

COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

December 2005 Volume 11 Number 11



BROADBAND WIRELESS
Endwave and GigaBeam
link New York's glitterati

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light from HB-LEDs**

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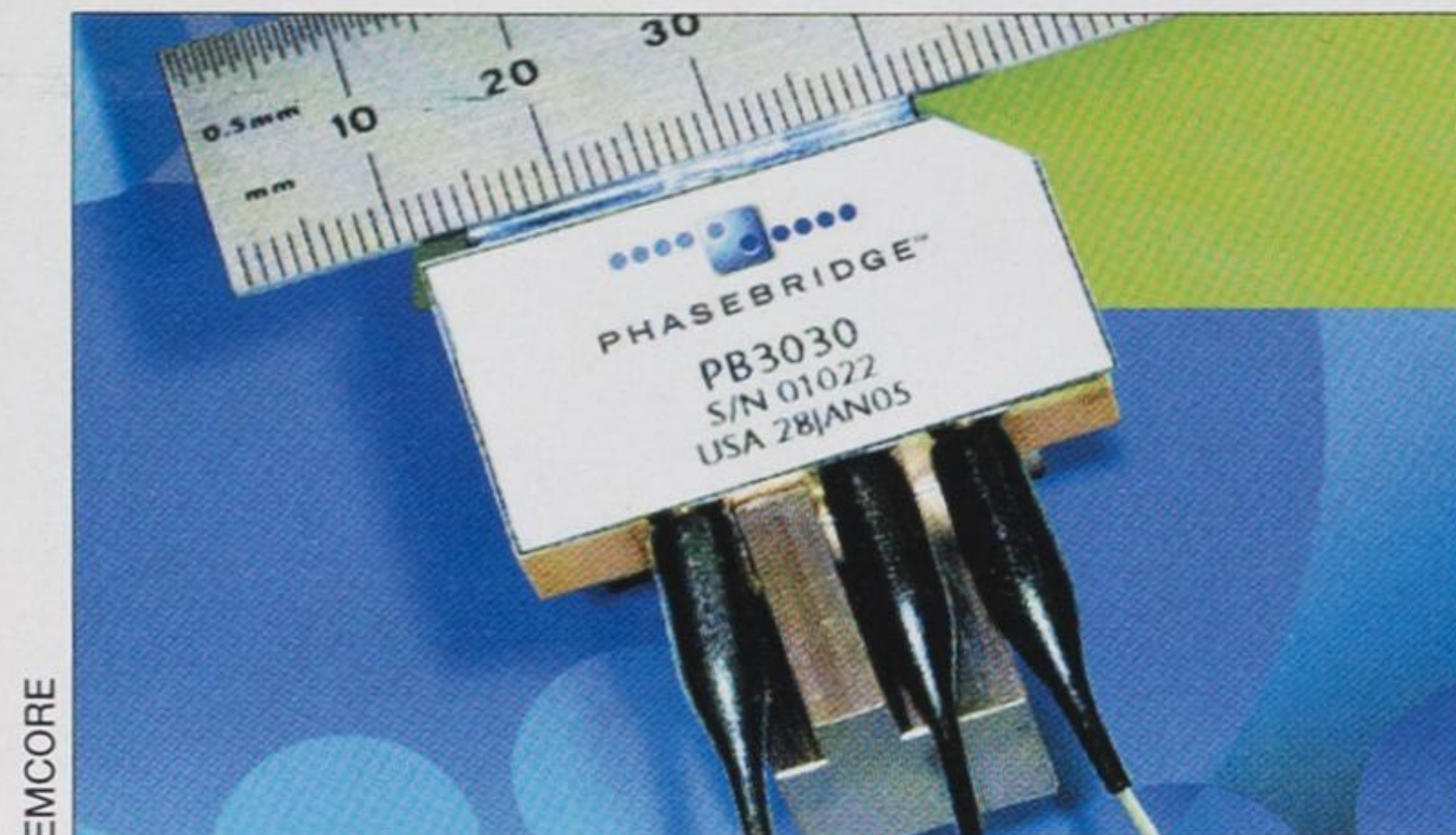
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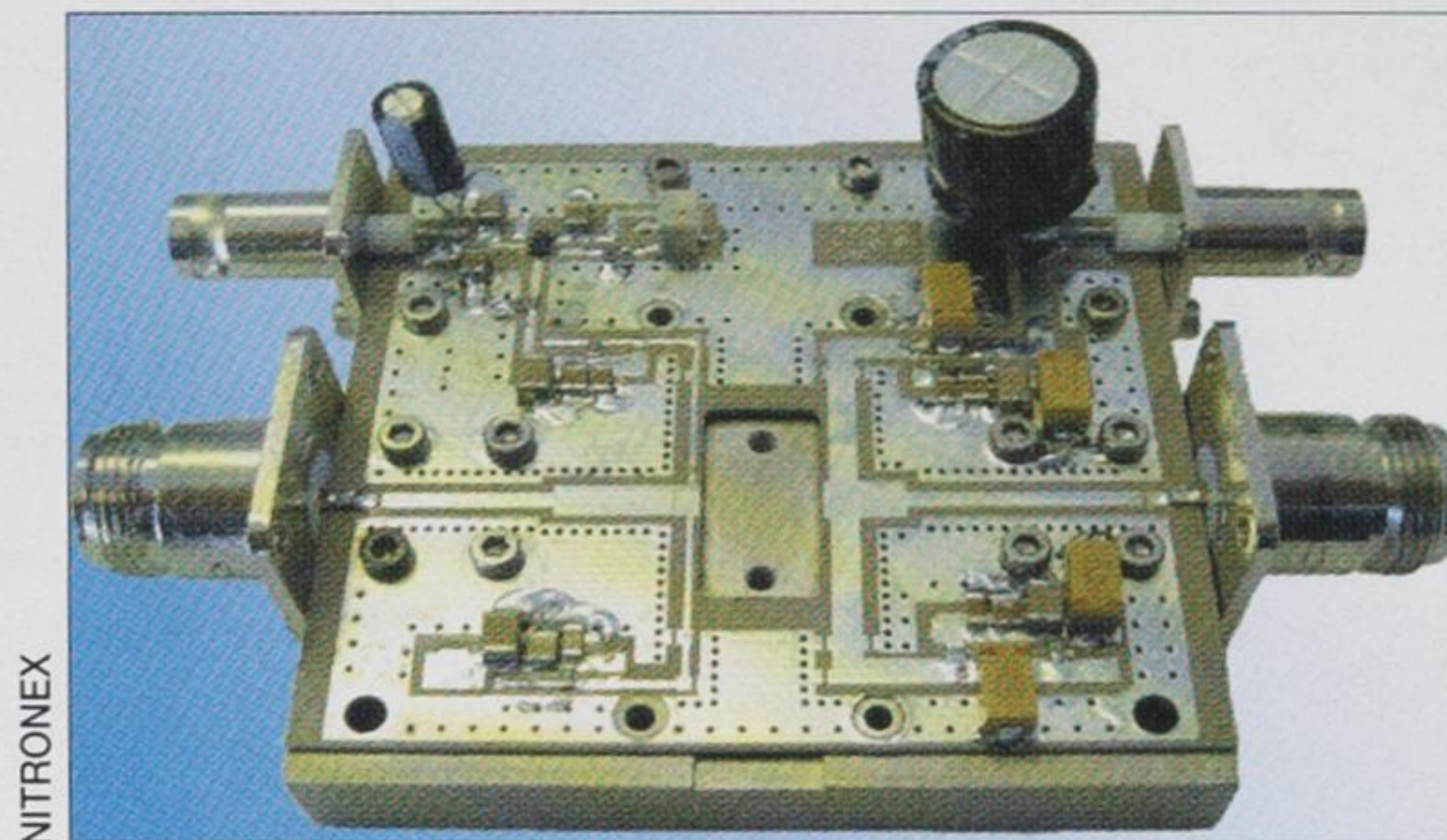
COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

DECEMBER 2005 VOLUME 11 NUMBER 11



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On the cover: GigaBeam is switching from silicon to GaAs and InP components to increase the data transfer rate of its broadband radio transmissions. The cover image shows a transmitter serving the residents of Trump Towers, New York, with high-speed wireless internet. Credit: GigaBeam.

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Editorial

Handset season strategies



It's the season for cell-phone handset makers and their suppliers to be jolly, as the public goes into retail overdrive. Usually, the Christmas holiday period is followed by a commercial hangover as credit card bills arrive and pockets are tightened. But this year RF Micro Devices (RFMD) – one of the III-V industry's biggest names – is expecting the opening quarter of calendar 2006 to be a little different.

Financial chief Dean Priddy is reckoning on a strong March quarter to follow RFMD's traditionally buoyant end to the year. The reason could be the company's belief that it is taking share away from its competitors in the high-end handset market; or perhaps that its top customer, Nokia, is witnessing a surge in sales of phones to China, where February marks the local holiday season.

What's good for RFMD can generally be regarded as being good for the wider compounds industry, but whether that will still be the case several years from now is open to debate. RFMD is rightly keen to promote itself as "technology agnostic", which means that its primary responsibility is to make the best products for its customers, regardless of the material from which its chips are made.

For the time being, GaAs will remain the material of choice for its power amplifiers, and the company will increase its GaAs consumption next year as it brings the production of PHEMT switches in house. But in the long run, this could all change. The key to RFMD's future strategy is integration. It sees future cell-phone architectures as two-chip solutions. This means one baseband chip, supplied by the likes of Texas Instruments or Intel, and one chip to do everything else. The "everything else" chip is what RFMD wants to supply, as it will give the company more content in each phone.

The big challenge is therefore integration. And efforts to integrate silicon with GaAs will prove crucial if GaAs is to continue cultivating its key commercial application in the long term.

Michael Hatcher

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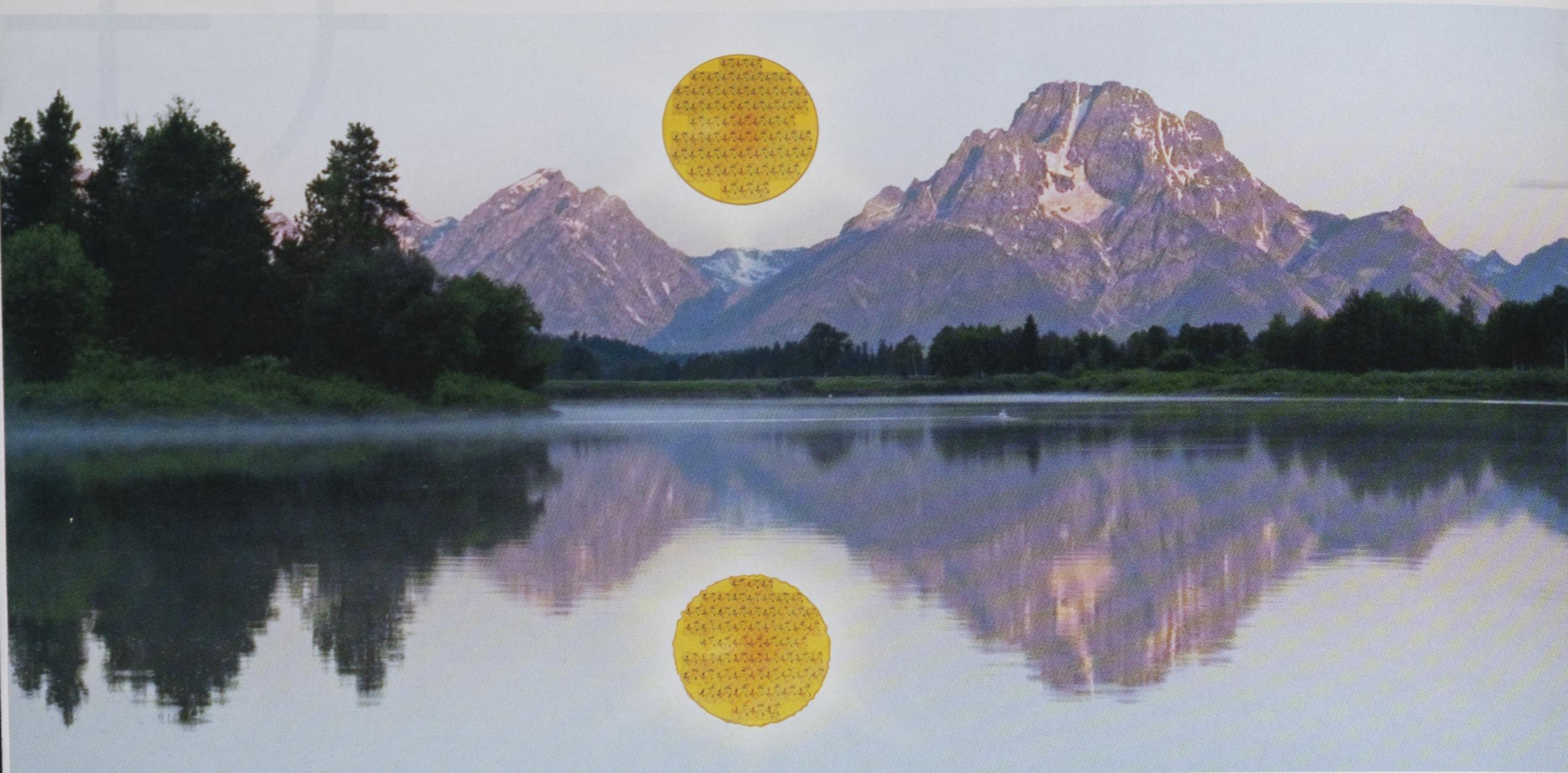
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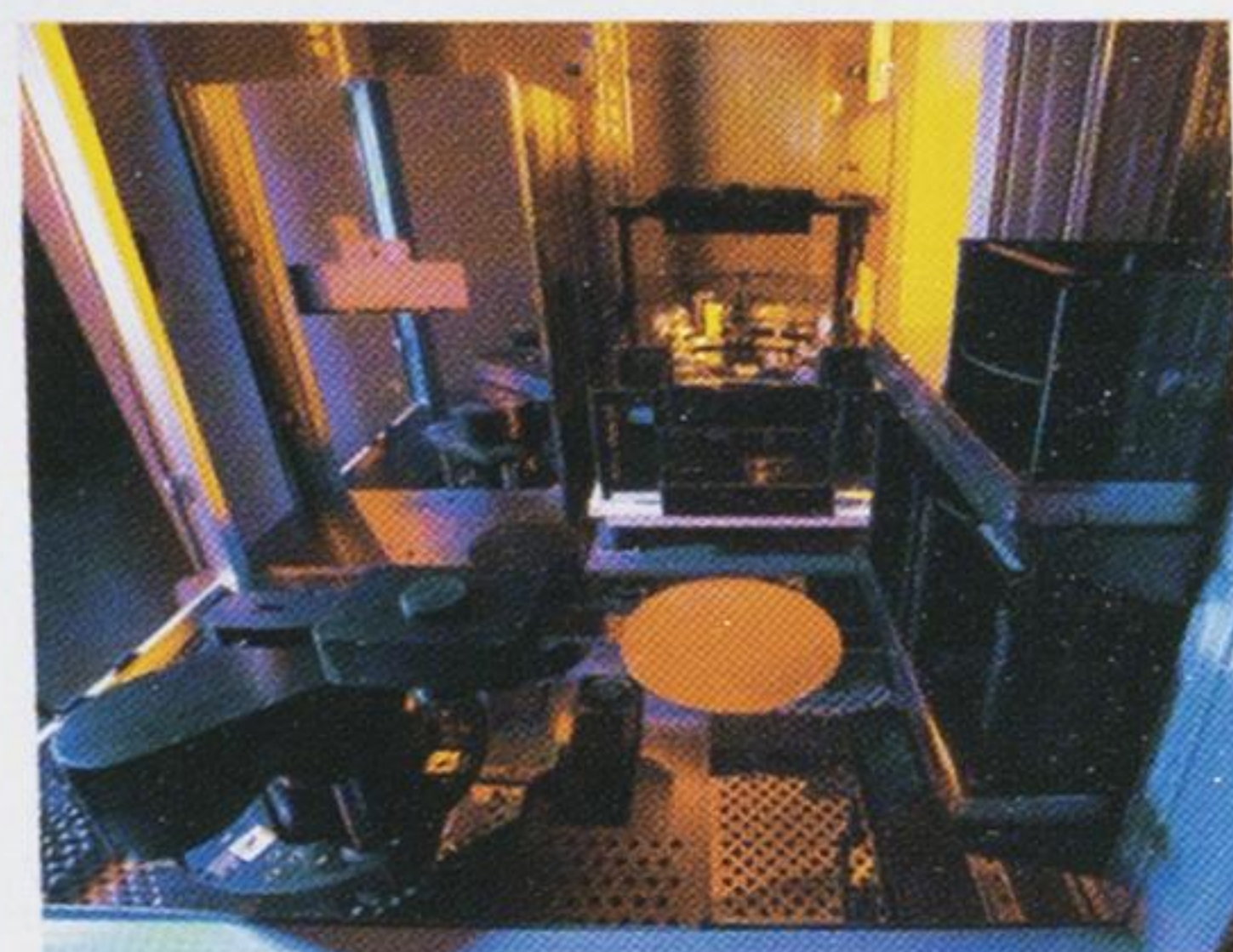
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Lumileds ignites battle with Taiwan duo

California-based LED manufacturer Lumileds Lighting is suing the Taiwanese companies Epistar and United Epitaxy Company (UEC), alleging that the two are infringing key patents relating to AlGaInP devices.

Lumileds seeks an exclusion order barring entry into the US of the accused LEDs, as well as products containing those LEDs, declared the company in a statement.

As well as filing a complaint to the US International Trade Commission, Lumileds is suing Epistar and UEC at the US District Court for the Northern District of California, seeking an injunction against future infringement, damages, and enhanced damages for willful infringement.

The complaint is the latest twist in a litigation battle that the three companies have waged for much of the past decade (see Patent fight timeline).

Previous episodes in the series of lawsuits have centered on the details disclosed in US patent 5,008,718, entitled LED with an elec-

Patent fight timeline

1999: Lumileds states out of court that UEC infringed the "718" patent; UEC sues Lumileds, saying the patent is invalid on grounds of "obviousness".
2000: Agilent, Lumileds file a counter-claim.
2001: Pending cases between UEC, Lumileds and Agilent are settled.
2003: Lumileds files against Epistar, citing

infringement of the same "718" patent.

2004: Pending litigation is settled when Lumileds grants Epistar a limited licence to use technology disclosed in several patents about absorbing-substrate AlGaInP LEDs.

2005: Philips Lighting buys out Agilent's half share in Lumileds; Epistar and UEC reveal that they are planning to merge.

trically conductive window, which Lumileds was granted in 1991.

The new litigation instigated by Lumileds cites the 718 patent, as well as two later patents (5,376,580 and 5,502,316) concerning a wafer-bonding technique awarded to Fred Kish and colleagues at Hewlett-Packard prior to the spin-off of Agilent Technologies.

Specifically, the accusations refer to the use of omnidirectional mirror adhesion LEDs by Epistar, and metal- and glue-bonding by UEC.



Yellow and red AlGaInP LEDs made by UEC use the disputed metal-bonding process.

Agilent's semiconductor business spawns Avago Technologies

By Michael Hatcher

Agilent Technologies has completed the sell-off of its semiconductor business, which has now begun operations as Avago Technologies.

Equity firms Kohlberg Kravis Roberts and Silver Lake Partners have taken control of the world's largest privately held semiconductor company in completing the \$2.66 billion deal.

Dick Chang, who was the business's most recent CEO under Agilent, retains his position at the renamed company. Chang said that Avago would now look to capitalize on its new independence to drive profitability.

While some media reports have claimed that the new owners plan to make Avago a pub-

lic company once again through separate IPOs for its different business segments, an Avago spokesman told *Compound Semiconductor* that this was not true. There is no specific plan for one or multiple IPOs, he said. Dick Chang and our new board have no such plans.

Avago has 6500 employees, offers 5500 products, raked in revenue of \$1.8 billion in fiscal 2005, and covers three key areas of the compound semiconductor business.

Although Avago sees itself primarily as a fabless operation, it owns three facilities where it manufactures III-V devices. These are a 6 inch GaAs fab in Fort Collins, CO, where it makes E-PHEMT power amplifiers

for cell phones among other III-V and silicon processes; a 3 inch VCSEL facility in Singapore, which is used for volume laser production; and a smaller 3 inch VCSEL fab in San Jose, CA, primarily focused on research and development work.

Avago uses many of its optoelectronic devices in optical mouse sensors, which can be based on either laser diodes or LEDs.

● As if to emphasize its strategy to steer away from semiconductors and focus on test and measurement, Agilent has acquired Molecular Imaging, a Tempe, AZ, firm that specializes in atomic force microscopes for applications in nanotechnology.

Substrate firms grab wide-bandgap funds

Two US companies that specialize in wide-bandgap substrates have won new funding to develop commercial products.

HexaTech, a Raleigh, NC, firm that is developing AlN substrates, has won \$8.9 million from venture capitalists to advance its product development, expand marketing, and strengthen its management.

Intersouth Partners led the Series A funding,

with HIG Ventures, Sevin Rosen Funds (SVR) and NC IDEA also making contributions. Craig Burson of HIG Ventures, John Glushik of Intersouth and Dave McLean of SVR will join the company's board of directors.

HexaTech was spun out of North Carolina State University in 2001 and uses a proprietary process that combines physical vapor transport with seeded growth to fabricate single-crystal AlN substrates.

This [funding] will enable us to accelerate the scaling of our AlN wafers to commercially viable sizes, significantly increase our

wafer production capacity, and develop new devices and strategic partnerships, remarked company CTO Zlatko Sitar.

Meanwhile, the giant silicon chemicals company Dow Corning has won \$3.6 million from the US Department of Defense, via the Office of Naval Research, to develop 100 mm-diameter device-quality SiC substrates.

There are plans for Dow's compound semiconductor solutions division to develop crystal growth technology along with wafering and epitaxy skills at its integrated SiC substrates operation in Auburn, MI.

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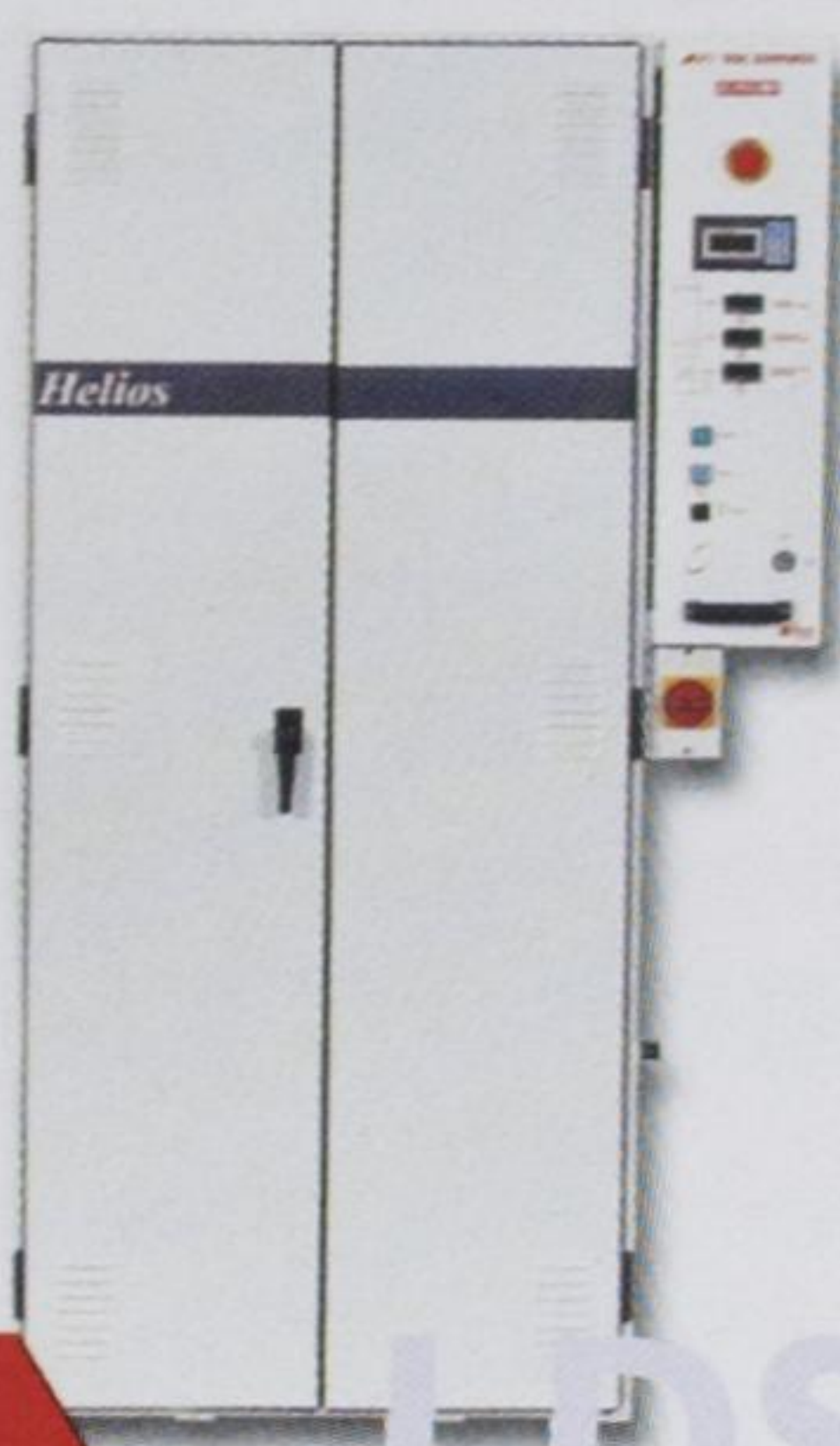
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GAAS & WIRELESS NEWS

Motorola taps into EDGE

Motorola, the world's second-ranked supplier of cell phones behind Nokia, has signed deals with rival GaAs chip makers Skyworks Solutions and RF Micro Devices (RFMD) over new technologies for EDGE handsets.

Skyworks and Motorola will work together on a next-generation radio transceiver, which Skyworks says will allow it to more than double its addressable semiconductor content in each mobile handset made by Motorola.

The technology is based on Skyworks' patented closed polar loop, flexible radio architecture, known as the Helios DigRF solution. "DigRF requires just 10 external components to implement a complete RF section with a digital interface," said the Woburn, MA, firm.

Meanwhile, RFMD has extended its penetration into Motorola's existing EDGE hand-



MOTOROLA

RFMD's Polaris 2 Total Radio chipset will be used in Motorola's V360 EDGE handset.

set portfolio with a deal to supply its Polaris 2 Total Radio chipsets into the V360 phone.

Endwave unveils rights plan as shares sink

By Michael Hatcher

The board of directors of RF module manufacturer Endwave Corporation has approved a share purchase rights plan, following an alarming slide in the company's stock value over the past few months.

Endwave has introduced the plan to protect it from what it describes as "abusive" takeover tactics, although the company said the plan was not a response to any particular proposal.

Under the plan, all stockholders received rights to purchase a new series of preferred stock on December 12, 2005.

In July, Endwave's share price peaked at \$55.41, giving the firm a value of \$627 million at the time. As the stock peaked, Endwave's biggest shareholder, Northrop Grumman, sold 1.4 million shares in the company, worth an estimated \$75.6 million.

Northrop Grumman continued to sell large

numbers of shares throughout July, including a deal valued at \$36.8 million on July 18, by which time the stock price had already plummeted to \$40. A flurry of activity followed in the summer, with Endwave's senior management cashing in stock options as the company's value continued to fall and Northrop Grumman sold off more of its holding. In September, Endwave said that it could not explain either the intense market activity in its stock or its price weakness.

As we went to press, Endwave was trading at \$10.50, 80% down from its summer high. Northrop Grumman remains the company's biggest shareholder, owning just over 10%.

• Endwave has signed a deal with Loea Corporation, a subsidiary of Trex Enterprises, to work on the design of 71–86 GHz subsystems for use in multi-gigabit wireless systems for last-mile communications.

In brief

• **TriQuint Semiconductor** is to use specialty electronics distribution company **RFMW** to distribute its products in North and South America. RFMW works exclusively on RF and microwave products, and offers component engineering support.

• **Raytheon** says that its APG-79 next-generation radar, which features III-V components, has enabled military aircraft

to fire high-precision missiles at multiple attack targets simultaneously – something that the company says has not been possible before.

• **Wicht Technology Consulting** in Germany says that the market for all types of RF MEMS components is set to rocket from just \$126 million in 2004 to over \$1.1 billion by 2009. Cell phones will provide the largest sector, it adds.

Hitachi Cable voted best SI GaAs substrate vendor

Japanese supplier Hitachi Cable topped a recent study that rated the different vendors of semi-insulating (SI) GaAs bulk substrates.

According to Strategy Analytics, which conducted the poll, Hitachi beat Freiberger Compound Materials (FCM) and Sumitomo Electric Industries (SEI) into second and third place respectively, with AXT and Dowa Mining rated in fourth place jointly.

"FCM, Hitachi Cable and SEI achieved the highest ratings for both technical and commercial parameters," said Strategy Analytics. While there was no discernible difference in the technical ratings achieved by the top three, the survey also took into account factors such as wafer pricing, wafer uniformity and lot uniformity among ten different parameters.

According to Strategy Analytics, SEI's rating was affected by the company's ten-

dency to keep its primary customers happy at the expense of smaller ones.

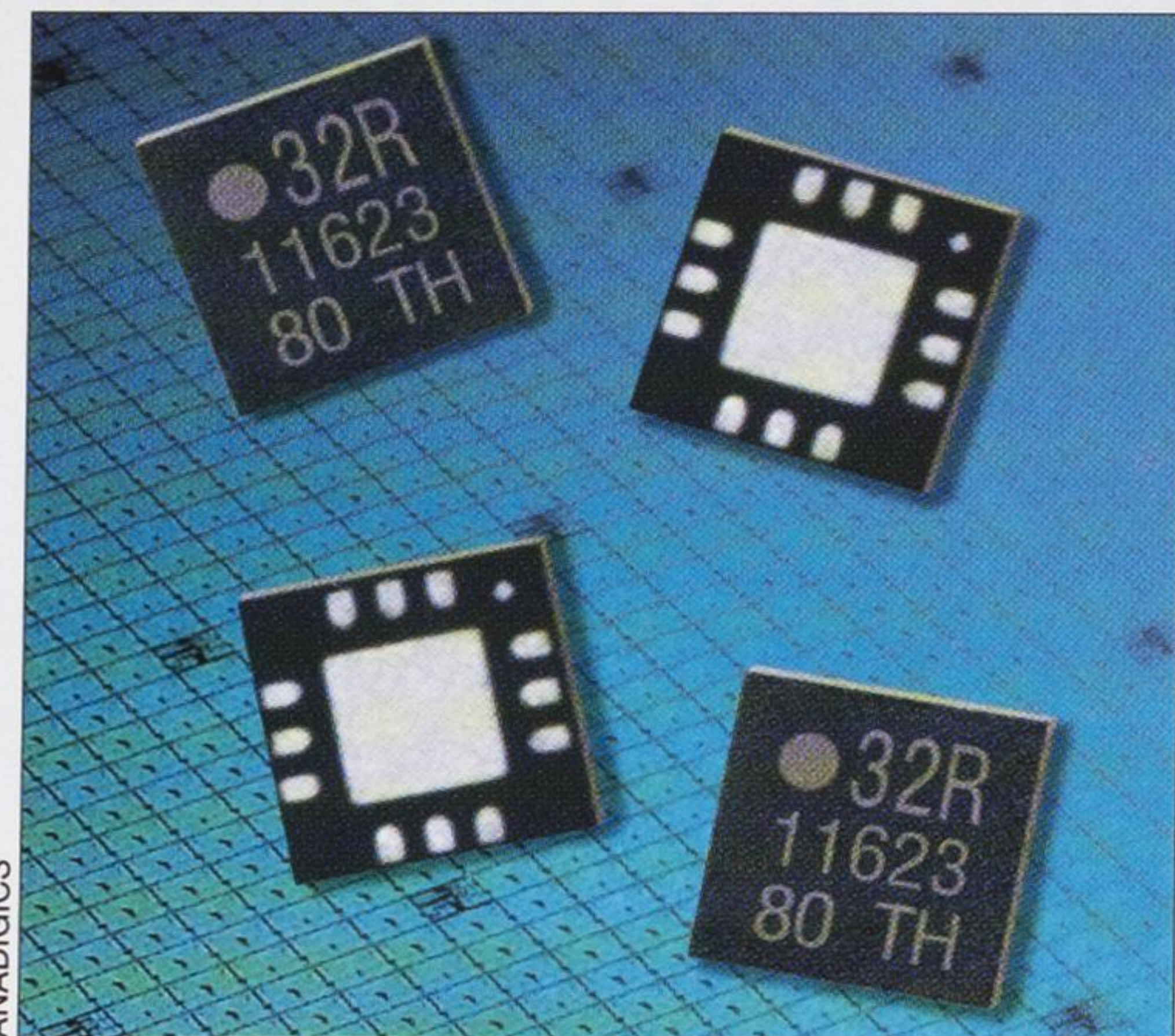
In a similar survey of SI epiwafer suppliers, Strategy Analytics concluded that suppliers from the non-Japan countries of the Asia-Pacific region rated highly because of their low wafer prices.

Singapore-based MBE Technology was awarded the top spot in the epiwafer supplier survey, with strong showings on price and other commercial parameters and "reasonable" scores on technical requirements.

"Despite some exceptional scores in certain categories, the overall performance of epiwafer suppliers has been poor when judged alongside end-user expectations," found the survey. "The industry delivered on flatness and test data in 2004, but these parameters were low on the list of priorities for the end-user."

With its eye on the automotive telematics market, US-based RFIC manufacturer Anadigics has introduced a new addition to its family of RF switches.

As a 10 W-rated PHEMT antenna switch, the AWS5532 can also be used in GSM, CDMA and WLAN mobile platforms. "The adoption of telematics in the automotive industry offers users many new services, including remote diagnostics, on-demand navigation, and fleet tracking," said Ali Khatibzadeh, who heads up the wireless products division at Anadigics' Warren, NJ, headquarters.



RFMD employs laser dicer at GaAs fab

RF Micro Devices (RFMD) has qualified a laser dicing tool in full production at one of its GaAs fabrication facilities.

The Greensboro, NC, company, which holds an estimated 44% share of the power amplifier (PA) market, is one of the biggest GaAs chip manufacturers in the world, and is the first to use a fully automated laser dicer.

Supplied by the Swiss company Synova, the system is unique in that it features a water jet to both guide the laser beam and cool the semiconductor wafer surface (see *Compound Semiconductor* June p29).

First used in medical applications, the Synova tool has since been employed for sili-

con wafer processing. However, developing the system to dice GaAs wafers has proved more problematic because of the toxicity of gallium and arsenic, which can be released during the laser-dicing process.

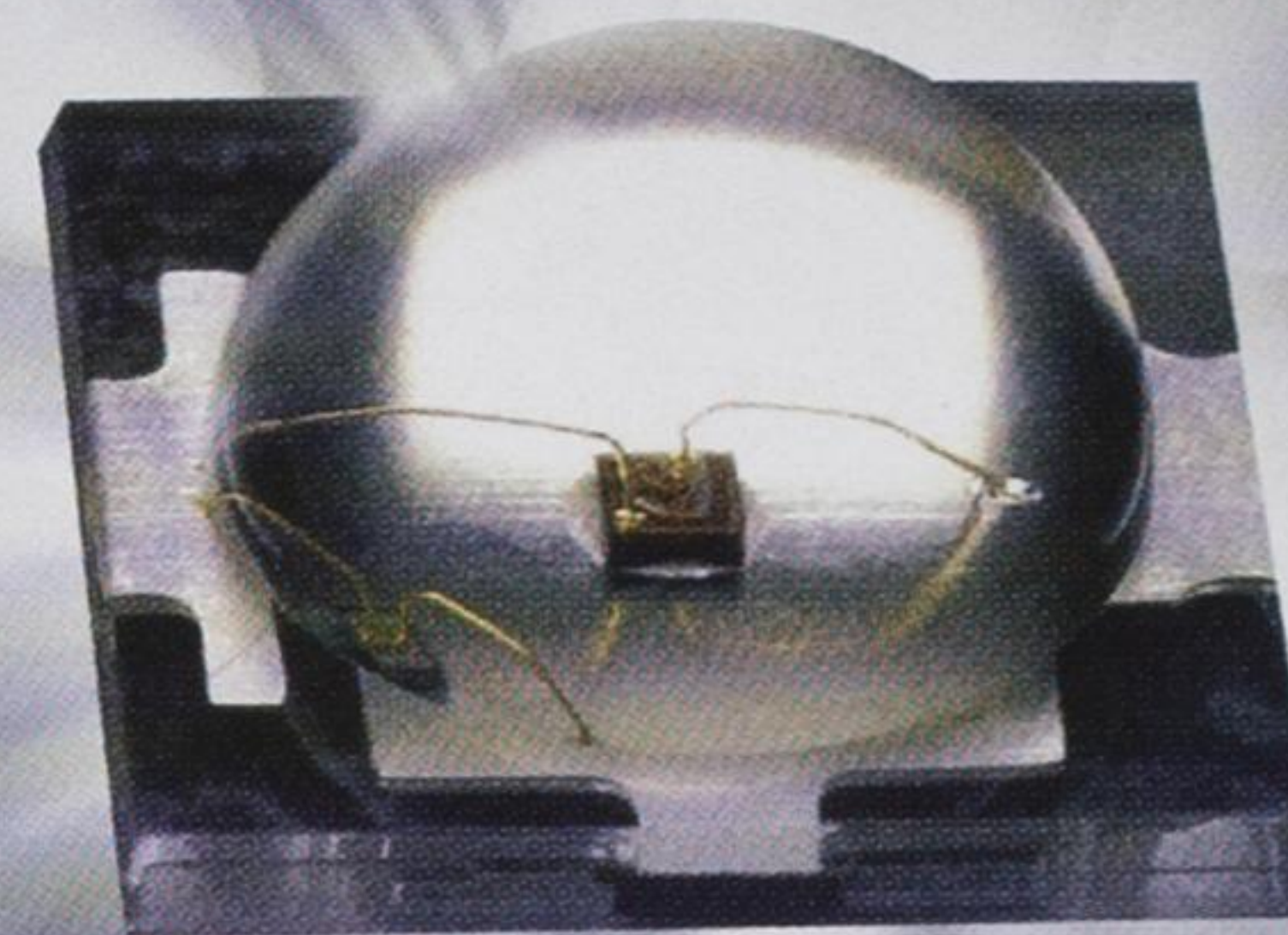
Synova claims that wafer damage and toxic contamination cannot be avoided with conventional "dry" laser dicing, although such systems have been trialled by GaAs chip manufacturers.

In the latest installation at RFMD, 100 μ m-thick GaAs wafers have been diced to give a 23 μ m kerf. According to Synova, through-cutting was achieved in a single pass of the laser beam at a speed of 50 mm/s.

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Q

I am experiencing high n type background doping levels in my MOCVD process when I grow GaAs and AlGaAs devices. I think the problem is in the arsine I use. I'm buying the best grade available. What can I do?

A

Higher background levels of n type dopants in GaAs and AlGaAs structures are caused by trace levels of germanium, silicon and sulfur species present in the arsine. As customer applications evolve, the purity requirements for arsine must as well. Until recently, background doping levels of $10^{15}/\text{cm}^3$ were considered acceptable in most applications. In general, most currently available high-purity grades of arsine can satisfy these requirements. However, process changes and demand for more sophisticated devices have resulted in the need for lower background doping levels. To address these more stringent requirements, Air Products is introducing Megabit™ III arsine, our purest grade available. Our new Megabit III arsine has significantly reduced the amounts of germanium, silicon and sulfur species. Testing done at an independent laboratory proved the effectiveness of Megabit III on thick gallium arsenide films, with excellent results. In all cases, the background doping level was $<<10^{14}/\text{cm}^3$. Our research has shown that Air Products' Megabit III arsine will perform more consistently and produce fewer defects in our customers' finished products.

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Showa Denko develops a passion for bright LEDs

Japanese chemicals company Showa Denko (SDK) has earmarked ultra-bright LEDs as a key part of its new business strategy, which it calls the Passion Project.

The company is better known in the wider semiconductor community for its high-purity ammonia products, used in etching applications, where it claims to have a 30% market share. In the past it has also developed 6 inch InP semi-insulating wafers and manufactured InGaP HBT epiwafers.

More recently the company began producing compound semiconductor devices, and in November SDK revealed plans to make high-brightness green and ultraviolet LEDs in large volumes.

In its latest business plan, SDK has identified ultra-bright LEDs as one of five impor-

tant product areas to be developed at "an accelerated pace".

The company expects to see growth in applications such as LCD backlighting, car headlamps and general lighting. "We aim to [make] ¥20 billion (\$167 million) in ultra-bright LED sales in 2008," SDK predicted.

Across the five businesses identified as growth areas, SDK has said that it will invest ¥200 billion over the next three years. Assuming that even a small share of this total is allocated for the development of its LED business, that still equates to an investment of several tens of millions of US dollars in compound semiconductors.

SDK also plans to grow its semiconductor materials business, aiming to almost double sales to ¥30 billion by 2008.

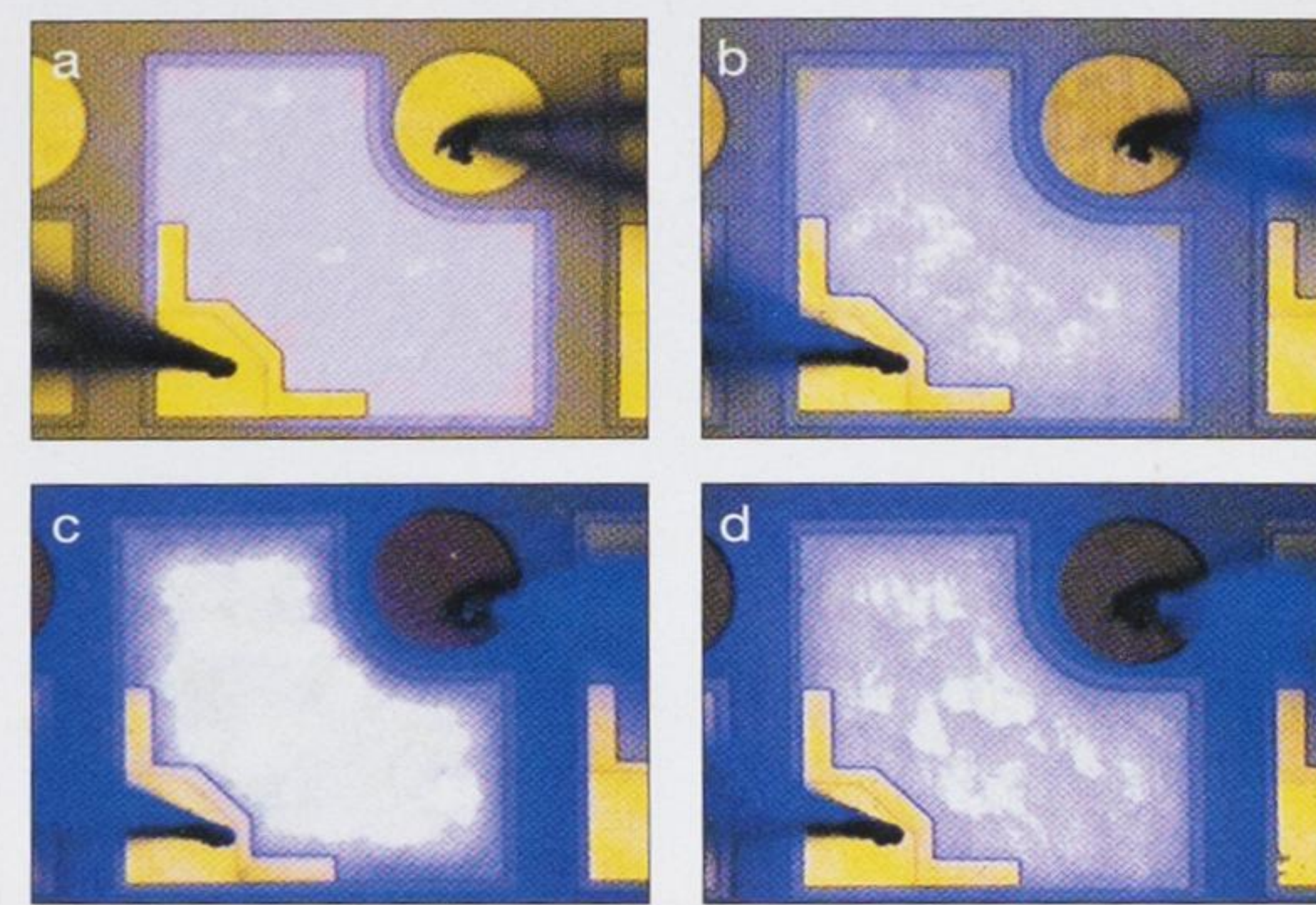
Holographic photonic crystals increase extraction efficiency

By James Tyrrell

Korean scientists have more than doubled the output power of GaN-based LEDs thanks to a holographic process that etches a two-dimensional photonic crystal (PC) into the device. The researchers say that their holographic method is a major improvement on previous work using electron-beam lithography, as the technique suits large-area processing with high throughput (*Appl. Phys. Lett.* **87** 203508).

Typically, a large portion of the light generated by an LED is wasted because of internal reflection and lateral waveguiding. By integrating a PC lattice within the device structure, LED makers have the opportunity to control photonic behaviour and improve light output. Researchers from Seoul National University used a two-beam holography set-up equipped with a He-Cd laser (325 nm) to write square-lattice PC patterns with periods of 300 nm, 500 nm and 700 nm. LED wafers were provided by Samsung's Advanced Institute of Technology.

The team found that its 500 nm lattice offered the best performance, with the device extracting 2.1 times more light than a conventional planar LED. "The only problem we



The LEDs containing photonic crystals with periods of 300 nm (b), 500 nm (c) and 700 nm (d) deliver a significantly higher output than the reference planar LED (a).

noticed was a slight increase in operating voltage, but this can be solved in the future," said Heonsu Jeon of Seoul National University.

Jeon thinks that the addition of a photonic crystal pattern should not cause any significant increase in the cost of the LED. "In the future, the laser holography method could [even] be replaced with a phase mask technique to suit a mass production environment."

James Tyrrell is a reporter for Optics.org and Opto & Laser Europe magazine.

HB-LED suppliers top 100

More than 100 companies now produce high-brightness (HB) LEDs at various levels of the vertical supply chain. That's according to the latest analysis of the industry by the market research firm Strategies Unlimited.

While the \$3.7 billion market for packaged HB-LEDs in 2004 was dominated by just a handful of key suppliers, the report indicates that there is still room for new companies to fill niches with either novel device packaging or innovative chip structures.

Bob Steele, the analyst company's director of optoelectronics programs, says that out of the 30 companies selling epitaxial wafers and/or HB-LED chips into the market in 2004, the top three suppliers accounted for over half of the sales of these materials.

Steele adds that the HB-LED industry is yet to become highly integrated. Out of the 74 companies analyzed, only 12 are vertically integrated from epiwafers and chip production through to the packaging stage.

And while 26 of the companies profiled in the report produce only epiwafers or chips, this does not represent the biggest single group – 36 firms purchase chips and produce packaged HB-LEDs.

Asia still dominates in terms of production, accounting for 76% of the packaged HB-LED market and 57% of merchant epiwafer and chip sales in 2004.

"In spite of some industry consolidation, we can expect to see new HB-LED suppliers continue to enter the market," said Steele.

Substrate impurities boost white output

Researchers from Meijo University, Japan, report that they have doubled the efficiency of white-emitting LEDs by producing a device that delivers 130 lm/W, according to the Japanese web-site *Nikkei.net*.

Team member Satoshi Kamiyama told *Compound Semiconductor* that the increased output was produced by employing a purple-emitting GaInN-based multiple quantum well for the active region and using impurities in

the SiC substrate for white light conversion.

This approach contrasts that taken by many LED makers, who use blue-emitting devices and color-converting yellow phosphors.

Kamiyama has also secured ¥40 million (\$330,000) to launch a company that will develop the GaInN-based LEDs. The cash will be spent on marketing the devices and on winning an additional ¥30 billion, which could be used to build a chip production line.

Industry in need of uniform standards

Mistrust between manufacturers of high-brightness (HB) LEDs and their customers is just one of several issues that the solid-state lighting (SSL) industry must address if it is going to succeed.

That's one of the findings of an analysis of the global market for HB-LEDs compiled by NanoMarkets, an offshoot of Communications Industry Researchers.

NanoMarkets predicts rapid growth in the market for LEDs in general, and for the

highest-brightness devices in particular.

However, the analyst company also says that the industry must address a range of problems for SSL to penetrate mainstream lighting applications. These include more transparency and co-operation between different levels of the industry supply chain, a greater marketing emphasis on the consumer benefits of LEDs, and new characterization standards.

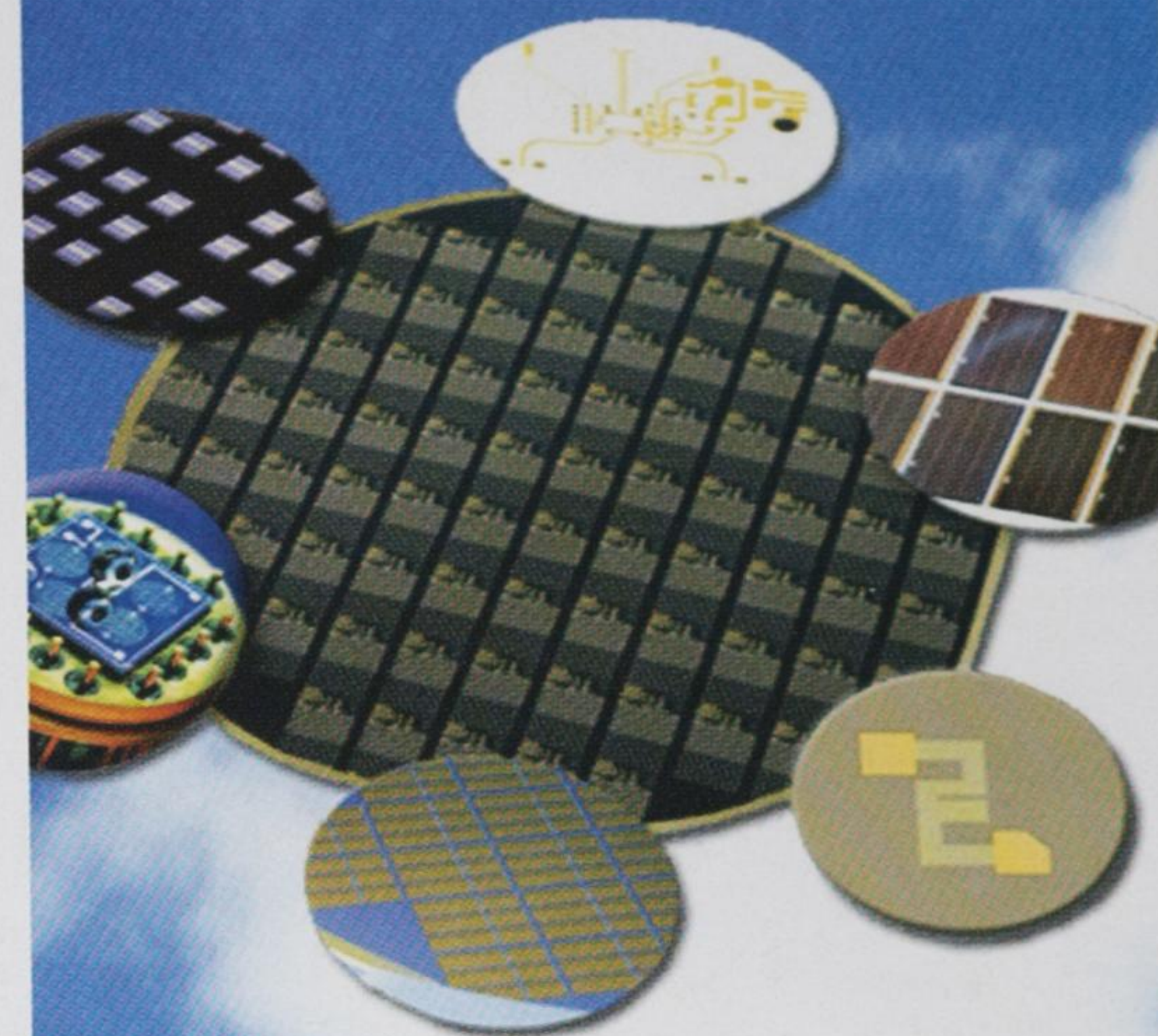
● Read more details about the NanoMarkets report on p19 of this issue.

In brief

● **KoBrite**, the joint-venture company set up by Kopin to mass-produce LED chips, has officially opened its Chinese facilities. The new three-building campus in Dongguan, near Hong Kong, will host GaN-based LED die processing activity, with epitaxy taking place in Taiwan.

● **Osram** says that improvements to the structure of its TOPLED range of power LED chips will enable the products to be used in applications that up until now have been dominated by traditional light sources. The advancement is said to produce 50–70% brighter AlInGaP devices.

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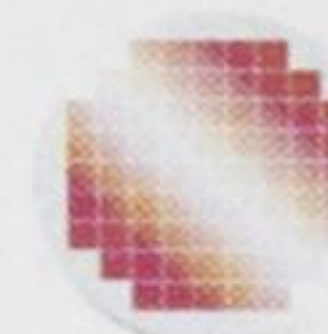
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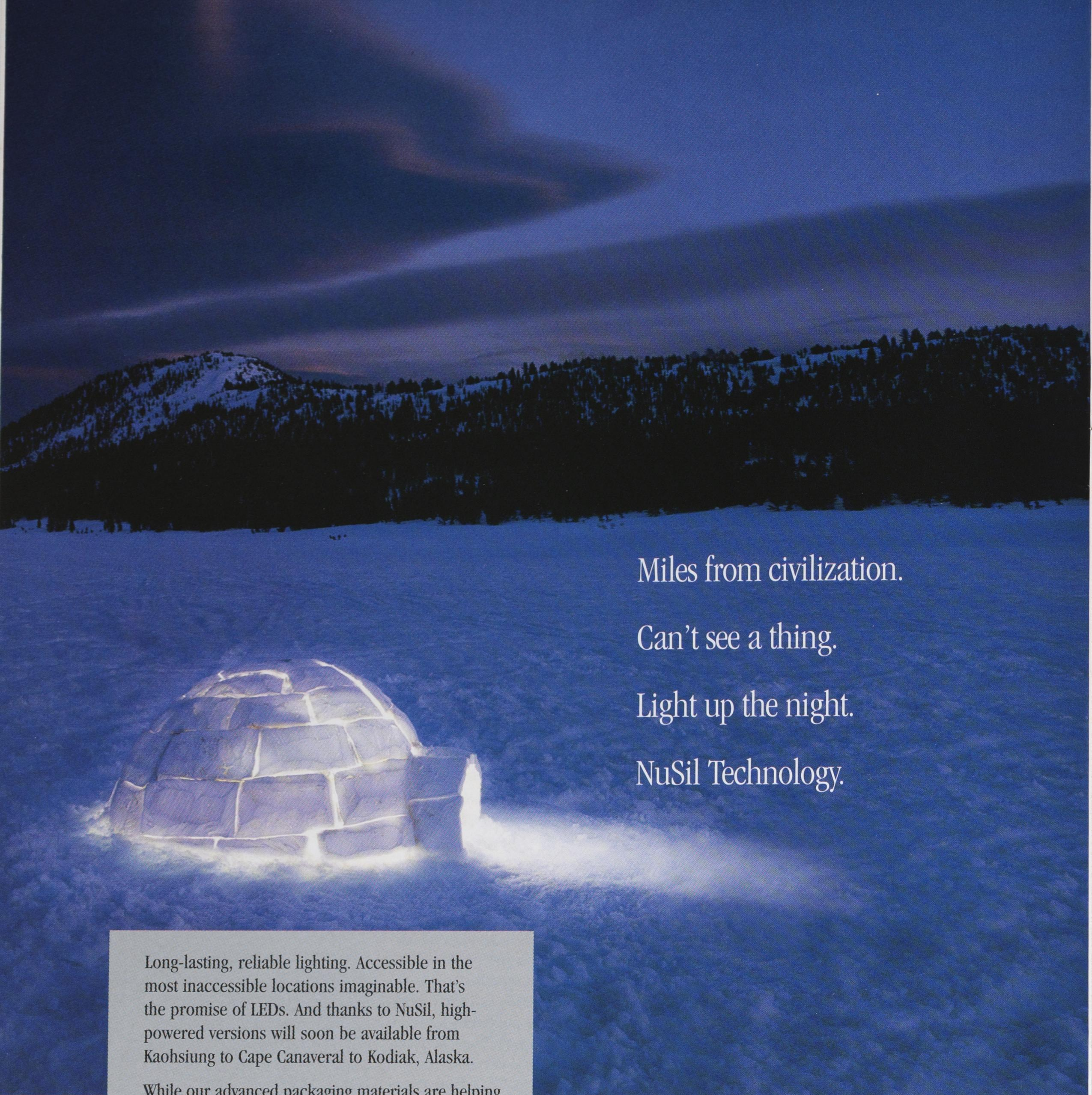
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Emcore buys gyroscope specialist Phasebridge

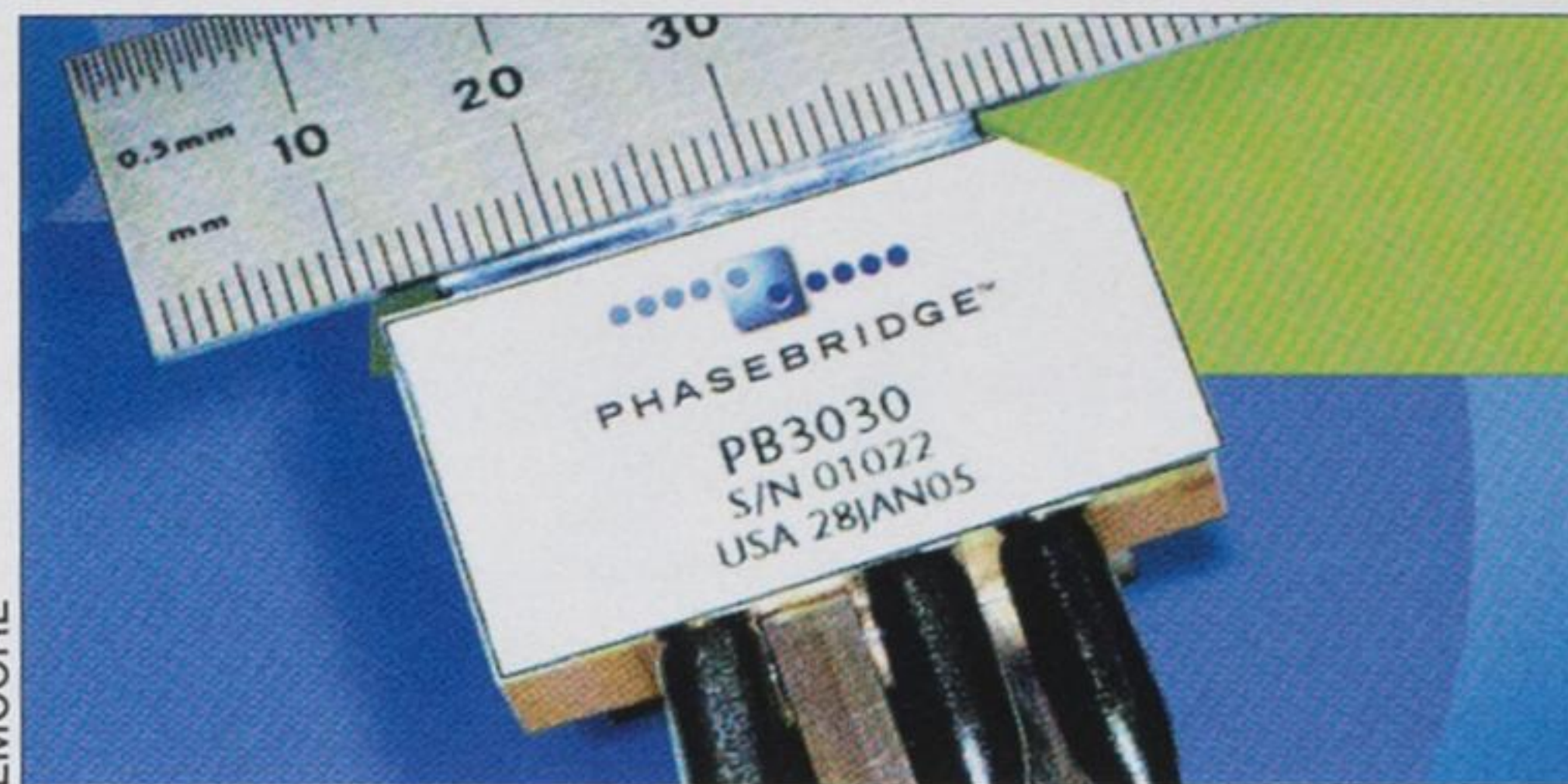
Materials, component and optical system supplier Emcore has acquired the California-based firm Phasebridge, which produces fiber-optic gyroscopes (FOGs) used in applications such as weapons and aerospace guidance.

The FOGs made by Phasebridge are based around a superluminescent LED chip manufactured on InP.

Phasebridge also makes multichip optical modules for applications such as RF delivery over optical fiber links, RF frequency synthesis and terahertz spectroscopy.

The Pasadena-based firm will be integrated into Emcore's Ortel division, which was formerly part of the Agere Systems optoelectronics business and is based close to Phasebridge in Alhambra, CA.

"Ortel will [now] be able to offer a broad set of component and subsystem solutions in the



Emcore can now offer three-axis fiber-optic gyroscope transceivers from Phasebridge.

FOG, RF, microwave and terahertz markets for a range of applications," said Hong Hou, Ortel's vice-president and general manager.

Earlier this year Phasebridge introduced a prototype three-axis FOG transceiver that it developed for the US Navy. The transceiver was said to be the first in the industry to integrate all three axes into a single package.

Brighter LEDs speed up water purification

Hydro-Photon, a developer of UV LED-based water treatment modules, has purified water at flow rates close to those required for individual water treatment systems.

Miles Maiden has increased flow rates this year by replacing existing UV LEDs with more powerful versions made by Remis Gaska's team at Sensor Electronic Technology and Asif Khan's group at the University of South Carolina.

Hydro-Photon's treatment chamber can now reduce the level of *E. coli*-spiked water flowing at 150 ml/min and 300 ml/min by 99.99% and 99%, respectively. The figures

are close to the values required for individual systems, which would typically work at a flow rate of at least 500 ml/min.

The latest work is also an improvement on the 38 ml/min rate for a 99.99% reduction of *E. coli* that was achieved earlier this year (see *Compound Semiconductor* May p15).

The latest LEDs used in the modules deliver a UV output of 7.34 mW, compared with 2.6 mW for the previous generation of emitters. The wall-plug efficiency of the UV LEDs has also risen from 0.63% to 1.52%, while the average forward voltage has reduced from 6.6 V at 65 mA to 5.9 V at 83 mA.

In brief

- The Semiconductor Industry Association (SIA) has forecast that the global optoelectronics market will grow by around 10% each year and be worth almost \$21 billion in 2008.

The prediction was part of the SIA's wider forecast for the entire semiconductor market, which it believes will surpass \$300 billion in three years' time. SIA valued the overall market at \$213 billion for 2004, adding that the optoelectronics sector was worth \$13.7 billion.

- Film maker Metro-Goldwyn-Mayer (MGM) says that it plans to release film and television titles from its library in Blu-ray format when the associated hardware is launched in North America, Japan, and Europe.

"Blu-ray technology, with its expanded storage capacity and increased interactive capabilities, allows us to continue to provide our customers with the best movie experience available," said Harry Sloan, CEO of MGM Studios.

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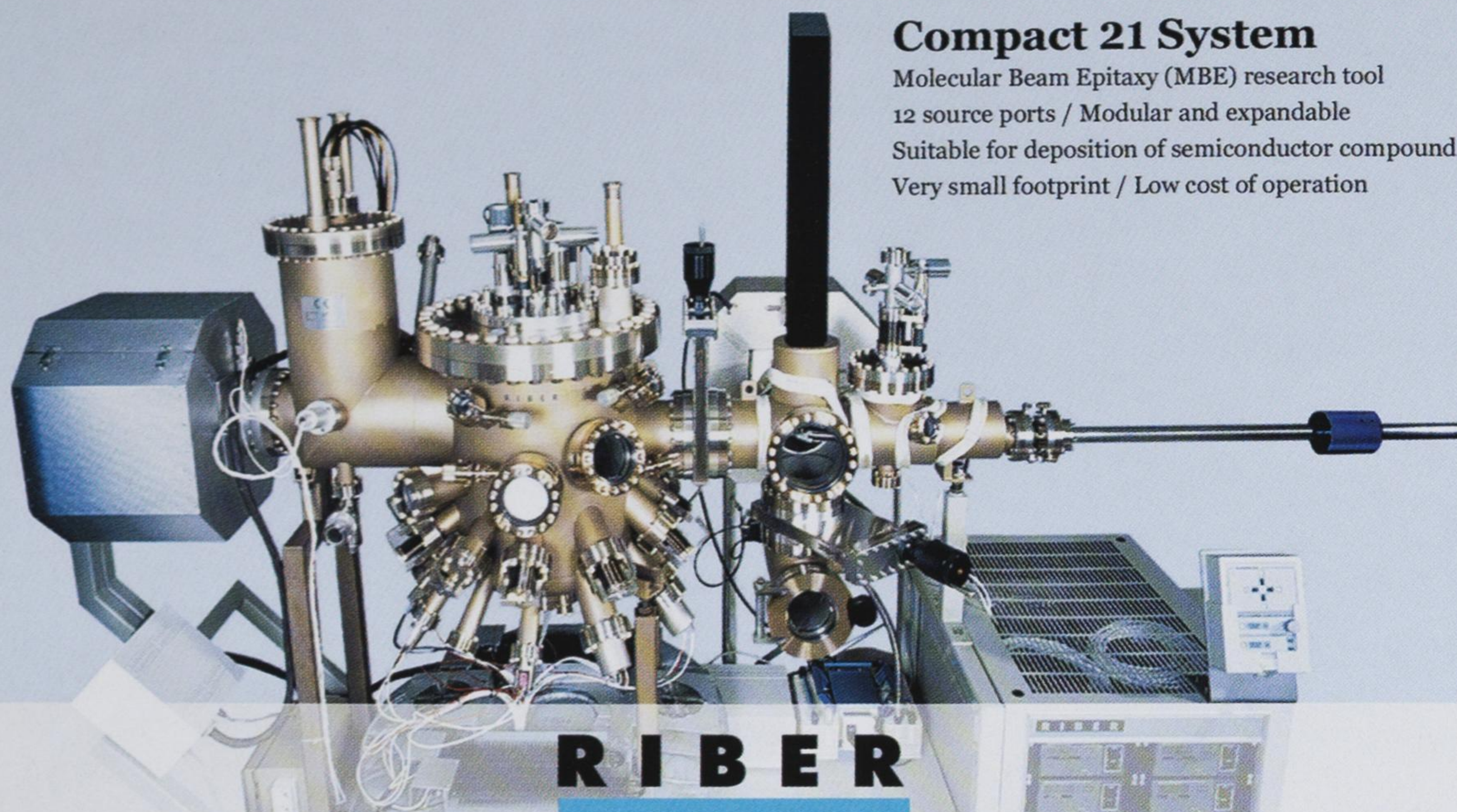


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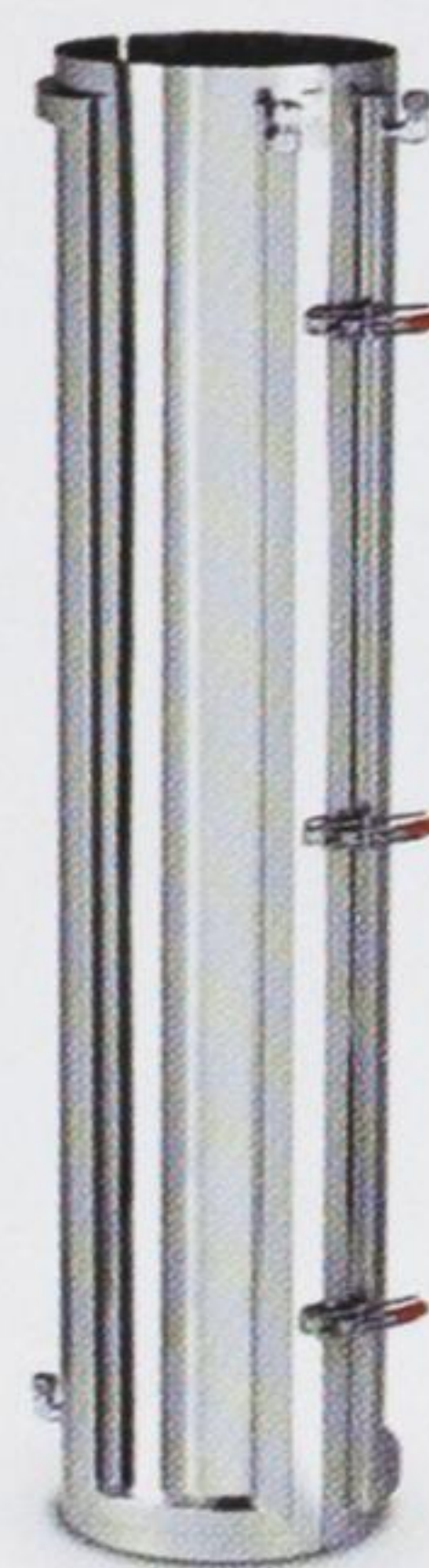
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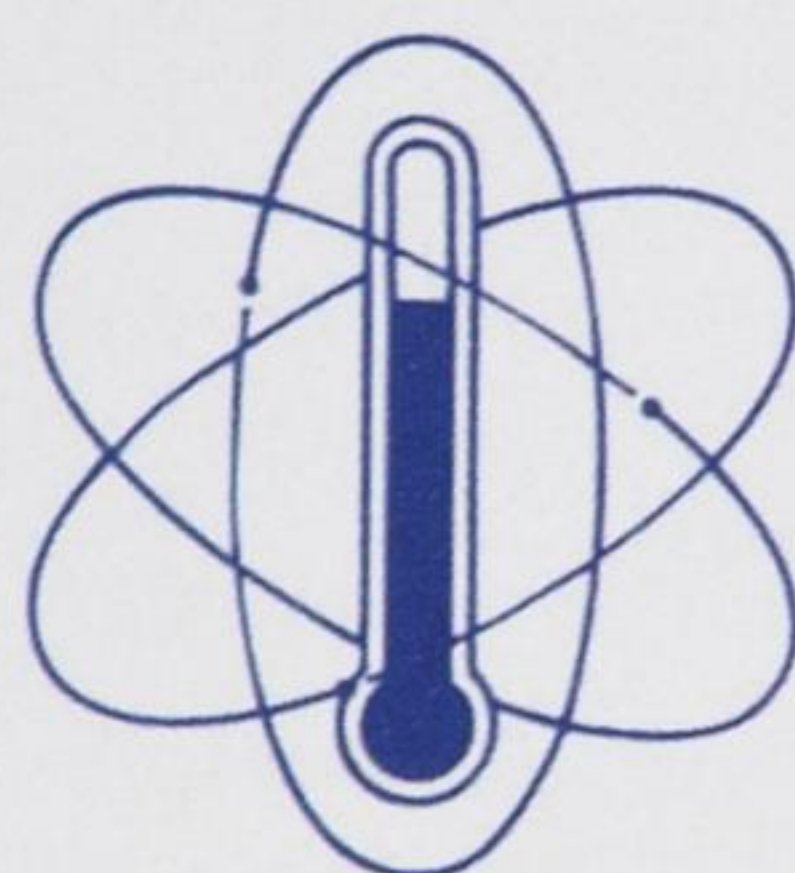


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Infinera gains as long haul improves

The global market for optical equipment used in communications systems has grown by 31% in the past year, claims a new report by analysts at Dell'Oro Group.

Alcatel ranked highest of the system vendors, sharing a worldwide market worth \$2.1 billion in the third quarter of 2005. The France-based company was followed by Nortel, Lucent and the Chinese firm Huawei.

"The optical market continues to exceed my expectations," said Jimmy Yu, Dell'Oro's director for optical transport research. "This was the fourth consecutive quarter of higher optical revenue in North America, keeping the worldwide optical market in a state of growth."

Long-haul applications are showing particularly strong growth in North America, and in the specific area of 10 Gb/s systems, photonic integration specialist Infinera appears to be stealing market share away from its more established rivals.

The company, which manufactures massively integrated chips at its own InP fabrication facility in Sunnyvale, CA, says that it ranked number one in Dell'Oro's latest survey of high-speed, long-haul optical network system suppliers.

"We are thrilled to rank first in the Dell'Oro figures only 10 months after we began shipping our product," said Jagdeep Singh, the co-

founder and CEO of Infinera.

The company has revealed details of five customers since it began officially shipping products in late 2004. Measured in terms of the number of 10 Gb/s wavelengths shipped in the third quarter, Infinera took a market share of 20%.

Infinera's photonic integrated circuits feature more than 60 optical components on a single chip, and are manufactured using MOCVD. The firm now deploys 100 Gb/s systems and is also planning to roll out 400 Gb/s versions over the medium term, believing that the data rate demanded by network operators will double every two years.

Firecomms reveals RCLED transceiver for in-car networks

Firecomms, an Ireland-based developer of high-speed semiconductor light sources, says that it has unveiled the world's first media orientated system transport (MOST) fiber-optic transceiver based on a high-speed resonant cavity LED (RCLED).

MOST networks are plastic optical fiber-based infrastructures deployed in cars to link various electronic systems, offering a low-cost alternative to copper cabling.

Firecomms' transmitter uses an RCLED – a device that is similar to a VCSEL but which has a much larger aperture and does not lase. The RCLED is integrated with a lens to



Firecomms hopes that car makers will turn to RCLED-based communications networks.

maximize coupling efficiency.

Firecomms' RCLED technology "offers improved device efficiency, high bandwidth (to 250 Mb/s), and excellent reliability", said CTO John Lambkin.

"Because our core light sources are signifi-

cantly faster than existing fiber-optic transceivers, we can provide our customers with the ability to migrate to next-generation systems while maintaining existing connectors and a plastic optical fiber architecture," added the company's CEO Declan O'Mahoney.

In brief

● **Optical Communication Products (OCP)**, which makes fiber-optic subsystems and modules out of its Woodland Hills, CA, base, posted a revenue of \$14.8 million in its final quarter of fiscal 2005, which ended on September 30.

The sales figure represented a sequential increase of 8.7% and was 12.5% higher than the equivalent period last year, highlighting what the firm's CEO, Muoi Van Tran, described as a "higher level

of activity" from customers.

● A new InP foundry service has been launched. **Svedice**, a firm with 14 employees based in Järfälla, Sweden, has customers throughout the world and is equipped with a 800 m² cleanroom and facilities that include MOCVD growth, materials characterization, etching and metallization.

The start-up can produce 1310 nm and 1550 nm fixed-wavelength and tunable lasers, and standard and avalanche

photodetectors for 2.5 Gb/s and 10 Gb/s applications.

● **Finisar** posted sales of \$86.6 million, up 6% sequentially and an increase of 22% year on year, for the second fiscal quarter ended October 31. Loss for the quarter was \$15.8 million.

In the current quarter the company has bought the optical transponder assets of Big Bear Networks for \$1.9 million in cash. "The acquisition expands our 10 Gb/s product offerings

and adds new 40 Gb/s transponders to our product line," said CEO Jerry Rawls.

● **JDSU** has acquired tunable laser manufacturer Agility Communications for \$67 million. The transaction comprised \$57 million in stock and \$10 million in cash.

The firm has also gained the approval of its shareholders to implement a reverse stock split in the range one-for-eight to one-for-ten at any time before December 1, 2006.

Hittite proves fabless benefits

Since its Nasdaq debut in August, Hittite Microwave's stock has already provided shareholders with a valuable return on investment. **Michael Hatcher** tracks the fabless IC company's recent moves.



The fabless approach has doubtless been a major reason why Hittite has been profitable in each of its last 13 years of operations.

If you invested in Hittite Microwave's initial public offering (IPO) back in the summer, then you will have already made a tidy profit for the approaching holiday season. But is it wiser to hold onto those shares, or to cash in the return at such an early stage?

Since late July, when the ticker name "HITT" made its debut, the stock price has enjoyed a steady climb from the IPO valuation of \$17 per share, easily outperforming the Nasdaq composite and just topping \$25 in mid-November as *Compound Semiconductor* went to press. Clearly, investors have been convinced by the Chelmsford, MA, company.

Massachusetts Institute of Technology (MIT) graduate Yalcin Ayasli, who founded Hittite back in 1985, saw a major return on his own investment through the IPO, which boosted the balance sheet by around \$52 million. With more than 16 million shares in the company, the Ayasli family's holding in Hittite now has a value in excess of \$400 million.

The name "Hittite"—a reference to an ancient people living in northern Syria some 4000 years ago—gives little clue as to the nature of the company's business. In fact, the secret of its success appears to owe much to the selection of a fabless business model to manufacture RFICs, modules and subsystems. Hittite uses seven different foundries to make its chips, which range from advanced silicon devices such as SiGe and silicon-on-insulator components to GaAs-based power amplifiers.

The fabless approach has doubtless been a major reason why Hittite has been profitable in each of its last 13 years of operations. And in its third quarter of fiscal 2005, which ended on September 30 (the second set of results to be announced since the company's IPO), Hittite's

profit margin looked particularly healthy. Overall revenue was only \$21.2 million, just one-tenth that of GaAs chip manufacturer Skyworks Solutions, for example. But on the bottom line Hittite posted an impressive profit of \$5 million, equivalent to \$0.17 per share, compared with Skyworks' \$3 million (\$0.04 per share).

As well as registering an impressive year-on-year revenue increase of 32.5%, Hittite is looking to expand its range of customers. In the most recent quarter, 57% of the company's revenue came from US sales, with the military, microwave and millimeter-wave communications, and broadband segments accounting for 70% of revenue. Increased sales into cell-phone, automotive and space applications are among the targets for the future. While Hittite CEO Steve Daly acknowledges that sales to cellular applications have softened slightly in recent months, specifically in Asia, he believes this to be a temporary slowdown, with the ramp of 3G communications globally providing very strong activity in general.

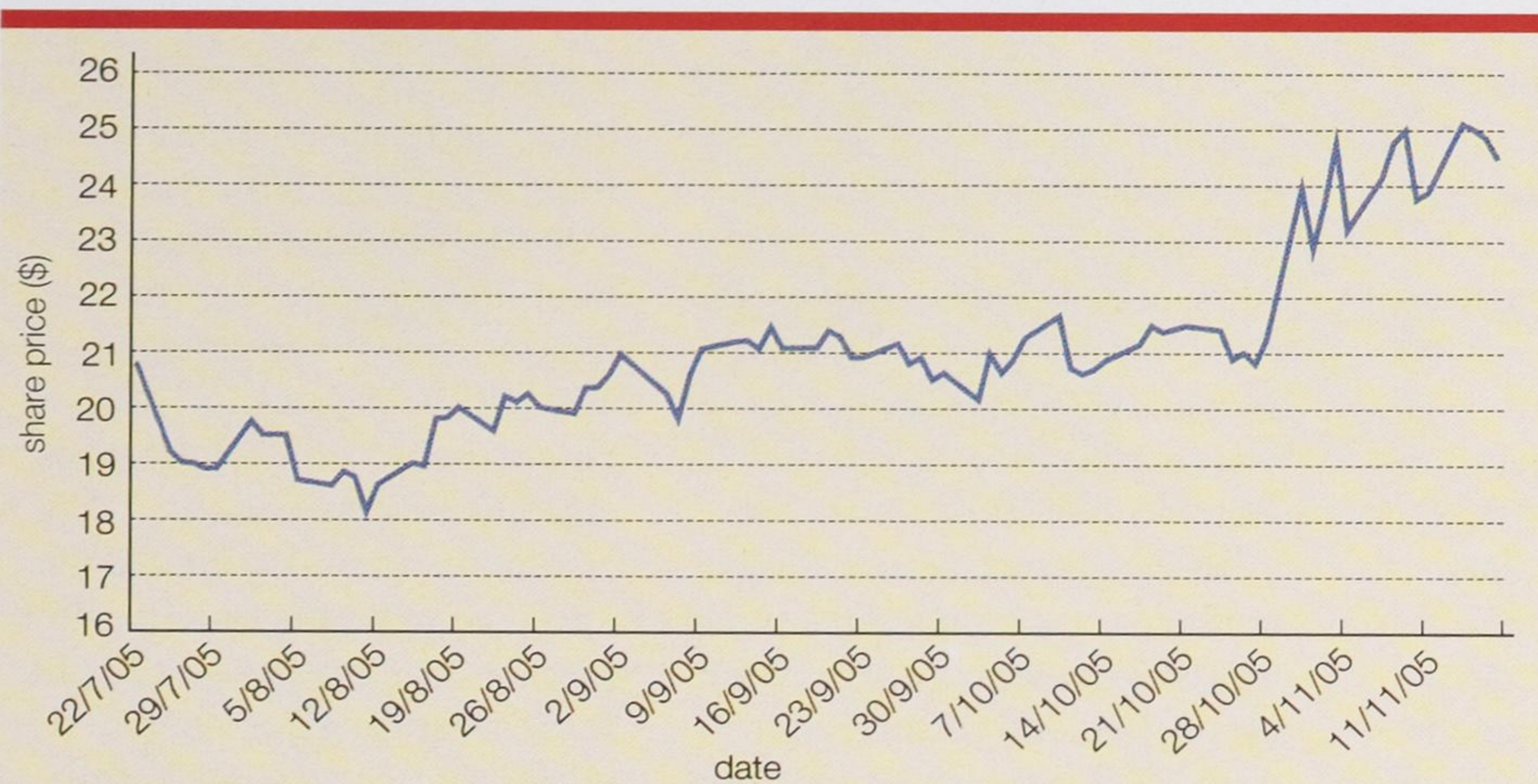
As well as generating \$6.4 million in cash from continuing operations in the September quarter, Hittite has also been busy on the acquisition front. In late August the company acquired Q-Dot, a research and development organization that specializes in designing mixed-signal silicon ICs, for \$2.2 million in cash. Traditionally Q-Dot has, like Hittite, been focused mainly on military applications for the US Department of Defense, with whom it has an existing backlog of projects worth \$3 million. However, the intention in the future is to broaden this applications base by targeting the commercial markets that Hittite has already penetrated.

Because of its fabless business model, Hittite is exposed to market forces resulting from fluctuations in the semiconductor foundries that it uses. With the booming cell-phone handset industry, many of these GaAs fabs, which include the pure-play foundry Global Communication Semiconductors, as well as TriQuint, M/A-COM and United Monolithic Semiconductors, have seen utilization rates grow in recent months.

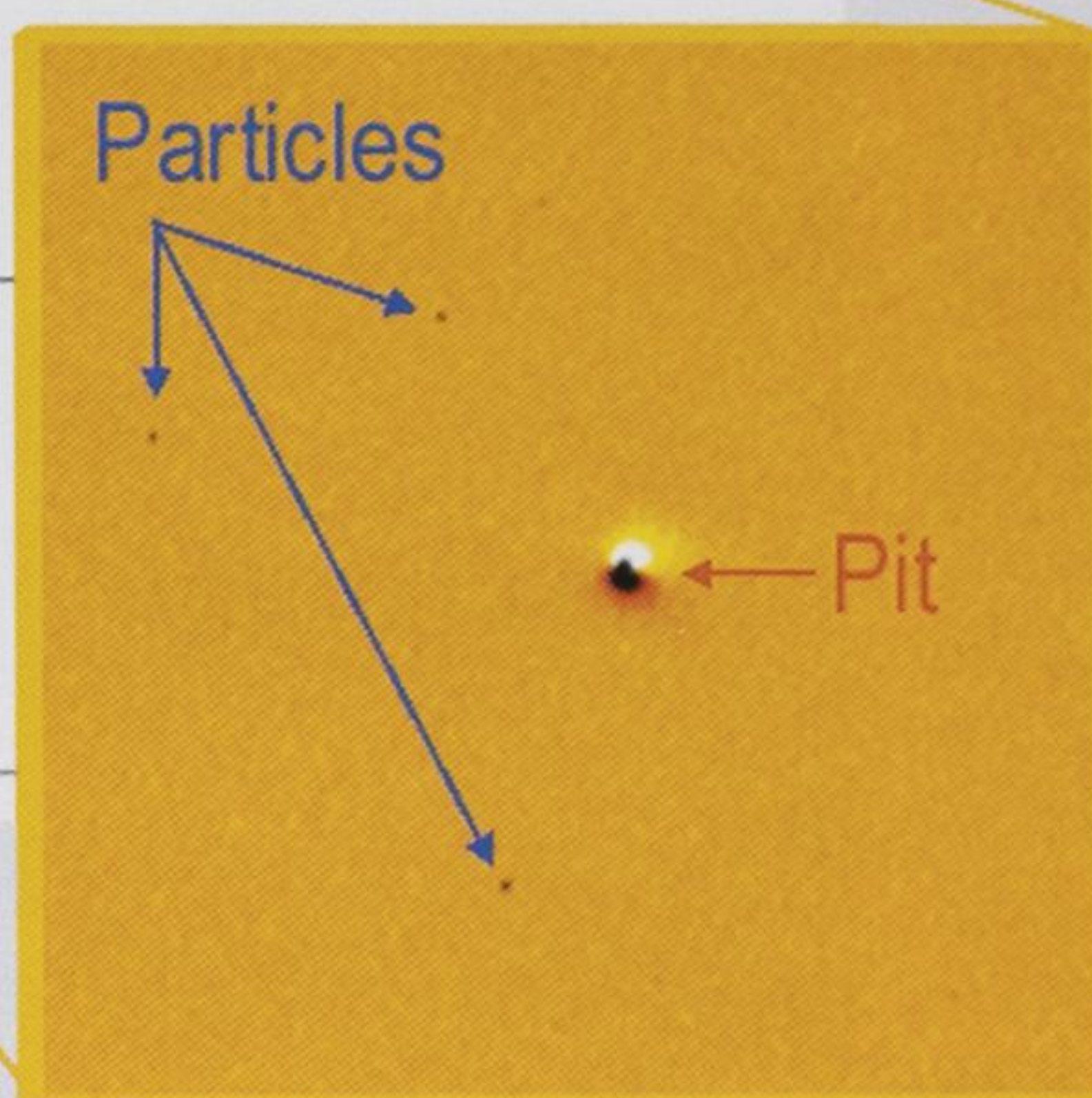
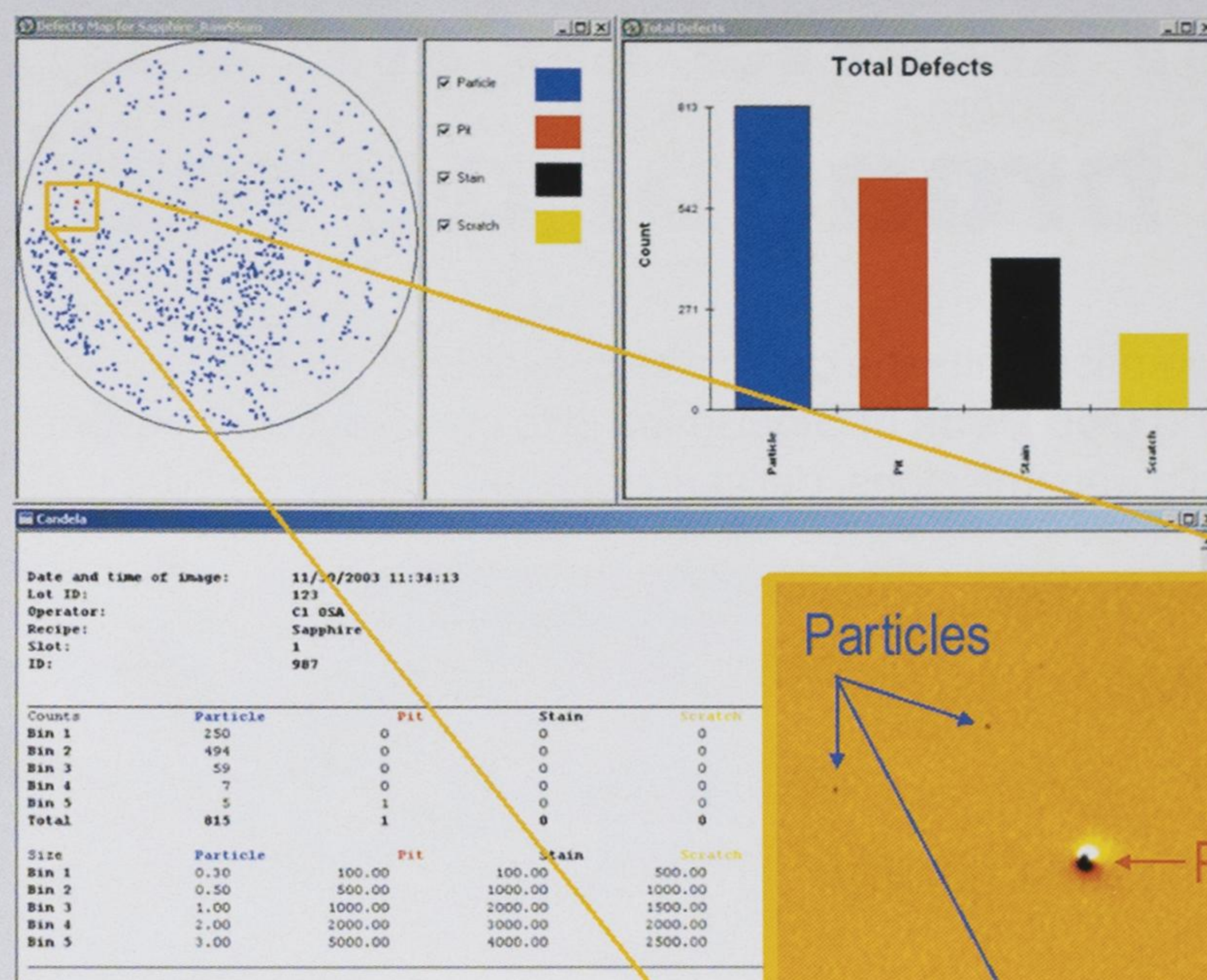
However, Daly says that this trend is not adversely affecting Hittite because the fabs are still running at around 50% capacity, which is not high enough to affect wafer prices or lead times.

Looking forward, Hittite's management has also raised its guidance for the final quarter of the calendar year on the back of a better-than-expected gross margin, with revenue expected to be in the \$22 million range and net profit of \$5.4 million–\$5.7 million.

With its impressive financial history and solid outlook, it would seem that Hittite shares are worth holding onto well beyond this holiday period.



Convincing: Hittite has outperformed the Nasdaq average since its July 2005 debut at \$17 per share, with a 46% increase in the stock's value by December.



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BROADBAND WIRELESS

GigaBeam turns to III-Vs for ultra-fast broadband radio

The cost of deploying fiber to the premise limits the data rates available to most US businesses. The solution, say **Doug Lockie** and **Don Peck** of GigaBeam, is to connect fiber networks to enterprises by millimeter-wave radio transmissions, delivering gigabit-per-second data rates.

Ask any incumbent telecom company to connect two individual gigabit-per-second local-area networks (LANs) and you will be offered 1,000 DSL lines, 647 T1 lines or 500 E1 lines. The copper plant that links users to the communications backbone was never designed to connect modern computers. Gigabit capacity exists in the fiber rings, the LANs, and the computers, but just a few thousandths of this speed is available in the local copper loop.

Fiber can be installed in the last mile, but this occurs infrequently. The 7,500 national and international long-haul fiber rings and the 100,000 local metropolitan rings deployed worldwide have only a few fiber-optic "laterals" connecting them to individual buildings. US businesses use Ethernet networks that operate at 1 Gb/s and computers that run at even higher data rates, and yet 95% of them have no fiber connection.

The lack of provision of fiber services to most buildings arises from the high cost of trenching (\$0.2–\$0.8 million/km in urban areas), and the 6–12 month wait for installation (caused by the time taken to gain access to private land). The process of laying underground cables has failed to keep pace with the advances in telecommunications and computing. For this reason a market exists for a lower-cost, millimeter-wave radio solution. Radio links can fulfill the demand for high-speed connections from premises to wide-area networks. In the US, 750,000 business locations could benefit from a radio link.

The aerial route

Millimeter-wave radio offering gigabit-per-second data rates can be deployed within a few days, and for a fraction of the trenching costs. These millimeter-wave high-data-rate radios usually cover a 1.6 km range. Although torrential rainfall can impede the propagation of these signals (see "When the rain comes down", p17), the technology can usually pro-



GigaBeam has deployed its high-speed radio transmitter at Trump Towers, New York City, where residents have the luxury of receiving fiber-equivalent access in their own apartment.

vide connectivity for all but five minutes per year. If customers are prepared to accept this very infrequent disruption, gigabit-per-second radio can serve the 80% of US businesses that are located within 1.5 km of a fiber network.

Today's microwave radios are limited by cost to 100–200 Mb/s data rates, predominantly because the regulatory agencies have authorized only narrow bands. However, because these rates are insufficient for today's needs, GigaBeam has worked with the Federal Communications Commission (FCC) to create rules and authorize the use of spectrum at 71–76 GHz, 81–86 GHz, and 92–95 GHz. The use of these bands was approved in October 2003, and since then GigaBeam has championed the adoption of similar legislation with regulatory agencies throughout the world.

The spectral bands centered at 73.5 GHz and

83.5 GHz are each 5 GHz wide. If low-order modulation formats delivering 1–3 bits/Hz are used, a low-cost 1–10 Gb/s transmission technology is viable. Although the 92–95 GHz spectrum has a 100 MHz band reserved for space-borne radios right in the middle of the band that limits transmission to a few gigabits, this data rate is still valued for next-generation networks.

In commercial environments cost dominates the decision-making process. In general, if you want a lower cost you turn to silicon. Intel has built silicon circuits that operate at 100 GHz, while IBM has used SiGe circuits to produce similarly impressive results. However, practical, longer-range radios cannot be built with silicon-based components, so GigaBeam has chosen GaAs MMICs for its transmitters. We have found that existing

When the rain comes down

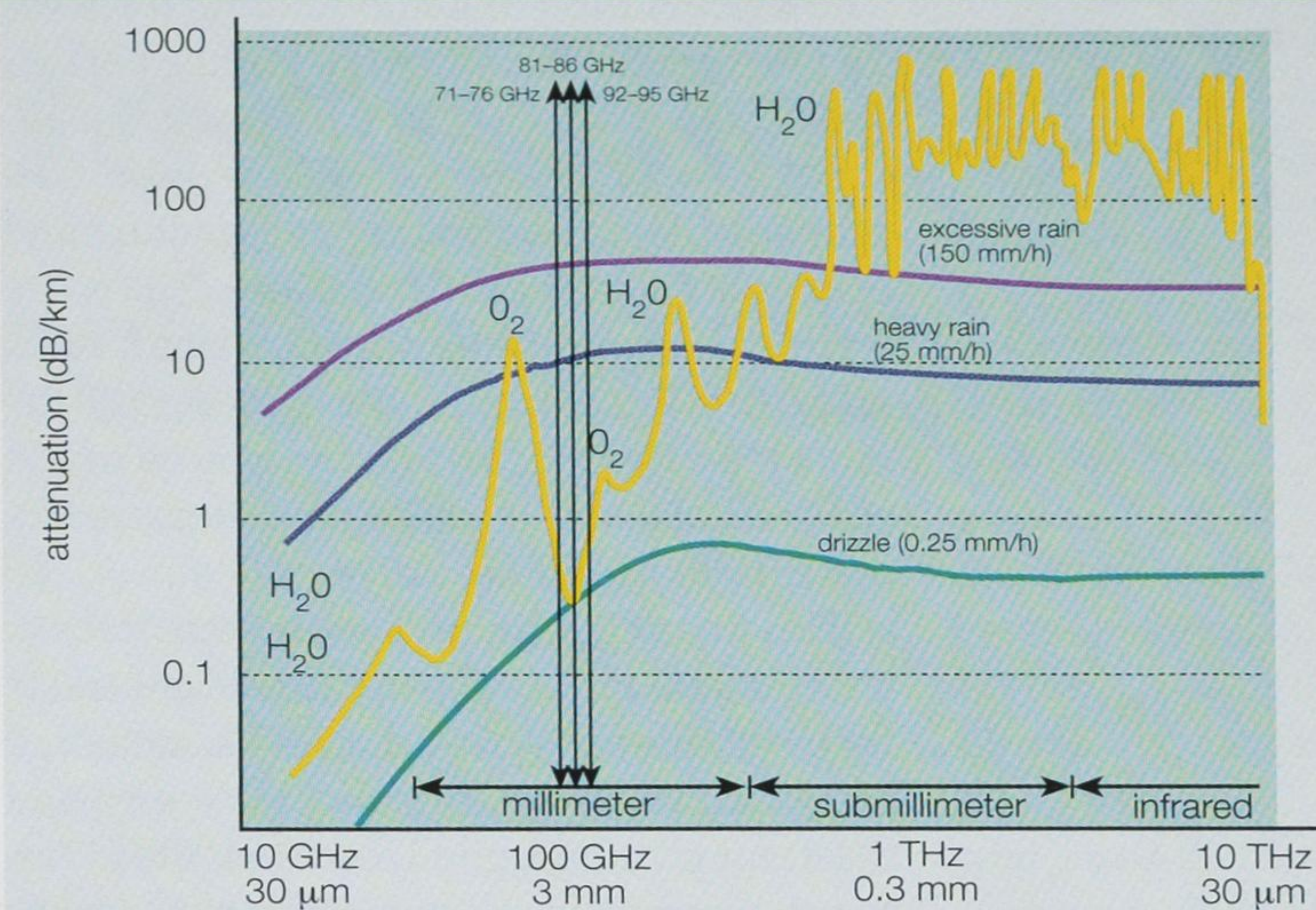


Fig. 1. When operating in the 71–95 GHz spectral range, rainfall and atmospheric gases can have a strong effect on signal propagation.

The weather strongly influences millimeter-wave propagation and limits connectivity (figure 1). The proportion of time when communication is lost because of bad weather is defined in terms of “nines”. Five nines is a maximum downtime of five minutes per year (99.999% availability), four nines is less than 50 minutes without connectivity per year (99.99% availability), and so on.

At the frequencies used by GigaBeam, rain produces greater signal attenuation than fog or atmospheric gases. However, a rainfall rate of 150 mm per hour occurs for less than five minutes each year (“five nines”) across about 80% of continental US and 90% of Europe.

In the past, radio communication operated at

frequencies that were largely unaffected by rainfall, and engineers used a rule of thumb that stated that increasing the link system gain by 4 dB doubled the range. Millimeter-wave applications, however, are significantly different.

The rule of thumb can be applied to millimeter-wave communication in clear air, but propagation through heavy rain that corresponds to a “five nines level” availability needs a further 50 dB of gain per mile to overcome the additional attenuation. With today’s technology, the weather limits cost-effective, practical, millimeter-wave gigabit-per-second links offering “five nines” availability to a range of 1.6 km.

So, for a 1-mile link using 50 dB gain antennas that are typically 0.6 m high, just

are outlined in “Requirements for radio subsystem components” (p18).

Among all of the performance parameters of millimeter-wave circuits, one that rarely receives sufficient attention despite its high importance for communication applications is the temperature dependence of the gain per stage. Each stage has a thermally induced gain variation of 0.1 dB per 10 °C that depends only

slightly on the actual gain of the stage.

A typical radio requires 60 dB gain to both transmit and receive signals, and must operate over a 100 °C temperature range. Since every gain stage contributes 1 dB of gain variation over the temperature range, the key parameter for radio applications is a high gain per stage.

GigaBeam has found that the GaAs circuits deliver sufficient gain per stage, unlike their

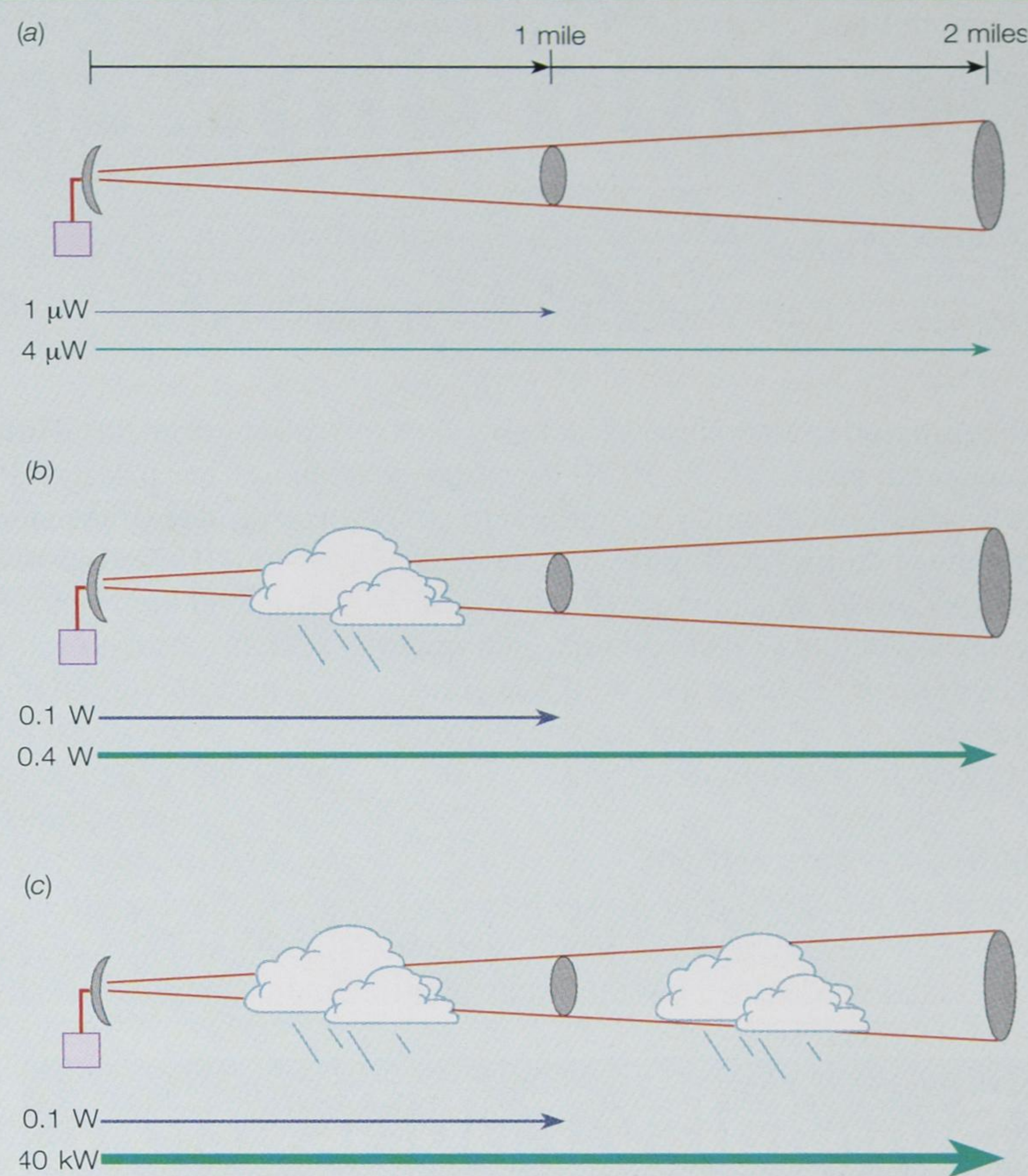


Fig. 2. (a) In clear air a transmitter emitting just 1 μ W is sufficient to cover a 1 mile radius. To transmit to 2 miles, 4 μ W would be required if the second mile was also in clear air. (b) With intense rainfall delivering “five nines” attenuation in the first mile, the transmitter’s power needs to increase to 0.1 W for a 1 mile radius, and to 0.4 W for 2 miles. (c) If rainfall occurred over both miles, a 40 kW transmitter would be needed for the second mile. This output power is not possible, so GigaBeam’s radio range offering “five nines” availability is restricted to 1 mile. However, if the customer accepts “four nines” coverage, a 2 mile range is possible.

1 μ W of power is required for transmission in clear air at 1.25 Gb/s using biphase shift keying modulation, assuming a –60 dBm threshold for 2.5 GHz

radio-frequency bandwidth. However, in adverse weather conditions nearly 0.4 W can be needed to deliver the same signal level (figure 2).

GaAs MMICs produced by Velocium, a commercial semiconductor division of Northrop Grumman, have produced excellent results at our frequency range.

The subsystems that form the millimeter-wave circuits include receivers, converters, transmitters, oscillators and modulators/demodulators (modems). The nominal performance parameters required by these parts

BROADBAND WIRELESS

Requirements for radio subsystem components

Receiver	Gain of 15–25 dB, noise figure of 2–5 dB.
Transmitter	Gain of 10–40 dB, power output (1 dB) 20–25 dBm. The FCC limits power output to 3 W, and it is desirable to produce this power if it is cost effective.
Oscillator	Phase noise of –100 dBc-Hz at 1 MHz offset for a 40 GHz center frequency. The active device contributes to this specification, but a “high Q” network is the primary driver.
Converter	Nominal 12–15 dB conversion loss.
IF strip	3–20 GHz (usually silicon), 30–70 dB of gain.
Modem	1–10 Gb/s at 3–15 GHz IF center (usually silicon).

silicon-based counterparts. Velocium's GaAs chips produce a total of a 10 dB variation, so little additional circuitry is required to compensate or deliver additional gain. However, silicon circuits producing a 20 dB gain variation require four to six additional gain stages to overcome the losses, as well as a similar number of circuits that typically use PiN diode actuators for gain compensation.

High data rates with InP

GigaBeam recently signed an exclusive agreement with Vitesse Semiconductor to use its VIP II HBT technology base for radio appli-

cations from 50 GHz to 300 GHz. Vitesse was chosen because its InP manufacturing process can produce transistors with f_t and f_{max} values of 400 GHz and 450 GHz, respectively, as well as deliver high yields for digital circuitry with several thousand gate equivalents. To the best of our knowledge this is the only manufacturing process that produces this number of gates with a high yield on InP, and we believe that it has the potential to deliver high-speed analog-to-digital converters.

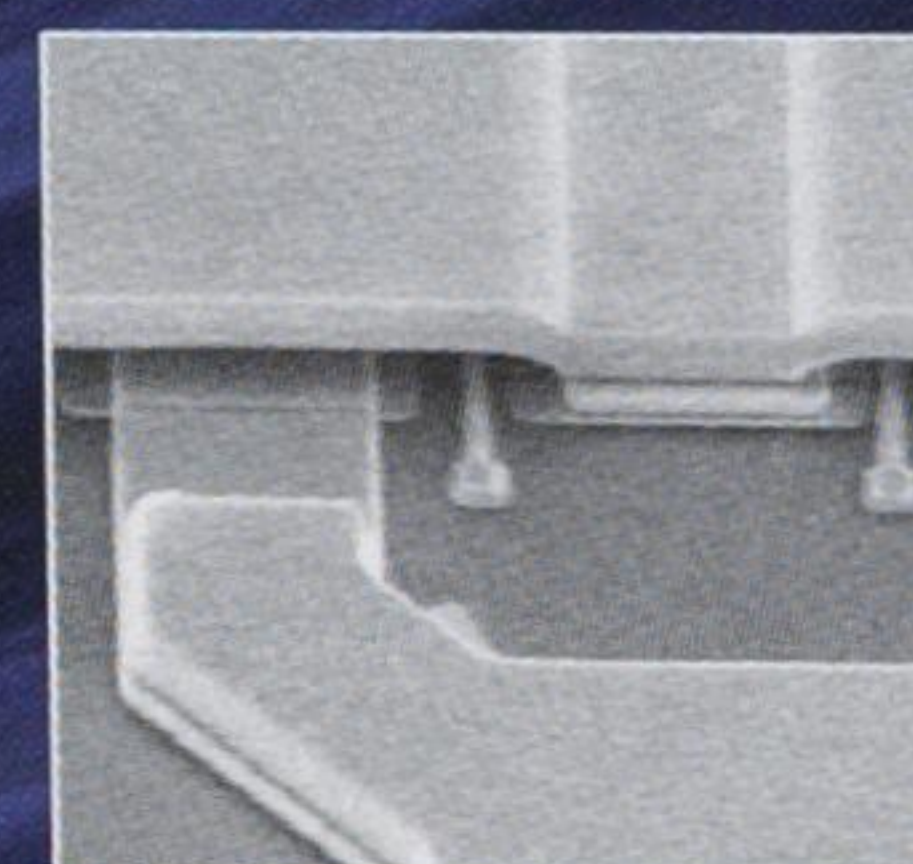
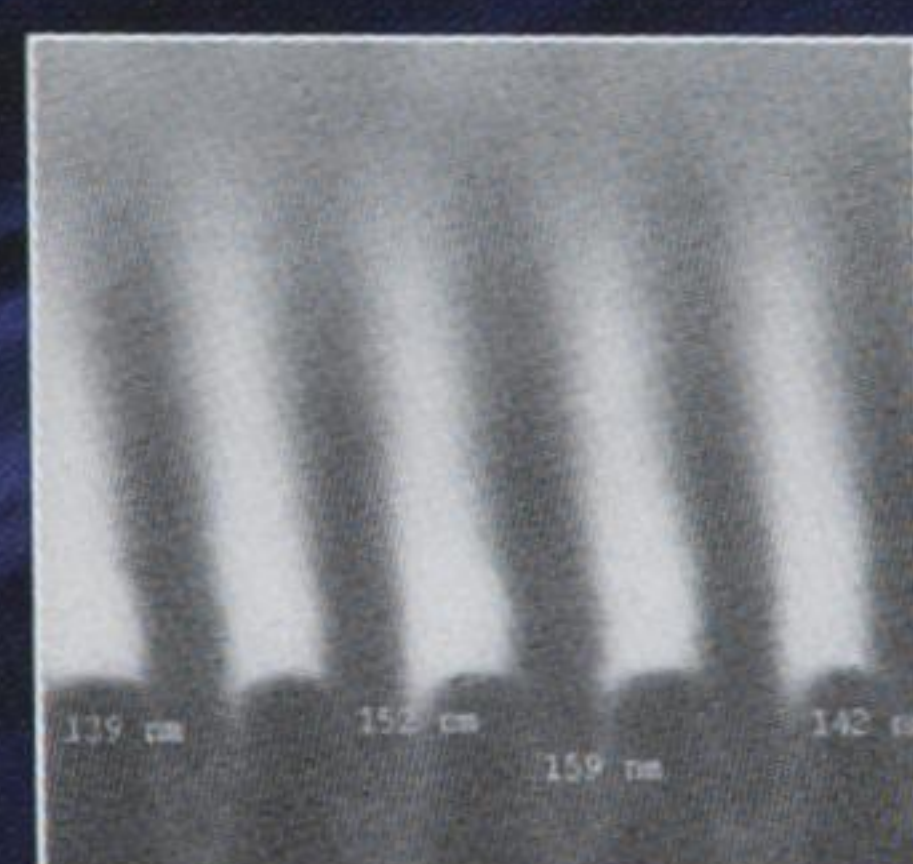
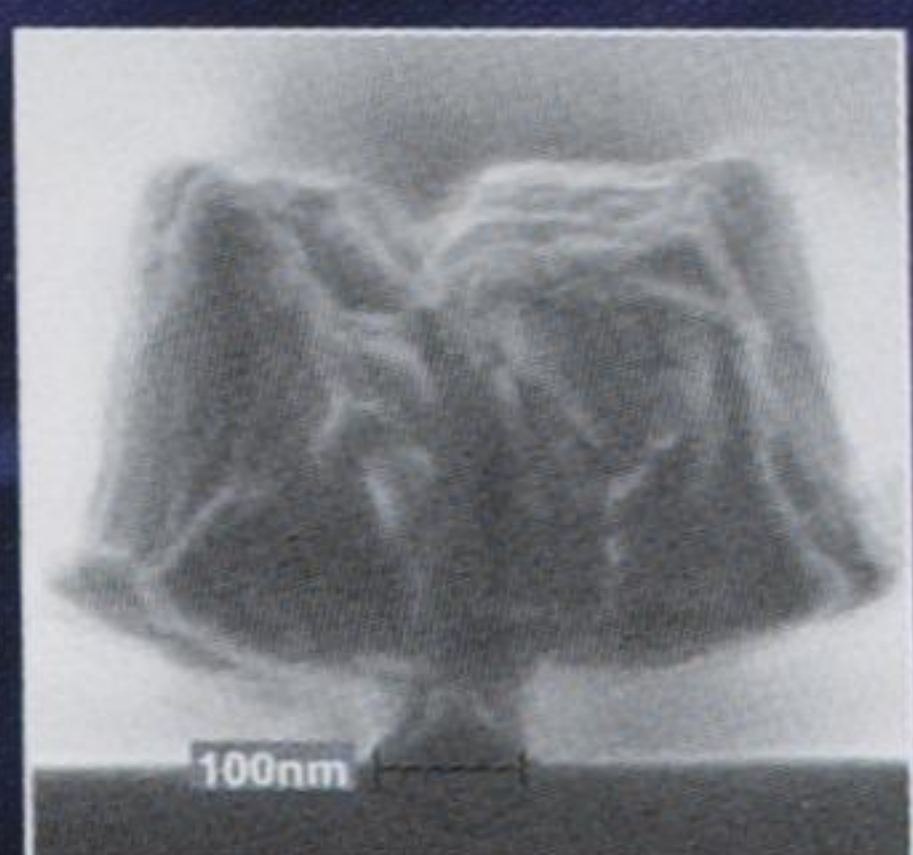
GigaBeam will use these circuits for several signal processing functions within the radio, and our main goal is to develop a 4–6 bit

A/D converter with a 90 GHz sampling rate. If successful, this A/D converter will enable a new generation of demodulators for 10 or 20 Gb/s links. The target is higher performance and lower cost for the advanced technology base. The first 10 Gb/s radio will probably deploy an analog architecture and operate at 3 bits/Hz, and make use of the entire 5 GHz band. Looking further ahead, even faster data rates are possible by using higher-order modulation schemes featuring 64 or 128 quadrature amplitude modulation processes and a digital architecture.

This year GigaBeam's radio transmitters have enabled the company to win contracts for installation in various locations, including Dartmouth College, Boston University, and the Trump Building in New York City. The development of radio transmitters featuring even faster data rates will only help to generate additional business.

Doug Lockie is GigaBeam's president and CTO (doug.lockie@gigabeam.com), and Don Peck is GigaBeam's vice-president of engineering (don.peck@gigabeam.com).

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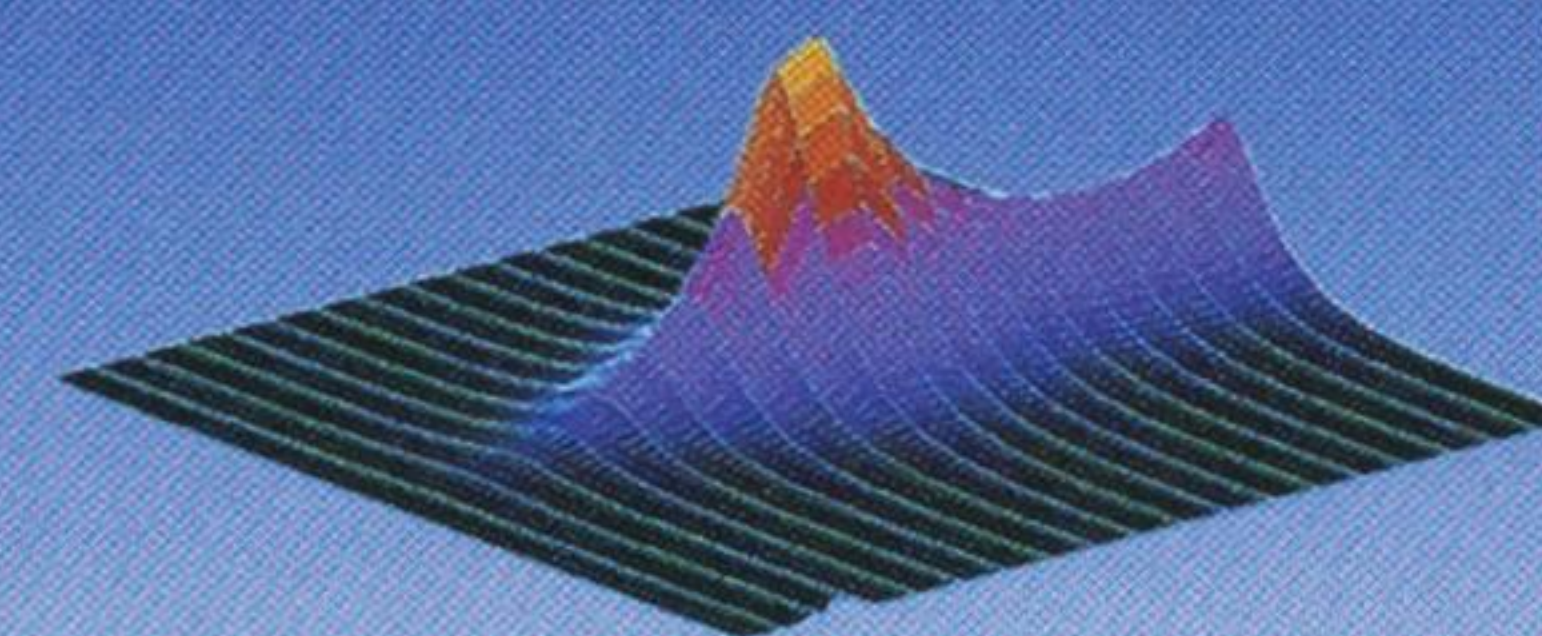
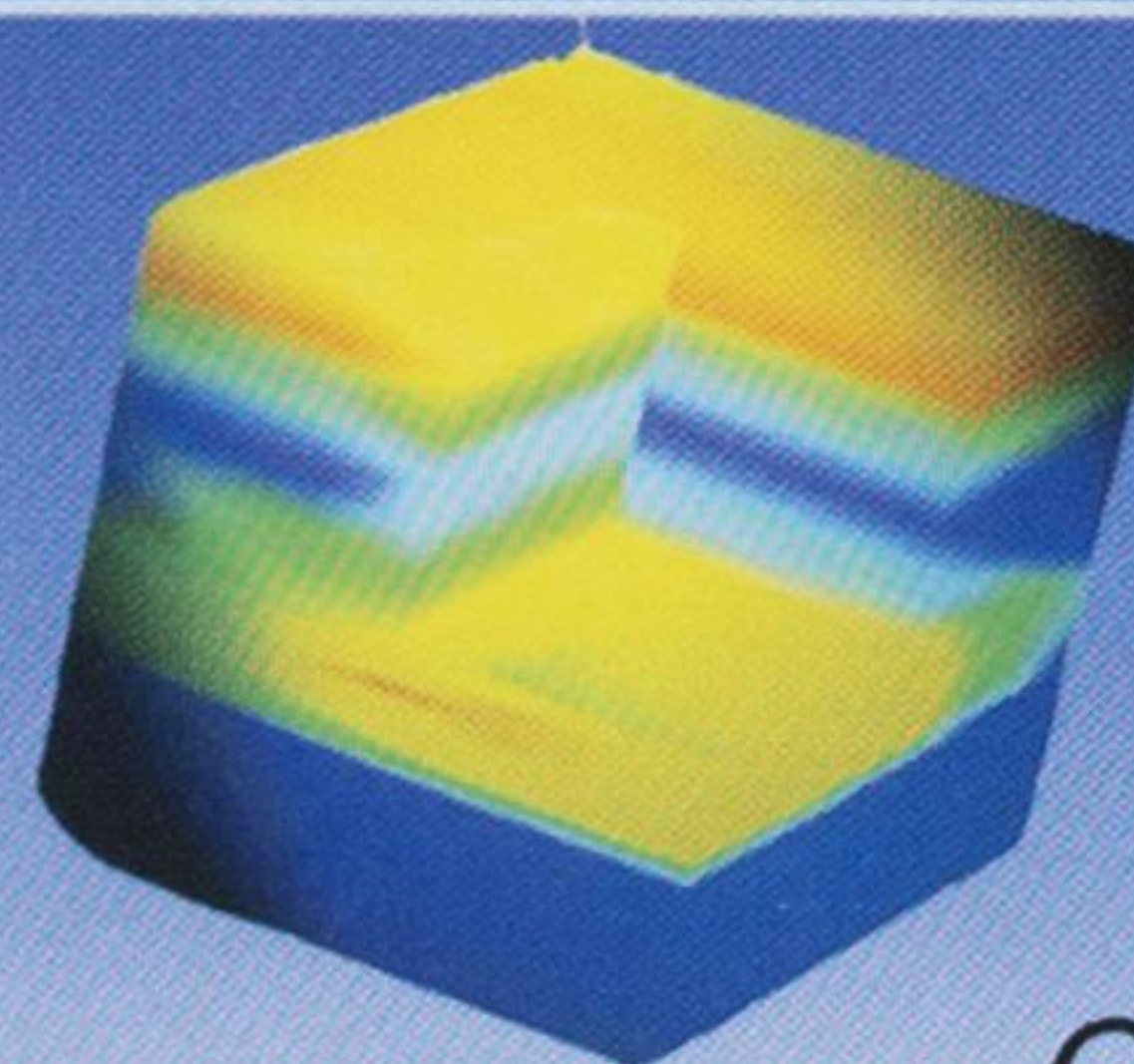
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Industry must work together to displace light bulb culture

HB-LED manufacturers should concentrate on building relationships with their customers in order to break down the incumbent culture based around the Edison light bulb, say analysts.

The penetration of high-brightness (HB) LEDs into the general lighting market seems closer to becoming a reality as manufacturers look to extend their applications base beyond cash cows like the mobile phone.

Improvements in LED chip structures and packaging will of course be fundamental to this switch, but technology alone will not be enough to create a solid-state lighting (SSL) market. According to some commentators, the HB-LED industry needs to change some of its ways to make this happen.

One of those commentators is the analyst firm NanoMarkets, which has just released its second market report on the HB-LED business. As well as providing the usual estimate of the size of the sector and its potential for growth, Rob Nolan and Lawrence Gasman from NanoMarkets have identified several problem areas that they believe the industry needs to address to keep growing strongly.

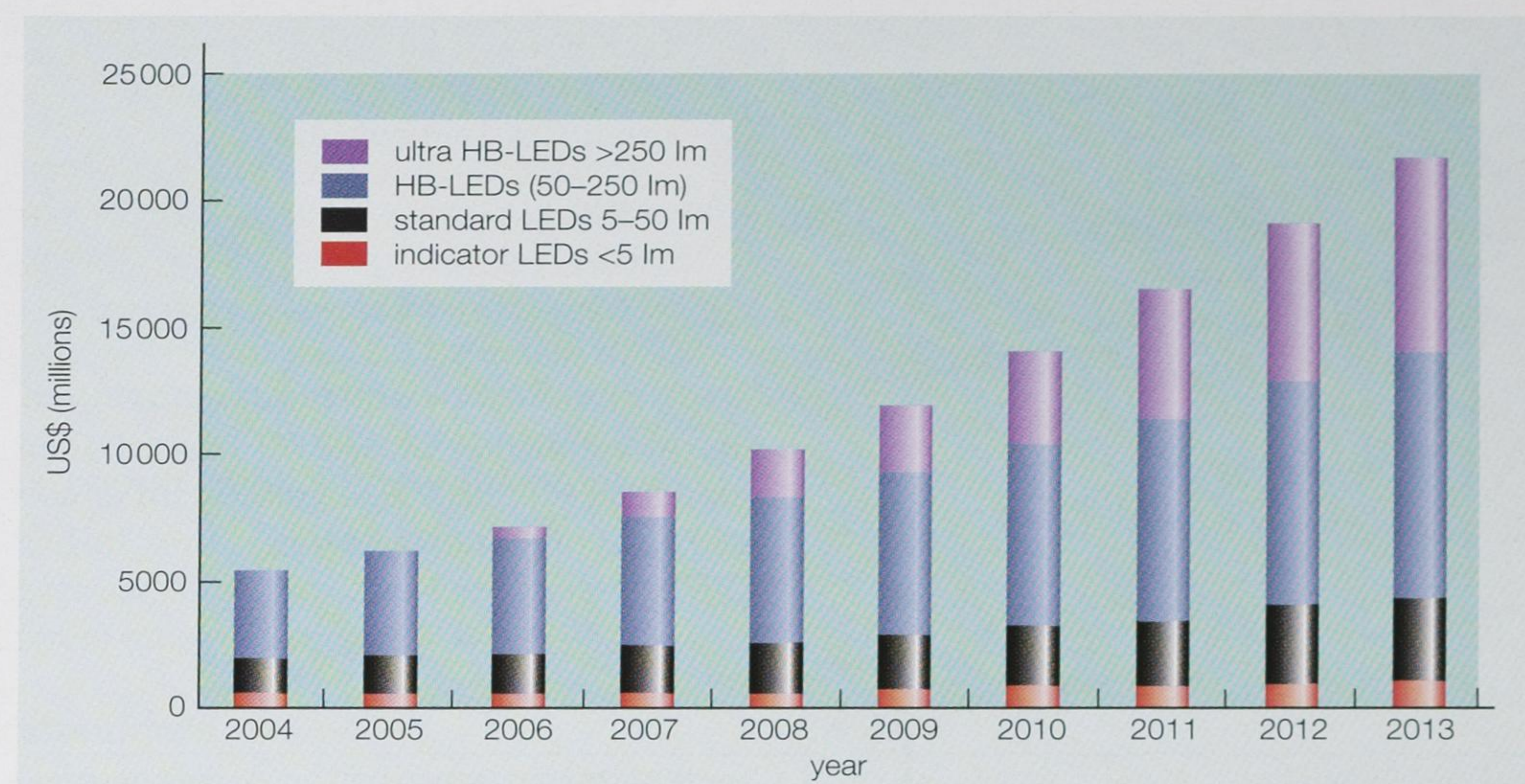
They value the HB-LED market (defined as packaged sources emitting 50–250 lm) at \$4.1 billion in 2005, and Gasman predicts steady if unspectacular growth over the next eight years as existing application areas increase in size. During that time there should be much faster growth in the “ultra-high-brightness” area, as HB-LEDs gain a foothold in more demanding applications such as automobile headlamps and general lighting.

Relationships

But the message from Gasman and others is that just relying on the technological superiority of HB-LEDs over conventional sources will not be enough to effect the latter’s replacement.

“Compact fluorescent lamps had [technological] advantages over incandescent lamps, but the industry did a poor job of selling that technology and it didn’t take off,” said Gasman of one recent attempt to take on the light bulb. While he believes that the HB-LED industry can do a better job, there remain plenty of issues that need to be addressed along the way.

One of these relates to the sometimes thorny relationship between HB-LED suppliers and



LED market growth according to analyst firm Nanomarkets. The eight-year forecast predicts a massive increase for “ultra-high-brightness” LEDs (packages emitting more than 250 lm). If automotive headlamp and general lighting applications kick in as the analysts predict, this particular sector could be worth an astonishing \$7.6 billion by 2013.

the lighting equipment makers that use the chips in their products. “There is a level of mistrust,” Gasman said, although this is not surprising in what is still a relatively young industry where technology is a key differentiator. “The lack of a consolidated effort by HB-LED manufacturers with OEMs has been a hallmark and a drawback for the HB-LED industry,” states the NanoMarkets report. It adds that chip manufacturers are too concerned about their patented chip designs being copied and made into cheaper products.

More important in the years to come, however, will be the relationships between chip manufacturers and their customers. In time these relationships will become just as valuable in terms of competitive advantage as technology patents are today.

With Philips now in complete control of Lumileds Lighting, things may start to change more quickly. This is a step that Gasman believes will be replicated by more big players in the lighting industry, although with General Electric’s stake in GELcore and Osram’s Opto Semiconductor LED sub-

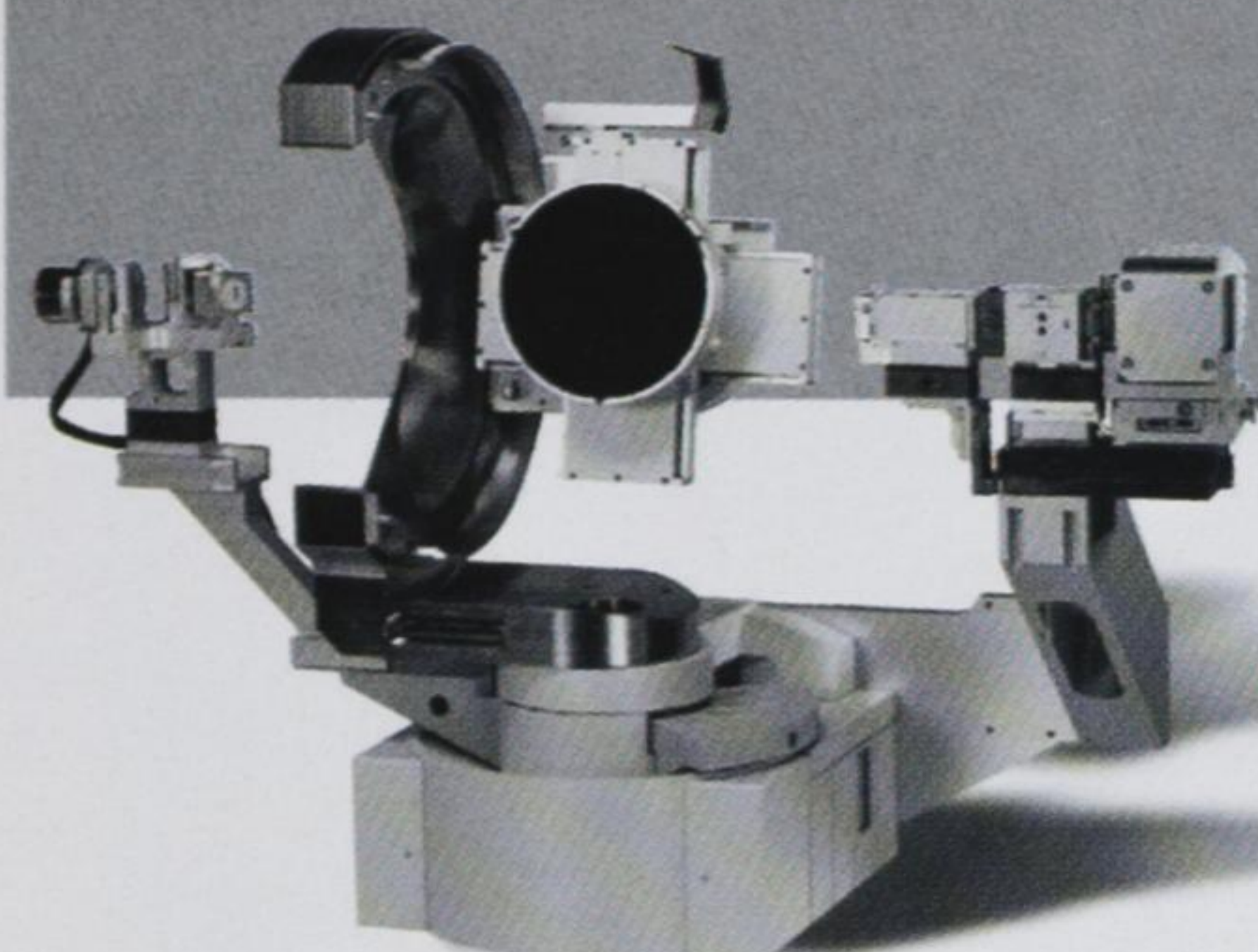
sidiary, it could be argued that the biggest players have already made this move.

Another analyst firm, Strategies Unlimited, has also been looking at the degree of vertical integration within the HB-LED business. It has just published the results of its latest industry survey, finding that over 100 companies are now involved in the supply of either HB-LED epiwafers, dice or packaged devices. Of those, 12 are described as vertically integrated.

Not everybody believes that a large degree of vertical integration is the best way forward for the industry, however. For example, at the recent LEDs 2005 conference in San Diego, Makarand Chipalkatti – the head of corporate innovation management at Osram’s Sylvania lighting business – argued against the idea. But he agrees that to challenge the light bulb culture HB-LED makers must become less obsessed by technology and increase collaboration to address issues of industry infrastructure, which he now sees as a priority. “It’s time to move to the next step,” he told delegates, urging them to work within industry groups to mount an effective challenge that

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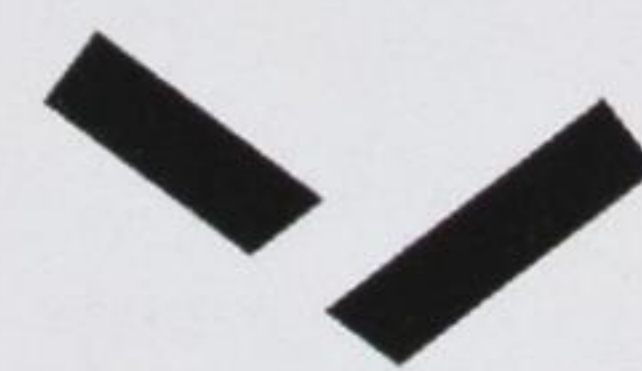
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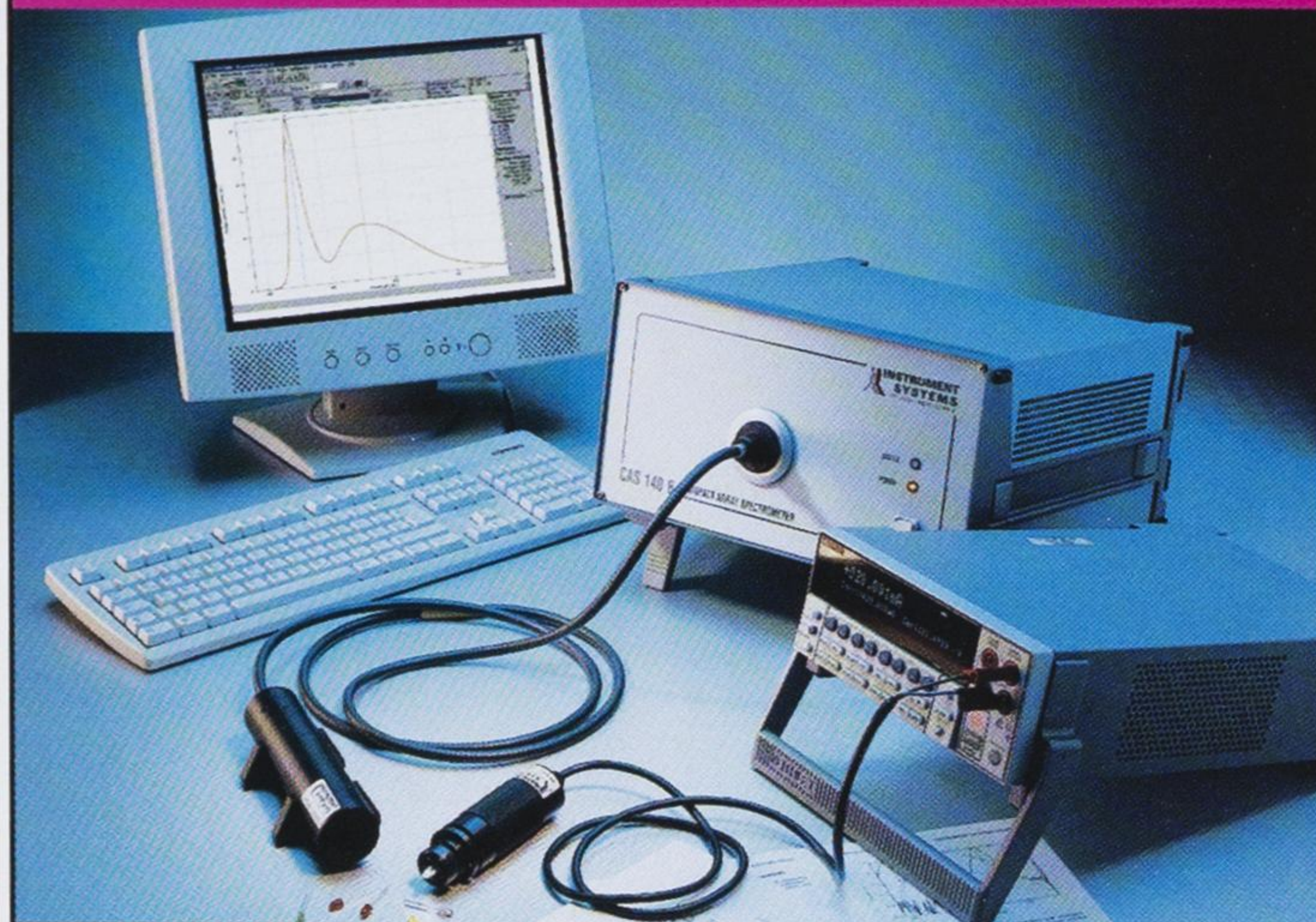


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White light for residential illumination

While the HB-LED industry faces up to the challenges of developing a rival infrastructure, technological innovation continues apace. Targeting general lighting applications, this warm-white source is the latest product for residential illumination manufactured by Lamina Ceramics, and is based on a combination of red, green and blue high-brightness chips.

Lamina has made the headlines in the past for its



Lamina's warm-white HB-LED is aimed at the home.

development of ultra-bright-light engines that emit several thousands of lumens and require a massive cooling system.

The company says that its new 95 lm source replicates the "warm-white" feel of ambient light in the home (3000 K color temperature), while emitting almost as much light as a 10 W halogen bulb.

The US company believes that the appeal of the warm-white source will encourage residential lighting designers and architects to mix solid-state lighting with conventional bulbs and halogen sources.

he regards as the biggest change in lighting for nearly a century.

But while the incumbent lighting industry, with the Edison bulb at its heart, is well defined in terms of its supply chain, the divisions in SSL are less clear. "In the SSL value chain, boundaries are more blurred and the innovation cycle is more rapid," said Chipalkatti.

Chipalkatti is also the chairman of the SSL section of the lighting systems division within the National Electrical Manufacturers Association in the US. Another industry association that he is closely involved with, and which is tied to one of the leading academic institutes involved in LED development, is the Alliance for Solid-State Illumination Systems and Technologies (ASSIST). Established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute in Troy, NY, ASSIST was set up to advance and promote LED technology, and Chipalkatti sees it as having a critical role in establishing the required SSL industry infrastructure.

Whether these efforts and the rapid innovation in HB-LEDs mean that the light bulb's days are numbered seems very unlikely, however. For the average consumer in the developed world, lighting is an inexpensive necessity that does not deserve or get much attention. Changing that mindset will mean that the SSL industry has to create a market that is different to the current one. The way to do this, believes Gasman, is by starting up an awareness campaign with consumers now, so that HB-LED lighting becomes an "awaited" and desirable technology, rather than one that takes the consumer by surprise.

The emphasis will need to be put on the fea-

tures that are unique to the technology, in particular the precise control over wavelength and brightness, as well as the ability to switch between different white-light "tones" at different times of the day.

Standards

Gasman also identified characterization standards as a priority for the industry to address. "The industry stands in dire need of uniform standards to measure the characteristics of HB-LEDs," thunders the NanoMarkets analysis. The old, existing standards, such as the color-rendering index (CRI), are simply not appropriate, it claims.

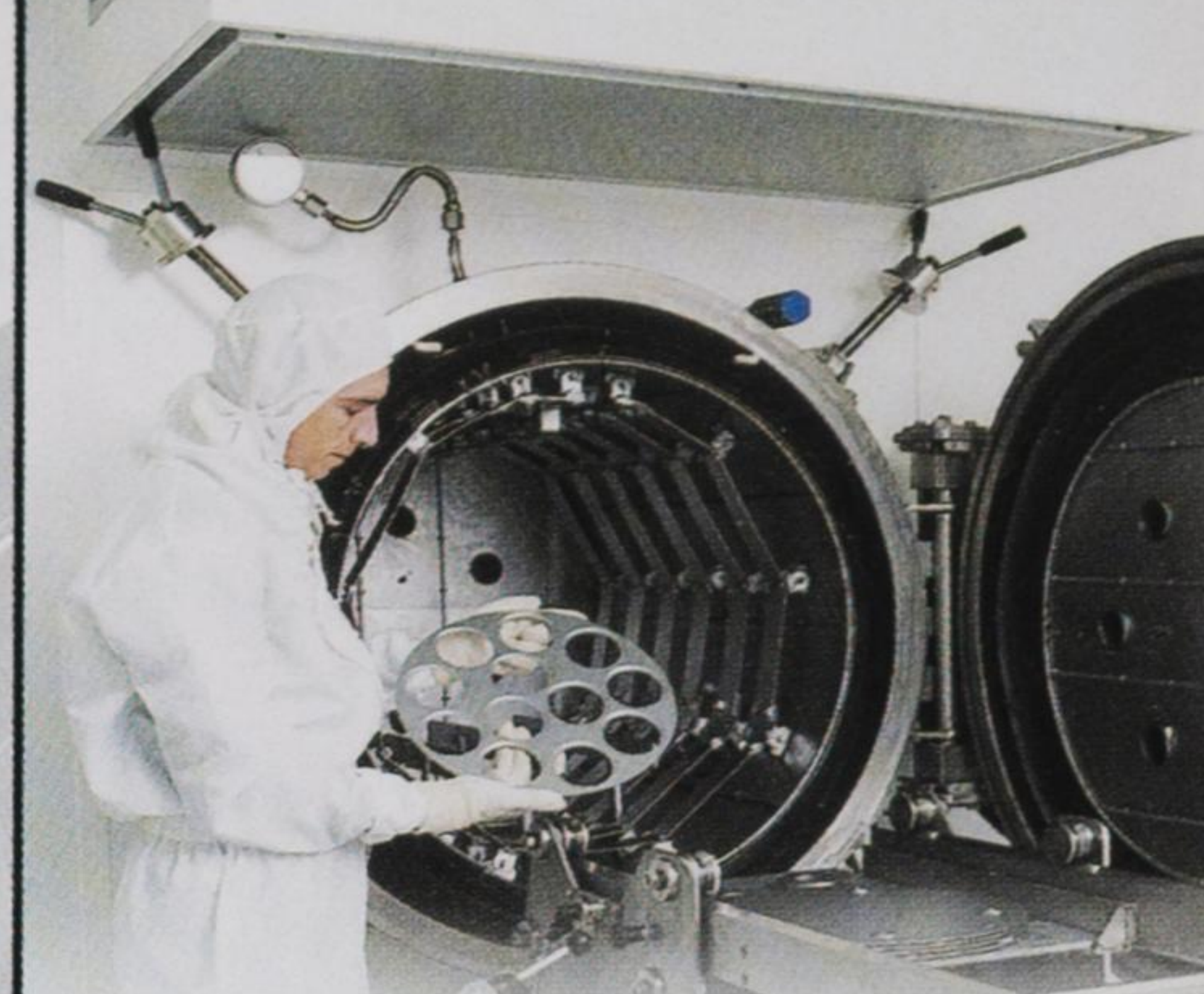
"Some experiments have indicated that human perception and liking for shades of white does not conform to the CRI," says the report. "In fact, [they] suggest that our liking for warm or cold white light varies according to the time of day and the ambient conditions."

A definition of the lifetime of HB-LEDs must also be agreed, says Gasman, who adds that packaging and drive electronics should be standardized. This fits in with Chipalkatti's vision of HB-LED light sources with a USB-type functionality.

For the HB-LED to ultimately prevail over the Edison bulb, it appears that the industry will need to address all of these issues while simultaneously solving the remaining technological problems to increase chip brightness. Only then will we find out just how accurate those optimistic long-range market forecasts are.

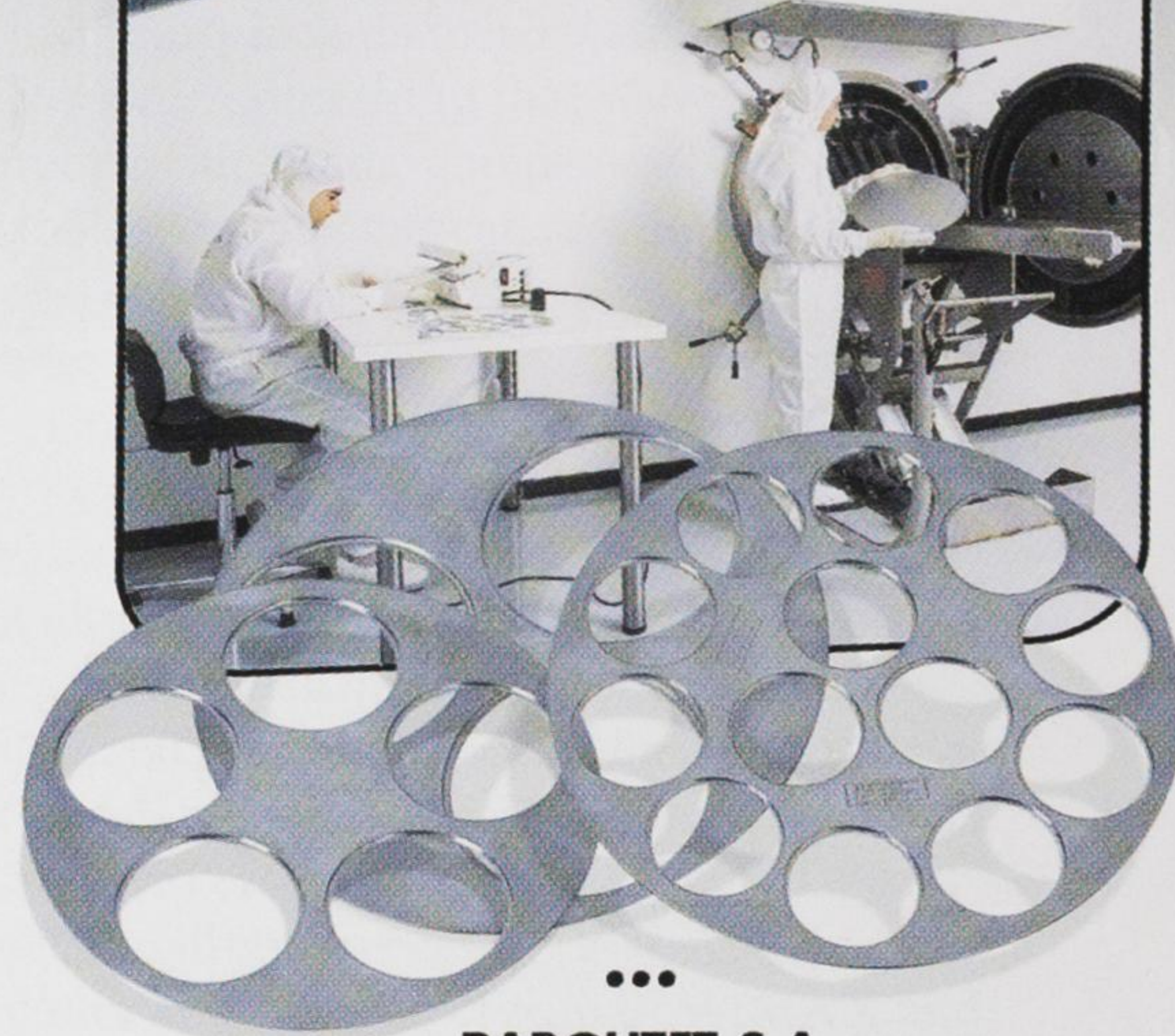
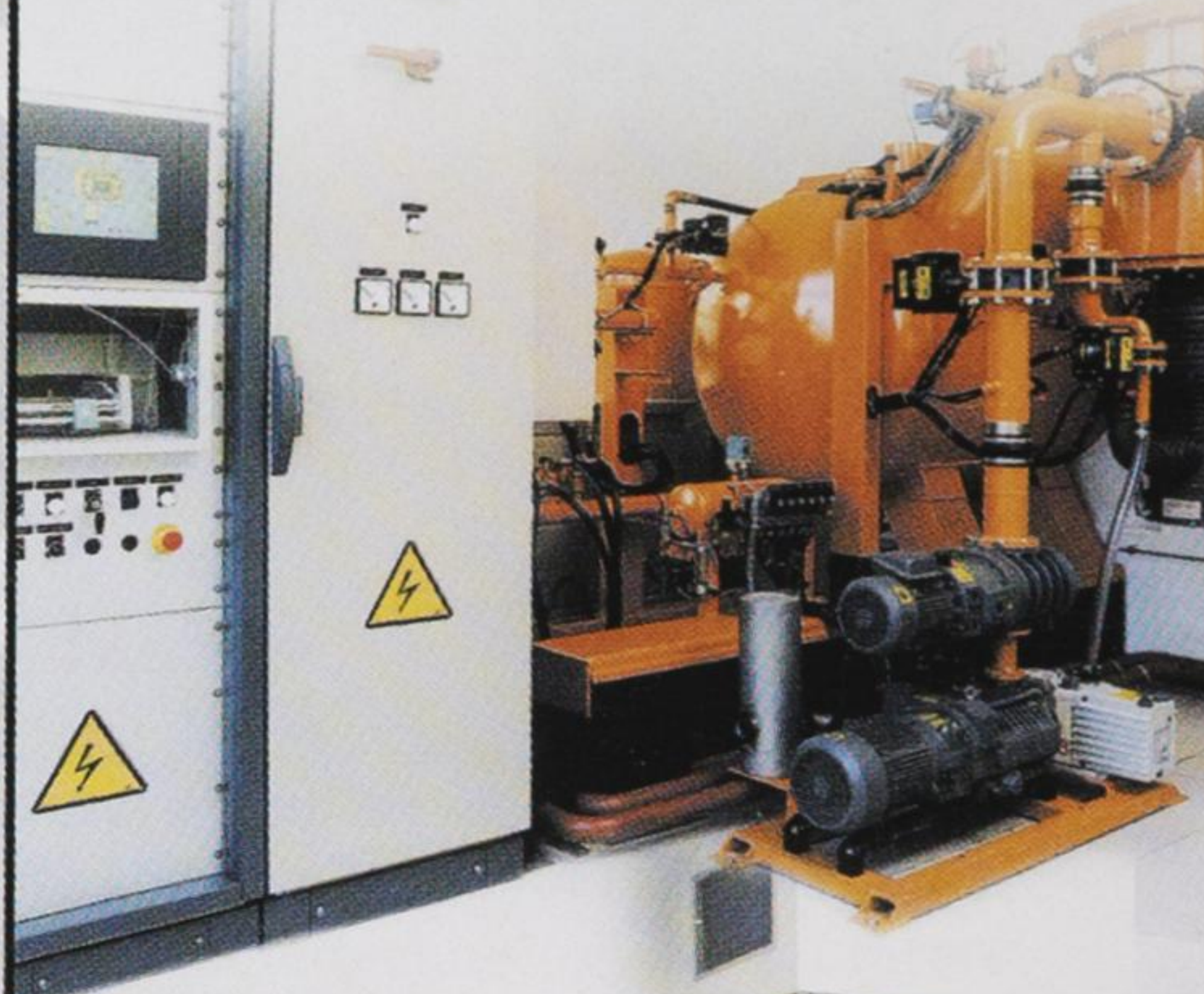
Details of NanoMarkets' report on HB-LEDs can be found at www.nanomarkets.net.

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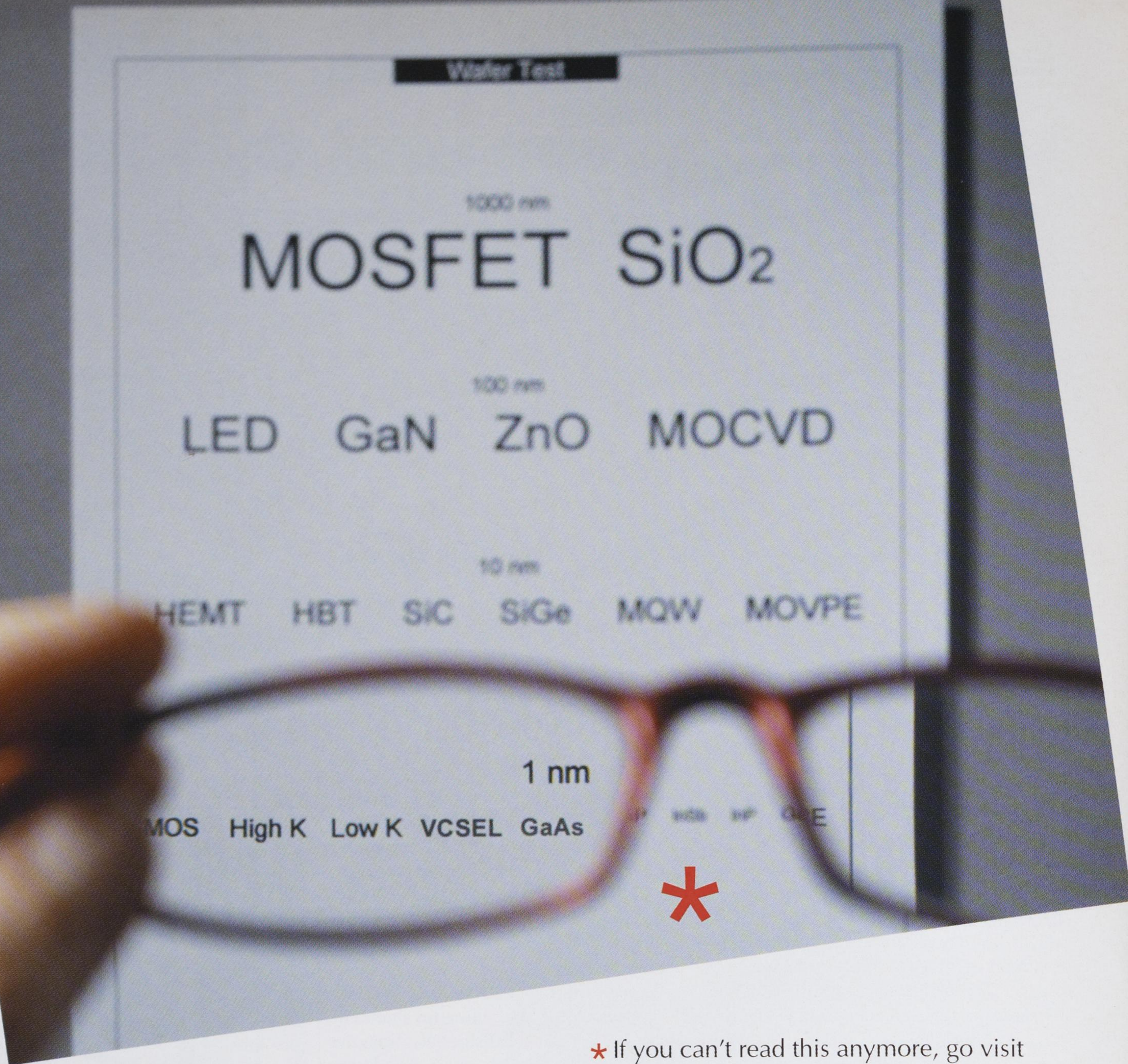


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WiMAX and WiBro emerge as major targets for GaN

New broadband wireless access protocols could provide a market for GaN transistors before any significant activity from the third-generation cellular business appears, writes **Michael Hatcher**.

Like many early-stage technological innovations, wide-bandgap transistors could legitimately be described as a solution in search of a problem. The power output, high-voltage and high-temperature operation of GaN, as well as the robustness and reliability of SiC-based microelectronics, are all very impressive. Such devices have attracted lots of attention and funding for research from the military sector, but genuine commercial applications remain scarce.

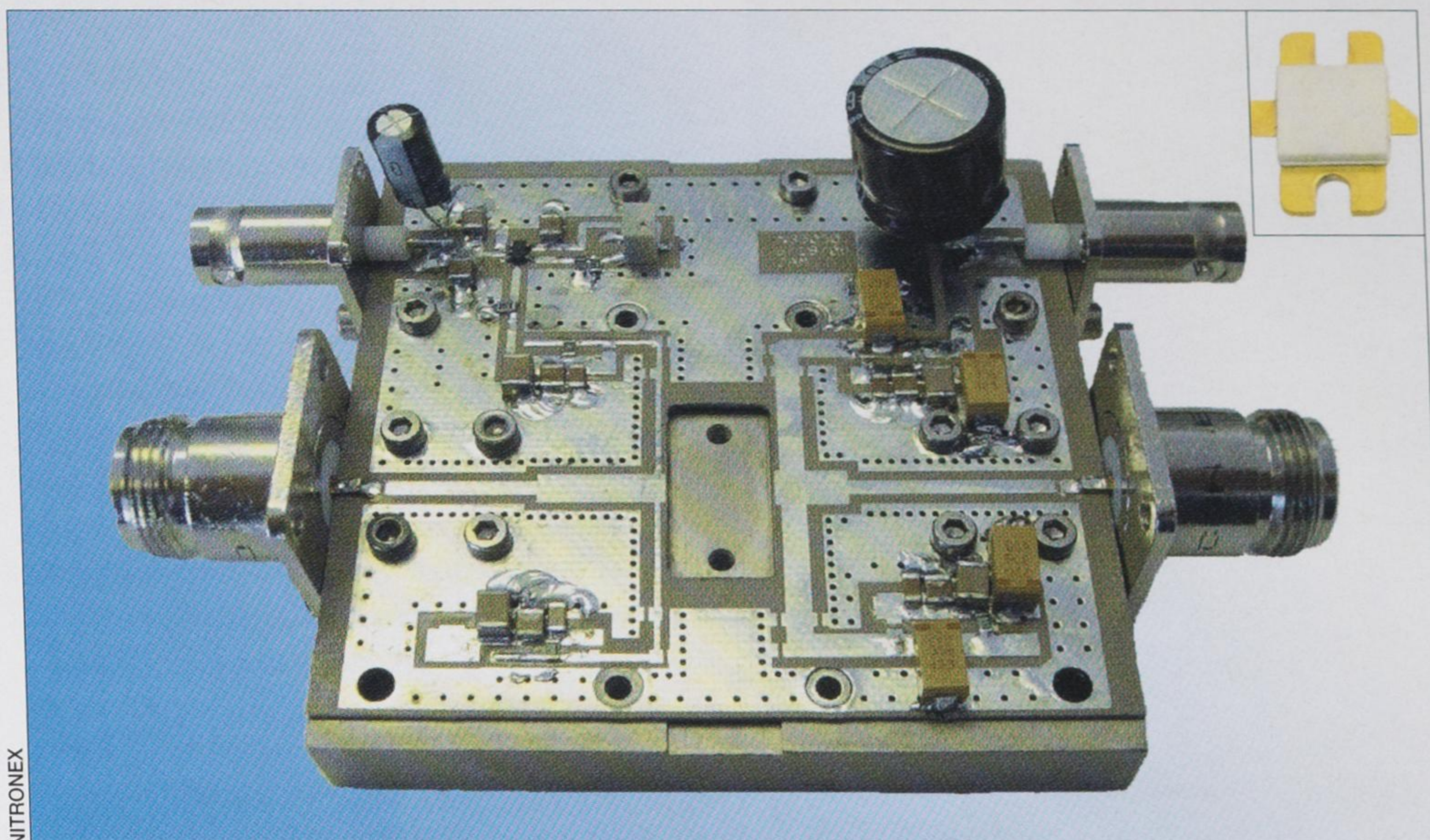
While third-generation cellular was generally regarded as the application that would usher GaN transistors into the mainstream, it now seems more likely that the emerging broadband wireless access protocol WiMAX will provide that opportunity. WiMAX (also known as IEEE standard 802.16e) will have to compete with many other broadband alternatives, but could be the preferred last-mile solution in areas that are underserved by wired broadband or high-speed cellular coverage.

Kevin Linthicum, the chief technology officer (CTO) at GaN transistor manufacturer Nitronex, certainly believes that WiMAX offers a big opportunity. The Raleigh, NC, company – one of the pioneers in GaN microelectronics – has just released its first commercial products for the WiMAX market, having sampled them to customers for the past year.

GaN versus silicon LDMOS

The Nitronex strategy is to target the application areas where silicon LDMOS is weakest. “In chasing LDMOS we’ve given up trying to compete on cost,” Linthicum told delegates at the Key Conference in Palm Springs, CA, in early November. “What we need to do is focus on areas where LDMOS might struggle.”

In practice, this means targeting high-frequency applications. Initially the WiMAX protocol will operate at 2.5–2.7 GHz and 3.4–3.6 GHz, with next-generation systems set to use the 5.725–5.85 GHz band. More specifically, Nitronex is looking to penetrate applications in WiMAX base stations rather



The Korean company RFHIC says that early next year it will start to deploy power amplifier products that feature 50 W GaN-on-silicon transistors developed by Nitronex (inset).

than target customer premise equipment.

Crucially, Nitronex has already snared one customer in the high-technology breeding ground of Korea. In early 2006, RFHIC, a company based in Suwon that sells RF components and modules, is expected to deploy WiMAX products from Nitronex that feature its 50 W GaN-on-silicon transistors.

The power GaN HFET devices measure 1 mm × 6 mm, and the chips feature a gate periphery of 36 mm. The amplifiers produce around 70 W in continuous-wave power at 28 V, with efficiency peaking at around 65%. Nitronex fabricates the devices by MOCVD to deposit a stress-mitigating transition layer between the silicon base and a 0.8 μm semi-insulating GaN buffer (figure 1). Linthicum says that at the moment the full process gives Nitronex a known-good-die yield of approximately 75%, while the company has recently used field-plate technology to increase power and gain characteristics.

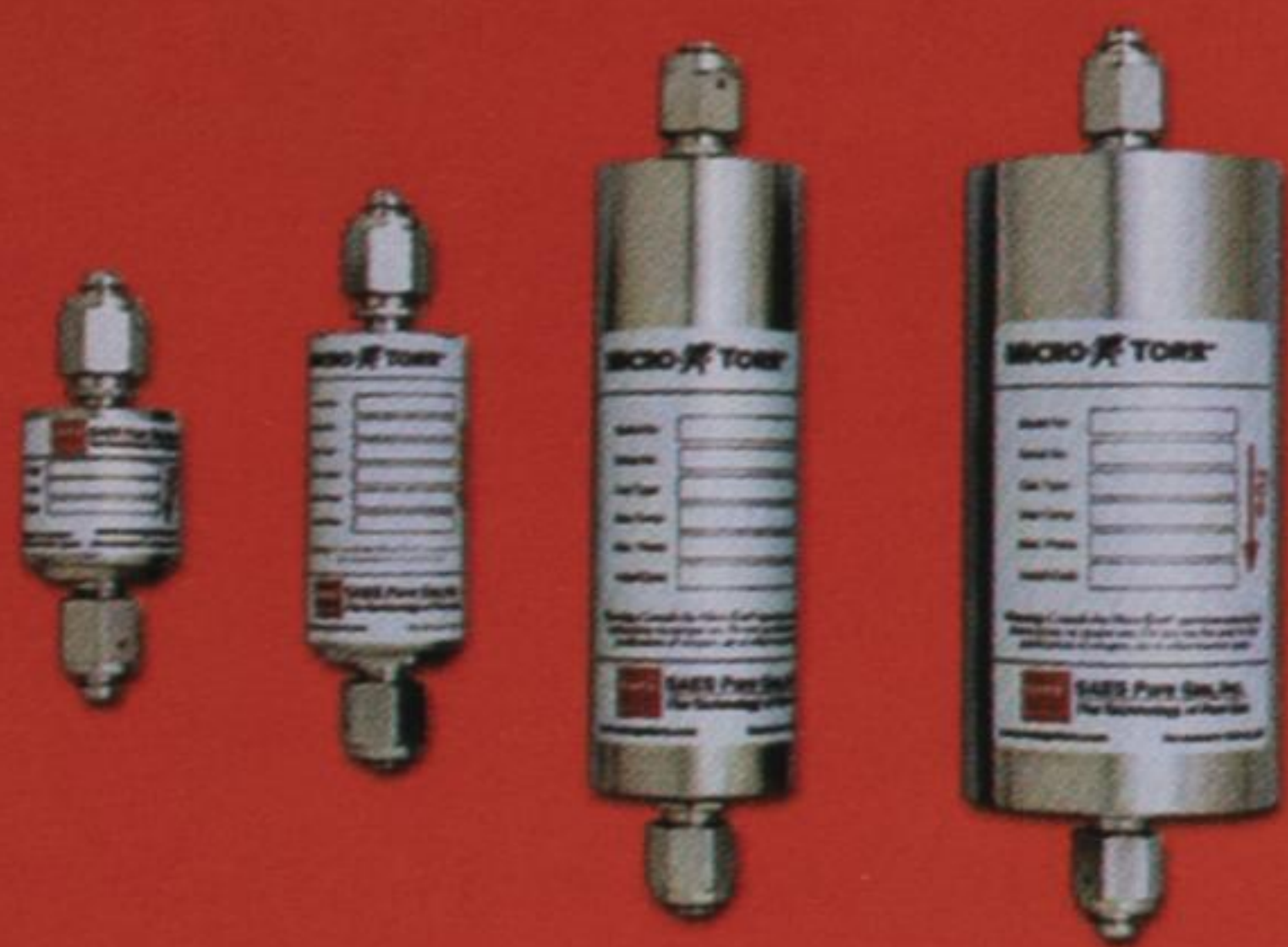
Although Nitronex manufactures its GaN transistors on a silicon base, the substrate

material is not quite the same as the conventional (100) crystal structure used in CMOS and LDMOS processing. Instead, Nitronex uses float-zone silicon with a (111) crystal orientation. The good news for Nitronex is that this is a scalable technology, and a future change to 6-inch-diameter wafers is expected. However, something that will prove more problematic for the company will be finding a toolset supplier that can provide GaN deposition equipment that is compatible with the larger wafers.

This is because LED makers dominate the world of GaN device manufacturing, and in this business much smaller substrates are typical. While pioneers such as Cree have begun the switch to 3 inch production (Cree now makes about 60% of its chips on 3 inch substrates), 2 inch fabrication remains a common choice.

However, switching to 6 inch GaN-on-silicon will not be necessary to serve the requirements of the relatively small WiMAX and W-CDMA base station markets, and more applications will need to be found to justify

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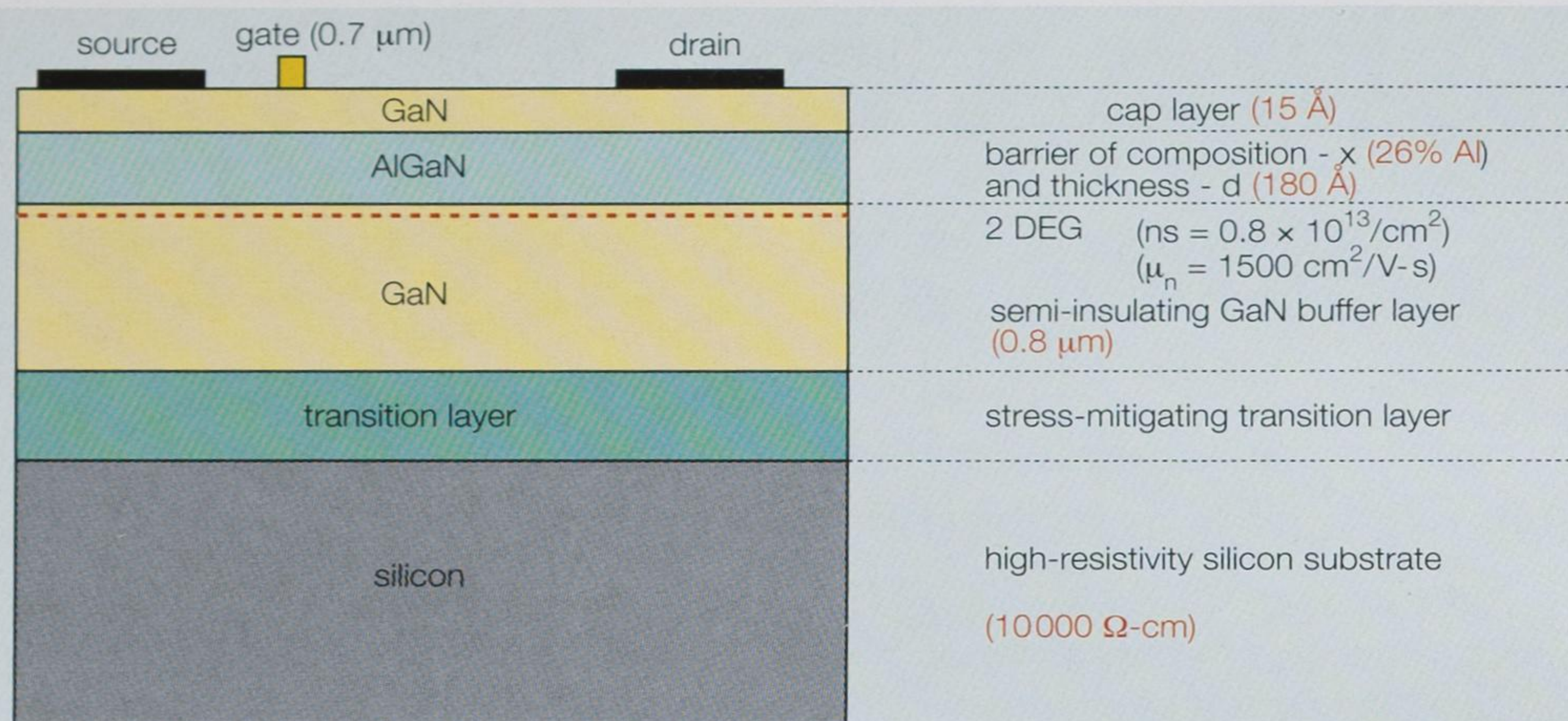


Fig. 1: Nitronex deposits a stress-mitigating transition layer on top of float-zone (111) silicon to fabricate its GaN HFETs. The chips will feature in WiMAX products in Korea in early 2006.

any drive towards greater manufacturing volumes at the larger diameter.

At the moment it appears that the WiMAX drive is being spearheaded in Korea, which has its own particular “flavor” of WiMAX, known as WiBro (short for wireless broadband). The Korean communications company KT Corporation is pioneering the deployment of this standard, which uses the 2.3–2.4 GHz frequency band.

KT joined the board of the WiMAX Forum, a global consortium pushing the technology, in November, and has since launched the first commercial WiBro service in Korea – a demonstration for industry executives and dignitaries at the Asia-Pacific Economic Cooperation’s annual event in Busan, south-east Korea. The WiMAX Forum president, Ron Resnick, said of that development: “KT has launched the world’s first mobile broadband network that is based on the soon-to-be-ratified IEEE 802.16e standard, which is at the core of mobile WiMAX.”

Products based on the WiBro standard are set to feature in the first mobile WiMAX systems, with a release due in late 2006, and Linthicum says that the Korean market is already exerting a considerable demand on Nitronex technology.

“The WiMAX and military markets will be the early adopters of GaN HFET power transistors,” added Linthicum, who expects to see revenue from these sectors within six months. Commercial deployment in W-CDMA base stations will take at least another 6–12 months to bear fruit, with the pace of design-ins determined by the need to introduce new architectures and broader-bandwidth power amplifiers (PAs). “The cellular market is very conservative,” Linthicum said, indicating that the like-

lihood of penetrating this sector with GaN technology may be even further off.

A matter of cost

Cost will be one of the key factors that decides whether or not GaN makes an impact. Direct comparison with silicon LDMOS is difficult to quantify, since the cost of silicon die can be such a fast-moving target. For Linthicum, a more relevant comparison can be made with GaAs: “GaN will need to debut in the range of commercial GaAs PHEMT pricing in order to be adopted in commercial markets,” he told Key Conference delegates.

Of course, Nitronex is not the only company to be targeting WiMAX applications with GaN amplifiers. Eudyna Devices sees WiMAX as a critical market for GaN, and the Japanese company has three product offerings in each of the 2.5–2.7 GHz and 3.4–3.6 GHz bands, ranging from 30 W to 180 W output.

Oki Electric, a second Japanese company with WiMAX in its sights, is taking a similar approach to that of Nitronex. Oki says that the high-performance amplification of its GaN-on-silicon HEMT, which has a 56 GHz cut-off frequency and an $f_{\max}$ of 115 GHz, results from the use of a so-called recessed gate structure (figure 2).

“We can contribute to the acceleration of WiMAX and next-generation wireless communication systems,” said Oki’s CTO, Harushige Sugimoto. “Volume shipments of such products are planned to start from 2007.”

While Oki and Nitronex are taking the silicon route to cutting transistor cost, Eudyna has chosen a more radical approach to making GaN devices more competitive. It plans to slash costs by using n-type SiC substrates designed for optoelectronic applications

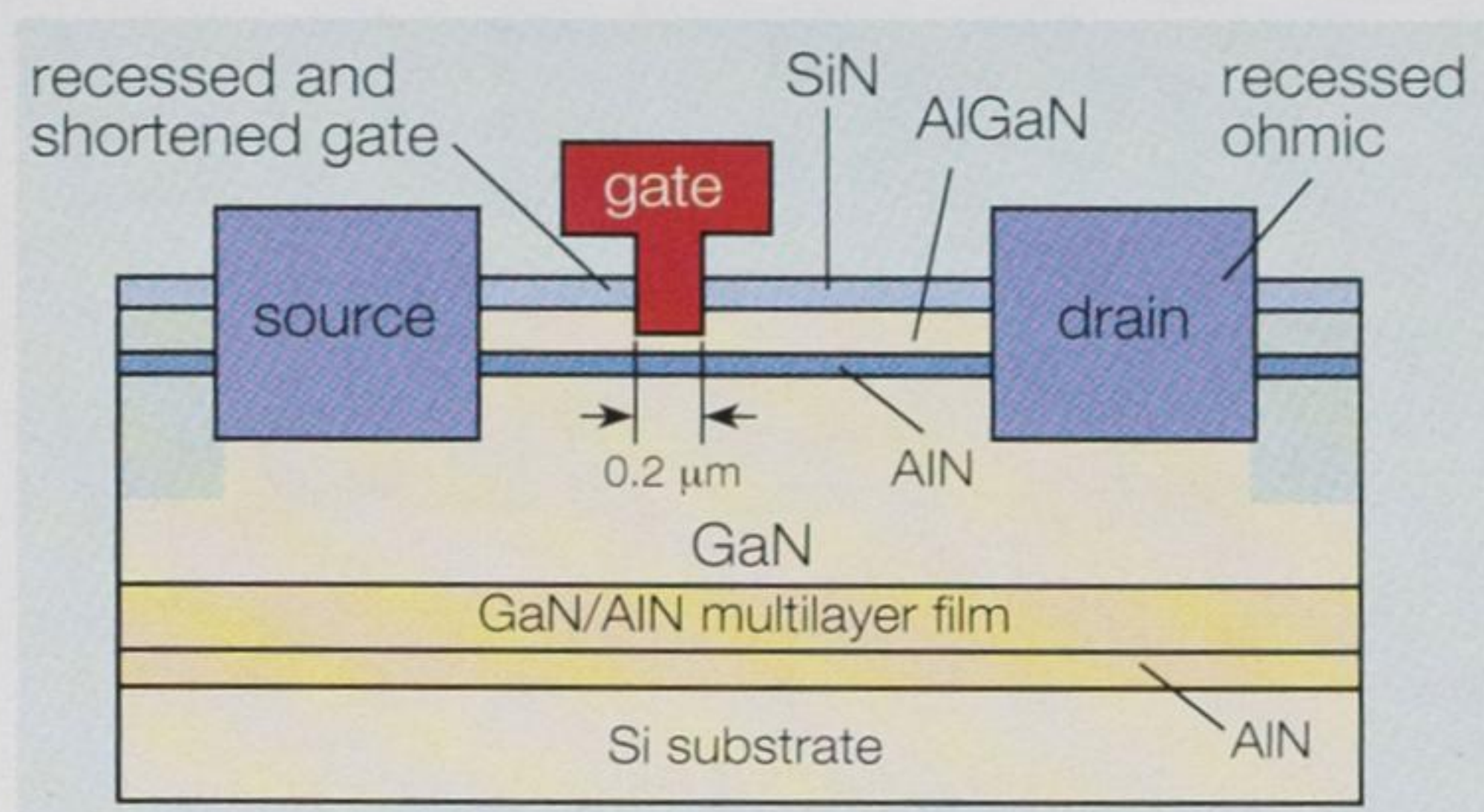


Fig. 2: Oki Electric attributes the good performance characteristics of its GaN-on-silicon HEMTs to the use of a recessed gate structure, which is said to reduce both parasitic resistance and leakage current.

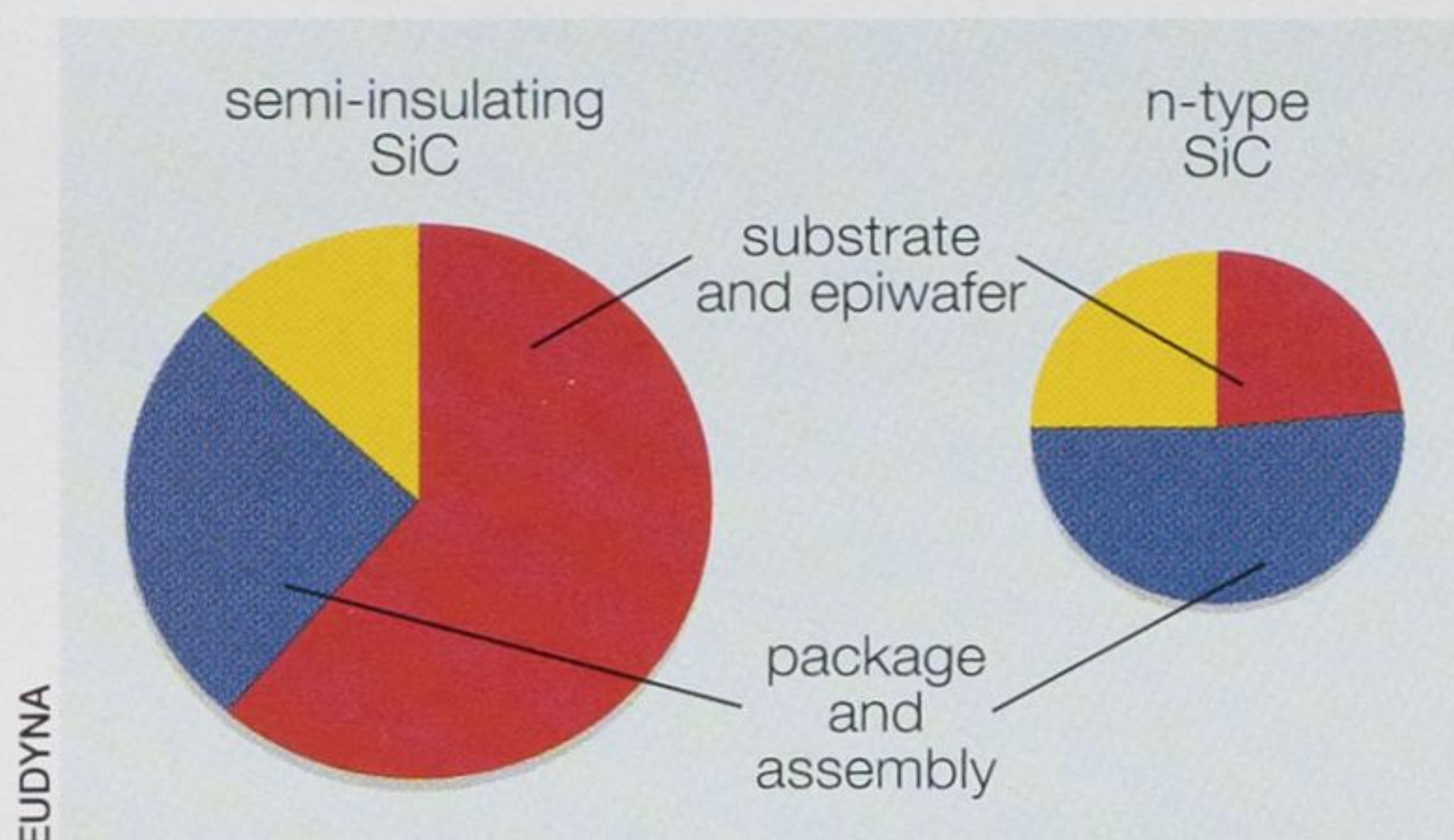


Fig. 3: According to Eudyna Devices, the best way to cut the cost of GaN transistors is to fabricate them using n-type SiC substrates. Eudyna's Yasunori Tateno says that this approach will reduce the overall cost of the device by as much as two-thirds compared with conventional semi-insulating SiC substrates.

instead of the conventional, and much more expensive, semi-insulating SiC material.

LED manufacturers grow GaN on top of n-type SiC, and by using an AlN layer grown by hydride vapor phase epitaxy before MOCVD of the active GaN layers, Eudyna believes it has solved the twin problems of parasitic capacitance and dielectric loss that are met with the unconventional approach.

Eudyna's Yasunori Tateno expects that the cost of devices can be drastically cut using this method (figure 3). "From a cost reduction point of view, we must use n-type SiC substrates," he told Key Conference delegates. Tateno added that Eudyna was planning to release devices manufactured on n-type SiC by the end of 2006. Initial results have been impressive, with amplifiers showing an output power of 101 W and a gain of 15.5 dB; but whether Eudyna's customers will be happy to rely on the use of such unconventional materials remains to be seen.

Tateno was keen to emphasize the high efficiency of GaN HEMTs for W-CDMA cellular applications, saying that if all 100,000 base

stations in Japan had their (relatively) inefficient silicon LDMOS devices replaced with GaN-based PAs, the savings could be huge – both in terms of dollars and the environment.

"If total base station efficiency was improved from 15% to 25%, electricity consumption would be reduced by 400 million kW hours, equivalent to 600 million kg of CO₂," claimed Tateno. Such a wide-scale deployment is far from a realistic scenario, partly because the key figure of merit is not only the efficiency of the PA chips, but the efficiency of the entire system that is based around it.

Efficiency boost

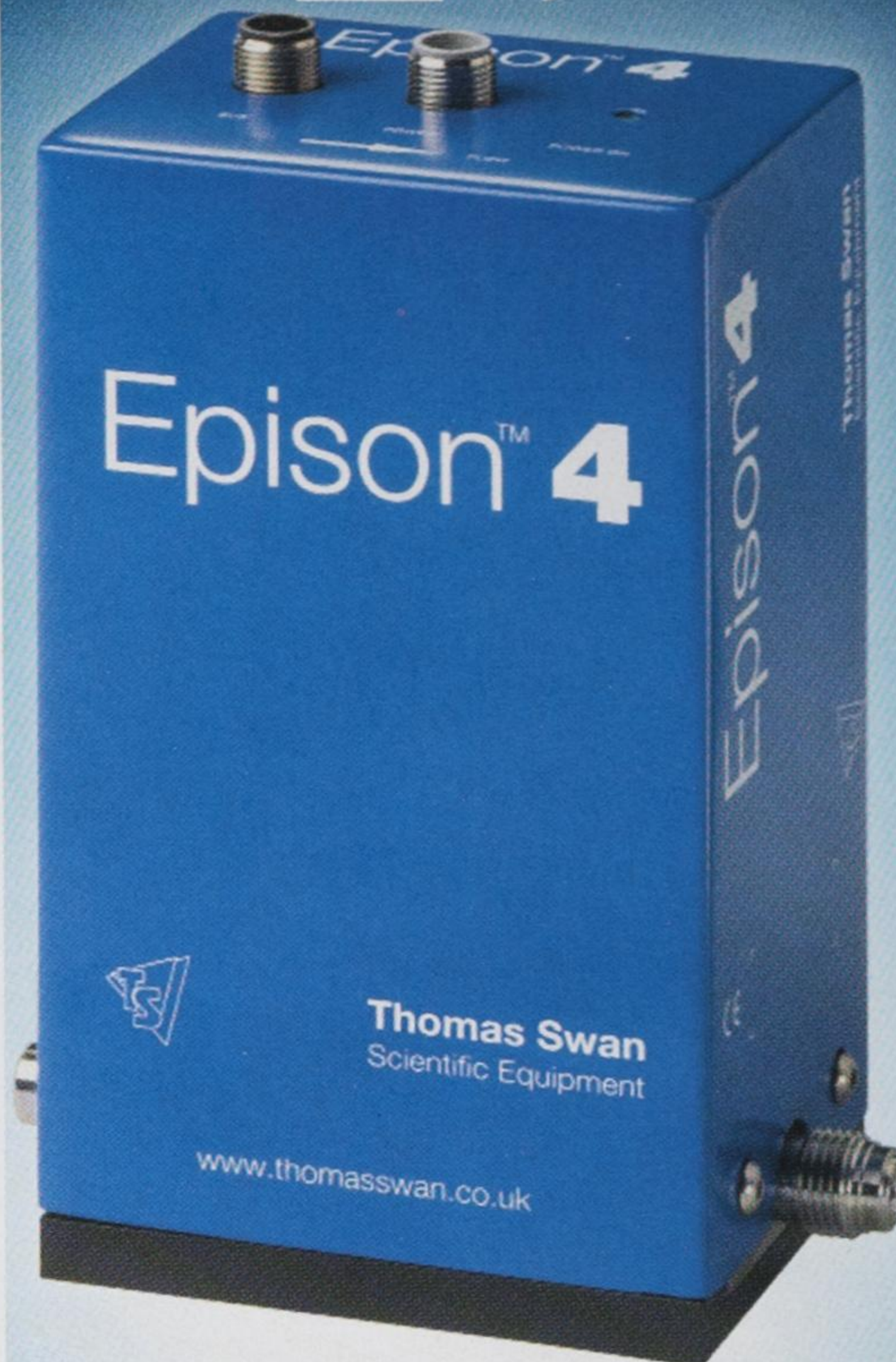
At the Compound Semiconductor IC Symposium, which was co-located with the Key Conference, an improvement in GaN-based PA efficiency proved to be one of the most popular talks of the week. Nitronex and researchers from the University of California San Diego (UCSD), collaborating with Qualcomm and Nokia, described a W-CDMA base station amplifier with overall power-added efficiency of 50%, which is thought to be the highest figure yet reported. "Measurement of the high-voltage envelope amplifier used in this work shows efficiency of 77% under W-CDMA signals," claimed the team. It concluded that combining GaN HFETs with advanced amplifier architectures would lead to "dramatic improvements" in base station PAs.

The key to the development is not just the use of a GaN transistor from Nitronex, but also the advanced amplifier architecture that it enables. In the UCSD set-up, an envelope-tracking bias system improves both linearity and efficiency. The design means that the amplifier operates closer to saturation, with the transistor maintained at a lower temperature. The dynamic peak voltage also reaches higher values than can be used in a constant drain bias voltage configuration.

According to Linthicum, envelope tracking is just one of several advanced designs that GaN transistors can enable. Others include Doherty configuration Class F amplifiers, as well as digital predistortion amplifiers.

While the combination of these novel architectures and the material properties of GaN may never quite knock LDMOS off of its pedestal in cellular applications, it appears that WiMAX is now the key application sector for wide-bandgap RF microelectronics, and the one where its commercial viability will first be proved. If WiMAX takes off, it could be just the problem that GaN has been looking for.

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Efficiency gains boost high-power LED performance

Designers are exploiting increasingly sophisticated strategies, such as surface roughening and incorporating photonic crystals, to boost efficiency and enhance light output. **Susan Curtis** reports.

Until recently, market penetration of high-power LEDs – defined as devices operating at 1 W or more – has been limited by performance and reliability concerns, as well as high deployment costs. But continuing improvements in light output and the efficiency of light emission are now yielding power LEDs that are starting to challenge other lighting solutions in a range of applications.

Today's power LEDs deliver 50–60 lm, enabling just 50 LEDs to produce the same light output as a 3000 lm fluorescent tube. At the same time, luminous efficacy has risen to around 60 lm/W, which far surpasses the performance of incandescent bulbs and is fast approaching the energy efficiency of fluorescent lighting.

As a result, high-power LED manufacturers are now working to develop products addressing the general illumination market, which is currently valued at around \$12 bn. However, real success in the mainstream lighting market will require manufacturers to reduce the price of LEDs, while continuing to deliver steady improvements in the device's luminous efficacy and total lumen output.

Increasing light output

In theory, it should be possible to produce more light by simply driving bigger chips, typically 1 × 1 mm, with higher currents. The Luxeon III, for example, delivers up to 190 lm at red–orange wavelengths by drawing 1.4 A, compared with a flux of about 25 lm for typical devices running at 350 mA.

However, most high-power LEDs convert only about 15% of the input power into light, with the rest being lost as heat. And yet LEDs must be protected from overheating, as sustained operation at high junction temperatures reduces the device's lumen output and shifts its emission wavelength. Improving luminous efficacy is therefore essential for producing more light from the same input power.

Continual advances in materials, fabrica-

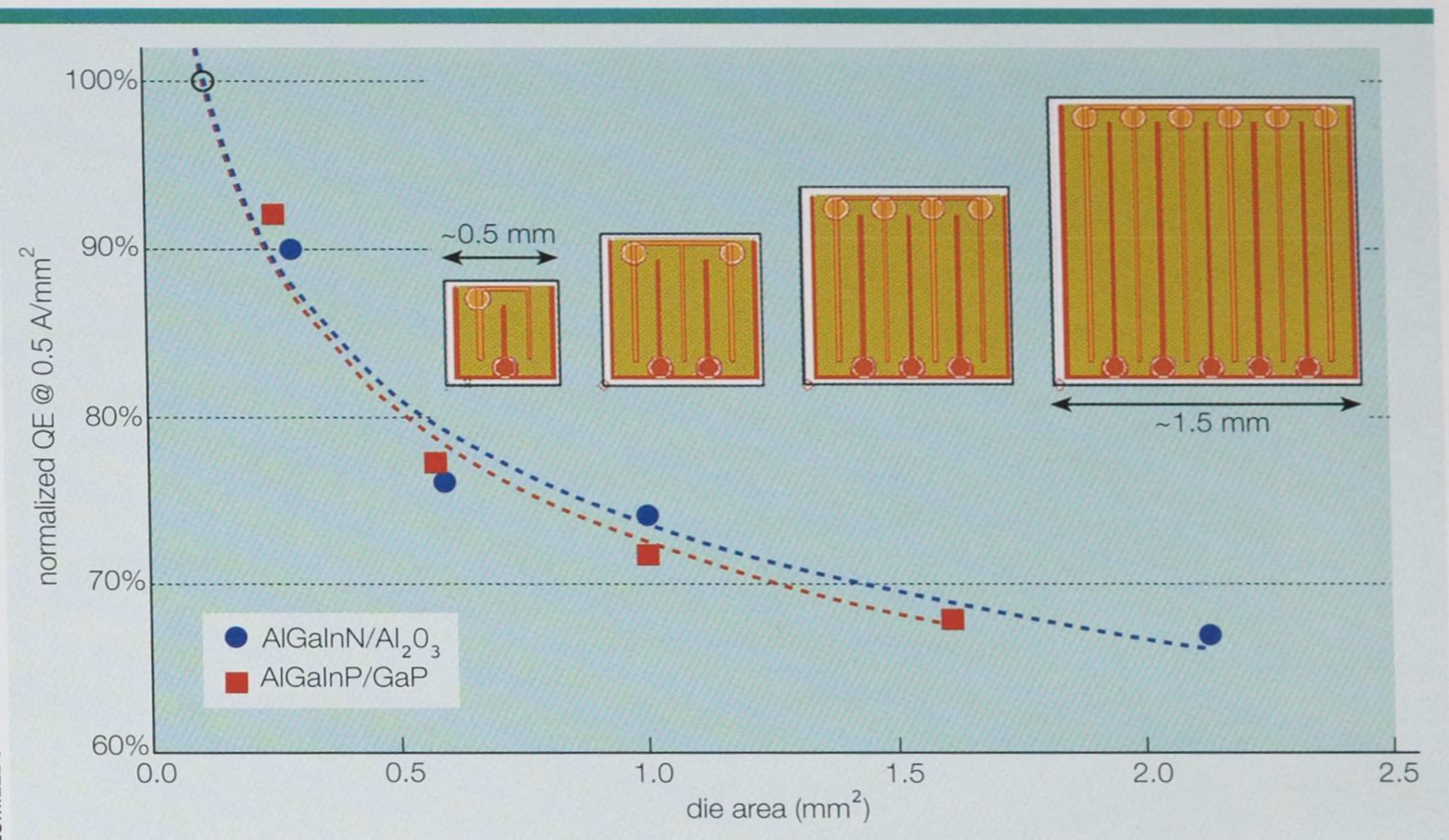


Fig. 1. The quantum efficiencies of AlInGaN and AlGaInP chips fall significantly as the die area is increased, mainly because less light is emitted from the sidewalls of the chip.

tion techniques and device structures have already produced LEDs with high internal efficiencies. The best red-emitting devices based on AlGaInP deliver internal quantum efficiencies (IQEs) approaching 100%, while GaN-based green and blue light emitters deliver IQEs of 50%, despite the large numbers of dislocations formed during epitaxial growth on a foreign substrate.

Although efforts are continuing to improve the IQE of GaN devices, larger gains in luminous efficacy are expected to come from increasing the device's extraction efficiency. In traditional LED chips, only a small proportion of the photons generated at the p–n junction leave the device. Since the semiconducting materials used to produce LEDs have a large refractive index, only those photons emitted within typically 17° of the normal direction can exit the chip's front surface. The rest are trapped by total internal reflection and eventually absorbed by the material, leading to heat generation rather than light extraction.

One particular problem for high-power

LEDs is that as the die area is increased, light extraction efficiency falls. Data from Lumileds show that the external quantum efficiency (EQE) of both AlGaInP and AlInGaN chips falls by about 20% as the die area is increased from 0.3 to 1.5 mm² (figure 1). This is partly because light emission from the chip's sidewalls is less effective for large-area die, as photons have to travel much further before reaching a surface, which increases internal absorption. This means that it is essential to improve the light emission efficiency from the chip's top surface.

Established techniques to increase the extraction efficiency include the use of a current-spreading layer, also known as a window layer, which ensures that light emission occurs over the full area of the p–n junction. Many leading GaN-based LED manufacturers also exploit a flip-chip geometry, with the device mounted face-down, which allows light to be extracted through the substrate rather than from the device's top surface. As well as offering higher extraction efficiencies, flip-chip

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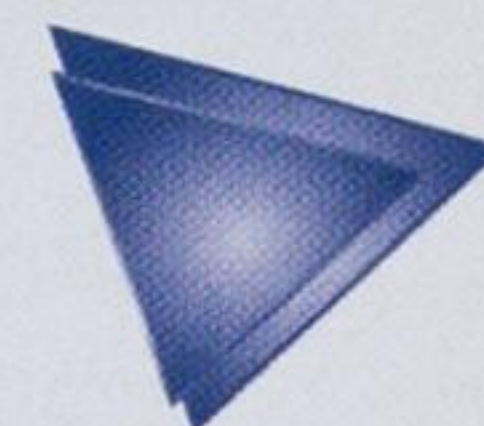
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For AlGaInP chips, the GaAs substrate absorbs all visible light, so either a reflecting structure has to be inserted between the active region and the substrate, or, better still, the GaAs substrate has to be replaced with a transparent GaP carrier. The use of transparent substrates, first pioneered by Hewlett-Packard (later Agilent) and now adopted by Lumileds, can deliver at least twice the luminous flux of equivalent devices grown on absorbing substrates, but requires complex and expensive processing technology to achieve wafer bonding with precise crystallographic alignment.

Texture and shape

Some chip manufacturers, notably Cree and Lumileds, also enhance their LEDs' external efficiency by shaping the die to reduce reflections and increase light extraction. Lumileds' truncated-inverted-pyramid (TIP) geometry can yield extraction efficiencies approaching 60% for AlGaInP chips, and R&D at the company indicates that TIP-LED chips measuring 1×1 mm can offer efficacies of 100 lm/W at 605 nm. However, TIP-LED structures are not suited to high-volume manufacturing, and although some of the light is extracted from the sidewalls, this emission is less effective for larger chip areas.

Several other approaches have been developed to combine high extraction efficiencies with more scalable processing technologies. One of the most successful is the use of surface roughening, which reduces internal reflections and scatters the light outwards. Shuji Nakamura and colleagues at the University of California, Santa Barbara, have combined laser lift-off with photoelectrochemical etching to produce regular cone-like features on the surface of a flip-chip GaN-based LED (figure 2). The power output from these LEDs increases by a factor of 1.9 after a 2 min etch, and 2.3 after a 10 min etch, compared with flat-surface devices.

Osram Opto Semiconductors has incorporated this concept into its latest generation of thin-film LED chips. Thin-film technology, which involves bonding the LED to a metalized carrier substrate before the original substrate is removed, offers a simpler, lower-cost alternative to transparent substrates, but on its own it does not deliver a high EQE. In the Osram approach, inclined microreflectors are formed in the top part of the epitaxial layer, before the structured surface is covered with

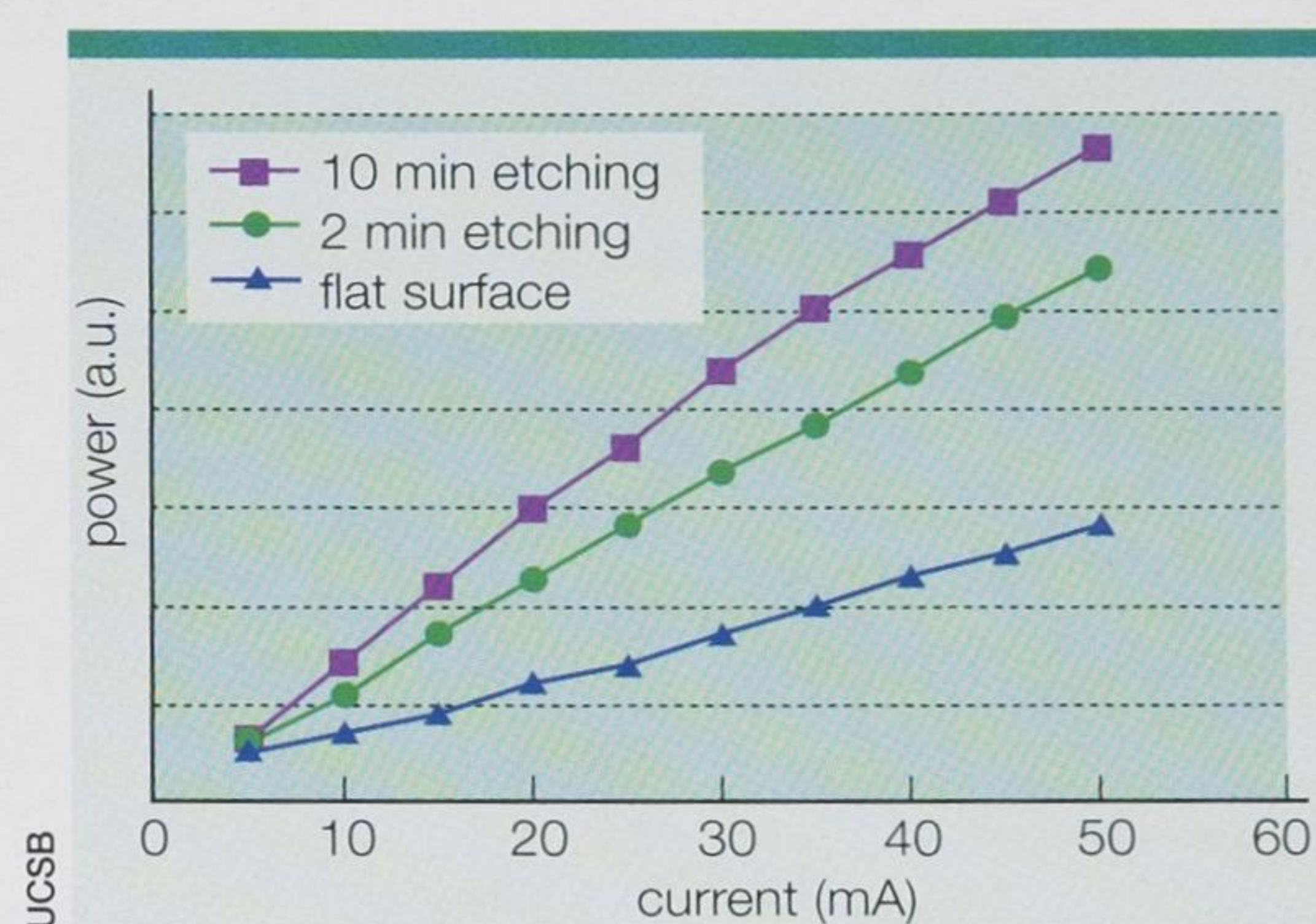
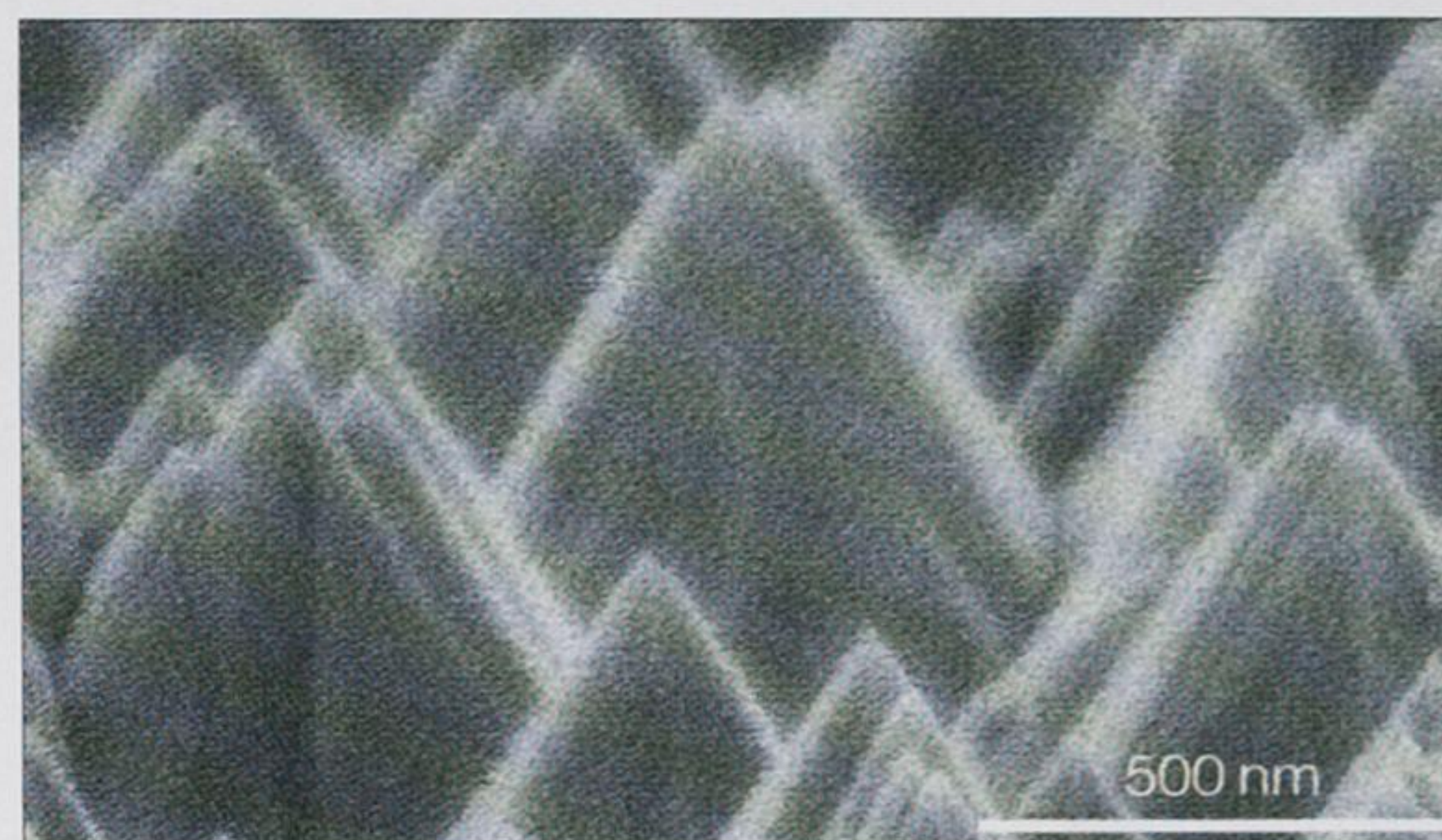
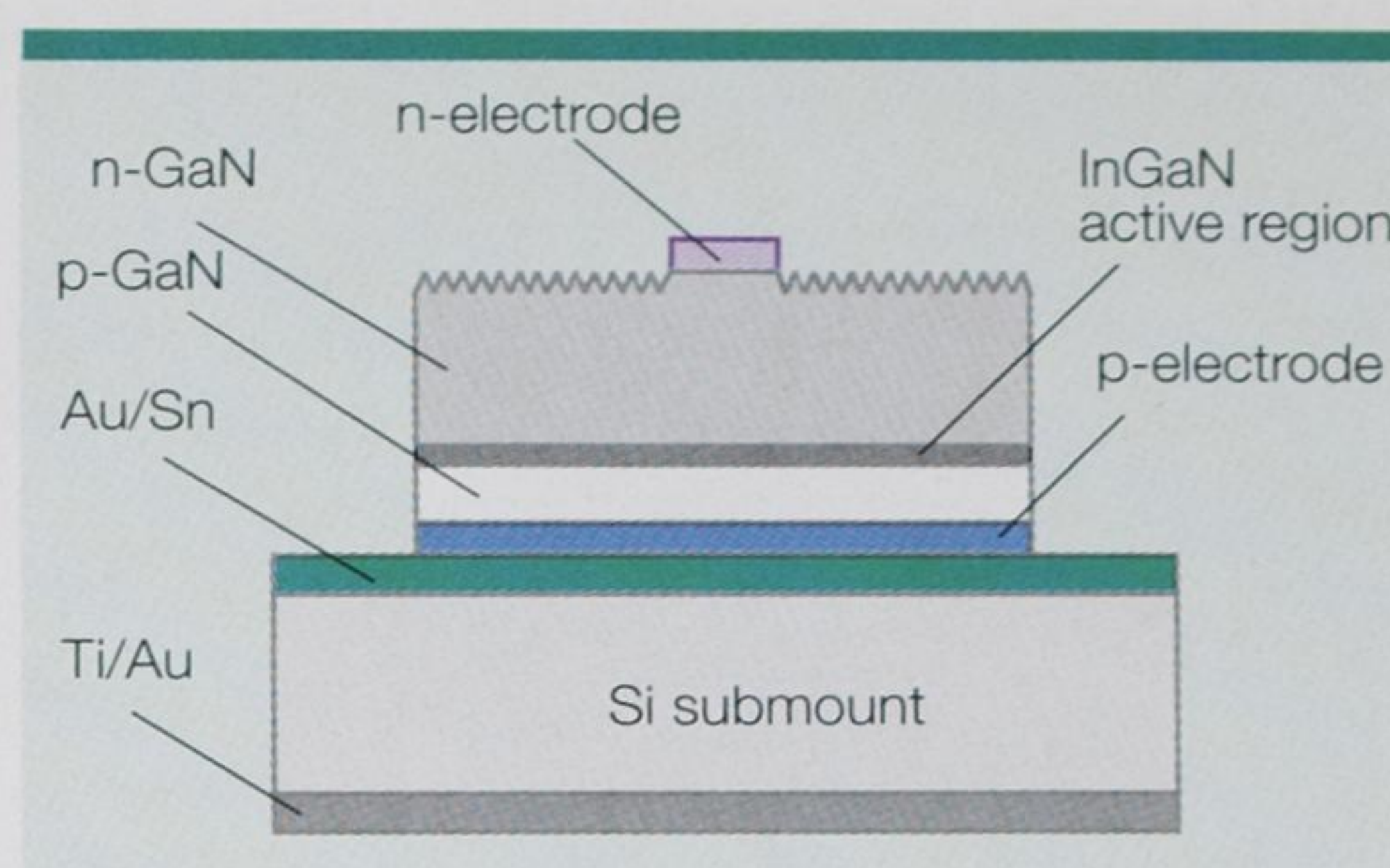


Fig. 2. A flip-chip GaN structure can be treated with laser lift-off and wet etching (top) to produce cone-like features on the surface (centre). Such devices deliver at least a two-fold increase in relative power compared with flat surface LEDs (bottom).

mirror layers and bonded to the carrier. The bonding interface need not be optically transparent, which allows the use of metal-to-metal bonding.

Tests indicate that the luminous flux from Osram's buried-microreflector LEDs is up to 70% higher than that from thin-film LEDs produced without microreflectors. The company's thin-film technology is already being exploited in its latest product release, the high-power Ostar LED. This 5 W device incorporates four thin-film chips measuring 1×1 mm², and the RGB version emits more than 120 lm from a package measuring 3×1 cm², with the light source consisting of one red, one blue and two green thin-film chips.

More sophisticated approaches to improving LED extraction efficiency include the use of a 2D photonic crystal, a regular array of

100–250 nm diameter holes formed in the current-spreading layer to guide light to the device's surface. This approach has been investigated by Sandia National Laboratories researchers in collaboration with Lumileds to improve the efficiency of blue GaN-based LEDs – in small-area LEDs (~ 0.036 mm²) they have reported a two-fold increase in brightness.

However, these small devices suffer from edge effects that limit the improvements that are theoretically possible with photonic crystals, while fabricating large-scale photonic structures remains a challenge. Current devices rely on electron-beam lithography, while research is continuing on new processing techniques that will enable the rapid patterning of large areas.

For example, Steven Brueck at the University of New Mexico has been developing a lithography technique that exploits interference between coherent optical beams to create a periodic pattern in a single large-area exposure that takes just a few seconds. A 1 mm² GaN-based LED produced by this method has been shown to deliver uniform light emission, but efforts are still underway to evaluate the effect of the photonic structure on the quantum efficiency of the device. Work is also continuing to produce a better engineered, full-wafer patterning tool.

Microcavity LEDs

Increases in light output can also be produced with microcavity LEDs, which are expected to yield high extraction efficiencies from planar, rather than shaped, LED devices. Planar devices are particularly important for telecommunications applications, in which the light emitted from the LED must be coupled into an optical fiber with a typical core diameter of 100 μ m. However, the EQE of standard planar LEDs that do not contain a microcavity is typically limited to a few percent, even when encapsulated in an epoxy dome.

Microcavity LEDs exploit optical confinement between two mirrors to modify the angular pattern of light emission, causing a large fraction of the light to be emitted into a resonant mode almost entirely contained in the extraction cone (figure 3). For example, researchers at Infineon Technologies in Germany and the Ecole Polytechnique Fédérale de Lausanne in Switzerland have fabricated a microcavity LED in a GaAs/AlGaAs device by forming distributed Bragg reflectors (DBRs) either side of the active region. This device's EQE was 14% into air and 20.6% with encapsulation into a

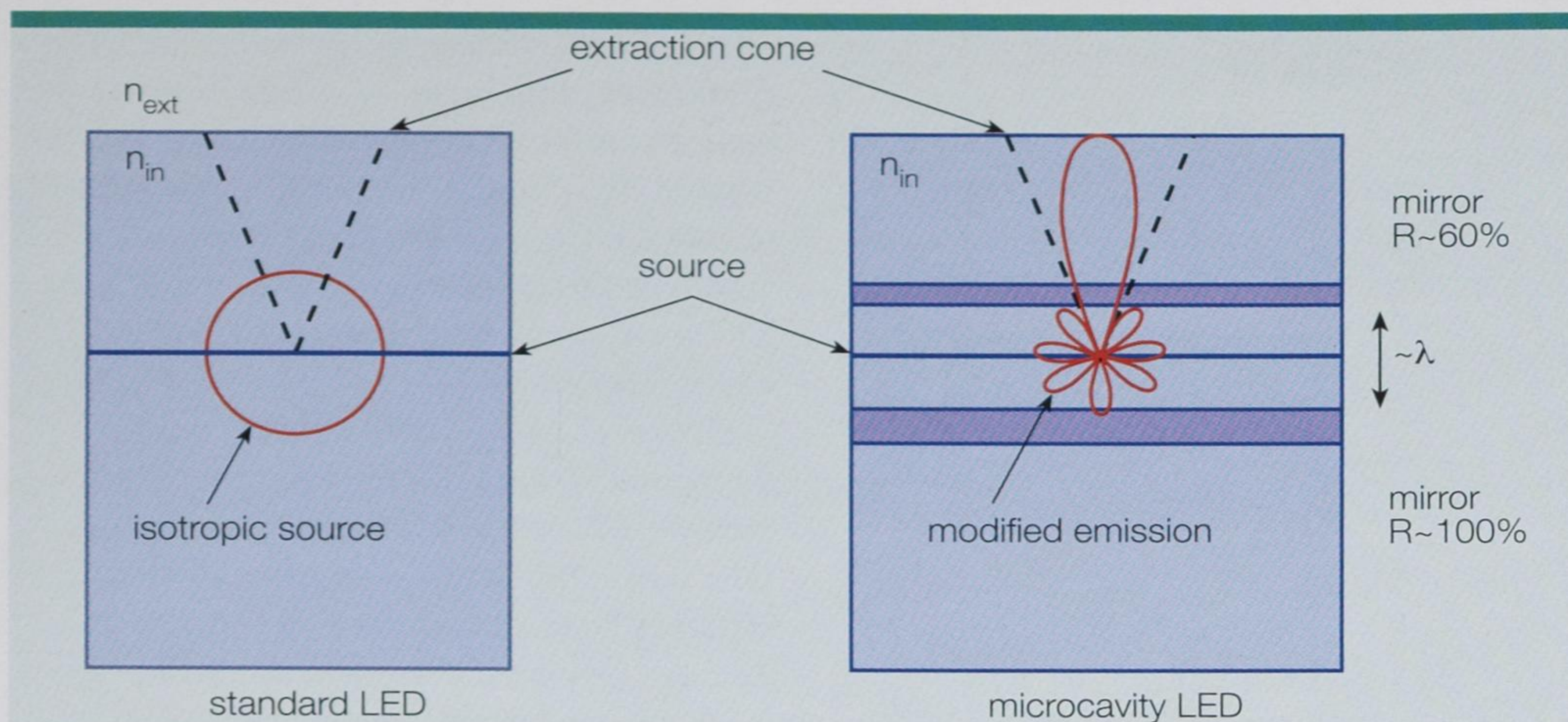


Fig. 3. In a standard LED (left) light is emitted isotropically from the source, but in a microcavity LED (right) the two closely-spaced mirrors that confine the light funnel a large proportion of the emission into an extraction cone.

lens-shaped epoxy dome.

Scientists at University of California, Santa Barbara, and the Ecole Polytechnique in Palaiseau, France, have calculated that the extraction efficiency from planar microcavity LEDs could reach 40%, provided that the structure's thickness and composition is controlled

with the required precision. Since most of the non-extracted light is trapped in lateral guided modes, the researchers believe that incorporating photonic-crystal structures into microcavity LEDs could further improve the EQE by scattering light towards the device's surface.

A group at Sandia National Laboratories are

LED Quarterly Insights

This article is based on the findings of *LED Quarterly Insights*, a subscription service from the publishers of *Compound Semiconductor* that provides regular analysis of the critical technology innovations and commercial opportunities in the highly dynamic LED industry. Over the year, the service will produce four reports that provide detailed commentary on high-power LEDs; performance and standards; white LEDs; and packaging and optics. *LED Quarterly Insights* is part of the Technology Tracking programme. For more information see www.technology-tracking.com.

also investigating this type of device in a two-year project that began at the end of 2004. The researchers plan to fabricate and test InGaN LEDs that combine a 400–460 nm photonic structure with a planar microcavity formed by conductive GaN/InGaN DBRs with the ultimate aim of doubling the device's EQE. ●

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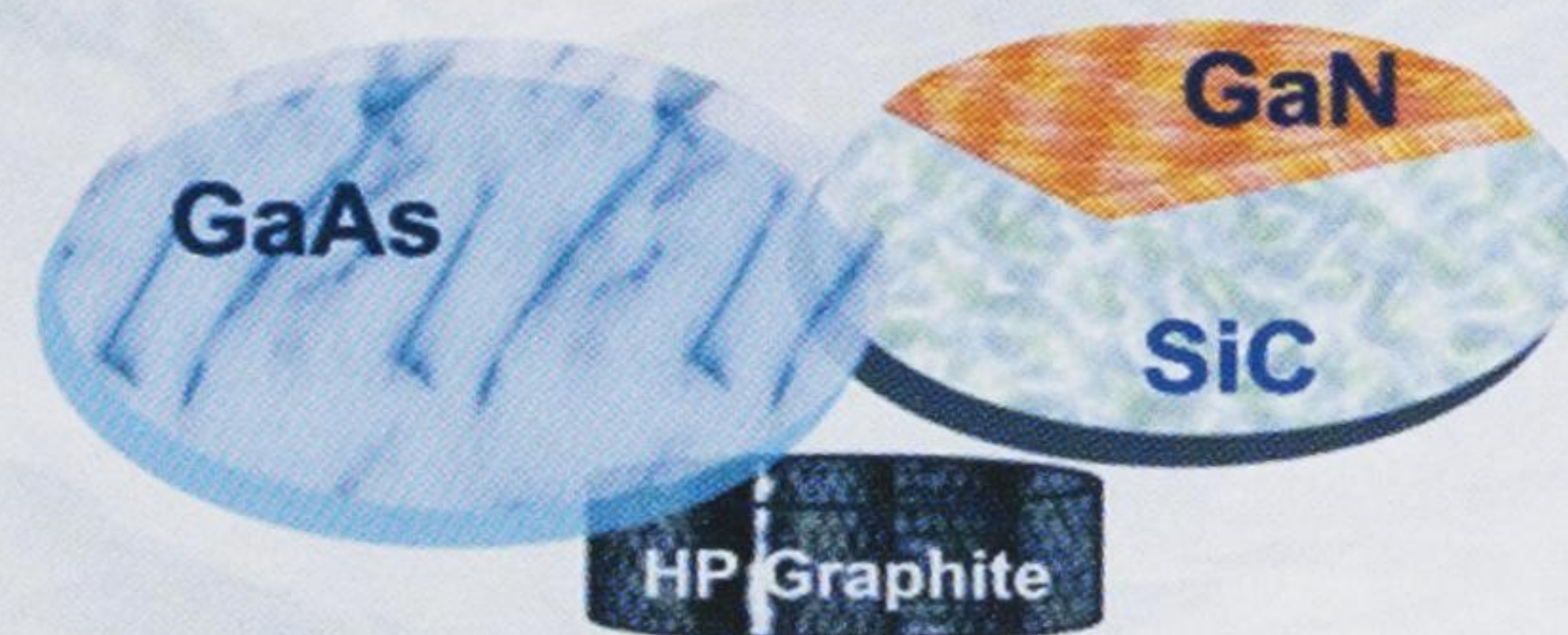
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Oxford has access to atomic layer patents

ASM International has granted a license that gives UK-based equipment manufacturer Oxford Instruments Plasma Technology (OIPT) access to its atomic layer deposition (ALD) technology.

The agreement covers more than 280 issued and published patents, and will enable OIPT to develop new products and processes.

ALD can be used to deposit extremely thin films, to make micromechanical devices, and has applications in semiconductor processing.

Matheson reshuffles

Specialty gas and gas-handling equipment supplier Matheson Tri-Gas has reorganized into four separate business units.

These are: industrial gases; electronic gases; specialty gas and equipment; and the Asian business organization.

Trikon seals merger

Trikon shareholders have approved the UK plasma etch and deposition equipment supplier's merger with Aviza Technology. The company will operate under the Aviza name.

Equipment sales

- Taiwan-based Huga Optotech has installed a **Thomas Swan** MOCVD reactor to make blue and green GaN-based LEDs.
- **Azzurro Semiconductors**, a Germany-based maker of 6 inch GaN-on-silicon wafers, has ordered a Thomas Swan reactor that features an EpiCurve wafer curvature sensor from **LayTec**.
- France-based MBE equipment supplier **Riber** has installed a research machine at Korea's biggest laboratory, the Electronics and Communications Research Institute.

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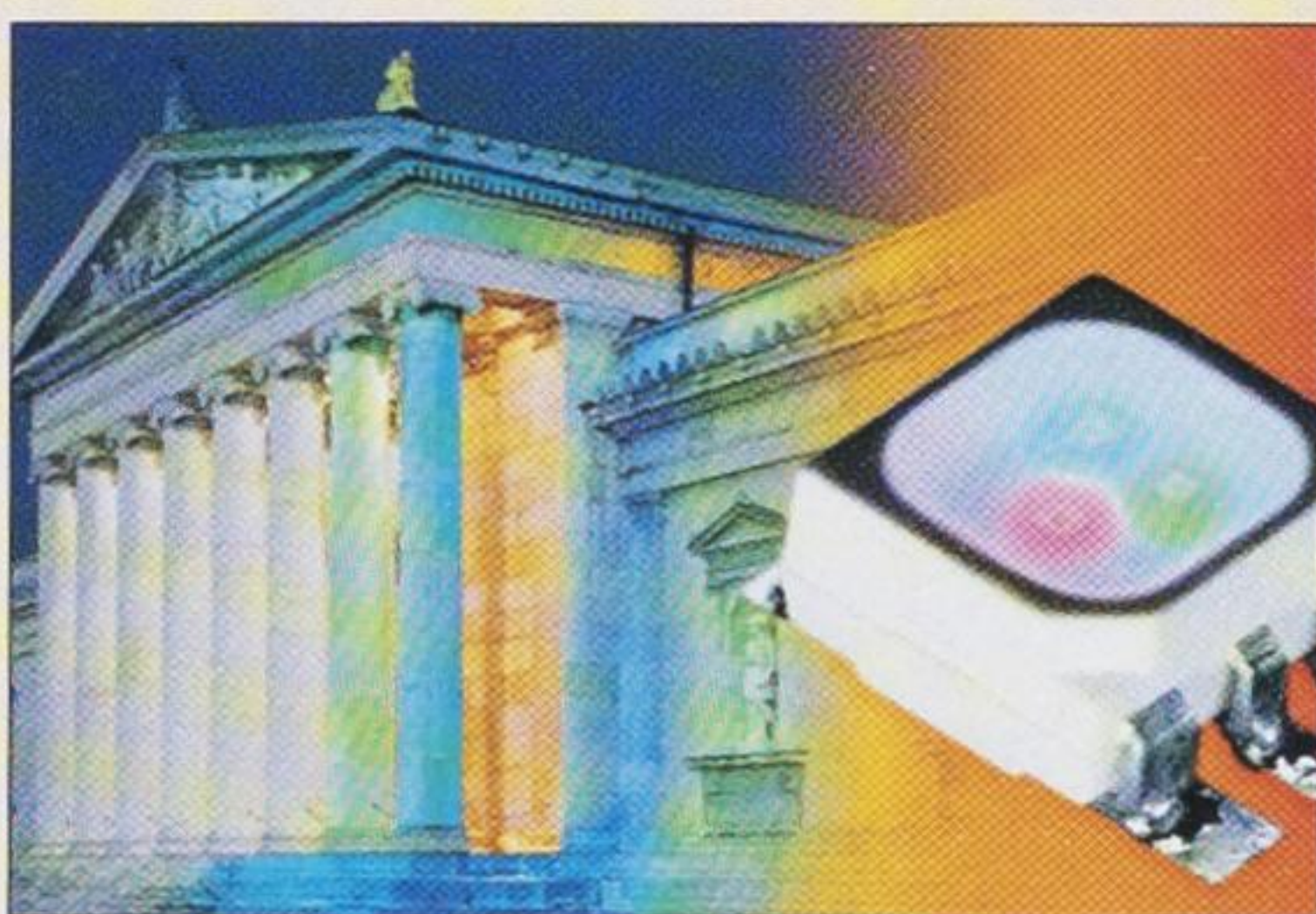


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Osram Opto Semiconductors

Promotion to power

With two to three times the output and five times the life span, the new 6-lead MultiLEDs from Osram Opto Semiconductors leave their predecessors firmly in the shade. All three chips (red, green and blue) are fabricated using thin-film technology and allow almost all the light to be emitted at the surface. This results in high optical efficiency and new applications, such as advertising and effect lighting. The optical efficiency of the brightest generation of chips of this size is 43 lm/W for red, 36 lm/W for green and 11 lm/W for blue.



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001 silicon improves GaN integration

Researcher Sylvain Joblot from STMicroelectronics and co-workers at France's CNRS research lab have grown GaN HEMTs on silicon (001) substrates, which they claim are better suited to the mainstream silicon industry than the silicon (111) substrates used by GaN-on-silicon HEMT manufacturers Picogiga and Nitronex (*Appl. Phys. Lett.* **87** 133505).

Silicon (001) substrates offer the same advantages for GaN HEMT manufacture, in terms of the combination of low cost and high thermal conductivity, as silicon (111) substrates that have already been used to produce transistors. However, because silicon (001) substrates are widely used by the silicon industry, transistors fabricated on the material are more suitable for integration with mainstream microelectronics.

However, several difficulties are associated with the growth of GaN layers on silicon (001) substrates. A large lattice mismatch (−16.2%) and a 113% difference in thermal expansion between silicon and GaN can lead to cracking of the epitaxial layers, a high density of dislocations, and the growth of undesirable domains of cubic GaN alongside the wurtzite form of GaN that is required.

Now Joblot and colleagues have managed to develop an MBE

process to produce crack-free GaN-based heterostructures on high-resistivity 2-inch silicon (001) substrates mis-orientated by 5° towards the [110] direction. After annealing the substrate at temperatures of up to 1150 °C to remove the native oxide layer, they grew an 80 nm-thick AlN buffer layer and a stack of 250 nm GaN and AlN layers on the substrate, followed by a 600 nm GaN layer, a 25 nm AlGaIn barrier and a 1 nm GaN capping layer.

Profiling a 10 × 10 μm area of the epiwafer's surface with an atomic force microscope revealed that the layer's surface roughness was typically 9–10 nm, while transmission electron microscopy images determined that the epiwafer had a threading dislocation density of 5–10 × 10¹⁰ cm^{−2}. X-ray diffraction measurements suggested that the structure contained only the wurtzite form of GaN.

HEMT devices were fabricated from the epiwafer, with a Ti/Al/Ni/Au stack forming the ohmic contacts. By measuring the sheet resistance of Hall bars and transmission line model devices, the team estimated that the transistor had a room temperature electron drift mobility of 730 cm²/Vs at zero gate voltage.

MOXtronics makes ZnO photodiodes and transistors

MOXtronics, a developer of devices based on ZnO and its alloys, has fabricated ZnO ultraviolet photodiodes and p-type FETs in partnership with Henry White's group at the University of Missouri, and South Korea's Seoul National University and Jeonbuk National University (*Appl. Phys. Lett.* **87** 153504).

The team claims that these achievements demonstrate that ZnO can be used to fabricate a wide range of devices, as well as showing that arsenic is a good dopant for creating the p-type form of this material.

ZnO devices are of interest because they are suitable for use in harsh environments such as nuclear reactors and space. The material has a higher radiation resistance than silicon, GaAs, SiC or GaN.

The photodiodes and FETs were grown by hybrid beam deposition (HBD), a technique which allows solid, vapor and gas source materi-

als to be used for crystal growth. According to MOXtronic's Yungryel Ryu, HBD was used because conventional growth methods, such as MBE and CVD, are unsuitable for producing high-quality ZnO crystalline films.

The team's ZnO photodiode has a peak sensitivity at 380 nm, and has a dark current below 10^{−6} A/cm². This indicates that it has the potential to detect ultraviolet light with low noise. Ryu says that MOXtronics will release ZnO-based commercial ultraviolet detectors in 2006, and that these will have a sensitivity three times higher than that of any other solid-state ultraviolet detector.

The ZnO MESFET produced by the collaboration has carrier mobilities of over 1000 cm²/Vs. "These large mobilities make ZnO a strong candidate for high-speed devices," remarked Ryu.

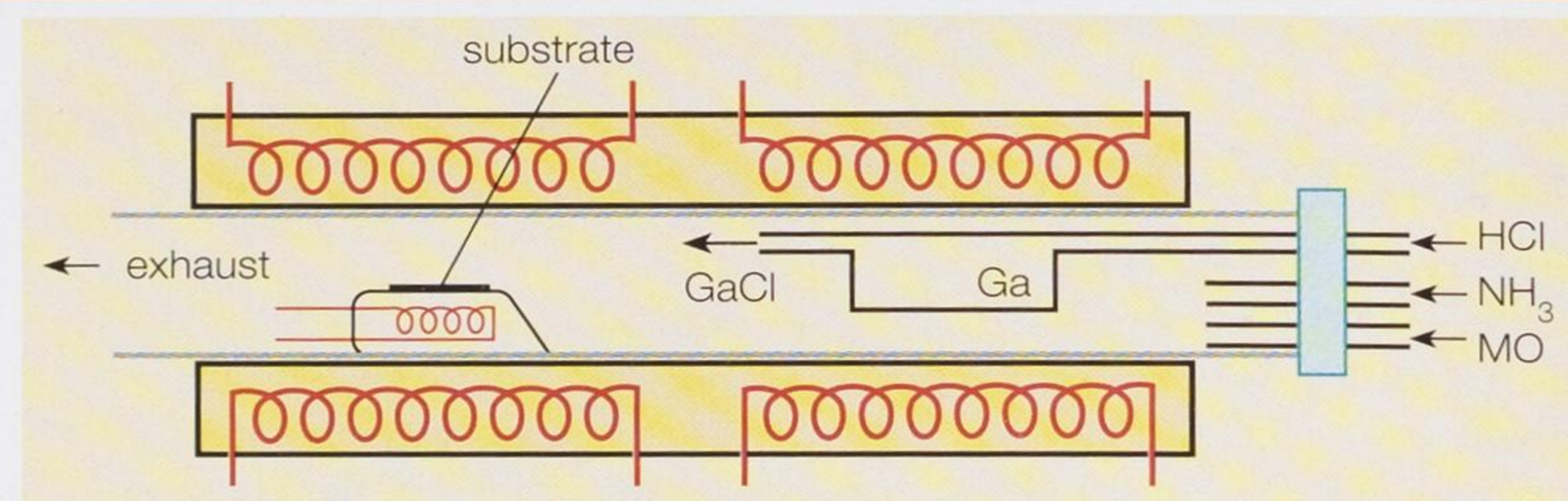
Complementary techniques offer better route to growth of GaN-on-sapphire epilayers

Scientist Glenn Solomon from Stanford University, in collaboration with US-based CBL Technologies and the Paul Drude Institute for Solid State Electronics in Berlin, Germany, has produced GaN-on-sapphire epiwafers in a single chamber using a combination of MOCVD and hydride vapor epitaxy (HVPE) (*Appl. Phys. Lett.* **87** 181912).

The team claims that the method offers a cost-effective and scalable means for production of GaN-based epilayers and devices, without the need for a separate reactor for each deposition step.

The approach enables growth of a high-quality GaN buffer layer at 500 °C by MOCVD, followed by the deposition of a thick GaN layer at 1025 °C at a much higher growth rate using HVPE.

The hybrid reactor uses an internal substrate heater (cold-wall heating system) for MOCVD growth, in the form of resistive heaters in the susceptor, and a hot-wall system for HVPE, using a multizone tube furnace (see figure above).



A combination of an external tube heater and internal substrate heater allows GaN growth by both MOCVD and HVPE in the same chamber.

The researchers deposited a 25 nm buffer layer on a 2-inch (0001) sapphire substrate at 500 °C by MOCVD, before using HVPE to grow a 12 μm-thick GaN layer at a rate of 25 μm/h.

Atomic force microscopy measurements of a 10 × 10 μm region of the sample's surface revealed a surface roughness, in term of the root-mean-square value, below 1 nm. Transmission electron microscopy images showed that the dislocation density decreased with distance from the buffer layer, and had an average value of 10⁷/cm² for the material within 1 μm of the epiwafer's surface.

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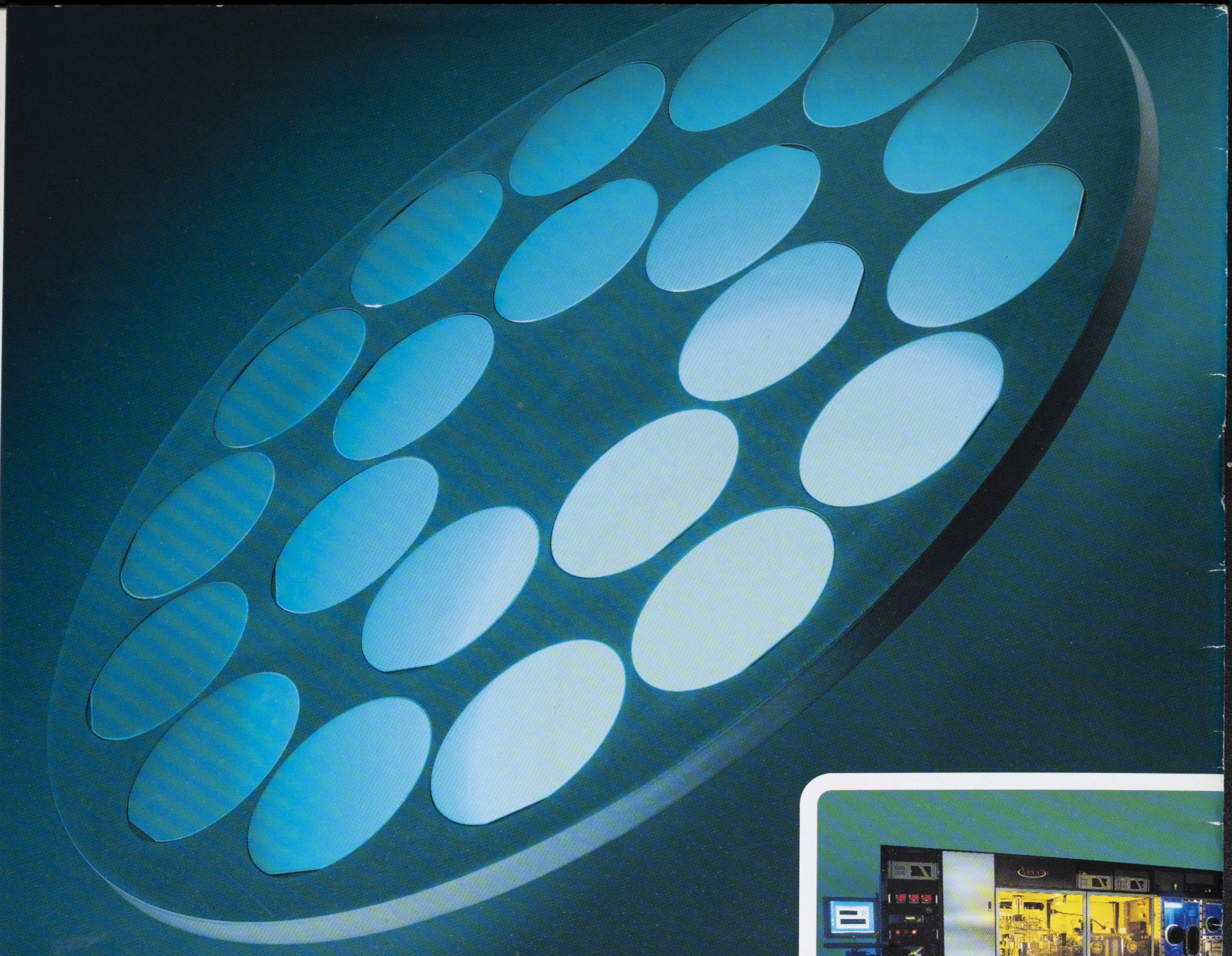
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