

COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

December 2002 Volume 8 Number 11



LIGHT-EMITTING DIODES
**Patent agreements, metal
bonding and laser scribing**

ALSO INSIDE

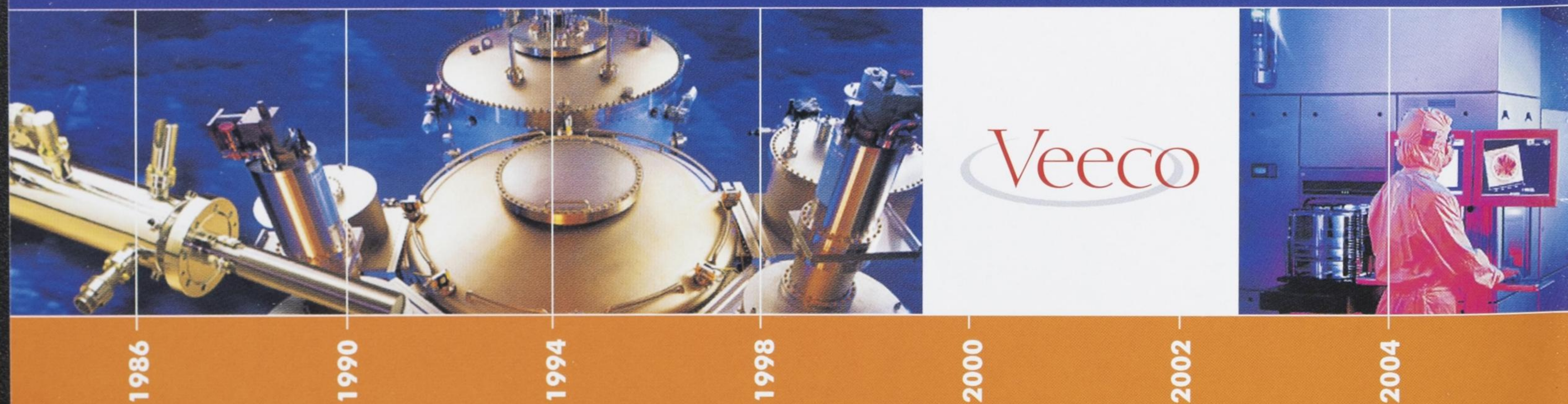
**Vitesse exits GaAs
manufacturing**

**Silicon LEDs
challenge GaAs**

**TriQuint buys
Agere's opto unit**

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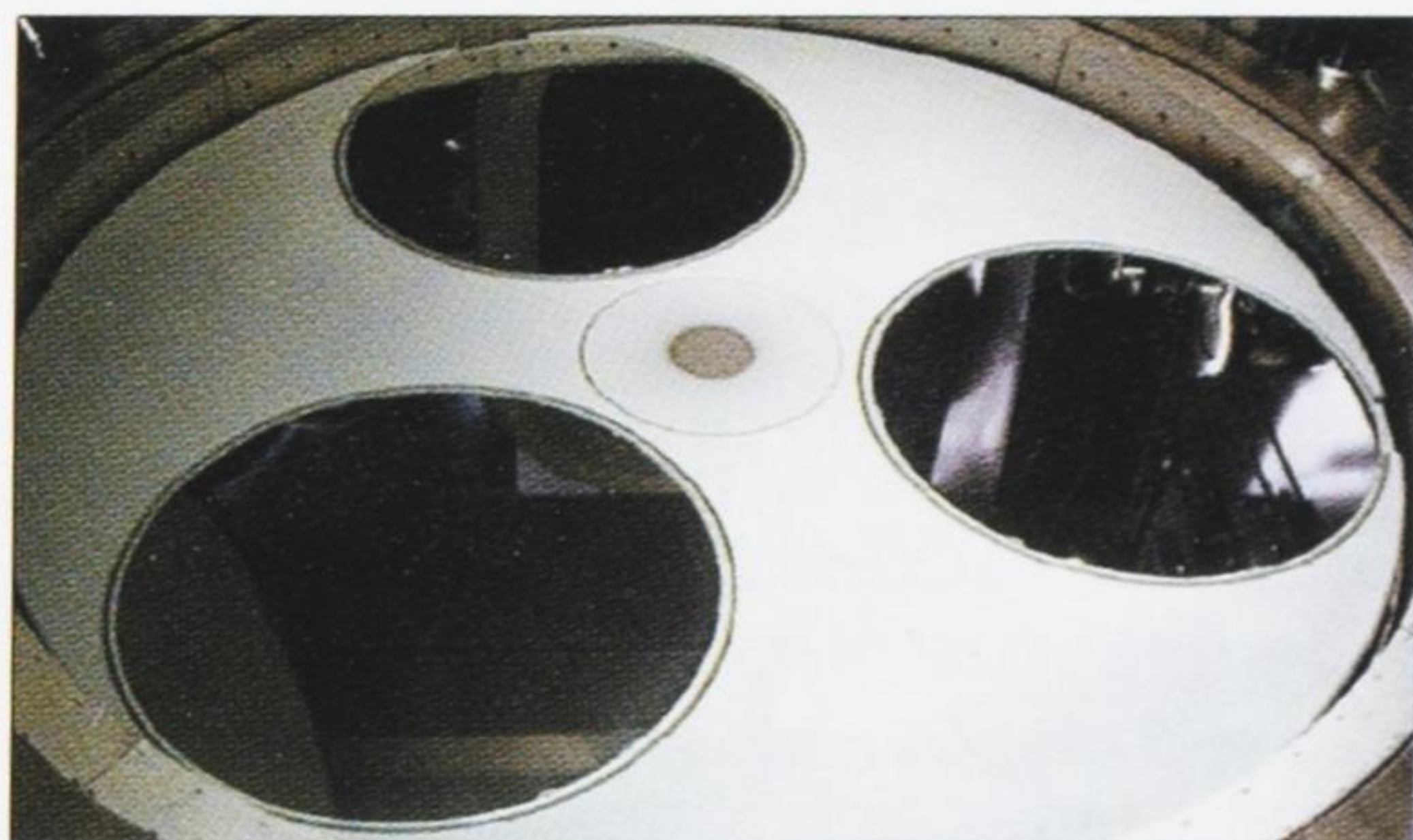
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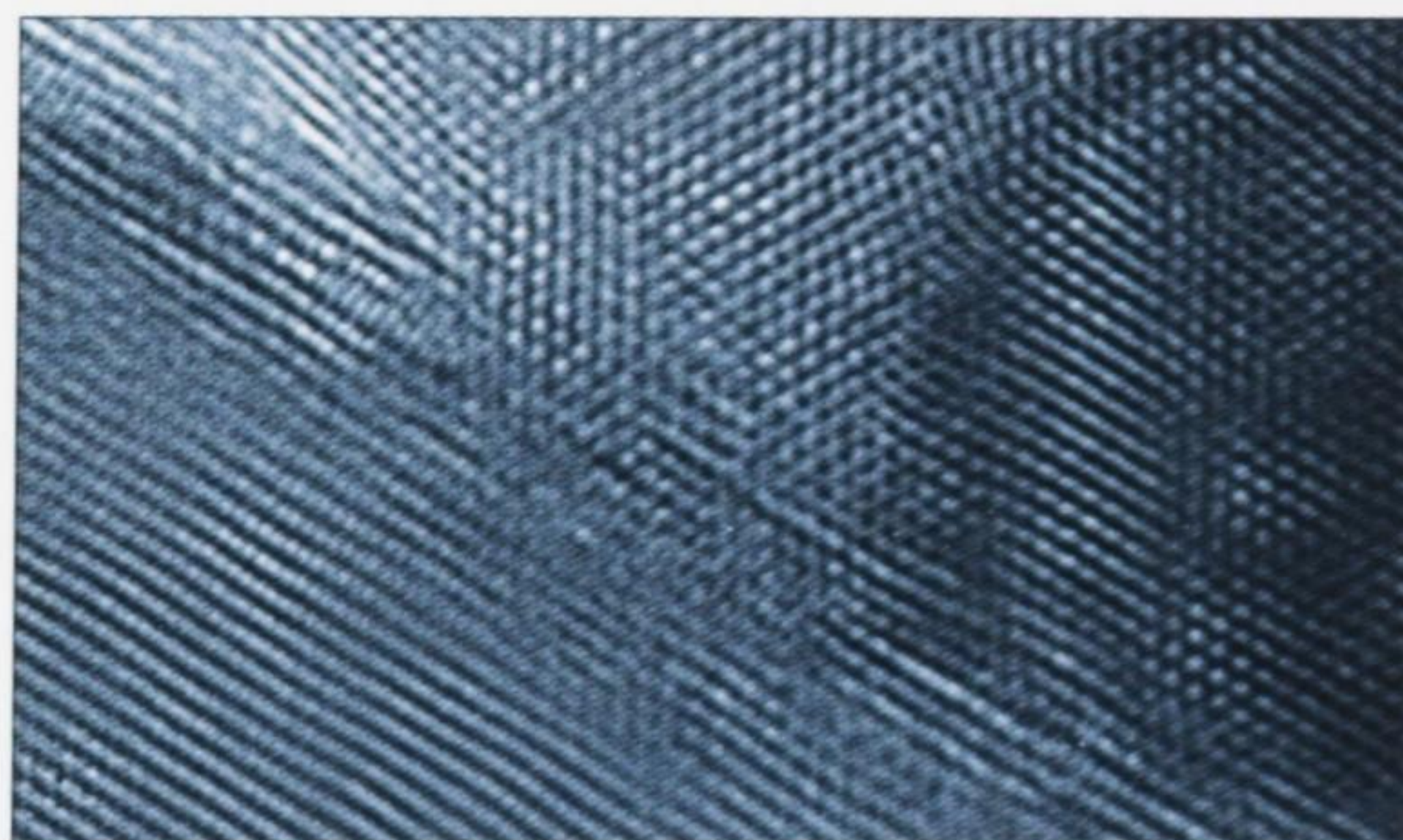
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Three-Fives and Silicon Heterostructures

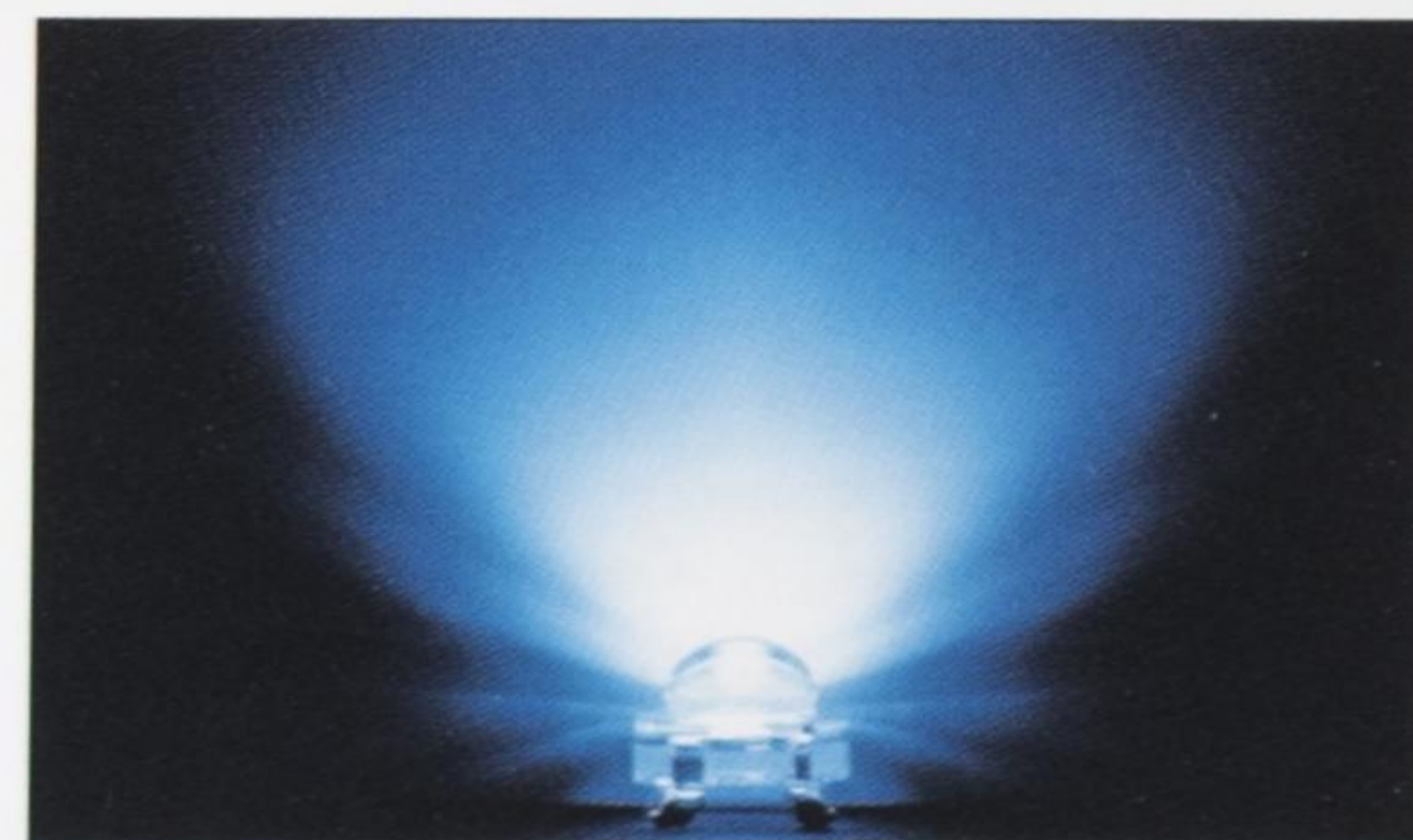
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On the cover: UV laser dicing is helping to raise yields and lower the production costs of GaN-based LEDs – see p29.

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SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

Editor Tim Whitaker
tim.whitaker@iop.org
Tel. +44 117 930 1233; Fax +44 117 925 1942

Technology editor Jon Newey
jon.newey@iop.org
Tel. +44 117 930 1192

Contributing editor Robert Metzger

Managing editor Marie Meyer
marie.meyer@iop.org
Tel. +44 117 930 1034

Publisher Geraldine Pounsford
geraldine.pounsford@iop.org
Tel. +44 117 930 1022

Advertising manager Dan Huckle
dan.huckle@iop.org
Tel. +44 117 930 1032; Fax +44 117 930 1178

Advertising sales executive Joanna Hook
joanna.hook@iop.org
Tel. +44 117 930 1033; Fax +44 117 930 1178

Production editor Ruth Aspinall
Ad production Rachel Sermon/Joanne Scriven
Circulation Laura Serratrice-Thomas
Art director Andrew Giaquinto
Technical illustrator Alison Tovey
Publishing director Richard Roe

Subscriptions

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Editorial board

Colombo Bolognesi Simon Fraser University (Canada); **Steven DenBaars** University of California at Santa Barbara (USA); **Andrew Johnson** QinetiQ (UK); **Robert Metzger** Georgia Institute of Technology (USA); **Rodney Moss** Agilent Fiber Optic Components (UK); **Shuji Nakamura** University of California at Santa Barbara (USA); **Dwight Streit** TRW (USA); **Toby Strite** JDS Uniphase (Switzerland); **Jacob Tarn** Epistar (Taiwan); **Gary Tomkins** Nortel Networks (Canada); **Andreas Waag** University of Ulm (Germany); **Gary Wicks** University of Rochester (USA); **Peter Zory** University of Florida (USA)

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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for \$95 by Institute of Physics Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Middlesex, NJ 08846. POSTMASTER: send address corrections to Compound Semiconductor, c/o PO Box 177, Middlesex, NJ 08846. US agent: Pronto Mailers Association Inc, 200 Wood Avenue, PO Box 177, Middlesex, NJ 08846.

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TriQuint buys Agere's opto business

By Tim Whitaker

TriQuint Semiconductor is to acquire a substantial portion of Agere Systems' optoelectronics business for \$40 million in cash, positioning the company as a supplier of both ICs and optoelectronic components. The move comes after Agere's announcement in August that it was seeking a buyer for all or part of this business, and that it was exiting the optoelectronics business as part of a corporate restructuring effort (see *Compound Semiconductor* September 2002 p3).

The transaction includes certain facilities, technology and products, including lasers, detectors, modulators, passive components, amplifiers, transmitters, receivers, transceivers, transponders and MEMS devices. The agreement does not include Agere's CATV transmission systems business, which is based in Alhambra and Irwindale, CA. Agere is continuing to look for a buyer for this business.

The Agere deal is the third major acquisition for TriQuint this year, after the company snapped up Infineon's GaAs IC business and selected parts of IBM's SiGe IC business. However, some analysts have expressed concern that TriQuint may have too much on its plate at the moment. "We believe that TriQuint's management may get distracted

at the risk of losing focus on strengthening its wireless business," said Dale Pfau of CIBC World Markets.

According to Ralph Quinsey, president and CEO of TriQuint, the acquisition makes TriQuint one of the world's leading suppliers of optical components and modules. "Clearly the market has been under a lot of pressure over the past two years, but we believe that this acquisition will position us for substantial revenue growth and profits when the market recovers," he said. "The consolidation of the operations and the restructured workforce will greatly reduce our costs compared with Agere's previous experience. We are extremely excited about this opportunity."

In the September 2002 quarter, Agere's revenue from its optoelectronics business was \$38 million, a drop of 39% compared with the previous quarter. For Agere's fiscal year ended September 30, 2002, the business TriQuint is acquiring had revenue of approximately \$192 million. TriQuint estimates that the business will generate between \$50 million and \$75 million in revenue for calendar year 2003, and is projecting that it will add to TriQuint's earnings per share by the fourth quarter of 2003.

As part of the deal, approximately 300

Agere staff working in R&D, process engineering, marketing, product management and assembly will join TriQuint. The companies anticipate closing the sale in early January 2003, subject to regulatory approval and other customary closing conditions.

Through a transitional manufacturing agreement, Agere will supply components for TriQuint for a short period following the close of the transaction, to ensure continued service to customers. Agere currently manufactures the majority of its components in a facility at Breinigsville, PA, which TriQuint will acquire after the transition period. TriQuint will also acquire the back-end assembly and test operations at Agere's facility in Matamoros, Mexico.

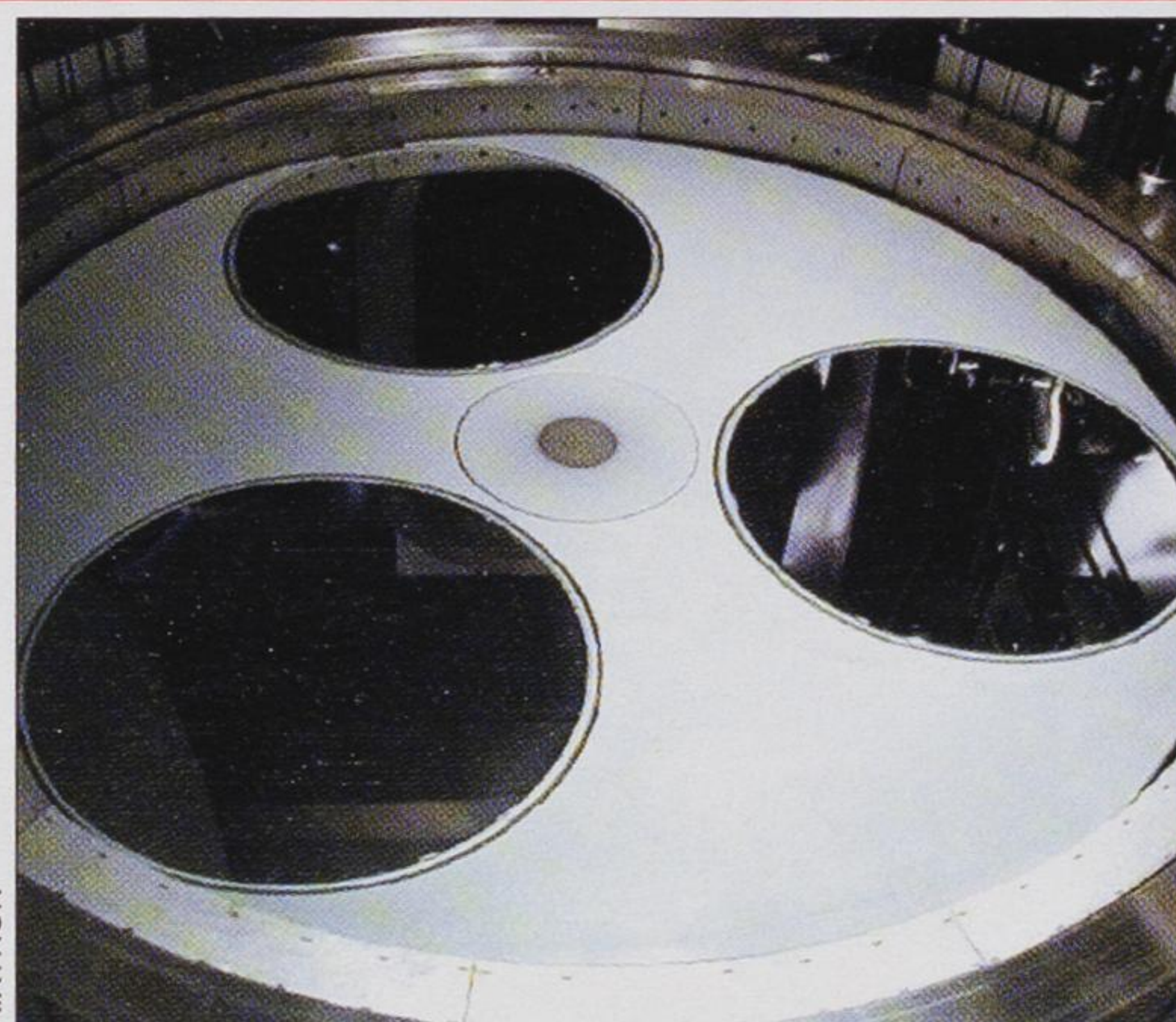
● TriQuint reported that its revenue for the September 2002 quarter was \$71 million, up 16% compared with the previous quarter. The company also recorded a gross profit margin of 35.4% and a net loss of \$9.2 million, or 7 cents per share. TriQuint said that the growth was driven largely by revenue from acquired businesses and strength in its new products for wireless phones. The company estimates that its revenue will grow slightly in the December 2002 quarter, and should be in the range of \$71 million to \$75 million.

Aixtron scales up to enable 8 inch GaAs epiwafer growth

By Jon Newey

MOCVD equipment manufacturer Aixtron has successfully grown epitaxial structures on 8 inch GaAs wafers supplied by Freiburger Compound Materials. Aixtron used numerical modeling techniques to scale up its existing multiwafer AIX 2600G3 machine to a multiwafer 8 inch configuration for the growth of GaAs-based structures. The company has already installed a number of AIX 2600G3 systems with customers for SiGe epitaxy on 8 inch Si wafers.

Aixtron provided the details of its 8 inch GaAs epitaxy in a late news paper at CS-MAX,



Aixtron has successfully scaled its AIX 2600G3 reactor to give a 3 x 8 inch configuration. The company says that its results from 8 inch wafers do not differ significantly from those on its established multiple 6 inch wafer platforms.

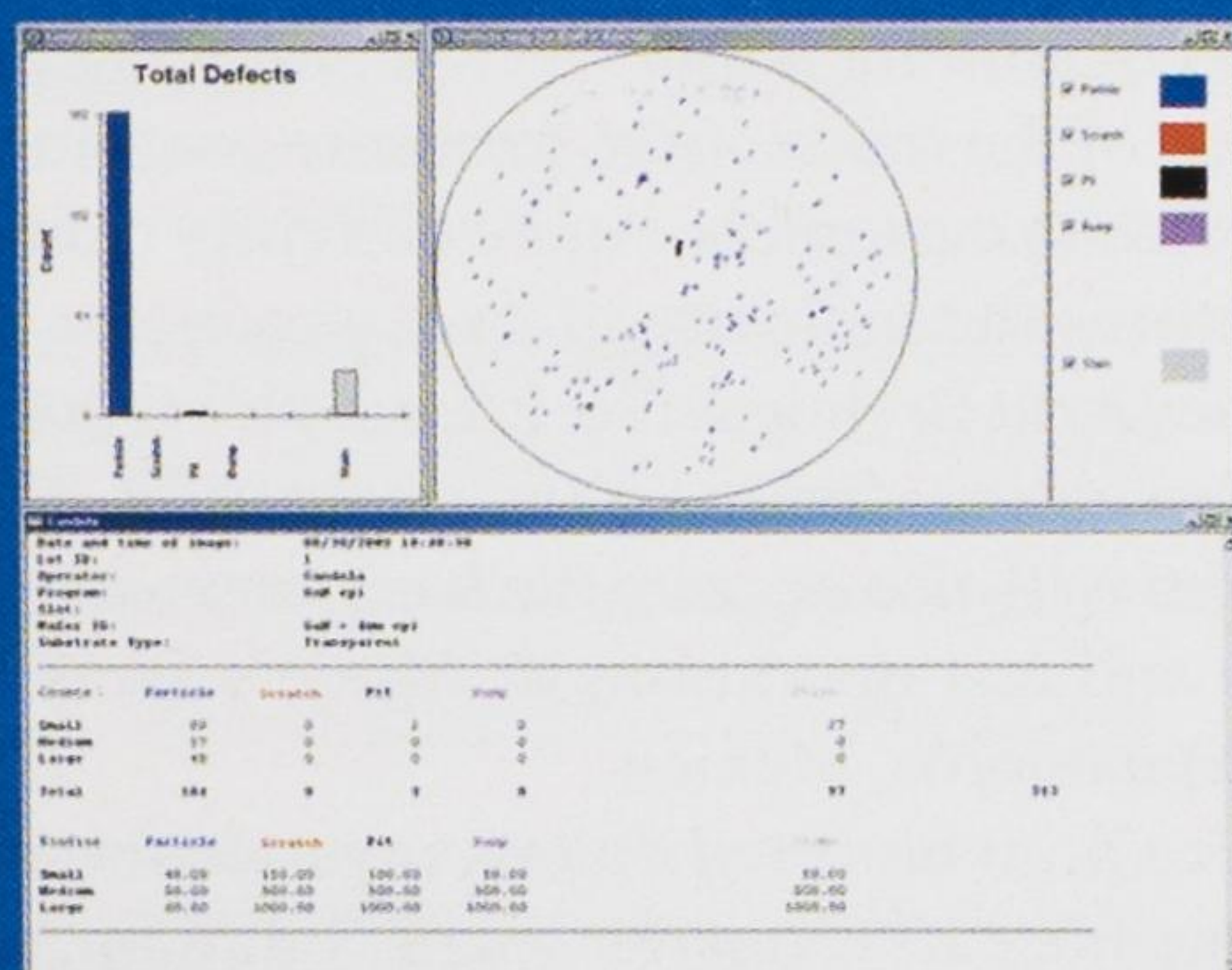
which was held November 11-13 in San Jose, CA. The company says that material quality and homogeneity for its 8 inch epitaxy does not differ significantly from the results obtained on its well established 6 inch systems. Uniformities of 1% have been achieved for AlGaAs layer thickness and Al composition across an entire 8 inch wafer.

Aixtron has also grown AlAs/GaAs DBR structures using the 3 x 8 inch system, with the modeled data for variation in growth rate across an 8 inch wafer agreeing with data obtained from actual growth runs very well. The thickness variation for a single AlAs/GaAs pair was 1% and the variation in Al content was less than 0.5%.

In recent years, a number of GaAs IC manufacturers converted from 4 inch to 6 inch process lines as production volumes of GaAs-based RFICs rose with the demand from >>

Nichia has signed separate patent agreements with Cree and Lumileds – see page 22

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applications such as mobile handsets. With the rise in demand came a need to reduce the selling prices of chips, forcing GaAs IC manufacturers to reduce production costs and increase productivity by moving to 6 inch wafers. Moving up from 6 inch to 8 inch wafers gives a further 1.8x increase in wafer area, allowing more large-area circuits to be made on a single wafer. The good epitaxial uniformity demonstrated by Aixtron is essential as it minimizes wafer-edge exclusion and gives higher on-wafer yield for large-area devices.

At CS-MAX, both Freiburger and Hitachi Cable were showcasing their 8 inch GaAs

substrates, although at present demand for these is almost non-existent. The move to GaAs IC production on 8 inch wafers is some way off, but Aixtron and others are still preparing for this eventuality.

"We are convinced that 8 inch GaAs will soon become the new standard for high-volume manufacturing, especially in the field of high-frequency electronics," said Bernd Schulte, executive VP and COO of Aixtron. "The continuous efforts of the compound semiconductor industry to increase its productivity will require larger substrates. Thus we decided to develop an MOCVD tool for 8 inch wafers as early as possible."

Vitesse planning to exit GaAs manufacturing business

By Tim Whitaker

Vitesse Semiconductor, the first company in the world to build and operate a 6 inch GaAs fab, is to exit the GaAs manufacturing business. The company plans to phase out its 6 inch GaAs fab in Colorado Springs, CO, by fall 2003, potentially through partnering with a foundry company.

The decision is part of Vitesse's ongoing transition from being a GaAs IC manufacturer working in the long-haul fiber-optic transport market, to being a broad-based fabless designer of CMOS products targeting markets such as storage and enterprise networks. These accounted for 70% of Vitesse's revenue in the September 2002 quarter, while the long-haul telecom market is now less than 15% of its business, down from 70% in the September 2000 quarter.

According to Lou Tomasetta, Vitesse's president and CEO, the Colorado Springs fab is operating at 10% utilization. "Even if we saw a complete recovery in the long-haul market by 2004, we would never be able to fill that fab again," he said. Instead, Vitesse is exploring all options for the fab, with a view to exiting the GaAs fabrication business during its current fiscal year, which ends September 30, 2003.

"We feel that the best option for our customers and employees at the fab is to team with a company that wants to operate a GaAs foundry strategy," said Tomasetta. "Vitesse would continue to buy products, but the foundry would find other customers and potentially bring other GaAs-like technologies into the fab." This might perhaps include

HBT- and/or PHEMT-related technologies; Vitesse's GaAs products are manufactured using the company's MESFET process.

GaAs products are no longer in production at Vitesse's 4 inch fab in Camarillo, CA. Instead, this facility hosts an InP activity, which the company describes as being in research mode with about 15 engineers. "With a combination of foundry customers and DoD grants, the facility is paying for itself as we develop the technology and various optical products," said Tomasetta.

Vitesse has also developed 40 Gbit/s electronic products, for which there is no market. "These are great products, but nobody cares," said Tomasetta, who added that by the time the 40 Gbit/s market picks up, the necessary products will probably be manufactured using 90 nm CMOS processes.

CMOS already accounts for 81% of Vitesse's total revenue, and that proportion will continue to increase. The move to a fabless model is therefore inevitable. "For a company like Vitesse, the only reason to have a fab is to do things you can't do with CMOS," explained Tomasetta.

Developing products using GaAs allowed Vitesse to reach the market two to four years earlier than companies that were relying on CMOS. However, CMOS always catches up, except for products such as optical devices (e.g. lasers and detectors) that will continue to require InP. While Vitesse designed its first 10 Gbit/s products using GaAs, these are all moving to CMOS. "If you can do it with CMOS, you have to do it with CMOS," said Tomasetta.

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European Headquarters Aachen · Germany
AIXTRON AG · Kackertstrasse 15-17 · 52072 Aachen
Phone: +49 (241) 89 09-0 · Fax: +49 (241) 89 09-40
E-mail: info@aixtron.com · www.aixtron.com

US Headquarters Chicago, IL
AIXTRON Inc. · 1670 Barclay Blvd. · Buffalo Grove · IL 60089
Phone: +1 (847) 215 - 7335 · Fax: +1 (847) 215 - 7341
E-mail: usinfo@aixtron.com

AIXTRON Korea AIXTRON cshs
4F, Korea Exchange Bank B/D · 358-1, Yatap-Dong
Bundang-Ku, Sungnam City · Kyoungki-Do, 468-828
Phone: +82 (31) 703 - 51 00 · Fax: +82 (31) 703 - 51 10
E-mail: koreainfo@aixtron.com

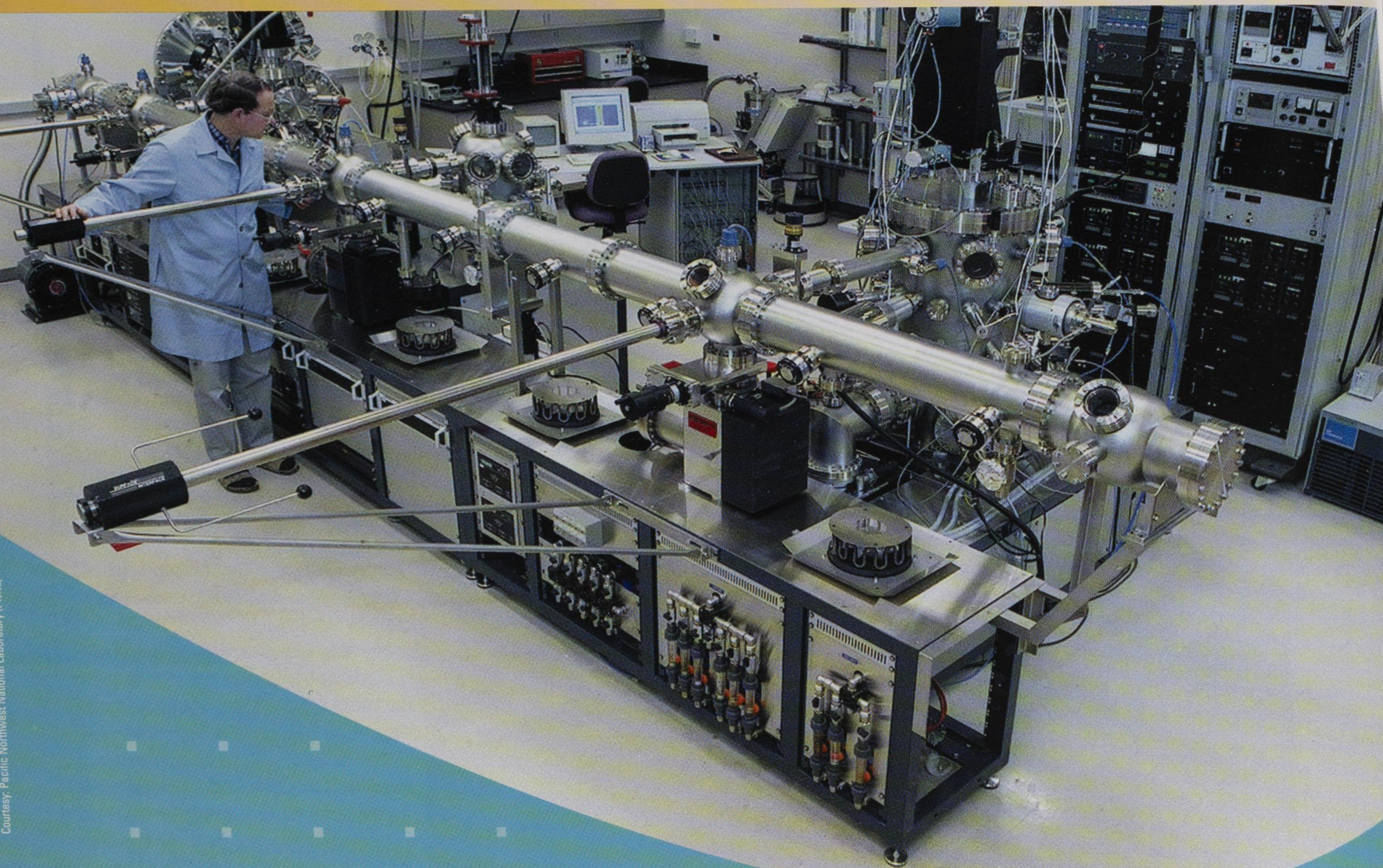
AIXTRON Japan Moritani & Co., Ltd · 8th Machinery Dept. · 1st Business Group
1-4-22 Yaesu, Chuo-Ku · Tokyo 103-8680
Phone: +81 (3) 32 78 - 61 31 · Fax: +81 (3) 32 78 - 60 03
E-mail: m8info@moritani.co.jp

AIXTRON Taiwan Challentech International Corp.
Pateh Road No. 1 · Lane 9 · Hsin-Chu, 300
Phone: +886 (3) 56 14 - 211 · Fax: +886 (3) 56 11 - 194
E-mail: hoton@challentech.com.tw

AIXTRON China AIXTRON AG · Shanghai Branch
Kuen Yang Building, Rm 1204
Zaojiabang Rd. 798 · 200030 Shanghai
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INSTRUMENTS

Umicore pulls out of Picogiga deal

By Jon Newey

The recent agreement that would have seen Belgian materials company Umicore acquire a significant stake in French epiwafer manufacturer Picogiga has fallen through. On October 28, Umicore decided to withdraw from the agreement, leaving Picogiga in a difficult position. Picogiga is carrying significant debt and has suffered a large drop in revenues. The deal would have seen Umicore acquire up to 47% of Picogiga, securing the cash-strapped company's immediate future (*Compound Semiconductor* November 2002 p6).

The successful conclusion of the deal relied on three conditions being met. The first two were agreed upon, namely short-term restructuring of the debt and the disposal of Picogiga's holdings in Swedish optical component manufacturer Modulight. Umicore's withdrawal centers upon the third condition, which involved the tax implications of the deal for Umicore. Part of the agreement meant that convertible bonds worth €38 million (\$38 million) would be converted into €4 million worth of Picogiga stock. The value of the additional shares would have placed a tax burden on Umicore, and it is the level of this taxation that Umicore apparently had an issue with.

"We do not agree with Umicore's decision because the amount of tax payable is small compared with the total cost of financial restructuring," Linh Nuyen, Picogiga's president told *Compound Semiconductor*. "The payable tax would be €1-1.5 million, compared with restructuring costs of €40-45 million."

However, Umicore's CFO, Marc Grynberg, thinks that Picogiga underestimated the size of the tax bill, and also thinks that a comparison of the tax bill with the overall

restructuring cost is irrelevant.

"What is relevant is the comparison of the tax impact with the amount of fresh cash injected into the company," said Grynberg. "The size of our investment was to be €5.5 million, and if a substantial part of that is eaten up by tax then the deal makes little sense. This is why this [tax issue] was specifically included as one of the closing conditions."

Picogiga is citing the disposal of its interest in Modulight as being the focus of a claim against Umicore for financial reparations. "Umicore asked us to sign an agreement to withdraw from Modulight business," said Nuyen. "We originally invested €7 million in Modulight and we sold this [share] back to Modulight for €1." Any award from Umicore for financial damages will give Picogiga time to find another solution and restart the debt financing processes that were interrupted by the Umicore agreement.

Umicore is making no secret of its desire to expand its materials and substrates business, but this is the second time this year that its attempt to do so by acquisition has run into trouble. Earlier this year, Umicore began negotiating to buy Sterling Semiconductor, a subsidiary of Uniroyal Technology involved in SiC substrate manufacturing. In that case, Umicore found something during the due diligence process that caused it to withdraw from the deal. However, this did not prevent Umicore from going ahead with its SiC plans (*Compound Semiconductor* November 2002 p21).

"It's not necessarily the case that because a deal does not work out we abandon our expansion or growth vision. We are still looking at ways of expanding our substrate manufacturing business," said Grynberg.

In brief...

Thoughtbeam closed down

Motorola has shut down its Thoughtbeam subsidiary, citing poor prospects for generating revenue on a reasonable timescale. Thoughtbeam planned to commercialize GaAs-on-Si technology (see *Compound Semiconductor* December 2001 p3), but found that defect levels were too high to make reliable and reproducible devices. The development activity is still ongoing at a low level through an agreement with IQE.

ADC shuts laser facilities

Following its announcement of plans to exit the optical components business (see *Compound Semiconductor* September 2002 p3), ADC has now ceased operations at its pump-laser manufacturing facility located in Vadnais Heights, Minnesota (formerly Spectracom), and at its tunable-laser manufacturing facility located in Jarfalla, Sweden (formerly Altitun).

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Cree reports huge surge in LED sales

In the September 2002 quarter, Cree's LED sales increased by 54% over the previous quarter to reach record levels. This was fueled by new design wins in a number of applications, including cell phones. Average selling prices increased by 4%. Driven by these figures, the company's revenue in the September quarter was \$48.8 million, the second-highest quarterly figure in Cree's history. The revenue figure represents a 29% increase sequentially over the June 2002 quarter, and a 13% increase compared with the September 2001 quarter.

The level of demand is such that Cree is now struggling to ramp up its capacity. In less than two quarters, Cree has moved from a situation of low demand to one of being capacity-constrained. "Our challenge has shifted to managing our capacity expansion to fulfill increased customer demand requirements," said Chuck Swoboda, president and CEO of Cree. "We grew so fast in the last quarter that all the excess capacity we had was used up. The bottleneck is our entire factory. We need to make more SiC wafers, grow more epi on them, and fabricate and test more devices." Also, Cree has recently gained several new large customers, and has

had to adapt its production capabilities to meet the specific performance requirements of each of these customers.

Due to continued demand, particularly for handset applications, Cree expects to ship "significantly higher volumes" of LEDs in the December quarter. "Orders for the quarter already exceed our current capacity," said Swoboda. Cree is targeting a revenue increase of around 5% to \$51 million in the December quarter, and hopes to see continued sequential growth in the March 2003 quarter, which Swoboda says will be limited not by demand but by the company's ability to expand.

During the quarter, 48% of Cree's LED revenue came from handsets, in which LEDs are used as backlights for screens and keypads. A further 24% of the total revenue came from blue, green and white LEDs for automotive interior lighting, particularly in European and Asian models. A further 11% came from displays, traffic signals and signage, and 17% was from general indicators, including gaming equipment.

Most of Cree's revenue came from mid-brightness chips, including the MegaBright, UltraBright and high-brightness products, which together accounted for 89% of sales.

Standard products made up 9% of sales, while top-range XBright chips accounted for the other 2%. The XBright chip went through some modifications before the first products were shipped to customers during the September quarter. Cree was forced to write-off some inventory (and charge it as an R&D expense of \$1 million) for first-generation devices that were never qualified by customers due to a packaging problem. "The chip has always worked, but it didn't offer a practical solution for our customer's packaging schemes, and so it has now been modified to fit these packaging needs," explained Swoboda.

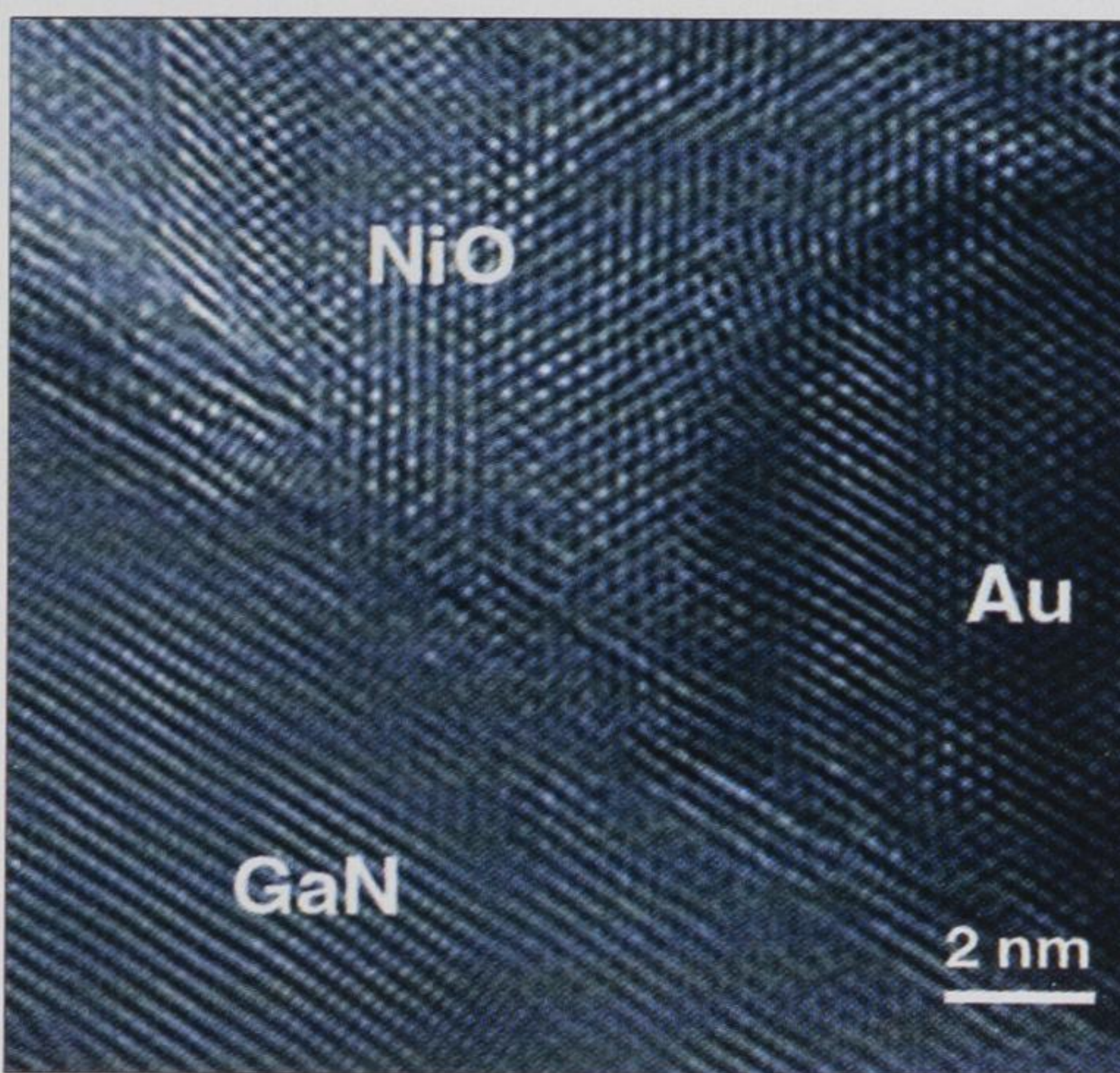
As well as raising the bar in terms of performance by introducing the XBright chip, Cree is at the same time trying to decrease the price/performance ratio. "We introduced XBright at around the price of the [lower performance] MegaBright product," said Swoboda. Cree also competes in certain high-volume, low-price segments of the market, particularly against emerging manufacturers in Asia. "The Taiwan approach is aggressive pricing," added Swoboda. "The key question is this: are any of these companies making money with their current price structures? Cree is."

Kopin announces novel ohmic contact technology for GaN LEDs

Kopin, in collaboration with North Carolina State University (NCSU), has developed a new ohmic contact technology for GaN that gives highly stable, low-resistance contacts. Details of the new Au/Ni/Au contact, which is formed epitaxially on GaN, were the subject of a paper in the November 18 edition of *Applied Physics Letters*. This is the first time that epitaxial contacts have been formed on GaN.

The new ohmic contacts, together with the previously announced NanoPocket technology, are the key to producing Kopin's CyberLite blue LED chips, which are as bright as others commercially available, but that require less than 2.9 V drive voltage at 20 mA (*Compound Semiconductor* September 2002 p11). The standard voltage for commercially available blue LEDs is 3.3 V.

The Au/Ni/Au contacts have lower resistance than conventional contacts because they



TEM cross-section of a Au/Ni/Au contact. Au is deposited by domain-matching epitaxy. Ni is deposited epitaxially over the top and sides of the Au, and annealed to form NiO. The result is NiO in contact with both GaN and Au.

are deposited epitaxially by electron-beam evaporation and are not polycrystalline. Two Au (224) planes match a single (2110) plane of GaN very closely. The Au can therefore grow on GaN by a process called domain-matching epitaxy, where integral multiples of lattice planes match across a film-substrate boundary. Ni is deposited on the Au epilayer followed by the top Au layer. The contact is then annealed in air, during which the bottom Au layer forms islands and the Ni is oxidized. The NiO forms epitaxially on the gold, as the two materials have a very close lattice match. NiO grows laterally over the Au as well as vertically so that after annealing the NiO is in direct contact with the GaN (see figure), resulting in a lower potential barrier and low-resistance ohmic contacts.

A contact resistance of approximately $10^{-5} \Omega\text{cm}^2$ has been measured, and lower values are expected as the layer thicknesses and the annealing conditions are refined. The contact is also very rugged, and is stable enough to endure high-temperatures (350 °C for 30 minutes) and extended harsh operating conditions.

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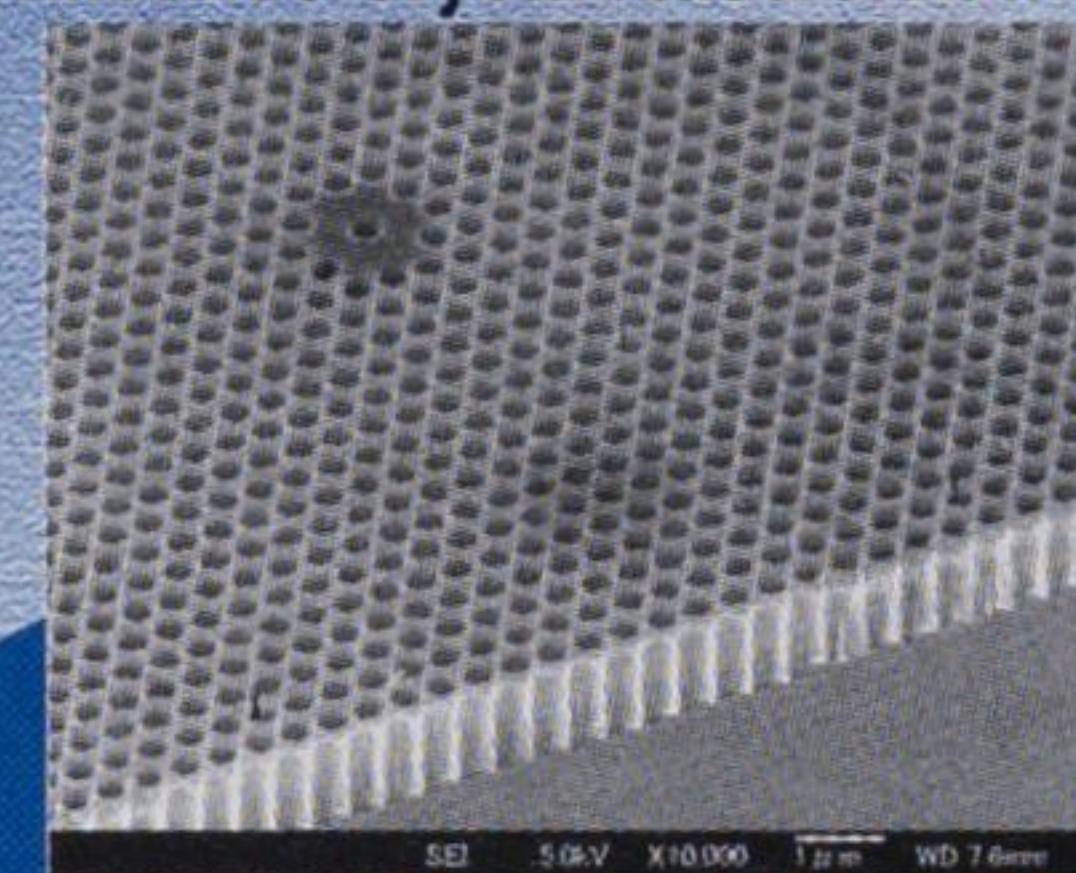
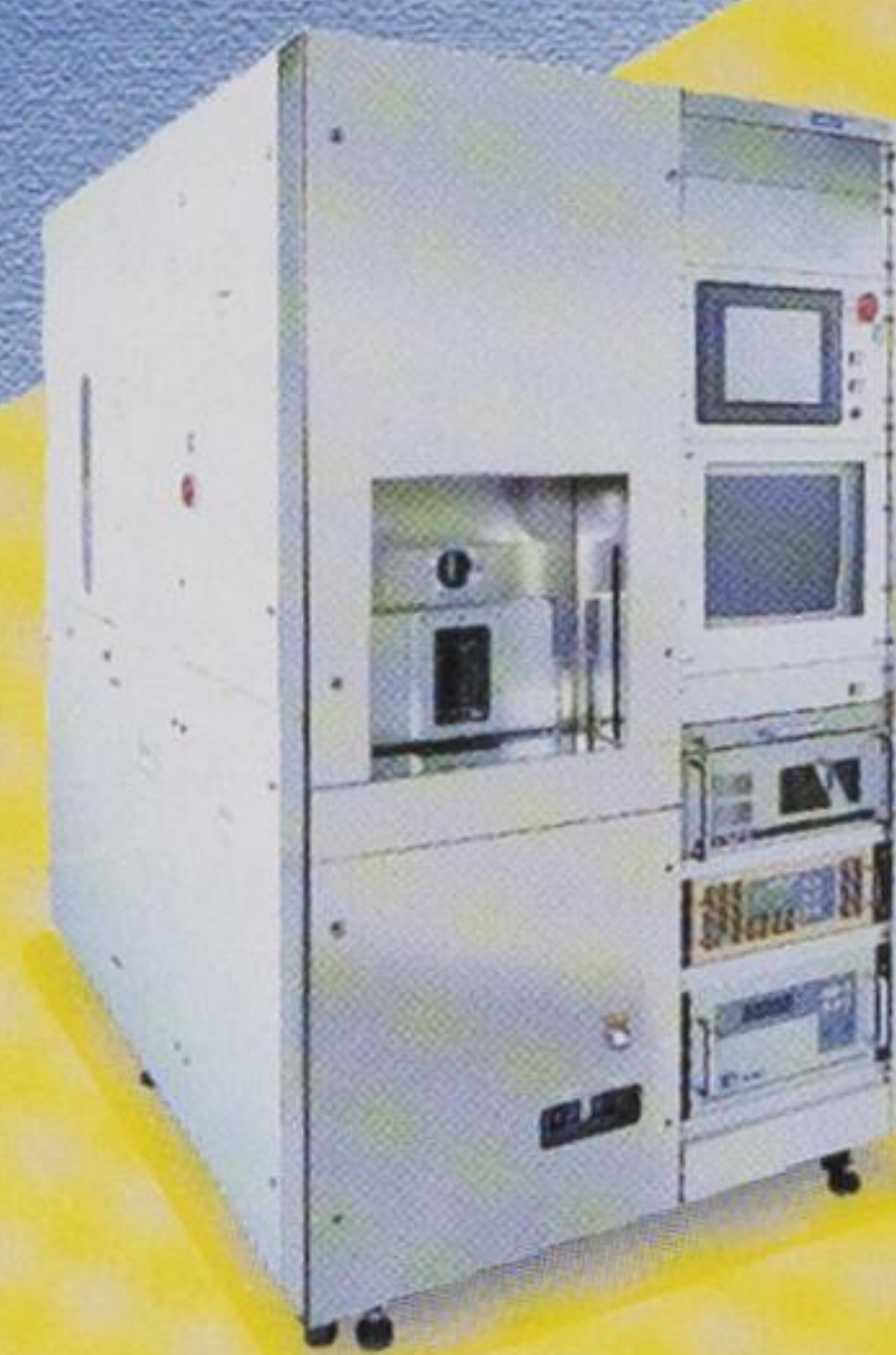


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RFMD goes to 6 inch, buys Resonext

RF Micro Devices will begin the production of GaAs HBTs on 6 inch wafers in early 2003. The company recently added a second fab with a capacity of 25,000–40,000 4-inch wafers per year to its original Greensboro, NC, facility (see *Compound Semiconductor* March 2002 p3). RFMD will now upgrade this second fab to 6 inch production following an increase in demand that has left the first fab – which has a capacity of 60,000 4-inch wafers per year – running at close to full capacity.

“In the March 2003 quarter we plan to begin 6 inch GaAs HBT production, which we expect will further reduce our cost structure,” said Dean Priddy, RFMD’s CFO and VP of administration. “Our technical team has also identified techniques we believe will improve our test yields by several [percentage] points.”

According to Priddy, capacity utilization at its two wafer fabs averages 75–80%, with around 50% utilization currently being experienced at the second fab, and almost 100% at the first. The extra GaAs real estate afforded

by the move to 6 inch wafers is expected to lower the company’s wafer costs by about 20%. This reflects the role of bigger GaAs wafers in accommodating more die and larger circuits. RFMD’s recently introduced (and fast-selling) PA modules are an example, says Priddy. These modules use die with increased dimensions as a result of a power control circuit integrated on chip.

The announcement of the move to 6 inch production came as RFMD reported record revenues of \$119.7 million for the September 2002 quarter. This represents a sequential increase of 15.2% over the previous quarter and an increase of 21.8% over the \$98.3 million reported for the September 2001 quarter. Illustrating the need to expand capacity, the company said that it is fully booked for the December 2002 quarter, and currently anticipates revenue of approximately \$128 million to \$132 million.

RFMD has also announced that it has acquired Resonext Communications, a pro-

vider of CMOS-based WLAN ICs from San Jose, CA. RFMD will issue \$133 million worth of its stock to Resonext shareholders to acquire the company.

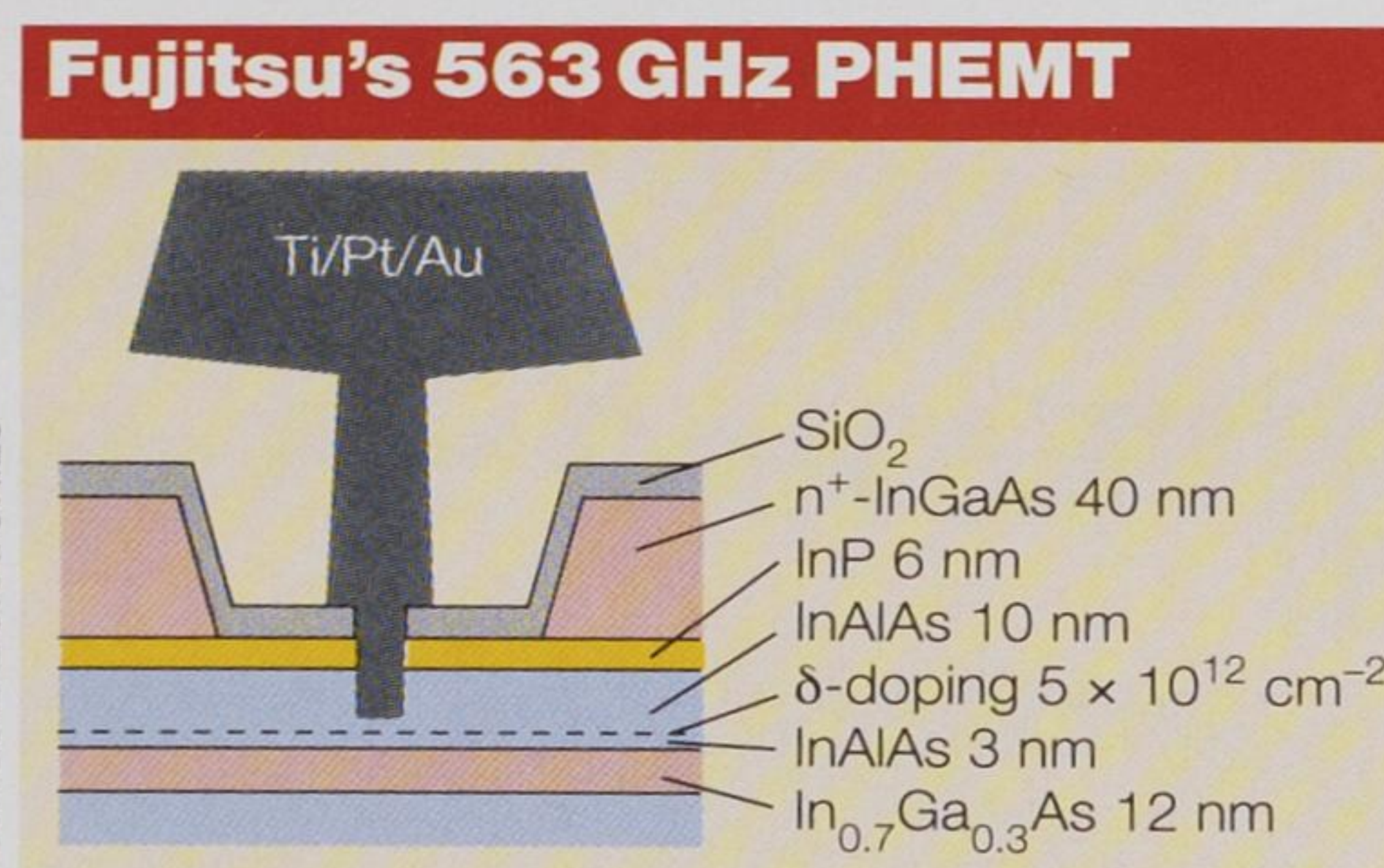
RFMD plans to use the technology and engineering resources that it will gain to design multi-mode products to integrate WLAN and handset functionality. Resonext recently introduced its first 802.11a baseband and 802.11a/b/g multi-band chipsets. The company says handheld device manufacturers are seeking lower power consumption and a reduced bill-of-materials, both of which are enabled by the higher levels of integration offered by Resonext’s products.

Specifically, RFMD will combine its GaAs HBT power amplifiers and WLAN transceivers with Resonext’s 802.11a/b/g CMOS chipset. RFMD says it is experiencing strong growth in WLAN chipsets, including the company’s 802.11b transceivers, which it estimates are now found in more than 20% of WLAN devices.

Fujitsu sets new speed record

A group at Fujitsu Laboratories in Japan has continued its run of record-breaking devices by reporting an InP-based HEMT with an f_t of 562 GHz, making it the fastest transistor ever made. The group has set records in the past for its lattice-matched and pseudomorphic InP-based devices. In *IEEE Electron Device Letters* (23(10) 573), Yoshimi Yamashita, Akira Endo and colleagues at Fujitsu, in collaboration with researchers at Osaka University and the Communications Research Laboratory in Tokyo, described the fabrication methods used to make the 25 nm gate length device.

The layers were grown by MOCVD onto a semi-insulating InP substrate, and the $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ channel was grown onto a 300 nm thick InAlAs buffer layer. The key to achieving high-speed performance lies in fabricating a device with a high In content in the



The spacing between the gate electrode and the InGaAs channel is reduced to 4 nm to minimize the short channel effect.

channel and the correct channel aspect ratio. Achieving the best aspect ratio requires the channel layer thickness and the distance between the gate electrode and the channel to be as small as possible to avoid a marked in-

crease in the short channel effect, which can impair the performance of devices with such small gate lengths.

The group were able to do this using what is described as a two-step recessed gate technique, which reduced the gate electrode-channel distance to just 4 nm. The source-drain spacing was 2 μm and the Ti/Pt/Au Schottky T-gate was 50 $\times$ 2 μm wide. The processing was also done at low temperature (below 260 $^{\circ}\text{C}$) to reduce fluorine contamination.

Hall measurements at room temperature showed a 2DEG mobility of 10,000 cm^2/Vs . The maximum drain-source current was 0.8 A/mm at a V_{gs} of 0.4 V. The pinch-off voltage was -0.45 V and the off-state breakdown voltage was below -1 V. The extrapolated f_t was 562 GHz and f_{max} was 330 GHz.

While such devices are still some way from being manufacturable in large volumes, they will eventually find use in future generations of mm- and sub-mm-wave devices.

GCS unveils new InGaP HBT process

Global Communications Semiconductors (GCS) has announced that it will offer a proprietary high breakdown voltage InGaP HBT foundry process to meet wireless infrastruc-

ture needs. The new process addresses the stringent requirements of infrastructure applications in terms of both performance and reliability, says Sam Lee, CEO of GCS.

“Until now, the only other choice was PHEMT,” said Lee. “GCS’s proprietary high breakdown voltage InGaP HBT process allows for a more compact IC, higher yield and a

superior combination of power and linearity. These are significant achievements considering the stringent requirements.” The process yields devices with a breakdown voltage of 24 V and f_t and f_{max} values of 35 and 65 GHz, respectively. Current gain is 70 and GCS says that for a 2 W PA, it has obtained an efficiency of 70% at 2 GHz with a 10 V bias.

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Celeritek loses PA module business from Motorola and signs deal to acquire Tavanza

Celeritek's revenue is set to fall sharply after news of a decision by Motorola that it will no longer seek second sources for its power amplifier (PA) modules. Motorola is currently in the process of transitioning from the 120v handset platform, for which Celeritek is the sole source of PA modules, to new handset platforms. Motorola had previously intended to have dual sources of supply for the new platforms, but has now discontinued this strategy and has already selected a sole source supplier other than Celeritek for one of its new platforms. Celeritek expects that module sales to Motorola will decline later this calendar year as the 120v is phased out. However, the company is developing new products that it believes will be attractive to Motorola and other handset makers in the future.

On November 11, following Motorola's

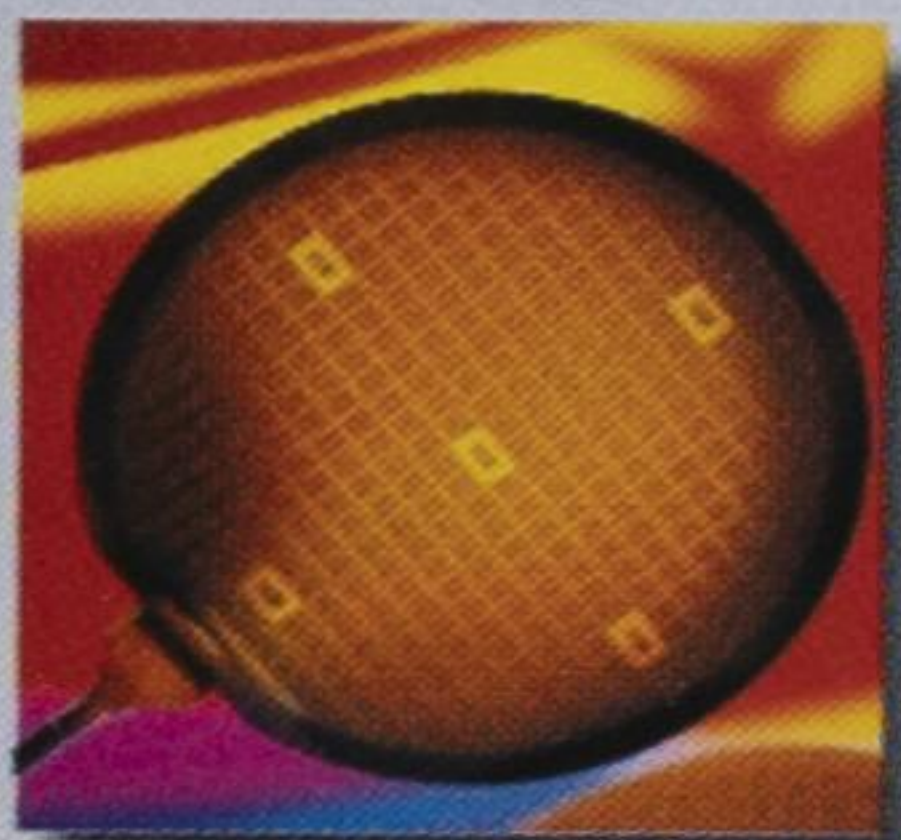
decision, Celeritek announced a reduction in its revenue forecast for the December 2002 quarter and beyond. In the previous two quarters, business from Motorola accounted for 56% of its revenues. Celeritek now estimates that in the December quarter Motorola will account for 25–30% of its revenues and that this will decrease further in the January 2003 quarter. The company reported slightly improving revenues and narrowing losses for its second quarter ending September 30. Revenues were \$15.5 million, up slightly from \$15.3 million in the first quarter and from \$15.1 million in the September 2001 quarter. The net loss for the September 2002 quarter was \$1.2 million, compared with a net loss of \$2.7 million for the same period a year ago. Semiconductor sales were \$11.4 million in the September 2002 quarter, up 21% sequentially as a result of increased ship-

ments of PA modules. Subsystem sales in the September 2002 quarter were \$4.1 million, down 31% sequentially.

Meanwhile, Celeritek has signed a definitive agreement to acquire Tavanza, a privately held, fabless designer of PA modules and components for cellular and WLAN products, based in Sunnyvale, CA. The terms of the agreement were not disclosed, although Celeritek noted that the acquisition will not have a material impact on its cash position.

Celeritek will leverage Tavanza's technology to address growing demand for the power-efficient, small-volume and cost-effective power amplifiers used in handsets and WLAN products. Tavanza has already sampled CDMA PAs to several Korean cellphone manufacturers, and Celeritek has opened an office in Korea in order to serve this growing market.

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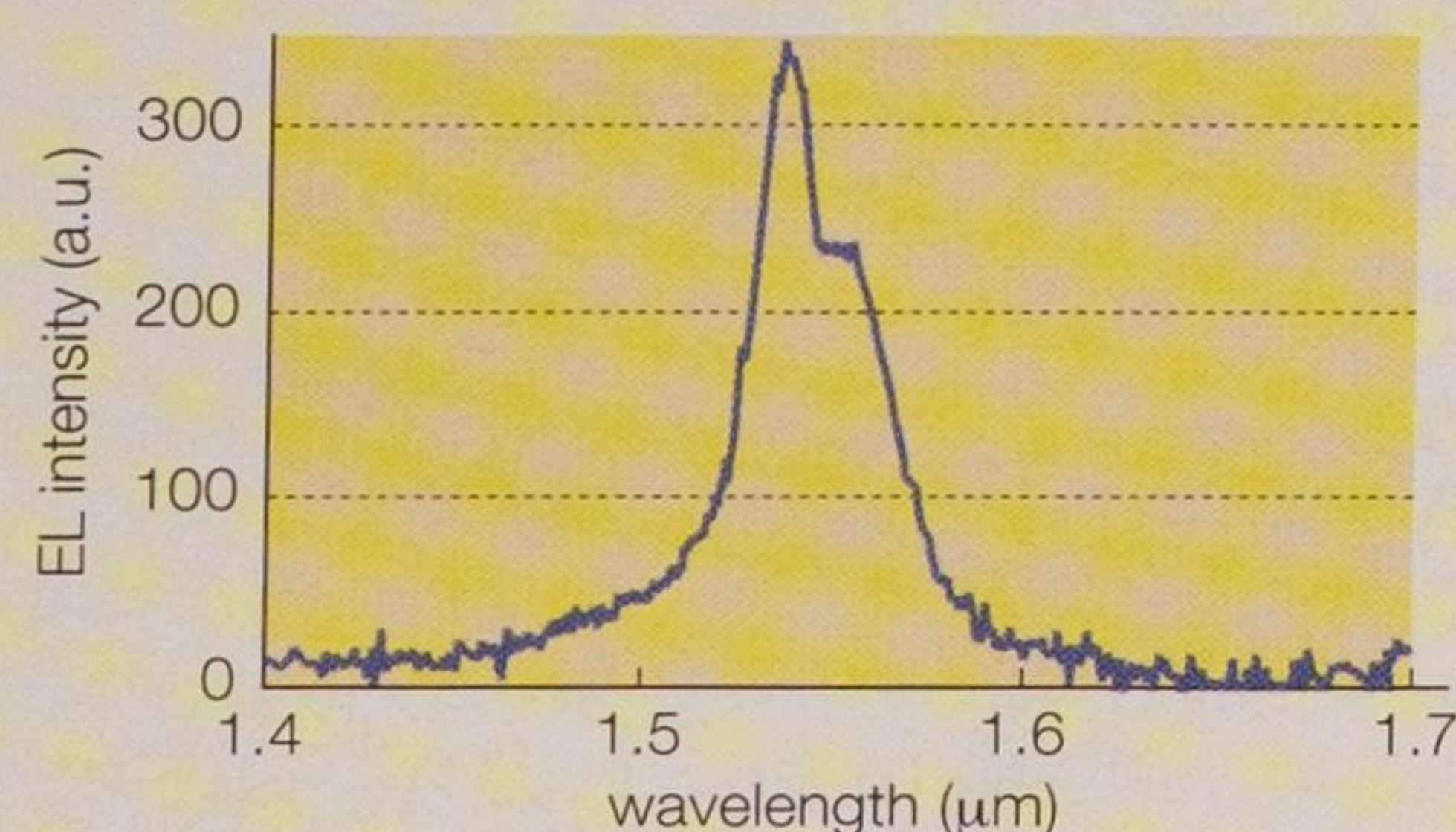
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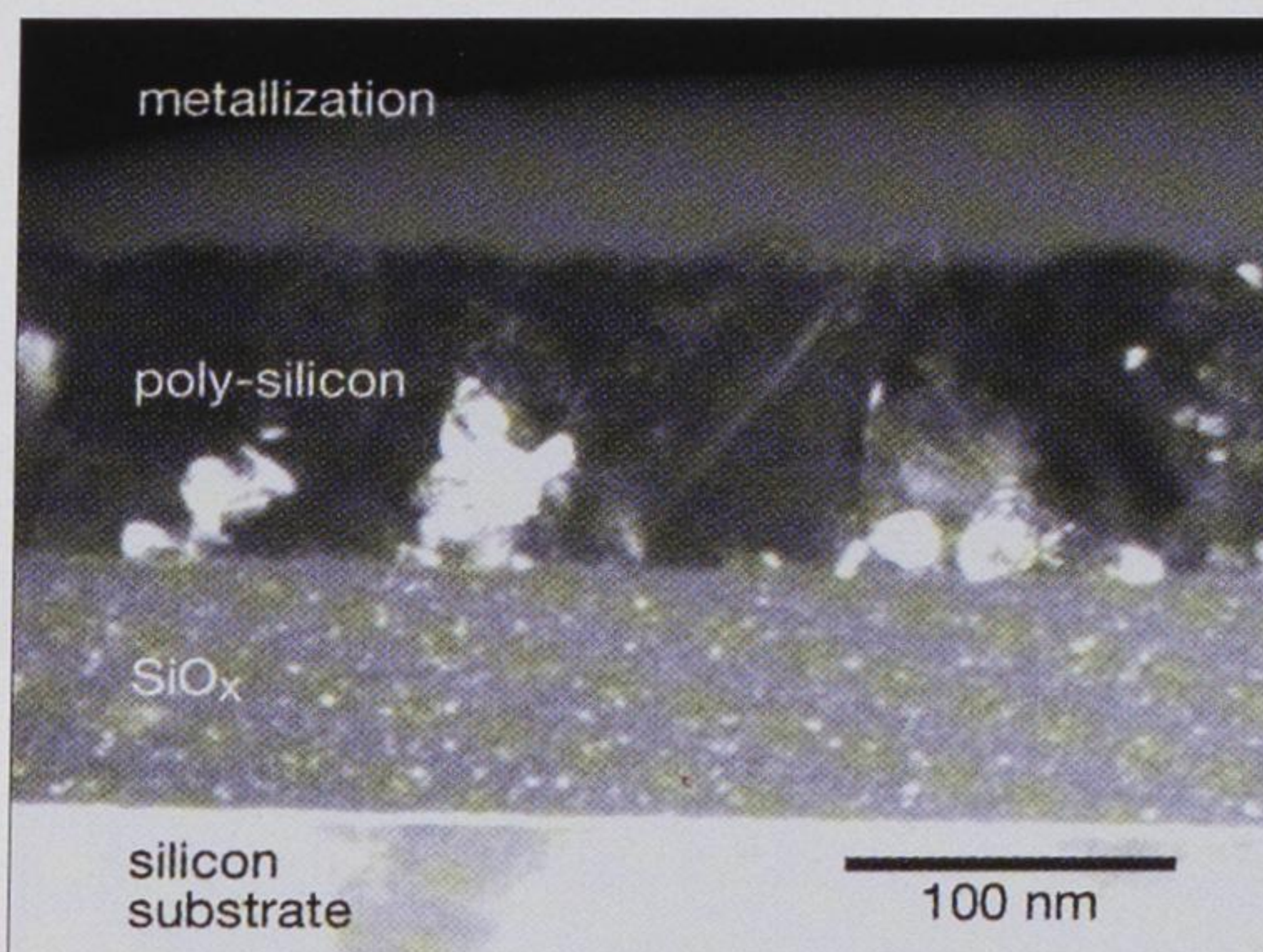
Electroluminescence (EL) spectrum at 300 K from an Er-doped silicon nanocrystal MOS device obtained under forward bias with a current density of 20 A/cm^2 .

STMicroelectronics (ST) has developed silicon-based infrared LEDs with efficiencies comparable to those of GaAs-based emitters. The company, which is the world's third-largest semiconductor manufacturer, announced that devices operating at $1.54 \mu\text{m}$ have an external efficiency of 10%.

Silicon is a poor light emitter due to its indirect bandgap. Even complex silicon-based LED structures can only achieve efficiencies in the 0.01–0.1% range. Last year, scientists at the University of New South Wales used techniques developed in the photovoltaics industry to achieve an efficiency of 1% (*Compound Semiconductor* October 2001 p39).

ST's trick is to use a structure in which ions of rare-earth metals such as erbium or cerium are implanted in a layer of silicon-rich oxide, i.e. silicon dioxide enriched with silicon nanocrystals. Electrical carriers are confined within the nanocrystals, which are 1–2 nm in diameter. The nanocrystals are coupled with the rare-earth ions in the silicon dioxide matrix. When the nanocrystals are excited by carrier injection, they transfer energy to the rare-earth ions, which then emit light of a frequency determined by the choice of rare-earth dopant. Absorption by silicon limits the emission wavelength of silicon-based LEDs to wavelengths above around $1.1 \mu\text{m}$.

A recent paper from researchers at CNR, the University of Catania and ST (all in Catania, Italy) described the fabrication of substoichiometric SiO_x ($x < 2$) films on a p-type silicon substrate by PECVD (Iacona *et al.* 2002 *Appl. Phys. Lett.* **81**(17) 3242). The films



Silicon nanocrystals are clearly visible in the SiO_x layer of this MOS device, which is not Er-doped (Franzo *et al.* 2002 *Appl. Phys. A* **74** 1).

were implanted with Er and then annealed at 900°C under nitrogen to activate the Er and to form silicon nanocrystals in the SiO_x layer. Electroluminescence was detected in MOS devices in which the Er-doped SiO_x films were used as the dielectric layer (see graph).

The approach has certain drawbacks; in particular it is difficult to inject current into the nanocrystals since they are embedded in a dielectric layer.

ST hopes to replace devices such as relays, transformers or discrete optocouplers with a patented structure in which two circuits, built on the same chip but electrically separated from each other by insulating silicon dioxide, communicate via optical signals using integrated silicon LEDs and detectors. The company says such devices will have numerous applications, where the power circuit needs to handle much higher voltages than the control circuit. Engineering samples will be available by the end of 2002. In the longer term, ST is investigating the optical distribution of clock signals in CMOS circuits that control optical data-transmission systems.

"The ability to combine optical and electronic processing on the same chip presents enormous opportunities for ST to be the first to develop new types of semiconductor products, especially as the technology is compatible with existing production process flows and equipment," said GianGuido Rizzotto, director of ST's Catania-based Corporate Technology R&D organization. The process was developed using the same pilot line that ST uses to develop new MOSFET and bipolar devices.

IBM's new transistor claims speed title

IBM has developed a transistor based on SiGe bipolar technology with a speed of 350 GHz, a record speed for a silicon-based device. The transistor uses IBM's fifth generation of SiGe technology, in which a novel vertical profile scaling technique reduces the height of the HBT. IBM expects that the new device will lead to communications chips with speeds of more than 150 GHz in about two years.

Intel aiming for phone-on-a-chip

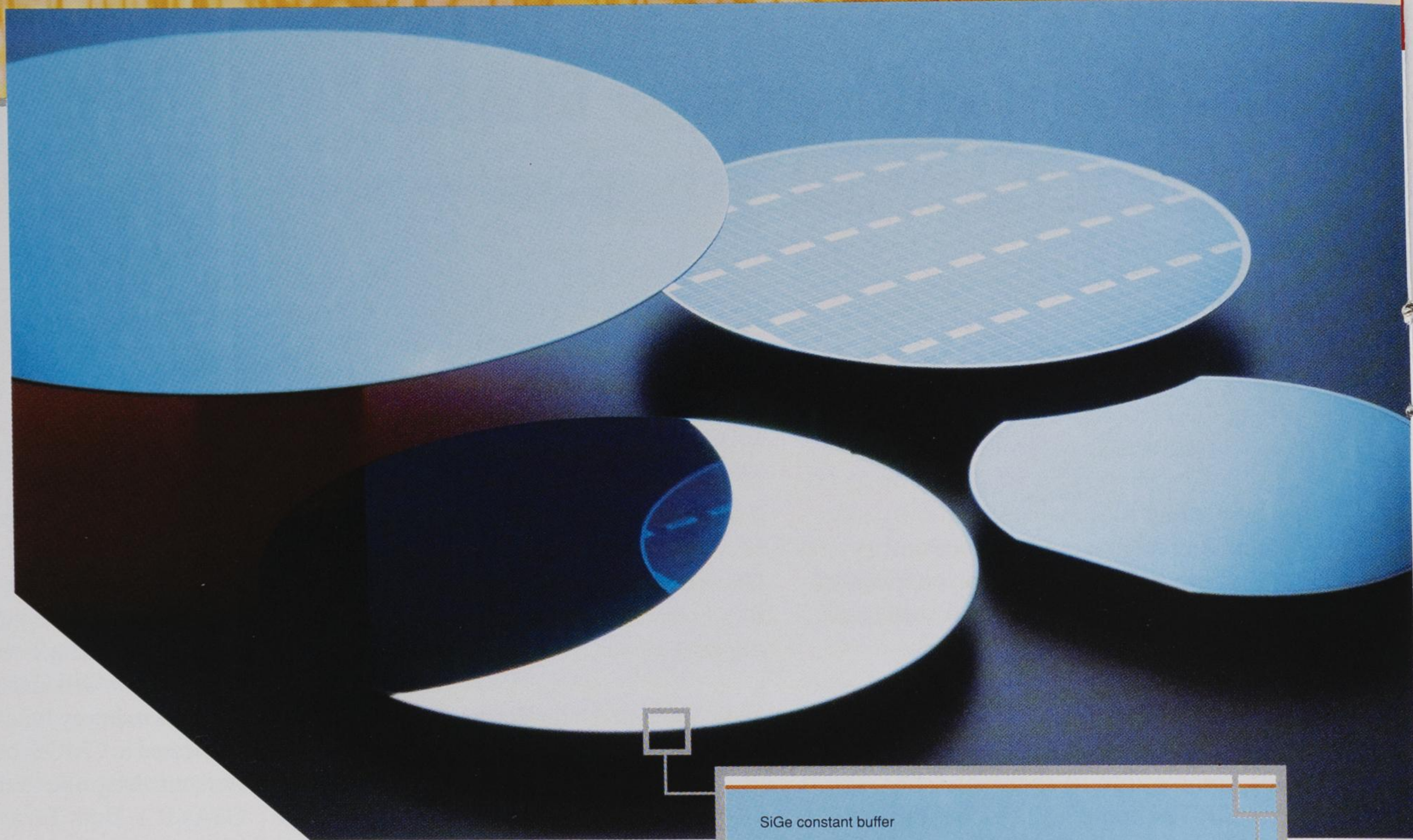
According to Reuters, Intel plans to put all the semiconductor functions required by a mobile phone onto a single chip by the middle of the decade. This will include not only the processing and memory functions, which are already fabricated in CMOS, but also the power amplifier, currently one of the key applications for GaAs ICs. Both Texas Instruments and Intel are rushing to integrate processing and memory functions onto a smaller number of chips. Texas Instruments has said that it will achieve one-chip integration of everything except the power amplifier by the end of 2004.

Communicant to get government finance

Communicant Semiconductor Technologies AG, a German SiGe foundry company, has received approval from the European Union (EU) for federal and state government subsidies of \$363 million in the form of cash grants and government loan guarantees. The EU approval also includes government guarantees on commercial loans. This approval is a key step in finalizing the debt financing by a major banking consortium for a \$650 million debt facility. In April, Communicant secured private equity of \$325 million. The total financing of \$1.3 billion will complete the funding for Communicant's foundry in Frankfurt (Oder), Germany.

"The approval of these government subsidies and commercial loan guarantees is an indication of the importance the EU has placed on establishing a world-class wafer foundry for highly advanced communications products in Europe," said Abbas Ourmazd, CEO of Communicant.

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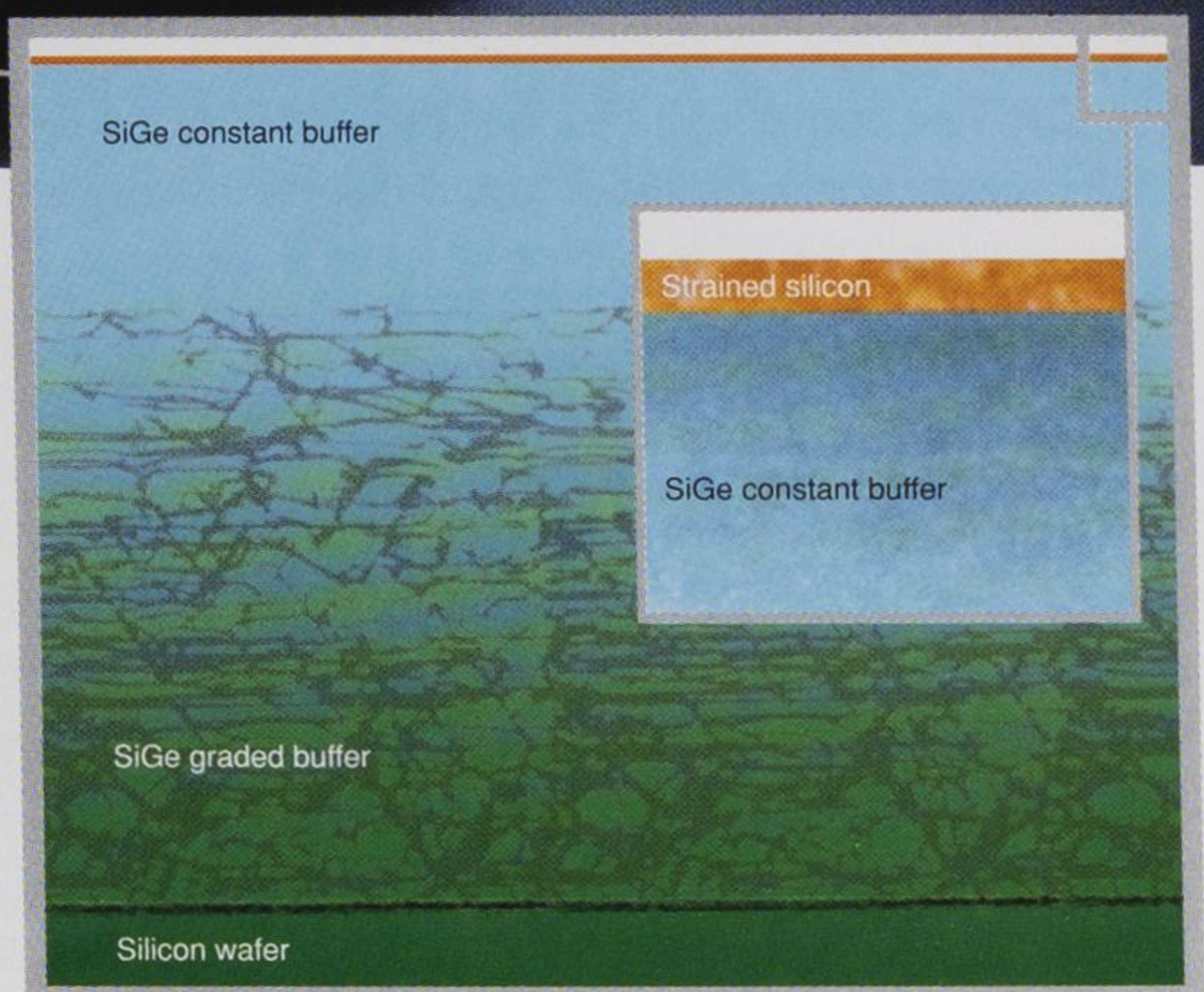


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Blue LED prices fall in Japan

Leading LED manufacturers in Japan, including Nichia and Toyoda Gosei, and mobile phone manufacturers have agreed that the price of blue LEDs will be cut by about 13% in the October–December quarter. Blue LED chips will now be priced at around ¥35 (about 30 cents), while white LEDs will sell for around twice that amount. The drop in LED prices is being driven by falling handset prices, even though more LEDs are now being used in each phone.

However, manufacturers in Taiwan, such as Epistar and UEC, believe that this will have little impact on their business. Taiwanese companies sell very few blue LEDs in Japan, and there is also a distinction between Japanese and Taiwanese suppliers in terms of performance, price and market.

The assistant manager of Epistar, Kuo Hung-Ming, says that there are various specifications for blue LEDs. “Nichia’s selling price of about ¥35 is mainly for the high-class blue chips used to make white LEDs by color mixing,” he said. “These are quite different from the blue LEDs supplied by Epistar to the mobile phone market [to illuminate blue screens].” Kuo Hung-Ming adds that the average selling price of blue LEDs in Taiwan is NT\$3–3.5 (9–10 cents), and Epistar

also sells some blue LEDs at NT\$1.8.

The sales price of blue LEDs made by Japanese companies has always been relatively high compared with those from Taiwanese manufacturers, and this is still the case even after the adjustment. There is little sign that the Taiwanese manufacturers will reduce their prices in the near future, since blue chips suitable for the mobile phone market are in short supply. Asked whether Epistar will reduce its selling price of blue LEDs, Kuo Hung-Ming replied: “how would this be possible when customers are still competing for good blue LED chips?”

Chou Tsung-Nan, assistant manager of LED packaging company Everlight, says that a reduction of blue LED prices will probably not occur before the first quarter of next year, due to a lack of supply. Chien Sung-Ling, spokesperson for Harvatek, a packaging company that buys blue LED chips from United Epitaxy, points out that there are more than 15 manufacturers producing blue LEDs in Taiwan. However, the quality varies greatly, and although some small companies frequently sell at low prices, blue LEDs that conform to the requirements of large international mobile phone companies are still in strong demand, and their prices remain relatively high.

Seiwa Electric to double production capacity in 2003

Seiwa Electric is planning to double its production capacity for blue LEDs next year. The company intends to invest ¥300 million (\$2.5 million) to expand production capacity at its main plant in Kyoto prefecture, Japan, to 4 million units per month in the next fiscal year. In comparison, Toyoda Gosei has a monthly production capacity of around 95 million LEDs.

As well as selling the LEDs themselves, Seiwa Electric will also develop and sell signalling products and other equipment that use the devices. Seiwa entered the blue LED market earlier this year, with a production method that the company claims does not infringe any of the patents owned by its rival, Nichia (see *Compound Semiconductor* June 2002 p9).

More uses for LEDs in car manufacturing

Several Japanese car manufacturers are increasing their usage of LEDs, according to the Nihon Keizai Shimbun newspaper. Toyoda Gosei will supply a combination rear light for braking and reversing, which will be used on a new Toyota vehicle named Wish. Ichikoh Industries will supply white LEDs to provide interior lighting in Toyota’s new Alford luxury minivan. Stanley Electric is already supplying white LEDs to illuminate instrument panels in Honda’s Accord cars, and the company has also produced a sample headlight containing 100 white LEDs.

New orders boost sales at Epistar

Due to new orders for the ultra-bright LEDs used in the latest-model mobile phones, Epistar had sales of NT\$204 million (\$5.9 million) in September, a rise of 18.6% compared with August and three times higher than last year. The company’s orders for blue and green LEDs during the fourth quarter of 2002 are 40% higher than its actual production capacity. It is estimated that blue and green LEDs will soon account for 50% of Epistar’s business.

News in brief from Japan

Powdec ready to grow 4 inch GaN HEMT wafers

Powdec KK will start to produce 4 inch GaN-based HEMT epiwafers in spring 2003. The company has succeeded in developing an MOCVD machine to grow the large-diameter wafers, and hopes to receive orders from chipmakers that operate 4 inch fabrication lines.

Hitachi produces GaInNAs laser for fiber-optic systems

The Central Research Institute of Hitachi has developed a GaInNAs laser for 10 Gbit/s fiber-optic systems. The laser operates at up to 80 °C, and for more than 8500 hours without deterioration. Hitachi used MBE to grow the device structures, and employed heat treatment to reduce the level of crystal defects and

enhance the performance of the lasers. In future, the company is planning to develop 40 Gbit/s devices.

Nitride Semiconductors signs sales agreement

Nitride Semiconductors, a Japanese firm that sells UV LED chips and epiwafers, has signed a sales agency agreement with MACNICA, beginning in September 2002.

Fiber-to-the-home services continue to grow in Japan

There will be 200,000 subscribers to fiber-to-the-home services in Japan by the end of this year, according to Takao Ninomiya of Furu-kawa Electric. The numbers could increase to 700,000 next year, and companies in Taiwan are expected to benefit from outsourced orders for components and subsystems.

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TDI samples p-type GaN substrates

TDI of Silver Spring, MD, is sampling 2 inch diameter GaN templates with p-type electrical conductivity. The template is grown by hydride vapor phase epitaxy (HVPE) onto sapphire substrates. To date, TDI and its competitors have only sold n-type GaN templates. The material is Mg-doped with concentrations between 10^{16} and 10^{18} atoms/cm³, and template thickness is available to customer specification.

"This is the first sampling of p-type GaN templates [grown] by HVPE technology," Vladimir Dmitriev, TDI's president and CEO, told *Compound Semiconductor*. "HVPE was first to grow high-quality, single-crystal GaN more than 30 years ago, but MOCVD was the first to successfully grow p-type material." For the growth of thick layers, HVPE has many advantages over MOCVD or MBE, says Dmitriev. The growth rate can be varied up to 100 μ m/hour, and the technique is relatively



The availability of p-type GaN substrates opens up new possibilities for device design.

simple. It does not require a leak-tight chamber and uses Ga metal instead of an expensive, difficult to handle metalorganic Ga source.

Dmitriev says that the p-type material opens up new opportunities for the design and development of GaN devices. "Historically, because the initial layer was always n-type, all designs for LEDs and lasers were made around n-type

material. The p-type template makes upside-down LED structures possible, removing the need for the highly resistive p-type material to be the top layer." Using a resistive p-type top layer requires large-area, semi-transparent electrodes to spread the current across the LED, but this also reduces the light output. Other more exotic methods to improve current spreading, such as buried tunnel junctions, have had limited success (*Compound Semiconductor* September 2001 p41).

The real breakthrough that would solve many of the problems facing GaN devices would be the availability of bulk GaN substrates. TDI is still pressing ahead with its bulk GaN substrate development program, and hopes to make them available in 2003. Meanwhile, TDI is selling n-type templates on sapphire and will move the new p-type templates into high-volume production in early 2003.

Rockwell wins two SiC contracts

Rockwell Scientific Company (RSC) has received two contracts for the development of SiC-based high-power devices. The first contract, worth \$1.8 million, has been awarded by the Defense Advanced Research Projects Agency (DARPA) to develop high-efficiency megawatt-class SiC power switches.

The aim is to develop devices capable of switching up to 25 A at 12 kV in miniaturized megawatt power systems. Such devices are needed in the electrical systems of future electric combat vehicles, ship propulsion systems and aircraft applications. Modeling software

specialist CFD Research Corporation is a sub-contractor to the program and will provide modeling and analysis of the electrical, thermal and mechanical performance of the device packaging, as this is potentially the weakest link in such high-power systems.

The second program, worth \$1.5 million, comes from the Air Force Research Laboratory and is for the development of a SiC-based motor drive module. The modules are intended to drive switched reluctance motors, the rotors of which have no coil windings or permanent magnets. The absence of perma-

nent magnets means that the motors can run efficiently at higher temperatures. All of the components in the motor system (motor, drive electronics and packaging) need to be able to operate at 200 °C.

"So far, a lot of effort has gone into the devices but very little into the periphery, such as packaging, thermal management and passive components," said Hsueh-Rong Chang, manager of RSC's power electronics department. "All these are important if we are to show the full potential of wide-bandgap technology."

RSC is partnering with Boeing on the motor drive project. Once 200 °C operation of the system has been demonstrated, it will then undergo trials in a Boeing aircraft.

Osram Opto's blue lasers live longer

Osram Opto Semiconductors, well known for its high-brightness LEDs, is also developing GaN-based blue lasers and has reported a steady improvement in the lifetime of its devices. In the last year, Osram Opto has increased the service life of its GaN-based blue lasers from 2 minutes to 143 hours of CW operation.

Osram Opto grows its laser structures on SiC substrates; this material has a better lattice match to GaN and a higher thermal conductivity than the sapphire substrates widely used for GaN epitaxy. The company has also brought its packaging experience from LED

manufacturing to bear on the task of optimizing the chip mounting for maximum heat removal. A new contacting process has halved the operating voltage of its lasers to 8 V. Other improvements, including smoother mirrors, have helped reduce the operating current to 96 mA. Output power is currently 1 mW.

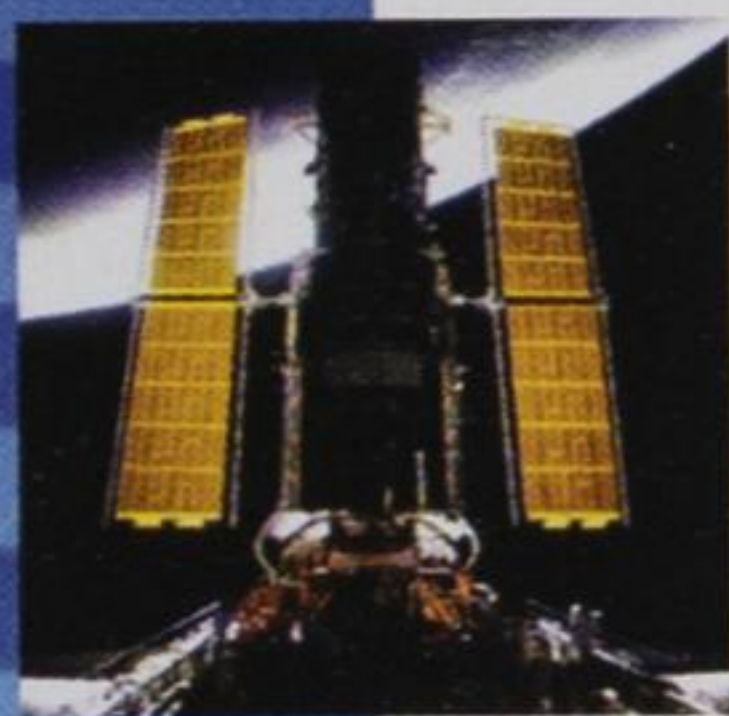
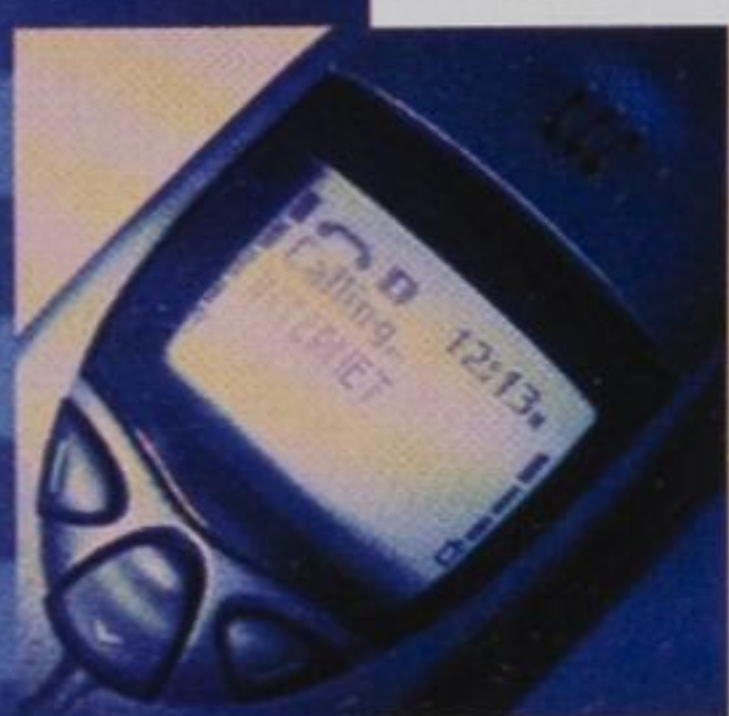
According to Volker Harle, head of development for InGaN devices at Osram Opto, the potential for optimization has not yet been exhausted. "There are still opportunities in the areas of epitaxy, chip technology and assembly, which we must exploit to further reduce the operating voltage and current," said Harle.

The work at Osram Opto is part of a project sponsored by the German government that began in August 2001. Other partners include

the Fraunhofer Institute for Solid-State Physics in Freiburg and the universities of Brunswick, Regensburg, Stuttgart and Ulm. The goal is to produce a prototype blue laser by July 2004. If current progress is maintained, then a market-ready product is anticipated by July 2005. However, the project is somewhat behind the benchmarks set by others around the world. SiC substrate manufacturer Cree also has a blue laser development program and grows the structures on its SiC substrates. In February this year, Cree announced that its 405 nm, 3 mW lasers had achieved a projected lifetime of 10,000 hours. Nichia already sells blue lasers commercially and broke the 10,000 hour lifetime barrier in 1997. Nichia grows its LED and laser structures on sapphire substrates.

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OCP acquires Cielo Communications

The recent company closure and merger activities in the optical components industry have continued with the announcement that Optical Communication Products (OCP) has bought VCSEL manufacturer Cielo Communications.

OCP makes fiber-optic subsystems and modules for metropolitan and high-speed premises networks at its site in Chatsworth, CA. Around 61% of OCP's outstanding capital stock is owned by Furukawa Electric Company Ltd. OCP bought Cielo, which

was privately held, to accelerate the integration of 1300 nm VCSELs into its multi-channel optical modules.

"We believe that single-mode long-wavelength VCSEL technology is a key enabling building block for the next generation of optical modules," said Muoi Tran, CEO and president of OCP. "The acquisition of Cielo Communications gives us the opportunity to expand our product portfolio to include optical modules based on 1300 nm VCSEL

arrays." At this year's OFC conference, Cielo displayed several 1300 nm products, including a 10 Gbit/s serial transponder and various parallel array modules.

Although the financial terms of the acquisition were not disclosed, the purchase price includes capital equipment, inventory and intellectual property. In addition, OCP has hired approximately 20 former Cielo Communications employees, and will continue to operate at Cielo's facility in Broomfield, CO.

Mitsubishi launches new high-performance pump lasers

Mitsubishi recently unveiled a high-power version of its 980 nm pump laser. The new ML861E5S has a very high peak power output of 1.1 W and kink-free power of 750 mW – achieved without catastrophic optical damage (COD). At the same time, the company launched the ML8627S, a 200 mW uncooled pump offering stable wavelength performance across a wide operating temperature range for metro applications.

Developed at the company's facilities in Kita-Itami, Japan, the new lasers are based on a GaAs/AlGaAs double-QW gain region. According to Mitsubishi's Daniel Chen, assistant VP of high-frequency products, device design improvements have led to high output powers, while also reducing the aspect ratio of the beam, making it more circular for improved light coupling into fiber.

"To prevent COD breakdown we adopt a window structure on both facets using quantum-well intermixing [QWI] with silicon

"To prevent COD breakdown we adopt a window structure on both facets using QWI with silicon ion implantation."

ion implantation," explained Chen. "The typical bandgap difference between the window and the active region is 150 meV, which is sufficient to suppress the absorption of laser light."

With a laser cavity length of 2.15 mm, devices typically operate with a threshold current of 110 mA. So far, pumps operating at 500 mW and 700 mA operating current have been successfully aged for approximately 500 hours at 50 °C.

Chen says that the n-type AlGaAs cladding

layer has a lower aluminum content, and therefore a smaller refractive index, than the p-cladding layer. As the optical fields locate in the higher refractive index region, the guided modes expand into the substrate and not into the ridge structure. The subsequent expansion of the near-field pattern reduces the far-field pattern in the vertical direction, reducing the aspect ratio of the laser beam to 2.5. The resulting beam divergence measured from far-field patterns is therefore around 8° (parallel) and 18° (perpendicular). This compares with approximately 30° (perpendicular) for typical edge-emitting lasers, and results in more efficient laser-to-fiber coupling.

The ML8627S uses the same facet coatings to stabilize the wavelength within ± 10 nm over a temperature range of 5 °C to 85 °C. The absence of cooling for the chip saves module space and lowers system cost. Facet coatings also offer a cost advantage when compared with the fiber gratings traditionally used in pump laser diode modules for long-reach and submarine-cable communication networks, said Chen. The 200 mW laser has a threshold current of 70 mA.

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Beam Express unveils optically pumped tunable VCSEL

A Swiss company, Beam Express, has demonstrated an optically pumped tunable 1550 nm VCSEL designed for metro optical networks. The laser has a tuning range of 38 nm and is notable for its tuning voltage of only 4 V. Beam Express says this figure is around one-tenth of existing tunable MEMS devices, and makes the VCSEL compatible with standard low-voltage drive electronics. In addition, the 980 nm optically pumped design leads to a CW single-mode power output of 1 mW from an aperture diameter of 5 μm , with 40 dB side-mode suppression.

Other companies that have developed long-wavelength VCSELs with tunable MEMS mirrors are Bandwidth9 and CoreTek, the now defunct Nortel subsidiary.

Beam Express is led by ex-Agilent executive Jean-Claude Charlier, who joined as CEO this April. Charlier says Beam Express has a unique wafer-fusion technique that allows it to integrate high-performance VCSELs with high-bandwidth MEMS tuning structures.

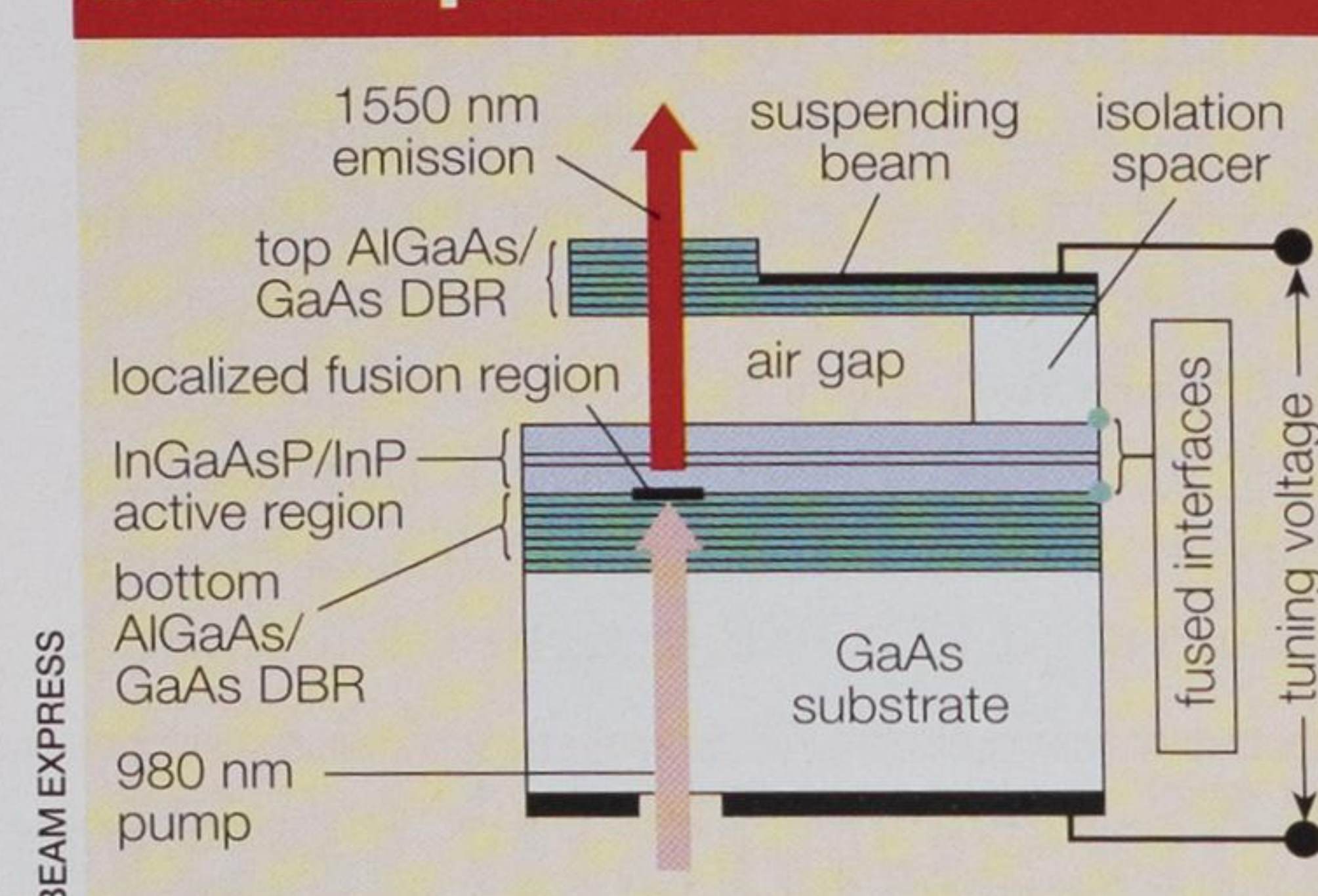
"The MEMS mirror can be electrostatically activated at very low tuning voltages and uses standard, low-cost electronics," said Charlier. "This approach is key to producing long-wavelength VCSELs with high yield and higher functionality, resulting in significant cost savings during component manufacturing."

Charlier adds that tunable lasers are key elements for reconfigurable metro networks, but will be commercially viable components only if their cost matches fixed-wavelength lasers. "Our tunable VCSEL meets this requirement due to the inherently inexpensive manufacturing process involved," he claims.

Beam Express is one of a number of spin-offs from the Lausanne branch of the Swiss Federal Institute of Technology (EPFL). It was founded in 2001 by a team from the Institute of Quantum Electronics and Photonics, and is based at the Scientific Park on the EPFL campus in Lausanne. Beam Express also has access to MOVPE growth facilities at EPFL's Laboratory of Physics of Nanostructures.

The company's device consists of an

Beam Express's VCSEL



The VCSEL uses a 980 nm optical pump and wafer fusion to achieve high-power operation with low-voltage MEMS tuning.

InGaAlAs/InP MQW active region and an air gap, which form a cavity sandwiched between AlGaAs/GaAs DBRs (see figure). The InP-based MQW material and the DBRs, consisting of 36 AlGaAs/GaAs pairs with 99.8% reflectivity, are grown separately, and the VCSELs are fabricated using wafer fusion. The top DBR (with a spacer) is fused to the top of the active region, the InP substrate is etched away, and the bottom DBR is then fused to the active region. The air gap for the MEMS tuning structure is produced by etching away part of the isolation spacer layer in the top DBR, which remains suspended by one or several narrow beams.

By structuring one or both of the wafers before they are fused together, fusion occurs only in localized regions on the wafers. This proprietary "localized wafer fusion" process leads to built-in lateral electric and optical confinement, without the need for post-fusion processing steps such as mesa etching and lateral oxidation.

Also, adjusting the size of the structures prior to fusion allows the cavity thickness, and hence the emission wavelength, to be altered. This so-called mesa trimming procedure enables the fabrication of multi-wavelength VCSEL arrays. This is an alternative approach to multi-step epitaxial growth, which the company says suffers from much lower yields.

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Schott increases its stake to take control of ULM Photonics

Schott Optovance has increased its stake in German VCSEL maker ULM Photonics to 52%, giving it a majority ownership of the two-year-old spin-off from Ulm University.

"Schott's investment comes despite the worldwide downturn in the telecommunications market," said Karl-Peter Merz, chairman of the board of directors of Schott Optovance. "We are pursuing attractive opportunities to apply ULM's VCSEL technology in applications inside and outside the telecom and datacom markets."

Due to current market conditions, Schott is restructuring its Schott Optovance division in Southbridge, MA, which manufactures high-density fiber management components for parallel optical interconnects. The company will be sold, spun-in or closed by the end of the year.

"Although Schott Optovance has developed a unique and strong technology basis," said Merz, "we are not able to forecast when a sustained turnaround of the telecommunications markets will take effect."

ISO certification boost for Applied Optoelectronics

Applied Optoelectronics Inc (AOI) has received ISO 9001:2000 certification for quality management at its Sugar Land, TX, facility, where it designs and manufactures semiconductor diode lasers. "It is very rewarding to verify that our internal system meets the requirements of this rigorous international standard," said Stefan Murry, AOI's director of marketing. "ISO 9000:2001 certification also provides our customers with an extra level of assurance that AOI has the systems to ensure a consistent, quality product."

APPLIED OPTOELECTRONICS



AOI recently released two new lines of 1550 nm analog lasers, one for use in the wideband fiber-optic repeaters employed in the wireless communications industry (see photo), and the other for cable television (CATV) systems.

European suppliers get more funding

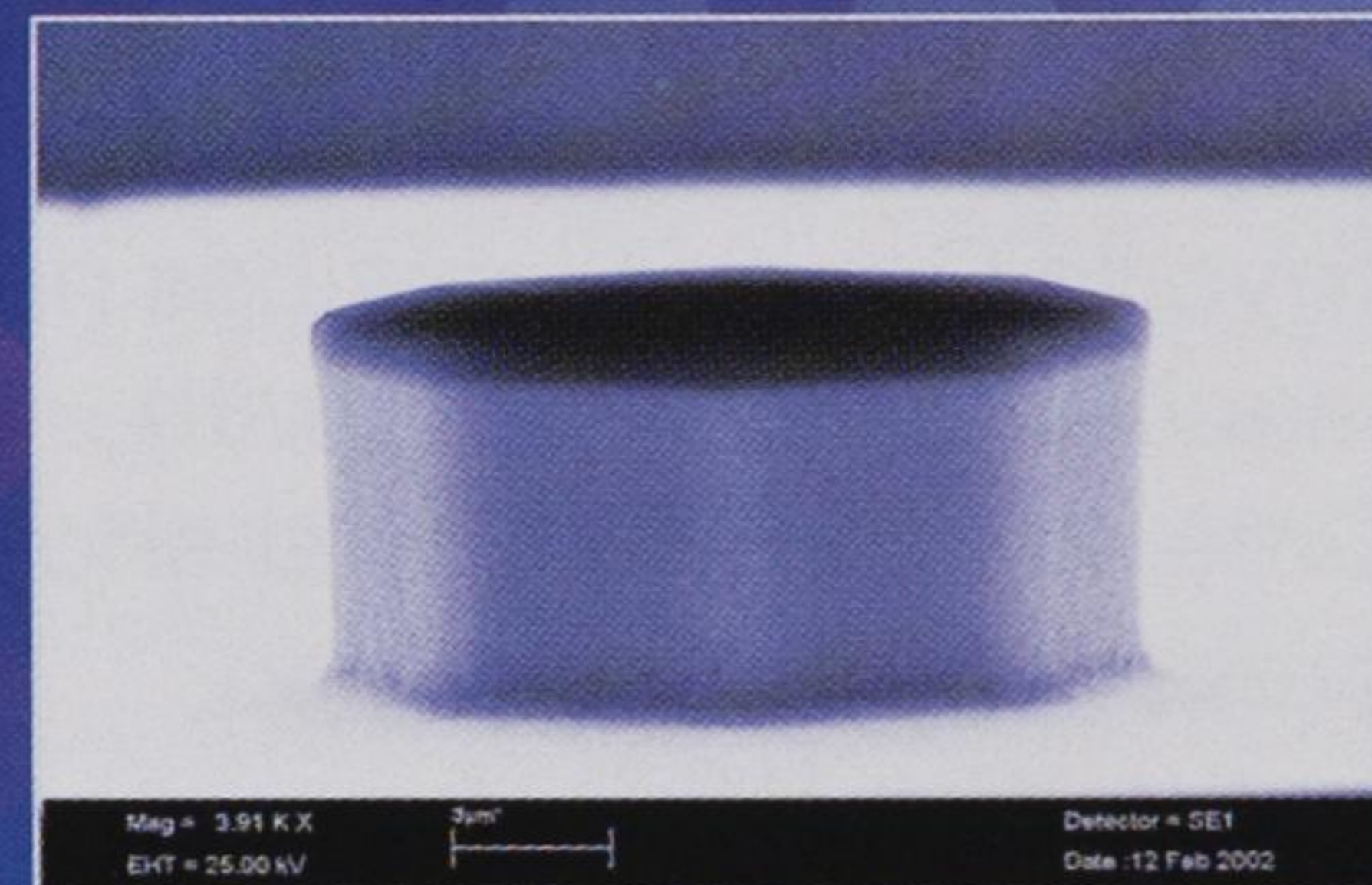
Several European fiber-optic component suppliers have received additional funding. Opto Speed, a developer and manufacturer of InP-based optoelectronic components, has secured a further €10 million (\$9.9 million) of second-round investment from ABN AMRO Capital. This adds to the previously announced €20 million of second-round financing announced in March 2002. Opto Speed will use the funds to open a US office, increase its sales and marketing activity, and for the further research and development of 10 and 40 Gbit/s optical components.

Fiber-optic component and transceiver manufacturer Optillion has concluded its Series C financing round, raising an additional \$15 million. Led by Crescendo Ventures,

Cisco Systems, ITACT and Investor AB, the latest round brings the total venture financing raised by Optillion to \$70 million during the past two years. The latest investment will be used to ramp production of Optillion's current 10 Gbit/s transceiver products and to support product development, marketing and sales. In line with current market conditions, Optillion will make some adjustments to its organization, including a reduction in workforce.

Intense Photonics of High Blantyre in Scotland, UK, has received additional backing of £750,000 (\$1.18 million) in its Series B funding round from the Italian venture-capital company Alice Ventures, adding to the £10.5 million awarded in August. The company, which is developing multi-functional single-chip devices using quantum-well intermixing technology, will use the funds to further accelerate the development of its product range and to strengthen its marketing effort.

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LIGHT-EMITTING DIODES

Licensing agreements stabilize

After settling its patent disputes with Osram and Toyoda Gosei, Nichia has now reached agreements with Cree and Lumileds that should prevent further litigation, writes **Tim Whitaker**.

This has been a remarkable year for the nitride LED industry. Twelve months ago the leading manufacturers – Cree, Lumileds, Nichia, Osram Opto Semiconductors, Rohm and Toyoda Gosei – were embroiled in a series of legal disputes over patents that spread uncertainty among customers and cost millions in legal fees. Now, thanks largely to an about-face by Nichia, many of these disputes have been resolved.

In the course of 2002, Nichia has reached patent agreements with Osram, Toyoda Gosei, Lumileds and, most recently, Cree. According to Noboru Tazaki, senior managing director and division chief of Nichia's Optoelectronics Products division, the November 13 agreement with Cree was "almost the final step of our aggressive plan of licensing and settlement of patent issues for this year". If Nichia is going to sign another agreement this year, it could well be with Rohm, since the two companies have a number of outstanding lawsuits between them.

As the company that took the lead in commercializing nitride-based LEDs, Nichia established an extensive patent portfolio and took a firm stance against licensing. The company initiated a string of infringement lawsuits against its rivals, particularly Toyoda Gosei. However, over the course of the past two years a number of judgements were passed that significantly weakened Nichia's position (see *Compound Semiconductor* September 2002 p3).

The joint statement from Toyoda Gosei and Nichia announcing their settlement agreement acknowledged the key role played by the former company in developing blue LEDs. Although Nichia started work on blue LEDs in 1989 and was first to commercialize the devices in November 1993, Toyoda Gosei began to develop blue LEDs in 1986

and was responsible for a great deal of technology in this area. Some of this technology ended up in Nichia's patents, as the Japanese courts seem to have acknowledged.

Patent agreements

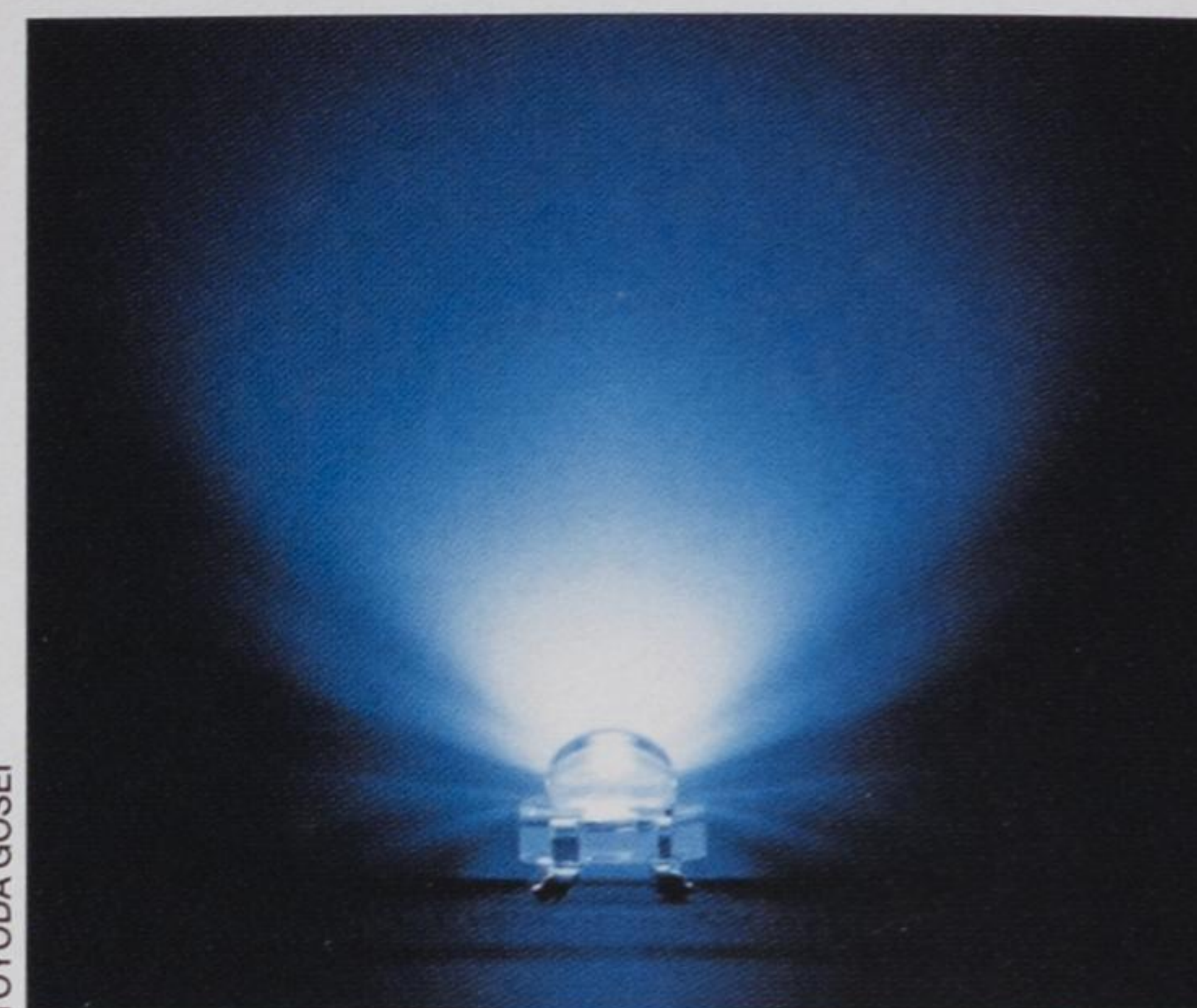
The individual agreements between Nichia and its four main rivals are very similar. Their main purpose is to end any existing lawsuits (although there weren't any in the case of Nichia and Lumileds) and to prevent future lawsuits from arising. Commenting on the Nichia-Lumileds agreement, Doug Silkwood, director of communications at Lumileds, said: "In essence, the two companies have agreed to use each other's intellectual property [IP] and not to sue one another." Similarly, Cree's president and CEO, Chuck Swoboda, said: "All litigation between Cree and Nichia is now completely ended. The agreement between our two companies is designed to let us work out disputes without litigation in the future."

Under each agreement, the participants are allowed to use each other's IP as described by certain patents; the agreements with Toyoda Gosei and Lumileds are quite broad, while the Osram agreement relates just to white LEDs. The Cree agreement relates to "nitride optoelectronic devices" thus including nitride LEDs and lasers but excluding, for example, any Cree IP related to SiC wafers or electronic devices.

Although some of the agreements include "cross-licenses", it is unlikely that royalty payments will be made. Both Lumileds and Cree were unable to comment on the issue of royalties. Nichia's agreement with Toyoda Gosei mentions that the companies will negotiate reasonable royalty payments in respect of future patents and products.

At present, the major financial implication of the deals is a reduction in legal expenses. Analysts at CIBC World Markets suggest that Cree currently has legal bills of around \$2 million per quarter. According to Chuck Swoboda, Cree and Nichia had the most in-depth legal battle of all the combatants, which consumed not only financial resources but also a large amount of staff time. "People underestimate how much of a distraction it is to both companies when they are in the middle of one of these disputes," he said.

The agreement between Cree and Nichia



Recent patent agreements will prevent any future lawsuits between the leading developers of blue, green and white LEDs.

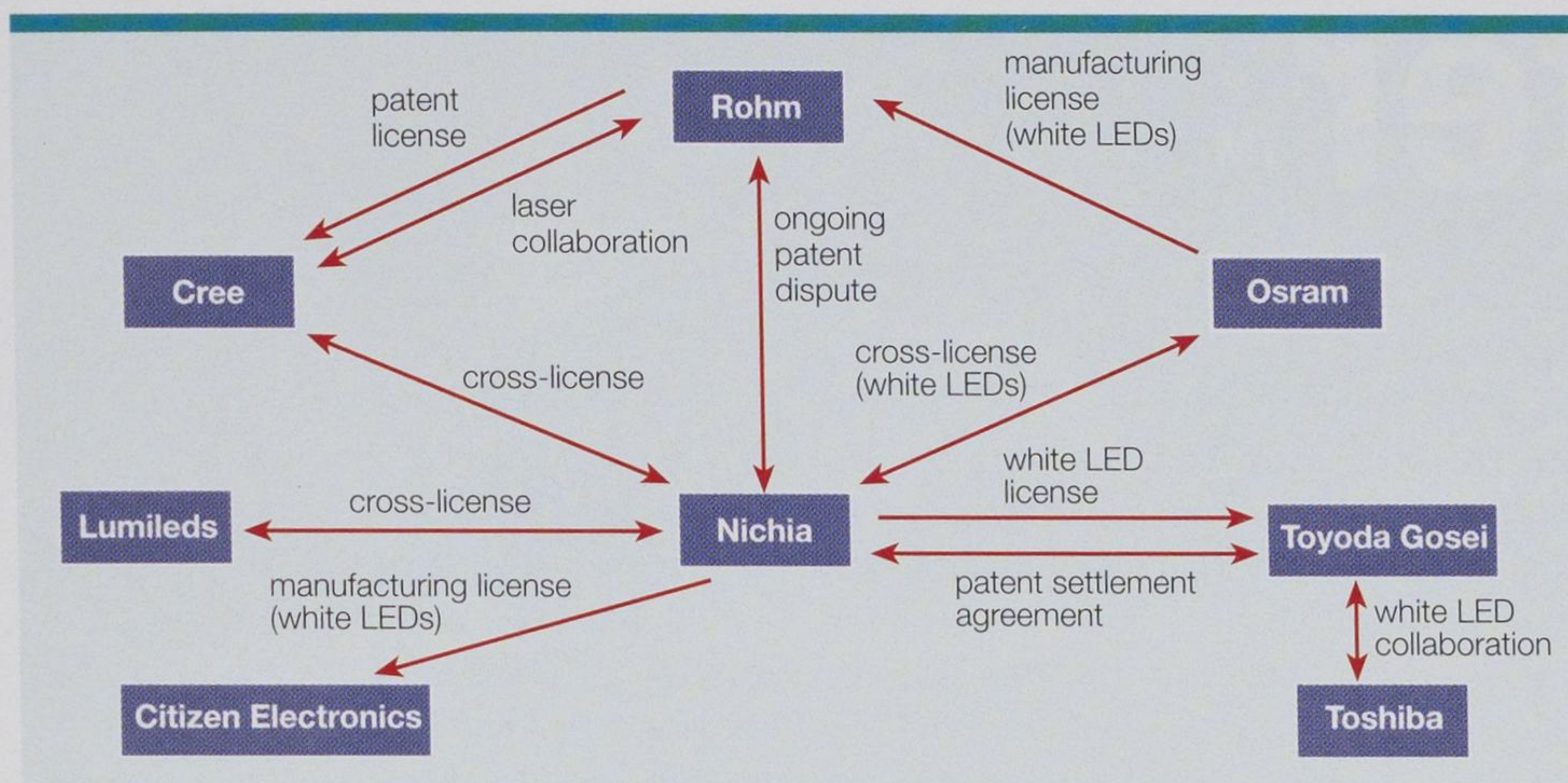
brings to an end a three-year dispute involving at least six separate cases. These included two infringement cases in Japan, in which Nichia sued both Cree and its Japanese distributor Sumitomo (these were under appeal after verdicts in favor of Cree and Sumitomo). After Cree filed a lawsuit in the US over a patent relating to lateral epitaxial overgrowth, Nichia responded with a counterclaim alleging infringement of four patents as well as trade-secret theft, filed against Cree, NCSU and Shuji Nakamura. There was also a second infringement suit filed by Cree, and an anti-trust claim filed by Nichia against Cree and Rohm. Cree is not involved in patent disputes with any other company.

Lumileds and Nichia

As well as averting patent disputes and associated supply issues, Lumileds and Nichia said that their cross-licensing agreement, announced on October 28, is also expected to accelerate the design of brighter LEDs by enabling each company to incorporate the R&D efforts of the other in new product development. This should hopefully pave the way for more rapid adoption of high-brightness LEDs for general lighting, by increasing the all-important lumens-per-dollar metric.

"Lumileds and Nichia have complementary technologies, so it makes sense to cooperate in the interest of advancing LEDs as a lighting solution for the 21st century," explained Nichia's Tazaki. "Cross-licensing will help accomplish that goal and expedite

Size nitride optoelectronics field



Intellectual property relationships between companies in the nitride optoelectronics field.

Osram grants white LED license to Rohm

The recent patent agreements have somewhat overshadowed an announcement that Osram has licensed its white LED manufacturing technology to Rohm. Osram has also indicated that it is open to approaches from other potential licensees.

Rohm will be allowed to make and sell white LEDs using technology covered by Osram's patents. The

technology, which was developed by Osram Opto Semiconductors, relates to white LEDs fabricated by combining blue InGaN-based chips with a suitable fluorescent converter.

"Over the years, we have built up a very strong position in the area of white LEDs and have a good deal of intellectual property at our disposal," explained Rüdiger Mueller, CEO of Osram

Opto Semiconductors.

The company is also looking for other licensees. "We are basically willing to grant licenses to other companies," said Mueller. "The demand for white LEDs is growing so quickly that for capacity reasons we are not able to provide all the products the market is calling for." In February this year, Nichia granted a similar manufacturing license to Citizen.

the development of brighter and more cost-efficient LED-based lighting."

According to Doug Silkwood, the agreement is quite broad. It includes Lumileds' AlInGaP technology (although there is no indication that Nichia plans to move into this area), and it is not market- or application-specific. "We cannot discuss either royalties or timelines, but the agreement does apply to future IP from both companies," added Silkwood.

Rather than settling an ongoing dispute, this is a pre-emptive strike to prevent any lawsuits between the companies. "There were no ongoing lawsuits between Nichia and Lumileds," said Silkwood, "but it was possible that disputes could have arisen in the future. Our agreement averts that possibility."

At present, the only information shared by Nichia and Lumileds is the IP contained in their respective patents. Asked whether there is an active development program between the companies, Silkwood responded: "There is nothing at this point, and nothing in the agreement, but the door is open."

Silkwood says that one key aspect of the agreement is that it could stimulate a dialogue between all players in the industry to develop standards. "The agreement indicates that two market leaders are talking to one another and considering the benefits of growing the whole industry rather than just increasing their own market share," said Silkwood. "We hope other LED manufacturers can now be prompted to start talking about worldwide standards."

Where does this leave the market?

Naturally, the companies involved have put a positive spin on their various agreements. Chuck Swoboda said: "These agreements will help the companies concerned to spend more time doing what they're supposed to do, which is focusing on their core business, driving the technology forward and getting products to market. From that standpoint I think the agreements are a positive sign for the market."

However, as the situation stands at present, only those companies directly involved in the agreements stand to benefit. As Swoboda points out, the companies that have settled are the ones that have been working on this technology the longest, and that have the broadest IP portfolios.

In the case of nitride lasers, for example, both Cree and Toyoda Gosei are now free to join Nichia in the commercial market without worrying about patent issues (assuming their products work), but what about other potential competitors such as Sharp, Sanyo and Sony? Sanyo has developed a structure that uses a GaN substrate, a vertical contact arrangement and ion implantation to provide confinement, thus circumventing key patents relating to InGaN-on-sapphire devices (see *Compound Semiconductor* May 2002 p10). Other entrants will be forced to find their own way around existing patents. Given the recent changes in the industry, the other option might be licensing.

One key question now is: what will Nichia do next? As the company that initiated the patent disputes with its competitors, will Nichia now commence legal proceedings against any other companies that it views as having infringed its patents? The most obvious targets are the large number of nitride LED makers in Taiwan. Alternatively, will Nichia offer to license its technology, in return for royalty payments, to existing and potential competitors? And furthermore, after its bruising battle with Toyoda Gosei, is Nichia in a position to challenge other companies, or should it actually be Toyoda Gosei that considers either licensing or litigation? The answers to these questions will be crucial to the future of the nitride optoelectronics industry.

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Metal bonding delivers high-power AlGaInP-on-silicon LEDs

Wafer bonding of AlGaInP LED epilayers to silicon substrates using metallic interlayers results in very-high-power devices, write **Pai Hsiang Wang and colleagues** from United Epitaxy Company.

United Epitaxy Company (UEC) has released the world's first 10 watt high-power LED. The device is made by bonding an AlGaInP LED epiwafer to a silicon substrate, after which the light-absorbing GaAs substrate is removed. A high-reflectivity metal layer is also inserted between the LED structure and the silicon substrate, in order to reflect the light that would otherwise reach the light-absorbing silicon substrate. Using both metal reflector and metal bonding technologies, a single high-power light emitter with a chip size of $2.5 \times 2.5 \text{ mm}^2$ can provide a total flux of more than 200 lumens.

The introduction of high-brightness AlGaInP red, orange and yellow LEDs in the early 1990s, followed by AlGaInN blue, green and white devices, has created many new applications – such as traffic signals, automotive lighting and full-color outdoor displays – for these highly efficient solid-state lighting sources.

Highly efficient LEDs have also started to replace conventional incandescent light bulbs and halogen lamps. However, although LEDs are more reliable than these other light sources, the extent of replacement has been quite low. One of the major reasons for this is that the price, in lumens per dollar, is too high. Incandescent bulbs cost about \$0.001 per lumen, while LEDs can only achieve around \$0.1 per lumen, which is about two orders of magnitude higher.

The other reason for the low penetration rate of LEDs into conventional lighting is that the total flux from a standard 5 mm LED package operating at 20 mA is only about 1 lumen. Many of the applications that use conventional incandescent bulbs or halogen lamps need a few hundred or even several thousand lumens. Hundreds or thousands of LEDs are therefore needed to achieve the same total light output, and the total assembly size can then be too large for some applications.

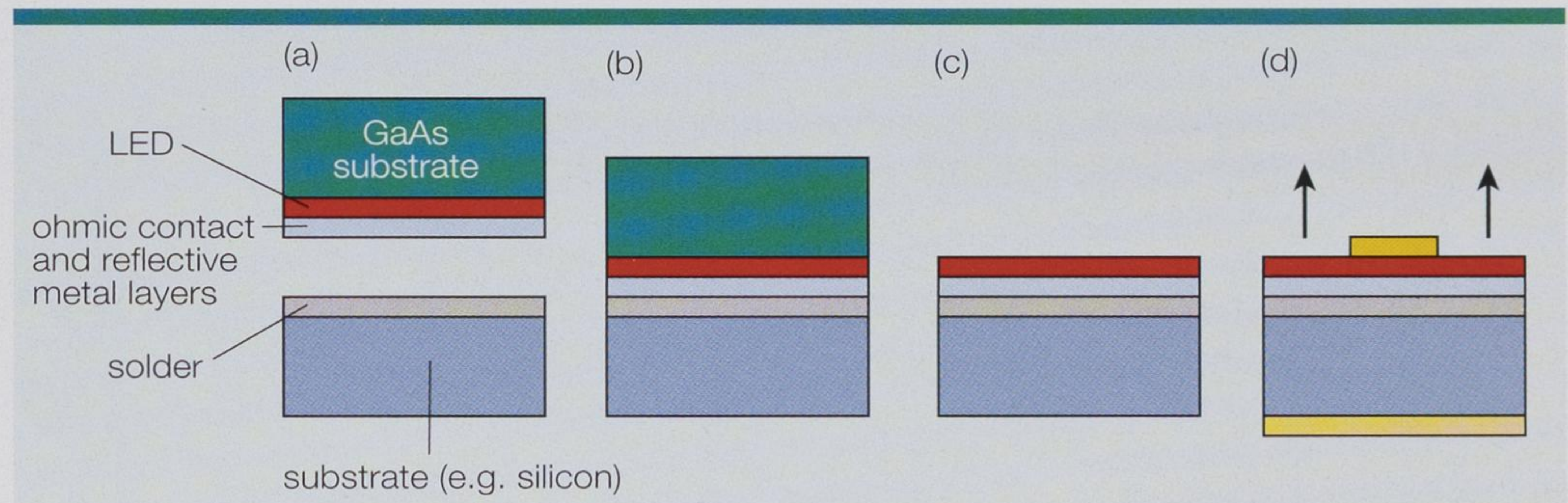
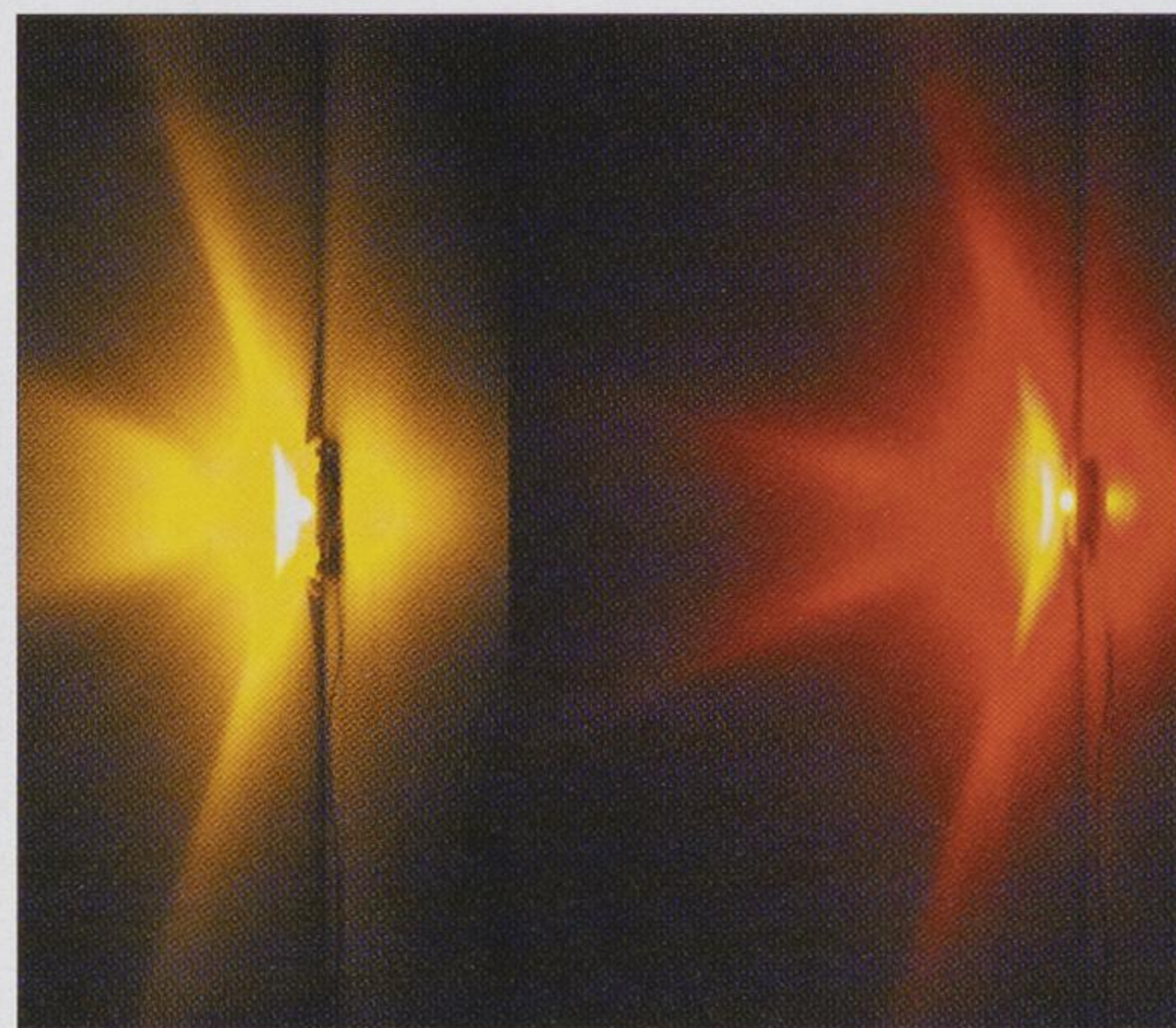


Fig. 1. The process flow for fabricating metal bonding (MB) LED chips. (a) An ohmic contact metal and a high-reflectivity metal layer are deposited onto an LED epiwafer, and a solder layer is deposited onto a substrate (silicon, metal, SiC etc). (b) The mirror metal and solder layers are bonded together at a low temperature. (c) The GaAs substrate is removed by lapping and chemical etching. (d) Top and bottom ohmic contact metals are deposited and annealed. Finally, the MB AlGaInP LED wafers are sawed into individual discrete chips.



Yellow and red AlGaInP-on-silicon LEDs that were fabricated using UEC's metal bonding process. The chip size for these devices is $2.5 \times 2.5 \text{ mm}^2$.

Improving performance

There are several different approaches to solving the above problems. First, if the luminous efficiency of a single $0.3 \times 0.3 \text{ mm}^2$ single emitter can be improved, the dollars per lumen value can be reduced. Luminous efficiency can be increased in several ways, including improvements in material qual-

ity, better design of LED epiwafer structure, using non-absorbing substrates, or using chip shaping or surface texturing to achieve higher light-extraction efficiency.

Second, the current injected into the LED per unit chip area (i.e. the current density) can be increased. If the light output versus drive current is quite linear up to higher current values without saturation, then the total flux from a single LED driven by higher current with the same chip size should be several times higher compared with operating just at 20 mA. The maximum current that can be injected into the LED chip is determined by two main factors. The operating current has to remain below the level that causes significant degradation, and also below the level at which the efficiency (in lm/W) starts to fall rapidly. LEDs are normally operated at a current density of around 20 A/cm^2 . However, some of the latest high flux LEDs can be operated at $70\text{--}80 \text{ A/cm}^2$.

Removing heat

Another approach is to adopt chip and package designs that provide better heat dissipation. AlGaInP and AlGaInN LED epiwafers are grown on GaAs and sapphire (or SiC)

LIGHT-EMITTING DIODES

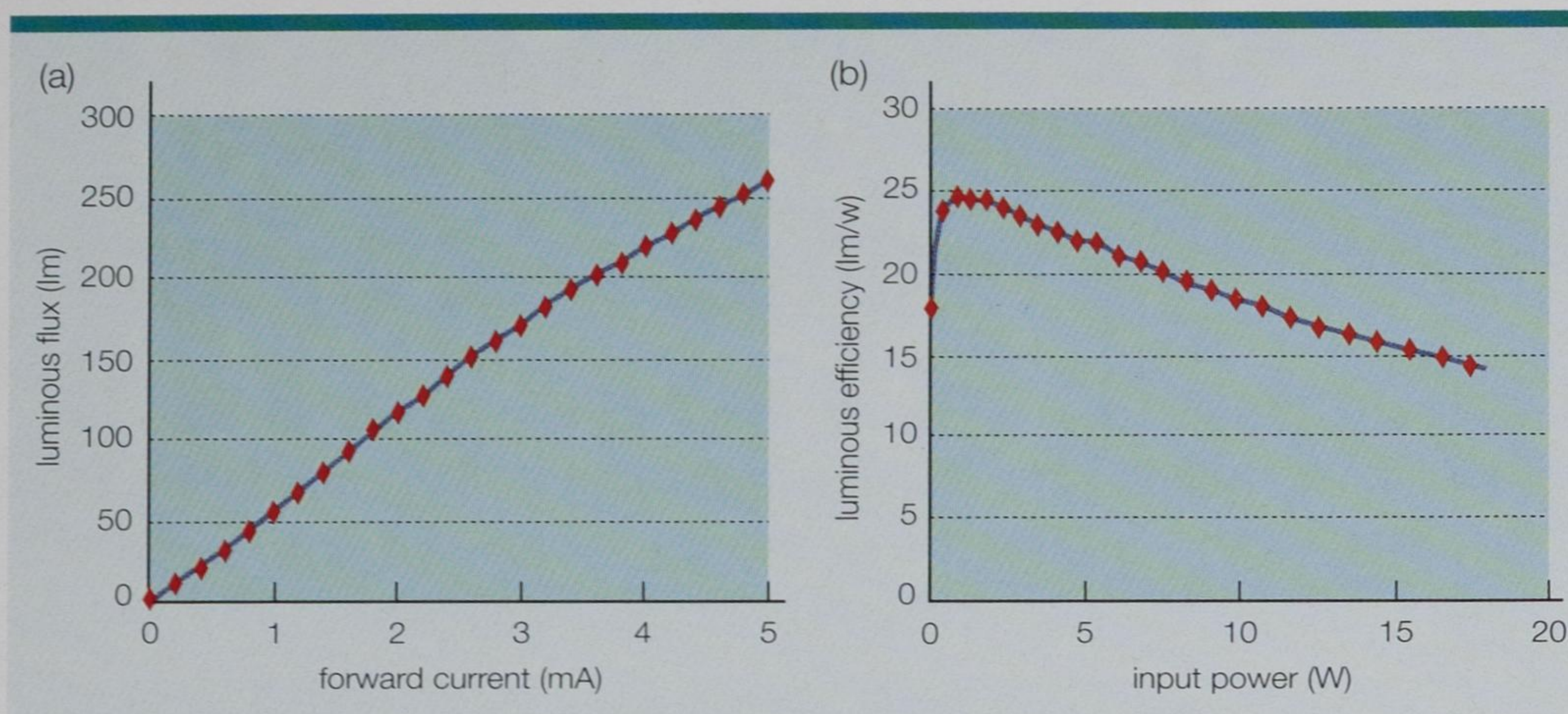


Fig. 2. The L-I (a) and luminous efficiency (b) characteristics of a high-power metal bonding AlGaInP-on-silicon LED with a chip size that measures $2.5 \times 2.5 \text{ mm}^2$.

substrates, respectively. As shown in the table, GaAs and sapphire substrates have relatively low thermal conductivity values of 44 and 35 W/m.K, respectively.

There are three different approaches to remove heat and lower the junction temperature more effectively. The first technique is to thin the substrate, while the second is to flip the chip, which positions the light-emitting p-n junction close to the heat sink. The third approach is to remove the original substrate that was used for growing the LED epilayers, and then transfer the epitaxial structure to an electrically and thermally conductive substrate.

The first approach is the easiest, but it is difficult to thin the substrate to less than 100 μm . The second approach is now used by Matsushita and Lumileds to improve both luminous efficiency and heat dissipation in GaN LEDs. However, the flip-chip process is complicated and expensive.

Many companies, including UEC, VPEC and AET in Taiwan, Osram Opto in Germany, Sanken in Japan and Oriol in the US, have used the third approach and announced the successful development of metal bonding (MB) LEDs, in which metal layers are used to bond the LED to a conductive substrate. This approach is now emerging as the most cost-effective method to make high-power LED chips.

Device fabrication

Figure 1 shows the schematic process for manufacturing MB-type AlGaInP high-power LED chips. The process starts with the epitaxial growth of the LED structure on a GaAs substrate. A grid-pattern ohmic contact metal layer and a high-reflectivity metal layer are deposited on the top surface of the LED epi-

Thermal conductivity

Substrate	Thermal conductivity (W/m.K)
GaAs	44
sapphire	35
silicon	145.7
SiC	490
aluminum	237
copper	401

Table showing the thermal conductivity values of a variety of substrate materials.

The total flux from a single metal bonding AlGaInP-on-silicon emitter is more than 200 lumens at 12 W input power.

wafer. To obtain high reflectivity in the 560–650 nm wavelength range, the reflector metal material can be chosen from either gold, aluminum or silver, all of which have a reflectivity of more than 90%.

The AlGaInP LED epiwafer with its metal reflector is then bonded to an electrically and thermally conductive substrate using a low-temperature solder layer. After bonding, the light-absorbing GaAs substrate is removed by either chemical etching or a combination of mechanical lapping and chemical etching. The top and bottom ohmic contact metals are then deposited and annealed. Finally, the metal-bonded AlGaInP LED epiwafers are sawed into individual discrete chips.

Figure 2a shows the L-I characteristics

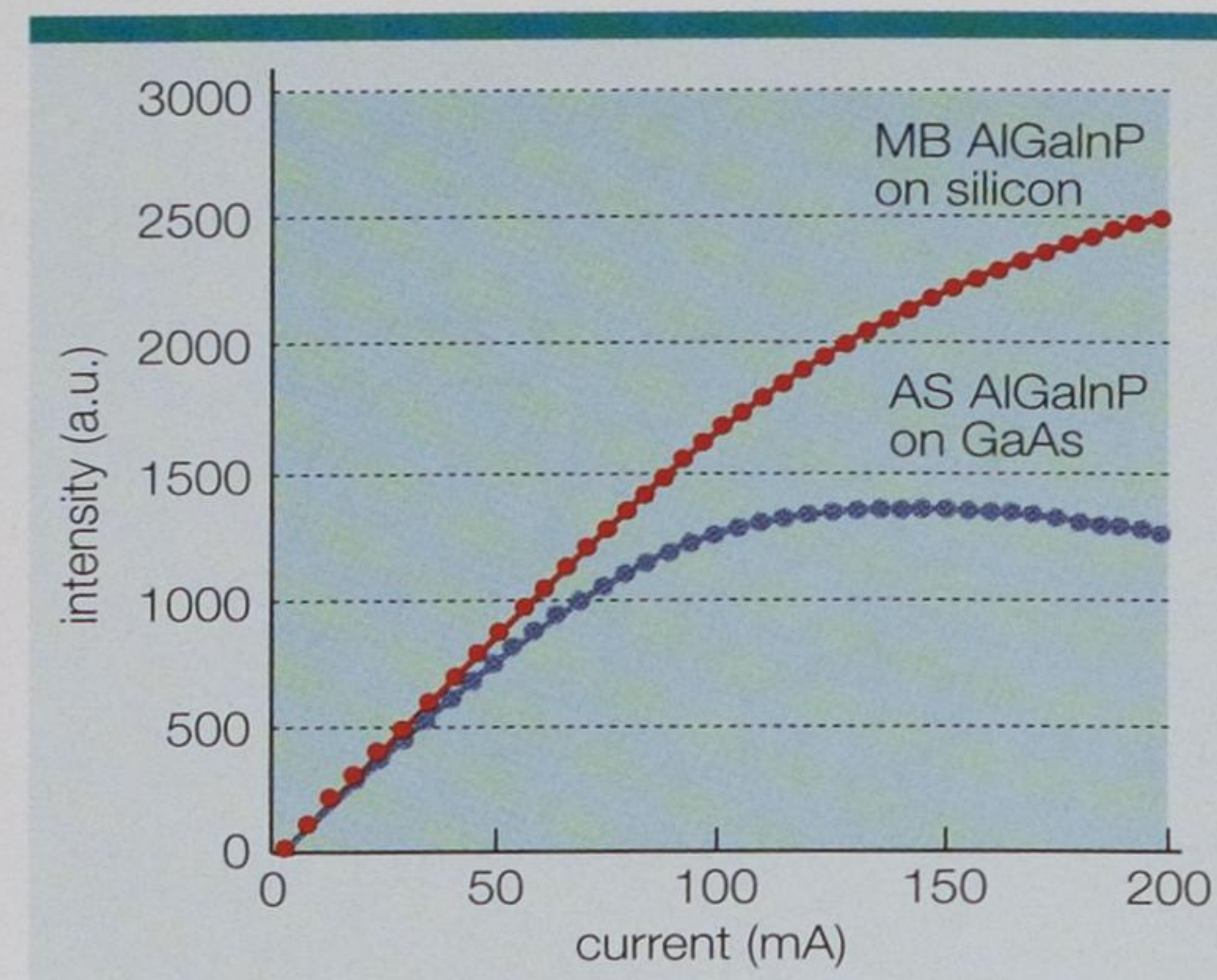


Fig. 3. A comparison of the L-I curves for absorbing substrate (AS) AlGaInP-on-GaAs and metal bonding (MB) AlGaInP-on-silicon LEDs measuring $0.3 \times 0.3 \text{ mm}^2$.

of a high-power MB AlGaInP-on-silicon LED with a chip size of $2.5 \times 2.5 \text{ mm}^2$. The light output increases linearly with drive current up to 5 A. The total flux from one single emitter is more than 200 lumens at 12 W input power, and the luminous efficiency is around 18 lm/W. Figure 2b shows that the efficiency falls slowly as the input power is increased.

Figure 3 compares the L-I characteristics of absorbing substrate (AS) AlGaInP-on-GaAs LEDs and MB AlGaInP-on-silicon substrate LEDs, for $0.3 \times 0.3 \text{ mm}^2$ devices. The highest brightness AS-type LEDs, which were chosen for comparison, are only about half as bright at 150 mA as the MB-type LEDs, reflecting the much better heat dissipation and light extraction capabilities of the latter devices.

Summary

UEC has been developing its metal bonding technology for AlGaInP LEDs on silicon substrates for about three years. The company plans to commence mass-production of these high-power AlGaInP LED chips in the first quarter of 2003.

Furthermore, UEC is improving a new technology that will bond the AlGaInP LED epiwafer to a metal substrate such as aluminum or copper, or to other good materials with high thermal conductivity. Samples of these new AlGaInP-on-metal high-power LEDs will be released later this year.

Pai Hsiang Wang, Kuang Neng Yang, Tzer Perng Chen and Chih Sung Chang are with United Epitaxy Company, Science-Based Industrial Park, Hsinchu, Taiwan, ROC. Email phwang@uec.com.tw.

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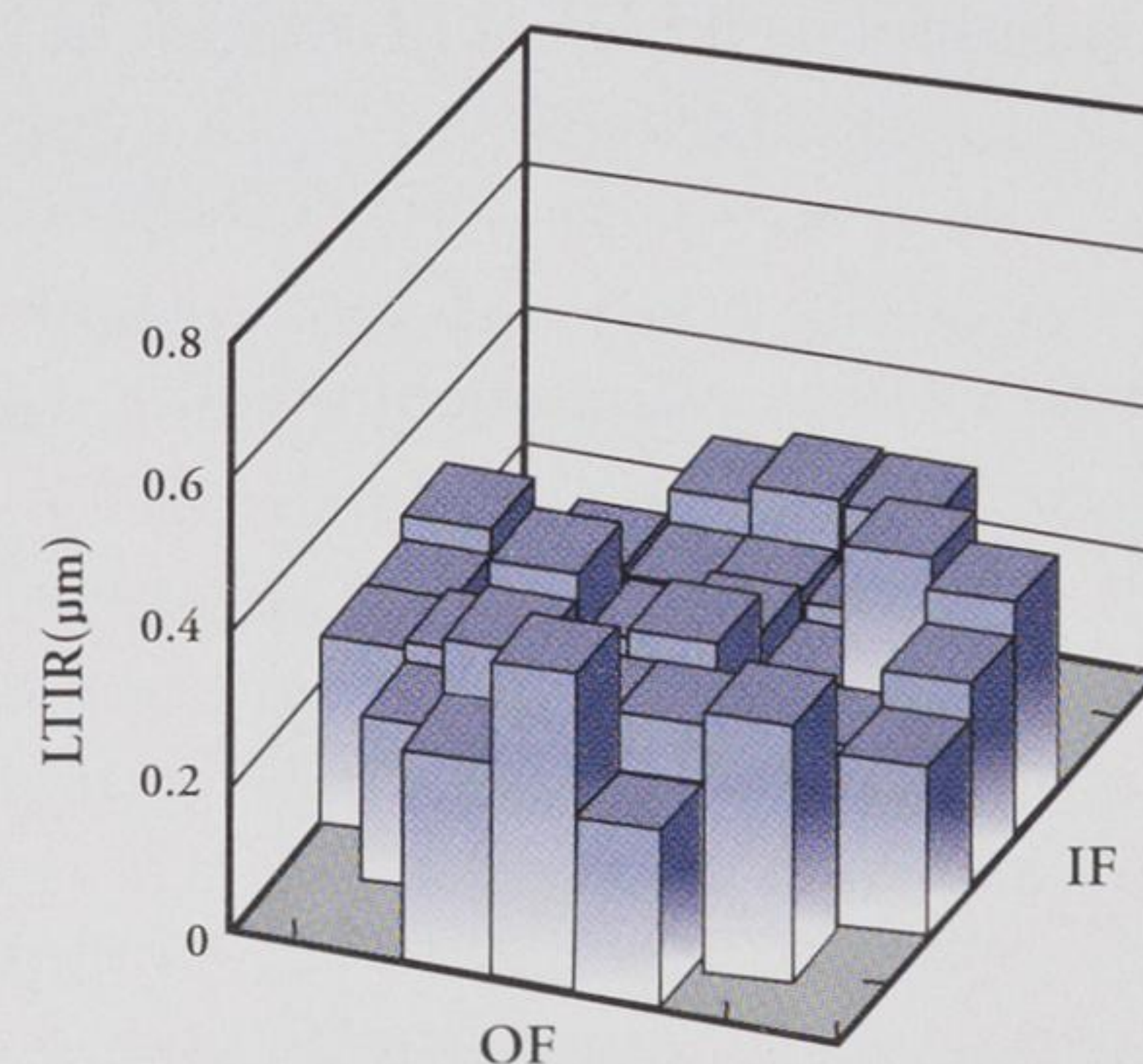
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Site size: 12mm (37sites), LTIRmax=0.40μm, TTV=1.52μm

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LIGHT-EMITTING DIODES

High-speed UV laser scribing boosts blue LED industry

Scribing sapphire or SiC wafers using UV lasers results in higher yield, higher throughput and reduced cost per die, according to **Jongkook Park** and **Patrick Sercel** of JP Sercel Associates.

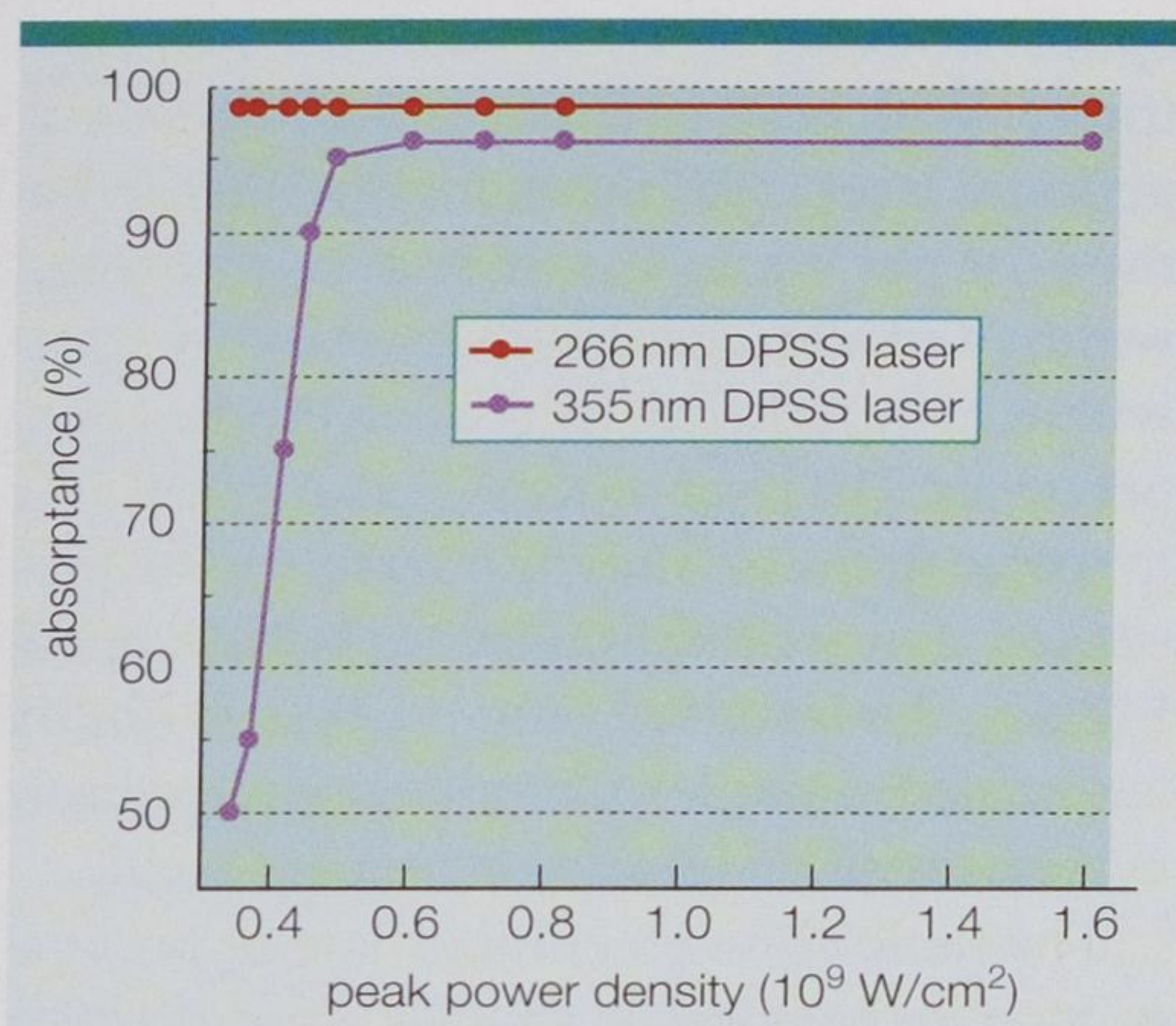


Fig. 1. UV laser light absorbance versus irradiance (W/cm^2) in LED-grade sapphire. The wafer thickness is $100 \mu\text{m}$.

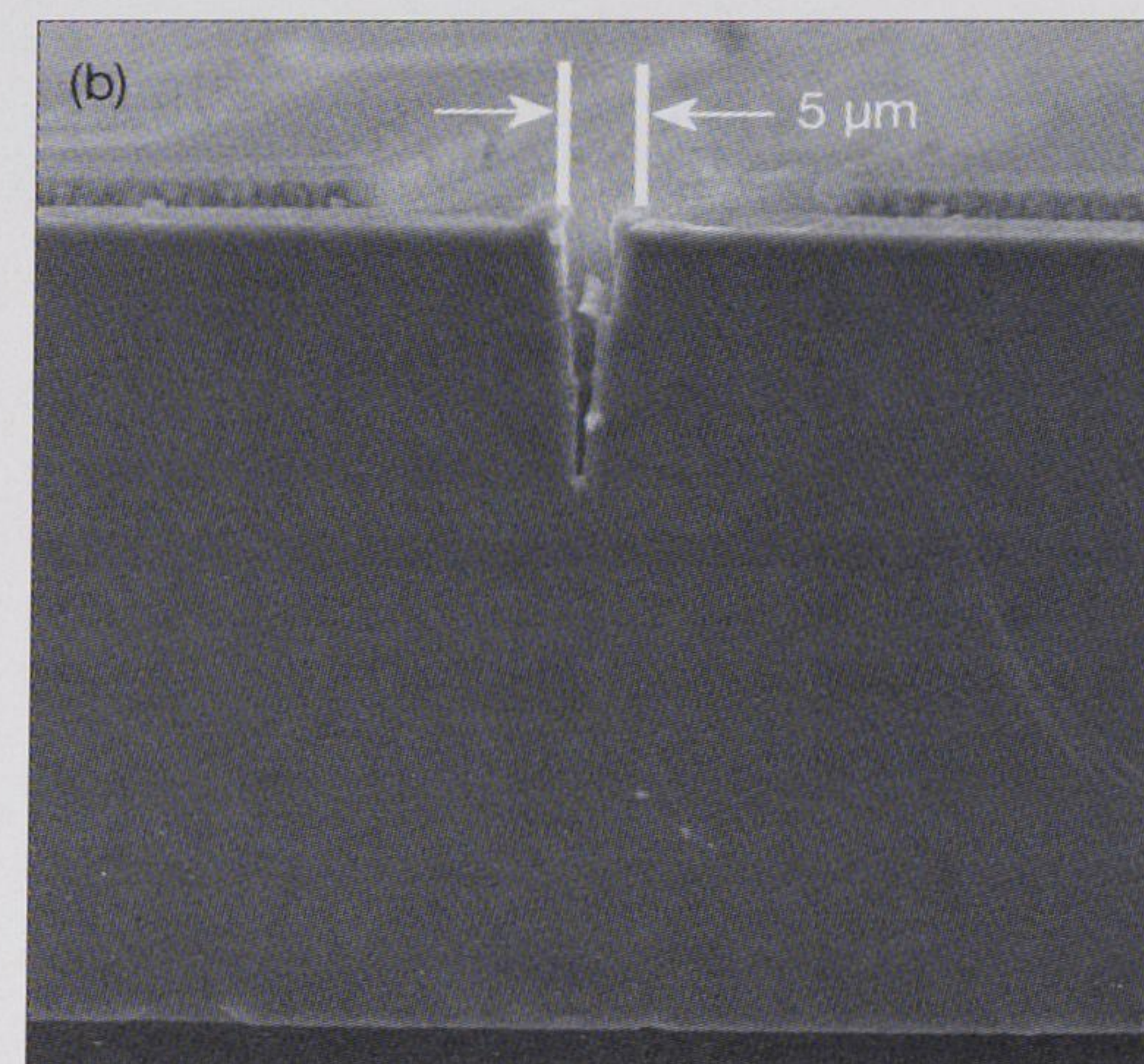
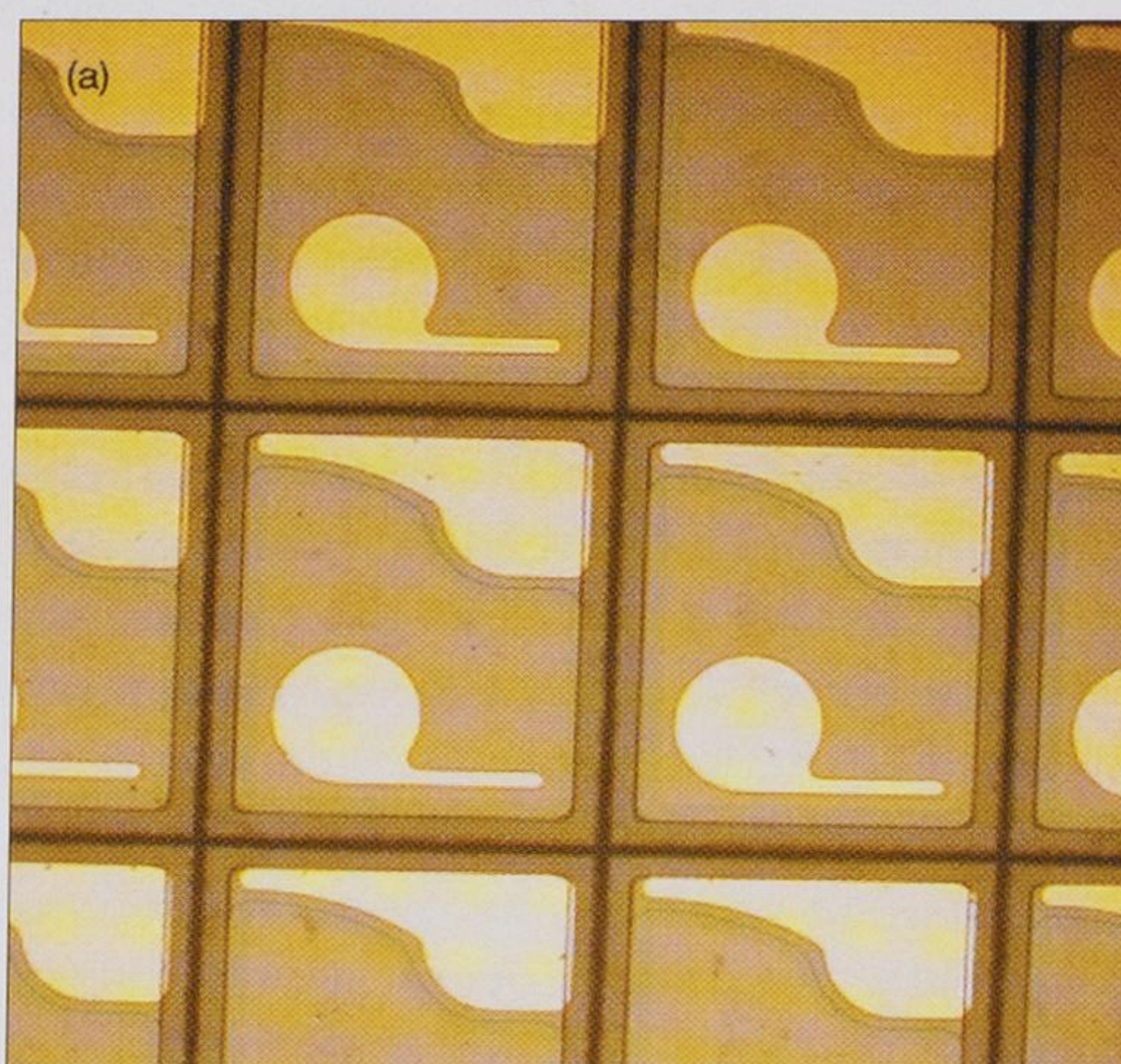


Fig. 2. A blue LED wafer (sapphire) scribed with a 266 nm DPSS laser system. (a) top view of $5 \mu\text{m}$ wide cuts in $50 \mu\text{m}$ streets. (b) wafer cross-section showing a $30 \mu\text{m}$ deep V-shaped cut.

Exploding worldwide demand for high-brightness blue-light LEDs has driven the development of new production processes to increase throughput, reduce cost and improve tool reliability. One area of particularly intense development is the die separation process.

Blue LEDs consist of multiple GaN-based layers grown epitaxially on a silicon carbide or sapphire substrate. SiC wafers are typically diced using high-precision saws, while sapphire wafer die separation is a three-step process. First, the wafer is thinned to a thickness of about $100 \mu\text{m}$. Then it is mechanically scribed with a diamond tool, and finally cleaved along the scribe lines by means of a fracturing machine. The extreme hardness of blue LED substrates and the small LED die size cause significant problems for both saw dicing and mechanical scribing, including low die yield, low throughput and high operating costs.

UV laser scribing is now emerging as an alternative method for separating blue LEDs. Compared with conventional separation methods, the UV laser scribing method dramatically increases die yields and wafer

throughput, while at the same time significantly reducing the equipment operation and maintenance costs.

The physics of UV laser scribing

When short-duration UV laser light pulses are tightly focused onto the wafer surface, each pulse is absorbed into a sub-micron thick surface layer, which then vaporizes. The vaporized material carries away the energy of the interaction, minimizing heat transfer to the surrounding material. This process is known as photoablation. In order to produce deep cuts, hundreds of successive laser pulses are required.

Moving the wafer under a rapidly pulsed, focused laser beam produces an extremely narrow V-shaped cut, the depth of which is controlled by the scan speed. Typically, these cuts terminate 30–50% into the thickness of the wafer. After laser scribing, the wafer is fractured using standard cleaving equipment. The V-shaped laser cuts act as stress concentrators, inducing well controlled fracturing with excellent die yield.

Efficient photoablation is required for laser scribing and depends strongly on two

properties of the UV laser light: wavelength and pulse duration. In general, photoablation benefits from a shorter laser wavelength and shorter pulse duration, for both optical and thermal reasons.

The key benefits achieved by short laser pulse duration are increased irradiance on target, and reduced heat transfer to the substrate due to the rapid absorption and ablation. For short laser wavelengths, the main benefits are improved optical absorption, reduced absorption depth, lower irradiance required for ablation and reduced cut width.

Shorter wavelengths impart more energy per photon. For SiC, optical wavelengths below 370 nm have photon energies that exceed the bandgap of the material, resulting in direct photon absorption. However, sapphire has a bandgap that is higher than the photon energy of any commercially available UV laser. Multi-photon absorption is therefore required to induce efficient optical absorption. Typically, the necessary irradiance (W/cm^2) for multi-photon absorption is very high. The efficiency of multi-photon absorption in sapphire is strongly wavelength dependent. Shorter wavelengths are absorbed more completely

LIGHT-EMITTING DIODES

Comparison of sapphire wafer scribing processes

	Diamond scribing	Excimer laser [†]	DPSS laser [‡]
laser wavelength (nm)	N/A	248	266 & 355
cut width (μm)	~1–2	15	~5
cut depth (μm)	N/A	30–35	30–35
throughput (wafers/hour)*	1	3	5
die yield	< 90%	> 99%	> 99%
operating cost (\$/wafer)*	80	8	< 2
uptime (including maintenance)	~90%	> 97%	> 99%
process automation	manual	fully automatic	fully automatic

*Assumes a typical 2 inch diameter sapphire wafer with 350 μm × 350 μm die pitch. [†]Based on JPSA IX-1000 ChromaDice excimer laser scribing system. [‡]Based on JPSA IX-300 ChromaDice II DPSS laser scribing system.

in sapphire, resulting in less heat input to the bulk material. Figure 1 shows the optical absorptance of industrial-grade sapphire at 355 and 266 nm, over a range of irradiances. Note that the maximum absorption at 355 nm is about 96%, while the maximum absorption at 266 nm is greater than 99%.

The combination of short wavelength and short pulse duration provide complimentary benefits of improved absorption and ablation at lower irradiance, reduced heat transfer to the substrate, smaller cut width, and larger area coverage of the beam spot. These combined benefits serve to optimize cut speed and cut quality. Further, the smaller cut width helps to minimize surface debris.

UV laser scribing technology

Industrial scribing systems using 248 nm KrF excimer lasers have been used in high-volume production since 1999. Due to the large pulse energy (typically 200 mJ) and low repetition rate (400 Hz) of excimer lasers, special beam delivery techniques are required to achieve the necessary scribing throughput. The delivery of a line beam on the wafer is achieved by illuminating a line-shaped mask with laser light, and then projecting an image of the mask onto the wafer using a near-field imaging system. This type of line imaging system limits beam utilization to approximately 10%. In practice, the minimum achievable cut width is 15 μm. To improve beam utilization, JP Sercel Associates (JPSA) has developed beam delivery systems that project multiple lines, significantly increasing cutting speed.

Recently, the developments in UV diode-pumped solid-state (DPSS) laser technology have resulted in lasers with sufficient average power to be considered for blue LED wafer dicing. A 5 W, 355 nm DPSS laser typically produces pulse energies of 0.1 mJ at a repetition rate of 50 kHz, permitting the use of a more traditional focal-spot beam delivery sys-

tem. The absence of a mask imaging system results in almost 100% beam utilization.

However, 355 nm DPSS lasers with pulse durations greater than 40 ns cannot achieve the necessary irradiance for efficient multi-photon absorption. Recent studies of LED performance suggest that LED light output is reduced by more than 10% by the 355 nm scribing process, regardless of laser pulse width. This performance degradation seems to be a direct result of the laser wavelength.

JPSA has recently developed a 266 nm DPSS laser scribing process, which inherits the advantages associated with the 248 nm excimer wavelength, while maintaining the fast processing speed of the 355 nm DPSS process. Cuts made with the 266 nm laser exhibit excellent edge quality, similar to the excimer process. In addition, the 266 nm process promises to match the throughput of the 355 nm process, despite the lower average power output of 266 nm DPSS lasers.

Figure 2 shows an example of a GaN-on-sapphire LED wafer processed using a 266 nm DPSS laser. The laser cut, with a width of 5 μm, forms a sharp V groove that is ideal for well controlled fracturing. Initial results indicate that the 266 nm scribing process solves the LED light output problem that is associated with the 355 nm process.

Economic considerations

Conventional saw dicing and mechanical scribing processes exhibit a number of problems when used with extremely hard SiC and sapphire substrates. Throughput is low, about one wafer per hour per system. Tool wear is also a significant issue; typically, dicing blades or diamond scribe tips are consumed at a rate of one per wafer. In addition, these processes are very sensitive to wafer flatness, and warped, crowned, or bowed wafers cannot be processed. Cut alignment is also a challenge. Streets between die must be large

to avoid cutting into devices and this results in a lower die count per wafer, which drives up unit cost. Lastly, saw dicing and mechanical scribing are labor-intensive processes. Process yield is directly related to the skill of the equipment operator.

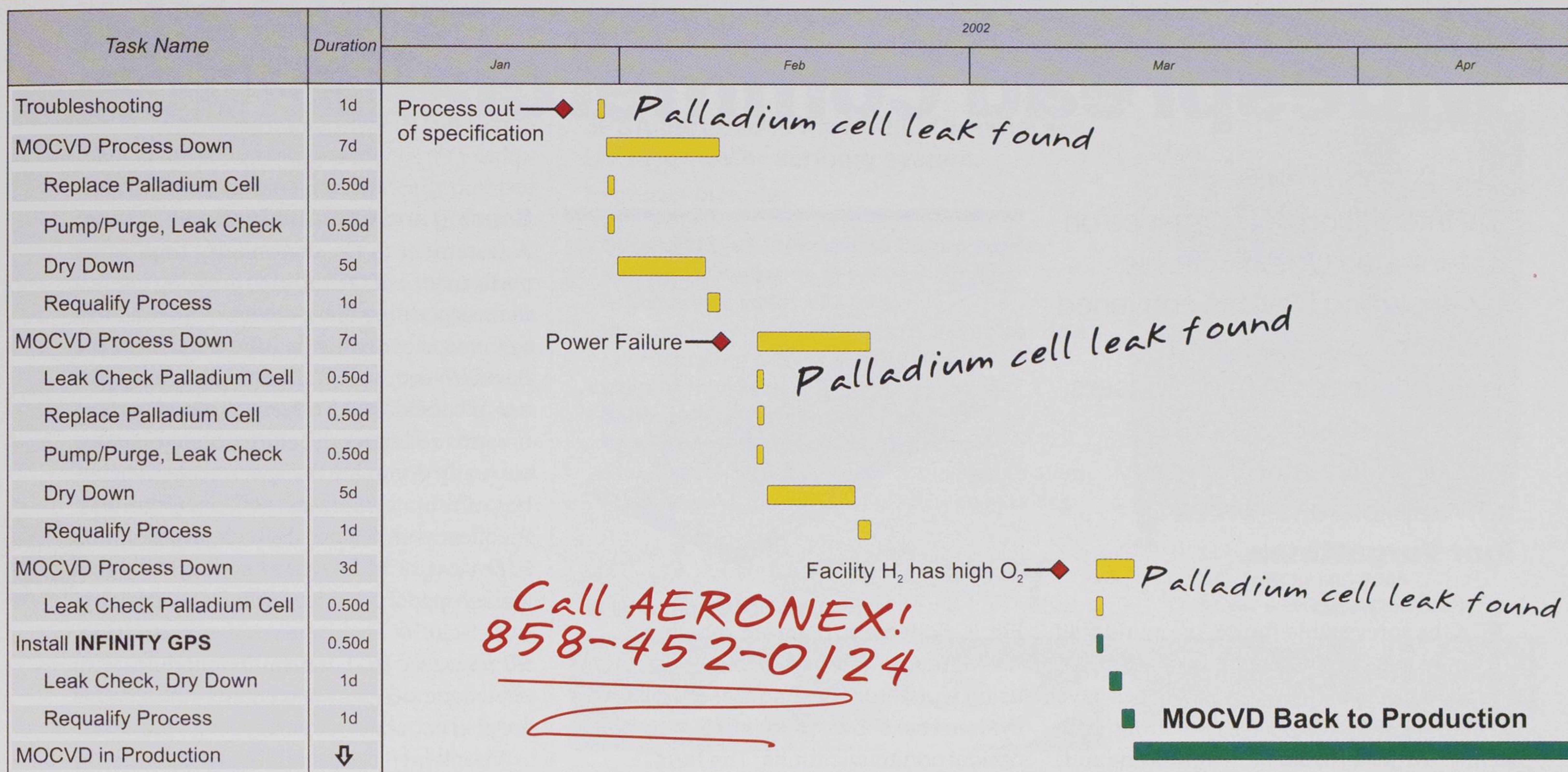
In contrast, UV laser scribing produces consistently excellent results with better than 99% yield. Throughput is high, up to five wafers per hour per system, and the non-contact nature of the laser process greatly reduces the cost of consumables. Using excimer lasers, the main consumable items are laser gas and optics, while DPSS lasers consume only electricity. With both excimer and DPSS lasers, periodic laser refurbishment is required, but the cost per wafer is minimal. Narrow cut widths and consistent alignment allow street widths to be reduced, increasing the die count per wafer. The laser process is also insensitive to wafer flatness, allowing wafers to be processed that would otherwise be scrapped. Finally, the laser scribing process is highly automated; a single operator can run multiple systems with no impact on process yield.

The table shows a comparison of process economics between mechanical, excimer laser and DPSS laser scribing. All data are based on a typical 2 inch sapphire wafer with 350 × 350 μm² die pitch. As the table shows, both the excimer and UV-DPSS processes deliver significant economic benefits in every aspect of the scribing process. For UV-DPSS lasers, the operating cost is estimated at less than \$2 per wafer, with uptimes easily exceeding 99%. Compared with mechanical scribing, the DPSS laser process improves wafer throughput by 500%, with a 97.5% reduction in operating costs. Added to that is the 10% increase in product yield, and the 15% increase in die count per wafer permitted by laser scribing.

In summary, conventional die separation processes are no longer practical in terms of throughput and cost. UV laser scribing is poised to become a key enabling technology that solves the significant manufacturing and economic challenges facing the blue LED industry. Not surprisingly, UV laser scribing has caught the interest of the world's leading blue LED manufacturers.

Jongkook Park (jpark@jpsalaser.com) is a senior applications engineer and Patrick Sercel (pjsercel@jpsalaser.com) is VP of Technology at JP Sercel Associates Inc, a manufacturer of UV laser micromachining and materials processing systems. Web www.jpsalaser.com.

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Mid-IR devices on the brink of widespread commercialization

The International Conference on Mid-Infrared Optoelectronic Materials and Devices convened in Annapolis to discuss the latest advances in mid-IR lasers, LEDs and detectors that are eagerly anticipated for many new applications, writes **Igor Vurgaftman**.

In the foreseeable future, we could find ourselves surrounded by mid-IR optoelectronic devices. These devices have tremendous potential for applications such as inter-office broadband wireless communication links, sensors monitoring environmental pollution, screening machines at airports and jamming lasers that render military aviation immune to threats from heat-seeking missiles. From September 8–11, around 130 researchers from 16 countries met in the unhurried setting of Annapolis, MD, at the Fifth International Conference on Mid-Infrared Optoelectronic Materials and Devices (MIOMD-V), to discuss the recent advances in lasers, LEDs, detectors and frequency converters that are behind these future applications.

Quantum cascade lasers

Quantum cascade lasers (QCLs) are the most mature coherent source for the 4.5–15 μm spectral region. In the QCL, each injected electron can emit multiple photons as it hops between conduction subbands arranged in a staircase-like geometry. State-of-the-art QCLs are capable of operating in CW mode at temperatures of up to 39 °C, and producing a few mW of optical power at ambient temperature.

Daniel Hofstetter of the University of Neuchâtel in Switzerland emphasized the importance of improvements in the QCL active-region design in lowering the threshold current density to 5 kA/cm² at room temperature. Thermal management has also

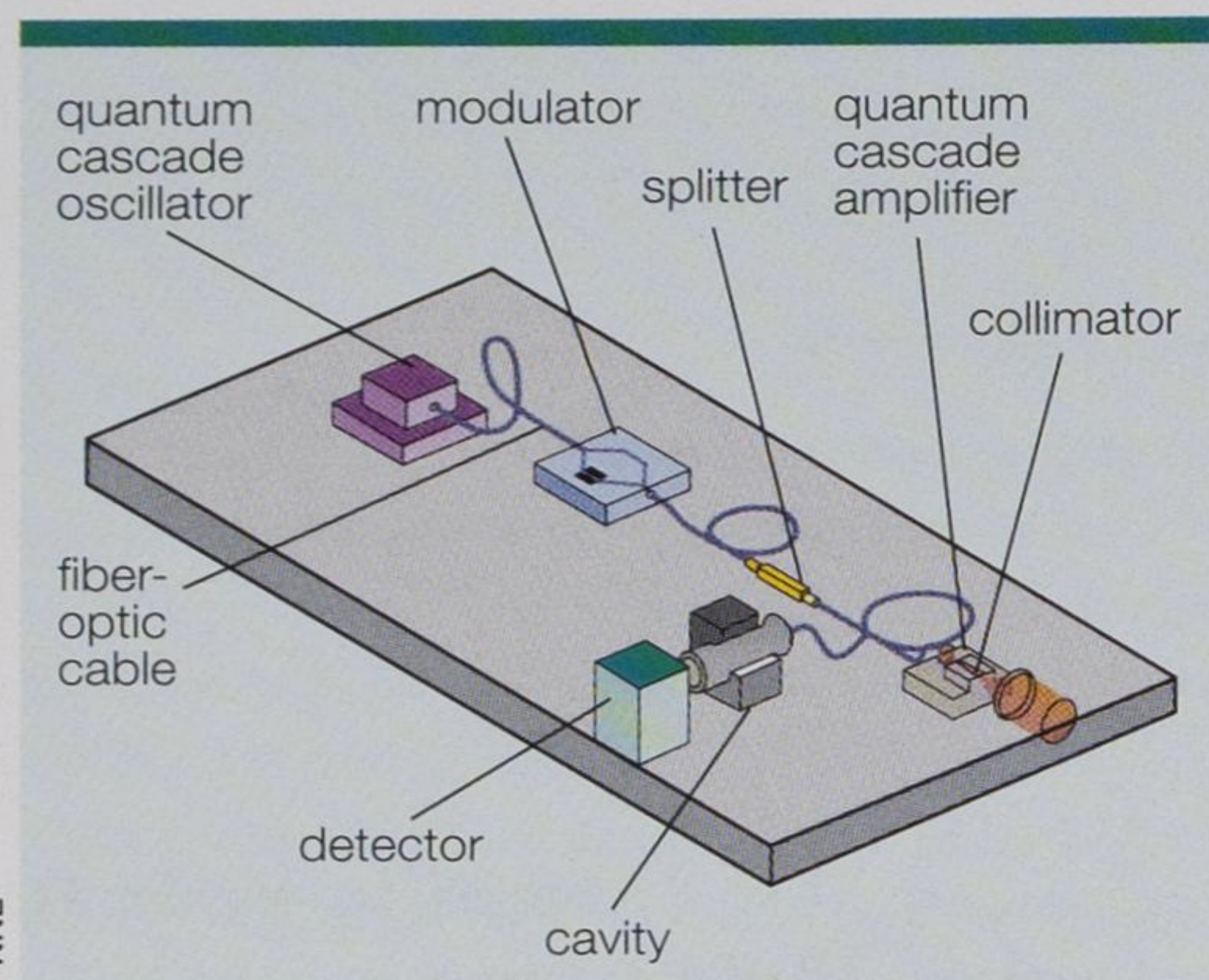


Fig. 1. Schematic diagram showing a “breadboard” integration experiment using a quantum cascade laser-based system that shows promise for free-space optical communications. The term breadboard refers to the size of the experimental set-up (30 x 60 cm), which is currently being miniaturized.

been improved through junction-side-down mounting of narrow-ridge devices on a diamond heat sink. Hofstetter also described single-mode DFB QCLs that are operated in CW mode up to 253 K, with a side-mode suppression ratio of 27 dB.

Although record-setting QCLs are based on the In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As material system on InP substrates, Cyrille Becker of Thales discussed the progress of AlGaAs-based devices on GaAs substrates and InAs/AlSb devices on GaSb substrates. The advantages of these combinations of materials include the considerable technological maturity of the AlGaAs/GaAs system and the potential for reduced thresholds in the InAs/AlSb system on GaSb.

GaAs-based QCLs emitting in the vicinity of 10 μm currently operate at temperatures up to 95 °C under pulsed excitation, and produce 60 mW of CW power at 77 K. Although electroluminescence and possibly a lasing signature have been observed from InAs/AlSb active regions, Becker concluded by saying that problems associated with electrical damage and low index contrast in the available cladding layers remain to be overcome.

Sensing and communication

A testament to the continually improving performance of QCLs is the growing interest in incorporating these devices into practical systems. According to John Schultz of the Pacific Northwest National Laboratory, the use of cooled QCLs offers a promising route towards reducing the clutter and noise that currently dominate the spectral characteristics of remote chemical sensors (figure 1). Frequency-modulated differential absorption LIDAR (or FM DIAL) experiments at distances up to 2.5 km have been encouraging, said Schultz in his invited presentation. Miniaturized QCL transmitter modules with chalcogenide-glass waveguide connections are also under development.

Meanwhile, it is prohibitively expensive to install fiber-optic links that would connect all the users of high-speed networks to the backbone. One potential bypass of this last-mile bottleneck that does not sacrifice much of the bandwidth is free-space optical propagation. Rainer Martini of the Stevens Institute of Technology, NJ, noted that compared with the 1.55 μm standard, free-space transmission in one of the mid-infrared atmospheric windows (e.g. near 5 μm or close to 8 μm) greatly reduces losses due to weather-dependent Mie scattering, Rayleigh scattering and scintillation. Martini argued that these windows would more than compensate for the lower detector sensitivity and poorer quality optics at the longer wavelengths.

QCLs have already demonstrated wide-open eye diagrams when they are digitally modulated with pseudo-random bit patterns at 2.5 Gbit/s. Martini described a very foggy morning in August 2001 where a QCL mid-IR link spanning a 200 m open-air path stabilized nearly an hour earlier than a similar near-IR link, as the haze gradually dissipated.

Type-II interband lasers

At present, the built-in lattice strain in QCLs needs to be accommodated, which makes them increasingly less attractive for wavelengths shorter than about 5 μm . In the 3–5 μm spectral region, the primary contenders among

compact coherent sources are narrow-gap antimonide interband lasers that use the type-II band alignment in the active region, where the difference in conduction or valence band energies of the two materials is greater than that in the bandgaps. Using type-II band alignment in the active region reduces non-radiative Auger recombination. Optically pumped lasers of this class have operated in CW mode up to room temperature.

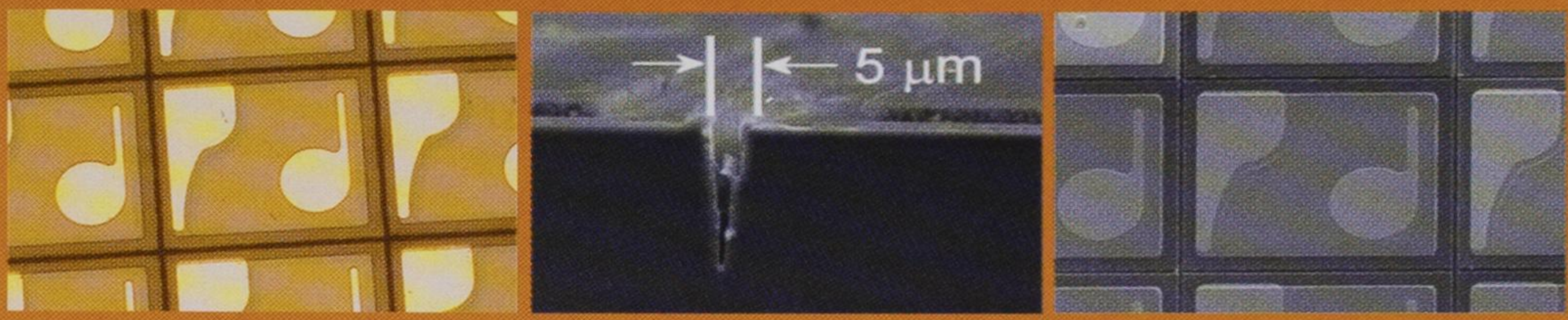
George Turner of Lincoln Laboratory described the integrated absorber approach to improve the optical-to-optical conversion efficiency of type-II "W" lasers. W lasers are antimonide-based lasers that have a type-II band lineup. They contain a superlattice structure with four layers per period in the active region, in which two InAs electron wells sandwich a GaInSb hole well. The InAs/GaInSb/InAs layers are separated by electron-confining barriers such as AlSb or a GaInAsSb quaternary.

The essence of Turner's approach is the combination of strong pump absorption in the integrated absorber with a relatively small number of periods (typically 10) in the active regions, which leads to a low internal loss. Since the integrated absorber structure has a slightly higher refractive index than the GaSb substrate, the need for Al-based cladding layers is eliminated.

The US Air Force also has a strong interest in such lasers operating from 2 to 5 μm for tactical applications. As Andrew Ongstad of the Air Force Research Laboratory (AFRL) reported, type-II W InAs/InGaSb lasers with Al-free cladding layers exhibit reduced divergence angles in the far-field pattern both parallel and perpendicular to the axis of the slab waveguide. AFRL's Ron Kaspi described an Al-free integrated absorber laser (with an InGaAsSb/InAs/InGaSb/InAs active region) that produced 8 W of quasi-CW power at 77 K. The current challenge for integrated absorber lasers appears to be reaching the high operating temperatures already demonstrated by other antimonide-based optically pumped lasers. Kaspi said that this could be achieved by enhancing the hole confinement in the active region.

To produce low angular-divergence light from high-power laser stripes several hundred microns wide, it is necessary to enforce the spatial coherence across the stripe. One such approach to this is the photonic-crystal DFB laser, in which the light in the waveguide is diffracted by a two-dimensional grating that

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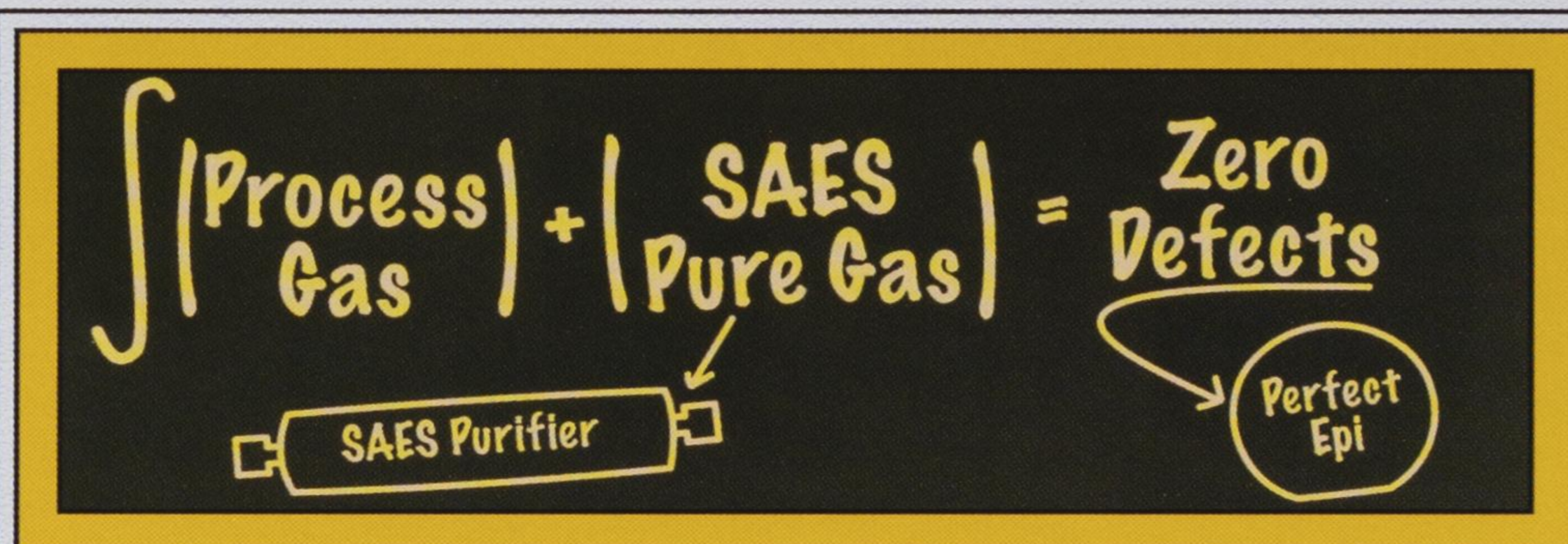
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simultaneously diffracts along two axes formed by the rows and columns of the grating (figure 2). The result is strong coherence across a wide stripe with no filamentation. Simulations predict much higher single-mode power than previous approaches. Jerry Meyer of the Naval Research Laboratory presented two experimental photonic-crystal DFB lasers based on etched GaSb photonic crystals and antimonide active regions on GaSb substrates, in addition to a theoretical surface-emitting version of the device.

In a recent development related to electrically pumped type-II lasers, John Bradshaw from Maxion Technologies, MD, reported single-mode emission with greater than 30 dB side-mode suppression, from an interband cascade laser that uses the staircase geometry of the QCL in conjunction with interband transitions in antimonide material. The device employed a DFB grating etched into a p-doped GaSb top contact layer.

Type-I interband lasers

InGaAsSb/AlGaAsSb strained QW lasers remain the dominant source for wavelengths shorter than 3 μm , with room-temperature CW operation of type-I diode lasers reported up to 2.7 μm . Joachim Wagner of the Fraunhofer Institute in Freiburg, Germany, described broad-area lasers that had been mounted junction-side-down and coated. These devices emitted 1.7 W of output power in CW mode and were designed to pump a widely tunable $\text{Cr}^{2+}:\text{ZnSe}$ solid-state laser. Another important application in this wavelength range is non-invasive optical blood glucose monitoring through human skin, which requires more modest powers of 10 to 20 mW.

Yves Rouillard of the University of Montpellier, France, reported 2.3 μm type-I lasers with CW threshold current densities (at room temperature) of only 189 A/cm². The maximum output power per facet was 630 mW at 10 °C, and was achieved with a combination of anti-reflection and high-reflection Si/SiO₂ coatings on the facets. The high output power was made possible by reducing the series resistance and by improvements in the junction-side-down mounting technology.

Mid-IR LEDs

Boris Matveev of the Ioffe Institute in Russia reviewed the progress on mid-IR LEDs and related photodetector structures with active regions of InGaAs, InGaAsSb/InAsSbP and InAsSb emitting at 3–5 μm . These devices display the best electrical characteristics

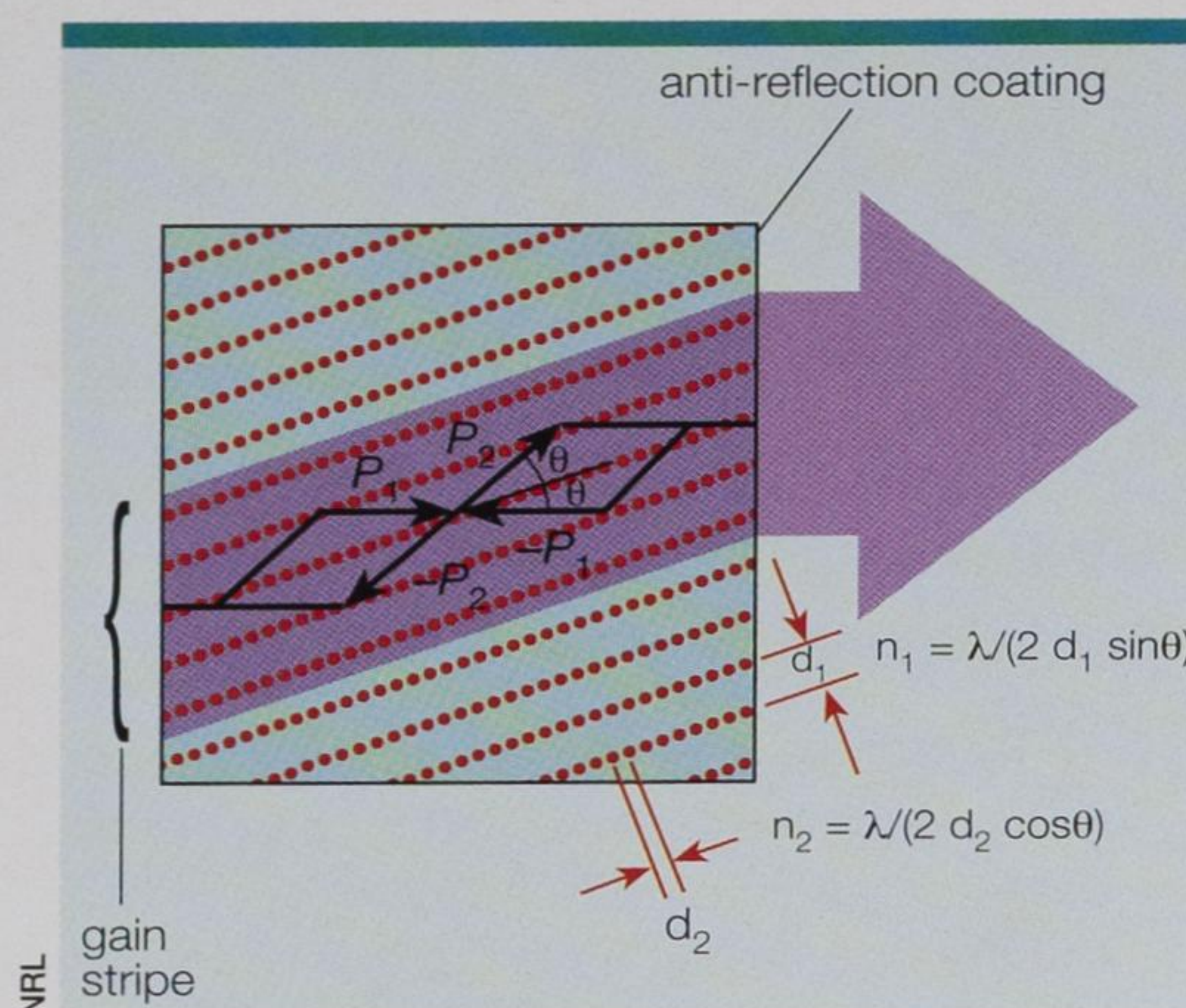


Fig. 2. The photonic crystal acts as a two-dimensional grating to diffract light in the waveguide along two axes, causing strong coherence and the emission of low angular divergence light from wide laser stripes. The diffraction processes couple waves P_1 and P_2 and also counter-propagating waves $-P_1$ and $-P_2$.

when epi-side-down mounting (flip-chip bonding) is used. Room-temperature output powers of up to 1 mW are possible when the devices are outfitted with a micro-immersion lens. Multilayer band-pass filters glued to the top surface improve the direction of the output and reduce the temperature shift of the emission peak.

An epitaxially grown mirror stack can also drastically increase the efficiency of light extraction and the fraction of the power coupled into a narrow cone along the vertical direction. The design issues and preliminary electroluminescence results for these mid-IR resonant-cavity LEDs were reviewed by Chris Phillips of Imperial College in London, UK.

Interband photodiodes

Apart from mid-IR sources, many applications also require efficient, scalable detectors operating in the same wavelength range. The main commercial detector technology covering a substantial fraction of the mid-IR spectral region is based on HgCdTe cooled to liquid-nitrogen temperatures. As explained by Steve Johnson of Raytheon, a major recent development in this technology has been the shift from growth on lattice-matched CdZnTe substrates to growth on (211)-oriented Si. To make the devices smaller and more flexible, and to reduce system costs, the operating temperature of the detectors must be increased by grading the energy gap at the

p–n junction, and by optimizing the doping profile of the devices.

Meanwhile, photodiodes based on InAs/GaInSb type-II superlattices are almost ready to challenge the predominance of HgCdTe. According to Frank Fuchs from the Fraunhofer Institute, the detectivity (D^*) of the best devices with cut-off wavelengths (λ_c) between 8 and 12 μm is in the 10^{11} – 10^{12} cmHz^{1/2}/W range. D^* is higher by nearly two orders of magnitude for devices with λ_c near 5 μm .

Photoconductivity measurements suggest that the minority carrier lifetime of these devices approaches 100 ns, although the detectors are still believed to be generation-recombination-limited at 77 K. An increase in the thickness of the absorbing layer coupled with diffusion lengths that are no smaller than the absorbing layer thickness should boost the internal quantum efficiency nearer to the values available to HgCdTe.

QW and QD IR photodetectors

Another interesting mid-IR photodetector technology relies on photon absorption resulting from transitions within the conduction band. The active regions of the photodetectors are based on quantum wells (QWIPs) or quantum dots (QDIPs). The advantage of the QDIP is a strong response for normal incidence radiation. Mohamed Missous from the University of Manchester Institute of Science and Technology (UMIST), UK, reviewed the characteristics of highly strained InGaAs/AlAs QWIP structures, which are capable of operating at wavelengths as short as 2.9 μm due to the very large conduction-band offsets. Detectors based on these structures are currently being pursued as moderately priced multi-component IR analyzers for landfill gases such as CH₄, CO, CO₂ and N₂O.

Sanjay Krishna from the University of New Mexico discussed normal-incidence QDIPs based on InAs dots in thin InGaAs quantum wells. These devices operate at 8.2 μm and at a temperature of 78 K, and displayed a detectivity D^* of 2×10^9 cmHz^{1/2}/W and peak responsivity of 0.3 A/W. QDIPs are expected to operate at higher temperatures than QWIPs due to the longer electron relaxation time once the photon is absorbed.

Presentations from MIOMD-V are available at www.miomd.org. Igor Vurgaftman is an electrical engineer at the Naval Research Laboratory in Washington DC. Email vurgaftman@nrl.navy.mil.

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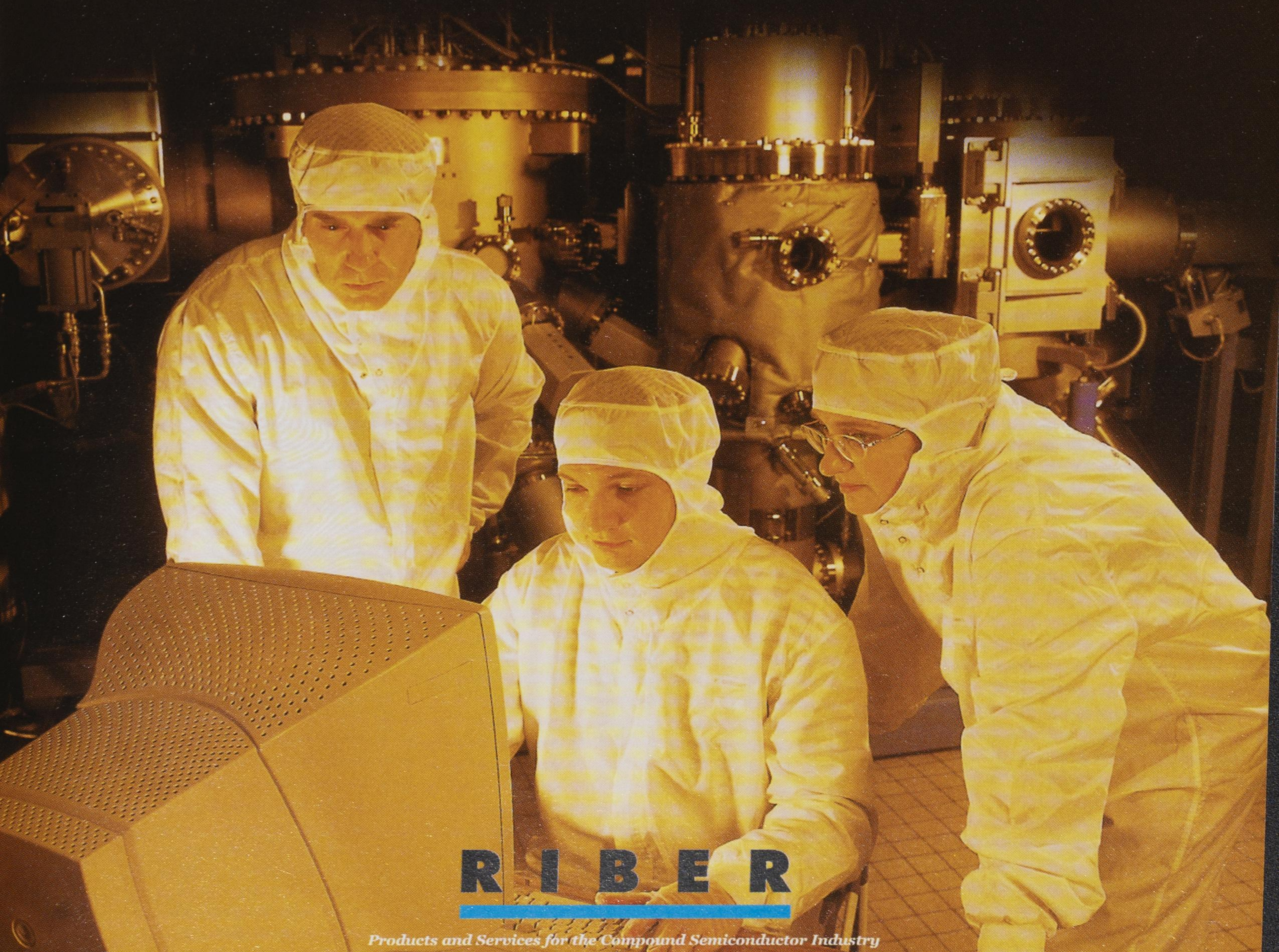
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Philips sells ellipsometry business to Jobin Yvon

Philips Electronics of the Netherlands and Jobin Yvon, a French manufacturer of equipment for optical spectroscopy, have finalized an agreement to transfer the ellipsometry product line of the former Philips Analytical to Jobin Yvon. The transaction includes metrology tools such as the table-top PZ laser ellipsometer and the PQ Ruby fully automated ellipsometer for 200 mm wafers. In July, Philips announced that it would discontinue its ellipsometry business, and later revealed that it was talking to potential buyers.

Philips Electronics sold its Philips Analytical business to UK company Spectris in July 2002. Spectris immediately sold the former Philips Analytical operation in Waterloo, Canada, to Accent Optical Technologies (see *Compound Semiconductor* September 2002 p30). This included the DCD Pro X-ray diffraction product and Philips Analytical's photoluminescence products. Philips Analytical now operates as PANalytical, a wholly owned subsidiary of Spectris, and is headquartered in Almelo, the Netherlands.

Sumitomo Electric opens US plant



Sumitomo Electric Semiconductor Materials' VP of sales, Scott Davis (far right), presides over the kagami-wari ceremony, where hammers are used to open barrels of sake.

Sumitomo Electric has opened its first US compound semiconductor manufacturing facility in Hillsboro, OR. The company held a ceremony in October to open the new 90,000 sq. ft building, where it will produce 6 inch GaAs wafers. Pilot production began at the \$20 million facility in January 2002, with volume production starting in June.

The opening ceremony was attended by many of the largest users of GaAs wafers

in the US, along with senior management from Sumitomo Electric in Japan, and Oregon government officials. "In establishing a manufacturing presence in this country, it was our sincere wish to be closer to our North American customer base, in order to provide better service and to form closer relationships," said Hishashi Sakamoto, the president of Sumitomo Electric Semiconductor Materials.

Alliance investigates impurities in GaN

Air Products and Pennsylvania State University are to continue with their collaborative research into the effects of gas source purity on GaN-based epitaxially grown structures. The work, which began in early 2002 and is part of a multi-million-dollar alliance between the two organizations, is evaluating

the effect of impurities on the structural, electrical and optical properties of structures grown by MOVPE. The work will also aid the development of new, higher purity ammonia sources for nitride growth.

The purity of source materials for epitaxy is becoming increasingly important in the compound semiconductor industry, but information on impurities and their impact on GaN-based devices currently lags behind what is known for other compound semiconductors.

Equipment sales

- **Leica Microsystems** (Wetzlar, Germany) has installed an electron-beam lithography system at **United Monolithic Semiconductors'** (UMS') GaAs fab in Ulm, Germany. UMS will use the EBP5000+ to define sub-micron gate electrodes and for wafer direct writing of patterns on GaAs-based HFET transistors.

- **Northrop Grumman's** Advanced Materials and Semiconductor Device Technology Center in Baltimore, MD, has purchased a D1 High Resolution X-ray Diffractometer from Bede Scientific. The instrument will be used for the characterization of GaN-based epitaxial structures for high-power, high-speed electronic devices.

- **Duke University** has ordered a GEN II single-wafer MBE system from **Veeco MBE**. The new system will be installed at Duke's Pratt School of Engineering in Durham, NC, and will be used to develop GaN-based devices for high-power wireless applications such as military radar and commercial base-station power amplifiers, as well as visible and ultraviolet optical applications.

- **Aixtron** has won a number of orders recently from LED and laser manufacturers in Taiwan and Japan. The company has received orders for four of its AIX 2600G3 HT Planetary Reactors configured for the growth of GaN-based LED epiwafers. Two of the reactors will go to **Epistar** (Hsinchu, Taiwan) and one each to **South Epitaxy Corporation** (Tainan, Taiwan) and **Highlink Technology Corporation** (Hsinchu, Taiwan). **Epitech Technology Corporation** (Tainan, Taiwan) has ordered an Aixtron AIX 2400G3 HT reactor for the mass production of GaN-based LEDs.

Aixtron has also announced the successful start-up of an AIX 2400 MOCVD system at **Seiko Epson Corporation** (Nagano-Ken, Japan). The new 8 x 3 inch configuration reactor will be used to grow GaInAsN-based VCSEL structures. **Rohm** (Kyoto, Japan) has purchased an AIX 2600G3 system for the mass production of AlInGaP-based ultra-high-brightness LEDs.

Insaco expands its facilities

Insaco, a precision fabricator of ultra-hard materials, including sapphire wafer carriers used by the GaAs IC industry, has completed a 12,000 sq. ft expansion to its production facility in Quakertown, PA. The new structure will

house state-of-the-art specialized equipment for ultra-precise fabrication and polishing applications. Insaco's precision machining business has grown steadily over the past few years, creating the need for the extra capacity.

People news

● **JMAR Technologies** (San Jose, CA) has appointed **Ronald Walrod** as its new president and CEO. Walrod, who will also join the board of directors, replaces interim CEO Joseph Martinez.

● **Nitronex** has named **James Vorhaus** as its new COO and **Richard Widin** as VP of business and legal affairs. Vorhaus has previous

experience of the RF power transistor business, having served with Filtronic and Raytheon amongst others. He was also the founder and president of tunable laser manufacturer Sparkolor. Widin joins from business management software producer Siebel Systems, where he was senior corporate counsel. Former Nokia technology and product manager

Paul Williams has been appointed managing director of Nitronex (Europe) Ltd.

● **Aeronex** has appointed **Keith Barnes** as regional sales manager for Aeronex's gas purification products in California, Oregon and Washington. Barnes has significant sales experience in the semiconductor and chemical industries.

Aeronex receives CE mark for purifiers

Aeronex has completed the tests for compliance to design and safety standards for pressure equipment of its 10M and 2500K gas purifiers and its class 4 vessels for bulk gas purification. Passing the tests means that the products can carry the CE mark, which is required for all electrical and pressure equipment sold in the European Union. The company's Infinity GPS product has also been awarded the CE mark for electrical safety and conformance to electromagnetic emission and immunity standards.

RSOFT opens new office in Japan

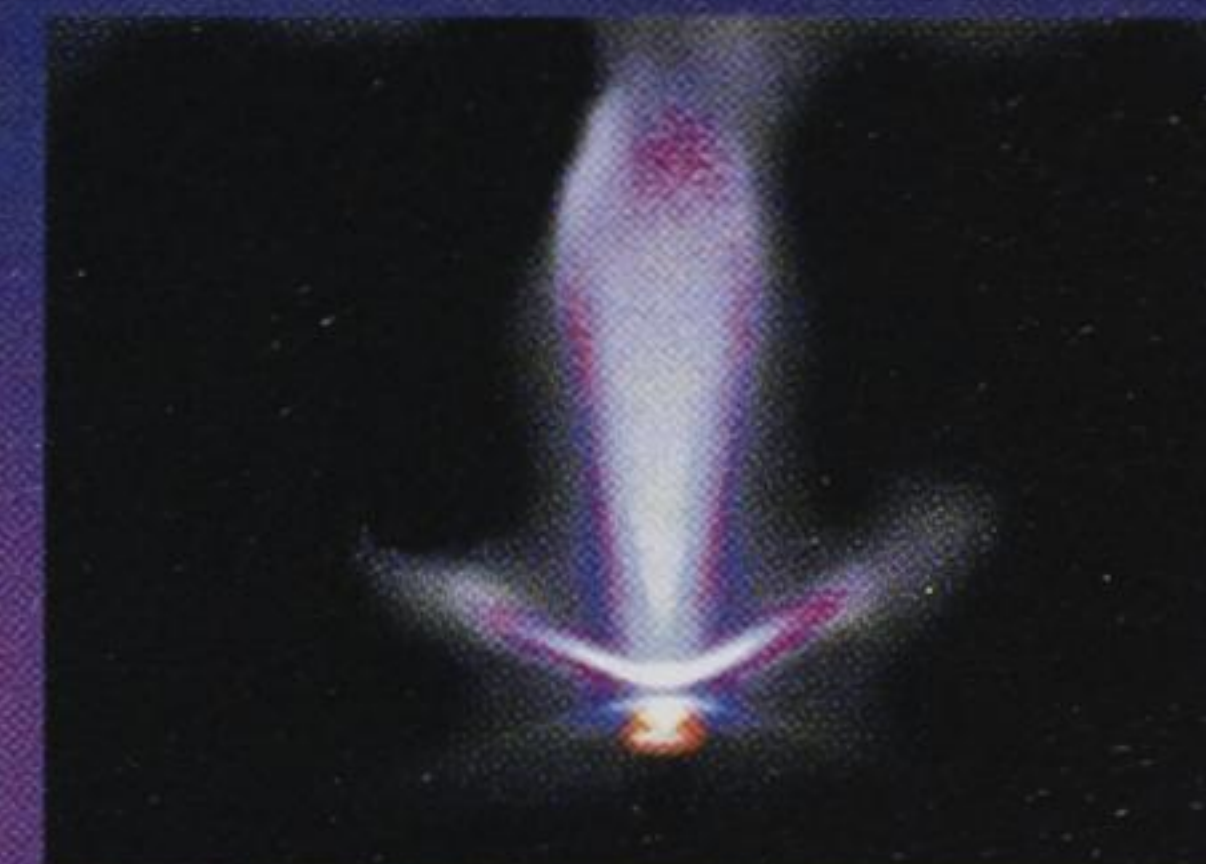
RSOFT Design Group has opened a Japanese headquarters in Tokyo to provide business development and customer support to the company's clients in that country.

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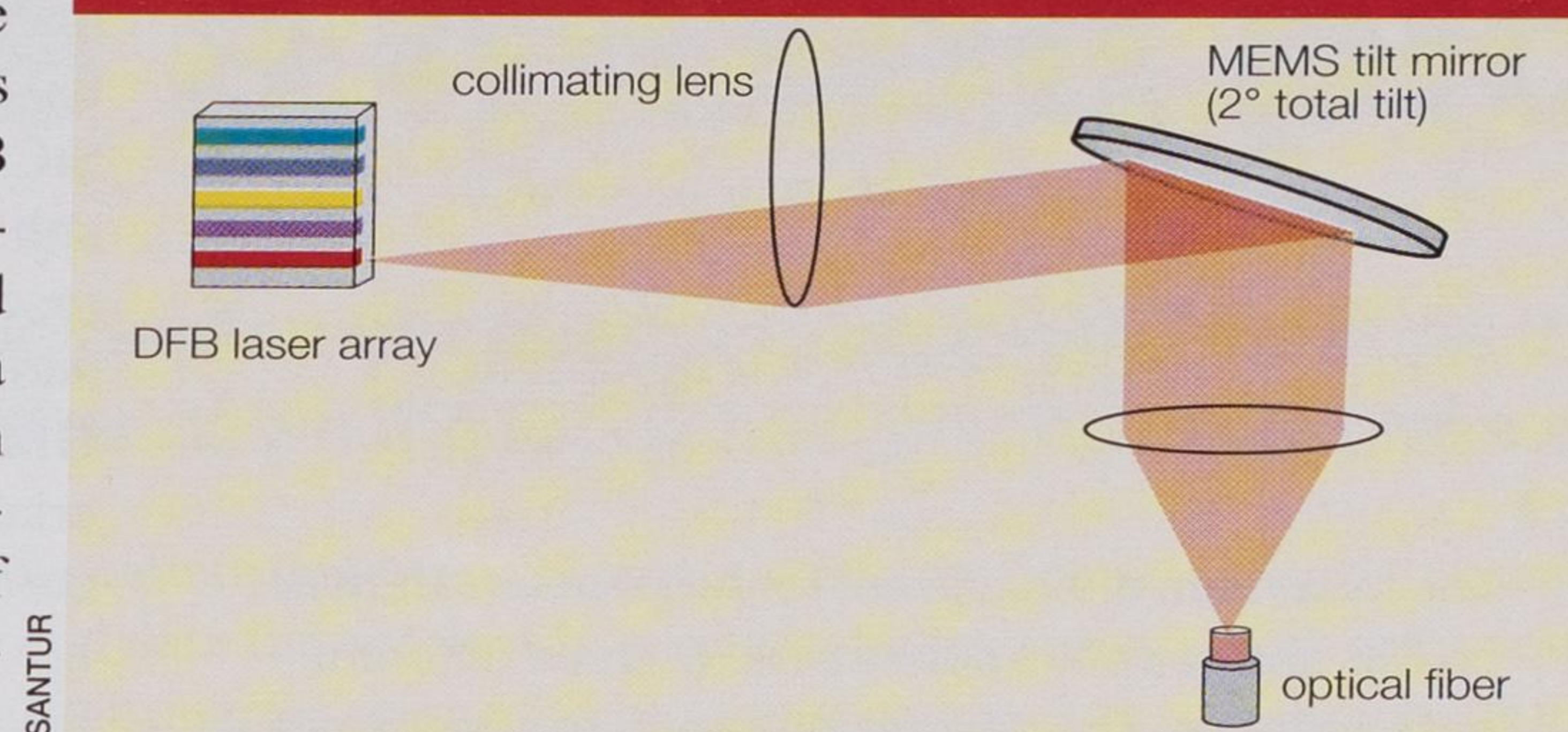
Santur simplifies C-band laser tuning

The tunable laser technology landscape is extremely fragmented. One school believes that tunable lasers must look and feel like standard DFB lasers to gain acceptance in the marketplace and meet reliability and robustness targets. Consequently, a number of Japanese companies such as Fujitsu and NEC have demonstrated tunable lasers using an array of different wavelength DFB lasers integrated together. Coarse wavelength selection is realized by selecting the laser closest in wavelength to the desired value, and fine tuned by changing the chip temperature. The challenge is in directing the light of the different

DFBs into a single output. The traditional method has been to integrate a passive combiner on-chip, then use an integrated amplifier to compensate for the accompanying $1/n$ loss, where n is the number of lasers.

Researchers at Santur Corporation of Fremont, CA, have recently demonstrated 20 mW output power from a laser with a novel method

Santur's tunable laser



Santur's new laser is tunable across the entire C-band and simplifies construction by integrating an array of lasers onto one chip. Each laser's output is selected by a MEMS mirror, thus eliminating the need for a lossy optical combiner.

of obtaining tunability across the entire C-band without using a complex and lossy integrated combiner (*Phot. Tech. Lett.* 2002 **14**(10) 1457). The paper describes an array of 12 DFBs monolithically integrated onto a single substrate. The chip is simple to manufacture as the only integrated components are DFB lasers with the same epitaxial structure. Each laser is individually addressable and a MEMS mirror placed in the focal plane of a collimating lens selects the output. Fine tuning is achieved by adjusting the chip temperature.

Not only does the MEMS mirror allow almost all the power of the laser to be coupled to the fiber, removing the need for an optical amplifier to compensate for losses, but it also compensates for misalignments in packaging. As a result, packaging tolerances can be relaxed from less than $1\text{ }\mu\text{m}$ to about $10\text{ }\mu\text{m}$, with a commensurate decrease in cost. A standard feedback loop maintains this alignment during the life of the laser.

Critical emitter-base spacing for InGaP HBTs

The extrinsic InGaP emitter layer in HBTs is used as a ledge to protect the exposed extrinsic base region and reduce surface recombination. In the past, researchers have studied the effect of the emitter ledge and the emitter-base spacing on AlGaAs/GaAs HBTs, finding that the critical spacing is $1\text{--}2\text{ }\mu\text{m}$. However, until now similar spacing studies have not been made for InGaP/GaAs HBTs. A collaborative effort between the National Chiao Tung University in Taiwan and GaAs foundry Global Communication Technology Corporation has addressed this issue (*Elec. Dev. Lett.* 2002 **23**(10) 576).

In this research, InGaP/GaAs HBTs with various emitter-base spacings from 0.2 to $2.0\text{ }\mu\text{m}$ were fabricated and analyzed. The critical spacing was determined through the analysis of the DC, RF and low-frequency noise of the InGaP/GaAs HBT devices. Saturation of the DC current gain occurred when the spacing was above $0.8\text{ }\mu\text{m}$. As the emitter-base spacing was increased, f_{max} reduced while f_t showed only a slight increase. For HBTs, another important parameter is the low-frequency noise. The noise reached a minimum when the spacing was $0.6\text{ }\mu\text{m}$ and increased by an order of magnitude to $1.2\text{ }\mu\text{m}$.

The result of this study showed that the critical emitter-base contact spacing for an InGaP HBT device is around $0.6\text{--}0.8\text{ }\mu\text{m}$, which is only about half that of AlGaAs/GaAs devices. At this optimal spacing range excellent RF and DC performances were simultaneously obtained.

Kopin improves graded-base DHBT performance

The trend for extending the operating time of portable electronics such as mobile phones has led to the steady lowering of operating voltages. Air-interface standards are also placing higher demands on the performance of devices such as HBTs. These demands include efficient linear power amplification, which in turn requires lower offset and knee voltages. A 100 mV drop in base-emitter turn-on voltage can result in a 2% increase in PAE. To this end, manufacturers of HBTs for PA modules have been actively researching ways to lower the turn-on voltage, including using InGaAsN base layers in DHBTs (*Compound Semiconductor* October 2002 p27). However, while successful at lowering the turn-on voltage, InGaAsN base regions show degraded minority carrier properties compared with GaAs, resulting in a lower current gain (β) and impairment of high-frequency performance.

At the GaAs IC Symposium (Monterey, CA, October 21–23) and in

a paper in *Electron Device Letters*, HBT epiwafer supplier Kopin, in collaboration with AWSC in Taiwan and TriQuint, reported the performance improvements achieved using DHBTs fabricated with an InGaAsN base layer with graded composition (*Elec. Dev. Lett.* 2002 **23**(10) 582). The graded base decreases the electron transit time, improving β and RF performance, and also lowering the knee voltage and significantly reducing the variation of β with device temperature.

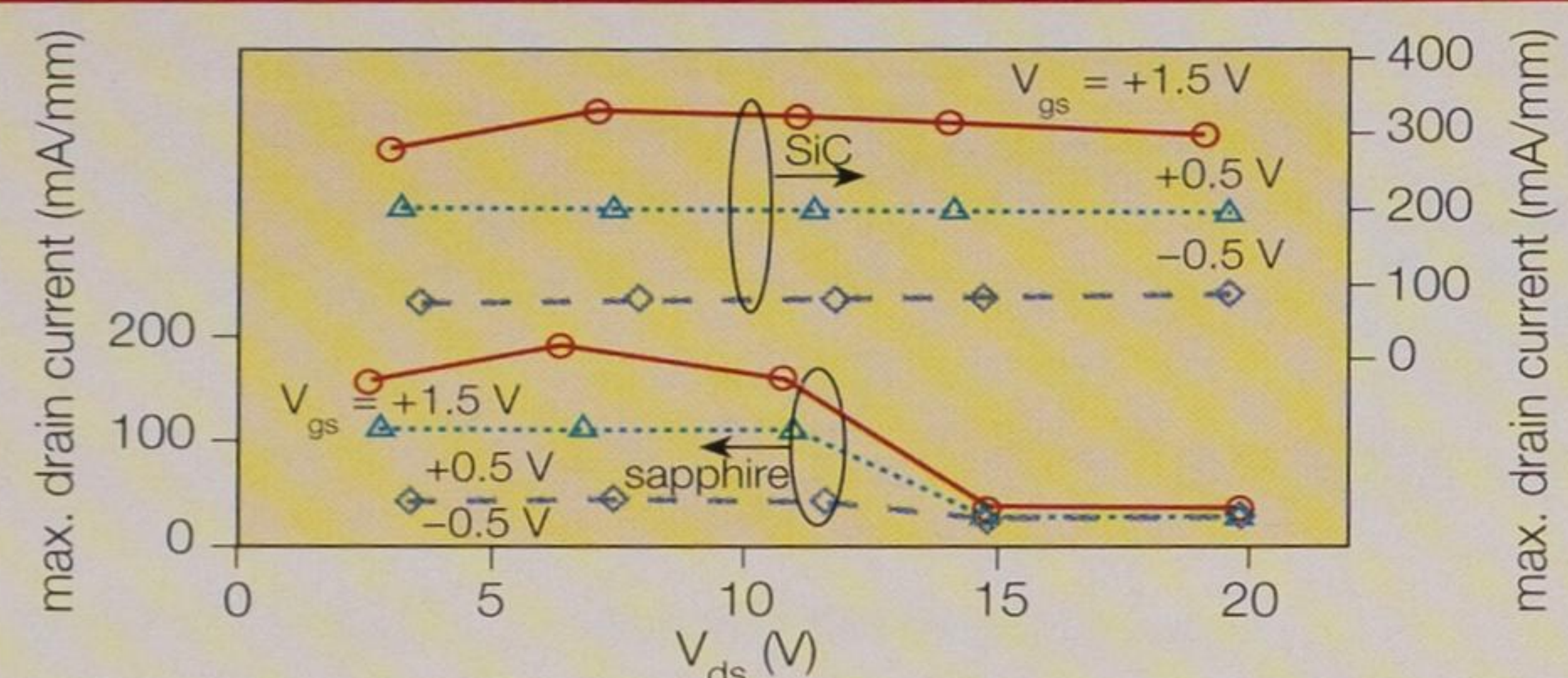
At a collector current density of 10 kA/cm^2 , β increased from 38 for an InGaAsN base of constant composition, to 64 for a DHBT with a graded base. For the graded base-layer devices, β increased by 3% as the temperature increased from 25 to $85\text{ }^\circ\text{C}$. Over the same temperature range, β dropped by 10% for an InGaP/GaAs HBT.

The variation in f_t and f_{max} with current density was measured for InGaP/GaAs HBTs, and the graded and constant composition InGaAsN base layers. The improvement in peak f_t for the graded base-layer devices compared with the constant composition InGaAsN base-layer devices was more than 10% and is a consequence of lower electron transit times in the graded layer.

SiC substrates alleviate drain current collapse

An important problem facing GaN-based HEMTs for high-power microwave applications is the occurrence of drain current collapse at high drain voltage. Takashi Egawa and colleagues at the Nagoya Institute of Technology, Japan, have studied the I_{ds} - V_{ds} characteristics of AlGaIn/GaN HEMTs on both semi-insulating SiC and sapphire substrates using a DC offset low-frequency (120 Hz) sinusoidal wave. Drain current collapse in the AlGaIn/GaN HEMTs on sapphire was much more severe than for the HEMTs on SI-SiC. In both, the current collapse is

Drain current collapse in AlGaIn HEMTs



The maximum drain current for AlGaIn/GaN HEMTs on SiC and sapphire substrates for three different gate voltages. The devices on sapphire show rapid drain current collapse beyond a V_{ds} of 10 V.

caused by the presence of deep traps associated with material defects. Two thermally activated deep traps ($E = 1.05$ and 0.04) were observed in the HEMTs on SI-SiC and three for the HEMTs on sapphire substrates ($E = 1.23$, 0.61 , 0.046). The researchers think the existence of an additional deep trap ($E = 0.61$ eV) in the HEMTs on sapphire corresponds to material defects and leads to the severe drain current collapse. White-light illuminated I_{ds} - V_{ds} characteristics supported the existence of a larger number of deep traps in the HEMTs on sapphire.

Low-threshold L-band DFB lasers pass 100 mW

The performance of semiconductor lasers operating in the L-band out to 1625 nm is degraded by Auger recombination that impacts slope efficiency and raises the threshold current. Researchers at Furukawa Electric in Japan have published details of an MOCVD-grown InP-based laser with an output power of 106 mW at 1625 nm (*Elec. Lett.* 2002 **38**(21) 1258). Through careful design of the barrier layers in the MQW active

region, carrier and optical confinement were optimized, resulting in a laser with 1625 nm emission, 11 mA threshold current, 0.39 mW/mA slope efficiency and an output power of 30 mW at 90 mA drive current. Maximum output power was 106 mW and sidemode suppression ratio exceeded 55 dB. The threshold current dependence on temperature was studied between 298 and 343 K, with the characteristic temperature (T_0) calculated to be 46 K. The T_0 for the L-band laser did not show additional degradation of threshold current stability with temperature over the group's C-band emitters. The results are encouraging for Furukawa's next generation of high-power L-band emitters for DWDM systems.

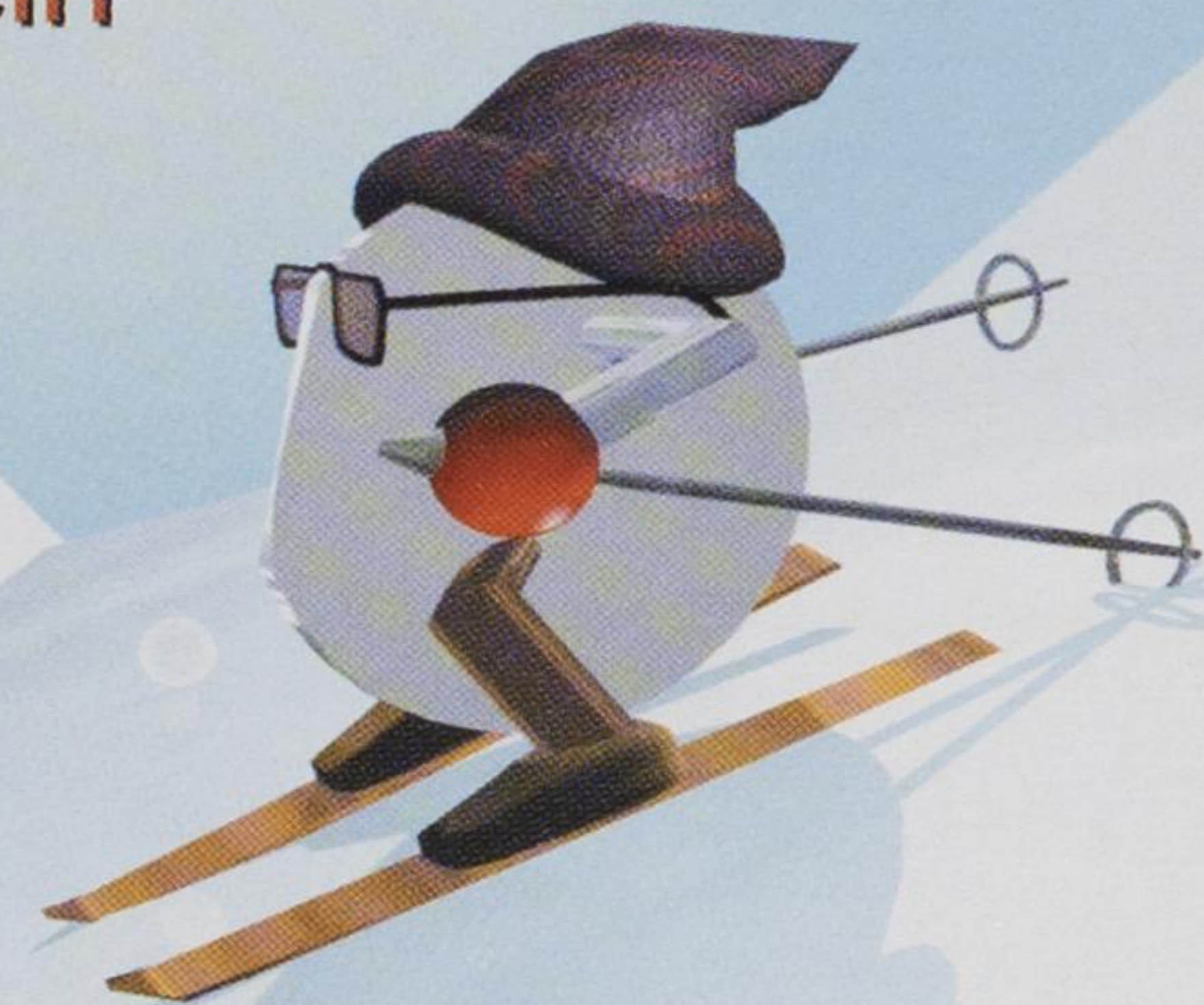
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September quarter results provide a mixed picture

The financial results for the September quarter bring reason for hope that the wireless IC industry is on the up. However, further down the food chain pricing pressure is a cause for concern.



The tough times for epiwafer vendors are continuing, as illustrated by Kopin's recent rollercoaster ride.

The pattern that began to emerge from the financial data for wireless IC manufacturers in the June quarter seemed to be continuing as data for the September quarter was released. TriQuint reported an upbeat quarter, Skyworks made an operating profit and cleared its remaining debt with Conexant, and RFMD beat its June quarter figures, which had been its best for two years. However, while the leaders in the GaAs IC business use both price and performance to gain an edge on the competition, lower down the food chain it seems that price is everything.

The tough times for epiwafer vendors are continuing, as illustrated by Kopin's recent rollercoaster ride. Just as the company reported revenues of \$21.9 m for the September 2002 quarter, up 5% sequentially and up 78% from the year-ago period, Kopin revealed that it had not reached an agreement over a supply contract with a major HBT customer. Although no names were mentioned, this customer is thought to be Skyworks, Kopin's biggest HBT customer. This situation left Kopin predicting a 25–30% decline in revenue for the December quarter, and the company was downgraded by several analysts. However, just days later analysts were saying that Kopin had finally reached a supply agreement with the customer, its stock rose and some analysts upgraded – although at the time of writing Kopin had not publicly confirmed the analysts' assumptions.

There is a high level of underused epiwafer production capacity out there. In its conference call, Kopin indicated that its HBT line is running at about 60% capacity,

a level that some epiwafer suppliers would be very happy with right now. Despite the work-through of epiwafer inventory by the GaAs IC manufacturers, demand is lagging behind supply, leaving buyers in a good position to push for heavy price cuts. Kopin's customer was almost certainly offered a very attractive price by another supplier, which Kopin was forced to match.

A bright spot for Kopin is its CyberLite blue LED venture (*Compound Semiconductor* September 2002 p11). The product is now sampling with customers and the company says that feedback has been good. Volume production is likely to begin early next year, with additions to Kopin's bottom line following shortly afterwards.

IQE's results provided further illustration of the tough conditions in the price-driven epiwafer market. The company's September quarter revenues were down 12% sequentially to €8.86 m (\$8.86 m) and down 32% on the year-ago period. In its results statement the company said it was experiencing intense pricing pressure and that while sales volume was almost unchanged over the previous quarter, prices were depressed. IQE has InGaP HBT wafers in qualification with several customers and anticipates turning this into improved revenue and market share in the short to medium term.

The pricing pressures on epiwafer vendors and direct pressure from the fabs have a knock-on effect for substrate and other material suppliers. In a panel session at October's GaAs IC Symposium in Monterey, AXT's VP of sales Bob Tobin made it clear that substrate suppliers were being leaned on very hard to reduce their prices. AXT's revenues for the September quarter were \$14.9 m, compared with \$19.2 m in the June quarter and \$22.8 m in the year-ago quarter, and the substrate division accounted for 78% of AXT's revenues for the quarter.

Equipment vendors

The number of underutilized MOCVD reactors spread around the world is of course bad news for the equipment suppliers, although the ramp up of production capacity for GaN-based LEDs in Taiwan is providing some comfort. Emcore's results for the September quarter showed a 25% increase in revenue to \$25 m over the June quarter. Revenues from its MOCVD equipment division were up 14% sequentially to \$11 m and the materials division turned in a 35% improvement to \$14 m. While such increases are good news, the figures

Recent financial results (revenue in \$ million)

	June quarter	September quarter	% change
Anadigics	23	21.3	-7
Celeritek	15.3	15.5	1.3
RFMD	103.9	119.7	15.2
Skyworks	137	150.7	10
TriQuint	61.2	71	16
Vitesse*	43	38.1	-11.4
Emcore†	20	25	20
Aixtron	36.1	35.3	-2.2
Kopin‡	20.8	21.9	5.3
IQE	10	8.9	-11

*Vitesse's business is now about 80% CMOS; †Emcore's revenue split is 45% MOCVD systems and 55% materials;

‡Kopin's revenue split is 45% epiwafers and 55% CyberDisplays.

Market overview

Company	Symbol	Closing price on Nov 22	52-week low-high	Market cap*
GaAs IC companies				
Anadigics	ANAD	3.15	1.59–19.60	96.3 m
Celeritek	CLTK	6.57	5.01–14.43	80.8 m
Endwave	ENWV	1.03	0.32–5.84	9.2 m
Multilink	MLTC	3.10	1.06–83.30	23.5 m
RF Micro Devices	RFMD	10.94	5.16–28.33	1.851 bn
Sirenza Microdevices	SMDI	1.38	1.10–8.49	41.1 m
Skyworks Solutions	SWKS	11.57	2.89–29.15	1.591 bn
TriQuint	TQNT	7.32	2.55–20.50	969.8 m
Vitesse	VTSS	2.80	0.62–15.50	562.8 m
Opto companies				
Agilent	A	18.25	10.50–37.99	8.517 bn
Agere	AGRa	1.65	0.50–6.30	2.705 bn
Alcatel Optronics	ALAO	4.08	1.50–9.63	67.3 m
Coherent	COHR	20.73	14.75–36.39	601.5 m
Cree	CREE	22.49	8.99–33.32	1.637 bn
JDS Uniphase	JDSU	3.11	1.58–12.44	4.392 bn
Stratos Lightwave	STLW	6.77	2.28–74.00	49.2 m
Semiconductor materials and equipment companies				
ATMI	ATMI	23.50	11.75–37.10	720.1 m
AXT	AXTI	2.19	0.94–17.15	49.3 m
Emcore	EMKR	2.95	0.98–17.04	108.3 m
Kopin	KOPN	5.60	1.93–19.05	388.5 m
Tegal	TGAL	0.55	0.13–2.00	7.9 m
Trikon	TRKN	4.98	3.25–15.90	69.8 m
Veeco	VECO	13.10	9.14–40.12	381.7 m
European companies (currency data in €)				
Aixtron	AIXG.F	6.50	4.03–30.00	410.4 m
Bede	BED.L	0.32	17.00–214.25	8.1 m
Bookham	BHM.L	1.40	40.00–185.00	199.5 m
Filtronic	FTC.L	1.83	26.00–451.75	141.2 m
IQE	IQE.L	0.11	3.50–196.75	20.0 m
Picogiga	PGIG.LN	0.50	0.37–5.62	3.3 m
Riber	RIBE.LN	0.78	0.55–5.66	14.7 m
STS	SRTS.L	0.14	5.50–173.00	4.9 m

*Market capitalization = # shares × current share price.

“Substrate suppliers are being leaned on very hard to reduce their prices.”

are a shadow of those reported just a year ago. For the year ended September 30, 2002, revenues were \$88 m (systems accounting for \$36 m of this) compared with \$185 m for the year to September 30, 2001. The \$36 m for the systems division represents a 73% decrease compared with the year to September 30, 2001. To illustrate just how bad things are for the MOCVD systems business, the decline in the systems revenue contribution actually accounted for 98% of the decline in Emcore's overall revenue for the year ending September 30, 2002.

Aixtron, which concentrates solely on MOCVD reactors, also reported steep declines. Its September quarter revenues were \$35.3 m compared with \$36.1 m for the June quarter and \$61.9 m for the year-ago quarter. The September quarter figures were below analysts' estimates and resulted in a slight downwards revision of the full year forecast. The company now expects 2002

revenues to be \$150 m–\$160 m, compared with 2001 revenues of \$240 m. Interestingly, 54% of Aixtron's sales come from Asia and 33% from the US, reflecting the company's push into the Asian market and the relevant buoyancy of the industry in that region.

GaAs fabs

Climb higher up the food chain and things look much healthier in some of the bigger GaAs fabs. Skyworks Solutions hit its target of achieving operating profitability in the September quarter, although the company made an overall loss when the restructuring costs of the Alpha/Conexant Wireless merger were accounted for. Skyworks is the leading supplier of PA modules (*Compound Semiconductor* September 2002 p7) and is by far the largest revenue earner in the business. Its September quarter revenues were \$150.7 m compared with \$137 m in the June quarter and \$99.4 m in the year-ago quarter. Skyworks continues to build its market share and is confident in its ability to carry on building, guiding for a 5% increase in revenues for the December quarter. The performance of its stock has been similarly impressive, rising from \$4 in early October to close at \$12.22 on November 27.

The skeleton in Skyworks' closet was the \$150 m short-term debt payable to Conexant in respect of Skyworks' purchase of Conexant's module assembly, packaging and test facility in Mexico. This issue has now been cleared with the placement of convertible bonds (redeemable in 2007 with a conversion price of \$9.05) that raised \$230 m. Skyworks cleared the \$150 m debt by paying Conexant \$105 m in cash and a \$45 m convertible debt instrument, and also dissolved a \$65 m credit facility with Conexant. The upshot of all this is that Conexant no longer has an interest in Skyworks' assets.

Further down the GaAs fab pecking order, the picture at Anadigics is somewhat different. The company reported a net loss of \$14 m on revenue of \$21.3 m for the September quarter. Revenue was down 7% compared with the \$23 m reported for the June quarter, but 31% ahead of the year-ago quarter. Another revenue drop is expected for the December quarter with \$19 m–\$20 m being forecast, although a cost-cutting program is expected to reduce the losses significantly.

The increase in revenues compared with a year ago is mostly accounted for by the wireless business (Anadigics' broadband business was flat from last year). Wireless revenues for the quarter were \$11 m, corresponding to a rise of 80% compared with the year-ago period, but down 16% sequentially. The company put the sequential decline down to lower ASPs and declining TDMA revenue. CDMA revenue grew considerably compared with last year, reflecting the company's pursuit of new CDMA customers in Asia. Anadigics' CEO Bami Bastami says the company is in the design-in phase, with more than 25 handset OEM/ODM customers, including tier-one manufacturers, for more than 50 wireless handset platforms, and that this activity will begin to add to the company's revenues in mid-2003. ●

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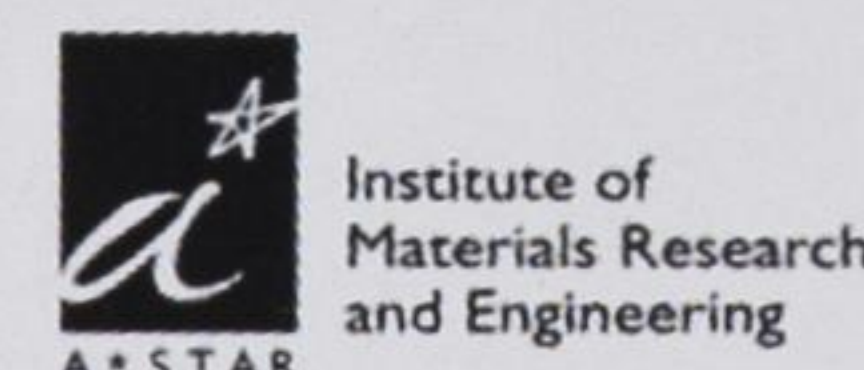
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