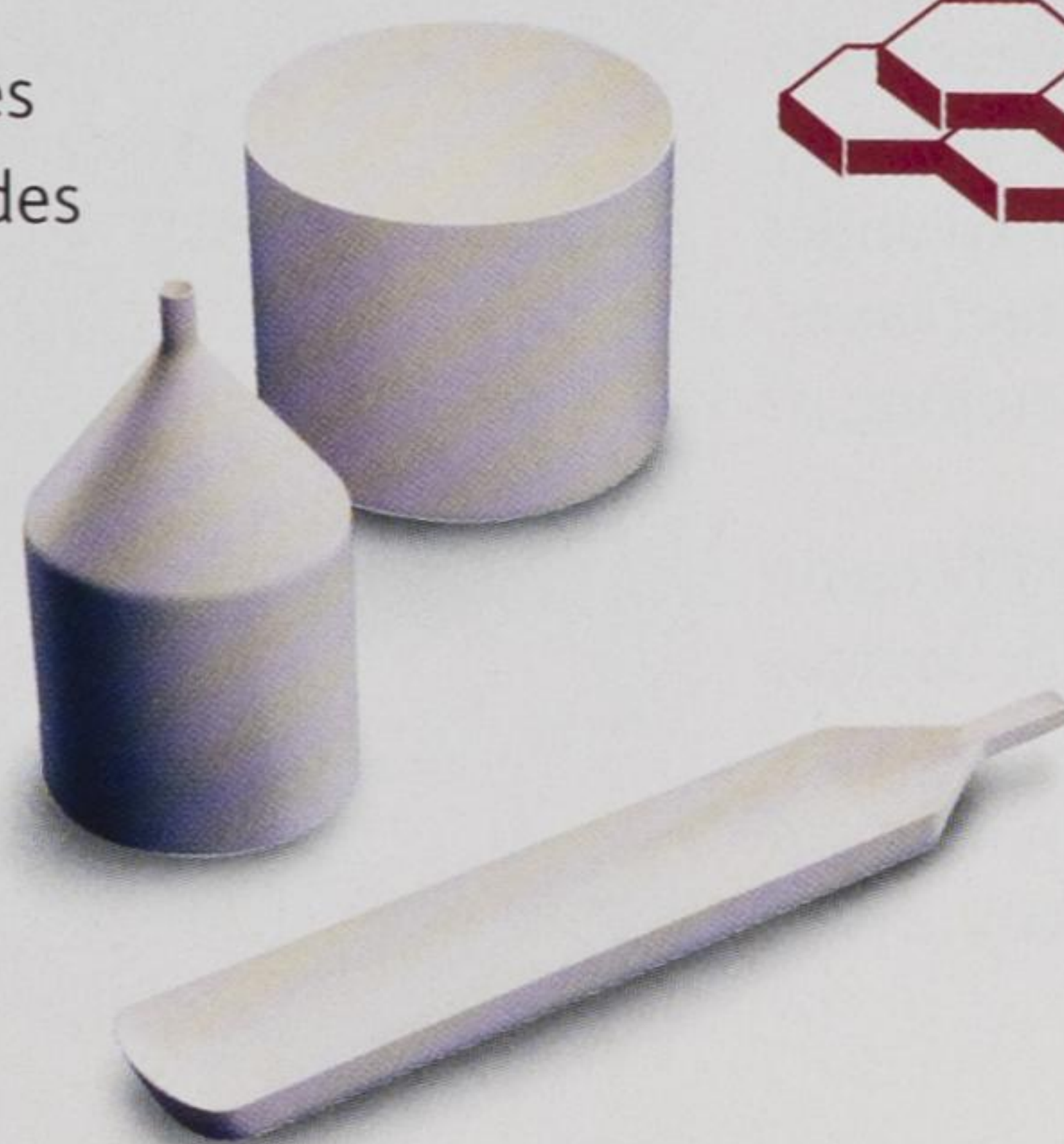
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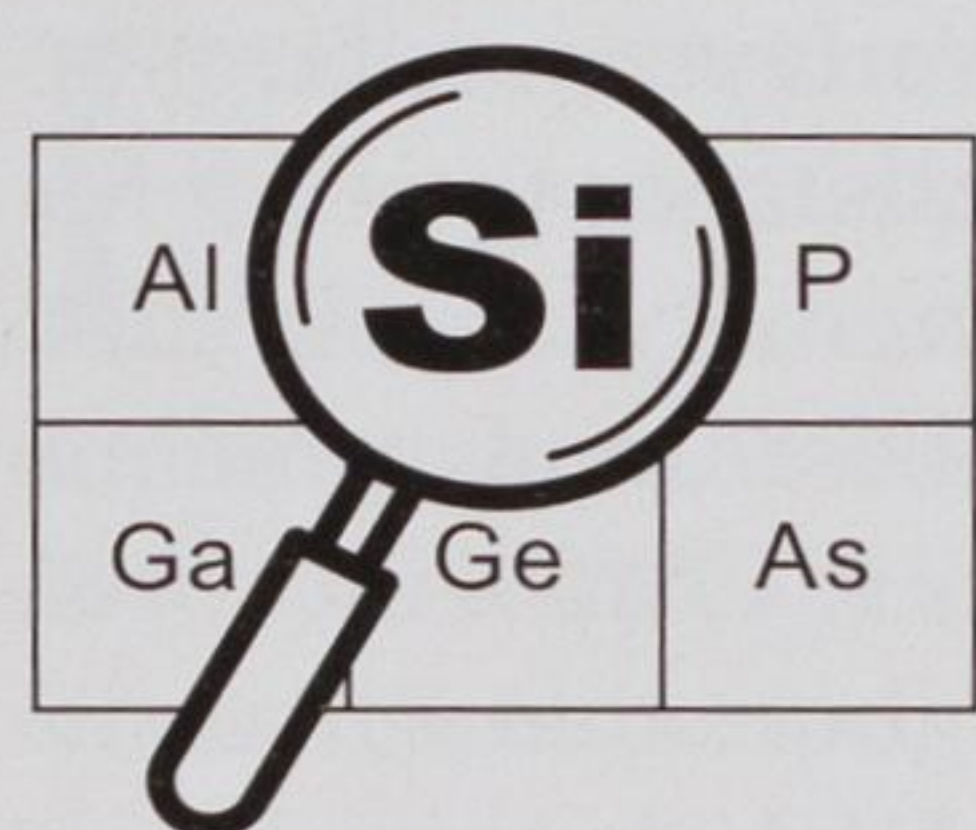
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FinFET process pushes gate lengths below 50 nm

With it becoming increasingly difficult and expensive to reduce the limits of lithography any further, researchers are now looking at new ways to shrink feature sizes.



The sub-50 nm capability of the FinFET approach is just as applicable to III-V materials.

The combination of surface topography and dry etching inevitably leads to the formation of sidewall spacers. When materials are deposited by CVD or sputtering processes they typically cover topography in a conformal manner. This means that the vertical thickness of the material deposited at the edge of a step approaches the thickness of the material deposited in flat regions, plus the height of the step. As a consequence, when flat field areas are cleared during dry etching, unetched material will remain at the edge of the steps – the spacer. This sidewall spacer, the width of which is the thickness of the deposited layer in the field regions, can only be removed through additional etching. However, rather than viewing this as an etching problem, it has recently been realized that this can be exploited as a lithography technique. Instead of etching away the sidewall spacer, the material that formed the step is selectively etched leaving behind a free-standing spacer, the width of which is the thickness of the original deposited material.

This approach has been pioneered by researchers at the University of California at Berkeley in the fabrication of CMOS FinFETs, so called because the free-standing sidewall spacers resemble fins. The researchers fabricated sub-50 nm features – dimensions that can

typically only be achieved by advanced E-beam lithography techniques (Choi *et al.*,a,b).

FinFETs should be of a great deal of interest to the III-V community for two reasons. They have the potential to push today's state-of-the-art CMOS production gate lengths from the current 125 nm to the sub-50 nm regime, providing large performance gains. But even more importantly the sub-50 nm capability of the FinFET approach is just as applicable to III-V materials, for example in the implementation of sub-50 nm gates for MESFETs and PHEMTs.

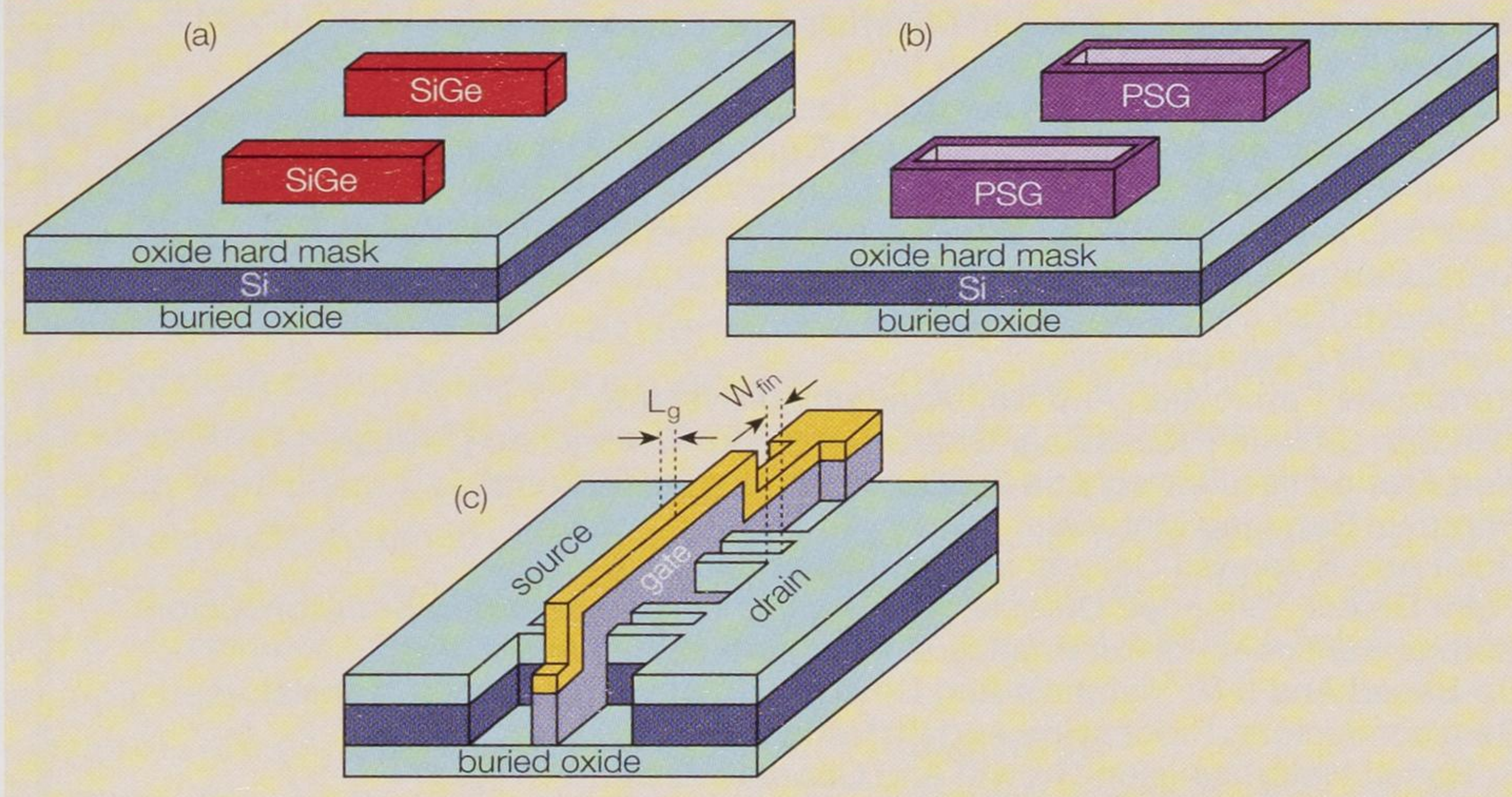
FinFET fabrication

The Berkeley researchers implemented a FinFET process for nanoscale CMOS applications, fabricating fins as narrow as 6.5 nm and gate lengths of 30 nm for both NMOS and PMOS devices. The process flow is shown in the figure. SOI substrates are typically utilized, in which the starting 100 nm silicon film above the buried oxide is thermally oxidized, giving a 50 nm surface oxide that protects the remaining 50 nm silicon layer during fin formation. As shown in the figure (a), a 200 nm SiGe layer is deposited by low-pressure CVD and patterned into sacrificial structures that will be used to form the sidewall spacers.

A vertical profile on the SiGe sacrificial structures is crucial in order to fabricate fins of minimal and controlled widths (sloped sidewalls produce larger sidewall spacer widths). Phospho-silicate glass (PSG) of 30 nm thickness is then deposited, and a subsequent anisotropic PSG spacer etch is performed to remove the PSG everywhere except at the sidewalls of the SiGe sacrificial structures. The SiGe structures are then selectively etched away leaving behind the free-standing PSG sidewall spacers, as shown in the figure (b).

Next, the source/drain regions are defined by conventional lithography, and the active region of the FinFET devices is defined by the combination of the photolithographically defined source/drain regions and the hard-mask PSG spacer fins. The active region is then transferred to the underlying hard oxide mask and SOI film by dry etching. Once the spacer PSG fin and the oxide layer beneath it are etched away, a free-standing silicon fin-gate connected between the active source and drain regions remains. The width of the gate is

The FinFET approach developed at UC Berkeley



The FinFET process uses sacrificial SiGe fins (a) that are used to form PSG sidewall spacers (b), which act as an etch mask to form the source and drain regions (c).

The FinFET has the potential of taking CMOS into both high-speed and high-frequency regimes.

that of the original PSG fin, though slight undercutting, which reduces the gate width by a small amount, may occur during etching.

The remainder of the process is fairly conventional, including the growth of a 2.5 nm gate oxide. The deposition of *in situ* doped poly SiGe is used for the gate material, which in turn is defined through conventional lithography (E-beam or optical). A standard ion implantation is used for the source/drain regions. The figure (c) illustrates the final dual-gate FinFET structure.

An obvious point of concern for such a structure is that the sidewalls of the active silicon channel have been defined by dry etching. This has the potential for sidewall damage in the form of surface states that could highly degrade carrier transport through the channel. Additional wet etching can be performed in an attempt to remove this damage, but this remains a critical area of further development for this structure.

Performance figures

The fabricated PMOS devices exhibited a drive current of 350 $\mu\text{A}/\mu\text{m}$ and a turn-on voltage (V_t) of -0.76 V , while the NMOS device had a drive current of 400 $\mu\text{A}/\mu\text{m}$ and a turn-on voltage V_t of -0.13 V . Both the devices operated at a bias ($V_g - V_t$) of 1 V and a V_d of 1 V. Unlike these FinFET devices, in a conventional CMOS process the NMOS drive current would be at

least twice that of the PMOS. The observed increase in drive current for the NMOS FinFET device is a symptom of inadequate dry-etch damage passivation of the gate sidewall.

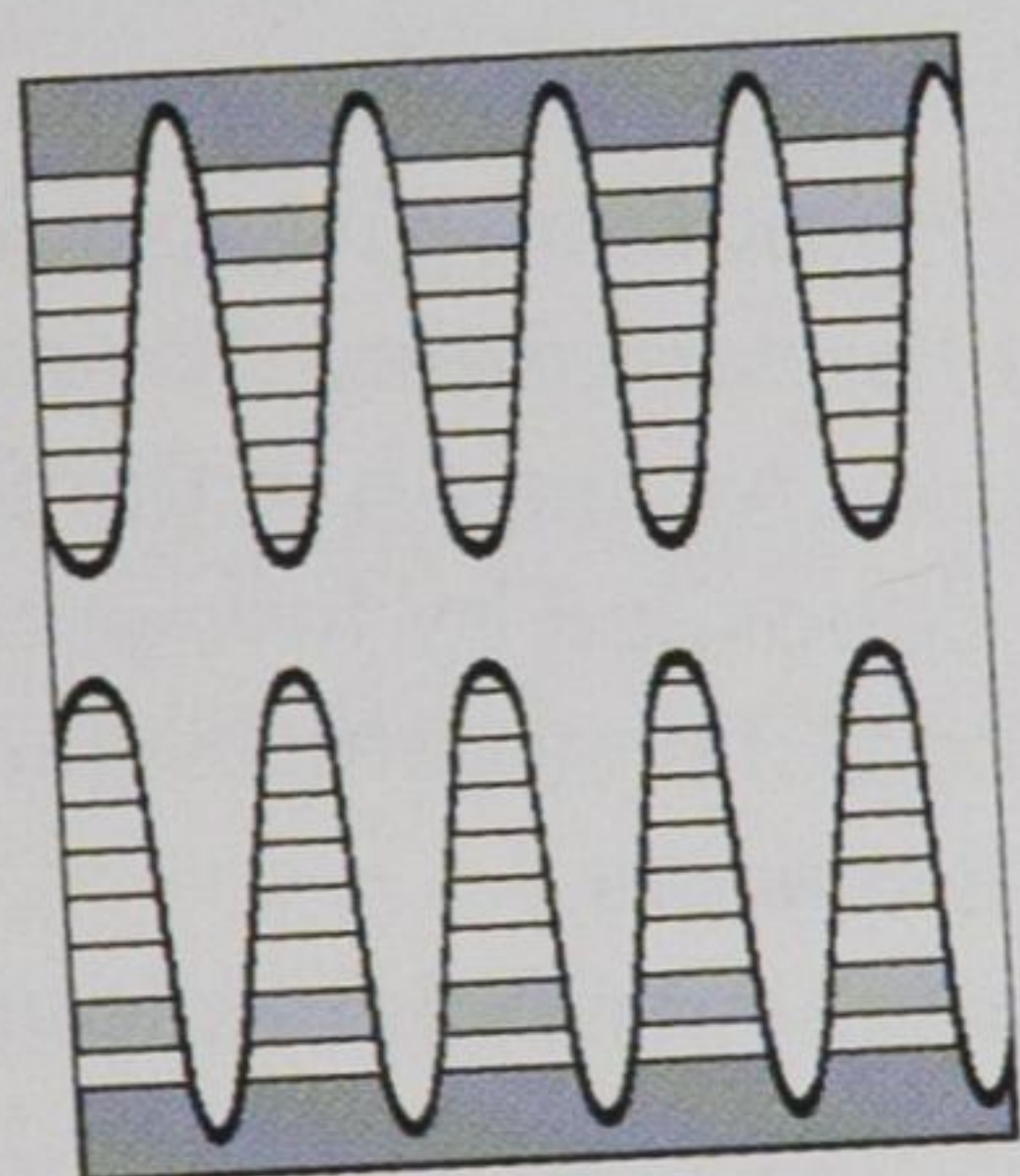
Future improvements

These devices are obviously not yet ready for production. However, the approach clearly shows that sub-50 nm gate length devices can be made which do not depend on highly sophisticated, expensive and often low throughput tools, but simply on the thickness of a deposited layer. Two things that could improve device performance are better passivation of the channel sidewall and the deposition of metal overlayers on the gate. These layers would reduce gate resistance (critical for RF applications), which will be extremely large in such a narrow gate width device. With these improvements, the FinFET has the potential of taking CMOS into both high-speed and high-frequency regimes that will compete with the highest performance III-V devices. However, as noted earlier, the same sidewall-lithography processes can also be applied to III-V materials, further improving their device performance too. ●

Further reading

Y-K Choi *et al.* 2002a *IEEE Elec. Dev. Lett.* **23**(1) 25.
Y-K Choi *et al.* 2002b *IEEE Trans. Elec. Dev.* **49**(3) 436.

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Wide Bandgap Substrates

Device makers fight it out to share in the 10 Gbit/s action

Despite a lack of customers, there is a lot of activity at the component level of the fiber-optic market. **Tim Whitaker** and **Richard Dixon** report from the recent OFC conference in Anaheim, CA.

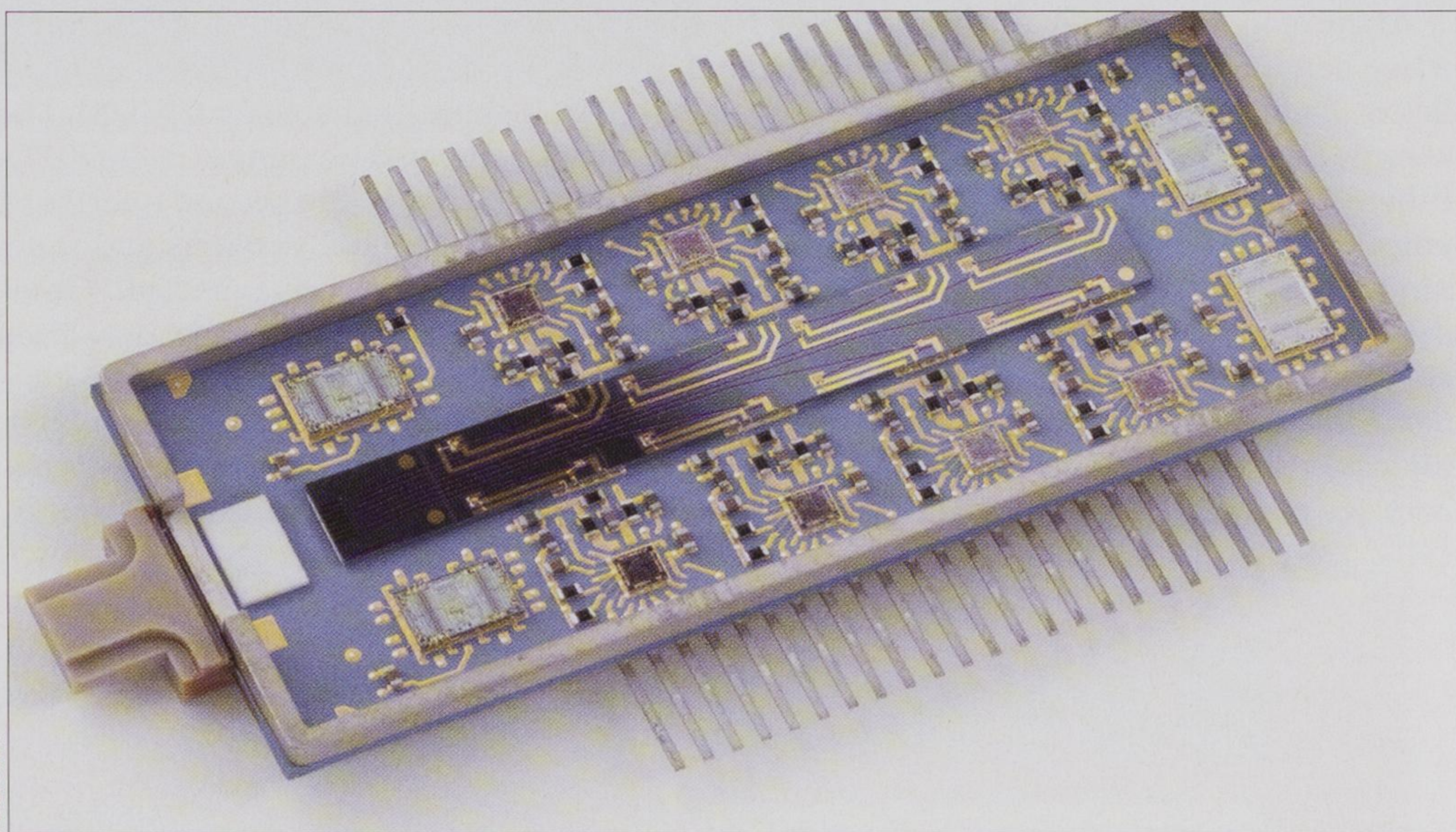
Fiber-optic component vendors face the fundamental problem that customers are few and far between. None of the device makers among the 1200 exhibitors at this year's Optical Fiber Communication conference, held on March 17–22 in Anaheim, CA, tried to pretend that they are having an easy ride at the moment. However, there is clearly a great deal of product development going on as companies prepare for recovery.

Device makers are focusing a great deal of their current effort on the 10 Gbit/s space, which is the "sweet spot" in the market at the moment. There are several key trends; one is to improve existing products by making them smaller, less power-hungry and of course cheaper. Another trend is to incorporate more functionality into modules while maintaining their cost and footprint. The third trend is to enhance functionality at the device level either through integration or by developing components with enhanced performance.

At OFC there was less evidence of activity in the metro area, which last year was touted as the saviour of the fiber-optic market. The development of 40 Gbit/s components was an area of great interest, but the current downturn has delayed this considerably.

New technologies

One of the most interesting aspects of this year's OFC was the number of companies seeking to bring new technologies to the commercial market. These take the form of advanced devices providing key advantages such as smaller size and lower power consumption and cost. Essient Photonics, a Scottish company founded in February 2002, has received \$7 million to develop devices based on resonant tunneling diodes, one example being a modulator requiring a drive voltage of only 100 mV (for more information see page 29). Meanwhile Zia Laser has reached several milestones in the development of quantum-dot lasers, which are highly



Bookham's new eight-channel transmitter. Lasers and monitor photodiodes are hybridized onto the silicon-based platform (center) which contains integrated waveguides.

temperature-insensitive and have ultra-narrow linewidths. The company, based in Albuquerque, NM, has manufactured a 1310 nm DFB laser on a GaAs substrate, and a 1550 nm tunable gain chip suitable for use in an external cavity laser that allows a maximum output power of 40 mW.

Irish start-up Eblana Photonics revealed that it is using photonic bandgap structures to manufacture pump and transmission lasers without regrowth. Microstructures are etched into the top surface of the laser structure to control the spatial and longitudinal modes, resulting in ultra-narrow linewidths. Nova Crystals is using wafer-bonding technology to fabricate InGaAs-based APDs on silicon, which have much higher performance than conventional APDs on InP (see page 32).

Integration

As well as demonstrations of wafer-scale integration, including both hybrid and monolithic approaches, many companies were showing

examples of module integration where more functionality is incorporated into the same package size. Agere Systems introduced what it claims is the industry's first cooled 10 Gbit/s transponder to transmit up to 80 km without any amplification. The CB64L2, measuring 3.5×4.5 inches, utilizes a 1550 nm electro-absorption modulated laser and an APD or a *pin* diode, and also incorporates the necessary electronic components including amplifiers and mux and demux ICs. Agere also introduced an uncooled TB64L1 transponder containing a 1310 nm DFB laser, with a reach of 40 km at 10 Gbit/s. Nortel Networks demonstrated a tunable transmitter module; the LG10M contains a widely tunable VCSEL, a GaAs Mach-Zehnder modulator, a variable optical attenuator, a wavelength locker and a power monitor.

Bookham Technology, which recently acquired Marconi Optical Components, showed several examples of the hybrid integration of active devices onto its silicon-

based ASOC platform. As well as integrating Genoa's linear optical amplifier (LOA), Bookham demonstrated a Multi-Channel Link consisting of separate eight-channel transmitters and receivers. Each transmitter contained eight lasers and eight monitor photodiodes hybridized on a single silicon chip, with laser drivers and other circuitry incorporated into the $20 \times 55 \times 5$ mm package (see image, p23). Each receiver contained eight photodiodes hybridized on a silicon chip with transimpedance amplifiers (TIAs) included in the package.

At the monolithic level, Agility conducted a live demo of its widely tunable InP-based lasers. Each device consists of a four-section sampled grating DBR laser with a monolithically integrated semiconductor optical amplifier (SOA) and an electroabsorption modulator. MetroPhotonics showcased a dynamic channel equalizer based on its echelle grating technology (see *Compound Semiconductor* July 2001, p87). The monolithic InP-based chip, about the size of a dime, contains two echelle gratings. The first grat-

ing separates the light by wavelength and distributes each channel into a separate waveguide, after which the light passes through an integrated photodiode. This device acts as both a channel monitor and a variable optical attenuator (VOA) to allow the channels to be equalized. The second echelle grating recombines the light before it leaves the chip.

ThreeFive Photonics has commercialized its first product, a single-chip receiver capable of detecting multiple wavelengths at 2.5 Gbit/s. The InP-based receiver employs a monolithically integrated arrayed waveguide grating (AWG) and features four channels covering 1525–1565 nm with a spacing of 100 GHz, making it suitable for CWDM. The operating temperature range is 0–70 °C. Samples will ship in the second quarter of 2002, with 16-channel versions and four-channel 10 Gbit/s receivers expected. "Optoelectronic integration using InP not only leads to very small systems at lower price levels – it also yields systems that are more robust, require less maintenance and repair, and consume less power. In some metropolitan areas,

power consumption is the most critical consideration," said CEO Wouter Deelman.

New companies

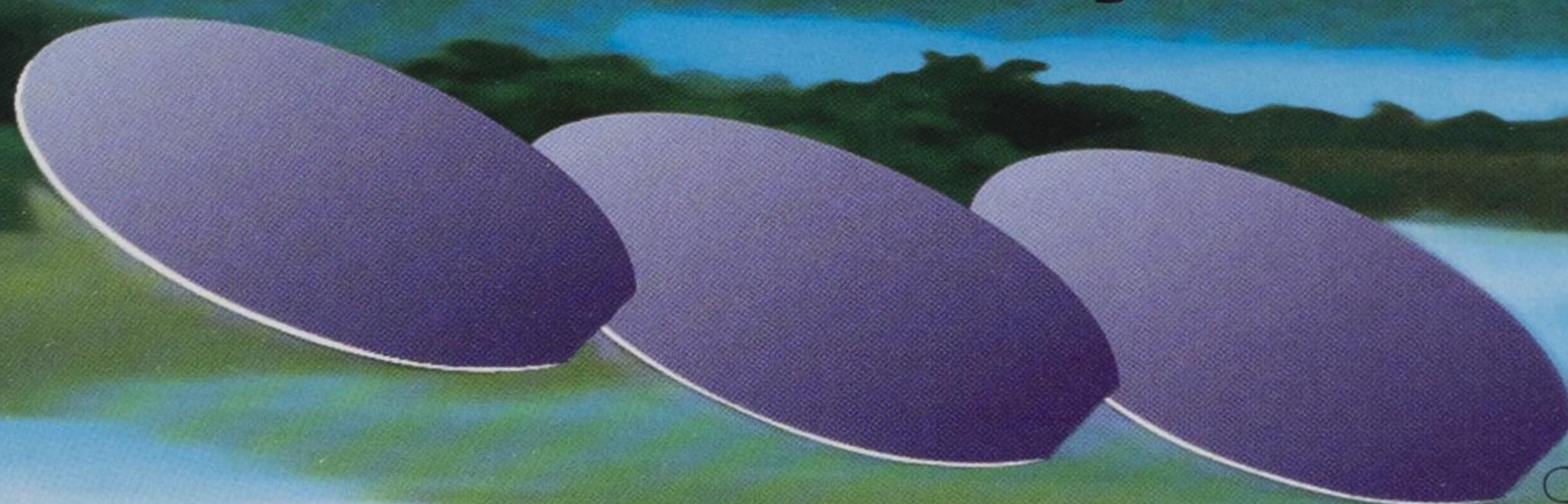
Several new companies made their debut at OFC, including Essient Photonics (see above) and Xindium Technologies, which is fabricating high-speed InP-based ICs (see *Compound Semiconductor* April 2002, p67). OEPic, founded in July 2000, designs and manufactures optoelectronic ICs for 10 and 40 Gbit/s systems. The company has an in-house InP wafer fab with gas-source MBE and MOCVD growth capabilities as well as sub-0.1 μ m e-beam processing, and also uses external foundries for GaAs-based devices. OEPic has received more than \$30 million from several venture capitalists and corporations. Its founders include Yi-Ching Pao, formerly at Litton and Filtronic, and Denny Houn, formerly at Agilent. OEPic's first products are a complete 10 Gbit/s chipset, priced at \$99 for bare die or \$199 as packaged parts. The chipset consists of an 850 nm VCSEL, a driver, a *pin* photodetector with an

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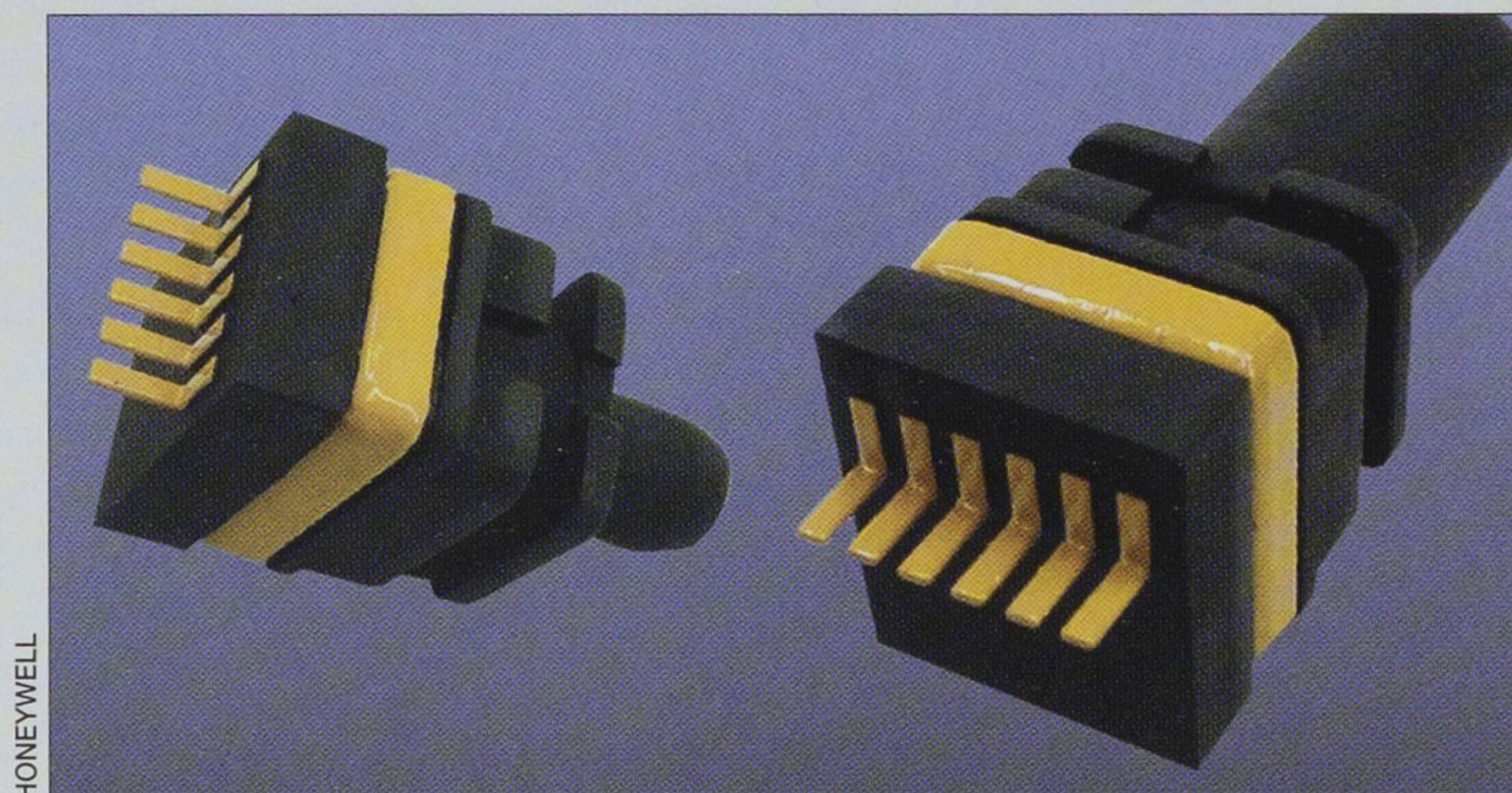
VCSELs target 10 Gbit/s applications and parallel interconnects

A number of VCSEL-based products were on show at OFC. As well as demonstrating its 10 Gbit/s serial transponder, which incorporates a directly modulated 1310 nm VCSEL, Cielo Communications launched several 1310 nm parallel array modules. The new family targets OC-3 (155 Mbit/s), OC-12 (622 Mbit/s) and Gigabit Ethernet (1.25 Gbit/s) applications up to 25 km on singlemode fiber. The separate transmit and receive packages contain arrays of eight or twelve VCSELs and *pin* photodiodes respectively. The arrays are currently shipping to development partners, with availability slated for the second quarter of 2002.

10 Gbit/s serial VCSELs

The VCSEL Optical Products business of Honeywell exhibited a new family of directly modulated 10 Gbit/s serial VCSELs and receivers designed for applications including 850 nm short-range multimode links compliant with the 10 Gigabit Ethernet standard. The VCSEL source is a directly modulated AlGaAs/GaAs device with a 10 μ m diameter oxide-confined aperture. The receiver contains an 850 nm *pin* detector and pre-amplifier.

During its manufacture, the VCSEL device undergoes



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Honeywell's new package is compatible with the footprints that have been specified in various multi-source agreements. It has a design similar to a ceramic microwave surface-mount package, and leads extending out the back for connection to a PCB board.

"Stabilaze", which Honeywell recently introduced as a method to manufacture 850 nm arrays. This approach includes burn-in procedures that ensure that the parameters of VCSELs in an array are constant within known limits. "The burn-in is done at the wafer level using a proprietary approach, and this guarantees a high level of quality before dicing," said Honeywell's Jim Guenter. "We also perform the standard wafer probing, including electro-optical and spectral measurements."

The new DC to 12.5 Gbit/s emitter features a threshold current of 3 mA and slope efficiency of 0.2 mW/mA measured at a power output of 0.35 mW. Power consumption is typically 10–20 mW. "In the

10 Gbit/s serial area we are introducing three types of device," said Guenter. "These include separate transmit and receive components, connectorized components and what we call optical front-ends. Optical front-ends contain the requisite components needed to mate to the fiber, but not the back-end of the receiver."

Honeywell is also looking to sample 1300 and 1550 nm VCSELs this year.

Large-aperture devices

At OFC, Zarlink released large-aperture 850 nm selectively oxidized VCSELs for 10 Gbit/s operation. The devices are designed for VSR optical interconnects and have a 12 μ m aperture (see *Compound*

Semiconductor April 2002, p56). The power penalty is only 0.5 dB over 300 m of high-bandwidth fiber at 80 °C. This provides a significant power margin for the IEEE 802.3ae 10 Gigabit Ethernet standard, which could result in better link performance and reliability, longer reach and lower costs.

The large-aperture design tends to introduce unwanted higher-order frequencies that lead to signal degradation. Zarlink says the design, which deliberately introduces losses that cancel the higher-order lateral modes, is more reliable than small-aperture VCSELs because a lower operating current density can be used.

Alvesta chooses Avalon

Alvesta, whose product range includes 10 Gbit/s four-channel transceivers for short-reach (100 and 300 m) applications, has selected Avalon Photonics as its source of VCSEL arrays. "The performance and reliability of Avalon's VCSELs has enabled Alvesta to deliver in volume the lowest-cost 10 Gbit/s optics solution in the market," said Robert Nalesnik, Alvesta's VP of marketing. "Four-channel VCSEL-based parallel optics provide compelling value for telecom and datacom backplane and multi-vendor optical interconnects."

integrated TIA and a limiting amplifier. "These first products are for short-reach applications at 10 Gbit/s, and will soon be followed by our longer-reach products fabricated in our own InP fab in Sunnyvale, CA," said George Bechtel, director of marketing. "We will put more emphasis on 40 Gbit/s parts when the market is ready."

Several new fabless companies are involved in the design of high-speed ICs for 10 and 40 Gbit/s applications. Centellax, based in Santa Rosa, CA, was founded in April 2001 by a team of device engineers including sev-

eral from Agilent. The company has developed a family of broadband amplifiers that is currently implemented in GaAs PHEMT technology, as well as mixed-signal ICs (mux, demux etc) implemented in SiGe and CMOS. The first product is the DA1A seven-stage traveling-wave amplifier, which can be used as a TIA, a small-signal gain block and as a driver amplifier for electroabsorption modulators. The DA series incorporates the company's patent-pending techniques to extend frequencies to as low as 30 kHz without expensive high-Q inductors and also to cas-

cade two amplifiers on a single chip. "The products reflect the design philosophy of our company – high performance, ease of use, reliability and a competitive price," said Julio Perdomo, Centellax's founder and president. The company is working with R&D groups and is selling products "in small quantities".

iTerra Communications, based in Fremont, CA, designs highly integrated driver amplifier and receiver products for 12.5 and 43 Gbit/s networks. One of its first products is a DC to 50 GHz GaAs MMIC amplifier which provides an output voltage of 8 V_{pp} to

Pump lasers provide higher powers

Just before OFC, Furukawa Electric announced a venture with Mitsui Chemical to produce high-power 980 nm laser chips. A new company, MC Fitel, will be established with 65% of the investment coming from Furukawa and the remainder from Mitsui. Headquartered at Furukawa's site in Chiba, Japan, the venture will be led by Yoshikazu Ikegami of the company's Optical Devices division. The alliance will exploit Furukawa's expertise in output signal stabilization and Mitsui's chip technology to create a decoupled confinement heterostructure chip with an output power of more than 300 mW.

Furukawa and Mitsui have been jointly developing high-power 980 nm chips since October 2000. MC Fitel aims to address rapidly the increasing market demand for 980 nm pump lasers.

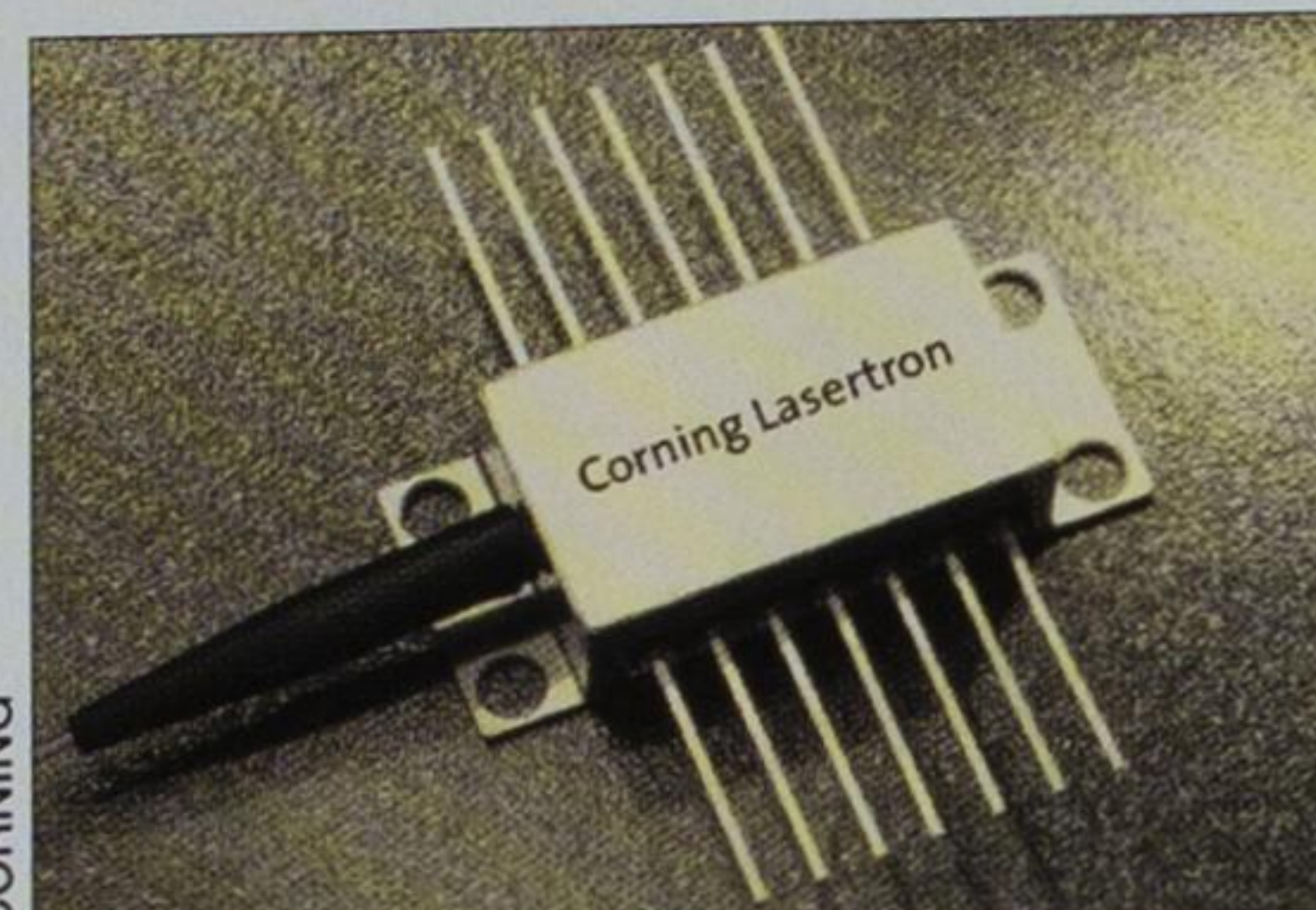
Corning enhances power

Corning Lasertron demonstrated new levels of power and

reliability from its pump lasers. The company gave a live demo of the CLT3.0, a 980 nm pump chip that delivers up to 600 mW of kink-free power and 500 mW of operating power over the lifetime of the product – doubling the power of Corning's current chip. The company also demonstrated a new 14XX nm Raman pump providing 420 mW of power.

Both chips are manufactured using a precision-etch process developed at Lasertron's site in Bedford, MA. "The process increases our chip power by an average of 30%, and chip-power efficiencies by more than 10%," said product manager David Bean. "The improvement also injects outstanding consistency into our process."

The process has been fully qualified with the 980 nm Optilock CLT2.2 pump chip, and has logged more than 1.5 million device-hours in reliability testing. Full qualification and acceptance have been received in the



Corning Lasertron has recently increased the output power of its 980 nm chips to 500 mW.

250 mW wavelength-stabilized Gibraltar 2 package. The firm has now introduced a fifth-generation Gibraltar 3 package, which is epoxy- and flux-free. The 980 nm version includes a getter to ensure high reliability.

Axcel unveils 980 nm chips

Founded in mid-2000, Axcel Photonics manufactures diode lasers, and revealed its first products – 980 nm pump lasers – at OFC. Available in chip or chip-on-submount form the pumps provide more than 360 mW of kink-free power, says the company, which is also set to introduce a 1480 nm

version with up to 300 mW output later this year. Axcel's 980 nm pump has a typical slope efficiency of 0.85 W/A and operating current of 0.5 A. Axcel grows its lasers by MOCVD and performs wafer processing, burn-in and testing at its facility in Marlborough, MA. The company also demonstrated a 980 nm device with 1030 mW of kink-free singlemode output power during OFC.

MSA guarantees packages

Alcatel, JDS Uniphase and Nortel have signed a multi-source agreement (MSA) for 960–980 nm pump lasers in uncooled mini-DIL packages. Targeting the wavelength range, the agreement covers terrestrial EDFAs. The MSA is expected to reduce significantly the size and power consumption of EDFAs used in metro and long-haul networks. Uncooled Mini-DIL pump modules will offer more than 100 mW, and will maintain this performance over the 0–70 °C temperature range.

drive a lithium niobate modulator. Another fabless start-up is DA-LightCom, based in Les Loges en Josas, France, which is developing 40 Gbit/s driver amplifiers and TIAs, and has a series of standard products at 10 Gbit/s.

Narrow channel spacing

One way to increase the capacity of a DWDM system is to reduce the spacing between channels. For ultra-dense WDM systems with a spacing of 25 GHz, stability and absolute accuracy are critical. Fiberspace, based in Woodland Hills, CA, has developed a wavelength locker technology, Gridlocker, that provides a wavelength accuracy of ± 250 MHz. The company's patented optical phase-locked loop (OPLL) technology incorporates a tuned Fabry–Perot etalon to provide a sharp optical frequency reference. The OPLL stabilizes the laser frequency by utilizing frequency modulation techniques to derive a phase-dependent error signal that locks the laser frequency to the peak of the Fabry–Perot transmission.

Fiberspace's product uses standard DFB lasers purchased externally and is tunable across a 3 nm range.

40 Gbit/s systems

Many companies are developing 40 Gbit/s ICs using InP, SiGe or even CMOS (see p35). Infineon, Bookham and Agilent jointly demonstrated a 40 Gbit/s system utilizing signal generation and test equipment from Agilent and SiGe mux and demux ICs from Infineon. Bookham supplied the GaAs PHEMT driver and a transmitter containing a DFB laser, broadband GaAs modulator and an integrated wavelength locker.

One of the highlights of the post-deadline session at OFC came from Lucent's Bell Labs, which claims to have doubled the distance record for high-bandwidth, ultra-long-haul transmission by sending 2.56 Tbit/s some 4000 km. The lab experiment used a 64-channel DWDM system, where each channel carried information at 40 Gbit/s. The ampli-

fiers were 100 km apart, and the experiment was made possible by a new coding scheme, differential phase shift keying (DPSK), together with extended L-band amplifiers, Raman amplifiers, forward-error correction (FEC) and optimal dispersion compensation. In related news, Deutsche Telekom has started field trials of Lucent's 40 Gbit/s LambdaXtreme Transport system, which can transport signals 1000 km without regeneration. Tim Sullivan, president of Lucent's Optical Networking Group, reports that the LambdaXtreme 40 Gbit/s system is already more cost-effective than 10 Gbit/s systems.

"The LambdaXtreme system delivers 40 Gbit/s wavelengths for 15% less than the cost of combining four standard 10 Gbit/s wavelengths," he explained. "Our 40 Gbit/s products are shipping now, and offer service providers a system that is able to meet all of their distance and capacity needs, while continuing to deliver significant savings in operational expenses."



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Tunable lasers

Many different types of tunable laser were on display at OFC. JDS Uniphase launched a narrowly tunable, high-power laser, while Quantum Devices showed a temperature-tunable DFB laser capable of delivering 15 mW of power and tunable across four adjacent ITU wavelengths using a 100 GHz spacing. Iolon exhibited a 20 mW external cavity device capable of tuning to more than 200 channels with 25 GHz spacing. "The 25 GHz channel spacing results from the integrated wavelength locker technology that Iolon incorporates into the Apollo laser module," said president and CEO John Clark. "This provides better than ± 1 GHz frequency accuracy over the entire tuning and operating temperature range, and the fact that our laser is continuously tunable made this possible without changes to the external laser cavity itself."

ADC announced a tunable laser based on its monolithic four-section DBR design with an integrated wavelength locker and proprietary control algorithm. The firm says it is the only manufacturer building widely tunable

lasers with built-in wavelength lockers in volume. The laser operates in the C-band and supports the 1529–1561 nm EDFA window, and tunes to a channel in less than 2 ms.

The LG10M, Nortel's new widely tunable 10 Gbit/s transmitter, has a GaAs Mach-Zehnder modulator, variable optical attenuator, wavelength locker and power monitor with a CW widely tunable VCSEL. The module, which covers up to 32 nm in the C- and L-bands, measures $80 \times 18 \times 12.5$ mm and uses a MEMS-based tunable VCSEL designed by Nortel's subsidiary Coretek.

Agility adds functionality

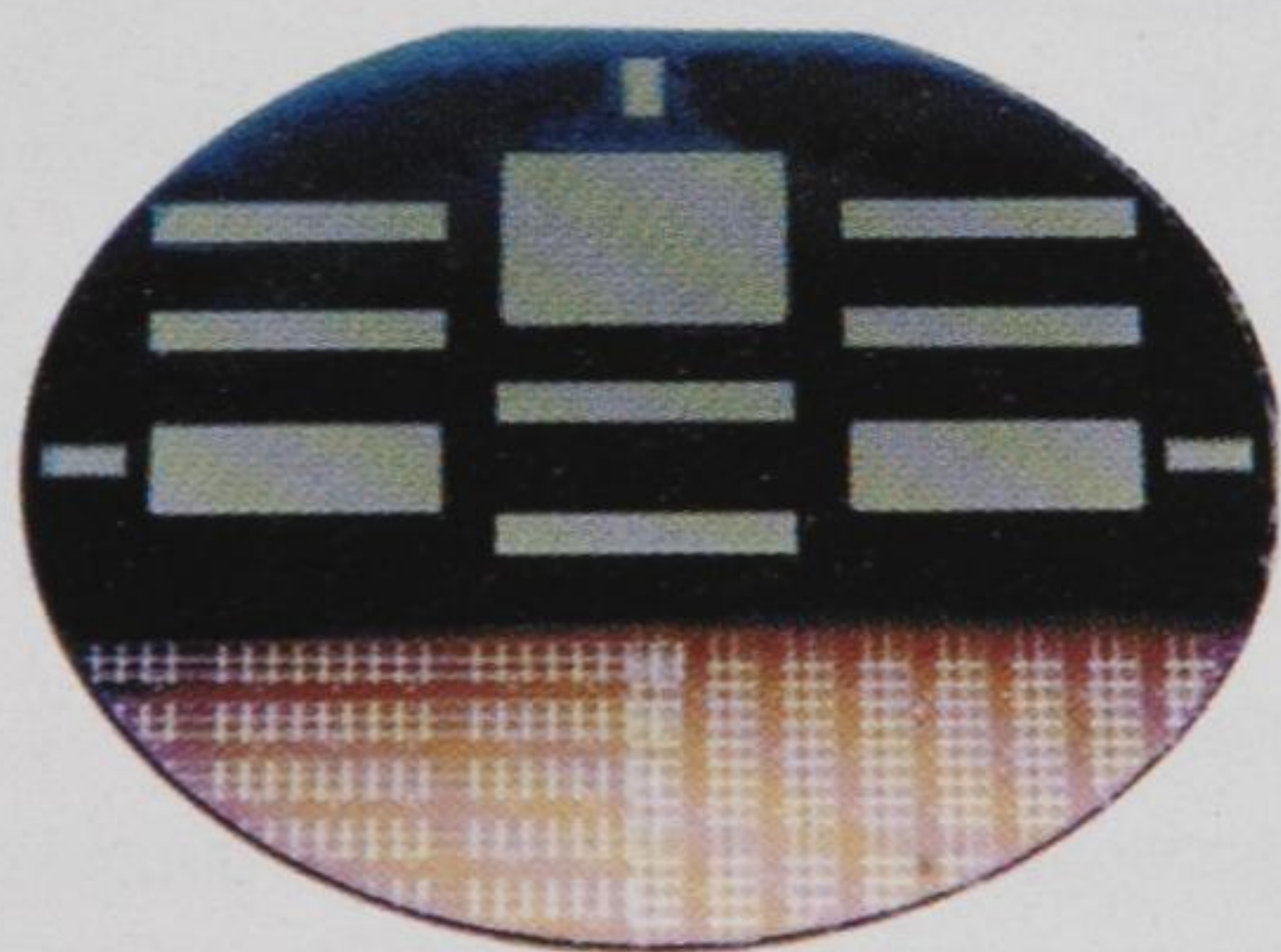
Agility Communications introduced two widely tunable products: the 3105, a 10 Gbit/s laser that delivers 10 mW of output power for long-haul applications, and the 4245, a lower-power 2.5 Gbit/s laser that targets metro applications. The same InP sampled-grating DBR laser is used in both products. Each chip contains six sections; these are gain and phase sections and two gratings for the laser, together with a monolithically integrated SOA and

electroabsorption modulator. Tuning is over 100 channels with 50 GHz spacing and available across the full C-band (1530–1565 nm). Production is slated for July.

In the 10 mW long-haul laser, the electroabsorption modulator is left open and a lithium niobate modulator is used instead. The lower-data-rate laser employs the InP modulator and operates at up to 2.7 Gbit/s for FEC support, with +3 dBm (2 mW) of output power in the C-band.

"Most of today's 10 Gbit/s architectures use lithium niobate to modulate the laser signal, and this is what our new 10 mW laser is designed for," said Arlon Martin, VP of marketing. "While lithium niobate is much more expensive, bulky and harder to connect to fiber, it provides excellent drive and on-off signal characteristics compared with InP modulators, and is suited to long-haul links or 10 Gbit/s operation. Our shorter-range device uses the integrated InP modulator because it is cheaper and does an excellent job at 2.5 Gbit/s, where most of the demand is currently situated in metro links."

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Essient Photonics brings new thinking to optical modulation technology

By Jon Newey

One of the new companies making its debut at OFC was Essient Photonics, a spin-out from Glasgow University in Scotland that specializes in optical modulators and photodetectors. These devices take advantage of the properties of resonant tunneling diodes (RTDs). The company has announced \$7 million in series A funding from Pond Ventures, a venture-capital firm that specializes in early-stage investment in European technology companies.

Essient's novel RTD-based technology for making 10 and 40 Gbit/s optical modulators and photodetectors will significantly lower the drive voltage and footprint compared with current devices. At OFC Essient announced that its modulators can operate with a drive of 0.1 V, significantly lower than the several volts needed for lithium niobate and InP- or GaAs-based devices. The new modulators are only about 5% of the size of a typical lithium niobate modulator.

The company is headquartered in Glasgow and is following a fabless business model. The funding will be used to take existing prototype devices through to the stage where they are suitable for sampling to commercial customers. "We are about six months away from getting devices to customers," said Jeremy Chappell, Essient's VP of marketing. Essient is using Compound Semiconductor Technologies in Glasgow to fabricate the devices in the current development phase, and other potential fab partners are also being assessed. "One thing that came across very strongly when speaking to potential customers was that they need reliability of supply, and for that reason we are looking at a couple of foundry partners," said Chappell.

How does it work?

Essient's approach makes use of a technology developed and patented by the company's founder and chief scientist Charles Ironside. This involves using the properties of RTDs in a novel way to modulate light.

RTDs use a quantum well between two thin barrier layers to create an electron resonator. Electrons incident on the double barrier can tunnel through the first barrier into the well and then reflect between the barriers, creating standing waves. Electrons of a specific energy

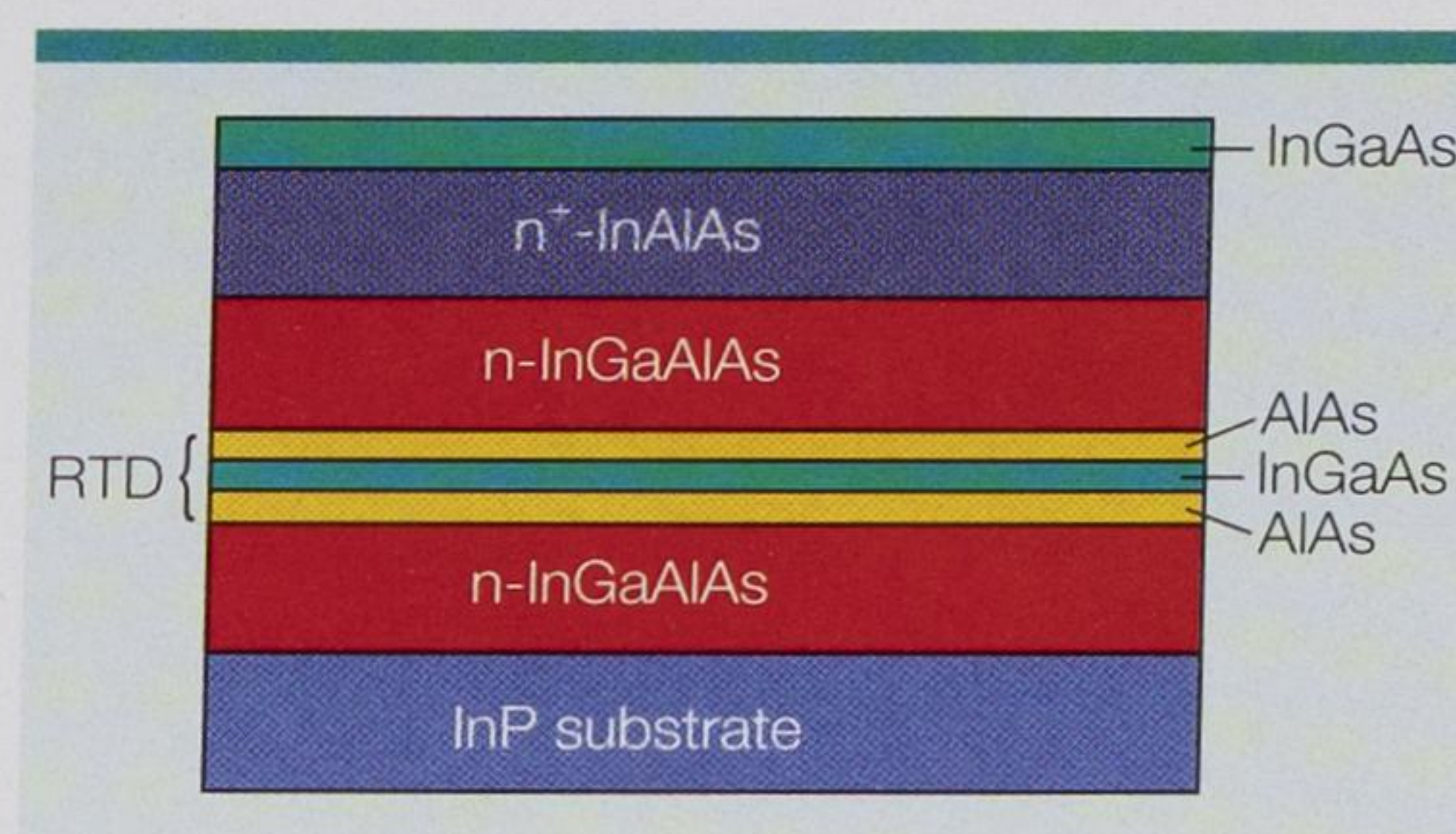


Fig. 1. The above structure forms the basis of Essient's approach. The RTD structure is sandwiched between InGaAlAs layers that form the waveguide core.

RTDs are of great interest because of their ability to operate at high frequencies and provide a large increase in current for a small applied bias voltage.

will constructively interfere, and so the standing waves created represent discrete energy states. Regions of negative differential resistance arise because of electron confinement and coupling in the well. The I-V curve of an RTD is characterized by peaks and valleys in the current as the bias voltage is varied. The peaks represent the bias condition at which resonance occurs, with the valleys being a bias point that prevents electrons passing through the energy states in the standing wave, effectively switching the device off.

RTDs have attracted much interest because of their ability to operate at high frequencies and provide a very large increase in current for a small applied bias voltage. An AC signal below 1 V can induce high-speed switching of the RTD and therefore the electric field it generates. Ironside has applied the RTD principle to waveguides, using the high-frequency change in electric field to shift the absorption band edge of a material, thus making an electroabsorption modulator.

Ironside's patent describing an RTD-based modulator represents the initial development of the idea, while more recent improvements are now subject to the patent application pro-

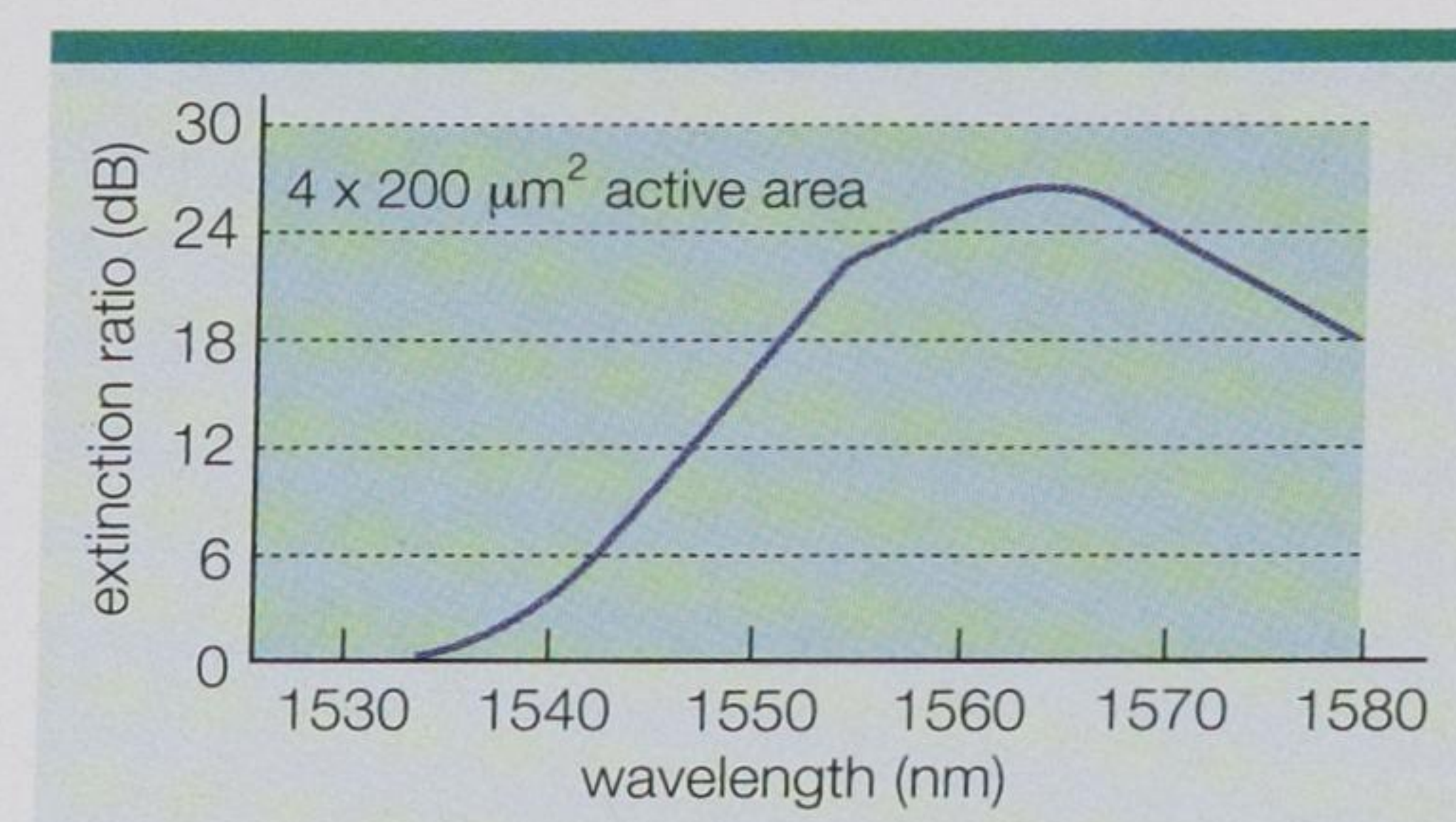


Fig. 2. The modulator extinction ratio depends on the RTD's peak-to-valley current ratio. For the early device described in the patent the extinction ratio peaks at 1565 nm.

cess. Though most RTD research to date has concentrated on GaAs/AlAs structures, Essient's RTD uses an InGaAs well with AlAs barrier layers. This enables the device to operate at telecom wavelengths and also gives a bigger difference between the peak and valley currents in the device's I-V curve.

The patent describes an RTD structure consisting of a 6 nm InGaAs QW between two 2 nm AlAs barrier layers (figure 1). The RTD is sandwiched between two InGaAlAs spacers that form the waveguide core. The InP substrate and a top InAlAs layer provide waveguide cladding, and an InGaAs contact layer is grown on the top cladding layer. Ridge waveguides are then etched and ohmic contacts deposited.

Early performance data

The patent describes typical devices with a $2 \times 100 \mu\text{m}^2$ active area. These have peak current densities of 20 kA/cm^2 with a peak-to-valley current ratio of 4. The difference between peak and valley voltages is 0.8 V. The modulator bandwidth and extinction ratio are related to the RTD's structure and electrical characteristics. The extinction ratio is directly related to the peak-to-valley current ratio in the RTD I-V curve. For a device with a $4 \times 200 \mu\text{m}^2$ active area the extinction ratio peaked at 28 dB for 1565 nm light (figure 2). Essient says that at present the devices can operate over a 50 nm range of wavelengths, an important feature for devices that may be used in WDM systems.

A key feature of Essient's technology is that in principle the device can operate in reverse as a light detector. The RTD will then act as an integrated amplifier for the photocurrent generated by the incident light.

QPI unveils lasers with circular beams

By Richard Dixon

Quantum Photonics Inc (QPI) is having a busy few months. The start-up manufacturer of InP laser diodes based in Jessup, Maryland appointed a CEO last November, secured over \$27 million in second-round funding in February, and introduced new products in time for the Optical Fiber Communications conference this March. These products include high-power InP sources suitable for free-space optical wireless communications and gain chips for external cavity tunable lasers.

Vertically integrated fab model

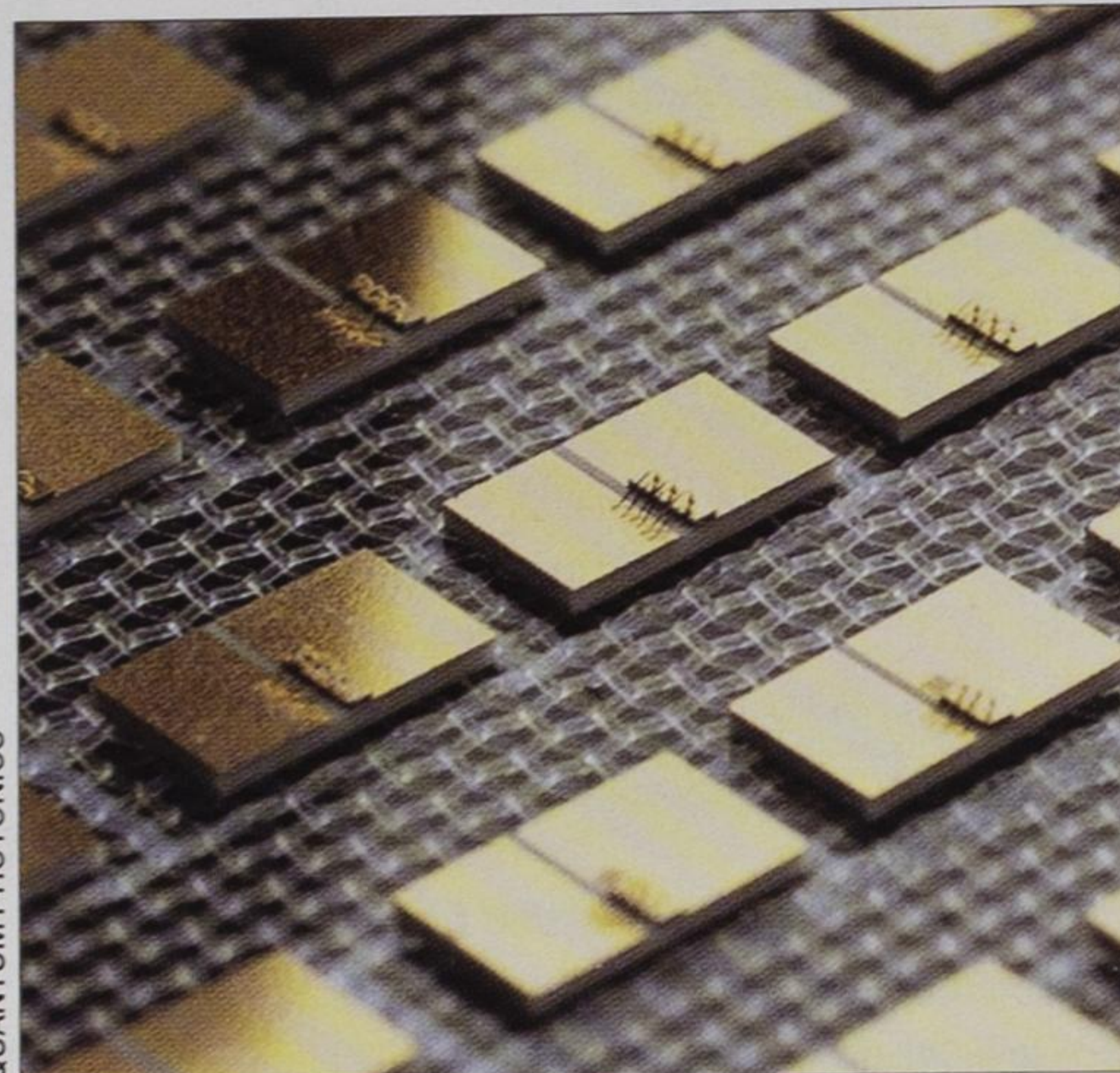
After receiving funding in mid-2000, the four-year-old spin-off from the University of Maryland began the development of Fabry-Perot laser diodes at a 40,000 sq. ft production facility that includes a 15,000 sq. ft cleanroom. At this site, which began operation at the end of 2001, QPI undertakes the epitaxial growth of InGaAsP MQW lasers on InP substrates using an MBE reactor. Wafers are processed into die, assembled, packaged and tested in house.

Lasers are available as bare die, chip-on-submount and in a range of packaging options. Specially designed heat sinks are also able to facilitate rapid testing and evaluation of the gain chips in customer applications. The company also plans to offer a fiber-coupled 14-pin butterfly package in the near future.

"At QPI our designs are based on ridge-waveguide structures, which provides us with a simpler manufacturing process than buried heterostructure laser designs," says CTO and co-founder of the company, Mario Dagenais. "Our technology allows us to avoid the re-growth processes typically needed to incorporate passive and active components. We also get a higher yield, which translates into lower production costs."

Single-angled facet gain chip

The company's InGaAsP/InP gain chip features a reflective facet coating on one end, and an angled facet with a simple anti-reflection coating at the other. The optical coating is performed by electron-beam deposition. Known as a single-angled facet (SAF) device, the waveguide is tilted 6–8° away from the normal to reduce the occurrence of reflection back into the device. The SAF laser exhibits an effective reflectivity of less than 10^{-5} , and this low residual reflectivity is the key to wide gain bandwidth (up to 150 nm). This wide op-



Quantum Photonics' first products include high-power InGaAsP laser diodes (shown here as chip-on-submounts).

A patented integrated InP waveguide design allows low signal loss between active and passive regions, and results in very small beam divergence angles in the transverse and parallel directions.

eration band is being leveraged by QPI's customers to make external cavity tunable lasers, or even superluminescent diodes, which find applications in network monitoring. QPI says that currently most companies are content with either C- or L-band wavelengths.

Other key operating parameters for the gain chip include a Fabry-Perot equivalent threshold current of 50 mA, a slope efficiency of 0.4 W/A and output power in excess of 100 mW CW at room temperature.

"In our single-angled facet device, the light in the waveguide hits the small angle produced by the facet, and effectively very little is coupled back into the waveguide," says Dagenais. This leads to a very low reflectivity at the facet, resulting in higher optical power being transmitted from the chip.

"This is exactly what you want for an external cavity laser," continues Dagenais. "If you put a filter outside the cavity, such as a grating that reflects the light at a particular

wavelength, the facet reflectivity remains very low over the whole spectrum of amplified spontaneous emission."

High-power laser diodes

QPI's high-power Fabry-Perot laser diode is also targeting eye-safe 1550 nm free-space optical wireless or remote sensing applications. Based on the same InGaAsP ridge-waveguide design, the laser operates in single transverse mode in the C- and L-bands. The company's standard InGaAsP device achieves 160 mW using a conventional facet coating design. Preliminary data sheets indicate an operating current of 450 mA, with threshold currents and slope efficiencies essentially the same as the SAF device used in a low loss cavity.

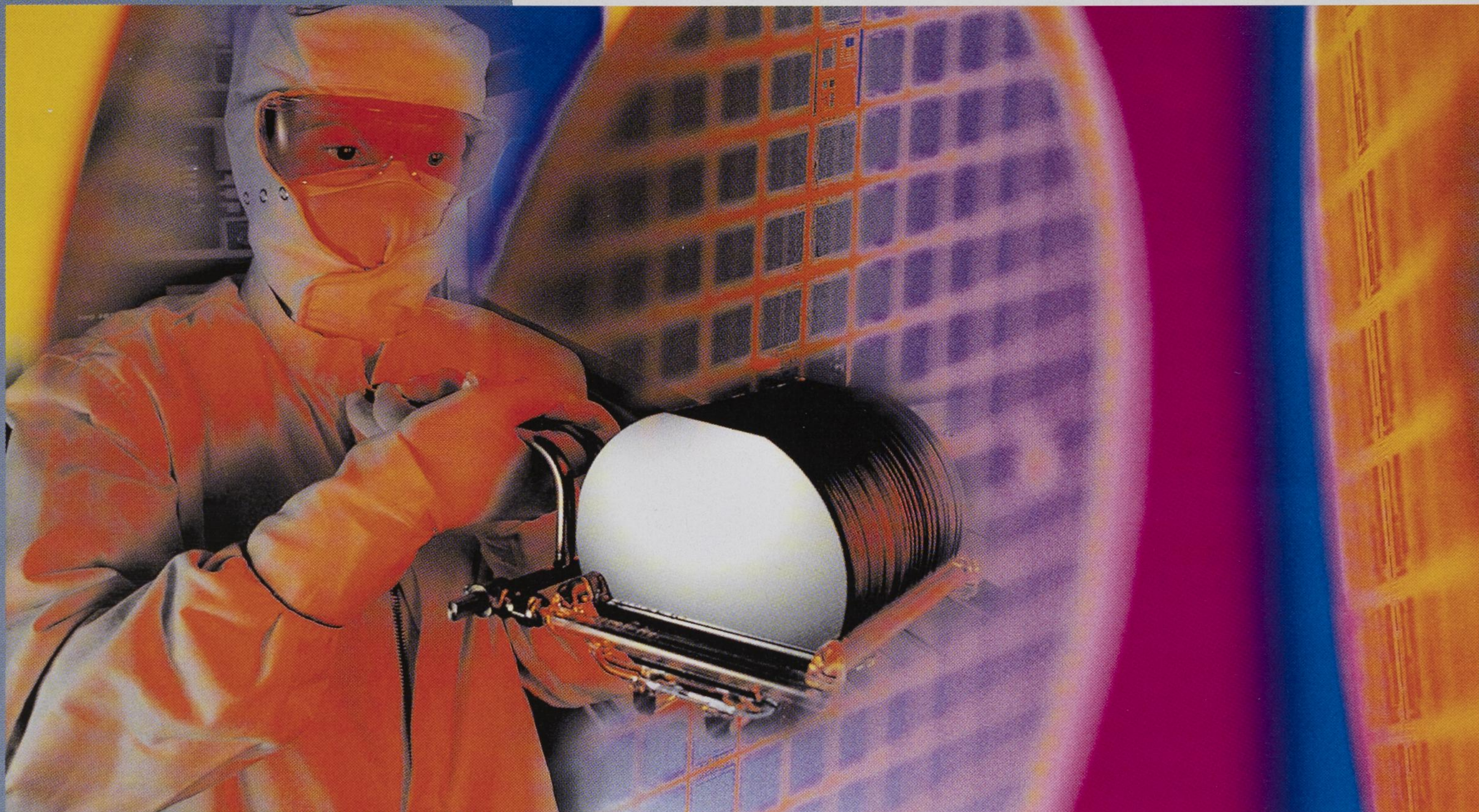
Circular beam properties

Both device types also benefit from the company's proprietary passive-active resonant coupler (PARC) technology. QPI monolithically integrates a passive InP waveguide with the ridge-waveguide laser, which leads to a low optical loss between passive and active components. "Our patented integration technology uses fewer processing steps and offers more robust and efficient coupling between active and passive optical elements," says Dagenais. "While this approach allows the integration of semiconductor amplifiers to make high-power devices, it also allows passive InP waveguides to control beam divergence and shape."

Both lasers feature a mode control option that produces almost circular output. For both chip designs, the transverse and parallel beam divergence angles are 26° and 25°, respectively, and a second option provides a wider divergence and a circular 30 × 30° beam. Without this option, the standard diode has beam divergence angles of 36° (transverse) and 14° (parallel).

"Using PARC we are able to shape the output of the laser so that the beam is larger and almost circular compared with that of a typical edge-emitting laser," says Dagenais. "This makes it much easier to couple to single-mode fiber, and the larger beam means that overall there is less divergence."

According to Dagenais QPI's near-term targets for the SAF device include pre-production by May and full Telcordia production by the summer. The high-power lasers are due for production during the fourth quarter of 2002. Semiconductor optical amplifiers are also on the company's development roadmap.



So who is the real MBE market leader?

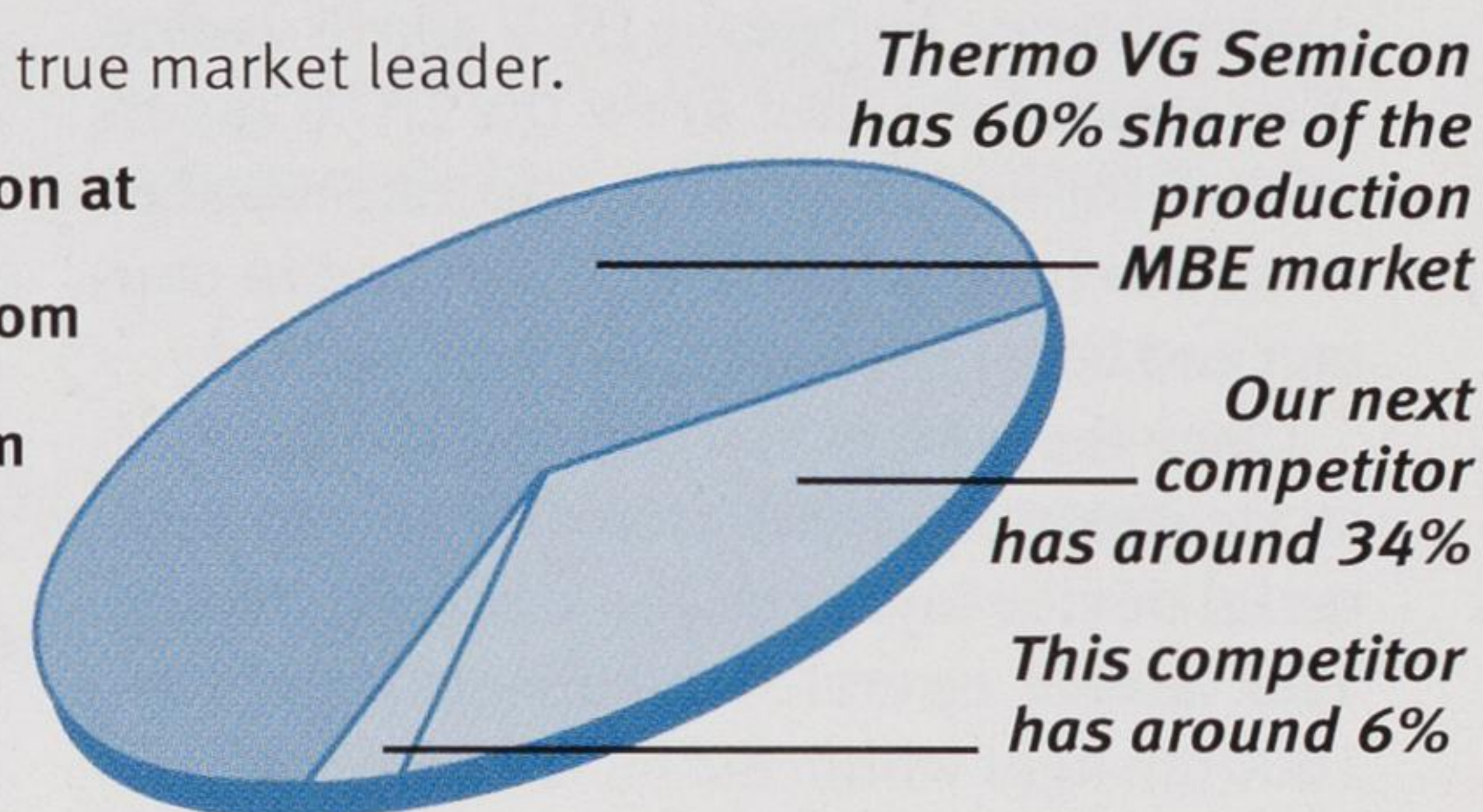
Our competitors claim to lead the MBE market. But you don't have to dig very deep to reveal what they don't want you to know.

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Nova Crystals takes InGaAs-on-silicon avalanche photodiodes to the market

By Rebecca Pool

Fiber-optic components manufacturer Nova Crystals claims to have developed an InGaAs-on-silicon APD with a difference. Touted at this year's OFC as "the world's most sensitive semiconductor for metro and long-haul optical networks", the 1300–1600 nm InGaAs-on-Si APD is said to have a record low excess noise, high gain bandwidth, and the same dark current and responsivity as commercial InP-based APDs.

Nova is gearing up to supply the APDs in sample quantities by the third quarter of this year. This has been achieved by developing a wafer-scale bonding technology that the company says successfully combines the light absorption advantages of InGaAs with the beneficial physical properties of silicon.

Overcoming InP obstacles

InGaAs-on-InP APDs are widely used in high-sensitivity 2.5 Gbit/s and 10 Gbit/s fiber-optic receivers, but InP material limitations restrict gain-bandwidth to around 80 GHz and lead to a high excess noise factor. Previous attempts to combine InGaAs with silicon, rather than InP, have failed because lattice mismatches have led to high dark currents, which are fatal to the device's operation. However, Yu-Hwa Lo and colleagues at Nova Crystals and the University of California, San Diego claim to have overcome these problems by using a proprietary wafer fusion technique that reduces stresses at the bonding interface.

The silicon part of the researchers' photodiode consists of an n^+ substrate, a 1 μm n -epitaxial layer and a thin p^+ -epitaxial layer, while the III-V layers comprise a 1 μm undoped InGaAs layer and two InGaAsP-on-InP p^+ contact layers. To fuse the III-V and Si wafers, the researchers first grew the III-V layers onto an InP substrate. Each substrate was then rinsed in hydrofluoric acid, placed in contact and heated at 650 °C for half an hour.

Once the wafers had bonded, the InP substrate was etched away leaving only the epitaxial device layers on the silicon substrate. The device operates by absorbing 1300–1600 nm light within the InGaAs layer. Photo-generated electrons are then injected into the silicon multiplication region.

Although they were unable to give extra de-

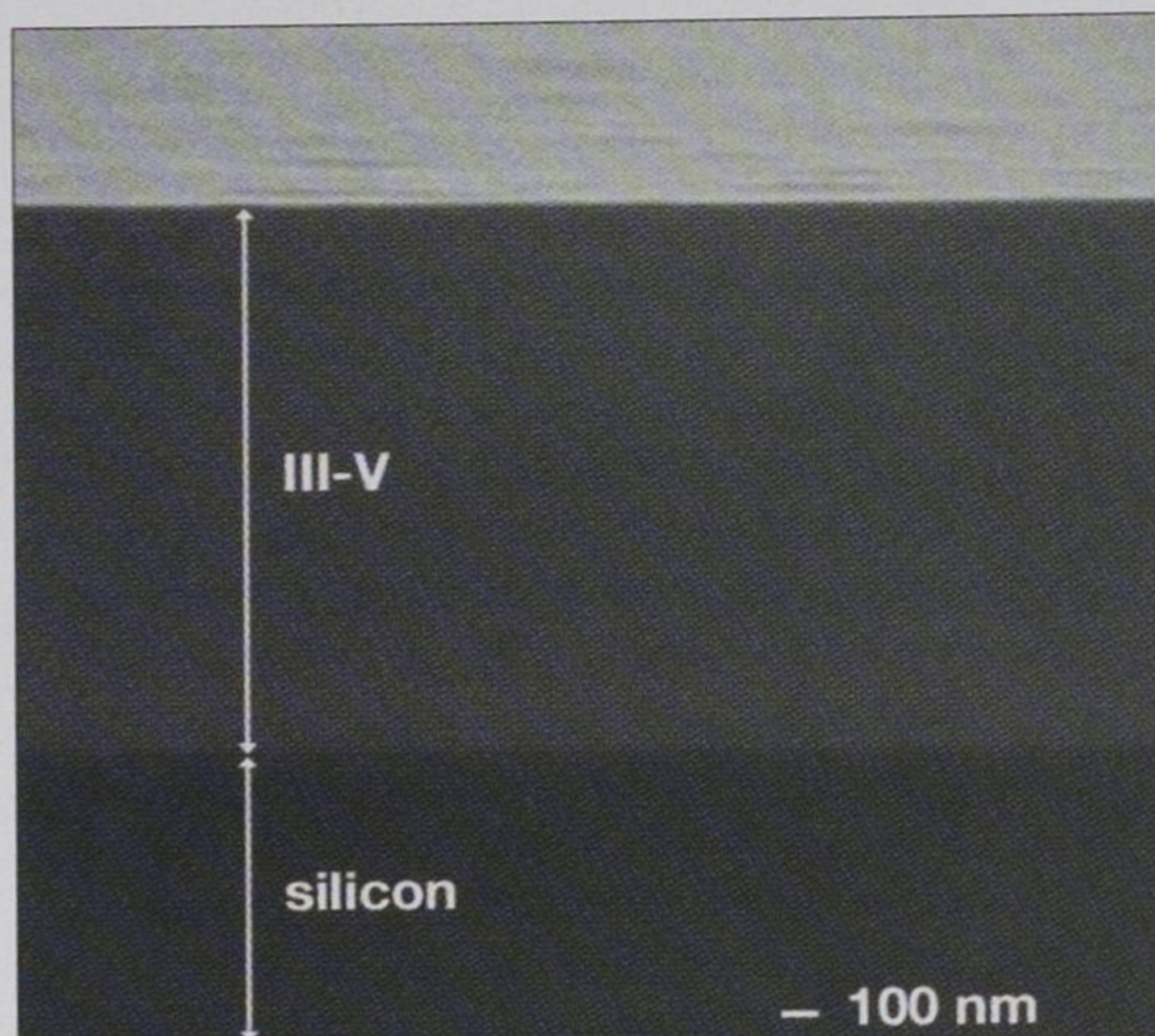


Fig. 1. A typical SEM cross-section of the bonded III-V/silicon interface shows that there are no microcracks or crystal dislocations present within this region.

"Yields have been considerably improved by reducing the thermal stress at the bonding interface, and are at similar levels to those achieved during InP-based manufacturing."

tails on the wafer fusion technique, the researchers say that while van der Waals forces hold the surfaces together on initial contact, prolonged heating leads to stronger covalent forces that bond the surfaces (see figure 1).

Wafer fusion success

"By optimizing the temperature and pressure cycles [during bonding] we have reduced thermal stresses at the interface," said Lo. "This prevents the generation of threading crystal dislocations, reduces tensile shear stress that can cause microcracks, and also eliminates peel stress that leads to debonding."

According to the researchers the lower thermal stresses are responsible for the device's dark current of 35 nA, while the use of silicon enables a record low excess gain noise factor of 2.2, both at a photomultiplication gain of 10. At a gain of 50, the excess noise factor is

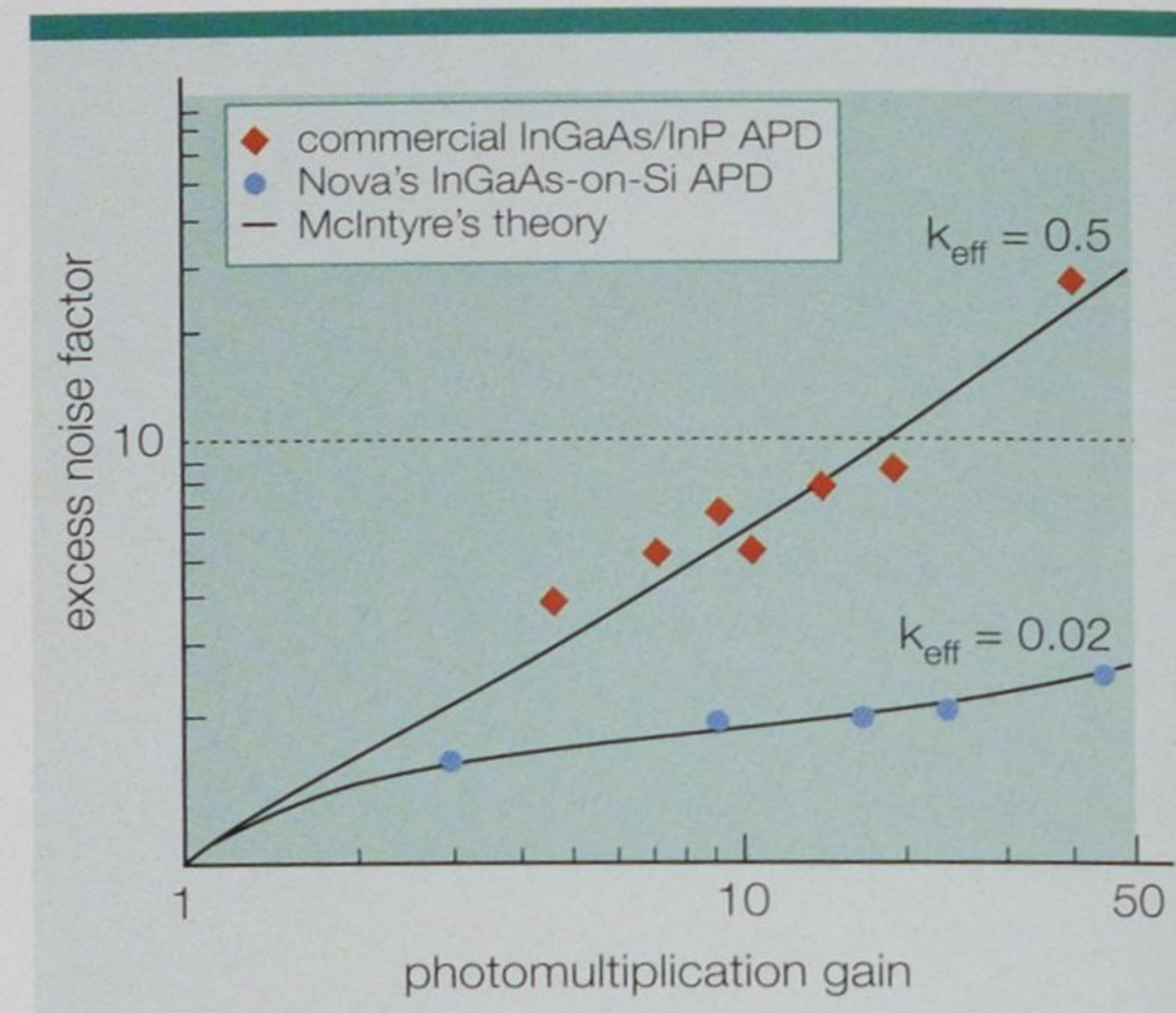


Fig. 2. The graph shows the lower excess noise factor of Nova Crystals' InGaAs-on-silicon APD compared with a commercial InGaAs-on-InP device.

only 2.8, compared with a value of 26 for conventional InP APDs (see figure 2).

The researchers have also reported gain-bandwidths of more than 140 GHz – with the potential to extend to 400 GHz – as well as a temperature coefficient of less than 0.03 V/°C. Compared with conventional InP-based APDs, the InGaAs-on-Si devices are expected to have a receiver sensitivity that is 5 dB higher, and a similar responsivity.

"Yields have been considerably improved by reducing the thermal stress at the bonding interface, and are at similar levels to those achieved during InP-based manufacturing," said Lo. "We can achieve wafer-scale manufacturing and the use of silicon substrates makes testing and packaging easier."

Nova Crystals is already beginning to work towards faster 10 Gbit/s and 40 Gbit/s versions of the InGaAs-on-Si photodiode.

In the June issue of

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CONTENTS

Indium phosphide ICs for 40 Gbit/s networks

p35

The path to indium phosphide production

p41

Substrate makers tackle the growing challenges of InP

p45

Indium phosphide ICs in strong demand for 40 Gbit/s networks

Backed by growing market interest and the availability of 4 inch substrates and epiwafers, several IC manufacturers are now developing products for 40 Gbit/s networks, writes **Tim Whitaker**.

Although fiber-optic links at telecom wavelengths rely on InP-based optoelectronic devices such as lasers and photodetectors, electronic ICs made with InP have yet to reach the commercial mainstream. However, as network equipment makers start to look more seriously at 40 Gbit/s systems, InP-based electronic and optoelectronic ICs are poised to make the crucial breakthrough.

Companies such as TRW and HRL have a long history of developing InP ICs for military and space applications. Now these companies (TRW through its Velocium subsidiary) are addressing commercial markets. They have been joined by firms such as Vitesse and Alpha in the US, NTT Electronics (NEL) and Hitachi in Japan, and by foundries such as Global Communication Semiconductors (GCS).

The key factor is performance. In a paper at this year's GaAs Mantech conference, Mike Sun of Alpha Industries' Sunnyvale Operations summarized the performance advantages of InP HBTs. "The most attractive features of InP DHBTs are low power consumption due to their low turn-on voltage, and a high Johnson limit due to the high breakdown of the InP collector," he says. "Also they allow moderate circuit integration levels up to a few thousand transistors, and offer the potential to integrate optoelectronic devices such as photodetectors."

So why is this happening now? A key factor is the growing demand for high-speed devices, which has led IC manufacturers to invest in the commercialization of their technology. The article by Velocium on p41 of this issue describes some of the crucial steps in transferring technology from the lab to the fab. In many cases it has proved possible to leverage the process steps and equipment used in GaAs IC manufacturing, but the availability of mat-

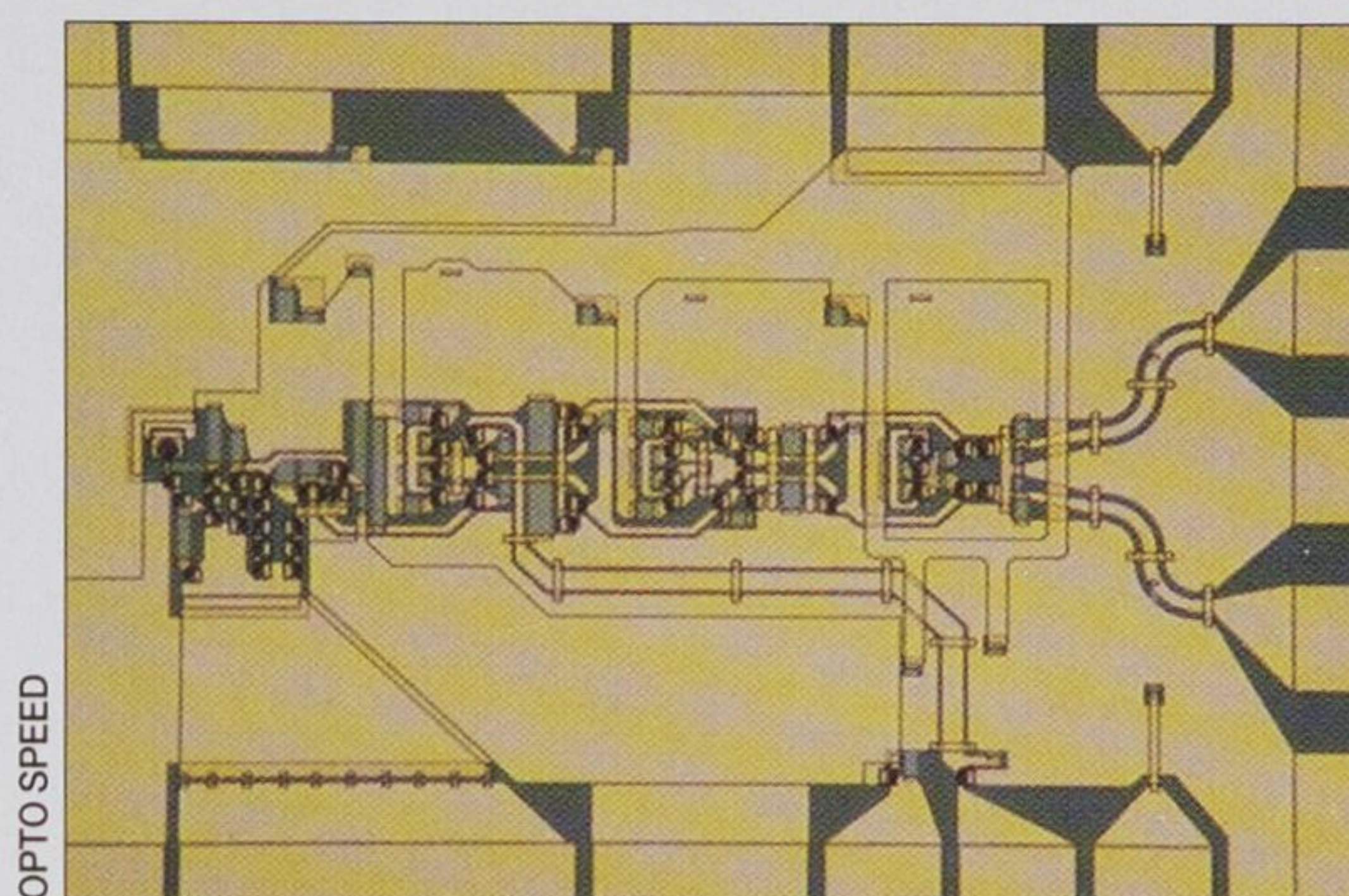


Fig. 1. Opto Speed's receiver IC contains an InGaAs *pin* photodiode monolithically integrated with an InP HBT-based TIA.

erials has been a different matter. A key factor in the birth of the InP IC industry has been the recent availability of 4 inch InP wafers with suitable properties (see p45). For companies lacking internal epitaxy capabilities, the availability of 4 inch InP epiwafers has also allowed them to establish their own processes.

Velocium

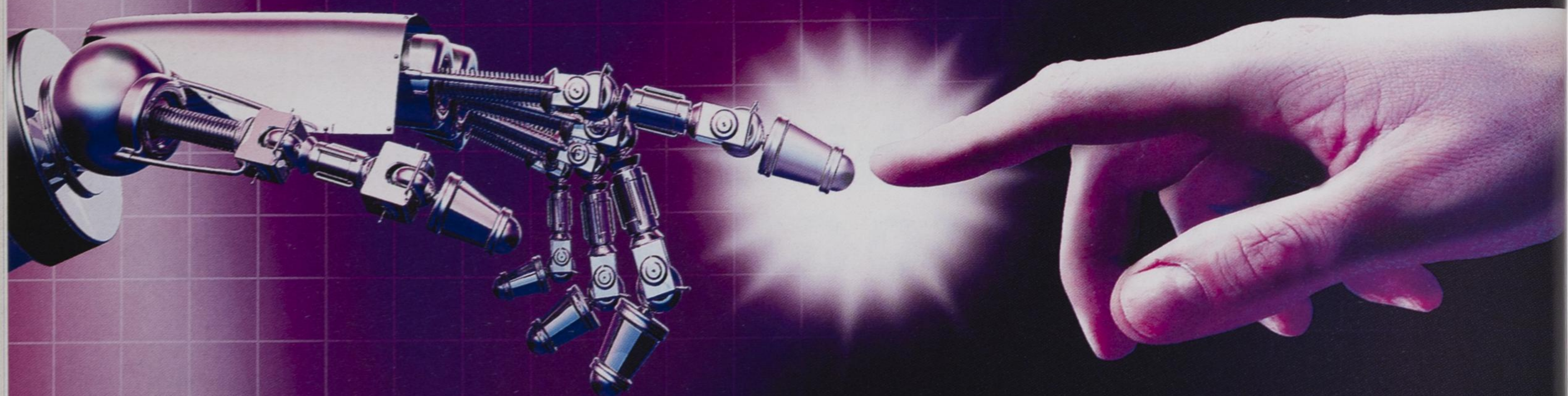
In May 2001 TRW formed a commercial subsidiary, Velocium, to manufacture and sell high-speed GaAs- and InP-based ICs for fiber-optic and wireless communication systems. The company built the world's first 4 inch InP line, and has now introduced a range of InP-based ICs, including a 40 Gbit/s photoreceiver, a 12.7 Gbit/s NRZ-to-RZ converter and a divide-by-2 frequency divider targeted at down-conversion or phase-locked loop applications. The latter product (DV2401) is rated at 27–43 GHz, although performance extends up to 50 GHz. Features include a dynamic divider design, a single –4 V power supply, on-chip termination (50 Ω to ground), single-ended input and differential output, and a die size of 1.1 $\times$ 2.0 mm².

HRL Laboratories

One indication of the level of interest in InP technology at the recent Optical Fiber Communication (OFC) conference was the appearance of HRL Laboratories of Malibu, CA. HRL's commercial activity in the fiber-optic market is complementary to the work being carried out on behalf of its owners – Boeing, General Motors and Raytheon – in the automotive, defense, commercial airframe and space businesses. According to Marko Sokolich, research department manager of IC Process Engineering at HRL, the cumulative demand for ultra-high-performance circuits in these five broad business areas is modest but important, and all the areas benefit from InP. "By serving these markets with our flexible, high-performance InP processes we are able to enhance yield, reproducibility and reliability in an efficient manner," he says. "In this way we are able to reduce all of our customers' costs to access this technology."

Sokolich says that HRL exhibited at OFC in order to showcase its InP foundry and design service capability. "We were particularly interested in educating the fiber-optics market about HRL's history of InP development, dating back to 1988," he says. "Our InP technologies have demonstrated a number of benchmark high-performance millimeter-wave and mixed-signal circuits over the past decade."

Recently, however, HRL has been engaged in the design and demonstration of high-speed digital circuits for 40 Gbit/s and higher fiber-optic communication applications. "Circuits built in our technology have gone into several OC-768 transceiver prototypes for various customers," says Sokolich. "In 2001 we shipped the wafer equivalent of 10,000–20,000 ICs for 40 Gbit/s systems."



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HRL offers a "modest volume" fabrication capability in state-of-the-art InP SHBT, DHBT and HEMT processes, as well as design services for fiber-optic communication building-block circuits. The company has developed a first-generation (G1) InP SHBT process with f_t and f_{max} values of 80 and 120 GHz, respectively, and a G2 InP SHBT process with f_t and f_{max} values of >150 and >180 GHz, respectively (see *Compound Semiconductor* October 2001, p51). During 2002, HRL plans to release a G2+ InP SHBT process with f_t and f_{max} values of >190 and 250 GHz, respectively, as well as a G2+ InP DHBT process with f_t and f_{max} values of 150 and 300 GHz, respectively, and a breakdown voltage (BV_{ceo}) of >9 V.

However, Sokolich believes that process parameters do not tell the whole story. "We believe that discrete transistor metrics are necessary but not sufficient for an IC technology," he says. "We have also demonstrated a number of important circuit-based metrics." For example, HRL has fabricated a static divide-by-2 IC operating at >65 GHz, and demonstrated a 60 GHz packaged version in its booth at OFC. Divide-by-4 ICs operating at >65 GHz and divide-by-8 ICs operating at >70 GHz have also been fabricated.

Other ICs include: a 2:1 mux and a 1:2 demux, both operating at >50 Gbit/s; a 40 Gbit/s modulator driver with $V_{diff} = 8 V_{pp}$ and $V_{se} = 4 V_p$; and 4:1 mux and 1:4 demux ICs operating at 40 Gbit/s.

Vitesse converts 4 inch fab to InP

Vitesse was one of the first manufacturers to announce its intention to use InP ICs for 40 Gbit/s applications (see *Compound Semiconductor* April 2000, p7). Vitesse's fab in Camarillo, CA, which originally manufactured GaAs MESFET products, has been converted to a 4 inch InP wafer fab. The company has developed a series of products and is also offering foundry services using its first-generation (VIP1) single-HBT process. According to Alan Huelsman, director of Vitesse's InP program, the process uses a mesa-isolated *npn* structure that leaves room for further advances through device scaling. "Implementation of this transistor design allowed us to bring up a manufacturable process with adequate performance in a very short period of time," he says. "Fab yield has been excellent and typically runs at about 85%. Circuits with less than 100 transistors often show 100% yield, and the largest circuit built to date in this process – a 4:1 mux containing 2500 transistors – shows very good yield."

The MBE-grown epilayer structure used by Vitesse includes an InP emitter and a Be-doped base, and aluminum interconnect technology was adopted from Vitesse's GaAs process. The transistor performance peaks at a collector current density of about 1 mA/ μm^2 , and the f_t and f_{max} values at this density are both >150 GHz. The BV_{ceo} is 4.2 V for the SHBT process, and a DHBT process with a BV_{ceo} of >7 V, targeted at lithium niobate modulator drivers, is under development.

"The VIP1 process was frozen in August 2001 to allow us to work with foundry customers," says Huelsman. "However, we have a process development team of about 12 engineers who are working on a second version of the process. By moving to smaller dimensions and making other improvements we expect to reach f_t and f_{max} values exceeding 200 GHz."

Huelsman says that Vitesse has built all the key building blocks for the OC-768 physical layer, including a transimpedance amplifier (TIA), a limiting amplifier, a 4:1 mux/demux pair and a driver with 3.5 V_{pp} voltage swing. The analog parts are all being sampled to customers.

Applications at 10 Gbit/s

For most 10 Gbit/s applications the extra performance provided by InP is not required, and so InP is uneconomical when compared with GaAs, SiGe or CMOS. However, this is not always the case; Vitesse has already introduced InP parts at 10 Gbit/s, including an RZ modulator driver and an integrated *pin*-TIA for 10 Gigabit Ethernet. "An RZ driver requires a bandwidth of about 30 GHz, and InP is required to achieve this level of performance," says Huelsman. "On the receive side the demand is for integration; the *pin*-TIA replaces both a GaAs or SiGe amplifier and an InP detector."

At OFC Velocium introduced a 12.7 Gbit/s NRZ-to-RZ converter that electronically converts NRZ signals into RZ format. Standard RZ systems use two modulators, one to create a train of pulses and the other to apply the signal; Velocium's converter eliminates the need for the pulse train. The converter operates at up to 12.7 Gbit/s, providing headroom for forward error correction, and has a power consumption of less than 1 W. "By utilizing an advanced InP process for our NRZ-to-RZ converter, we can meet the higher bandwidth performance required for RZ modulation at lower power, compared with alternative solutions," says Velocium's Frank Kropschot. "From a system perspective, the converter

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eliminates the need for an additional optical modulator, therefore reducing overall system cost and complexity."

Optoelectronic integration

In addition to the high performance of InP-based electronic ICs, another driving force for introducing these devices is the prospect of integration with optical functions. Starting with *pin* diodes and TIAs, this could lead to the integration of arrayed waveguides (AWGs). Alan Huelsman says that Vitesse is already working with foundry customers to develop both active and passive InP-based optical products.

In fact InP integration is by no means a new phenomenon. Opto Speed, an optoelectronic component manufacturer based in Switzerland (see p13), first introduced monolithic InP receivers in 1999. These consist of an InGaAs *pin* photodiode monolithically integrated with an InP HBT TIA. At the recent OFC meeting, Opto Speed announced a new family of optical front-ends for RZ and NRZ applications at bit-rates exceeding 40 Gbit/s, which are based on these integrated devices (figure 1).

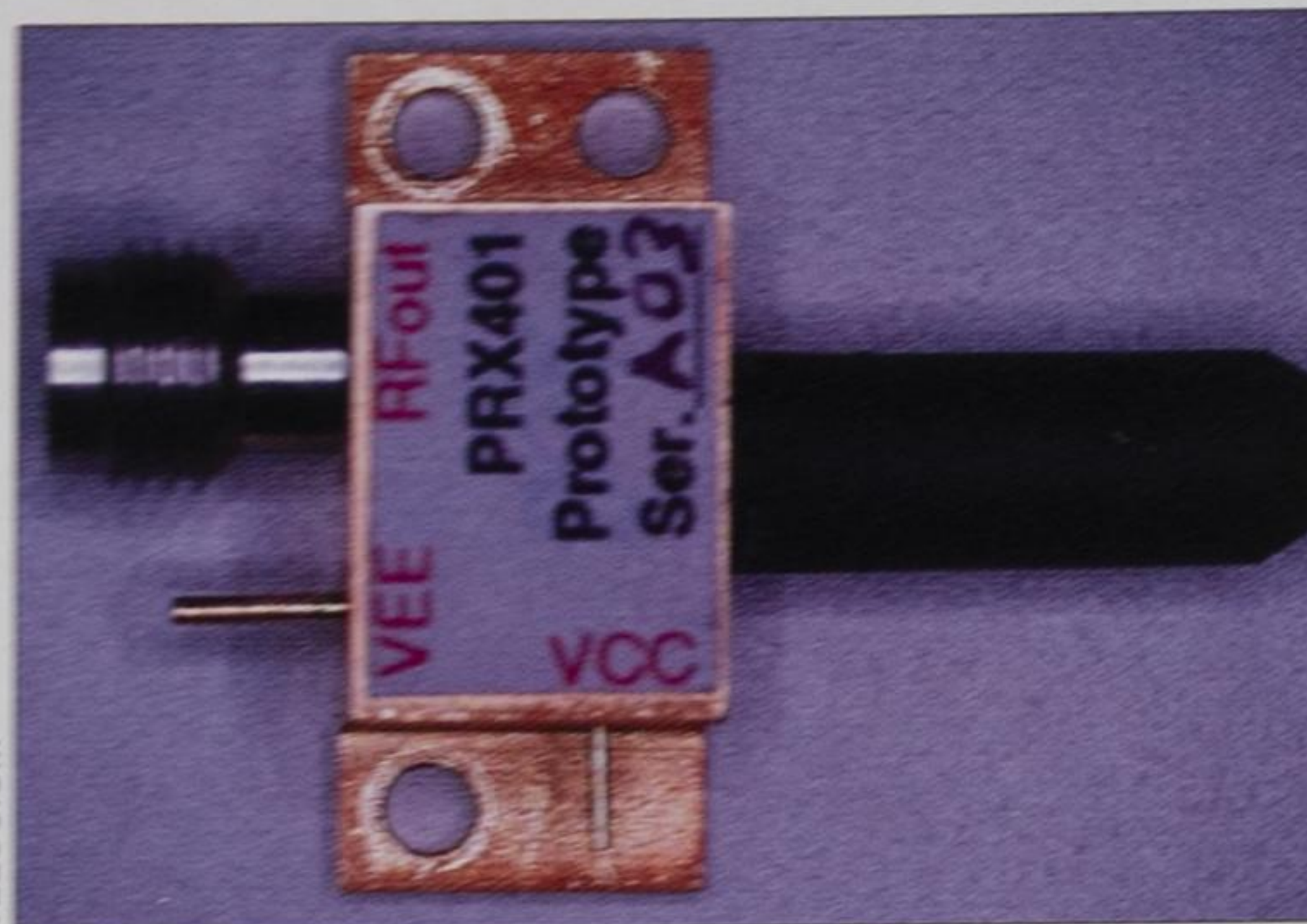


Fig. 2. This 40 Gbit/s photoreceiver contains an integrated *pin* photodiode and TIA.

The modules, measuring $15 \times 15 \times 4 \text{ mm}^3$, have a responsivity of 0.45 A/W, a sensitivity of -9 dBm, a -3 dB bandwidth of 35 GHz and a power dissipation of 800 mW.

Similarly Velocium has introduced the PRX401, a 40 Gbit/s photoreceiver designed for use in VSR SONET, SDH, datacom transponders, digital video, avionics and test instrumentation. The 34 GHz bandwidth product contains an InGaAs *pin* photodiode monolithically integrated with an InP HBT TIA, and has a 70 V/W conversion gain. The power dis-

sipation is 90 mW, and the device is available as a bare die or a connectorized module measuring $9.4 \times 22.9 \times 8.9 \text{ mm}^3$ (figure 2).

IPAG teams with Multilink

Another company developing optoelectronic components and ICs based on InP is Innovative Processing AG (IPAG), based in Duisburg, Germany. IPAG has extensive in-house capabilities, including MBE and MOVPE growth, and has developed both HBT and HEMT InP processes. Along with *pin* diodes and electro-absorption modulators, IPAG has developed a 43 Gbit/s *pin* diode monolithically integrated with a traveling wave amplifier (TWA). IPAG's front-end receiver module containing the *pin*-TWA circuit has a -3 dB bandwidth of 45 GHz, an optical input power of +6 dBm and a conversion gain of 50 V/W at 1550 nm.

IPAG recently entered into a collaboration with Multilink Technology, a fabless supplier of GaAs digital and mixed-signal ICs based in Somerset, NJ. The companies will work closely to develop 40 Gbit/s *pin* diode receivers, TWAs and monolithically integrated devices. "IPAG focuses on InP as the most attractive candidate



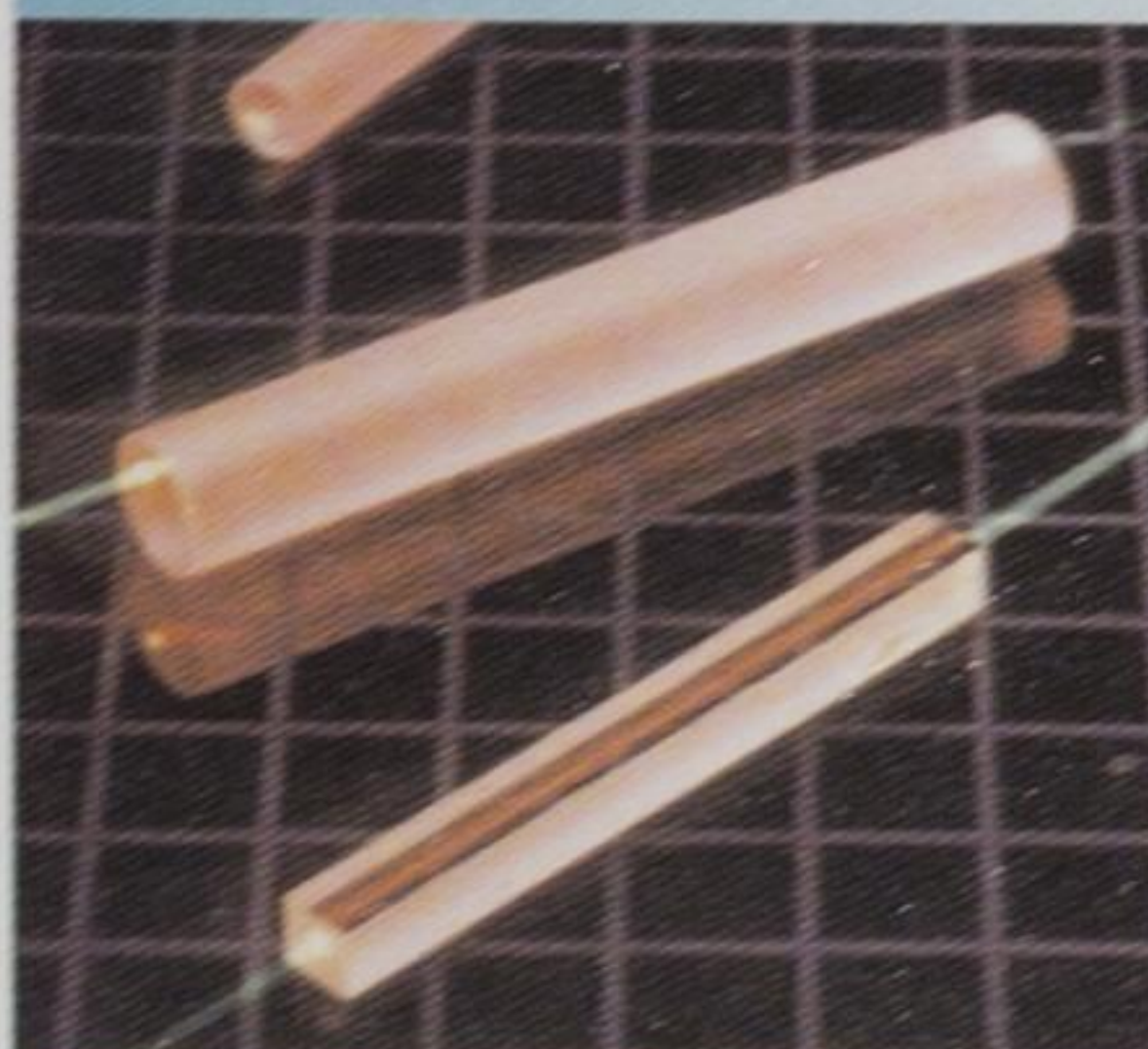
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for the monolithic integration of high-speed electronic and photonic devices," says IPAG's CEO Ralf Bertenburg. "With our extensive knowledge and access to a complete InP processing line, we are able to establish a standardized InP process technology with high yield."

A minority equity investment in IPAG will grant Multilink early access to critical optical and optoelectronic devices. Multilink will work closely with IPAG on system and component requirements and packaging, and will also act as the exclusive channel for IPAG's line of integrated optoelectronic receivers.

Japanese companies

Not surprisingly several Japanese companies are developing InP devices for 40 Gbit/s systems. At OFC, NEL demonstrated ICs based on a 0.1 μm InP HEMT process with f_t and f_{max} values of 200 and 350 GHz, respectively. The company unveiled a 50 Gbit/s 4:1 mux module incorporating a D-type flip-flop and a clock distribution unit, and also exhibited a 2:1 selector, a 1:2 demux and a toggle-FF. OpNext, the spin-off from Hitachi, has also developed 40 Gbit/s parts, including an InP HBT modulator driver, an InP post-amplifier and a 40 GHz clock recovery circuit, which operates in conjunction with SiGe 4:1 mux and 1:4 demux ICs. In June 2001 OpNext announced a joint development program with Velocium for 40 Gbit/s GaAs and InP ICs.

GCS backs double HBTs

Foundry company GCS has developed 4 inch InP SHBT and DHBT processes that take advantage of various process modules (photolithography, thin film, etch etc) used for the company's InGaP/GaAs HBTs. The InP process uses a device structure with an InP emitter and a C-doped base, and incorporates a high-yield, low-loss planar interconnect technology. A device with a $1 \times 3 \mu\text{m}^2$ emitter operating at a current density of 100 kA/ cm^2 , had f_t and f_{max} values of >160 GHz and a BV_{ceo} of >3.5 V. At a higher current density of 160 kA/ cm^2 , an f_t value of 200 GHz was extrapolated.

Reliability is vital to commercial digital communications applications. According to a paper at the GaAs Mantech conference, the reliability issues of InP HBT technology remain unresolved (Nguyen *et al.*). GCS has addressed reliability in a fundamental manner. In the device structure, the use of an Al-free emitter (InP rather than InAlAs) and a C-doped base (as opposed to using Be) are claimed to enhance reliability, while a non-alloyed ohmic

metal contact scheme enhances the robustness of the devices under high current drive. A proprietary passivation technology has also been developed to ensure surface cleanliness.

One of GCS's customers is Inphi, a fabless company developing high-speed InP ICS (see *Compound Semiconductor* April 2002, p28). Another fabless design house, GTRAN, has developed its own process for InP ICs and is using external foundries, including GCS.

Xindium and UIUC

Xindium Technologies, a year-old spin-off from the University of Illinois at Urbana-Champaign (UIUC), is also developing commercial InP-based ICs. The company will undertake pilot production and seek to license its processes to commercial foundries (see *Compound Semiconductor* April 2002, p67). At this year's GaAs Mantech conference, a paper from Xindium and UIUC described an

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InGaAs/InP SHBT process with f_t and f_{max} values of 160 and 252 GHz, respectively, for a $2 \times 5 \mu\text{m}^2$ device (Shen *et al.*). These values were recorded for C-doped SHBTs grown by GSMBE on 2 inch wafers, which had a base doping level of $4 \times 10^{19}/\text{cm}^3$ and a collector thickness of 3000 Å. GSMBE is capable of higher base doping levels due to hydrogen passivation in MOVPE. In integrated *pin*/SHBT structures, the reduction in base resistance is crucial for higher RF performance.

Alpha Industries

In fall 2001 Alpha Industries announced plans to develop a commercial InP HBT process (see *Compound Semiconductor* September 2001, p6). The company has implemented an InP/InGaAs/InP double HBT structure using commercially available epitaxial material grown on 4 inch substrates. The process leverages Alpha's InGaP HBT technology and uses many of the same back-end steps, such as passive NiCr resistors, MIM capacitors, spiral inductors and metal interconnections (figure 3). As these steps are often yield-limiting for GaAs HBTs, Alpha expects the InP HBT tech-

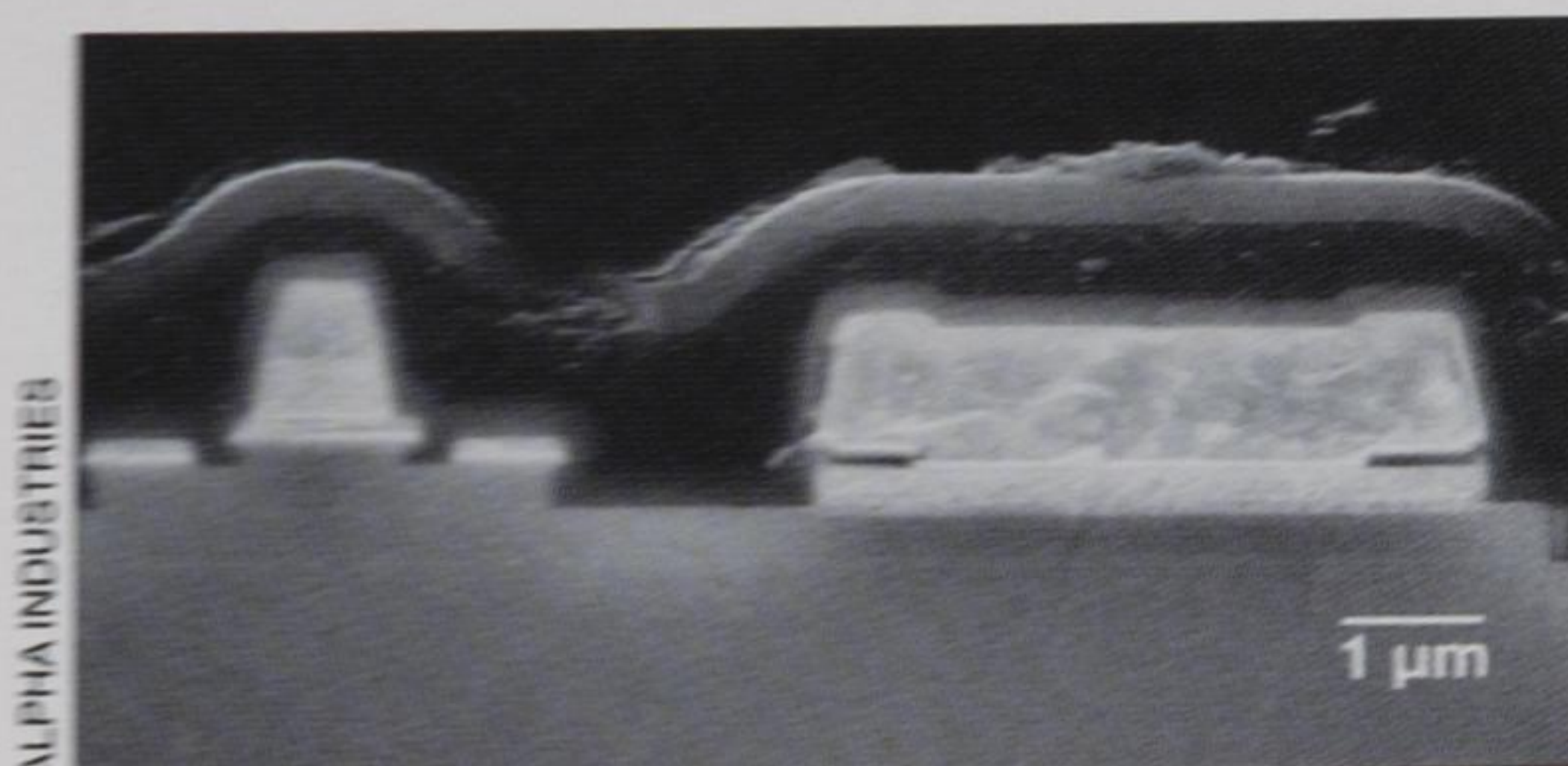


Fig. 3. SEM cross-section of Alpha's non-self-aligned $1.2 \times 8 \mu\text{m}^2$ InP DHBT.

nology to show similar circuit yields and integration levels to those of the GaAs process. The InP DHBT process is non-self-aligned and achieves critical dimension control between the emitter and base contacts. A typical $1.2 \times 8 \mu\text{m}^2$ device with a 200 nm n-InP collector showed f_t and f_{max} values of 160 and 190 GHz, respectively, and a BV_{ceo} of 7 V (Sun *et al.*).

An indium phosphide future

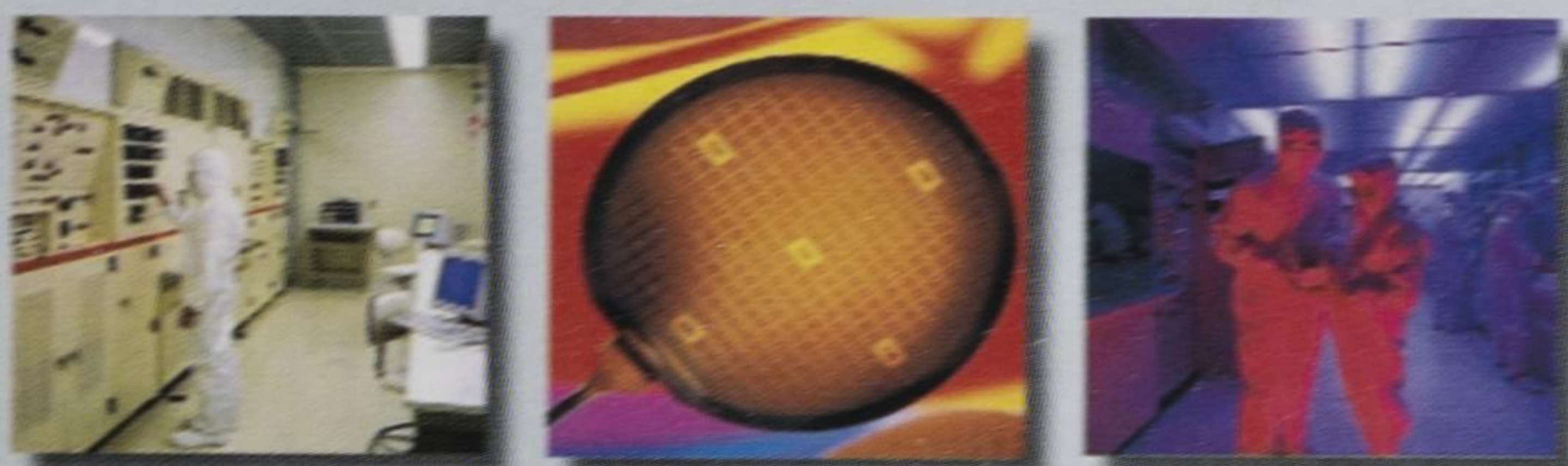
Opinions vary as to which 40 Gbit/s ICs will be made with InP, while companies such as IBM, AMCC and Infineon argue that SiGe can handle most functions for 40 Gbit/s networks. At OFC, AMCC introduced SiGe mux and demux

ICs to complement its 40 Gbit/s TIA and modulator driver. Inphi, which has developed 4:1 mux and 1:4 demux ICs in InP, is using a GaAs PHEMT foundry process to manufacture its modulator driver ICs until suitable InP DHBT processes are available. Similarly, Velocium unveiled a 40 Gbit/s modulator driver IC at OFC, which was manufactured using a GaAs PHEMT process. The 50 GHz bandwidth driver gives 8 V_{pp} output voltage at 43 Gbit/s.

When 10 Gbit/s components were first introduced, GaAs had little competition. Now, advanced SiGe and GaAs technologies are already challenging InP as 40 Gbit/s applications gather momentum. However, it does seem certain that the confluence of market demand, the availability of 4 inch substrates and epiwafers, and the activity of a number of major IC manufacturers, will push InP into the mainstream at last.

Further reading

N Nguyen *et al.* 2002 *Proc. GaAs Mantech conf.* (San Diego, CA) 26.
S-C Shen *et al.* 2002 *ibid.* 22.
M Sun *et al.* 2002 *ibid.* 30.

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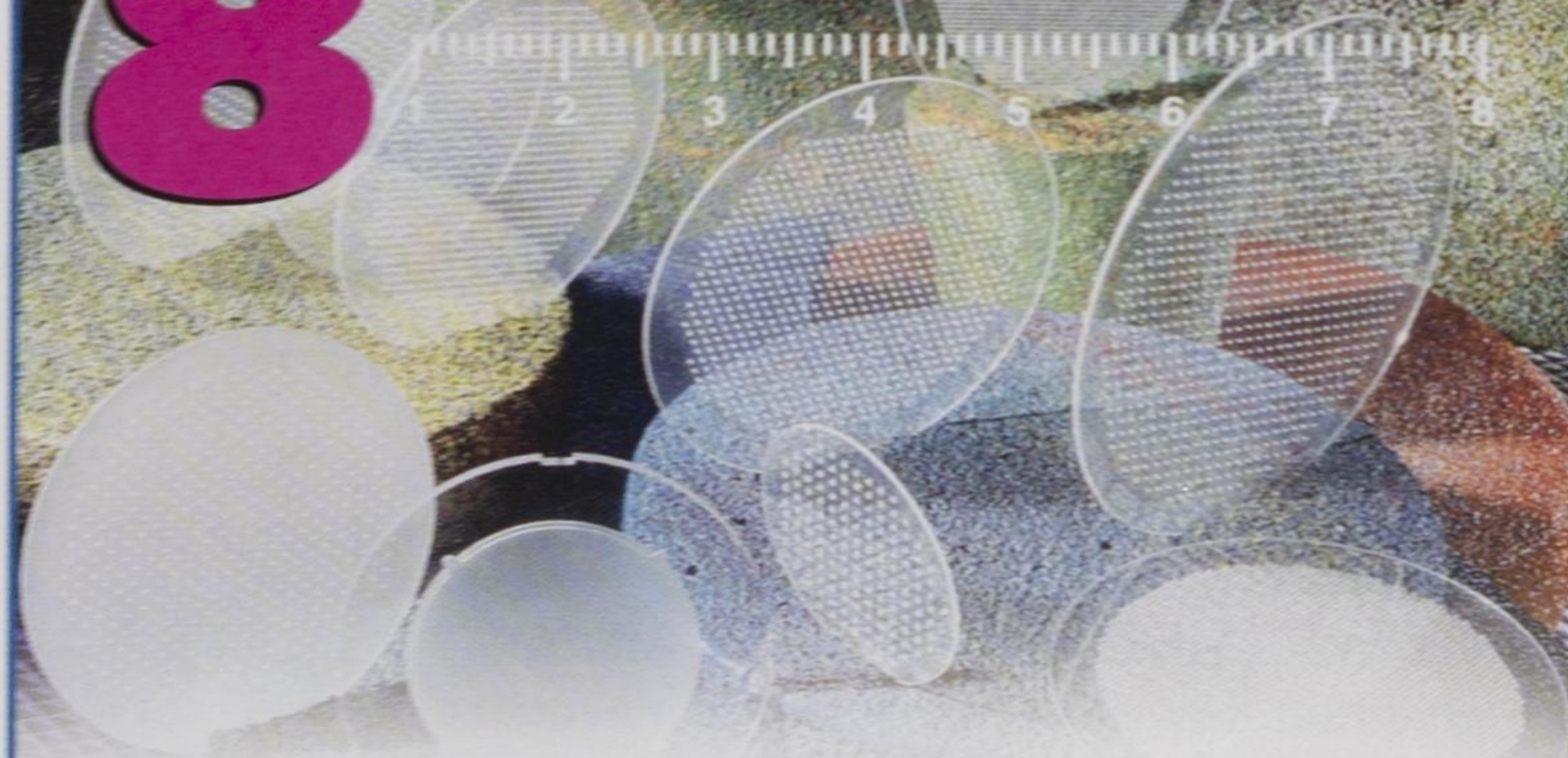
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The path to InP production

Companies aiming to transfer indium phosphide technology from the lab to the fab can learn a great deal from the experiences of the GaAs industry, writes Velocium's **Dwight Streit**.

The history of commercially viable technologies in the semiconductor industry can be viewed as a number of consecutive shifts in process technology. The first commercially viable transistors were fabricated from germanium, but in the early 1960s they were quickly surpassed in terms of performance and cost by devices based on silicon. Today silicon clearly dominates the semiconductor industry, thanks in part to the consecutive developments in process technology that made Si-based devices more capable in terms of integrated functionality, and also made them lower in cost.

A third commercially viable technology – gallium arsenide – emerged in the late 1980s from the world of compound materials, and we have yet to see the emergence of a compound semiconductor technology that can displace GaAs as the material of choice for high-performance, high-volume commercial applications. However, devices based on a new technology just beginning to emerge from the laboratory and based on indium phosphide and its derivatives constitute the fourth wave in semiconductor materials. InP clearly offers compelling performance advantages over GaAs in fiber-optic, millimeter-wave and even wireless applications. We believe that these advantages will provide the differentiation for InP to eventually displace GaAs as the chosen technology in the compound semiconductor industry.

Market forces

All new semiconductor technology begins in the research lab, where success is measured by the ability to produce a handful of devices that set new performance standards. However, before the technology can be adopted into higher volume consumer applications, huge challenges must be overcome. The fourth wave of semiconductor technology, InP, faces the same barriers to adoption that all new technologies encounter. Attempting to force a technology into the commercial market will inevitably lead to failure – but where there are compelling advantages for the customer, a suc-

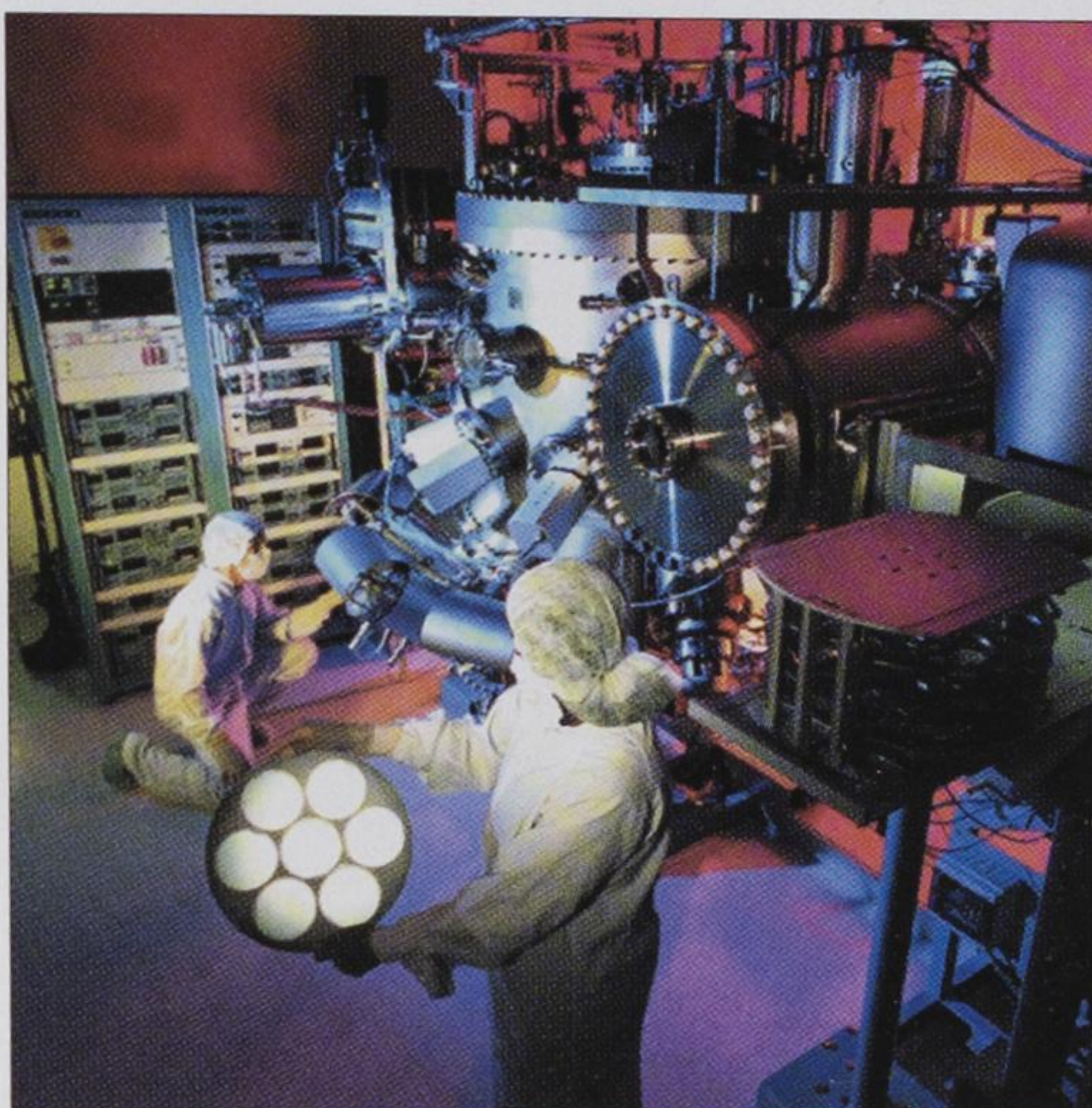


Fig. 1. High-volume production MBE systems are used for both GaAs and InP.

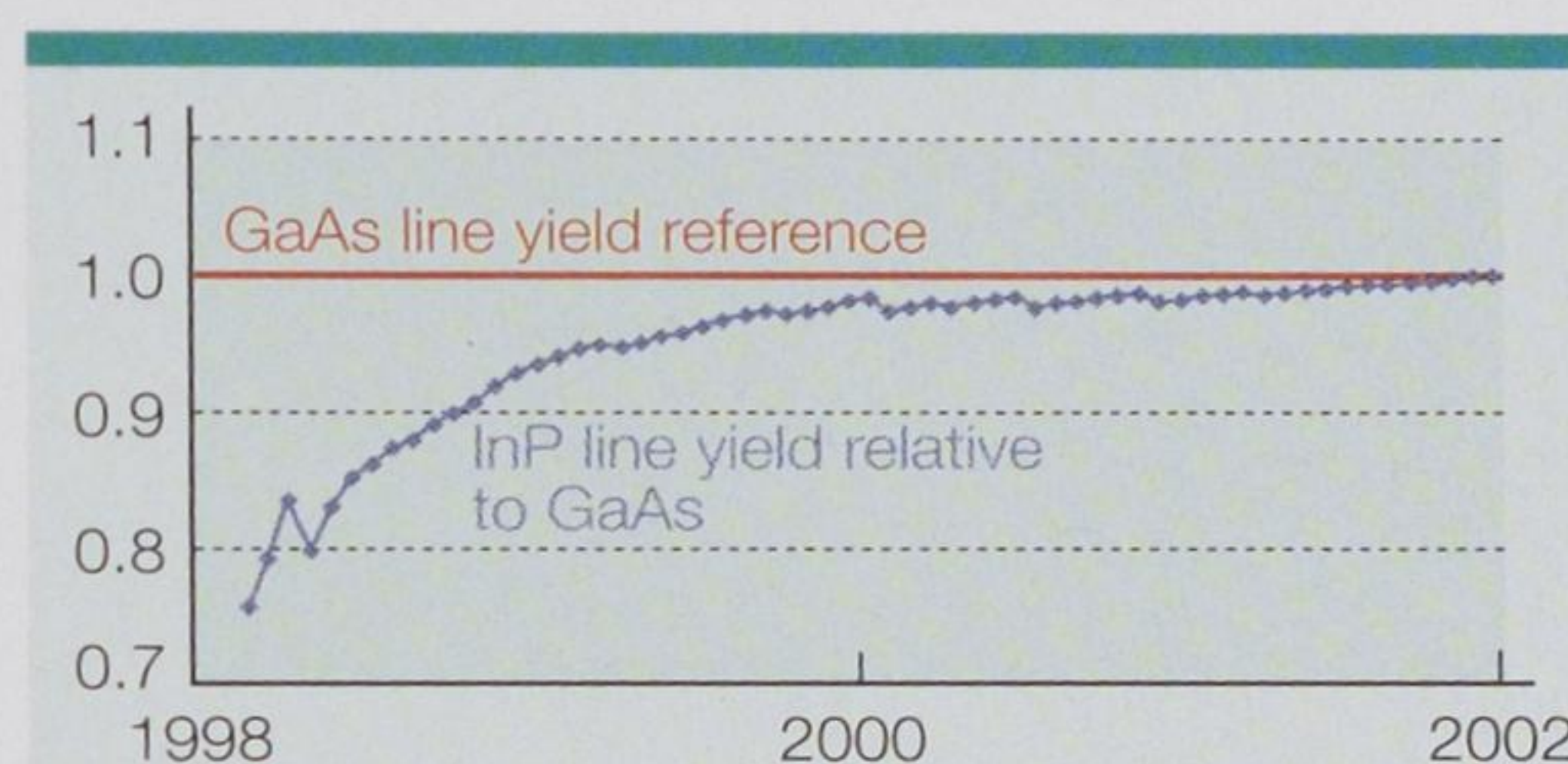


Fig. 2. A comparison of yields over time for InP and GaAs production lines.

cessful market launch is virtually unstoppable.

For InP-based devices, customer pull in several target markets is undeniable. In the fiber-optic arena, InP is the only semiconductor technology that allows photodetectors and lasers to be integrated on the same substrate with other analog and mixed signal functionality, providing advances in integration and cost reduction that could spur significant paradigm shifts in this market. In the wireless industry, InP-based amplifiers provide significant performance improvements, such as lower power consumption, high linearity and low temperature sensitivity, that significantly enhance the battery life and reception in current handset designs. In millimeter-wave applications that are beyond the capabilities of GaAs or Si, InP devices

can easily be fabricated for passive imaging and other applications that are just emerging in the marketplace.

New technologies need coordinated accomplishments on a number of fronts to make the leap from the research lab to the production line. This was true for Si, and it was also true for GaAs. Fortunately, most of the equipment and process innovations that took GaAs into production just a decade ago can also be applied to InP production. Although there are specific alloy differences, advances in epitaxial equipment, including multiwafer MOCVD and MBE systems (figure 1), are used in both InP and GaAs production, as are technologies such as dry etching and substrate thinning. Since the manufacturing infrastructure is the same for both technologies, there is no need for large investment in new fabrication line equipment to switch to InP. Furthermore, substrate vendors are now making great strides in the development of large-diameter InP substrates, just as they did for GaAs a decade ago.

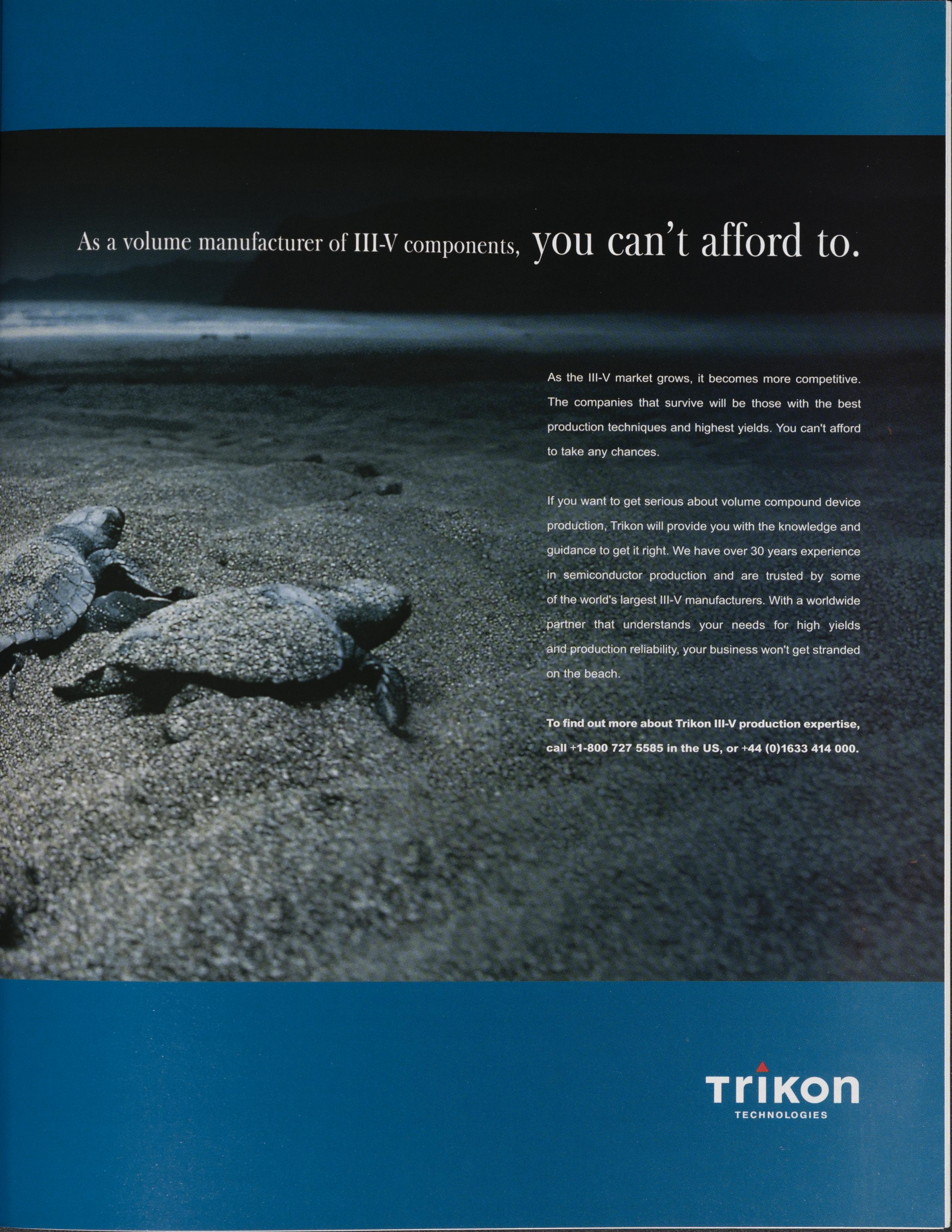
Up the learning curve

When GaAs technology was initially funded for defense and aerospace applications, it took more than a decade to make the transition into commercial applications. InP is making that same transition today, going down the path initiated for GaAs in the early 1990s. In 1993, TRW announced plans to produce GaAs HBTs for the commercial marketplace. This was initially received with skepticism, as the HBT was perceived to be neither reliable nor manufacturable in high production quantities. Today, the GaAs-based HBT is used in many high-volume consumer applications and is the technology of choice for several commercial telecommunications applications. This includes products from an industry leader, which licensed TRW's technology and holds close to 20% of the worldwide GaAs MMIC market for wireless applications. We are now seeing InP follow the same ramp up in terms of substrate size and quality, generating a concomitant reduction in price and the

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Still, the advantages of InP process technology are often overshadowed by concerns regarding the cost, yield and reliability of a process technology in its formative years. The lack of InP processing experience that is rife in the market today is perhaps the greatest barrier, as companies attempt to move the InP process from the research lab into the production line. In other words, regardless of InP's superior performance, a cost-effective manufacturing process is required in order to allow this technology to compete effectively in the marketplace.

One approach has been to model the InP process development on proven, high-volume GaAs HBT production processes. Lessons learned from the GaAs transition are applicable to the InP scenario. For example, the process flow in the GaAs HBT process is directly transferable to the InP HBT process.

Challenges for volume production

For any new technology to gain acceptance and long-term success in the market, it must have not only the ability to be produced in volume, but also must have proven reliability – the key to the initial application. InP HEMT MMICs are already proving themselves in challenging in-orbit applications. In this way, the stringent reliability requirements of satellite components are actually paving the way for commercial, terrestrial applications of InP.

A key facet of technology adoption, the ability to produce any technology in volume, must be designed into the semiconductor process during the development phase. However, this capability only comes into its own when the fabrication line is fully exercised. As volume production increases, the cost for any semiconductor device – including those made using InP – will come down. As processing experience improves and yields rise (figure 2), prices for a wide range of components decrease by factor of two or more through the life cycle of a typical device.

Initial production snags are to be expected when new technologies transition from R&D to prototype to volume production. Ge, Si and GaAs all experienced growing pains, and InP can benefit by examining the types of problems encountered by GaAs. When initial attempts to commercialize GaAs were made several years ago, the availability, cost and reproducibility of GaAs substrates were a challenge, as was establishing a reproducible

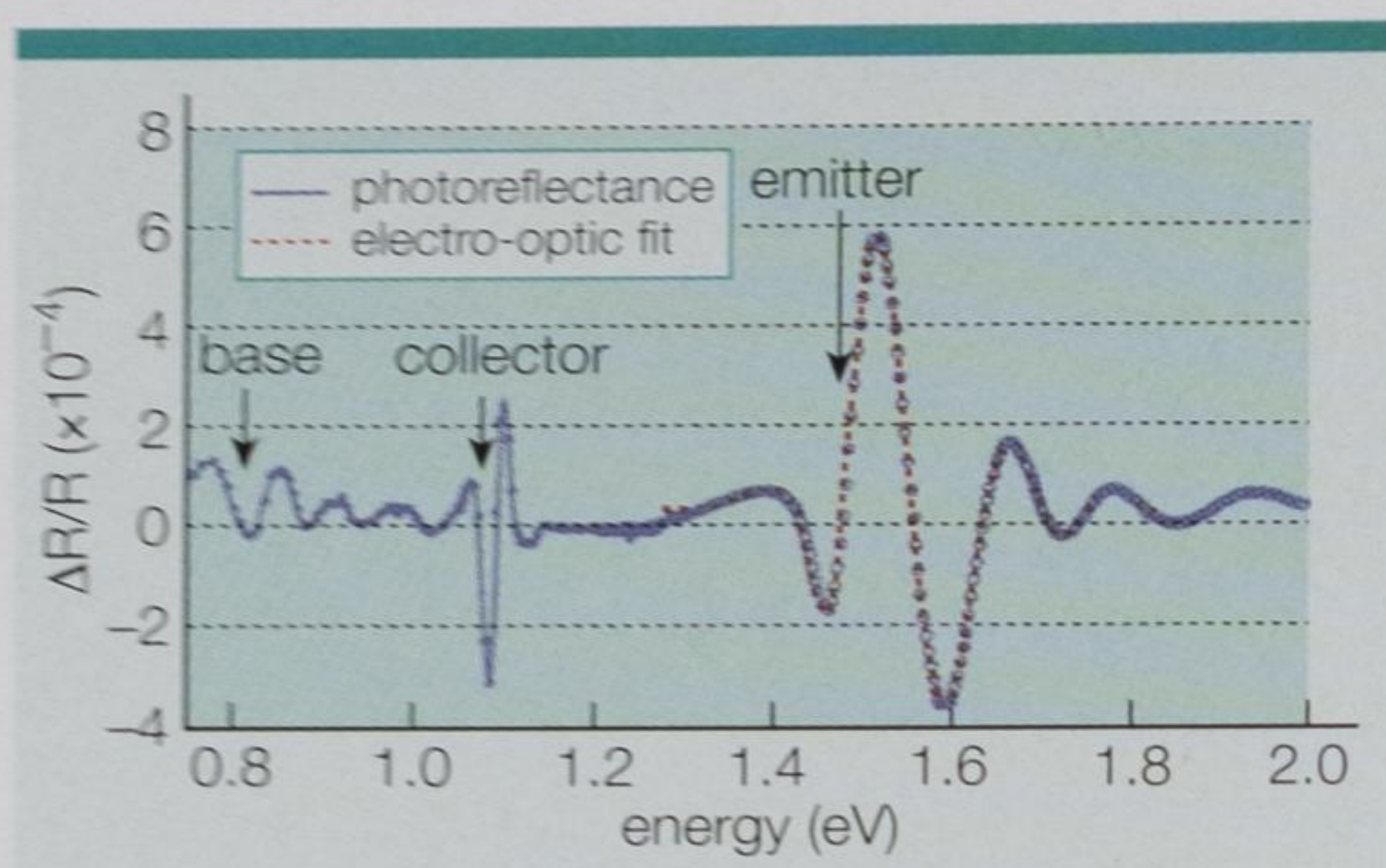
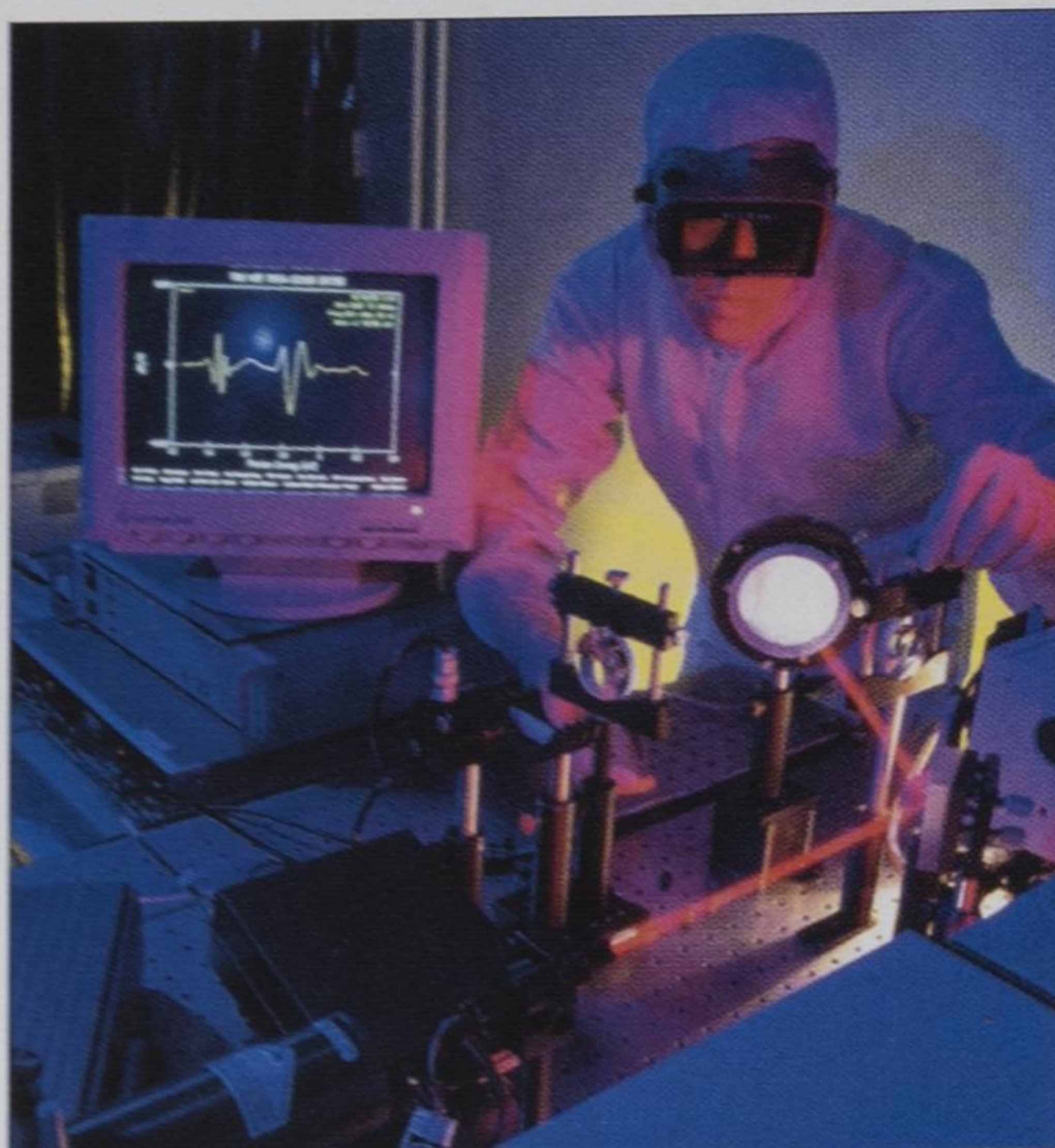


Fig. 3. Non-contact photoreflectance InP HBT material characterization.

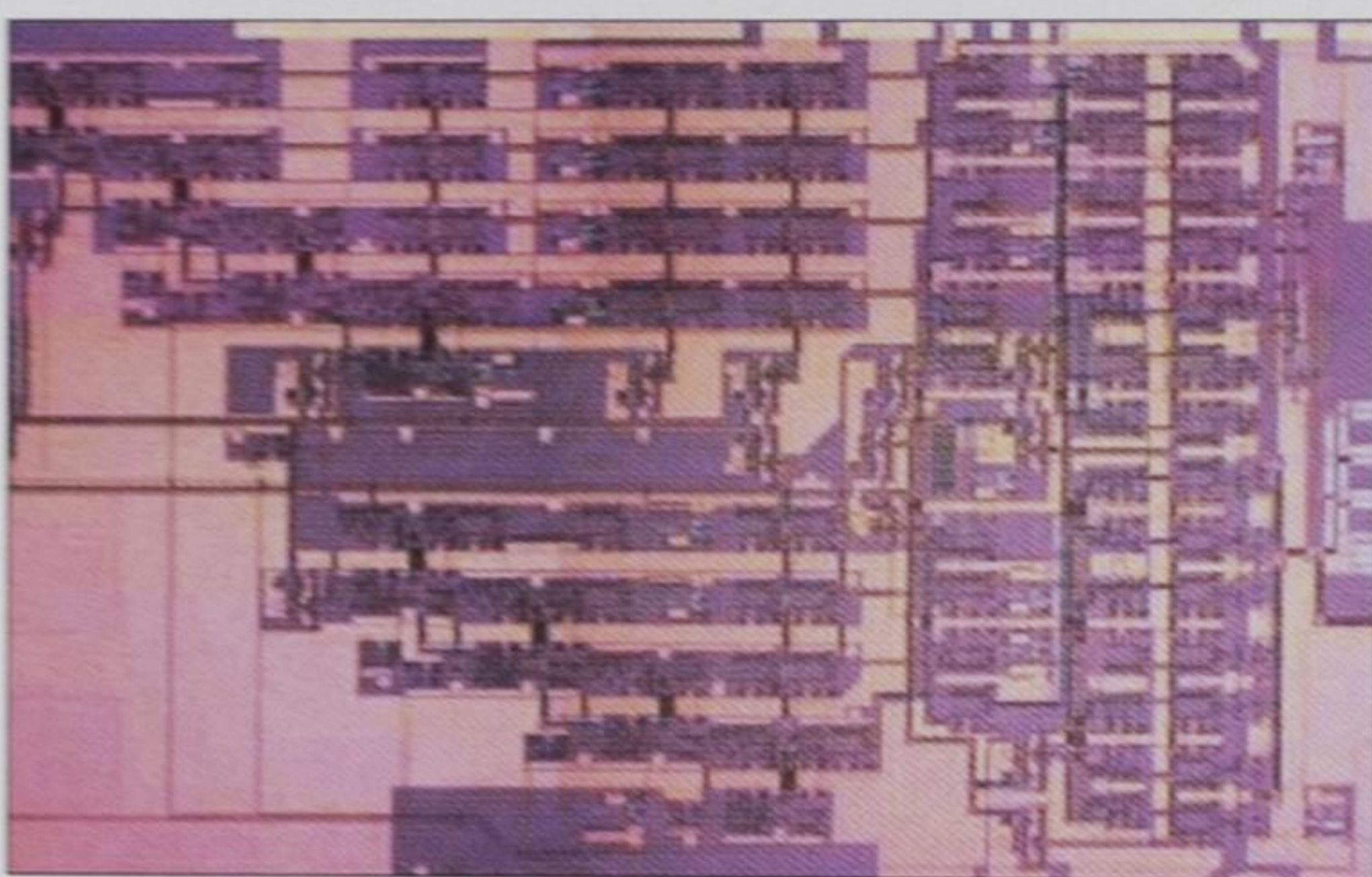


Fig. 4. A direct digital synthesizer made with InP HBTs. This 3000-transistor circuit had a first pass functional yield of 80%.

GaAs HBT production process. A backside process for thinning and fabricating GaAs substrates was also critical. The result was a high-volume, cost-efficient GaAs production line. When applied to the InP production process, these lessons expedite volume production.

Production challenges aside, the cost of materials is another factor, and one already addressed through the GaAs experience. Wafer processing requires some of the most expensive materials, and HEMT and HBT devices are only as good as the materials with which they are built. Extensive material char-

acterization and a complete understanding of the material quality before processing is the key to success for InP devices (figure 3). Establishing correlations between material characteristics and device performance for both GaAs and InP is a prerequisite for stable and successful fabrication, and fundamental physical modeling enables theoretical correlation to actual results.

At present, InP lithography is several generations behind Si, yet InP still yields performance that far exceeds that of any production Si process. As InP moves to smaller geometries, this performance differentiation will increase significantly. SiGe HBT devices with 0.13 μm emitters cannot compete with InP HBT devices with emitters 10 times that size. Just imagine what will happen to circuit performance as InP HBTs are reduced to sizes approaching that of Si today. The InP HEMT has the highest performance of any transistor, with published results for integrated circuits operating at 220 GHz, far in excess of the results of any other substrates. Figure 4 shows an example of InP HBT production capability.

Conclusion

New technologies such as InP first generate excitement in university and government laboratories, as well as corporate research and development centers. Reputations made as "firsts" are published and presented at key conferences, but, as the technology matures, researchers often lose interest and move on to other firsts. However, this phase of technology development is actually the most important, and in many ways the most difficult. The companies that are successful in transitioning these technologies into production are not necessarily the first to publish. Success will be found by the company that can transition an exciting technology into a viable commercial application, long after the researchers have moved on to more exciting projects.

A final key to success is to ensure that the research engineers – the people who developed the technology – participate in the transition from research to prototype to production, only moving on to new research endeavors after they have achieved full production. Rather than merely throwing the technology over the fence to the production people, the correct approach should be a team effort involving all who participated in the birth and nurturing of the new technology. ●

Dwight C Streit is president of Velocium, a TRW company. Web: www.velocium.com.

Substrate makers tackle the growing challenges of InP

As demand increases for high-speed indium phosphide ICs in fiber-optic networks, wafer manufacturers must strive to keep pace. **Rebecca Pool** discovers some of the issues involved in supplying high-quality InP substrates grown using different techniques.

Today's material of choice for 10 Gbit/s fiber-optic communications is GaAs. But as telecom vendors ramp up to 40 Gbit/s, microelectronics chip makers are turning to InP to give their chips the required extra speed. Deborah Clark, a III-V process engineer at Nortel Networks of Canada says that a shift from GaAs to InP-based integrated circuits is critical in order to realize these higher transmission rates.

"The best f_t and f_{max} for high-speed GaAs [chips] in production [today] are 110 GHz," she says. "There may be higher speed GaAs-integrated circuits in the literature, but we must move from development to production. We need better than 150 GHz for 40 Gbit/s systems, hence [we have a need for] InGaAs/InP and GaAsSb/InP HBTs."

However, speed is not the only factor that must be taken into account when producing high-performance integrated circuits, especially if you are a microelectronics chip maker. Chip processing is largely performed at the wafer level, so an easy way to keep costs down and realize economies of scale is to build more chips on a larger wafer. To meet this need, substrate makers are now focusing on the development of semi-insulating 4 inch InP, rather than the more established 2 and 3 inch single-crystal boules.

As with past advances in wafer manufacturing, the move towards 4 inch InP wafers has its problems. At last year's GaAs IC Symposium, Clark presented a paper entitled "Evaluation of 4 inch InP(Fe) substrates for the production of HBTs". According to Clark,

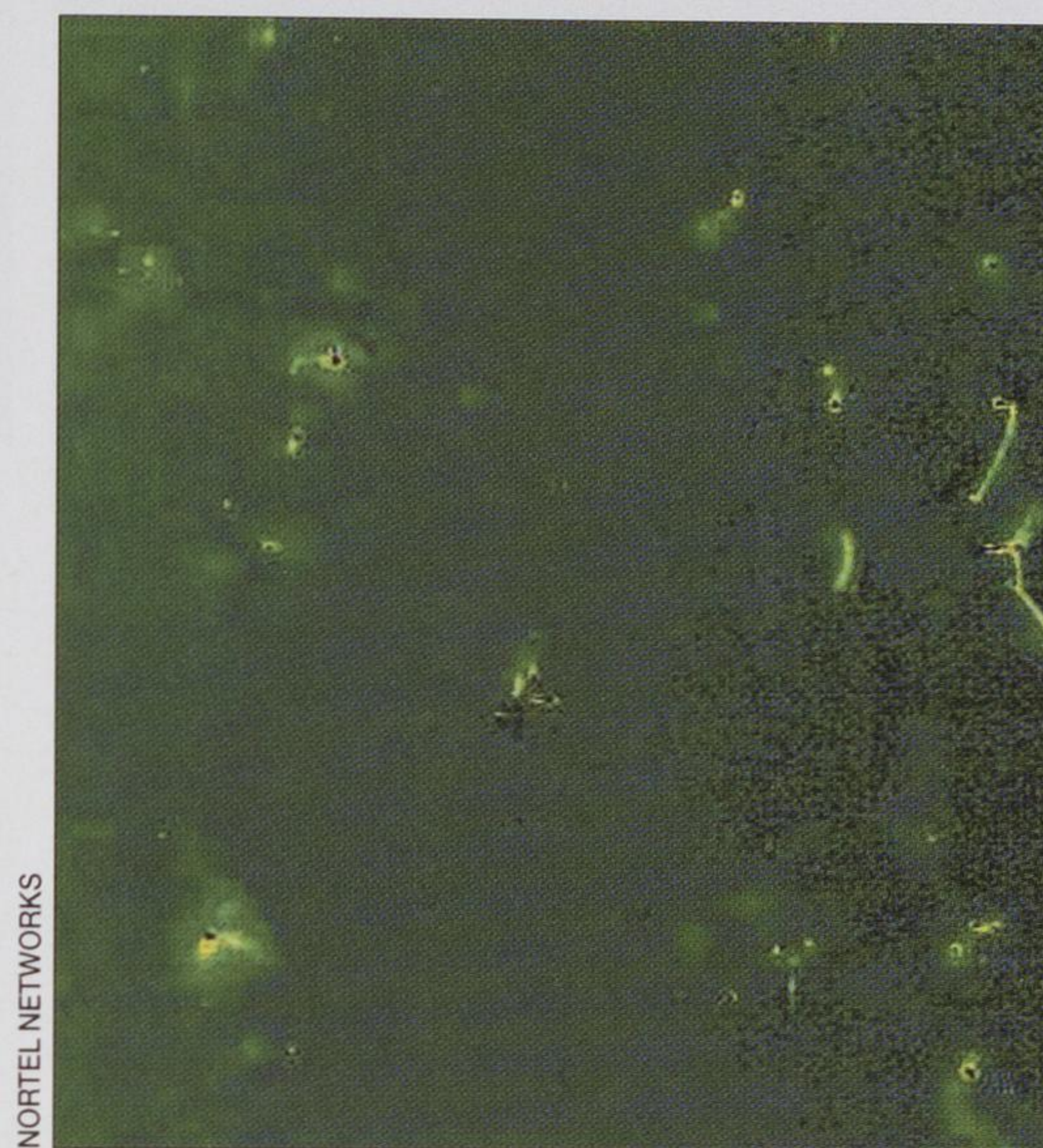


Fig. 1. High-resolution photoluminescence of a 4 inch InP(Fe) VGF-grown substrate. The bright spots and lines reveal dislocations that have clustered around regions of reduced iron concentration.

Nortel Networks wanted to compare the crystal quality of semi-insulating substrates that had been grown by either the liquid encapsulated Czochralski (LEC) method or the vertical gradient freeze (VGF) technique.

Using a range of techniques including high-resolution scanning photoluminescence and asymmetric crystal topography, Clark characterized the wafers for surface defects. Typical defects included an uneven distribution of iron – the dopant added to InP to make it semi-insulating – as well as dislocations, slip, polycrystallinity, long-range strain and twinning. Overall wafer properties such as wafer flatness were also investigated.

Growing pains

Clark discovered that the characteristics of the wafers she studied varied depending on the method by which they were grown. For example, 4 inch wafers that were grown by LEC tended to suffer from high concentrations of defects, increasing from the seed or tail end of the boule. In contrast, defect densities were lower in the VGF-grown wafers.

These defects typically stem from an uneven iron-dopant distribution, a problem that plagues any wafer maker regardless of the growth technique, and leads to dislocations clustering around localized regions of reduced iron concentration. Clark believes that the higher thermal gradients which are used in LEC growth enhance this effect in these boules (see figures 1 and 2).

As well as controlling the dopant distribution, wafer makers also have to stop the iron segregating out of solution to form iron precipitates that can damage a wafer surface during polishing. Clark noticed this effect in both the LEC-grown and VGF-grown wafers.

From her studies, Clark says that of the other defects, wafers grown via LEC tend to suffer more from long-range strain and slip while wafers grown via VGF can exhibit severe twinning. Neither, however, encountered significant problems with polycrystallinity and all the manufacturers have recently improved wafer flatness.

To conclude her work Clark says that the crystal quality of 4 inch InP(Fe) wafers grown by VGF was comparable to smaller diameter InP(Fe) and 4 inch GaAs substrates also grown by VGF. On the other hand, for 4 inch InP(Fe) grown by LEC techniques, the defects were not as well controlled as smaller diameter InP(Fe) substrates or 4 inch GaAs substrates grown by the same technique.

Comparing growth techniques

Ask Clark whether she would rather use wafers grown by LEC or VGF and her answer is: "We haven't done enough work on InP to say that one growth technique is better than another, but the analytical data supports the conclusion that VGF is best. To date, Nortel Networks has only used VGF wafers for the growth of InP HBTs."

LEC is still a clear contender, however, and Clark says that although LEC boule manufacturers may have initially been slow to invest in 4 inch semi-insulating InP wafers, they have since developed boule and wafer annealing that gives a better dopant uniformity and fewer defects. One LEC boule man-

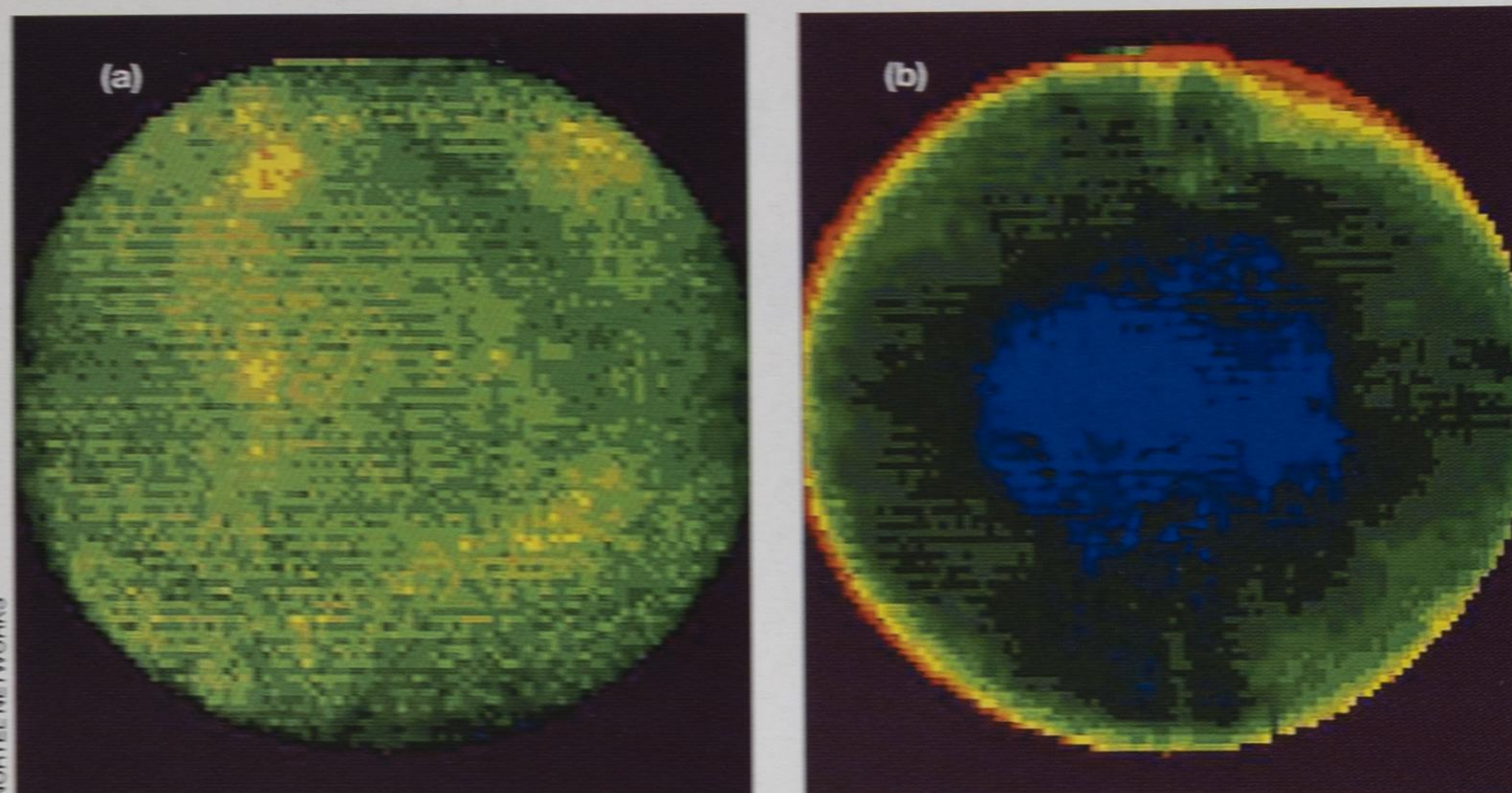


Fig. 2. Time-dependent charge measurement shows the differences in resistivity across a VGF-grown (a) and LEC-grown (b) 4 inch InP(Fe) substrate. The changes in resistivity, which are more prominent in the LEC substrate, correlate with variations in the distribution of iron.

ufacturer that would certainly agree with Clark on this point is the Japanese company Nikko Materials.

Nikko Materials is the InP and CdZnTe wafer-making arm of Japan Energy Corpora-

tion. Presently supplying 2 and 3 inch semi-insulating InP wafers at volume production levels, the company is already taking orders for 4 inch wafers at limited production volumes. Other companies that have been sup-

plying small volumes of 4 inch semi-insulating LEC-grown wafers are Sumitomo Electric of Japan and US-based M/A-COM.

Kurt Williams, product manager of Nikko Materials USA attributes the company's 4 inch wafer progress to its ability to deliver high quality and reproducible wafers at the right time, rather than rushing lower quality wafers to market. "InP is a difficult material to work with, and producing the 4 inch wafers has been a challenge," he explained. "But we have taken the time to refine the quality of our 4 inch wafers and customer feedback shows that our timing has paid off." Indeed the company has just received qualification for its wafers from one of its customers, Velocium, a leading InP IC manufacturer.

Industry shift

Nikko Materials first started work on 4 inch InP wafers last year in response to what was seen as a fiber-optic industry move towards InP devices for next-generation ICs. Williams believes that GaAs devices are now reaching their limits and says that his company has seen a sharp increase in demand for semi-insulating InP wafers. "In the near future, I'm guessing at two to five years, we will see the manufacture of semi-insulating InP wafers at volume production levels," he said.

Not only is Williams confident that a market is ready and waiting for 4 inch InP wafers – Nikko Materials has recently doubled its manufacturing capability purely to meet the demand for 4 inch wafers – he is also certain that LEC is the right growth technique to tackle this technology.

Boule makers that use LEC typically grow their boules under pressure in order to maintain stoichiometry, but steep temperature gradients often occur that lead to crystal defects. Williams says that by using phosphorous control LEC, the company can manage the temperature gradients and reproducibly make 4 inch InP wafers that have improved dislocation densities.

So if defects have not proved to be a problem for Nikko, then what has? Williams says that the main challenge the company has experienced moving from 3 to 4 inch wafers has been equipment scaling and also polishing the more fragile wafers. "But the main reason we haven't simply jumped from 2 inch to 4 inch, and won't jump from 4 inch to 6 inch, is demand and whether people are willing to pay the cost," he added.

So while Williams firmly believes that the future of LEC for 4 inch InP wafers is bright,

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Fig. 3. Defects in a VGF-grown 4 inch InP(Fe) wafer are highlighted by asymmetric crystal x-ray topography. The map shows twinning, slip and slight polycrystallinity.

what of the the rival growth process VGF? UK-based Wafer Technology, the substrate manufacturing arm of UK epiwafer supplier IQE, has chosen to concentrate on VGF for its GaAs manufacturing and is now investigating the technique for 4 inch InP. US-based AXT also manufactures InP(Fe) 4 inch wafers via VGF.

VGF InP wafers have only recently become commercially available, but Ian Grant, technical director at Wafer Technology, believes that wafers grown in this way could become the market leaders. "I think that the VGF method could dominate because it produces crystals with reproducible properties and optimizes crystal quality," he said. "This is a prime requirement for the materials and VGF is already dominating in GaAs."

But while VGF-grown boules are relatively free from stress-related defects such as dislocations, they are historically plagued by twin formation as the crystal diameter expands from the seed to the size of the cylinder in which it is being grown (see figure 3). Grant says, however, that optimizing the angle at which the crystal is grown out of the cylinder is one approach that solves this problem.

Grant adds that crystal quality is not the only consideration, and that cost of production is also an important factor. "For LEC growth the dislocation density is higher, but there is a trade-off between material quality and cost," he said. "There is a potential for LEC to have lower production costs, but if the key is to achieve material specifications, with cost being less critical, then VGF will have the advantage."

Grant is however a little skeptical about the demand for these wafers in today's economic climate. "There was an increase in the demand for these wafers, but I think it then collapsed because of the economic downturn," he said. "There is increased activity in the use of InP for higher performance devices though, so this is a temporary setback. In terms of a large-scale change (from GaAs to InP) this isn't happening yet."

But despite market conditions, Grant believes that LEC- and VGF-grown 4 inch InP wafers will be able to take advantage of the 4 inch fabs that are already established for GaAs wafers. "Four inch InP substrates for microwave ICs will lead the uptake in volume," he explained. "This will happen on the back of GaAs experience, which is conveniently timed because GaAs in the larger capacity fabs has moved to 6 inch and therefore freed up 4 inch capacity."

The future is 6 inch

InP 4 inch wafers are not the only technology on the minds of the industry's leading substrate manufacturers; 6 inch wafers are also in the pipeline.

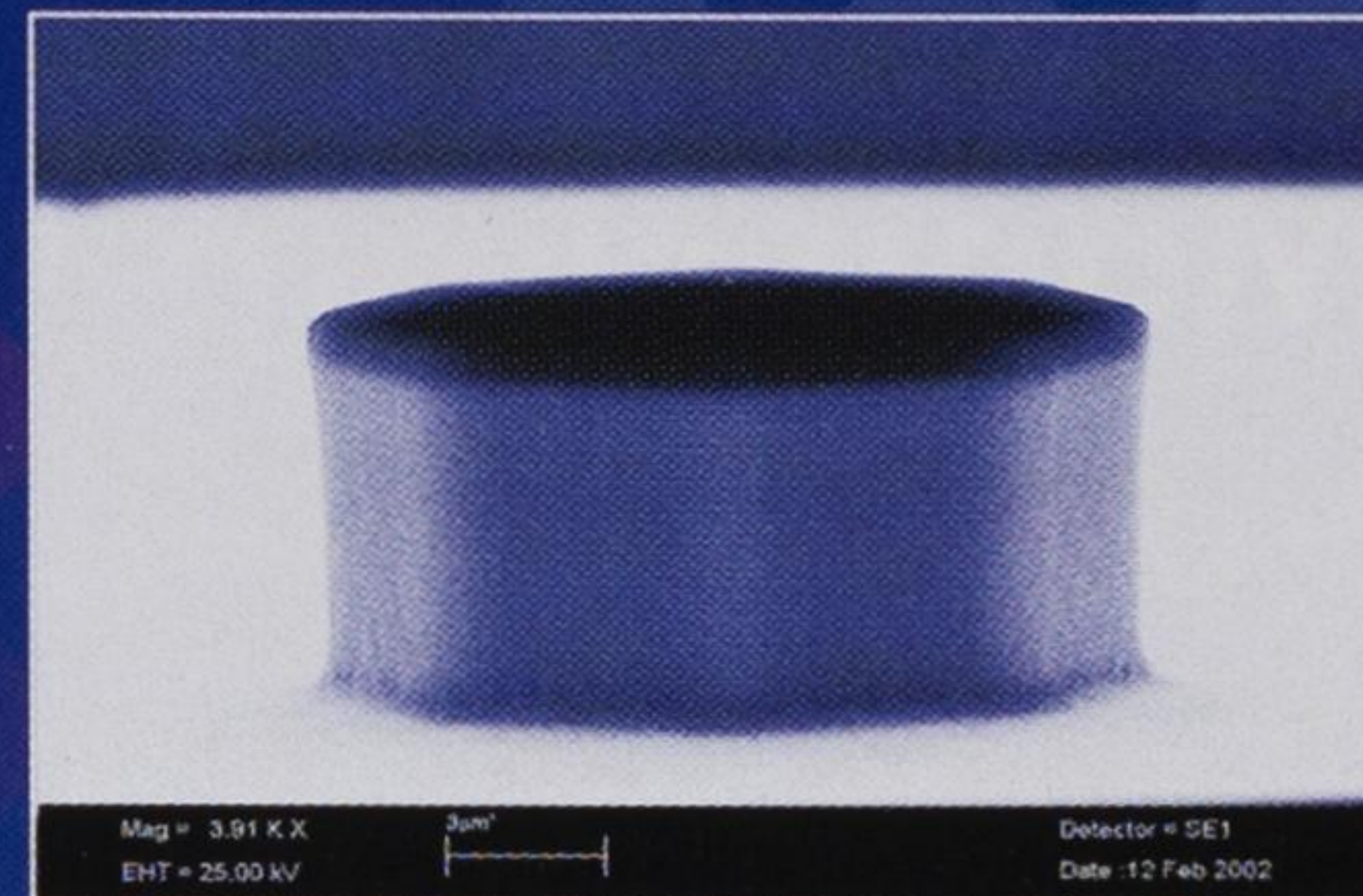
Grant says that scaling up to 6 inch wafers should not be a problem, but that meeting the required specifications could prove to be more troublesome. "It would be difficult to have bulk properties that are competitive with existing materials," he said. "Generally, as you go to larger sizes, dislocation densities increase."

Grant believes that delivering 6 inch wafers also depends on market conditions and who will take the risk first. "There was a 10 year lag between 4 and 6 inch GaAs wafers," he said. "This may well happen faster with InP, but people need to take a lead in the development of 6 inch substrates."

Kurt Williams of Nikko Materials has said that 6 inch InP wafers are "in the works" for his company, but he is reluctant to commit to a timescale.

However, it would seem that Showa Denko KK (SDK), the semiconductor business of Japanese technology company Showa Denko, has decided to take a gamble. The company has recently started shipping sample volumes of its 6 inch semi-insulating InP wafer, which is manufactured by the company's proprietary "hot wall" LEC technique. SDK is now planning to make 500 wafers a month by the end of the third quarter this year (see p4). Without a doubt InP substrate manufacturers and IC companies worldwide will all be following their plans avidly.

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HB-LEDs continue progress towards solid-state lighting

High-brightness LEDs continue to penetrate automotive, displays, signage and decorative lighting markets, says **Richard Dixon** in the second of two reports from the recent Strategies in Light conference.

Although the market for high-brightness LEDs stalled in 2001, remaining flat at \$1.2 billion, sales of these devices are set to recover this year. In fact, last year's lull in sales in no way reflects the current enthusiasm and technical innovation in the industry, with new applications for LEDs continuing to be the driving force behind the constant push for improved performance. Some of these applications are described here in the second of two reports from the Strategies in Light conference, held in San Francisco on February 7–8 (for part one, see *Compound Semiconductor* April 2002, p51).

Reliability hinders display makers

According to Dario Tabakovic of Stella Vista America, 2001 was not the best year for display companies. More than 100 of the LED display companies that have emerged in recent years, and four of the top ten, have gone out of business in the last two years. One reason Tabakovic gave for the glut of new LED screen manufacturers was that the cost of entry into the LED display business was not high. Tabakovic also highlighted a problem with current LED quality assurance practices that in some cases have led to reliability issues with large-area screens, which must last at least five years to justify the initial high cost of purchase and installation.

Despite binning, a practice employed by companies to collect devices of a certain wavelength and brightness into batches of known performance, many LEDs failed to reach the required quality level. Tabakovic expressed the hope that new standards addressing the needs of screen makers would be adopted.

Auto industry provides a big market

Inside an automobile LEDs are widely used to light the dash and instrumentation, indicators, switches and radio-display backlights. Aldo Kamper of Osram Opto Semiconductors revealed that Audi currently uses more than



Fig. 1. Osram Opto Semiconductors supplied the white LEDs that are being used in the front headlamps of the Ford Tonka F-350 concept vehicle.

200 LEDs in its models, and 320 in its top range A8. This includes more than 90 devices in both the dashboard and radio, 60 LEDs to illuminate climate-control indicators and 25 in switches. Osram estimates that around 90% of new European cars have LEDs in the radios and 80% have them in the dash clusters. Branding has taken place in this market, with each maker realizing the value of the statement made by the creative use of interior lighting: VW uses blue, BMW employs orange and Saab has chosen green.

On the exterior of the car, LEDs for the front headlamps are also being actively developed and are not far from becoming a commercial reality (figure 1). A big effort is being made to develop high-power chips, as well as optical designs for efficient light coupling.

According to Kamper, around 1000 lm per light cluster is needed for low-beam operation, and up to 3000 lm for high-beam operation. Osram is now developing a compact light source that achieves 500 lm per assembly, which is sufficient to allow a dual-beam cluster that is suitable for low-beam operation with side parking lights.

These applications benefit from the improvement in the company's standard chips. Last year its InGaN blue devices gained 60% in output power using the ATON chip, which is shaped to increase light extraction (see *Compound Semiconductor* February 2001, p7). Osram now plans to increase the output power a further 30% by flipping the device. Not surprisingly, this LED has the internal working title of NOTA.

This year new packages are also expected, including a high-power housing called the Dragon. This is expected to accommodate the heat from a high-brightness chip operating at up to 1 W. Further out, novel LED displays could also benefit the motorist.

Ron Steen, director of lighting research at Schefenacker Research USA, described some new approaches to automotive exterior lighting, including taillight clusters. Schefenacker has a diverse product portfolio that it has recently broadened with the acquisition of Global Light Industries. Global Light is a German manufacturer of LEDs covering the full visible range (see *Compound Semiconductor* February 2001, p11). Steen noted that the LED

HIGH-BRIGHTNESS LEDs

industry is still characterized by a lack of available packaging options, but that Global Light has some exciting injection molding technology that overcomes this drawback. Global Light uses molding to encapsulate its own chips and produce custom designs in a range of complex forms.

Schefenacker has since produced ultra-thin center high mounted stop lamps, scheduled for production next year. These fixtures are 10 mm deep instead of the typical 30 mm. Steen showed additional lighting examples developed for several recent concept cars, including light strips.

Dialight's Gary Durgin described LEDs in other areas of transportation (figure 2), including trains, planes and buses (85% of which are now fitted with rear LED brake-light clusters).

Jason Posselt discussed LumiLeds' approach to encouraging LED adoption, which involves producing lighting systems and fixtures capable of retrofit, in addition to fully integrated system designs. The company is partnering with suppliers of driver electronics and power sources and is offering different radiation patterns suitable for a range of applications. These include beams with Lambertian, batwing, collimated and side-emitting patterns. The side emitter is called the Infinity and is set for introduction later this year.

LumiLeds continues to work on phosphors, and is searching for lower correlated color temperature values with improved color rendering (the target is 2700–3500 K for indoor lighting). The alternative approach to making white output using RGB color mixing is also being investigated.

Nichia describes LED roadmap

Nichia was unusually candid about its LED product roadmap, in part because it is now taking competition from companies such as Cree more seriously (see *Compound Semiconductor* March 2002, p66). Mineo Sei, head of sales in the company's Optoelectronics Division, said Nichia will be targeting reliability and is aiming at 30,000 hours for 50% lumen depreciation instead of the current 10,000 hours.

He also said that Nichia would be targeting the white LED backlighting market for cell phones with full-color displays. Already popular in Japan and Asia, demand for these displays will rise as cell-phone manufacturers introduce models with color screens to replace the simple green backlighting. To serve this market, the company has developed surface-mount InGaN white devices in 1.0 and 0.8 mm thick packages. These devices will also target



DIALIGHT

Fig. 2. Dialight, an LED lighting system manufacturer, gave numerous examples of LED transportation products, including a blue elevated taxiway LED fixture for airports. The light pipe/reflector design reduces impact-related damage.



SWEDISH ROAD ADMINISTRATION

Fig. 3. Sweden has employed LEDs for road lighting for the first time. Placed initially at a dangerous stretch of highway, the new light poles have already helped to improve road-safety statistics.

PDAs, hand-held video cameras and digital still cameras. Nichia also revealed its plans for high-flux LEDs, and has since released 1 × 1 mm high-power chips (see *Compound Semiconductor* April 2002, p15).

Cree's power chip

Norbert Hiller covered the major advances in Cree's GaN LED technology, which included its new high-power blue XBright InGaN-on-SiC chips. Cree's new blue and UV LEDs in standard 5 mm lamps for displays and traffic signs are now the brightest in the industry.

Companies such as LumiLeds, Uniroyal and AXT have been working on large-area high-power chips, and Cree is also active in this field. The company previewed its XBright 900 Power Chip LED, which delivers 10 times the brightness of its standard XBright chip. The new power UV device is 0.9 × 0.9 mm and

operates at 405 nm with an output power of 250 mW at 350 mA. A 470 nm blue device delivers 150 mW at 350 mA. Cree has also laboratory tested a packaged version of the blue device using a TO-39 header and non-optimized heat sinking, to achieve white LEDs with a total output of 30 lm at 350 mA.

LumiLeds is still leading the development of white LEDs for general illumination applications, where sheer lumen output is more important than overall device efficiency. The company's Luxeon chips have been available since mid-2001, and combine a high output power chip, heat sinking and packaging to make a reliable source that delivers 30 lm/W or 150 lm per LED for white devices. Updated reliability results reveal that Luxeon white devices suffer very low lumen depreciation over a 6000 hour span, and only 30% degradation after 50,000 hours.

One of the keys to the reliability of Cree's white device is a silicon-based opto-coupling gel, replacing the traditional epoxy that can yellow under exposure to the short-wavelength radiation.

Microsemi gets the blues

Microsemi revealed more of its blue LED plans. The company's new blue UltraBright LED, the UPBLED470A, combines a package called the Optomite and uses Cree's die. Manuel Lynch, VP of business development, said that the company is still considering several different approaches to LED development. "While our patented power packaging technology is chip agnostic, Microsemi will use the technology that best fits the advantages of our Optomite package," he said.

Microsemi's other main chip development partner is Nitronex, a company that is developing a method to grow GaN on 4 inch silicon substrates. Microsemi is working on a chip-scale method of encapsulating these chips into glass packages to address the reliability issues of white LEDs (see *Compound Semiconductor* August 2001, p19).

Microsemi said that it expects to sample its white LightChip emitters this summer, with production starting as early as the end of the year. The company also described its LED driver product line, which includes a future intelligent driver that will provide constant brightness and power as the device ages.

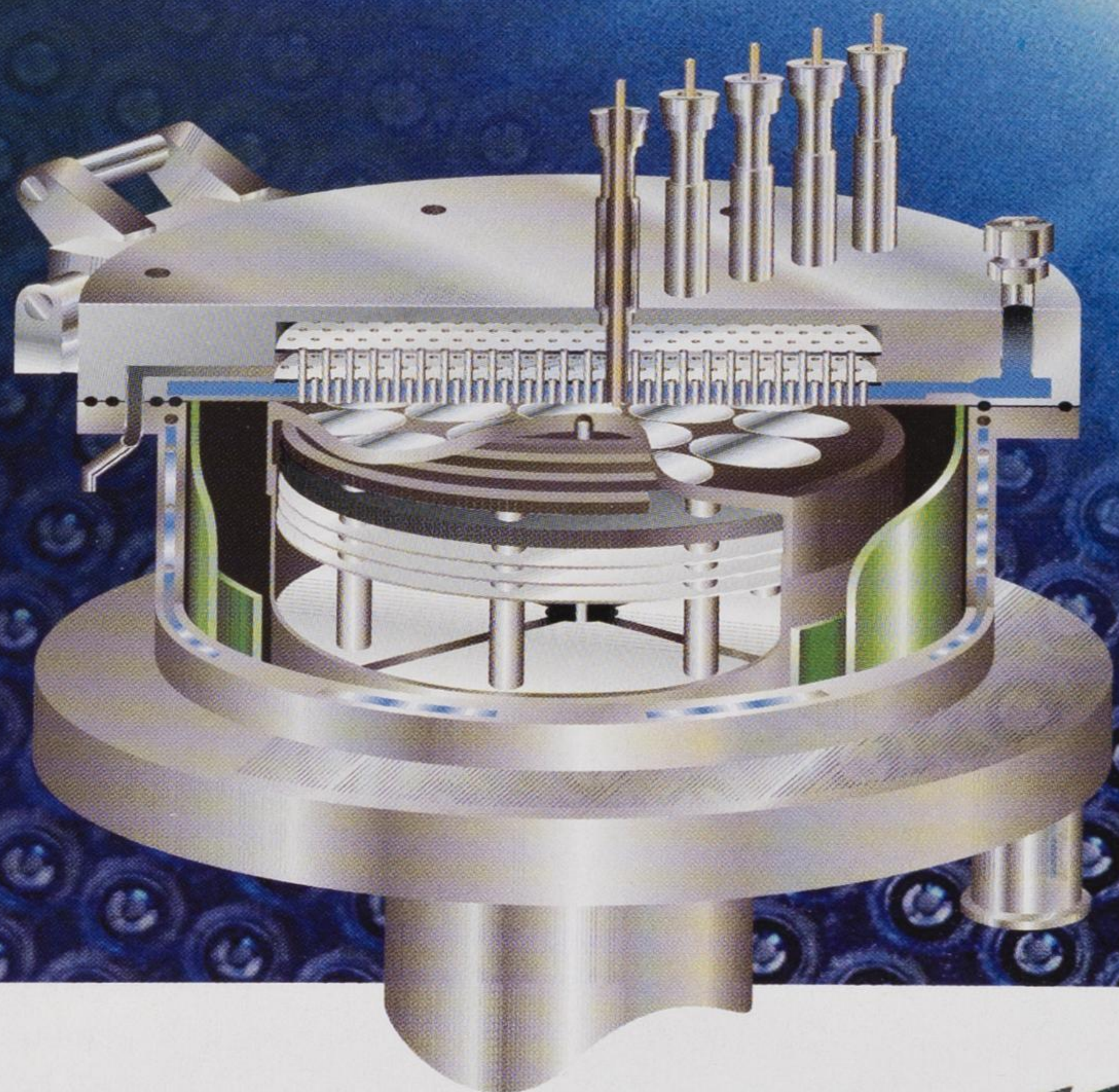
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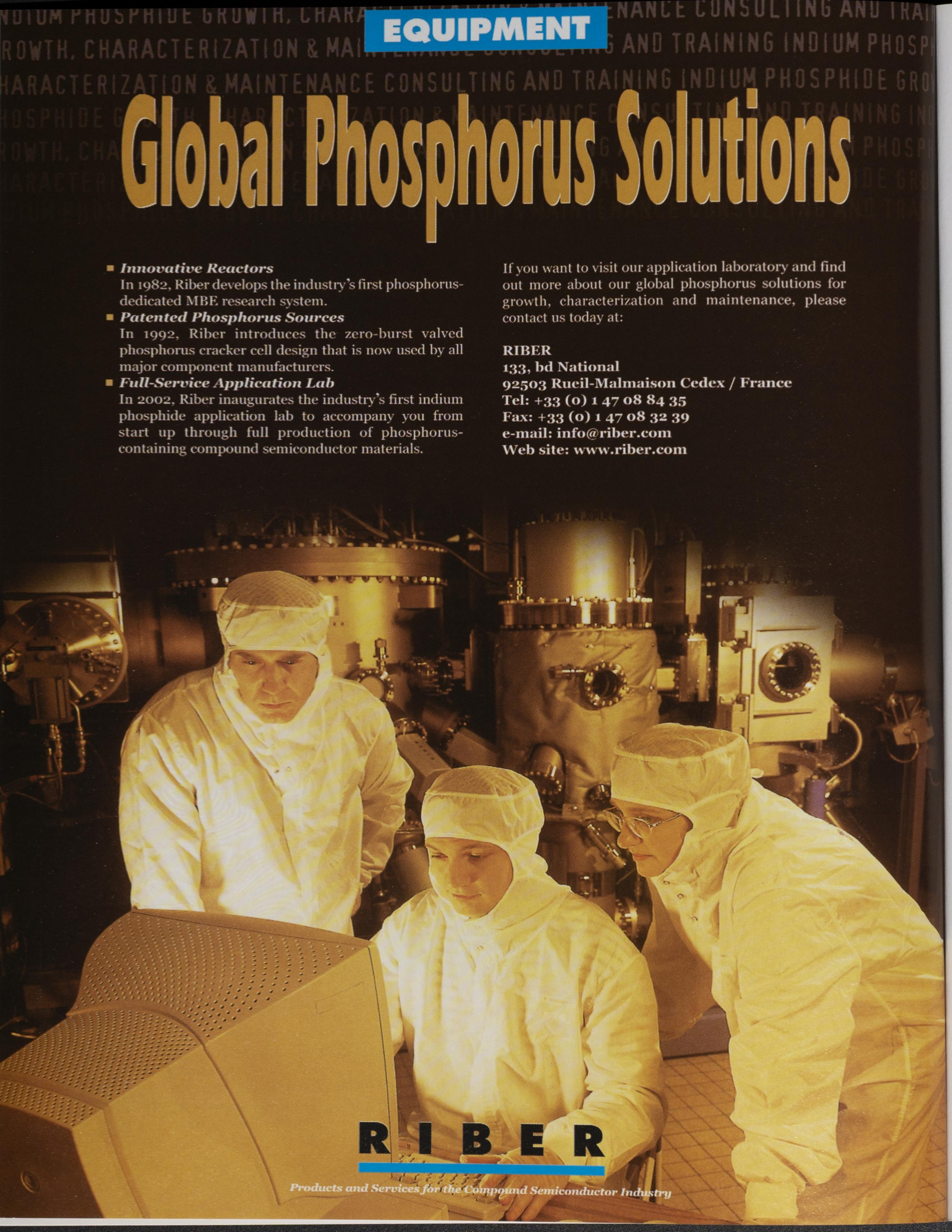
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Products and Services for the Compound Semiconductor Industry

ing lamp, power source, wiring and standard socket, said Roland Haitz, who recently retired from Agilent Technologies. Haitz described the evolution of the LED industry and presented a historical perspective that now forms the backdrop to recent US LED lighting initiatives.

Agilent's progress with white LEDs for use in general illumination is driven by the cost per kilo lumen, with a target of \$5–10 per klm and efficiency in excess of 150 lm/W by 2010.

Haitz said that solid-state illumination sources could save 10% of the total US electricity consumption, or \$100 billion annually. Most of these savings (up to 70%) will directly benefit the consumer. Conversely, the LED industry must bear 70% of the risk. "If society wants to enjoy the benefits of a technological revolution, it must provide the incentive to make it happen quickly," said Haitz, who believes that funding initiatives to advance solid-state lighting should come from government (*Compound Semiconductor* September 2001, p76 and March 2000, p34).

Both the US and Japan are involved in such initiatives. Arpad Bergh of the Optoelectronics Industry Development Association described progress with the Next-Generation Lighting Initiative, a US effort to seek federal funding for an industry-wide development program for solid-state lighting. The program has gained momentum over the last 18 months, and is currently under consideration by the Senate, with authorization expected sometime this summer.

Specifically, the initiative requires funding for a partnership between the Department of Energy, academia, national institutes and an industry-led consortium of the major LED and OLED manufacturers. Berg says that white LEDs are expected to begin replacing incandescent lamps within five years, and both LEDs and OLEDs will eventually challenge the larger area, more efficient fluorescent lamps. Targets include 150 lm/W by 2012 and 1000 lm output per lamp at a cost of less than \$15 per klm.

Kohtaro Kohmoto from the Japan Electric Lamp Manufacturers Association said the Japanese LED industry produced 9.3 billion LEDs last year. For the high-brightness variety, he described ongoing efforts to standardize these devices for general illumination applications. Kohmoto said the mismatch between the vocabulary used in the LED and the conventional lighting industries (including optical and electrical characterization methods) was hindering white LED development.

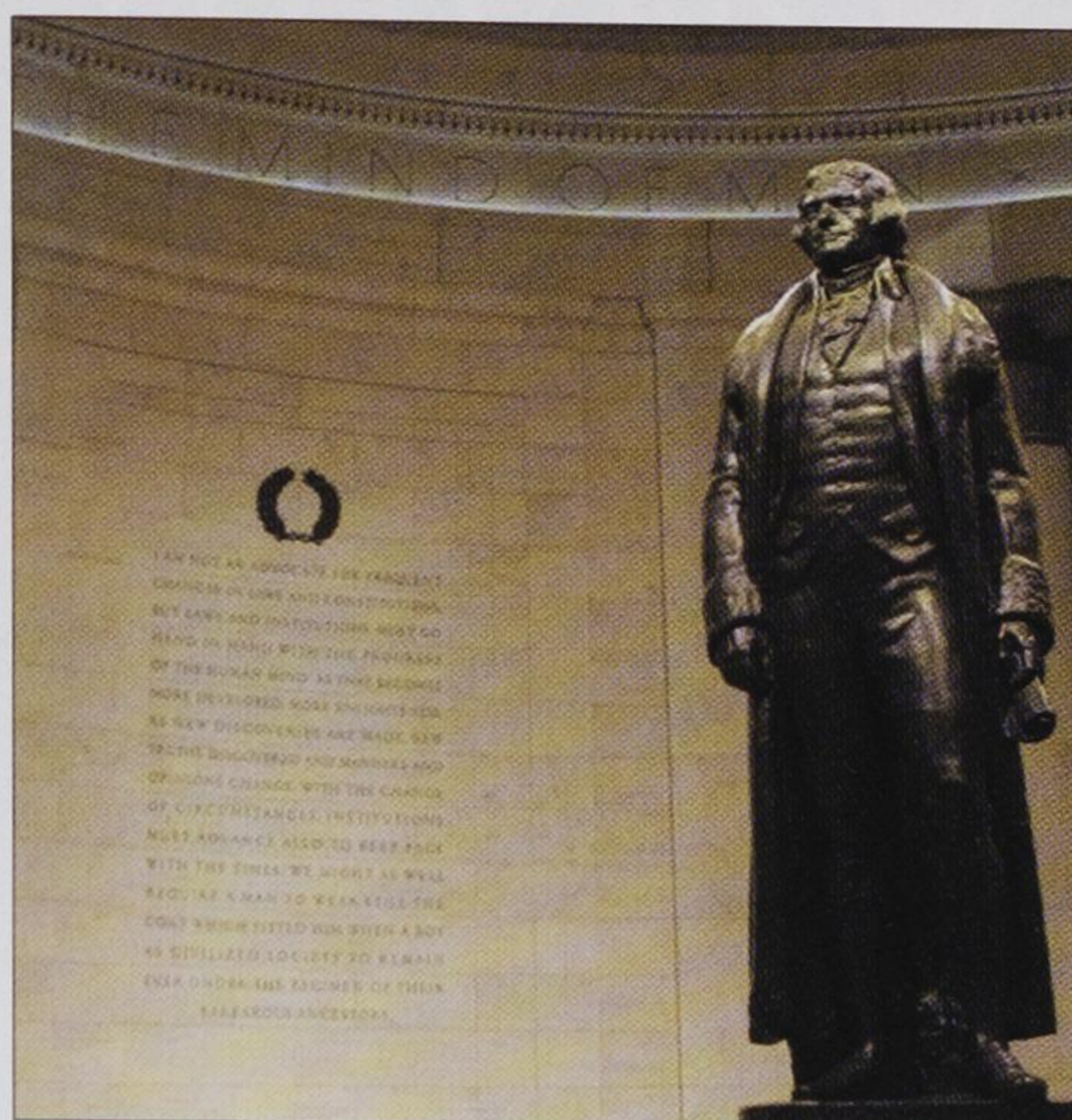


Fig. 4. The Jefferson Memorial is a recent example of an architectural lighting application. Here, the LEDs are used to illuminate the surrounding cove.

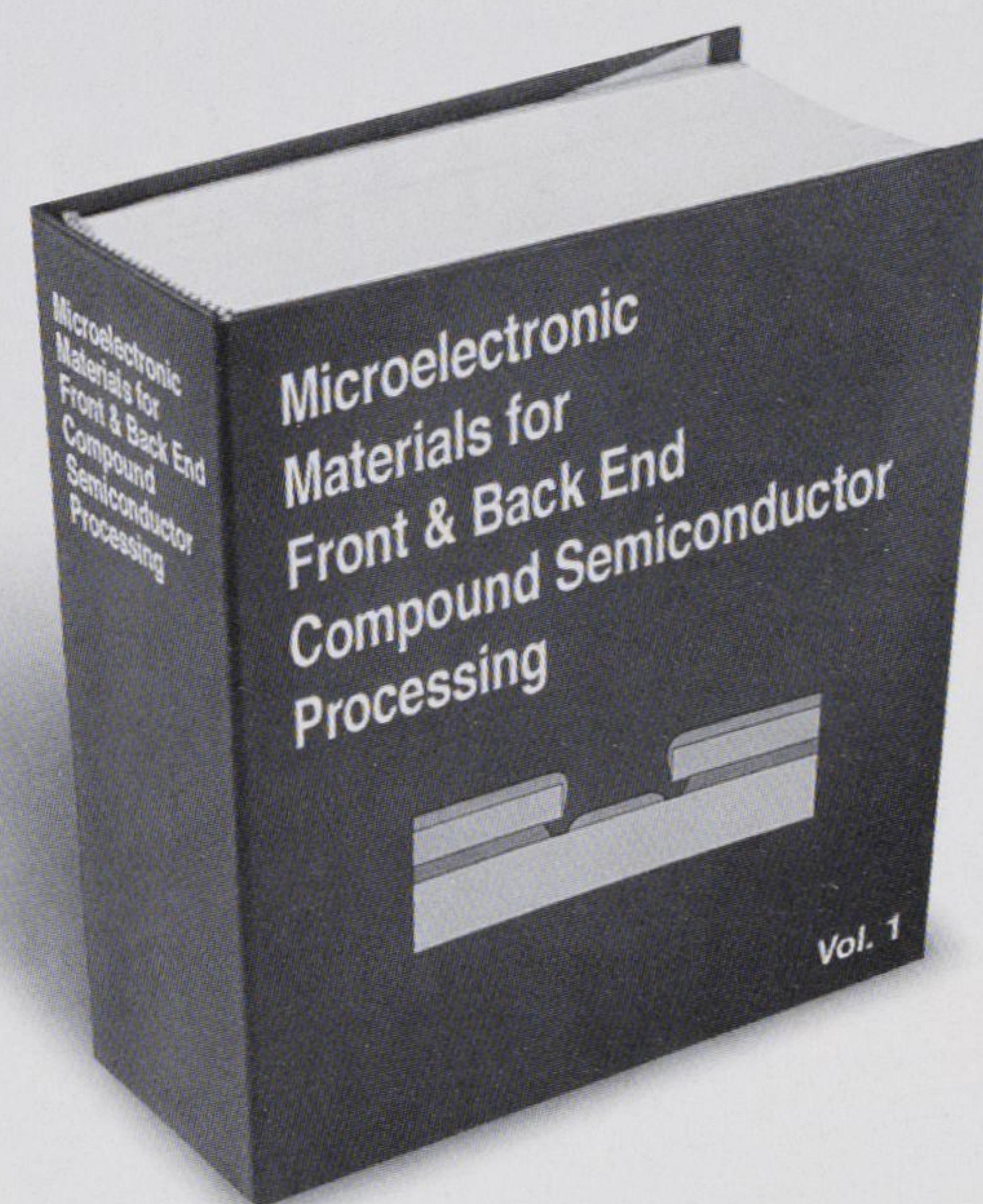
LED road lighting in Sweden

Lars Bylund of the Pelk Design Group described the use of LEDs as a substitute for high-intensity discharge lighting in Sweden. LEDs are being examined as an energy-efficient light source that can help reduce road accidents during the country's long dark winter or from hazards such as snow smoke from large vehicles, which causes poor visibility. The sources are very bright and can be seen from up to 4 miles away (figure 3). So far, an experimental setup of 550 poles on a 10 mile stretch has been well received. White LEDs supplied primarily by Nichia are employed, and solar cells are used to further reduce energy costs. The main problem has been with people stealing the LEDs, says Bylund.

York Kennedy, a lighting designer from Galleos Lighting Design, described several architectural applications for LEDs, which included decorative uses in casinos and new installations such as the LEGO Imagination Center in Anaheim, California.

According to Kennedy, LEDs allow new freedoms with lighting design and exciting possibilities with color manipulation. His wish list included more options for cove (figure 4), path and step lighting, standard adapters, ceiling panel lighting fixtures and more architectural and sculptural products. The latter could include light bars and squares. The cost of LEDs remains the dominant factor governing their widespread use, he said, but in many cases the beam angles are still too small. From a designer's perspective it is not desirable to see the source directly, rather a washed out or spread light is required. ●

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VCSEL testing cuts lead times

Scott Jennato, Joe Jablonski and Don Feuerstein look at a new approach to VCSEL testing that promises to increase wafer yields, cut manufacturing costs and reduce time to market.

As data-hungry consumers demand more information at faster rates, the makers of chips for communications applications are racing to fabricate devices more quickly and efficiently. VCSELs have found favor in datacom applications as they are easily coupled to fibers and can be tested at the wafer level. But although production processes for 850 nm VCSELs have already been proven, and 1310 nm VCSEL production is not far behind, wafer yields are a problem and often only reach 50%.

Today's price demands coupled with intense competition mean that the pressure is on for chip makers to raise wafer yields and make faster chips at lower costs. To this end, manufacturers are now looking towards simple, automated test systems for wafers that combine electronics for laser diode control and measurement with optical measurement and motion control platforms. The new wafer test systems promise to offer just this (figure 1).

Detectors cause testing problems

There are several important parameters to measure when testing a VCSEL, including threshold voltage, radiant flux and spectral characteristics. Previous-generation test systems typically comprise a probe station, operating software and an optical detector, but a drawback of these systems has been that the accuracy depends on the setup parameters.

For example the detector, typically a photodiode, has to be aligned with the VCSEL to ensure it captures all the emitted light. Previous systems have relied on a large-area diode to ease alignment and maximize light capture, but changes in the diode's responsivity as light hits it at different points have hampered results.

Light polarization also poses problems for VCSEL testing systems with photodiode detectors. As the polarized light from a VCSEL hits the photodiode, some is reflected away from, rather than transmitted into, the photodiode. This leads to power losses and, again, inaccurate measurements.

So how can chip makers increase their yields if they can't even accurately test their chips for defects? German probe-station maker Suss

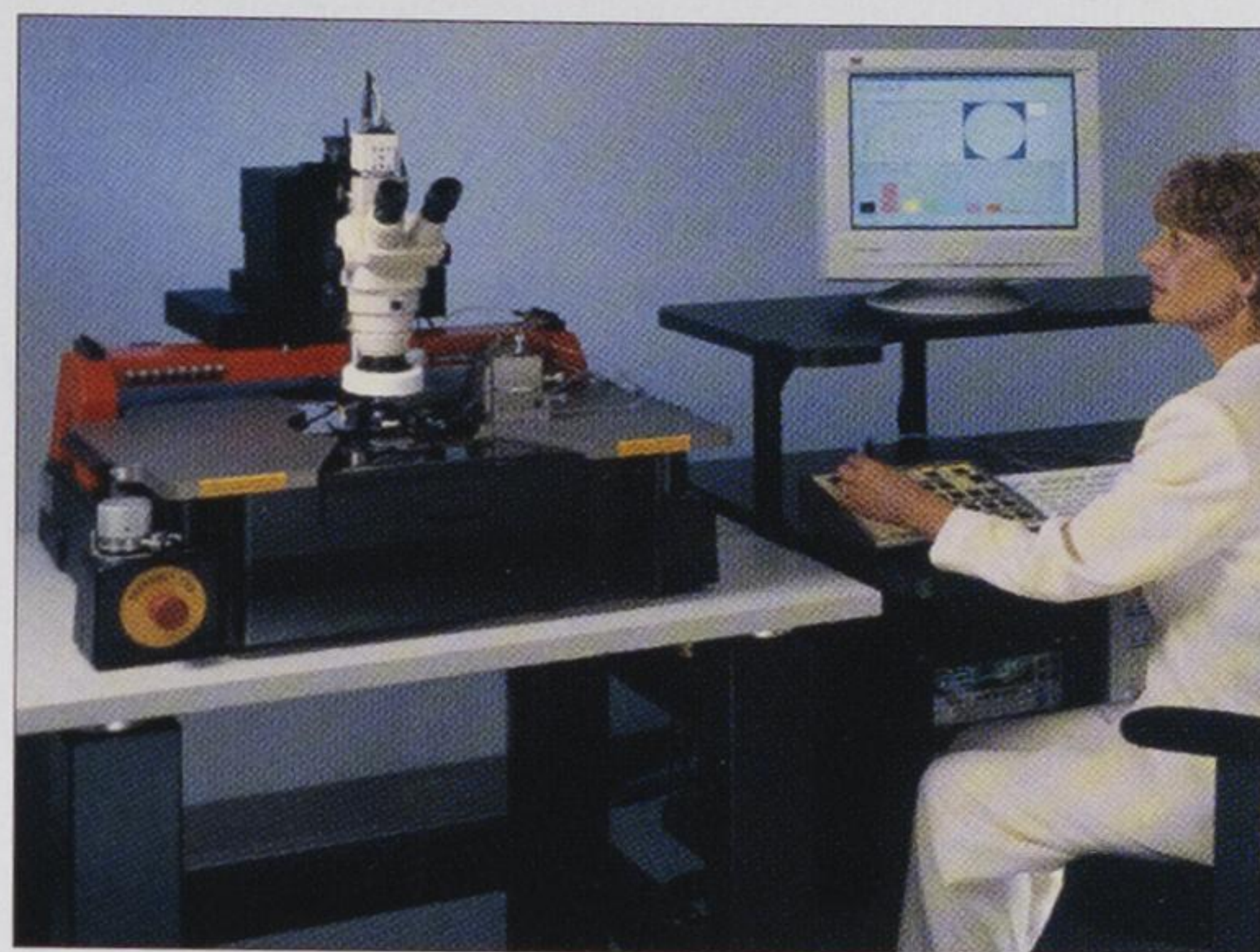


Fig. 1. The wafer probe system from Suss Microtec and Labsphere – shown here testing a blue LED – comprises a Suss Microtec PA200 probe system, along with a Labsphere detector assembly, which includes an integrating sphere detector.

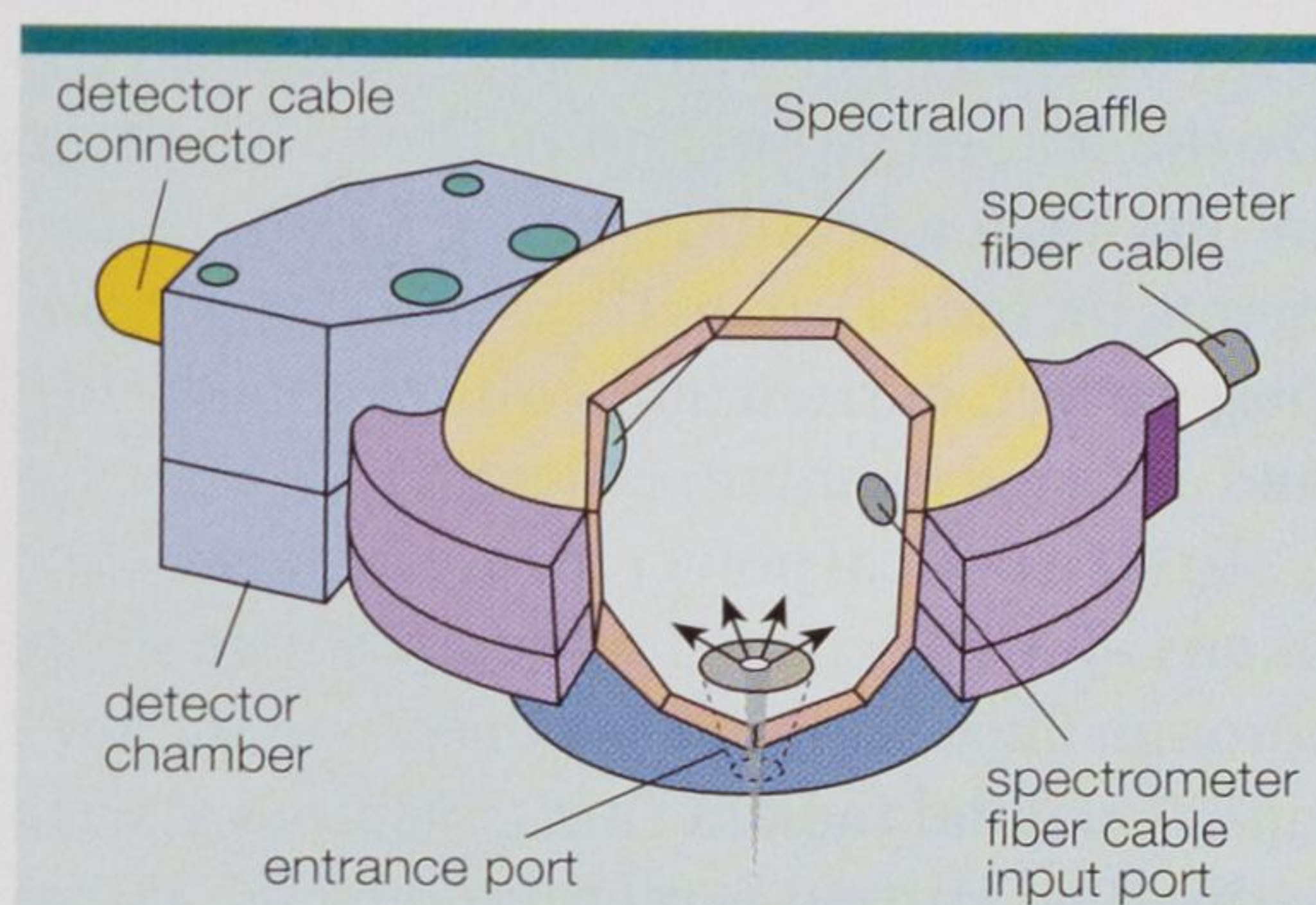


Fig. 2. The integrating sphere is about 1 inch in diameter and is attached to a detector and spectrometer. The Spectralon baffle shields the detector from direct, incoming light.

Microtec and US optical measurement company Labsphere believe they have the answer.

Last year the two companies joined forces to create an automated laser diode wafer-level test system for VCSELs. Designed for high-speed diode characterization, the system comprises a probe station, control software and, unlike past test systems, an integrating sphere that houses the detector.

Integrating sphere tackles flux

Used to measure optical radiation, the prime function of Labsphere's integrating sphere is to spatially integrate radiant flux from a light source such as a VCSEL (figure 2). Different spheres exist for different applications and, unlike photodiode detectors, an integrating

sphere designed for VCSELs can capture the total radiometric flux emitted from the devices.

The sphere consists of a spherical shell which has its interior coated with a propriety high-reflectance thermoplastic called Spectralon. This material diffuses the incident light. The sphere also has an input port and a photodiode detector mounted on its exterior wall. The input port is machined into the sphere's wall, and different sizes can be chosen depending on the application. The photodiode detector is made of either silicon, for wavelengths up to 1100 nm, or InGaAs or Ge for longer wavelengths.

Light enters the sphere via the port, strikes the diffuse interior surface and scatters equally in all directions. This scattered light or radiance is no longer polarized, which solves the reflectance problems that plagued old-style detectors, and also means that light incident on the detector is an accurate measurement of the device's power. Test results are also less sensitive to the alignment of the detector with the VCSEL. In fact, even with alignment offsets as high as 2–3 mm in the x-direction, the correct reading can still be obtained.

The diffuse scattering of light has another advantage. Since the material scatters in all directions, any point on the inside of the sphere is illuminated equally. The detector can therefore be placed at any location on the exterior wall to give the same reading. The setup is designed, however, so that the detector's field-of-view does not overlap with the direct area

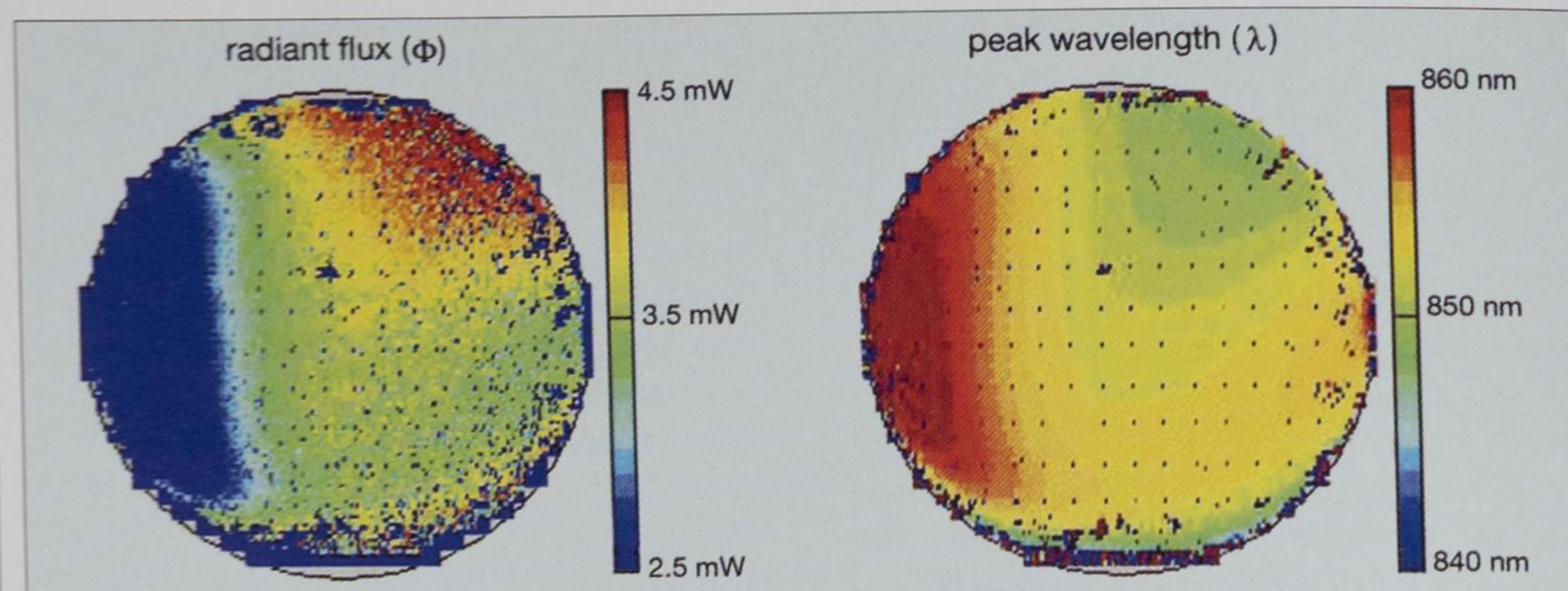


Fig. 3. Wafer maps reveal the variation of optoelectronic properties – in this case radiant flux (total optical power) and peak wavelength – of individual devices across a wafer.

of illumination from the incoming laser light. This ensures that the light is scattered and uniformly integrated before striking the detector.

Putting the sphere into practice

A key advantage of VCSELs is that they can be tested on the wafer prior to dicing. This makes testing cheap and also saves costs by avoiding additional processing steps on faulty chips. The wafer probe system developed by Suss Microtec and Labsphere can characterize the optoelectronic properties of each die in less than a second (figure 3). Measurements include radiant flux, spectral properties, power, current and voltage thresholds, and external quantum efficiency.

To take optical power measurements, such as an L-I-V sweep, multiple currents are swept through the laser diode via the probe station's tips. The total radiant flux generated at each individual current is measured by the integrating sphere, and the silicon or InGaAs detector generates a current proportional to the light collected. A meter is used to measure the current, and prior calibration of the device against a standard enables this current to be easily translated into a traceable total optical power or radiant flux measurement.

As well as radiant flux it is crucial to measure the VCSEL's spectral characteristics, such as center wavelength and bandwidth. To do this a fiber is attached between the integrating sphere and a spectroradiometer or optical spectrum analyzer (OSA). The spectroradiometer or OSA breaks down the light into its spectral components, ready for recording, and also houses a thermoelectric cooler that controls the system's thermal stability and reduces dark current.

To help achieve fast, accurate and repeatable testing, the wafer sits on a motorized prober stage that moves in three dimensions. To ensure uniform and repeatable results, a

Suss industry-standard wafer prober is used to index each device prior to testing.

Although fast test results are crucial, a manufacturer also needs to have confidence in the accuracy and repeatability of the results. This means the results have to be traced back to a standard supplied by a national laboratory such as the National Institute of Standards and Technology (NIST).

Test results from earlier systems rely heavily on the system setup, which, coupled with the problems of using a large-area detector, means that test results are not repeatable. This makes traceability to a known standard difficult. However, by using an integrating sphere in a test system that is less sensitive to setup conditions, traceability is easier. The spectral characteristics of the integrating sphere detector are also easily traceable to a NIST tungsten-halogen lamp.

Early detection saves money

As the pace of bringing components to market accelerates, VCSEL manufacturers need to operate with higher yields and improved reliability. Low-cost manufacturing is crucial and the early identification of any process or design problems is key.

Wafer-level testing of VCSELs moves device verification to the earliest possible step in the process. This saves time and money by avoiding subsequent costly production steps on defective units that will eventually be scrapped. Wafer probe systems that contain integrating spheres will enhance reliability by identifying critical performance criteria as early in the process as possible.

Scott Jennato is director of marketing and new product development, and Joe Jablonski is manager of new product engineering at Labsphere. Don Feuerstein is sales and marketing manager at Suss Microtec.

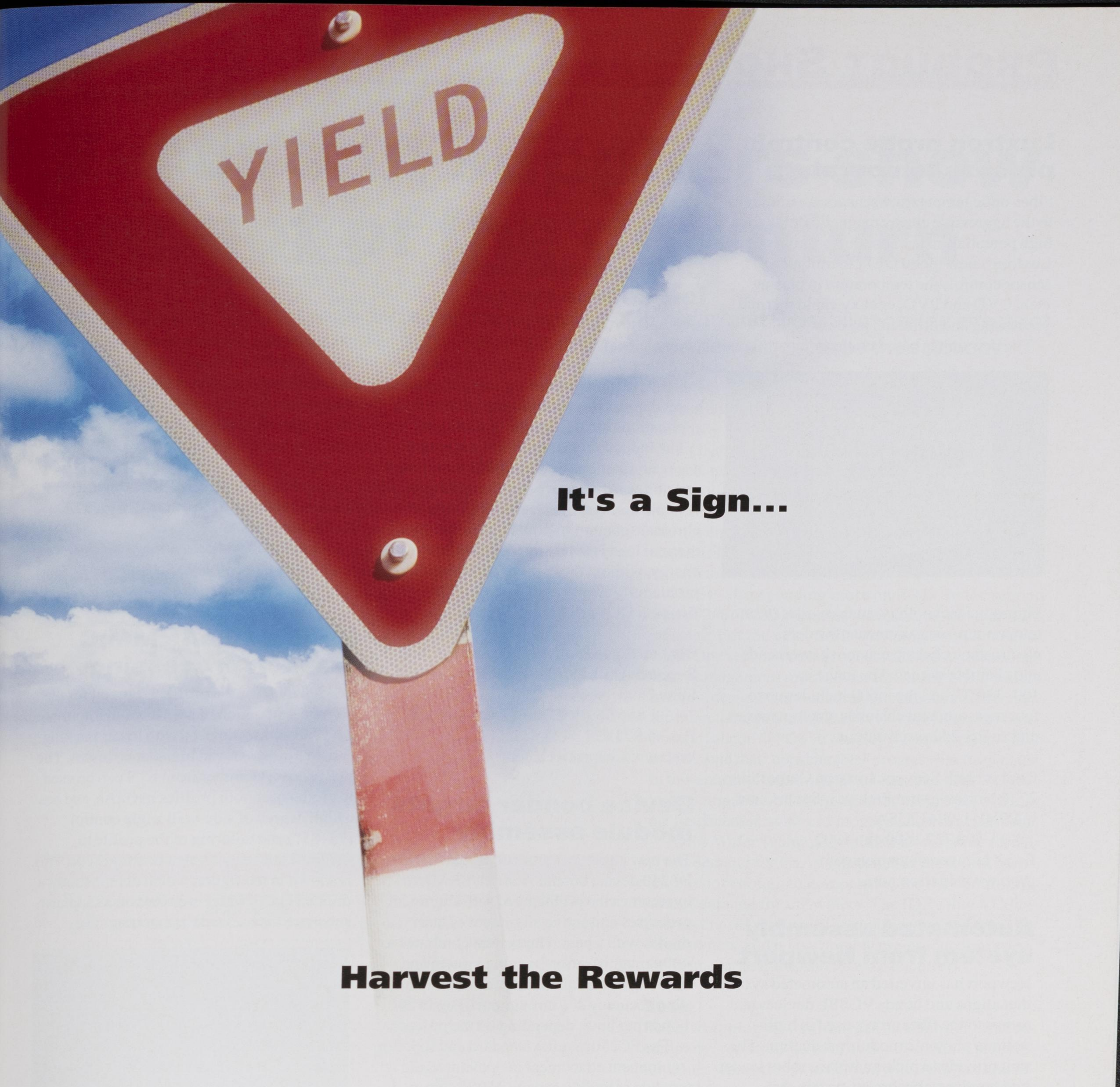
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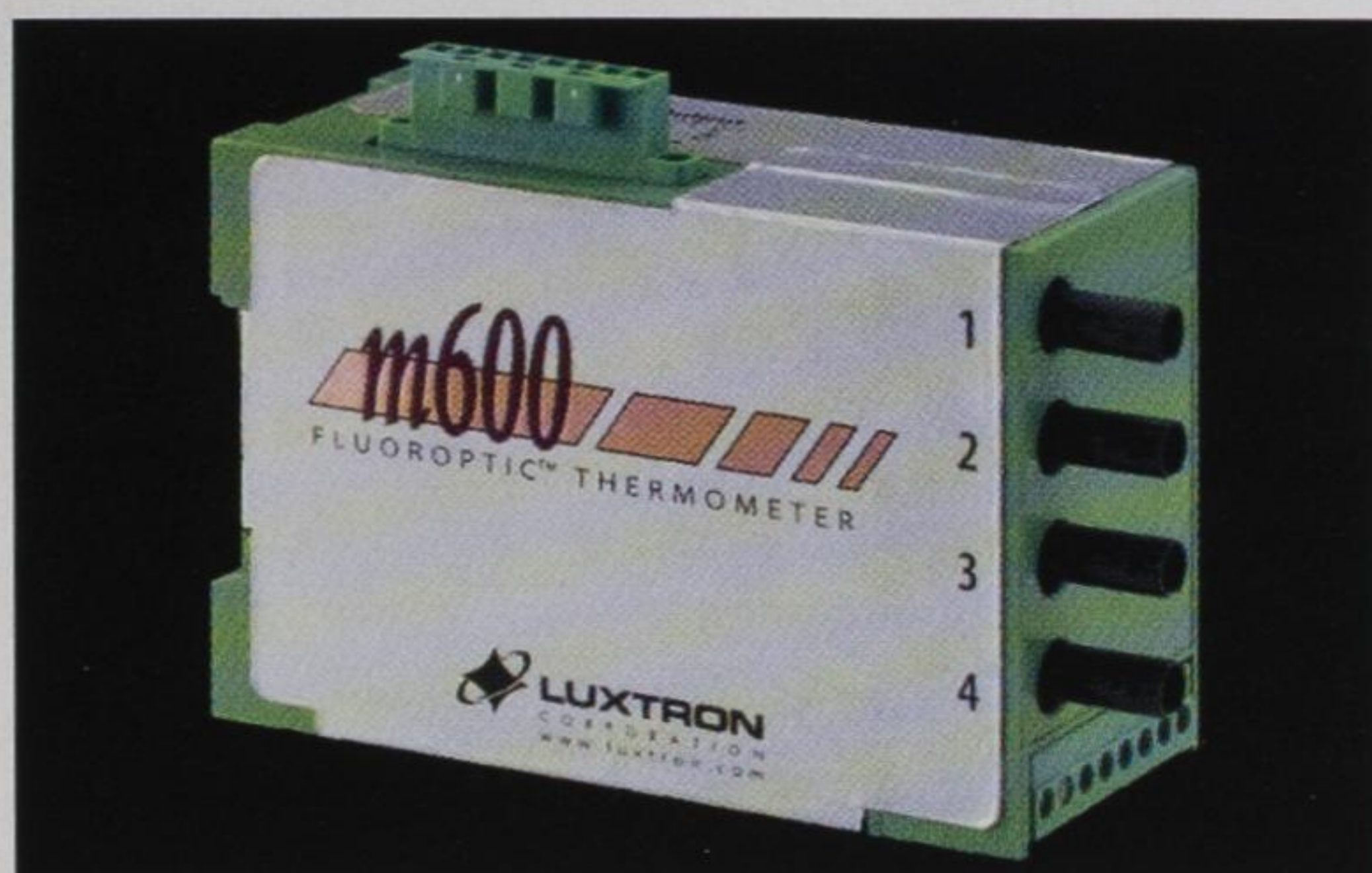


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The new unit is based on the company's



Fluoroptic technology, and provides *in situ* temperature measurement of wafers, electrostatic chucks, reactor showerheads and chamber domes. The range is 100–330 °C, and the m600 includes up to four measurement channels, analog outputs and an RS-232 serial output.

Contact Judi Seavers, Luxtron Corporation, 2775 Northwestern Parkway, Santa Clara, CA 95051-0941, USA

Tel. +1 408 727 1600 ext. 1902

Email j.seavers@luxtron.com

Web www.luxtron.com

Automated assembly system from Newport

Newport has unveiled an automated system that aligns and bonds VCSEL devices and arrays to the fiber arrays used in high-volume photonic module production. The unit provides a pick-and-place robot loader and bonding-attachment system that uses an automated epoxy dispenser with UV curing light.

A machine vision alignment system is used in place of dedicated tooling fixtures to register parts to accommodate the diverse range of VCSEL configurations currently in use. The system can handle a wide variety of packages or carriers such as waffle packs or Auer boats, as well as third-party programming environments through the company's Integra software interface.

Contact Kamran Mobarhan, Newport Corp, 1791 Deere Avenue, Irvine, CA 92606, USA

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OAR expands its RF ion-source range

A complete range of RF ion sources is now available from OAR in 25–150 mm diameters. The new sources are intended for substrate cleaning, ion-beam etching, ion-beam deposition or ion-assisted deposition applications including optical coatings.

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Device bonder targets module assembly

The new passive alignment process for the FC250 device bonder from SUSS MicroTec overcomes the problems of self-alignment processes and active alignment of laser diodes with fibers. The system combines a 400× magnification imaging system and bonding arm to maintain sub-micron bonding accuracy at a throughput of up to 250 bonds per hour, depending on the process.

The FC250 handles standard and flip-chip component attachment in optoelectronic module assembly at up to 450 °C. It can apply forces from the 10g needed for laser diodes to the high forces needed for thermocompression bonding of indium or gold bumps, which can reach 200 kg.

Contact Anja Maria Hastenrath, SUSS MicroTec, Schleissheimer Str. 90, 85748 Garching-Munich, Germany

Tel. +49 89 340 834 17

Fax +49 89 340 834 10

Email anja@positiopr.com

Cartridge provides process flexibility

Users of MRSI dispensing systems now have the option of a quick-changing cartridge. The new system has a modular cartridge that includes the pump auger and chamber as well as the dispense needle. This cartridge can be removed from the pump and stored with the fluid while a second cartridge is installed.

The development allows the pump from both MRSI-170 and MRSI-175Ag dispensers to be switched from a high-volume application, such as dam and fill, to a more precise application, such as silver-filled conductive epoxy.

Contact Dan Crowley, MRSI, 101 Billerica Avenue, Building 3, North Billerica, MA 01862-1256, USA

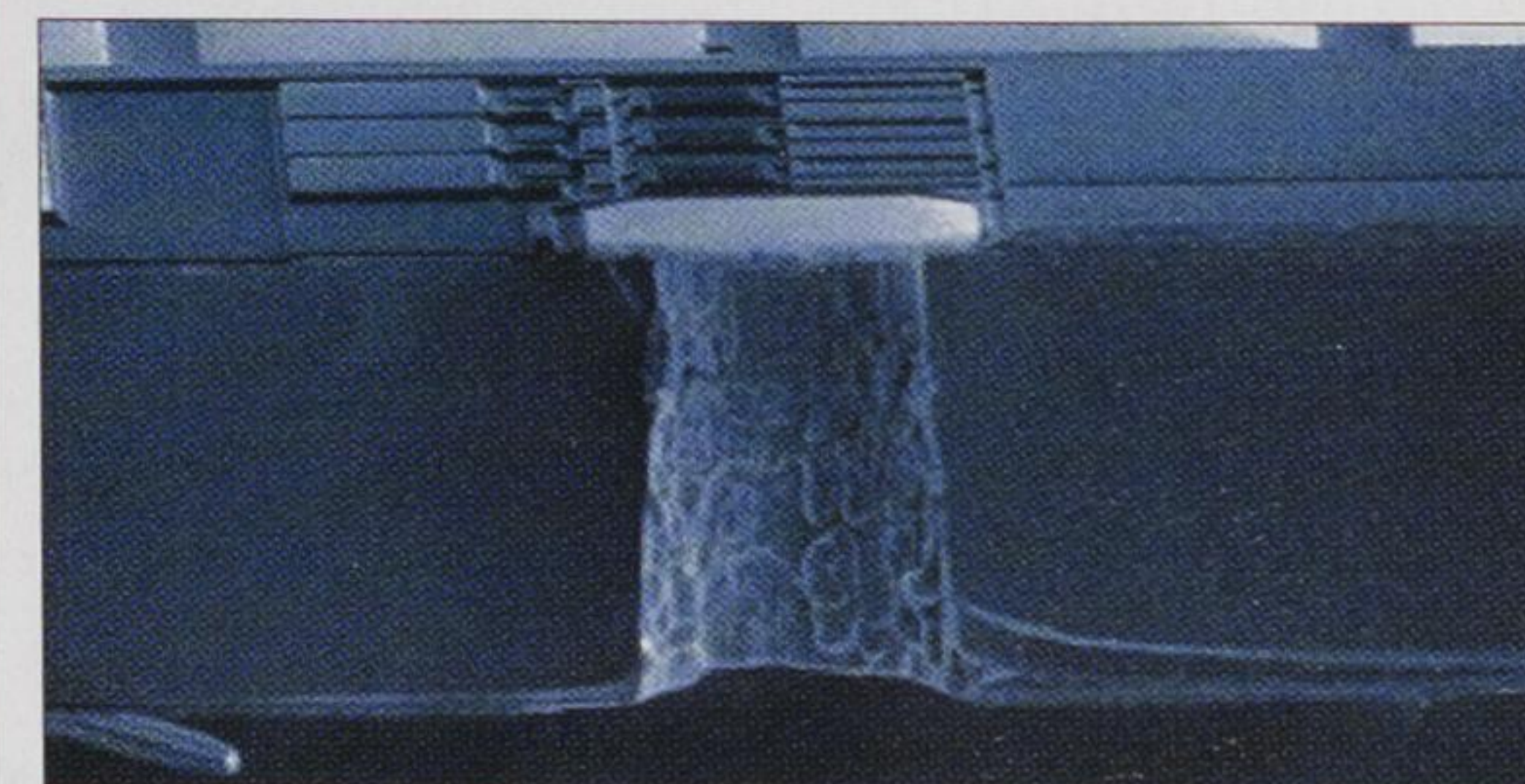
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ICP aids GaAs MMIC via etch processing

Control over the via profile is crucial for the volume production of MMICs and important when designing devices with lower packing densities and reduced impedance losses. The ICP process chamber from STS can be used to produce smooth profiles in GaAs, and has a high degree of side-wall angle control (75–85°) and tailoring of the profile to facilitate subsequent metalization steps. This is shown in the figure, which demonstrates a thinned GaAs wafer mounted on a sapphire substrate for backside via etching. The



high-throughput process can achieve etch rates of up to 6 µm/min for 50 µm via sizes on wafers up to 150 mm in diameter.

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European suppliers show impact of the downturn

Financial results from materials and equipment suppliers IQE, Bede and Riber all show the effects of the slowdown in the second half of 2001. Will R&D spending and new products be the solution?



In late March leading epiwafer vendor IQE reported sales of £42.05 m (\$63.07 m) for the 2001 calendar year, up 40% over the previous 12 months. However, sales for the fourth quarter declined 27% compared with the same period in 2000, and shipments in the second half of the year declined nearly 40% relative to the first half. The company reported an operating loss of £3.47 m compared with a profit in 2000 of £1.995 m.

In the fourth quarter, IQE's management reported that they saw "definite signs of improvement" in the

wireless market, with some "significant" new production orders from customers. However, these gains were offset by further deterioration in the optoelectronic market. Gross margins suffered, dropping from 15.8% to -1.3% in the third quarter. Management said this was the result of "operational gearing", which is another way of saying that the company has high fixed costs that do not change with output - i.e. the same problem of underutilizing fab capacity that is dogging all companies in the semiconductor industry.

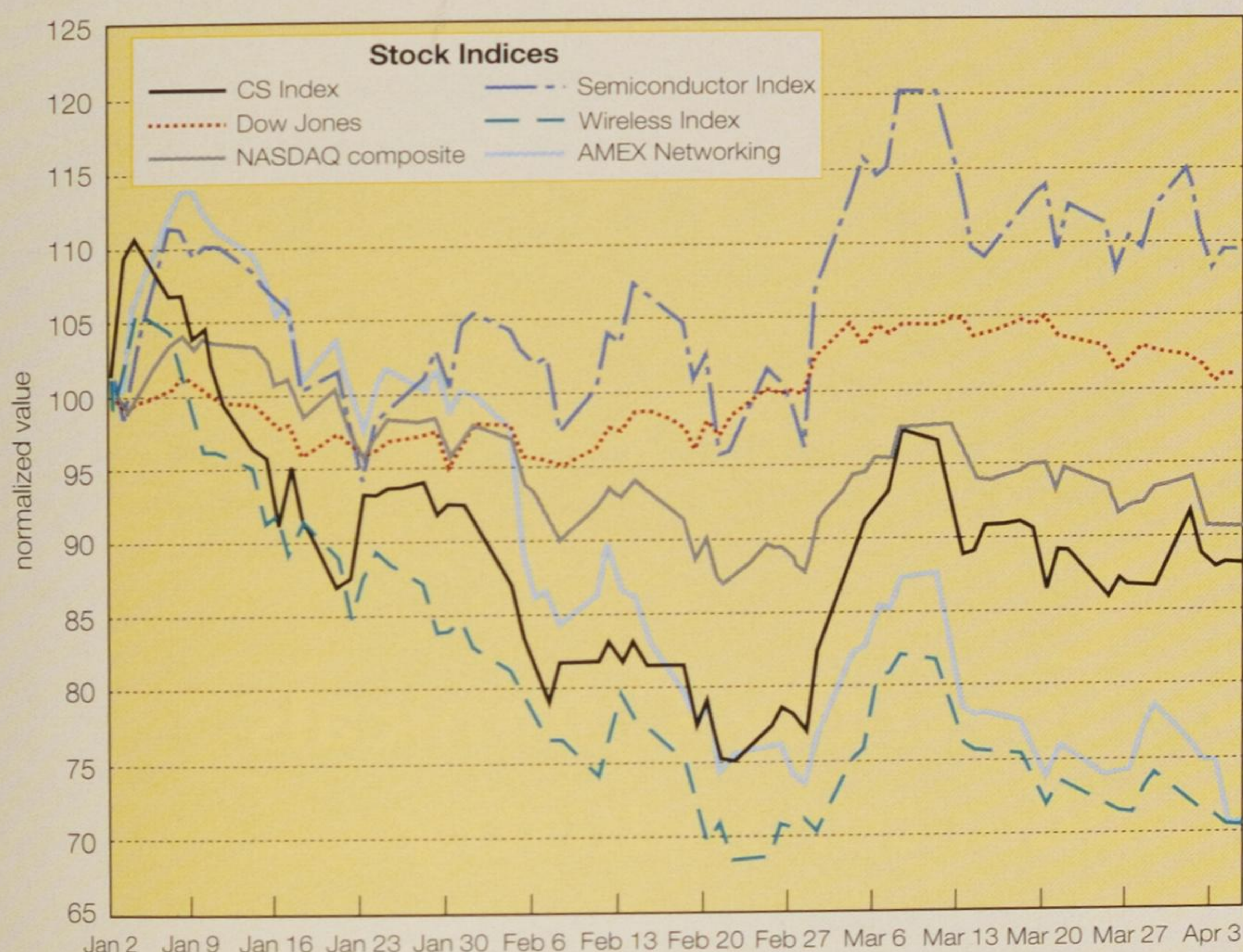
R&D spending at IQE (£ '000s)

Quarter	Revenue	R&D expense	R&D as % of revenue
Q4 '01	7696	894	12%
Q3 '01	8234	1602	19%
Q2 '01	13,158	757	6%
Q1 '01	12,959	539	4%
Q4 '00	10,478	458	4%
Q3 '00	6431	289	4%
Q2 '00	6857	578	8%
Q1 '00	6351	545	9%

IQE is also spending more on R&D. In the second half of 2001 R&D expenses were £2.5 m, just over 15% of sales. For the year, R&D spending more than doubled. One result is new products for the wireless market. Management reports that IQE's InP HBT wafers are now designed into several new products. However, the main focus of the R&D effort is the Motorola Three-Five on Silicon (TFOS) technology. Drew Nelson, CEO of IQE, said that "considerable" progress has been made in this area, and the firm is in discussions with "several large companies on early-adopter programs". IQE is the first licensee, with a 15 month exclusive agreement.

IQE's Wafer Technology division saw some recovery in demand for GaAs substrates in the fourth quarter, but not enough to compensate for the continuing lack of demand for InP wafers. The IQE Silicon Compounds division is now in the qualification process with 18 customers, and is also running pre-production orders for "some large European IC manufacturers".

Industry indices



Bede

Bede, wrapping up its first year as a publicly traded company, reported its results for 2001 on April 10. Revenues were up 35% to £6.6 m, with a pre-tax loss of £400,000 compared with a loss of £100,000 in 2000.

CEO Neil Loxley said that 54% of revenue came from the compound semiconductor market and 11% from silicon. A total of 65 characterization systems were delivered in 2001. The leading product with 26 units shipped was the QC200, a wafer-mapping X-ray diffractometer used largely for analyzing compound semiconductor wafers.

Bede also shipped two systems from its new "FAB" line of fully automated X-ray tools intended for the high-volume manufacturing of both compound and silicon semiconductors. Bede is the first company to attempt

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In the fourth quarter, IQE's management reported that they saw "definite signs of improvement" in the wireless market, with "significant" new production orders from customers.

Market overview

Company	Symbol	Closing price on April 12	52-week low-high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	13.65	13.50-41.45	603.7 m	N/A
Anadigics	ANAD	11.78	9.40-25.38	360.1 m	N/A
Celeritek	CLTK	9.74	8.95-16.91	118.5 m	N/A
Conexant	CNXT	10.88	6.57-18.11	2.781 bn	N/A
Endwave	ENWV	0.80	0.60-2.49	28.6 m	N/A
Multilink	MLTC	2.03	1.88-18.40	152.6 m	N/A
RF Microdevices	RFMD	18.15	9.16-37.50	3.038 bn	N/A
Sirenza Microdevices	SMDI	5.91	2.98-17.00	176.1 m	N/A
TriQuint	TQNT	11.25	8.90-32.73	1.475 bn	N/A
Vitesse	VTSS	8.23	6.65-39.20	1.648 bn	N/A
Opto companies					
Agilent	A	32.80	18.00-41.18	15.215 bn	N/A
Agere	AGRa	3.55	3.10-9.50	5.806 bn	N/A
Alcatel Optronics	ALAO	4.85	4.04-32.81	80.0 m	N/A
Coherent	COHR	33.59	25.05-45.55	963.3 m	47.99
Cree	CREE	12.90	12.40-36.65	936.7 m	N/A
JDS Uniphase	JDSU	5.38	4.74-29.50	8.128 bn	N/A
Stratos Lightwave	STLW	3.02	3.00-14.25	203.1 m	N/A
Uniroyal Technology	UTCI	0.55	0.27-10.11	15.4 m	N/A
Semiconductor materials and equipment companies					
ATMI	ATMI	30.38	14.50-32.73	926.1 m	N/A
AXT	AXTI	9.68	8.55-41.65	216.7 m	N/A
Emcore	EMKR	9.67	7.59-44.13	353.6 m	N/A
Kopin	KOPN	8.26	4.29-19.05	570.9 m	N/A
Tegal	TGAL	1.25	1.00-3.45	17.9 m	N/A
Trikon	TRKN	13.35	6.96-16.72	172.1 m	15.33
Veeco	VECO	33.69	19.90-57.50	978.2 m	60.18
European companies (currency data in €)					
Aixtron	AIXG.F	19.65	18.55-30.00	1.27 bn	38.26
Bede	BED.L	2.71	2.77-3.49	78.5 m	N/A
Bookham	BHM.L	1.55	1.55-3.01	219.85 m	N/A
Filtronic	FTC.L	5.98	4.94-7.36	440.1 m	N/A
IQE	IQE.L	1.91	1.71-3.20	313.2 m	97.08
Picogiga	PGIG.LN	3.80	3.41-5.95	24.55 m	N/A
Riber	RIBE.LN	3.40	3.10-5.40	63.65 m	24.13
STS	SRTS.L	2.56	149.00-173.00	80.21 m	N/A

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

to introduce X-ray characterization into the silicon industry, and the FAB tools, which are able to accommodate wafers up to 300 mm, are a major part of its forward strategy. Bede has a long-term agreement with "a major semiconductor manufacturer" (believed to be Intel) to supply up to 20 FAB300 systems over a 2-3 year period. The first system under this contract was shipped in January.

Bede has a confirmed order book of £1.8 m, not including the Intel order. While management says that this figure is "lower than that which the level of qualified prospects would normally imply", Loxley said, "Once general economic conditions improve, latent demand should generate significant continued revenue growth in 2002."

Riber

Revenues at Riber decreased 17% in 2001 to €34.2 m (\$30.1 m), compared with €41.2 m in 2000. However, Riber managed to stay in the black, reporting profits of €3.2 m compared with €7.0 m in the previous year.

Shipments of production MBE systems declined 26.4% compared with 2000, as a result of fewer orders for MBE6000 (multi-6 inch wafer) machines from the wireless market.

However, this was partially offset by increased deliveries of MBE49 (multi-3 or 4 inch) machines for optoelectronic applications. The company also saw component sales increase to €5.6 m, which was 16.6% of total sales. Sales of R&D systems accounted for 7.6% of total revenues.

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

International Conference on MOVPE

Berlin, Germany

Web: www.icmovpe-2002.de

3-7 June

IEEE MTT-S International Microwave Symposium

Seattle, WA, USA

Web: www.ims2002.org

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

24-25 June

Semiconductor 2002

Edinburgh, UK

Web: www.semiconductor2k.com

24-26 June

Device Research Conference

Santa Barbara, CA, USA

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

26-28 June

Electronic Materials Conference

Santa Barbara, CA, USA

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

8-12 July

7th Optoelectronics and Comms Conf.

Yokohama, Japan

Web: www.bcasj.or.jp/oecc2002

14-17 July

Optical Amplifiers and Their Applications

Vancouver, Canada

Web: www.osa.org/oaa

15-16 July

PhoPack 2002

Stanford University, Palo Alto, CA, USA

Web: www.cpmt.org/scv

17-24 July

Semicon West

San Jose, CA, USA

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

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.

Advertisers' Index

Addon	15	Japan Energy	39
Advanced Ceramics	20	Laytec	10
Aeronex	8	Microchem	53
Aixtron	5	Philips Analytical	12
Bandwidth Semiconductor	40	Praxair	34
Bede	IFC	PROWtech	18
Crystal Systems	38	QinetiQ	28
CS Clean Systems	19	Raboutet	56
CS-MAX conference and expo	7	Riber	52
DCA Instruments	OBC	Rohm & Haas	IBC
Dynatex	16	SAES Pure Gas	11
Electronic Materials Conference	22	Samco	18
Emcore	ii, 57	Solkatronic	14
EMF	54	Surface Technology Systems	47
Epichem	60	Tekcore	4
III-V Reclaim	24	Thermo VG Semicon	31, 33
Indium Corporation of America	46	Thomas Swan Scientific Equipment	51
Integrated Systems Engineering	4	Trikon	42, 43
IntelliEPI	28	Unaxis	27
IQE	36	Veeco-Applied Epi	48
Insaco	40	Wafer Technology	37

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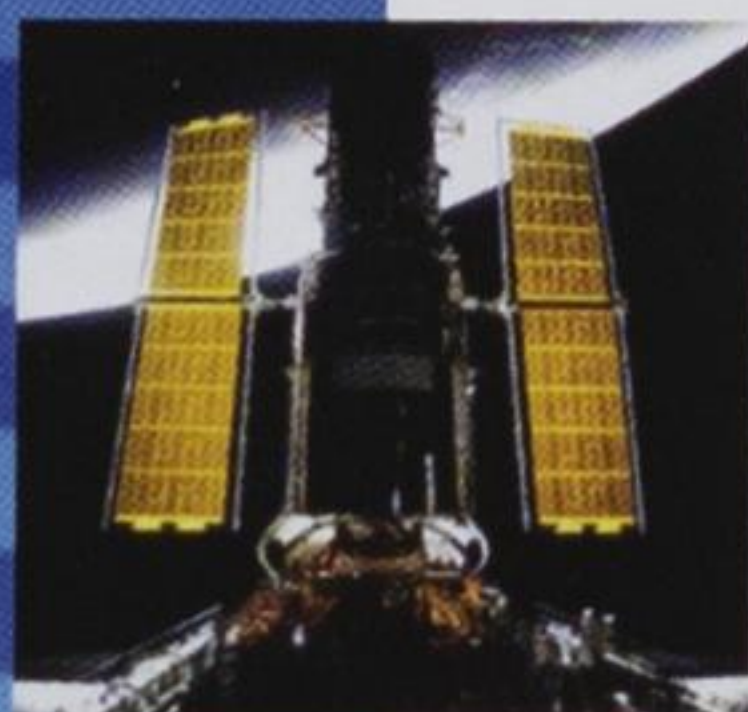
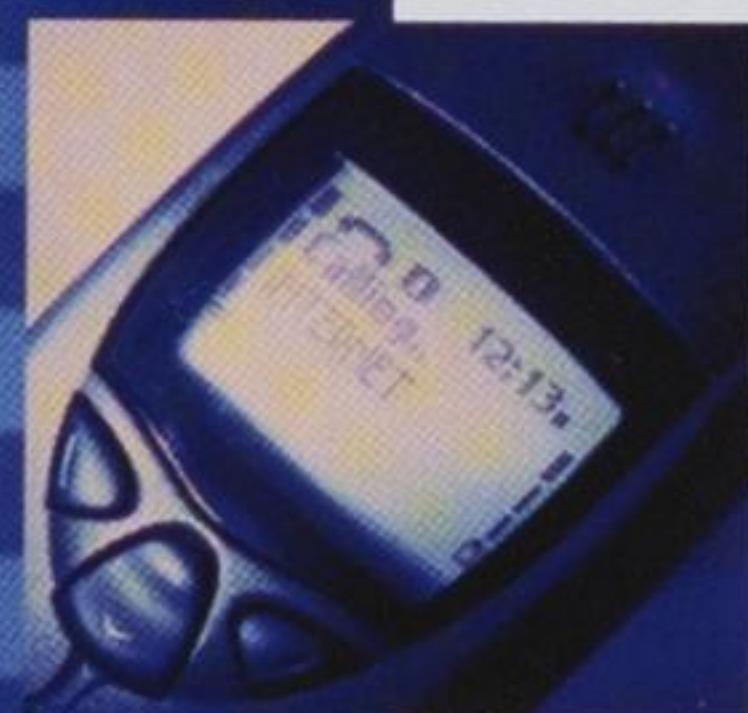
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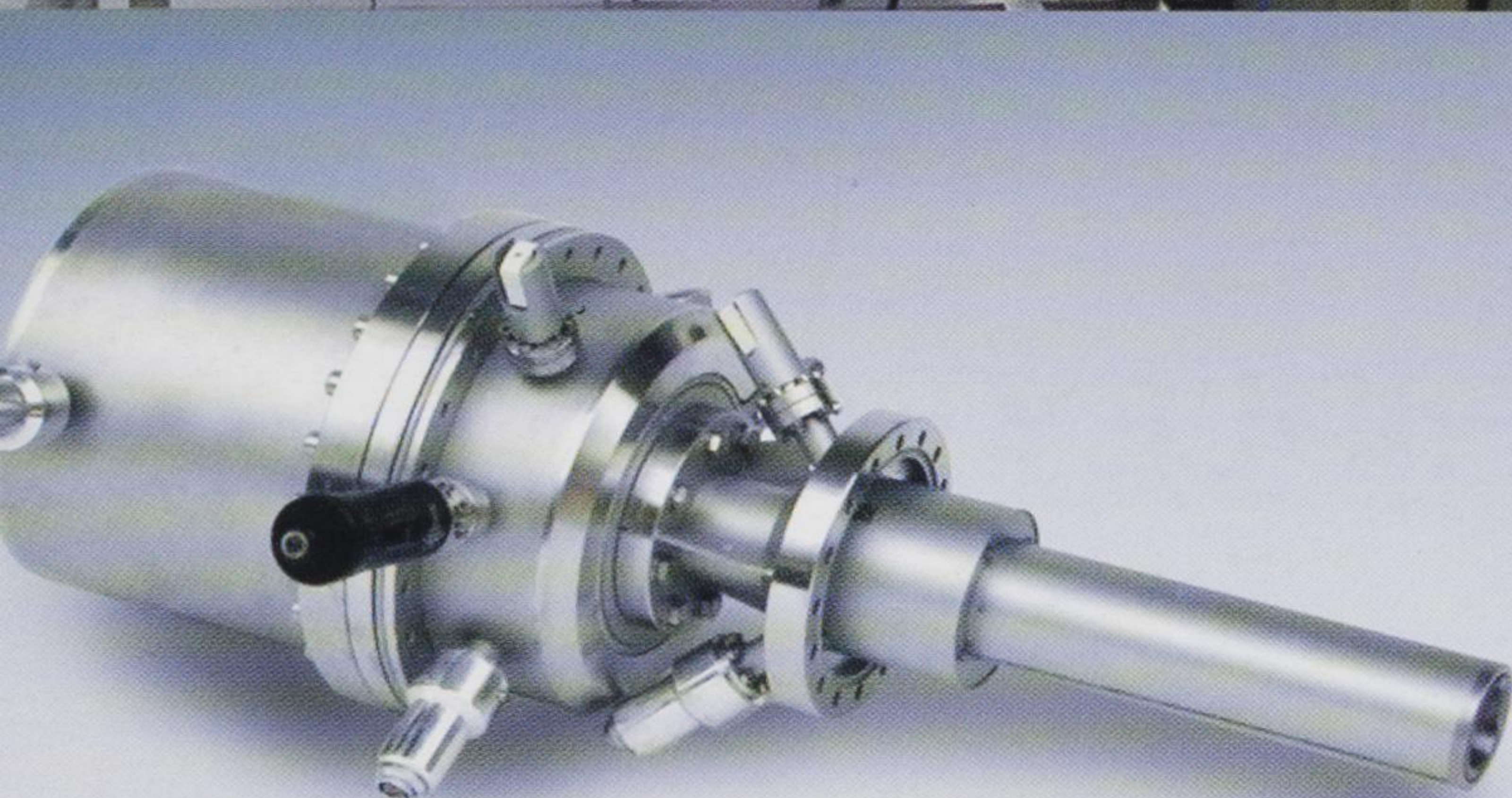
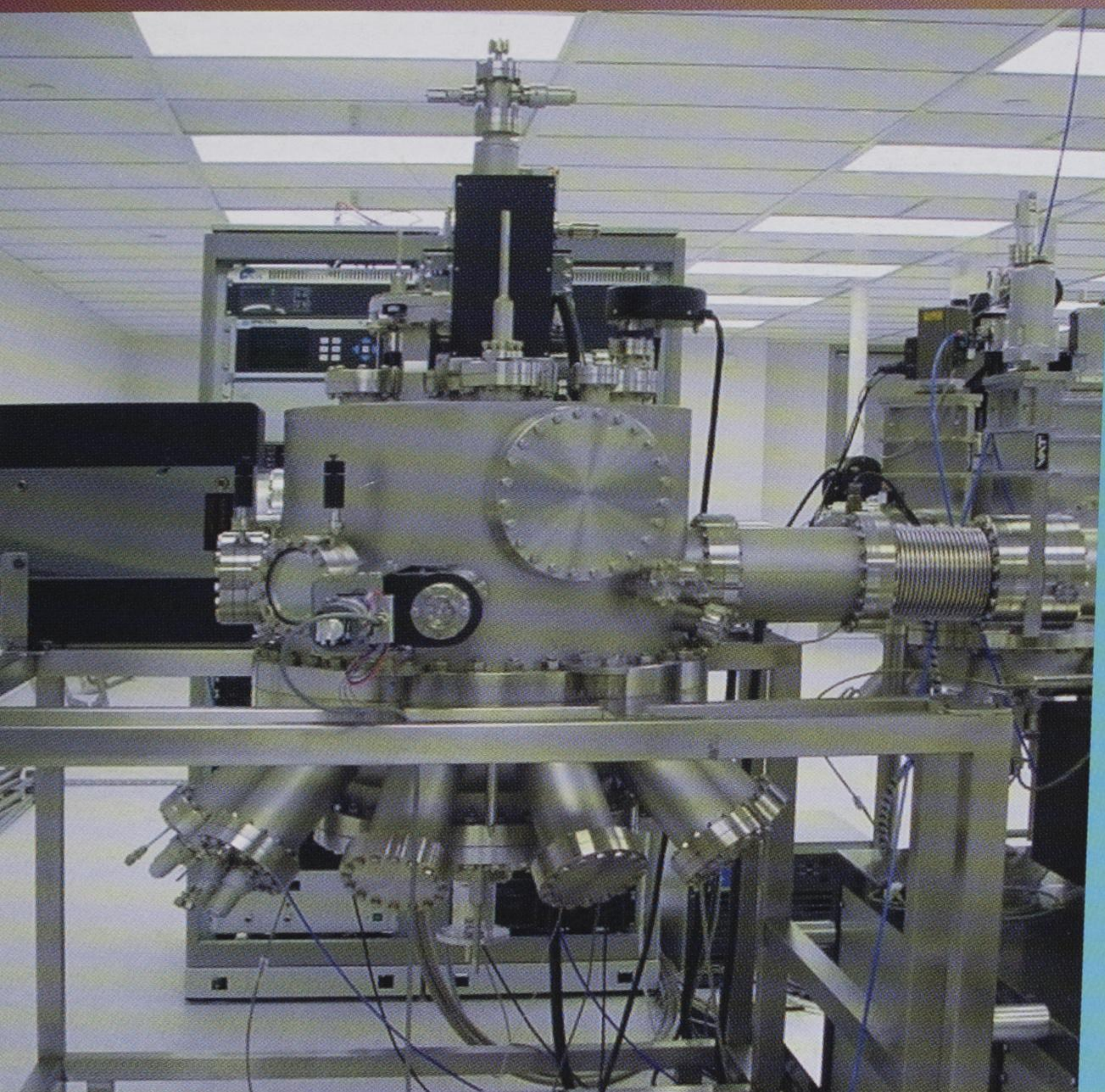
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