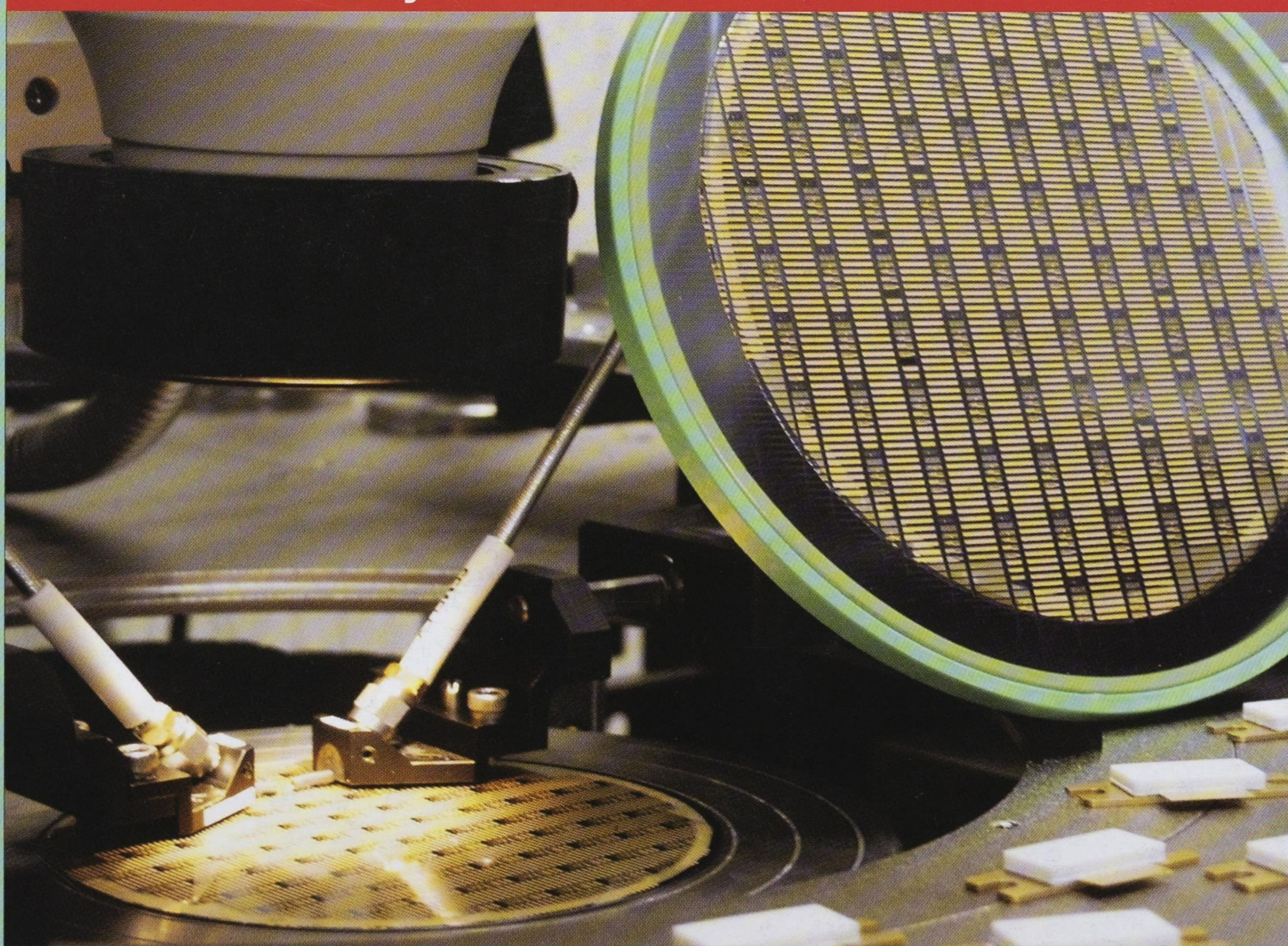


COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

July 2004 Volume 10 Number 6



GALLIUM NITRIDE **Wide-bandgap electronics** **near commercialization**

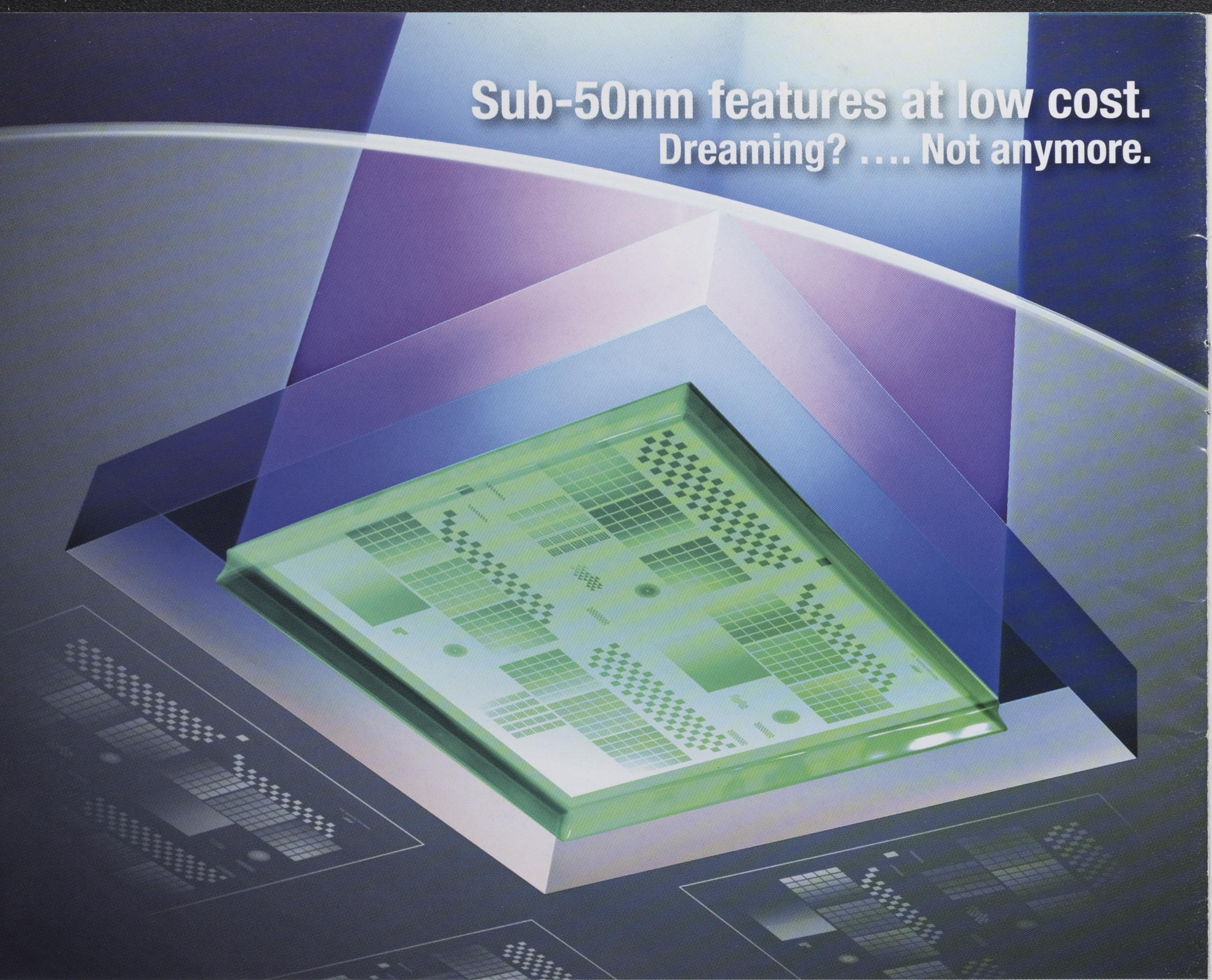
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**End of the road for
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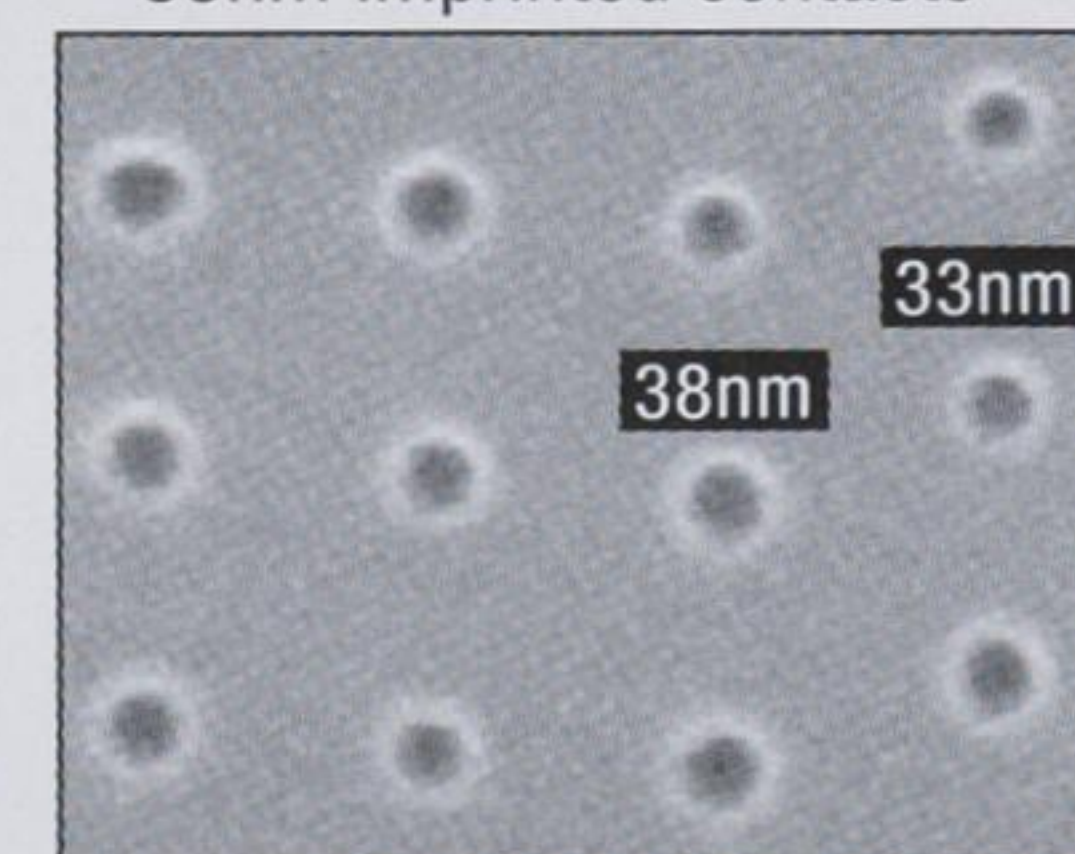


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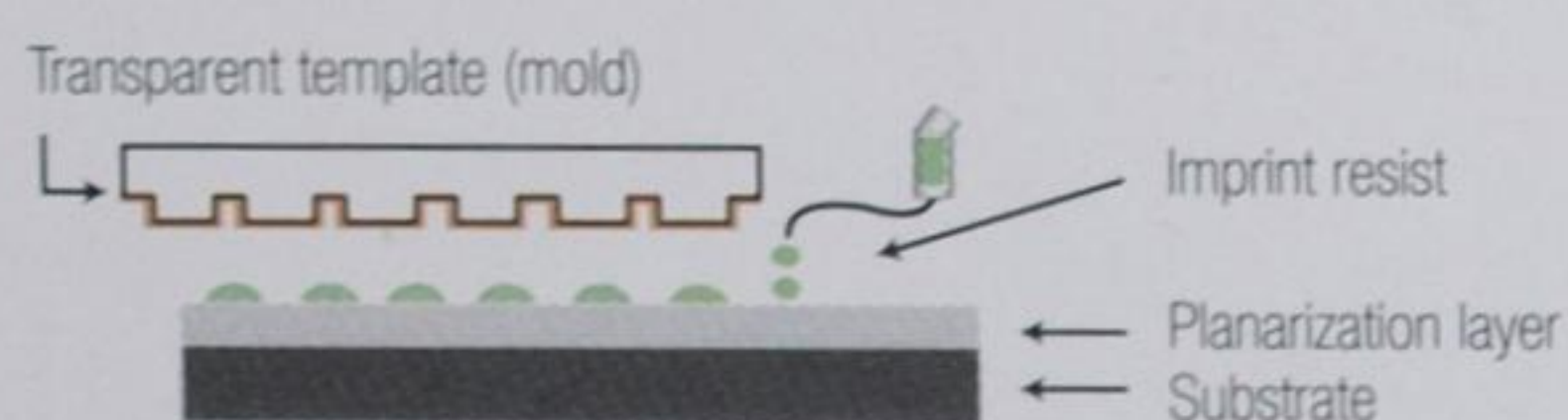
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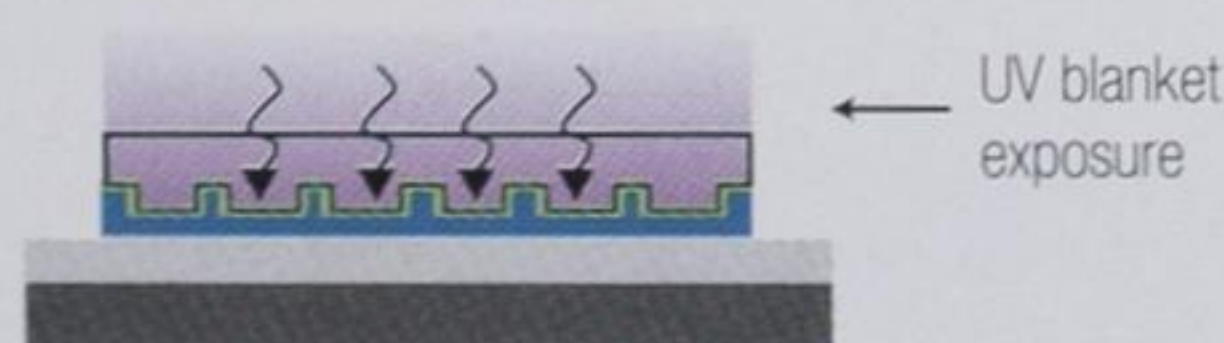
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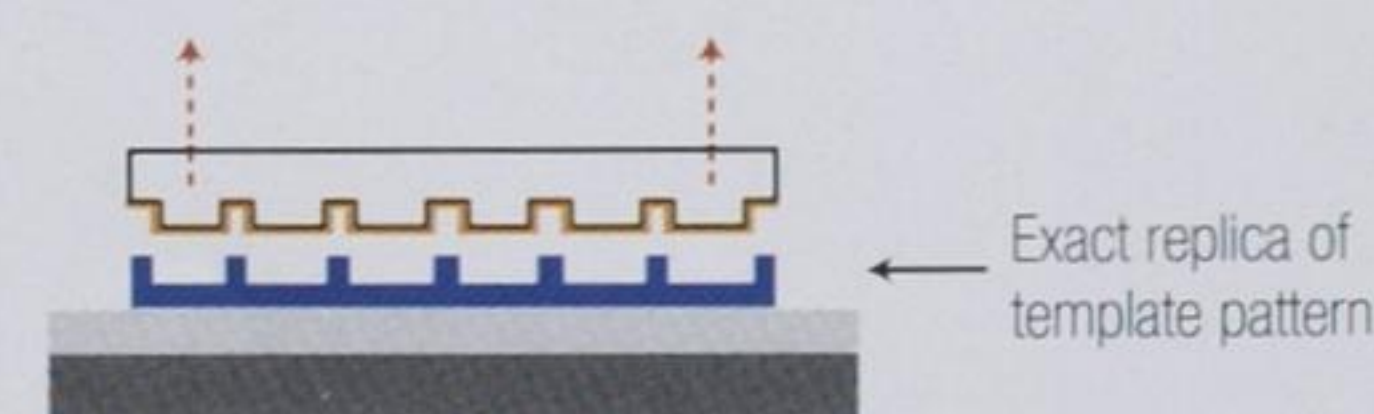
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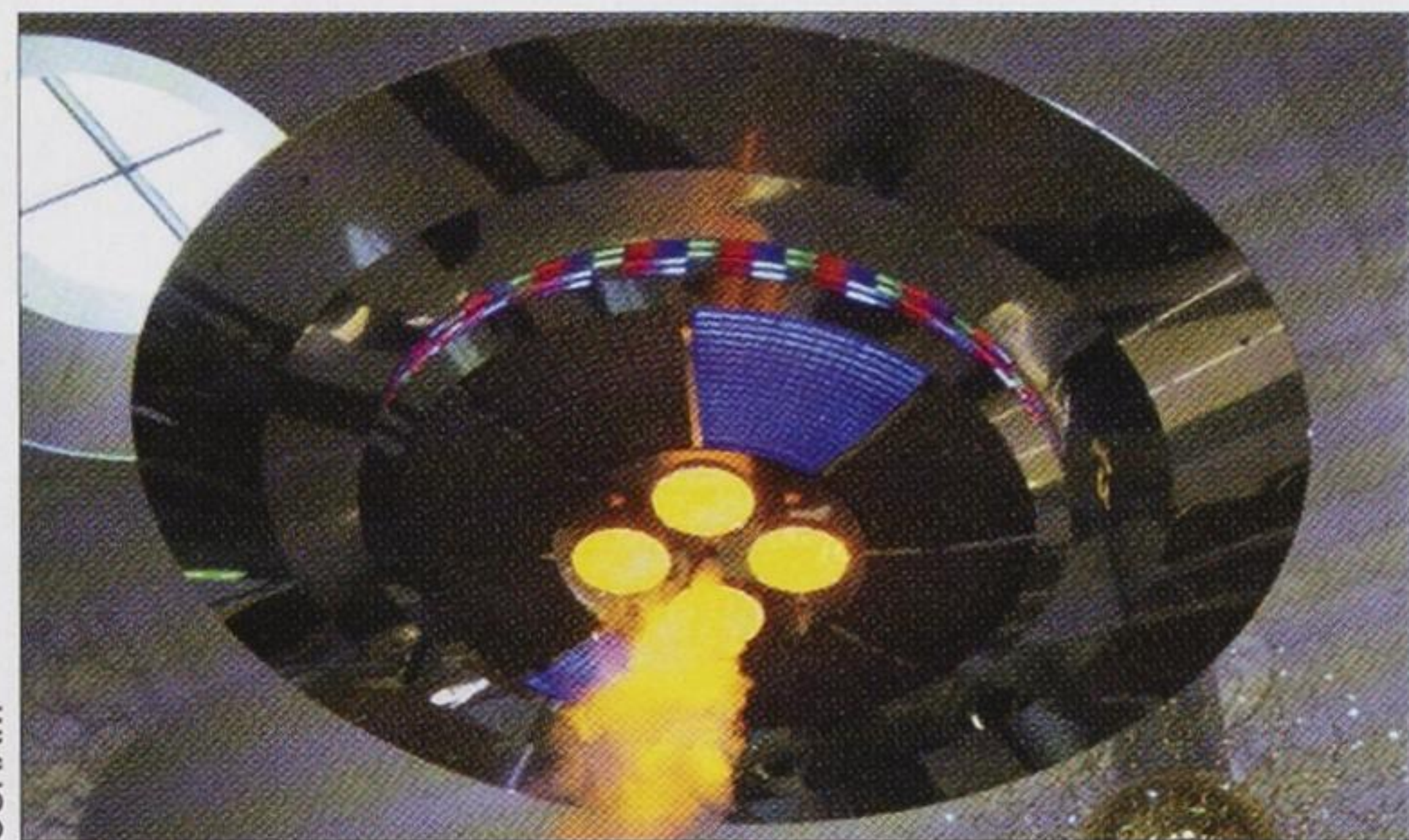


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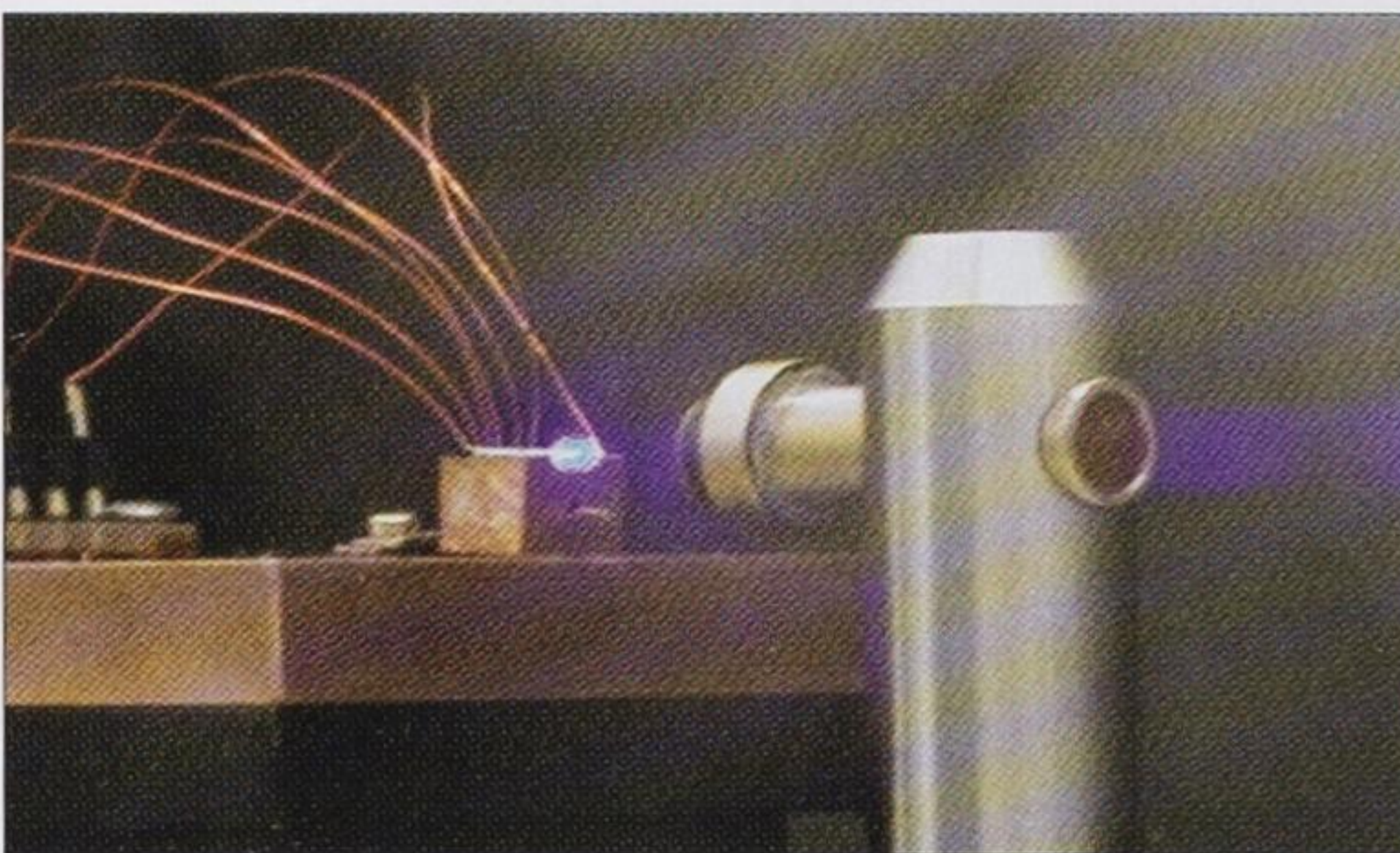
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Three-Fives and Silicon Heterostructures

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On the cover: GaN-based devices for use in cellular infrastructure are close to becoming a reality – see p13 and p27. Credit: Nitronex.

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Editorial

Bookham brings curtain down on 40 years of GaAs progress



Bookham Technology's decision to stop making GaAs-based RF devices at its Caswell facility is a sad one for the industry. Although it was not producing in particularly large volumes (its expertise was mainly limited to high-value MESFET and PHEMT MMICs for defense and space applications), the plant had a significant role in the history of the compound semiconductor industry going back as far as 1962.

Established by the Plessey company during the Second World War (the location deep in the English countryside was deemed much safer from aerial bombardment than the company's main plant in Ilford, near London), Caswell's original role was also in defense applications, developing aircraft radio components.

After some initial work on pure silicon, Caswell researchers produced the first GaAs MESFET in 1964, a technology that became commercialized in 1970. This was followed in 1976 by the first GaAs FET-based MMIC, and development continued apace in the 1980s and 1990s with a series of amplifiers, chipsets for phased-array radar applications, ICs for wireless LAN, X-band chips and broadband amplifiers.

After a production fab was established in 1985, Caswell was for a period the UK's only commercial GaAs facility, and when acquired by Marconi it was upgraded for 6 inch wafers. Marconi spotted that the GaAs technology developed for radar jamming was also useful for long-haul optical transmissions, and the scene was set for the next chapter of Caswell's story.

Ironically, the money that was then ploughed into the development of optoelectronic devices led directly to the selling off of the Caswell facility to present owners Bookham as part of Marconi's restructuring efforts.

Demand for X-band chips and the like could never sustain operation of a 6 inch GaAs production facility alone, and with the continued softness of the fiber-optic market, Bookham's decision appears to have been unavoidable.

Michael Hatcher

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Cree and Sumitomo sign \$160 m deal

By Tim Whitaker

Nitride LED manufacturer Cree has signed an agreement with Sumitomo Corporation that will see the Japanese company purchase \$160 million worth of Cree's LED products during Cree's fiscal year ending June 2005.

Chuck Swoboda, Cree's president and CEO, said: "This new agreement is the largest purchase commitment in Cree's history and highlights the strength of our partnership with Sumitomo and our Japanese customers."

Last year, Sumitomo, which sells Cree's LED chips to packaging companies in Japan, made a commitment to buy \$100 million of chips during Cree's 2004 fiscal year, representing around one-third of Cree's annual revenue if its fourth-quarter target is met.

The latest deal is subject to end-customer demand and other terms and conditions. As part of the agreement, Cree and Sumitomo also announced the extension of the current distribution relationship through Cree's fiscal year ending June 2007.

"We believe the growth in Japan is representative of the strong worldwide demand for our LEDs," said Swoboda. "New products are driving end-customer demand and helping us expand our relationships with the major LED packagers."

Koichiro Kusano, general manager of Sumitomo's Electronic Materials & Equipment division, said: "We expect shipments to

Japanese customers during the 12 months ending June 2004 to exceed our contract commitment, and end-customer demand continues to grow."

Both companies anticipate that the purchases will cover Cree's full line of LED products representing its standard-brightness, mid-brightness and high-brightness devices, including MegaBright, XBright and XThin LEDs.

● Cree has raised its revenue target for its fourth fiscal quarter, which ended on June 27, 2004. The prediction has increased from \$83–85 million, announced earlier in the quarter, to a range of \$85–87 million, thanks to increased demand for LEDs.

Nokia loses ground as global cell phone handset sales increase

Worldwide sales of cell phone handsets totaled 153 million units in the first quarter of 2004, according to market research firm Gartner. This figure represents a 34% increase on the first quarter of 2003. As a result, Gartner has forecast that total handset sales will exceed 600 million units in 2004.

"Another record quarter of mobile phone sales resulted from an Asia-Pacific market buoyed by purchases for the Chinese New Year, healthy growth in emerging markets and surprising numbers of people in mature markets choosing to upgrade their phones," said Ben Wood, principal analyst at Gartner.

Although each of the top five vendors – Nokia, Motorola, Samsung, Siemens and Sony Ericsson – saw an increase in sales, Nokia's share of the overall market dropped markedly. The Finnish company's global market share plummeted by over 5% to 28.9%, although it remains the clear market leader.

"Nokia's dramatic drop in market share resulted from a weak product portfolio and the decision by operators in Europe to source more phones from Nokia's competitors," explained Wood. Nokia's loss was distributed evenly among its competitors, each of which recorded an increase in market share of less than 2%.

Lumileds opens factory in Malaysia

Lumileds Lighting is opening a new plant in Malaysia to meet increasing demand for its high-brightness Luxeon LEDs. The facility, located in a 200,000 sq. ft building, will replace the company's Penang factory this summer, tripling both floor space and manufacturing capability. The new line also includes the first warm white LEDs available in volume.

"This move will allow us to stay ahead of the demand curve and enable us to handle our growth projections for the foreseeable future," said Greg Crema, Lumileds' vice-president of worldwide manufacturing. Lumileds expects its workforce to double once all production

lines are fully deployed. It could also expand services such as calibration, reliability testing and failure analysis.

Manufacturing at the new larger plant began in April. To reduce disruption, simultaneous production currently takes place at both sites, with complete transfer to the new site expected this month.

● NEC-Mitsubishi Electronics Display, a producer of flat-panel monitors, has unveiled large LCD prototype displays using Lumileds Luxeon LEDs. NEC-Mitsubishi used the LEDs for backlighting a 21.3 inch LCD monitor with a resolution of 1600 × 1200 pixels, and a 23 inch LCD monitor with 1920 × 1200 pixels. The RGB array is particularly good for backlighting red colors, compared with conventional technology.

Laser diode reaches 70% efficiency

Two US companies working under the super-high-efficiency diodes (SHEDS) program set up by DARPA have made dramatic progress in raising the wallplug efficiency of laser diodes.

nLight Photonics of Vancouver, WA, claims to have made a laser diode operating at 70% efficiency, thought to be a new record. nLight's VP of advanced technology, Jason Farmer, added that the company has also achieved over 300 W in continuous-wave mode at 808 nm, and over 50 W at 1470 nm.

Meanwhile, Wisconsin-based Alfalight has reached 65% wallplug efficiency with a device emitting 3 W at around 970 nm. The laser's structure has been improved in several ways to reach this figure.

Alfalight says that the "dramatic" improvement in overall efficiency was achieved by improving the internal injection efficiency through strain adjustments to the quantum-well barriers. The doping profile of the laser's separate confinement heterostructure layer has also been modified, leading to a reduction in the device's overall built-in voltage.

DARPA has set its contractors the goal of making a 480 W diode stack operating at 80% efficiency by September 2006.

**Improved laser design
pushes wallplug
efficiency to 65%
see p37**

Sale of infrastructure business to WJ leaves fabless EiC focused on handsets

RF semiconductor and multichip module manufacturer WJ Communications of San Jose, CA, is to acquire the wireless infrastructure business belonging to EiC Corporation. EiC designs, develops and manufactures RFICs, primarily for wireless communications products, in particular power amplifiers (PAs) for cellular base stations, repeaters, wireless LAN, cable television and optical networks.

Although EiC will continue to make PAs for cell phone handset applications, the terms of the deal will see WJ acquire the company's 4 inch GaAs fabrication facility in Fremont, CA, which is also home to the company's corporate headquarters.

"EiC will now become a fabless semiconductor company, which will allow us to serve the high-volume handset market without having to commit large amounts of resources to a wafer fab," said EiC president Jerry Curtis.

Part of the deal is an agreement under which WJ will supply EiC with wafers made at the Fremont fab. "Longer-term, we will open up our supply to other foundries, which will allow our customers the volume and assured supply they need for the dynamic handset market," Curtis said.

WJ will pay around \$12.5 million in cash and stock for the EiC RFIC wireless infrastructure product line, intellectual property,

existing raw materials and manufactured products, plus HBT semiconductor manufacturing processes to make high-reliability 5 V, 12 V and 28 V devices.

EiC could receive a further \$14 million over the next two years, depending on the revenue these InGaP HBT products generate. WJ expects the acquired portfolio to contribute \$8–10 million in revenue over the next year, and added that there is minimal overlap with existing WJ products.

"The experienced team of experts coming from EiC will help us to accomplish our goals as we grow our RFIC business in the coming years," said Michael Farese, WJ's CEO.

Growth returns to base-station chip market

The market for semiconductor chips used in wireless base stations is finally growing again. That's according to a new report from the US-based market analyst IDC, whose study suggests that the market, which includes baseband, transceiver and power amplifier (PA) products, will grow from \$1.9 billion this year to \$2.4 billion in 2008.

Not surprisingly, the introduction of 3G services is expected to drive most of this growth. IDC predicts that the 3G segment, which includes W-CDMA, CDMA2000 and the upcoming TD-SCDMA standards, will generate annual growth of 28% in base-station chip revenues over the next four years as existing networks are upgraded.

Additional growth is expected as demand for basic voice services in other parts of the world increases. "We believe that further cost reductions delivered at the chip level for key baseband, transceiver and PA subsystems will jump-start expansion and upgrades to data-enabled cellular networks," said IDC program manager Sean Lavey.



3G upgrade: Nokia's UltraSite base station is designed for GSM, EDGE and W-CDMA multimedia networks. Nokia and the Norwegian operator Telenor Mobil recently signed an agreement for the expansion and EDGE upgrade of Telenor's GSM network.

He cited increased standardization activity and a migration to "off-the-shelf chip approaches" as the major trends to follow in the base-station market, with the role of semiconductor vendors expected to grow.

The invention combines active analog techniques with a microwave distributed approach. The result is a multistage, direct-coupled distributed topology that can provide high gain and multidecade frequency operation.

Joseph Johnson, Sirenza's CTO, said: "Amplifiers that provide multidecade performance are key components for defense customers and electronic equipment manufacturers."

Sirenza awarded amplifier patent

Sirenza Microdevices, a fabless designer and supplier of RF components based in Broomfield, CO, has been awarded a US patent (no. 6,727,762) entitled "Direct coupled distributed amplifier".

RFMD acquires Bluetooth specialist

RF Micro Devices (RFMD), a provider of radiofrequency ICs for wireless applications, has completed its acquisition of Bluetooth specialist Silicon Wave.

Commenting on the acquisition, Frank Morese, vice-president of RFMD's wireless connectivity business, said: "We believe our combined strengths and unique technology place us in an extremely strong position to capture growth in the explosive Bluetooth market. Industry research forecasts that Bluetooth will grow more than six-fold over the next three years."

Freescall appoints Mayer as CEO

Freescall Semiconductor, Motorola's chip subsidiary that is expected to be spun off later this year, has named Michel Mayer as its new chairman and CEO. The appointment takes effect immediately.

Mayer, formerly with IBM Microelectronics, will head a \$4.9 billion global operation, with chip design, manufacturing and sales activities in more than 25 countries.

"Michel Mayer has a unique combination of operational experience, leadership skills, customer focus and technical expertise, making him the ideal choice," said Ed Zander, chairman and CEO of Motorola.

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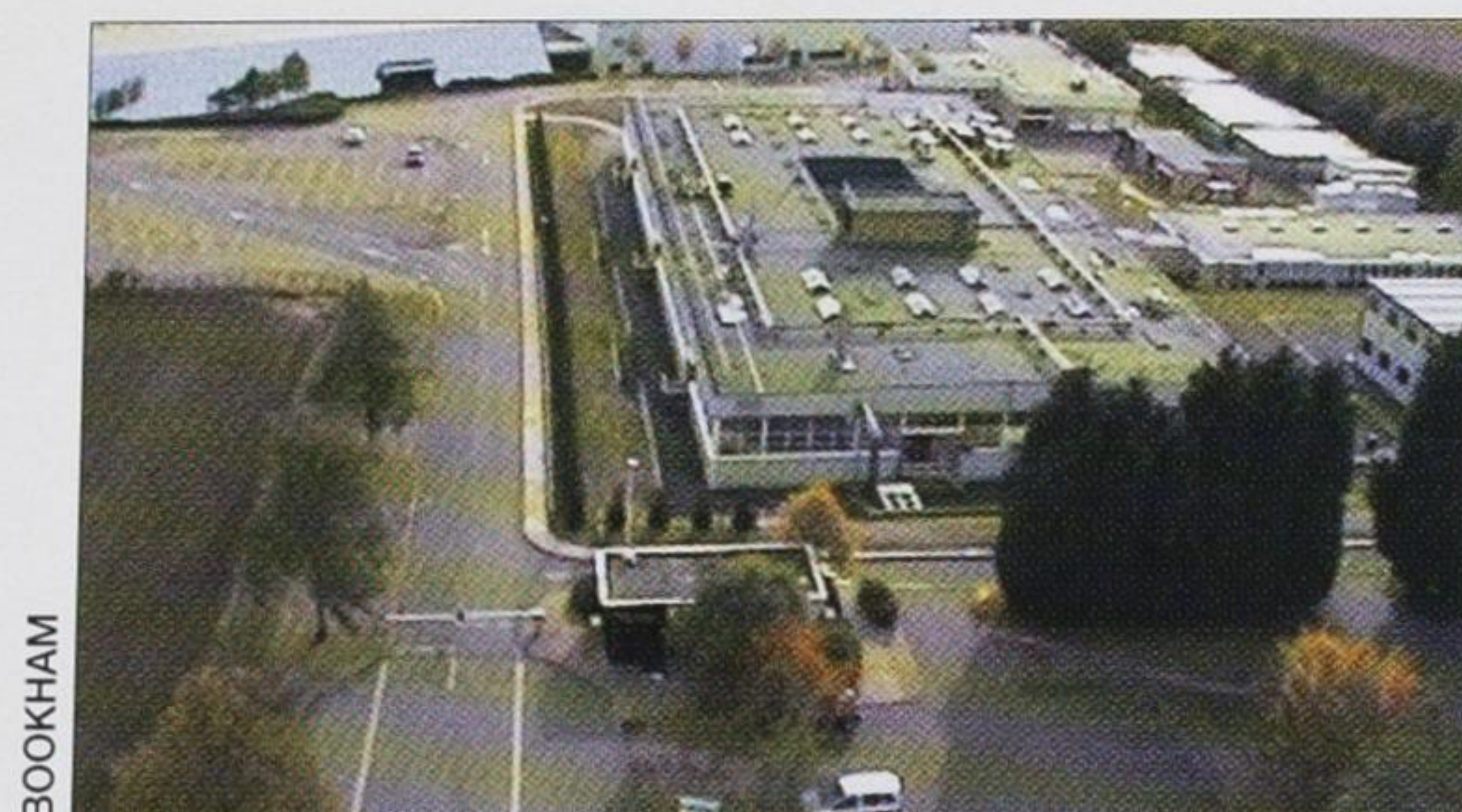
Bookham halts 6 inch GaAs production at Caswell

By Richard Stevenson

Bookham Technology, the optical and RF component manufacturer, is to mothball the 6 inch GaAs line at its historic Caswell, UK, site, with the loss of 60 jobs. The decision will leave the company with "no GaAs at all", although it still has a 3 inch InP line.

The move is part of a strategy, announced earlier this year, to cut costs by 25% across the company. According to a spokesperson, the 6 inch GaAs line had only two customers and order visibility was poor.

The 6 inch line was used to make PHEMT and MESFET products, which had been transferred from the 3 inch GaAs facility. Bookham expects to make a significant saving from the line closure, but has not disclosed figures. It added that JCA Bookham, the subsidiary that makes GaAs-based RF microwave amplifier products used in defense applications, was not a significant customer. JCA Bookham was formed in March 2004 when Bookham acquired New Focus and its subsidiary, JCA



BOOKHAM
Bookham has halted production of GaAs devices at its Caswell plant. Work on GaAs epitaxy at Caswell began in 1962, and the production fab was established in 1985.

Technology.

The GaAs facility was upgraded for 6 inch manufacturing in 2000 when it was owned by Marconi. Work on GaAs at Caswell goes back to 1962, and the site produced the world's first GaAs FET in 1970, followed by the first published GaAs FET-based MMIC in 1976.

Liam Devlin, director of RF Integration at the UK-based electronics design house and

consultancy firm Plextek, told *Compound Semiconductor*: "It's very sad that the GaAs facility at Caswell has ended like this." He now expects Bookham to concentrate on its optoelectronics market.

Sympathetic though Devlin was, he didn't believe Bookham had handled the situation well: "It wasn't very courteous to offer customers two weeks to do a last-time buy."

It has been a tough month for Bookham's UK employees, as they were also told that around 600 jobs would go at the packaging plant in Paignton. The transfer of Bookham's packaging operation to China has been on the cards since the company acquired a facility in Shenzhen when it bought New Focus.

Around 400 jobs, many in research and development, will remain at the former Nortel Networks facility, which Bookham says will remain the company's packaging "center of excellence".

● See *Compound Semiconductor* March 2004 p25 for more details on Caswell's history.

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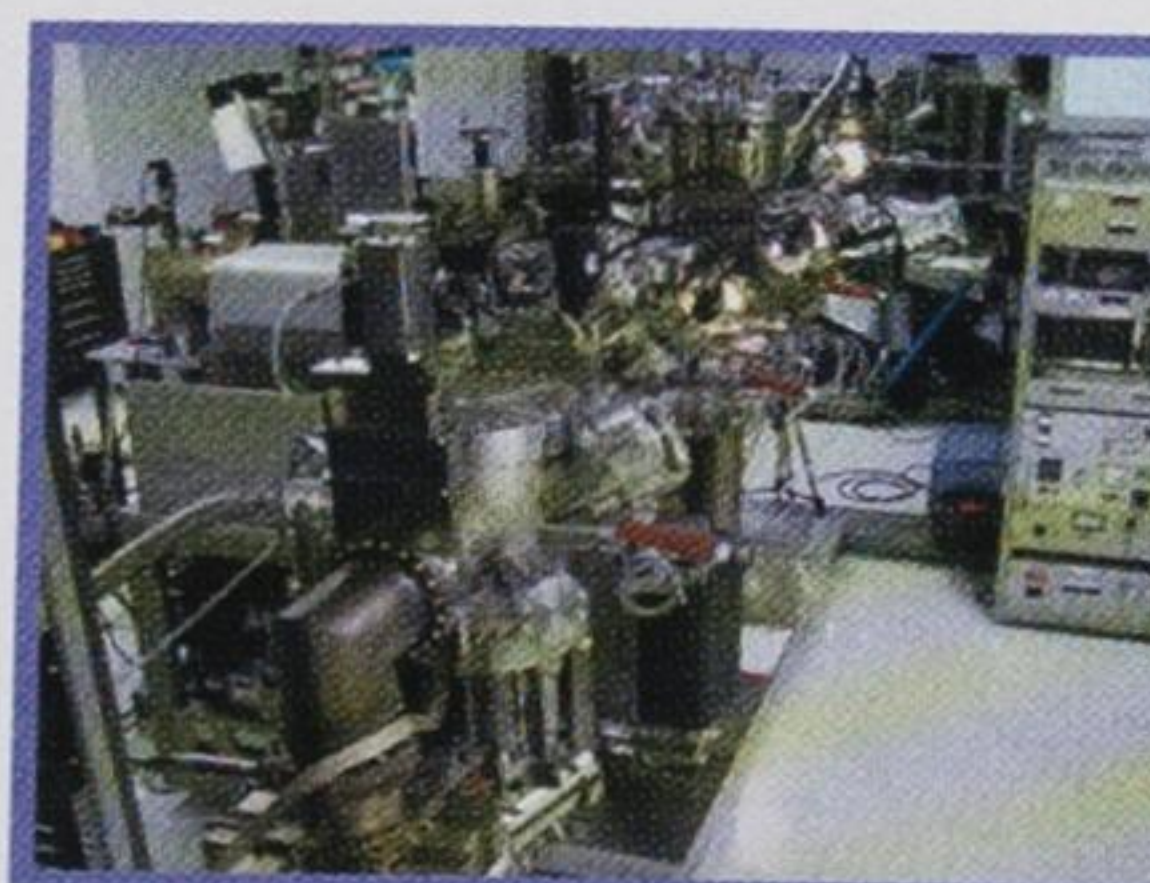
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Nichia files white LED patents lawsuit

By Tim Whitaker

Nichia has filed a lawsuit against the US retailer Sharper Image Corporation to prevent it from selling products containing white LEDs that infringe Nichia's US patents. The Japanese LED manufacturer has also successfully persuaded two other companies to start using Nichia's white LEDs in place of devices made by Nichia's rivals in Taiwan.

Sharper Image describes itself as "a specialty retailer that is a leading source of new, innovative, high-quality products that make life better and more enjoyable". One such product is a mini-torch, including an LED flashlight attached to a key-ring.

In a lawsuit filed in the US District Court of Northern California, Nichia alleges that the white LEDs used in the flashlight infringe the claims of US patent number 5,998,925. There is no indication as to which company manufactures the offending white LEDs.

Nichia has requested that Sharper Image be prevented from selling the mini-torches,

and also that damages should be awarded. The 925 patent describes a white LED fabricated by combining a blue LED chip with a cerium-doped yttrium-aluminum-garnet (YAG) phosphor material – the standard white LED structure used by Nichia.

Nichia has also reached agreements with two different companies without resorting to legal action. One of these agreements is with Optronics Inc, a US-based marketing and distribution company. Optronics had been selling products, manufactured by Chinese companies, which incorporated white LEDs made by companies in Taiwan.

Nichia claimed that the white LEDs infringed its US patents, and in April Optronics acknowledged the infringement. The company also agreed to purchase white LEDs from Nichia in the future, to avoid further infringement. In a similar case, an unnamed Japanese-affiliated company in Taiwan agreed to stop marketing LED products containing white LEDs made in Taiwan.

Again, the company agreed to start using white LEDs supplied by Nichia.

Nichia issued a statement aimed at its competitors that have signed licensing agreements with Osram Opto Semiconductors in relation to white LEDs. Nichia was keen to stress that, despite a cross-license agreement between Nichia and Osram, a license granted to a third party under Osram's patents does not imply a license under Nichia's patents.

● Nichia aims to double LED production capacity at its Tatsumi manufacturing site in an attempt to counter Asian competition, according to the Japanese newspaper *Nihon Keizai Shimbun*.

It believes that by increasing production it can be more competitive, and increase its share of lower-end markets, such as LEDs for lighting cell phone keypads. The company will construct a six-storey building, costing ¥4 billion (\$360 million), and install manufacturing equipment worth ¥20–30 billion, according to the report.

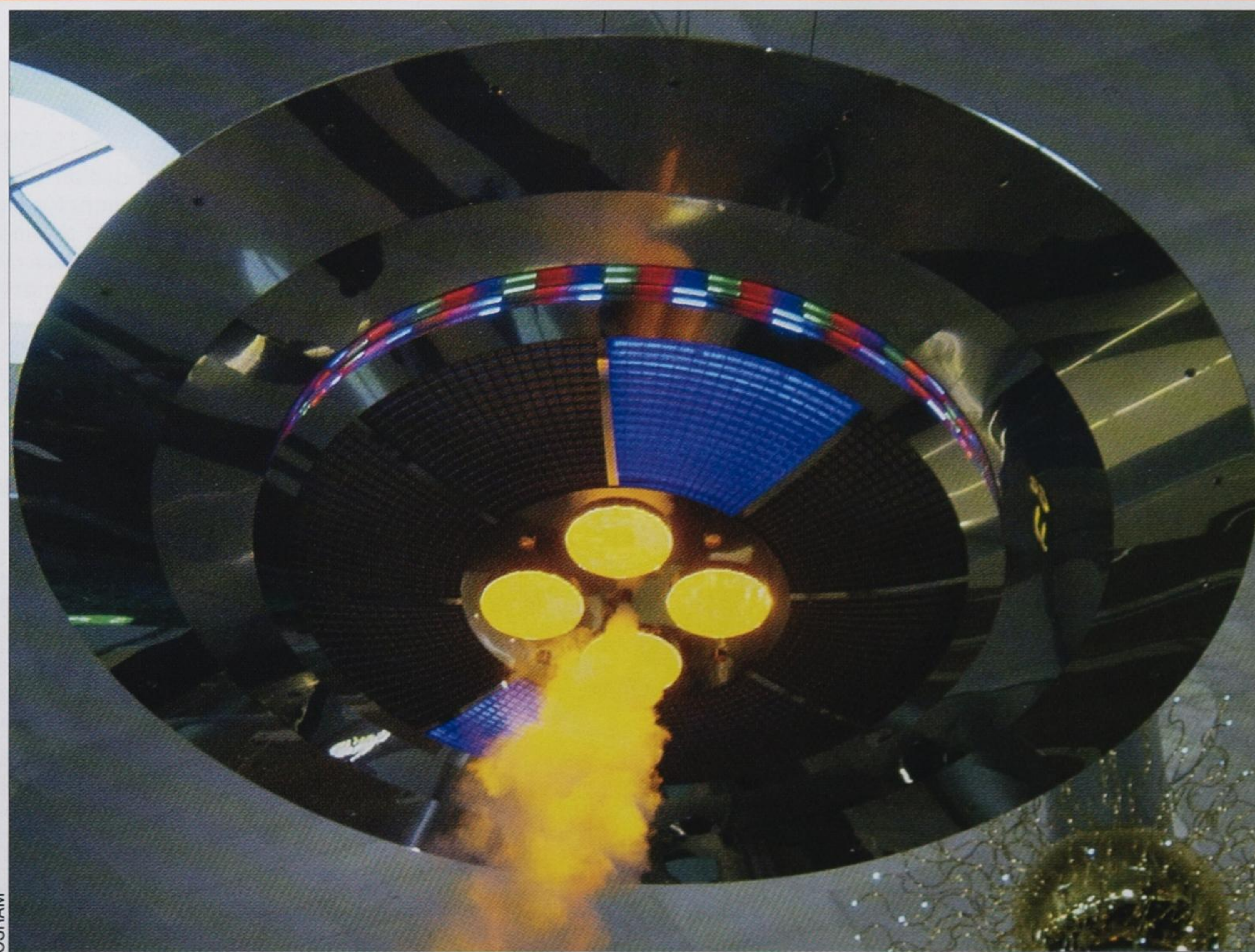
Toyoda Gosei builds second GaN factory

Toyoda Gosei, the Japanese manufacturer of GaN-based LEDs, has established a facility in Takeo City, Saga Prefecture, Japan, that will serve as the company's second production base. Construction on the new facility began in April 2004, and LED production is scheduled to commence in May 2005.

Currently one of the world's largest manufacturers of nitride LEDs, the company has a single factory in Heiwacho, Aichi Prefecture. The new Kyushu plant will enable the company to meet growing demand for blue LEDs and will also diversify its production base, lowering the risk of production loss in the event of earthquakes.

The new plant will operate as the optoelectronics division, Kyushu Branch, on a 1.4 ha site at Takeo Industrial Park. It will have 3300 m² of floor space after initial construction, with scheduled expansion to 7800 m² by 2006. Toyoda Gosei plans to invest ¥1.6 billion (\$14 million) in the project in 2004, ¥7 billion in 2005, and a further ¥7 billion in 2006.

Monthly production capacity at the Kyushu Branch is expected to reach 200 million chips in 2006. The facility will be staffed with about 80 employees initially.



Passengers at Dubai International Airport can now look forward to a spectacular sight in the Sheik Rashid terminal. Five "UFOs", each 6 m in diameter and containing more than 8500 LEDs, appear to hover in the air, producing breathtaking lighting effects thanks to LED technology from Osram Opto Semiconductors. The lights on the futuristic objects are switched on and off in a controlled sequence to simulate UFOs taking off and landing. Special optics are used to generate tightly focused beams.

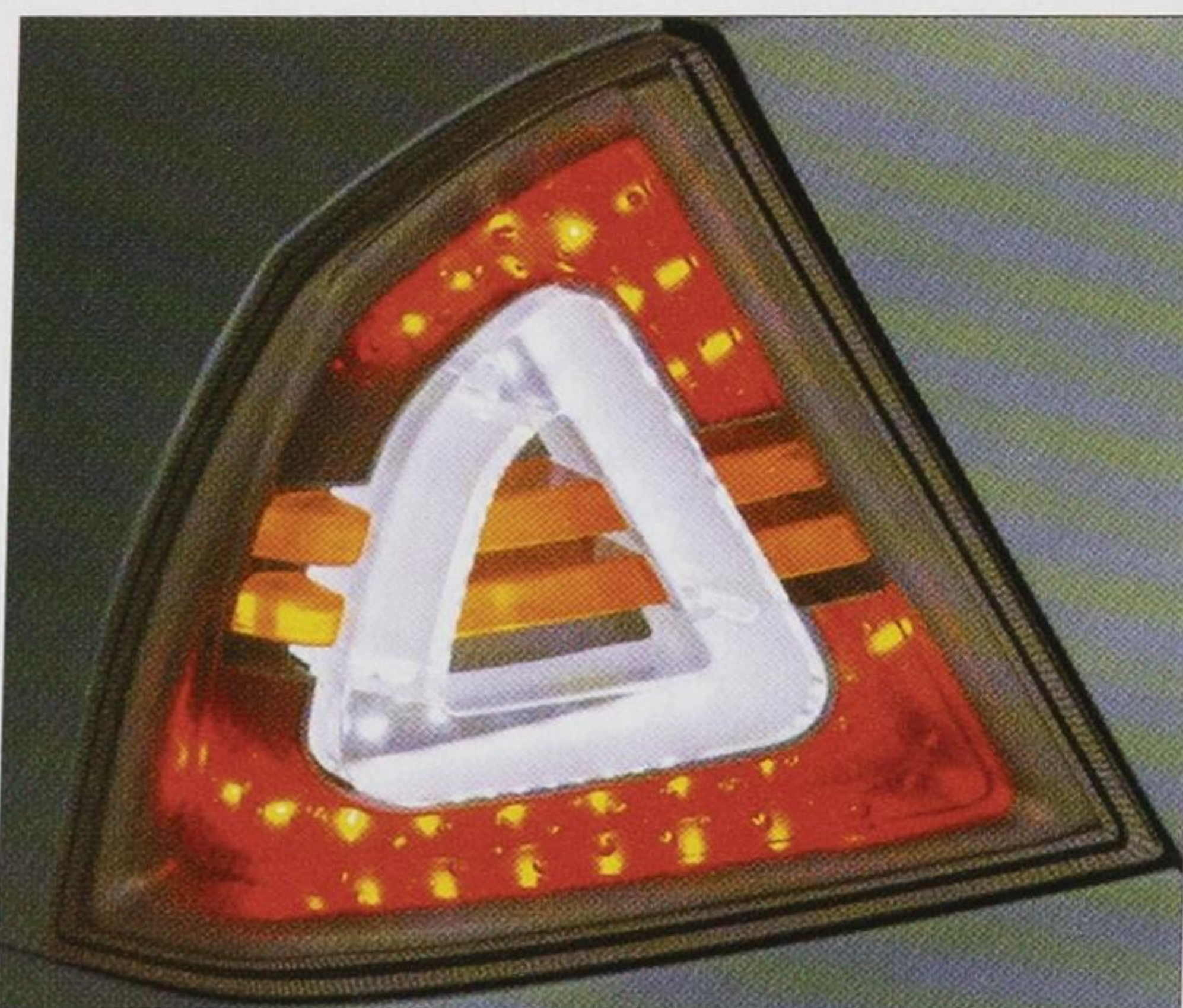
Osram accuses Dominant over LED patents

Osram Opto Semiconductors of Regensburg, Germany, has accused Dominant Semiconductors, a Malaysian manufacturer of LEDs, of patent infringement.

The complaint, filed with the US international trade commission, comprises two basic technologies. The first group covers technology that enables LEDs to emit white light from a single semiconductor chip. Applications for these LEDs include backlighting for cell phones and automobile dashboards.

The second group of patents concerns electrical connection structures used in LEDs, including high-power LEDs used in automobile lighting applications such as interior lighting and rear combination light systems. Osram has requested an order to prevent a wide range of Dominant's LEDs, and products containing them, from being imported to the US.

● Osram has joined forces with the Ford Motor Company to produce a "Focus Concept" car, using Osram's LEDs for many external lighting functions. The car, launched at the Auto China Motor Show 2004, uses Osram's Golden



Various Osram LEDs are used in the rear combination lamp of the Ford "Focus Concept". The white power TOPLED is used for the reverse, tail and indicator lamps.

Dragon and TOPLED ranges of LEDs for front-turn indicator lights, reversing lamps, brake lights, and tail and indicator lights. Osram claims that its LEDs have offered Ford engineers more flexibility, allowing them to produce reliable and efficient 3D lamp designs.

Arima and Tyntek to produce more LEDs

Taiwan-based LED makers Arima Optoelectronics and Tyntek are set to increase their AlGaInP LED capacity. According to a report from *DigiTimes.com*, the two companies are ramping up in a bid to compete with Epistar and United Epitaxy Company, two of Taiwan's leading manufacturers.

Arima is expected to increase capacity to 450 million chips per month by the end of the year, while Tyntek's collaboration with Visual Photonics Epitaxy Company will see volumes double to 80–100 million chips per month.

Arima recently merged with Kingmax Optoelectronics, which has already boosted monthly capacity from 200 million to 350 million chips. According to the report, Tyntek's photodiodes and phototransistors recently passed tests for automotive applications set by BMW and Audi. Current monthly volumes are about 2 million units, and Tyntek is said to be expecting further verification from Ford, General Motors and Toyota.

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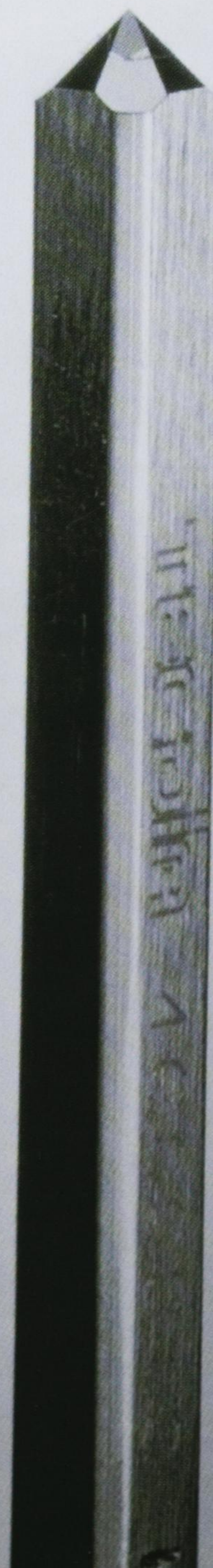
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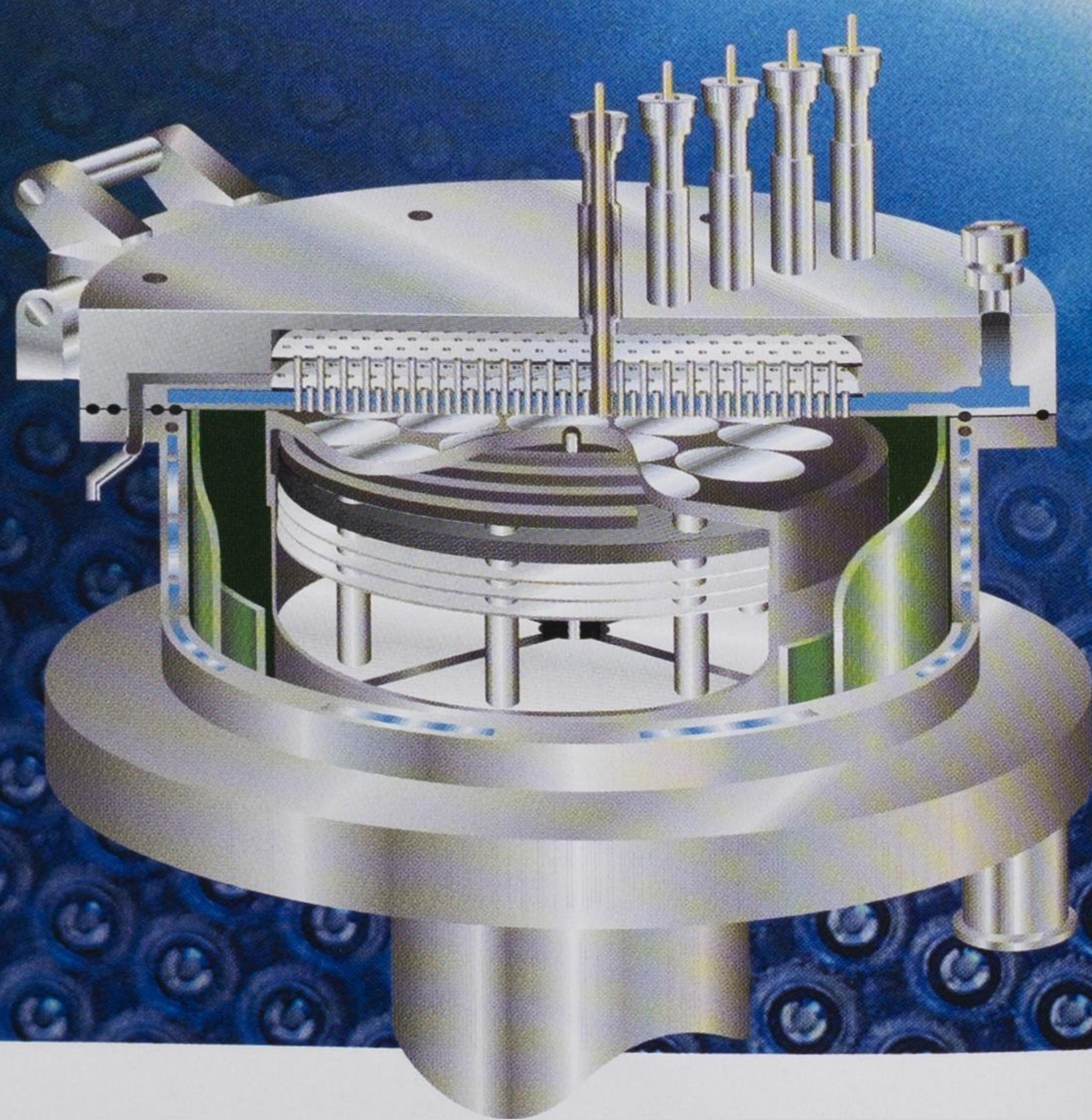
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GaN HEMTs look set to go commercial

Michael Hatcher reports from Miami Beach, Florida

At the CS Mantech conference back in May, GaN electronics emerged as a strong theme, with an entire session devoted to GaN amplifiers, as well as a number of other presentations on the subject.

Rockwell Scientific Company (RSC), RF Micro Devices (RFMD), Eudyna Devices and Nitronex were among the companies updating attendees on the latest developments.

Karim Boutros detailed recent progress at RSC, where the GaN HEMT process has been “successfully” scaled from 2 inch to 3 inch semi-insulating-SiC substrates. This should lead to significant cost reduction in the future by doubling the number of MMIC die produced per wafer.

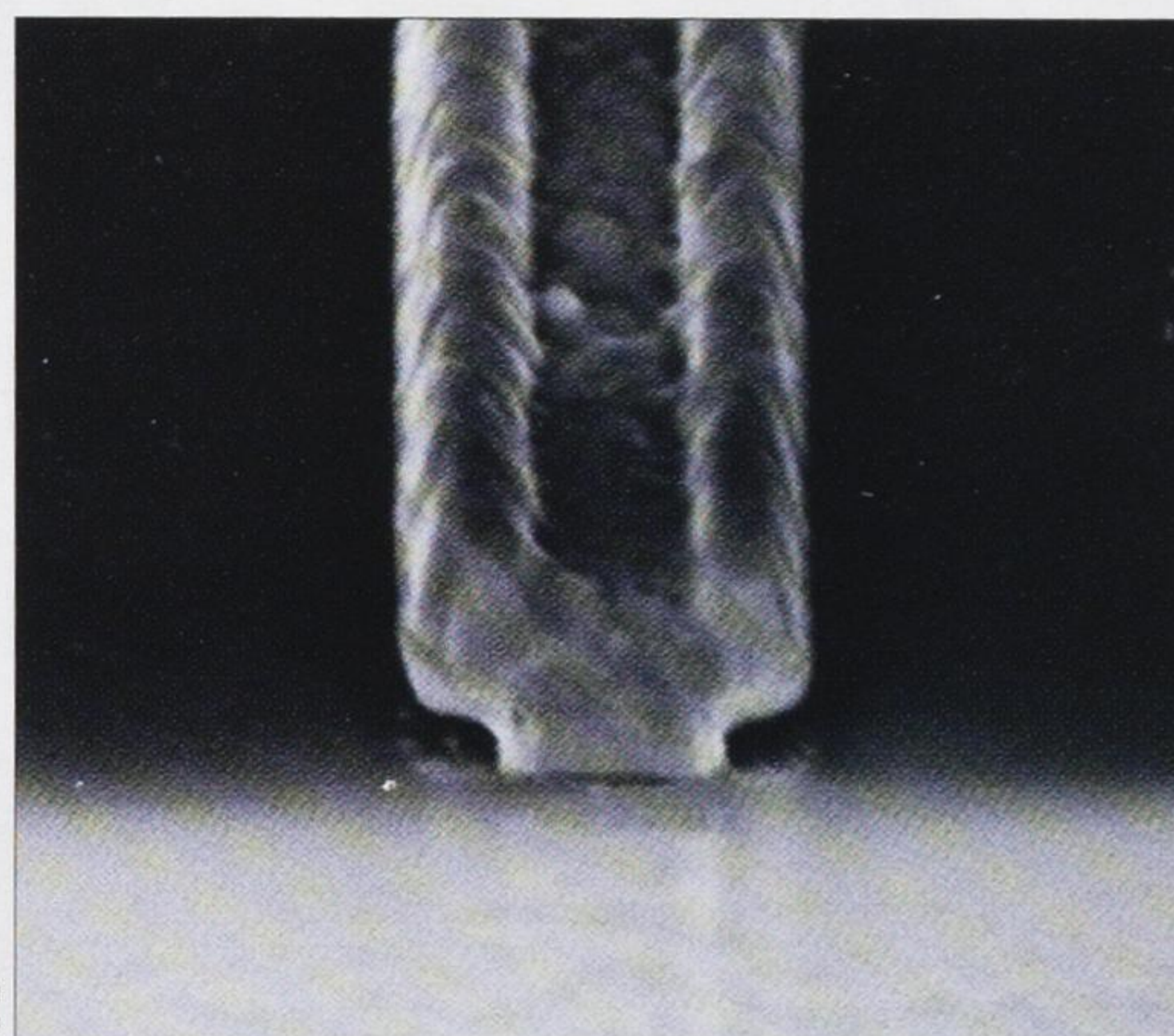
Boutros said that RSC has a capacity of 50 wafers per week for the “high-yield” GaN HEMT process, which uses a $0.18\text{ }\mu\text{m}$ gate-length technology. Working with 2 inch wafers, this has led to what he believes is the world’s highest power density for 40 GHz operation of 2.8 W/mm . At 38 GHz, the figure rises to 3.4 W/mm , along with 10–12% power-added efficiency (PAE) and 5 dB gain.

With 3 inch substrates, variations in epilayer thickness have led to similar variations in device properties, said Boutros. He calculated a 10% uniformity for RF device performance. He also quoted figures showing an output power of 2.5 W and 47% PAE for an $8\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$ device operating at 3 GHz.

While Rockwell has been transferring to 3 inch production, Eudyna Devices has been pushing the upper limits of GaN HEMT device performance. Eizo Mitani from the company’s US office in San Jose, CA, described the development of a 36 mm gate periphery AlGaIn/GaN HEMT capable of 150 W output power and 54% PAE. Operating at 2.1 GHz, the gain reached 12.9 dB at 63 V.

Mitani stressed that with reliability being a key issue for GaN HEMTs, the Eudyna device showed stable operation, with no degradation in power or gain for 1000 h. “This is the first report of stable operation at 60 V,” he said. In W-CDMA mode, the saturated peak power figure reached 174 W, thought to be the highest yet reported, and Mitani said that the device looked promising for third-generation base-station power amplifiers (PAs).

Over at RFMD, the emphasis has been on developing manufacturable GaN HEMTs.



Researchers at the US Air Force Laboratory fabricated a GaN HEMT for mixed-mode applications, using electron-beam lithography to create this T-gate. The gate length is $0.32\text{ }\mu\text{m}$, and the low-noise device is said to have excellent power performance.

Director of GaN materials Joe Smart told the Miami Beach audience that the advantages offered by GaN will enable base-station builders to significantly change the design of their installations. For example, there is a strong desire to reduce the degree of cooling that is currently required, and to move the antenna and PA closer together in a bid to reduce the estimated 50% transmission loss between the two.

The high-temperature operation enabled by GaN devices will remove the requirement for air-conditioning and enable tower-top mounting of amplifiers in base stations – closer to the antenna. Smart estimates the total addressable market for GaN-based PAs to be worth the equivalent of 10,000 4 inch wafers, and is expecting the infrastructure market to follow the path of the handset market. “Base-station components will mature like [those found in] cell phones,” Smart told delegates.

RFMD has a pilot production facility with approximately 50 wafers (2–4 inch SiC substrates) in progress at any one time, and Smart told delegates that the vertically integrated RFMD business could produce a device from scratch in around eight days using its custom-built reactor. He added that a new, dedicated fab would not be required for GaN HEMT production, and that RFMD would use its existing fab, which is currently used to make GaAs PHEMTs.

RFMD’s reactor can handle up to eight 4 inch wafers, and up to 36 2 inch wafers in a

two-tier arrangement. Unlike Eudyna, RFMD will concentrate on producing a 28 V device initially, as this is what its customers want in the first instance. Smart added that field plate work had “dramatically” improved reliability of devices under RF stress.

It is not just wireless base stations that could provide a healthy market for GaN HEMTs. Tony Quach from the US Air Force Laboratory (AFL) described the US military’s efforts to develop the technology for mixed-mode applications, in particular a GaN HEMT amplifier operating in the X-band (8–12 GHz) for use in phased-array radar systems.

Quach said that his team had made a low DC power dissipation low-noise amplifier (LNA) and a corresponding high-power amplifier using a $0.32\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$ GaN HEMT device (see image). A PA made with the same device type showed 30.9 dBm output power, 8 dB gain and 39% PAE at 10 GHz.

The AFL fabricated its HEMTs on an insulating 4H-SiC substrate using MOCVD, with the device structure consisting of a $1\text{ }\mu\text{m}$ GaN buffer layer and a 25 nm $\text{Al}_{0.24}\text{Ga}_{0.76}\text{N}$ barrier layer.

The LNA produced by Quach and colleagues yielded a low DC power dissipation of 7.5 mW in the X-band, with Quach saying that the work “will have major implications for future radar and communication systems where transmit and receive functions require increased integration within a single technology platform”.

Nitronex is another company at the forefront of GaN development, and Allen Hanson from the Raleigh, NC, company described the optimization of 28 V devices used in linear applications. Nitronex’s process uses a silicon substrate, with inherent economic advantages. Hanson said that with 1500 wafer starts in the past year, the technology was now adopting a “production” feel.

Using a similar process flow to that seen at GaAs MMIC foundries, Hanson said that Nitronex had altered its epitaxial process in response to problems encountered with drain leakage, and had reduced the effect by two orders of magnitude.

With a device yield of 77.6%, the Nitronex HFET showed 5.8 W output and 32.3% PAE in the W-CDMA band, and Hanson said that he expects large volumes of devices to be needed before long.

● For more on GaN HFETs, see p27.

Etched facets produce reliable long-wavelength surface-emitting lasers

By Tim Whitaker

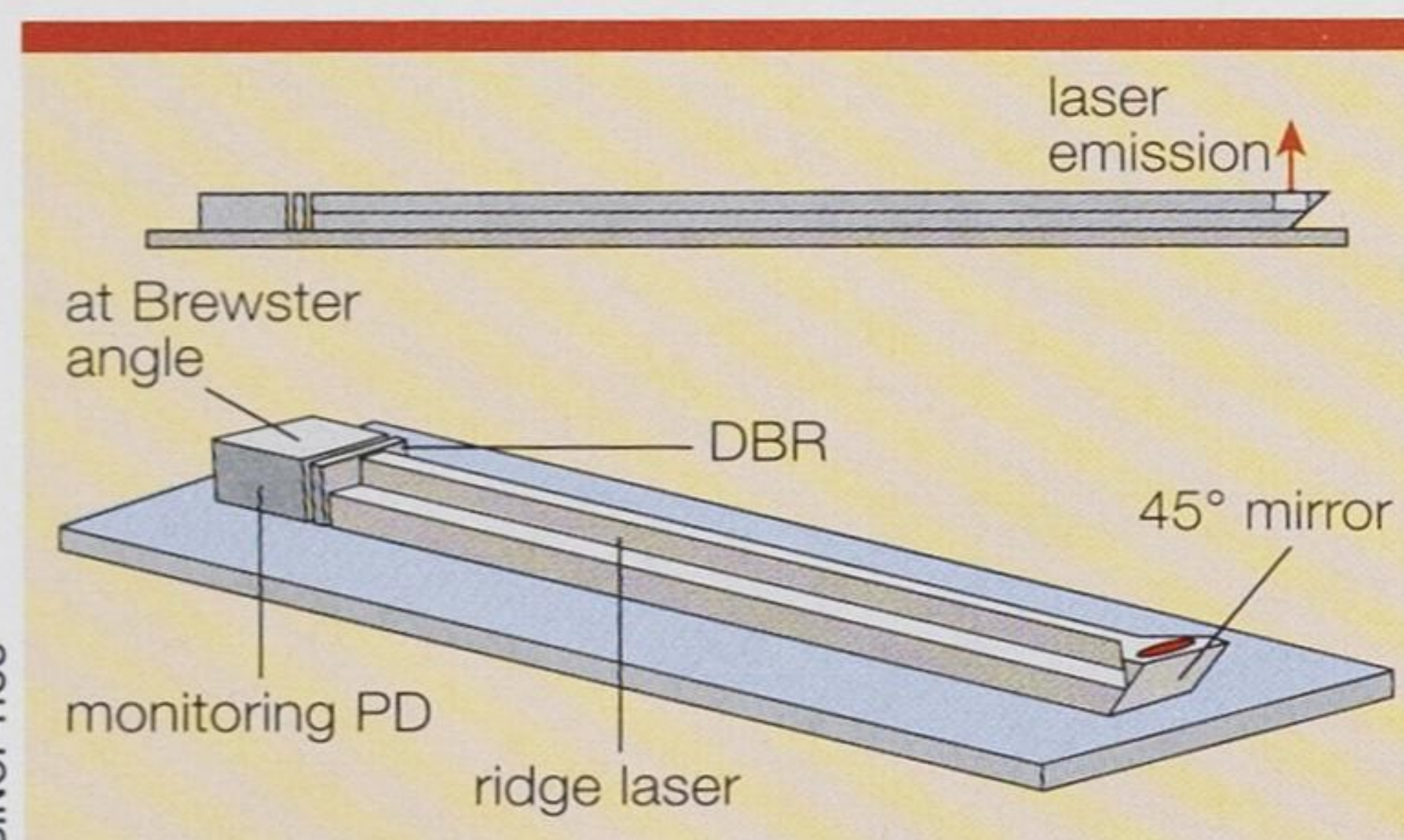
BinOptics, a developer of integrated photonic devices based in Ithaca, NY, has announced the availability of a new class of surface-emitting lasers manufactured using the company's proprietary etched-facet technology (EFT) platform.

The new horizontal-cavity surface-emitting laser (HCSEL) integrates a horizontal laser cavity with a 45° etched reflecting mirror to direct the output beam vertically. BinOptics says that its device combines the power and high reliability of an edge-emitting laser with the low cost and ease-of-packaging of a VCSEL.

"The process allows us to build and test the devices on-wafer, then singulate and package them," said BinOptics' chairman Alex Behfar. "We can also readily integrate more functionality on a single chip, such as adding monitoring photodetectors."

Founded in November 2000, BinOptics is privately held, with financing from two venture-capital funds and Stanford University. The company is located in the Cornell Business & Technology Park in Ithaca, where its facilities include a cleanroom for processing as well as test capabilities. The EFT was invented by scientists at Cornell University, and, as its name implies, uses etching rather than cleaving to fabricate the laser facets.

The cleaving operation is often one of the most costly and lowest-yield steps in manufacturing conventional edge-emitting lasers. "Conventional cleaving processes tend to have poor reproducibility with the possibility of undesired mechanical breakages," said



The HCSEL device consists of a ridge waveguide laser with an etched 45° facet at one end of the cavity and a DBR at the other. It is also possible to integrate a monitoring photodetector (PD).

Alan Morrow, BinOptics' vice-president of technology development. "In contrast, the etching of facets defined using high-precision photolithography results in unprecedented uniformity and yield as well as the capability to build structures that are impossible to realize with conventional techniques."

Conventional lasers also need to be aligned with the crystallographic planes of the InP wafer, so that the facets can be fabricated along certain cleavage planes. The etching process does not require this type of alignment. Furthermore, BinOptics says that its proprietary processes can be applied to other material systems, such as GaAs and GaN, opening up a variety of new device options.

BinOptics' first HCSEL product is an InP-based 1310 nm Fabry-Perot laser designed for uncooled operation at a data rate of 2.5 Gbit/s with an optical output power of 20 mW and a slope efficiency of up to 0.3 W/A. The

device is available with or without an integrated monitoring photodetector (MPD).

As shown in the diagram, the HCSEL is a ridge waveguide laser with a 45° etched facet at one end to direct the laser emission perpendicular to the surface. The other end of the cavity is a distributed Bragg reflector (DBR), again fabricated by etching, with an optional MPD outside the cavity.

Generally, the reflectivity of cleaved facets is modified using optical coatings, but this is not required for the BinOptics approach. "We circumvent the need for facet coatings for reflectivity modifications since we are able to integrate highly reflective DBRs with our etch-facet lasers," said Behfar.

The advantages of VCSELs operating at 850 nm were so compelling that VCSELs rapidly became the transmission source of choice in datacom applications. These benefits include on-wafer testing, inexpensive packaging, and the ability to fabricate one- and two-dimensional arrays on the same chip for easy coupling with fiber arrays or electronics.

These advantages have not been fully realized for VCSELs at 1310 nm because of materials issues such as the difficulty in obtaining high-reflectivity mirrors in the InP material system. Such issues lead to low power and poor yield, negating most of the cost benefits.

BinOptics says that its 1310 nm HCSEL enables the advantages of VCSELs to be realized at longer wavelengths, and also allows monolithic integration of the MPD to further reduce cost.

● More information about BinOptics is available at www.binoptics.com.

JDS Uniphase acquires E2O for \$60 million

JDS Uniphase (JDSU), one of the leading manufacturers of fiber-optic components, has purchased E2O Communications for approximately \$60 million in cash. The move will strengthen JDSU's position in the data communications market.

E2O was founded in 1998 and is headquartered in Calabasas, CA, with a manufacturing plant in Singapore. The company manufactures multi-gigabit-rate fiber-optic subsystems for the computer storage, Internet and telecommunications markets. Its optical

transceivers support various Gigabit Ethernet, Fibre Channel and other standards.

"The acquisition of E2O provides JDSU with additional expertise in low-cost manufacturing, greater economy of scale, and other infrastructure cost synergies that we believe will lower costs now and for the future," said Don Bossi, president of JDSU's transmission products group.

He continued: "We believe these synergies and the strong cultural fit between the two companies make this a lower-risk path to

expand our role in one of our fastest-growing markets." E2O was a supplier to major datacom customers, and the acquisition has enabled seven new companies to join JDSU's existing customer base. H C Lee, president and chief executive officer of E2O, will join JDSU as vice-president of the combined datacom business unit.

E2O's revenue in recent quarters has been in the region of \$5 million. The company also brings strong research and development capabilities and leading technology to JDSU, such as its long-wavelength VCSELs targeting 10 Gbit/s operation.

Solid growth forecast for fiber-optic components

By Michael Hatcher

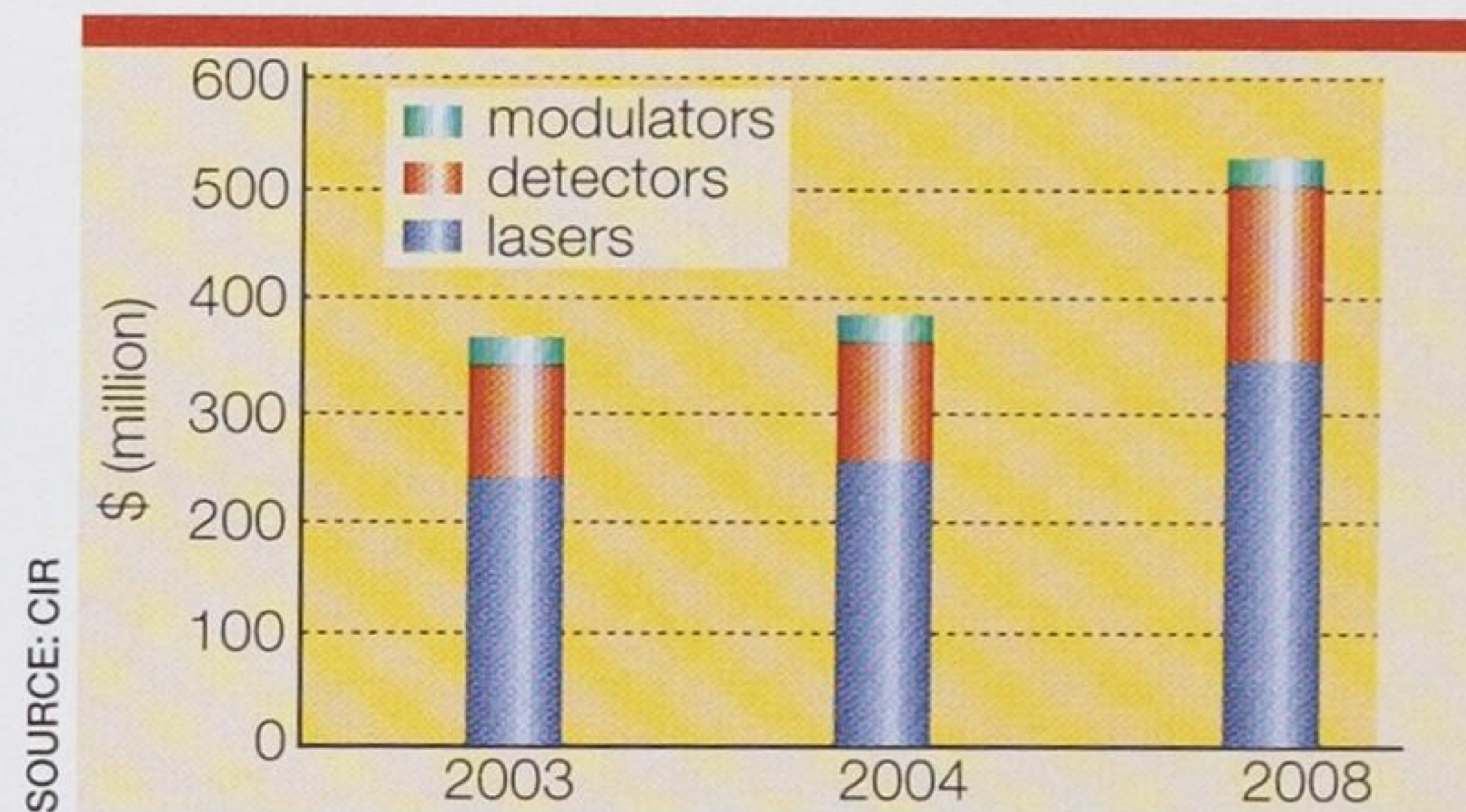
Steady growth is returning to the market for active components used in fiber-optic networks, claims a new report. Communications Industry Researchers (CIR) predicts that the market for optical and electronic transmission components will grow from just over \$1 billion in 2003 to \$1.6 billion in 2008.

According to the US-based analyst company, sales of lasers, detectors and modulators in particular will grow 5% in value from the 2003 figure of \$368.7 million to reach \$387.5 million in 2004. By 2008, this is expected to grow to almost \$530 million.

Opportunities in the optical networking business are shifting from public networks to the enterprise, and towards Ethernet and Fibre Channel applications in particular, claims the CIR report. CIR's Lawrence Gasman told *Compound Semiconductor* that with 10 Gb Ethernet applications finally breaking through, the fiber-optic market was looking much healthier than of late.

Although lasers and detector sales are expected to increase steadily over the next five years, a fall is predicted in the market for modulators. Fixed-wavelength distributed feedback (DFB) lasers, used predominantly in WDM applications, currently make up the biggest single segment. DFB devices have around double the market share of both Fabry-Perot lasers and VCSELs, which are much more widely used in Ethernet applications.

On the detector side, the market is divided evenly between PIN and avalanche photodiode (APD) products. PIN detectors dominate



SOURCE: CIR

Modulators will make up an increasingly small proportion of the market for fiber-optic components, according to CIR.

Top 5 vendors by market share

JDS Uniphase	19.3%
Eudyna Devices	11%
Agilent	9.8%
Boookham	9.7%
Finisar (incl. Infineon)	7.8%

SOURCE: CIR

in Fibre Channel and Ethernet applications, while APDs have the upper hand in WDM. JDS Uniphase is still the top-ranking vendor of active components by market share. Eudyna Devices, the Japanese firm created by the merger between Fujitsu Quantum Devices and Sumitomo Electric's electronic devices division, now sits in second place.

Agilent and Bookham take third and fourth spots with an almost identical market share, while the acquisition of Infineon's product line will propel Finisar into fifth place.

More details can be found in CIR's report, *Optical Transmission Components Forecasts and Market Share Analysis*.

In brief

● Five Japan-based companies have signed a multisource agreement for miniature 10 Gb/s devices. **Eudyna Devices, Mitsubishi Electric, Oki Electric, Opnext and Sumitomo Electric Industries** say that the devices covered are capable of transmitting over 20 km or more.

● **Finisar**, the Sunnyvale, CA, optical component and subsystem manufacturer, reported total revenue of \$185.6 million for fiscal 2004, which ended on April 30. In its

fourth quarter, Finisar made a net loss of \$24.5 million on sales that rose 43% on the equivalent period in 2003 to \$57 million. The company made a net loss of almost \$114 million in 2004.

● **Denselight Semiconductors**, which manufactures optoelectronic chips based on InP, says that its superluminescent LEDs (SLEDs) are now carrying live traffic in optical networks. The SLEDs are the only such devices to be Telcordia-qualified, it says.

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 **ACCENT**
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Newport set to buy Spectra-Physics

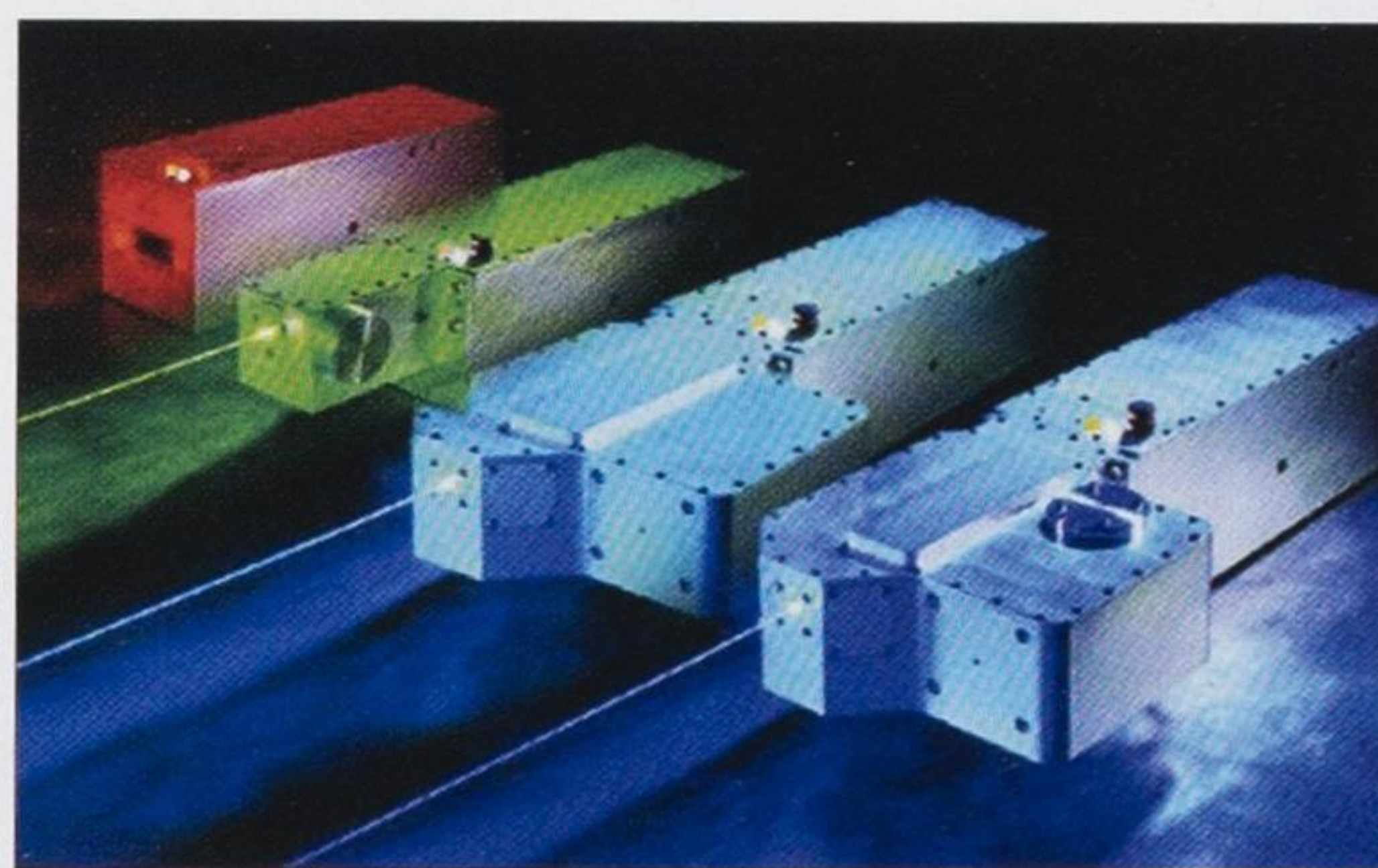
Newport Corporation has signed a definitive agreement to purchase Spectra-Physics, the optical technologies business of Thermo Electron Corporation, for \$300 million.

Newport supplies a wide range of advanced-technology products and systems, including automated assembly and test systems used in the manufacture of electronic and communication devices.

Spectra-Physics is one of the world's leading suppliers of lasers, and has a vertically integrated manufacturing facility in Tucson, AZ, that produces high-power laser diode bars and modules. Spectra-Physics Semiconductor Lasers was formerly known as Opto Power Corporation.

The purchase price comprises \$200 million in cash, \$50 million in Newport Corporation common stock, and a \$50 million promissory note bearing 5% interest and payable in 2009. The deal is subject to regulatory approval, and is expected to close this month.

"This unique combination brings together



Newport will acquire the Spectra-Physics product portfolio, which includes a high-power laser diode manufacturing facility in Tucson, and the "Hippo" series of diode-pumped solid-state lasers shown here.

what we believe are the technology leader in lasers and the technology leader in photonics instrumentation, motion control and automation to create a photonics industry powerhouse," said Robert Deuster, Newport's chairman and CEO. "The combined company will become the premier global resource for

customers who need to make, manage and measure light."

The acquisition is expected to create a company with around \$400 million in annualized sales. Newport reported sales of \$134.8 million in 2003, while Spectra-Physics had sales of approximately \$200 million.

Newport's sales for the first quarter of 2004 totaled \$42.4 million, an increase of approximately 27% compared with \$33.3 million in the first quarter of 2003. Spectra-Physics' first-quarter 2004 sales were up 16% to about \$58 million, versus approximately \$50 million in the comparable quarter of 2003.

Deuster added that he expected the deal to create many new and expanded opportunities for Newport in markets for photonics, biophotonics and nanotechnology. The acquisition will add more than 5000 products sold by Spectra-Physics to the 10,000-plus products offered by Newport. The combined company will have more than 2000 employees and 15 manufacturing plants in five countries.

Sony makes triple-wavelength laser source

Sony has developed a three-wavelength optical source that could drive the convergence of three different recording media formats.

Capable of playing and recording Blu-ray discs, as well as conventional DVD and CD media, the optical head prototype features lasers emitting at 405, 660 and 785 nm in a single package.

The three laser emissions are dealt with by a single optical system featuring two separate optoelectronic integrated circuits (OEICs), one for the Blu-ray format and a second that handles both CD and DVD wavelengths. The more complex optical design means that 20 parts are used in the prototype head, compared with just seven for a standard DVD/CD. However, Sony's stand-alone Blu-ray head already requires 19 parts even without the

extra CD/DVD capability.

The prototype optical head measures 82 x 50 x 32 mm, similar to that of Sony's existing Blu-ray product. Conventional DVD/CD heads are about half this size.

Although Sony's laser chip package is said to be a "single unit", it actually features two separate chips. In the company's schematic representation, a chip containing the GaAs-based red and near-infrared sources sits on top of the GaN-based device required for blue-violet emission.

According to Sony, the three sources will not emit light simultaneously. The company says that it is targeting commercialization of the three-wavelength head within two years. It plans to reduce the number of parts used and improve reliability.

Modulight supplies lasers for meteorology

Modulight, a supplier of semiconductor laser products based in Tampere, Finland, has entered into an exclusive multiyear agreement with another Finnish company, Vaisala, to supply specialized laser diodes for Vaisala's new products for meteorological applications.

"This agreement gives us new opportunities in environmental measurements and helps

to provide unparalleled quality products to our customers," said Hannu Tuominen, division director of Vaisala Solutions.

Vaisala develops and manufactures industrial and environmental measuring products, and has customers that include national meteorological services, aviation, road and rail authorities, and public utilities.

Intune launches gas and oil well sensor

The yield of oil and gas wells could be increased by a new instrument that analyzes changes in the properties of laser light transmitted and reflected through an optical fiber strapped to a pipe in a well. Intune Technologies' AltoWave5500 is a sensor that performs temperature, pressure or strain measurements in the oil, gas and civil engineering industries.

John Dunne, CEO of Intune Technologies, said that oil extraction is often undertaken blindly. "Active electrical sensing is sometimes used, but with high temperatures and dangerous gases it is not suitable for permanent deployment," he explained.

Along the fiber, typically at intervals of 100 m, are inserted fiber Bragg gratings, each providing reflectance at different wavelengths, and also 20 cm lengths of metal. Changes in temperature or pressure around the metal inserts alter the local strain in the fiber, changing the properties of the light transmitted through it.

A semiconductor laser scans from 1528 to 1568 nm in 0.0001 nm steps, and examination of the light diffracted reveals the temperature, pressure or strain in the local environment of each sensor.

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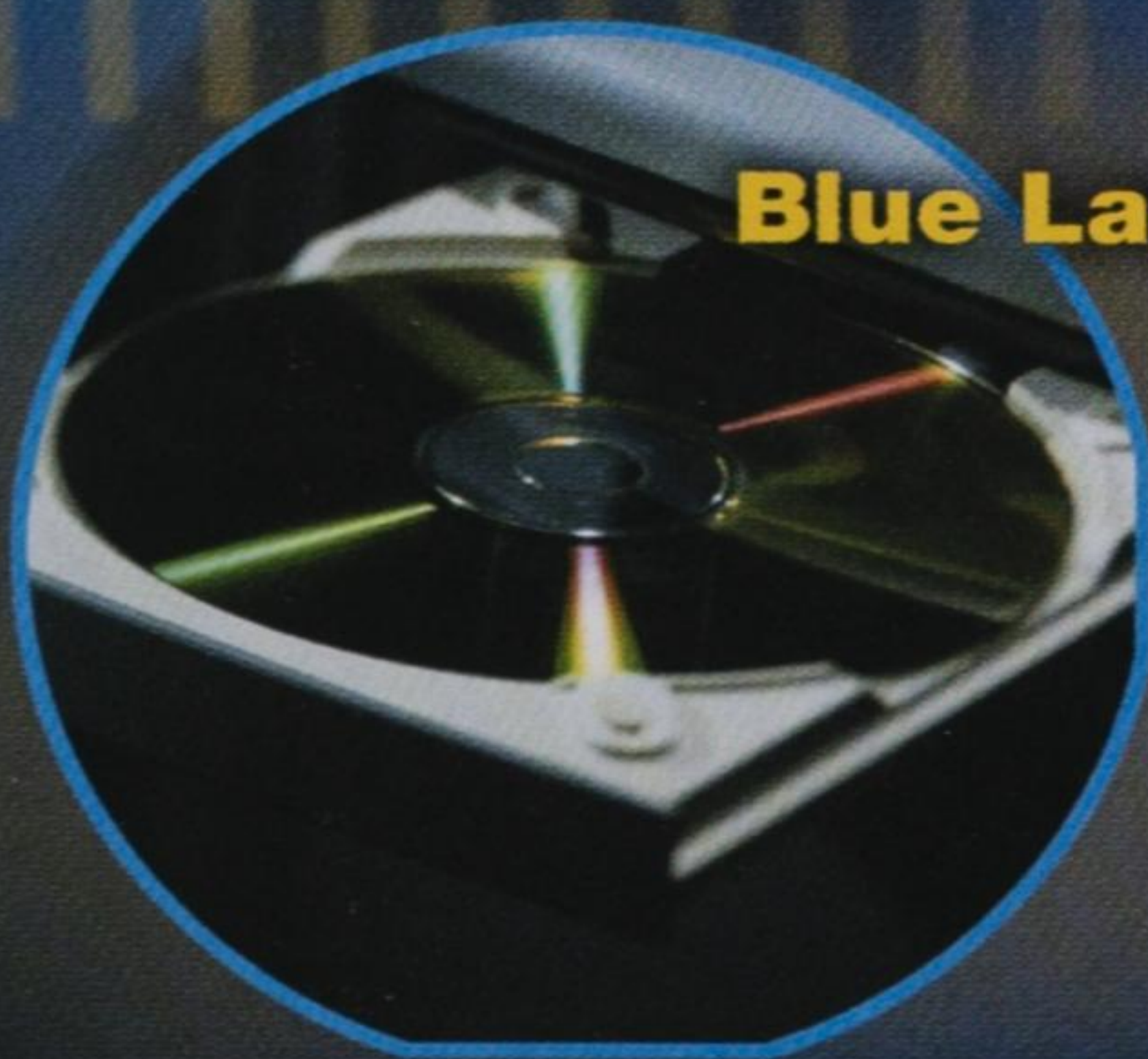


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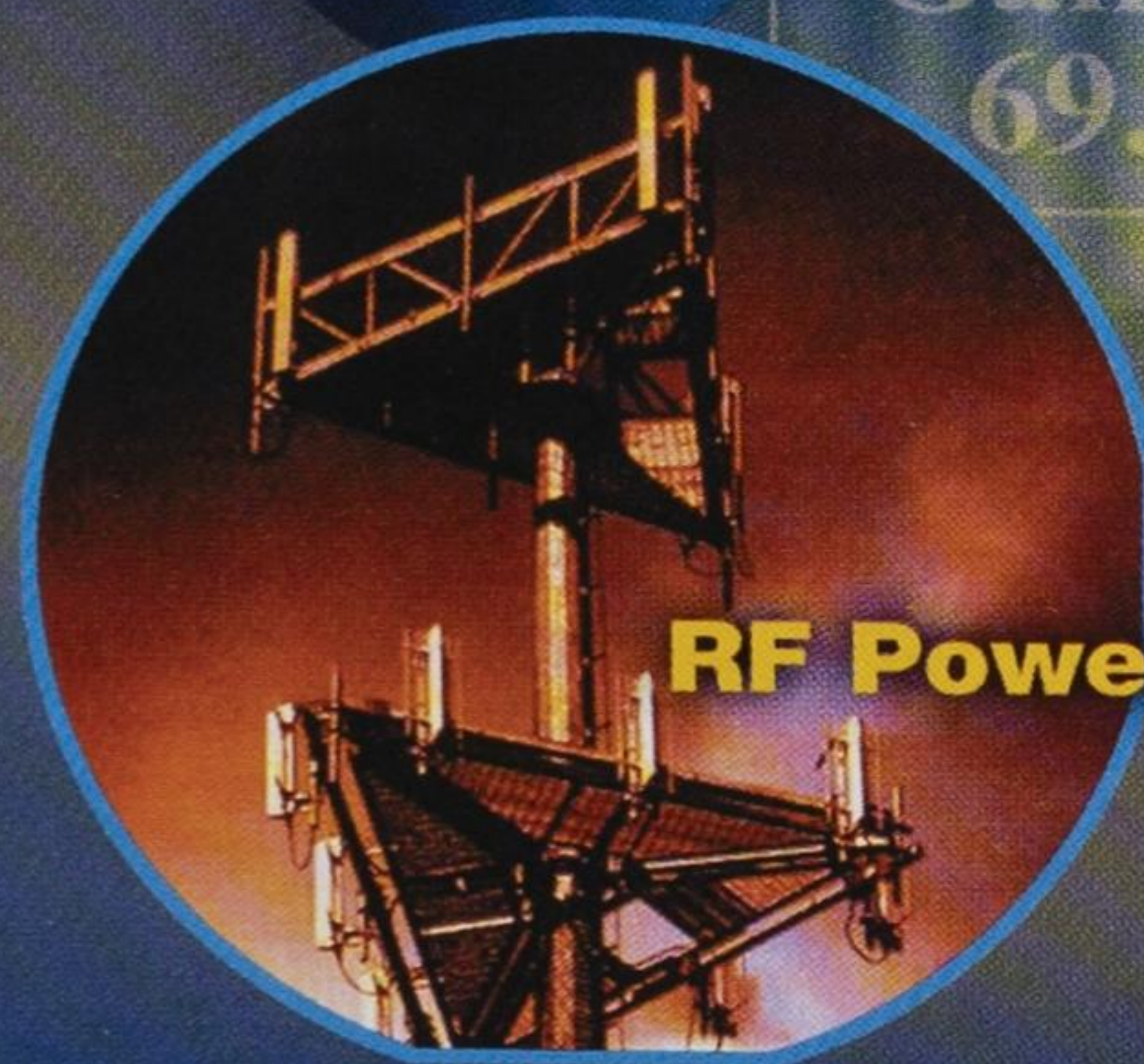


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AmberWave Systems secures \$21 m backing

AmberWave Systems, the Salem, NH, company that specializes in strained-silicon technology, has raised \$21 million in its latest financing round.

Venture capital group 3i acted as the lead investor, and was joined by previous investors Adams Capital Management, Arch Ventures, Telesoft Partners and The Hillman Companies.

According to AmberWave and 3i, the investment ranks in the top five financing rounds of semiconductor companies in the first six months of 2004.

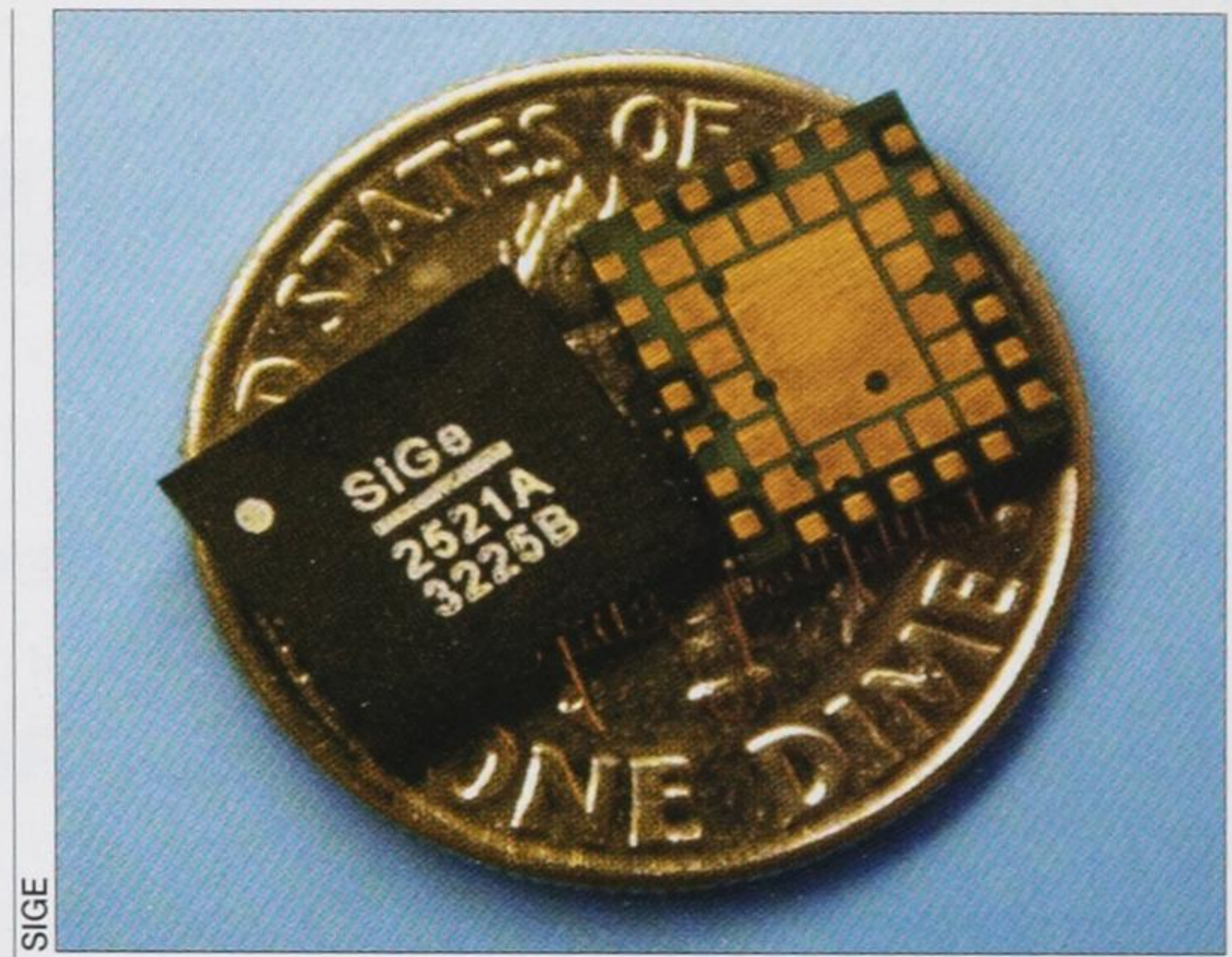
AmberWave's technology allows chip manufacturers to increase the speed of

CMOS-based circuits by 17% at equivalent power consumption. Chips operating at the same speed as standard CMOS-based ICs enjoy a 34% reduction in power consumption.

The technology was developed at MIT and AT&T Bell Laboratories, and AmberWave has more than 100 issued and pending patents.

"The semiconductor industry's biggest players – IBM, Texas Instruments, Intel, Motorola, Toshiba, TSMC to name a few – are announcing their interest in strained silicon," said Robert Faubert, AmberWave's CEO.

3i partner Marko Maschek will now join AmberWave's board of directors.



SiGe Semiconductor, based in Ottawa, Canada, has released the SE2521A, a custom variant of its SE2526A device. The chip is designed to enhance coverage and reduce implementation costs of 54g wireless LAN products sold by Broadcom Corporation. "SiGe Semiconductor's capabilities fit well with and support our strategy to deliver products that will greatly improve the Wi-Fi user experience," said Brian Bedrosian, senior product line manager for Broadcom's home and wireless networking business unit. The SE2521A is currently being adopted by customers of Broadcom's 54g wireless LAN products. The module is ramping to production for supply to this rapidly growing market, which SiGe Semiconductor expects to reach in excess of 80 million units this year.

European researchers develop advanced hafnium high-κ process

Research at the Franco-Italian semiconductor manufacturer STMicroelectronics, carried out in conjunction with Aixtron and CEA-Leti, has led to an advanced process technology for the creation of ultrathin transistor-gate insulation layers.

Using an atomic vapor deposition process and Aixtron's reactor technology, the research team claims that it has produced $\text{HfO}_2/\text{SiO}_2/\text{Si}$ stacks with an equivalent oxide thickness of 1.15 nm, and leakage current densities of 0.068 A cm^{-2} at 1.5 V.

The process targets low-power applications at the 65 and 45 nm CMOS transistor tech-

nology nodes, and significantly reduces transistor leakage current by the deposition of "high-κ" gate-insulation material.

"These proof-of-concept results are a first for this process technology," said Daniel Bensahel, project leader and front-end program director at STMicroelectronics. The technology will assist with the demand for miniaturization of microelectronics, as described by Moore's law, via the international technology roadmap for semiconductors.

CEA-Leti, based in Grenoble, France, is a microelectronics and microtechnologies research laboratory.

Gennum buys SiGe's optical IC product line

SiGe Semiconductor has sold its Lightcharger product portfolio to fellow Canadian firm Gennum Corporation in a cash deal. The value of the deal was not disclosed.

The Lightcharger portfolio includes SiGe-based transimpedance amplifiers (TIAs) and limiting amplifiers operating at 1.25, 2.5, 4 and 10 Gb/s. As part of the deal Gennum is also acquiring the SiGe development team, largely based in the UK, in addition to product-related test equipment.

"The acquisition of 10 Gb/s TIA products complements our CDR [clock/data recovery] products for the 10 Gb/s XFP [eXtensible Filtering Pipelines] optical transceiver mar-

ket," said Gary Beauchamp, vice-president and general manager of data communications products at Gennum. "This acquisition also gives Gennum immediate entry into all other 10 Gb/s optical transceiver markets, the new 4 Gb/s fiber channel (storage) optical transceiver market, and the established 1.25 and 2.5 Gb/s transceiver markets."

"We will work closely with Gennum to ensure a seamless transition for our optical customers, who will benefit from Gennum's broader range of products," added Jim Derbyshire, CEO of SiGe Semiconductor.

Gennum already has design teams based in Burlington and Ottawa, Canada.

IBM's detector ideal for interconnects

Researchers at the chip manufacturing giant IBM have developed a high-speed photodetector based on germanium-on-insulator technology. The detector is compatible with the CMOS chip manufacturing process and is said to be ideal for use in optical interconnects.

"This is a major step towards overcoming the biggest bottleneck in system performance, the interconnect between chips," said T C Chen, IBM Research's VP of science and technology. "Optoelectronic components such as these photodetectors will be essential for future high-performance computing."

IBM's photodetector operates at 29 GHz, suggesting that it could be used to detect signals of over 50 Gbps. At an operating voltage of 1 V, it detects 850 nm light (the conventional output wavelength of GaAs-based VCSELs) with an efficiency of about 40%, two orders of magnitude better than silicon.

GaN substrates offer high

GaN substrates are manufactured by only a handful of companies at prices prohibitive to volume production, but offer great potential for high-performance devices. **Richard Stevenson** reports.

The GaN component market was worth \$1.35 billion in 2003 according to market research firm Strategies Unlimited. By 2007 this is predicted to soar to \$4.5 billion, with GaN-based LEDs, lasers and electronic devices contributing \$4 billion, \$402 million and \$129 million, respectively.

However, unlike well established GaAs and InP-based components, GaN-based devices are almost exclusively grown on foreign substrates such as sapphire (Al_2O_3) and SiC. Growth on foreign substrates is not ideal, as differences in lattice constant and coefficients of thermal expansion result in high defect densities and compromised device performance. However, traditional methods of manufacture such as the Czochralski and Bridgman techniques are not available to GaN substrate manufacturers, due to the extremely high temperatures and pressures required to melt the materials.

Today, GaN substrates are produced by vapor-phase transport or epitaxial-type growth by a small number of companies, including Cree, Kyma, TopGaN and Sumitomo Electric. Wafer sizes are small and prices are high, and it is likely that volume products such as LEDs will continue to be fabricated on sapphire for the foreseeable future. Alternative hybrid options with higher dislocation densities are also available. For example, the US substrate supplier TDI produces GaN-on-sapphire templates, which reduces production times and equipment downtime.

Cree focuses on 2 inch substrates

Cree, based in Durham, NC, develops and manufactures semiconductor materials and devices using SiC, GaN and Si substrates, and is one of the largest companies with GaN capability. Its technology was acquired by purchasing ATMI's fledgling GaN technology business unit, a deal completed in April 2004 for \$10.25 million. Today, it offers 330 and 400 μm thick GaN wafers in three sizes (10 mm, 18 mm and 2 inch) and at various

grades, with dislocation densities as low as $3 \times 10^6 \text{ cm}^{-2}$ and usable surface areas of between 80 and 95%.

George Brandes, head of Cree's GaN division, said: "Our aim is to produce GaN substrates for the optoelectronic and electronic device community. Right now we are shipping conductive wafers to a number of optoelectronics manufacturers. We also sell and ship semi-insulating GaN substrates, targeting electronic devices such as high-frequency, high-power amplifiers." Brandes was not willing to disclose Cree's production capacity, the size of the GaN division, or wafer prices. However, *Compound Semiconductor* has learned that some researchers have paid in the region of €2000 (\$2400) for a 0.5 inch GaN substrate.

Cree uses a hydride vapor-phase epitaxy (HVPE) approach to produce GaN material. It has demonstrated production of a 3 inch substrate, although Cree is focused on improving 2 inch material, as it believes most firms want to manufacture at this size. The company has two different processes: a single-wafer approach and a cost-effective boule-based approach, which it claims produces many substrates of higher-quality material. Commercial GaN substrate reactors are not available, and Cree, like other GaN substrate manufacturers, uses a custom-designed reactor. Lack of commercially available reactors arguably stifles development of GaN substrates. Brandes commented: "Clearly, if you could go out and buy a machine today that would yield wonderful results with a click of the button then the field would accelerate. But a lot of know-how goes into these machines. Right now I see substrate manufacturers choosing to keep their technology in-house."

Brandes is optimistic about the technology: "GaN is a viable product right now. You can go out and buy 2 inch material, it is decent quality, and as we go forward prices will be more competitive, and device applications will broaden. Nothing intrinsic in how we make our substrates leads me to believe that

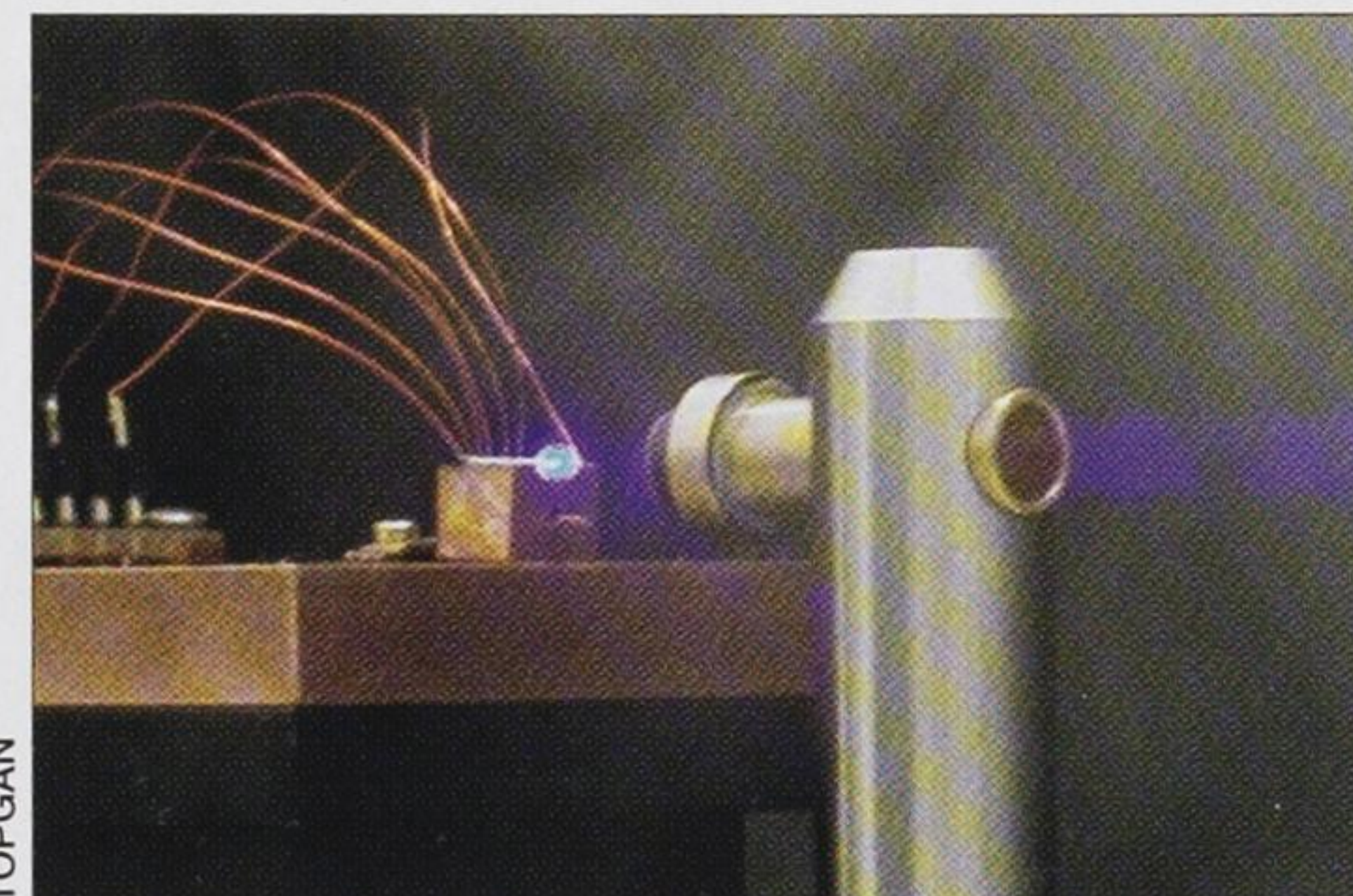


Fig. 1. Blue-violet emission from a GaN-based wafer produced by TopGaN. The lasers have outputs of up to 1.9 W per facet, emit in the 390–430 nm region, and are fabricated on GaN substrates.

the cost will not be competitive. Boules aren't expensive, the materials aren't expensive, and the manufacturing processes are known."

Kyma to produce 4 inch prototypes

Kyma Technologies, formed in 1998 and based in Raleigh, NC, employs about 20 people. It aims to be a world-class GaN substrate supplier, and has no plans to make epiwafers. Over the last year it has expanded production capacity, shipping more substrates to optoelectronic customers. Kyma has already demonstrated prototype 3 inch substrates, and by the end of the year aims to ship 3 inch substrates to customers, and also to produce prototype 4 inch substrates for microelectronic applications.

Ed Pugh, Kyma's CEO, told *Compound Semiconductor* that demand for substrates is very high, with enquiries from all over the world. "Customers have approached us for applications that they can't achieve on SiC or sapphire. In particular, they seek out GaN for low dislocation densities and subsequent improvements in device performance. They will at least evaluate GaN." Pugh revealed that optoelectronic customers were only interested in 2 inch material, better suited to development than production. He acknowledged that Si and sapphire already have a foothold, and that GaN substrates will find it difficult to compete in terms of price, but believes substrate prices will fall due to process improvements, and greater supply and demand.

Kyma uses a fast-growth vapor-phase process to fabricate GaN substrates. The tech-

h performance at a price

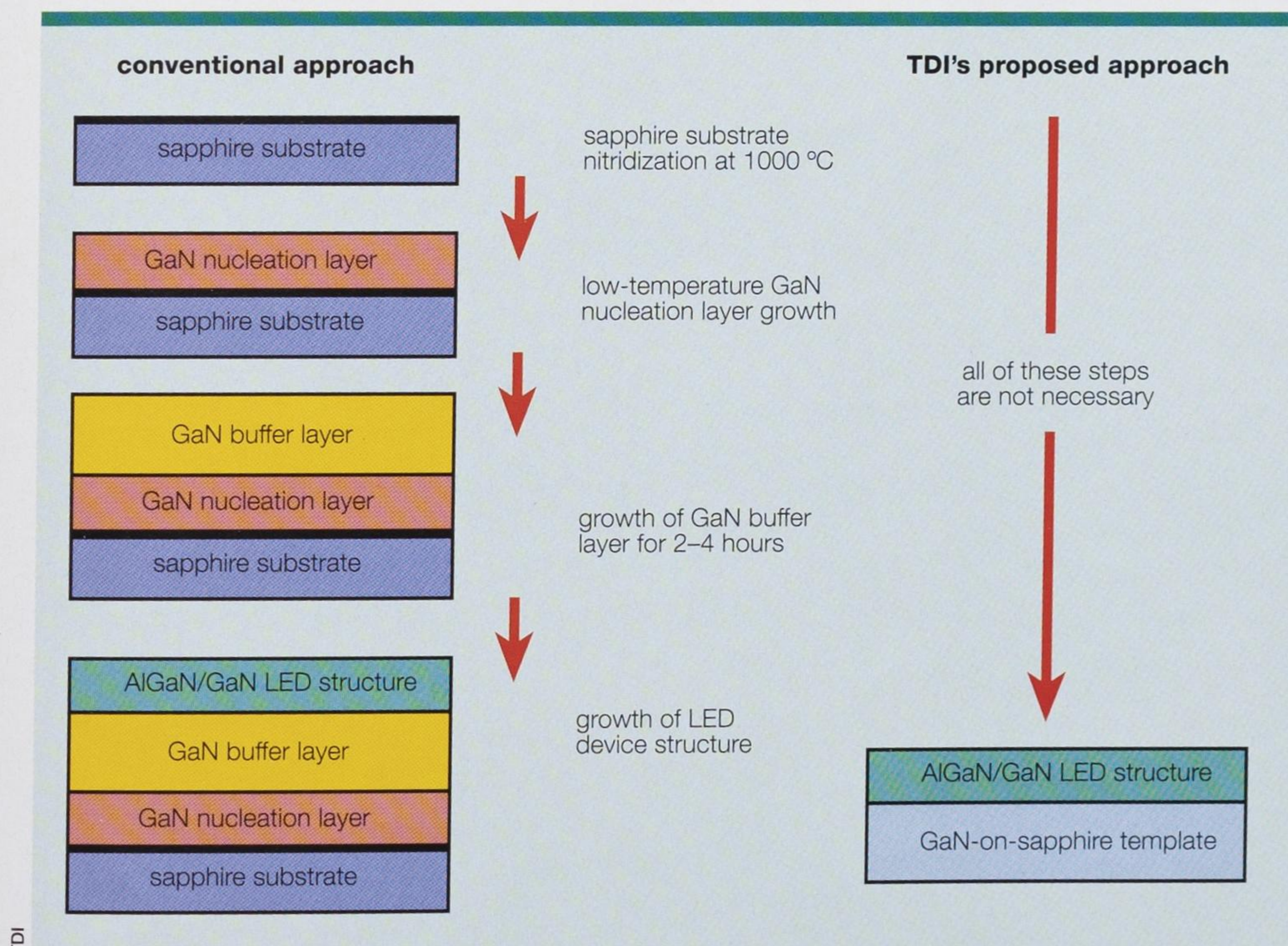


Fig. 2. GaN-on-sapphire templates eliminate many growth processes required to make LEDs on sapphire substrates, enabling faster production and reduced reactor downtime.

nology combines a chemical vapor-phase process to grow bulk GaN material and a vapor-phase process, licensed from North Carolina State University, to provide a starting template. According to Kyma, the process has a growth rate up to 10 times faster than any other commercialized deposition process for nitride-based materials.

Extreme growth conditions

TopGaN is a spin-off from Unipress, the High Pressure Research Center operated by the Polish Academy of Sciences in Warsaw. Founded in 2001, it employs about 20 people. It has retained an academic outlook, with universities forming the majority of its customers.

TopGaN has produced GaN substrates using relatively extreme growth conditions, with pressures of 15,000 atm and temperatures of 1600 °C. One growth can produce 20–30 crystals of 10 mm in diameter, exhibiting dislocation densities of only about 100 cm^{-2} . Mike Leszczynski, vice-president and head of epitaxy, explained: "It's not a growth technique for millions of wafers, but just for spe-

cial devices." Recently, laser diodes with a $15 \mu\text{m} \times 500 \mu\text{m}$ cavity and output powers per laser facet of 1.89 W have been made using these substrates (figure 1). TopGaN claims that this is the highest power reported for nitride-based lasers on any substrate.

However, TopGaN is unable to extend this growth technique to 2 inch material. Instead, it begins with a $5 \mu\text{m}$ thick MOVPE-grown layer of GaN on a 2 inch sapphire substrate, patterned for epitaxial layer overgrowth (ELOG). The high-pressure growth conditions used result in a liquid-phase epitaxy process, enabling growth of stripes with a dislocation density of 10^6 cm^{-2} over more than 20 μm , compared with 2–3 μm for ELOGs grown from the gas phase by MOCVD or HVPE.

Template solution?

Today GaN substrates are too expensive for both commercial production and academic research. For example, despite nitride research dominating the recent 12th International Conference on MOVPE, only a handful of groups used GaN substrates. An interim solu-

tion for growers is offered by TDI, which sells GaN-on-sapphire templates in 2, 3 and 4 inch sizes. TDI employs about 20 people and occupies a 3200 m² facility in Silver Spring, MD. It currently ships hundreds of 2 inch wafers per month, and also some 4 inch material.

Vladimir Dmitriev, TDI's president, explained the benefits of using templates over sapphire substrates for growth of LEDs. Growth times and material costs are reduced, since all the steps up until the growth of the LED structure are removed (figure 2). In addition, reactors require less maintenance due to the decreased deposition of GaN, reactor downtimes are reduced, and lifetimes of reactor components are increased. Templates also circumvent problems associated with growth of the foundation layer, which may be subject to intellectual property issues. A typical growth sequence for blue LED production with sapphire substrates involves pre-treating the substrate by heating it to between 1000 and 1100 °C, depositing a nucleation layer at 600 °C, and then growing a 2–4 μm GaN foundation layer at 1000 °C, before finally growing the LED structure, which has a thickness of about 1 μm . For LED growth, TDI's GaN templates can offer several benefits.

TDI uses a HVPE process to deposit 2–5 μm of Si-doped GaN on sapphire substrates with a deposition rate 100 times that of MOCVD growth. It believes that the material quality associated with the HVPE process, which has a yield of over 90%, is actually higher than that of MOCVD. Dislocation densities are 10^8 cm^{-2} , and are expected to decrease as the growth process is improved.

Laser diode possibilities

Until GaN substrate prices fall substantially, sapphire, which costs \$40–50 for a 2 inch substrate, will remain the first choice for volume production. In fact, for GaN-based LEDs, which are today successfully produced on foreign substrates, manufacturers may never transfer to GaN. Competition could instead come from TDI's substrates, which cost \$120 for a 2 inch wafer. However, for laser diodes, GaN substrates are a much more attractive proposition, and here a market for GaN substrates may develop.



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Atomic force microscopy helps improve GaN LED performance

With LED manufacturers narrowing device quality requirements, improvements to structural and optical properties of epiwafer surfaces have become critical. **Doru Florescu** from Veeco Instruments describes GaN-based LED layer optimization using atomic force microscopy.

As GaN-based LEDs expand into large-screen backlighting, outdoor signage and general illumination applications, manufacturers are seeking to improve the optical output efficiency of devices. Enhancements to packaging designs are one way of addressing performance thresholds to improve the device quality. Optimizing the surface morphology of LED constituent layers has become another key approach. Atomic force microscopy (AFM) has shown promising results in characterizing and helping to optimize GaN-based layers grown by MOCVD. In conjunction with finely tuned process parameters, AFM helps to significantly reduce surface defects, and ultimately contributes to brighter and more efficient devices.

Surface topography

Improving GaN epilayers via AFM involves analyzing epitaxial surfaces measured at the nanoscale level. To obtain high-resolution images (typically with sub-Angstrom vertical and nanometer-scale lateral resolution), AFM uses small probes to monitor surface topography through direct, non-destructive contact with material samples. Unlike methods that can damage sample surfaces due to poorly controlled frictional forces, Veeco's "tapping mode" technique incorporates an intermittent contact process that avoids dragging probes across surfaces during scanning.

Tapping mode AFM uses a probe with an end radius of only a few nanometers attached to a flexible cantilever. To provide a high-resolution image, the probe tip intermittently contacts the sample surface. During raster-scanning, the cantilever is oscillated at or near its resonant frequency, typically 100–400 kHz, depending on the type of cantilever, using a piezoelectric crystal. Changes in epilayer surface features modify the oscillation amplitude during the scan, generating a precise topographical image in a non-destructive manner. Since physical contact between the probe and

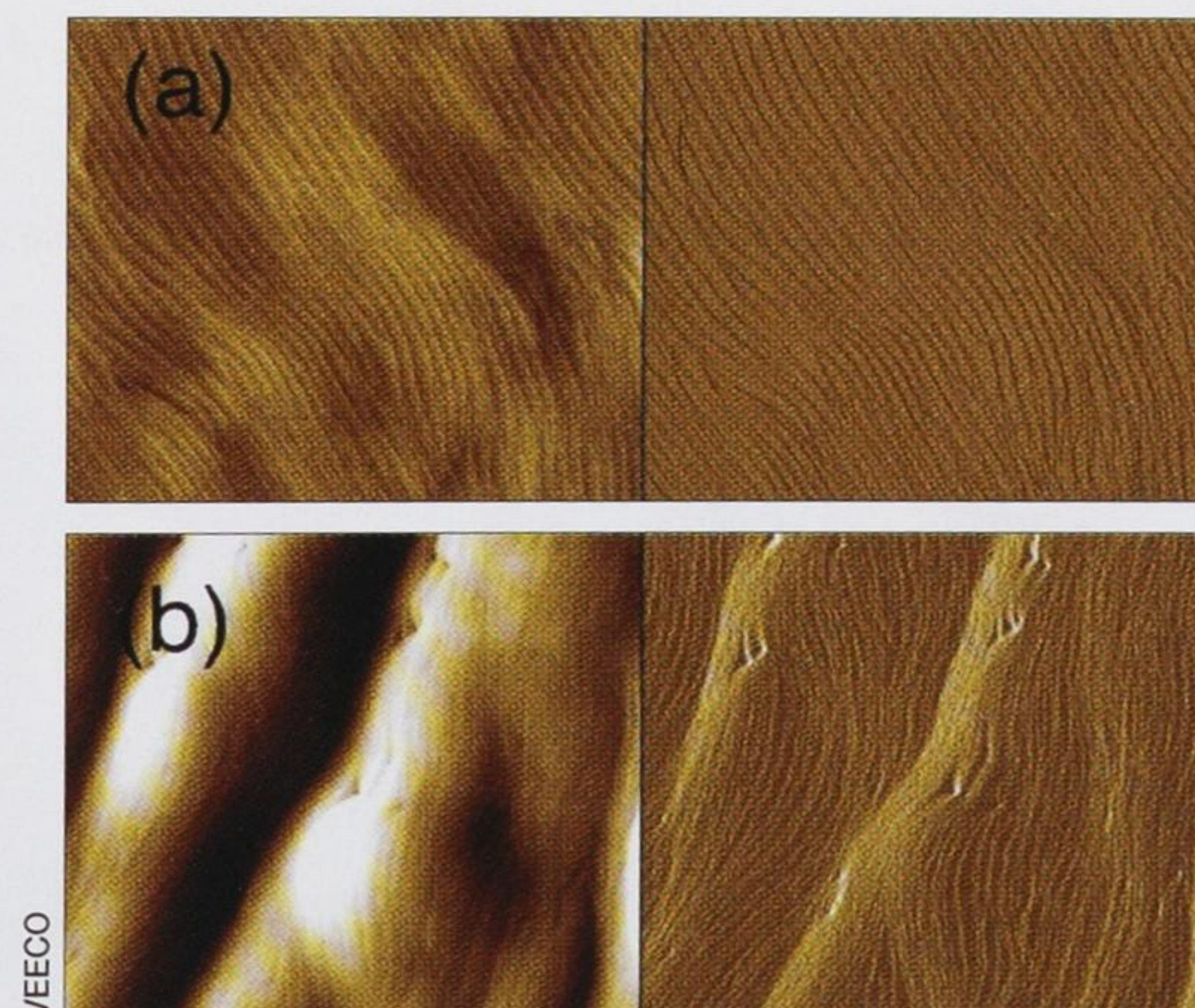


Fig. 1. Simultaneously acquired height (left) and amplitude (right) AFM images ($5\ \mu\text{m} \times 5\ \mu\text{m}$) of Si-doped GaN layers. Amplitude images (RMS of the cantilever amplitude signal) provide a slice through the height image, and show features more clearly. The vertical scale, dZ , which is the maximum vertical distance between the highest (white) and lowest (black) data points in the image, is 10 nm. (a) Smooth surface with atomic terrace lines and few dislocations. (b) Rough surface showing grain boundaries (alternating dark and light features) and a large number of dislocations pinning the atomic terrace steps. Top-view images such as these represent surface height.

sample is limited to short "taps", shear is effectively eliminated. This leads to long-lasting probes and higher-resolution images.

Using nanoscale AFM surface morphology readings, growers can implement multistage optimization processes to attain smooth surfaces and control doping levels throughout device structures. Surface features such as "V-groove" defects that negatively affect performance can be minimized and controlled. In the case of MOCVD-grown GaN devices, 470 nm LEDs with an unpackaged chip-level output power in the 4–4.5 mW range and forward voltage less than 3.2 V at 20 mA have been consistently achieved.

Fine-tuning LED structures

When used properly, AFM can be an effective tool for reducing the roughness of GaN-based LED surfaces at each layer in the structure, monitoring dopant levels in certain layers, and helping to determine substrate quality. Because substrate surface morphology can dramatically impact the quality of subsequently deposited films, selecting a substrate with the appropriate physical properties can be pivotal. For example, although widely used for GaN growth, sapphire substrates have lattice parameters that are not an exact match to GaN. The high density of crystalline defects caused by this mismatch amplifies the importance of the surface finishing of sapphire substrates. Using the detailed view provided by AFM, potential problems such as surface contamination and scratching due to aggressive polishing are easily observed and avoided.

The major benefits of using AFM to optimize growth are realized in the n-type, active and p-type layers of GaN structures. Using material samples grown on an MOCVD platform, AFM proved an effective method for improving yield quality via its monitoring of the effects of growth condition adjustments. For bipolar, vertical GaN-based optoelectronic devices, silicon-doped GaN is the leading material for n-type layers, with a smooth surface essential for achieving sharper interfaces in LEDs. AFM provides a clear indication of surface quality, with a smooth surface showing atomic terrace lines and few dislocations, and a rough surface showing evidence of grain boundaries and numerous mixed dislocations (figure 1). Since the n-type layer is used as a template for the active region, subtle adjustments in the MOCVD process based on AFM observations of this layer can greatly improve overall device performance.

Due to the tunable bandgap energy of InGaN, multiple quantum wells (MQWs) are commonly used as active layers for blue and green LEDs and laser diodes. Similar to the n-type layer, smooth surfaces are critical for

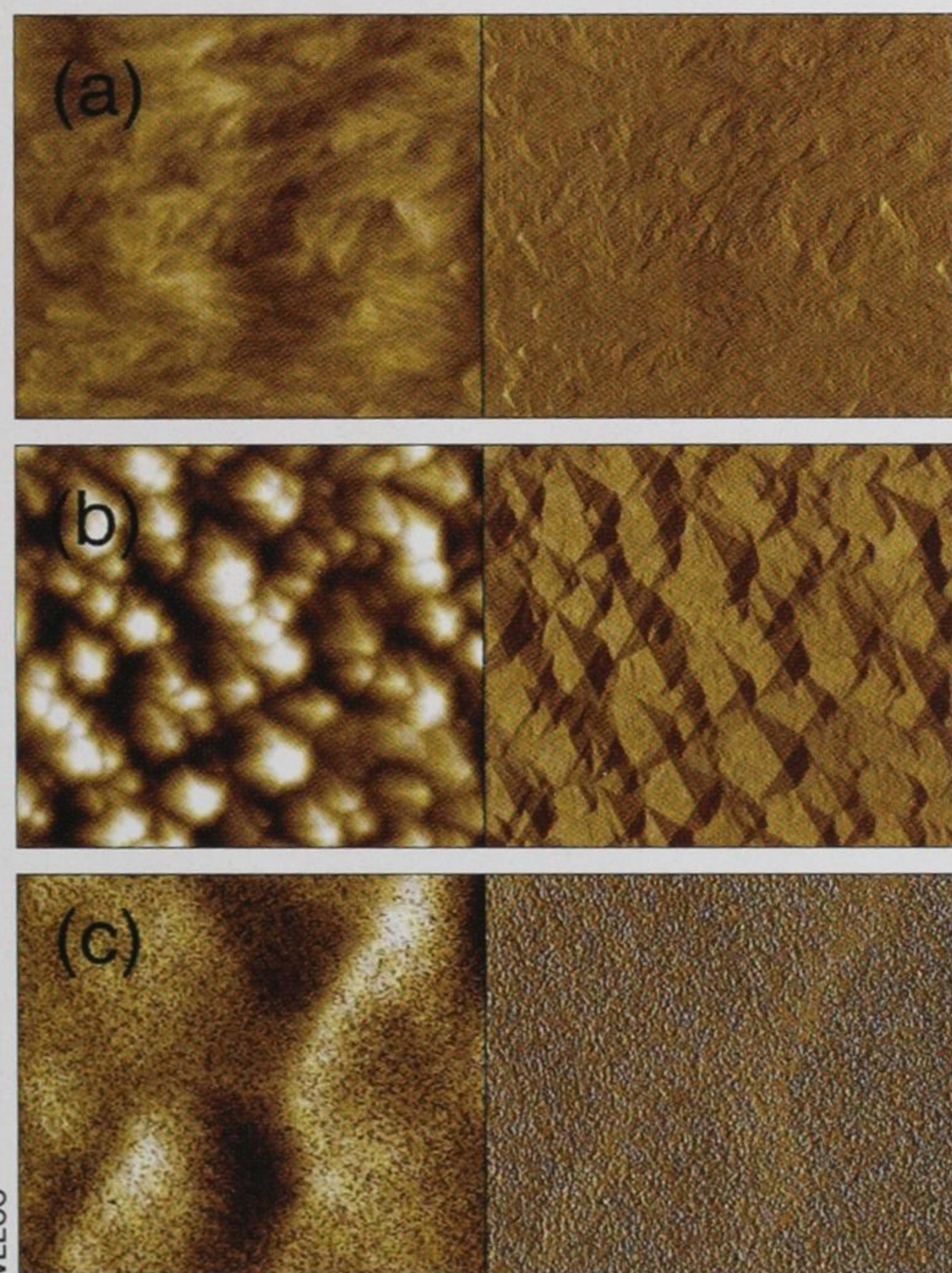


Fig. 2. AFM height and amplitude images ($50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$; $dZ = 80\text{ nm}$) of three magnesium-doped, MOCVD-grown GaN layers placed directly above the active region in GaN LEDs. (a) Smooth surface with very few features. (b) Rough surface displaying pyramid-like features indicative of improper magnesium doping control. (c) Somewhat smooth surface, but with a high degree of cracking, which negatively affects the heat/light extraction from the device.

high-power applications. In this case, AFM can screen for cracked surfaces and inclusions that are detrimental to thermal stability. Surface morphology of p-type layers also affects device performance. Since the p-type contact is fabricated directly above this layer, it is especially important to maintain smoothness to enhance light and heat extraction from the device. Optimized growth conditions for magnesium-doped GaN p-type layers result in few surface features, while non-ideal conditions display pyramidal features and a high degree of cracking (figure 2). In all of the layers described, as well as the substrate material, AFM can be used as both a sampling tool to monitor and calibrate manufacturing processes, and as a developmental tool for engineering new structures.

Optimizing the active layer

To demonstrate the contributions of AFM optimization phases to LED performance, a four-period InGaN/GaN MQW active region of a blue GaN LED structure was monitored.

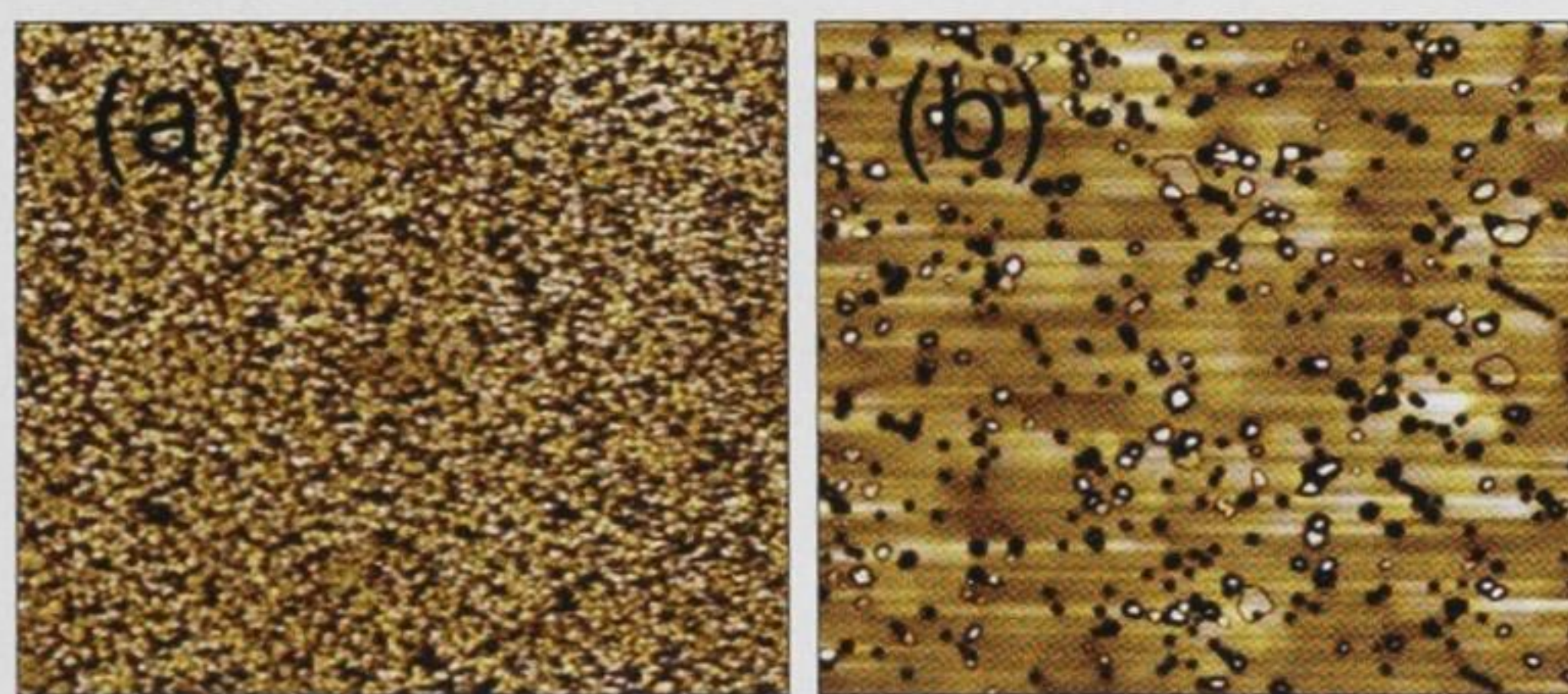


Fig. 3. $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$ height images of typical four-period InGaN/GaN heterostructures used as active regions for 470 nm LEDs; $dZ = 30\text{ nm}$. (a) Initial measurements showing a highly defective surface with severe cracking and a high density of voids. (b) Second-stage MQW structure optimization indicating a smoother surface with typical V-shaped pits (dark, non-uniform features) and inclusions (white, irregular features).

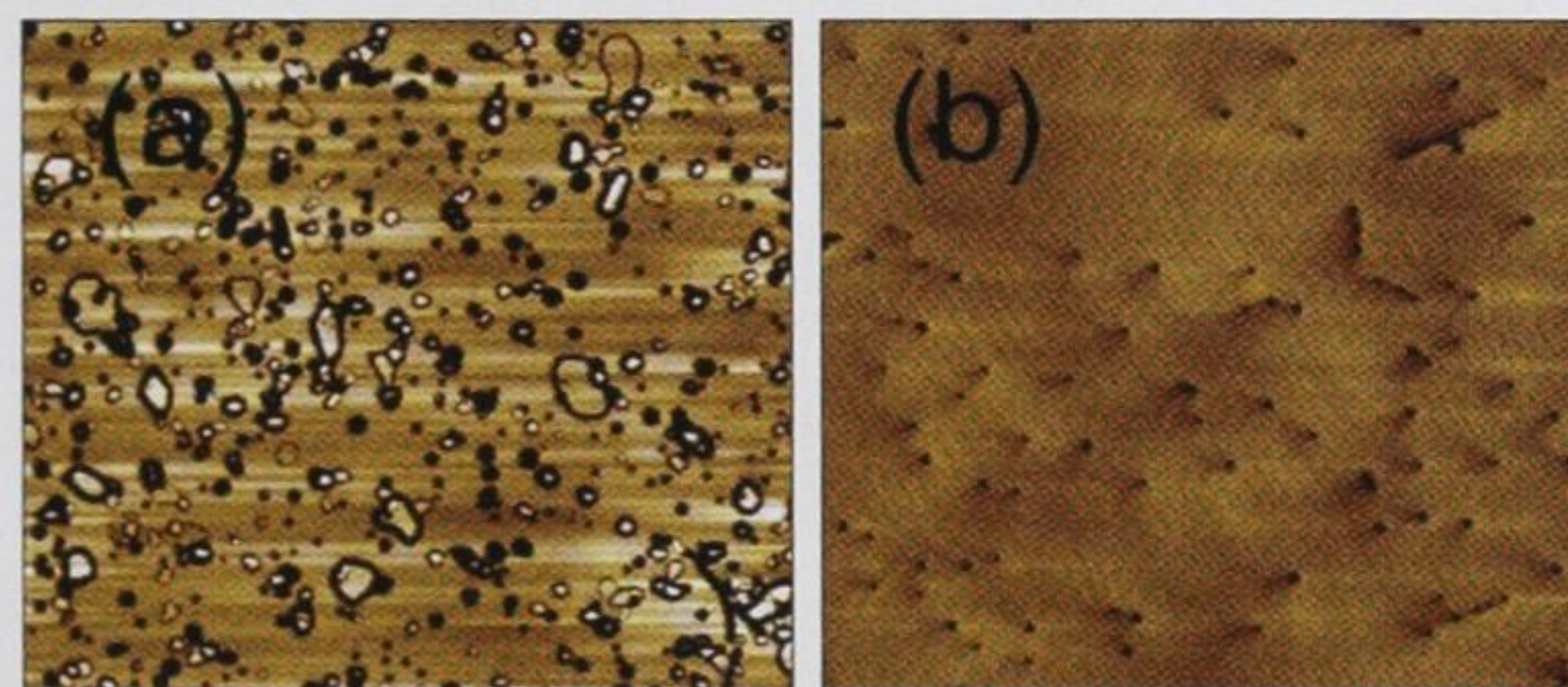


Fig. 4. $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$ height images, with $dZ = 30\text{ nm}$. (a) Second-stage MQW structure development. (b) Third-stage optimization showing a high degree of smoothness, reduced density of V-pits and no inclusions. LEDs fabricated from (b) emitted 4–4.5 mW at 470 nm.

By improving the quality of quantum heterostructures using AFM feedback as a reference, positive results are clearly visible on surface morphology images and these translate into increased device output power.

In the initial stage of development, a highly defective surface is easily observable (figure 3a), with dZ/RMS values of $38.12\text{ nm}/4.69\text{ nm}$, where RMS is the root mean square of height deviations. The image surface area differential (ISAD), another indication of surface roughness, is 5.29%. (The ISAD is the difference between the image's 3D surface area and its 2D footprint area, and for a perfect surface would be 0%.) Severe cracking leading to a high density of voids governs this active region surface. After adjusting growth conditions, a smoother surface with atomic terraces, typical V-shaped pits and inclusions is formed (figure 3b). The dZ/RMS values are now $65.72\text{ nm}/3.00\text{ nm}$ with an ISAD of 2.18%, with the higher dZ number possibly attributed to the presence of inclusions effectively elevated above the surface plane. To evaluate the

effect of the device optimization between these two phases of AFM-based development, full LEDs were fabricated using the samples described. The unpackaged, chip-level output power improved from the 1.2–2.0 mW range to the 2.5–3.0 mW range.

Using the same technique, further improvements to the optical and electrical properties of the structure were achieved by reducing the density of V-defects associated with indium-rich regions and completely suppressing the occurrence of inclusions. Using a typical morphology sample from the second stage of development (figure 4a), dZ/RMS values of $63.41\text{ nm}/5.87\text{ nm}$ were found with an ISAD of 4.8%. By precisely tuning the growth process to account for the second-stage findings, a surface with a high degree of smoothness, reduced density of V-pits and no inclusions was achieved (figure 4b). The new dZ/RMS values were $15.30\text{ nm}/0.52\text{ nm}$ with an ISAD of only 0.047%. As with the first set of improvements, full LEDs were fabricated and integrating sphere measurements were conducted. The unpackaged, chip-level output power improved from the 2.5–3.0 mW range of the second stage of development to the 4.0–4.5 mW range for the third stage of development. In addition, the third-stage sample exhibited improved thermal stability as revealed by photoluminescence measurements before and after the growth of p-contact GaN layers.

These atomic-level improvements promise to help LED manufacturers to produce the brighter, more efficient GaN-based devices that are required for future solid-state lighting applications.

Further reading

Ting *et al.* 2003 Morphological evolution of InGaN/GaN quantum well heterostructures grown by MOCVD. *J. Appl. Phys.* **94** 1461.
 Florescu *et al.* 2003 Investigation of V-defects and embedded inclusions in InGaN/GaN multiple quantum wells grown by metal organic vapor deposition on (0001) sapphire *Appl. Phys. Letts* **83** 33.
 Florescu *et al.* 2004 Using AFM to control and enhance structural and optical properties of GaN-based LEDs grown by MOCVD *Veeco Applications Note* **AN80**.

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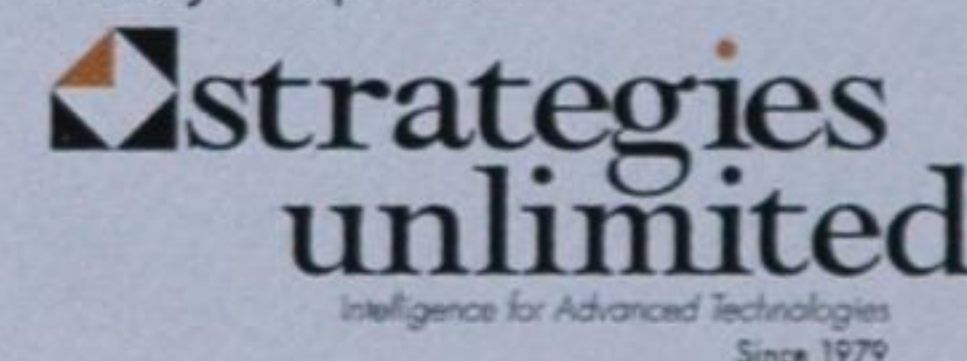
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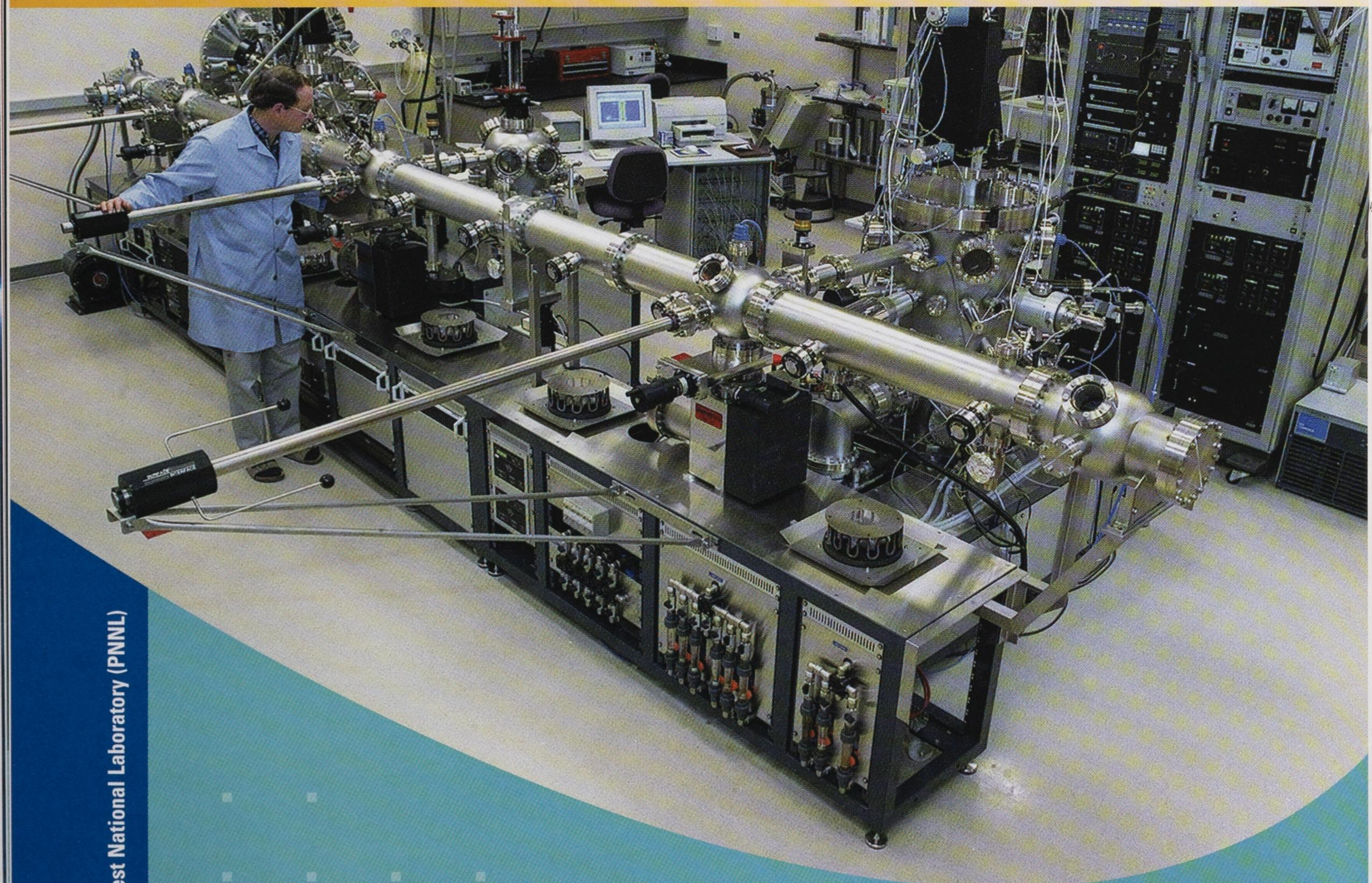


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GaN transistors and power amplifiers close in on commercialization

With the cellular infrastructure industry promising to offer III-V device manufacturers the first substantial application market for GaN-based electronics, **Ed Piner** reports on the latest efforts to push commercialization of AlGaIn/GaN HFET technology at Nitronex Corporation.

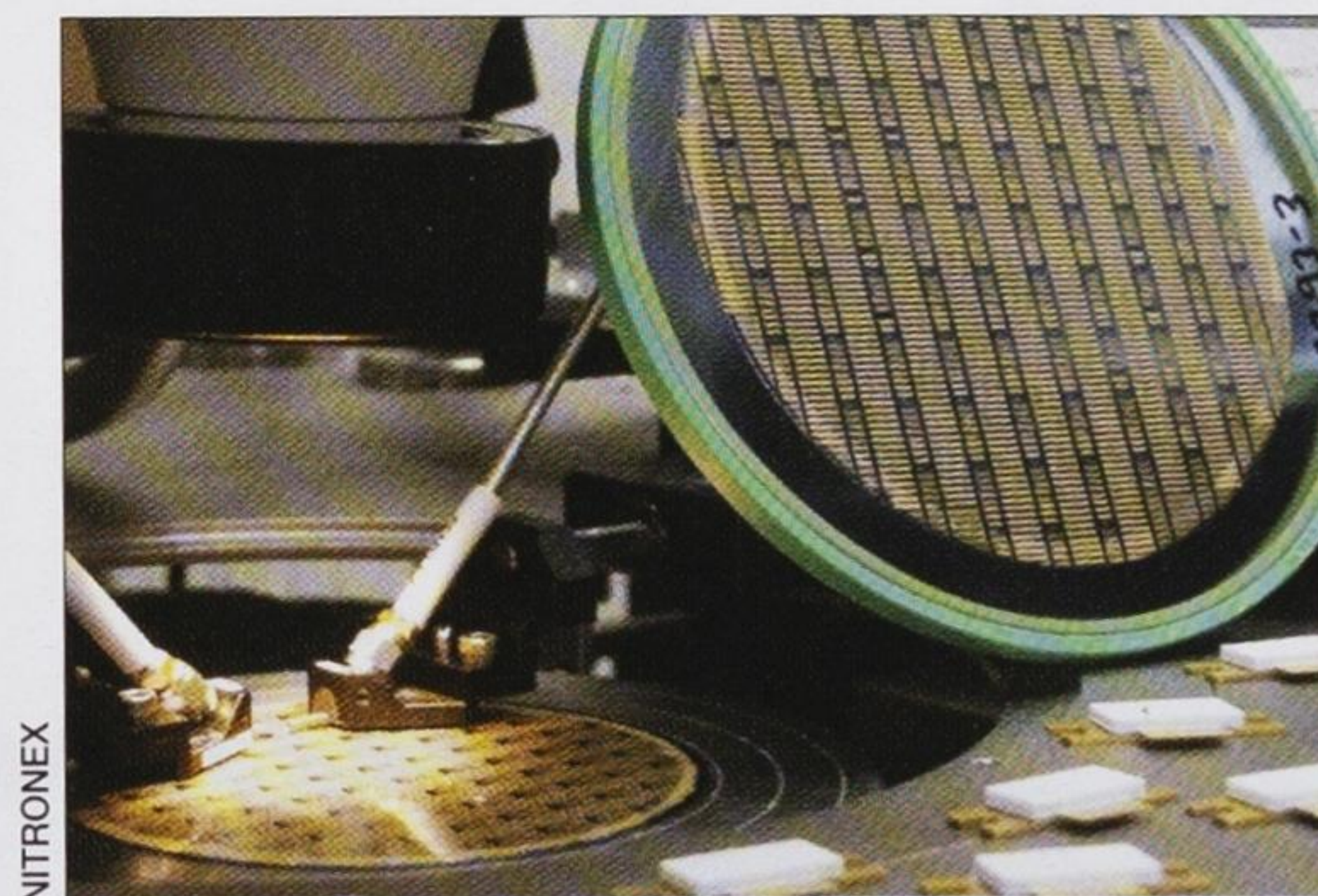
AlGaIn/GaN heterostructure field-effect transistors (HFETs) significantly extend the design space of microwave power amplifiers due to their high breakdown field, high electron saturation velocity and high operating temperature. For example, AlGaIn/GaN HFET structures can achieve gate-to-drain breakdown voltages of around 100 V/ μm and maximum current densities exceeding 1 A/mm, resulting in power densities several times higher than commercially available devices.

At the product level, these superior attributes translate into higher operating voltages which simplify system design, result in smaller chips and packages, and enable higher device impedances that can extend the achievable bandwidths. Early-generation AlGaIn/GaN HFET devices already show competitive performance compared with incumbent technologies, and further improvements are foreseen with more advanced device structures.

To be viable in commercial or military applications, operational performance must be complemented by adequate device stability and reliability. Most existing reliability studies on GaN focus on the stability of individual components, such as ohmic or Schottky contacts, and are typically limited to small sample sizes at the laboratory level. We have completed a comprehensive high-temperature operating life (HTOL) test that predicts excellent 20 year life stability.

GaN-on-silicon

A patented technology known as SIGANTIC has been developed by Nitronex that allows growth of high-quality GaN-on-silicon substrates. Using this technology, along with our GaN wafer fabrication facility, a power trans-



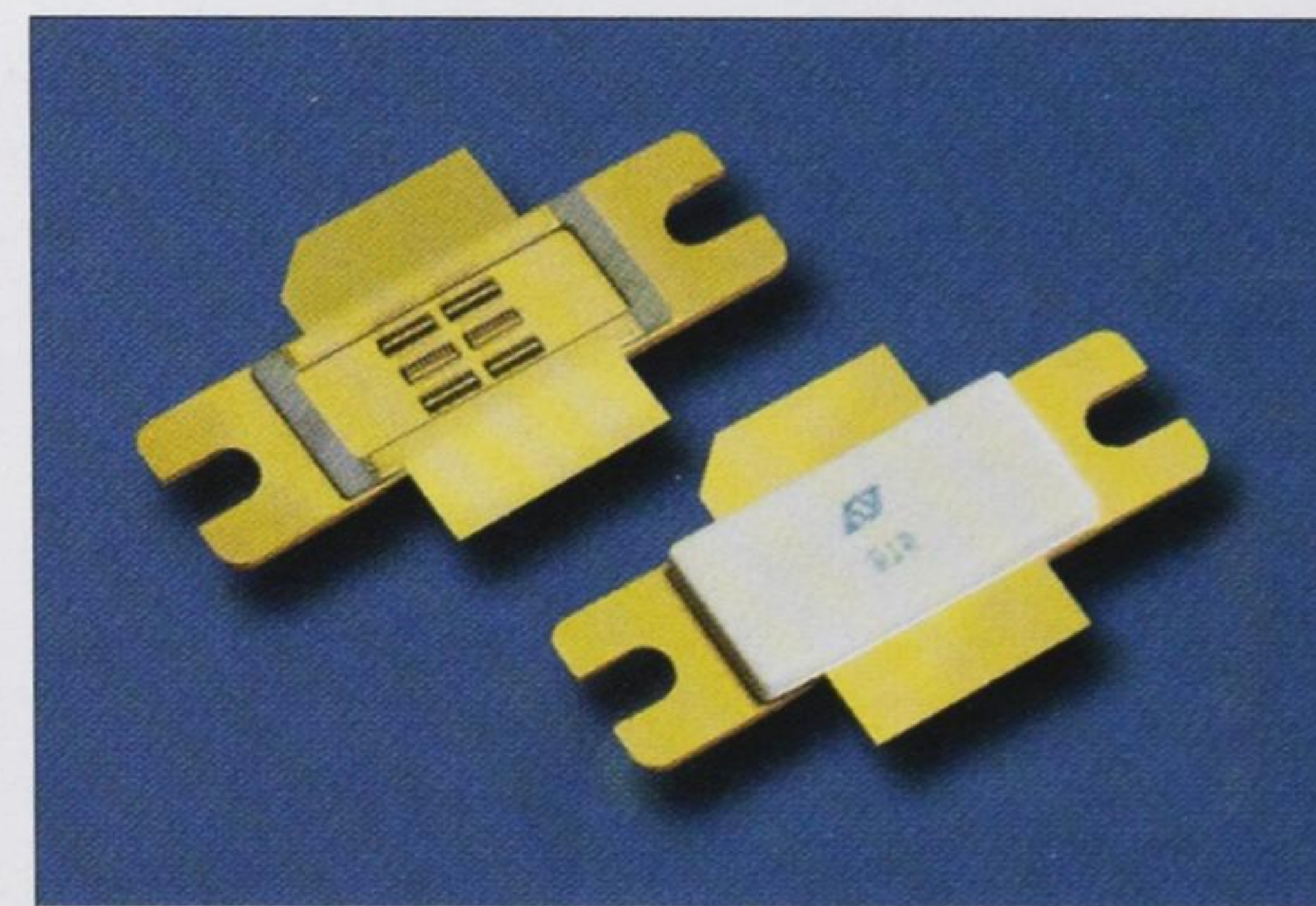
Nitronex processed 1100 GaN HFET wafers in 2003, and performed extensive lifetime and reliability tests on devices.

Rapid scaling from 2 inch to 100 mm diameter wafers has been achieved.

sistor technology designed specifically for the output stage of third-generation wireless base stations has been developed and tested.

Following the success of solving the difficulties that the silicon substrate crystal structure and accompanying material properties posed for GaN growth, the benefits of the GaN-on-silicon platform technology are now being fully realized. First, the rapid scaling from 2 inch to 100 mm diameter wafers has been achieved, providing a means to reach the quantity, manufacturability and cost requirements of today's mature commercial semiconductor-processing fabs.

An equally significant achievement has been the development of a stable, uniform and repeatable device-fabrication process. This achievement was the result of the ability to



Packaged AlGaIn/GaN HFET devices.

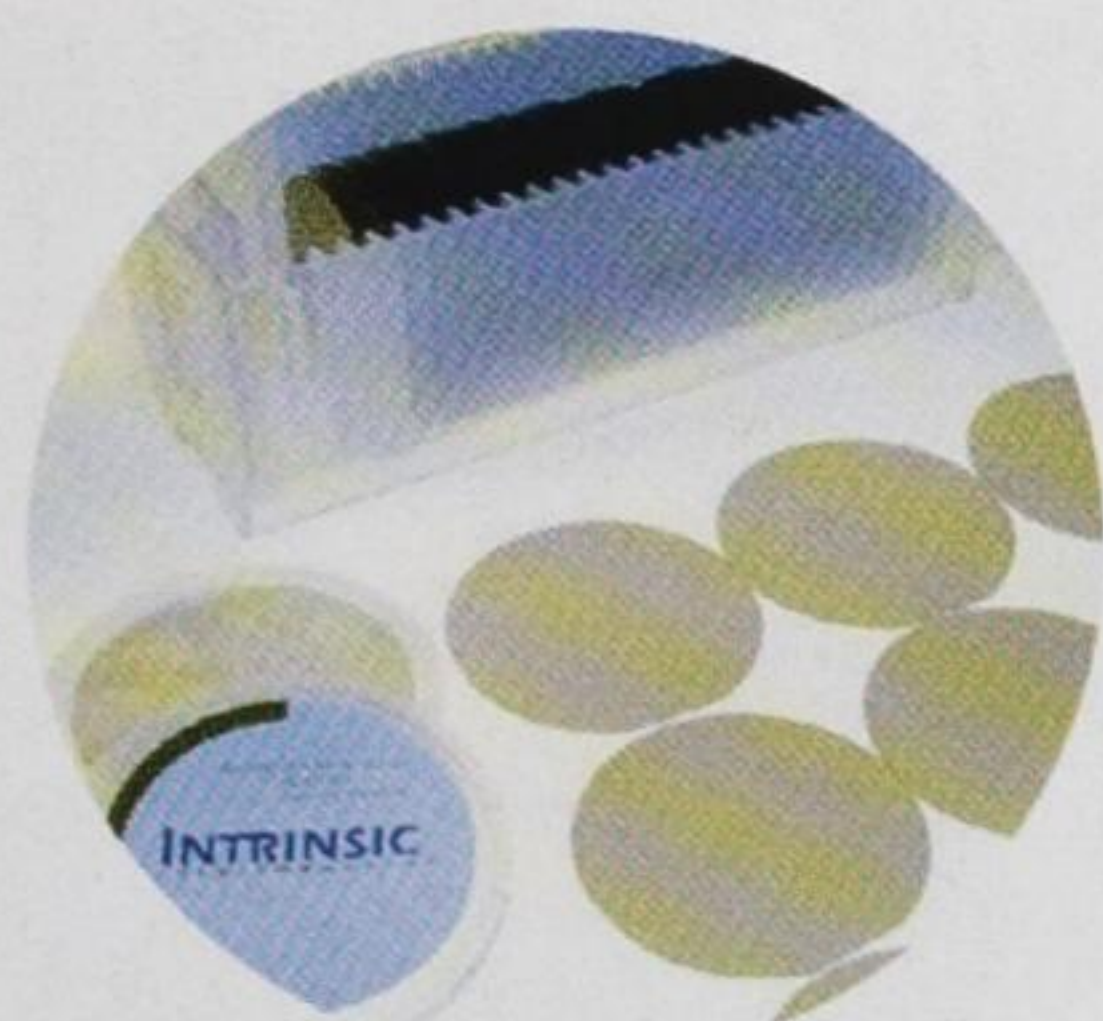
run high volumes of GaN wafers and establish a manufacturing baseline through a processing fab employing standard 100 mm equipment, and exploiting the mature state of silicon processing for backside and packaging technologies. These silicon technologies include thinning, backside via, and Au-Si eutectic die attachment.

The economic advantage of silicon substrates has allowed this substantial volume of wafers to be produced during process development. During 2003, our 100 mm fabrication facility processed more than 1100 AlGaIn/GaN HFET wafers, with a large percentage of these processed through assembly. A selection of packaged devices from each wafer is subjected to extensive DC and RF testing. With this data set, performance trends can be identified and correlations clearly established that would be lost to statistical variation in smaller sample sizes.

A significant level of engineering activity is constantly under way in order to meet performance and yield targets. A variety of methods is employed, including design of experiments, split lots, and physical simulation. Additionally, a percentage of the capac-

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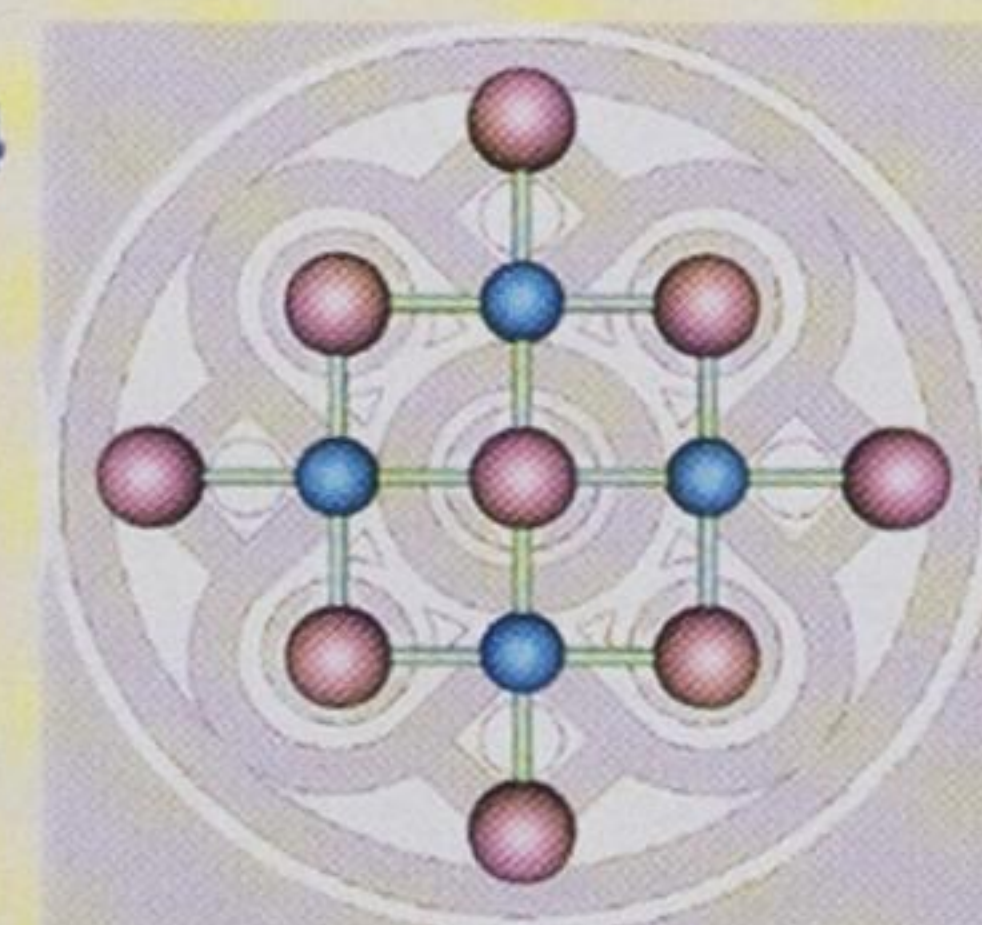
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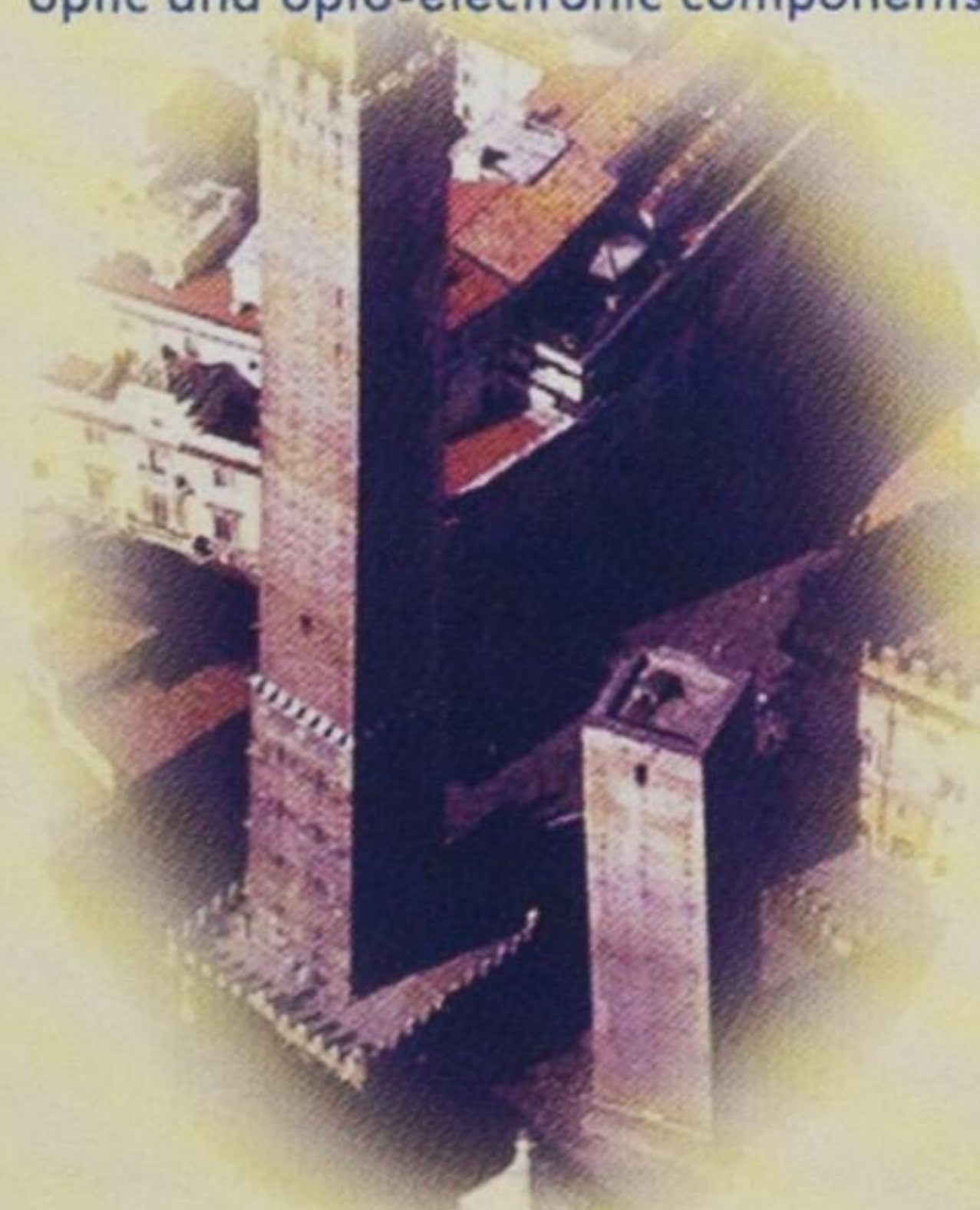
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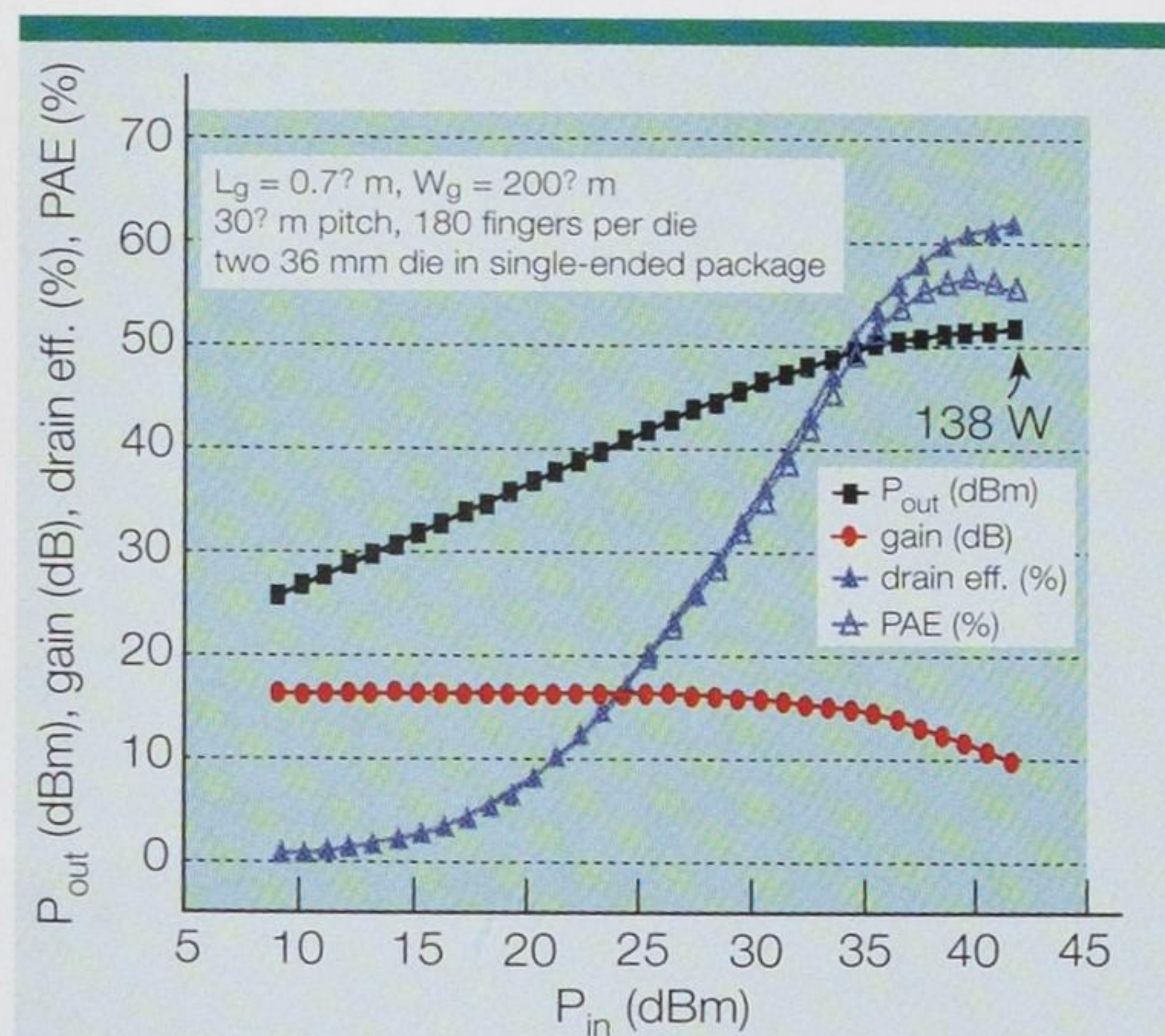


Fig. 1. RF CW power sweep performance at 2.14 GHz of a 36 mm gate periphery AlGaIn/GaN HFET transistor grown on a silicon substrate demonstrating 138 W, 16.3 dB small signal gain, and 62% drain efficiency.

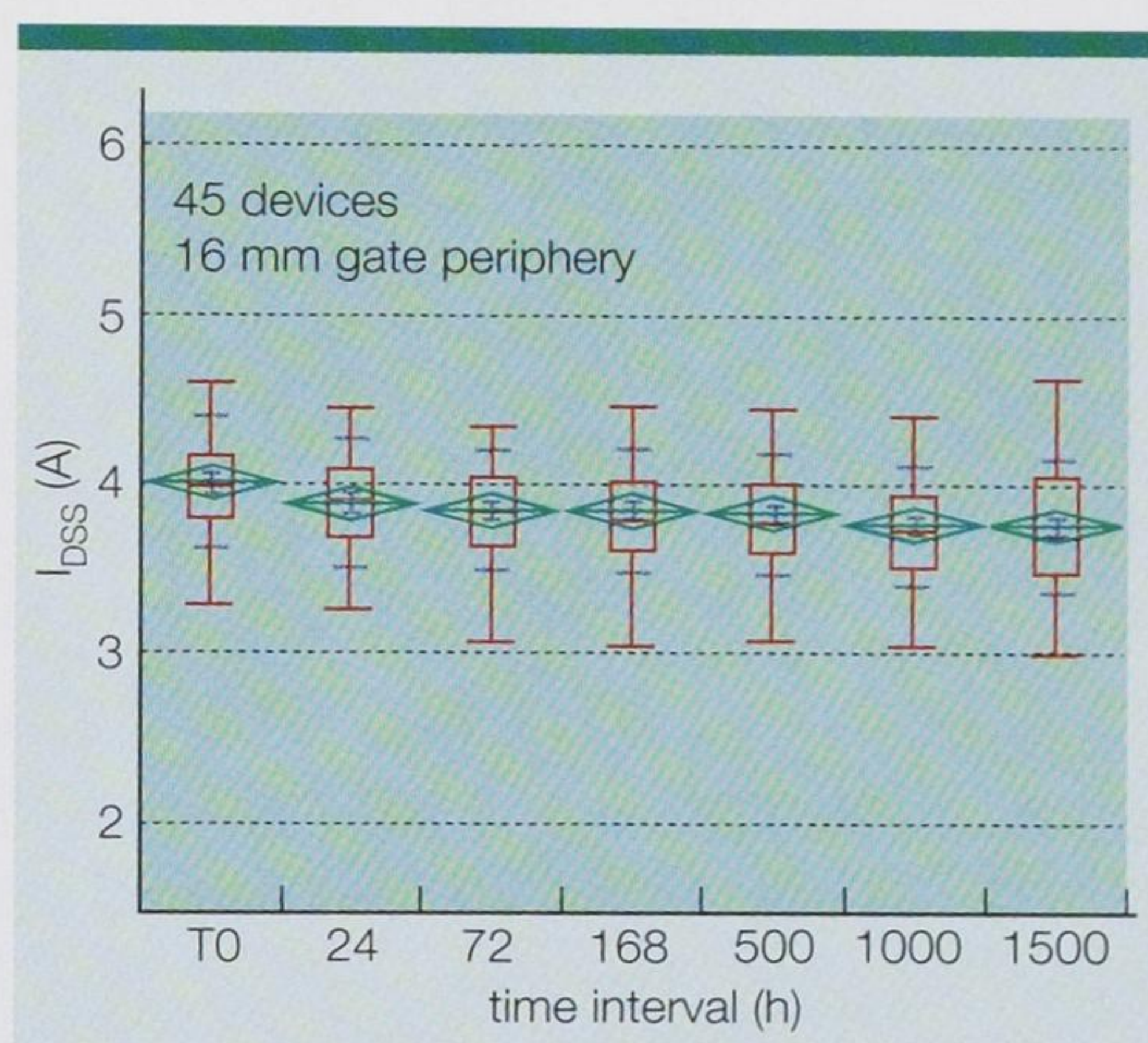


Fig. 2. 200°C junction temperature operating life test of 45 devices: saturated current performance over 1500 h with 100% device survivability and a 6% degradation. Each bar represents the entire data set.

ity is always dedicated to running lots of standardized process flow, referred to as baseline lots. All recipes, procedures and tests associated with these lots are maintained under revision control. The process delivers a constant standard of devices for product development, reliability studies and customer sampling. Baseline lots also serve to provide a relatively large body of data against which many experiments are assessed. Changes to the baseline are only adopted following the completion of a qualification event. A qualification event typically involves anywhere from 4 to 24 wafers, and includes data collection through packaged testing.

RF transistor performance

Using a scalable transistor power cell, large gate periphery devices have been designed and fabricated. Typical device geometries range from 30 to 75 mm total gate peripheries fabricated on 1×6 mm die. With power densities of about 2 W/mm, these devices exhibit more than 60 W of total saturated continuous-wave (CW) output power with correspondingly high efficiency. The devices are optimized for operation at 2.14 GHz and are designed for good thermal dissipation, which is critical for high-power devices. Furthermore, these large single-chip devices can be combined in standard microwave packages to yield even higher total output power levels.

The performance requirements for the output power stage of third-generation wireless base stations are challenging for any device technology. The application requires that the devices are able to deliver an amplified signal with minimal signal distortion, while still

operating at high efficiency and high output power levels. The choice of operating conditions for these devices is key to delivering the desired performance. We have determined that the optimal conditions for single-tone performance differ from those under W-CDMA modulation. The parameters that have a significant impact on the performance include the quiescent bias current, the source impedance and the load impedance. Transistors in this application are typically operated in a "backed-off" condition, with output power levels more than 6 dB below the full or saturated capability of the device. The peak output power for these devices needs to be in the range of 60–240 W, with a corresponding drain efficiency of 55% or higher, in order to be competitive.

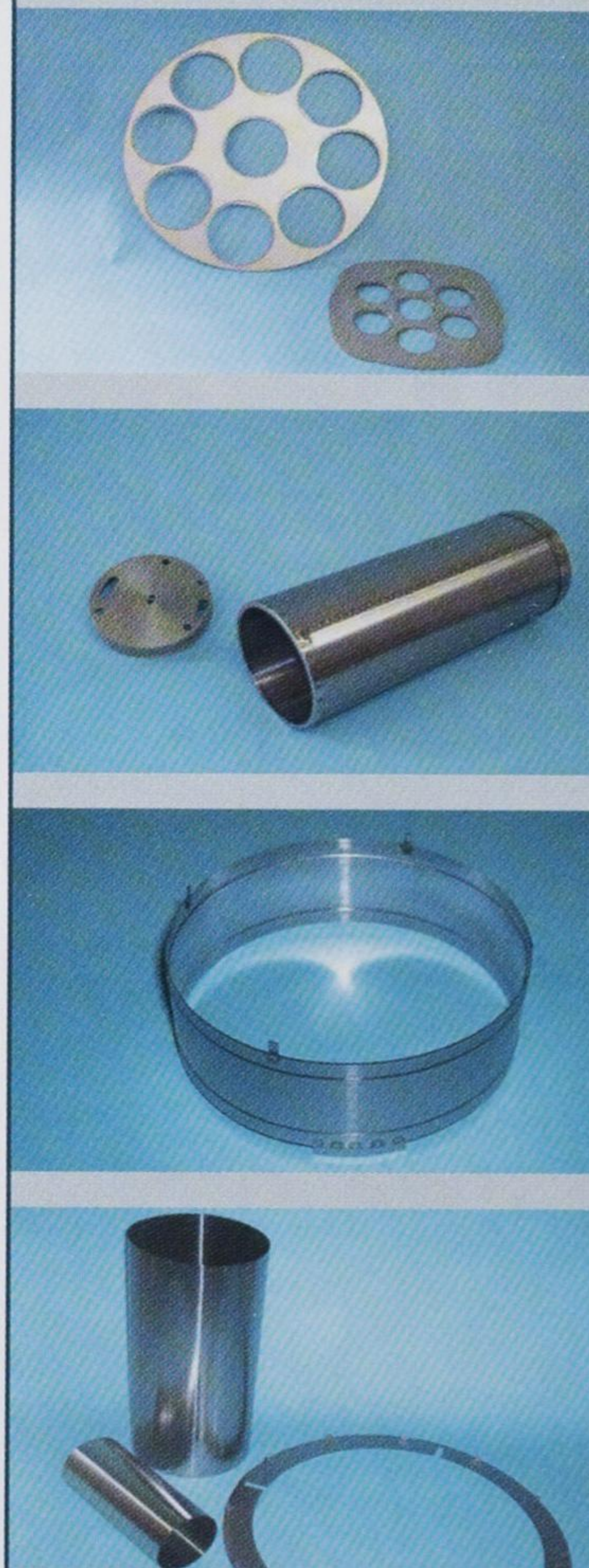
The performance of a Nitronex device under CW RF drive with an unmodulated single-tone input at 2.14 GHz is shown in figure 1. The dual-chip AlGaIn/GaN HFET-on-silicon device, mounted in a single-ended package, has a total gate periphery of 72 mm and a gate length of 0.7 mm. The operating condition for this device is a quiescent current (I_{dq}) of 2 A and a drain voltage (V_{ds}) of 28 V. The device demonstrates 16.3 dB of small signal gain, 62% drain efficiency, and a saturated output power of 138 W, a record output power for a GaN-on-silicon device at 28 V bias.

GaN device stability

Each wafer from the baseline production process is sampled for wafer-acceptance testing. The standard procedure is to sample a minimum of five devices from each wafer. The devices are subjected to a 24 h HTOL

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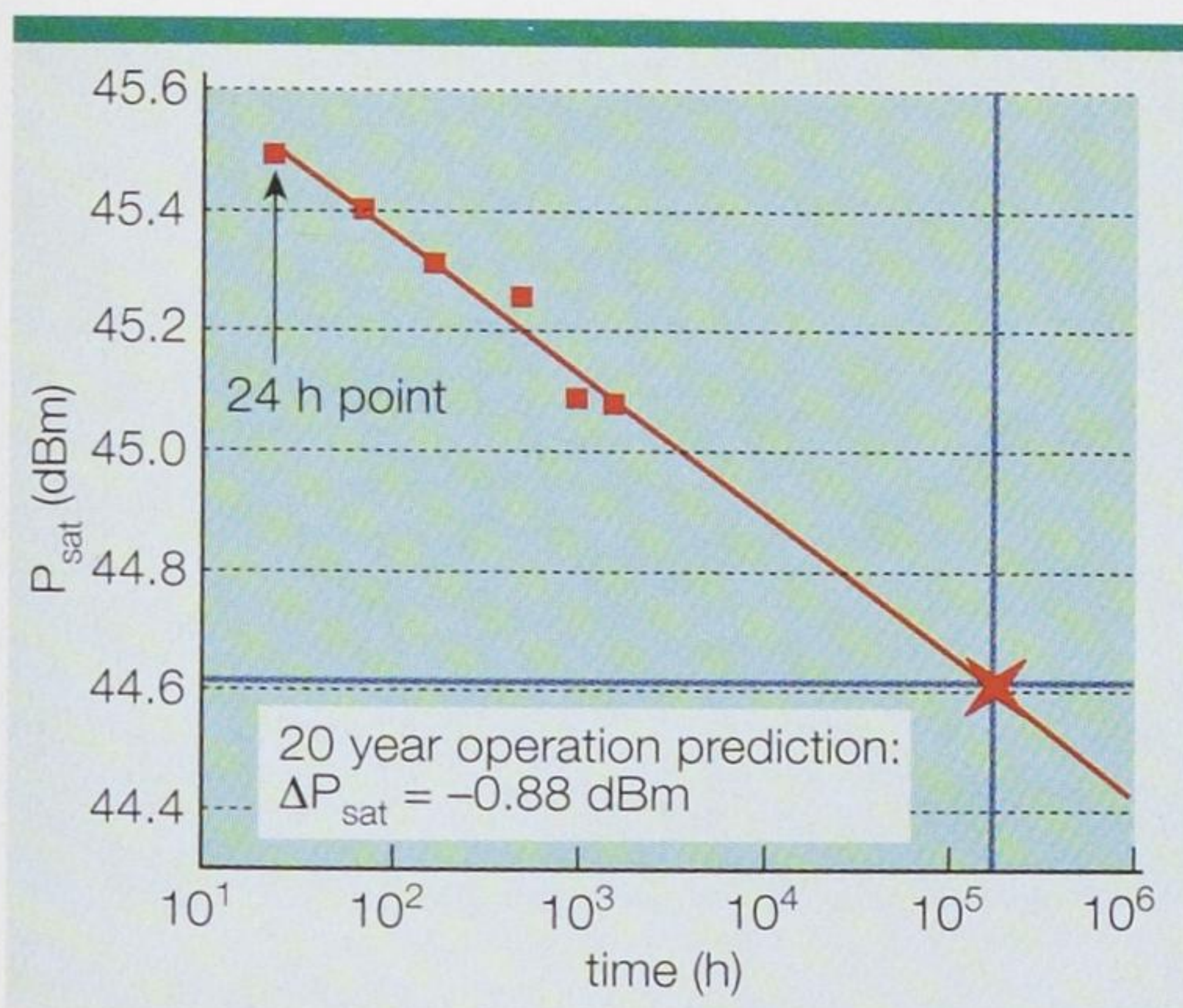


Fig. 3. 200°C junction temperature operating life test of 45 devices: median saturated RF power over 1500 h of operation, with an excellent projected 20 year stability of less than 1 dB degradation.

burn-in test. The test is performed using a custom-built system capable of biasing up to 100 devices at a dissipated power level of 90 W each. The HTOL system uses liquid cooling to maintain a base-plate temperature of approximately 22 °C.

The burn-in test is intended to stabilize the device performance and to provide a first glimpse at the reliability behavior. The criteria for device failure during burn-in are either catastrophic (device burn-out) or a change in any parameter greater than $\pm 15\%$, or ± 0.5 dB. For our GaN devices, no burn-out while under bias has been observed.

GaN-on-silicon is able to meet the manufacturability and reliability requirements of today's more demanding applications.

Using the same set-up as described above, a 1500 h HTOL test has been performed on 45 devices with a 16 mm gate periphery. The samples were taken from five wafers representing three different process lots. One device from each wafer was used as a test control. The means for each parameter from the 24, 48, 168, 500, 1000 and 1500 h test down-points have been empirically fitted to log curves.

The results for drain-source saturation current (I_{DSS}) are shown in figure 2. Each bar represents the entire data set with 100% of the devices surviving the HTOL test. The satu-

rated current is stable, with a degradation of 6% over the duration of the test. Furthermore, when the 24 h burn-in effect is negated, the DC parameters tested are extrapolated to change less than 10% over 20 years.

The results for saturated output power (P_{sat}) are shown in figure 3. Projecting the curves forward, we find that the P_{sat} degradation is also stable, and is expected to change less than 1.0 dB from 24 h through 20 years.

Further testing has indicated that the infant mortality levels have remained consistently below 1%. Additionally, AlGaIn/GaN HFET devices have passed a battery of additional reliability tests. These include temperature cycle ($-65/150^\circ\text{C}$ over 250 cycles), autoclave (121°C , 15 psi and 96 h), and electrostatic discharge testing at 500 and 1000 V.

Commercial applications

Of immediate commercial interest, the emerging third-generation wireless cellular networks are designed to provide high-data-rate services beyond traditional voice. To support these higher data rates, third-generation air interfaces such as W-CDMA place severe constraints on the linearity of the power amplifier and associated power transistors. On the base station side, silicon lateral diffused metal oxide semiconductor (LDMOS) devices are the present technology leader, owing to their excellent price-to-performance ratio compared with other commercially available technologies such as GaAs HFETs and silicon bipolar junction transistors. Although LDMOS has supremacy, AlGaIn/GaN HFETs are beginning to show their long-held research and development promise as contenders for high-power transistor applications.

Generally, SIGANTIC can be applied to both optoelectronic and microelectronic device structures. The fundamental properties of GaN offer much potential for high-power, high-frequency applications. GaN-on-silicon is able to meet the manufacturability and reliability requirements of today's more demanding applications. Equally important, the use of silicon substrates will ensure the economical viability of the technology. Given the high power densities and breakdown voltages achievable with this technology, it will prove enabling to many future applications. ●

Edwin Piner is director of materials engineering at Nitronex Corporation, Raleigh, NC, US. He acknowledges support from his colleagues at Nitronex, and the Office of Naval Research. E-mail: epiner@nitronex.com.

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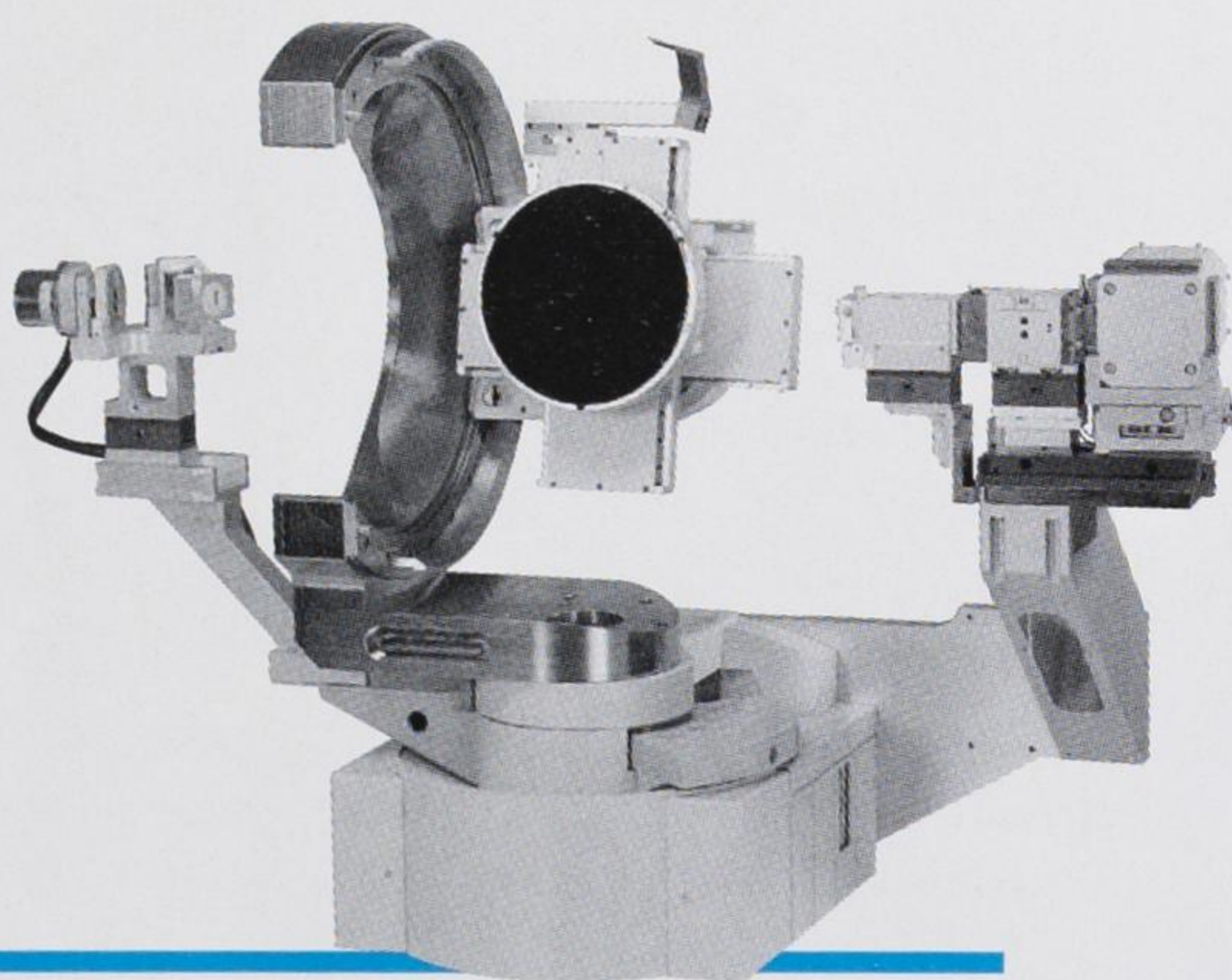
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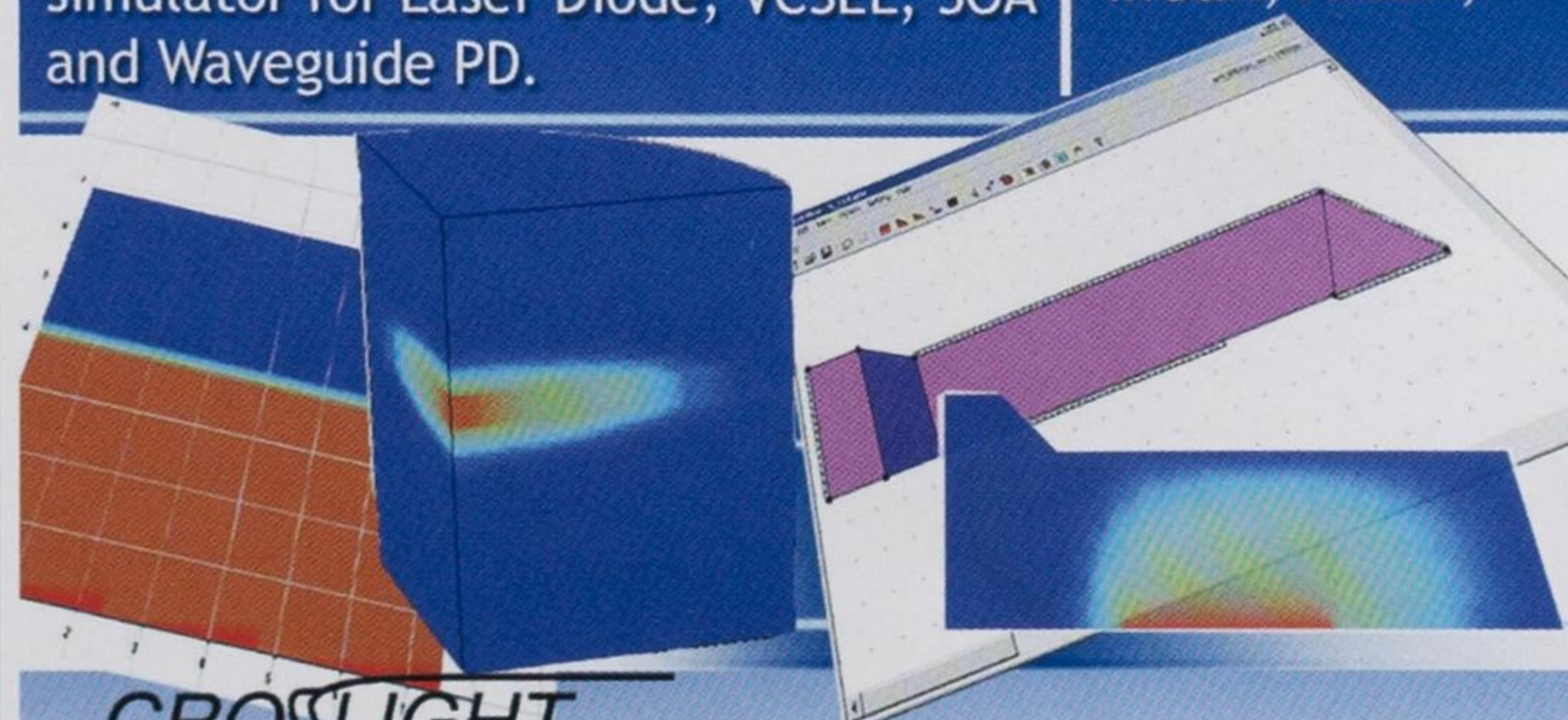
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Satellite and last-mile links offer mm-wave prospects

High-speed wireless broadband data communications is expected to create a diversified, multibillion-dollar market for millimeter-wave devices in the next five years. According to **Ed Weatherwax**, the key areas are cellular infrastructure, two-way satellite terminals and terrestrial broadband access.

Despite the current challenges in the telecommunications market, bandwidth needs continue to grow, and this in turn is creating opportunities for manufacturers of high-frequency communications equipment. Cellular operators deploying 2.5 and 3G mobile networks are using high-frequency (>10 GHz) wireless backhaul solutions and installing three times more cell sites than existing networks, with backhaul data rates that are two to four times higher.

Cost-effectively bridging the gap between the fiber infrastructure and paying customers is also an issue for fixed network operators. Although high-frequency radios have, for several years, provided data rates of more than 10 Mbit/s without the need to bury cable, attempts to provide access via this technology (for example local multipoint distribution service, or LMDS) have not been successful to date. The key issues are the need to own spectrum licenses, stringent performance criteria and high equipment costs.

However, the revitalization of the market for two-way satellite services, coupled with the recent reallocation of several GHz of spectrum above 70 GHz, is creating demand for high-frequency devices. Prices are already decreasing due to technology improvements, such as high-yield monolithic chips and automated assembly, tuning and test. This could push the total annual volume for >10 GHz radios to more than 1 million units.

Terrestrial cellular infrastructure

New cellular phones and the resulting new service offerings will require a large expansion and reinvestment in existing networks. Estimates suggest that more than 1.7 million backhaul and infrastructure high-frequency radios will be required by 2006. The widespread deployment of wireless "hotspots", with the corresponding need for backhaul connectivity, could drive growth in this market segment. The market in 2003 was around



Fig. 1. Xytrans' VSAT outdoor unit in field trials with a Telesat K_a-band equipped satellite.

250,000 units, with a value of \$300–500 million. This segment represents growth from the traditional low-volume military uses for high-frequency components and subsystems, but is not currently a high-volume market.

Two-way satellite terminals

The two-way satellite terminal or VSAT (very small aperture terminal) market is a recent entrant into the commercial high-frequency product market. Existing two-way services offered at K_u-band (12–18 GHz) have not achieved the broad market acceptance that was expected, despite benefits such as global access, rural connectivity, and integration with broadcast services. The most likely users of VSAT services in the US are the 25–40% of customers who live in rural areas not covered by terrestrial broadband alternatives. If only 1% of rural households require broadband connectivity, this still represents around 3 million potential subscribers. However, there are fewer than 500,000 K_u-band system users, mainly because of service problems and high service charges.

Next-generation K_a-band (26–40 GHz) systems are expected to offer better service at a lower cost by leveraging smaller spot beams, dynamic bandwidth allocation, smaller antennas, and other technological innovations. The result for the customer is that K_a-band offers

significantly more overall system capacity than K_u-band, enabling lower service pricing.

Although deployment of K_a-band satellites has been delayed, current plans call for K_a-band satellite service deployments in 2004/2005 with a potential for 6 million subscribers by 2007. This represents a large market opportunity for the high-frequency community, but also some difficult challenges.

Although a number of license awards and orbital allocations have been made over the last 9 years, many ventures set up to provide bandwidth on demand, Internet access and HDTV services via K_a-band either failed or were delayed. Contributing factors included the general telecom downturn, acceptance of low-cost DSL and cable terrestrial access solutions, and the lack of success for K_u-band solutions. More importantly, the satellite industry was unable to construct profitable enterprise or consumer service offerings due to the high cost of infrastructure/bandwidth and terminals.

Renewed interest

Despite the slow start of K_u-band services, systems such as DirecWay have now connected more than 250,000 two-way subscribers, which has sparked renewed interest in K_a-band services. Plans are now more modest, typically using hybrid K_u/K_a-band satellites, are driven by strong industry leaders, and are mostly based on capturing the enterprise market first. Planned K_a and hybrid K_u/K_a-band systems are shown in the table overleaf, including the Telesat system (figure 1).

Even with a stronger emphasis by these new players on enterprise and military users, there remains a major push to reduce overall system costs, which are driven by the space segment. The ground terminal cost is another area of focus. Historically, RF assembly in the ground terminal has been a major cost driver, particularly at K_a-band. High levels of integration and automation have driven a significant amount of labor and material cost from the

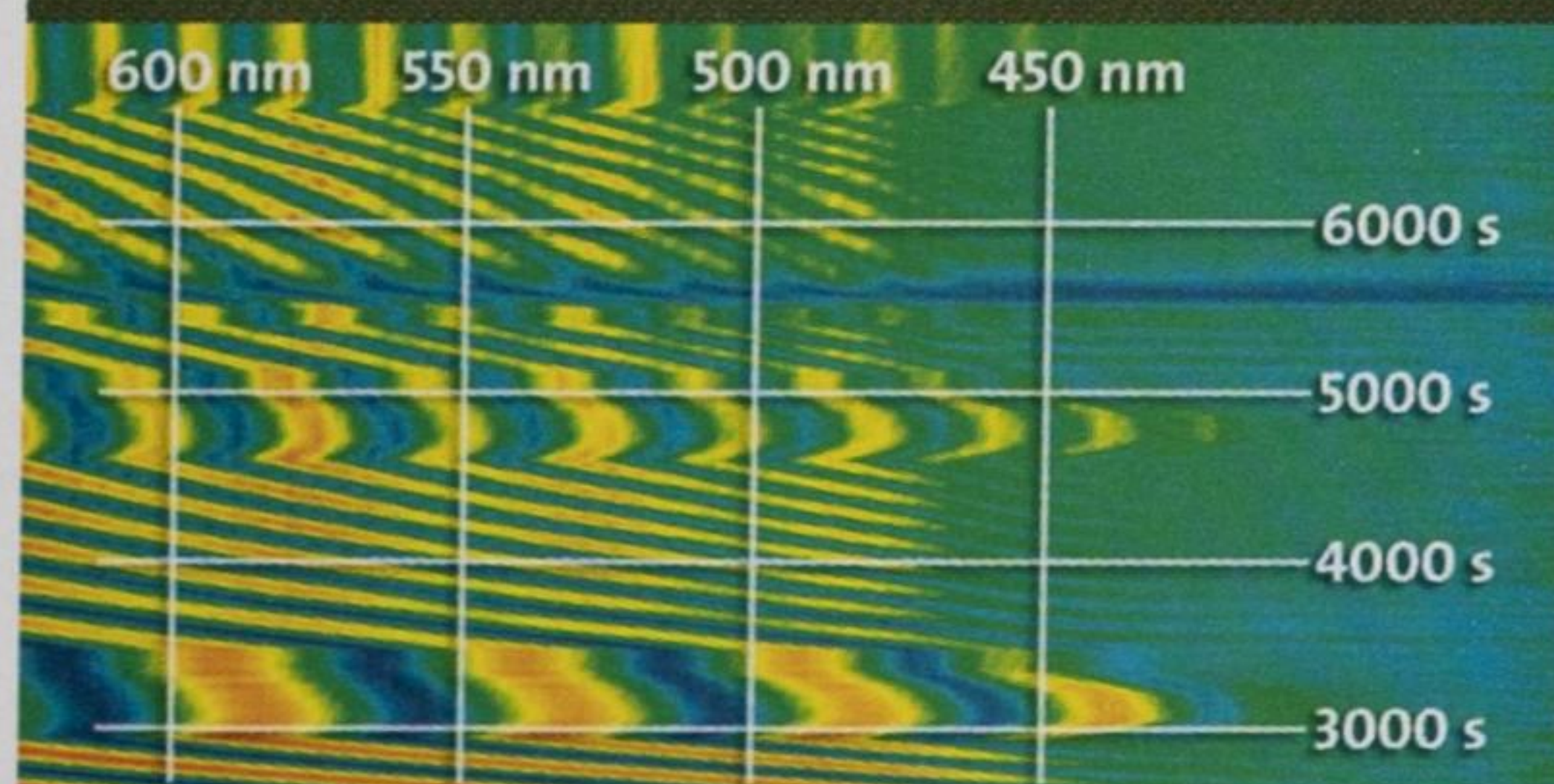
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System	Coverage	Total no. satellites and band(s)	First satellite launched (x) or expected date
EchoStar	Americas	3 K _u /K _a	X
Astra (SES)	Europe	2 K _u /K _a	X
Intelsat/Skynet	Americas	11 K _u /K _a	X
Telesat	Americas	3 K _u /K _a	X
Eutelsat	Europe	2 K _u /K _a	X
Superbird (SCC)	Asia	3 K _u /K _a	X
Spaceway (Hughes)	Americas	12 K _a	2004
WildBlue	Americas	5 K _u /K _a	2004
EuroSkyWay (Alenia Spazio)	Europe	2 K _u /K _a	2004
Americom2Home (SES)	Americas	5 K _u /K _a	2004
iPStar (Shin Satellite)	Asia	1 K _u /K _a	2004
PanAmSat	Americas	13 K _u /K _a	2005
Pegasus	Americas	5 K _u /K _a	2005
Astrolink (Lockheed, Northrup, Telespazio)	Americas	5 K _a	not known
other		13 K _u /K _a	X

module; however, a key cost driver remains the MMIC chipset, and in particular the need to achieve the desired output power. Terminal requirements are in the 1–3 W range, depending on the desired antenna size, data rate, modulation format and other factors. As shown in figure 2, MMICs represent 40–50% of the cost of the assembly, and this figure is expected to grow to 65–70%, following improvements to the remaining parts of the assembly.

Although current and planned improvements will allow RF assembly vendors to approach the price targets of terminal suppliers and service providers, all parties must work together to drive MMIC chip costs down through circuit compaction, improved yields, higher levels of integration and other approaches. Ultimately, terminal costs will determine whether K_a-band systems will be used for enterprise networks only (hundreds of thousands of units) or for consumers as well (millions of units).

Terrestrial broadband access

For millions of businesses and even residential users outside a fiber ring, the only feasible high-speed broadband network connection option remains a “last-mile” (or “first-mile”) fixed wireless link. Although DSL, T1/T3 and cable technologies offer solutions to many users, a large worldwide population remains unserved. It appears that low-frequency alternatives such as Wi-Fi (802.11) and WiMAX (802.16a) will solve the consumer/SOHO needs, but the deployment of higher-frequency networks, for example LMDS for access applications, is still very limited.

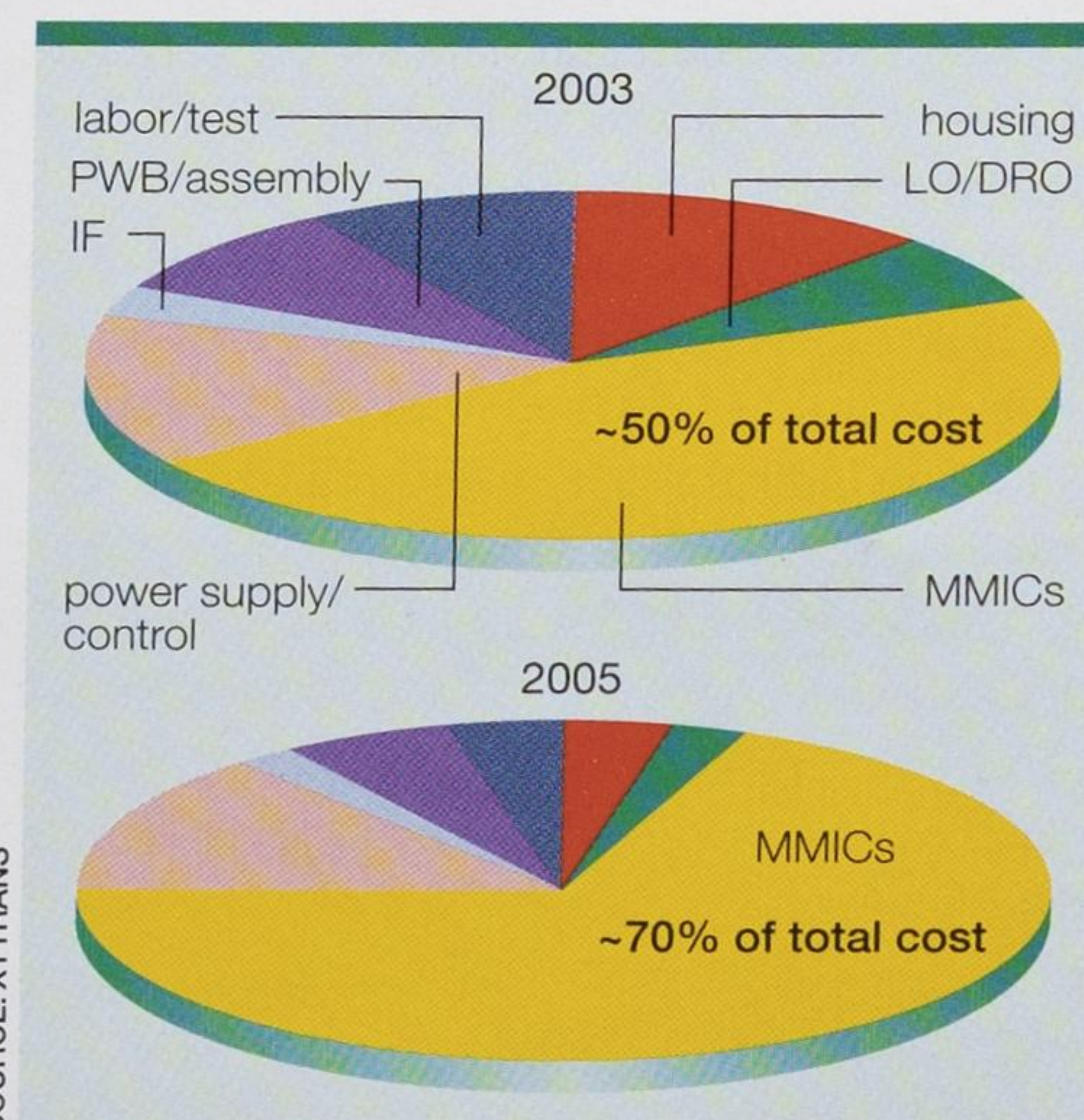


Fig. 2. Cost comparison of 3 W MMIC chipsets for VSAT applications. For 1 W chipsets, MMICs represented 40% of cost in 2003 and 65% of cost in 2005.

However, there is an increasing demand for enterprise-level connectivity to support Ethernet deployments, which are happening at a rate of more than a million 1 Gb Ethernet switch ports per month. 10 Gb ports are now being deployed, and projections call for 100 Gb Ethernet performance by 2007. Connection of these ports to the fiber infrastructure is moving very slowly, with fiber trenching virtually halted and current-generation wireless technologies limited to about 622 Mbit/s.

Alternatives that provide 1 Gb-plus data rates are available, but these have limitations. Radios in the 60 GHz band are unlicensed, increasing the probability of interference, and are limited by low power and atmospheric

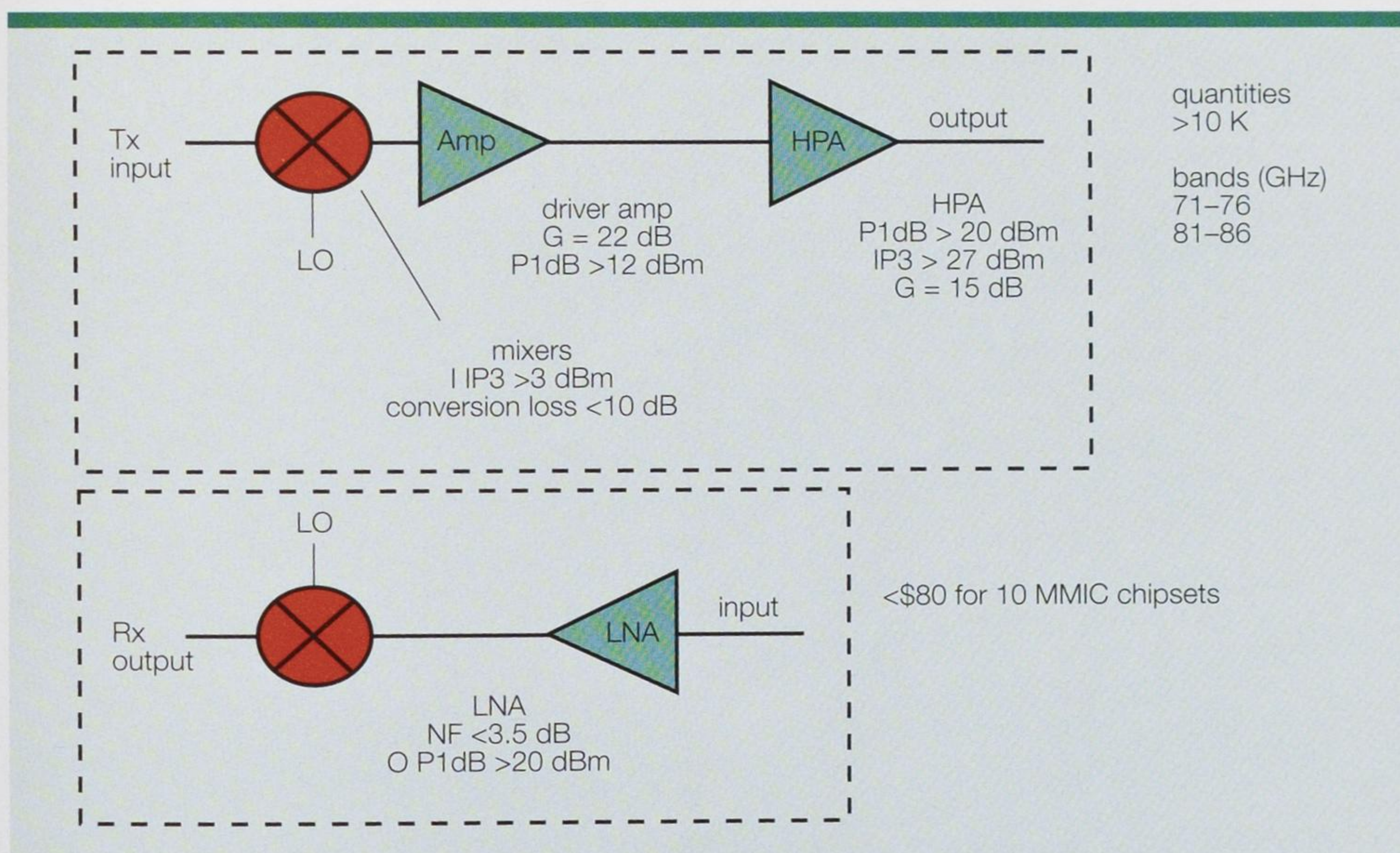


Fig. 3. Chipset cost targets and specifications for 70/80/90 GHz radios.

effects to very short-range applications. Free-space optics links have not received widespread acceptance due to weather effects, and solutions that improve availability (combinations of free-space optics and 60 GHz links) result in higher cost.

A new alternative has emerged with the release of rules for the 71–76, 81–86 and 92–95 GHz (70/80/90 GHz) bands. The industry-driven rules provide broad bandwidth consistent with the development of high-capacity bridging products without the limitations of the current licensed spectrum. Because broad-bandwidth frequency blocks are available in the 70/80/90 GHz bands, and because atmospheric effects are conducive to the development of radios with appropriate transmission ranges, the communications industry saw an opportunity to create rules that would enable simpler, lower-cost radios.

There is a general consensus that the major market for devices in these bands will be access links to the 8000 fiber-connected points-of-presence (POPs) in the US. There are also approximately 750,000 business buildings with more than 20 employees, of which only 5% have fiber connections. However, approximately 75% of these buildings are located within 1 mile of a POP. The business opportunity is to bring each of these buildings online with fiber-like capacity by leveraging the benefits of the spectrum available at 70/80/90 GHz.

Transceiver costs

The transceiver cost will be a key issue in developing cost-effective equipment at

70/80/90 GHz. Cost goals for links in these bands are in the \$2000–10,000 range (\$1000–5000 per radio) in quantities of 10,000 or more, depending on the data rate required. Figure 3 provides top-level specifications and cost targets for the MMIC chipset for these radios. Some of the parameters are set to enable upgrades to higher radio data-rate performance, and can be relaxed for low-cost, relatively low data-rate applications. The performance of the resulting chain permits operation with 1–10 Gbit/s data rates at > 1 mile range with 99.999% availability.

This emerging segment presents a challenge as well as an opportunity for MMIC and subsystems suppliers. There are only a limited number of MMIC chipsets available in these bands today, and they are not optimized for high-performance communication links. Estimates suggest that shipments of more than 1 million units are possible if performance and cost targets can be reached, although one must be mindful of the previous predictions of similar volumes for access products from the prior generation of systems at 20–40 GHz. However, growing demand and the adoption of user-friendly licensing and rules compatible with lower-cost systems, combined with the interest of major manufacturers, makes this an extremely viable market segment for high-frequency equipment manufacturers. ●

Ed Weatherwax is vice-president of business development at Xytrans Inc, a manufacturer of high-frequency transceivers and outdoor units operating at 10–100 GHz. See www.xytrans.com for more information.

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Improved laser design pushes wallplug efficiency to 65%

Rob Williamson and **Manoj Kanskar** report on dramatic improvements in the power conversion efficiency of high-power laser diode bars, enabling higher-reliability devices and new applications.

High-power laser diodes, with optical output power ranging from a few watts per emitter to nearly 100 W per bar, power a wide range of laser systems and end applications. The output of these diodes can be used directly, for example for materials processing and medical applications, or to pump a wide range of other sources, such as diode-pumped solid-state lasers, fiber amplifiers and fiber lasers.

Although semiconductor laser diodes can be made with emission wavelengths ranging from ultraviolet (below 400 nm) using GaN and similar structures, all the way to the mid-infrared (beyond 3 μm) with lead-salt devices, the highest-efficiency laser structures currently known utilize III-V materials that emit from 750 to 1100 nm. These InGaAs/(In)GaAsP materials can reliably produce several watts of optical power from a $1 \times 100 \mu\text{m}$ output facet. When combined in an array to form a laser bar, such devices can produce in excess of 60 W continuous-wave (CW) output, and more than 100 W in quasi-CW (<4% duty cycle at several kHz repetition rate).

This range includes 808, 915, 940 and 976 nm, important wavelengths for optically pumping the absorption lines of rare-earth-doped laser crystals such as Nd:YAG, erbium/ytterbium-doped glass for optical amplifiers and lasers, and a host of other crystal-dopant combinations. These systems are used to convert the multimode output of the laser diodes to a high-quality single-mode output, shift the wavelength, and enable the creation of high-energy pulse trains. Furthermore, the pump light can be used directly, focused, or fiber-coupled for uses such as printing, marking, soldering and brazing, cutting metal, heat-treating and illumination.

Fundamental improvements to pump laser performance, especially efficiency, can have far-ranging implications, including lower cost, improved reliability, and portability. Ultimately, it could enable high-power laser systems emitting hundreds of kilowatts.

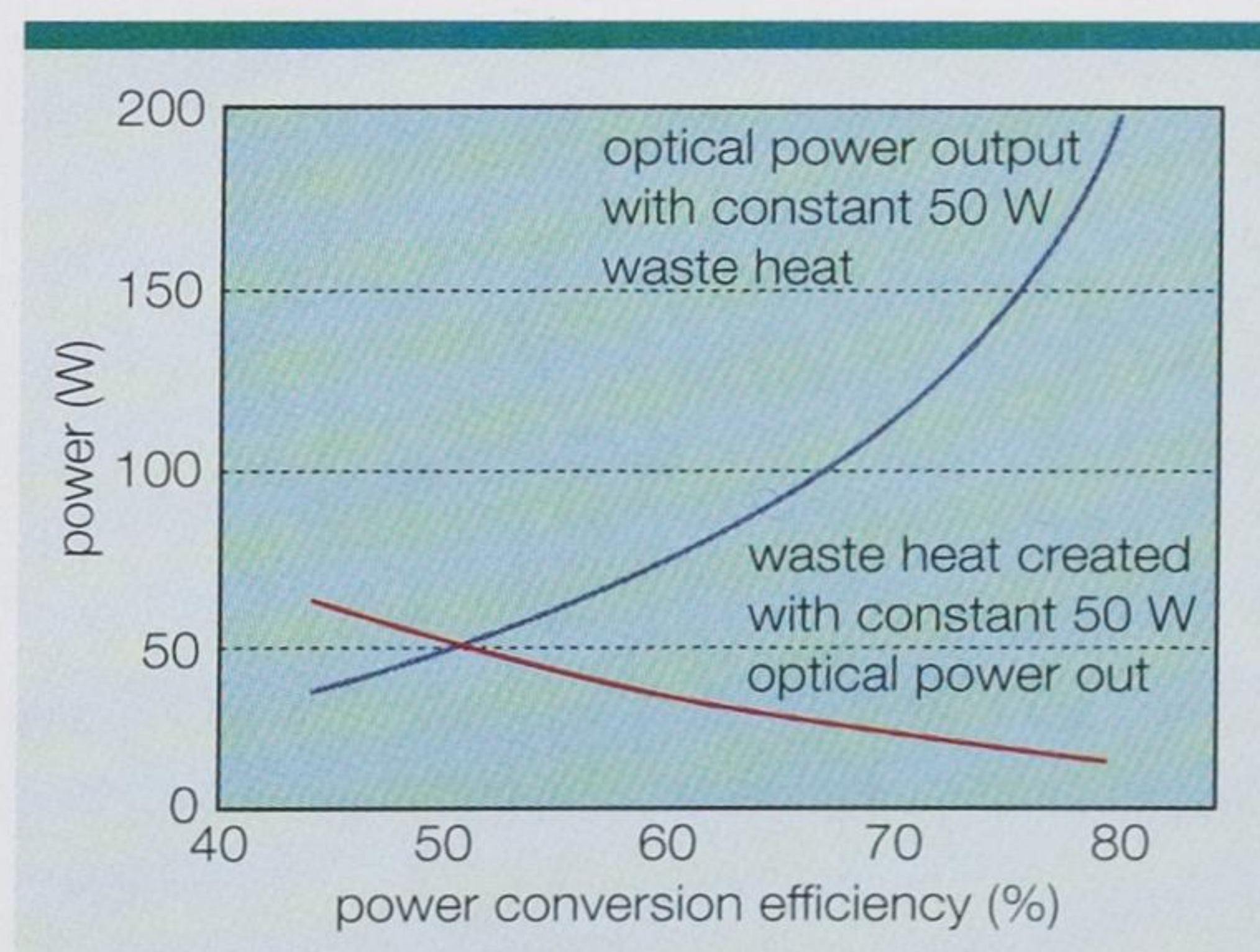


Fig. 1. Improved power conversion efficiency enables higher output power and greater reliability. Two calculated scenarios are depicted here. The blue curve shows the drastic increase in optical output power with efficiency improvement when waste heat is held constant at 50 W. The red curve shows the decrease in waste heat versus efficiency at 50 W optical output.

Why efficiency matters

Current state-of-the-art production diode pump lasers can provide just over 50% of “wallplug” or electrical-to-optical power conversion efficiency (PCE). This means that in producing 50 W of usable laser light, the diode also generates 50 W of waste heat, which must be removed to maintain a safe diode junction temperature. Furthermore, the cooling process itself suffers from poor efficiency and necessarily consumes considerably more power than it is able to remove from the laser diode. A typical cooling system removing 50 W of diode waste heat will itself dissipate in excess of 150 W.

To improve diode efficiencies, DARPA has set up its Super-High Efficiency Diode Sources (SHEDS) program. The organization has set its contractors the tough target of reaching 80% wallplug efficiency under the project.

The maximum useful laser output power is not currently limited by the diode or semiconductor structure itself, but by heat transfer from the junction and the cooling

mechanisms used to remove the heat. Needless to say, mounting methods and novel cooling mechanisms are also currently a very active area of research and development.

Since diode lifetime is determined by the Arrhenius law and is therefore exponentially related to the operating temperature, controlling the heat output is of the utmost importance to laser reliability (Kanskar 2003). Less heat generated means less strain on the cooling system, more tolerance to thermal conductivity variation, and a lower junction temperature. Improving the diode efficiency directly impacts the diode lifetime and the maximum output power achievable.

Figure 1 illustrates how increasing the diode efficiency has a supralinear effect on the attainable output power, assuming a constant waste heat load of 50 W (blue curve). Conversely, as shown by the red curve, holding the optical output power constant at 50 W significantly decreases the waste heat generated.

Loss mechanisms

The heart of a laser diode is the quantum well (QW) in the middle of a p-n junction, which forms an “artificial atom”. The well is tuned to have an appropriate energy level structure conducive to producing a population inversion when an electrical current is applied to the p-n junction and forms the laser gain medium. To complete the laser diode, an optical waveguide is added to keep the generated photons inside the QW structure, and a pair of mirrors – one on each end of the waveguide – forms the optical cavity.

Figure 2 outlines the various loss mechanisms and their impact on the final efficiency of a typical 970 nm laser bar with 50 W output power and 50% wallplug efficiency. Stepping through the pie slices in the figure counterclockwise:

Below threshold, a certain amount of drive current is consumed, simply to attain population inversion in the laser. Furthermore, there are non-radiative mechanisms which consume

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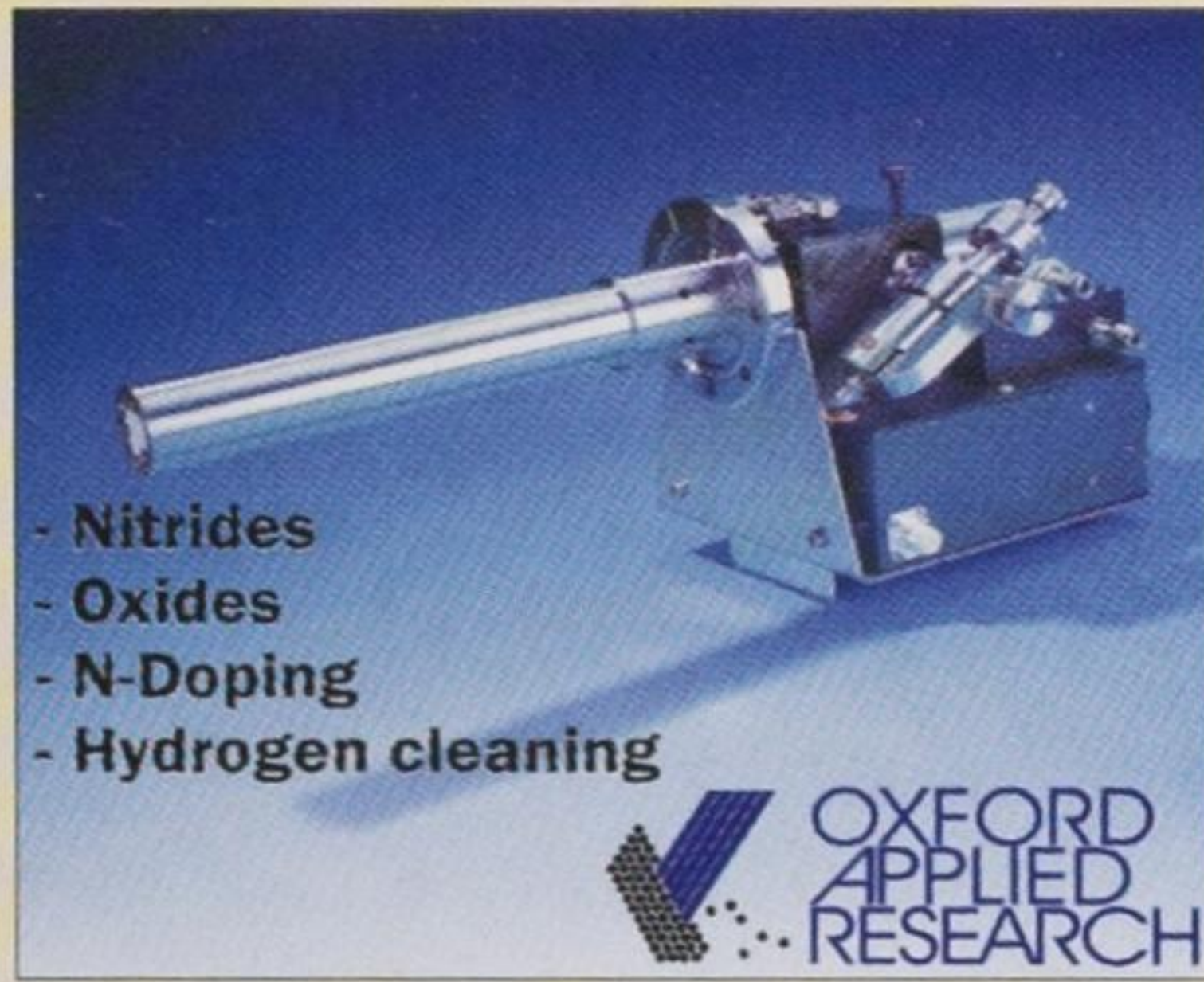
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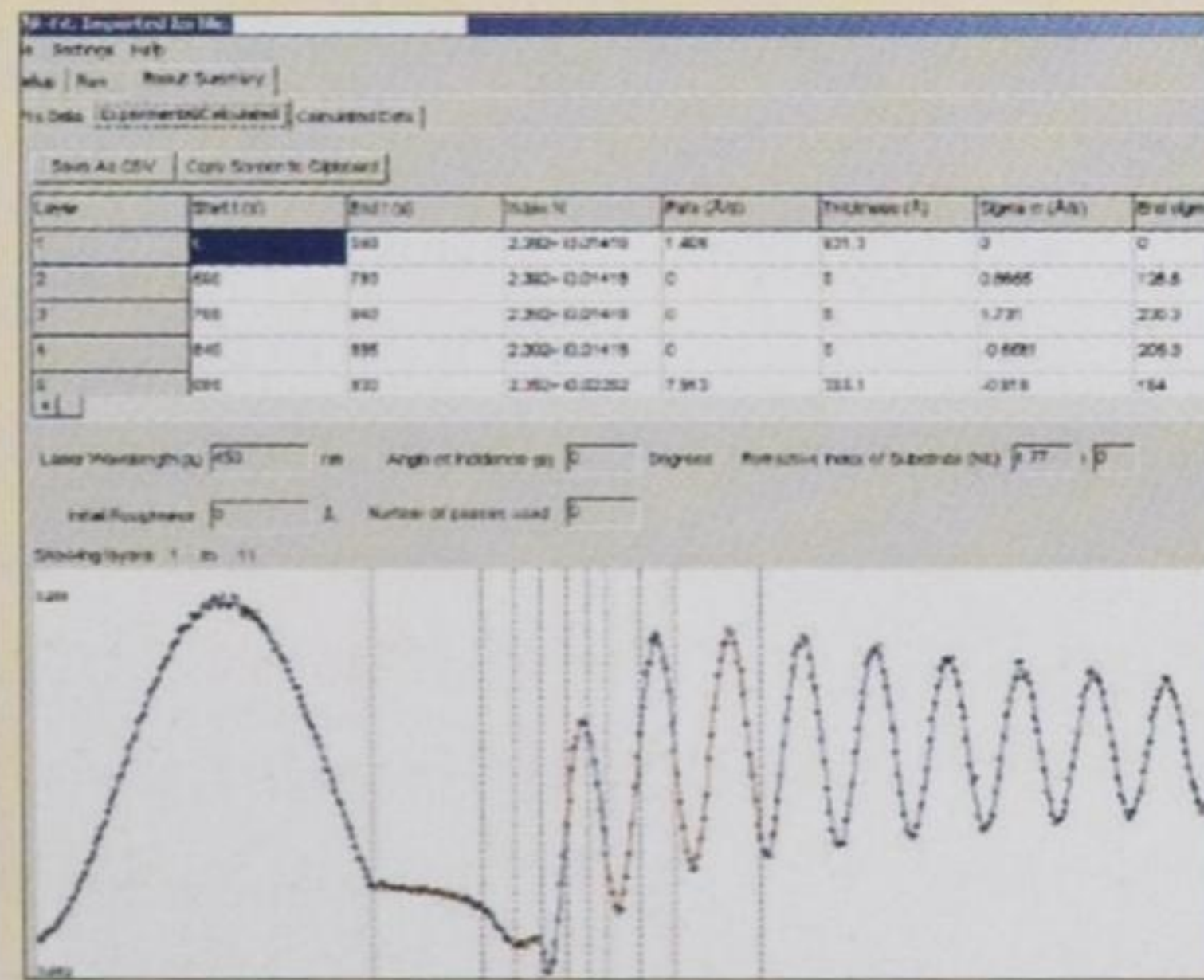
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Free-standing GaN production

CrysTec GmbH

CrysTec announces 2 inch wafers of two of the most promising candidates for the production of free-standing GaN as a basic material for the development of blue laser diodes and similar nitride applications. NdGaO₃ (011), NdGaO₃ (101) and LiAlO₂ (100) now complete CrysTec's substrate product program for nitride films, which already consists of sapphire, ZnO, MgAl₂O₄, SrTiO₃, ZrO₂:Y, MgO and silicon.



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The CDP system from Logitech Ltd (Semicon West, booth #5643) is ideal for global planarization of III-V wafers and delayering ICs/MEMS devices for fault analysis and reverse engineering. The fully automated control panel allows process parameters to be stored for future use, helping to ensure end result repeatability. This, coupled with a low cost of ownership, makes the CDP particularly useful for testing of new CMP

slurries, pads and templates for off-line analysis, and off-line trials of new CMP processes without stopping production runs.

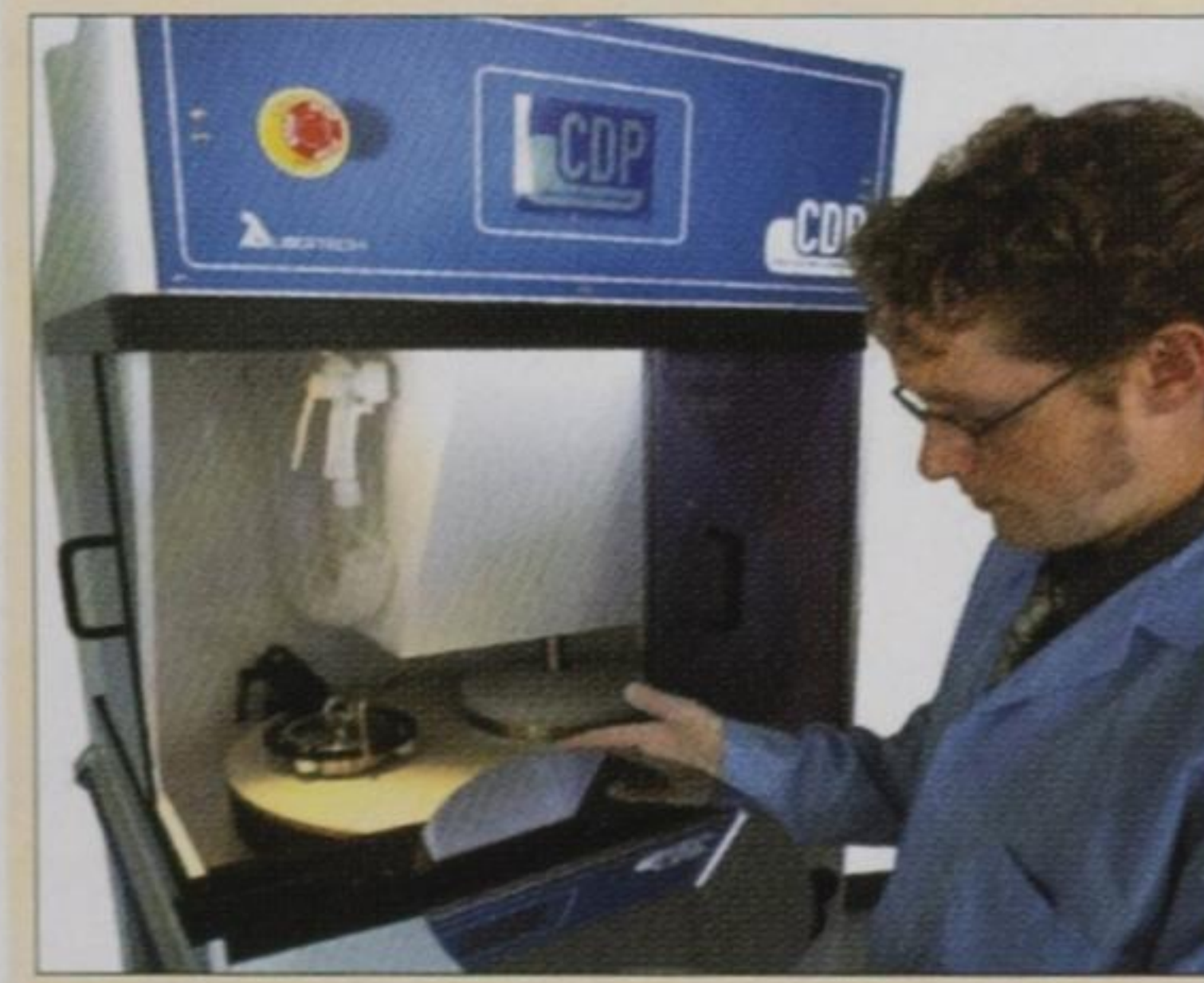
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carriers. These constitute about 6% of the loss. **Carrier leakage** accounts for another 8% of the loss; these are electrons and holes that do not effectively recombine to produce photons in the gain medium.

Joule heating is the most significant factor, introducing another 16% of the loss. It results from the effective series resistance of the diode, which includes contact resistance as well as bulk resistance in the heterostructure itself.

Band alignment loss of 6% reflects the band structure of the QW along with the misalignment of various heterostructure interfaces, characterized by the built-in voltage of the device.

Scattering and absorption losses of 14% reflect the fact that not all photons generated stay in the waveguide and that imperfect mirrors, scattering within the QW, and free-carrier absorption reduce the lasing efficiency.

Improving efficiency

The expression for the maximum power conversion efficiency, $p_{\max}$, tells us that there are several key ways to improve the laser's wallplug efficiency (Bour 1989): maximize the external differential quantum efficiency (EDQE), which is proportional to slope efficiency; and minimize the overall built-in voltage required to drive carriers into the QW, the series resistance and the threshold current.

Since the overall built-in voltage is only weakly dependent on temperature, the temperature dependence of $p_{\max}$ is primarily determined by the temperature dependence of EDQE. It is therefore of paramount importance to improve the thermal properties of the device by maximizing the characteristic temperature coefficient for the EDQE and minimizing the junction temperature rise. An increase in EDQE and reduction in overall built-in voltage will have the most significant impact on peak wallplug efficiency.

At Alfalight, we have recorded dramatic initial improvements in efficiency by improving the internal injection efficiency through strain adjustments to the QW barriers. This in turn directly increases the EDQE. Additionally, the built-in voltage has been reduced by modifying the doping profile of the laser's separate confinement heterostructure layer. This preliminary optimization effort has resulted in a peak wallplug efficiency of 65% near 970 nm (Kanskar 2004).

Figure 3 shows a summary of these results with a plot of the output power, drive voltage and efficiency as a function of drive cur-

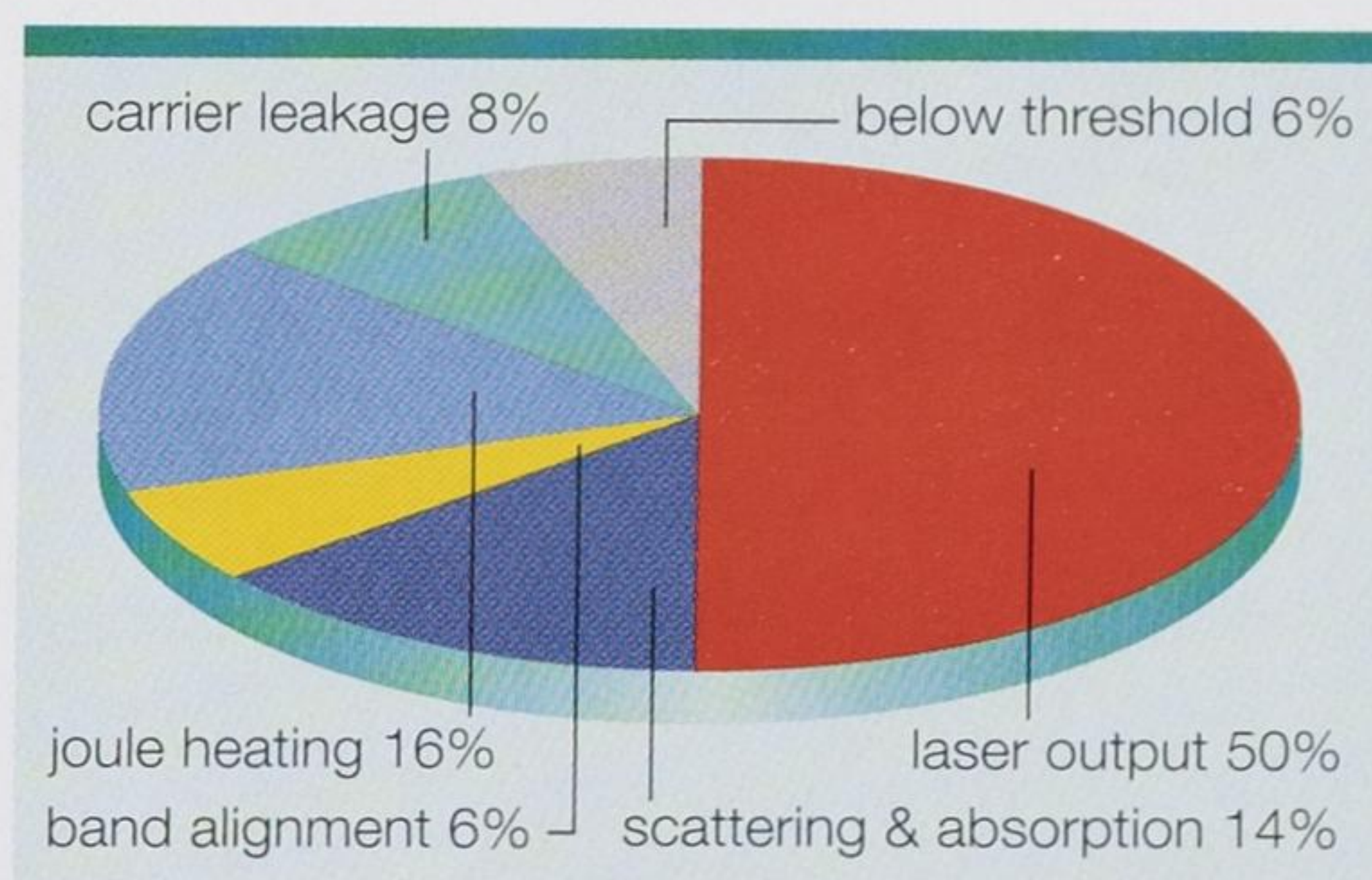


Fig. 2. Theoretical power budget for a 970 nm laser diode bar with 50 W output, showing the relative contribution of various loss mechanisms to the overall laser efficiency. Each of the structures required to make the laser function suffer from loss mechanisms that can prevent the photons from fully participating in the lasing process, thus reducing the overall efficiency.

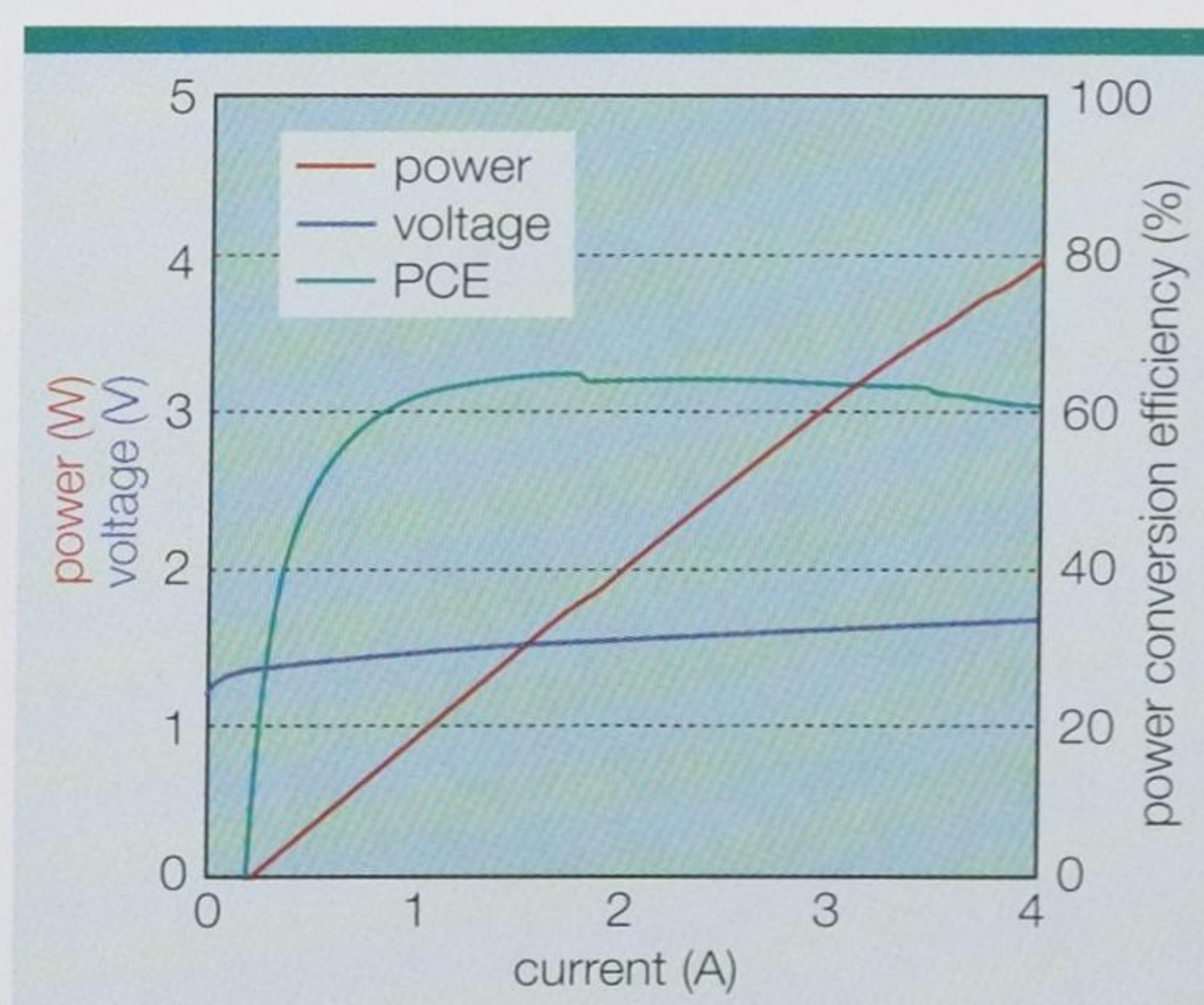


Fig. 3. Power-current-voltage (LIV) and wallplug efficiency plots of a 100 μm stripe width laser diode with 1 mm cavity length; heat-sink temperature is 20°C. Peak power conversion efficiency is 65%.

rent for a single 1 mm long 100 μm stripe emitter. Note also that the drive voltage stays below 1.65 V even at 4 A drive current, reflecting the reduced built-in voltage of this heterostructure design.

Reaching the 80% goal

A two-pronged approach is expected to deliver additional improvements in efficiency. Incremental changes to each of several design parameters will continue to improve the performance of these devices, but reaching the DARPA target will rely on more challenging techniques that fundamentally affect the laser structure and design.

For example, the below-threshold loss may be further reduced by making fundamental changes to the gain medium. One of the methods that we are pursuing is to use a quantum

dot (QD) gain medium buried in a high-bandgap barrier material. Due to the decreased dimensionality of carriers in the QDs, the threshold is expected to be dramatically reduced. Also, the characteristic temperature of a QD structure is expected to be significantly better than that of QW lasers.

In another approach to tackle threshold loss, we are growing QWs on (110)-oriented GaAs wafers. A QW grown in this orientation has higher oscillator strength, which increases the intrinsic gain and reduces the lasing threshold. Both of these methods are challenging approaches to improving efficiency, but the payoff is significant and will likely be necessary to reach the goal of 80% PCE.

Carrier leakage, although partially addressed in the previous results, can be further improved with incremental adjustments to the confinement structures and through the use of higher-bandgap materials and lateral carrier confinement.

Joule heating will be further reduced by lowering the ohmic contact resistance via high dopant concentration at the metal-semiconductor interface and through special annealing methods and metallization schemes. Overall series resistance will also be reduced by optimized doping of the waveguide and cladding layers.

Band alignment losses, although addressed to some extent here, can be further improved through compositional grading and delta-doping of the heterostructure interfaces.

Scattering and absorption losses will also be considered for further PCE improvement. Improved optical confinement and optimized overlap with the QW can decrease the scattering losses, while judicious choice of doping profile will reduce free-carrier absorption loss.

By implementing many of these incremental improvements, we believe that 65% efficiency can be achieved in production-quality bars within one year. ●

Further reading

Bour *et al.* 1989 *Appl. Phys. Lett.* **66** 2813.
Kanskar *et al.* 2003 *SPIE Proc.* **4995** 196.
Kanskar *et al.* 2004 *Solid State Diode Laser Technology Review Proc.* (paper DIODE-1).

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Investigation prompts reshuffle on AXT board

AXT, the California-based manufacturer of compound semiconductor substrates, has implemented senior management changes after an internal investigation revealed that the company was not complying with certain product-testing requirements.

Morris Young loses his previous titles of chairman, president and CEO at AXT, and is now responsible for improving and expanding the company's operation in China.

Donald Tatzin, former CFO, becomes interim CEO. Wilson Cheung, previously AXT's vice-president and corporate controller, has been promoted to CFO.

The investigation into AXT's working practices revealed that some requirements for product testing, as well as the supply of product test data to its customers, were not being complied with.

The company says that it is now imple-

menting measures to ensure future compliance, such as training programs for employees involved in production, testing and quality assurance. However, some customers appear to have seen enough already.

"In some cases our customers have agreed to work with us to review product specifications and testing requirements for the benefit of both parties. Other customers have canceled outstanding orders until the issue is fully resolved," admitted Tatzin.

Having delayed its financial update for a month pending the investigation, AXT finally reported that revenue for the quarter ending March 31, 2004 was \$9.8 million, up \$0.7 million from the previous quarter. The operating loss was \$2.5 million.

AXT expects to make a loss of \$2.4–2.6 million in the current quarter. Cash and cash equivalents on March 31 stood at \$16.6 million.

Aixtron breaks even and predicts profits

Aixtron, the MOCVD equipment manufacturer, reported an operating loss of €0.1 million (\$0.12 million) for the quarter ending March 31, 2004. This represents an improvement on the loss of €7.1 million for the equivalent quarter in 2003.

Aixtron's revenue for the recent quarter was €25.4 million, up 36% from the same quarter in 2003. The revenue split was 74% from Asia, 13% from the US and 13% from Europe.

"This is now the fourth consecutive quarter of increased demand," said Aixtron's CEO, Paul Hyland, pointing to continued growth of the LED market as the reason for the increased demand for the company's products.

Aixtron's cash and cash equivalents position has slightly improved, standing at €47.1 million, up €1.8 million from the previous quarter.

Akzo Nobel's source material simplifies red laser epitaxy

A collaboration between Akzo Nobel High Purity Metalorganics (HPMO) and EpiWorks, a developer and manufacturer of epiwafers, has produced AlGaInP-based laser material using tertiarybutylphosphine (TBP).

The benefits of TBP over phosphine (the standard precursor) for volume production of lasers were clearly highlighted, with no maintenance required during the entire development campaign of 30 runs.

In addition, existing equipment required no modification, and little or no evidence of accumulation of white or red phosphorus in either the phosphorus traps or tubing leading to the traps was observed.

In stark contrast, Akzo Nobel HPMO estimates that 5–10 preventative maintenance cycles would have been required for the same number of runs had it used phosphine instead. The device structure grown was a previously published red laser design, intended to operate at 670 nm. Akzo Nobel HPMO claims that the TBP process enabled high-quality AlGaInP layers with several different Al compositions to be grown at low temperatures and relatively low V/III ratios.

Akzo Nobel HPMO is yet to receive device performance results.

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