

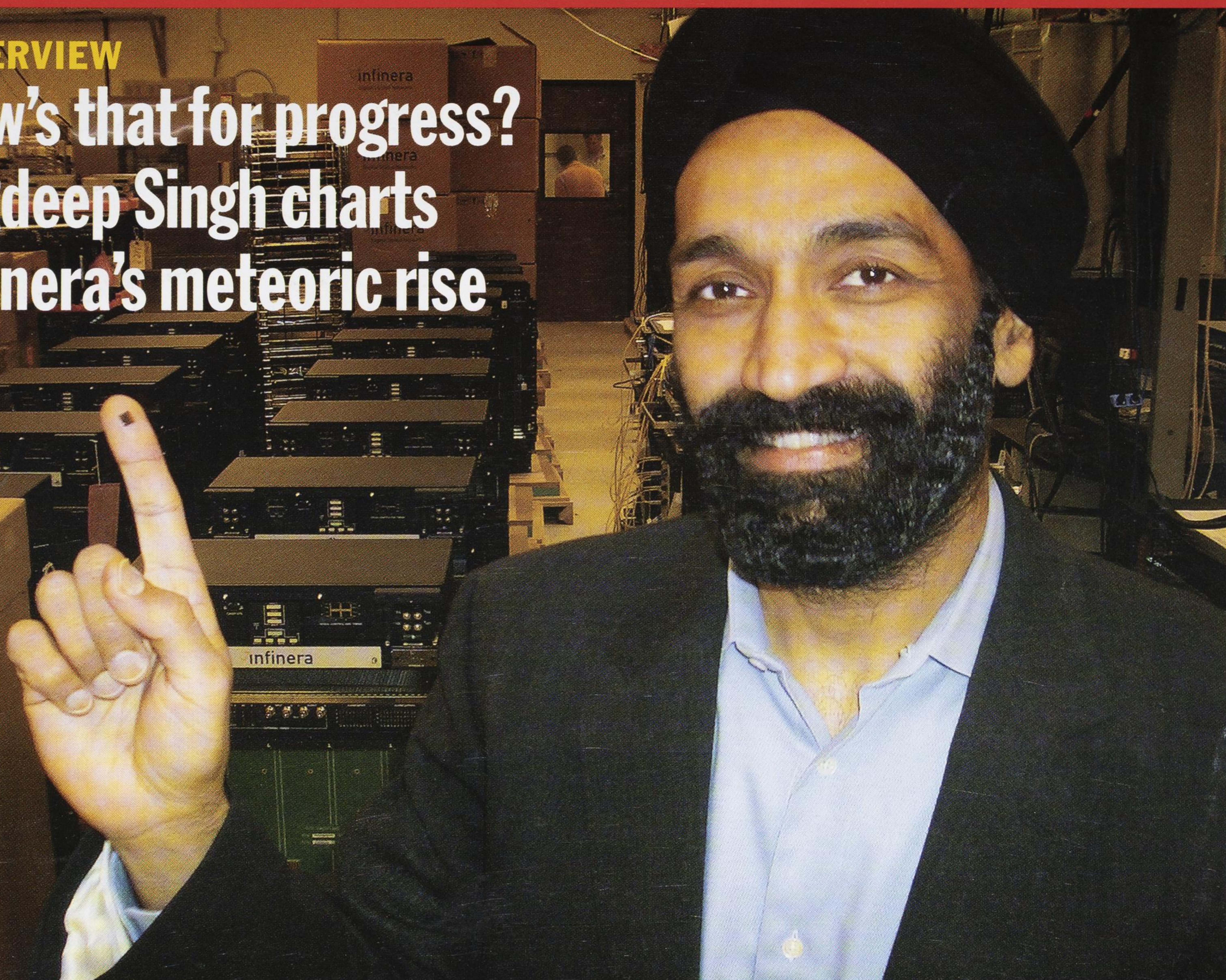
COMPOUND SEMICONDUCTOR

May 2006 Volume 12 Number 4

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

INTERVIEW

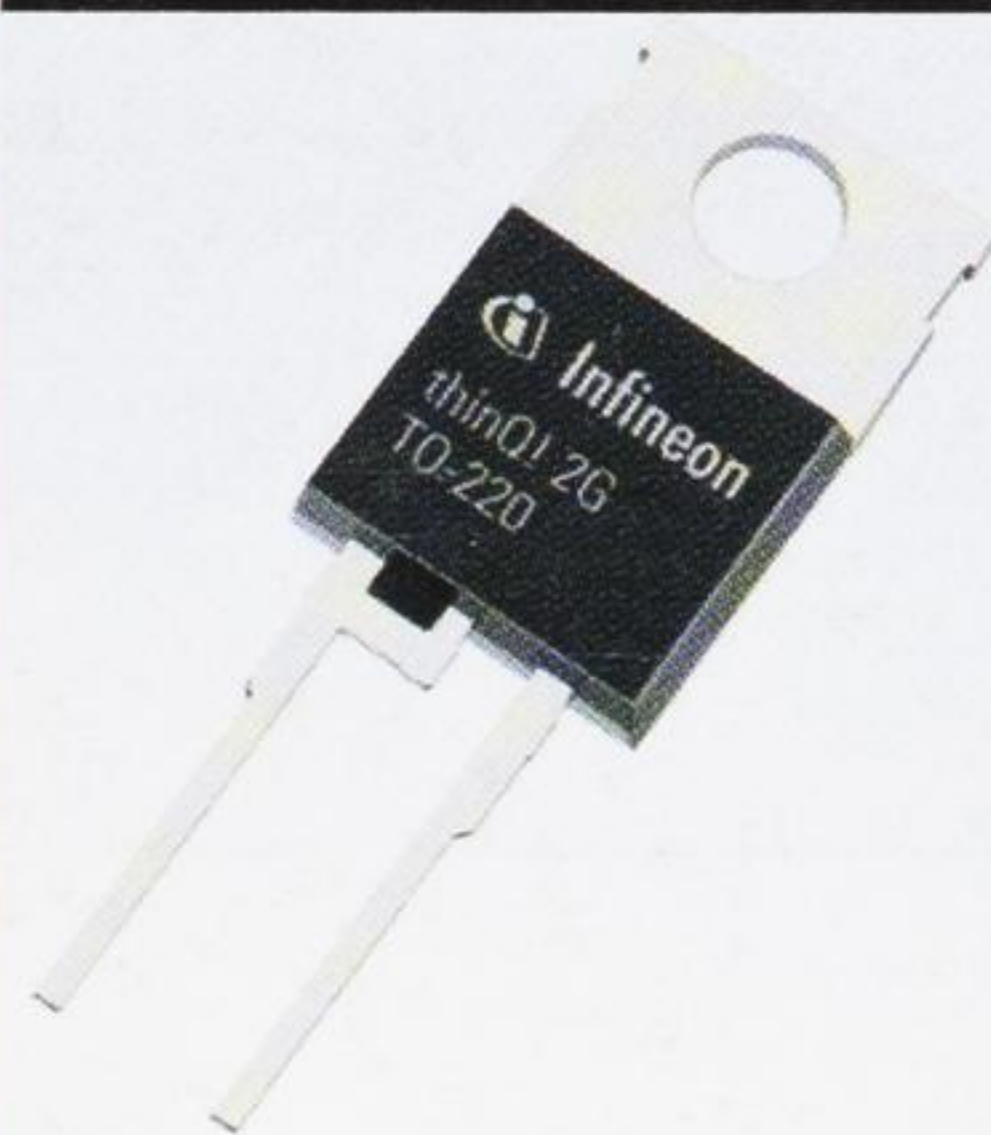
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Jagdeep Singh charts
Infinera's meteoric rise



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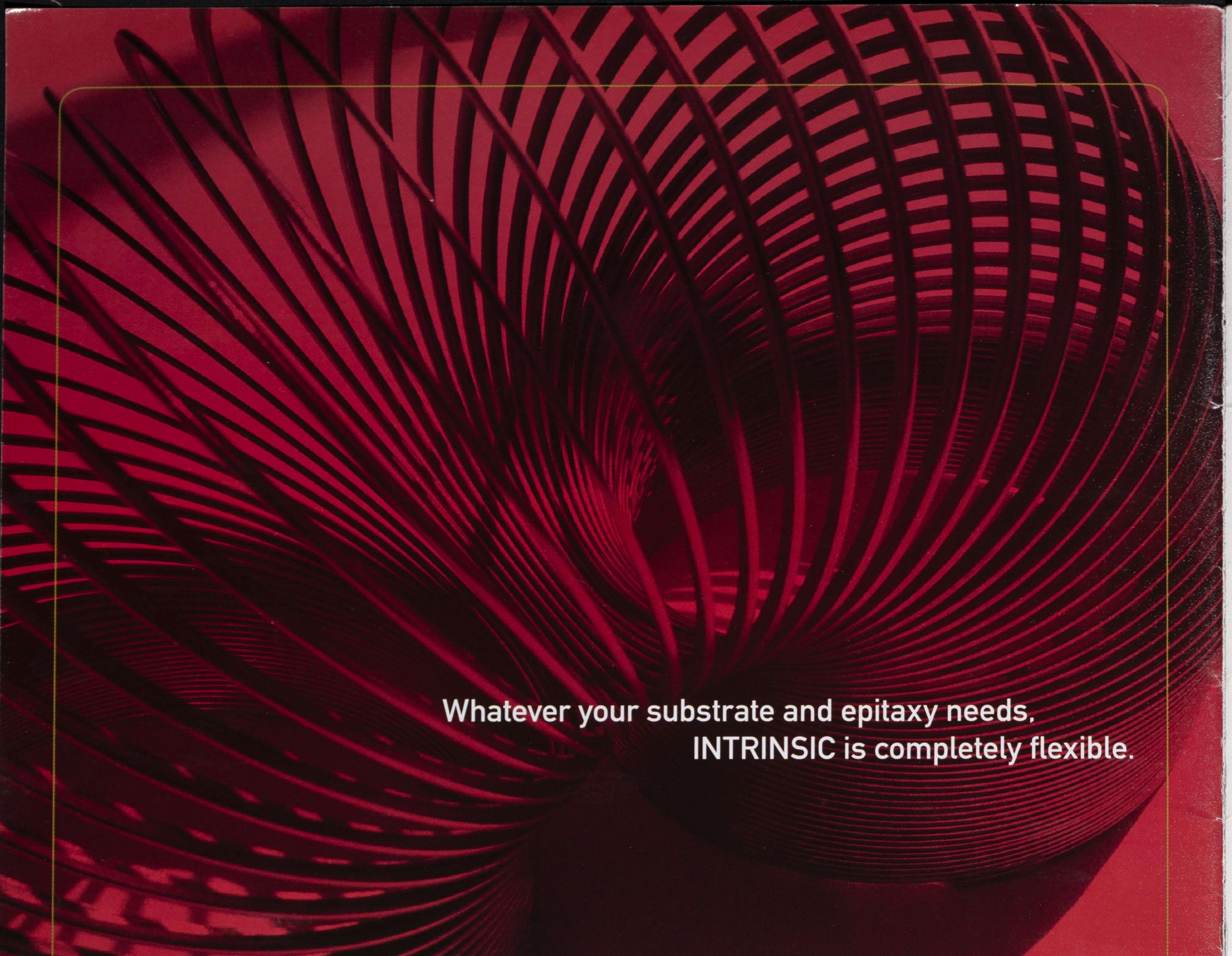
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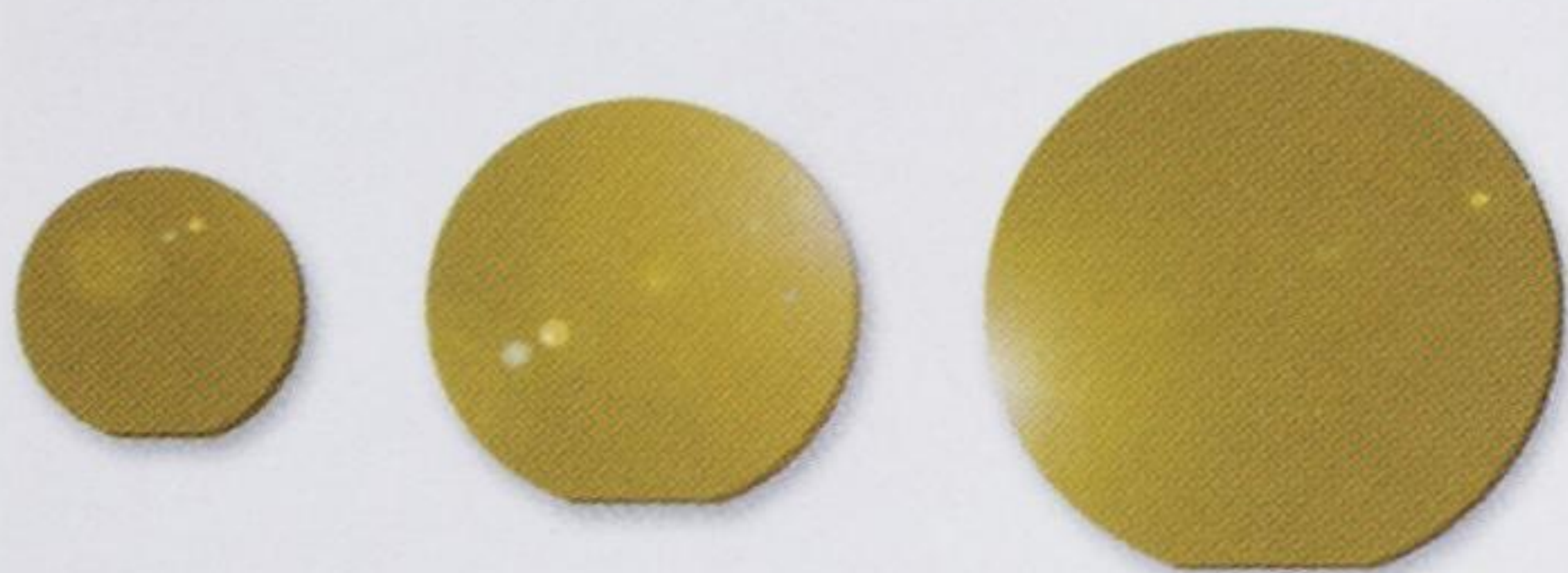


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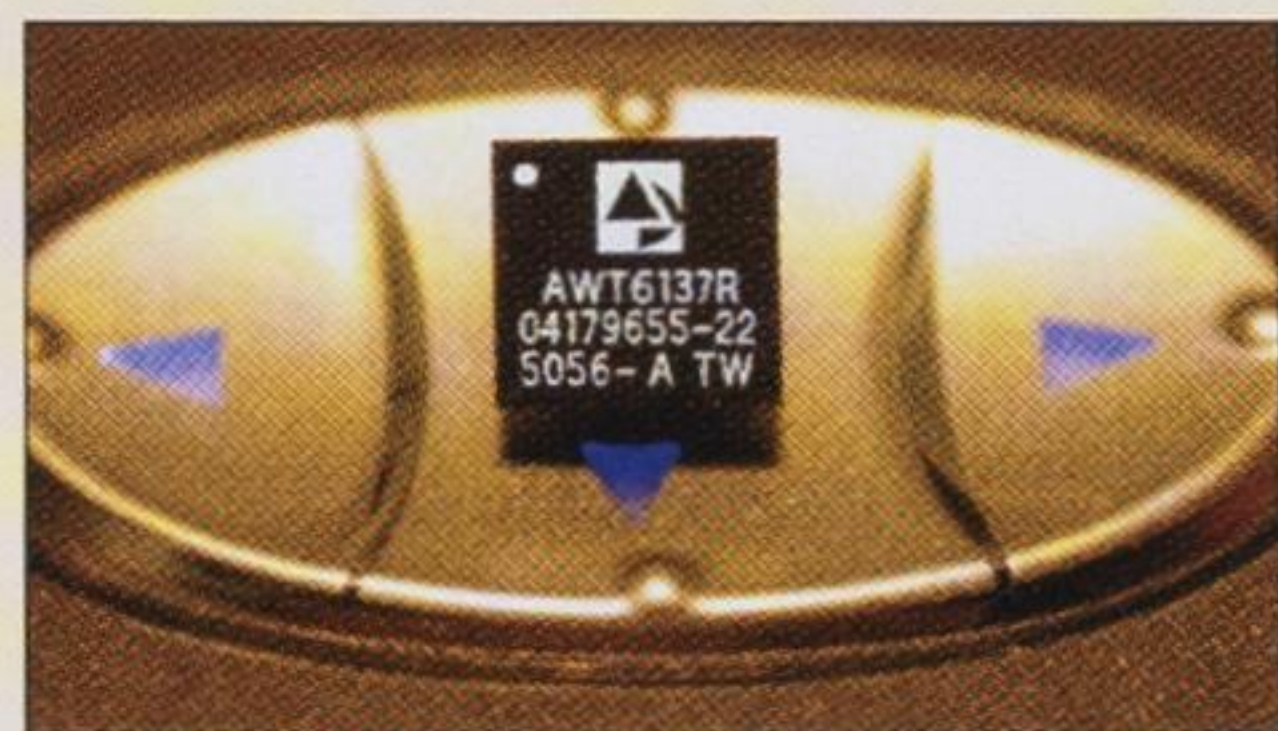
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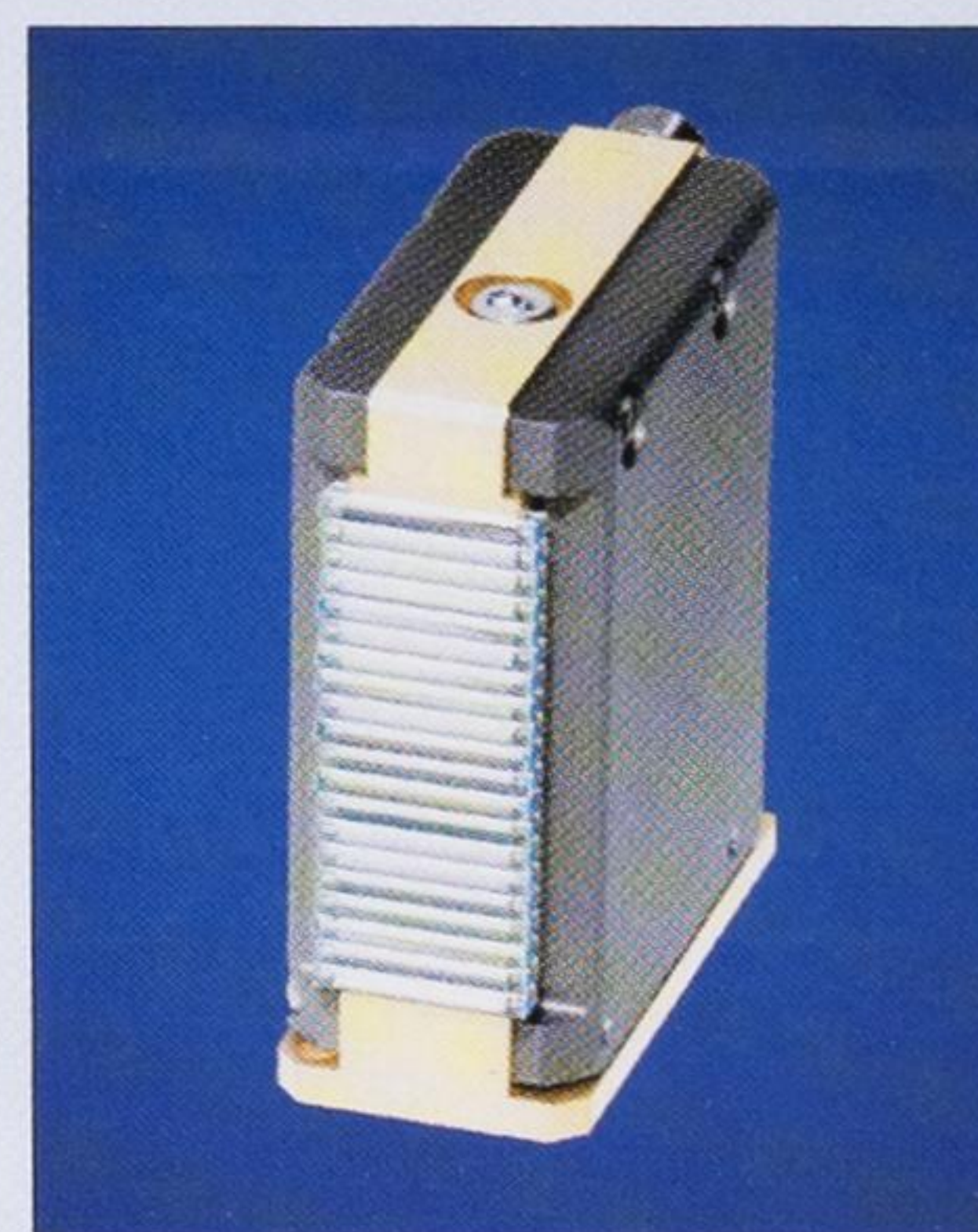
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Increasing the wavelength range unlocks new markets for nLight. **p26**

Main cover image: Jagdeep Singh has founded four start-ups in his time, and his latest venture has proven the wisdom of going against the grain.

Editor Michael Hatcher
michael.hatcher@iop.org
Tel: +44 117 930 1013. Fax: +44 117 925 1942

Features editor Richard Stevenson
richard.stevenson@iop.org
Tel: +44 117 930 1192

Consulting editor Tim Whitaker
tim.whitaker@ledsmagazine.com
Tel: +44 117 930 1233

Senior sales executive David Iddon
david.iddon@iop.org
Tel: +44 117 930 1032. Fax: +44 117 920 0977

Business development manager Rosemarie Guardino
Guardino@ioppubusa.com
Tel: +1 215 627 0880. Fax: +1 215 627 0879

Circulation manager Jackie King
jackie.king@iop.org
Tel: +44 117 930 1218. Fax +44 117 930 1178

Publisher Sarah Chilcott
sarah.chilcott@iop.org
Tel: +44 117 930 1020

Senior production editor Ruth Leopold
Ad production Joanne Derrick, Mark Trimmell
Art director Andrew Giaquinto
Technical illustrator Alison Tovey
Publishing director Richard Roe

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Editorial board

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Mega-merger fallout



Telecom system builders Lucent and Alcatel used to be a pair of big-hitters in the III-V business. Back in 2000, the US firm's highly automated facility in Pennsylvania and the French company's domestic and Italian operations were regarded as being among the leading fabs in the world.

That's all history now, with Avanex and CyOptics in control of these slimmed-down operations. But the "merger" between Alcatel and Lucent will still have a big effect on the compound semiconductor industry.

That's because active III-V components – lasers, detectors and amplifiers – are at the heart of the next-generation networks that companies like "Lucatel" are now poised to deliver. The big opportunity for them is to construct these networks, which will incorporate "triple play" and even

"quadruple play" services to homes and businesses across the globe. That means voice, Internet and data traffic all traveling through fiber-optic systems, enabling services such as television- and voice-over-IP, digital radio, and video on demand.

The big problem network builders face is that these networks will be extremely expensive, and they are already under financial pressure from their own customers, the service providers. To finance the build-out, they have been compelled to join forces.

Now, there's no doubt that this development will ultimately mean that more optoelectronic components are required, and that total chip volumes will need to increase. But the combined might of Lucent and Alcatel will also be able to apply massive price pressure to its suppliers, and that's where things start to look a bit scary for today's optoelectronic component and module vendors.

For the 25 or so suppliers still fighting to stay afloat in this market, it's going to get interesting. The likelihood is that "Lucatel", as well as rivals that are expected to follow from similar mergers, will also simplify its supply lines. Ideally, it will want to deal with one company to serve all of its optoelectronic component needs. This will play into the hands of the broader-based vendors like JDSU – at the expense of the smaller companies that currently serve a niche. It will be survival of the biggest.

Michael Hatcher *Editor*

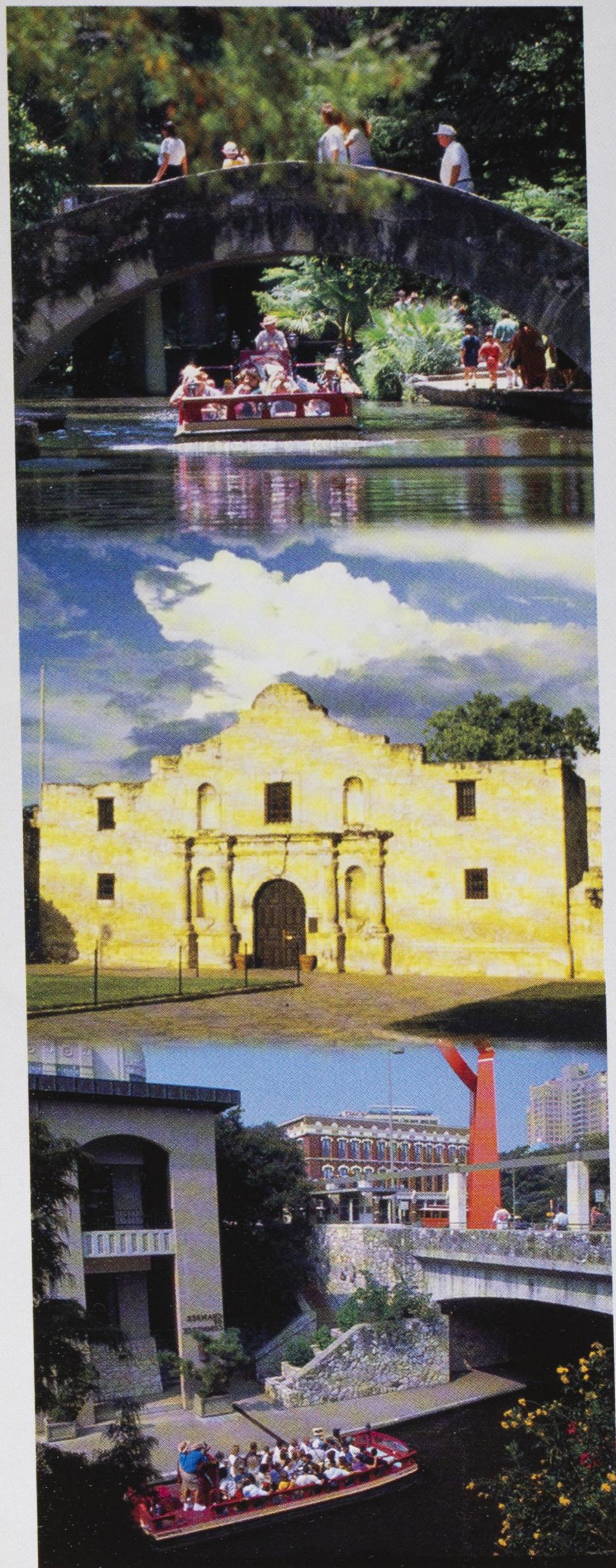
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"Ideally, 'Lucatel' will want one company for all its optoelectronic component needs."

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MANUFACTURING

Demand 'will send GaAs producers into overdrive'

A sudden upsurge in sales of mobile phones will see total shipments break the 1 billion barrier this year, claims a new report from market analyst Strategy Analytics.

The predicted growth – largely fueled by strong sales from Nokia and Motorola meeting robust demand in emerging markets like India – would represent a 22% jump on last year's figure of 817 million shipments.

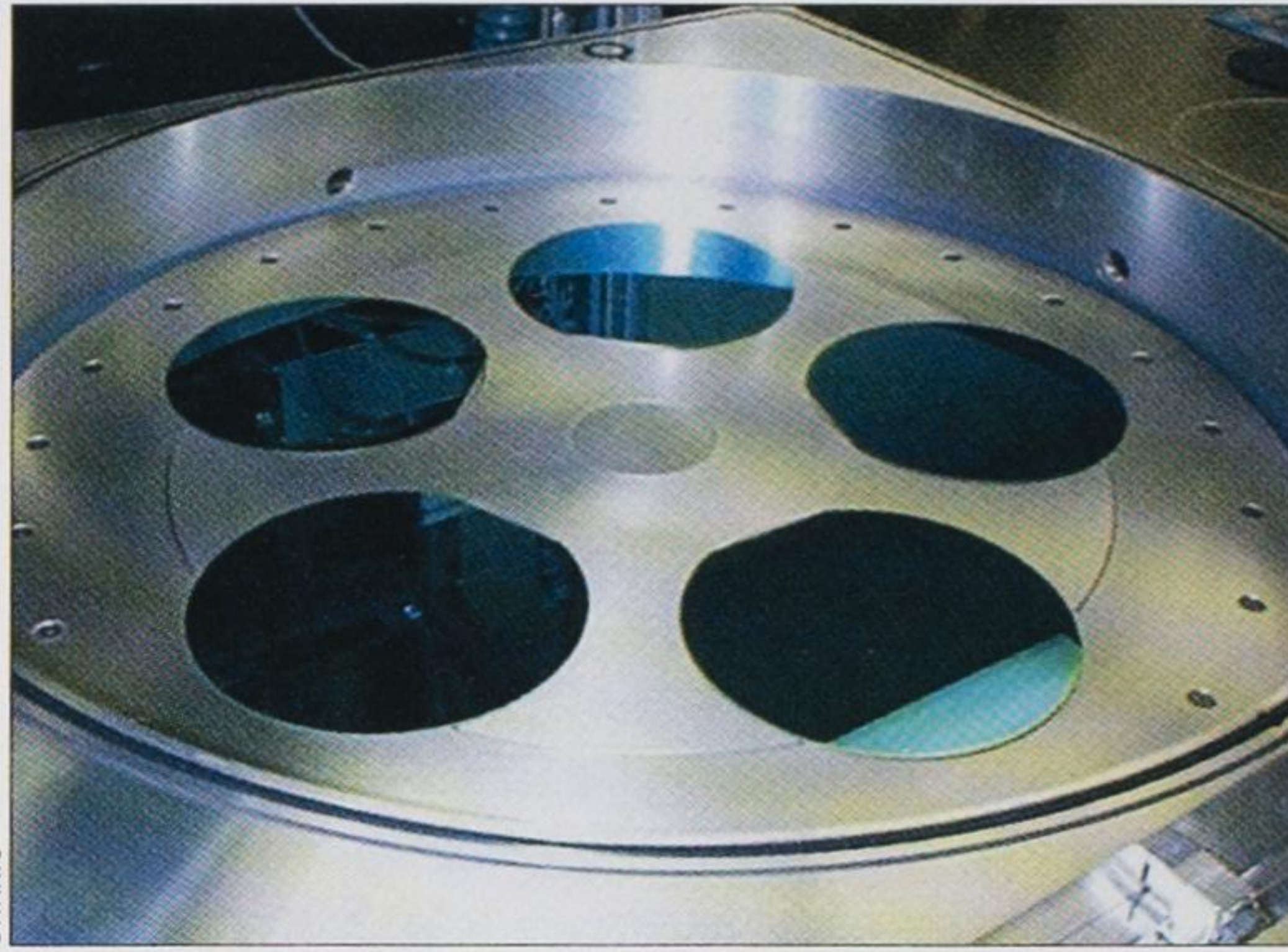
According to the analyst company, GaAs fabs will need to go into overdrive to meet the vastly increased demand for HBT and PHEMT die in front-end modules, particularly as uptake of GaAs-heavy advanced phones is now increasing strongly.

"We are seeing the move to PA-switch modules, increasing the overall GaAs content in products being sold," said Asif Anwar at Strategy Analytics. "The increasing number and size of HBT and PHEMT die going into front-end modules will lead to a significant increase in the overall GaAs real estate. As the handset moves to accommodate multiple bands, then the switches also need to become more complex, which increases the size of the switch die."

The analyst predicts a huge knock-on effect on GaAs substrate vendors. "Volume demand for substrates will grow by over 150% from 2005 to 2010," he said. Anwar's colleague Stephen Entwistle added that fab utilization will approach 100% in the next two to three years, and warned: "Substrate suppliers will need to increase material output and make any necessary investments to ensure that they can continue to meet demand. Otherwise, these suppliers risk losing market share."

This investment in new manufacturing equipment is already happening. Germany-based Freiburger Compound Materials (FCM), one of the top three suppliers of semi-insulating GaAs substrates, has added new furnaces to meet the increased demand. The company says that it is able to meet all customer requirements, and that it anticipated the ramp to some degree. Other GaAs material suppliers have been able to utilize existing capacity that has been idle since the downturn that followed the boom back in 2000.

Anwar reckons that the rapid increase in demand already being felt by the likes of RF Micro Devices, TriQuint Semiconductor and Anadigics is set to continue. "When you model these trends in terms of number of die,



The entire GaAs industry, from substrate vendors to chip manufacturers, is having to meet rapidly increasing demand from booming cell-phone sales.

wafers or substrates, then you see a significant increase in demand over the next two to three years," he said. "We believe companies like RFMD, Skyworks, TriQuint, and Anadigics are running fabs with high utilization rates right now."

While RFMD has already initiated its \$80 million investment in extra fab capacity to meet that demand, commercial foundry manufacture remains slack – although Anwar believes that this may soon change as companies like Skyworks, which has used foundries previously, reach maximum capacity.

However, California-based Global Communication Semiconductors (GCS), a pure-play foundry, is already witnessing strong demand for cell-phone components. GCS says that more than half of its revenue comes from GaAs-based PAs and switches, and it has a very healthy order backlog. Wireless infrastructure chip company WJ Communications recently signed a second-sourcing deal with GCS for GaAs and InGaP HBT wafers.

Anwar also says that the increase in demand could benefit substrate supplier AXT. "I think that AXT can focus on re-establishing its reputation. Trying to go head-to-head with either SEI or FCM at a RFMD or Kopin account would be difficult for them right now, but in 12 months' time it could be a different story."

AXT posted total revenue of \$8.5 million for the first three months of 2006, up from \$6.6 million in the same period last year. Despite registering a loss of \$2.2 million, the California-based company with operations in China is expecting a big increase in demand during the coming months.

NEW FAB

APT starts construction of SiC site in Bend, OR

High-power semiconductor specialist Advanced Power Technology (APT) has begun building its SiC manufacturing facility in Bend, OR. The company, which will soon be acquired by California-based Microsemi, recently signed an exclusive foundry-supplier licensing agreement over SiC technology with defense contracting giant Northrop Grumman.

Microsemi CEO James Peterson and local senator Gordon Smith attended the groundbreaking ceremony at APT's Oregon site.

Military applications of SiC include radar, hybrid power systems, electric power control and distribution, electronic jamming, and wideband communications systems.

The licensing agreement also allows APT to develop commercial applications of SiC microelectronics, such as more efficient electric power transmission, PC and server power supplies, and hybrid electric vehicles.

However, APT says that it will not be manufacturing components for the advanced transformers that Northrop Grumman's electronic systems division is due to develop for the US Navy under an \$8.9 million Defense Advanced Research Projects Agency effort.

These transformers will be based on SiC MOSFETs, insulated-gate bipolar transistors and PIN diodes. Because of SiC's excellent high-temperature performance, the transformers will need much less cooling.

OPTOELECTRONIC COMPONENTS

OCP sells VCSEL assets to Furukawa for \$1 m

Optical Communication Products (OCP) has completed the closure of its Colorado semiconductor operation, where it used to make long-wavelength VCSELs based on dilute-nitride structures.

It had acquired the business from Cielo Communications for \$5 million back in October 2002. OCP has sold the remaining assets of the advanced VCSEL business to Furukawa, its major shareholder, for \$1 million – along with a license to manufacture the devices.

Despite a profitable recent quarter for the Woodland Hills, CA, firm, CEO Muoi Van Tran is predicting a revenue downturn. He also says that OCP is seriously considering a move to sell products into the fast-emerging fiber-to-the-home sector. Currently, more than 90% of OCP's products are deployed in metropolitan-area networks, with the remainder found in storage- and local-area networks.

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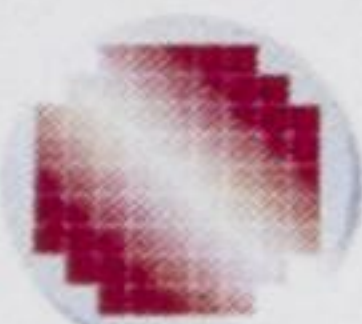
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INDUSTRY THE MONTH IN RFICS

GaAs RAMP

Kopin buys extra kit to meet soaring HBT demand

HBT epiwafer specialist Kopin has signed a multi-year supply agreement with Aixtron, under which it will increase its GaAs HBT manufacturing capacity by 50% over the next two years. Booming sales of wireless handsets, in particular the latest phones that require more sophisticated power amplifier components, are behind the capacity ramp.

"Our customers have been rapidly increasing their forecasted demand for HBT transistor wafers," said Kopin CEO John Fan. "These new systems will enable us to increase both 4 and 6 inch wafer capacity, throughput and efficiency."

Fan added that Kopin needs to add the extra

capacity quickly. Not only is demand for wireless handsets increasing faster than predicted, but the latest multimode phones require more GaAs HBTs per handset.

The first two new MOCVD systems will be installed at Kopin's Taunton, MA, facility, and are scheduled for commercial epiwafer runs later this year. Kopin will also ramp up utilization of existing systems at both its Taunton facility and at KTC in Taiwan, a licensed manufacturer of the transistors.

The new equipment from Aixtron will be the German supplier's latest high-volume "Integrated Concept Platform" tool, which supports both 12 x 4 and 7 x 6 inch manufacturing.

BiFETs

Latest patent wins by Anadigics imitate BiCMOS technology

Anadigics has significantly expanded its intellectual property portfolio with the award of five US patents for advanced RFIC designs. Three of the patents relate to ICs that combine a bipolar structure with a field-effect transistor.

The company has enjoyed success with its BiFET structures that feature on-die integration of bipolar and field-effect transistors, particularly in advanced cellular applications and the wireless LAN market through key chipset partners such as Intel and Qualcomm.

The five new patents should help Anadigics to maintain that position as it concentrates on its high-end product offerings and WiMAX services begin to get a commercial roll-out.

They should also enable the production of advanced devices with a smaller die size, in a similar fashion to the way that the silicon industry has combined the two types of structure in BiCMOS. "There has been no viable way to realize this concept in GaAs-based technologies for large-volume commercial applications," said Anadigics in the most recently-awarded patent.

That patent, number 7,015,519, details how Anadigics makes the BiFETs that feature in its so-called "InGaP-plus" technology. The manufacturing method shows how to fabricate an integrated pair of GaAs-based HBTs and FETs on a semi-insulating GaAs substrate.

The first epitaxial layer features the FET



Anadigics' BiFET structures feature in many of its new power amplifier products, and the company increasingly sees this integrated approach as a key differentiator between itself and its rivals in the GaAs business.

structure. Next, a highly doped, thick layer of GaAs is deposited. This second layer serves as the cap layer for the FET and the sub-collector layer for the HBT. The HBT is then fabricated via a second set of epitaxial layers.

Anadigics was also granted one patent describing a new method for improving the efficiency of ICs used in power amplifiers, and another disclosing a method to optimize an amplifier over a wide range of power levels.

INVESTMENT

Endwave seeks acquisitions after cash boost from Oak

High-frequency RF module supplier Endwave says that it is looking to make acquisitions following a \$45 million cash injection from Oak Investment Partners.

The Sunnyvale, CA, company sells microwave modules to the likes of Nokia and Siemens for wireless infrastructure applications, as well as millimeter-wave modules for defense and security use. Because of the high frequencies used, GaAs-based chips lie at the heart of many of its products.

Oak, which originally backed Endwave with venture funds prior to its initial public offering of stock, has now purchased 300,000 shares at \$150 each. The cash significantly strengthens Endwave's balance sheet, although the Californian firm says that it was not needed for ongoing business operations.

Endwave has just enjoyed a record first quarter, in terms of revenue, posting sales of \$13.7 million, compared with \$9.1 million one year ago. Much of that business came from its three key customers in the wireless arena – Siemens, Nokia and Nera Networks.

While Nokia and Endwave have a long-standing supply relationship, until recently Nera and Siemens sourced RF modules internally. Siemens and Endwave have now entered into a multi-year contract and the German company accounted for 30% of Endwave sales in the recent quarter. "Sales growth was led by strong demand from Siemens and Nera, and driven primarily by 3G network expansion in Western Europe," said Endwave CEO Ed Keible.

Keible added that defense and security applications were growing fast and accounted for \$3.2 million sales in the recent quarter. Industrial giant L3 Communications' acquisition of fellow Californian firm SafeView, which makes imaging scanner systems based on millimeter-wave technology using Endwave modules, should help that figure to expand in the future.

Despite the record opening quarter to the year, Endwave still posted a net loss of \$1.2 million. The company will therefore be keen to ensure that any acquisitions it does make will boost its profitability.

FINANCIAL RESULTS

Revenue reports confirm buoyant mood in industry

Financial results from the industry's leading GaAs chip manufacturers confirmed the sense of optimism currently surrounding the RFIC business, with many companies announcing record-breaking quarterly revenues.

Greensboro-based RFIC specialist RF Micro Devices turned in a \$16.3 million net profit for fiscal 2006, which ended on March 31. The figure shows a massive improvement on RFMD's 2005 fiscal performance, during which it recorded a net loss of \$66 million, and reflects both market-share gains and an upsurge in demand for mobile phones.

TriQuint Semiconductor also reported a sharp upturn in its financial results. The Hillsboro, OR, company posted total sales of \$87.9 million in its latest quarter, which also ended on March 31. That represented a 4% sequential increase despite the traditionally slow start to the calendar year, and a 31% hike from the equivalent period in 2005.

While other leading GaAs companies are reporting a similarly improving picture, TriQuint CEO Ralph Quinsey attributed the recent boost to some successful product

launches. "The favorable results validate our progress towards our long-term goals of innovation, profitable growth and market share gains," he said.

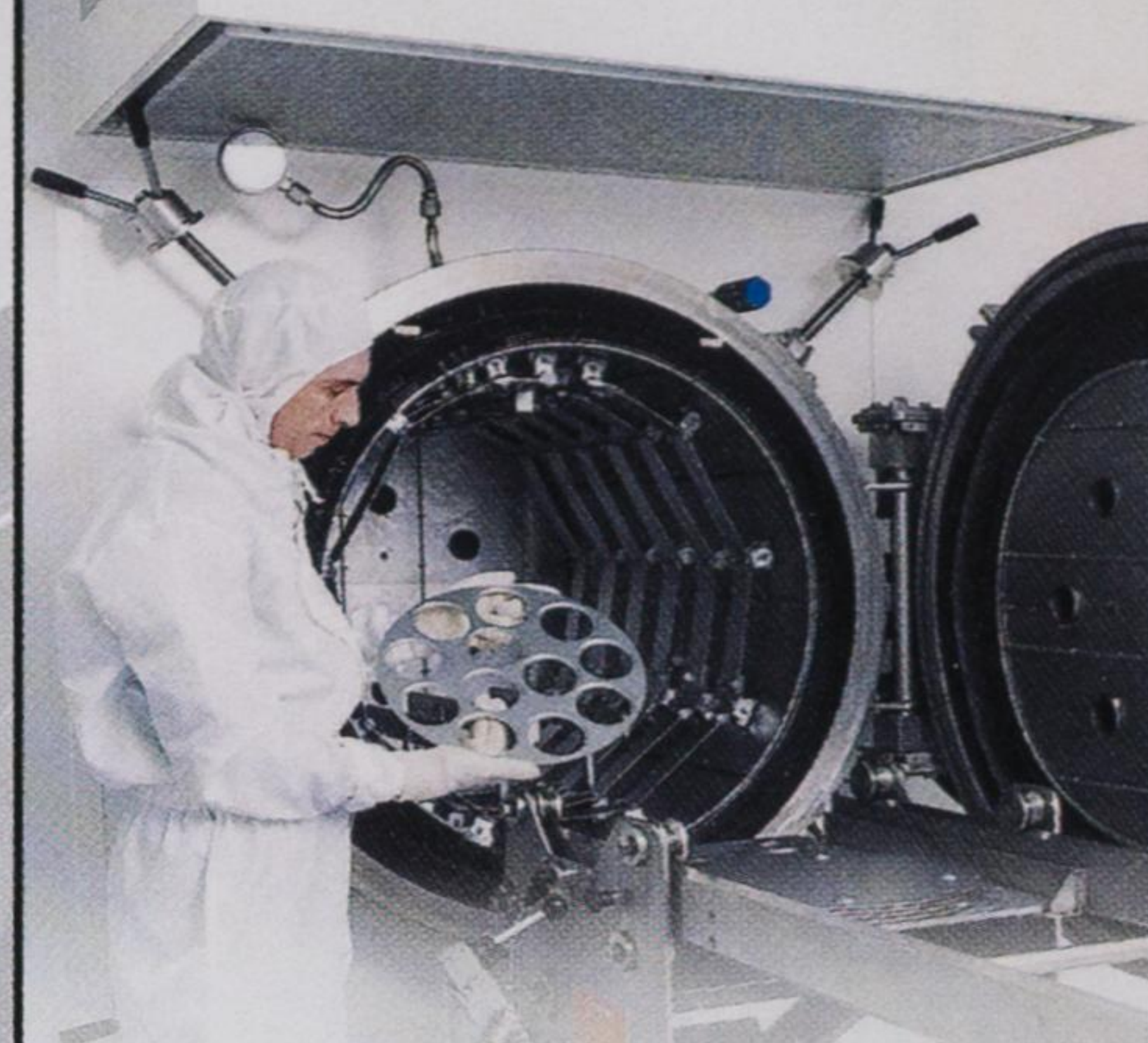
Quinsey added that TriQuint's revenue outlook for 2006 was improving as a result, and the company now predicts an increase of between 34% and 37% over the 2005 sales figure of \$294.8 million. TriQuint is also looking stronger on its bottom line, registering a profit of \$2.2 million in the latest quarter, compared with a loss of \$7.7 million during the same period last year.

Based on its current number of diluted shares, TriQuint expects to make a total net profit of somewhere between \$11.3 million and \$18.4 million during the current fiscal year.

Anadigics also posted much-improved finances thanks largely to healthy demand for high-end cell phones that require more complex RF architectures. The Warren, NJ, firm reported sales of \$35.7 million, up 7% sequentially despite the traditionally downward seasonality of the cell-phone market, and up 64% on the equivalent period last year.

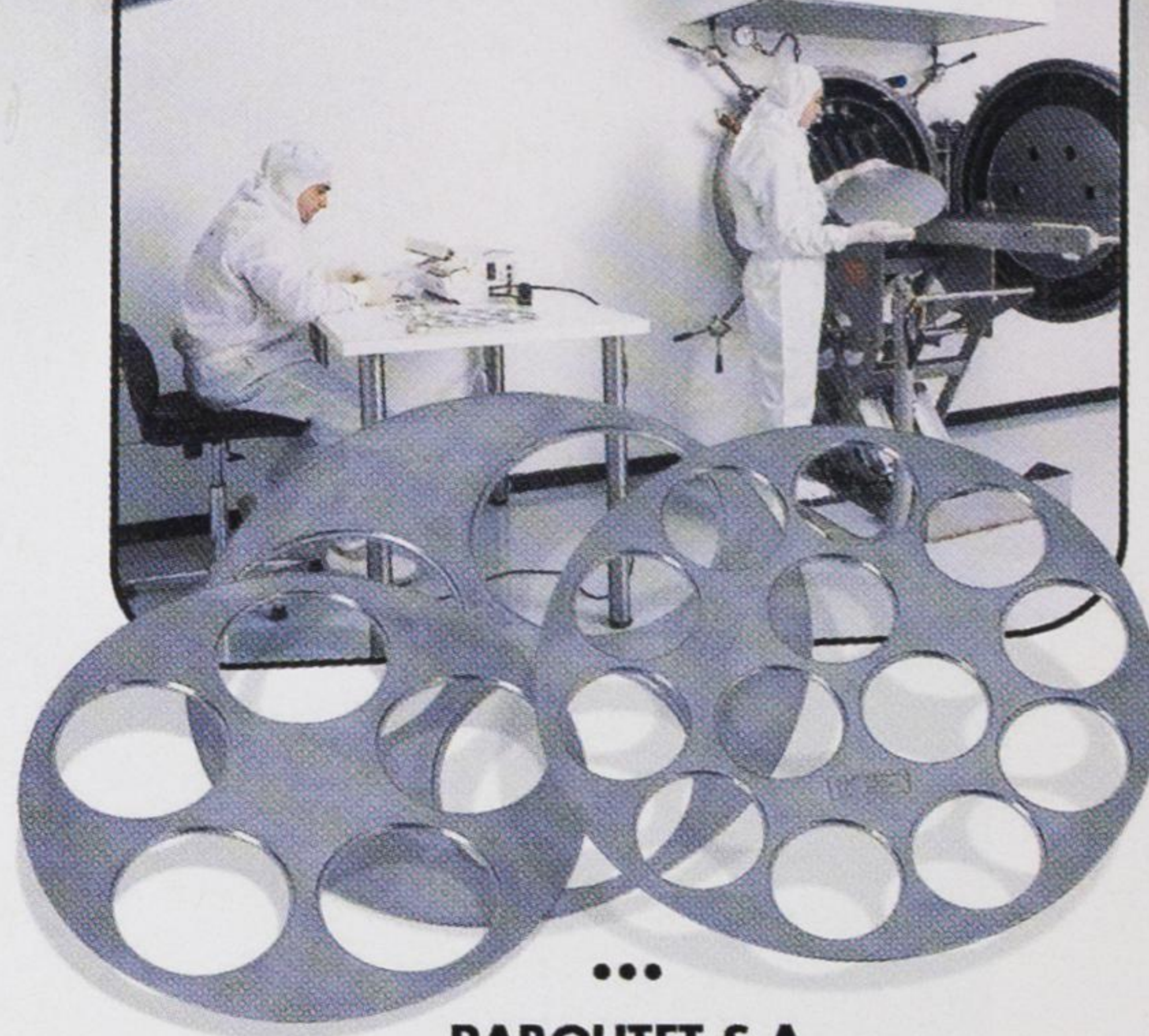
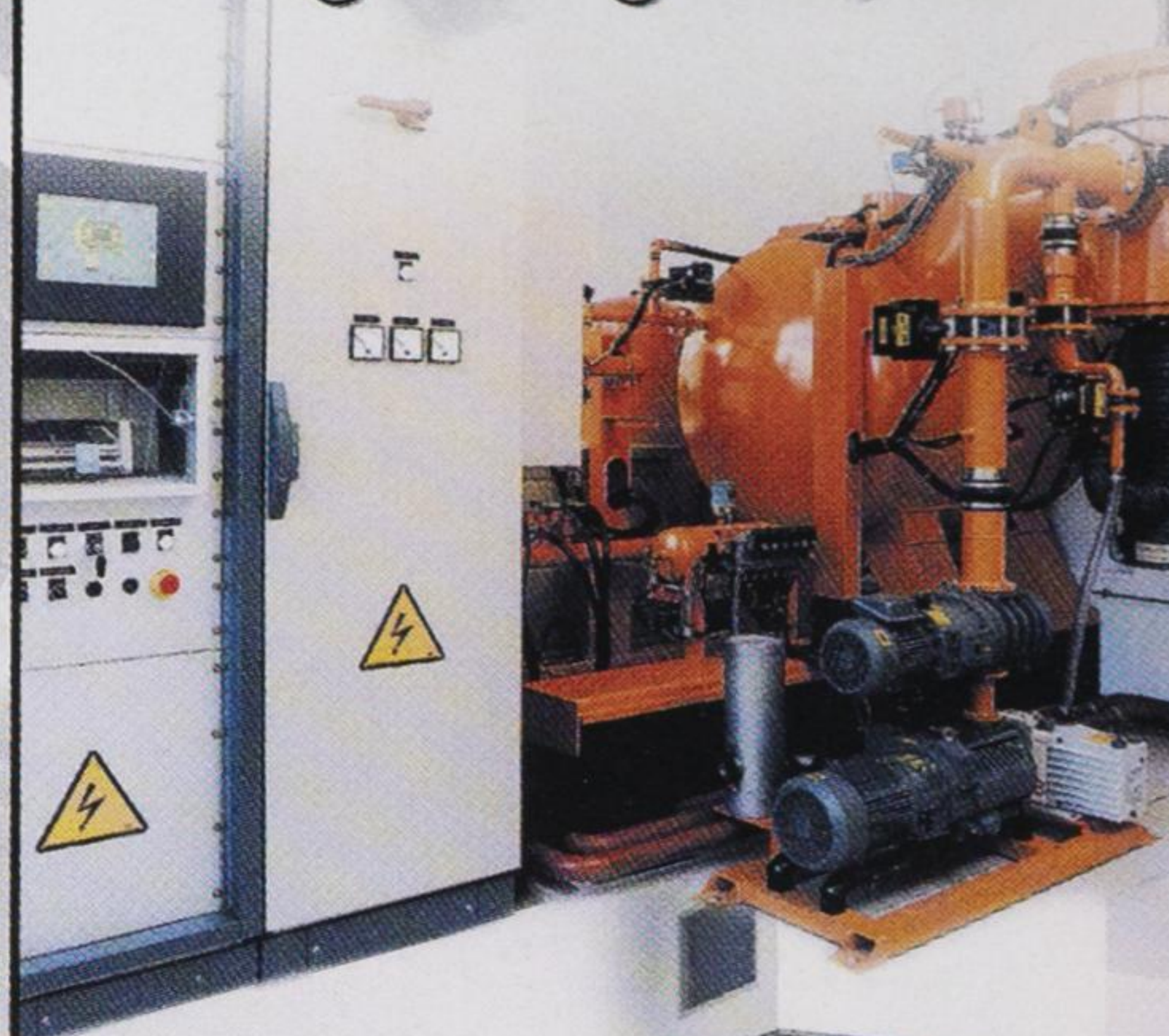
"Growth was driven by strong demand for GSM/EDGE/W-CDMA power amplifiers, wireless LAN and tuner ICs," said Anadigics CEO Bami Bastani. "Our market share expansion and increased content in these key growth markets represent a powerful combination."

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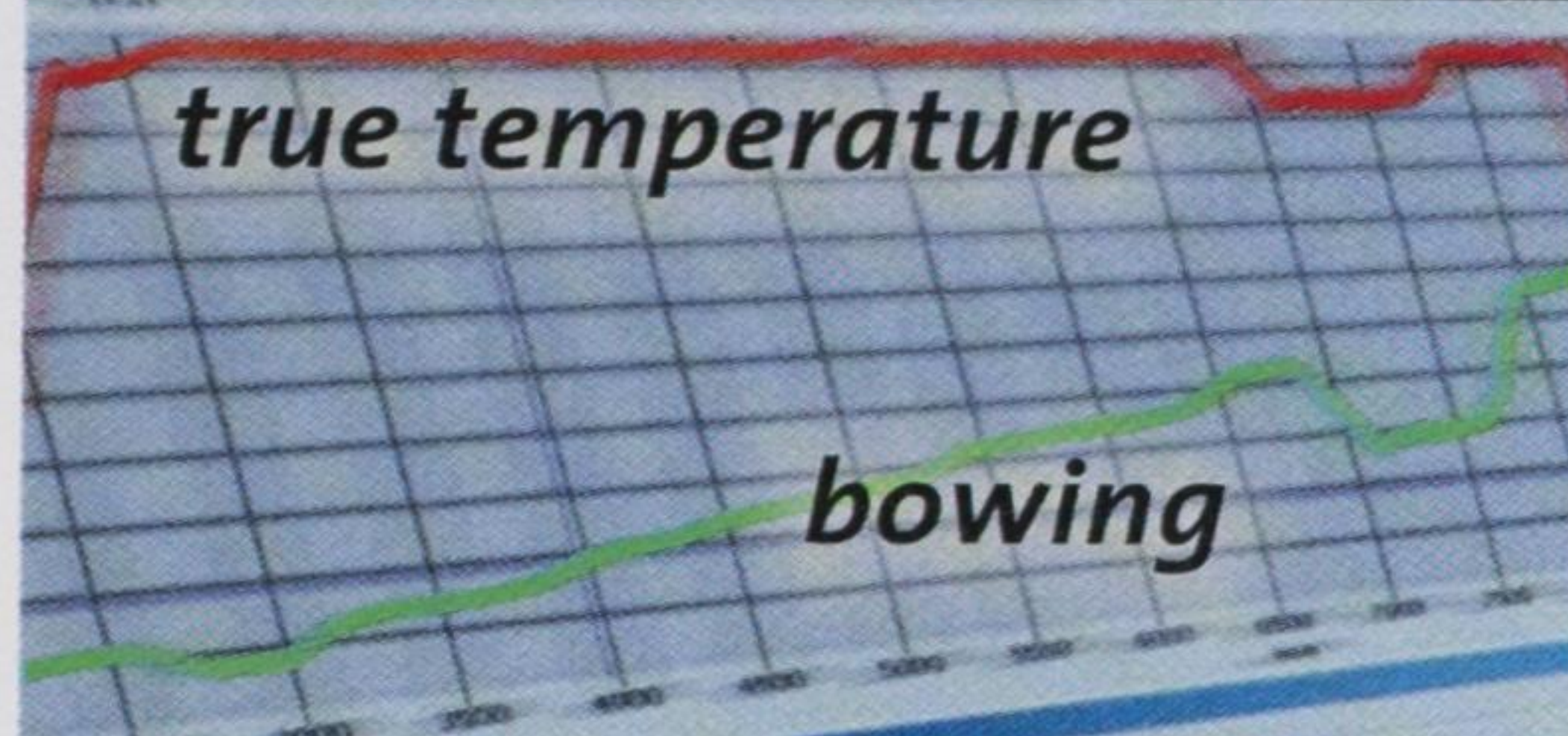
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No Surprises!

INDUSTRY THE MONTH IN HB-LEDs

FINANCIAL RESULTS

Cree output hit by capacity squeeze

LED chip and SiC wafer supplier Cree hit a revenue high of \$107.7 million in the quarter that ended on March 26, but was limited by capacity constraints across the production of high-brightness LEDs, XLamp products and Schottky diodes.

Ramping LED demand for mobile applications caught the Durham, NC, company by surprise, said CEO Chuck Swoboda in an investor call to discuss the latest results. "It caught us a little off guard and we weren't well positioned for the spike," he explained.

Cree is still transitioning from 2 to 3 inch wafer production, and Swoboda said that 83% of its LED chips were now produced in the larger format, along with 65% of its SiC wafers. Some relief to the current constraints should soon be felt as Cree switches production from its existing fab in Durham to its

new facility in Research Triangle Park, although this transition will impact volumes in the short term.

Swoboda indicated that the ramp in demand had been sudden, and had appeared only in the last four to six weeks. A similar squeeze caused by mobile demand is affecting some suppliers of GaAs-based RF components.

The CEO also said that the development of Colorwave, Cree's LED backlighting product for large-scale TV and monitor screens, was progressing nicely and that the company should meet its target of seeing a commercial deployment within the current calendar year.

Cree made a net profit of \$24 million in the quarter, compared with \$20.7 million during the equivalent period last year. It expects to post sales of between \$106 million and \$110 million for the current period.

MANUFACTURING

Nichia settlement prompts Taiwan ramp

Ongoing consolidation of the LED chip manufacturing industry in Taiwan and a thaw in relations between Nichia and Epistar appear to be driving a sharp upturn in output volumes from the region.

Nichia and Epistar settled their intellectual property dispute amicably, reportedly following Epistar's promise to respect Nichia's patents. Nichia added that the settlement had been aided by the fact that it had always maintained a good relationship with United Epitaxy Company (UEC), whose operations were taken over by Epistar in a deal that closed late last year.

The addition of UEC has strengthened

Epistar's capacity for GaN chip manufacture considerably. According to a report from *Digitimes.com*, Epistar will more than double its blue LED capacity from 150 million chips per month to 350 million this year. Epistar recently purchased five new reactors from Aixtron for GaN production, while Veeco reported that Huga Optotech, Highlink Technology and Epitech Technology had all placed "multi-unit" orders in the first quarter of 2006.

South Epitaxy, whose acquisition of Epitech will result in a doubling of AlGaAs capacity to at least 300 million chips per month, and a similar number of blue LEDs, has also reportedly signed a supply deal with GaN specialist Toyoda Gosei, again a result of Nichia relaxing its intellectual property position. Yet more capacity increases are expected at Arima Opto, which has acquired a majority stake in Advanced Epitaxy Technology and Formosa Epitaxy.

INTELLECTUAL PROPERTY

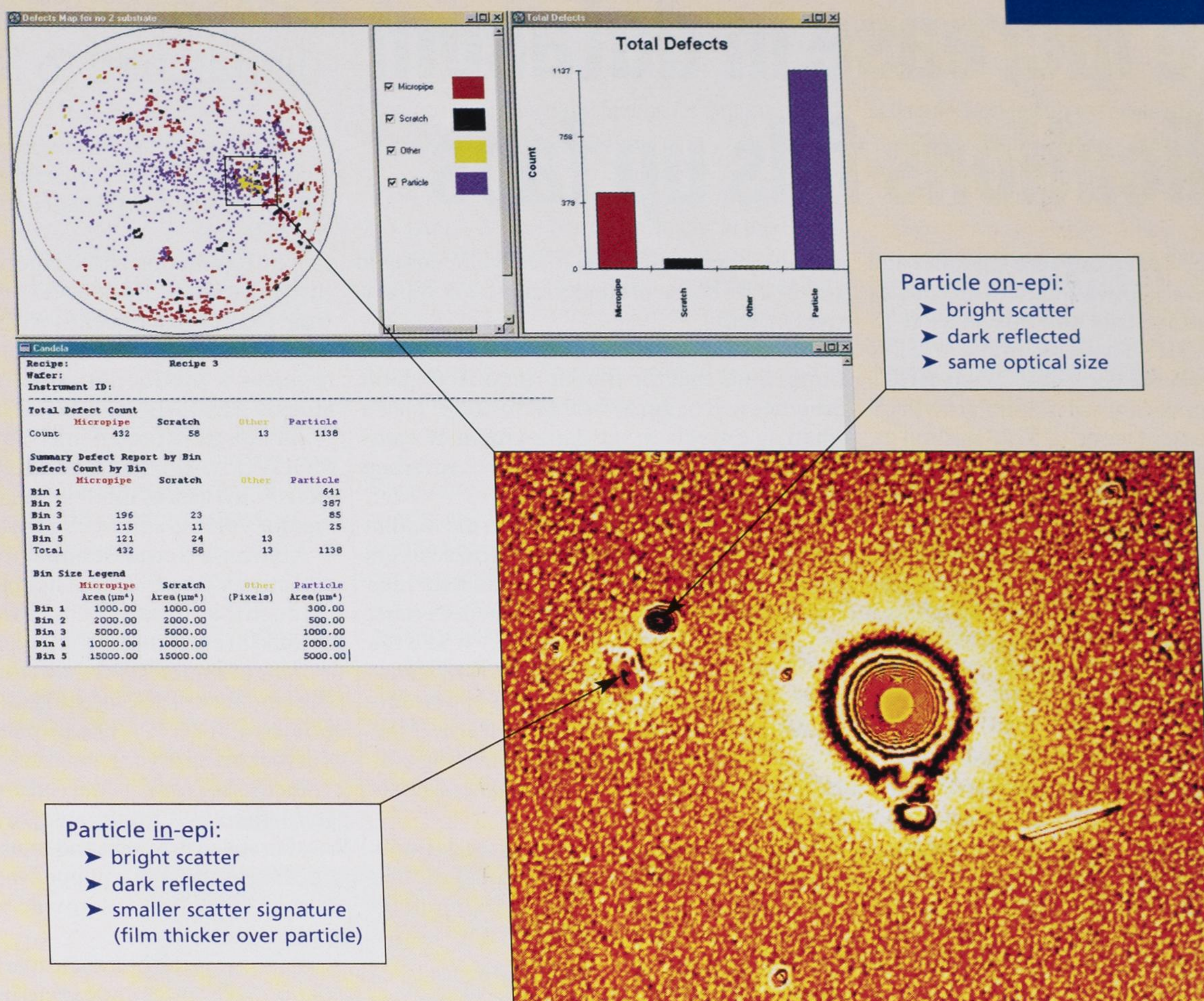
Big hitters share patent access

"Big five" HB-LED manufacturers Toyoda Gosei and Lumileds Lighting have signed a deal allowing the two companies to have mutual access to some of their key chip technologies. Under the terms of the deal, Japan-based Toyoda will be able to use Lumileds' AlGaInP technology for high-brightness red LEDs, while both firms will share valuable intellectual property relating to GaN-based blue emitters.

According to a joint statement issued by Toyoda and "Philips Lumileds", as Lumileds is now known, the agreement will allow the

companies more freedom in their development efforts. "By facilitating research at both companies, new developments in LED technology are anticipated, including an acceleration of research to improve the luminosity of LEDs."

According to a report in the Japanese newspaper *Nihon Keizai Shimbun*, Toyoda has seen a significant drop in sales of LEDs over the past couple of years, and the development of brighter chips for general lighting applications is seen as a key part of its plan to turn around the business.



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MARKET REPORT

Huge increase in datacom applications fills up fabs

Increases in the speed of Fibre Channel and Ethernet datacom applications will drive sales of optical components for this market to \$1.34 billion in 2011. That's according to Daryl Inniss at the research company Ovum-RHK. He expects average annual market growth of 11% from its current value of \$728 million as Ethernet transceivers increasingly transition from 1 Gbit/s to 10 Gbit/s for local-area network (LAN) deployment.

At the same time, Fibre Channel applications for storage-area networks (SANs) are expected to increase in speed to 4 Gbit/s and, from 2009 onwards, 8 Gbit/s. Such fast data rates will be required to handle bandwidth-heavy applications, such as video delivery over IP networks.

Developments higher up the telecommunications food chain, such as the planned merger between Lucent and Alcatel, are being driven largely by the expected switch to IP delivery of all voice, data, text and video applications.

Companies such as Finisar are already witnessing strong demand for transceivers that are based on III-V optoelectronics, and the use of wafer fabs is increasing accordingly. In the past couple of years, Finisar has jumped from seventh place in a list of the top-ten optical-component suppliers for datacom applications to second.

Inniss says that while fab utilization rates generally remain at 30–40% on average, there has even been recent talk of new fabs for some specific product lines. "However, there are still too many fabs on the whole," he was quick to point out.

The growing datacom market should at least give fab-owning companies a chance to

increase their utilization rates while demand for their in-house products remains comparatively weak.

A veteran of Bell Laboratories and JDSU, Inniss adds that the transition to 10 Gigabit Ethernet will begin to take off in 2008. That's when he expects to see deployment of modules and ports to cover 300 m links over legacy multimode fiber.

But with many active players in the market jostling to supply the millions of transceivers that are required every year by customers such as Cisco Systems, component vendors must provide cost-effective solutions. "While the market demand for higher-data-rate transceivers presents excellent revenue opportunities for component suppliers," warned the analyst, "I am worried that the challenging cost requirements create unhealthy financial positions for them."

"Furthermore, the market needs to define a form-factor that gives vendors the opportunity to recoup the research and development invested to produce the high-data-rate transceivers," he added.

In another market forecast, the Irish analyst company Research and Markets said that it expected the worldwide revenue from sales of optical components (including III-Vs) used in communications and computing to grow rapidly. It predicts that the convergence of voice, data and video transport will see the market rocket from its current size of \$2.9 billion to \$7.6 billion in 2012.

● Full details of these component forecasts can be found at the companies' websites at www.ovum.com and www.researchandmarkets.com respectively.

SOLAR CELLS

Mass-production kit dispatched to Russia

Saturn JSC, a Russian company that supplies photovoltaic systems for satellite applications, is to mass-produce GaAs-based solar cells for the first time.

The Krasnodor-based company, which has just ordered an AIX 2600G3 MOCVD reactor from German equipment-vendor Aixtron, says that its new solar-cell manufacturing program requires a production system that can be quickly established.

Although Aixtron has supplied many MOCVD reactors to Russian customers previously, the sale of this 8 × 4 inch system is the first for volume solar-cell manufacture.

Aixtron's Bernd Schulte, the company's executive VP and COO of its compound semiconductor unit, said, "Other institutes have invested in our systems for research and development of materials for satellite solar cells. [But] the Saturn JSC order is the first volume commercial MOCVD equipment in Russia with the capability for solar-cell production."

According to Aixtron, Saturn JSC is well established as a major supplier to both the Russian space program and international projects, having already equipped more than 1000 spacecraft with solar-power and storage-battery systems.

After a long downturn, the market for triple-junction solar cells appears to be picking up steam. Boeing recently won a deal to supply three huge communications satellites, all of which will be powered by GaAs-based technology (*Compound Semiconductor* January/February 2006 p10). The Chinese government is also driving demand for germanium substrates and epitaxial equipment with its own aggressive satellite program.

And while terrestrial deployment of III-V concentrator cells is still in its infancy, Emcore is gearing up to supply these products for five separate commercial programs this year.

JOINT VENTURE

Fujitsu and Mitsui come together to join the dots

Fujitsu and Mitsui have set up a joint venture called QD Laser (QDL) that will develop and manufacture semiconductor lasers based on quantum-dot structures.

The two industrial giants are providing start-up funds of ¥290 million (\$2.5 million) through their corporate venture-capital units, with Fujitsu owning 61% of QDL and Mitsui 39%.

The quantum-dot technology has been developed by Fujitsu Laboratories in collaboration with Yasuhiko Arakawa's research

group at the University of Tokyo.

Fujitsu says that commercializing quantum-dot lasers will let it increase its already sizable share of the market for optical transmission devices in the US and Japan.

"Fujitsu will also be able to enhance its competitiveness in the optical-access market, for which fully fledged global expansion is anticipated," added the company.

Quantum-dot laser structures have long been seen as the ultimate in semiconductor

laser technology. Because of the quantum effects inherent to what are effectively zero-dimensional active regions, they potentially offer temperature-independent operation and therefore no need for cooling, low power consumption and very-high-speed operation.

QDL will be headed up by president and CEO Mitsuru Sugawara from Fujitsu Laboratories. Fujitsu's corporate lab has also worked on semiconductor optical amplifiers for optical communication applications.



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...Underutilization hits Bookham

Bookham says that underutilized production capacity at its Caswell III-V facility is largely to blame as it forecasts a loss before tax and other deductions of \$10–12 million for its latest quarter. The chip, module and subsystem maker, based in San Jose, CA, originally expected the figure to be close to break-even.

...Osram claims 808 nm milestone

Osram Opto Semiconductors says that it has developed laser bars with an electro-optical conversion efficiency of 64%. The bars are prototype versions of a new generation of diode lasers that the German company expects to commercialize in two years.

...Alfalight targets 50 W with DARPA

Alfalight of the US has won \$4.7 million from the US Defense Advanced Research Projects Agency (DARPA) to develop and commercialize a 50 W single-emitter laser diode. The 18 month project, part of DARPA's Architecture for Diode High Energy Laser Systems (ADHELS) program, is

intended to produce the means for a multi-kilowatt diode-laser system.

...UK consortium sets up research center

III-V groups at Cambridge University in the UK are founding a research center that is to focus on strategic, "pre-competitive" technologies for optoelectronics, nanoelectronics and displays. The facility is sponsored by SiC material supplier Dow Corning and involves research teams led by Ian White and Michael Pepper.

...Sanyo plans chip spin-off

Consumer electronics firm Sanyo is planning to turn its semiconductor business into a separate entity. According to Reuters, the Japanese company will spin off the loss-making division in July, and eventually plans to raise capital through a share issue in the new business.

Although Sanyo's semiconductor products are primarily silicon-based, the company also manufactures laser diodes, mainly for DVD applications. It was a pioneer of AlGaInP devices emitting at 635 nm and more recently it

had been working on the development of GaN-based blue lasers. It also makes AlGaAs lasers that emit in the 780–830 nm range.

...European firms plead for research cash

III-V companies in Europe are demanding more funding for photonics research. The Photonics 21 group, which includes Aixtron, Bookham and Jenoptik, says a lack of investment in R&D could hamper Europe's competitive edge in photonics and risk job losses.

...InGaAs and QWIP cameras make debut

France-based infrared-detector specialist Sofradir is sampling Sirius, a detector based on quantum-well infrared photodetector technology. Sirius is one of a line of products Sofradir is introducing which it claims are affordable, high-performance, large-format infrared detectors. Meanwhile, Sensors Unlimited, now owned by US aerospace giant Goodrich, has released an InGaAs-based high-frame-rate, high-resolution, shortwave infrared (SWIR) camera operating at 900–1700 nm.

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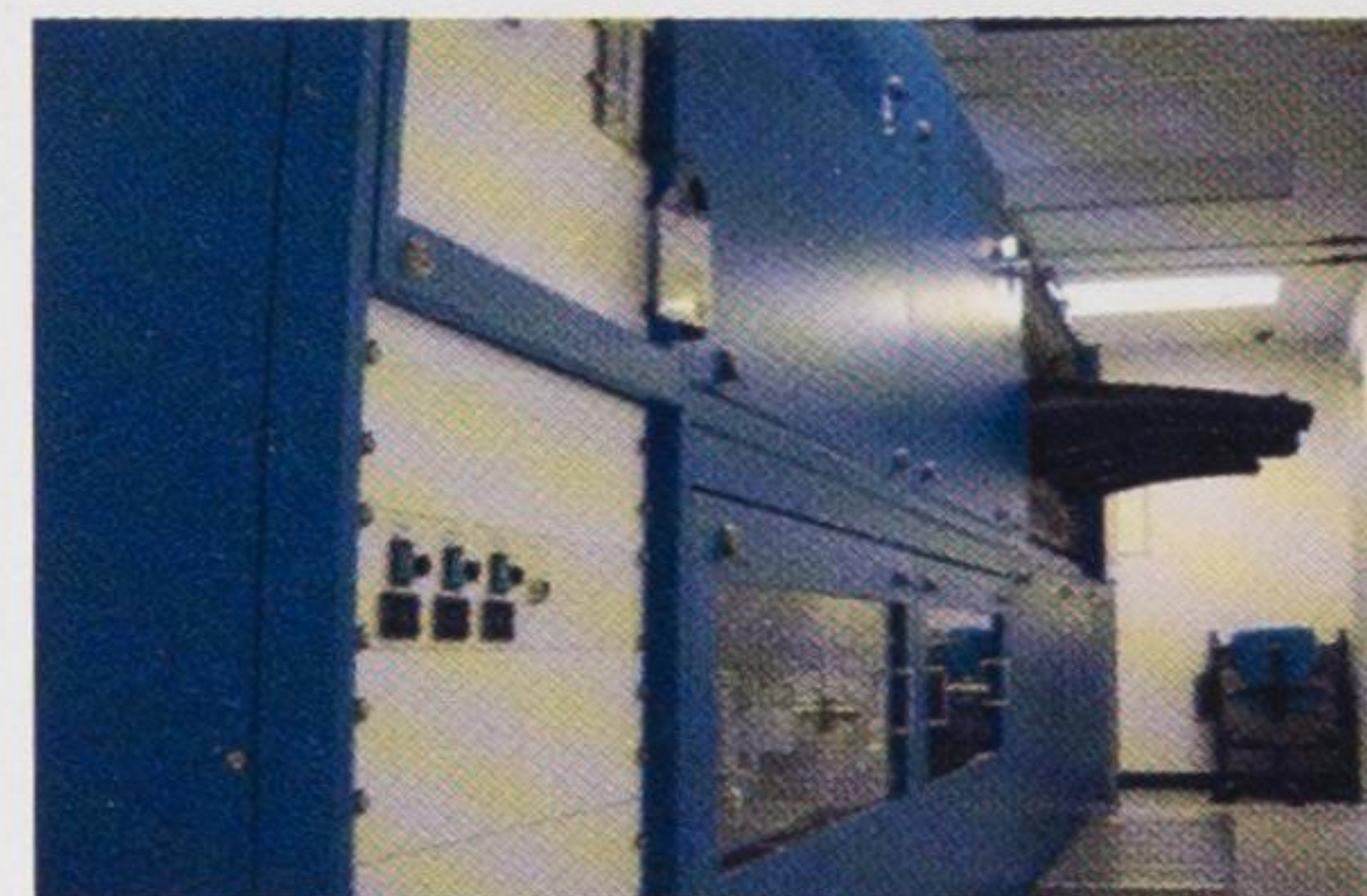
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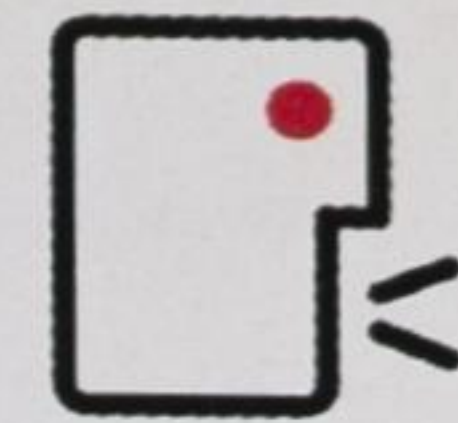
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Innovation depends on consolidation

Despite improving markets, massive chip vendor consolidation is imminent – and vital to sustain innovation, says Bookham's **Giorgio Anania**.



Giorgio Anania is president and chief executive officer of Bookham Inc, based in San Jose, CA.

After several years of huge and painful industry retrenchments and restructurings, there are increasing signs that communications investment is returning, and that markets are growing again. Has the communications industry finally turned the corner?

Unfortunately for the optical-component sector, the answer has to be "only partly". While any recovery is welcome, little has really been done to address the fundamental problem facing vendors: crippling price competition as the result of a hugely overcrowded industry.

About 25 component vendors with sales of more than \$10 million per quarter, plus numerous start-ups, are competing in a \$3 billion annual market. Though the market has probably entered a five-year cycle of low-double-digit growth, the revenue pressures at the telcos will continue to be passed down to the equipment OEMs, which will seek to consolidate to maintain margins. All this adds up to more pricing pressure on optical-components companies, unless they too start consolidating.

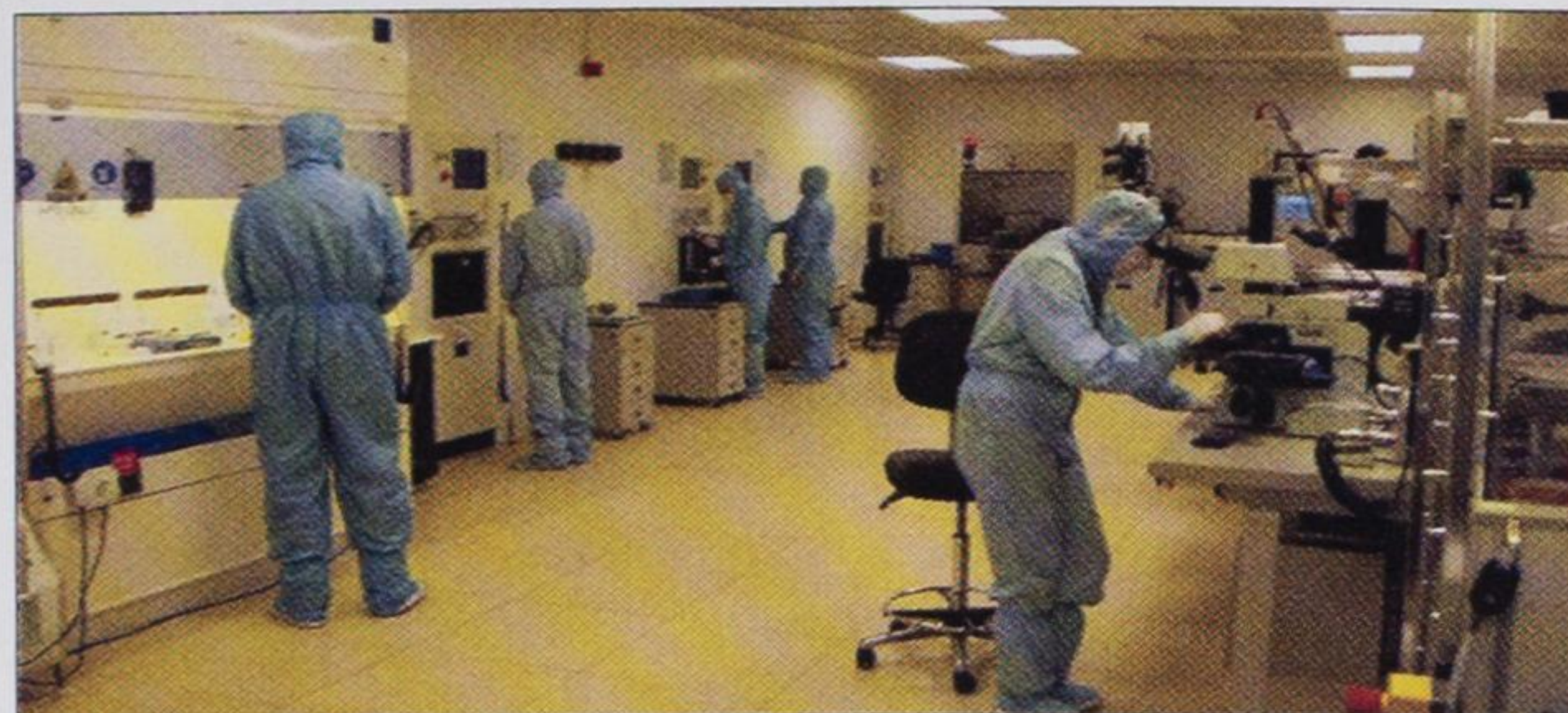
At equipment vendors and telcos, this consolidation is clearly beginning to accelerate. It all starts at the telcos. The erosion of revenue from their voice traffic is speeding up and is no longer hidden by growth in wireless services. Their response is to deploy new technologies that can significantly reduce operating expenses and bring in new revenues, such as reconfigurable networks based on packet-switched traffic, converged broadband services, and fiber-to-the-whatever (FTTX). This has increased the need for investment at a moment when telcos' finances are already under pressure. So they resort to mergers to generate economies of scale and to put continuing pressure on their suppliers, the optical equipment OEMs.

Recent telco mergers, such as Verizon-MCI and SBC-AT&T, will probably act as a trigger for further restructuring. Pressure has moved down to the equipment OEMs, and the Lucent-Alcatel merger is likely to stimulate similar consolidation. The result – fewer but more powerful downstream customers – will further weaken the hand of the leading optical-component players if they do not respond. Put simply, this industry is not grabbing the opportunity to consolidate ahead of its customers and move decisively to recreate pricing advantage and economy of scale.

Three ways to survive

There are two to three times more optical-component vendors than a stable, profitable, innovative market can reasonably support. The number needs to come down to about half-a-dozen or so leading players. Contract manufacturers aside, there are three types of players that would plausibly participate in such a drastically reduced population.

The first would be product-focused players that are strong in narrow, well-defined niches. Over time, they are likely to lose contact with the major OEMs, which increasingly prefer to deal with a small number of broad-



Bookham's Caswell fab is crucial to the company's future.

President Giorgio Anania says that Bookham can become very profitable – providing that a consolidated industry structure presents the company with the large manufacturing volumes that it needs to accommodate the high fixed cost of the fabrication plant.

based strategic suppliers. But they can generate a profitable business supplying the "horizontal" players offering a broader supply of optical components. They are the "sub-suppliers".

A second type would specialize in component and module design and outsource almost everything else, but remain broad-based suppliers to the OEMs. They would buy chips from, say, Japanese suppliers, assembly from contract houses, and specific components from sub-suppliers which they then incorporate into modules. This leaves a lot of value in the hands of the outsourcers and the components-focused players, but allows flexibility and low capital costs, and has obvious appeal to smaller vendors that lack the resources to engage in large-scale fabrication.

Near-term, they could cut costs very quickly. Longer-term, however, the lack of added value would likely make them uncompetitive in attacking the larger commoditizing sections of the marketplace. Over time, these "variable-cost-structure channel players" would probably focus increasingly on exploiting niches, which may reduce their relevance to the key OEMs.

The third remaining type is the broad-based vendor, vertically integrated from semiconductor technology to finished optical components, modules and subsystems. The major part of the value chain is kept in-house, allowing such companies to use low-cost production and to win business based on optical semiconductor innovation and leading-edge chip fabrication – the major source of differentiation to date. Necessarily available only to the large players, this approach depends on having sufficient component volumes to cover the high fixed costs of vertical integration, and is less flexible than the variable-cost play. However, given scale, this business model can become the most profitable.

Bookham is of this third type, fully vertically integrated from semiconductors to subsystems. Already quite profitable at the margin (i.e. incremental sales provide high incremental profits), Bookham can become very profitable if it participates in a consolidated industry structure that provides it with high volumes over

which to spread the huge fixed costs.

Japanese vendors have always taken this approach. They have a long-term view and continued to invest aggressively in semiconductor technology even during the downturn. Most western players (Bookham is one of the exceptions) haven't done this. The result is that the Japanese vendors are bringing out new devices just as the market is beginning to revive – and vendors without fabs are increasingly beginning to buy from them. This can only strengthen the vendors in Japan by increasing their manufacturing scale.

Those Japanese companies have a further scale advantage. Unlike western component-makers, they are not standalone companies but part of major conglomerates, such as Fujitsu, Mitsubishi and Sumitomo. So the cost of their optical-component research and production facilities is offset by selling into all of the markets where the mother company is present – DVD read/write lasers for consumer electronics, industrial lasers, and more. This guaranteed end-user market is crucial for scale.

In the West, as a standalone industry we need to be able to do the same. As an independent company, Bookham has to recreate that captive market by investing in areas that can use its fab capabilities and chip designs, exploit its existing assets, and win those customers on its own. We have, for example, directed our telecoms EDFA laser-pump technology into industrial-laser applications – a growing and profitable market. Our thin-film technology used in telecom is being targeted at life sciences and consumer market displays. Our

recent acquisition of Avalon, which is strong in optical sensing and short-reach datacoms applications, is another step in this strategy of increasing our technology capabilities and market opportunities, all feeding into the same fabs and generating greater effective scale.

Compelling financial logic makes restructuring inevitable, as well as a smarter spreading of the asset and knowledge base of the optical-components players beyond telecom into many other markets. But it is not just the optical-component industry that needs this change – so do the OEM customers.

Differentiation allows profitability, whether it is optical-components companies or their customers – the network OEMs. OEMs will have to be increasingly aware of optical-component technology coming down the pipe in two or three years, so they can back the right horse. With fewer, more powerful component vendors, the interdependence between them and OEMs will increase sharply. This will make it much easier to marry component-development roadmaps to network-product roadmaps, and bring innovation to market quickly, cost-effectively and with less risk. Early adoption and two-way commitment are prerequisites.

Innovation will be crucial to the realization of next-generation networks and the new-era communications they promise. But this will be maximized only if players from both the component and equipment sides of the business know that the other is still going to be there several years down the line – and they both need to make sure it happens.

“This industry is not grabbing the opportunity to consolidate ahead of its customers.”

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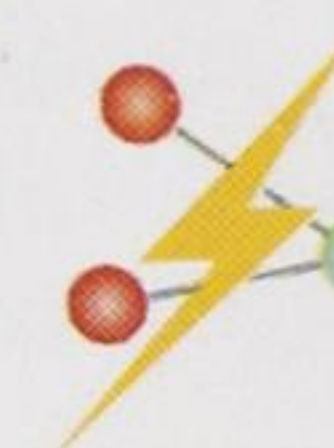
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TELECOMMUNICATIONS

System giant to pile on the pressure

The merger between telecom system giants Lucent Technologies and Alcatel will affect the supply chain all the way down to the III-V component level and play into the hands of broad-based suppliers, as **Michael Hatcher** reports.



In for the long haul: Alcatel's optical networks rely on III-V chip technology manufactured by US company Avanex.

Billed as a merger of equals, the hook-up between US telecommunications giant Lucent Technologies and its French counterpart Alcatel has been five years in the making.

Back in 2001, merger of equals may have been an accurate description. But Alcatel has outperformed Lucent since then and has effectively taken over the US company. Alcatel will have a 60% shareholding once the merger has cleared regulatory and shareholder approvals, and although Lucent CEO Patricia Russo will be at the helm, she will be moving across the Atlantic and becoming a *Parisienne*.

Broadly speaking, the two companies have a range of complementary systems that, coupled with the ideal geographic breakdown of sales that the combined entity will have, makes the merger look good on paper. And while both companies have long since moved away from the vertically-integrated corporate structures that saw them build III-V wafer fabrication facilities in the 1990s, the deal will still have a profound effect at the chip level.

Lucent and Alcatel have massive strength in both wireless and optical networks that rely on III-V technologies, but it is in the optical components sector that the effects will be most noticeable.

Product overlap appears minimal in the big-picture view, but that isn't quite the case with the optical offerings. According to Ovum-RHK analyst Daryl Inniss, both Lucent and Alcatel have long-haul (over 1000 km) solutions, both are active at what he calls the "optical edge", where technologies such as FibreChannel and Gigabit Ethernet dominate, and both supply metropolitan systems. Some of those systems will inevitably become redundant.

Nevertheless, Inniss says that the solid growth seen in the fiber-optic components sector for the past two years will continue, despite some initial negative impact caused by system redundancy. A much bigger effect is likely to be noticed in component and module selling prices. "The merger is going to strengthen the customer base, and a bigger system vendor will be able to apply more price pressure," he said. If, as seems likely, there are more mergers among systems companies, then that pressure will only be compounded.

Inniss reckons that this will effectively mean survival of the biggest for the remaining component vendors, as the merged Lucent and Alcatel would want to minimize the number of vendors it deals with and ideally use one supplier for all of its optical needs: "To better control its supply chain and decrease its costs, [the merged company] would want fewer, and more stable, suppliers," he argued. "JDSU is the only supplier that you could call a 'one-stop shop' for optical solutions and it

stands to benefit."

With Alcatel in control it might seem that Avanex, the Fremont, CA, company that acquired Alcatel's wafer fabs in 2003, could also stand to benefit from the merger. But although Avanex inherited strong technologies in the long-haul DWDM sector, Inniss says that the firm has been hampered by a weakness in its transceiver portfolio for the datacoms and access parts of the networks, and applications such as FibreChannel. "Avanex is one that could be in trouble," said the analyst.

That does not mean to say that Avanex will go out of business. Alcatel still has a major stake in the company, a supply contract that does not expire until late 2007, and its long-haul systems rely on Avanex expertise. Much more likely is a merger or acquisition that sees Avanex become part of a larger business of the kind that Alcatel and Lucent would want to deal with.

But who would buy Avanex? JDSU has a highly acquisitive history, but probably does not need to add the Avanex technologies to its portfolio. A more likely candidate, at least when considering product lines alone, would be Avago Technologies, the Agilent spin-off. Whether or not that is a likely deal will largely depend on the financial details and cash positions involved, but the mix of VCSEL-based datacom solutions from Avago and long-haul DWDM products from Avanex would make a good fit in theory, says Inniss.

Alcatel CEO Serge Tchuruk and Russo both say that the ability to spend more on research and development is the leading reason behind their deal. Since neither company now runs a components business, that won't mean more money for chip development directly, but the lasers, amplifiers and detectors that underpin the optical network remain critical.

Much of that optical innovation originated at Lucent-owned Bell Labs, which will now be divided in two. III-V research is likely to continue at the portion of Bell Labs dedicated to US government research, which is considered to be too sensitive to fall into French hands. It will become a separate entity in its own right, while the remaining portion will surely focus on network-level innovation.

Whatever happens, the era of Bell Labs as a driving force in the commercial semiconductor world looks to be over. The birthplace of the laser and transistor must now look forward to new challenges and serving new masters. "This is a defining moment in the industry," said Russo. "It is on the cusp of a switch to all-IP networks – for voice, data, video and text."

That switch will ultimately drive production of III-V fiber-optic components to much higher volumes than today. In the short term it will put intense pressure on the weakest of the remaining component vendors.

"Datacom solutions from Avago and long-haul products from Avanex would make a good fit."



LASER DIODES

Fiber laser boom spurs single emitters

Fiber laser specialist and semiconductor fab owner **IPG Photonics** is building a second chip facility as demand for its high-power systems heats up.

Manufacturers of high-power single-emitter laser diodes are set to benefit from the fast-growing demand for so-called fiber lasers that are finding increasing use for industrial machining applications such as welding, bending and cutting.

According to a new report from Strategies Unlimited, fiber lasers are rapidly penetrating the \$2 billion annual market for industrial lasers, threatening to displace more conventional high-power laser systems and increase diode consumption.

Unlike conventional lasers, which rely on crystal rods or gas tubes, coupled with excitation sources such as flash lamps or diode laser bars and finely tuned optics, a fiber laser system is very simple. The excitation medium is the fiber itself, which is doped with rare-earth elements like erbium and ytterbium. This is pumped using a single laser-diode emitter similar to those used in telecommunications applications.

Report author Tom Hausken expects the market for fiber lasers to grow at a compound rate of 35%, to reach nearly \$700 million by the end of the decade. The overall industrial laser sector is expected to grow at only 9% during the same period, to reach around \$3 billion.

"[This] will expand diode consumption, through the substitution of both lamp-pumped solid-state lasers and carbon dioxide lasers, as well as organic growth," Hausken said, pointing out that fiber lasers are enabling some completely new applications in the medical and sensing markets that conventional systems have been unable to penetrate.

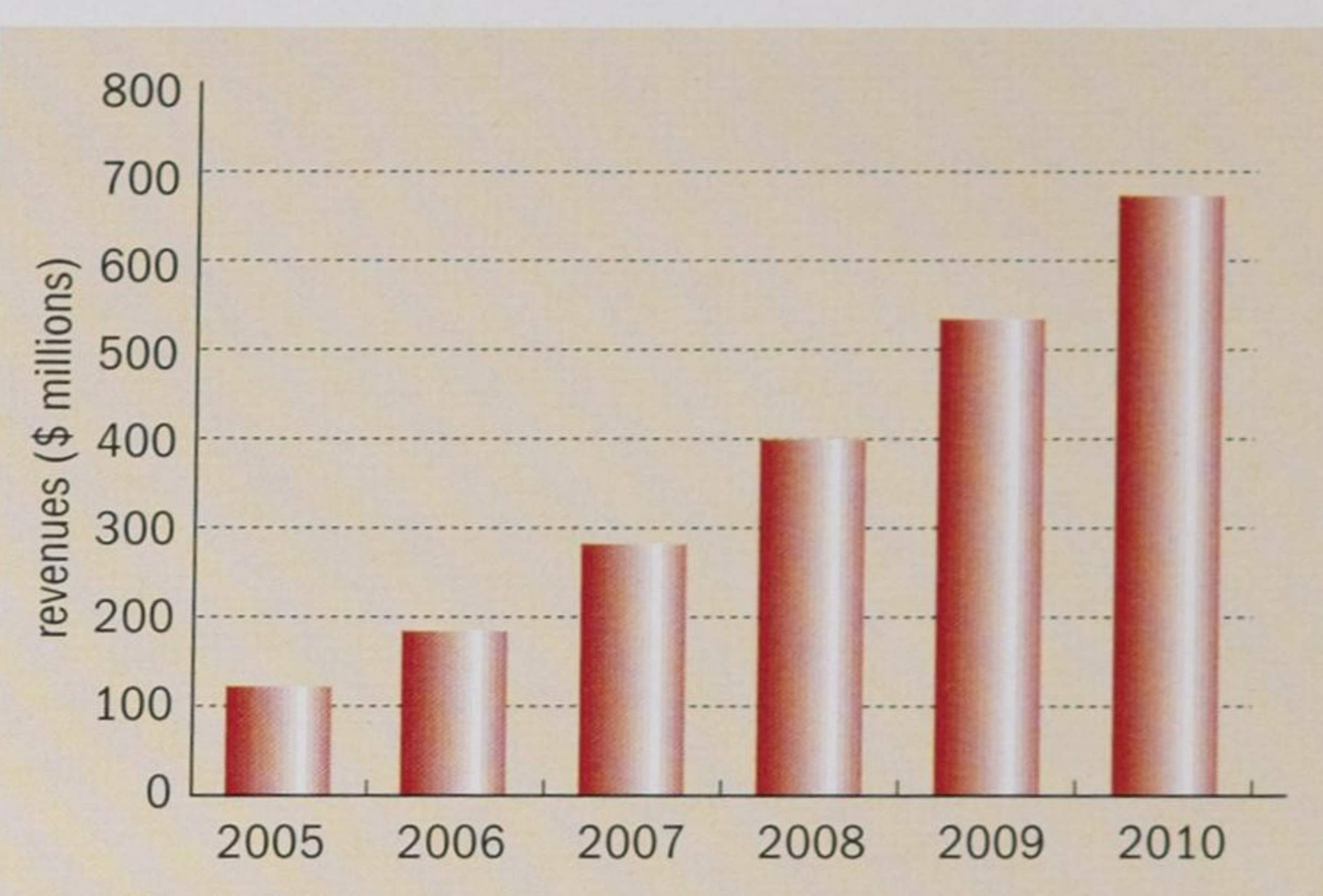
Fiber lasers are very efficient, compact and cheaper to own in the long run, but the customer base for industrial materials processing is a relatively conservative one and the technology has been regarded as potentially unreliable as it relies on a single excitation source. That view now appears to have changed. Currently worth a little over \$100 million in annual sales, the fiber laser sector is dominated by one company – IPG Photonics.

Headquartered in Oxford, MA, the privately owned firm was founded by Valentin Gapontsev in 1991. It has a semiconductor wafer fab in Oxford, where it manufactures 6–10 W single-emitter diodes using MBE.

IPG claims that it is now the world's biggest maker of diode lasers, when measured in terms of megawatts of power deployed per year. It estimates total shipments equivalent to 1 MW (equivalent to 100,000 individual 10 W diodes) in 2005.

The company is now planning a big ramp in diode production, and is building a second wafer fab to accommodate the increase. IPG's director of industrial market development Bill Shiner told *Compound Semiconductor* that it expects to deploy 2 MW cumulative diode power this year, rising to 6 MW in 2008 as applications in metal cutting in particular begin to take off.

Revenue figures show a similar story, with a compound growth rate of 60% over the past three years to reach just under \$100 million in 2005, making it one of



Fiber laser sales currently represent only 6% or so of the industrial laser sector. According to analyst Tom Hausken's forecast, this share will increase to more than 20% by the end of the decade, providing a big growth market for high-power single emitters.

the top 10 laser manufacturers worldwide according to Hausken. He reckons that the spectacular growth could see it make a top-five ranking in 2006.

Making just one basic type of laser has allowed IPG to keep its costs relatively low. Shiner stated that IPG's mounted chips cost just \$2 per W, a figure that rises to \$6 when they are fiber-coupled. He added that IPG is now qualifying 20 W sources to further reduce this.

A certain mystery shrouds the exact nature of IPG's diodes, especially given that the company has kept its cards close to its chest by not patenting its III-V technology. IPG has been involved in a patent battle with JDSU, settled some years back. In late 2000 it signed a two-year diode supply deal worth \$66.7 million with SDL, prior to the latter's acquisition by JDSU and the decision by IPG to make its own chips.

JDSU also makes fiber lasers, but the Californian company only has a small market presence. "JDSU and IPG are really the only ones with this vertically-integrated structure in the fiber laser market today, although that may change," Hausken said. "One would expect the usual long-term trend towards stratification of the supply chain [and] outsourcing the supply of diodes. However, there is no hint that this is imminent."

Most major-league conventional industrial laser companies, for example Trumpf and Rofin-Sinar in Germany, also take a vertical approach, since an internal supply of diodes is regarded as critical. While IPG faces the challenge of coping with a big expansion in manufacturing volume and sales, Hausken believes that one of the big players could complicate the picture with an acquisition.

The analyst adds that although JDSU could still mount a challenge, he is impressed with IPG's efforts thus far: "IPG has made itself into perhaps the leading manufacturer of high-power laser diodes, in units. It has done this using MBE machines, concentrating on a minimum number of designs, and by being very smart about it all."



INFINERA

Digital vision threatens incumbent telcos

Infinera's **Jagdeep Singh** tells Richard Stevenson how his digital vision has beaten the skeptics and is revolutionizing optical networks.



Infinera CEO Jagdeep Singh puts his finger on the company's success: 100 Gbit/s receivers and transmitters based on the photonic integrated circuits that are manufactured at its InP wafer fab.

Jagdeep Singh: start-up king

Jagdeep Singh has founded four communications start-up companies.

His entrepreneurial highlights include:

1993: Airsoft, a firm that was subsequently bought by Shiva Corporation for \$65 million in 1996.

1998: optical switching firm **Lightera Networks**, which was sold a year later to Ciena for \$550 million.

2000: local telecom service provider **OnFiber Communications**.

2001: Infinera.

Infinera only started shipping systems featuring its 100 Gbit/s receivers and transmitters 15 months ago, but it has already brushed aside the likes of Alcatel and Nortel and grabbed the top spot for 10 Gbit/s long-haul market wavelength deployments.

It's a meteoric rise that company founder and CEO Jagdeep Singh puts down to a focus on digital networks and a skepticism for the all-optical networks that were seen as the holy grail when the firm was founded in 2001. According to Singh, the all-optical vision had a major flaw – it meant that the carriers no longer had access to the bits that they were carrying. To Singh that approach made as much sense as selling airplanes that could fly all day but couldn't land. "It doesn't help the airlines to fly planes – it helps them to pick up and drop off passengers."

It's the same with network operators who make their money by adding, dropping and manipulating traffic, says Singh. With all-optical networks it is only possible to add and drop at the endpoints, but this restriction can be overcome by turning to digital networks featuring components that deliver optical-electrical-optical (OEO) conversions. "We took on a blasphemous position of saying that OEOs are good, and we've been vindicated by the all-optical network never taking off," remarked Singh.

After several years of development, Infinera had built an InP wafer fab in Sunnyvale, CA, along with the products it needed for its digital networks, but it still had to convince potential customers to go with a start-up company offering a new technology. "The way we overcame this was pure economics," said Singh. Customers could

immediately see the cost savings that our technology made possible, and were frightened of being priced out of the market if they stood still while their rivals went digital.

According to Singh, the company's system costs are lower than those of the incumbent analog networks because they use fewer components and are easier to upgrade and maintain. With Infinera's approach, its InP-based OEO chips are inserted in the network at points up to 100 km apart, and information is transferred digitally, which aids fault-finding because the bits can be seen directly.

Infinera's vertical integration has also been instrumental in converting the company's vision for digital networks into system sales. "It all comes down to the specifications of the performance of each device," explained Singh. "What is the right specification for those hundreds of parameters? It has to simultaneously meet two needs. One is that it is manufacturable, and the second is that you can build a real network with it." Part of the solution was to get the chip engineers to work side-by-side with the system specialists.

Infinera's disruptive technology has shaken up the pecking order in the long-haul market, but no other firm has responded by launching its own photonic integrated technology. This does not surprise Singh, who argues that many of the telecom chip makers such as Bookham have been focused on cost cutting, and cannot afford to pursue a technology that requires \$200 million of investment.

Infinera's growth has actually had a mixed effect on optical component manufacturers. It buys some optical components such as filters to put into its systems, but the deployment of its own receiver and transmitter chips eats into sales of lasers and detectors. "In the long term we're killing their business model, but in the short term we're their customers," quipped Singh, who added that Infinera's low system costs are now having a knock-on effect of pushing down component prices.

It looks like Infinera will have a rosy future as it wins an increasing market share in long-haul, regional and metro networks. Its current excess fab capacity will be able to accommodate this growth, and Singh predicts that an upgrade will not be needed for several years. The success could even drive Infinera's annual sales towards the \$1 billion mark, which would fuel the case for a launch onto the stock market.

In fact, Singh believes that an IPO over the next couple of years is a distinct possibility, with the timing dependent on market conditions. And if that does take place, it would represent both a massive pay back for Singh and a vindication of his digital vision.

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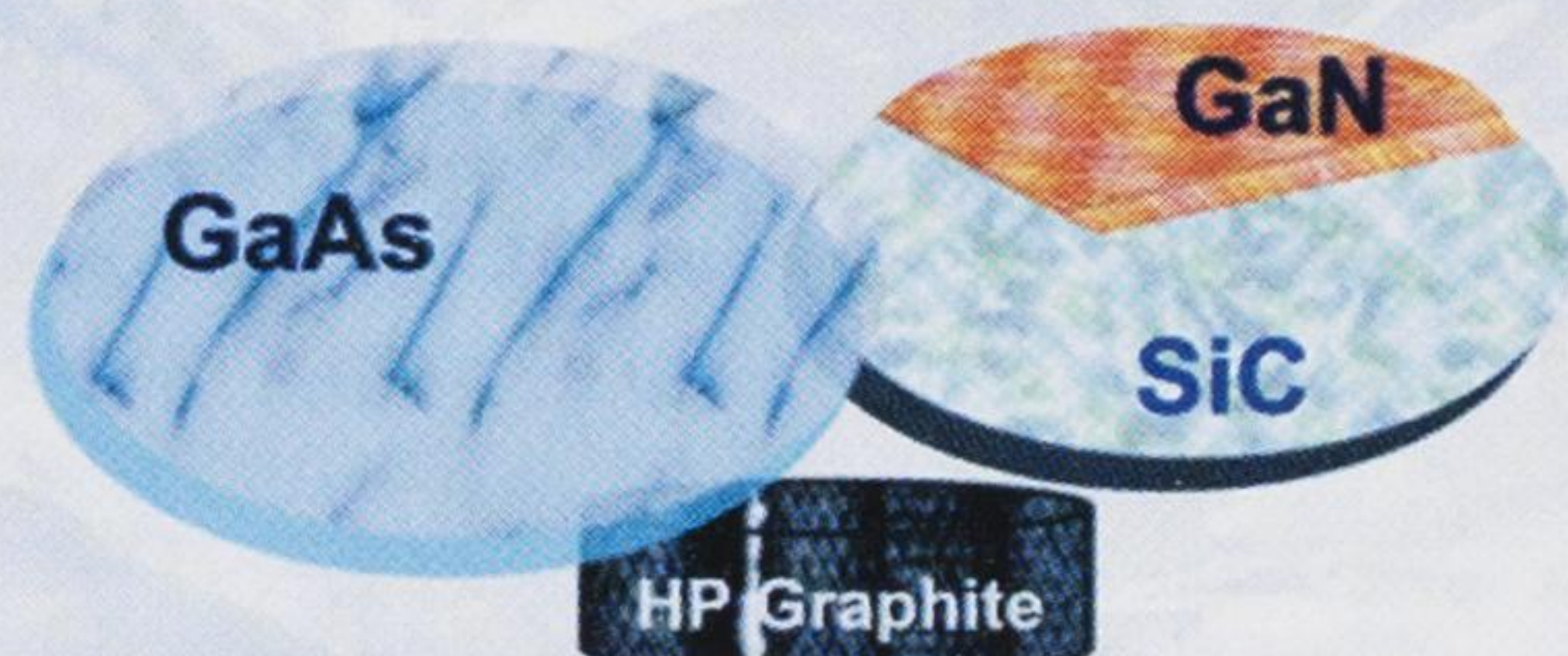
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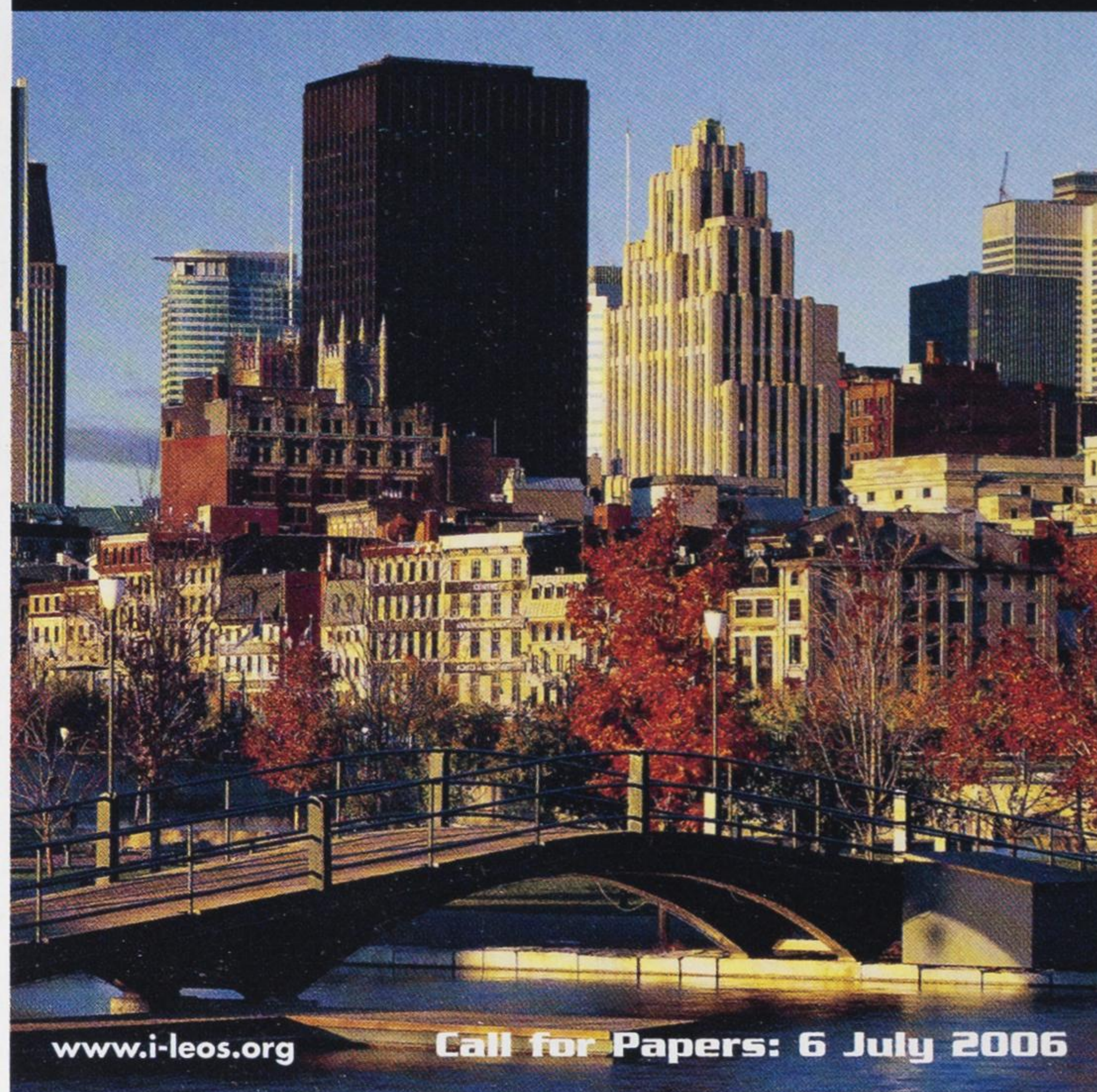
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Hybrid design improves diode robustness and boosts efficiency

Infineon's new second-generation SiC diodes combine the established advantages of the Schottky structure with the better high-voltage characteristics and surge-current handling of a p-n junction. The result is a more rugged product that is better suited to medium- and high-power applications, say **Kerstin Hubel** and **Markus Hallenberger**.

Infineon launched the first commercial SiC Schottky diode in 2001, and since then these devices have become a benchmark for virtually lossless operation. They can deliver highly efficient switching at frequencies up to several hundred kilohertz, and have been deployed as the boost diodes in power factor correction units of switched-mode power supplies operating in continuous-current mode.

However, SiC diodes remain more expensive than their silicon equivalents due to higher material costs. In addition, their resistance increases greatly with temperature – known as a positive temperature coefficient for resistance – a typical effect in a majority carrier device. This behavior has significant consequences because current surges cause thermal runaway, a condition that ultimately leads to device failure.

As a result, designers have investigated the surge-current requirements for equipment start-up cycles and fluctuations in the mains supply to set the diode's current rating. So in practice, SiC diodes with current handling capabilities well beyond those required are chosen for regular operation, adding to their cost and hampering deployment in cost-sensitive applications.

In addition, SiC diodes also lack stability at voltages above the diode's specified operating voltage. Ideally, a wide safety margin is needed between its rated voltage and the actual breakdown voltage (the reverse voltage that causes the device to start conducting).

An improved design

Addressing all of these issues, Infineon has recently launched its second-generation (2G) "thinQ!" 600 V SiC diodes. These devices can operate at voltages well above their specified rating, have a very high surge-current capability, and also deliver the advantages of first-generation diodes, such as zero reverse recovery charge at high breakdown voltages.

The thinQ! 2G design, which we refer to as a "Merged pn Schottky (MPS)", is a combination of a

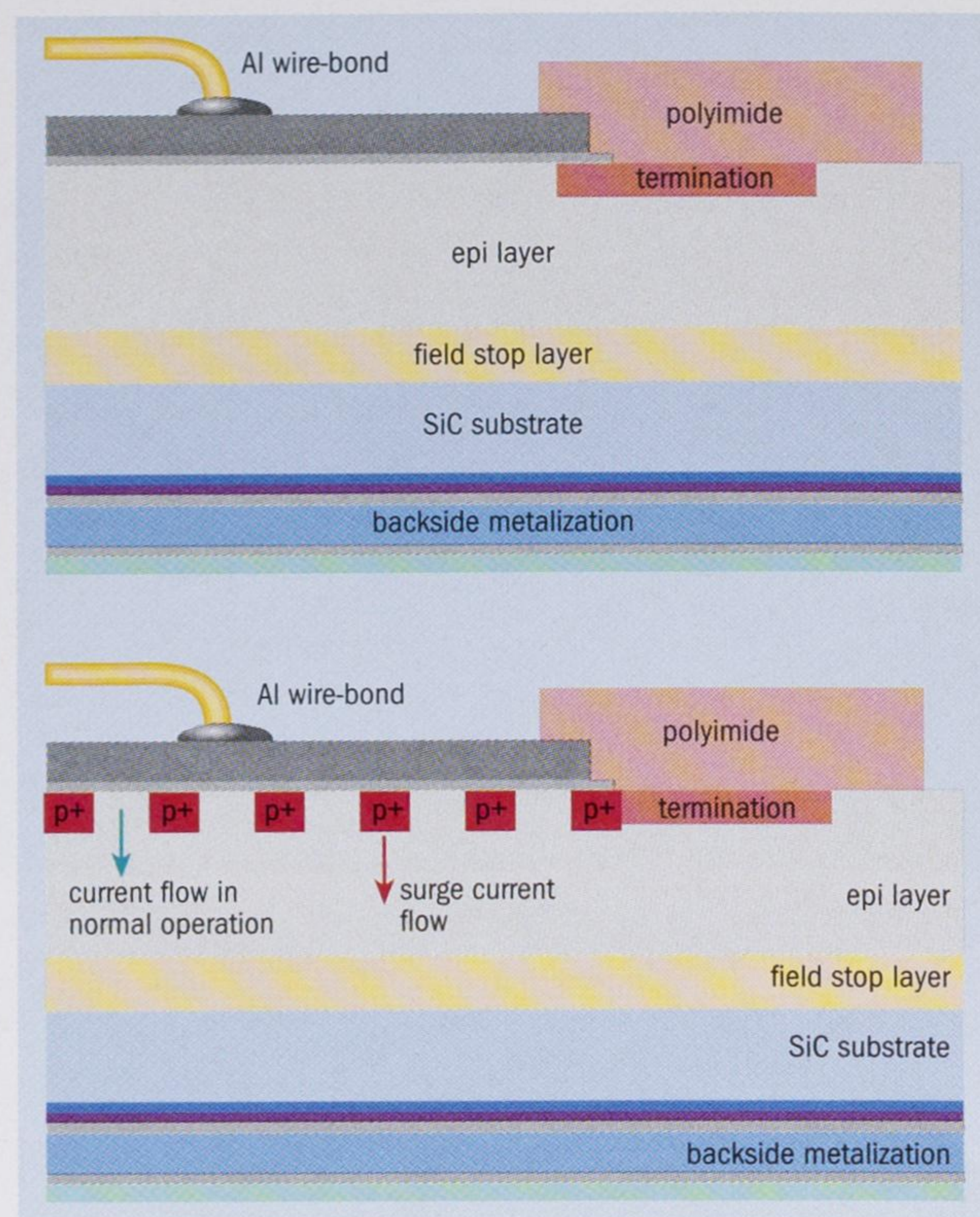


Fig. 1. Infineon launched its first-generation SiC Schottky diodes in 2001 (top). These devices could be used for applications requiring efficient switching due to the diode's zero reverse recovery charge behavior, but they were unable to cope with high surge currents and higher voltages. The second-generation thinQ! diodes (bottom) address both of these concerns through the addition of p-doped islands that cause the device to combine the advantages of a p-n junction with those of a Schottky diode.

p-n diode and a Schottky diode. This mix of the two technologies allows the device to combine the high-efficiency switching behavior of a Schottky diode with the strong surge-current capabilities of a p-n junction. The idea for unifying the two types of device is not new, and was first discussed by researchers from KTH University in Stockholm, Sweden, at the first international conference on SiC and related materials in 1999. However, up until now this hybrid approach had only been used for reducing the field stress at the Schottky interface. This enabled the combination of higher blocking voltages, low thermionic field emission and small tunneling leakage currents.

The structure of our MPS diodes and our first-generation SiC devices are compared in figure 1. The MPS diodes feature a Schottky interface for low-



Infineon is now manufacturing second-generation diodes, which have a blocking voltage of 600 V and a current rating of 4–16 A, at its fab in Villach, Austria.

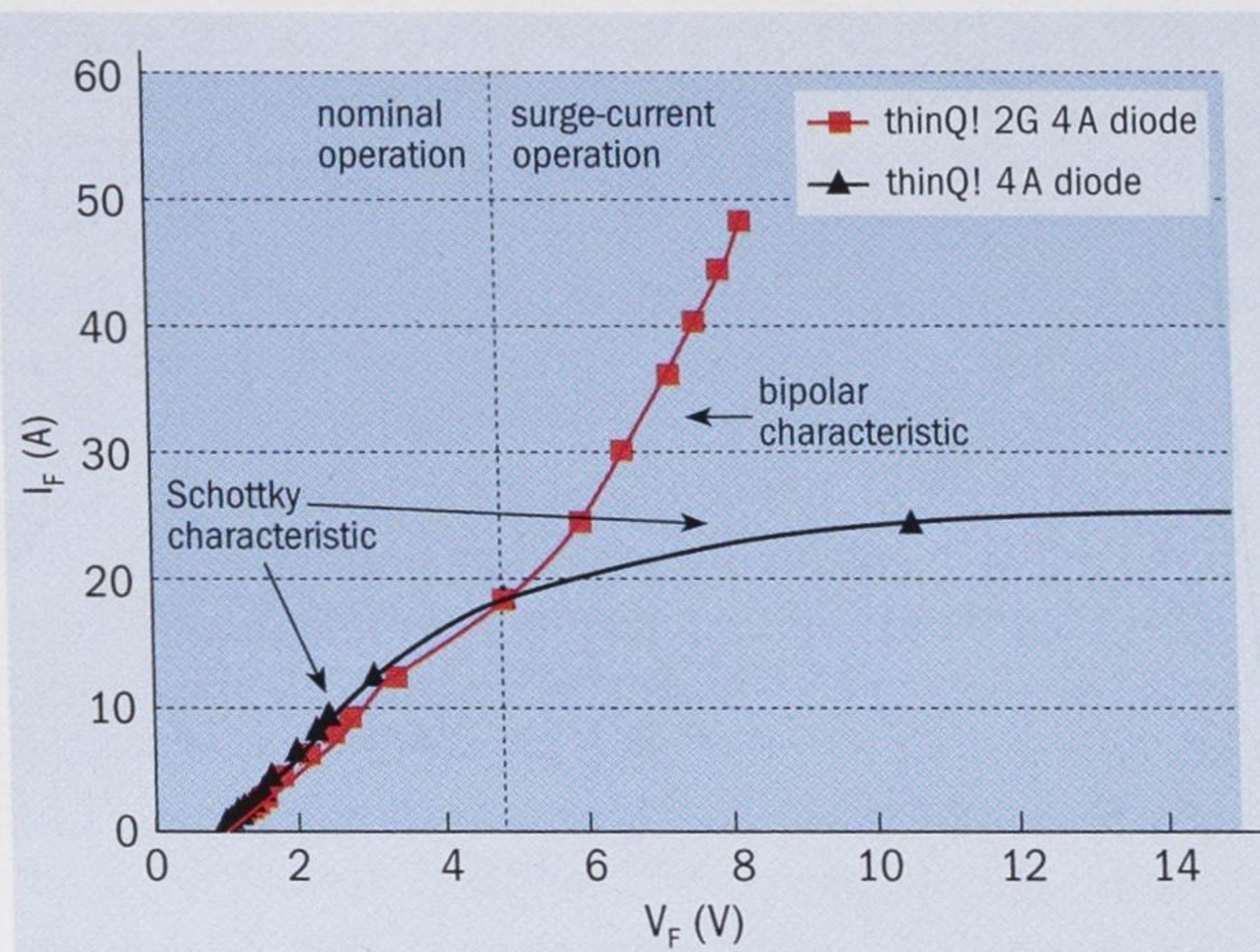


Fig. 2. Infineon's thinQ! 2G device marries a Schottky diode with a p-n junction. The result is a device offering Schottky behavior up to about 4 V and bipolar characteristics at higher voltages.

current operation, a p-n interface for higher current operation and floating p-doped islands. The idea to incorporate islands within the structure originated in low-voltage silicon Schottky diodes, where the approach reduced leakage current through shielding of the Schottky interface. When the technology is applied to SiC, the merged p-doped areas form emitter structures through a low ohmic connection to the p-doped regions and deliver two benefits – improved surge-current handling and breakdown voltages well above the rated value of 600 V. Higher currents can be handled because the device switches from a unipolar to a bipolar current path during surges. This happens when the p-n junction's threshold forward voltage of about 4 V is reached (see figure 2). The p-doped islands pin the breakdown location and

Second-generation benefits

Parameter	thinQ! 6 A	thinQ! 2G 4 A
Continuous forward current, I_F , for a case temperature $T_C = 100^\circ\text{C}$; $*T_C < 140^\circ\text{C}$	6 A	4 A*
Surge non-repetitive forward current, $I_{F,SM}$ (sine half-wave) for a pulse width, t_p , of 10 μs ($T_C = 25^\circ\text{C}$)	21.5 A	32 A
Non-repetitive peak forward current, $I_{F,max}$ ($T_C = 25^\circ\text{C}$, $t_p = 10 \mu\text{s}$)	60 A	132 A
" i^2t " value, $\int i^2 dt$ ($T_C = 25^\circ\text{C}$, $t_p = 10 \text{ ms}$)	2.3 A^2s	5.1 A^2s
Total capacitive charge, Q_C ($V_R = 400 \text{ V}$, $T_C = 150^\circ\text{C}$, $dI_F/dt = 200 \text{ A}/\mu\text{s}$)	21 nC	8 nC

Infineon's second-generation (2G) 4 A-rated diodes have a higher performance specification than their 6 A-rated first-generation counterparts, which makes them ideal replacements for these components. For example, the 2G diode is able to handle more than twice the surge current of its forerunner and its " i^2t " value indicates that the device offers greater reliability.

lead to homogenous avalanche current distribution over the chip's entire active area, which increases the breakdown voltage.

Hidden benefits

The improved current handling of the thinQ! 2G diodes is not noticeable under regular operation. This is because the device behaves like a conventional Schottky diode (such as our first-generation IFX SiC Schottky diode) with zero reverse recovery charge and a positive temperature coefficient. However, at high forward currents the thinQ! 2G diodes are essentially temperature-independent, in terms of their I-V characteristics, which prevents the thermal runaway that causes device failure.

Our current-voltage measurements on a 6 A-rated

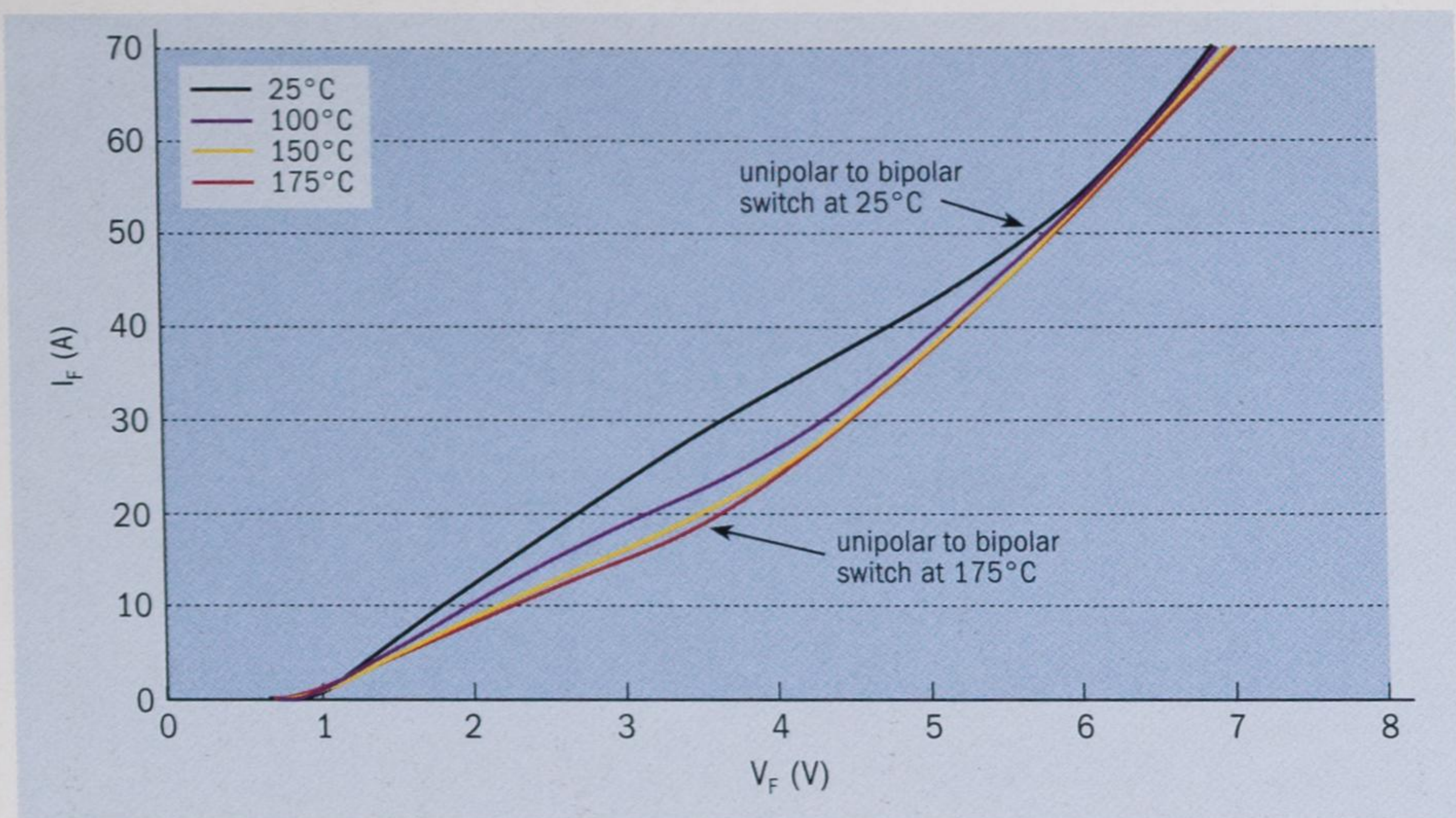


Fig. 3. The 6 A thinQ! second-generation diodes can tolerate current surges of more than 70 A, which helps prevent device failure due to current spikes. The result should be more reliable equipment.

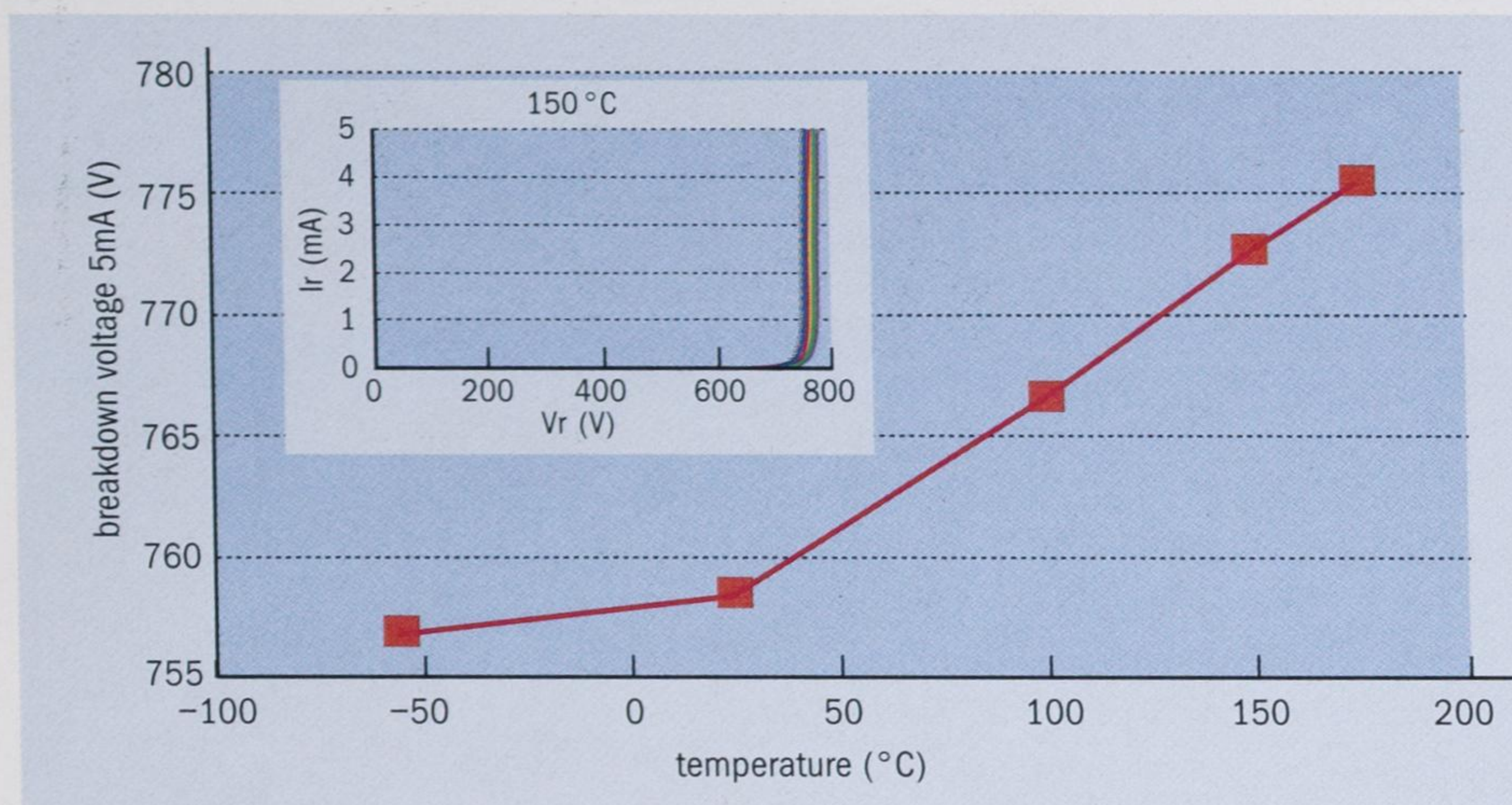
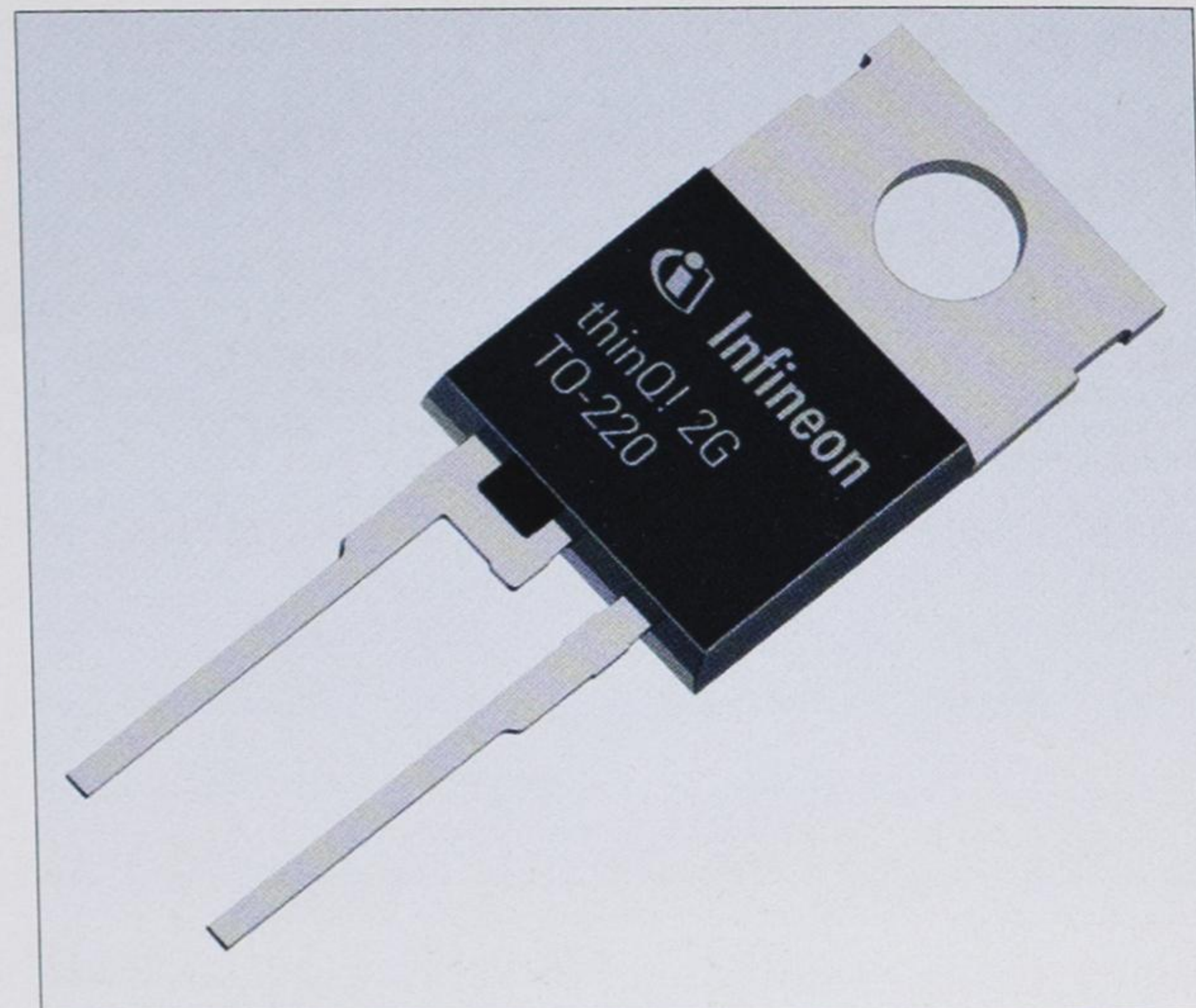


Fig. 4. The thinQ! second-generation 600 V diodes have an avalanche onset at 750 V, shielding the Schottky contact from excessive field peaks. The inset graph shows the high level of uniformity of the breakdown characteristics of a set of Infineon devices that are operating at a reverse current of 5 mA.

thinQ! 2G MPS diode, using 400 μ s pulse widths and initial case temperatures from 55 to 175 °C, are shown in figure 3. At all temperatures the devices switch from unipolar to bipolar behavior at higher voltages, which protects against thermal runaway, thereby reducing device failure and improving equipment reliability. Figure 3 shows that at a case temperature of 25 °C the unipolar to bipolar switch occurs at less than 6 V, but at 175 °C this transition falls to below 4 V.

These measurements also show that our latest diodes deliver a threefold improvement in the maximum value for the surge non-repetitive (isolated) forward current. This means that they can handle higher peak currents, which improves reliability. Product testing also reveals that the “ i^2t ” value, which is a guide to the diodes’ robustness to pulse currents, is two-and-a-half times higher for the new devices.

The MPS approach also allows thinQ! 2G diodes to withstand substantial avalanche current at breakdown conditions – something that is not possible with our first-generation diode or any other SiC diode on the



Infineon's second-generation products, which were launched this March, are available with current ratings of 4, 5, 6, 8 and 16 A.

market (see figure 4). The p-doped islands produce two separate benefits, as they shield the Schottky contact from excessive field peaks, while localizing the breakdown away from the surface. This means that the thinQ! 2G diodes can even deliver highly repeatable avalanche characteristics and a stable performance during voltage spikes that exceed the given operation voltage.

The positive temperature coefficient of the thinQ! 2G diodes that produce these characteristics offers an increase in the reliability, immunity and ruggedness of high-power electrical equipment. Power factor correction (PFC) devices that are normally connected to the mains mostly use bulk capacitors in their PFC stages. However, during transient voltage spikes the performance of these capacitors at voltages above the device's rating is very poor. These applications would be better served by our thinQ! 2G devices, which are less affected by the spikes because of their high actual breakdown voltage.

For most PFC power supplies the diode current rating is determined by the peak current through the PFC diode under non-standard operating conditions, such as start-up or power drop-out. The thinQ! 2G devices provide a surge-current capability that is more than double the regular current, which allows designers to select SiC diodes based on the nominal current in the circuit. This means that in many situations a 6 A SiC first-generation Schottky diode can be replaced by a lower-rated device, such as a 4 A thinQ! 2G diode (see “Second-generation benefits” table, p19). This will drive a shift in the entry point for SiC diodes towards lower power levels, and subsequently increase the number of markets that can be addressed by our thinQ! 2G products.

Further reading

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About the authors

Kerstin Hubel (left) (kerstin.hubel@infineon.com) is responsible for silicon carbide schottky diodes product marketing at Infineon, and Markus Hallenberger (right) (markus.hallenberger@infineon.com) is the company's technical marketing engineer for high-voltage discretes and silicon carbide diodes.



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Complementary growth technique promises improved LED performance

LED performance could be improved by switching production to GaN substrates, which reduces dislocation densities. However, a better solution is to combine HVPE and MOVPE into a single process, says researcher **Glenn Solomon**.

Epitaxial crystal growth is a critical element in many semiconductor device technologies. And, while successes in fabrication and device design are equally important, epitaxial crystal growth is the foundation upon which everything is built. Or, is it? Inherent in the success of nearly all epitaxial growth is an underlying native substrate, but because bulk crystal growth has reached such a level of refinement in terms of quality and price, this platform for growth is often taken for granted.

In fact, the success of many devices can be traced to the wide availability of high-quality native substrates, with silicon, GaAs and InP obvious examples. There are exceptions, such as HgCdTe for mid-infrared detectors, but by and large without a native substrate one should think twice – and then a few more times – before launching a new material system into the marketplace.

GaN, though, is at least at first glance perhaps a different beast. Its emergence as an electronic and optoelectronic material has all the ingredients of a good myth. It begins with a researcher toiling away in an area of little interest to our community in the confines of a privately owned company with an unrelated core business, and has led to the creation of emergent GaN-based markets such as solid-state lighting, blue and near-ultra-violet lasers and detectors, and high-temperature electronics. GaN is remarkably resilient to defects and is a good optical emitter, despite having dislocation levels of 10^9 cm^{-2} that would kill luminescence in GaAs. However, despite this success, reductions in dislocation density can help to make highly reliable GaN products, which brings us back again to the importance of a good substrate.

GaN-based devices suffer from various problems such as poor contacts and difficult processing, but the substrate issue dominates even though it has been with us from the beginning. The reason why it is so difficult to grow a bulk crystal comes down to the incredible bond strength of the nitrogen molecule, which leads to a very strong gallium-nitrogen bond and a high melting point for GaN. For circumstances anywhere close to normal conditions, GaN dissociates into liquid



Combining the strengths of HVPE and MOVPE allows high-quality GaN films to be grown on sapphire substrates in a single process. This horizontal gas-flow reactor features a raised platform for the substrate, and carrier and process gases that are introduced from the right-hand side. Independent heating of the substrate holder and reactor walls provides suitable conditions for both types of growth process.

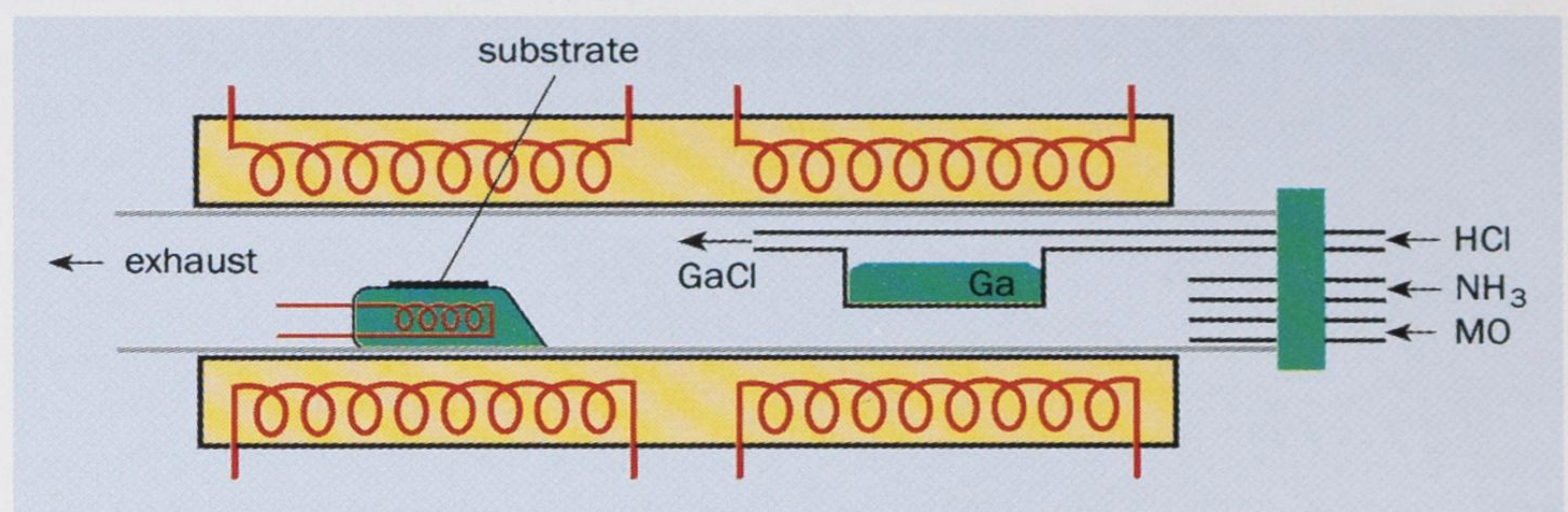


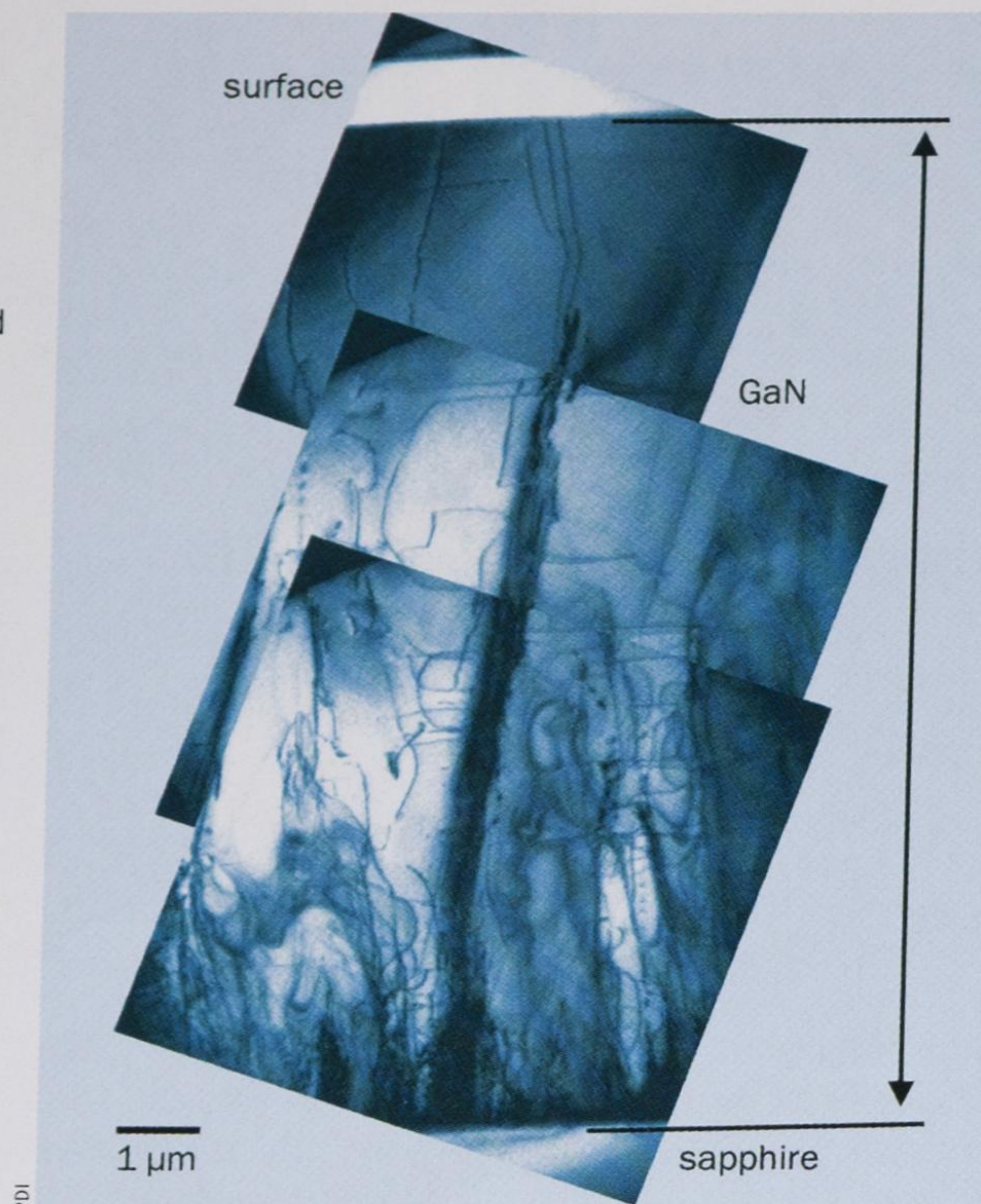
Fig. 1. HVPE growth requires the reactor walls to be hotter than the substrate, but MOCVD demands the opposite profile. Both of these needs can be met with independent heaters for the walls and substrate, which allows the more suitable technique to be used for each part of the GaN-on-sapphire growth.

gallium and nitrogen gas before it melts. Only by going to extremely high pressures of 6 GPa at 2220 °C can molten GaN be formed, because at these conditions the melting temperature drops below the dissociation temperature and a nitrogen overpressure allows GaN crystals to form from the melt.

This approach has been used by several groups, beginning with Polish consortium Unipress in the mid-1990s. The crystals are good and have dislocation densities of 10^2 cm^{-2} , but scaling has been extremely difficult and even today the technique is limited to the production of 10 mm substrates.

Consequently, several companies in Asia, Europe and North America are exploring an alternative approach to GaN substrates production using the well-established hydride vapor-phase epitaxy (HVPE) process. Although this is much more costly than the bulk-crystal substrate process, it is inexpensive for a VPE process and can deliver growth rates of at least 100 $\mu\text{m/h}$ on multi-wafer platforms. It is also better

Fig. 2. TEM cross-sectional images, taken by Achim Trampert at the Paul Drude Institute in Berlin, reveal the threading dislocations in the 12 μm thick GaN-on-sapphire epilayer grown by the combined HVPE–MOVPE approach. The threading dislocations, which appear as dark lines, are concentrated at the GaN–sapphire interface and decrease as the film’s thickness increases. The dislocation density of GaN material within 1 μm of the surface is 10^7 cm^{-2} .



suited to the growth of low-impurity III-V films than MOVPE, but is rarely used for device fabrication. This is primarily because the technique cannot offer the precise thickness control and sharp interfaces demanded by many structures. In addition, the extremely high epitaxial growth rates that are possible with this approach are not in demand, and very low impurity levels are less important in p-n junctions.

However, the HVPE process is well-suited to making relatively large free-standing GaN substrates by depositing a several hundred micron-thick GaN film on a sacrificial substrate such as sapphire and then removing the substrate. Currently, though, this is a difficult and low-yield process. This is partly because of crystal growth and processing issues such as surface roughness and etching. But the main issues are film stresses that result from the thermal and lattice mismatch between the GaN and sapphire that can cause thick layers of GaN to bow or even crack, and make the final separation of GaN from the sapphire substrate difficult. Progress is being made, but substrates produced in this way are expensive, and in the near future will only be suitable for high-cost devices requiring low defect densities, such as GaN lasers. Consequently, an alternative approach is needed for successful commercialization of a range of lower-cost GaN devices.

Our approach addresses the issues associated with substrates and growth as a single entity – as opposed to isolated substrate and epitaxy problems – and focuses away from the laser market that is already best served by expensive GaN substrates. Our aim is to affordably reduce the defect density in a broad spectrum of GaN-related devices grown on foreign substrates, and we believe this can be achieved by combining HVPE and MOVPE in a single process. This allows HVPE to

provide an inexpensive high-growth-rate process for the low dislocation-density thick buffer layer, and MOVPE to contribute a very thin, initial starting layer and the final device layers (see figure 1, p23).

MOVPE, not HVPE, is used for buffer-layer growth for several reasons. Firstly, HVPE’s high growth rate hinders accurate thickness control of the low-temperature buffer layer (~25 nm). It also tends to lead to parasitic depositions that can re-enter the gas stream after the reactor is heated for subsequent growth, due to the relatively low substrate temperature compared with the growth chamber and gallium source. Excess chlorine atoms can also cause etching during HVPE growth for temperatures below 800 °C that favor GaCl_3 formation.

Although combining HVPE and MOVPE growth in one reactor has many advantages, it has previously been avoided because the two growth processes have different requirements. The MOVPE chemical reaction is strongly exothermic and produces a positive net entropy change with temperature. Higher temperatures increase the driving force and deposition is most favorable in the hottest region of the growth system, which should be the substrate area. In contrast, the HVPE reaction is weakly exothermic, with a negative change in entropy – as temperature increases the driving force decreases. Deposition is greatest in the coolest part of the growth system, within decomposition limits. The HVPE reaction is also a near-equilibrium deposition method and at ~1000 °C, a typical growth temperature, the driving force for HVPE deposition is just 3% of that for MOVPE. This means that the HVPE process produces fewer point defects than MOVPE, but also creates interfaces that are less sharp, which is why the latter technique is preferred for heterostructure growth.

Combining the growth methods

We have unified the two methods by combining a cold-wall approach for MOVPE growth with a hot-wall approach for the HVPE process. During the MOVPE process a resistive heater under the substrate raises the wafer’s temperature above that of the reactor walls, which are unheated. For HVPE growth the situation is reversed, and the multi-zone external tube furnace heats the surroundings more than the substrate.

Using this combined process we have grown a 12 μm thick GaN layer onto a 2 inch diameter (0001) sapphire substrate. After the substrate was cleaned, etched and loaded into the reactor, it was heated to 1000 °C for thermal cleaning. The reactor’s temperature was then lowered to 500 °C using the cold-walled resistive heating configuration for MOVPE growth of the 25 nm thick buffer layer. The external heater then raised the temperature of the wafer to 1025 °C for recrystallization and the growth of 12 μm of GaN by HVPE.

AFM measurements over $10 \times 10 \mu\text{m}$ areas show a root-mean-square surface roughness of less than 1 nm, while cross-sectional TEM reveals the dislocation networks (see figure 2). These images identify a dense network of threading dislocations that appear as dark lines concentrated at the GaN–sapphire interface. Most dislocations are curved and some are even bent into the

“Our approach comes from addressing the issues associated with substrates and growth as a single entity.”

basal plane, suggesting that they can interact, annihilate, or tie themselves up and limit propagation. The upshot is that this epitaxial process can efficiently reduce dislocations during the growth. Most of the action occurs within a few microns of the GaN–sapphire interface, where the dense tangle of dislocations diminishes dramatically, and after 12 μm of growth the surface's dislocation density drops to the 10^7 cm^{-2} range.

Although the reduction in GaN dislocation density by two orders of magnitude to 10^7 cm^{-2} is significant, it is still too high for the GaN substrate market. However, for a major reduction in dislocation density it is neither time-consuming nor expensive, and could benefit lower-cost commodity markets where GaN substrates would be too costly, such as LED-based general lighting.

If so much is possible with just 12 μm of growth, why shouldn't we turn to even thicker buffer layers to cut the dislocation density even more? Firstly, as can be seen in figure 2, the greatest reductions in dislocation density occur close to the GaN–sapphire interface, and additional growth brings diminishing returns. More importantly, further growth has a downside, as greater thicknesses increase the accumulated thermal and lattice mismatch strain, which can reduce device performance and reliability and can cause the material to bow.

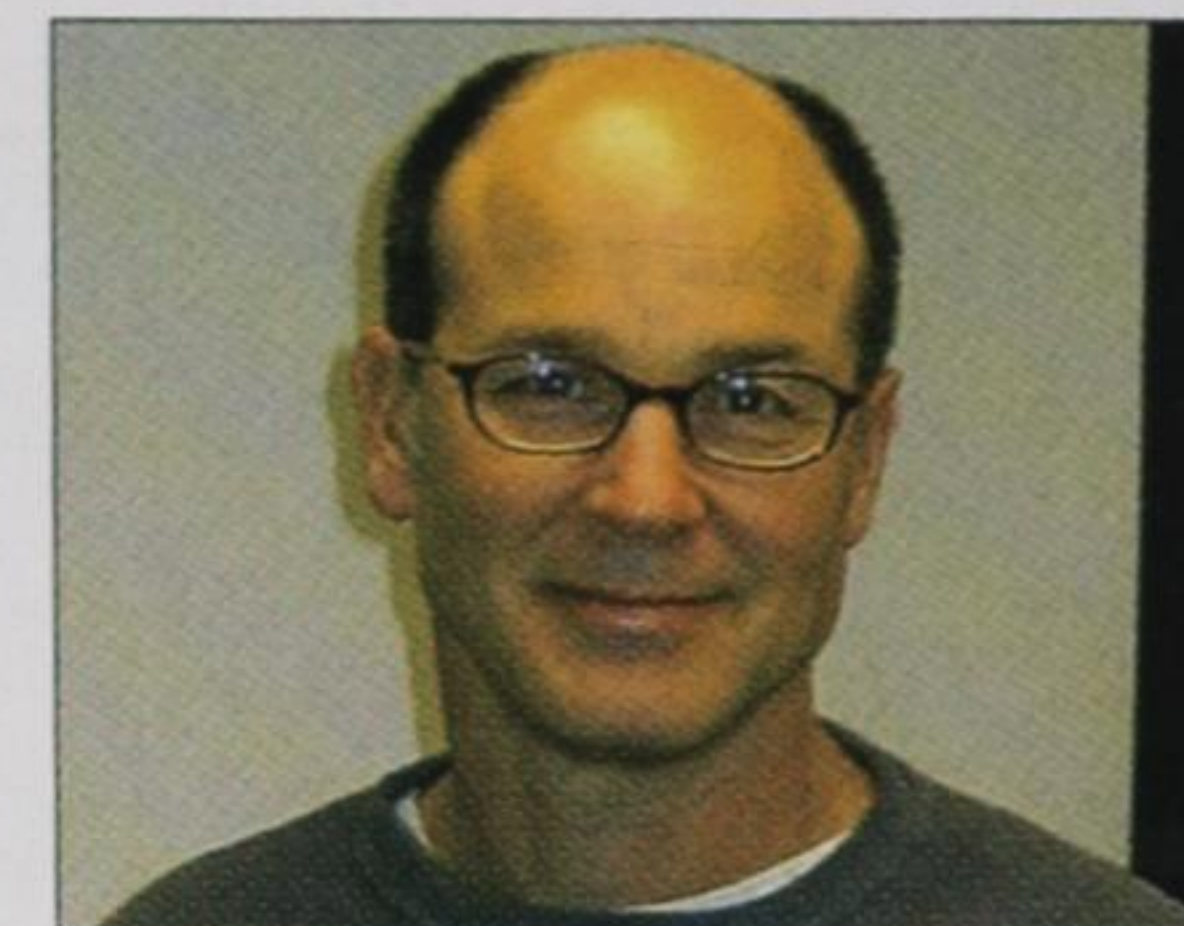
The improvements in crystal-growth quality produced by growing very thick layers are seen by the continued reductions in the full-width at half-maximum

(FWHM) values from our high-resolution X-ray diffraction rocking-curve measurements. Measurements on the 12 and 50 μm thick films show that the FWHM of the X-ray peaks from the symmetric (0002) and asymmetric (2021) reflections reduce from 460 and 450 arcsec to 300 and 280 arcsec, respectively. This shows that the thicker films do produce an improvement in crystal quality, but bowing becomes significant in these films, which prevents them making good large-area substrates.

Free-standing GaN substrates will have an important role in the continued improvement of GaN-based devices, especially in situations where performance can justify the significant substrate costs. However, lower-cost products are currently better served with a simple hybrid MOVPE–HVPE crystal growth process. This approach allows the most suitable process to be used for the low-temperature starting layer, the thick buffer layer and the heterostructure, and can form high-quality devices in a single reactor using one continuous growth process. ●

Acknowledgments

David Miller at CBL Technologies has played a significant role in all phases of this work. Thanks to Oliver Brandt, Klaus Ploog, Manfred Ramsteiner and Achim Trampert of the Paul Drude Institute (PDI) in Berlin, Germany, for film characterization and discussion, and the PDI for their support.



Glenn Solomon has just started nanostructures and quantum optics research at the Physics Laboratory at NIST, Gaithersburg, after leaving his acting professorship at Stanford University's Electrical Engineering Department. He founded CBL Technologies with David Miller in 1996 to develop free-standing GaN substrates. Recently, the company has switched to developing its patented thick-film approach to GaN growth, and the development of VPE equipment, which is described in this article.



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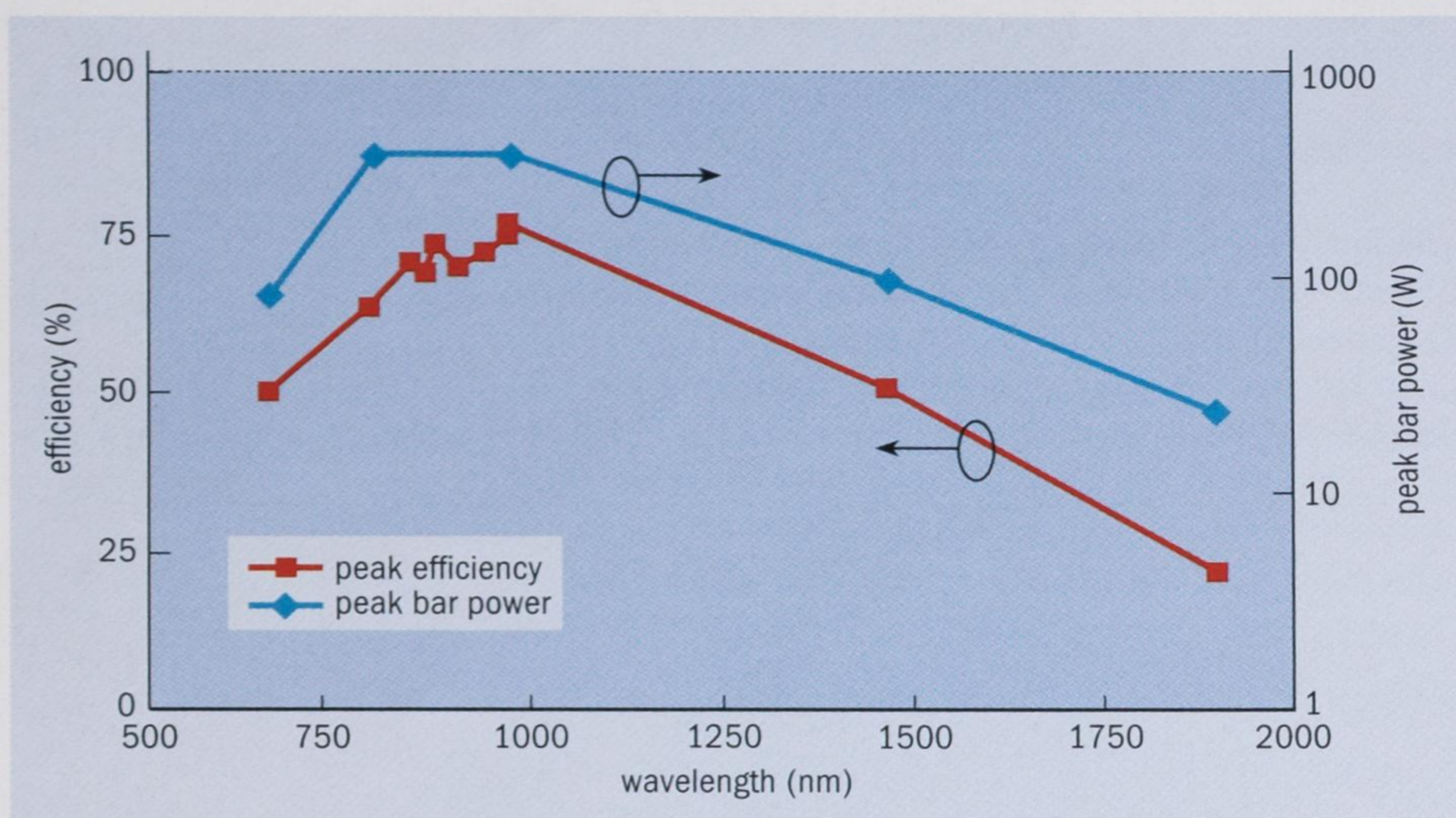
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nLight expands wavelength range in order to attack new markets

nLight is aggressively targeting medical applications, displays, eye-safe communication and atmospheric sensing by extending the wavelength range of its high-power diode bars. **Richard Stevenson** reports on 660 nm and 1.9 μm emitters that feature record output powers.



nLight's diodes that span the wavelength range from 660 nm to 1.9 μm can address a range of applications as diverse as photodynamic therapy, illumination, gas sensing and eye-safe sensing.

Manufacturers of infrared laser-diode bars are continually increasing their emitters' efficiency, with progress spurred on by the US Department of Defense's (DoD's) three-year super-high-efficiency diode-sources program. This initiative, which runs until September, has already seen companies such as nLight, Alfalight and JDSU all approach the 80% efficiency target. The improvements will aid the country's battlefield laser weapons, because increased efficiency cuts heat generation and allows refrigeration units to be smaller and easier to maneuver.

The processes that are used to fabricate these efficient infrared emitters are also applicable to the production of efficient lasers operating at other wavelengths. This has not escaped nLight, which has been developing laser diodes at both longer and shorter wavelengths than the DoD's focus on 880–980 nm. The US-based company is now offering cooled 12 W diode-bar packages at 665, 680 and 690 nm, and has just started development of 1900 nm lasers.

nLight's director of device technology, Paul Crump, says that the increased wavelength range is opening up

its addressable markets. According to Crump, the market for medical applications of diode lasers was worth more than \$100 million in 2005 and is growing at a frenetic pace. Applications enabled by new wavelengths include fast-growing sectors such as photodynamic therapy, where a laser activates drugs within the body. Red lasers are also in great demand for illumination and display applications, says Crump, and nLight is shipping volume products in all of these fields. Meanwhile, bars operating at around 1900 nm can be used to pump holmium-doped crystal lasers, for eye-safe communication and for atmospheric sensing.

Two factors restrict the peak power output of red-emitting lasers – thermal rollover and facet failure due to catastrophic optical mirror damage (COMD).

Thermal rollover occurs when the device temperature rises and causes the carriers to jump straight out of the quantum wells and into the contacts. This can be addressed by cryogenic cooling, says Crump, but it also increases system complexity and cost.

An alternative approach to combating the effects of thermal rollover involves designing a laser with a deeper quantum well, which improves carrier confinement. However, these red-emitting lasers have to be built on GaAs substrates and employ the AlInGaP material system that has a relatively small bandgap range. Crump explains that the greatest degree of confinement could be produced with an AlP cladding region, which has a 2.45 eV bandgap at room temperature. However, this layer is extremely strained when grown on a GaAs substrate, which limits its thickness. As a result, alloys with even smaller bandgaps are often used to form the cladding region. So in practice the maximum possible confinement voltage is only 0.5 eV, and for many commercial devices it is just 0.25 eV. This is much less than the 0.6 eV confinement energy for 980 nm commercial diodes.

Cooling without cryogenics

Although nLight avoids cryogenics, it does employ water cooling to limit thermal rollover effects and improve diode-bar output power. This may not suit applications demanding high portability, but is fine for car production plants and doctor's surgeries. The firm is also improving the bar's output power by balancing the trade-off between the number of emitters and the thermal performance, because having more emitters increases device output and operating temperature.

The second factor that restricts reliable high-power diode emission is COMD – a failure mechanism initi-

"It's harder [to use aluminum to build diode lasers], but if the technology is up to it, it's not a fundamental barrier."

Paul Crump
nLight

ated by photoabsorption at the laser's facets that produces a rapid rise in local temperature. Absorption occurs because the free bonds that are formed during the cleaving process to define the laser's cavity oxidize to form mid-bandgap traps. Many diode manufacturers, including nLight, have developed various passivation techniques to reduce COMD by coating the facets with a wider bandgap material that does not absorb the laser's light.

COMD is particularly important for 660 nm lasers because the photon's energy is relatively high and the diode needs to incorporate aluminum-containing materials that are very reactive. However, Crump points out that highly reliable telecom lasers have been built with aluminum-based compounds, adding, "It's harder [using aluminum], but if the technology is up to it, it's not a fundamental barrier." The problems can also be partially avoided by using an InGaP quantum well, as aluminum then only features in the barrier layers that are subjected to a much lower optical-power density.

By addressing the problems associated with thermal rollover and COMD, nLight's engineers have fabricated 660 nm laser bars that deliver a peak optical output power of 90 W. "I don't believe anyone else has published results anywhere near us in terms of power," claimed Crump.

The emitters, which were grown on 3 inch GaAs substrates by low-pressure MOCVD and are based on the AlInGaAsP material system, have a width of 1 cm and a 1.5 mm cavity length, and feature standard dielectric high- and low-reflection coatings on the rear and front facets. The bars have 30% fill factor, defined as the ratio of the individual emitter widths to the spacings between the emitters, and were cooled by a copper microchannel heat sink that is fed with 0.5 l of water per minute at a temperature of 10 °C.

The approach indicates that output powers in excess of 200 W are possible with higher fill factors, with device degradation due to COMD limited by nLight's passivation technique. Crump reckons that it will be possible to produce commercially reliable 30 W diode bars.

Beyond telecom wavelengths

nLight has also been developing 1.9 μm diode lasers that are an extension of the company's 1 cm-wide 1.5 μm diode bars that produce more than 100 W. These InP-based sources contain InGaAs quantum wells and InGaAsP barriers and are less affected by COMD because the photon's energy is only one-third of that of a red-emitting laser.

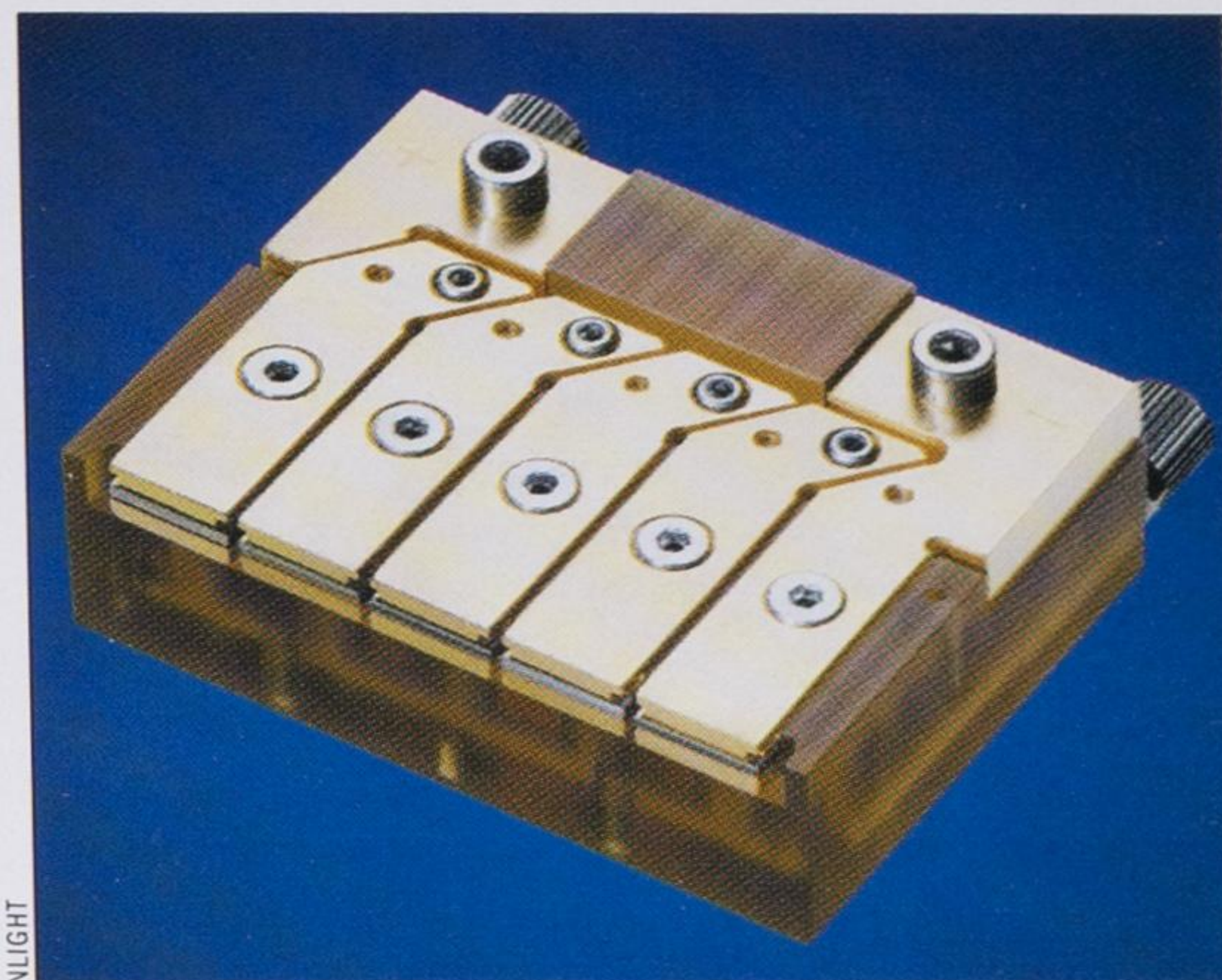
However, they do have strain-related issues that result from the additional indium content needed to reach the longer wavelengths. Although low levels of crystal strain can benefit laser performance, higher levels lead to material deformation and a higher defect density, or phase-segregation of the alloys into regions of differing composition. Both effects reduce device performance, but can be avoided by careful control of the growth conditions, says Crump. According to him, various well-established methods are available, includ-

Integration, integration, integration

nLight, which is based in Vancouver, WA, and was founded in 2000, now employs more than 100 staff. The company has its own manufacturing facility that allows all manufacturing processes to be carried out in-house. The 56,000 ft² fab features a 23,000 ft² Class-1000 cleanroom equipped for high-volume epitaxial growth, facet coating and passivation, packaging and final device testing.



nLIGHT



nLIGHT



nLight targets many markets with a range of laser-diode products, including single-emitter packages, conduction-cooled and actively cooled diode bars, and vertically and horizontally stacked arrays.

ing optimization of the ratio of group III to group V gases, the growth rate and temperature, and by balancing the compressively strained wells with opposing tensile-strained barriers.

The other issue restricting the output power of long-wavelength laser performance is carrier loss due to Auger recombination. This effect – which reduces threshold current and temperature performance, and is 10 times stronger at 2 than at 1.5 μm – is caused when the electron-hole pair transfers its energy to a third carrier instead of combining to emit light. Auger recombination is very temperature-sensitive and limits the maximum output power in these devices. Because this loss mechanism is a three-carrier process, its rate is proportional to the cube of the carrier density, so reducing the threshold current improves laser performance. A lower threshold means fewer carriers and less Auger recombination, improving high-temperature performance and increasing output power.

By using the low-threshold-current designs to minimize Auger recombination and heat sinks to control the device's temperature, nLight's engineers extracted 23.5 W at 1916 nm, from 1 cm-wide diode bars featuring a 1 mm cavity length and a 20% fill factor. Crump believes that nLight has again produced the most powerful bars ever at this wavelength, giving the company a head start at both ends of its range. This puts nLight in a strong position to capture the emerging markets for these wavelengths and drive up manufacturing volumes of its wide range of laser diodes.



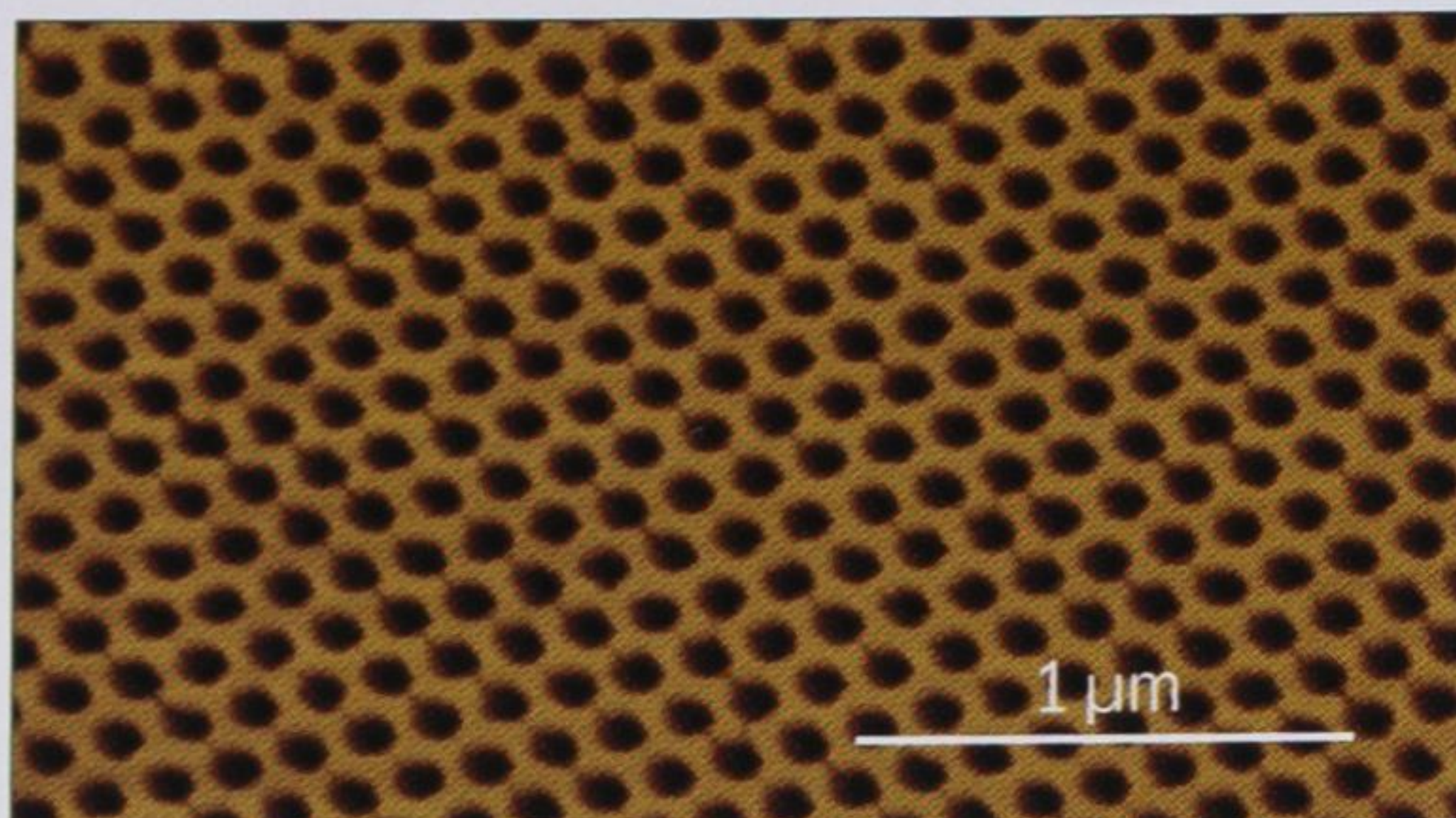
GaN OPTOELECTRONICS

Photonic-crystal LED achieves lift-off

Shuji Nakamura, Steven DenBaars and co-workers at the University of California, Santa Barbara, in partnership with Henri Benisty from the Charles Fabry Institute of Optics in Orsay, France, claim to have fabricated the first LEDs that feature photonic-crystal-assisted light extraction and are made using laser lift-off.

The team believes that its approach can improve the performance of GaN LEDs by combining the increased extraction efficiency of photonic structures with the efficient thermal dissipation and broad injection area produced by laser bonding onto a different substrate.

The LEDs were fabricated by growing a 2 μm -thick GaN buffer, a 2 μm -thick n-doped GaN layer, five InGaIn quantum wells and a 300 nm p-doped GaN layer on a sapphire substrate. After adding a RuO₂/Ni/Ag electrode, the wafer was covered with gold, flipped and bonded to an AlN ceramic substrate. Sapphire was removed by laser lift-off, before the GaN layer was thinned by chlorine-based reactive ion etching and an electron beam defined the photonic-



The photonic crystal has a periodicity of 215 nm that can be identified with atomic force microscopy.

crystal structure (see figure).

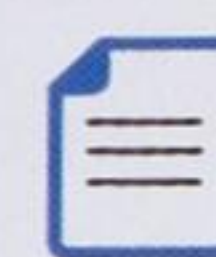
Unfortunately, the LED's ability to dissipate heat was ruined during the photonic-crystal formation process, which prevented any reliable comparison between the light-extraction efficiencies of patterned and unpatterned devices.

Team-member Auréline David told *Compound Semiconductor* that the damage was probably caused during a gold etch step that removed too much material and led to the melt-

ing of the substrate during current injection. "To solve this we had to deposit more metal onto the substrate to decrease its thermal resistance. However, the LEDs were partially shorted during this metal deposition because of a minute misalignment of the lithographic mask," she added.

David believes that the accident could be avoided by fabricating the photonic crystals earlier in the process and cannot foresee any fundamental limit to the fabrication of photonic-crystal LEDs using laser lift-off.

The team was able to measure angle-resolved spectra from the photonic-crystal LEDs and did observe "photonic bands" but the emission was relatively weak due to absorption by the metallic layers. Device modeling showed that this loss could be significantly reduced by coating the structure with silver instead of gold.



Journal reference

A David et al. 2006 *Appl. Phys. Lett.* **88** 133514.

PHOTODETECTORS

Quantum wire promises highly sensitive array

Researchers from Japan's National Institute of Advanced Industrial Science and Technology have built an InGaAs/InAlAs quantum-wire phototransistor with a room-temperature sensitivity of up to 350 kA/W.

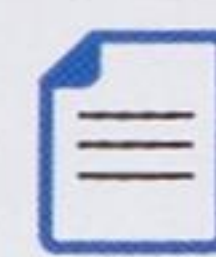
The visible-wavelength detector is claimed to combine the sensitivity of an avalanche photodiode (APD) or photomultiplier tube (PMT) with a *pin* diode's suitability for detector arrays.

The researchers say that APDs and PMTs are not ideal for arrays because their high bias voltage has the potential to damage the silicon charge amplifiers that are used alongside them, while *pin* diodes have sensitivities of just 1 A/W.

The detectors were produced by growing

an InGaAs/InAlAs quantum-wire structure by MBE on a semi-insulating InP V-groove-patterned substrate before forming recess, source and drain contacts.

Measurements with light from a tungsten lamp determined that the device's sensitivity was greater than 300 kA/W from 500 to 750 nm, and highest from 600 to 700 nm.



Journal reference

M Ogura et al. 2006 *Electron Lett.* **42** 413.

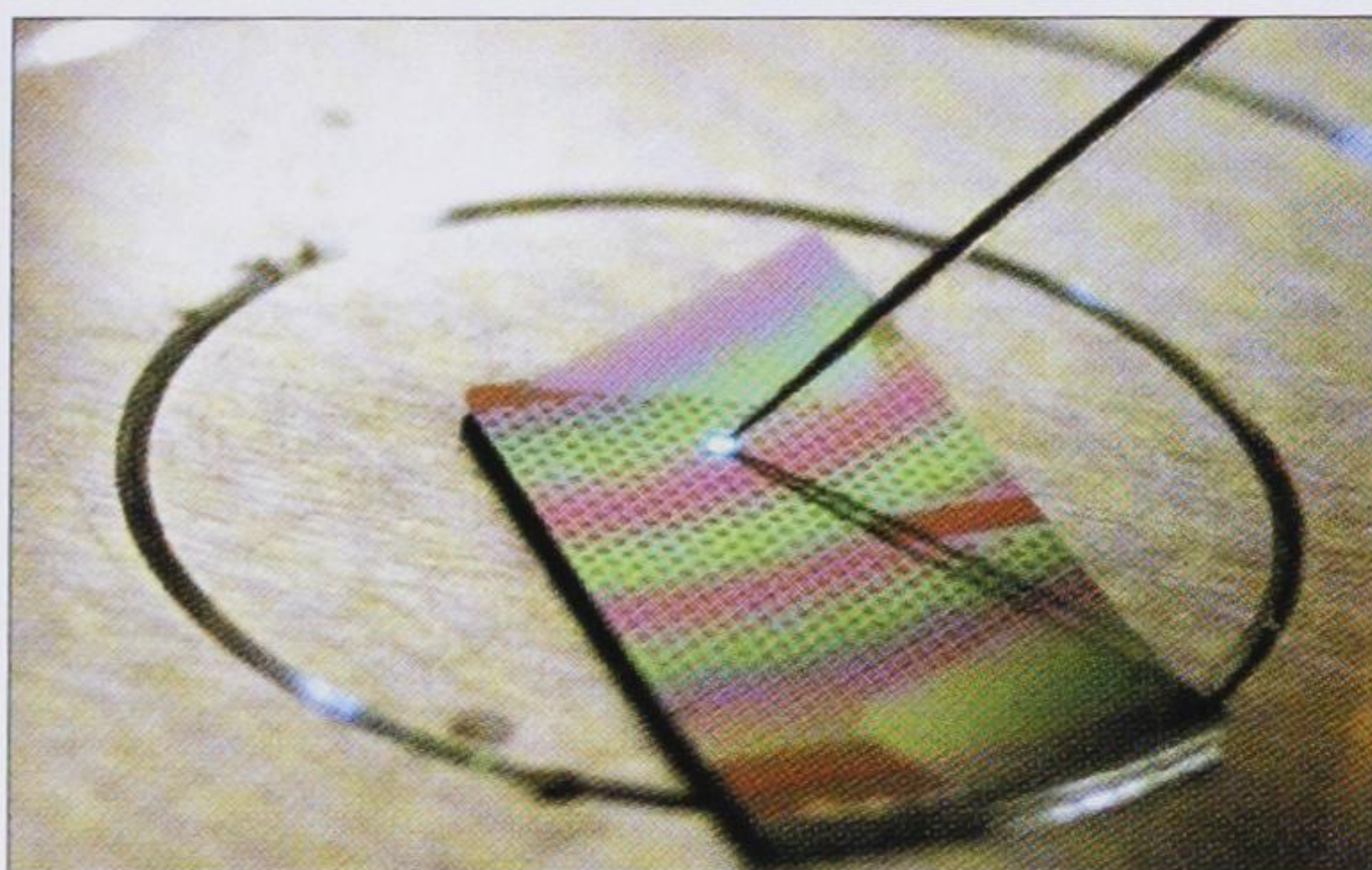
GaN-SILICON INTEGRATION

GaN LEDs make leap to silicon (001) substrates

Researchers at the Otto-von-Guericke University in Magdeburg, Germany, have taken an important step towards the integration of optoelectronics with CMOS silicon technology by fabricating the first GaN LEDs on silicon (001) substrates.

GaN LEDs have previously been produced on silicon (111) substrates, but depositing the device on silicon (001) is much more challenging because the substrate and epilayers have different lattice symmetry.

The team's GaN LEDs were grown using an Aixtron single-wafer MOCVD reactor on a silicon (001) substrate that had been etched to produce an oxide-free, hydrogen-terminated surface. A 20 nm-thick AlN seed layer was



The GaN LEDs grown on silicon (001) substrates can produce electrically stimulated emission and could aid the integration of optoelectronics with CMOS technology.

deposited first, followed by a 200 nm-thick AlGaIn layer, a 2 μm -thick GaN layer containing four thin AlN interlayers to prevent crack formation, a multiple-quantum-well active region and a p-doped capping layer.

An *in situ* curvature and reflectance tool was used to monitor the growth. "The curvature

monitoring allows easier adjusting of the AlN interlayer growth temperature and thickness," said team-member Fabian Schulze, "and the reflected intensity is useful for estimating the interface roughness."

Photoluminescence measurements showed that the LED had a peak emission at 455 nm and weaker yellow luminescence. Blue electroluminescence was produced by electrical injection through a metallic probe onto a Ni-Au contact, with the substrate's backside forming a second contact (see figure).

The team has not yet progressed to integrating its devices with CMOS circuits, but Schulze says that there are promising results from AlGaIn/GaN FETs grown on silicon (001) substrates and fabricated in standard industrial production lines.



Journal reference

F Schulze et al. 2006 *Appl. Phys. Lett.* **88** 121114.

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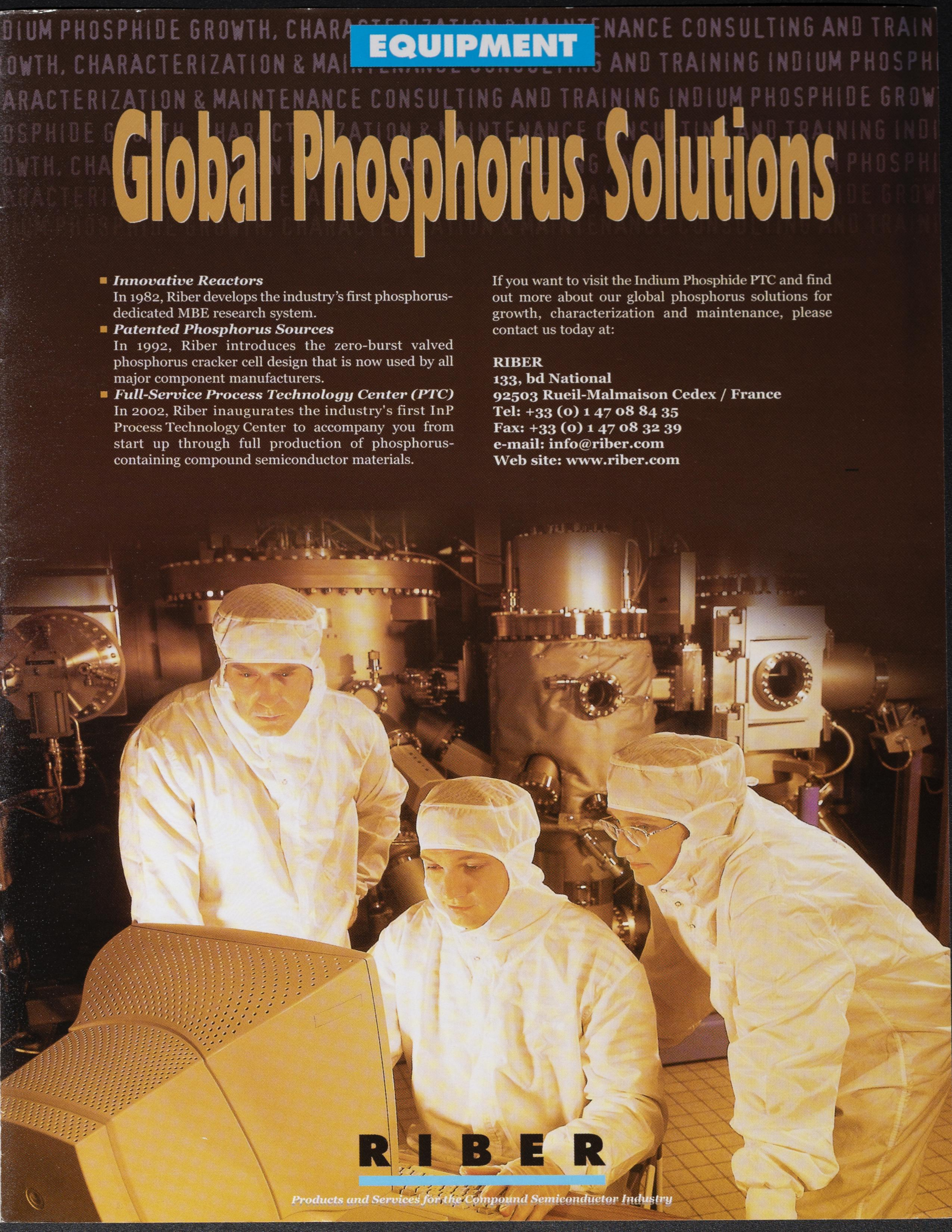
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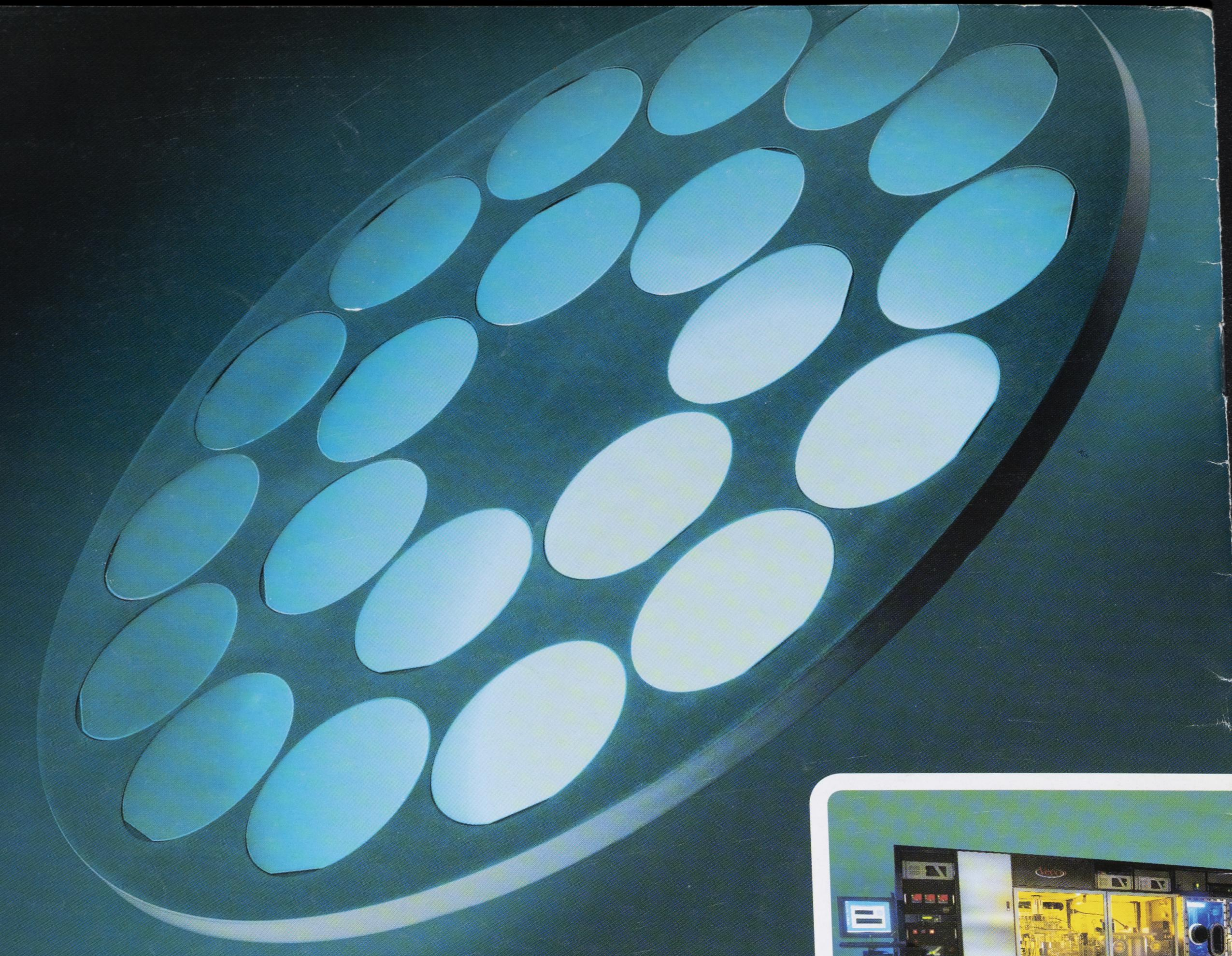
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