

COMPOUND SEMICONDUCTOR

April/May 2009 Volume 15 Number 3

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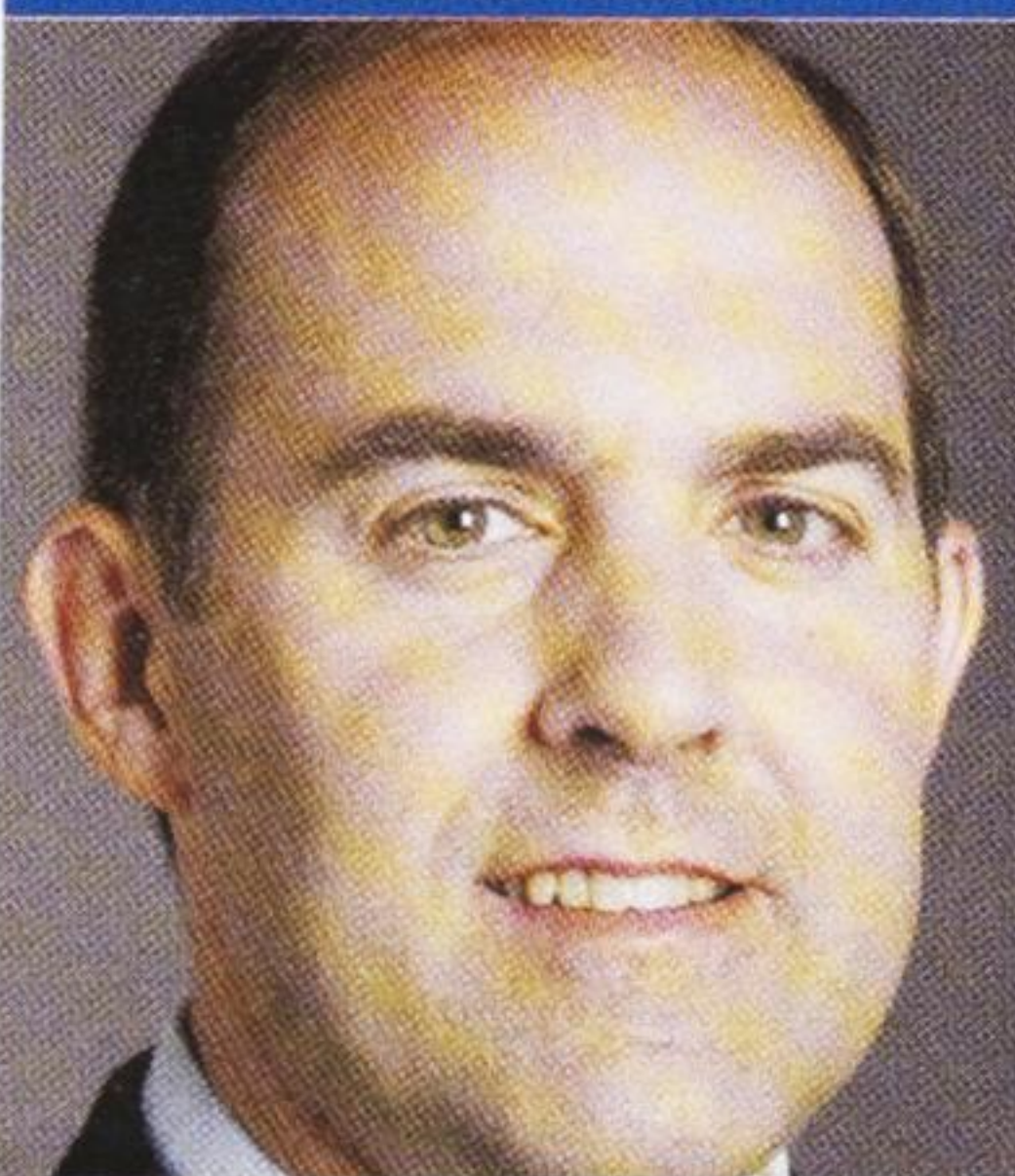
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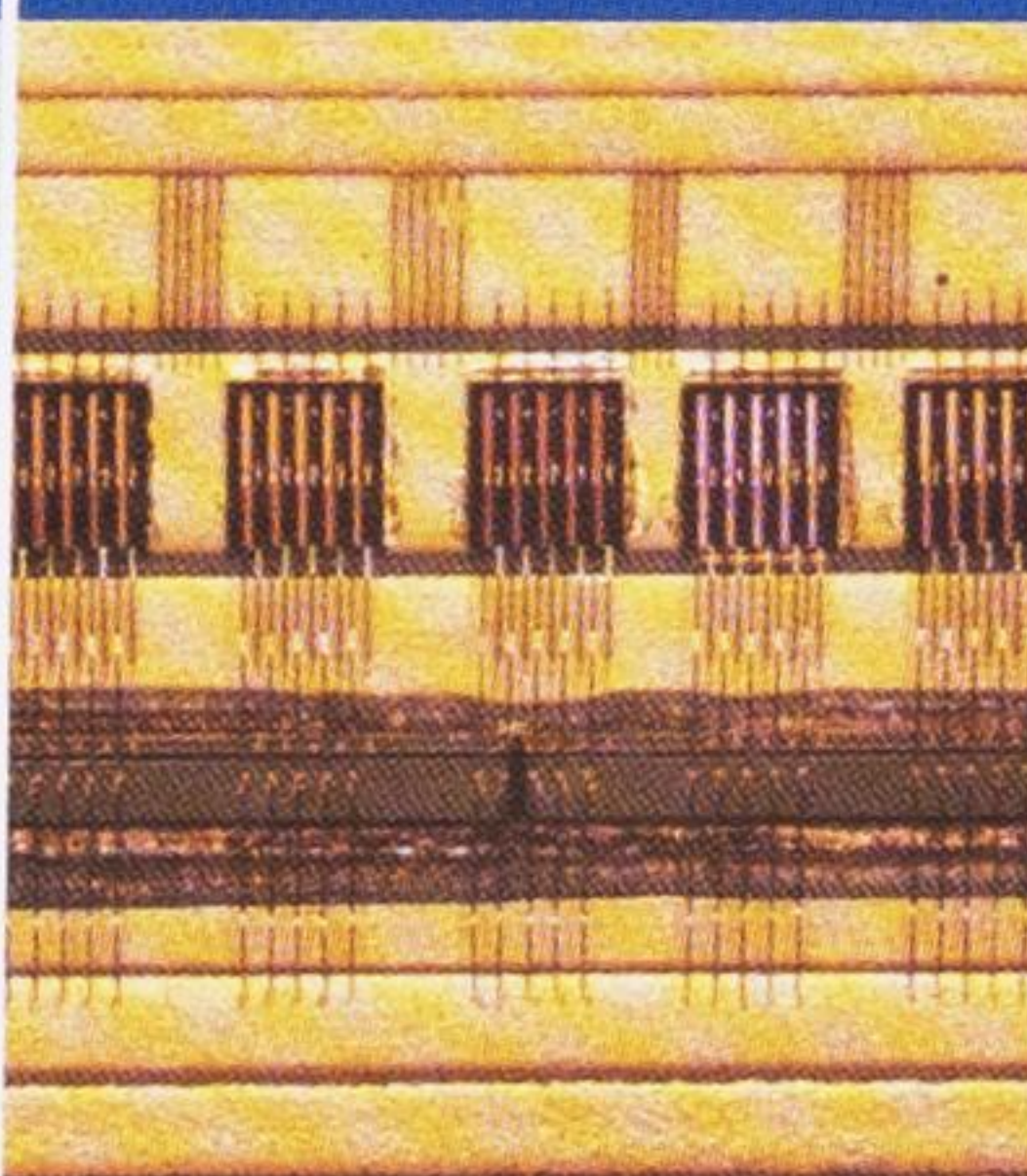
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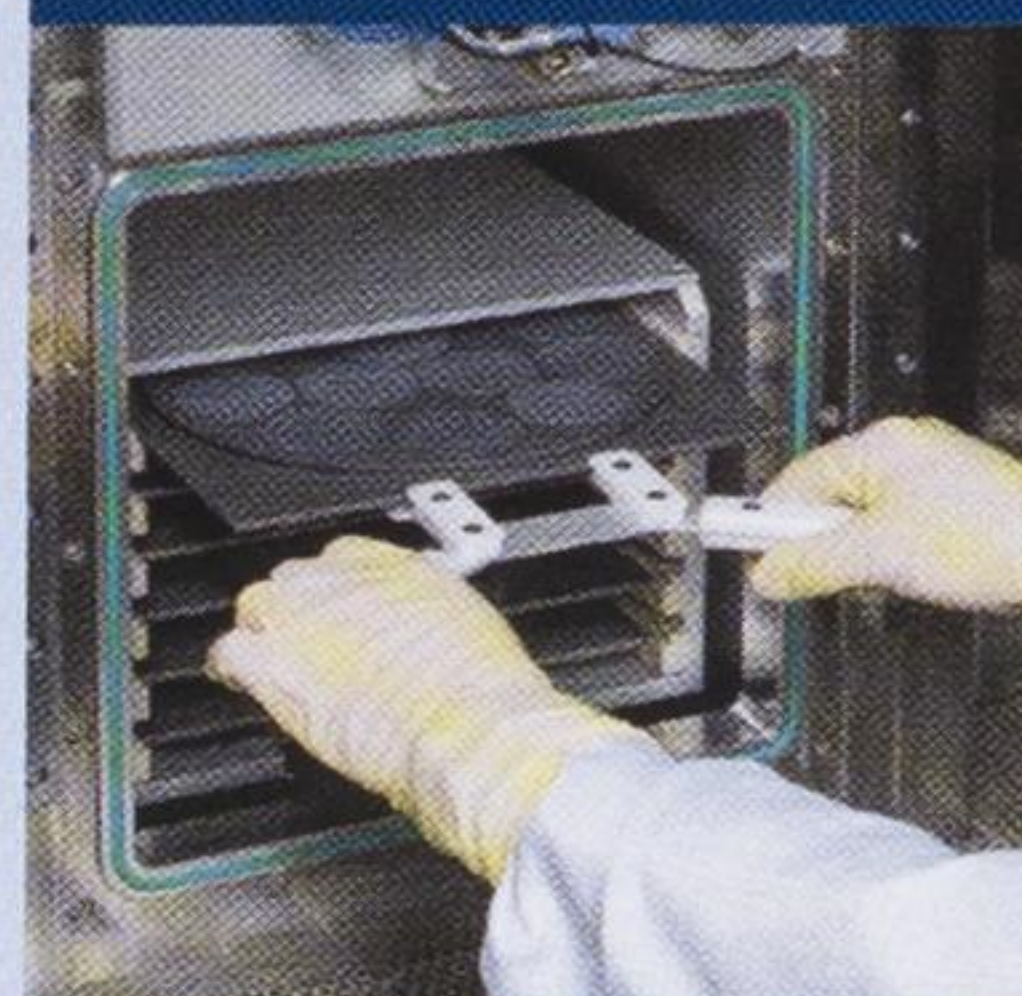
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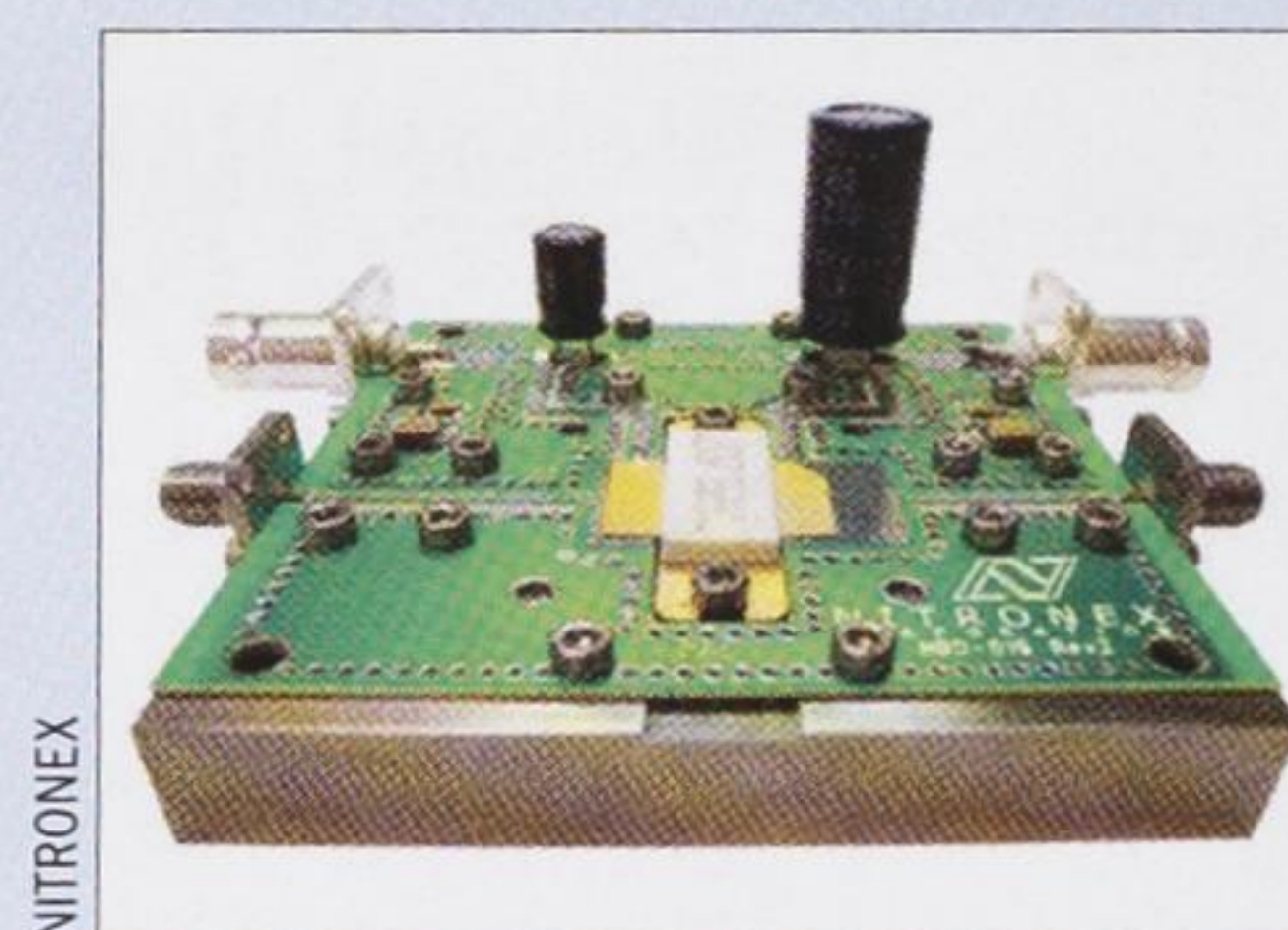
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Emergency aid

Nitronex has developed a range of GaN HEMT broadband amplifiers for military and emergency service radios. **p41**

- 44** **Research Review:** Thinner dots boost detector sensitivity...ZnO combats droop...Metamorphic laser hits 10 Gbit/s modulation.

Main cover image: Figures in the GaAs manufacturing industry are calling for a standard for qualification testing of PA modules. Modules from TriQuint are shown without their familiar plastic overmolding. See p25. Credit: TriQuint Semiconductor.

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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 8 times a year for \$188 by IOP Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Middlesex, NJ 08846. POSTMASTER: send address corrections to Compound Semiconductor, c/o PO Box 177, Middlesex, NJ 08846. US agent: Pronto Mailers Association Inc, 200 Wood Avenue, PO Box 177, Middlesex, NJ 08846.

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EDITORIAL

\$49 m? Whistle for it



Reliable. It's not always the most flattering description of something. That reliable old car – sure it got you from A to B, but didn't it lack a little style, a little *je ne sais quoi*?

Maybe so. But right now, reliability is "in". And Robert Ferro, the man who blew the whistle on the not-so-reliable HBTs made at TRW in the 1990s, is "in" to the tune of nearly \$50 million. But the astonishing award – thought to be the biggest such settlement ever granted in the US – would never have come about if TRW had tested the reliability of the compound semiconductor devices properly, or come clean about their failings.

Rewind to 1995. Ferro is a scientific researcher at Aerospace Corporation. He discovers that the reliability of TRW's GaAs HBTs is not up to scratch – certainly not for their critical satellite applications.

However, TRW and Ferro's employer have signed the all important non-disclosure agreement. So even though Ferro reports that the HBTs are likely to fail under high electrical current operation, TRW refuses to let that be known to anybody else, including its customer – no less than the US government.

Forward to 2001, and, sure enough, a satellite fails in orbit. The knock-on effect delays subsequent launches. But still the cover-up continues, with Ferro's original results suppressed from a report for the US Air Force. Then Ferro, followed by the government, sues TRW.

Astonishingly, there's a Hollywood ending: Ferro is vindicated and gets a whopping pay-off to boot. If I were a movie producer, I'd have already bought the film rights.

But the message is clear – overlook reliability at your peril. And not just in satellites. At the moment it is a critical subject for makers of solar cells. Triple-junction cells, which have proved themselves worthy of long-term satellite operation, now have to be shown to be just as robust in terrestrial concentrators, where good system lifetime will be crucial for economic operation. Any loss of confidence in the technology could be fatal to the prospects of the fledgling concentrated photovoltaics industry.

Michael Hatcher *Editor*

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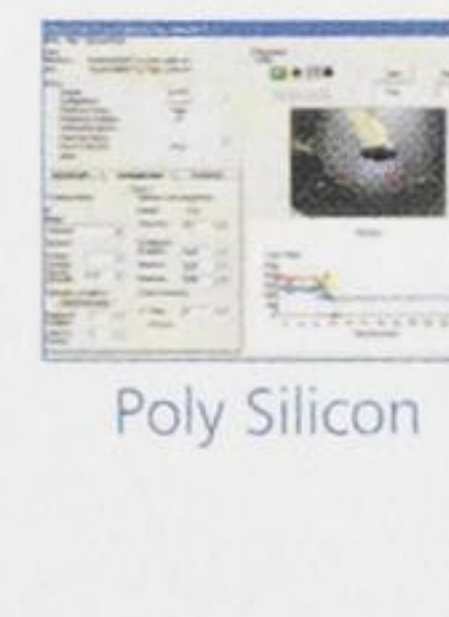
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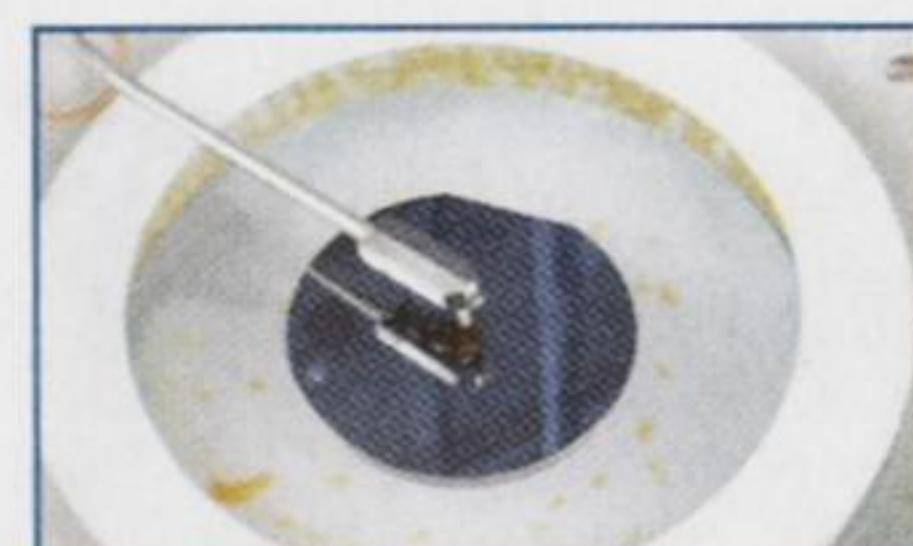
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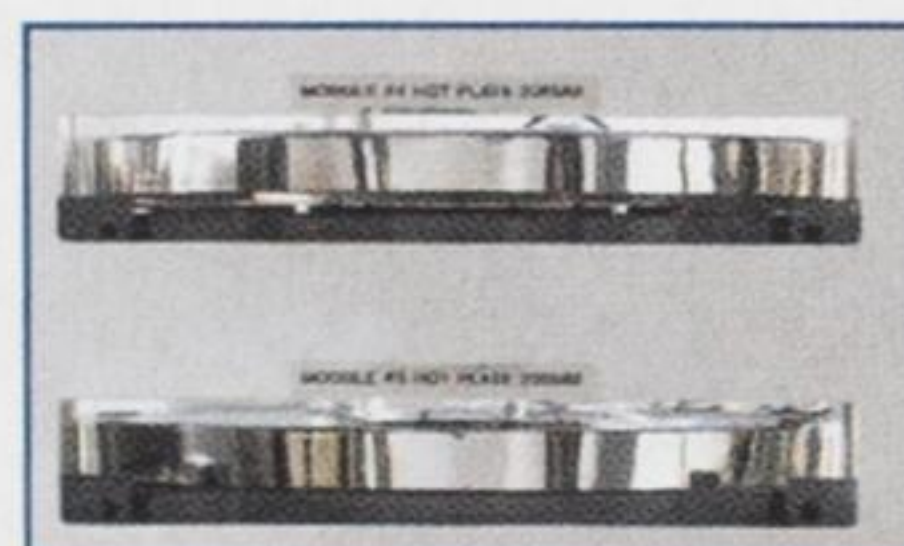
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RELIABILITY

HBT whistle-blower gets \$48.8 m reward

Northrop Grumman has reached a \$325 million agreement to compensate the US government for a cover-up concerning faulty transistors deployed in satellites.

The HBTs, produced by GaAs pioneer TRW between 1992 and 2002, were supplied to the US National Reconnaissance Office (NRO) and involved in critical failures on an orbiting satellite in 2001. Several other government programs then delayed the launch of their satellites, eventually replacing the affected HBTs they had used.

Robert Ferro, now a senior engineering specialist at The Aerospace Corporation, discovered in 1995 that the HBTs in question were likely to fail under high electrical current operation. After TRW tried to conceal his findings Ferro went it alone, suing the company in the California courts under the US False Claims Act. He initiated the suit in 2002 – the same year that Northrop Grumman acquired TRW.

The US government began investigating the case in 2003, eventually finding that TRW had failed to properly test and

qualify its HBTs. TRW had also integrated defective HBTs into NRO satellite equipment, then misrepresented and concealed reliability information, the government found. Having drawn these conclusions, the government joined Ferro's suit in November 2008 and then announced the \$325 million out-of-court settlement with Northrop Grumman on April 2.

The False Claims Act requires the US government to give the whistle-blower in such cases between 15 and 25% of what it recovers. In this case Ferro, who is also on the organizing committee of the Reliability of Compound Semiconductors Workshop, gets \$48.75 million. "Today's settlement is the largest one ever paid by a defense contractor in a whistle-blower case and the second largest settlement ever involving defense contractor fraud," claimed Philips and Cohen LLP, Ferro's law firm.

"The conclusion of the case came as a bit of a surprise to me," Ferro told *Compound Semiconductor*. "I was on vacation when my attorney told me that an agreement

had been reached. I have no feelings of ill will towards anybody – I am still working with Northrop Grumman and have a lot of respect for many of the people there."

Just a month before the satellite problems began emerging, the law firm says, TRW also concealed from the government a massive recall of cell phone equipment using similarly defective HBTs. It also says that TRW sanitized a report from The Aerospace Corporation commissioned by the US Air Force, in which Ferro tried to include his 1995 results, under the premise of a non-disclosure agreement. Not only did TRW remove that work, it also removed references to other warnings that it had received about its HBTs.

However, Northrop Grumman still denies any wrongdoing and will not ultimately make any payment to the US government. Instead it has agreed to settle an outstanding \$1 billion claim that it had against the government for a missile program cancelled in 1995 for \$325 million. The missile claim and the HBT claim offset each other.

SOLID-STATE LIGHTING

Samsung readies LED spin-out venture

Samsung Electronics and Samsung Electro-Mechanics are establishing a joint venture that is focused purely on LED development and manufacturing, called S-LED.

Samsung Electro-Mechanics has typically focused on making white LEDs for mobile phone backlights, although it is now moving towards brighter devices suited to backlighting of large LCD televisions.

S-LED's operations are now being organ-



Samsung's ultra-modern Haptic Beam

LED-powered projector phone is just one of its many products set to benefit from the establishment of a dedicated LED manufacturing subsidiary.

ized, in parallel with the availability of Samsung's latest LED edge-lit LCD TVs in the US. The 40, 46 and 55 inch 6000 and 7000 series TVs became available in

March at prices ranging from \$2,299.99 to \$3,599.99. Its higher-performance 8000 series LCD TVs will become available in the US in May, and models from the other two series will be released through June.

This comes after Samsung's "Haptic Beam" became the first commercially available mobile phone to feature a projector display powered by LEDs. Korean network operator KTF introduced the phone in February. The handset is reportedly capable of projecting a 50 inch image under ambient light conditions and went on sale in Korea in February at \$500. It will hit the European market in April or May.

MERGERS AND ACQUISITIONS

Sirenza founder buys M/A-COM Technology

John Ocampo acquired microwave and radio frequency semiconductor component manufacturer M/A-COM Technology Solutions on March 31 for up to \$90 million.

Ocampo owns the GaAs Labs semiconductor private equity fund and founded Sirenza, the fabless GaAs manufacturer bought by RF Micro Devices in November 2007.

The deal sees Ocampo pay defense and aerospace firm Cobham \$30 million in cash, \$30 million in loan notes secured on M/A-COM, with another \$30 million dependent on future revenue.

"We are thrilled to have the unique opportunity to acquire one of the best known companies in the RF and microwave space," said Ocampo. "M/A-COM is an icon in our industry. We look forward to leveraging the company's products and technologies as platforms for future growth."

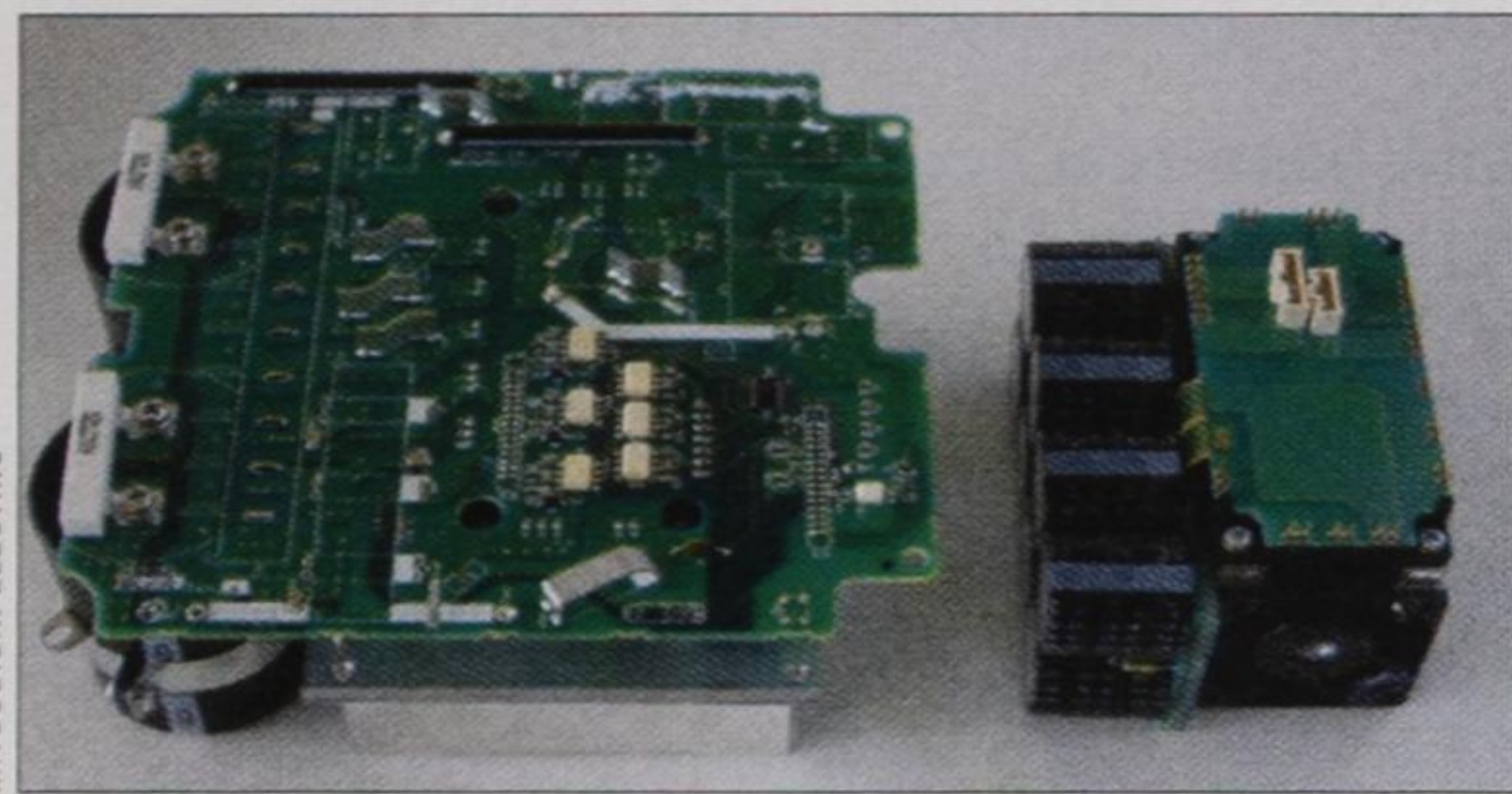
Asif Anwar of industry analyst Strategy

Analytics commented: "We see this acquisition as a positive for M/A-COM. The prior expertise and focus of the personnel at GaAs Labs should bring a number of benefits to the company, not least of which will be an understanding of the core trends in the semiconductor market."

GaAs Labs took a minority stake in another fabless GaAs component maker, Mimix Broadband, in 2008. After specializing in fabless companies throughout his career to date, Ocampo now gains M/A-COM's Lowell, MA, fabrication facility.

POWER ELECTRONICS

Japanese companies continue SiC thrust



By combining six SiC Schottky barrier diodes and six SiC MOSFETs, Mitsubishi Electric has shrunk its prototype inverters (right) to a quarter of the size of silicon modules (left) and cut power losses.

Industrial giant Nippon Steel has broken into the exclusive ranks of SiC substrate makers selling production volumes of 4 inch wafers. The company officially released substrates that boast dislocation densities between 10^3 and 10^4 and less than 1 micropipe per square centimeter, on April 1.

Meanwhile, Mitsubishi Electric has unveiled a SiC prototype inverter module that reduces DC-AC power conversion losses by 70%. The Japanese giant's module uses SiC devices in place of silicon transistors to make the efficiency gain. It is one-quarter of the size of typical silicon IGBT-based products and is rated at up to 11 kW.

Mitsubishi Electric told *Compound Semiconductor* that it will use the technology in commercial products such as air conditioners, photovoltaic inverters and elevators by early 2011.

Tatsuo Ohmori, general manager of Mitsubishi Electric's Advanced Devices Technology Laboratory emphasized that Mitsubishi is working to reduce the cost of its SiC devices prior to commercialization. Applying Nippon Steel's high-temperature manufacturing expertise to SiC crystal growth technology could well help Mitsubishi achieve this.

"A special process is needed to control the very high temperature, above 2000°C," explained Takayuki Yano, who heads up Nippon Steel's advanced technology development. "The steel-making process also uses very high temperatures. Controlling this kind of process is our strong point."

A major Japanese device manufacturer and a number of other compatriot research groups have already been using sample substrates from Nippon Steel. Now the company is launching a full repertoire of 2, 3 and 4 inch 4H crystal polytype semiconducting SiC substrates onto the market.

Japan is leading the way in SiC research,

driven in part by the specific inclusion of wide-bandgap semiconductors in the governmental "Cool Earth-Innovative Energy Technology Program". This program calls for 6 inch SiC wafers to be available by 2015, with a 10^2 dislocation density per square centimeter target.

Nippon Steel is seeing that call echoed by its potential clients. "We believe that our customer will need to have 6 inch or some kind of large diameter wafers very soon, so we think that we have to prepare for this kind of situation," Yano said.

● Not to be outdone by its Japanese rivals, German semiconductor giant Infineon has introduced its third-generation thinQ SiC Schottky diodes. Compared with the second generation, the device capacitances of the third-generation diodes are 40% lower, which reduces switching losses. Full production is slated for early spring.

LITIGATION

Manufacturers resist Rothschild suit

Panasonic and Toshiba have emerged as the major non-US companies actively defending themselves against accusations of infringing Prof. Gertrude Neumark Rothschild's optoelectronic device doping patent.

Out of 44 manufacturers originally named in the US International Trade Commission (ITC) case, the Japanese companies are the only ones officially offering resistance. The ITC has the power to stop US imports of LEDs and laser diodes that infringe the patents, and products that contain them.

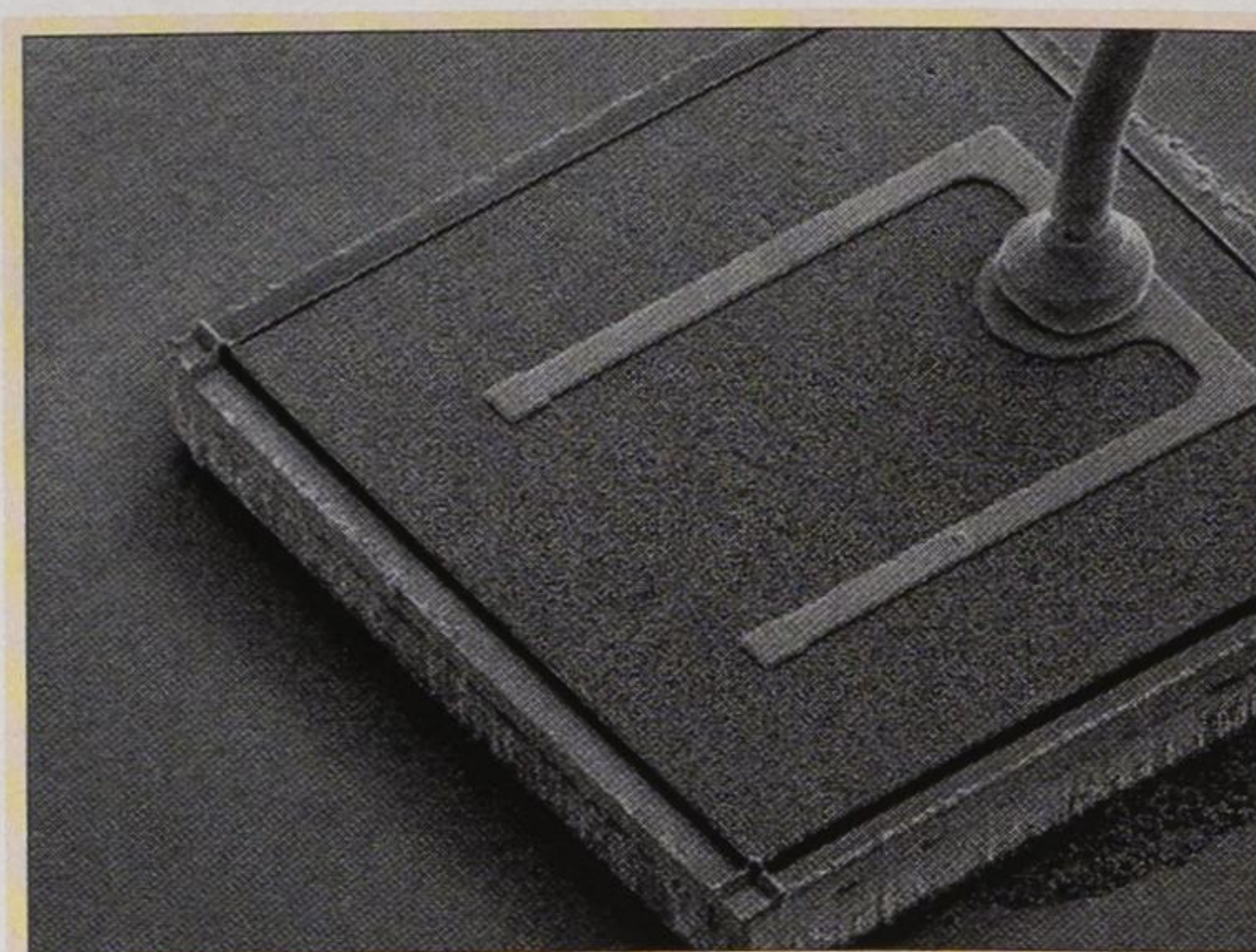
Some 21 firms have now settled with and gained licenses from the retired Columbia University academic, while the ITC announced on March 31 that it will extend its investigations to six more Asian companies.

"We're currently locked in significant litigation with Panasonic and Toshiba," confirmed Al Jacobs, counsel for the emeritus professor, on returning from taking testimony from other respondents in Taiwan.

From the original 44, one further mobile phone manufacturer has also just settled. Around five companies remain that might still contest the case, Jacobs revealed.

The ITC added Taiwan's Chi Mei Lighting Technology, Tekcore, Toyolite, Tyntek and VPEC, plus China's Sanan Optoelectronics to its investigations on the Rothschild case on March 31. "It would appear that one or more of those companies are interested in having a discussion," Jacobs told *Compound Semiconductor*.

Panasonic and Toshiba join Cree in the minority of optoelectronic device manu-



A recent analysis has suggested that Seoul Semiconductor's P9 LED still uses die from SemiLEDs, even after their partnership saw both companies sued by Nichia. A teardown from Canadian chip characterization laboratory MuAnalysis published on March 17 found that a GaN chip used in Seoul Semiconductor's Z-Power LED P9 series possesses SemiLEDs' trademark flexible copper substrate. Nichia has only recently concluded long-standing patent cases with both SemiLEDs and Seoul Semiconductor. When the case was first filed Seoul's position was that most of the die for its P9 came from Cree, which already held a license from Nichia, and not SemiLEDs.

facturers that have decided to defend themselves against Rothschild's patents. Preparations for a hearing between Cree and Rothschild in the Southern District of California, separate from the ITC case, are ongoing. Jacobs has just been appointed lead counsel for Rothschild in that case also.

CRYSTAL GROWTH

GaN substrate firm targets June launch

A UK company looks set to open up the limited supply of free-standing GaN substrates, as it moves into pilot production.

Wang Nang Wang, founder of University of Bath spin-out NanoGaN, says that progress on wafer yields and quality should see a commercial launch in June. "We are producing free-standing GaN in collaboration with our Japanese partners to get the full characterized specification," Wang said.

With two vertical hydride vapor-phase epitaxy (HVPE) systems in place NanoGaN is also in the process of planning its next expansion stage. "It is time to seek further funding or production partners to expand the production capacity," Wang said.

NanoGaN previously gained £500,000 (\$733,302) in June 2008 from private investors, in part to build a vertical HVPE system

according to NanoGaN's patented design, in collaboration with a commercial MOCVD equipment manufacturer.

The bulk material that these systems produce, and is later sliced into NanoGaN's substrates, is deposited on to a buffer of GaN nanocolumns formed on top of a SiC, silicon or sapphire substrate.

In other bulk GaN manufacturing methods this initial use of non-native substrates is a source of poor wafer quality. The lattice mismatch and differing coefficients of thermal expansion between the substrate material and GaN cause bowing and cracking as the boule cools down.

The nanocolumns in NanoGaN's approach relieve this strain, allowing thicker and better-quality bulk crystals. NanoGaN's partners are now assessing the real-world effectiveness of the resulting substrates.

"We have to prove that our products have much lower bowing and strain," Wang explained. "We also need feedback from manufacturers to validate that free-standing GaN products provide the benefit of improved yield rate in laser diode and high-power thin GaN LED fabrication."

PHOTONIC INTEGRATION

OneChip brings InP PICs 'to the home'

OneChip Photonics is hoping to use photonic integration to slash the cost of making optical transceivers for fibre-to-the-home applications. Specifically, the Canadian start-up says that it can combine all of the components found inside the transceiver onto a single photonic integrated circuit (PIC) made from InP.

The start-up gained \$16.5 million funding in March having reached triggering targets on cost, manufacturability and yield.

OneChip claims that its chips are built using fewer manufacturing steps than other PICs, which translates into higher yields and hence lower costs. The company has designed device structures that allow them to make complex chips without any regrowth steps. "We only do lithography and etching, and out pops the transceiver at the other end," said the start-up's chief executive Jim Hjartarson.

The PIC eliminates the need to align individual components, meaning that the transceiver can be built, assembled and tested without manual intervention. "The only assembly is aligning the fibre with the chip, and this is all done with robotic pick-and-place machines, so it is almost entirely automated," said Hjartarson.

OneChip declined to say which foundries will make its chips, but one of them is likely to be the Canadian Photonics Fabrication Center in Ottawa, which got a C\$22.3 million funding boost from the Canadian government last year.

There are around 33 million FTTH subscribers worldwide, but that figure is set to grow to 100 million by 2013, according to research by consultancy firm Ovum.

This means that OneChip is addressing exactly the kind of market that pundits say will benefit most from the high-volume, low-cost manufacturing processes associated with photonic integration.

The start-up was founded in 2005 by Valery Tolstikhin, who had previously worked on InP PICs at another Canadian start-up, MetroPhotonics. OneChip has a staff of about 30, and hopes to grow to twice that number before the end of the year.



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...\$77 m for GaAs keyboard sensors

Toronto-headquartered Micromem has signed a five-year deal to supply 5 million keyboard circuits that incorporate GaAs sensor technology. The \$77 million order will see the circuits used in Unotron International's washable keyboards, with fabless Micromem due to receive \$5 million revenue in 2009.

...Aqualite buys LED tools

MOCVD and scribing equipment suppliers have revealed that Wuhan, China, based GaN LED maker Aqualite has recently taken delivery of their products. Aqualite is exploiting Portland, OR, based Electro

Scientific Industries' AccuScribe 2112 laser scribe. It is also using three 31 x 2 inch Crius close-coupled showerhead MOCVD reactors from Aixtron in Aachen, Germany.

...Avago and Emcore in laser spat

The US International Trade Commission is investigating a complaint made by Singapore-registered Avago Technologies that Albuquerque, NM's, Emcore is importing products into the US that infringe its patents. Avago is enforcing US patent numbers 5,359,447 and 5,761,229, which were filed by Hewlett-Packard and relate to VCSELs and intensity-controlled lasers, respectively.

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OPTOELECTRONICS

Osram stresses green light on projectors



This year, Osram is intending to ramp green emitters that combine an infrared optically pumped semiconductor disk laser with a frequency-doubling non-linear crystal to generate 530 nm light.

Osram Opto Semiconductors has reaffirmed that it will introduce compact green lasers in 2009 after mobile projector company Microvision failed to complete its testing because of the lack of these components.

Each of the green lasers features an 808 nm AlGaAs laser diode that pumps a 1060 nm-emitting semiconductor disk laser, which Osram grows on a GaAs substrate. The laser's emission is then converted to green light by a process known as frequency doubling, or second harmonic generation.

"We are preparing the ramp-up of green lasers with second harmonic generation," said Thomas Hoefer, head of laser projection at the Regensburg-headquartered company.

After successfully demonstrating display engines using Osram's products in June 2007, Microvision is waiting for deliveries of green lasers before it can launch products. Despite receiving lasers that Microvision put into its trial products in September 2008, CEO Alexander Tokman said during the company's full-year financial results announcement on March 5 that further progress was slower than hoped. "The longer-than-expected development cycles and lack of a detailed delivery schedule for green lasers has made it challenging to complete final product testing and customer agreements," he said.

Responding to *Compound Semiconductor*, Osram says that its lasers meet size and power consumption specifications and are making "substantial progress" towards commercialization. "A green laser for small mobile projectors is more challenging than conventional high-power green lasers," Hoefer said. "We have spent much effort following the increase in customer requirements."

The German company says that second harmonic generation lasers will remain the technology of choice in coming years, but has also just reached a landmark for individual diodes.

In an *Applied Physics Letters* paper published on February 27, Osram researchers described an electrically pumped 500 nm-emitting diode. Although this is not truly

green, the company claimed that this was the longest-wavelength InGaN emitter reported to date.

"The 500 nm laser is based on our blue laser technology," commented Uwe Strauss, Osram's director of semiconductor laser technology. "To go to longer wavelengths, we put more indium into the quantum well, but we also needed a detailed understanding of the device as well as the growth processes to achieve high material quality."

AIXTRON

Industry trends favor larger LED makers

The global recession has done away with a number of long-term LED chip supply deals, leaving some manufacturers unable to see beyond their next month's sales.

So says Aixtron, the number-one supplier of the MOCVD tools used to produce LED die. The German firm cited this situation to explain its own inability to give a detailed outlook on future business.

On the back of a strong final quarter of 2008 the Aachen-headquartered company aims to at least break even in 2009. But it is clear that if the current order environment continues, some LED makers will not be able to do the same.

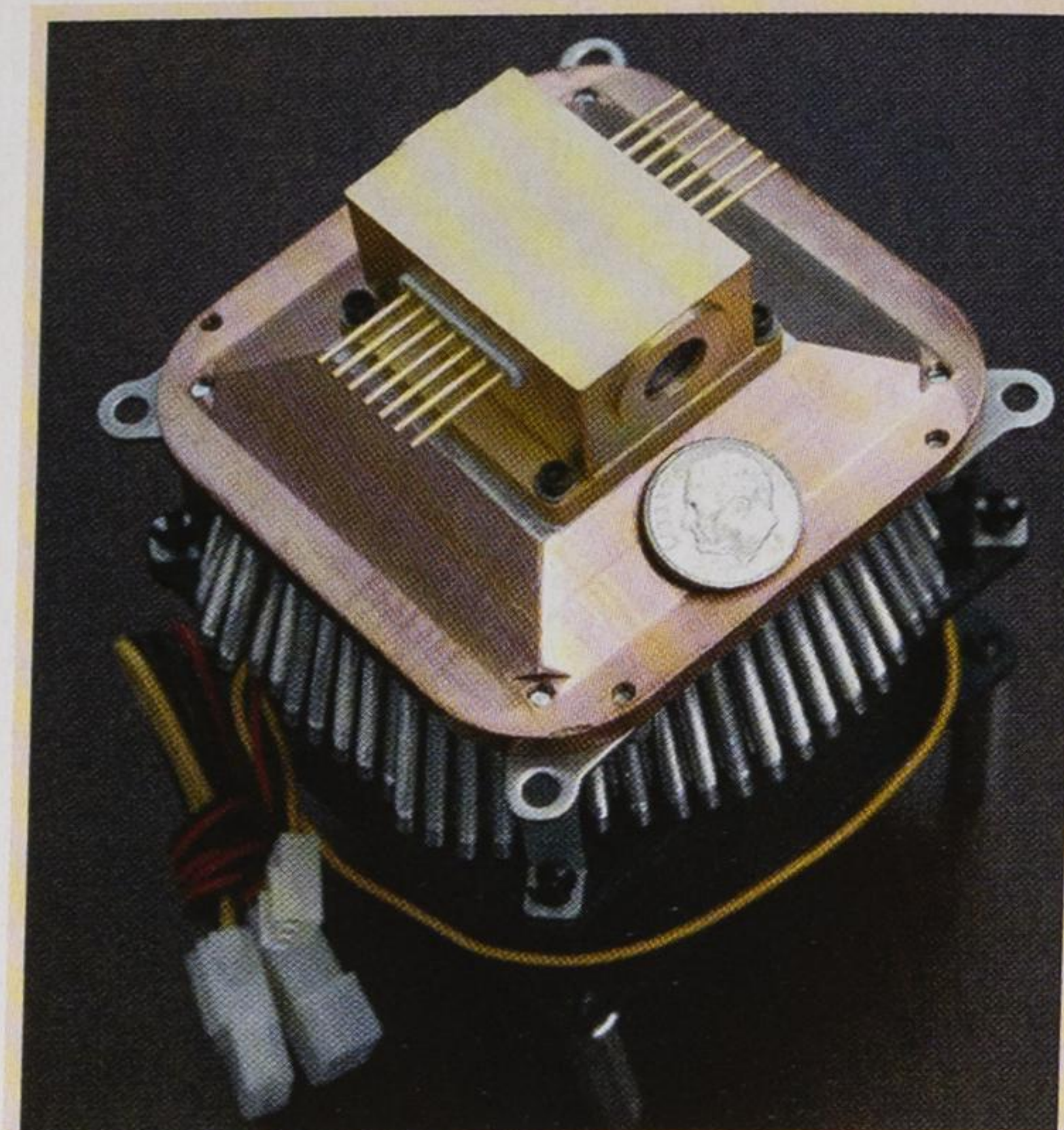
"The inventory channels have been emptied and the business that comes along is short-term, without any visibility," said Aixtron's chief executive officer Paul Hyland, describing his customers' trading environment. "I think that we're in for a period of volatility. If it goes on like this for some time there is risk to the smaller players."

Aixtron has taken the unusual step of cutting its order backlog by €17 million (\$21.8 million) to allow for possible cancellations and push-outs caused by the economic situation.

Although this has accelerated the backlog figure's fall to €105 million, a €53.1 million drop from the quarter ended September, Hyland stressed that no actual cancellations have yet been made. "We should not lose sight of the fact that the medium- to long-term outlook for the LED market has never been better," he said.

In 2008 the company's revenues increased by 28% to an all-time-high of €274 million, expanding its profits 33% to €23 million. Aixtron is now targeting revenues of at least €170 million to break even in 2009.

The equipment vendor has itself deployed a Rohm and Haas VaporStation to deliver trimethylgallium into one of each of its Crius and Planetary reactors at its Aachen applications and demonstration center.



Two rival system makers have established a significant market toehold for quantum cascade lasers (QCLs), driven by quite different applications. Cascade Technologies of Stirling, Scotland, has been negotiating a supply agreement with what it calls "a major global corporate" for 1.3 μm wavelength leak-detection systems on an aerosol filling line. Meanwhile, Santa Monica's Pranalytica has introduced 2 W QCL systems emitting at 4.6 μm for use in defense infrared countermeasures. This adds to its existing military 1 W QCL offerings, already in production. Unlike Cascade, Pranalytica is vertically integrated and produces all of its own InGaAs/InAlAs/InP QCLs. One such laser is shown here integrated into an air-mount package, to protect it from extreme vibration.

According to Aixtron's technology vice-president Johannes Kaeppler, replacing labor-intensive bubblers with centralized systems like VaporStation can increase the output from their MOCVD reactors. Aixtron was able to use the VaporStation to produce GaN films with the same quality as bubblers, without the need for calibration runs that they normally demand.

"Future reactor generations will have significantly higher throughputs, which will increase metalorganic consumption," Kaeppler told *Compound Semiconductor*.

Raised metalorganic precursor consumption demands simplified supply, he says. VaporStation achieves this by delivering vapor from a central source cabinet in high-purity carrier gas via a series of pipes to up to 10 reactors. The cabinet can accommodate a 20 kg cylinder full of precursor.

Kaeppler sees large LED manufacturers – dominated by Asian companies – as the most likely users of these systems. However, he believes that it will also be applicable for producing photovoltaic cells and more general III-V device manufacture.

Introduction of centralized delivery systems might also enable semiconductor manufacturers to outsource more aspects of precursor supply, Kaeppler points out. "Central metalorganic supply could become a service, which is very similar to the practice in the silicon industry," he said.

GaAs RATIONALIZATION

PA makers cull China production sites

RF chipmaker Anadigics has discarded its plans for capacity expansion in China in favor of a hybrid manufacturing model.

During the final quarter of 2008 the company paid off its \$13 million obligation for the Kunshan, China, fab that it originally announced plans for in April 2007. Anadigics is now qualifying foundry partners to provide alternative capacity and expects to receive revenue from products that they make in the second half of 2009.

Meanwhile, rival power amplifier manufacturer RF Micro Devices (RFMD) is to part with more than 100 staff as it reorganizes its back-end manufacturing and operating expense structure. RFMD will now close its Shanghai test and assembly operations, combining some of the functions into its Beijing site and outsourcing others.

This move is set to be completed before the end of September, although the exact impact on headcount is currently not known. However, the company also laid off around 100 sales, administrative and R&D staff worldwide in a separate action

before the end of March. Around half of these losses were at RFMD's Greensboro, NC, headquarters.

RFMD's chief financial officer Dean Priddy told *Compound Semiconductor* that taking some of the work done in Shanghai on at its other sites and outsourcing the rest will enhance RFMD's overall manufacturing efficiency.

Combined with steps already taken, these actions will put RFMD's expense model where it needs to be, Priddy says. "Assuming revenue comes in about where we planned, you're going to see significant improvements in our financial performance."

He also emphasized that any reductions in R&D had been carefully planned to not impact critical projects for key customers or strategic development programs. Together the operating expense and manufacturing restructuring will cost RFMD \$17.5 million for employee benefits, cancelled leases and obsolete equipment.

Anadigics is also exploring ways to further limit salary expenses with its revenues sliding from a peak of \$80 million in June 2008. December's quarterly sales of \$45.2 million were down 22% sequentially and are set to fall another 35% in the period ended March.

The Warren, NJ, firm made around 100 employees redundant at a cost of \$2.1 million in the December quarter, contributing to its overall \$36.4 million quarterly loss. It predicted another \$1 million of voluntary redundancies and retirements in the following period. Anadigics' cost-saving measures included instigating periods of mandatory leave for all US employees.



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...European wafer makers hire for growth

German epiwafer vendor Azzurro Semiconductor and Dutch sapphire substrate firm CrystalQ have taken on seasoned executives to advance their businesses. Azzurro has appointed Erwin Wolf, the former Osram Opto Semiconductors, Inc, CEO who also has power semiconductor and optical communications industry experience, as its CEO. CrystalQ has appointed Peter W van Strijp, former CEO of Philips' solid-state lighting business as the chair of its supervisory board. Peter Stormberg, former CTO of Philips Lighting, has also joined the board.

...Raytheon gets \$23.9 m for GaN

Defense giant Raytheon has been awarded \$23.9 million to move into the third phase of

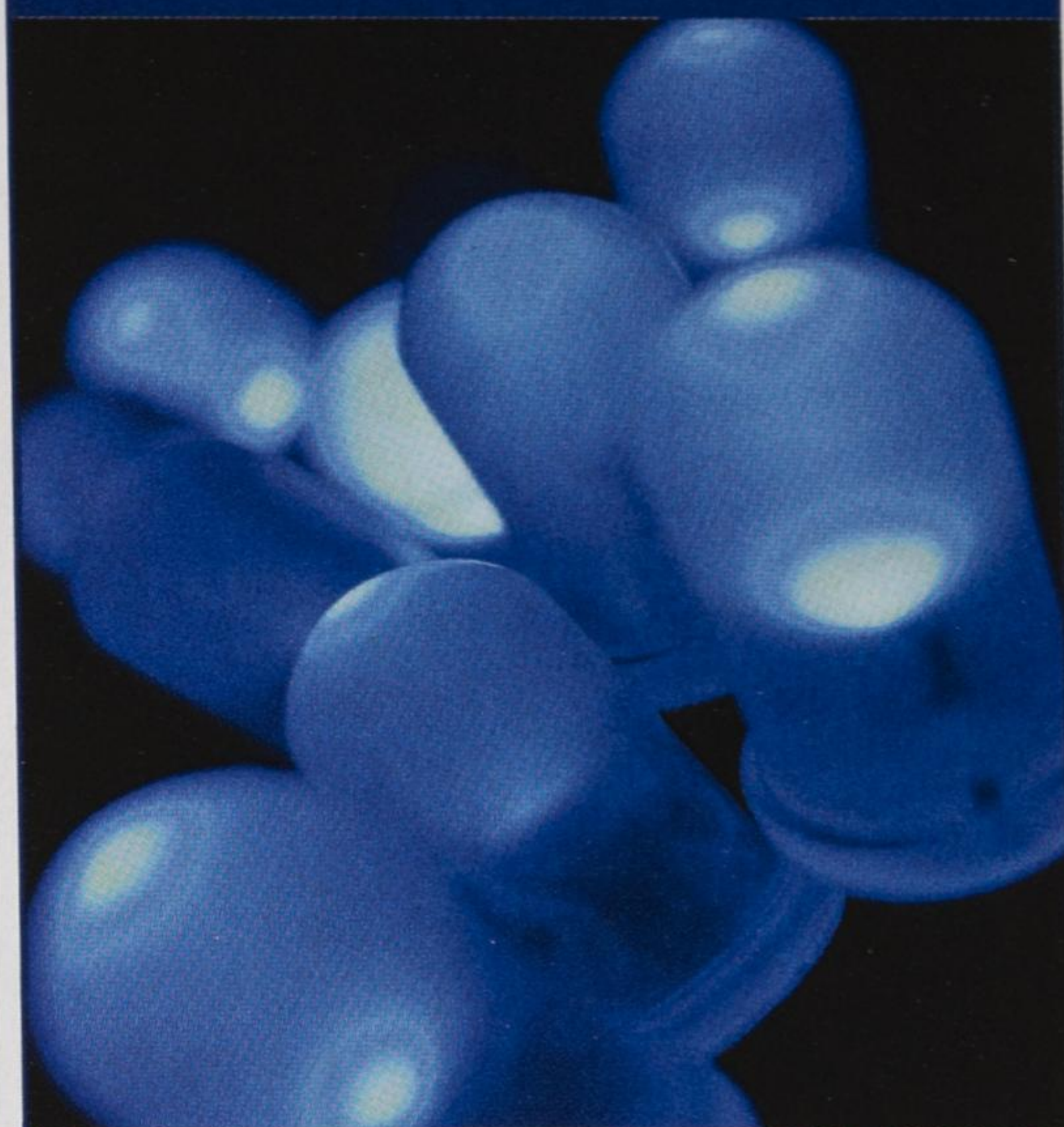
the US Defense Advanced Research Projects Agency's Wide-Bandgap Semiconductor (WBGS) program. This 38-month stage will use GaN to improve the performance of missile defense radars, exploiting the results of Raytheon's prior WBGS Phase 2 and MDA-funded programs.

...GaSb gets thermal power cash

UK epiwafer supplier IQE's subsidiary company, Wafer Technology, will lead a £2 million (\$2.9 million) project to develop GaSb thermophotovoltaic technology. Lancaster University and QinetiQ will join Wafer Technology in using alloys including InAsSb and InGaSbN on 4 inch GaSb substrates to generate electricity from waste heat at temperatures below 1000 °C.

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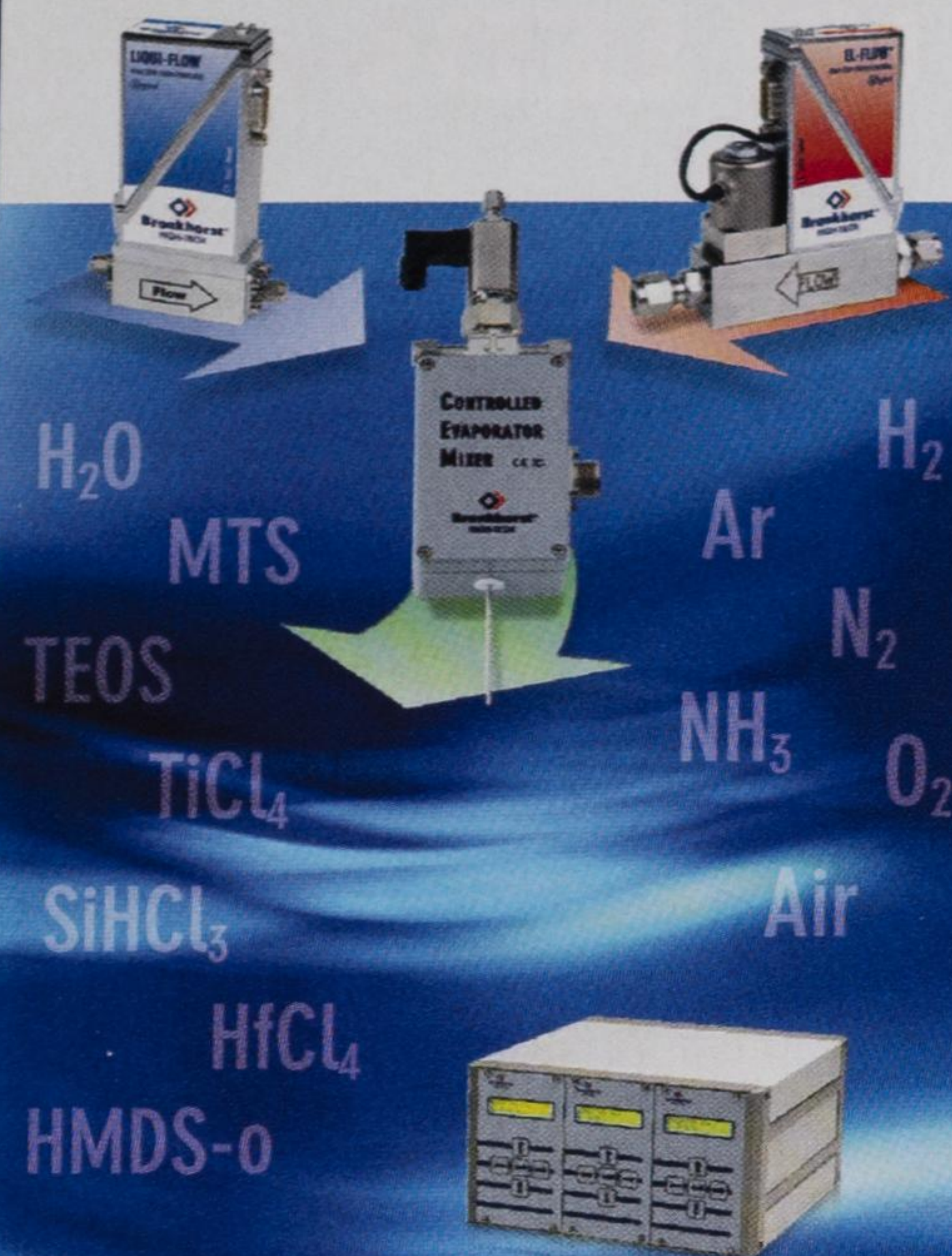


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INDUSTRY UPDATE

HIGH-POWER LASERS

Diode firms missing fiber-laser window



During tests at White Sands Missile Range, the IPG Photonics diode-powered Avenger became the first combat vehicle to use a laser to shoot down a UAV.

Sales of high-power laser diodes for industrial machining systems are expected to fall by nearly one-quarter because of the global recession. California-based market research company Strategies Unlimited makes the prediction in its latest report *Fiber and Industrial Laser Market Review and Forecast – 2009*. Tom Hausken, director of photonics and compound semiconductors at the firm, says that the market for diode pumps used in high-power systems for welding, cutting and drilling will drop from \$180 million in 2008 to \$140 million this year.

This is, however, less precipitous than the wider market for industrial laser systems, which is expected to drop 32% this year and will not recover to 2008 levels until 2013.

High-power fiber laser producers are benefitting as manufacturers increasingly turn away from bulkier, more complex and less energy-efficient designs, such as CO₂ lasers or flashlamp-pumped systems. But Hausken believes that makers of high-power diodes are missing out because of the dominance of one fiber-laser company – IPG Photonics.

“The best thing that could happen for JDSU and other aspiring suppliers of diodes for pumping fiber lasers is to help create a competitor to IPG that can buy large quantities of their diodes,” said Hausken.

More than 30 companies supply fiber lasers, but Hausken says that the window of opportunity for diode companies is closing: “Time is running out, because two of the leading contenders – Trumpf and Rofin-Sinar – will prefer to supply their diodes internally, not from merchant suppliers.”

The impact that IPG’s fiber-laser products is having on its rivals was echoed by a mobile laser system featuring its high-power diodes. December 2008 saw the multi-kilowatt output laser demonstrated as part of Boeing’s “Avenger” mobile defense

system at a New Mexico missile range.

In the same financial quarter IPG said that it earned \$24.8 million from similar high-power lasers, up 32% from the same period in 2007. “We believe that in North America, our competitors are getting very few orders for high-power lasers, and that the orders are coming to IPG,” said Tim Mammen, the company’s chief financial officer.

Mammen underlined the importance of the Avenger trial in showing that the tracking technology required to shoot down a moving object with a laser worked. IPG says that customers will soon release further results based on similar products.

In the December quarter IPG recorded \$58.2 million revenue. That total figure is down from \$62 million in the prior quarter, just as IPG’s profits fell from \$10.9 million to \$9.1 million sequentially.

IPG expected revenues to fall below \$50 million in the period to March, down 10% year-over-year, but as Hausken points out, its competitors are faring even worse.

SOLID-STATE LIGHTING

US signs off \$25 m for LED lighting research

Legislation approved by the US government will provide another major financial boost for research into solid-state lighting.

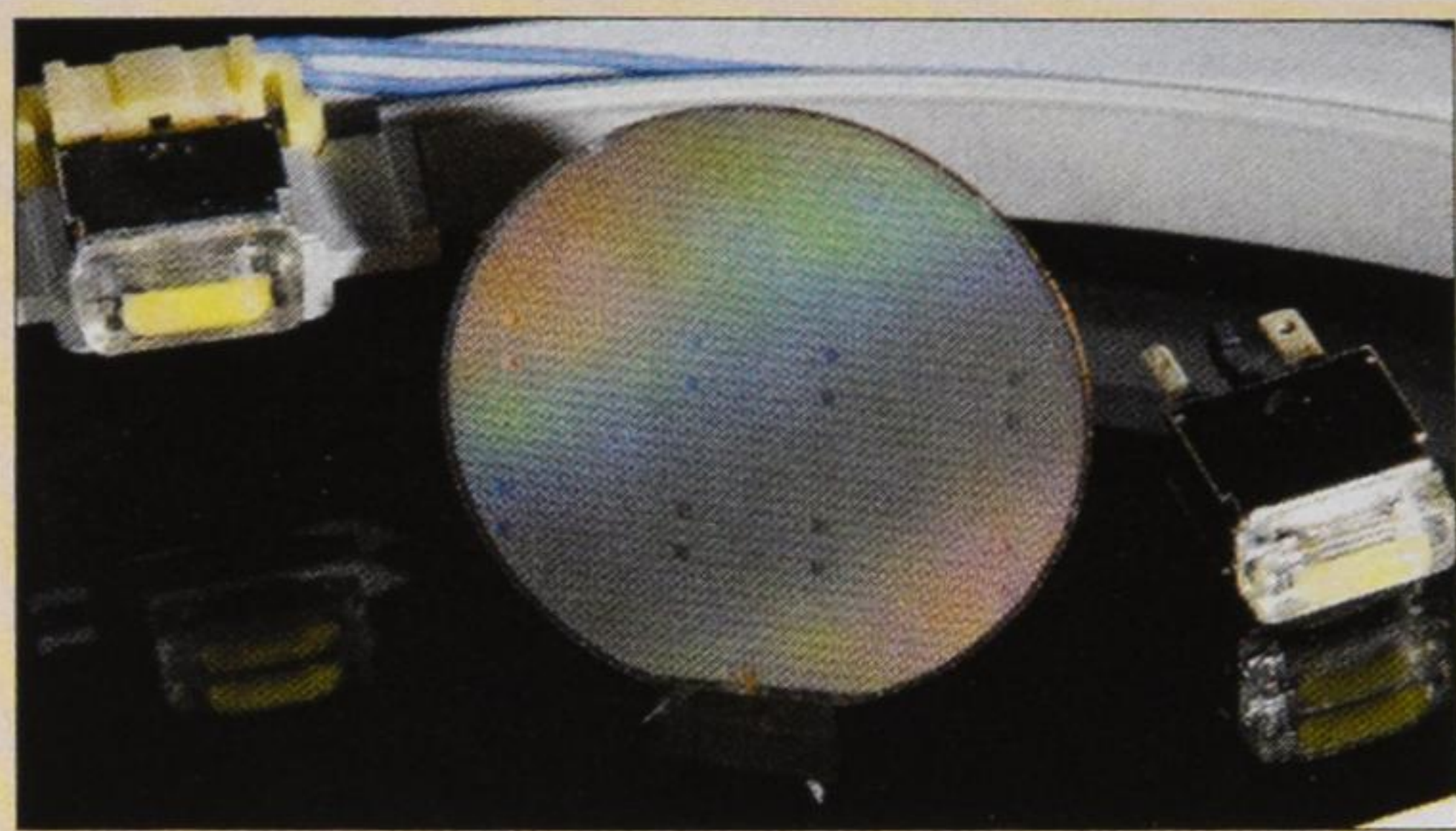
The Fiscal Year 2009 Omnibus Appropriations Bill, a \$410 billion spending plan running from March until September this year, earmarks “no less than” \$25 million for solid-state lighting R&D.

It also provides \$33 million for the Commercial Buildings Initiative, at least some of which is set to be used to install LED-based luminaires in highly energy-efficient buildings. In addition, the new legislation hands overall responsibility for developing Energy Star specifications for solid-state lighting to the Department of Energy (DOE).

Until now, the DOE and the Environmental Protection Agency (EPA) had been developing different Energy Star specifications, something that had led to significant inter-agency wrangling.

When contacted by *Compound Semiconductor*, the EPA provided this statement: “The 2009 appropriations bill does not speak to EPA’s role in Energy Star and solid-state lighting. The administration is working to clarify any confusion on this issue.”

Additional funding allocated under the Recovery and Reinvestment Act of 2009, perhaps better known as the US economic stimulus, will also be spent on four research solicitations that are set to be announced by the DOE over the next few months.



Chipmakers Epistar and Forepi are participating in a Taiwanese collaboration looking to overcome the need to convert AC mains current to DC to power LED lighting. Developed by Taiwan's Industrial Technological Research Institute (ITRI), "AceLED" die have two quantum-well layers, which emit light alternately as the current changes from positive to negative half-cycles. An ITRI spokesperson told *Compound Semiconductor*: "Some products will be provided in June."

At the end of March, the DOE selected two non-polar GaN LED research projects in the Core Technology awards. These and five other Core Technology Research programs will cost \$10.4 million in total and non-government partners will provide an average of 24% of costs.

Rensselaer Polytechnic Institute and Kyma Technologies will collaborate on producing high-efficacy green LEDs by "polarization controlled" MOCVD. This effort will focus on improving the poor internal quantum efficiency of deep-green emitters through growth on GaN oriented to avoid piezoelectric polarization fields.

Stealth-mode start-up Kaai, Inc., which counts luminary University of California, Santa Barbara, academics Shuji Nakamura and Steven DenBaars as advisors, will focus on the 400–460 nm emission wavelength range. They will develop LEDs produced on GaN's non-polar m-plane, targeting internal quantum efficiency above 90%.

SUBSTRATE MANUFACTURING

Yin exit exposes AXT as buyout target

Semiconductor substrate and materials supplier AXT ought to be an acquisition target for other companies in the GaAs industry supply chain.

That's according to two analysts reacting to the shock resignation of AXT's CEO, Phil Yin, on March 18. Richard Shannon from Northland Securities suggests that rival GaAs substrate supplier Freiberger could be the most likely buyer, because the German

company and AXT have been fighting for market share over the past couple of years. Shannon also thinks that an acquisition by epiwafer foundry IQE, AXT's largest customer in 2009, could make sense.

Rusty Cannon, president of RKC Capital, agrees that with AXT's total stock market valuation now worth less than its cash and restricted deposits, it's a good time to buy.

The two analysts say that Yin has been pivotal to AXT's recent success, which has

seen the company resurrect supply deals with the likes of Skyworks Solutions and RF Micro Devices. That said, both Shannon and Cannon feel that AXT's remaining management – under the stewardship of CFO Wilson Cheung for the time being – will be able to maintain key customer relationships in the near term.

They say that AXT can continue to take market share and believe that the firm is starting to emerge from the slump.



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SOLAR POWER

CPV companies exploit custom cells



By switching to III-V cells, Amonix has reached 25% efficiency with the 7700 systems that it likens to an oversized billboard that “wakes up in the morning, faces the sun and follows it throughout the day”.

By electing to use compound semiconductor rather than silicon solar cells, Amonix has produced its first photovoltaic systems to reach 25% efficiency.

The newly released Amonix 7700 concentrated photovoltaic (CPV) system was demonstrated at the Renewable Energy World Conference and Exposition in Las Vegas in March.

The leap in efficiency comes largely from replacing the 27.6% efficient back-junction silicon cells that Amonix had manufactured itself with 37% efficient GaInP/GaAs/Ge triple-junction cells. Its silicon manufacturing history allows Amonix to process the cells prior to integration into modules, providing an extra level of optimization.

The 53 kW Amonix 7700 panel operating at the University of Nevada, Las Vegas, boasts a 77 foot wide and 50 foot high receiving surface. That assembly is the company's largest to date, featuring seven semi-truck sized “megamodules”, each containing 36 solar modules.

Amonix has also converted its five-megamodule systems to use compound semiconductor cells and is currently deploying that format in a 250 kW installation for the Southern Nevada Water Authority. Construction on that site was due for completion before the end of April.

The Torrance, CA, company started using compound semiconductors after winning US Department of Energy funding to produce low-cost concentrators in collaboration with cell producer Spectrolab in 2007. Since then it has signed a long-term supply contract for 200 MW of high-efficiency cells from an unnamed supplier.

Amonix's rival GreenVolts is following a similar custom-cell approach. It has invested

in leading the exploitation of a new generation of III-V multi-junction solar cells and sees this as a key element of its strategy.

The San Francisco CPV company, currently in the process of building its “GV1” power plant, is joining forces with the US National Renewable Energy Laboratory (NREL) to develop advanced cells.

The two-year project, to which NREL is committing \$0.5 million and GreenVolts a “significant match” on top of this amount, will focus on the inverted metamorphic (IMM) structure – which until recently held the world record for solar-cell efficiency.

Bob Cart, the GreenVolts CEO, told *Compound Semiconductor* that using a proprietary cell design would provide the company with a significant advantage: “I believe that long-term success for a CPV system will be the result of a close relationship between the solar-cell provider and the system designer,” said the CEO. “Only then can you truly make a meaningful leap forward in overall system efficiency, reliability and cost.”

Cart's plan is to provide system, optics and optoelectronic integration expertise as the NREL team works to develop a customized version of the IMM structure that is suited to GreenVolts' approach. Although it will be intimately involved in the IMM cell development, GreenVolts does not plan to manufacture its own cells in the future. Instead, a foundry partner will be employed to scale up to volume requirements.

● For more on Bob Cart's approach to CPV technology, see p22 of this issue.

RF ELECTRONICS

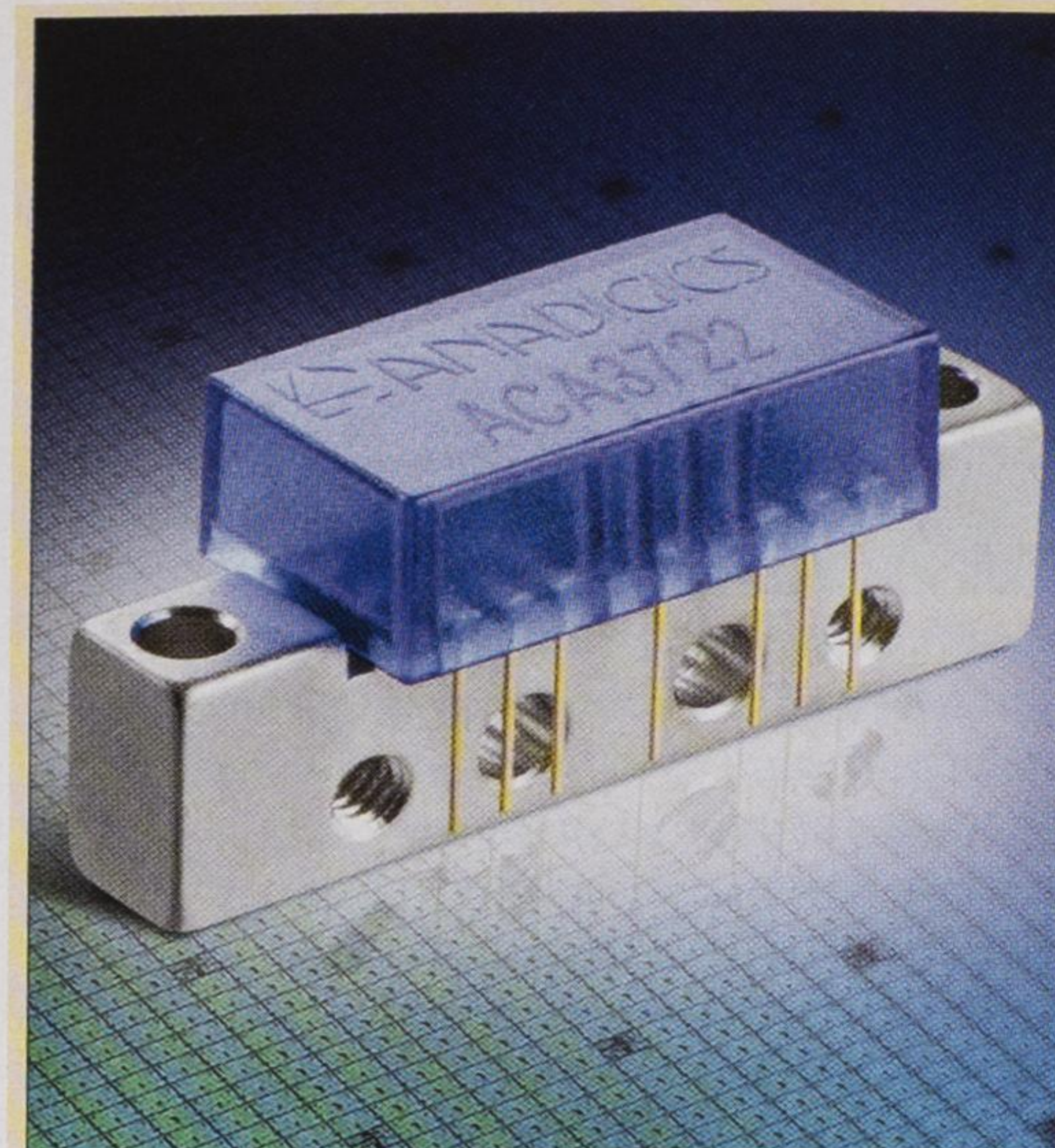
Analyst cautions upbeat Skyworks

An investment analyst has warned on Skyworks Solutions' future prospects, despite the company saying that it's poised to gain as handsets shrink and transmission standards' data rates increase further.

Todd Koffman of Raymond James downgraded his assessment of the Woburn, MA, company on March 24, after Sony Ericsson issued a profit warning for the first quarter of 2009.

Koffman points out that Sony Ericsson was Skyworks' second-largest customer in the three months ended December. “Skyworks is the primary supplier across the majority of Sony Ericsson's handset designs,” he wrote. “Sales to this key customer will decline.”

As the cellphone industry looks set for shrinking sales volumes in 2009 for the first time since 2001, Koffman suggests that Skyworks' recent strong financial per-



GaAs manufacturer Anadigics has launched a series of “hybrid” line amplifiers for cable TV infrastructure, competing for market share in this area for the first time. The 870 MHz, 24 V amplifiers use the industry standard SOT115J hybrid package, in which the Warren, NJ, company combines its MESFET technology with other discrete components. Fabless Santa Rosa, CA, GaAs company TriAccess Technologies released 75 Ω amplifiers that work for applications up to 1000 MHz and operate on 24 V around the same time. Manufactured at TriQuint's foundry, TriAccess's amplifiers feature linearization circuitry included on the die, rather than around it, which helps to lower power consumption.

formances will soften.

The company has consistently maintained impressive profit margins, potentially leaving management with few remaining cost-cutting options for further improvements. He also believes that Skyworks cannot continue to grow market share in the way that it has at top customer Samsung.

“The company's share gains at top-tier handset and smartphone [manufacturers] (primarily at the expense of a wounded Anadigics) may have run their course,” Koffman wrote.

Nevertheless, Skyworks remained the only handset power amplifier (PA) manufacturer anticipating a profit in the first quarter of 2009. Skyworks' general manager of front-end solutions, Greg Waters, explained that in helping to miniaturize and lower the costs of cell phones the company's InGaP BiFET devices gave it a particular market advantage. “If you do any switching internal to a PA, BiFET allows you to do it in an integrated form that's very low cost,” Waters told *Compound Semiconductor*.

These BiFETs enabled the recent launch

of industry-smallest 3 mm×3 mm wide-band CDMA PAs, most commonly used in handsets based on reference designs from US semiconductor firm Qualcomm. Waters points to this relationship as underlining the increasing strength of Skyworks' reputation in the handset industry.

BiFETs also play a role in Skyworks' early products for LTE – the ongoing long-term evolution of the 3G wideband CDMA standard. Here they handle the 4G protocol's demands for more-accurate waveform reproduction in as cheap and small a module as possible. These products have given the company a head-start on its rivals that will stand it in good stead as the standard develops, Waters claims.

"Everything from a PA to a module has been provided for LTE, and I think as you look at the early movers, almost exclusively they're using Skyworks products," he said. "If you pop most of the prototypes or the early units shipping right now, you're likely to find a Skyworks logo under it."

OPTICAL COMMUNICATIONS

Opnext cuts back as Cisco takes stock

Optical component and module supplier Opnext has kicked off its new financial year with a change of CEO and a raft of measures designed to stem its expenditure.

Taking the helm on April 1, one of new chief executive Gilles Bouchard's first moves was to cut his own pay by 10%, as the company simultaneously reduced its 800-strong workforce by the same proportion.

Following Opnext's acquisition of Stratalight last year, those measures have been in the works for some time. More recently, Opnext has taken a knock from inventory reductions at network-building giant Cisco Systems, which is responsible for around one-third of Opnext revenues. According to analyst Paul Bonenfant at investment firm Morgan Keegan, the latest round of cost cuts were: "positive and necessary, given recent accelerated cash burn". "Opnext isn't out of the red (yet)," he added.

Opnext confirmed to *Compound Semiconductor* that the restructuring will take place across all of the company's operations and manufacturing headcount. "Through the integration [with Stratalight], we have built a stronger, more focused Opnext," said a spokesperson.

Bonenfant says that after a "horrible" January, and only marginally better February, many vendors at the Optical Fiber Communication conference held in San Diego in March had indicated improved orders.

INP MANUFACTURING

Laser diode fabs change hands

Kawasaki, Japan, based optoelectronic component manufacturer Optrans has acquired the speciality ultra high-speed InP microchip division of NTT-AT. Included in the deal is a former NTT-AT

InP development team, two patents and the division's MOCVD chambers. Optrans now plans to ramp this development facility to production scale, targeting an output of 12,500 wafers per year.

In the US, laser diode supplier Thorlabs Inc of Newton, NJ, has acquired Jessup, MD, based Covega Corporation, a vertically integrated provider of InP components and modules. The financial details of neither deal were made public.



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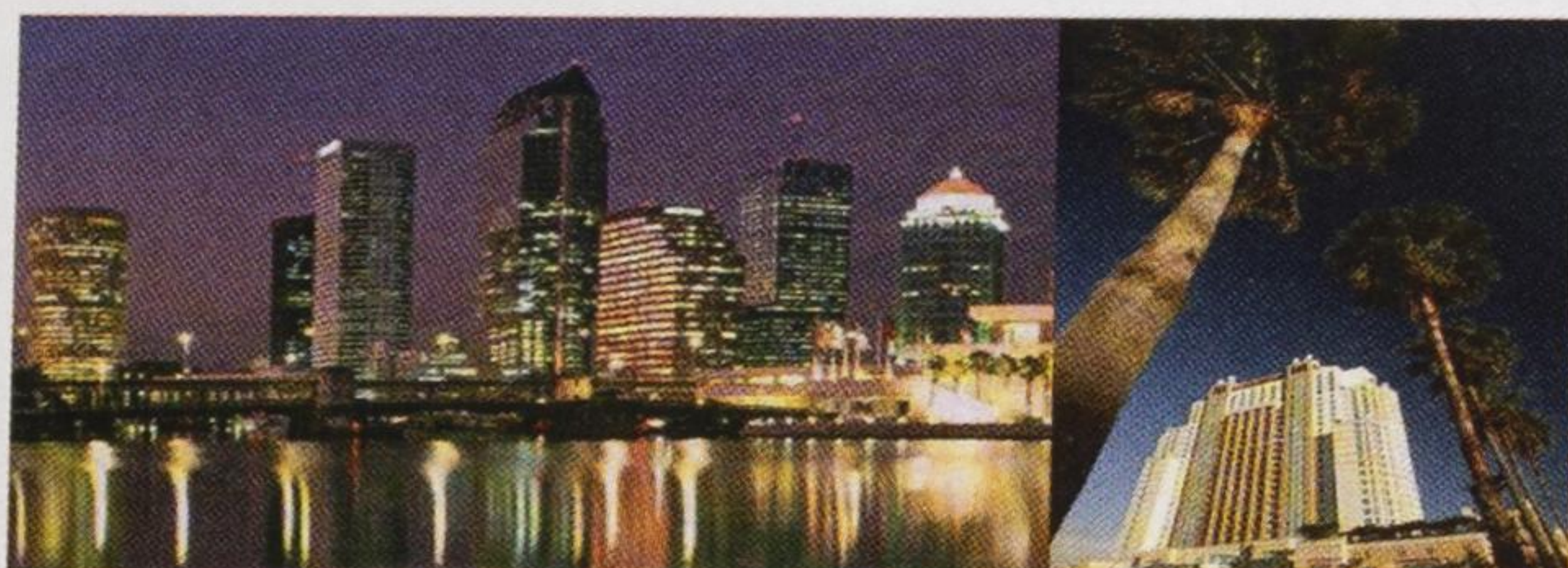
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GaAs DEVICES

2010 earmarked for handset rebound

The global recession delivered a short, sharp shock to the GaAs supply chain in late 2008. Is it too soon to begin talk of the new “r-word” – recovery? **Michael Hatcher** asks industry analyst **Asif Anwar** whether we are “past the bottom”.

The GaAs industry will shrink by at least 5% in 2009 – an inevitable victim of the global recession hitting sales of cell phone handsets and laptop PCs. However, in the words of Asif Anwar, this is no repeat of 2001. And by early 2010 a recovery should be well under way.

At the start of the decade, the GaAs industry was a slower-moving animal. Bloated by heady, premature expectations of explosive bandwidth demand, and a handset supply chain stuffed with excess inventory, the bubble burst in spectacular fashion. According to Anwar, a GaAs industry specialist at Strategy Analytics, it took until 2003 for that inventory to clear.

This time around, things are very different. Up until the final quarter of 2008, the general expectation was that handset sales would slow in the holiday quarter, but still show a small increase on the previous three months.

Only then, but with remarkable speed, did the global recession hit. Handset manufacturers acted swiftly, cancelling orders to ensure that the mistakes of 2001 were not repeated, and inventory channels were kept lean. “It didn’t hit until the final quarter,” said Anwar. “But it was a short, sharp shock.”

The analyst believes that this rapid shutdown was a good thing: “In the short-term, it has had a severe impact,” he said. “But over the longer term it means that we don’t have to work through [excessive] inventory.” Thanks to that early, decisive action, which rapidly permeated down the GaAs supply chain to materials and epiwafer companies, a recovery of sorts appears to be upon us already.

With its strong exposure to the smartphone segment of the handset industry – which is expected to prove more resilient to the recession – the epiwafer specialist IQE ought to be among the first to benefit from any early signs of a rebound. And the UK firm is now predicting this in the second half of 2009, even though visibility remains limited.

So are we past the bottom of the slump? “Right now, we are still in a holding pattern,” reckons Anwar. “It depends on the focus of the customer. In smartphones, I think we are past the bottom now. But there is probably still a way to go, and the lower end of the market is recovering more slowly.”

Unit shipments of handsets are still expected to decline by somewhere in the region of 10% in 2009. And because GaAs-guzzling smartphones will only represent about one-fifth of all mobile handset sales, GaAs revenues specifically associated with handsets will drop by some 15%, predicts Anwar.

It almost certainly means that the \$5 billion GaAs

industry that Anwar had been anticipating by 2012 will not come to fruition. But there are some bright spots in the wireless world: aside from the smartphones, the emergence of the netbooks – products pitched between the laptop PC and a high-end handset – being one of the most recent to appear.

Although in 2001 the anticipation of a hyper-connected world of seamless broadband data links was a fallacy, eight years later this is exactly what consumers are used to: a world where any connected device must handle bandwidth-devouring e-mail clients, plus video clips, music and spreadsheets.

The netbooks that have emerged from that demand come with an extra layer of connectivity. Whereas a conventional laptop PC might feature a couple of GaAs-based power amplifiers and a switch for wireless LAN connections, netbooks are set up for both Wi-Fi and cellular. Indeed, many netbooks are sold “free” as part of a broadband cellular package.

That all adds up to more GaAs in the RF stage, tuned to cellular frequencies. The market might only amount to 20 million units or so this year, but with the additional GaAs content needed, netbooks could soon start to have a serious impact on wafer volumes. Industry talk also suggests that the likes of Nokia and Apple might enter the netbook scene.

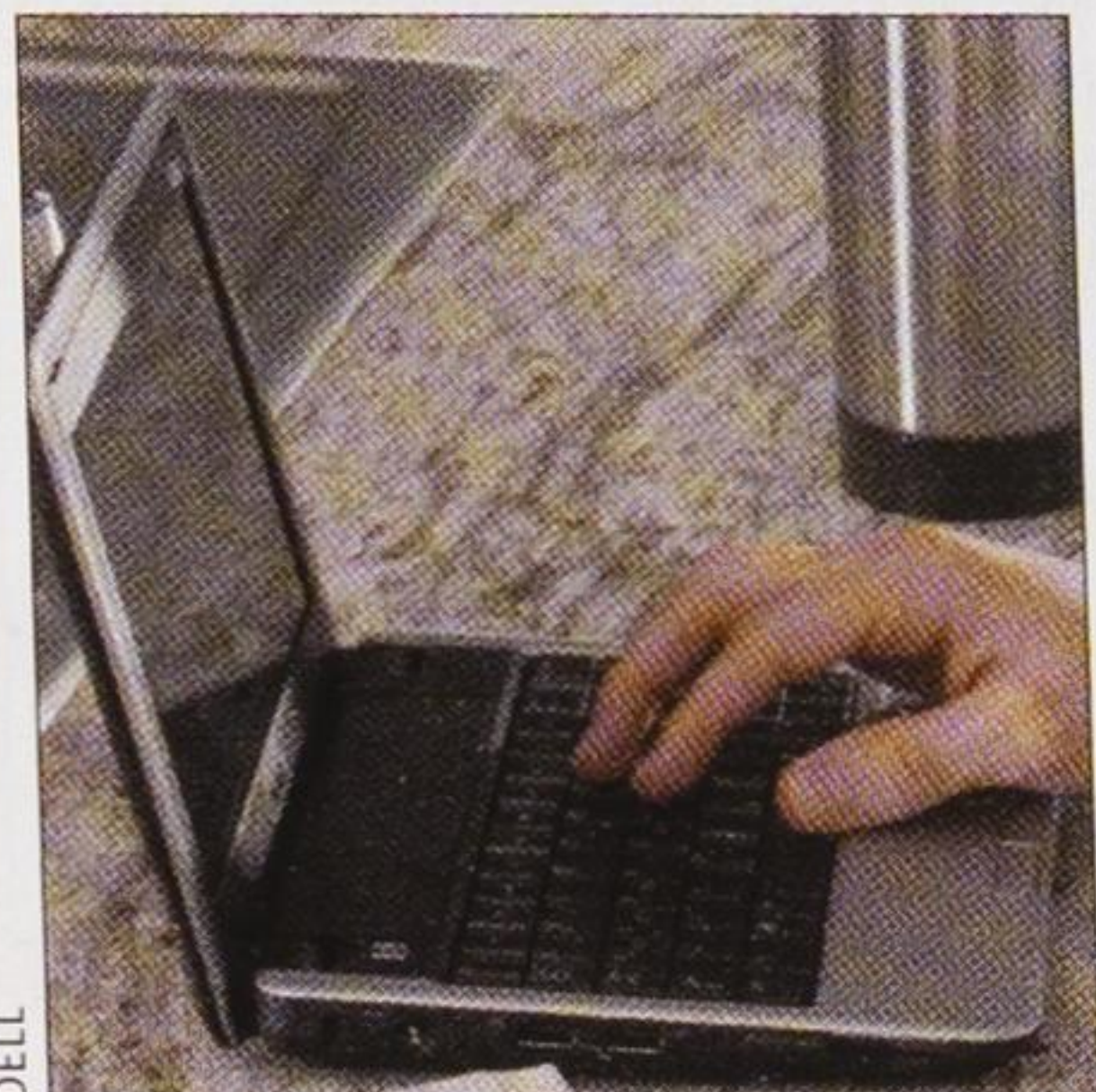
Recessions tend to be the times when breakthrough technologies are developed, as companies with the combination of foresight and available resources exploit firms that are busy struggling with the more day-to-day concerns of staying afloat.

Could that happen in 2009, with GaAs usurped by a breakthrough power amplifier process fabricated in silicon or SiGe? Anwar thinks not. “You need 18–24 months to get into the handset supply chain, so any silicon or SiGe power amplifier makers would have to get in right now,” he said. “We would have already seen this by now, if it was the case.”

Although these competitor technologies would have a window of opportunity in the current recession, if Anwar is right then the window will slam shut by the end of this year. And while silicon power amplifiers for GPRS handsets are available, this is a market in decline. GaAs still rules for wideband-CDMA – the 3G protocol that will dominate power amplifier shipments in the coming years.

Another traditional partner to recession is the pressure to consolidate, something that the GaAs industry is certainly no stranger to. But again, Anwar thinks differently this time. That is in part due to the credit crunch – who could raise the finance to launch a serious swoop right now?

“GaAs-guzzling smartphones only represent one-fifth of handset sales.”



Half laptop and half smartphone, netbooks like Dell’s Inspiron “Mini”, shown here, need both a Wi-Fi and a cellular connection – meaning more GaAs content.

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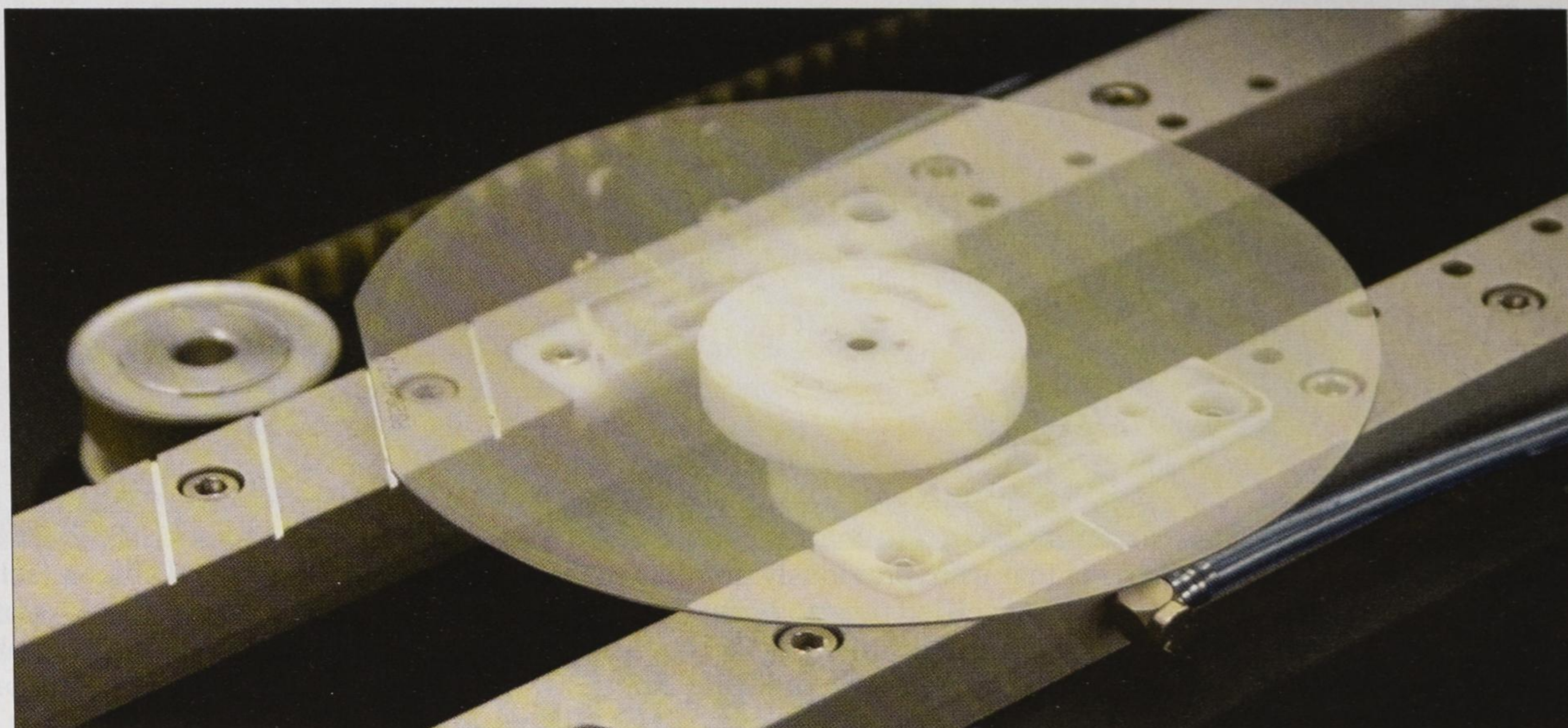
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GaN ELECTRONICS

What is the best substrate for GaN?

IQE's **Bedwyr Humphreys** argues that GaN grown on 100 mm SiC is the only commercial solution for GaN RF products, while GaN grown on silicon continues to search for a niche.



IQE's GaN portfolio includes GaN-on-SiC, GaN-on-silicon and GaN-on-sapphire epiwafers, which are manufactured at IQE RF.

In much the same way that GaN-on-sapphire is the clear-cut leader for high-brightness LED manufacture, GaN-on-SiC is today's winning ticket for wireless/RF products based on the nitrides. GaN-on-silicon is yet to make its mark in either of these markets, but it is still seen as the most promising material combination for achieving the holy grail of high device performance from a chip grown on a low-cost large-diameter platform.

In the case of LEDs, it's difficult to envisage the displacement of GaN-on-sapphire with GaN-on-silicon at the high end of the market in the near future, unless there's a technological breakthrough. If the recent progress in the development of free-standing GaN is maintained and migrated onto larger-diameter material, who would argue against a switch to high-power LED production on this native platform.

The GaN wireless/RF market, like the LED sector, is currently debating the merits of different types of substrate, and silicon is being considered once again as a low-cost platform that can energize and catalyze the market. However, defense is the only real market today, and in this sector performance is the main driver for success.

The focus on performance makes GaN-on-SiC the only contender, because it is the only combination that can fulfill market demands. While GaN-on-silicon continues to improve, its gain and thermal performance are not good enough for most defense applications, and it is difficult to see this type of transistor undergoing a performance hike that will enable it to compete with GaN-on-SiC at the highest level.

Of course, all is not perfect in the GaN-on-SiC world – issues relating to substrate quality have dogged this

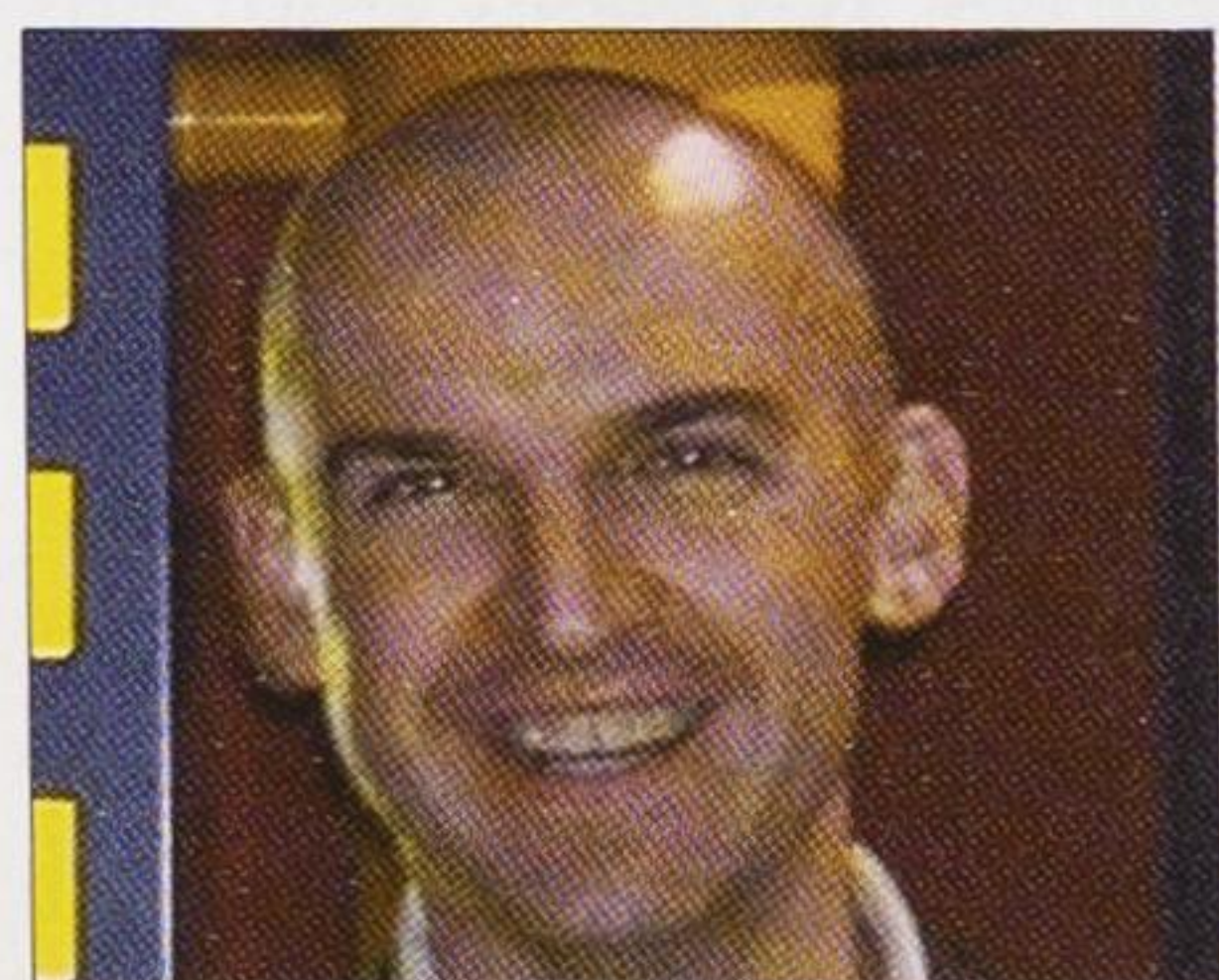
technology for many years. But over the last 18 months these concerns have been swept away through improvements in the uniformity and reproducibility of material quality. Today, the greatest challenge for SiC is cost, with 3 inch semi-insulating (SI) SiC costing 20 times that of a silicon <111> equivalent.

Several vendors are working towards a reduction in material cost by migrating to larger substrates. US substrate suppliers Cree and II-VI are leading the way by producing very-high-quality 100 mm material that should have a lower cost per unit area than its 3 inch sibling by 2010, and become even more affordable further down the line. So does this mean that the price of SiC will eventually reach parity with that of silicon? Probably not, but does it really need to?

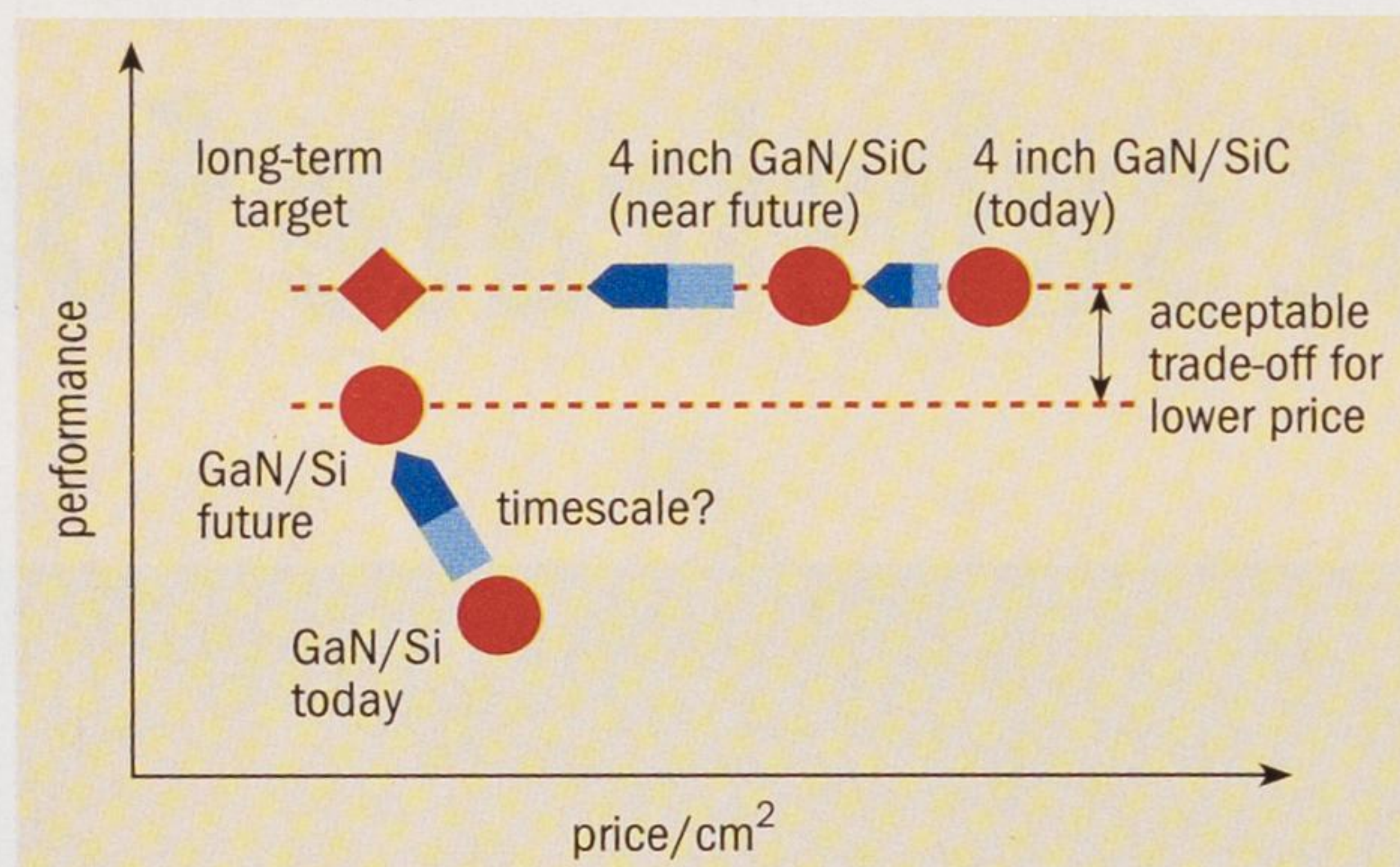
The inferior performance of GaN-on-silicon is also preventing it from enjoying success in many commercial RF applications, particularly radar. However, is it possible that GaN-on-silicon researchers can exploit a cost advantage over GaN-on-SiC and catapult this device's performance to the state of the art, before GaN-on-SiC prices fall substantially?

While it's impossible to know what lies ahead, it is clear that the longer that it takes for GaN-on-silicon to make incremental performance improvements, the more likely it is that GaN-on-SiC becomes a stronger competitor in terms of cost, due to the inevitable gains that come from economies of scale and progression up the learning curve. The market analyst Strategy Analytics forecasts that four-fifths of the GaN wireless/RF market will use SiC by 2012, and it wouldn't be surprising to see this materials technology grabbing all of that market.

Where GaN-on-silicon may play a major role is in



Bedwyr Humphreys is IQE's group business development director for GaN products. E-mail BHumphreys@IQEP.com. He thanks Shiping Guo, IQE RF's director of R&D, and Ivan Eliashevich, IQE's director of sales and business development, for assistance with this article.



Although GaN-on-silicon transistors have far lower production costs than those based on GaN-on-SiC, inferior performance is hampering penetration into today's defense applications.

wireless/RF products for emerging (not yet imagined) applications, requiring moderate performance at low cost, which could appear as the market blossoms. This scenario is not unusual – there are numerous examples of lower specification products with good economic credentials that fill, or even create, a gap in markets that were previously dominated with expensive, over-specified products.

A further opportunity for GaN-on-silicon, which offers massive potential, is power electronics. Here, success requires the overthrow of the incumbent technology, silicon, while seeing off the threat from

another emerging wide-bandgap technology – SiC. While silicon majors in low cost and SiC offers the promise of high performance, GaN-on-silicon has the attributes to excel on both of these fronts.

Although cost is the primary motivator in the power electronic market, alternative technologies that only offer a reduction in expenditure are not guaranteed to enjoy success, because there is a financial penalty associated with the switch from one type of device to another. Consequently, new technologies have to offer a tangible, compelling value proposition in the form of significantly improved functionality. GaN-on-silicon is potentially up to this task, thanks to its combination of improved efficiency, reduced size, greater reliability and long-term potential for integration with silicon transistors.

The GaN power electronic market is still at an embryonic stage, but when sales do take off they have the opportunity to grab a share of a market that has been valued at \$3.5 billion by Yole Développement. Investment is certainly not lacking in this class of device – it is just a question of whether progress is rapid enough to fend off competition from SiC or a new, advanced silicon technology.

IQE is continuing to develop GaN-on-silicon, GaN-on-SiC and GaN-on-sapphire technologies, with the aim of tailoring production and development activities towards providing the most appropriate technology for the relevant market.



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MOBILE WORLD CONGRESS

GaAs firms ready PA revolution

Andy Extance finds that 3G integration, improved call times and 4G standards give the power amplifier community cause for optimism at the 2009 Mobile World Congress in Barcelona.

The depiction of the current recession has in some places neared that of a financiers-jumping-out-of-windows crisis. Following mainstream news, it seems inconceivable that 47,000 delegates attended the GSM Association's Mobile World Congress (MWC) in Barcelona in February. Yet they did, even if the drop in attendance from 55,000 in 2008 and ensuing fall in exhibition traffic caused dissatisfaction. Although GaAs manufacturers' booths were among the most deserted, each company had a clear vision of where they expect the industry to head this year.

A more realistic picture of the world's financial situation was painted by economist Jeffrey Sachs, advisor to UN Secretary-General Ban Ki-Moon. He summarized the scale of the challenge faced by the wireless industry in the face of the recent \$35 trillion decline in paper wealth. Although that figure is roughly 70% of one year's global income and has shocked consumers into a major spending decline, he does not believe that the world will see a 1930s-style "great depression". He said that emerging markets would lead the way out of the recession, and that wireless communication will have a crucial part to play both there and in the wider economy.

"The technologies that are embodied by this sector are a source of massive productivity gains and massive inclusion of different parts of the world

that lead directly to their economic empowerment," Sachs said. "This is true from the poorest villages in the world to the largest market."

The biggest opportunity in the developing world energizing the MWC was from the licenses granted by China to operators of third-generation (3G) mobile networks. Among GaAs chip manufacturers, RF Micro Devices (RFMD) has released a revitalized range of power amplifiers (PAs) to capitalize on this, targeted at the CDMA transmission standards covered by the Chinese licenses. Skyworks Solutions also launched a range of five wideband CDMA PAs that it claims are the smallest on the market. Meanwhile, TriQuint Semiconductor is relishing the increased demand that network rollouts may herald for its base station component business.

There was a feeling of welcome surprise from some in the GaAs community that China chose to grant all three licenses at the same time. Granting only the license for the China-specific TD-SCDMA 3G protocol first would have given home-grown manufacturers an advantage. By releasing all three, China has given the wider industry an early taste of the power of fiscal stimulus.

Hopes for a quick follow-up with Indian 3G network licenses were dashed, however, as news emerged of conflict with the country's military



The 2009 Mobile World Congress was held at the Fira Montjuïc, Barcelona, Spain, on 16–19 February. The congress featured 1300 exhibiting companies and occupied more than 57,000 m² of exhibition and hospitality space – a footprint that was 11% larger than the previous year.



Jeffrey Sachs, director of the Earth Institute at Columbia University and advisor to UN Secretary-General Ban Ki-Moon, emphasized the leading role that wireless technologies will play in the recovery from recession.



Prototype handsets that use LG's industry-first LTE modem chipsets, as modeled by Paik Woo-hyun (center), the company's chief technology officer, Ahn Seung-kwon (left), head of LG's mobile division, and Choi Jin-sung (right), head of LG's Mobile Communication Technology Research Lab.

needs. The licenses, initially slated for January, now look set to be granted in the second half of 2009.

With 3G handsets often containing more than three PAs, the expansion of the technology across the globe looks like good news in terms of GaAs manufacturing volumes. Currently, several different PAs ensure that mobile devices are able to communicate with networks using protocols from 2G GSM up to wideband CDMA and HSUPA – the highest-speed 3G transmission standard. However, PA making firms are now vying to integrate these functions into a single PA module and thus reduce GaAs costs for handset makers. In Barcelona both TriQuint and RFMD unveiled their integration strategies.

Converge and control

TriQuint's Unified Mobile Front-End, or Triumph, will bring together what is typically one PA module for GSM, GPRS and EDGE standards and three wideband CDMA and HSUPA PA-duplexer modules. "This has two advantages," Paul Cooper, strategic marketing manager for handset products at TriQuint, told *Compound Semiconductor*.

"It has an advantage for the mobile device manufacturer of a single source for all of the PAs, one preferred vendor, lower assembly costs and a smaller size. It's an advantage for us because [where currently] we may be mixed and matched with different vendors, we're getting all of the PA spots in one." Other than this, Cooper would not be drawn on the technical details of the development-stage architecture, which is unlikely to earn revenue until 2010.

RFMD's RF6460 converged architecture is also still in development, in collaboration with a platform provider that supplies the basic systems underlying brand-name handsets. That effort has already shown in the lab that it's possible to combine the necessary signals. RFMD says that it also has a head start in developing converged architectures thanks to previously released RF3267 and RF6266 combined wideband CDMA/HSDPA PAs that it is shipping in volume to Samsung.

"If you were to imagine this solution minus the GSM/EDGE, the multiband capability through wideband CDMA/HSPA, this is a solution that we've been shipping to tier-one customers for about two years," said Ben Thomas, business development manager for RFMD's components business unit. "The challenge is taking that solution, adding a mode switch, which leverages our PHEMT technology, and adding the capability to do GSM/EDGE."

RFMD will begin sampling the RF6460 in the second half of 2009, with full release dates expected to be announced in 2010.

Despite the competition between their products, there are common strategic elements underlying RFMD and TriQuint's approaches to converged front ends. For example, as well as offering lower costs and simpler design these products must increase the length of call time in between phone recharges.

Although Skyworks' offerings in Barcelona

avored reduced size over the highest level of amplifier convergence, it plans to place call time at the top of its 2009 priority list. "Even more than size and integration, people want to see better battery life and extended call time," explained Greg Waters, Skyworks' general manager of front-end solutions. "Over the next 12 months you're going to see very dramatically improved talk time from Skyworks."

Much discussion at the MWC centered on 4G standards, with the GSM Association-sponsored LTE protocol grabbing many headlines. US telecoms firm Verizon unveiled a roadmap for LTE deployment in 2010, as well as the equipment vendors that it has chosen to support the rollout. Subsequently, Skyworks and Anadigics laid claim to providing PAs for the only high-profile prototype LTE handset on show in Barcelona, produced by LG.

RFMD and TriQuint concede that the frequency set to carry LTE signals initially, 2.5 GHz, is too far away from the frequencies of existing standards to include in their converged architectures. So, even when their more-integrated products hit the market, the early mobile devices aimed at LTE are likely to have PAs "bolted on" for the 4G standard.

Skyworks' major promotion at the MWC revolved around two PA modules and four front-end modules targeted at LTE in the 2.5 GHz band. In contrast, RFMD, although working in this area, believes that it's too early to unveil its technologies. And even though his company has already introduced its first products in this area, Skyworks' Waters agrees that changes are likely to be seen in the implementation of LTE, sooner rather than later. "It will become part of the wideband CDMA waveform," he predicted.

This close relationship between bands will be exploited by Anadigics in its effort to address 4G standards. "We have found that many of our existing UMTS products [addressing standards such as wideband CDMA] are suitable for LTE," explained Bruce Webber, Anadigics' director of marketing for wireless products. His company's wireless design team is working with what Webber calls "solid partners" who are involved in the standard-setting process. These partners will advise Anadigics on how best to make its existing products most suitable for LTE. "We're relying on them for some guidance on what they need in a power amplifier," Webber said.

At the MWC, Anadigics launched a PA that covers the whole frequency region from 2.3 to 2.7 GHz, suitable for LTE and the more-immediate WiMAX 4G standard. Major WiMAX backer and Anadigics customer Intel made much of the 135 commercial deployments that its 4G standard has seen. While truly mobile WiMAX will only begin to make an impact this year, its ability to provide broadband in countries with poor telecommunications infrastructure is an example of the power of wireless technologies. It's this underlying power that has helped to keep the MWC – in spite of the poor economic situation – a vibrant event, and will continue to sustain GaAs firms through the recession.

SiC Material Defects Impact Device Performance



By Tom Pierson

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Reducing silicon carbide (SiC) material defects and increasing reliability of SiC devices will accelerate the commercial potential of this technology. One of the most opportune and exciting commercial opportunities ahead for SiC is the hybrid electric vehicle (HEV). HEV components are moving from silicon-based devices to SiC-based devices to power the electric motor. The reason is simple - the silicon chip has to be cooled to maintain device junction temperature around 85°C. To accomplish this, a dedicated water-cooling system different from the one responsible for the engine is required. HEV manufacturers are aiming to reduce cost by implementing SiC-based electronics that can readily withstand temperatures exceeding 150°C, thereby eliminating the need for a second water-cooling system. This transition will enable power module savings of approximately 15%.¹

The strict reliability requirements of the automobile industry demand that SiC device quality control begin at the substrate level. A recent article published by National Institute of Advanced Industrial Science and Technology (AIST) reports on the use of optical surface analyzer (OSA) technology for improved quality control of SiC materials.² OSA inspection combines the elemental principles of scatterometry, ellipsometry, reflectometry, and topographical analysis to detect and classify defects in substrates and epitaxial layers. Figure 1 shows data images collected from OSA scans. Defects shown include: SiC triangle defect (upper left), sapphire substrate scratch (lower left), SiC polytype defect (center), SiC wafer edge scratches (upper right), and GaN epi pit (lower right).

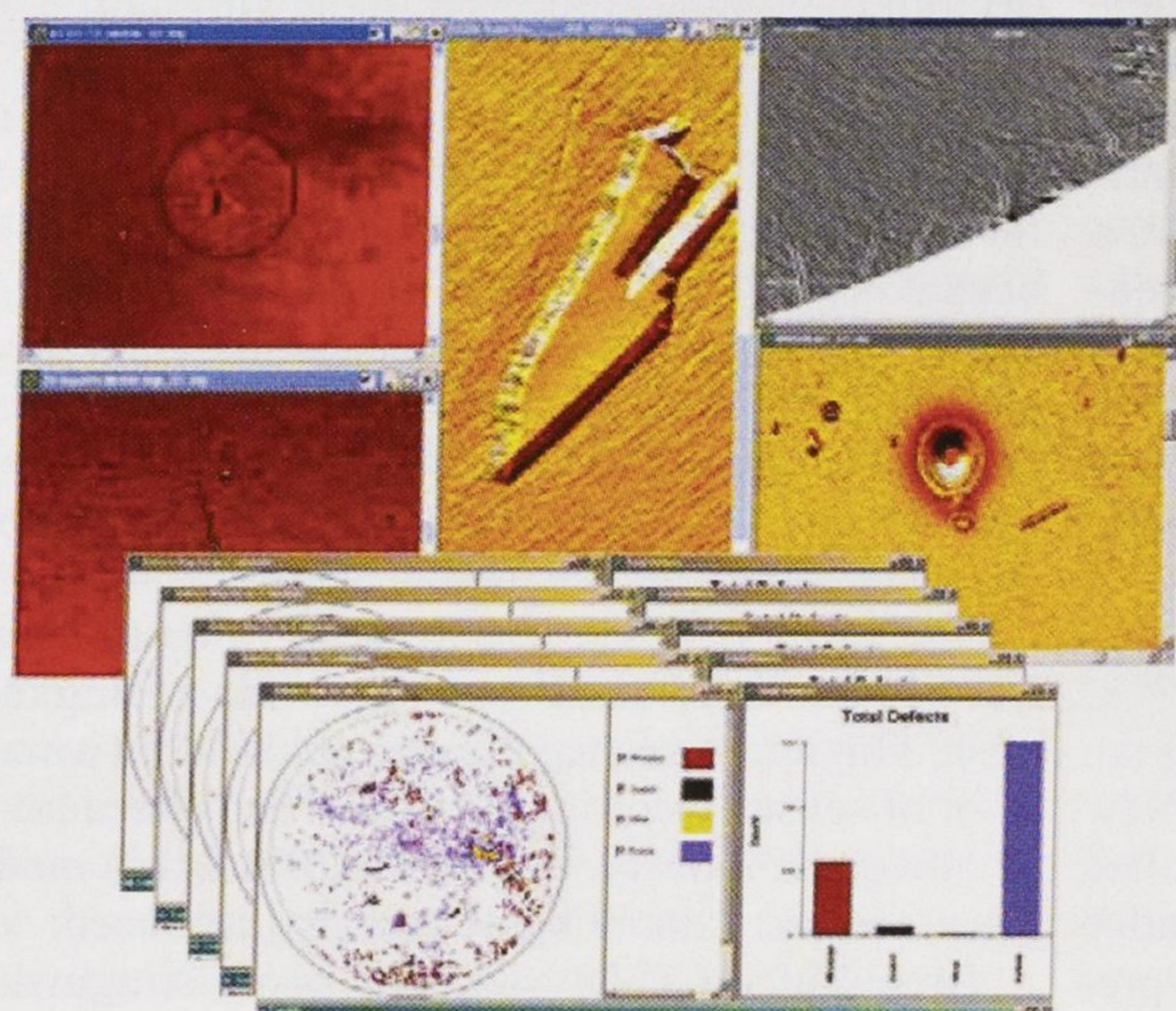


Figure 1. Advanced 4-channel imaging of OSA technology for defect analysis and identification of mission-critical defects of interest (DOI). Automatic defect classification software provides the most advanced recipe creation for DOI classification. High-throughput scanning analysis delivers summary reports including defect maps, log files, and automated pass/fail assignments.

The article from AIST states, "There is a great need for an in-line, high-speed and non-destructive inspection system capable of evaluating and analyzing the quality SiC wafers for SiC power devices. We have examined whether the laser-based optical non-destructive inspection system by KLA-Tencor meets these requirements."

As SiC high-power devices move to larger-area dies, substrate and epi defectivity becomes more critical than ever. The Hatakeyama, et. al. report continues, "At present, the defect density of a commercial device-grade SiC wafer may be between 5 and 10 cm⁻², the target defect density is less than 0.5 cm⁻²." It is reported that high defect densities on epitaxial wafers will pose a major yield problem during mass production of SiC devices. To investigate the impact of epi defects on device characteristics, the AIST research team fabricated MOS capacitors. Time zero dielectric breakdown (TZBD) and lifetime tests were performed and it was reported that the poor quality of epi degraded both the breakdown voltage and reliability of the MOS capacitors.

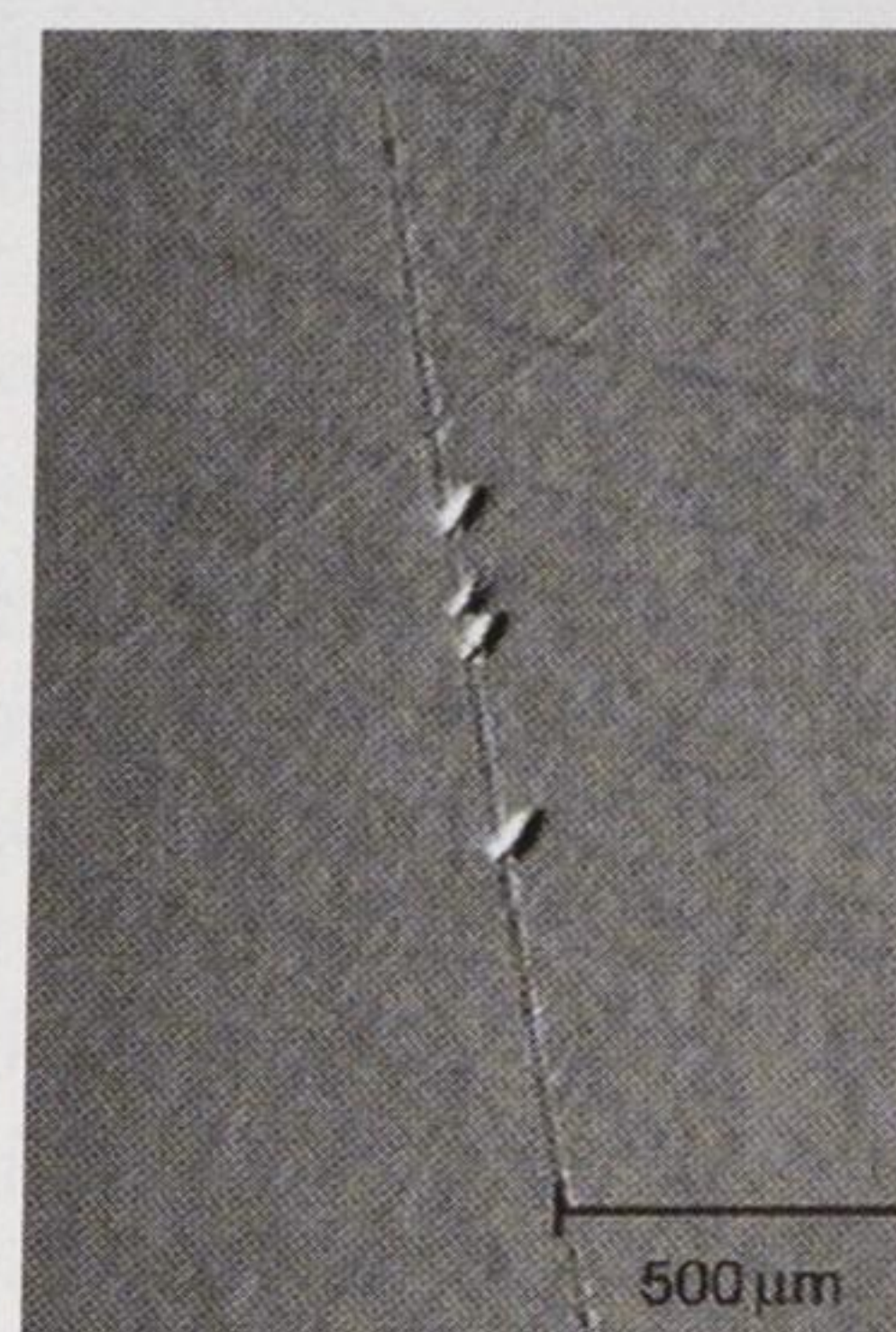


Figure 2. Topographic OSA image of SiC carrot epitaxial defect caused by substrate scratch.

The AIST research team also investigated micropipes which are known killer defects on SiC wafers that have long impacted device yield. The researchers used OSA inspection to automate the detection and classification of micropipes to map the density and location. Micropipes were later verified by stereomicroscope. The team also linked SiC substrate scratches to subsequently grown "carrot" epitaxial defects formed along the substrate scratches as shown in Figure 2.

OSA technology is being used by industry leaders to monitor production lines, identify mission critical defects of interest, and create process-specific recipes to detect and classify killer defects. Today more than half of all SiC wafers produced worldwide are inspected with OSA technology.

ACKNOWLEDGMENTS

KLA-Tencor would like to thank the research team at AIST for their investigation and report.

1. Status of the SiC power devices market: If only we had a switch... Yole Development, July 19, 2007.

2. T.Hatakeyama, et. al. Evaluation of the quality of commercial silicon carbide wafers by an optical non-destructive inspection technique. National Institute of Advanced Industrial Science and Technology (AIST), Journal of Crystal Growth 310 (2008) 988-992

SOLAR POWER

GreenVolts takes concentrator

As Bob Cart sailed the seas for months on end, he bemoaned the feeble output from his yacht's solar panels, and wondered how this technology could ever generate affordable electricity. Back on dry land he has designed a lightweight tracker system with parabolic mirrors, launched GreenVolts and is now leading the build of a 2 MW power plant. **Richard Stevenson** reports.

Concentrator photovoltaics (CPV) stand at a crossroads. The supply chain for building these solar-energy systems is falling into place, but the technology must demonstrate that it is capable of delivering cost-competitive, reliable power on a large scale if it is to achieve commercial success.

The proof of the viability of this technology – which concentrates the sunlight by factors of several hundred onto multi-junction cells – could come from the performance data of a handful of kilowatt-scale plants under construction. This includes a 2 MW plant for Pacific Gas and Electric Company (PG&E), which is being built by GreenVolts of San Francisco, CA, on an 8 acre site at Tracy, about 50 miles east of the Bay area.

"It's a full-on commercial power plant with a 20 year power purchase agreement with one of the nation's largest utility companies," asserted Bob Cart, GreenVolts' CEO. "It's an opportunity to get real field data at a considerable scale, and to understand installation and permitting, electrical wiring and losses, equipment and maintenance, and all of the other issues that go into building a power plant."

When this facility is up and running it will give a welcome insight into the true cost of electrical generation with CPV. Comparisons of projected and actual performance will also be possible, and the facility should eventually help to answer the most pertinent question – can CPV plants deliver acceptable performance levels for 20 years or more?

Setting sail

Cart formed GreenVolts in 2005, following an 18 month sailing trip from San Francisco to New Zealand and back. During this voyage he mulled over ideas for a new business venture and concluded that renewable energy, and solar in particular, presented the greatest opportunity. Large solar panels were installed on his yacht, but they produce little power and were very expensive. He wondered how solar energy could ever generate electricity at a cost comparable to existing technologies.

"I started researching different possibilities,



GreenVolts is constructing a 2 MW facility on an 8 acre site in Tracy, California trackers, with a diameter of nearly 6 m. Electricity is generated by using parabolic

studying patents and doing analysis, and then I spent another year in the garage developing and tinkering." Cart then entered and won a business plan competition and a grant application with the Californian Energy Commission. Raising \$45 million in two funding rounds followed along with signing the power plant contract with PG&E in summer 2007.

The current focus is the construction of one of the largest CPV plants in the world, which was scheduled for completion this year. However, the deadline has been pushed back to June 2010 due to the deterioration of financial markets. "In a capital-constrained economy it makes sense to slow the deployment, deploy enough to test and get data, and take advantage of a couple of opportunities for innovation that we had planned for the next generation."

Cart's original plan was to rapidly deploy an earlier generation of the technology while raising more cash. This approach may appear reckless, but it makes a lot of sense, according to him. That's because the photovoltaic industry has seen a 20% fall in module costs for every doubling of capacity produced.

GreenVolts' CPV system has two distinguishing features: it uses parabolic reflectors rather than mirrors to focus sunlight and it has a novel tracker system that circumvents the need for a concrete base.

Lenses are popular because they can be manufactured from a single part that concentrates the light and protects the module from the environ-



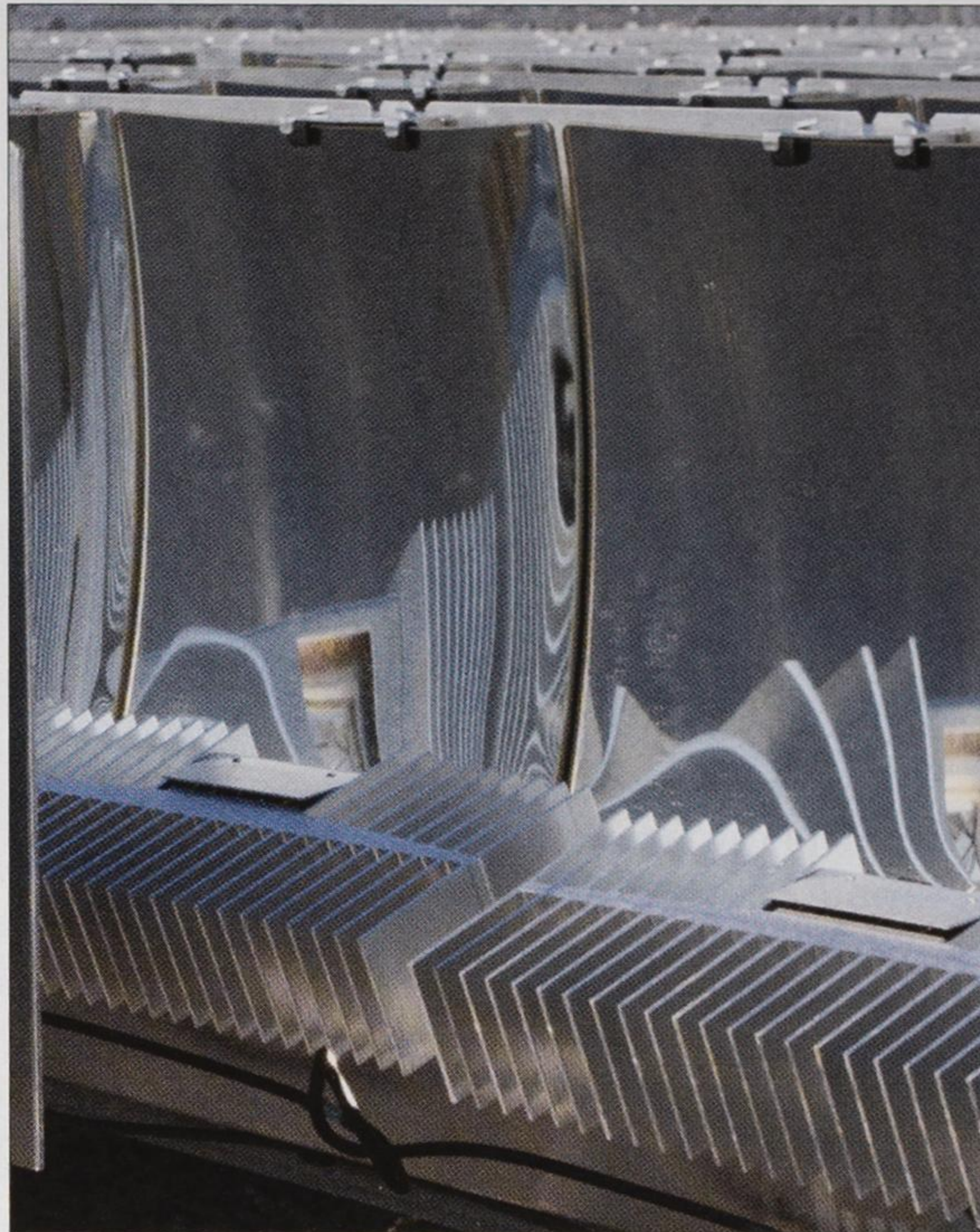
Bob Cart

GreenVolts CEO **Bob Cart** has more than 20 years of executive experience at manufacturing and technology companies. While he was CEO of precision machine tool manufacturer Industrial Cutting Die, he led the sale of the company to Enefc International. Then followed 18 months at sea, before he launched GreenVolts in 2005.

r photovoltaics into new waters



California. This large plant will feature hundreds of 3 kW, two-axis metal-framed parabolic mirrors to focus the sunlight onto multi-junction photovoltaic cells.



BOTH IMAGES: R. STEVENSON

ment. However, there are some concerns about the reliability of plastic lenses, says Cart, and silicones mounted on glass can be very expensive.

High losses are another issue for lenses. Those deployed in CPV are not conventional, solid lenses, which are too expensive, but far thinner Fresnel designs made from a set of concentric annular sections known as Fresnel zones. Scattering occurs at the intersection between zones, leading to optical losses. "As you increase the concentration ratio, you either have to have more grooves or make the material thicker," said Cart. "If you make the material thicker you have more absorption and greater cost, and if you increase the number of grooves, you have more facets and more losses."

Parabolic mirrors are simpler and deliver a higher quality of the light to the cell. "There is no practical limit to the concentration," said Cart. "We're already at 625 $\times$ in our first generation and now we are testing at concentrations well beyond that." Higher concentrations will make thermal management more challenging, but it is the obvious route to driving down generation costs because the multi-junction chip currently accounts for one-fifth of the cost of the entire system.

Maintaining a high tracking accuracy is another major hurdle to increasing concentration. Most systems use expensive steel and concrete structures to support an array of modules off the ground, but this

subjects the small gearboxes used to position the optics to very high loads, according to Cart. "We are using a big, wide ground base. This gives us the support of the ground with no concrete." The design also places less demand on the gearing system, which consumes less power as a result.

Interest in CPV has rocketed over the last few years, and the two leading multi-junction cell manufacturers, Emcore and Spectrolab, are likely to face competition from other chip makers. Cart has some advice for new players looking to enter the market: "I think there is a concept that there will be a large number of CPV companies and they all want the same thing, a standard little chip. That is fundamentally wrong." Ultimately, he doesn't expect the number of CPV companies to be any higher than the number of cell companies, and points out that each optical system will require a different approach.

Successful chip makers will be the ones that partner closely with a small number of systems companies, says Cart, to develop products and manufacturing processes that meet their needs. It is no surprise, therefore, that he urges the chip companies to talk to their potential customers: "Find the requirements and dig in deep – don't make the assumption that they understand the requirements." Heeding his advice will hopefully allow CPV to take the correct turn at the crossroads and ultimately become a competitive source of solar energy. ●

"There is a concept that there will be a large number of CPV companies and they will all want a standard little chip. That is fundamentally wrong."

Bob Cart
GreenVolts CEO

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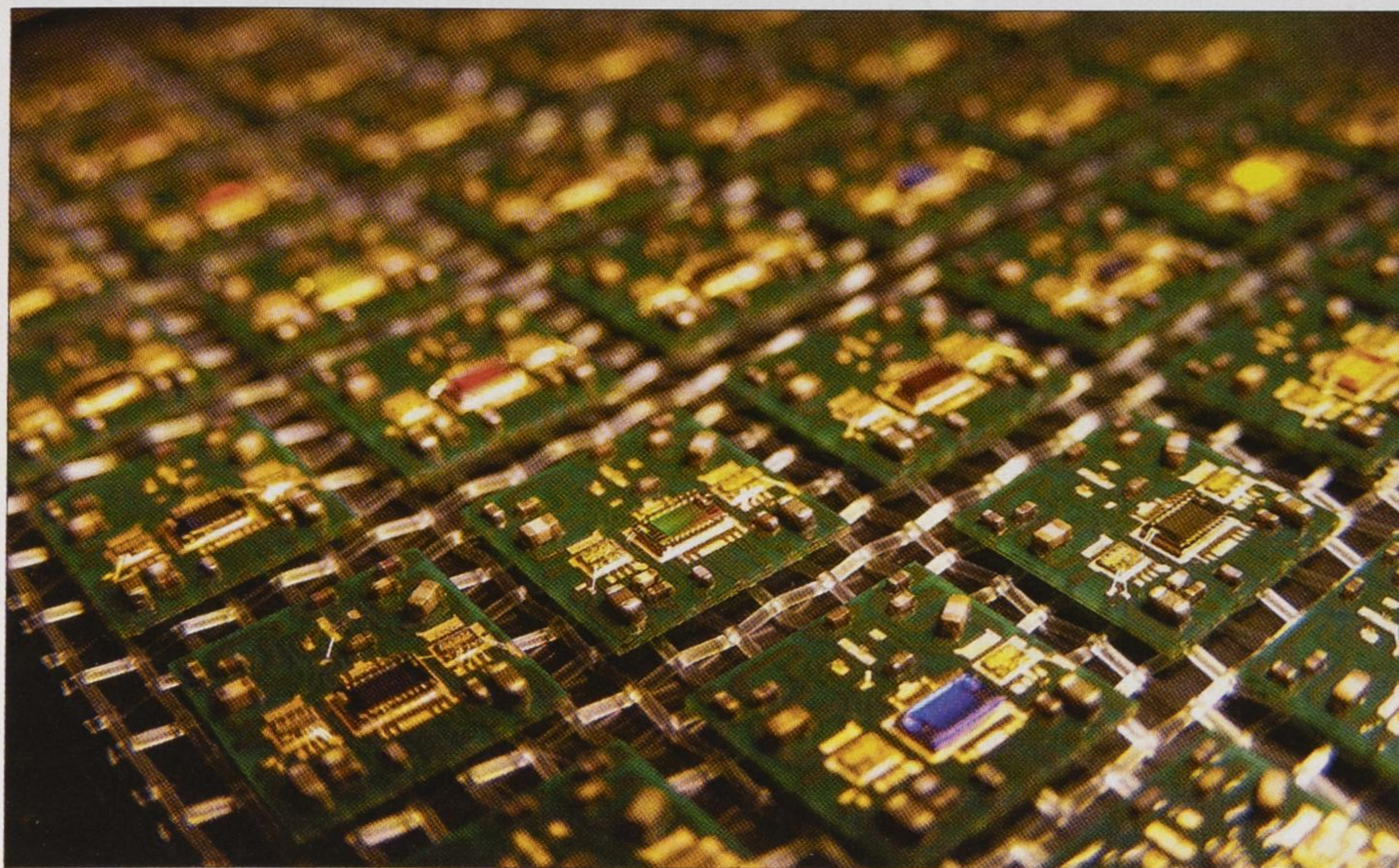
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GaAs MANUFACTURING

PA makers seek module standard

JEDEC standards offer the assurance that high-volume electronics manufacturers are producing quality goods, but they are not all well suited to RF chips. **Andy Extance** learns how the GaAs industry plans to resolve its qualification issues.



Laminate modules – like these TriQuint GSM PAs, shown without plastic overmolding – and the GaAs chips used in them are stressed more than intended in tests developed for silicon devices.

Not all semiconductor components are created equal. The III-V niche typically benefits greatly from processes and products developed initially for larger-scale silicon manufacturing. However, the differences between the two are not limited to the differences in chip volumes produced.

This much is clear when considering the varying functions that III-V and silicon die perform. That fact is masked because, once the whole manufacturing process is complete, one semiconductor package looks much like another. When it comes to testing the final packages, this appearance has proven to be a reasonably reliable guide. Consequently, testing standards devised for silicon have been transposed to compounds, and consumer electronics manufacturers often use them to assure the suitability of semiconductor modules for their products. Members of the GaAs manufacturing community are now questioning the wisdom of following this approach.

The mechanism through which this quiet transformation is occurring is JEDEC. JEDEC was incorporated in 1999 as an independent association from its previous existence as the Joint Electron Devices Engineering Council of the US Electronic Industries Association. With headquarters in Arlington, VA, the organization provides a forum in which the world's leading semiconductor manufacturers work together to develop open industry standards across a wide range of sectors covered by JEDEC's com-

mittees. Formed from volunteer participants in the industry, it's JEDEC's JC-14.7 subcommittee for GaAs reliability and quality standards that's looking after the interests of cell phone power amplifier (PA) manufacturers and related organizations.

"If you talk to the phone manufacturers, they do have specific requirements for reliability," explained Bill Roesch, fellow for reliability science at GaAs manufacturer TriQuint Semiconductor and member of the JC-14.7 subcommittee. The lack of dedicated standards means that GaAs manufacturers can find themselves tackling different testing challenges at different customers, Roesch explains. "The people at RFMD and Skyworks have suggested that we do need our own standard because so many of the users of laminate-based modules have different qualification requirements. They'd like some standardization."

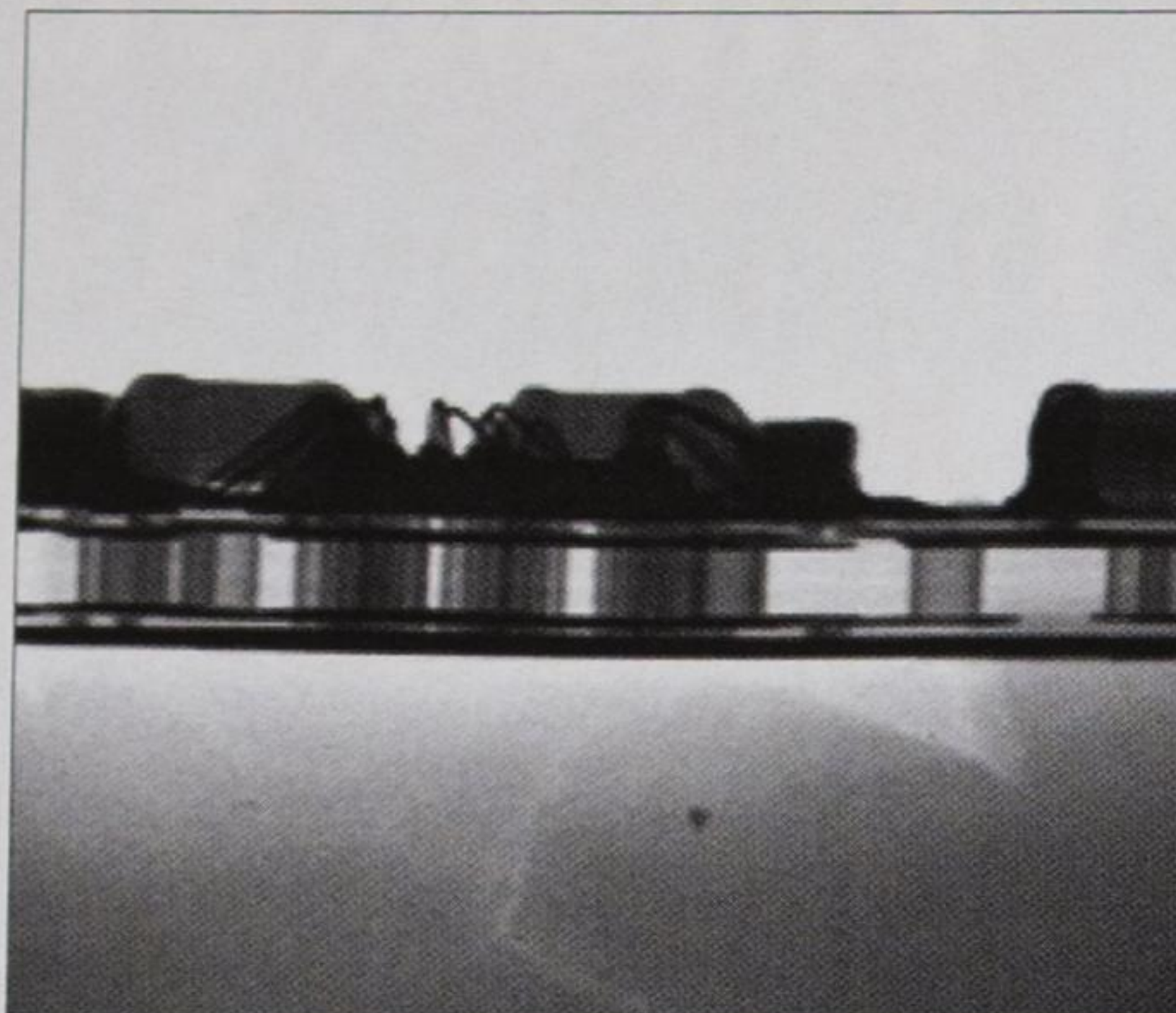
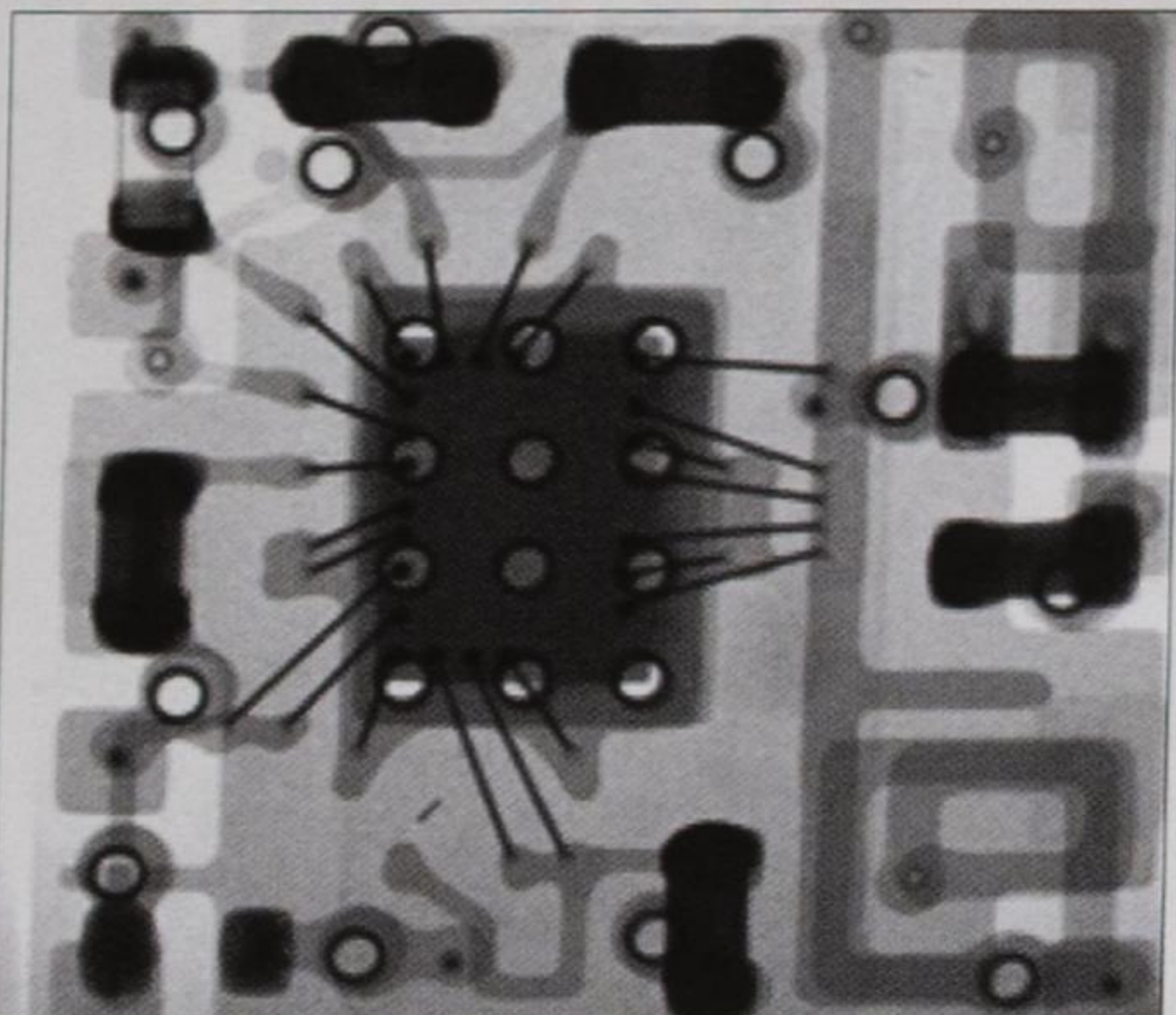
In October 2008, at the Compound Semiconductor Integrated Circuit Symposium in Monterey, CA, Roesch drew up a list of about 20 reliability testing issues particular to GaAs laminate modules. There, members of the PA-making community voted on which they saw as most critical to develop standards for. "We had votes from M/A-Com, RFMD, Freescale and TriQuint, and the one that came out as the most important was acceleration factors," Roesch said.

In semiconductor reliability testing, it is common to stress packaged chips at 85°C and 85% relative humidity, where they would be expected to survive 1000 hours under bias before being passed for use in subsequent manufacturing. An increasingly popular approach called HAST – highly accelerated stress testing – reduces this to just 96 hours by raising the temperature to 130°C.

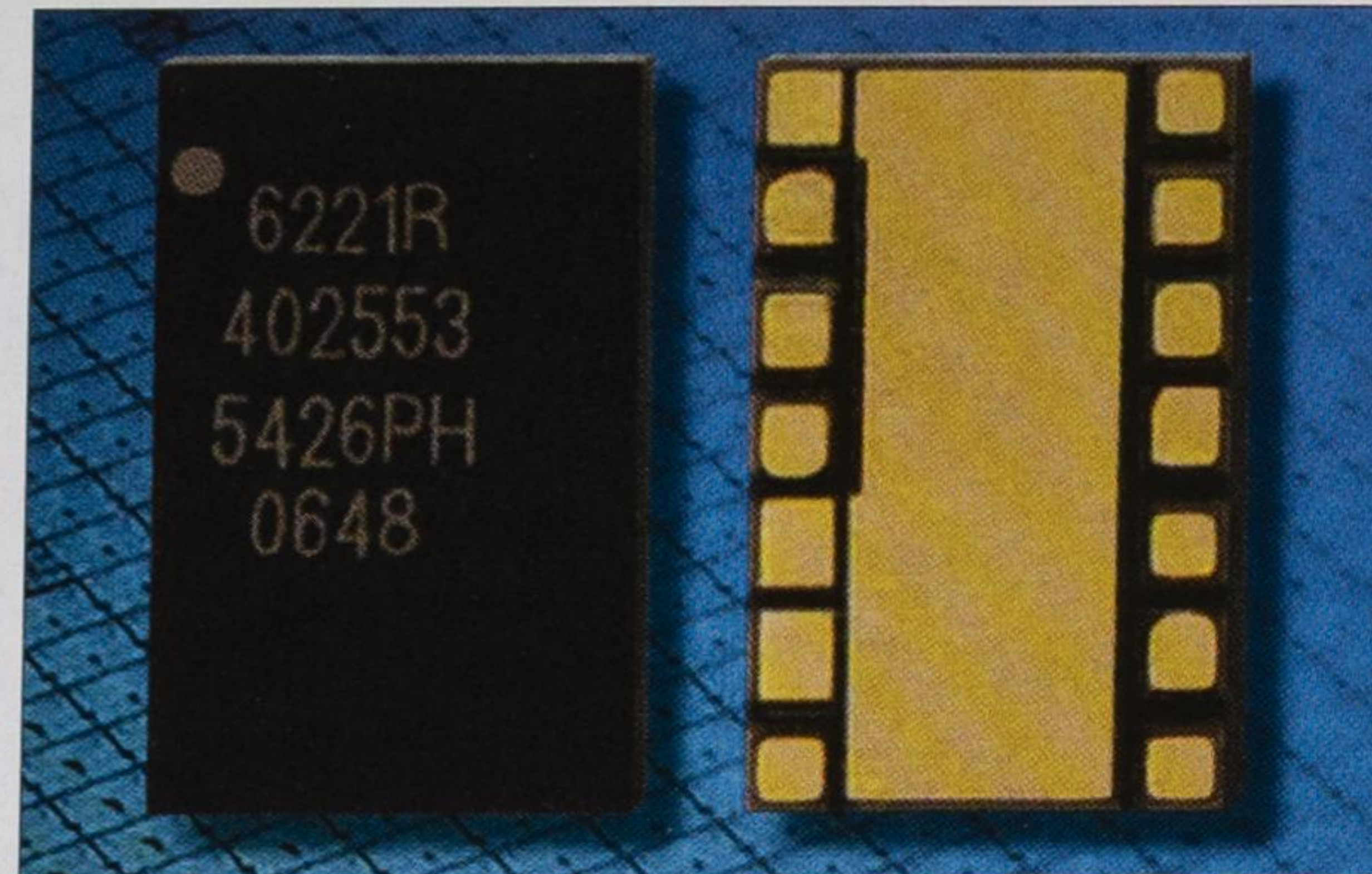
"It's 10 times faster, but that acceleration is based on silicon devices," explained Roesch. "What we've found is that for compound semiconductors the acceleration is much higher. So, a 96 hour HAST test is actually much harder on our devices than it is on a silicon device because of the different failure mechanisms."

The laminate modules into which PAs are packaged are also generally specific to the GaAs industry. Some members of JC-14.7 believe that these may also respond differently under HAST conditions – via delamination, for example – than the chip packages that the test standard was designed for.

A second area of concern surrounds RF testing. The unique RF capability of GaAs is central to its importance in cell phones, so it's perhaps unsurprising that silicon standards do not measure up. In fact, although a reliability testing standard that passes a digital signal through a chip exists, there isn't one



A typical overmolded laminate module contains at least one GaAs die and support circuitry, which normally includes passive components like resistors, capacitors and inductors.



Anadigics' wideband CDMA/HSPA PA is a typical example of the laminate modules that JEDEC is developing a standard for.

for RF signals. "There really is no standard to say what that should be," said Roesch. "What frequency should it be? Should it be sine wave, should it try to simulate the actual phone signals, should we put the device in 1 dB compression or 3 dB?"

Finally, the industry representatives who gathered in Monterey specified that any new standard should take into account failure mechanisms occurring only in compound semiconductors, although at this point these are not precisely defined.

Roesch is now charged with producing an early draft standard for the three key issues that emerged in Monterey. That draft will then be up for discussion at the 2009 International Conference on Compound Semiconductor Manufacturing Technology – better known as CS Mantech. While much of the industry is already represented, Roesch says that he would welcome additional input prior to or indeed during that event, to be held on May 18–21 in Tampa, FL. "We would definitely like to have input from everybody that's building PA modules," he said.

Specified advantages

The ultimate aim of developing this standard is to provide tests assuring cell phone manufacturers that the GaAs chips will work for long enough. Having one such hurdle specify that all PA modules must clear before use would be a big advantage to the chip-makers, says Peter Ersland, JC-14.7 chair.

"It allows us to bring to our potential customers a prescribed set of tests used to assure the quality and reliability of the products that we're selling," said Ersland, who is also a senior principal engineer at M/A-Com Technology Solutions. "A second benefit is that it allows the customers an easier way to see how products compare. If we have a set of standards that all GaAs manufacturers are expected to comply with, then you can compare across companies more easily."

Before any such qualification can be used, chip-makers must determine how long a typical product that passes the test can be expected to continue operating for. This initial mean-time-to-failure – or "life" – test for compound semiconductors must also take their individual properties into account. To date this is what JC-14.7 has been responsible for developing and administering, with a standard known as JEP-118.

"GaAs technologies have a set of failure mechanisms that may be unique when compared with

other semiconductor technologies," Ersland said. "To identify how those mechanisms are going to evolve over the life of a product, in many cases we need a slightly different set of tests than most of the silicon industry." The aim of this life test is to work out how an individual product fails and whether or not it has been operating for sufficiently long when it does so.

"If you think about GaN, right now they're in that mode of trying to make sure that the devices will actually last for a reasonable length of time," explained Roesch. "Most of their work is a life test to find out what fails and how long it would last. With new technologies that's usually shorter than what people would want."

"We would definitely like to have input from everybody that's building PA modules."

Bill Roesch

The new qualification standard that Ersland and Roesch are trying to develop would come into play when the JEP-118 life tests have been performed extensively, yielding a mature, reliable device. It, like the range of self-developed qualification tests called for by cell phone makers and legacy tests from silicon firms, assesses a greater number of chips for a more limited length of time than is typical for life tests.

Qualification tests, like the HAST test, are intended to prove that products will last long enough to keep the average consumer happy. If JC-14.7 is successful in creating a widely accepted standard, the net result will be subtle but significant. From the standardized tests will emerge data that are more meaningful to GaAs manufacturers and their customers – smoothing business between the two in the process.

● If you have any suggestions to make about qualification testing for GaAs devices prior to CS Mantech, contact Bill Roesch at bill.roesch@tqs.com.

Further reading

WJ Roesch *et al.* 2002 *GaAs Reliability Workshop Proceedings* 69.

Microsemi puts SiC on the radar

Radar's latest challenge is to uncover details of objects at vast distances. Vacuum tubes and silicon electronics are not up to the task, but Microsemi's SiC static induction transistors can aid this quest by delivering long, powerful pulses at a high duty cycle, says **Mike Mallinger**.

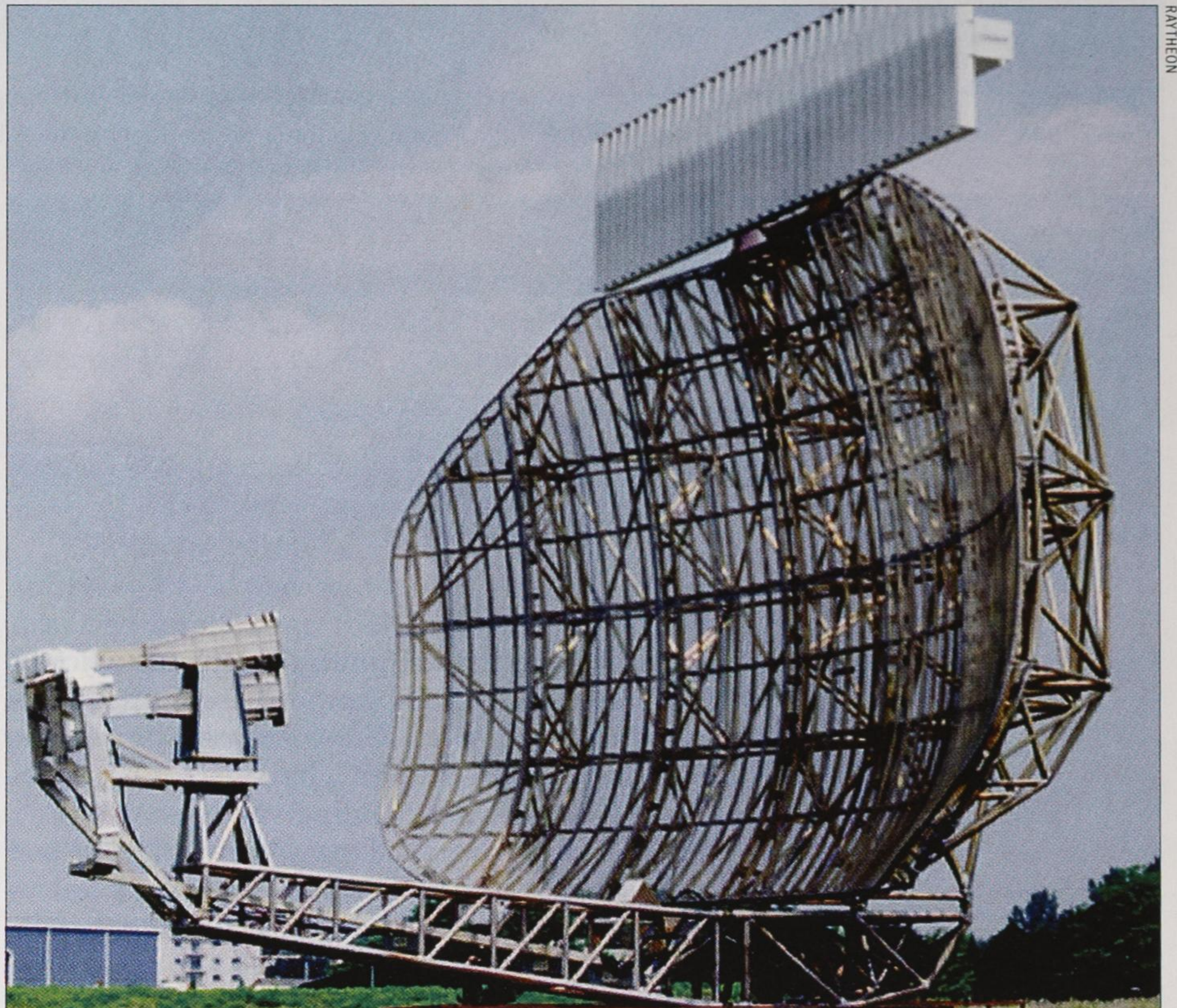
The versatility of radar is on the up. The systems that saw widespread deployment in the Second World War were only capable of searching the sky for objects. By the 1980s they could identify ballistic missiles, and since the atrocities on September 11, 2001, there has been a desire to take radar capability to an even higher level. The current goal is for relatively affordable radar for defense and commercial markets that operates over distances of 500 miles or more, while delivering detailed information regarding the identity of aircraft and missiles.

If radar is to reach this level, it will require the introduction of a new technology for the generation of electromagnetic pulses with frequencies of 0.1–4 GHz. If the purpose of radar is just to search the sky, then short pulses of less than 1 μ s at a low duty cycle of 1% are adequate, which can be produced by vacuum tubes. But these tubes cannot be used for identification – this requires far longer pulses, in combination with higher duty cycles. Silicon is up to this task, and can produce pulses that are 1000 times longer than those generated by tubes, in combination with duty cycles of at least 10% and some form of pulse compression.

The strengths of SiC

The drawback of using silicon is lower peak powers (typically 300 W at 300 μ s) that reduce the radar's operating range. Combining elements can address this – the US Pave PAWS (phased array radar warning system), built at the height of the cold war to detect and track sea-launched intercontinental ballistic missiles, has a range of more than 3000 miles. However, this system has more than 2000 elements, a component count that makes long-range silicon-based radar too expensive for commercial markets.

To meet today's goal – affordable, long-range radar that delivers an unprecedented level of detail – requires a new solid-state technology that offers affordable systems with operating pulses of 1 ms or more, higher duty cycles and output powers that are far higher than those of silicon devices. At Microsemi, which is headquartered in Irvine, CA, we believe that we have the answer in SiC. This wide-bandgap semiconductor can be used to create transistors with very high levels of performance, including peak output powers of 1.4 kW from a



Raytheon's ASR-23SS L-band radar is designed for air traffic control and can track more than 1000 targets simultaneously. It represents the current state of the art for L-band radar and is deployed in many locations throughout the world. This radar was designed a few years ago and features silicon RF power transistors. Microsemi's SiC RF static induction transistor technology will provide Raytheon with the ability to extend the life of the system and offer performance enhancements such as increased power output, extended pulse width and a higher duty cycle.

single device. Pulse lengths of 1 ms or more should soon be realized from transistors delivering a peak output of 750 W.

SiC devices can deliver longer, more-powerful pulses at a higher duty factor than silicon equivalents because they can operate at higher voltages. Transistors built from this wide-bandgap material can also operate at higher temperatures, which allows higher power densities and smaller chip sizes, thanks to the greater thermal conductivity of SiC.

Other compound semiconductors also have superior intrinsic properties to silicon. GaAs, for example, has enjoyed great success in the handset market.

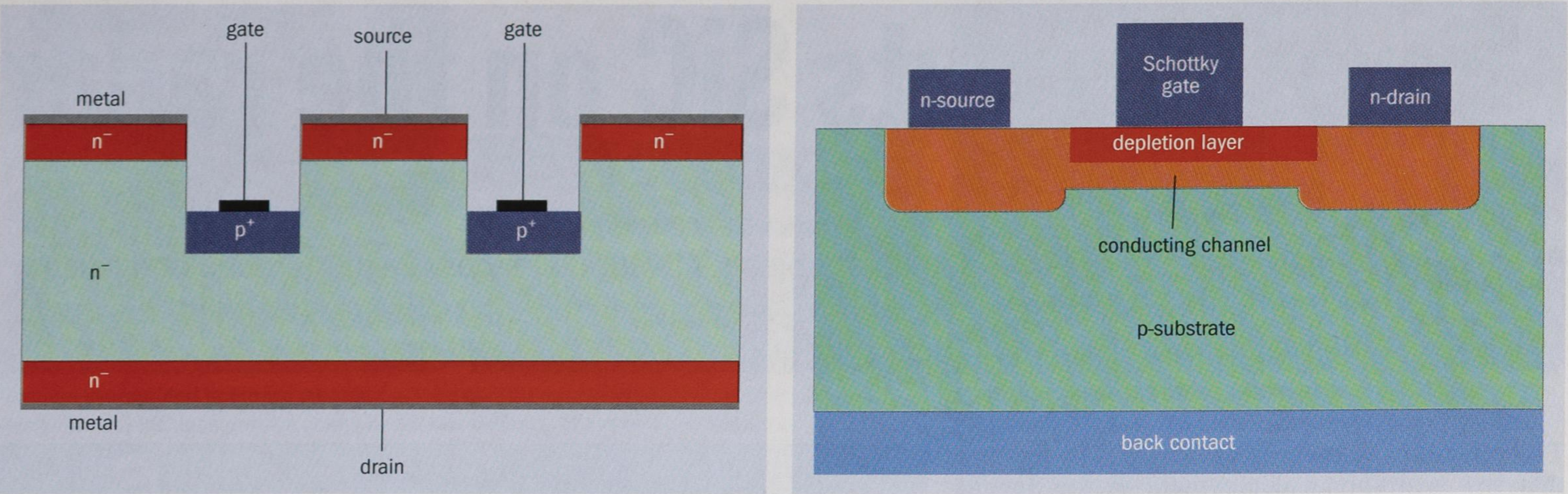


Fig. 1. (left) Microsemi has developed a static induction transistor for covering the VHF band through to the L-band. This vertical geometry device is operated in triode mode and can produce high power gain. **Fig. 2.** (right) For higher frequencies, such as the S-band and beyond, Microsemi has developed a MESFET.

Table 1. Radar frequencies

Frequency band	Frequencies
VHF	138–144 MHz and 216–255 MHz
UHF	420–450 MHz and 890–942 MHz
L	1215–1400 MHz
S	2300–2500 MHz and 2700–3700 MHz

Not all of the bands that are listed above are available for radar use. Those shown in bold type are the most active at this time. Recently some radar bands have been set aside for use in newer wireless applications.

However, devices made from GaAs operate at lower voltages than those built from SiC and this limits the peak output power. GaN, meanwhile, shares many of the attributes of SiC, but again it produces transistors with lower operating voltages.

Our devices are designed to cover radar bands that are allocated by the International Telecommunications Union (table 1). The lower frequency bands, such as 138–144 MHz and 420–450 MHz, are used for long-range search and air route surveillance. Several systems operating at these frequencies also incorporate the capability to penetrate ground foliage. Higher frequency radars are used primarily for short-range air traffic control.

We cover the VHF band, through to the L-band, with a SiC static induction transistor (SIT) (figure 1). This device employs a vertical geometry, which leads to superior breakdown voltages and power densities compared with lateral structures, such as LDMOS, MOSFET and MESFET transistors. The SIT is operated in triode mode, which enables high voltage gain at operating voltages of up to 125 V. This leads to a high power gain without large excursions in current.

S-band and higher frequencies are covered with a MESFET (figure 2). This type of transistor has a lateral structure and can operate at high frequencies and voltages thanks to the short channel length and low chip parasitics.

Epiwafer growth is outsourced, which leaves

us to focus on chip architecture, wafer processing and the design and manufacture of the finished product. With this approach we can exploit the expertise of epitaxial growth specialists, who are constantly improving the material quality of this wide-bandgap semiconductor.

Our devices are grown on 3 inch SiC, but we will make the transition to 4 inch material when this size becomes more readily available. We are investigating the quality of SiC substrates produced by a variety of manufacturers and have found that although the variations are significant, they are narrowing all the time. We are also evaluating the quality of epiwafers produced by several companies and have found small to moderate differences across suppliers. By working with various epiwafer and substrate suppliers we will qualify multiple sources at both levels, and ultimately ensure quality and consistency in production volumes at reasonable prices.

Chip fabrication is carried out in-house, including the key process steps of pattern generation (with ASML 5X steppers), materials etching, high temperature implanting and annealing, passivation and metallization. Many of these process steps employ tools that are also used for silicon processing. However, specialized equipment that operates at high temperatures is needed for the implanting step and subsequent annealing. The equipment that is shared between both materials has been adapted to reflect the unique characteristics of SiC, while ensuring a high level of consistency of the finished product.

We have produced SIT chips for VHF and UHF radar applications ranging from 1 × 1 mm to 1 × 2 mm in size. This includes the first solid-state devices to operate at peak powers above 1 kW.

The full 1000 W transistor has seven chips wired into the package. Each chip has five active areas, known as cells, and the final transistor uses 32 cells, which are each capable of producing a peak output of 45 W and 36 W at VHF (156 MHz) and UHF (450 MHz) frequencies, respectively. Dividing the chip into a handful of active areas aids transistor

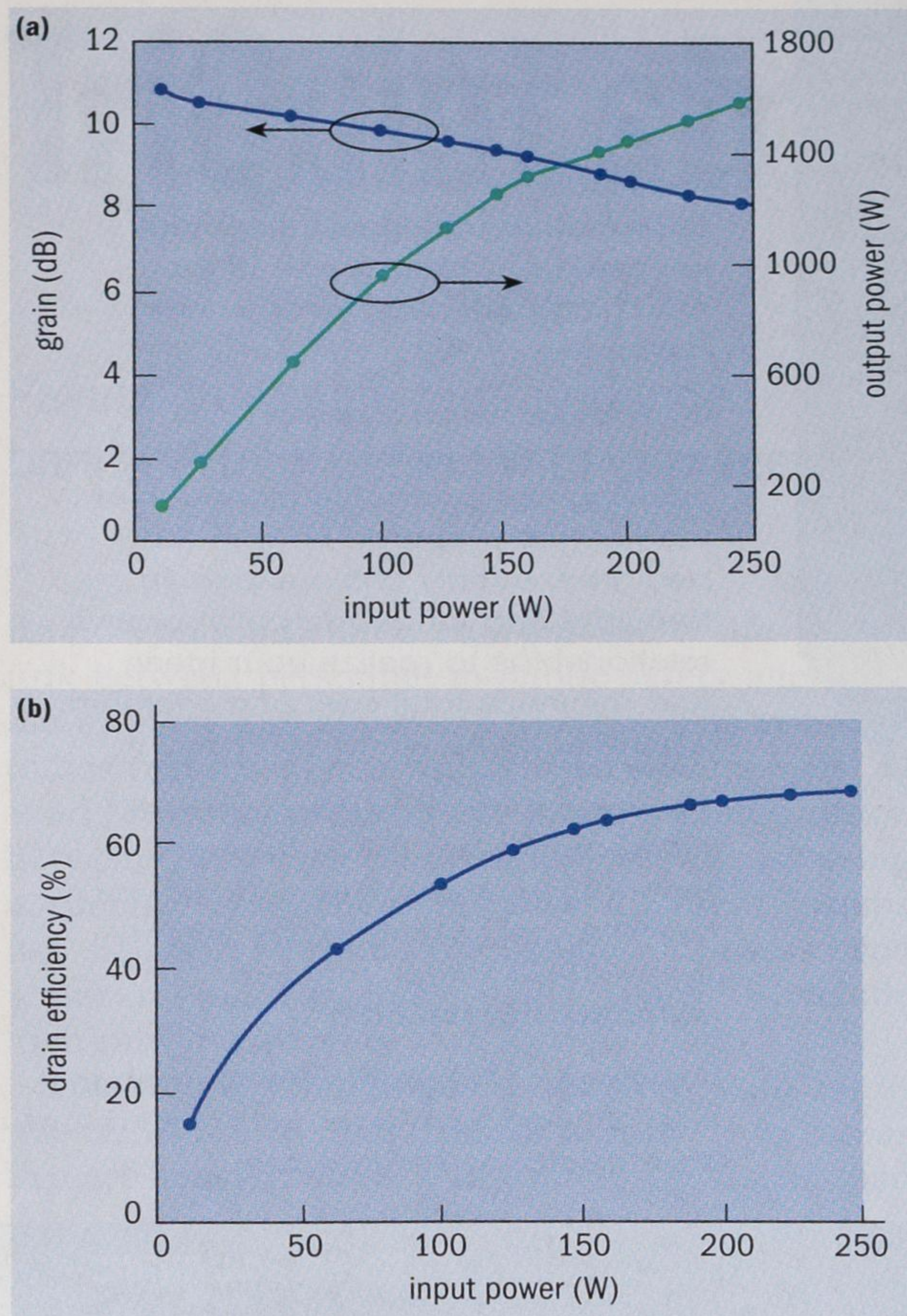


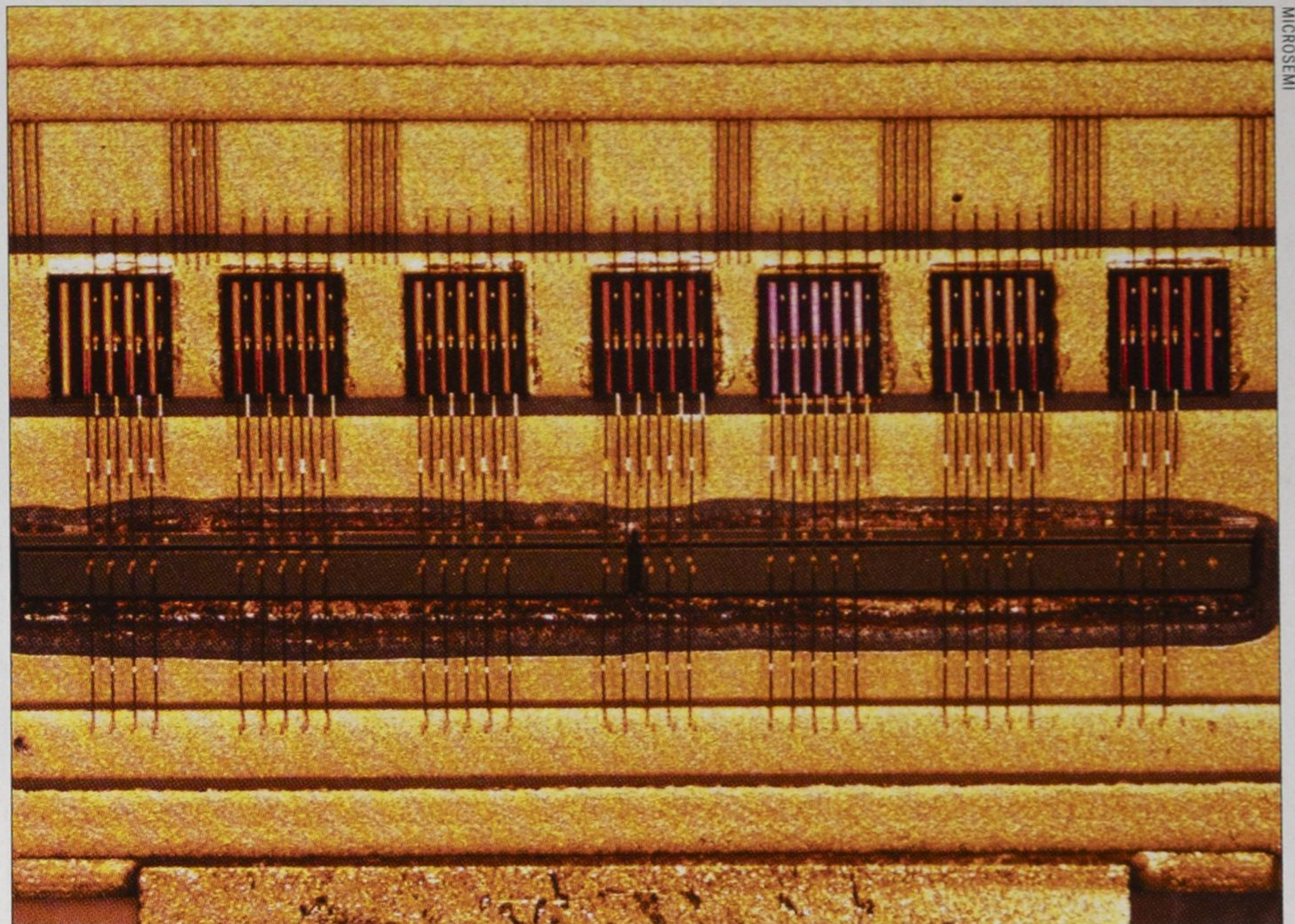
Fig. 3. Microsemi's transistors can deliver more than 1.5 kW at 156 MHz, using 300 μ s pulses and a 10% duty cycle (a). At this output power, drain efficiency is almost 70% (b).

performance because it enables low inductance connections and good thermal distribution, leading to improved operation at higher frequencies. As the frequency is increased, the active cell size gets smaller and more cells are employed on a chip.

Our transistors are routinely tested at a 10% duty cycle using medium and long pulses with widths of 300 μ s and 1 ms (figure 3). However, we have also studied our SITs under extended pulse width and duty factor, and the results show the capability of SiC for higher voltage operation. One of our SITs, which is run at 100 V and adjusted to operate at 200 MHz, produces 800 W from 1.8 ms pulses and an 18% duty cycle. This output is more than three times higher than that of the best silicon products.

Pump up the power

The performance of VHF and UHF products produced from SIT epiwafers via several growth runs has recently been evaluated. These transistors deliver high peak output powers, power gain and drain efficiency, in combination with a low reduction in output power over the duration of the pulse, when operated over the 100–125 V range. These results have encouraged us to generate high-performance products for the frequency range 1.2–1.4 GHz, and for applications relating to avionics equipment, which operate in the 960–1215 MHz band. Other



Microsemi's SiC device is the first solid-state transistor to operate at peak powers above 1 kW. It features seven chips, which each have five cells that hit a peak output of 45 W in the VHF band.

plans include the development of a higher peak power chip that produces more than 2 kW, which will require a larger package.

In addition, we are developing high-performance subassemblies that will enable our customers to quickly implement their latest system design. During the last 12 months we have introduced a series of power solution modules, which have terminal impedances of 50 Ω and use a pair of devices mounted on a carrier. This approach promises to enable the operation of SIT products at higher power levels within a short time frame.

Another target is a 2 kW output from a single SIT. This will require a complete review and analysis of the entire chip and package structure, including efforts to improve thermal management and device and circuit layout for a targeted operating frequency band. Each element will be modeled, fabricated and tested to identify key performance characteristics and trade-offs. Customer demands mean that we will require chips that are about 50% larger than our existing designs, in combination with larger packages. This device should be completed by early 2010.

We are also gearing up for the manufacture of SiC MESFETs that are able to serve high-power S-band applications operating between 2.7 and 3.5 GHz. The gain produced by these transistors is at least 2 dB higher than silicon equivalents, and they can also handle longer pulses and higher duty factors. These products are planned for release late this year and will complement our silicon BJT products serving the same frequency band. By releasing SiC products that span the VHF to S-band, we will enable our customers to benefit from the deployment of this new form of solid-state technology.



About the author

Mike Mallinger is a director of business development in the Microsemi power products group. He has expertise in the marketing and product development of RF/microwave power transistors and has been a founder of companies that specialize in these products, including Acrian and GHz Technology (now Microsemi PPG RF in Santa Clara, CA).

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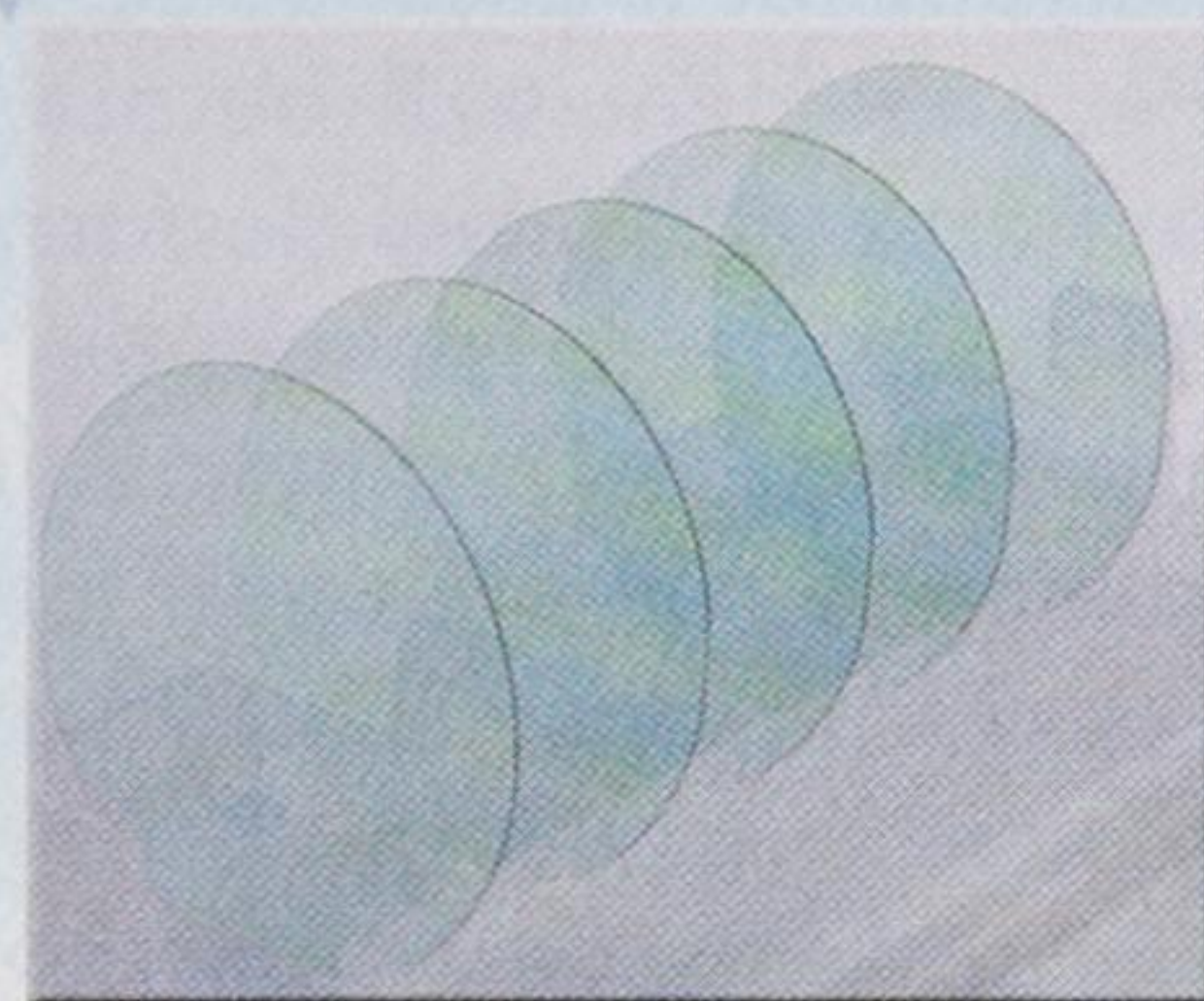
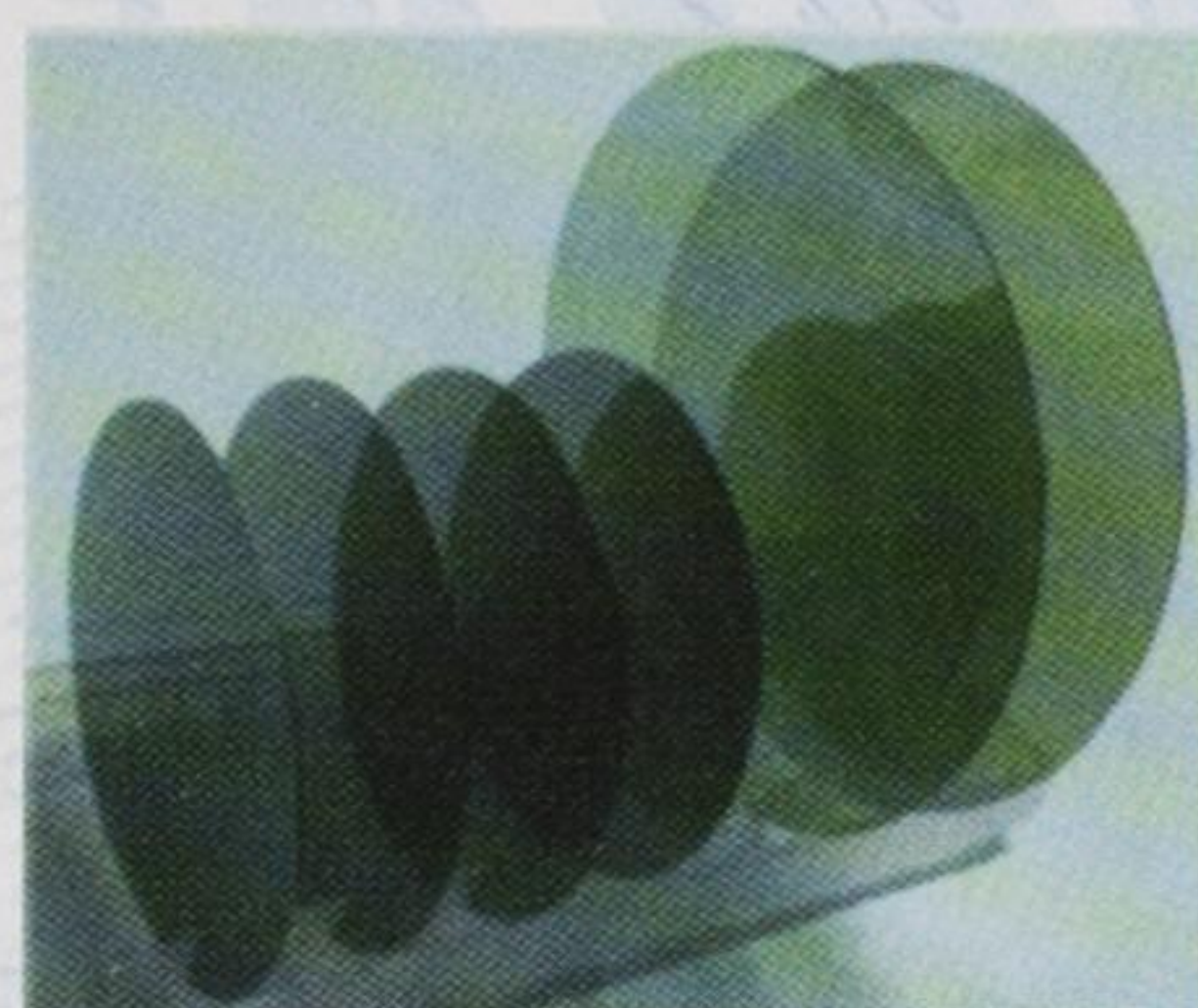
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TriQuint stretches the sweet spot

Paying great care to impedance matching has paved the way to production of incredibly wide bandwidth amplifiers with unprecedented efficiency, say TriQuint's **Mike Lincoln** and **Mark Andrews**.

Radio communication can provide a life-saving link between personnel in public safety agencies, the military and anyone in distress. The two-way radios that have been widely used since the end of World War II have enabled effective communication between personnel on countless occasions, using a specific frequency. Because different groups use different allocated frequencies, all users need wideband radio systems, which typically include high-power capability.

The unique challenges associated with high-power, wideband amplifier design leads to radios that are heavier, more costly and less efficient than those operating in narrowband applications, which have a far wider choice of high-efficiency RF transistors for amplifier construction. However, at TriQuint Semiconductor, we have developed a patent-pending technology that will revolutionize high-power wideband amplifier design. And best of all, it's not only applicable to two-way radio communications – it can also serve many other applications, including lab amplifiers, jammers and some forms of repeaters.

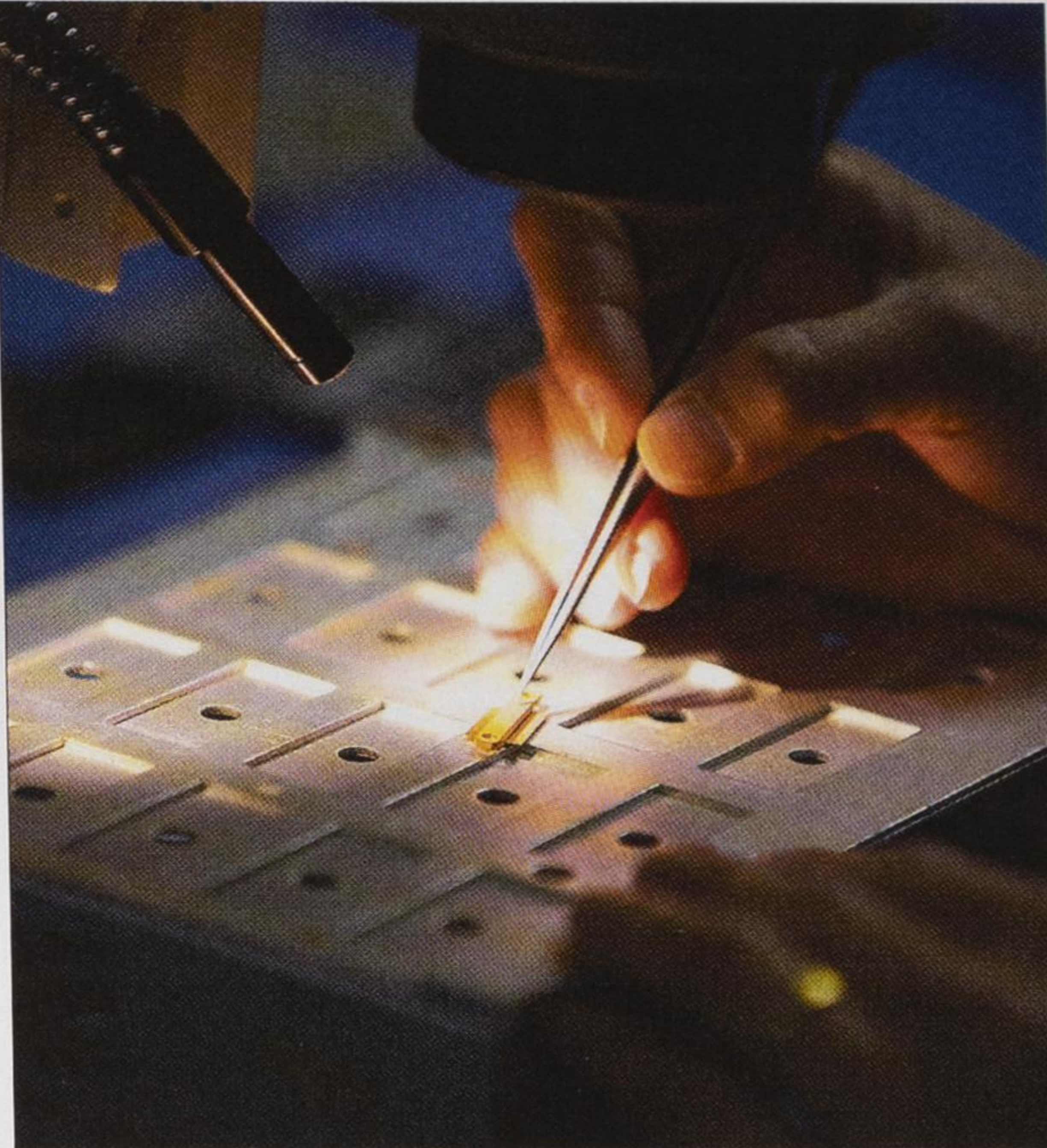
Our latest high-power transistor family has delivered a dramatic hike in wideband amplifier efficiency, and it is now being designed into broadband systems around the globe. The portfolio features discrete, 10–50 W output, RF transistors that can boost multi-octave (500 MHz–3 GHz) amplifier efficiency from 25–35% to 45–55%.

To fully appreciate the significance of our breakthrough, it is imperative to understand the elements common to wideband and narrowband systems.

Impedance issues

At the simplest level, an RF amplifier has to transform a small signal into a larger one. Typically, RF transistors produce 8–22 dB of RF gain, but this is inadequate for many RF systems that require a gain of 40 dB or more from the power amplifier (PA) section. Greater gain can be achieved by linking multiple amplifiers together, with one amplifier feeding the next. The signal increases at every stage, until it meets the required RF output power, and this can be transferred to an antenna or other final load.

As the signal travels from one amplifier stage to the next, impedance matching is needed at these interfaces to maximize energy transfer from the



A technician in TriQuint's Boulder, CO, Design Center inspects lead coplanarity of a prototype PowerBand device.

source of the signal to the load. Ideally, the amplifier circuits contain “matching networks” that match the source to the load at every stage. However, if the matching isn't perfect, some of the signal reflects off the load (known as the return loss) and is driven back towards the source, which reduces efficiency, gain and output power.

To meet the high-power requirements for applications such as two-way broadband radios and RF jammers, large RF power transistors need to produce between 10 W and several kilowatts. These transistors must be big enough to meet the RF power output requirement, but not so large that they hamper efficiency. As they get larger, impedance decreases, and this makes it harder to build matching networks that can transform this impedance to a higher level.

The transistor RF output power is calculated in the same way as DC power – it is simply the product of voltage and current at a given time. Consequently it is possible, for example, to produce a 120 W output from a 12 V, 10 A signal or a 28 V, 4.3 A signal. However, impedance matching is much easier with transistors that operate at higher voltages, such as 28 V compared with 12 V.

RF power transistor manufacturers provide

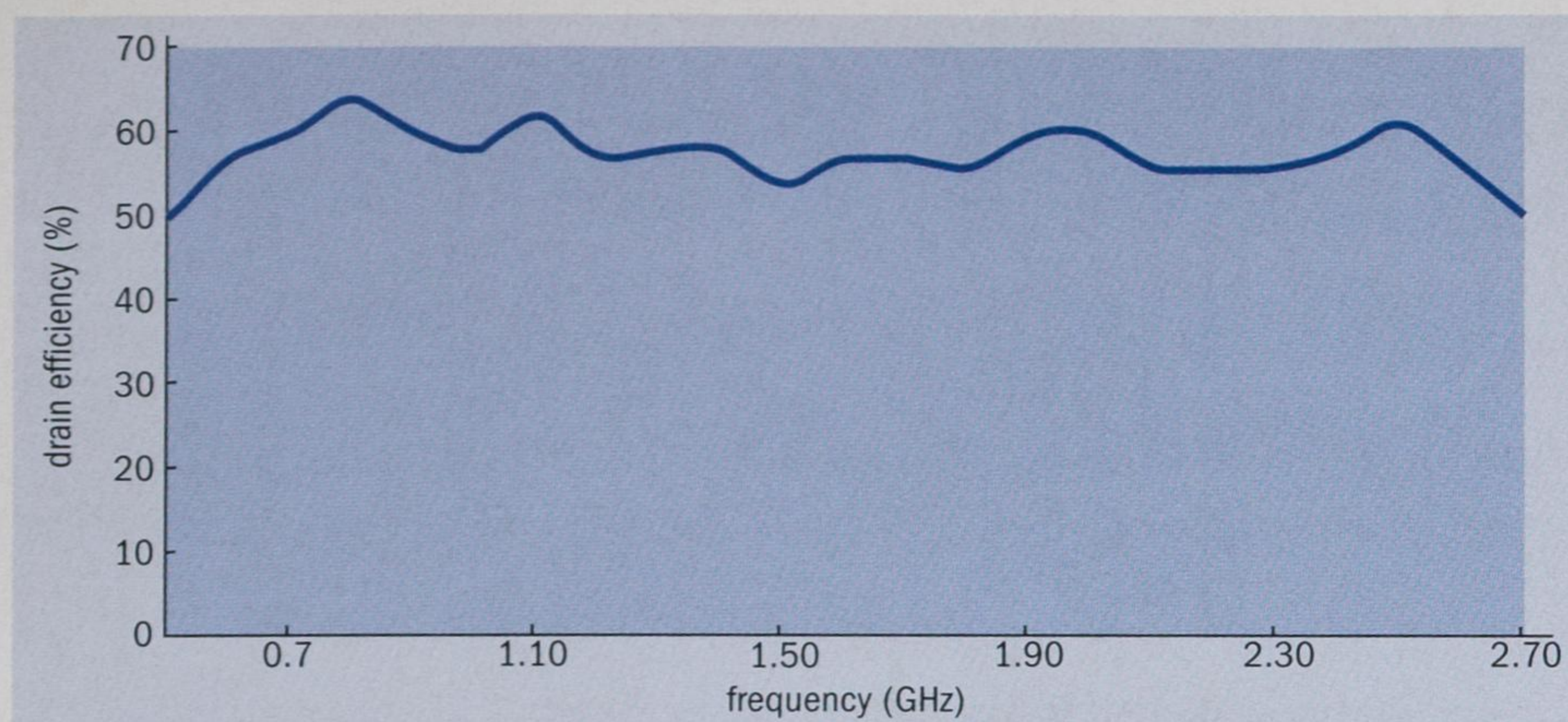


Fig. 1. Measurements in a broadband test fixture demonstrate that TriQuint's PowerBand devices deliver exceptional efficiency across an unprecedented bandwidth.

impedances and associated device performance in the form of load-pull and source-pull data tables and associated graphs. But engineers tackling these designs have discovered that gain, efficiency and output power require different impedances for peak performance. The challenge is to identify a “sweet spot” that offers the best trade-off in performance for a particular design goal.

High-voltage III-Vs, such as our GaN transistors, generally produce a far lower capacitance per watt of RF output power than those of devices fabricated using other process technologies. The lower capacitance translates into higher impedance and explains why high-voltage GaN-based power transistors are deployed in narrowband systems that require very high output power from a single-ended amplifier. Broadband designers also like to take advantage of the impedance benefits of GaN, which enable them to build matching networks operating over a greater bandwidth for a given output power.

On a per-device basis GaN is more expensive than incumbent technology, such as LDMOS, but its system-level cost savings are undeniable. In fact, turning to an advanced technology such as GaN is often the only sensible way to construct a system with aggressive design goals.

While advanced semiconductors have simplified wideband designs, and in many cases turned the impossible to the possible, performance is overshadowed by narrowband designs with far higher efficiencies. Even wideband GaN-based amplifiers only deliver 25–35% efficiency in the final PA stage.

Obstacles to going wide

Wideband designs face two additional challenges over their narrowband siblings. First, matching network impedance varies with RF signal frequency, and a circuit that works well at one particular frequency will deliver inferior energy transfer at higher and lower frequencies.

The other challenge is that device impedance changes with frequency and in the opposite direction. This leads the designer to see that as the signal frequency moves away from the center point – either

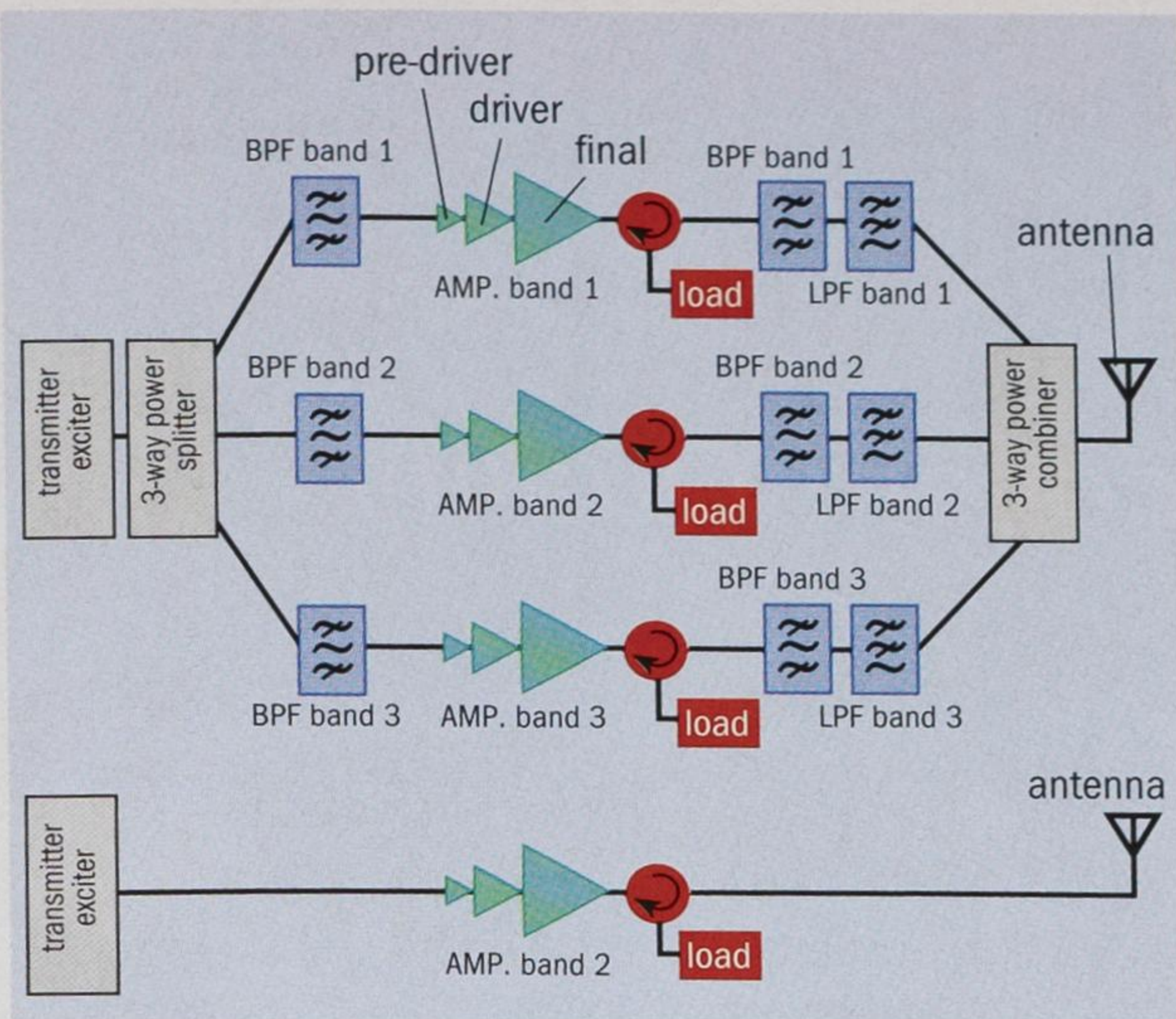


TriQuint's initial PowerBand family (top) consists of six devices that employ LDMOS and GaAs pHEMT technology, and offer an efficiency of 45–50% or more across a bandwidth that can span 500 MHz to 3 GHz. 100 W products based on GaN technologies will be added to the portfolio this year (bottom).

increasing or decreasing – differences between the impedance of the device itself and its matching circuit increase. Generally, gain is sensitive to the input match, while efficiency and RF output power tend to be more sensitive to the output match. The upshot is a very poor performance in all major areas, if the techniques of narrowband design are transferred to a wideband application.

Successful wideband amplifier designers address all of the challenges of narrowband designs, while simultaneously dealing with the added complexity of creating matching networks that continuously provide the RF power transistor with acceptable impedance over frequency changes of two octaves or more. If this wasn't enough, many RF power transistor manufacturers fail to provide load and source-pull data across the entire useful frequency band of a given device.

Designers in the rare position of having access to an automated source and load-pull tuner system can measure the device impedances across the entire band of interest. However, they will often find that impedances required for stable, high-performance operation are beyond the abilities of traditional matching networks. To address this, engineers tend to design smaller amplifiers (in terms of RF output power), which have adequate impedance to provide good performance. These are combined



Conventional designs (top) can be simplified with PowerBand technology (bottom). Although each design is unique, reduced part count, efficiency improvements and true wideband coverage — more than two octaves — is commonly achieved.

together to meet the desired RF output power. But this approach has high development and system costs, and produces large, heavy amplifiers. If the bandwidth is too great, designers resort to “channelizing” or breaking the frequency band into sections, creating amplifier stages that only target frequencies in a given range. Again, this comes with a huge financial, size and weight penalty.

We have approached the challenges of wideband design from a different perspective. Our starting point was a study of the various approaches to broadband matching and the resulting impedances across a given frequency band. We set a goal of creating an RF power transistor that would perform well in such an impedance environment, and placed an emphasis on output power and efficiency.

The results are dramatic: we now have a range of six products that are based on GaAs and LDMOS process technologies, which can deliver 45 and 55% efficiency over bandwidths of up to 500 MHz–3 GHz (figure 1 and table 1). These can utilize more than 75% of the devices’ rated narrowband P1dB output power capability, which is three times that of most transistors built with traditional approaches.

Missing data

The challenges of wideband design are often compounded by a lack of data provided by RF transistor manufacturers; data provided rarely reveal how devices would perform in a wideband application. Yet there are many instances where narrowband devices are marketed as suitable for broadband use, even though the data supplied fail to accurately characterize the performance for applications requiring greater than 2 GHz coverage. In many cases, narrowband data is only published at the high and low ends of the device’s intended frequency range.

It is far more useful to publish gain, efficiency and output power at the “instantaneous bandwidth”, which

Table 1. TriQuint’s PowerBand portfolio

Part number	Technology	Operating voltage (V)	Bandwidth (GHz)	Power P1dB (W)
T1P2701012-SP	pHEMT	12	0.5–2.7	10
T1P3002012-SP	pHEMT	12	0.5–3.0	20
T1L2003028-SP	LDMOS	28	0.5–2.0	30
T1P3002028-SP	pHEMT	28	0.5–2.0	20
T1P3003028-SP	pHEMT	28	0.5–2.0	30
T1P3005028-SP	pHEMT	28	0.5–2.0	50

More information is available at www.triquint.com/prodserv/markets/military/powerband.cfm.

is the device performance in an RF fixture with bias circuitry and matching network in place. The device can then be tested from one end of the frequency band to the other, with no changes required to the circuit or device. This differs from testing a device at a range of frequencies in various test fixtures, each attuned to work well at a single frequency.

Our PowerBand data sheets list instantaneous bandwidth RF performance and narrowband RF performance in the RF specifications section. Source and load impedances are also provided along with RF gain, efficiency and P1dB output power performance levels in the form of a table. These data have been generated by placing a given device in the stated impedance environment across the entire band of operation in 100 MHz increments. In addition, optimal input and output impedance of the matching network from the low end to the high end of the band is provided graphically on a Smith chart.

Broadband designers benefit from narrowband data, because they expose the degree of trade-off between wideband and narrowband performance. They also allow engineers to design narrowband amplifiers and exploit the benefit of greater flexibility compared with internally matched devices, thanks to the application of a single device to multiple product platforms. For example, two-way communication radio manufacturers produce a family of radios operating at different frequencies. In this case, one PowerBand device can serve three or more designs, whereas the traditional approach requires a different internally matched transistor for each application variation. Broadband amplifiers can also aid non-telecom systems designers, which often struggle to source internally matched RF power transistors that can operate in their band of interest.

There is no getting away from the fact that high-power amplifier design is difficult, and high-power, broadband design pushes that even farther. Until now, performance-reducing compromises were inevitable to meet the operating goals. But thanks to PowerBand, breakthrough levels of efficiency plus greater bandwidth coverage are now possible from RF transistors with output power levels of 10 W (P1dB CW) and 50 W (P1dB pulsed). We are aware that many applications require even higher output power and we plan to introduce a GaN-based 100 W P1dB CW device to the PowerBand portfolio. ●



About the authors

Mike Lincoln (left) is the original founder of Colorado-based Peak Devices, which was acquired by TriQuint in 2007. He is currently TriQuint’s PowerBand marketing director for the company’s portfolio of high-power, wideband RF transistors. **Mark Andrews** (right) is TriQuint’s strategic marketing communications manager for networks and defense/aerospace product marketing.

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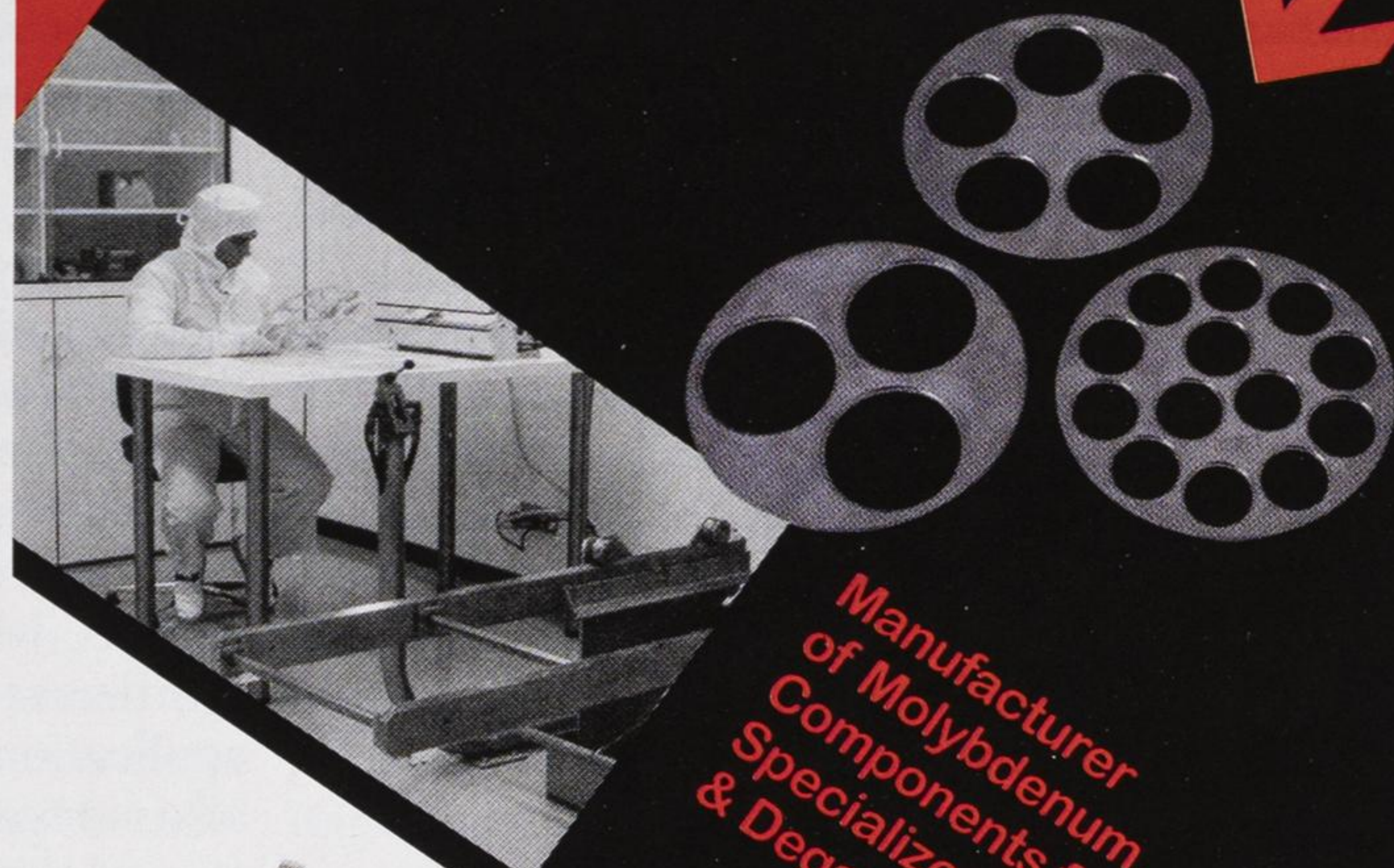
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LEDs get ready to take to the skies

Photonic quasicrystals and a droop-combating layer can create efficient LEDs with well-directed emission for navigational, taxi and landing lights in aircraft, and backlighting cockpit displays.

Duncan Allsopp and **Philip Shields** describe the progress made under the UK's "Novelels" project.

Solid-state lighting is making an impact. Niche applications are emerging that can enjoy the benefits of high-brightness LEDs where the overall advantages of solid-state lighting outweigh concerns over luminous efficacy and long-term color control.

One area where LEDs are poised to make significant inroads is on aircraft, and our team from the UK is working towards that goal through a project entitled "Novel LEDs for efficient lighting solutions (Novelels)". This aims to advance GaN LEDs and demonstrate this technology in a new generation of cockpit displays and high-reliability external lighting units for aircraft. We are backed with £1.7 million (\$2.54 million) from the UK's Technology Strategy Board and are led by LED lighting system manufacturer Enfis Technology. Other partners in this three-year effort that kicked off in summer 2007 include end-users Agusta-Westland and Airbus UK, a pairing that is responsible for defining and qualifying cockpit displays and external lighting units. GE Aviation and Enfis have the role of developing new lighting systems featuring the University of Brunel's novel phosphors and optical coupling technology created by Exxelis Ltd. Underpinning all of this effort are innovations in GaN LED technology and epitaxy, pioneered by the University of Bath, IQE and Enhanced Photonics, a new spin-out company from the University of Southampton.

One of our primary motivations for the project is to improve the performance of LCD displays, which are widely used in aircraft cockpits. All aircraft, and especially helicopters, demand displays with rugged backlighting, which generally takes the form of a "serpentine" tube and diffuser, covering the active display area.

Serpentine lamps are not ideal – they introduce a single-point failure for the entire display, unless two or more are employed together. There are other weaknesses too. Drive electronics can introduce electromagnetic interference close to sensitive navigational equipment, due to the high voltages required by the lamp; and the inefficiency of the system increases the fuel payload and exhaust emissions.

LED backlights can overcome these problems, while delivering improvements in the clarity of the display. By selectively dimming and brightening areas of the backlight in response to the displayed



image, it is possible to increase the display's apparent contrast range. And sequential strobing of the backlight allows moving images to appear sharper, while also easing detection of moving objects.

Applications of solid-state lighting for aircraft are not confined to displays – LEDs are already providing navigation lighting (the red, green and white lights deployed on the aircraft's wing tips and tail). In addition, LEDs could be used in taxi lights, landing lights and searchlights, where they could deliver weight savings, greater robustness and a cut in airline maintenance costs. LEDs could also allow aircraft designers to apply novel approaches to exterior lighting, such as beam pattern alteration and steerable lighting, which does not require moving parts or bulky optics. Aircraft aerodynamics could be improved, alongside a reduction in weight. Finally, the compactness of the LED could allow it to be deployed in novel exterior lighting applications that are out of bounds for conventional lighting, due to installation restrictions. However, these opportunities will require improvements in LED technology, from epitaxy all the way through to packaging. Achieving aircraft external lighting based on such improvements in LED technology is the other main aim of the Novelels project.

One of the LED's biggest limitations arises from the high refractive index of the chip. The large refractive index difference with air causes most of the light generated in the active layers to be trapped in the device by total internal reflection, before it is

Aircraft cockpits incorporate several LCD displays. These are backlit with a single lamp and its failure is a major concern. Turning to a handful of LEDs for backlighting improves reliability and increases the apparent contrast range by selectively dimming and brightening areas of the display.

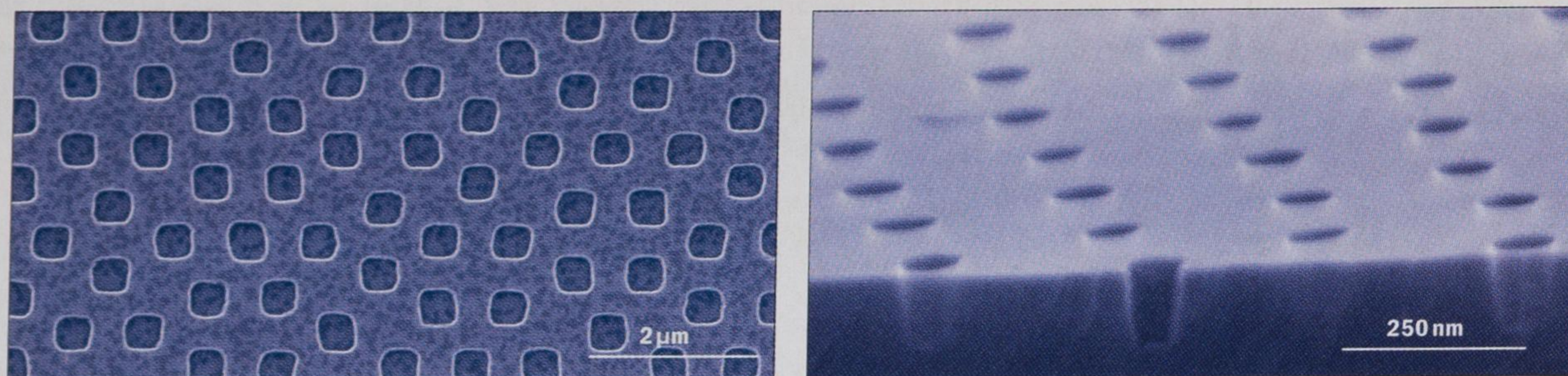


Fig. 1. Quasiperiodic photonic crystal structures enable the LED's spectral emission profile to be tailored to a specific application.

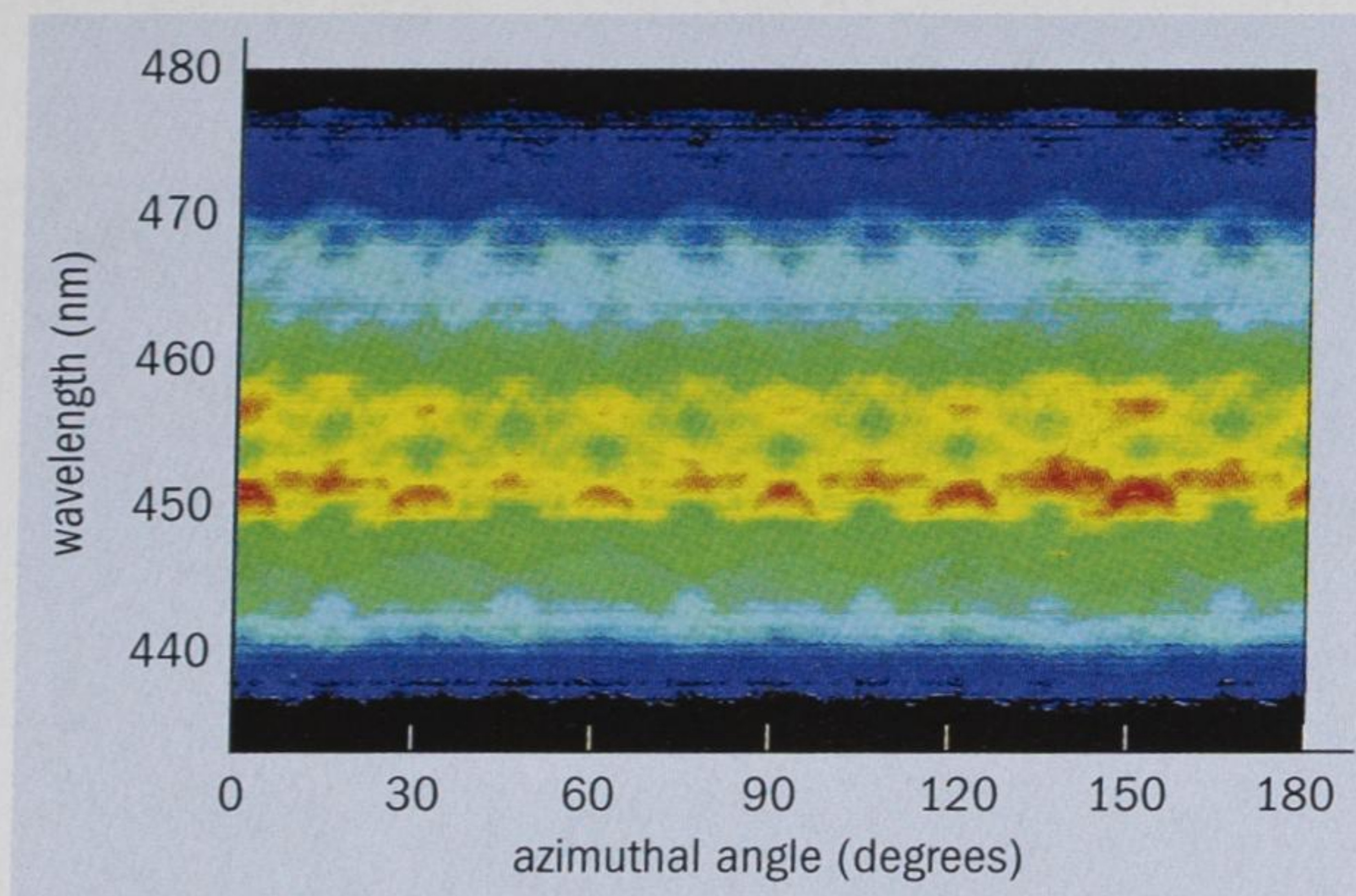


Fig. 2. This plot of photoluminescence intensity (transverse electric polarization) as a function of emission wavelength and azimuth angle, for an LED with a 730 nm pitch PQC etched into its surface, reveals the 12-fold symmetry of the etched structure. Integrating the light output power over all wavelengths washes out variations resulting from this symmetry.

ultimately reabsorbed.

A primary objective of our project is to incorporate photonic crystal structures into LEDs, which increase device output by extracting light that would otherwise be confined to waveguide modes inside the chip. Photonic crystal structures that are etched into the LED's surface can act as a two-dimensional diffraction grating, scattering light that would otherwise be trapped in guided modes.

Scattering occurs at several zenith and azimuth angles, which are determined by the Bragg condition. (The zenith angle is the angle made with respect to the vertical axis. The azimuth angle is essentially equivalent to the angle of longitude on a globe). While zenith-angle light dependence is an advantage for LEDs serving displays and other aerospace applications, any dependency on the azimuth angle is a drawback because it produces uneven illumination of the display.

To overcome this, we have developed photonic quasicrystal (PQC) structures with a square-triangular tiling pattern that lacks short-range symmetry but exhibits long-range order. These structures reduce the influence of the azimuth angle on the scattered light intensity, but retain the desirable zenith-angle dependence of the light output. Enhanced Photonics and the University of Bath are leading the investigation of technologies to optimize the PQC design to meet the aerospace requirements.

PQC structures are formed by defining a square-triangular tiling pattern of circles with electron-beam lithography, and etching down into the p-type layer of a GaN-based LED with a Cl_2/Ar plasma (figure 1). Altering the pitch of the PQC tiling adjusts the zenith angle of peak emission intensity.

LEDs with a PQC structure have been fabricated by members of the Novelets team. These devices feature a 730 nm pitch PQC etched into the surface. The 12-fold symmetry of these structures can be seen in the light power output variations with the azimuth angle at a given wavelength (figure 2). While apparent for a single light wavelength, this variation is washed out when the light power is integrated over the whole emission band, illustrating the advantage of PQC structures over periodic photonic crystals.

Even without optimization of the PQC or the LED, these emitters produce a 60% enhancement in light extraction efficiency. Simulations predict that even higher extraction efficiencies should be possible with PQC structures, and research continues to identify the factors that inhibit the performance of the LEDs produced in the lab. These simulations can also calculate the shape of the emitted light intensity profiles, which are a close match to experimentally observed values.

Another early milestone for our project was the demonstration of thick GaN layers grown by HVPE. These form the basis of freestanding GaN templates, a promising alternative to the sapphire substrates that are used to produce the vast majority of today's LEDs, which have a 13% lattice mismatch with GaN. This mismatch gives rise to a very high density of misfit dislocations that act as non-radiative recombination centers, limiting the device's internal quantum efficiency.

Switching the growth platform to SiC or silicon does not alleviate the high misfit dislocation density in the nitride film, unless steps are taken to mediate lattice mismatch. Even then, reducing the dislocation density by a factor of 2–3 orders of magnitude – the level that's probably needed for ultra-efficient LED lighting – is a tough proposition. Freestanding GaN templates, however, could overcome this technology-limiting problem. By growing thick layers of GaN, dislocations on inclined crystallographic planes meet and mutually annihilate, leaving a low-defect-density platform for LED growth. These templates could lead to a reduction in parasitic resistances, if

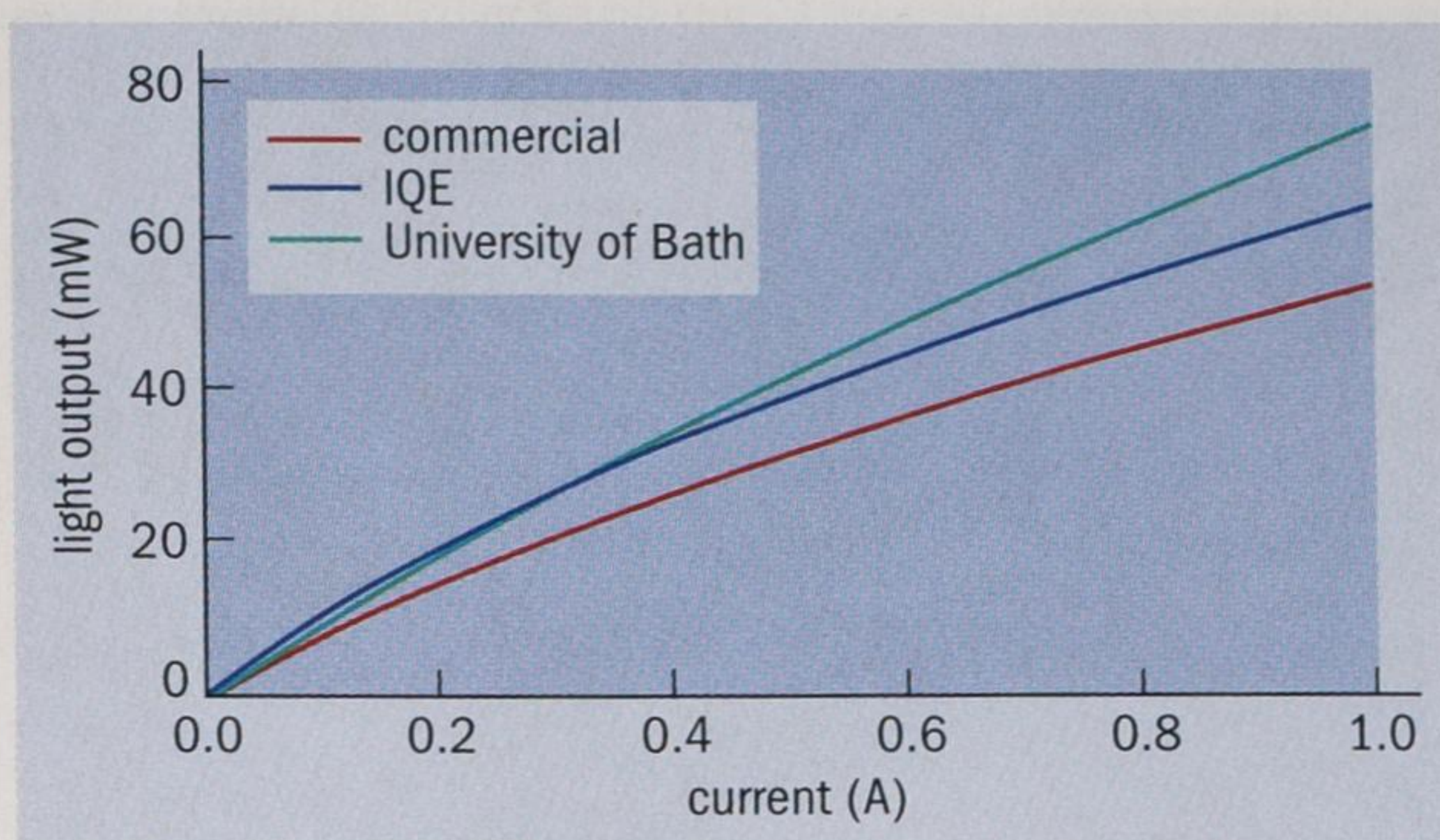


Fig. 3. The efficiency of LEDs produced by IQE and the University of Bath both exceed that of a commercial equivalent. Tests were performed by probing the chips on a 50 mm diameter wafer under pulsed conditions to minimize Joule heating effects. LEDs fabricated by IQE (from its first series of epitaxy) have the highest light output at low drive currents, an indication of high quality and promising control of the dislocation density.

electrically conducting GaN can be deposited.

LED manufacturers targeting solid-state lighting have strived to improve device efficacies at high current density. Efficacy falls as drive currents are ramped up but innovative designs can combat this droop. The cause of droop is being intensely debated within the research community, but a consensus appears to be emerging that Auger recombination – probably assisted by phonon interaction – is the root cause of efficiency droop in the best quality material, which has low dislocation densities.

Combating LED droop

Our team, led by a partnership between IQE and researchers at the University of Bath, is developing InGaN/GaN heterostructures that mitigate the effects of Auger recombination and have a very low dislocation density. One advanced design under development incorporates a wide InGaN well just below the active multi-quantum-well region. This well acts as a reservoir for electrons, leading to improved carrier injection efficiency into the active region. However, the well also has a secondary benefit – it enables the growth of InGaN barriers with an alloy composition closer to that of the well, which decreases the lattice mismatch between these two layers. This reduces the polarization field across the quantum wells, brings the electrons and holes closer together, to increase the radiative recombination rate. The upshot is a lower carrier density, reduced Auger recombination and more-efficient LEDs.

Lateral LEDs measuring 1 mm × 1 mm have been produced with this design that have side contacts to the n-type region. These devices emit at 460 nm and have a higher efficacy than a commercial equivalent at drive currents of up to 1 A (figure 3). Given the known limitation of non-uniform current injection in side-contacted LEDs, these results are highly encouraging because the commercial device has a roughened upper surface on the p-layer to enhance light output. In comparison, the Bath LED was grown on a

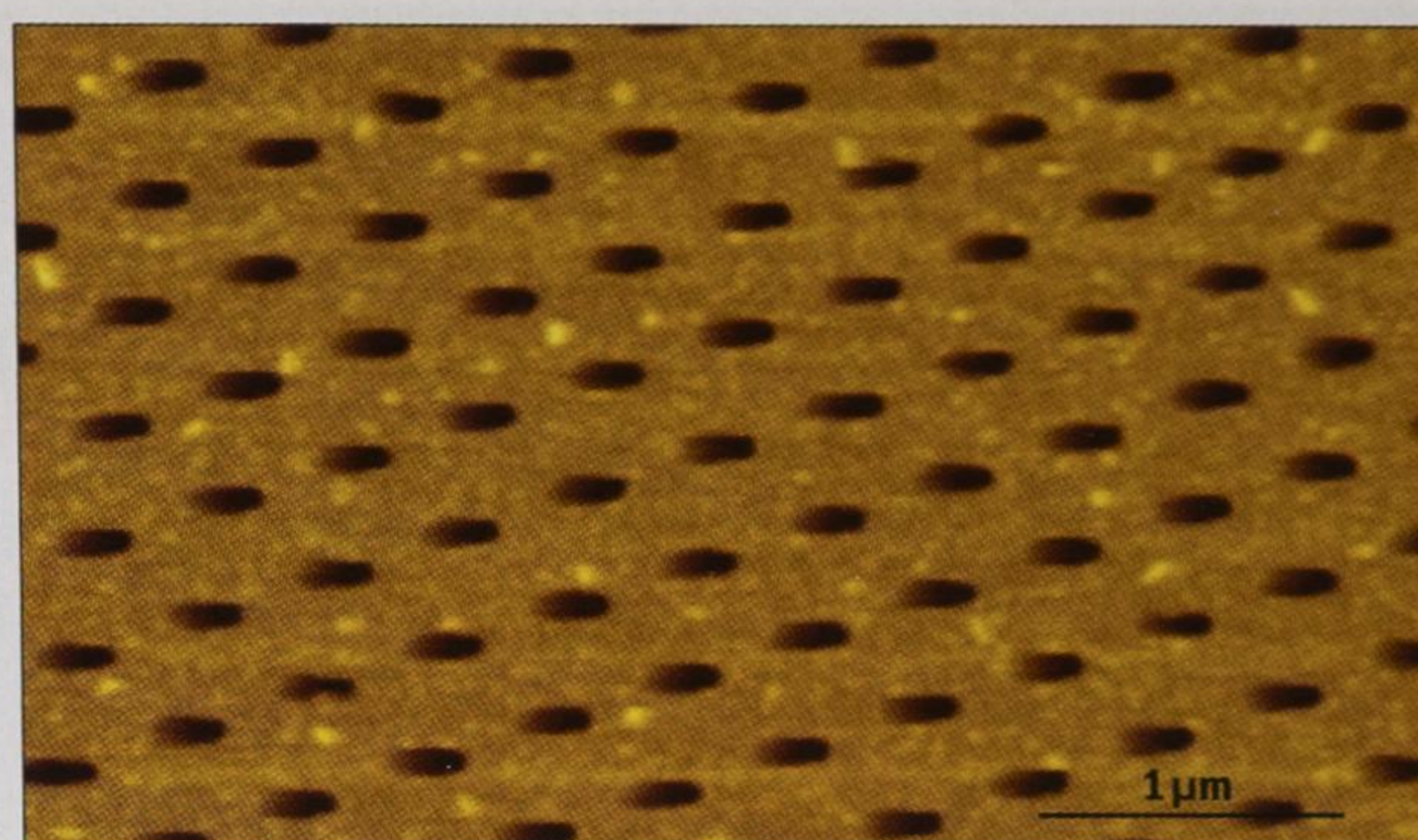


Fig. 4. This atomic force microscopy image shows the patterning of a section of a 100 mm diameter sapphire substrate by nanoimprinting.

patterned substrate, but had no upper surface roughening. Devices have also been fabricated by another member of our team, IQE, which were produced on a smooth substrate, had a smooth upper surface, and were therefore not optimized for high light extraction yet delivered a superior performance to the commercial LED used for comparison. Efforts at IQE and Bath are continuing, with the focus on improving epitaxial designs for high-brightness LEDs.

Members of our team are also trying to increase the LED output by reducing light trapped by total internal reflection. One common technique for increasing LED light extraction centers on the growth of nitride layers on roughened or patterned substrates, because this cuts total internal reflection. A possibly superior approach is to insert a photonic crystal structure at the substrate interface, which can direct the light output, just like a PQC in the upper surface of the chip. This potentially reduces absorption loss in the highly imperfect GaN-sapphire interface layer, as well as diffracting the light upwards.

We have recently started to develop patterned substrates, which are formed by a low-cost nanoimprinting technique. Reactive ion etching has created an array of 300 nm long, 130 nm wide and 100 nm deep holes in sapphire, with a period of 450 nm. Efforts at Bath have revealed that reductions in the dislocation density result from the creation of these nanostructures at the buffer-substrate interface.

Our portfolio of promising results obtained from the Novelel project will help to drive improvements in GaN LED technology. In addition, through GE Aviation and Agusta-Westland, our team has demonstrated prototypes of new generations of cockpit displays. Researchers at Brunel are playing their part by developing novel phosphors for converting blue light to white light, and engineers at Exxelis are encouraging new designs for display optics. As this project passes its halfway stage the research results are encouraging and it is on track to deliver its primary objectives – a new baseline for cockpit displays and low-cost exterior lighting on aircraft.

Further reading

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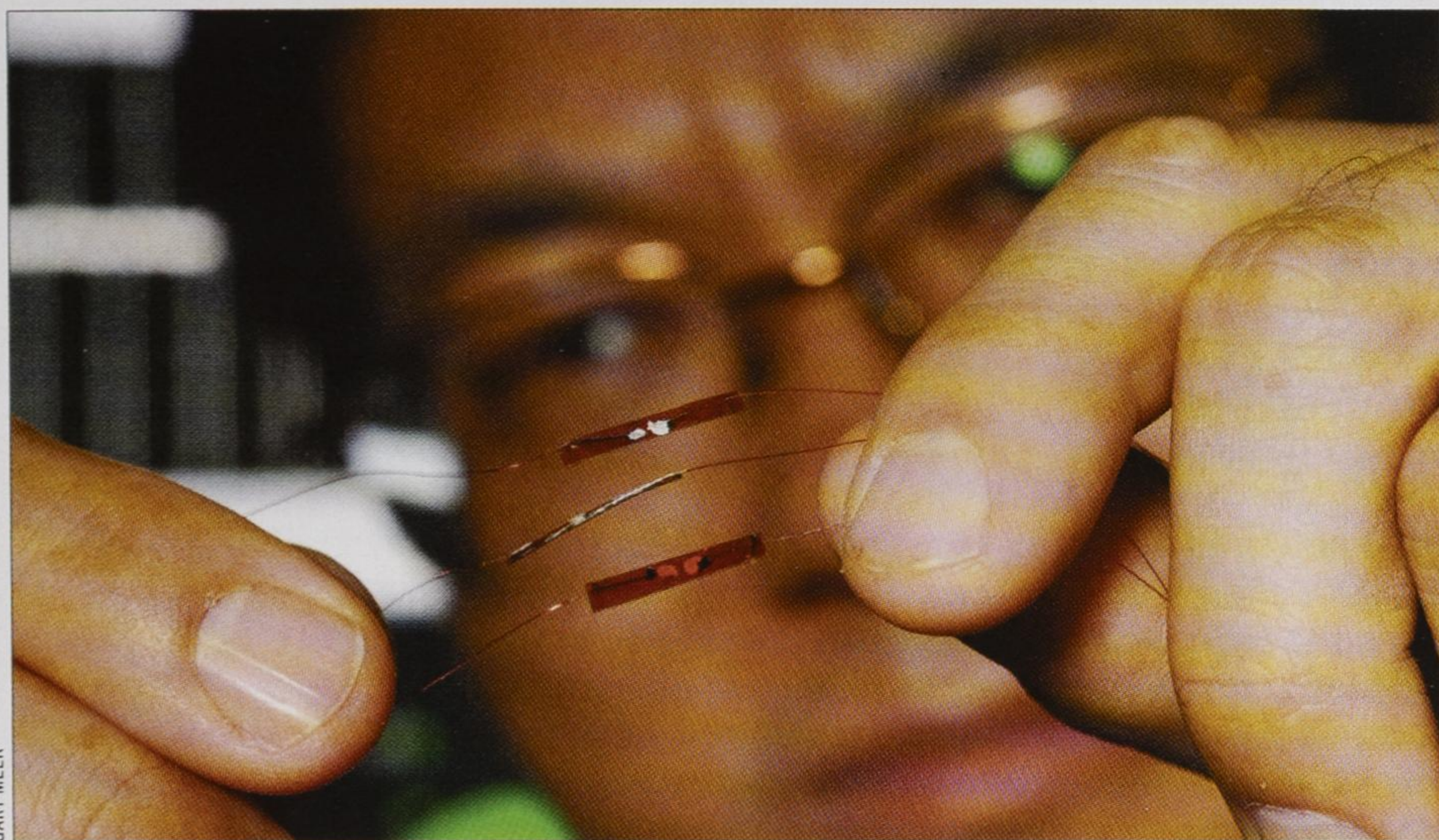


About the authors

Duncan Allsopp (left) is a member of the Optoelectronics Group, University of Bath, UK, and currently a Royal Academy of Engineering/Leverhulme Trust senior research fellow. He has previously worked at Ferranti Electronics and British Telecom Research Laboratories. **Philip Shields** (right) is a research fellow at the University of Bath. He is responsible for laser diode and LED device processing, and has a particular interest in novel device designs.

Exploiting nature's secret stash

Phone-charging shoes? Wireless light switches? Photovoltaics that harness the warmth of radioactive isotopes? Energy harvesting is starting to gain momentum, finds **Jon Cartwright**.



Piezodyne, a spin-out of Zhong Lin Wang's group at the Georgia Institute of Technology, is developing devices that generate electricity from the bending of ZnO nanowires.

We are, by most accounts, a wasteful bunch. If you are sitting in an office, the chances are that most of the energy produced by the heaters is disappearing outside rather than keeping you warm. If you have your computer switched on, it could be frittering four-fifths of its maximum power consumption simply doing nothing. Just by reading to the end of this article you could expend around 100 kJ of energy—though beware that doing anything else will almost certainly be a bigger drain.

Most people rarely acknowledge the energy that is lost to the environment. Rather than chase it, we have opted to generate more. The past 35 years have seen a tripling of world electricity demand, which has predominantly been met through the burning of additional fossil fuels. With less than a 3% contribution to global energy production, those technologies that exploit what is already around us—solar, wind and tidal power, for example—barely feature.

Recently, however, and partly in response to the drive for lower carbon footprints, scientists have started to rethink the possibilities for salvaging wasted energy—what they term “energy harvesting”. They are finding ways to capture the heat lost from buildings, the idle power drain of computers or the motions of the human body, and to convert it into useful, clean electricity. But that is not all: energy harvesting permits devices that are free from a bat-

tery or an external power source. With these restrictions removed, the devices can be placed or moved anywhere, scaled to dimensions smaller than ever and designed to exist without maintenance.

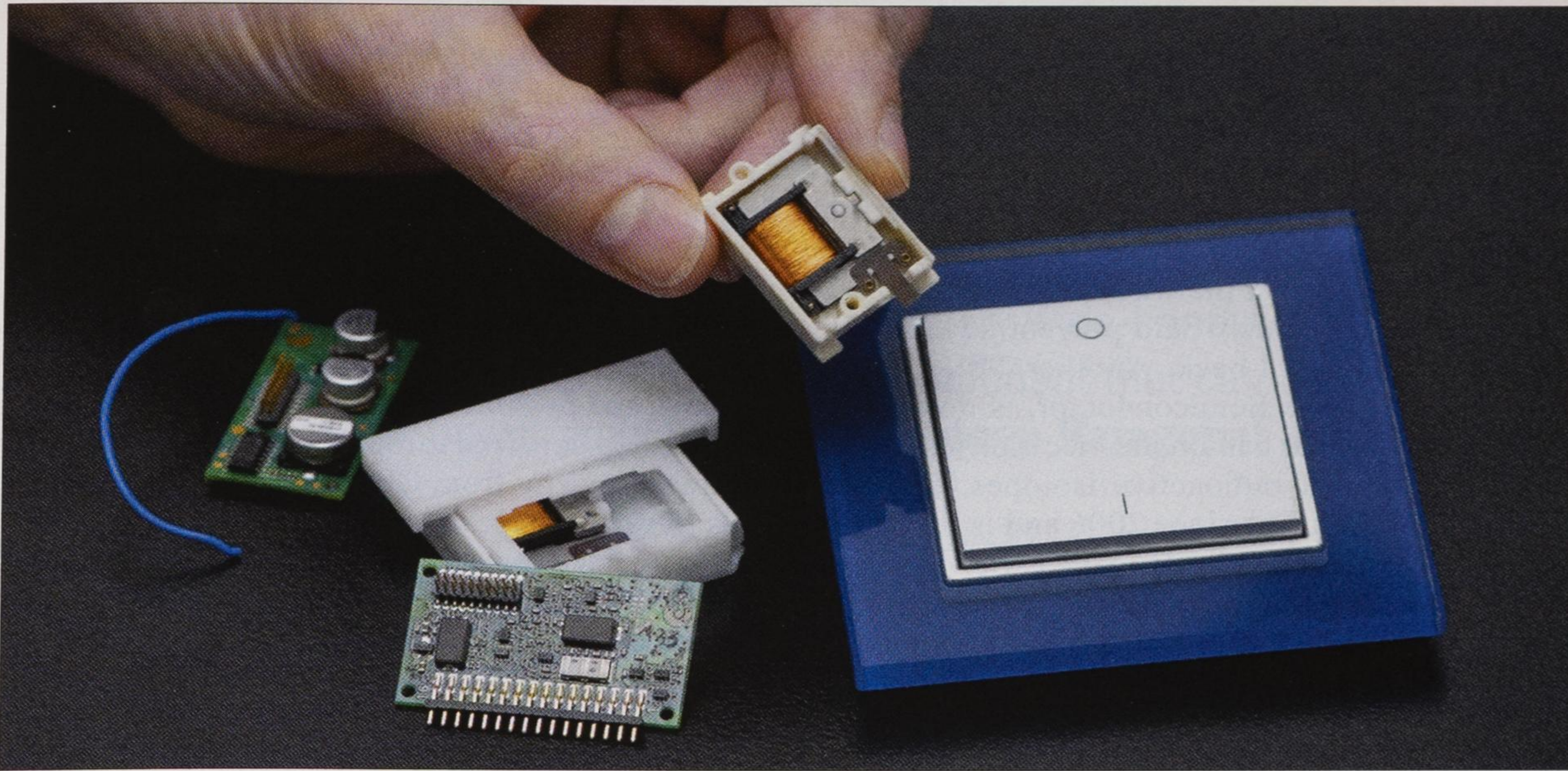
Bending power

Zhong Lin Wang of the Georgia Institute of Technology, GA, focuses on nanoscale devices. He works with ZnO, one of a handful of compound semiconductors that exhibit piezoelectricity—generation of an electric potential when the material is put under stress. In 2000 Wang realized that he could use a vapor-liquid-solid technique to grow ZnO cheaply and simply. His version of the technique involves patterning specks of a catalyst, such as gold, on a substrate. A variety of elaborate ZnO nanowire structures are then created by varying the flow rate and temperature of a ZnO-graphite vapor that impinges on the patterned substrate.

The trick to harvesting energy with ZnO nanowires is to put them in contact with a metal. This creates a Schottky barrier—essentially a diode—which allows electric current to flow in only a single direction. Bending the nanowires in one direction drives charge into the metal; bending the other way means that the charge cannot flow back. Wang calls this current generation process “piezotronics” and he is already developing it for several potential devices via his company, Piezodyne.

Devices that Wang has in mind include nanowire energy harvesters that could be built into the flexible soles of shoes to charge a mobile phone while walking. Or, in a more advanced system, they could be woven into a fabric so that every movement generates electricity. He has been working on this topic for four years: “I believe that in about five years you will see something utilize this technology, in areas like implantable medical devices, mechanical sensors, or powering personal electronics.”

The option to use Wang's piezotronics inside the human body separates them from existing piezoelectric energy harvesters. For example, passengers entering the Yaesu end of Tokyo station over the Christmas period might have noticed a display light-up with 1 mW of power each time a traveller walked through a turnstile. But this gadget, like most other piezoelectric energy harvesters, is based on the ceramic lead-zirconate-titanate (PZT)—a toxic substance. In comparison, ZnO, a standard



Installing new light switches in established buildings normally requires extensive rewiring. However, this can be avoided with self-powered wireless light switches, which have been developed by Siemens spin-off EnOcean.

ingredient in sun cream because of its light-absorbing properties, is benign. "If you use PZT in your body," joked Wang, "you're in trouble."

Taking the heat

Piezoelectrics are not the only energy-harvesting technology to benefit from the nano treatment. Scaling down dimensions can also increase thermoelectricity, the charge flow that results from a heat gradient across a substance, which is most significant in materials that conduct electricity well but heat poorly. In the 1920s researchers found that they could improve thermoelectrics by alloying them with certain metals to introduce defects, which reduce thermal conductivity while maintaining electrical conductivity, but this only took the materials' efficacy so far. Last year, however, a group led by Zhifeng Ren of Boston College, MA, showed that it is possible to boost efficacy by powdering thermoelectrics into nanoparticles.

Ren's group works with the compound semiconductor Bi_2Te_3 , which is the most widely used thermoelectric. Traditionally researchers melt Bi_2Te_3 and then cool it slowly, in such a way that it crystallizes in a preferred direction. Ren's group skips this stage and instead grinds the material into particles 20 nm across before hot-pressing them into ingots. "The whole process is a lot cheaper, a lot faster and uses less energy," said Ren.

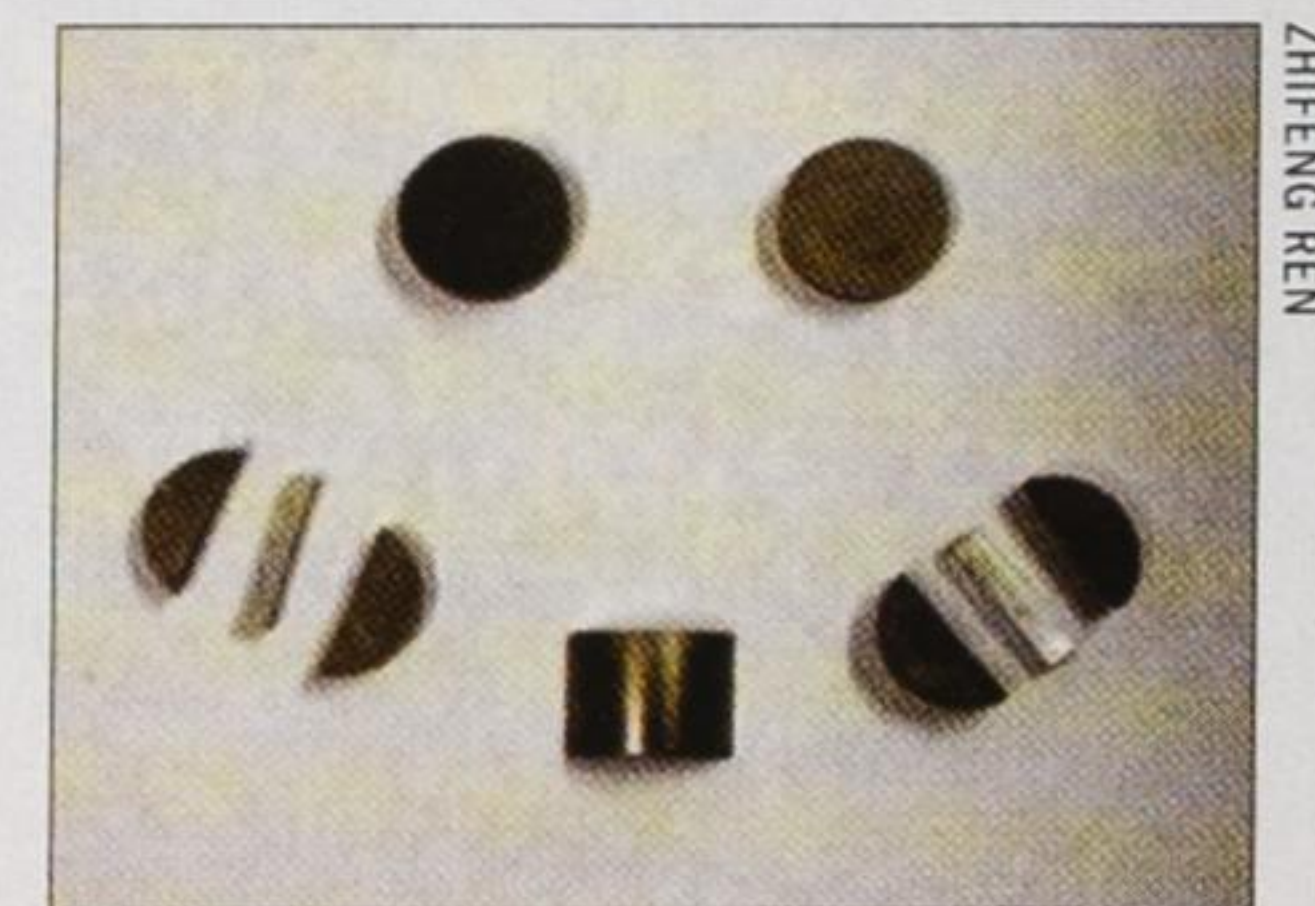
These nanocrystalline ingots have a lower thermal conductivity than single, large crystals. This is because phonons – packets of vibrational energy – scatter at each of the numerous crystal grain boundaries, slowing heat propagation. The result is a peak efficacy of 1.4, some 40% better than researchers had previously achieved. What's more, the peak occurs at 120°C, a higher temperature than other thermoelectrics, which makes this material more valuable for harvesting energy from hot environments.

In fact, almost any hot environment could be

suitable for thermoelectrics: chimneys, steam turbines, computer circuits, the human body, even panels that have been placed outside to warm in the sun. Although it will be later this year before Ren's start-up company, GMZ Energy, produces the first prototypes of its energy harvesters, other firms employing the less-efficient single Bi_2Te_3 crystals have products on the market. Thermo Life, based in the US, manufactures 9 mm diameter thermoelectric devices that can generate up to 100 μW for a 10°C temperature gradient, while Micropelt, based in Germany, is selling sample devices half the size that can generate 1500 μW with the same temperature gradient. For more extreme environments, the Japanese electronics firm Furukawa is developing 5 cm² thermoelectric devices based on skutterudite, a cobalt arsenide mineral, which are claimed to generate 33 W when placed beside a vehicle's 720°C exhaust pipe. "Potential applications are everywhere," said Ren. "And [the technology] is solid-state; there's no moving parts. So the lifetime is long."

The applications of thermoelectrics overlap another heat-exploiting technology – thermophotovoltaics (TPVs). Like conventional photovoltaics, TPVs convert electromagnetic energy into electrical energy, but they differ by focusing on the infrared part of the electromagnetic spectrum. In practice this means that TPVs need another layer in front of the photovoltaic cells, called a thermal emitter, which radiates infrared photons when it gets hot.

Many TPV companies are still in the development stage. Last year, at the end of a three-year project funded by the UK's Technology Strategy Board and the EPSRC (Engineering and Physical Sciences Research Council), a UK consortium led by CIP Technologies announced that it had fabricated a device based on InP – a departure from the usual GaSb – with an efficiency of 12%, breaking the record of 9%. The consortium is now hoping to win more funding to develop a multi-junction version, using InP, which



Ingots of Bi_2Te_3 can generate thermoelectricity. This material's electrical conductivity is much better than its thermal conductivity, and the charge flow can be used to produce electrical power.

has efficiencies as high as 25%. This could be used for collecting stray heat from domestic boilers, furnaces and glass manufacturing plants.

Meanwhile, MTPV Corporation, a start-up based in Boston, MA, believes that it can boost TPV efficiencies to 50% or more by placing the thermal emitter very close to the cell. The goal is to separate these two by less than the wavelength of the infrared light, because this would prevent any photons from being reflected back. Another TPV specialist, US-based Spire Semiconductor, is developing an InGaAs cell that can create electricity from the lasting warmth of radioactive isotopes. The project has been running since 2006 and is backed by \$600,000 of funding from NASA.

For at least one company, energy harvesting is already proving a highly worthwhile venture. Starting in 2001, the Siemens spin-off EnOcean, which is based in Oberhaching, Germany, commercialized a range of self-powered wireless light switches based on PZT piezoelectric technology, and later on dynamo (electromagnetic coil) technology. One of the advantages of such switches is that they can be moved between a building's dividing walls without rewiring, which can cut costs by as much as 80%. In 2005, the famous Semperoper opera house in Dresden commissioned EnOcean to install its lighting because it refused to have cable routes drilled into

its 19th-century Baroque ballroom. The company has already sold more than 50,000 energy harvesting devices, with revenue doubling every year.

Not everyone has a winning story to tell, though. Lewis Fraas founded JX Crystals, a Boeing spin-out, in 1992, which pioneered the idea of generating electricity using TPVs wrapped around flame burners. They netted contracts from NASA, the army and the navy for different GaSb TPV devices. But there were issues integrating the TPVs into effective systems, and by 2001 investment had dried up. Now JX Crystals survives through silicon photovoltaics contracts, mostly from China, and by selling GaSb cells to various research labs across the world.

Fraas thinks that the problem lies with a lack of investment, which is preventing a fall in compound semiconductor manufacturing costs. "It's always an investment, it's not a technology problem," he said. "Investment for scaling up infrared cell supply, or investment in scaling up for lower cost."

It is undeniable that interest in energy harvesting is mounting. An idea that arguably dates back millennia to the invention of the waterwheel, it is only reawakening recently in light of new technology. But it remains to be seen whether any of the nascent ventures will find it too difficult to reap rewards from energy harvesting or whether, like EnOcean, they will find it as easy as switching on a light. ●

About the author

Jon Cartwright is a freelance journalist. He is based in Bristol, UK.

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Nitronex targets military radios

Military and emergency services are looking for very-wide-bandwidth radios with exceptional reliability, minimal weight and low cost. One component that can help to meet these needs is Nitronex's GaN HEMT power amplifier, claim **Pradeep Rajagopal** and **Ray Crampton**.

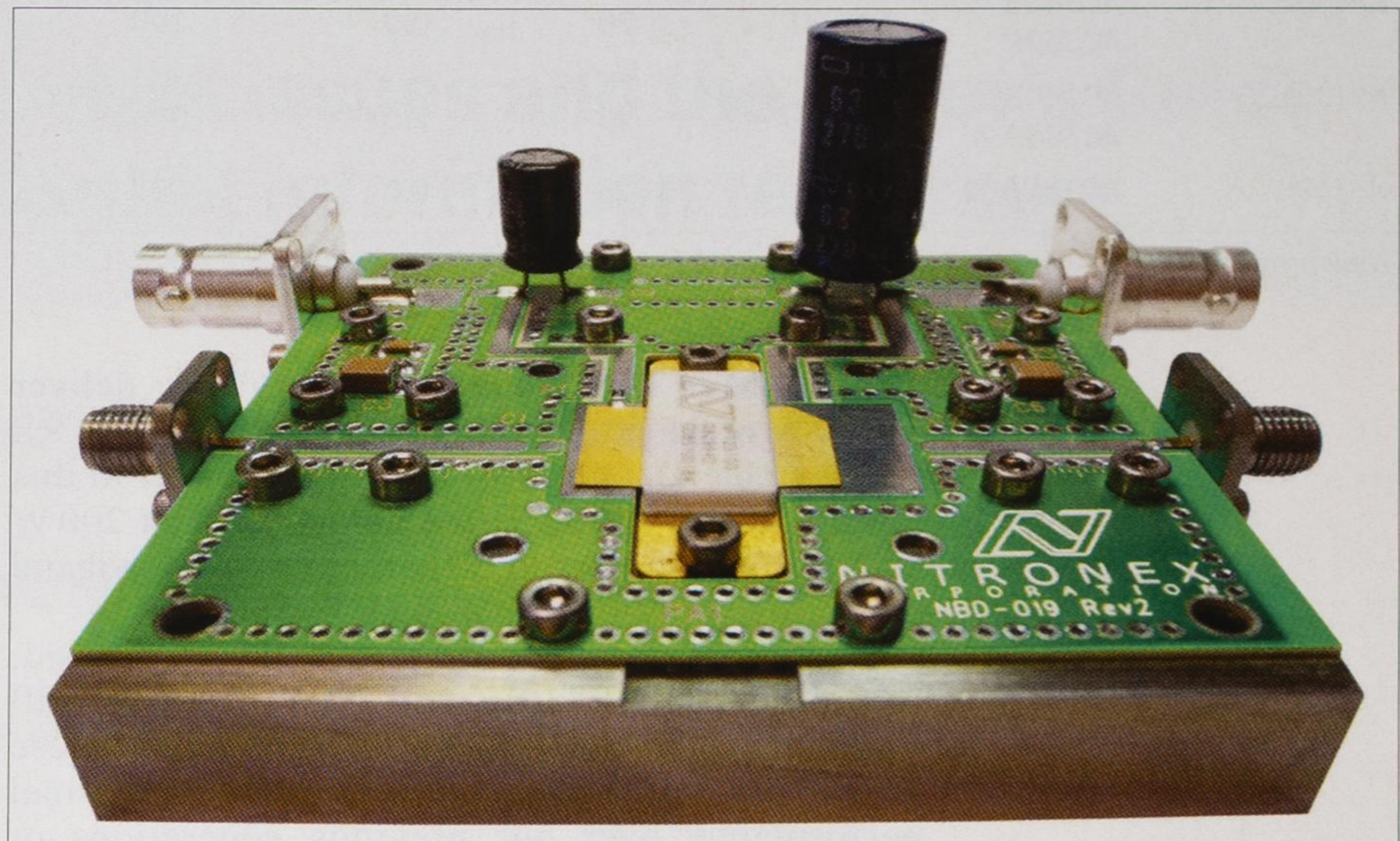
There is a growing demand for communication systems offering an increasingly rich user experience. In the commercial world, it is now the norm to rapidly download massive files via high-speed internet connections. And as smartphone sales extend beyond corporate users, consumers are starting to access high-definition video streaming, music downloading and live webchat via their handsets. Although it is often invisible to the end user, such feats of communication are the culmination of co-ordinated efforts by a multibillion dollar industry that is continually addressing network bottlenecks to improve bandwidth and coverage.

The US Department of Defense (DOD) demands even higher levels of system performance for military communications. In recognition of the needs across the various services, the US government initiated the Joint Tactical Radio Systems Joint Program Executive Office (JTRS JPEO) in 1997. More recently it has developed a vision that it describes as a tactical, mobile wireless global information grid.

Fulfilling this vision will enable all of the DOD and public safety communication systems – such as those used by firefighters and law enforcement agencies – to co-operate seamlessly, while exchanging vast amounts of information in a secure, reliable way. JTRS spans ground, air and space domains, and incorporates the needs of ground troops, mobile units (hummers and tanks), airborne platforms (manned or unmanned, surveillance, logistics and offensive mission objectives), maritime (carriers, cruisers and destroyers), fixed sites (command and control centers) and satellites. The move to JTRS will eliminate existing differences between various platforms, which has led to the diverse family of radios that are in operation today.

The engines of these wireless communication systems are RF PAs. Network performance is reflected in their capability, which is governed by the power transistors that are employed in the transmit chain of the amplifier. We believe that GaN HEMTs fulfill the JTRS requirements.

JTRS-compliant radios have to deliver power amplification across far wider bandwidths than commercial wireless infrastructure. Ultimately, JTRS will cover 2 MHz–2.5 GHz and enable universal software-defined radios. The interim goal,



Nitronex has developed a range of GaN HEMT broadband amplifiers for military and emergency service radios. This includes the NPT25100, the central component in this package, which covers 0.5–2.7 GHz, produces 16.5 dB of gain and delivers a continuous-wave output of 90 W.

however, is for amplification at 30–1000 MHz and 1000–2500 MHz. At the antenna radio, power levels are 5–200 W, so output stages must produce a minimum of double this to compensate for the losses between the final stage and the antenna.

When the operating bandwidth exceeds an octave, trade-offs are needed between the transistor technology and the size and efficiency of the system for a given output power. Wider bandwidth requires an increase in the number of impedance transformation sections, leading to a larger, more complex, and more expensive and lossy overall system.

These trade-offs are based on the inherent properties of the materials that are used in the transistor, so a change in transistor technology is needed to substantially improve system performance. GaN HEMTs, which have a far higher power density than silicon equivalents, provide an immediate advantage to the broadband designer – higher impedances for a given power level. The higher impedance enables a less complex, more compact matching structure, and ultimately a smaller, lighter, more efficient and more capable radio.

We have developed a family of broadband discrete

Table 1. Nitronex's portfolio of GaN power amplifiers

Part number	Package	Band (GHz)	Supply voltage (V)	Test frequency (GHz)	CW output power P_{SAT} (W)	Power gain (dB)	CW drain efficiency at P_{SAT} (%)	Thermal resistance ($^{\circ}\text{C}/\text{W}$)
NPTB00004	PO150S	DC-6.0	28	2.5	5	19.5	55	23
NPT25015	PO150S	DC-3.0	28	2.5	23	14.0	58	6.3
NPT35015	PO150S	3.0-6.0	28	3.5	18	11.0	48	6.3
NPT1012	AC200B	DC-6.0	28	3.0	25	14.0	65	4.0
NPTB00025	AC200B	DC-4.0	28	3.0	25	13.5	65	5.3
NPT1004	PO150S	DC-4.0	28	2.5	40	13.5	55	4.3
NPTB00050	AC360B	DC-4.0	28	3.0	50	11.5	60	3.2
NPT35050A	AC780B-2	3.3-3.8	28	3.5	65	12.5	45	2.0
NPT1010	AC360B AC360P	DC-2.0	28	0.9	100	18.7	65	1.4
NPT25100	AC780B-2 AC780P-2	0.5-2.7	28	2.5	90	16.5	62	1.8
NPT1007	AC780B-4	DC-1.2	28	0.9	200	18.3	63	1.0

New products are shown in bold, preview products are in italic.

GaN HEMTs with these attributes. They deliver 5–200 W of RF power and satisfy the needs of JTRS radios (table 1). Our most powerful product in this family, the NPT1007, is the industry's first 200 W GaN HEMT. It aims to offer maximum broadband power to the designer in a small footprint.

Some new products are also being developed, including the NPT1010 and NPT1012 that will be launched in the first half of this year. These transistors deliver a 20–30% increase in thermal performance over our previous generations of products, which leads to higher broadband power. The improvement stems from the combination of a 50 μm thick GaN die and the latest packaging and die attach technologies, which unite to deliver industry-leading thermal performance for broadband communications. Our customers have already verified power performance over the broadband frequency needed for JTRS radios.

One of the key strengths of GaN HEMTs is their ability to operate at high voltages, such as 48 V. This increases the device's power density, which tends to increase the impedance and lower the output capacitance per unit of output power. Thanks to this benefit, it is possible to simplify the design of high-power broadband amplifiers with a reduced size and improved system efficiency.

We are developing the technology needed to support 48 V operation. This requires new device designs to manage the higher electric fields and dissipated power, so that the transistor's lifetime can be guaranteed to commercial and military standards.

Meeting customer requirements

Not all radios contain a high voltage supply and the lower-power JTRS radios, such as Handhelds and Manpacks that are used by foot soldiers, typically supply lower voltages. This means that they cannot always take advantage of the high voltage capabil-

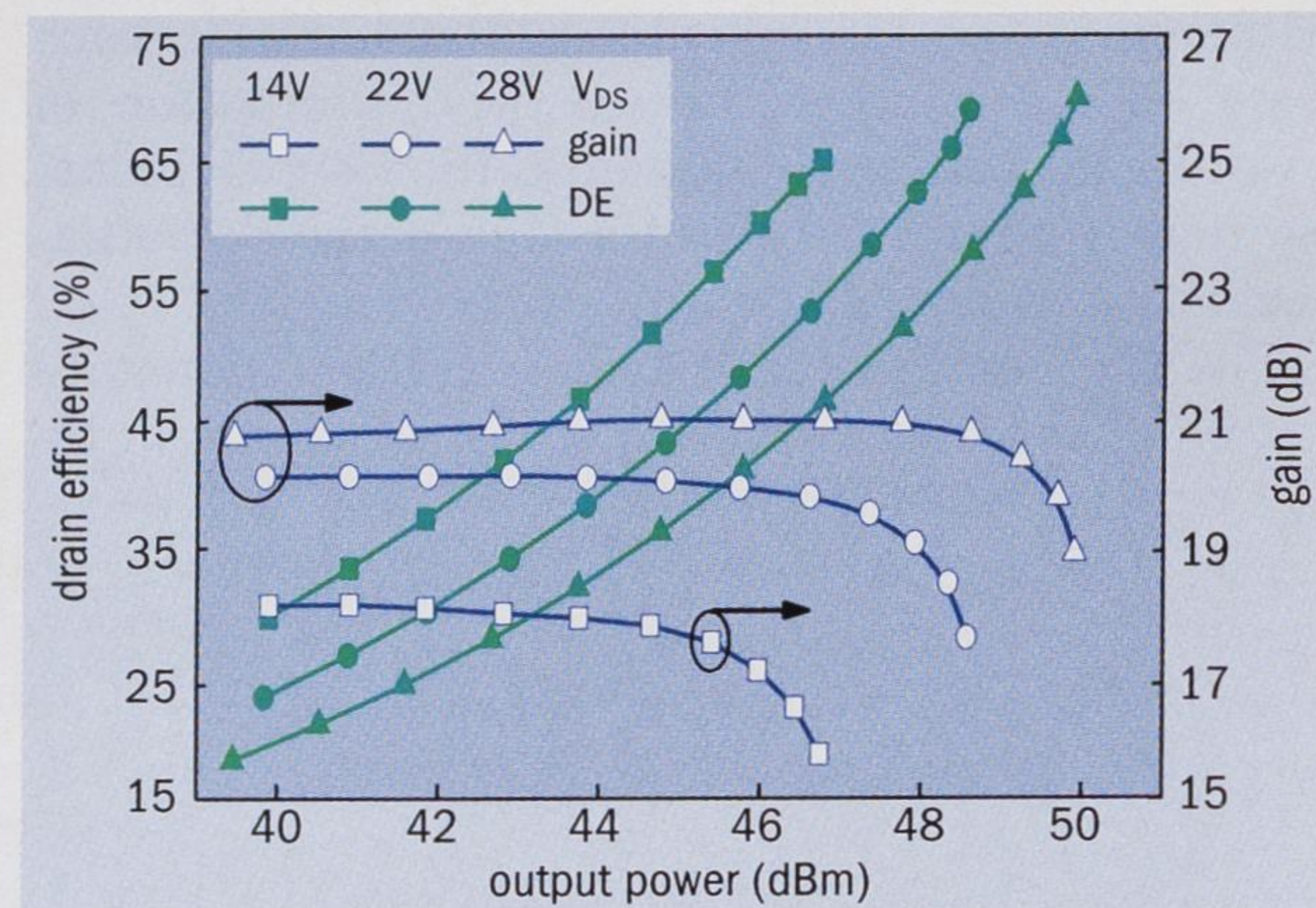
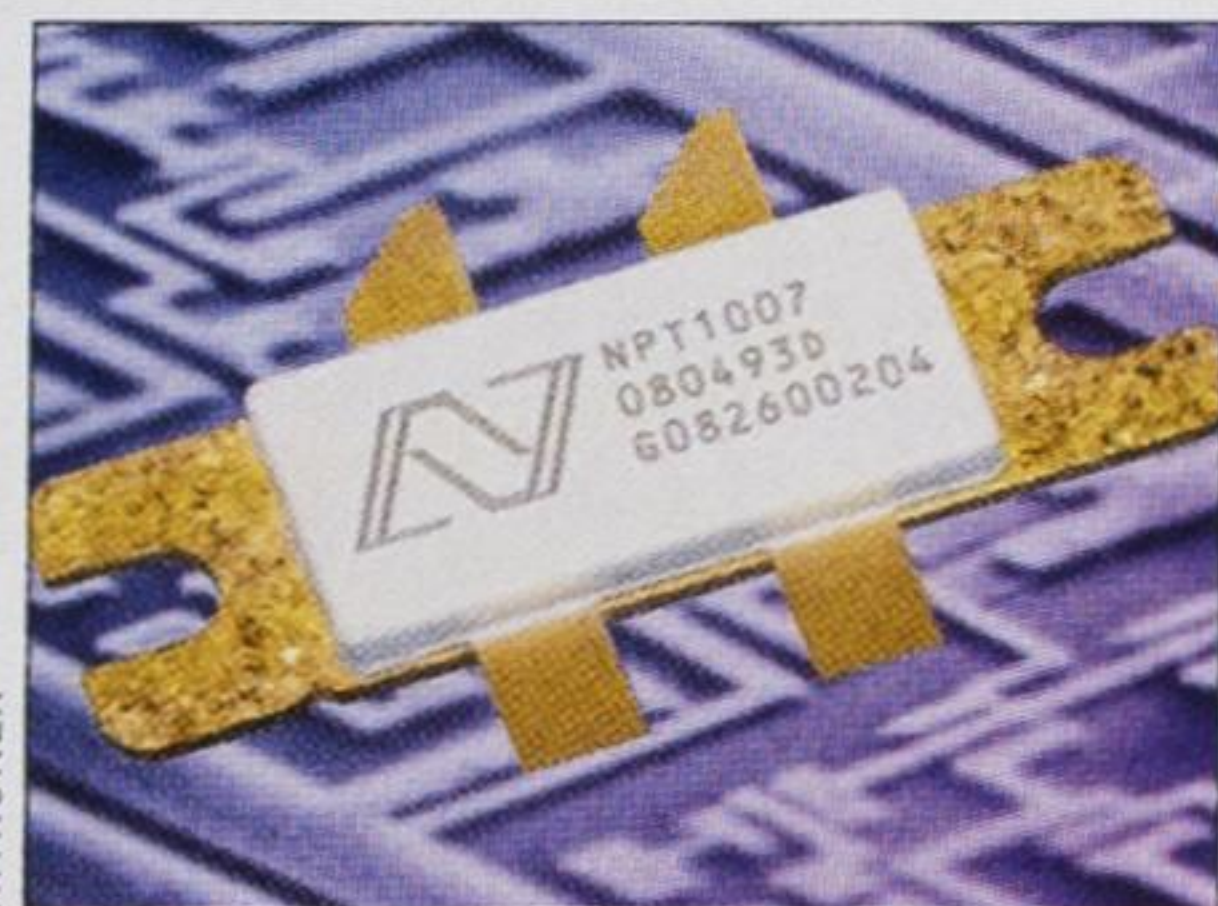


Fig. 1. Nitronex's 14–28 V, 100 W HEMT allows designers to use the drain voltage to maximize power and efficiency at linearity, for a given thermal constraint. This capability is vital to the development of next-generation high-efficiency PAs using envelope tracking (ET) architectures. In ET, the drain voltage is modulated with the envelope power of the input signal such that the GaN HEMT is often operated near saturation. Successful implementation hinges on the underlying transistor technology operating at high efficiency across a wide supply voltage range.

ity of GaN HEMTs. Employing voltage converters to supply higher voltage is not a worthwhile solution either, because this reduces the overall system efficiency. Although there may come a time when higher-power radios on larger platforms can operate GaN HEMTs at 48 V, smaller radios currently use 14–28 V operation, with the exact voltage depending on the individual radio design.

Consequently, it is essential for GaN HEMTs to deliver good performance across a wide range of operating voltages, rather than a great performance at a single voltage. We have addressed this issue with a transistor design that produces high gain and efficiency across the 14–28 V range (figure 1). With this approach, designers can use the drain voltage



The NPT1007, the industry's first 200 W GaN HEMT, is aimed at providing maximum broadband power to the designer in a small footprint. It has the added convenience of a push-pull, four-pin configuration.



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3. Which of the following most closely describes the place where you work?

(tick one box only)

B1 ☐ Semiconductor fab or foundry

B2 ☐ Corporate semiconductor research center

B3 ☐ Academic/government semiconductor research center

B4 ☐ Epiwafer supplier

B5 ☐ Manufacturer of systems/components using compound semiconductor devices

B6 ☐ Semiconductor equipment or semiconductor materials company

B7 ☐ Finance or investment firm or market research/analysis

B10 ☐ Fabless chip supplier/developer

B9 ☐ Other (please specify) _____

4. What semiconductor materials/processes are used/developed at the place where you work? (tick all that apply)

C1 ☐ III-Vs: arsenides

C2 ☐ III-Vs: phosphides

C3 ☐ III-Vs: nitrides

C4 ☐ III-Vs: antimonides

C5 ☐ II-VIs

C6 ☐ SiC

C7 ☐ SiGe, SOI, epitaxial oxides, other silicon heterostructures

C8 ☐ Other (please specify) _____

5. What types of semiconductor device are manufactured or developed at the place where you work? (tick all that apply)

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D2 ☐ InP ICs or discretes

D3 ☐ Wide bandgap ICs or discretes

D4 ☐ Devices employing SiGe, SOI or other silicon heterostructures

D5 ☐ Telecom laser diodes

D6 ☐ Non-telecom laser diodes

D7 ☐ VCSELs

D8 ☐ LEDs

D9 ☐ Solar cells

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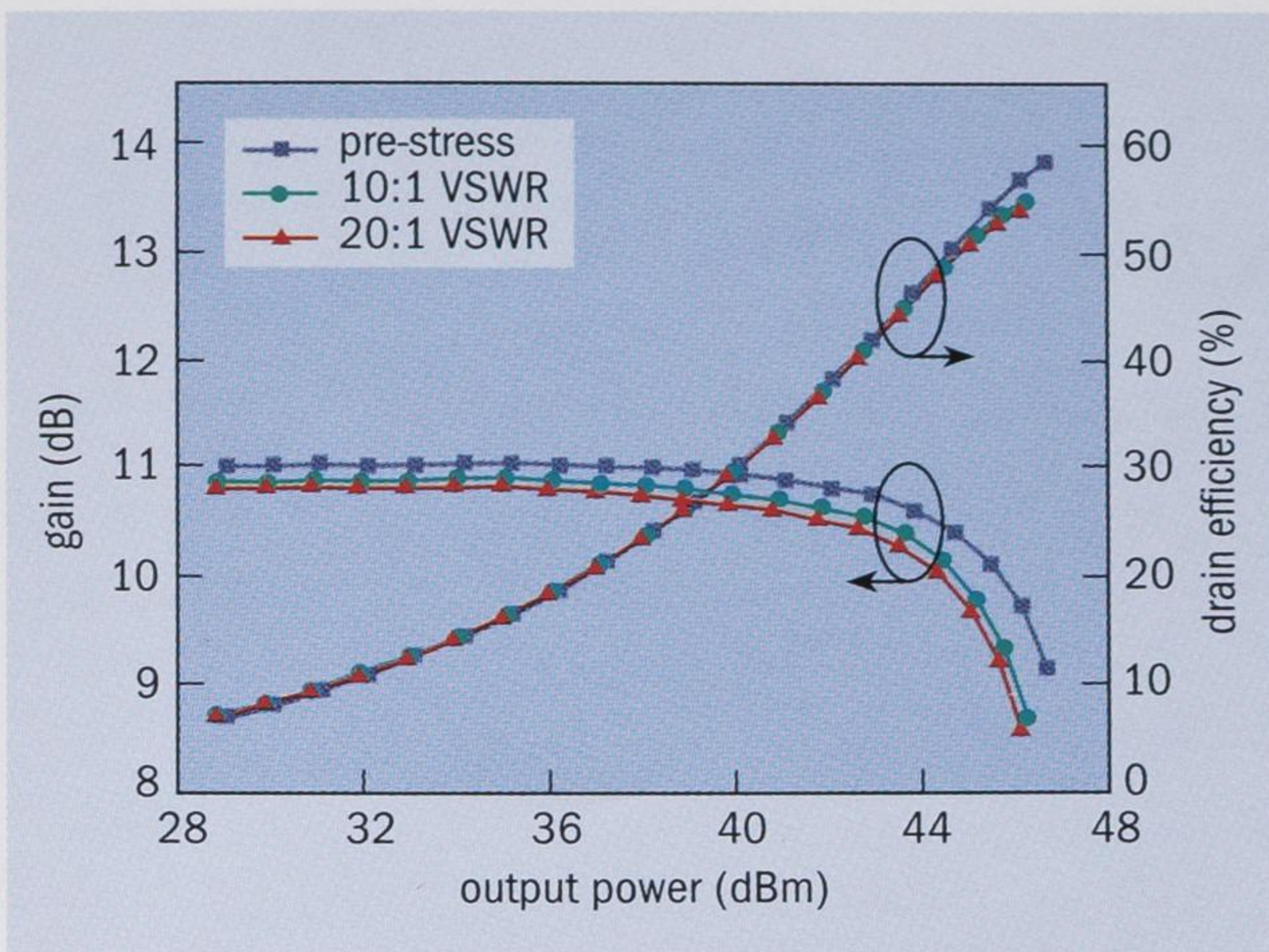


Fig. 2. Nitronex's GaN HEMTs can withstand the high-voltage standing wave ratios (VSWRs) that military radios are subjected to. Continuous-wave power sweeps of a typical NPTB000050 transistor show little degradation after exposure to a 20:1 VSWR.

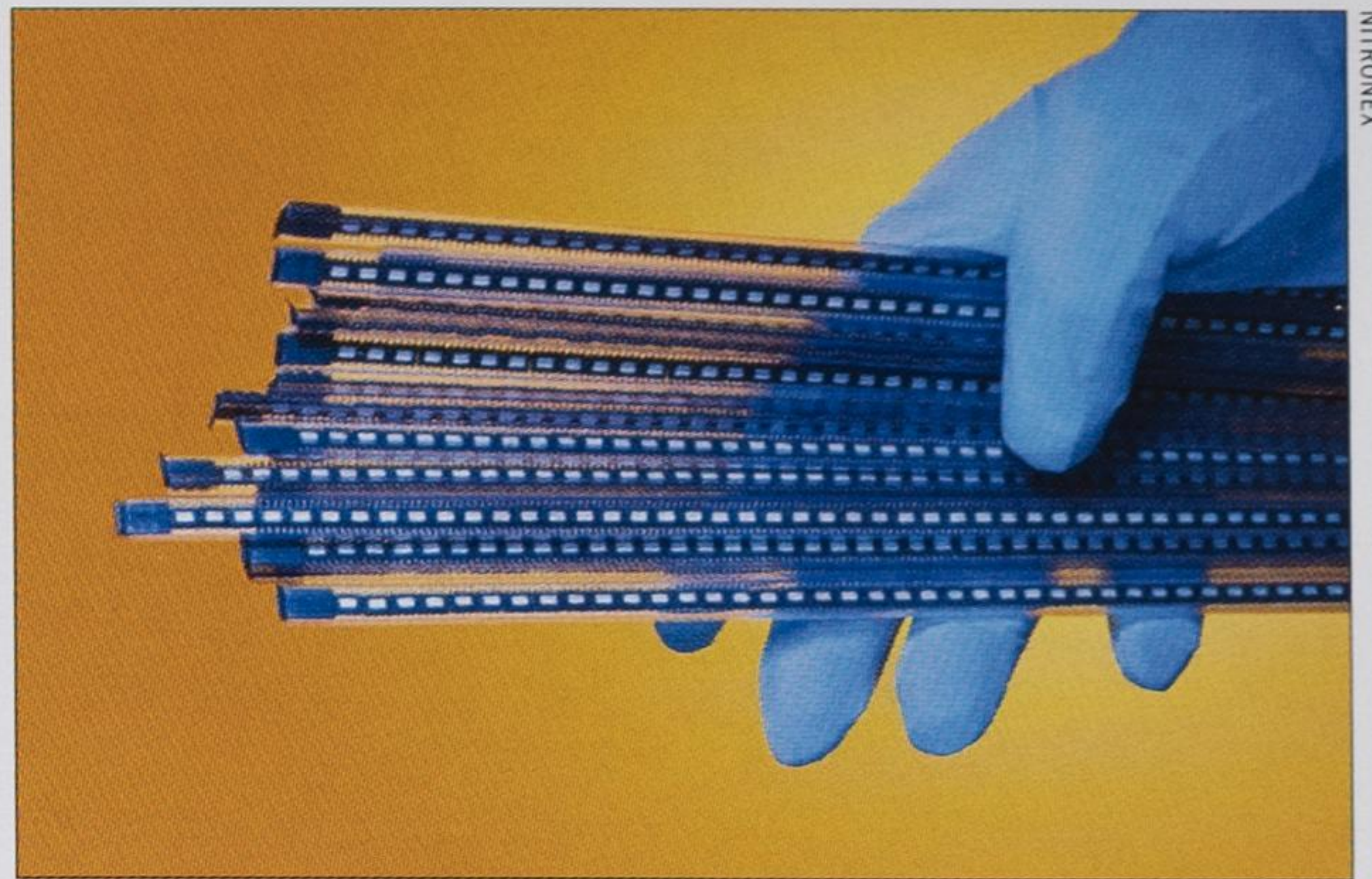
as a variable to meet their system's unique needs, and maximize power and efficiency at linearity for a given thermal constraint.

Ruggedness is another key requirement for next-generation military tactical radios, which are often subjected to high-voltage standing wave ratio (VSWR) conditions. This can occur when a radio is turned on without the antenna connected or, in an extreme case, when an antenna attached to a vehicle is damaged in combat while the radio is transmitting. Such events create an infinite VSWR condition and the radio, and hence the transistors, have to survive without catastrophic failure.

GaN HEMTs have a far higher breakdown voltage than silicon LDMOS devices, and radios built with the wide-bandgap semiconductor are far less likely to fail under harsh voltage conditions at a stable operating temperature. Our devices are designed to be immune from catastrophic failure at high VSWR ratios and tests show that they can survive with minimal performance change when subjected to a 10:1 VSWR at the 3 dB compression point with the package flange at 90°C.

In addition to the requirements for power and efficiency over bandwidth, inherent ruggedness, and a small footprint coupled to low weight, the DOD has started to push for lower costs. We are well positioned to meet the goal for long-term cost reduction by driving down costs associated with development, production and operation through improvements in system efficiencies and lifetimes.

Designers and business managers generally want more than just performance guarantees before fully adopting a new semiconductor technology – reliability, for example, must be proved before a designer will be willing to initiate a design effort. To address this particular issue, our products are subjected to a series of stress tests as part of the qualification process. JEDEC and MIL standards, in combination with customer input, are used to define the tests and conditions. Unlike every other GaN HEMT manu-



Low-cost plastic packages can also be used to house Nitronex's broadband driver devices in the 5–45 W range.

facturer, we perform a full qualification of GaN HEMT products and share our results in the public domain – they are available on our website.

Our ability to perform high-quality manufacturing and product qualification stems from the development of a process to manufacture GaN HEMTs on a high-quality 100 mm silicon platform. We have produced 15,000 GaN HEMT wafers on our 100 mm line, which is a sufficiently high volume to provide statistically significant sample sizes. The large number of growth runs has also helped to reduce development costs and improve product quality.

Other potential concerns for business managers include the health of the supply chain, long-term costs, redundancy in capacity and customer service. Many GaN HEMT manufacturers produce their devices on SiC, which means that they are dependent on a couple of suppliers of high-resistivity SiC substrates. By working with 100 mm silicon since 2002 we have avoided this issue, while benefiting from numerous substrate vendors, thanks to the use of a common platform.

Looking in both directions

We have just passed our 10-year milestone, and during this first decade our company has devoted a great deal of effort to systematically solving problems in epitaxy, fabrication, device design, reliability and product development. We have now reached the position where GaN HEMTs can fulfill their promised benefits to wideband power amplifier designers. A new generation of products will be released shortly, satisfying our customer's demand for significantly improved thermal performance.

We believe that the focus of attention will soon switch from the performance of the GaN HEMTs to the capability of the systems in which they are deployed. These systems could be serving soldiers in battle in the hot, dusty deserts of Iraq and Afghanistan, assisting unmanned airborne vehicles transmitting videos back to a control center or aiding a firefighter trying to communicate with armed services while dealing with the aftermath of a natural disaster. GaN HEMTs will contribute massively to the efforts of all of our services.



About the authors

Pradeep Rajagopal (left) has worked for Nitronex for 10 years and currently has a role in strategic marketing. He has an MS in materials science and engineering from NCSU. **Ray Crampton** (right) is Nitronex's director of marketing. He has previously held the positions of strategic marketing and systems engineering manager at Texas Instruments, and prior to that he worked for Sirenza Microdevices.



INFRARED IMAGERS

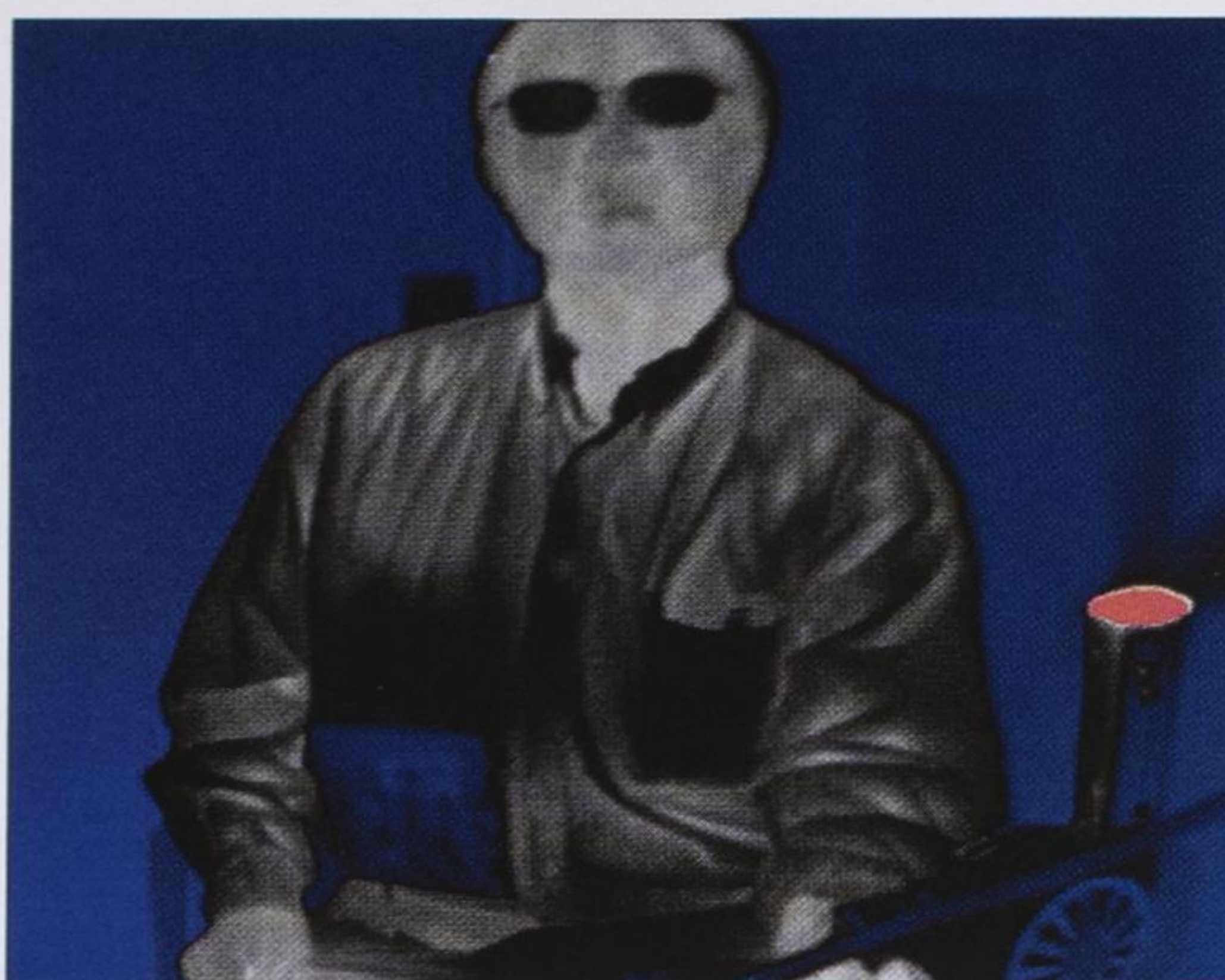
Thinner dots boost detector sensitivity

Although quantum-well infrared photodetectors (QWIPs) have better spatial uniformity and temporal stability than their more expensive mercury cadmium telluride-based rivals, they suffer from low sensitivity to incoming light at normal incidence.

But this weakness can be addressed by replacing the quantum wells with sub-monolayer quantum dots (SML QDs), according to researchers from the Jet Propulsion Laboratory (JPL), start-up firm Infravision Systems and the University of Illinois at Urbana-Champaign.

This US team has fabricated a range of SML QDIPs that have a peak response between 7 and 10 μm , and normal-incidence to 45° responsivity ratios of up to 44%, which is four times higher than those associated with conventional QWIPs.

However, the researchers point out that their devices are far from optimized, because the inclined-incidence responsivity is still far stronger than that of normal-incidence.



The sub-monolayer quantum-dot infrared photodetector reveals a plate hidden beneath the shirt. The plate blocks heat flow and appears blue.

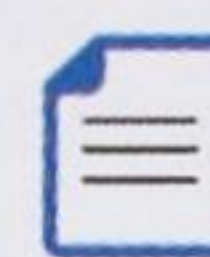
Ideally, QDIPs would have a dominant normal-incidence response from the strong ground to first excited state transition.

Efforts have been motivated by a desire to improve on the performance of QDIPs

with Stranski-Krastanov QDs. “The standard Stranski-Krastanov QD wastes 40% of the InAs deposited on forming the wetting layer,” said JPL’s David Ting, “[but] the sub-monolayer QD puts all of the InAs deposited into formatting 3D nanostructures.”

Using less InAs to form each QD reduces the strain in the epistructure and could lead to fabrication of higher-sensitivity detectors with more layers.

The US team has produced a range of SML QDIP structures on GaAs substrates. These feature 30 or 40 GaAs quantum wells, each containing two symmetrically placed SML QD layers. A 1024 × 1024 pixel detector with a 19.5 μm pitch has been fabricated from the 40 QW structure. This has a reflection grating to boost photoresponse and can produce clear infrared images up to 80 K.



Journal reference

D Ting et al. 2009 *Appl. Phys. Lett.* **94** 111107.

LEDs

ZnO combats droop

The addition of a p-type ZnO layer to GaN LEDs can reduce droop – the decline in device efficiency at higher drive current densities – according to researchers at the University of Missouri-Columbia and ZnO specialist MOXtronics.

Light output at high drive currents increased by up to 40% compared with control devices when a 200 nm thick arsenic-doped ZnO layer was deposited onto commercially available blue GaN LED epiwafers.

MOXtronics CEO Henry White explains that the research was driven by a hypothesis that droop is caused by electron overflow.

Adding a p-type ZnO layer with a hole concentration an order of magnitude higher than p-type GaN can stem this flow, thanks to increased radiative recombination in the active region.

“We also examined whether the enhancement might be due to better current spreading or improved light extraction, and concluded that the enhancement that we were observing was not due to these factors,” said White.

P-type ZnO was grown on 450–455 nm LED epiwafers produced by several commercial vendors. These *c*-plane structures had been deposited on patterned and non-patterned substrates.

Hybrid beam deposition was used to add the ZnO layer. This technique is comparable

to MBE, but employs a ZnO plasma source, which is produced by illuminating a polycrystalline ZnO target with either a pulsed laser or an electron beam, and a high-pressure oxygen plasma created by a radio-frequency oxygen generator. “Considerable effort was required to determine optimal growth and layer conditions,” admitted White.

Epiwafers were processed into 1 mm × 1 mm chips, with an indium tin oxide layer providing the transparent p-type contact. These devices showed no increase in forward voltage compared with a control sample.



Journal reference

BJ Kim et al. 2009 *Appl. Phys. Lett.* **94** 103506.

TELECOMS

Metamorphic laser hits 10 Gbit/s modulation

NTT researchers claim to have produced the first direct modulation from a 1.3 μm laser grown on a GaAs substrate.

The 200 μm long device operates at 10 Gbit/s and temperatures of up to 85 °C, and promises to provide a low-cost, uncooled source for optical networks.

InP-based lasers are the incumbent technology for these networks, but are hampered

by carrier overflow from the active region at high temperatures. Both metamorphic and dilute nitride lasers that are grown on GaAs substrates address this weakness, but the latter suffers from nitrogen-induced defects, says NTT’s Masakazu Arai. “The advantages of our laser are good crystal quality and good mass producibility using MOCVD.”

The epitaxial structure of NTT’s device comprised a 1.6 μm thick $\text{In}_{0.12}\text{Ga}_{0.88}\text{As}$ buffer, a 100 nm thick $\text{In}_{0.1}\text{Ga}_{0.9}\text{As}$ layer, a laser structure featuring n-type InAlGaAs and p-InGaP cladding layers and an InGaAs double-quantum-well active region.

Selective wet etching produced a ridge laser with multimode emission that peaked at 1.26 μm . Spanning the 1.3 μm range used in telecom networks will require a shift in the device’s output wavelength and Arai says that this can be realized through an increase in the indium content of the buffer.

Other targets for future work include reliability studies, efforts to reduce electrical resistance and a switch to DFB structures that offer longitudinal mode control.



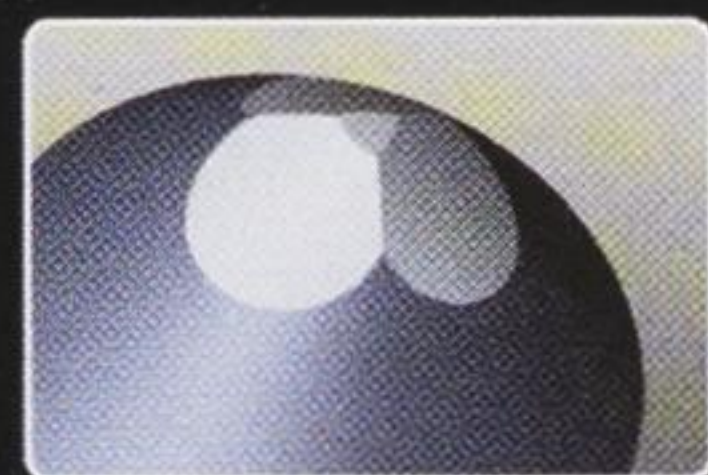
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M Arai et al. 2009 *Electron. Lett.* **45** 359.

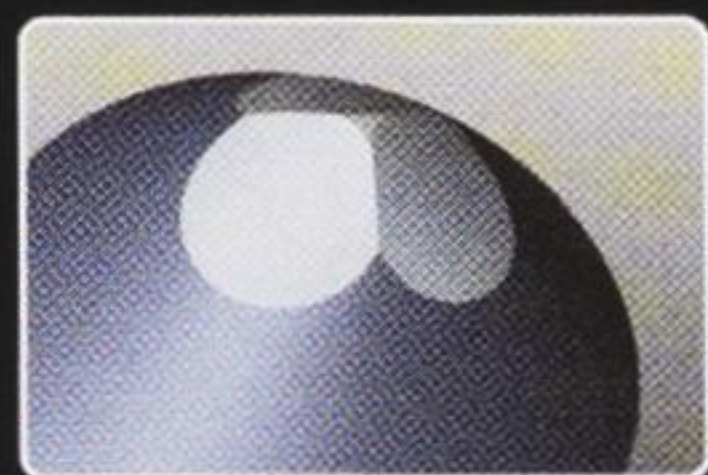


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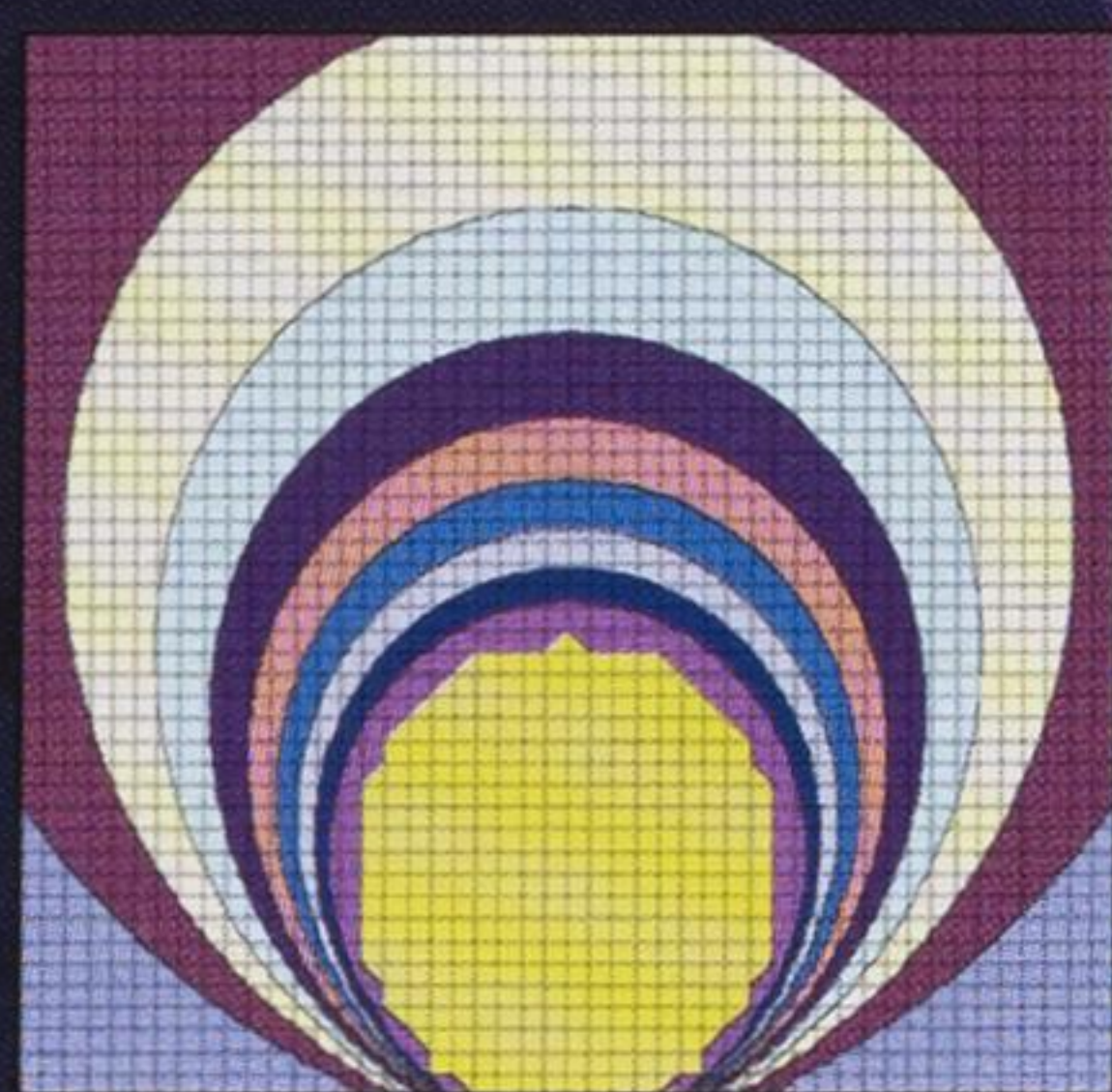
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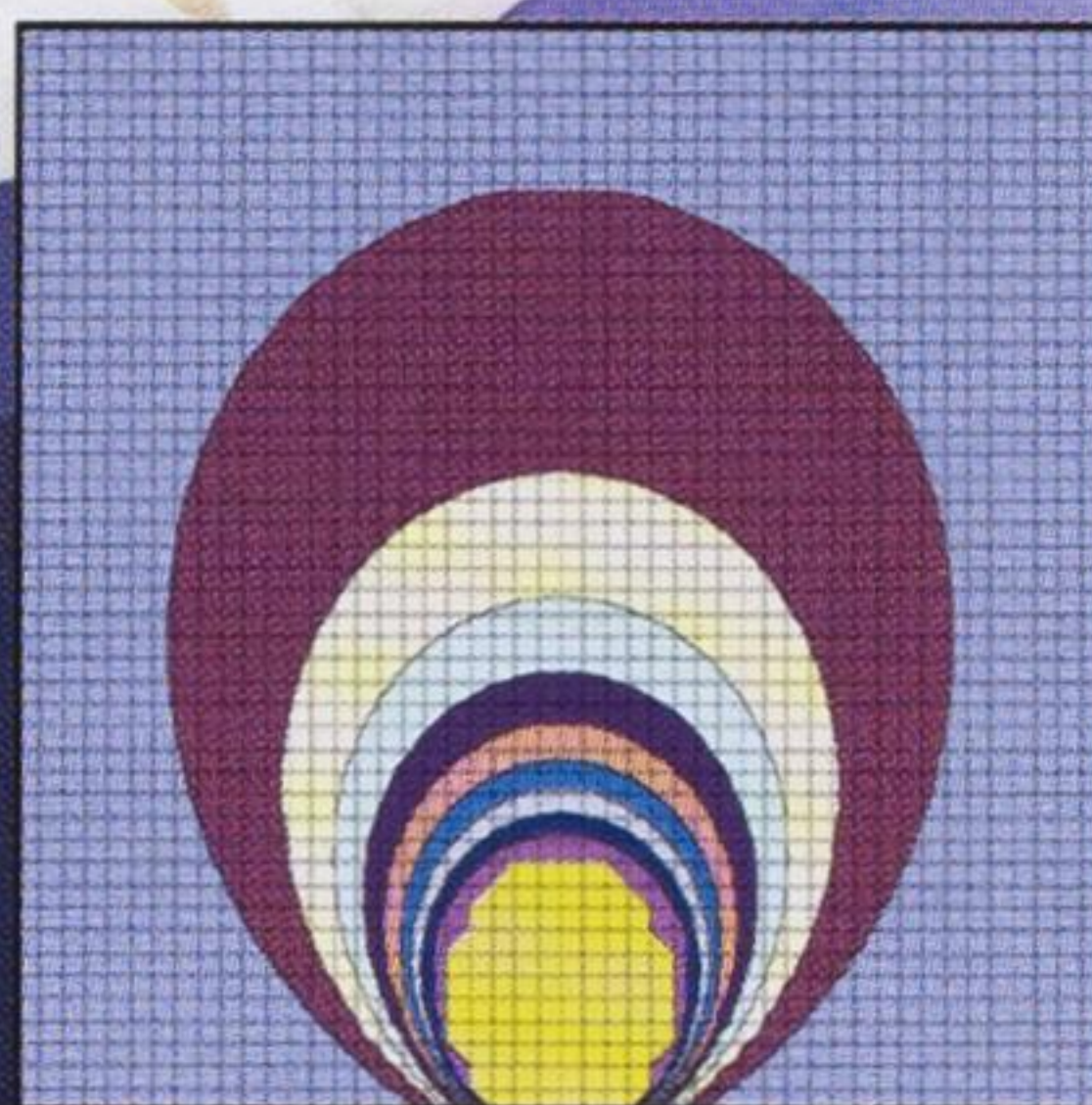
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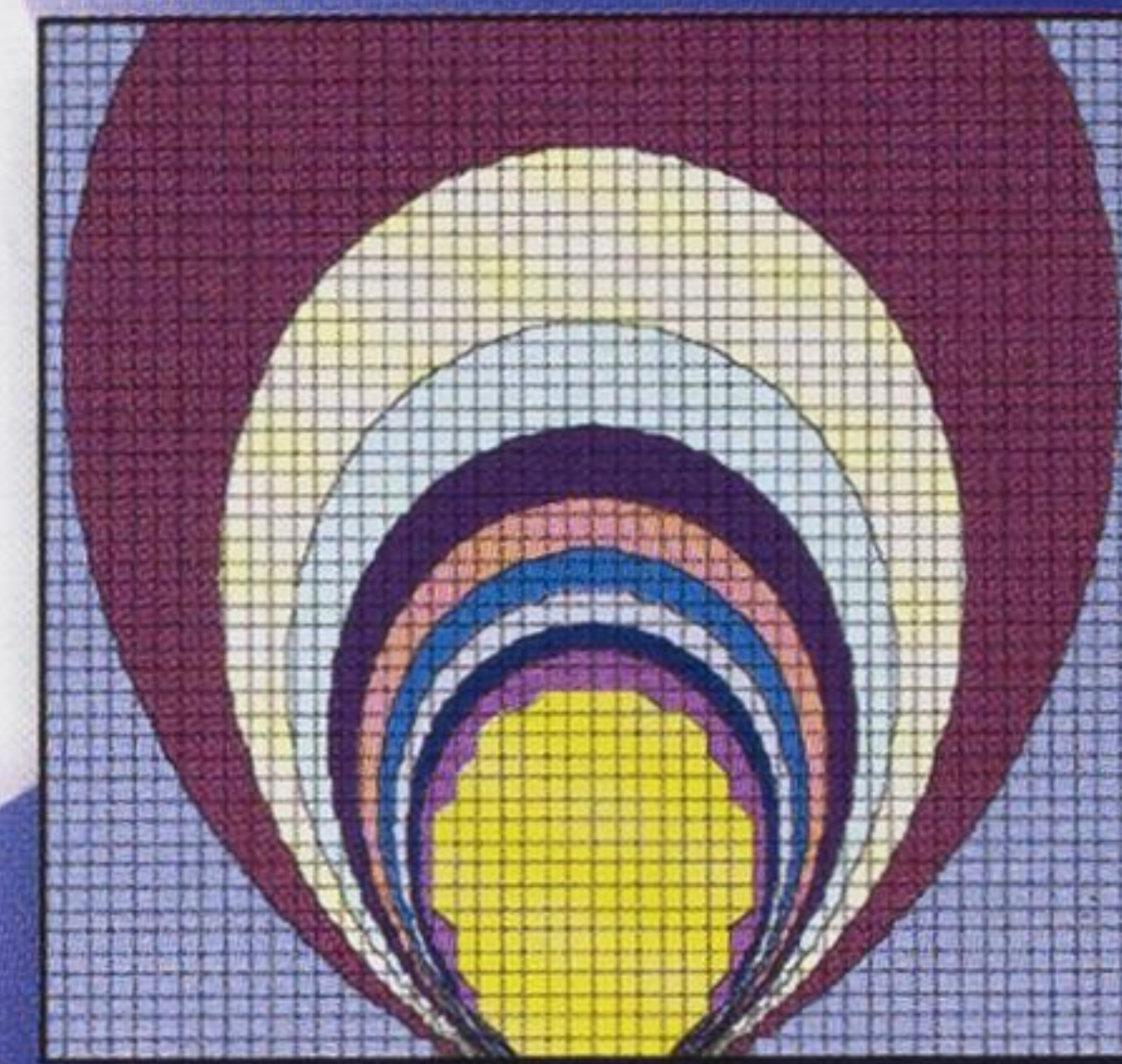
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