

COMPOUND SEMICONDUCTOR

January/February 2007 Volume 13 Number 1

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Printing nitride nanostructures

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Forever diamond?

Both LEDs and power
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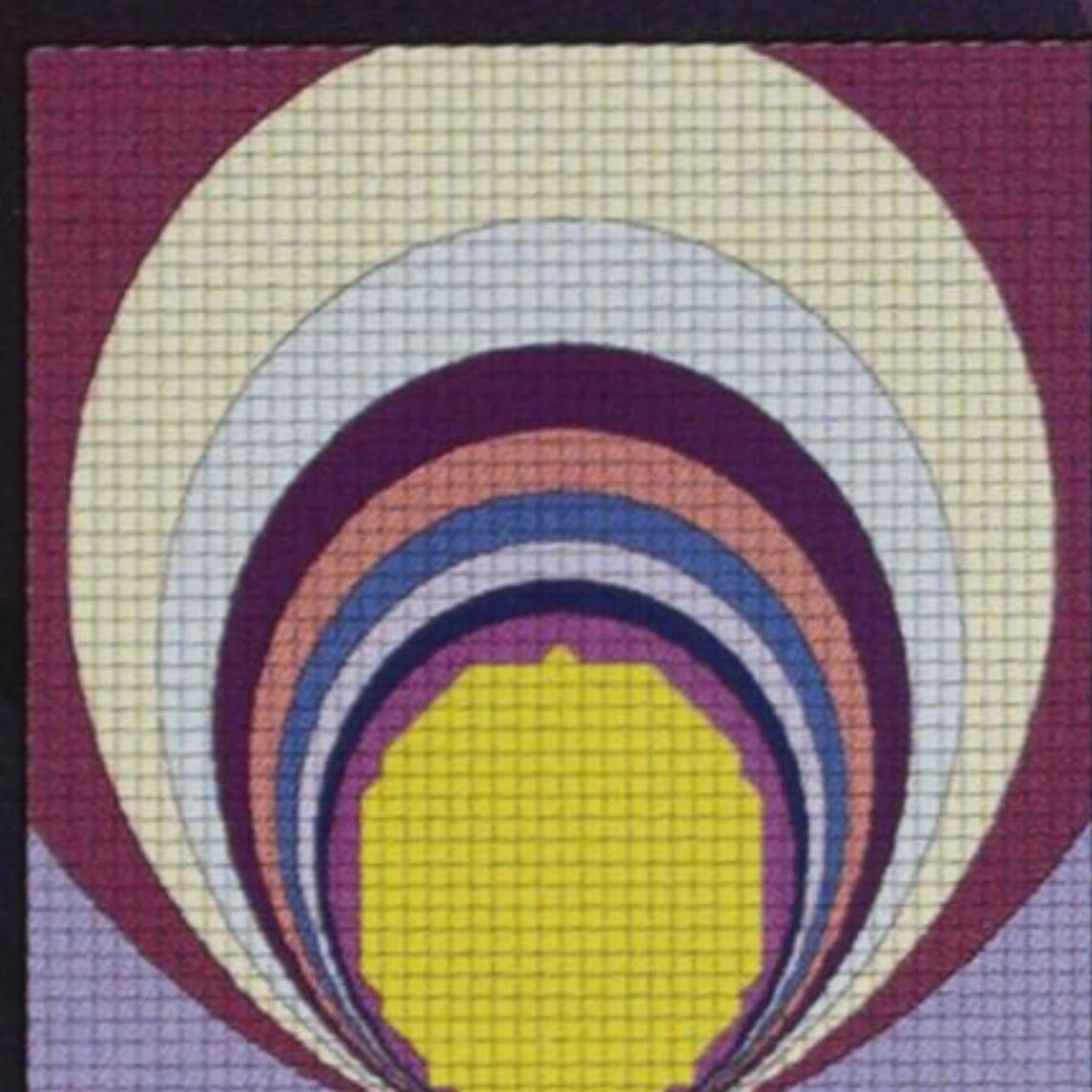
INTERVIEW



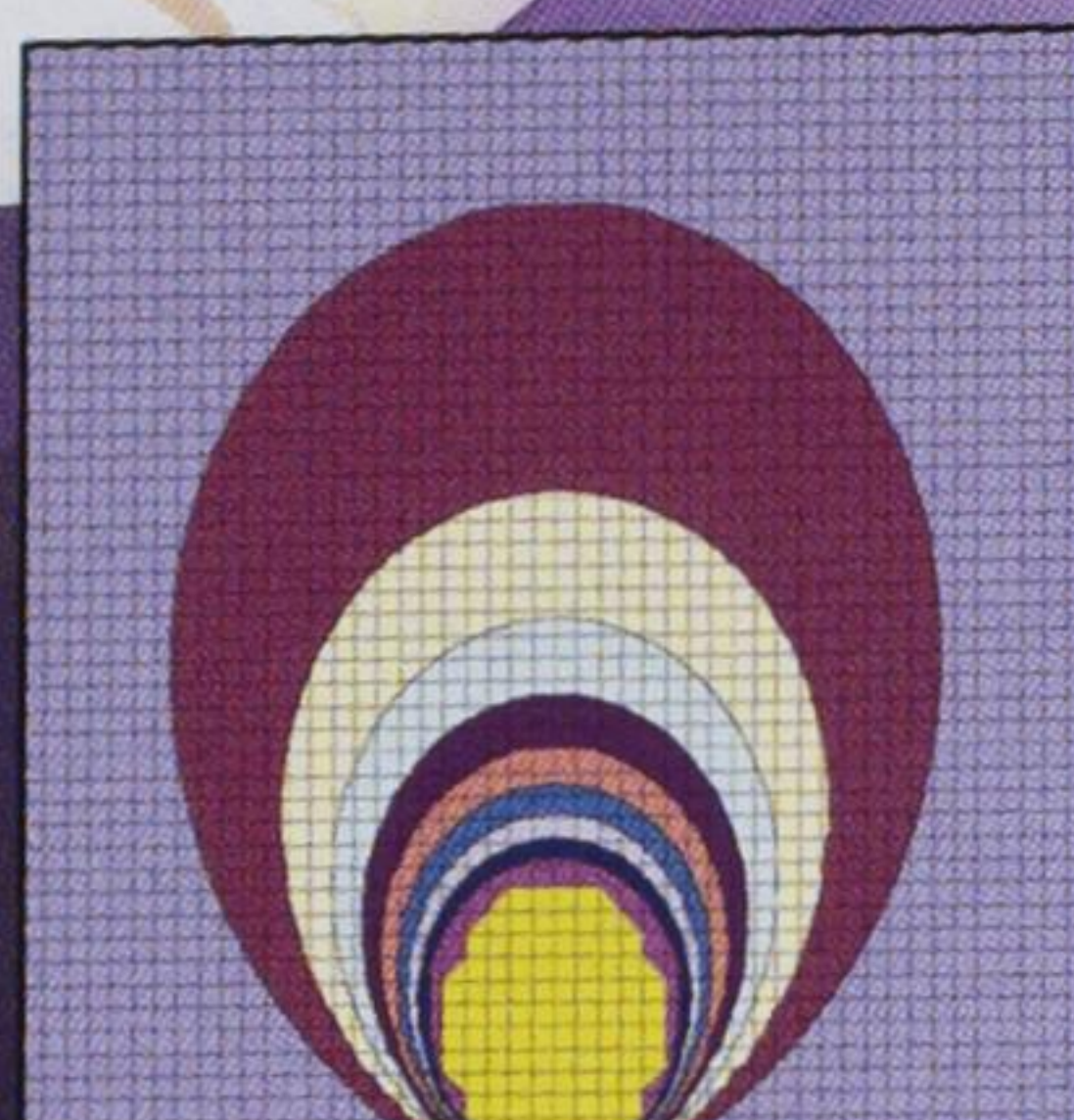
Free radical

How do GaN light emitters
really work? Cambridge
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Humphreys has
developed a theory. **p14**

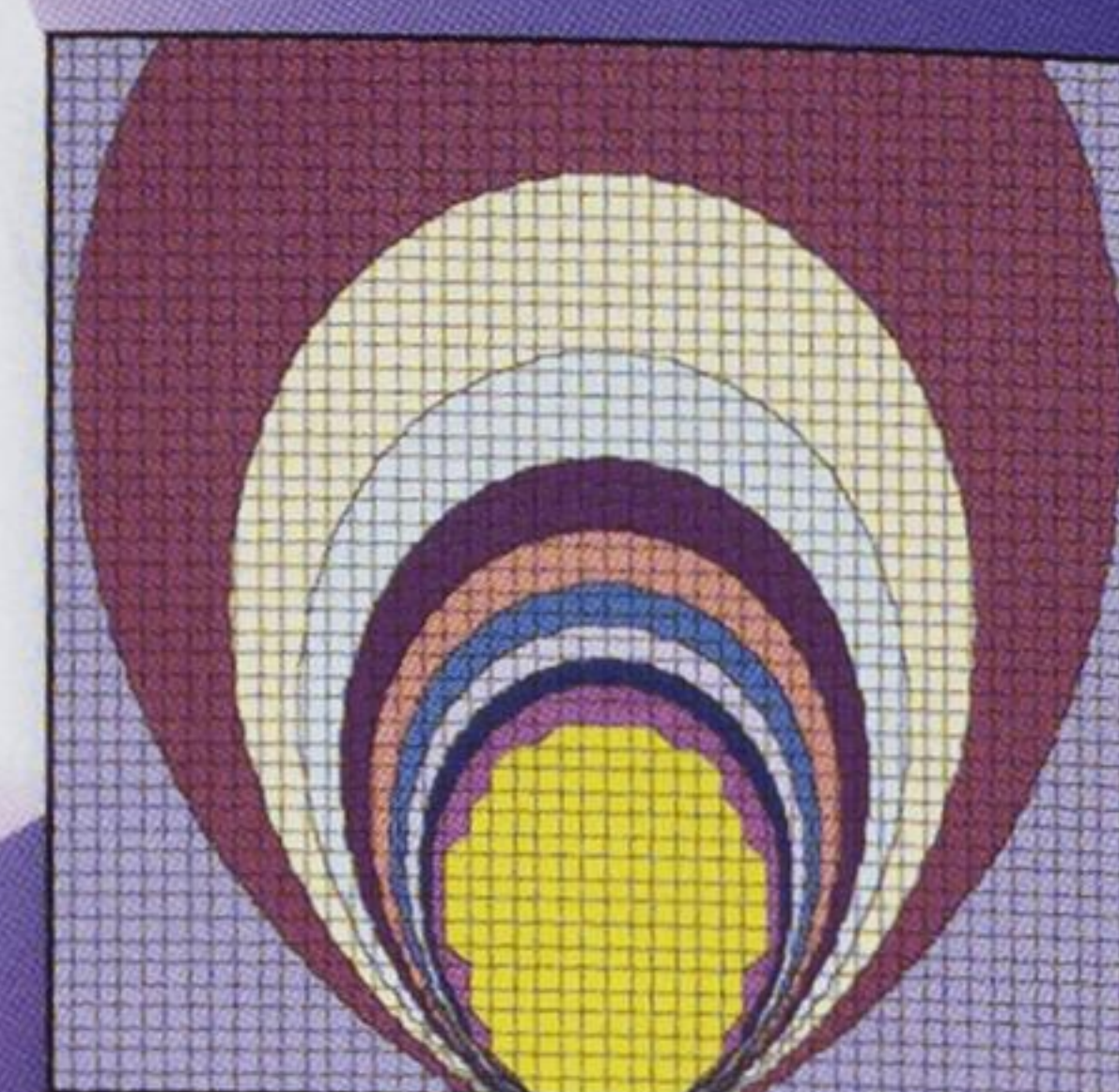
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Nichia says that deep-ultraviolet LEDs are not yet powerful enough to be commercially viable. **p10**

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Good investment

Colin Humphreys talks about promoting and investing in solid-state lighting as part of a national program for energy saving. **p15**

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European researchers are developing high-frequency transistors based on a variety of radical technologies to power security-camera systems, probe distant galaxies and boost computer performance. Richard Stevenson investigates.

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Already the darling of venture capitalists, the solar energy market has now attracted the attentions of the semiconductor community's biggest equipment supplier. Michael Hatcher finds out exactly where the opportunity for compound semiconductors lies in a sector that is virtually monopolized by silicon.



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Equipment vendors are identifying major opportunities in village and grid-connected utility-scale deployments for III-V solar technology. **p20**

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Limited lifetime

Wireless products have a lifetime of just a few years, so swift launches are vital – by using software that speeds up the design process, improvements can be made. **p25**

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- 32** **Research Review:** Printing technique integrates materials...Dashes beat dots for high-power laser...AlN stretches out photodetection range.

Main cover image: GaN, silicon and carbon nanostructures are combined on a single substrate with a stamping method developed by US researchers. See **p32**.

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EDITORIAL

Where's Europe's lighting strategy?



The most efficient way to convert electrical energy into useful light is, as we know, to use semiconductor diodes. For white light, the best current technology is GaN. With the global move to implement more energy-efficient technologies in all walks of life, LEDs – and GaN in particular – are the subject of generous government-funded programs around much of the world.

But, as this month's interviewee Colin Humphreys notes (p14), the UK's strategy in this area seems somewhat dishevelled. While the US, Japan, Korea and China all have well-established solid-state lighting initiatives that cover the entire lighting industry supply chain, the UK's plans are conspicuous by their absence. And that is despite being home to some of the leading research groups in III-V semiconductors, such as Humphreys'.

One obvious reason for this is that the UK does not have a domestic LED chip manufacturer to bang the drum and bend government's ear. Another problem is that the development of such a disruptive technology for such widespread application is something that the UK cannot tackle on its own.

"With the global move to implement more energy-efficient technologies in all walks of life, LEDs are the subject of generous government-funded programs."

In other words, it is the sort of thing that the European Union was set up to deal with: a multinational problem in need of a multinational action plan. After all, with Philips and Osram, Europe is home to two of the three biggest lighting companies in the world, as well as two of the five biggest LED makers. Strange, then, that the EU is relatively low-profile when it comes to the development of solid-state lighting. While the Photonics21 promotional group of firms (including Philips, Osram and Aixtron) has

identified solid-state lighting as a key strategic area for Europe to exploit, there appears to be no EU equivalent of Japan's next-generation lighting initiative or the US Department of Energy's solid-state lighting program.

This ought to change. To meet its stated aim of reducing energy waste and carbon dioxide emissions, the EU should focus more on economically beneficial measures such as funding semiconductor lighting programs like the rest of the developed world and less on draconian, anti-economic moves such as tax hikes on commercial flights.

Michael Hatcher *Editor*

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Optoelectronic Device Yield

By Frank Burkeen

Senior Product Marketing Director at KLA-Tencor
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The last decade has seen the evolution of many new optoelectronic devices which affect our daily lives. Automobiles, cell phones and PDAs, digital cameras, and computers contain an increasing number of microdisplays, high-brightness light-emitting diodes (HB-LEDs) and power devices based on compound semiconductor manufacturing techniques. With our ever-increasing consumption of these devices, this market growth and rapidly emerging technologies place tremendous pressure on manufacturers to get product to market.

Automated defect inspection has been a critical part of the semiconductor manufacturing process for detecting manufacturing problems early to reduce costs and increase product yield and performance. In the optoelectronics world, these defect inspection techniques translate as semiconductor wafer materials, in addition to silicon, are often used. The use of automated defect inspection has much less pervasiveness in optoelectronics wafer processing than in silicon wafer processing, but that is changing with the ever-present need to reduce costs and increase yield. A number of global manufacturing facilities are employing an Optical Surface Analysis (OSA) inspection technique that combines the elemental principles of scatterometry, ellipsometry, reflectometry, and topographical analysis to detect and classify defects in optoelectronic substrates and films.

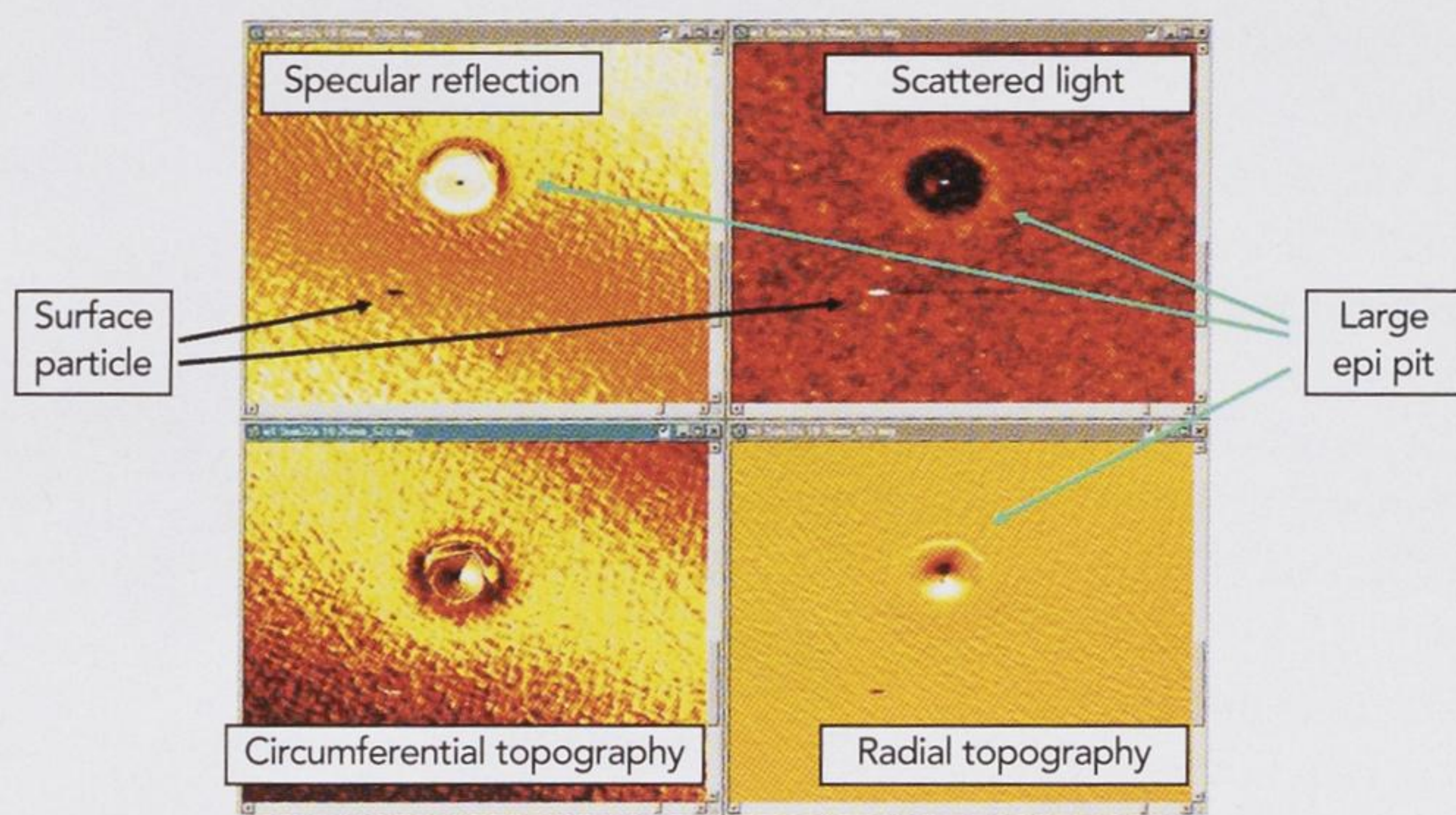


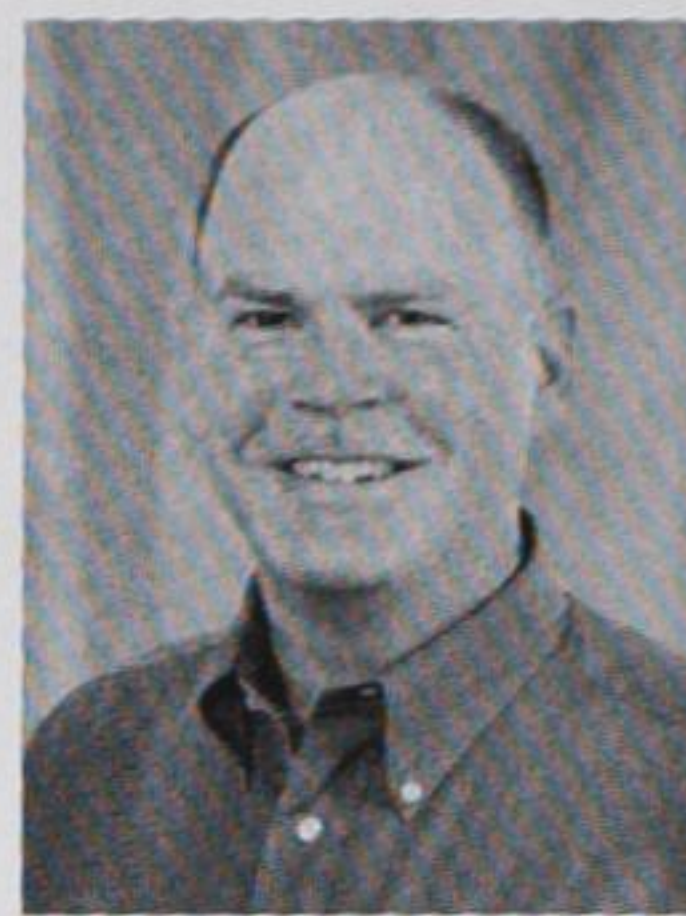
Figure 1: Defect images from four OSA signal types from a sapphire wafer with GaN epitaxial layers.

HB-LEDs

HB-LEDs are composed of multiple epitaxially grown layers of GaN and AlGaIn, and are usually grown on one of two types of substrates: silicon carbide or sapphire. These have different advantages and disadvantages, but share one major downside. Due to the fact that the epitaxial layers are not latticed matched to the substrate, the defect density in the epitaxial layers is much higher than in homoepitaxial processes (such as in GaAs or Si epi layers). Fig. 1 shows the same portion of a wafer (about 2 mm by 2 mm in size), with two types of defects visible. The optical signatures for these two defects are clearly different and can be recognized separately by the OSA software.

POWER DEVICES

Some SiC-based power device manufacturers rely on manual microscope inspection with the process being very time consuming and not capable of finding all critical defects. OSA can be used to detect and classify defects in SiC substrates and epi



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layers automatically. As an example, the surface of GaN HEMT wafer contains an AlN buffer layer, a GaN layer, and an AlNGaN surface layer grown on a SiC substrate. Inspection can be performed in various stages of the manufacturing process of these devices. Fig. 2 shows a micropipe defect and a crystal defect commonly called a triangle defect, which only appears in topography signals. Micropipes appear as elongated defects in OSA images, making them easy to detect and classify.

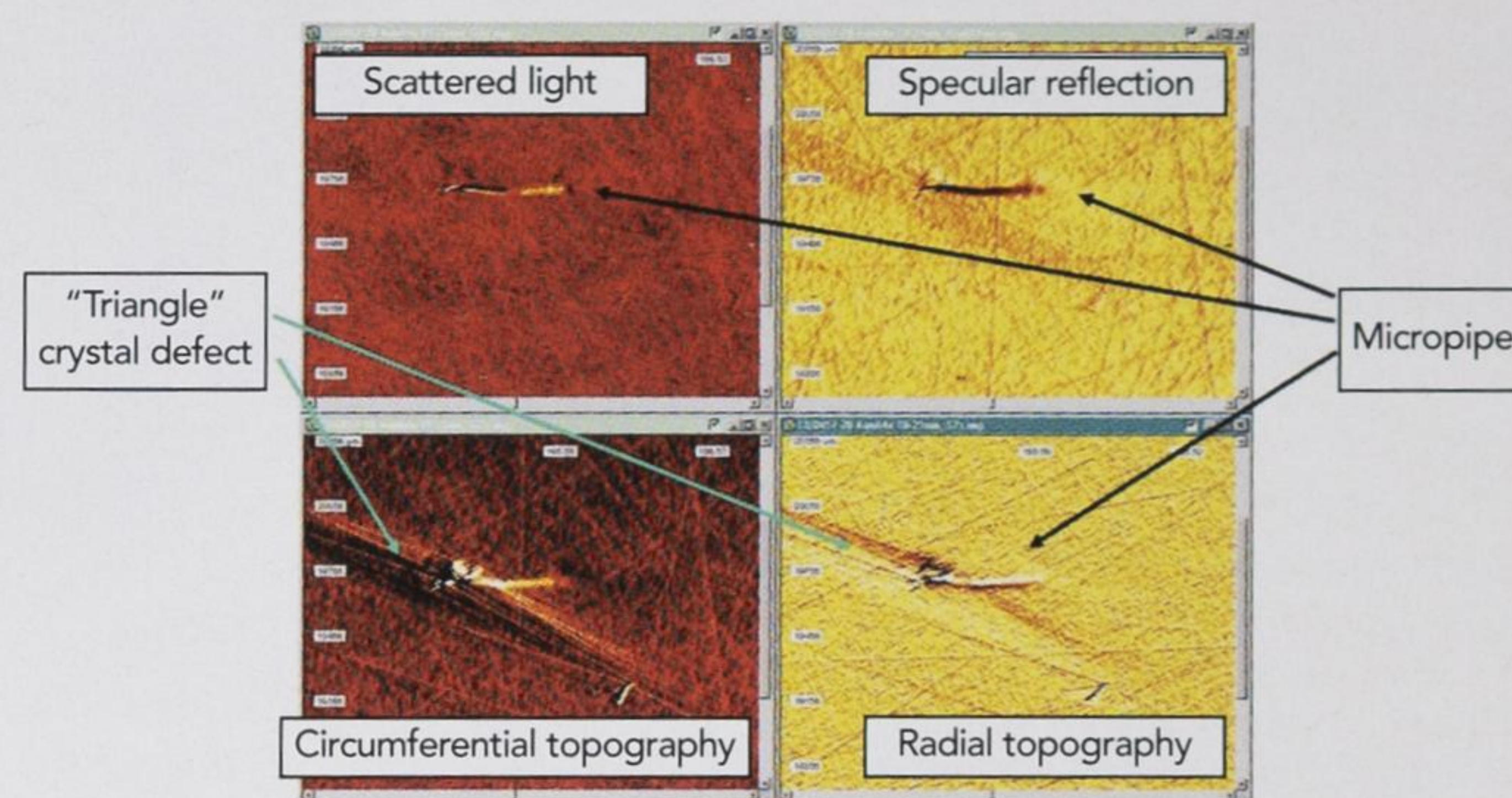


Figure 2: Defect images from four OSA signal types from a SiC wafer.

MICRODISPLAY

A new generation of CMOS imagers, LCoS displays, and digital light processing devices have been widely adopted into many consumer products. Many manufacturers have relied for years on manual microscope inspection making the process time consuming for 100% inspection. Inspection of the glass substrate and coated layers is challenging because defects such as stains from washing processes remain transparent and difficult to identify visually. Defects as small as 1 micron in size in advanced imagers have the potential to create blurry images where the manufacturer has to scrap the devices, thus lowering yields and profitability. The OSA system for glass wafer inspection is very sensitive to residues and other thin films.

Manufacturers must find new ways to optimize their new product processes and decrease defect rates to stay profitable and competitive. Relying on manual optical microscope inspection is no longer an alternative at high volume rates and when every new device generation is more complex. Manufacturing processes require sufficient data about each and every process in order to create a defect yield management strategy that is effective and competitive. OSA technology can help manufacturers to automate the defect inspection process for optoelectronic devices, and this technology can be employed in incoming substrate inspection, post-clean wafer inspection, and after epi and film deposition processes.

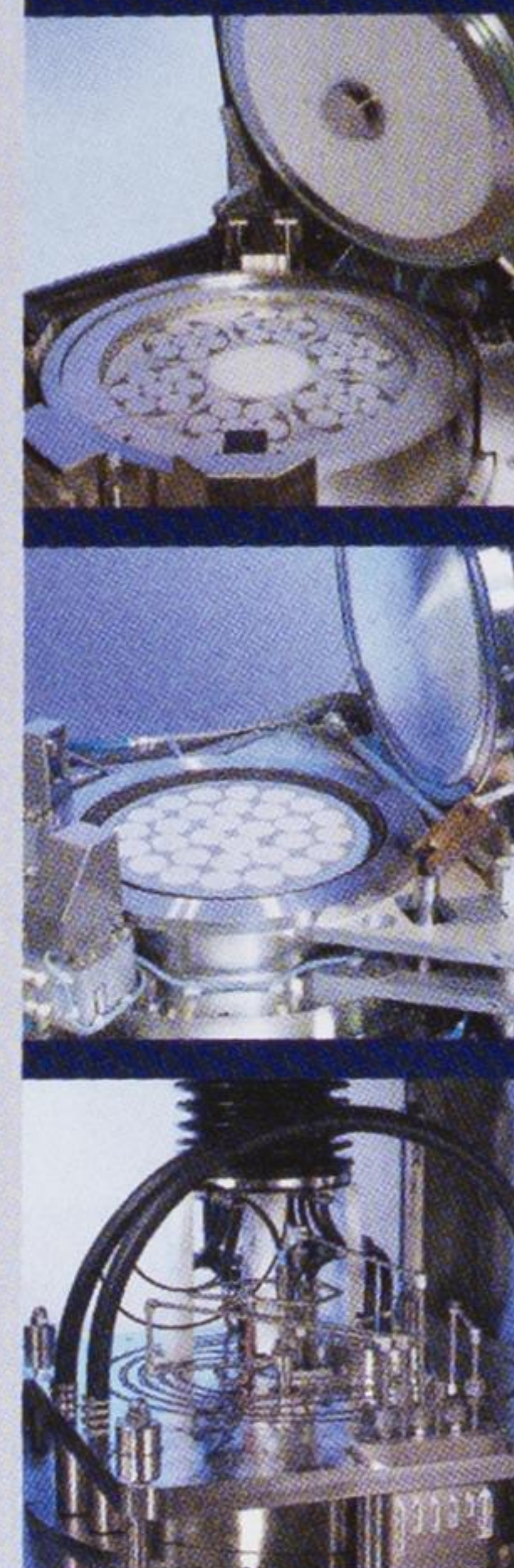
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PERFORMANCE

WIDE-BANDGAP SEMICONDUCTORS

SiC radar modules now 'proven', says Lockheed

For the first time, a radar system fitted with SiC-based transmit/receive modules has performed live tracking of aircraft.

Lockheed-Martin's solid-state S-band radar tracked airplanes flying through the busy New York-Philadelphia corridor in northeastern US. Previously, the SiC radar had only performed computer-simulated tracking.

According to Lockheed, the better heat tolerance of SiC components compared with conventional technologies enables greater power output, which translates into a longer range over which the radar can operate.

"Transmit/receive modules are the most critical components of a solid-state antenna," said Lockheed, adding: "We consider the SiC modules are now proven. Through 2007, we will run the [system] through a series of continuously more demanding tests to further define the capabilities."

Inside the systems, the SiC modules generate and transmit S-band signals over the full face of the radar, receive the reflected radar signal, amplify it for processing, and electronically steer the RF beam in space.

Although this first live demonstration involved commercial aircraft, Lockheed's primary motivation for the development is for military applications. As well as providing longer-range radar, the SiC modules allow more precise target discrimination.



Powered up: Developed for the US military, Lockheed-Martin's scalable solid-state S-band radar is the first SiC-based system to perform live aircraft tracking.

Lockheed told *Compound Semiconductor* that, based on its success with the new radar system, it could deliver the first radar for military use within three years of receiving a contract.

SiC and GaN are both considered key compound materials for next-generation radar, and are being developed around the world. "GaN is the next technology beyond SiC," Lockheed said. Major development programs in the US, Japan and Europe are focused on the military and commercial applications of GaN.

In a related development, Raytheon – another US defense contractor – says that its GaN chips have passed a key testing milestone that demonstrates the reliability of the technology for military applications.

GaN-based MMICs developed by Raytheon's Integrated Defense Systems completed 8000 h of testing at elevated temperatures, which approximates to an operational lifetime of 80 000 h, or more than nine years.

Like SiC-based radar, the GaN MMICs could be used to trade-off increases in range, sensitivity and search capability against the size of the radar antenna. "GaN technology can reduce the antenna size by half, while more than doubling the search volume," claims Raytheon. Smaller antennae would reduce the cost of a radar system and make it easier to transport. Using GaN is expected to deliver a 10 fold increase in signal power compared with current systems.

Lifetime tests are set to continue throughout 2007, along with independent validation of the test results.

LOGIC CHIPS

InGaAs HEMTs – the successor to CMOS?

A research team at the Massachusetts Institute of Technology (MIT) says that its improved InGaAs HEMT process could make the compound material a serious contender for advanced logic applications – if and when the silicon CMOS roadmap runs out of steam.

Continued shrinking of silicon MOSFET transistor size by advanced lithography has so far ensured that logic devices have kept pace with Moore's law. However, the continuation of this approach is expected to hit a fundamental barrier in 10–15 years and, as yet, researchers have failed to find a solution.

"Unless we do something radical pretty soon, the microelectronics revolution might come to a screeching halt," said Jesús del Alamo from MIT.

Del Alamo and colleague Dae-Hyun Kim say that although InGaAs has always been regarded as a very attractive material for use

in logic transistor channels, HEMTs based on this compound have previously reached their scaling limit at a 100 nm gate length.

However, in new research presented at December's International Electron Devices Meeting in San Francisco, Kim and del Alamo showed that this scaling problem can be overcome by using a much thinner InAlAs barrier layer. The Singapore-based wafer foundry MBE Technology grew the device epilayer material on InP substrates.

With a barrier thickness of 3 nm instead of 11 nm, their $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ HEMTs showed excellent drive-current and gate-delay characteristics, and a transconductance that scaled nicely with gate length.

On the down side, some of the devices featuring an even thinner layer of InAlAs (0.5 nm) suffered from excessive gate leakage. Despite this trade-off, del Alamo reckons that the gate leakage problem can be solved, and that with optimized contacts InGaAs HEMTs could be "the technology of choice when the CMOS roadmap comes to an end".

Compound semiconductors aren't the only option, of course. Development of so-called

"high-k" gate dielectric materials are thought by many to offer the best solution, but there is no guarantee that this approach will work.

As a result, many leading research teams are now attempting to develop compound materials, which are intrinsically "faster" than silicon because of higher carrier mobilities, for logic applications. Indeed, it is the silicon logic industry's biggest and best-known exponent – Intel – that has funded the del Alamo team at MIT.

Intel's director of transistor research and nanotechnology Robert Chau said that the MIT team's work showed some exciting results at the low supply voltage of 0.5 V. "[This] is a very important research milestone," Chau commented.

InGaAs HEMTs are just one of the III-V options for post-CMOS logic, however. Freescale Semiconductor in particular has been working on GaAs-based MOSFETs, where the main difficulty has been developing a suitable oxide material for the gate of the transistor. The Freescale team uses gadolinium in a GdGaO_3 gate oxide compound for its MOSFET structures.

CHIP MANUFACTURING

RFMD set to outperform market peers

Impressed by a strong outlook for sales in early 2007, Jefferies and Co investment analyst John Lau expects wireless technology provider RF Micro Devices (RFMD) to outperform its peers in the RF semiconductor market.

After checking the latest supply chain inventories in Asia, Lau, who covers several semiconductor stocks, says that the GaAs chip maker will perform much better than previously anticipated in 2007 and 2008.

"We believe that RFMD will continue to gain market share to become one of the largest RF semiconductor makers in the world," Lau said. He has now increased his revenue estimate for RFMD's fiscal year 2007 (which runs until the end of March) by \$9 million to nearly \$1.02 billion. The Greensboro, NC, company seems certain to break the billion-dollar revenue barrier for the first time in its current fiscal year.

Lau has also raised his target share price for the firm from \$10 to \$11, even though its stock has traded between \$6 and \$8 between summer 2006 and January 2007.

"RFMD continues to fill up its fabs," added Lau. "Phase two [of the expansion] is almost ramped and will start delivering returns by the back end of fiscal 2007."

The analyst also indicated that a more diverse set of applications are within RFMD's scope. "The expansion will focus on increased production of GaAs PAs for the cellular and notebook PC markets and gives RFMD the flexibility to switch capacity at older, depreciated fabs to GaN production (set to ramp in fiscal 2007) for the infrastructure market."

"The capacity will also mean that RFMD can perform in-house wafer-level packaging, module assembly and flip-chip packaging, thus reducing production costs," Lau added.

That increased manufacturing efficiency, along with the sale of its low-margin Bluetooth business to Qualcomm late last year, will also improve RFMD's profit margins.

Another trend in RFMD's favor is the continued consumer shift from GPRS cell-phones to more advanced enhanced data rates for GSM evolution (EDGE) technology. Many high-end

cellular handsets operating with EDGE and wideband-CDMA platforms contain \$7 worth of RFMD components, and sales of 690 million such handsets are predicted by 2009.

As part of the drive to fill up its new device fabrication capacity, RFMD has launched two new types of switch for use in cell-phones, cellular infrastructure and wireless LAN applications. The move is expected to result in extra revenue from the new line of switch products, as well as improved profit margins within its own cell-phone transmit modules.

The RF1200 is a single-pole double-throw switch that is designed for wideband-CDMA applications. It is made using a 0.5 μ m PHEMT process. The second new product, RF1450, is a single-pole four-throw switch, and addresses the needs of multimode wideband-CDMA.

RFMD's CEO, Bob Bruggeworth, said at January's Needham Growth Conference held in New York that the increased internal production of GaAs PHEMT switches was one of the key factors contributing to the company's improving profitability.

SUBSTRATES

Kyma Technologies reshuffles senior management

GaN substrate specialist Kyma Technologies has won a development contract worth up to \$3.3 million and parted company with Mark Williams, one of its co-founders.

The new development contract is with the US Air Force Research Laboratory and Missile Defense Agency, which are co-funding Kyma's development of semi-insulating native GaN material for improved radio-frequency FET

devices. Georgia Tech's Russ Dupuis will take the lead in epitaxial growth of FET layers.

In a reshuffle of its senior management team, Kyma has promoted Ed Preble to COO. Williams has left the company, which he co-founded in 1998. Preble is a graduate of the legendary Bob Davis research group at North Carolina State University that has spawned many of the region's compound semiconduc-

tor companies.

CEO Keith Evans says that with the defense contract in place, plus an impressive list of collaborators from leading institutions now working with its substrate material, Kyma is making good progress with a notoriously difficult material in its bulk form. A collaboration with the Polish company TopGaN has recently resulted in blue laser structures.



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...Backhaul market peaks out

The market for GaAs chips used in cellular backhaul applications – the high-frequency point-to-point links between individual base stations and a central controller station – will peak in 2007. According to a new report published by Strategy Analytics' GaAs and Compound Semiconductor Service, demand will flatten out after that as growth in unit shipments slows. Asif Anwar, the author of the market analysis, said that GaAs chip manufacturers will need to innovate to stay ahead of the increasing threat from silicon technologies. "We believe a

move towards packaged parts and multifunctional chips and/or multi-chip modules will help GaAs companies to offset competitive threats," Anwar said.

...Tegal strikes Skyworks deal

GaAs transistor manufacturer Skyworks Solutions is to install a new cluster etching system at its 4 inch wafer facility in Newbury Park, CA. Skyworks, which makes AlGaAs and InGaP HBTs, as well as the more advanced "BiFET" GaAs devices at the southern California fab, will use the Tegal tool to etch thin films such

as SiN that are deposited onto compound semiconductor epiwafers in the chip manufacturing process.

...Freescale ramps InGaP offering

Freescale Semiconductor has unveiled four broadband GaAs- and InGaP-based RF amplifiers set for volume production from May 2007. The Austin, TX, chip giant says that the new devices deliver high gain and linearity over bandwidths ranging from DC up to 6 GHz. The specific chip types include a GaAs HFET, an InGaP HFET and two InGaP HBTs.

MERGERS & ACQUISITIONS

IQE travels east and completes cash deal for MBE Technology

IQE, the UK-based independent epiwafer foundry, has continued its drive for global expansion with the acquisition of Singapore-based MBE Technology.

The two companies agreed a cash deal valued at S\$23 million (US\$14.9 million) and as MBE Technology was already profitable, the deal will immediately add to IQE's bottom-line financial performance.

Founded in 1993, MBE Technology had annual revenue of about \$15 million and a strong customer base in the Far East, including one major supply deal with a large Japanese firm.

To help pay for the acquisition, IQE raised £4.5 million (\$8.9 million) by placing 25 million shares on London's AIM stock exchange on December 27. £3.8 million of that raised cash was used in an initial payment to MBE Technology. The balance of the deal – £3.8 million – will be funded by the issue of loan notes repayable from January 2008 onwards.

This latest move by IQE follows a similar deal to acquire Emcore's Electronic Materials Division (EMD) in August 2006.

Now with MBE-based epiwafer manufacturing sites in Singapore and Bethlehem, PA,

and MOCVD facilities in Somerset, NJ, and at its Cardiff headquarters, IQE has firmly established itself as a dominant force in the pure-play foundry business.

CEO Drew Nelson said of the latest move, "Following the acquisition of EMD in August, we have now completed our strategy of becoming the leading supplier of wafers to the global wireless industry, providing all the required wafer technologies."

The still-booming wireless market is predicted to double the amount of GaAs material required by makers of mobile handsets, cellular base stations and broadband wireless links over the next few years.

Between now and 2009, predicts market research company Strategy Analytics, nearly 200 million 802.11n broadband wireless systems will be shipped – many of which are likely to use high-value GaAs components such as HBTs or BiFET devices (see "Behind the Headlines", p13).

● *IQE added in a trading update that it had accelerated development of BiFET epiwafers at its Somerset, NJ, facility, where demand for wireless products is exceeding expectations.*

TRANSISTOR DEVELOPMENT

Pseudo HBT delivers speed of 845 GHz

Milton Feng and his team from the University of Illinois at Urbana-Champaign has once again broken the world transistor speed record, this time with a 845 GHz pseudomorphic heterostructure bipolar transistor (PHBT).

As usual, the research team used the International Electron Device Meeting to reveal transistors with a record cut-off frequency – the semiconductor industry's equivalent of the land-speed record.

The latest achievement is an InP/InGaAs device that operates at "only" 765 GHz at room temperature. However, when cooled to -55 °C, reduced base and collector transit delays combine with smaller charging delays at the transistor's collector to deliver the higher switching speed of 845 GHz.

Feng has been at the forefront of the US military-funded drive towards a transistor with terahertz switching speed for a long time and his team's previous efforts include a 562 GHz PHEMT, and both single and double HBTs exceeding 500 GHz.

However, to reach terahertz speeds, single and double HBTs would require unrealistic current densities exceeding 300 mA/μm². The

scalability of PHEMTs is also limited, says Feng, because to switch at these very high speeds they have to be biased at close to their breakdown voltages.

Feng reckons that his PHBTs, which are so-called because their base and collector regions feature pseudomorphically graded InGaAs structures, offer a possible solution, largely because their cut-off frequency has an accelerated dependency on current density.

The latest results demonstrate this and suggest that a terahertz transistor would draw a plausible current density of only 28 mA/μm².

Having previously made a 710 GHz PHBT, Feng and colleagues broke the speed record by reducing the size of the transistor's base finger mesa region. The smaller mesa drastically reduces the extrinsic base-collector junction capacitance, which enhances electron transport throughout the structure.

"By scaling the device vertically, we have reduced the distance that electrons have to travel," explained Feng's graduate student and co-author William Snodgrass. "Because the size of the collector has also been reduced laterally, the transistor can charge and discharge faster."

AIR
PRODUCTS

Ask the Expert



Rajiv K. Agarwal, Ph.D.

Lead
Research
Engineer

Q

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

A

Higher background levels of n type dopants in GaAs and AlGaAs structures are caused by trace levels of germanium, silicon and sulfur species present in the arsine. As customer applications evolve, the purity requirements for arsine must as well. Until recently, background doping levels of 10¹⁵/cm³ were considered acceptable in most applications. In general, most currently available high-purity grades of arsine can satisfy these requirements. However, process changes and demand for more sophisticated devices have resulted in the need for lower background doping levels. To address these more stringent requirements, Air Products is introducing Megabit™ III arsine, our purest grade available. Our new Megabit III arsine has significantly reduced the amounts of germanium, silicon and sulfur species. Testing done at an independent laboratory proved the effectiveness of Megabit III on thick gallium arsenide films, with excellent results. In all cases, the background doping level was <<10¹⁴/cm³. Our research has shown that Air Products' Megabit III arsine will perform more consistently and produce fewer defects in our customers' finished products.

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COURT RULING

Epistar shrugs off Lumileds 'victory'

An initial ruling by the US International Trade Commission (USITC) has decided that Epistar, based in Taiwan, is infringing a patent owned by Philips Lumileds.

USITC judge Sydney Harris ruled that metal-bond AlGaInP LEDs made by United Epitaxy Company, which is now part of Epistar, infringed Lumileds' 5,008,718 patent.

However, when Lumileds filed its claim back in November 2005, it also accused Epistar of patent infringement over other AlGaInP products based on omnidirectional mirror adhesion (OMA) and glue-bond chips.

As a result, Epistar is claiming a moral vic-

tory: "The [judge] found that the Epistar OMA and glue-bond LEDs do not directly or indirectly infringe any of the claims of the patents."

The Taiwanese company adds that the adverse ruling over metal-bond LEDs will have little impact on its business anyway: "Epistar is ready to go into production with a new generation of metal-bond series LEDs, which Epistar believes will obviate the issues with the '718 patent altogether."

"Even if the USITC adopts Judge Harris's infringement finding regarding metal-bond LEDs, the impact on Epistar will be small."

Lumileds appears to dispute that sentiment,

and is pushing for the USITC to award damages relating to what it sees as "willful" infringement of the '718 patent. It is still seeking an order from the USITC to stop imports of both the LEDs in question, and any products featuring them, to the US.

However, Epistar says that it will petition for the USITC to reject the initial ruling of infringement over metal-bond LEDs, as it maintains that this finding was based on incorrect interpretations of two claims within the '718 patent.

The final determination from the USITC, which should settle the outstanding damages claim, is not expected until May 8 2007.

EPITAXY EQUIPMENT

Veeco reveals 'futureproof' K-series MOCVD reactor

Veeco Instruments claims that its new line of "K-series" MOCVD reactors feature an easily upgradeable design that will enable compatibility with future characterization or processing modules.

The company, which also designs and sells MBE equipment, added that it had already sold five of the new system to high-brightness LED manufacturers in orders worth approximately \$10 million.

The K300 and K465 tools for GaN device manufacturing are claimed to offer 50% greater throughput compared with similar production tools, as well as reconfigurable reactor and source modules. Veeco also claims that

they feature the industry's only fully automated four port expansion-ready hub for future equipment upgrades.

At the heart of the new systems is the familiar TurboDisc GaNzilla II reactor. An automated hot carrier transfer system allows wafer carriers to be loaded at any time during the process cycle, with the reactor remaining under vacuum. This transfer system runs at about 300 °C, with no changes to any parts required between individual processing runs.

Veeco CEO Ed Braun said that one of the key aspects of the K-series systems was its ability to meet future requirements of LED manufacturers as chip performance demands

continue to evolve: "Veeco's platform will give our HB-LED customers a long-term cost-of-ownership advantage, plus the technology to achieve their LED brightness roadmap aims."

Veeco and its rival Aixtron have both reported very strong orders for MOCVD equipment in recent months, as chip manufacturers gear up and develop new volume processes to make LED chips for applications that place a high demand on performance, such as LCD backlighting and car headlamps.

Towards the end of the current decade, the demands of general lighting applications will likely require even better performance from chip makers and their MOCVD reactors.

MATERIALS DEVELOPMENT

Cermet negotiates GaN-on-ZnO agreement with Georgia Tech

Cermet, which specializes in wide-bandgap semiconductors, has signed a royalty-based license deal with the neighboring Georgia Institute of Technology (GA Tech) that covers GaN-on-ZnO white LEDs.

Unlike current commercial white LEDs, which require a phosphor to convert blue or near-ultraviolet light from a chip into white light, the new approach is phosphor-free and relies only on the interaction between the two semiconductor materials.

Research by Cermet and GA Tech has shown that high-quality layers of GaN can be grown directly onto a ZnO substrate by MBE, with etch-pit densities in the 10^6 range, lower

than the defect levels in conventional devices grown on SiC or sapphire material.

Epilayer growth by MOCVD is also possible, although the hydrogen gas generally used in this technique tends to react with ZnO at typical growth temperatures.

Phosphor-free devices emitting low-intensity white emission have already been made and improving the electro-optic efficiency is the key area that Cermet is now focusing on.

Cermet CEO Jeff Nause told *Compound Semiconductor* that the company is also working to produce devices with different white color temperatures to demonstrate the versatility of this novel material.



Automotive design specialist Pininfarina used 15 lighting clusters, each fitted with eight Power TopLEDs supplied by Osram Opto Semiconductors, to create daytime running lights in the headlamps of this Ferrari P4/5. Each LED is equipped with a ThinGaN chip, providing an efficiency of 40 lm/W.

CHIP MANUFACTURING

SDK and Arima ramp up AlGaInP capacity

Showa Denko (SDK), the diversified Japanese chemicals company that also manufactures high-brightness LEDs, is scaling up its AlGaInP chip capacity with a ¥1.5 billion (\$13 million) investment.

SDK's upgrade will include an expansion of MOCVD capability to manufacture more epiwafers, with the company planning to increase chip production from 30 million units per month to 100 million.

Expansion work is due to begin in February and is expected to be completed in the third quarter of 2007. "We are seeing a sudden increase in the amount of orders we receive from overseas customers," commented the Tokyo-headquartered company.

SDK is expecting demand for ultra-bright AlGaInP LEDs to grow at an annual rate of around 40% over the next five years, driven primarily by large-area display backlighting and automotive applications of the technology. The company now expects to post over ¥2 billion in revenue from sales of red, yellow and orange emitters in 2007, and double that in 2008 after the fab expansion is completed.

AlGaInP epitaxy and device production forms a key part of SDK's "Passion" project, with which it hopes to enter a whole range of fast-growing industries. The company also sells semiconductor processing materials, makes epiwafers for SiC-based power devices, and is developing GaN-based LEDs.

It claims to be the only company that is able to provide ultra-bright full-color RGB LEDs, including novel "pure green" GaN devices emitting at 555 nm, and believes that these will have a major impact on the general lighting market from 2010 onwards.

Meanwhile, Arima Optoelectronics, based in Taiwan, is to scale up its own high-brightness AlGaInP LED chip volumes with a new TurboDisc MOCVD reactor from Veeco Instruments. Arima's expansion is also in response to demand for automotive applications of red, orange and yellow LEDs, such as stop and turn lamps.

Following recent consolidation among Taiwanese LED manufacturers, Arima is now a key player in the global LED business, while the company also makes laser diodes.

And like its main domestic rival Epistar, Arima has been scaling up production capacity recently. In September 2006, Arima ordered three MOCVD machines from Aixtron, also destined for AlGaInP production at its Houko and Dashi wafer facilities.

DISPUTE

Nichia denies global impact of Seoul ruling

Nichia has issued a firm rebuttal to claims made by the LED maker Seoul Semiconductor (SSC), Korea, that a recent court ruling in Seoul could have an impact on pending Nichia litigation in the rest of the world.

In December, the Korean Intellectual Property Office (KIPO) ruled in favor of Baron Tech from Korea in a case against Nichia relating to LCD backlights. SSC says that the side-view white LEDs under dispute in the case were worth around \$200 million in annual sales from Nichia to its Korean customers.

SSC, which is a major customer of Nichia's arch-rival Cree, added that the decision could have an impact on another lawsuit between SSC and Nichia that is currently pending in the US district court of Northern California.

However, Nichia has refuted this suggestion, indicating that the KIPO ruling was the result of "particular and peculiar" circumstances that only apply in Korea. "The [KIPO] decision will not have any impact on the validity of foreign counterparts in the US, Taiwan, Japan or China," Nichia said in a statement.

The Japanese chip maker even claims that because maintaining its design patent would be difficult under the unique Korean system, it had already decided to abandon the case before the court decision was even made.

Meanwhile, Seoul Semiconductor says that its LED development has resulted in a single-die white source that can emit up to 100 lm/W. Importantly, Seoul is claiming the high efficacy figure for chips that operate at the 350 mA drive current required for general lighting.

The "P4" emitter produces 240 lm at its maximum drive current. Two types of commercial device are available – one operates at a typical efficacy of 100 lm/W at 350 mA and the other is rated at 80 lm/W. Initial products will emit a white color temperature of 6500 K but a wider range (2800–8500 K) is in development.

"Conventional LEDs have been known to emit more than 100 lm with several dies," said Seoul Semiconductor CEO Jung Hoon Lee. "The P4 is the only LED product in the world with 240 lm via a single die."

Seoul says that the high luminosity was reached through its proprietary phosphor and packaging techniques, and it would appear that further improvements are in the pipeline.

According to the firm's statement, we can look forward to a 135 lm/W source in 2008 and more incremental improvements are expected to lead to 145 lm/W performance. To put that lumens per watt figure into context, a typical fluorescent lamp operates at 70 lm/W, while traditional incandescent bulbs deliver 15 lm/W.

COMPOUND SEMICONDUCTOR FOUNDRY SERVICES



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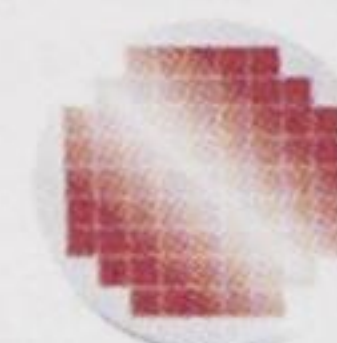
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GAN EMITTERS

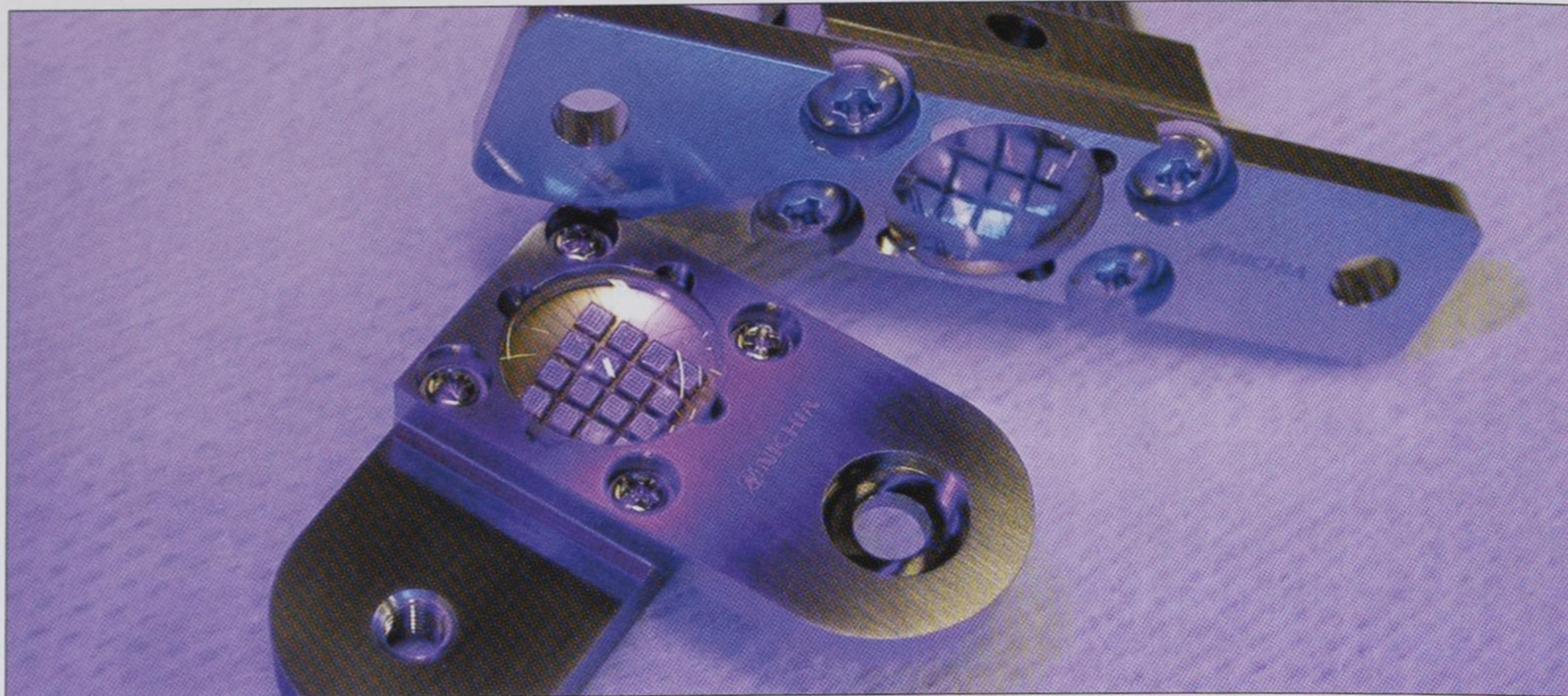
Nichia doubts viability of deep-ultraviolet LEDs

Nichia, the Japanese company that pioneered the development of GaN-based LEDs and lasers, believes that deep-UV LEDs are “not commercially viable”.

Takashi Mukai, who is the director of Nichia’s Nitride Semiconductor Research Laboratory, told *Compound Semiconductor* that the company has no plans in the near future to develop any devices operating at shorter wavelengths than its current 365 nm LEDs.

“We are focusing on producing high-power 365 nm LEDs and 375 nm for laser diodes,” Mukai added. Nichia already sells a 375 nm laser that emits 20 mW. He believes that although some applications for deep-UV emitters could emerge, the output power of current devices is way below what is needed.

Nichia will concentrate on developing low-power devices for applications like photocatalytic deodorizing used in air conditioning systems and refrigerators, and to identify counterfeit banknotes. Mukai expects high-power devices to be used in resin curing and photolithography.



Nichia will focus on near-UV emitters such as this 365 nm array, as it believes that deep-UV LEDs are not yet viable.

In 2006, the Korean firm Seoul Optodevice and deep-UV LED specialist Sensor Electronic Technology signed a deal designed to ramp up production of the AlGaIn-based LEDs emitting at wavelengths as short as 255 nm for water and surface sterilization applications.

However, Mukai cites problems in the p-doping of these AlGaIn structures as one key reason why they are not, in his opinion, ready for commercialization. Mukai says that a more efficient dopant than magnesium must be found to create more powerful devices.

OUTSOURCING

Xponent foundry deal signals shifting strategies

In a strategic move that highlights an accelerating shift towards outsourced wafer processing of optical telecommunication devices, Xponent Photonics has established a foundry deal with Global Communication Semiconductors (GCS).

GCS, which is more well known as a high-end GaAs wafer foundry that, among other things, manufactures RF components for US military applications, will fabricate optoelectronic devices employing proprietary laser and PIN photodiode processes developed by Xponent and GCS.

GCS told *Compound Semiconductor* that GaAs- and InP-based wafers would be made for Xponent. Although GCS would not reveal details of the number of wafer starts required, the firm described the Xponent deal as being a “multi-million dollar business” annually.

Xponent chief executive Jeff Rittichier claimed: “With the completion of the GCS transfer in late winter, Xponent will be the world’s only completely fabless volume producer of optical components.”

Although the optical components boom of the late 1990s saw a lot of companies build their own wafer fabs to make proprietary III-V optoelectronic chips, the subsequent bust has convinced many of the remaining companies that the best solution is now one based on

an outsourced foundry model.

“Our business in optoelectronic device processing is growing very quickly,” explained GCS’s Simon Yu. He added that although optoelectronic wafers only account for a very small percentage of the foundry’s overall volumes, revenue from these applications was worth more than 20% of its sales.

Yu added that he expected more companies to follow the strategy taken by Xponent and Syntune, the Swedish laser vendor that recently agreed a foundry deal with CyOptics.

“We are confident that Xponent will benefit from our 4 inch high-volume wafer manufacturing capabilities to stay ahead of market competition,” explained Jerry Curtis, CEO of the Torrance, CA, pure-play foundry.

Xponent’s technology is based on a technique called “surface mount photonics” (SMP). According to the Monrovia, CA, company, using SMP means that its extended-reach Fabry-Perot lasers and photodetectors can be made without any manual processing steps.

Features of SMP processing include wafer-scale test and burn-in, passive alignment on flip-chip die bonders and a simple encapsulation step instead of hermetic packaging. Xponent is targeting the fiber-to-the-premises sector of the optical communications market with its components.

EXECUTIVE MANAGEMENT

All change in the Emcore boardroom

Emcore has announced a boardroom reshuffle that sees Hong Hou, previously general manager of the firm’s Ortel fiber-optics division, appointed as its chief operating officer.

Hou replaced Scott Massie, who has now left the company. With current CEO Reuben Richards planning to become Emcore chairman following the firm’s 2008 annual shareholder meeting, Hou has also been offered the chance to become Emcore’s next CEO.

After moving to Emcore in 1998 from Sandia National Laboratories, Hou helped to launch the firm’s photovoltaics division, which is expected to grow rapidly as multijunction solar cells based on III-V compounds begin to take a share of the terrestrial solar power market.

Also departing the boardroom as part of the reshuffle is Richard Stall, who helped to found Emcore in 1984. Stall, who has also served on the Emcore board for the past 10 years, will however stay at the firm as its solar power division’s CTO, executive VP and general manager.

Like Hou, Stall was a member of the technical staff at AT&T Bell Laboratories, where he was responsible for the development of MBE technologies. “With the election of Hong Hou, the board will continue to have a strong technically advanced director,” Stall advised.

START-UPS

EpiCrystals scoops venture award

By Jacqueline Hewett

Finnish start-up EpiCrystals believes that its DeCIBEL semiconductor laser platform has all the characteristics to enable the production of compact projector engines. Power-scalable and with no need for free-space optics, the lasers are inexpensive, easily mass-produced and suit projection applications ranging from handheld to home theatre.

"We think that we have the most suitable technology for handheld projectors when you compare it with other approaches," commented EpiCrystals' CEO Tomi Jouhti. "Not many competing technologies can be fitted into handheld devices."

The three-color DeCIBEL platform uses frequency-doubled semiconductor diode lasers that are based on GaAs to generate red light. Specific quantum well regions generate light at 625 nm. The sources can be sold individually or combined with conventional blue and green lasers to produce a compact RGB module.

"We are aiming at 50 mW per color per emitter," said Jouhti. "We have a fully power-scalable design and a large array could go up to 5 W for home theater or office projectors, for example. Our aim is to provide the laser sources – we are not interested in manufacturing the overall projection engine."

Jouhti adds that EpiCrystals' core competences are in the laser design and generating red light. "We use a novel semiconductor material for the red and conventional materials for the blue and green," he said. "We have combined several pieces of laser technology in a new way and this is what we have patented."

"For low-power devices for handheld projectors in mobile phones, we are looking at chip prices of \$1 to a few dollars per color in large volumes in the millions per year mark," Jouhti continued.

EpiCrystals is providing samples to selected



EpiCrystals CEO Tomi Jouhti and Janne Konttinen collecting the European Venture Contest gong at an award ceremony held in Lisbon in December 2006.

customers this year and hopes to make the devices commercially available in 2008.

Having spun out of the Optoelectronics Research Centre of Tampere University of Technology in 2003, EpiCrystals secured seed funding the following year. The company is now looking to close its first round of funding.

EpiCrystals also won the 2006 European Venture Contest, beating off 484 other hopefuls from across the region. It is the only pan-European competition with an exclusive focus on top technology ventures showing "the ambition and potential to reshape their industry and conquer the international market".

Jacqueline Hewett is editor of Optics & Laser Europe magazine.

MANUFACTURING

Yokogawa cuts the ribbon on huge new fab

Yokogawa Electric, the Japanese measurement, control and IT firm, has finished building its huge photonic components factory.

A company source informed *Compound Semiconductor* that the fab was due to be "fully functional" by January 15, adding: "The new factory has a huge manufacturing capacity."

According to the firm, the large capacity of the fab will enable it to satisfy growing world-wide demand for high-speed photonic components based on compound semiconductor chips.

Yokogawa is moving its photonics division from Tokyo to the fab in Sagami-hara and is

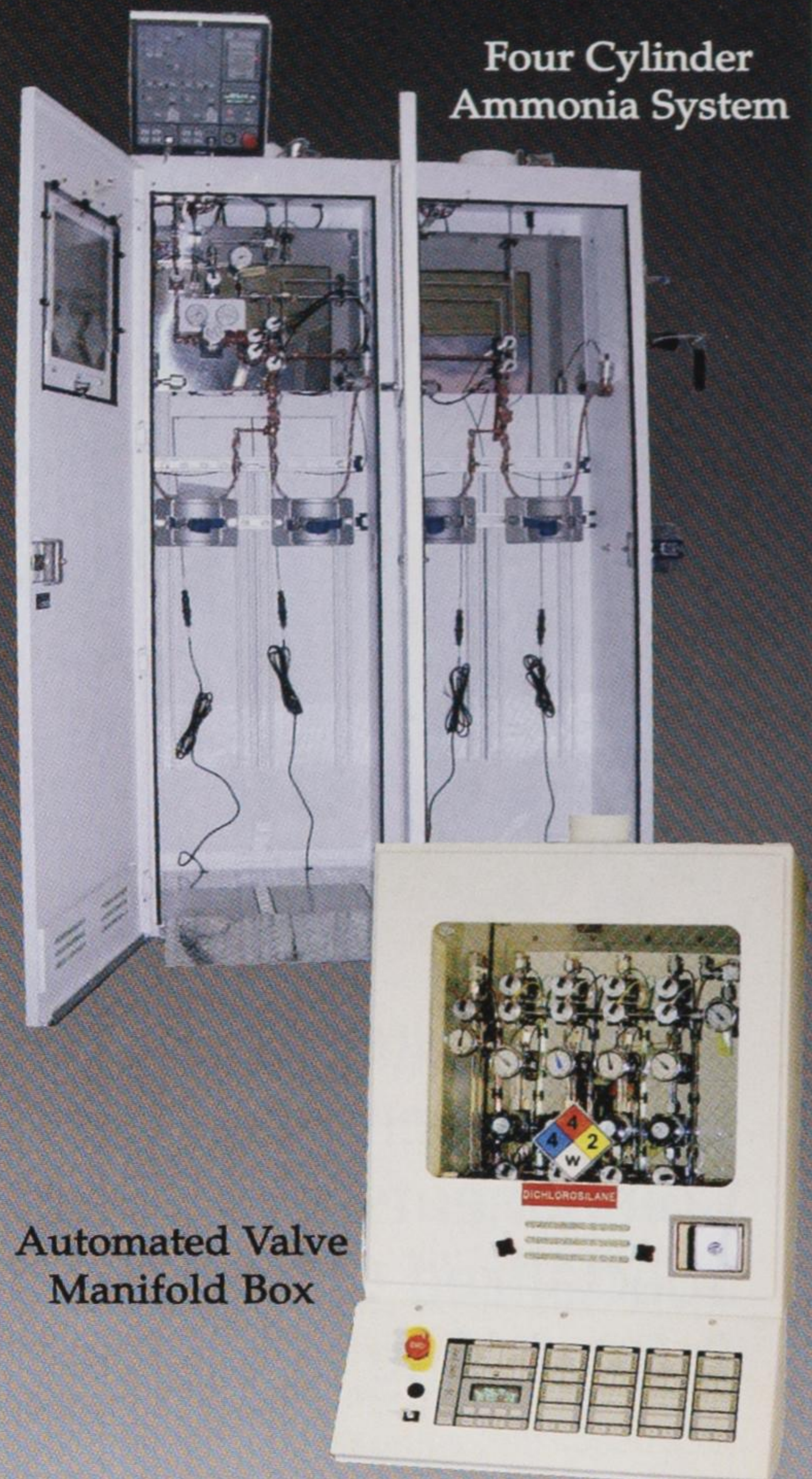
adding extra production lines to meet the growing demand for 10 Gb/s and 40 Gb/s components used in fast optical communications.

Earlier this year, Yokogawa signed a deal to supply high-speed III-V components to networking giant Fujitsu. It also bought an MBE machine from French equipment supplier Ribier, with which it is planning to make HBTs.

Yokogawa revealed plans to construct the \$230 million fab in June 2005, along with details of a very fast optical packet switch that it had developed for 40 Gb/s optical networks. The five-storey building will house around 200 staff.

GAS DELIVERY AT ITS PEAK

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TECHNOLOGY LICENSE

Osram Opto Semiconductors and Coherent develop laser TV

By Matthew Peach

Osram Opto Semiconductors is to develop red, green and blue laser technologies based on Coherent's patented chip designs for consumer devices like "laser TV" and mini-projectors.

Coherent has signed a licensing deal with Osram that allows the use of Coherent's optically pumped semiconductor lasers (OPSL) in laser-based projection displays.

The license allows Osram to develop and deploy red, green and blue lasers employing Coherent's intellectual property in consumer applications like projection television and so-called pocket projectors for hand-held devices.

"Coherent has developed and shipped multi-watt RGB lasers and demonstrated laser projection television utilizing our OPS technology," said John Ambroseo, Coherent's president and CEO. "We believe Osram is an excellent technology partner with the resources and business model necessary to develop this technology for

the next phase of the consumer display market."

Coherent says that the main hurdle to the adoption of laser technology for the consumer product market is cost. Therefore, licensing the technology to a high volume/low cost manufacturer, such as Osram, is necessary to achieve the economies of scale necessary to penetrate the consumer market. However, Coherent will continue to be involved in high-value applications, such as flight and ship simulators and digital cinema projectors, where cost is not as much of an issue.

● At the International Consumer Electronics Show in January in Las Vegas, US, the Japanese electronics giant Sony showed off two next-generation televisions based around III-V technology. They included an 82 inch television with LED backlighting and a 55 inch television that uses a laser projection system. *Matthew Peach is a freelance technology journalist based in Bath, UK.*

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INFRARED IMAGING

InSb camera would help cricket umpires

Compound semiconductor detectors are at the heart of a thermal imaging camera that could be used to decide whether or not batsmen playing cricket should be given "out".

When a bowler fires a cricket ball into a batsman's bat or protective pads at speeds of up to 100 mph, the split-second collision produces friction and therefore a brief blast of low-level heat. The mid-infrared light emitted can be picked up by a highly sensitive camera that was originally developed for defense applications by the French company CEDIP.

CEDIP's Emerald IR cameras, which were

used by Australia's Nine Network to cover the recent Ashes series of cricket matches between Australia and England, are built around a focal plane array sensor that is based on InSb chips. The 640 x 512 pixel arrays detect in the 3-5 µm wavelength region and the chips are sourced from an external supplier.

Although the technology is not yet being used by the umpires who adjudicate the game, it can easily tell whether a ball has flicked the edge of a player's bat – and therefore whether or not they should be given out if the ball is caught by an opposition fielder or adjudged to be leg-before-wicket.

"It's the best technology I've seen," former England captain and Channel Nine commentator Tony Greig told Australia's *Herald Sun* newspaper. "Now there is something that can tell you if there's an edge or not."

EPIWAFFER DEVELOPMENT

Bandwidth Semiconductor hooks up with NASA

Epiwafer foundry Bandwidth Semiconductor, based in the US, has won a \$0.6 million contract from NASA's John Glenn Research Center to develop a compound that produces electricity from waste heat.

Called thermophotovoltaics (TPV), the technology works in a similar way to the semiconductor solar cells that convert sunlight into electric power and has also been investigated by General Motors in the past. Bandwidth and

NASA will work on InGaAs structures that can harness mid-infrared energy. The agency is interested in using TPV to generate electricity from the heat produced by radioactive isotopes, as this could be useful as a power supply during lengthy missions into space.

Bandwidth already manufactures III-V epiwafers for solar energy applications and claims to have more than 10 years of experience in TPV development.

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GaAs ICs

Broadcom bets 'n' is the next big thing

A favorite among the many "next big things" that are anticipated to increase sales of GaAs ICs, the high-speed 802.11 "n" protocol will improve the wireless LAN user experience, claims leading RF component supplier Broadcom. **Michael Hatcher** reports.



In the world of broadband wireless communications, a lower-case character is more significant than it might first appear. For wireless LAN, where the IEEE's 802.11 standards are critical, currently the "big" letter is "n".

Wireless LAN protocol has evolved rapidly over the past few years. First there were the "a" and "b" designs, operating at 5 GHz and 2.4 GHz, respectively. Although the higher-frequency "a" standard boasted the faster rate of data transfer, "b" had a much greater reach and it was the latter that became the most widely deployed.

Next up was "g", which combined the better aspects of the two previous standards. Since 2004, this particular version of the protocol has held sway and unit shipments have rocketed.

According to figures published in May 2006 by Strategy Analytics (see graph), 141 million wireless LAN systems shipped in 2005. That figure was expected to rise to 185 million for 2006 and 228 million this year, as demand for wireless connectivity continued to boom.

However, for makers of GaAs ICs, the landscape of this market is a little different to that of cellular handsets. GaAs-based transistors dominate the power amplifier (PA) slot in cell-phones, with a market share approaching 90%. But in wireless LAN, the different RF requirements and less stringent constraints on board space have seen a more even spread between SiGe-, silicon CMOS- and GaAs-based PAs.

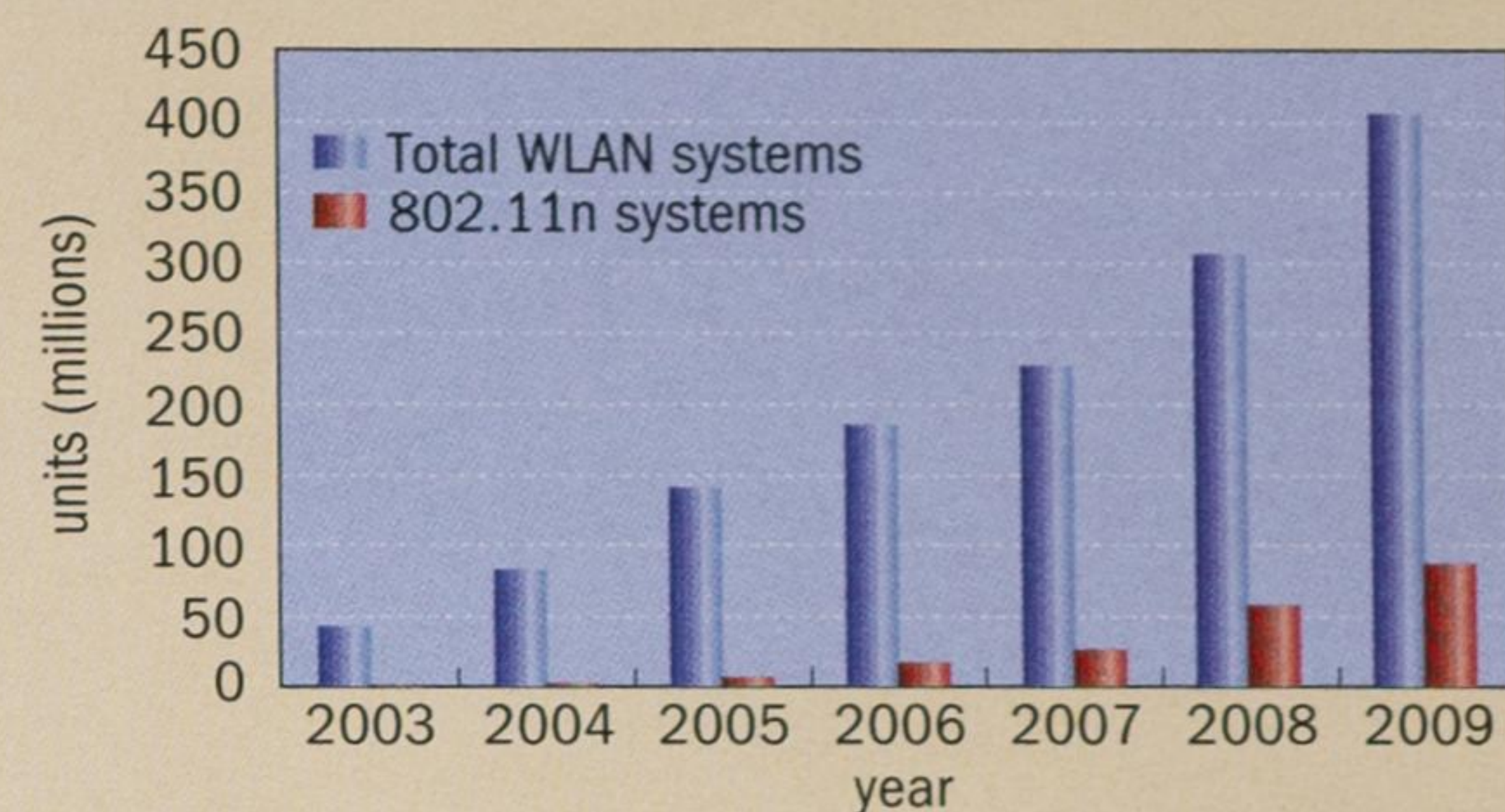
That could change, as the need for faster, more reliable connections, for data-intensive applications such as transferring large image or video files, gathers pace. This is where the advantages of the new protocol, 802.11n, really start to play out.

Bill Bunch is the director of 802.11n product management for Broadcom's home and wireless business unit. "We're really excited about 802.11n," Bunch told *Compound Semiconductor*. "The key thing to note is the overall improvement in user experience – a lot of people don't quite understand the quantum leap that 802.11n represents, but it is a fundamental upgrade."

Worries over regulatory issues and the ratification of the standard are now a thing of the past, Bunch added. Although some specifics of "n" are still to be nailed down (it is still officially referred to as the draft 802.11n standard), the major players have been in collaboration and Bunch says that the specifications were effectively solidified around a year ago.

Broadcom has become the single biggest player in the wireless LAN space, so the decisions that it takes have implications for the rest of the food chain. Traditionally, it had been a champion of silicon-based technology and announced the first all-CMOS 802.11b transceiver in September 2003. This chipset had all the major components, including the PA, on a single silicon die. And although it has also worked with GaAs specialists like Anadigics, many of its 802.11g products featured SiGe-based PAs from SiGe Semiconductor.

802.11n looks a little different. Broadcom has hooked up with Skyworks Solutions. The Woburn, MA, GaAs



On the up: it's not quite of hockey-stick proportions, but the slice of the overall wireless LAN market that will be taken by high-speed 802.11n connections is set to increase to 20% within three years. The trend towards higher-performance, smaller modules should favor GaAs-based solutions over SiGe and CMOS.

chip manufacturer is supplying front-end modules for Broadcom's "Intensi-Fi" chipset. The deal is not exclusive, but it looks like being a lucrative one for Skyworks and the reasons behind it are a direct result of the "user experience" of broadband wireless.

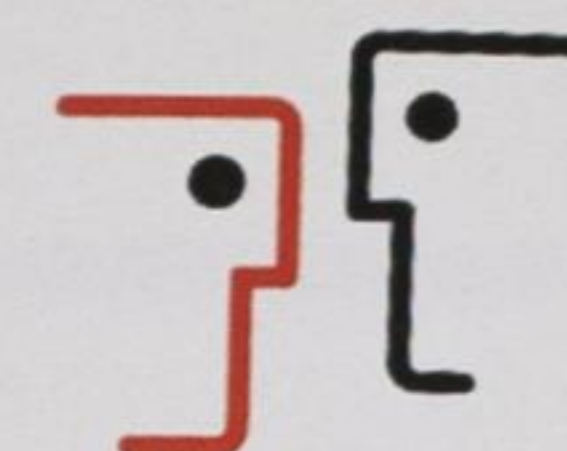
So what exactly does the new protocol offer the user? Bunch says that although the "g" standard offered a pretty good connection speed at close proximity to the local transmitter (around 24 Mbit/s), when users moved to the other side of their house the connection speed tended to drop closer to 3–5 Mbit/s or fail altogether. When it comes to data-heavy applications a large fall in connection speed is not a good user experience. "Even with only a small movement, it is possible for the connection speed [of "g"] to vary a lot," Bunch said.

"n" delivers 180 Mbit/s and a connection speed less affected by the relative positions of transmit and receive ports because the latest chipsets use a multiple-path input and output to smooth out spatial variations.

This is significant for component makers because it means that more RF chains are required inside the chipset. For a start, maintaining multiple 802.11n signals requires at least two PAs. Add to that the requirement for some dual-band systems operating at both 2.4 and 5 GHz, and you're up to four PAs. With the extra space needed and the tougher linearity requirements at the faster connection speeds, the superior performance of GaAs ICs compared with SiGe and silicon CMOS starts to become significant.

"The best price:performance ratio tends to win the business," said Bunch. "And Skyworks did well meeting this." That is not to say that Skyworks or GaAs is in all Broadcom's 802.11n chipsets. "It's a bit of a stretch that all 802.11n requires GaAs. In time, we will get to system-on-chip solutions. At high powers, GaAs will play a role."

By December 2006, Broadcom had sold 2 million 802.11n units in what looks certain to be a critical growth area for GaAs IC makers in 2007. 802.11n shipments still make up less than 10% of all wireless LAN system unit sales. By 2009 the proportion will be more like 20%.



NITRIDES

Humphreys rocks the InGaN boat

Working at the esteemed department of materials science and metallurgy at the University of Cambridge, UK, **Colin Humphreys** is arguably the GaN community's most candid researcher. **Jon Cartwright** visited his laboratory – the Cambridge Centre for Gallium Nitride.



UNIVERSITY OF CAMBRIDGE

How did your controversial views on light generation in GaN originate?

When GaN was first brought out as an LED, the most remarkable thing was that it emitted bright light despite having a huge dislocation density. Dislocations quench light emission, so people couldn't understand this. The belief developed that indium-rich clusters form in the InGaN quantum wells. These clusters would be a couple of nanometers across and would be away from where the dislocations were. So the light emission would also be separated from the dislocations. Everyone believed it because you could see these clusters in an electron microscope and analyze them as being indium-rich.

However, one day I had a research student who said: "Look, I've just turned the electron beam on to a very low intensity and when I study the first few frames there are no clusters at all!" This meant that these clusters must have developed under the beam in the electron microscope – they're not normally there in the material.

How did people react to this finding?

When we presented the work at an international nitrides conference, there was a stunned silence at the end. "There's something wrong with your materials," someone said. So we looked at material grown at other [fabs], like Nichia's, who claimed to make very bright LEDs by engineering the clusters. But again we found no clusters at all.

What is your alternative explanation?

Along with Phil Dawson at Manchester University, we proposed another mechanism, which was based on atomic structure. If you conduct a high-resolution electron micrograph of the quantum wells you find that the lower interface – the interface between the GaN and the InGaN – is sharp, but the upper interface has many more steps of atomic height on it.

These steps create extra strain energy in the quantum wells. And because the piezoelectric effect is high in these materials the strain creates a potential variation, which confines the electrons and holes. So it is nanoscale confinement that makes it unlikely for a dislocation to quench the light emission.

Is this mechanism now accepted?

When we published a paper at the end of 2003, we were alone in saying this. The nitrides semiconductor conference in [September] 2005 at Bremen had an evening symposium devoted to debating "do clusters exist?". I said they didn't, some said they did and others said maybe. But people are slowly coming around to it. Now, I think, 70–80% of the world agrees with us.

Shuji Nakamura's recent *Nature Materials* paper suggested that localized chains of indium atoms cause the localization. Does this fit your theory?

They say there is no gross indium clustering, which is in agreement with what we're saying. The paper proposes that there are indium fluctuations giving rise to localized chains of two or three indium and nitrogen atoms, and it's those chains that are causing the localization.

There are two things I think about this: one – that in a random alloy you will indeed get these localized chains, so the analysis is fine. But what is actually causing the localization of the electron-hole pairs? I don't think that they have actually calculated what the localization energy is in their paper. We can show [in our mechanism] by calculation that the steps on the InGaN quantum wells can create sufficient potential difference to cause localization.

I think in principle both [of our suggested mechanisms] could cause localization, but we're not yet sure which one is dominating. We need to find that out.

Is it vital to have such a fundamental understanding?

In blue LEDs, dislocations don't seem to quench the light emission. But when you go into the UV it is important because there is much weaker localization and dislocations have an enormous effect on light emission. If we can understand the localization then we may be able to increase it. Nobody has successfully done that yet.

You have just secured a joint £1 million (\$1.97 m) grant. How do you plan to spend it?

One application will be to develop the emission of UV-LEDs. But we also want to promote solid-state lighting. If we could get them into houses faster, LEDs would save a lot of energy. We have a contract with the Department of Trade and Industry on the reliability of LEDs.

People have assumed the lifetime of blue and green LEDs is 100,000 h, but it's based on the fact that red LEDs have been around a long time and they last for 100,000 h. In Singapore, where they have LED traffic lights, all the LEDs in the red lights work. But in the green ones a third of them aren't working at all and that's because they're InGaN. A Chinese solid-state lighting delegate whom I met said: "Many public buildings in Beijing are lit by white LEDs. But now they're dark – they're dead!" The white LEDs last for a few 1000 h or less and the problem is all in the packaging – the chip itself is fine. If you have the right packaging they could last for 100,000 h.

Now, Japan's government has got a national program in solid-state lighting, as has Korea and Taiwan. Even George Bush's America has a national program! But we [in the UK] have nothing. Lord Jenkin [a baron in the UK House of Lords] said to me: "It's a scandal!" We're doing world-class work here and the funding other people get is so high because the returns are so great. The lighting market is worth more than \$12 billion a year. So to put in a few million dollars is a good investment.

What industrial collaborations do you have?

Thomas Swan Scientific Equipment donate us the growth equipment and maintain it free of charge. And another good collaboration is with Forge Europa located in Cumbria, who sell LED-based products. We're their research wing. Recently we've been talking to another UK company with whom we have a project to grow GaN on 6 inch silicon substrates that could each contain 100,000 LEDs. If our work is successful for growing on six-inch silicon, they will manufacture in this country. There will, at last, be a UK LED manufacturer.

What specific projects are you focusing on?

The first project under the grant is studying localization, from the deep-UV right through to the green. The second is to reduce dislocation density.

The third project is non-polar and semi-polar growth. All [commercial] blue LEDs and lasers feature hexagonal GaN grown along the c-axis. This is called the "polar direction" and is the [direction of the] built-in electric field across the quantum well.

This electric field keeps the electrons and holes apart and so it delays their recombination. But there are other crystallographic directions you can grow along in GaN where there aren't these electric field effects and so you should get brighter devices.



JON CARTWRIGHT

We have been growing this material for about nine months and it is at least as good as other published results. Now we have got a major project grant to improve the growth, which should boost the intensity in blue, white and green LEDs.

What are the main applications for UV-LEDs?

One is water purification. Life has developed in the absence of deep-UV radiation because the Earth's atmosphere cuts it out. So life has not developed any defence mechanism against it.

There's a particular wavelength at approximately 270 nm that just kills everything by destroying the nucleic acid in DNA. So if you irradiate impure water with this wavelength it kills off all the bacteria and the viruses, mosquito larvae – everything. In the developing world you could have pipes to people's houses with a ring of deep-UV LEDs that kill all the bugs as the water flows through.

In 2004, the *British Medical Journal* stated that more than half the hospital beds in the world were taken up by patients suffering from diseases

related to impure water supplies. These diseases will, essentially, kill more people than global warming. They will probably kill more people than AIDS. Deep-UV LEDs could help to solve what is probably the biggest problem in the developing world.

"Deep-UV LEDs could help to solve what is probably the biggest problem facing the developing world – impure water supplies."

Colin Humphreys

University of Cambridge

Chip innovators eye airport

European researchers are developing high-frequency transistors based on a variety of radical technologies to power security-camera systems, probe distant galaxies and boost computer performance. **Richard Stevenson** investigates.

The events of 9/11 have changed our lives. Plane travel requires longer check-ins through increased security, while unidentified liquids have the capacity to ground aircraft. Unsurprisingly, there has also been a surge in the development of high-performance millimeter-wave screening systems that are able to expose dangerous and hidden substances (see figure 1), and consequently the transistor chips which are needed in the detectors.

Screening systems can distinguish between various objects by comparing their emissive and reflective properties at frequencies of tens to hundreds of gigahertz. But the radiation emitted by objects at these frequencies is weak, so the signals have to be amplified before detection. Transistor-based amplifiers produce the necessary signal gain and both GaAs – and InP-based technologies can be designed to operate at 94 GHz, 140 GHz and 220 GHz, the atmospheric windows where absorption is relatively low. These transistors also need to have low noise characteristics so that the amplifiers can produce sufficiently high contrast images.

At the Fraunhofer Institute for Applied Solid State Physics (IAF) in Freiburg, Germany, a team is developing HEMTs to meet these needs. The devices are less noisy than HBTs and are the foundation for many different components like amplifiers, mixers and detectors, which can all be formed on the same chip.

The IAF team's metamorphic InAlAs/InGaAs HEMTs have a 100 nm gate-length, an f_T of 220 GHz, an f_{max} of 300 GHz and an estimated mean time to failure of 30 million h. These devices amplify signals at 94 GHz, 140 GHz and 220 GHz (see figure 2), and are grown on 4 inch GaAs substrates. Michael Schlechtweg, the Fraunhofer IAF's head of RF circuit development, says that this platform offers benefits over InP in terms of cost, robustness and greater design freedom in the InGaAs layer composition.

With these components it is possible to make active and passive imaging systems that are analogous to cameras taking pictures with and without a flash. The primary contrast mechanism for these images is the temperature difference between objects. In the outside environment variations in temperature are significant and so passive systems can be employed, but for indoor screening active illumination at the detection frequency is required.

Active systems will be needed for airport security applications, while passive systems can serve a wide



Fig. 1. Substances that are now banned on flights can be exposed by active millimeter-wave imaging. (a) hides a nail file, sugar, artificial sweeteners, cocktail needle, copper wire and paper clip. (b) shows a paperclip. (c) and (d) are amplitude (c) and phase (d) images produced at Fraunhofer IZPF, a partner of Fraunhofer IAF.

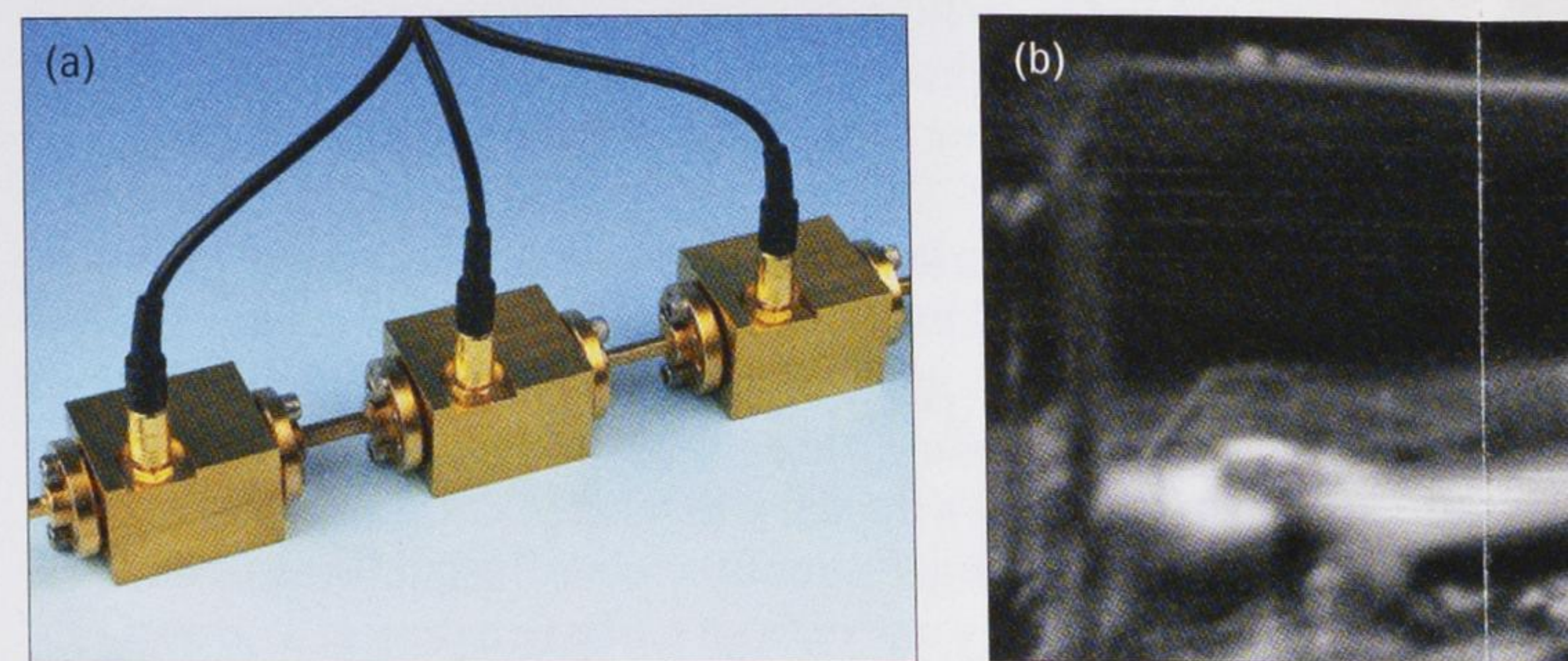
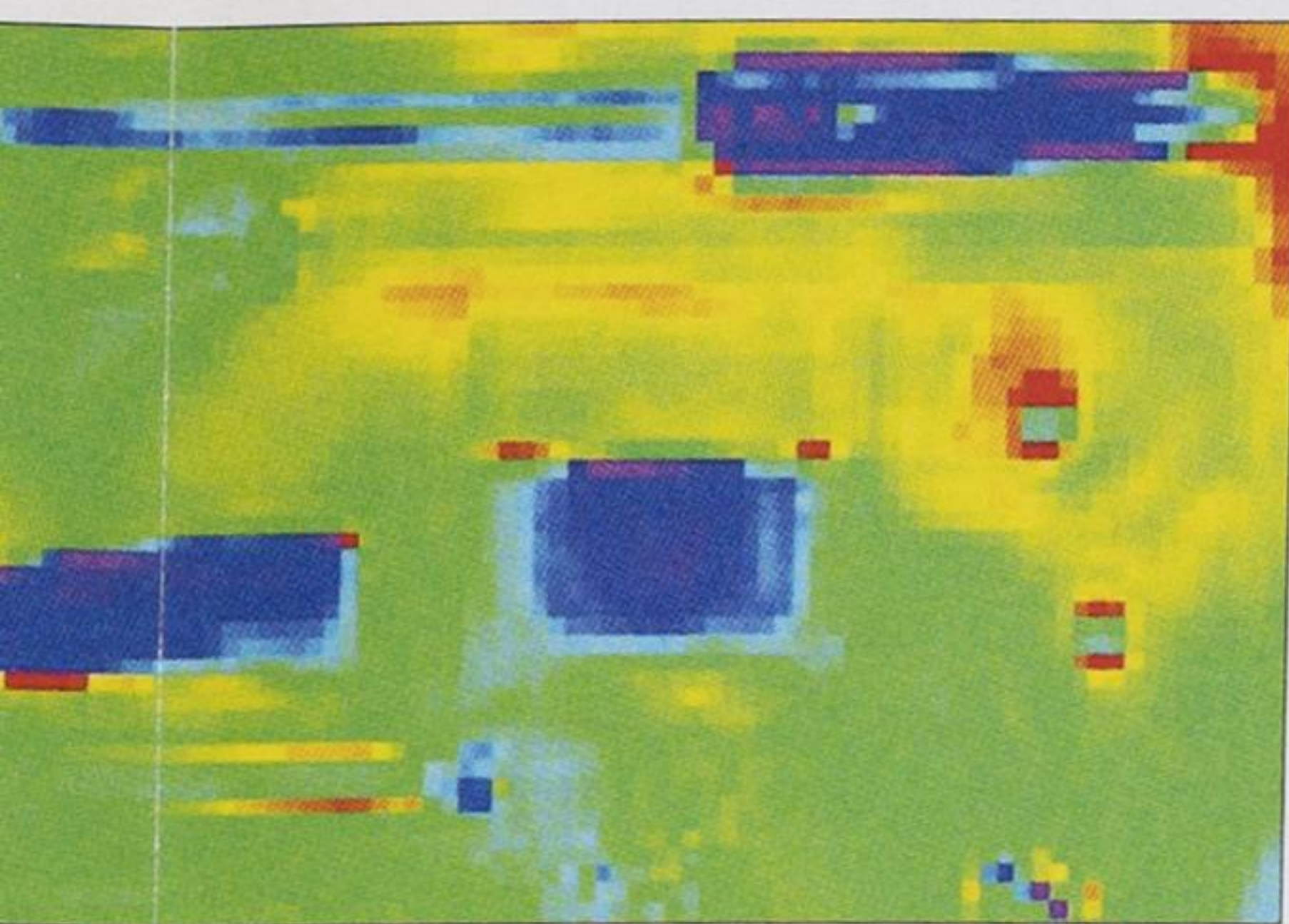


Fig. 3. Connecting three IAF 220 GHz low noise amplifier modules, the Fraunhofer team produced a 217 GHz (a). This enabled the first-ever passive millimeter wave imaging at 220 GHz (b).

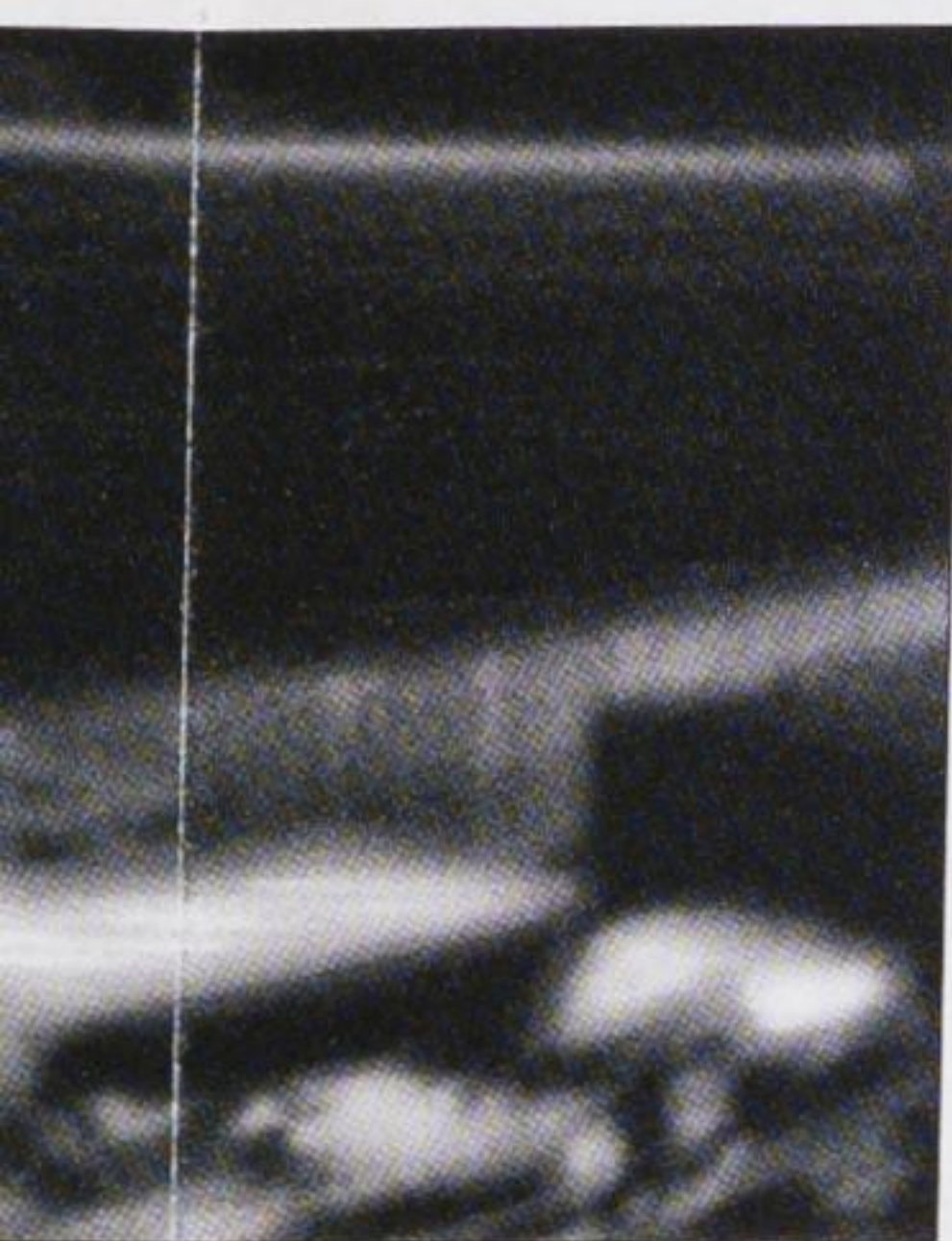
variety of other applications. This includes observations from space of the Earth's climate for weather forecasting and studies of climate change, and measurements of the cosmic background radiation that should be beneficial to cosmologists.

IAF is predominantly directing efforts at 94 GHz MMICs based on HEMTs, which are designed for both active illumination and detection elements. Systems incorporating these circuits will probably be available within the next few years. However, IAF transistors have also been used in the first complete MMIC-based 220 GHz passive imaging system, which was built late last year in partnership with the Research Institute for High Frequency Physics and Radar Techniques in Wachtberg, Germany (see figure 3). Higher frequen-

port surveillance equipment



millimeter-wave imaging technology. The package and paper clip (b), but they can be seen in the of Fraunhofer IAF.



ofer team produced a small signal gain of more than 50 dB from between 209 and 20 GHz (b), which can be compared with an optical image (c).



cies improve the spatial resolution of the images or enable reduced antenna size.

The IAF team has scaled gate lengths to 50 nm, boosting gain, reducing noise and increasing f_T and f_{max} to 400 GHz and 420 GHz, respectively.

Frequency triplers

Faster, more powerful chips based on InP are on the agenda at the Microwave and Terahertz Technology Lab, Chalmers University, Sweden. Instead of working with transistor technology Jan Stake's team is developing heterostructure barrier varactor (HBV) diodes that were invented there in 1989 (see box "HBV design" p18). These devices do not generate high-frequency emission themselves, but can triple or quintuple the

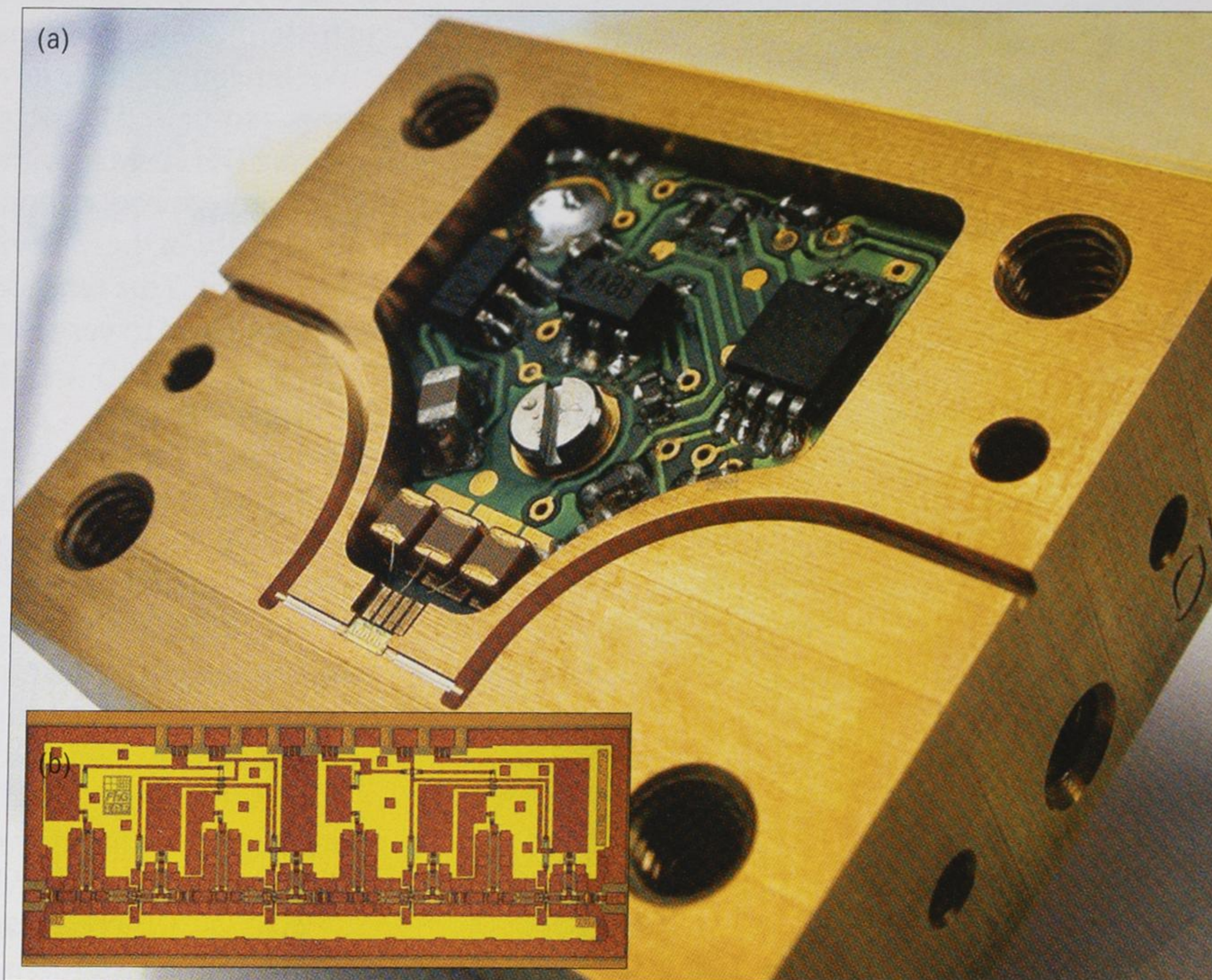


Fig. 2. At the Fraunhofer Institute a research team has developed 220 GHz low noise amplifier modules (a) that feature four-stage cascade low-noise amplifier MMIC chips measuring $1 \times 2.5 \text{ mm}^2$ (b).

frequency produced by another source efficiently.

The Chalmers group is targeting the frequency range from 200 GHz to 2 THz, which includes the so-called "terahertz gap", a range of frequencies that are not accessible with conventional transistors or quantum cascade lasers. Work at the lower end of this frequency range is being conducted under a Swedish defense project that is developing active imaging systems at 210 GHz for security applications. HBVs could boost the output power of these active systems, thereby improving image contrast. At higher frequencies HBVs could also be used in space-based radio astronomy instruments that can identify cosmic gases by measuring their absorption spectra.

Stake thinks that the group's most impressive result is a HBV tripler that delivers 0.2 W at 114 GHz. "It's not a very high frequency, but it is still a good result," says Stake. According to him, this latest device will fulfill the need for a more powerful lower-frequency source with which to pump high-frequency HBVs.

Stake adds that the main challenge associated with making high-performance HBVs is maintaining high-quality epitaxy throughout the structures, which are relatively thick. In fact, he wants to develop thicker devices by widening the buffer layer from the $0.5 \mu\text{m}$ used today to several microns. This should cut series resistance, leading to a decline in conversion loss.

However, progress has been hampered by problems

"Industry is not interested in developing a process to grow this structure, so we had to do it in-house."

Jan Stake
Chalmers University

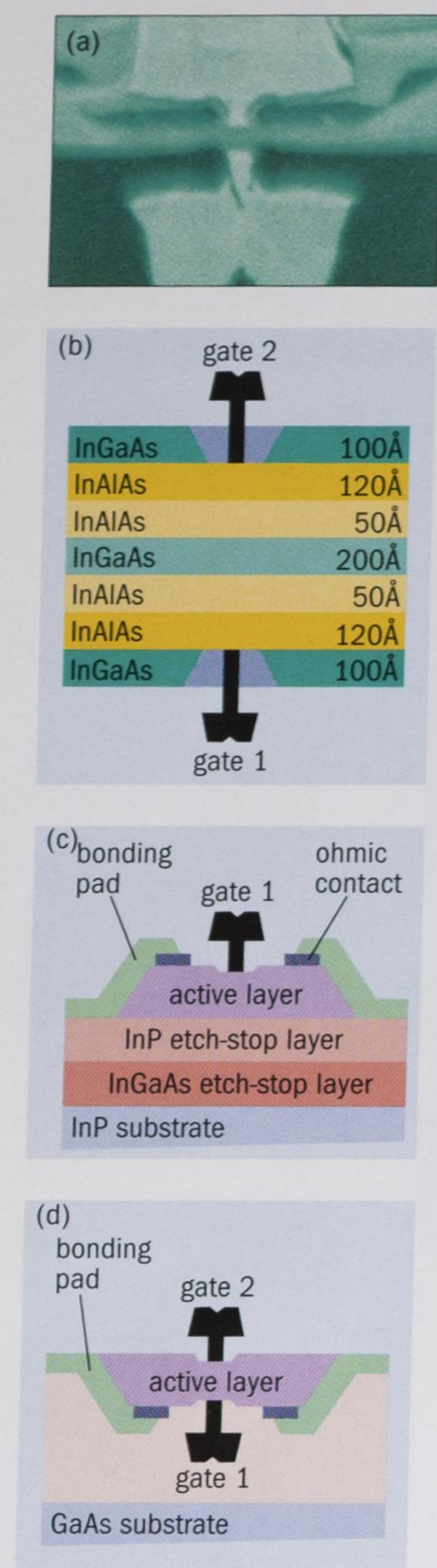
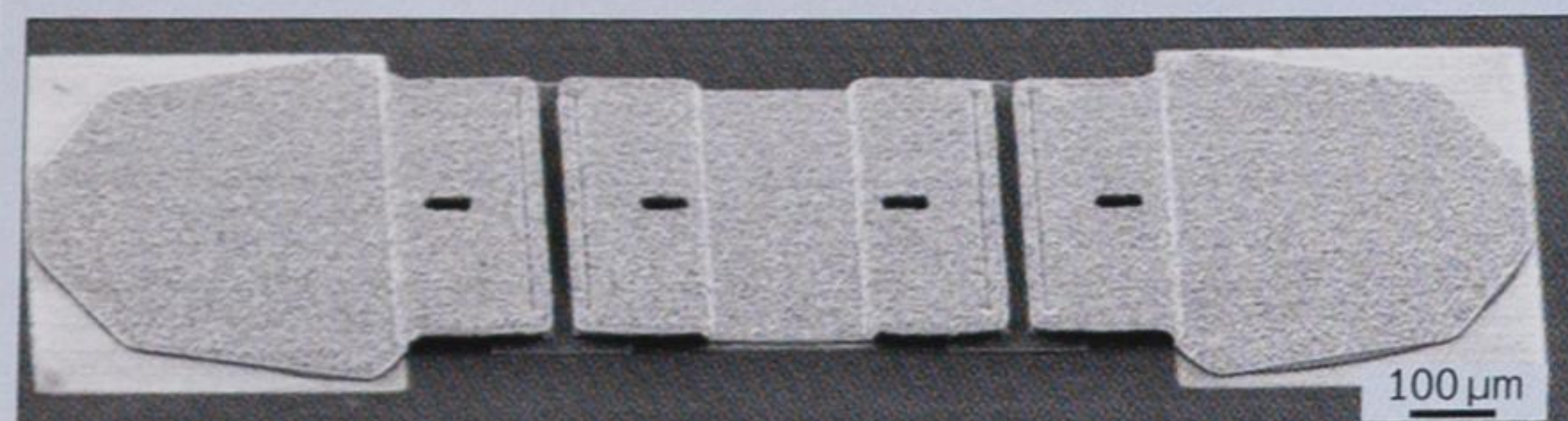
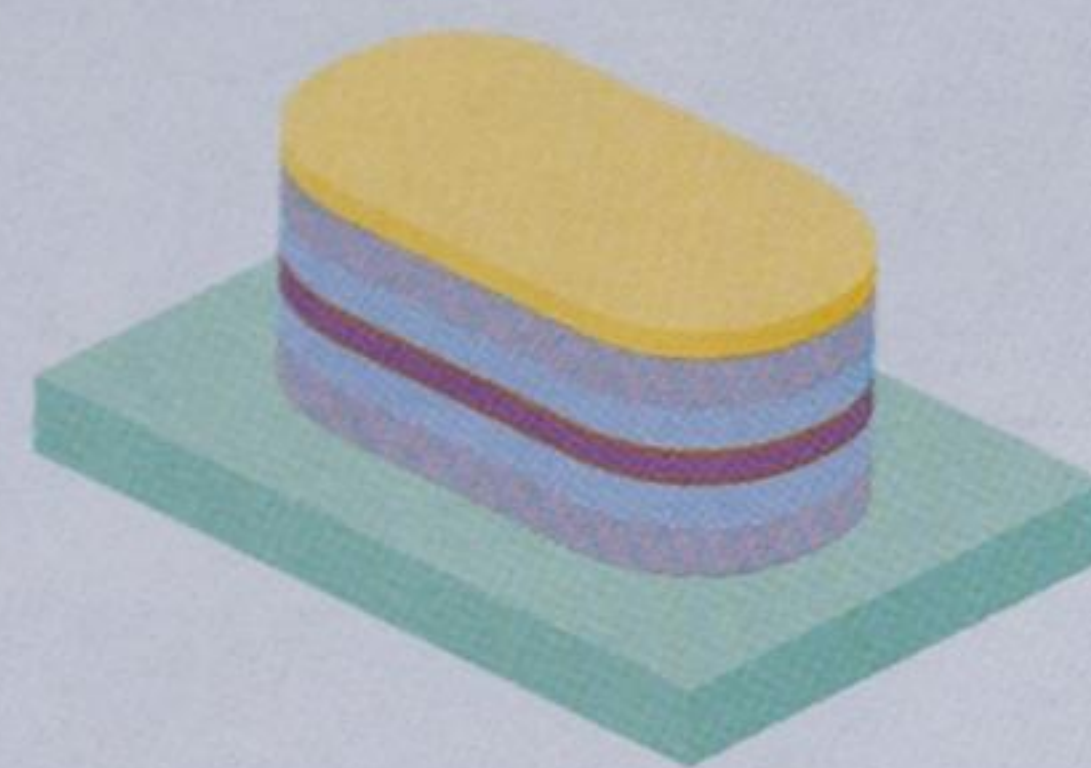


Fig. 4. The double-gate HEMTs made at the University of Lille consist of a 200 nm-thick InGaAs buffer, a 100 nm-thick etch stop layer and an active region of various InGaAs and InAlAs layers (a), (b). Device fabrication starts by forming a conventional HEMT (c). Adhesive bonding is used to form the second gate with a benzocyclobutene polymer that is applied to the epiwafer and GaAs substrate (d). Etching with various acids removes the InP substrate and the InGaAs and InP etch-stop layers before a second gate is made using the same process as the initial gate.

HBV design

contact metal
contact n^{++} InGaAs
modulation n^{+} InGaAs
spacer InGaAs
barrier InAlAs/AlAs
substrate S.I. InP



Heterostructure barrier varactor (HBV) diodes are single-channel devices that feature a barrier inside the heterostructure and are essentially an evolution of the resonant tunneling diode. However, unlike a diode, the device's capacitance is symmetric, while its current-voltage behavior is anti-symmetric. This enables the device to generate odd harmonics. The other advantage of the HBV over the diode is that it can generate higher powers if more barriers are added to the device.

At Chalmers University the HBVs are grown on InP before being flip-chip mounted onto an AlN platform that combines a high thermal conductivity with low transmission lines for improved losses.

in maintaining the indium-to-gallium composition ratio. Outsourcing the growth process has also proved impossible. "It's still such a niche application that industry is not interested in developing a process to grow this structure, so we had to do it in-house".

Additional gates

At the University of Lille, France, researchers are trying to raise the operating frequencies of InP-based HEMTs by taking the unusual step of adding a second gate. Nicolas Wichmann, who is heading the project, says that they need to take this radical approach because conventional HEMT performances cannot be improved by more scaling of device dimensions without severe trade-offs. Without any redesign, the HEMTs are limited to an f_T and an f_{max} of typically 500–600 GHz.

Wichmann and his co-workers have developed a process to make double-gate (DG) HEMTs, in which the gates can be either connected together or operated separately (see figure 4). When these gates are connected they reduce short channel effects, such as poor control of the electron concentration in the channel by the gate electrode, and boost transconductance.

The team has evaluated this new design by comparing the features of its DG HEMTs with conventional T-gate HEMTs that have an identical gate length of 100 nm. With its gates connected, the DG HEMT showed double the transconductance and a 30% rise in f_{max} to 288 GHz, but f_T fell by 8% to 192 GHz.

Although encouraged by the results, Wichmann admits that the DG HEMT's need for gate alignment

will make it harder to manufacture than its conventional cousin: "It's directly correlated to the precision of the e-beam system. If the gates are misaligned, charge control efficiency and charge confinement are not optimal." However, he points out that the DG process is only of comparable difficulty to that used for HBT production, which involves an etching undercut to define device dimensions.

Wichmann's team is now focused on another innovation – so-called velocity modulation transistors. These are DG HEMTs with two channels that have different charge transport properties. Modulating the electron velocity in these devices has a similar effect on drain current. This removes the intrinsic capacitance and should lead to very high cut-off frequencies.

Esoteric materials

The defense technology company QinetiQ is also developing high-speed transistors at its site in Malvern, UK. However, its approach involves using a more esoteric material, InSb, that provides the highest electron mobility and saturation velocity of any semiconductor. These properties are able to deliver transistors with very high speeds, low operating voltages and low power consumption.

Tim Ashley, who heads QinetiQ's InSb development, explained that the work began over a decade ago under funding from the Ministry of Defence (MoD). The aim was to investigate the potential of InSb and then advise the MoD of the implications. "At that time the only example of an InSb transistor was a thin-film device with a current on-off ratio of two", says Ashley, "and that's not a lot of good to anybody."

More recently the company teamed up with Intel. "We've been focused on pushing the technology forward with a view to examining its potential for microprocessors," explained Ashley. The partnership has produced quantum well FETs with a 85 nm gate length that have been designed to assess the parameters for digital operation and have an f_T of 340 GHz and a current on-off ratio of more than 1000.

QinetiQ's efforts are not the first attempt at developing III-Vs for logic applications. Supercomputer manufacturer Cray actually owned a 4 inch GaAs line before selling it to M/A COM in 1995. However, Ashley believes that the landscape has changed: "The complexity that's required for microprocessor circuits is so high that silicon has always kept ahead. What's changing now is that the silicon industry is looking to see what materials can be used to keep Moore's law running." The silicon industry is looking at a range of materials, says Ashley, and it's too early to claim that they've focused on any one in particular.

Ashley's team is also developing analog FETs that could tackle the same types of applications as those targeted by the researchers at Freiberg, Chalmers and Lille, but with the added benefit of the low power consumption linked with InSb. This conversion will implement variants of structures already employed on other III-V FETs, according to Ashley, who hopes to present work on these developments later this year.



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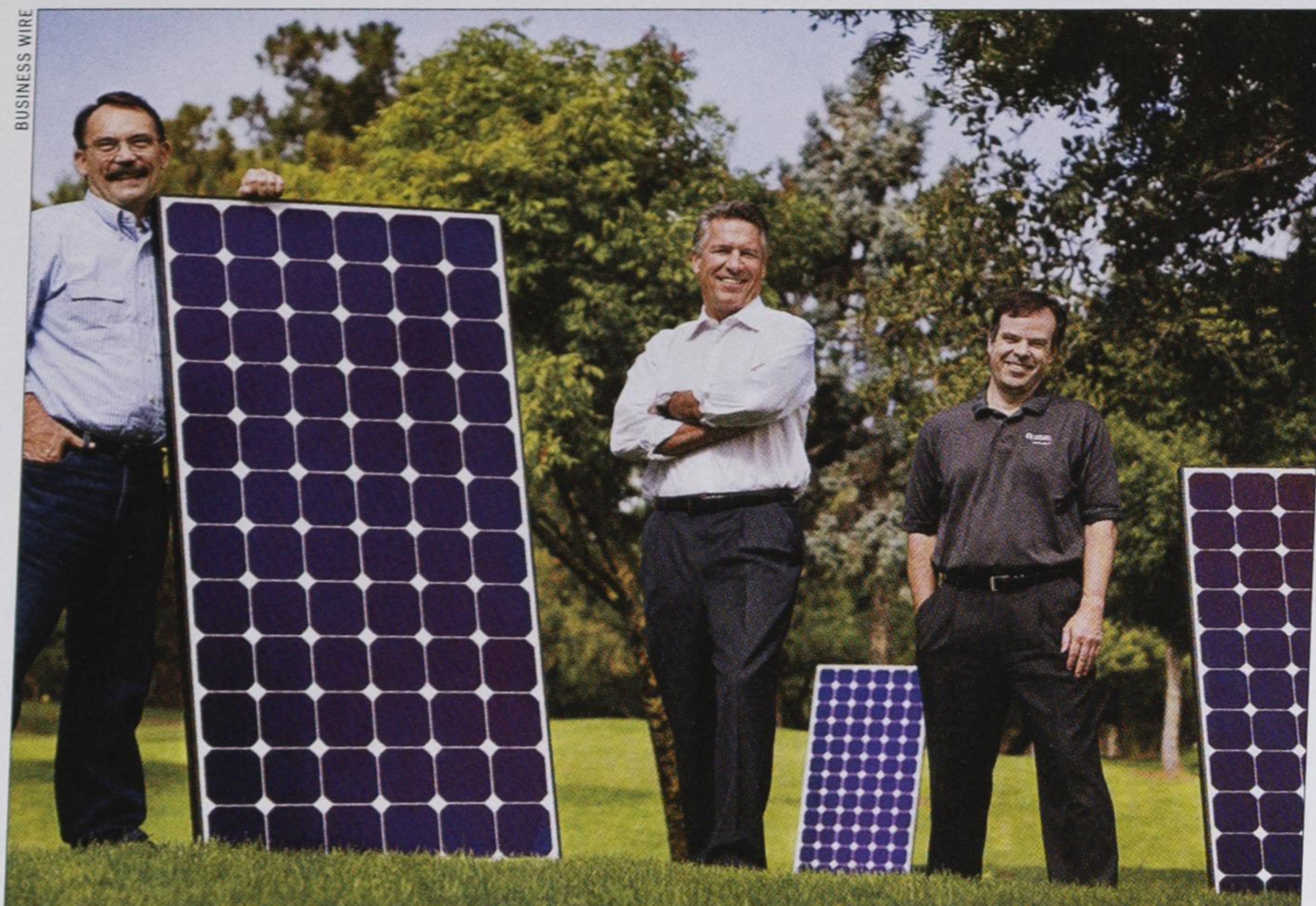
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Solar power: getting down to business

Already the darling of venture capitalists, the solar energy market has now attracted the attentions of the semiconductor community's biggest equipment supplier. **Michael Hatcher** finds out exactly where the opportunity for compound semiconductors lies in a sector that is virtually monopolized by silicon.



Going solar: Applied Materials' executives Charles Gay, Mike Splinter and Mark Pinto (left to right) at the launch of the company's solar power strategy. CEO Mike Splinter says that the solar photovoltaic equipment market has reached the inflection point that Applied Materials has been waiting for – where the company's manufacturing equipment can drive down the cost per watt for solar energy consumers.

solar power production 2004 - 2010

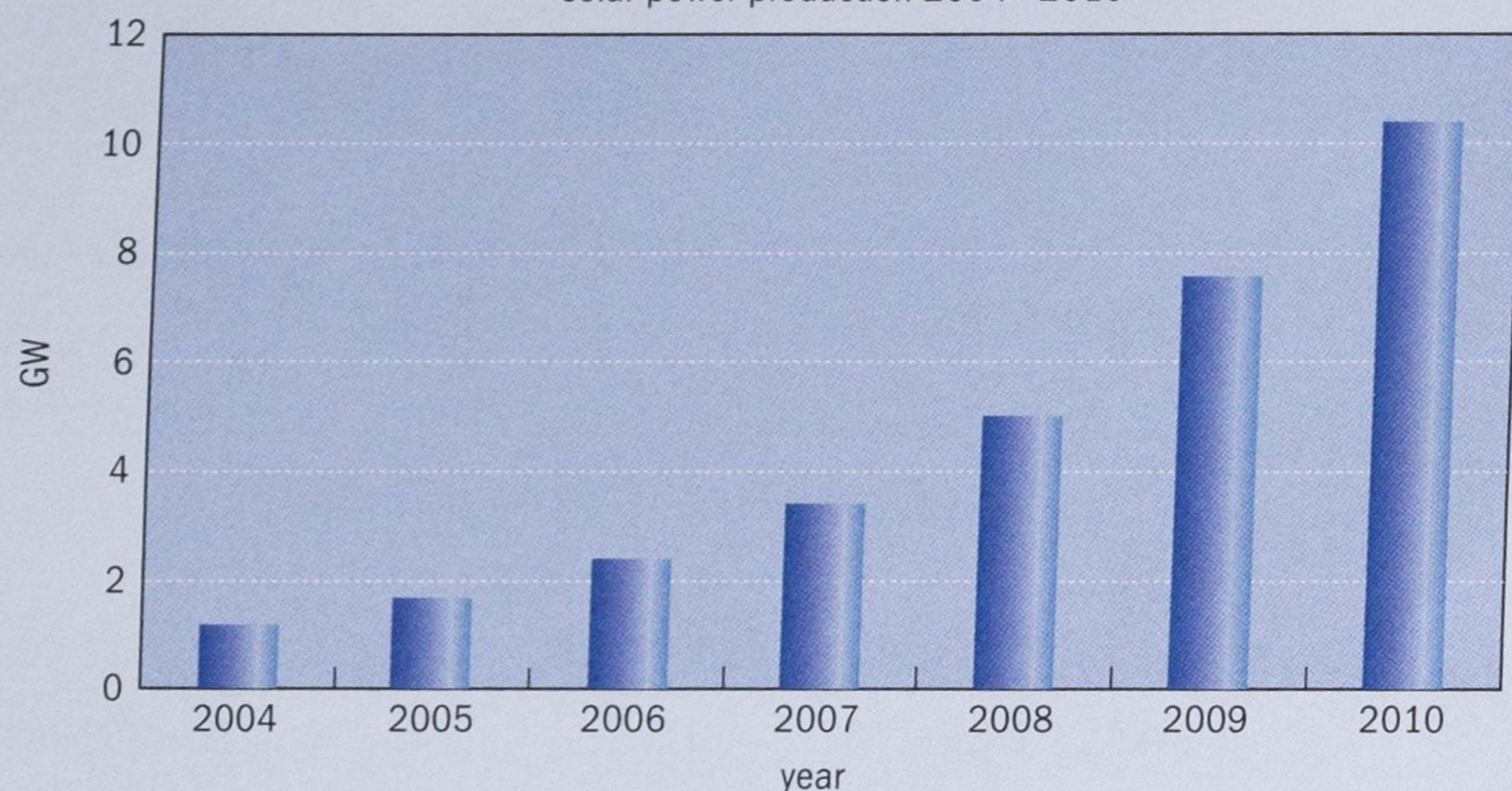


Fig. 1. Solar power production is expected to continue its dramatic ascent for the rest of the decade and beyond. Figures from Photon Consulting say that supply will reach more than 10 GW by 2010.

When Applied Materials launches a corporate strategy to target a new application area, you know that it must be something big – really big. The Californian equipment vendor has more employees than this magazine has subscribers (9314 – see page 2) and with an annual turnover of \$7 billion, any market has to have massive

financial potential for it to take a serious interest.

So last September, when Applied Materials launched its strategy to reduce the cost per watt of solar power during the 21st European Photovoltaic Solar Energy Conference, the event marked one of the most significant points in the evolution of the industry.

According to Applied Materials, the overall market for solar equipment is expected to soar from approximately \$1 billion in 2006 to more than \$3 billion in 2010. During that time, the technology is expected to move through a major transition, gear-shifting up from small-scale generators of 20–40 MW to sophisticated gigawatt-rated power stations capable of supporting much larger communities.

Of course, Applied Materials is focused squarely on the largest slice of the solar energy business – that which is powered by silicon semiconductors – and will supply PVD/CVD, plasma-enhanced CVD and sputtering equipment to cell manufacturers. But the company's timing is prescient and is important for the compounds sector too. Whether you measure revenue, company profits or generated power, this market is booming. High-profile Wall Street investment banker J Peter Lynch sums it up like this: "Photovoltaics is already the fastest growing industry in the world."

In their most recent annual report, market analysts at Photon Consulting measured global solar power production at 1.7 GW for 2005, barely a blip (less than 0.01%) on the scale of total global power demand – but still a big hike on the 2004 figure of 1.2 GW. In 2006, that number is expected to be 2.4 GW, representing year-on-year growth of nearly 50% (see figure 1).

"Initially, this 40 to 50% annual expansion of production raised concerns that a glut might reduce prices and margins," said Michael Rogol, lead author of the Photon Consulting analysis. "However, interviews with 400-plus solar power executives and policy makers... have fortified our conviction that demand will significantly exceed supply through the end of the decade and that prices are likely to remain high."

According to figures published by the Organization for Economic Co-operation and Development the original forecast for solar energy production in 2005 had to be revised upwards by 60% and this over-achievement is what caused the current shortage – and resulting high price – of the silicon used in most solar cells.

This supply and demand problem is where the market opportunity for concentrator systems based on compound materials really starts to emerge. Put simply, there is not sufficient crystalline silicon feedstock to meet the unexpectedly rapid ramp in demand, despite

the fact that production of the high-purity material required is expected to rise from 32,000 t last year to more than 85,000 t in 2010 (figures from Photon Consulting). The upsurge in demand for solar power will far outstrip that increase.

By the end of the decade, predicts Rogol, solar power generation will have hit the 10 GW mark. The disparity between this increase and the available crystalline silicon suggests that a substantial, widening gap in the market will exist for other technologies. At the moment, these only account for 9% of solar power generation, or 0.15 GW. In 2010, however, the proportion of solar power that comes from non-silicon technologies will grow to 20%, standing at approximately 2 GW.

Concentrator technology featuring III-V cells will share this sub-sector of the wider market along with cadmium telluride, copper indium gallium selenide, amorphous silicon and non-semiconductor approaches, so the big question for the likes of Emcore, Spectrolab and Sharp is just how much market share can their multijunction technology grab? At the moment, they are confident that it will be a lot.

The key advantage that concentrators have is the ability to dramatically reduce the cost of every watt generated by solar power – despite the relatively high expense of the individual cells. Emcore's Earl Fuller puts it like this: "[It's] the largest knob available for making expensive solar cells less expensive."

Speaking late last year, Hojun Yoon from Spectrolab neatly illustrated the scalability of multi-junction concentrator technology. If a football field was completely covered in 17% efficient silicon solar cells, he said, it would produce around 500 kW. The same area of multi-junction cells under a concentration of 500 suns would increase that figure by a factor of a thousand to 500 MW – a power output that is far higher than even the very biggest solar installations currently operating.

Critical element

Of course, the cell is just one element – albeit the most critical one – in any solar power generator. A major reason why solar power development has not been even more prolific is because the added costs of each module and system are relatively high, when compared with the relatively small number of watts generated (see figure 2). All of the glass, metal and plastic components that are needed to make up the so-called "balance of system" add to this cost. The best way to offset the cost is to use the highest efficiency cells available so that each watt produced costs less to convert.

So a critical target to reduce conversion cost has been to get the conversion efficiency of the bare cell up into the 40–50% range. Working with the US Department of Energy, Spectrolab has now reached 40.7%, a figure ratified by the National Renewable Energy Laboratory. Fuller says that Emcore will also breach the 40% mark in 2007, while Yoon reckons that 45% is achievable by 2010, assuming that the current average annual increase of around 1% is maintained. As the technology improves, the downward pressure on the key \$/kWhr metric is dramatic (see figure 3).

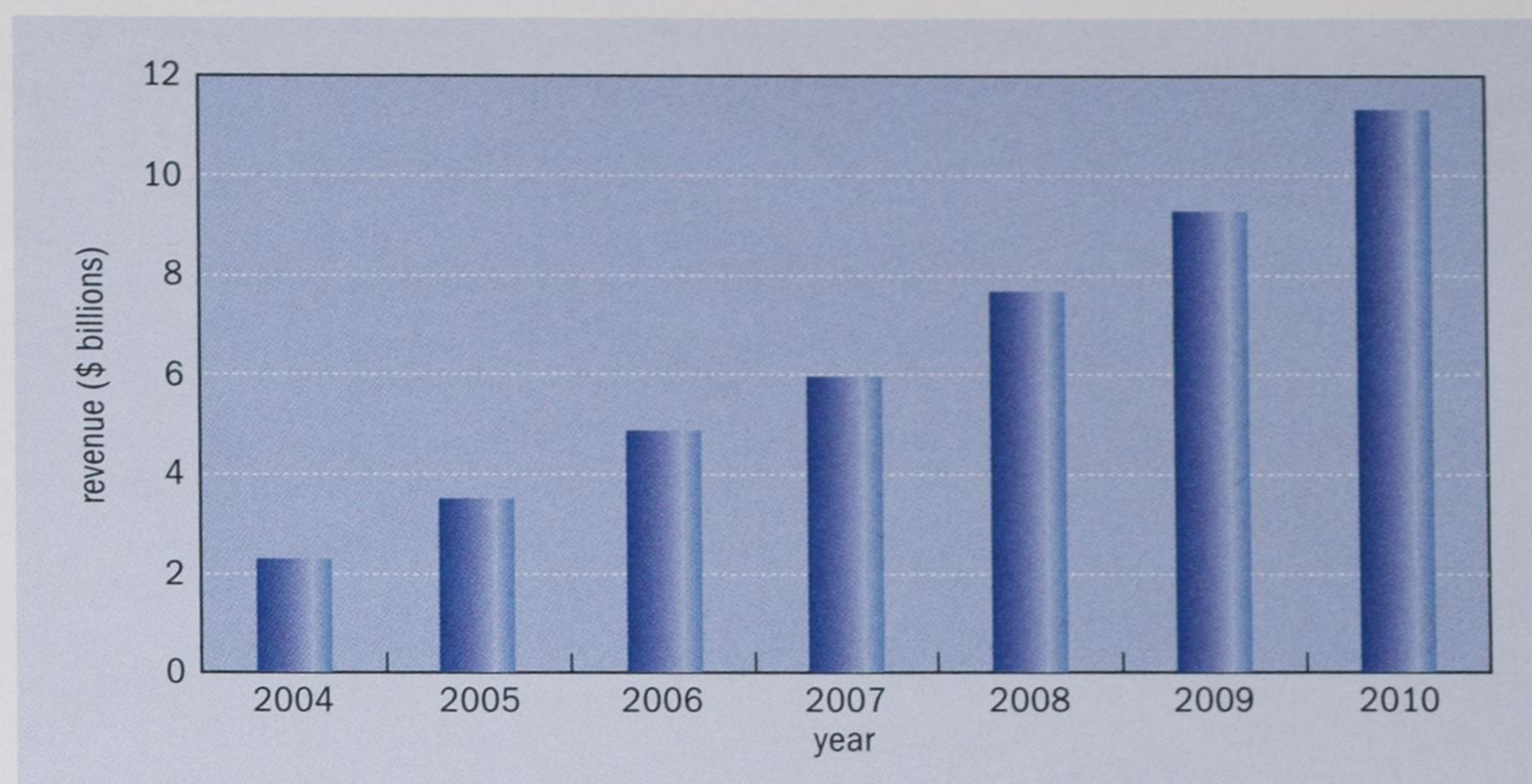


Fig. 2. The solar cell is only one part of the system, but it is estimated to account for one-third of the overall solar sector. The market for bare cells alone is expected to jump to more than \$11 bn in 2010, but 80% of those cells will be based on silicon. III-V chip manufacturers will have to fight against other non-silicon solutions for the remaining market share. Source: CLSA Solar Power Sector Outlook/OIDA.

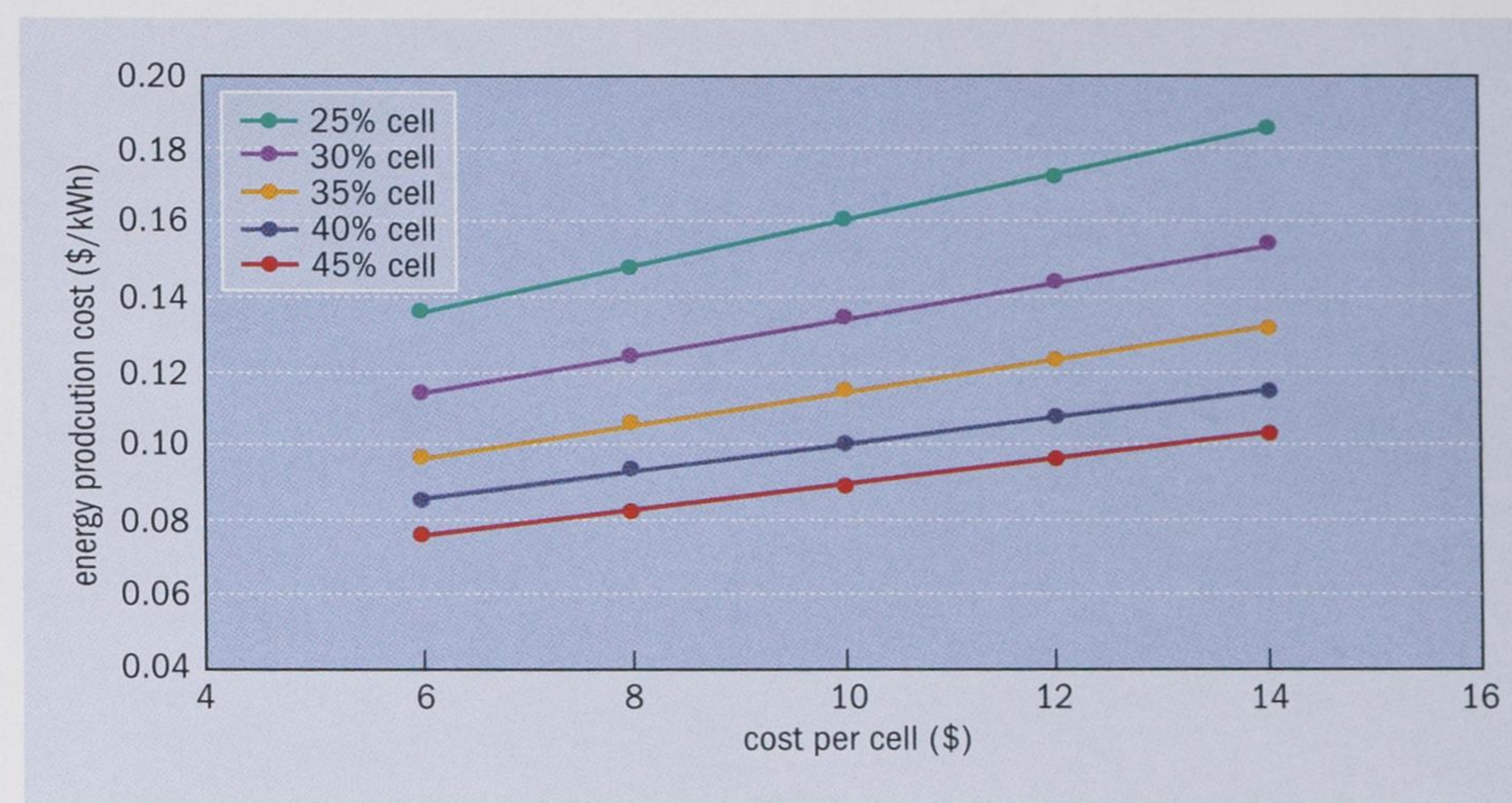
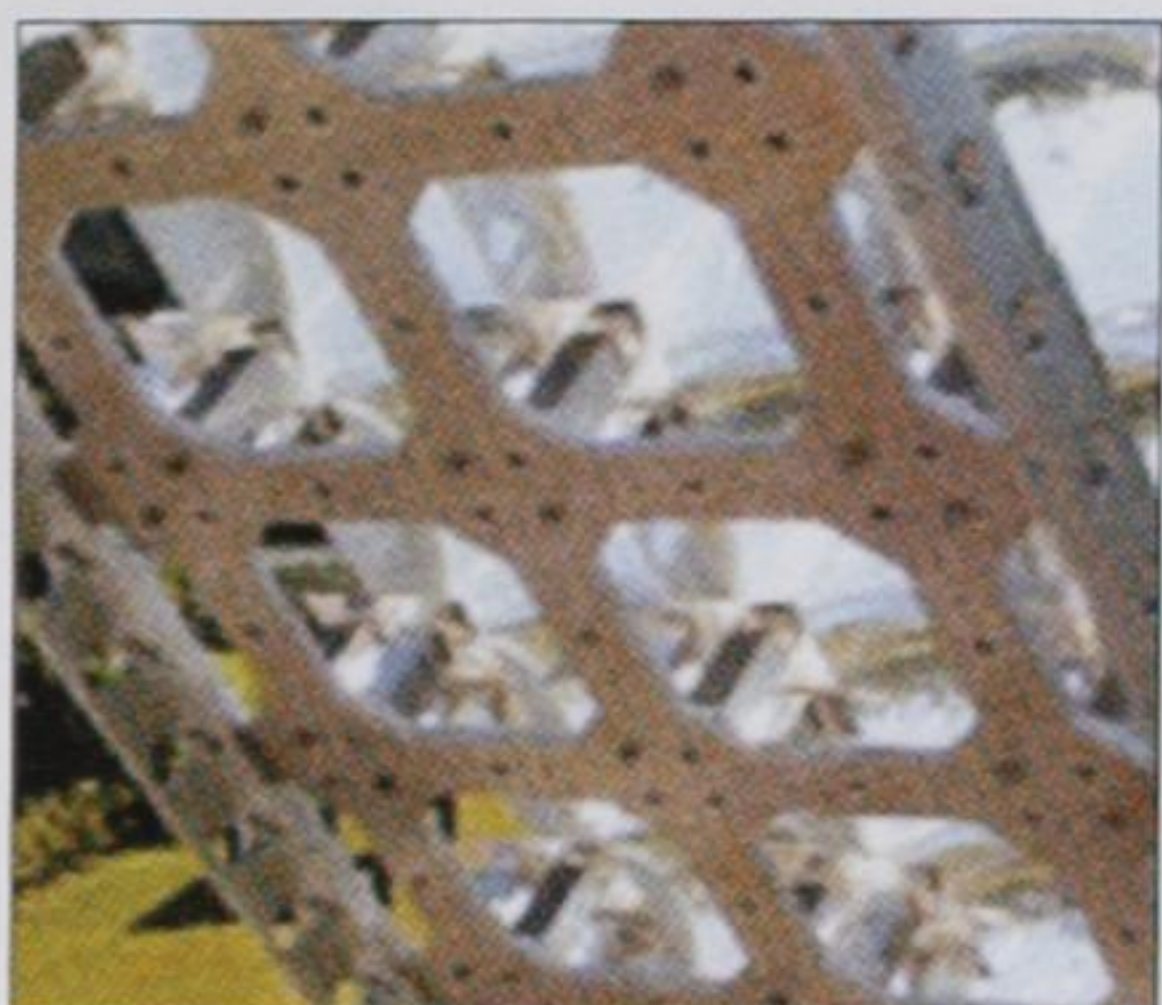


Fig. 3. Increasing the efficiency of the converter cell has by far the most significant impact on the cost of electricity generation. This graph from Spectrolab demonstrates how the production cost of each kilowatt-hour can be reduced to less than \$0.10 with 40 or 45% efficient cells.

At its Albuquerque, NM, facility, Emcore has eight MOCVD reactors ready to churn out solar cells on 4 inch germanium, equivalent to an annual terrestrial power generation capacity of 50 MW. The company's ultimate goal is to get the cost of a solar power plant down to just \$2/W (Photon Consulting estimates the current average module price to be \$4/W and full installation at \$8/W) and drive generating costs after installation to below \$0.1/kWhr. But exactly where will these systems be deployed? According to Fuller, off-grid village power and grid-connected large-scale solar farms – expected to be worth 16% of a \$1 billion market by 2010 (or about 80 MW of demand) – will be the key applications that deliver III-V solar its initial foothold in the market.

Just across the street from Emcore's Albuquerque fab is Sandia National Laboratories, with which Emcore is collaborating on module and system development. Achieving higher conversion efficiencies will require new cells with even more junctions and that



Utility-scale deployments

such as this installation featuring Emcore cells (top) are where we will initially see III-V solar technology, but rooftop installations for large apartment buildings could also be feasible. In Japan, Sharp and Daido Steel have developed this 500-sun concentrator (bottom), which produces an output of 3 kW.

will mean some very complex material deposition, possibly through the integration of InGaN-based alloys to improve short-wavelength conversion.

Like Fuller, Yoon sees a major opportunity in village and grid-connected utility-scale power production, but he adds another, potentially very lucrative, possibility – rooftop power. For rooftop applications, different concentrator designs would be required, but the rewards for penetrating this higher-volume application successfully could be huge. Rather than powering individual houses, where cost and installation difficulties would be prohibitive when compared with silicon technology, he thinks that concentrator systems could power large apartment blocks housing perhaps a few hundred residents. In Japan, Sharp and Daido Steel have already demonstrated such a prototype system that produces 3 kW at a 500-sun concentration.

Although the market value for solar power systems is set to rocket, the rewards may not be felt quite so strongly by epitaxy equipment manufacturers. Yoon says that Spectrolab could already make enough cells to generate 200 MW using half of its existing capacity.

A dramatic shift?

Wherever they end up being deployed, there is little doubt that III-V cells will have an increasing impact on terrestrial solar power generation. Recent supply deals such as the order for half a million Spectrolab

cells for use in an Australian power station have demonstrated an initial acceptance of the technology. More should be forthcoming: Emcore's late-2006 strategic investment in WorldWater and Power includes provision for a major supply deal that could dwarf anything seen so far. In Spain, solar system maker Isofoton has agreed a collaboration with local energy company ENDESA that includes the demonstration of GaAs-based concentrator systems for future deployment. And California's SolFocus, recently showered with venture funds, says that concentrator cells are the practical solution to the silicon shortage.

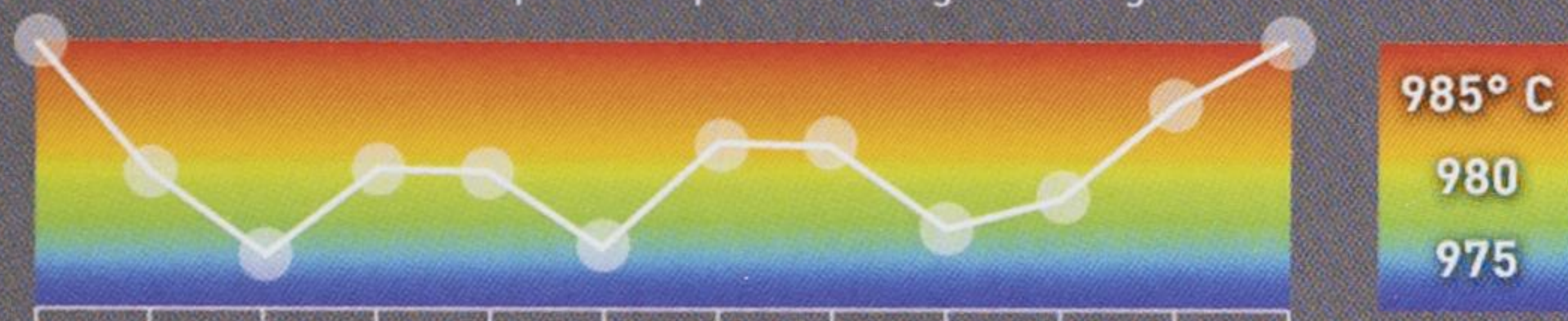
As Fuller pointed out, there has already been a dramatic technological shift in satellite power supplies from silicon to III-V cells. "In the mid-1990s, 80% of satellite power was generated by silicon solar cells," he said. "Today, 80% of satellite solar power is generated by III-V multi-junction cells."

Fuller also posed the unanswerable question: "Can III-V's prominent position in the space power market result in the same market diffusion [on Earth]?" Perhaps. But, given the greater number of rival technologies, allied to the fervent, perhaps fleeting, financial interest in solar energy, perhaps not. Even so, with high oil prices and worries over global warming set to continue there will likely be a very large pie available – and even a small slice of that could mean big wins for compound semiconductors. ●

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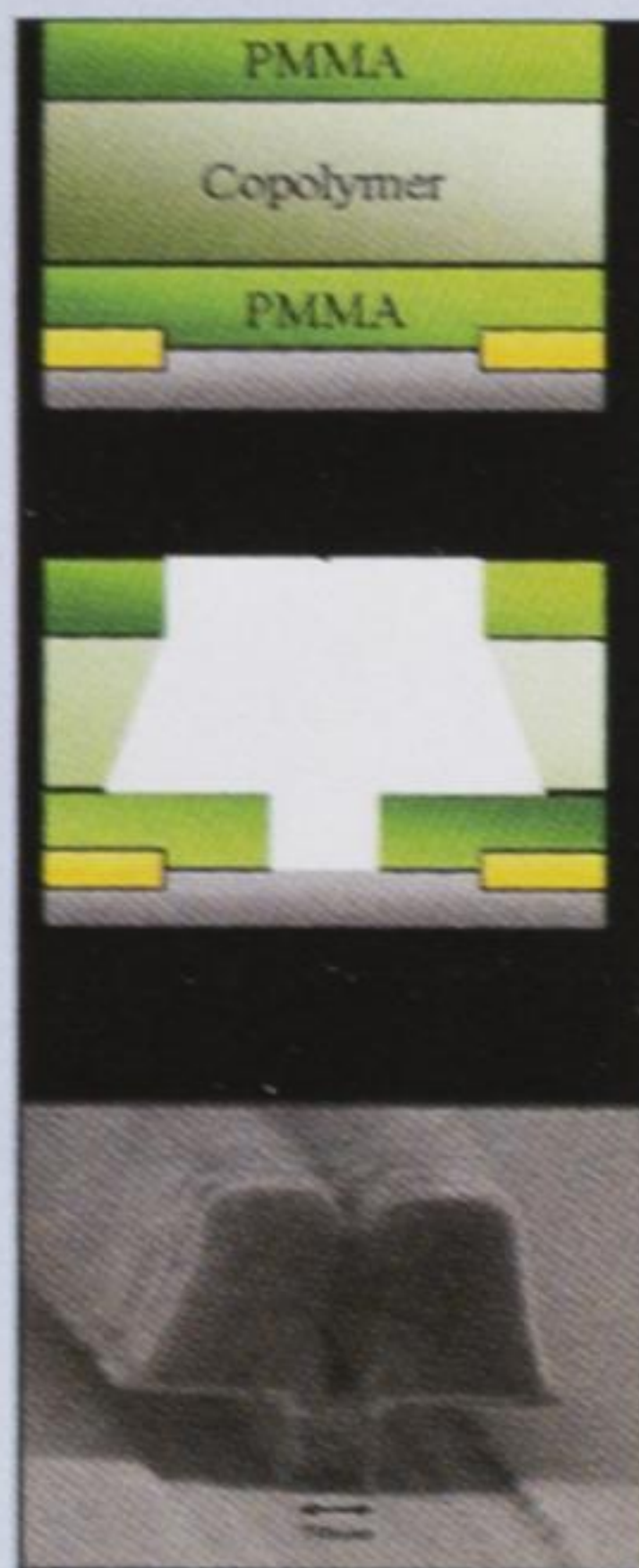
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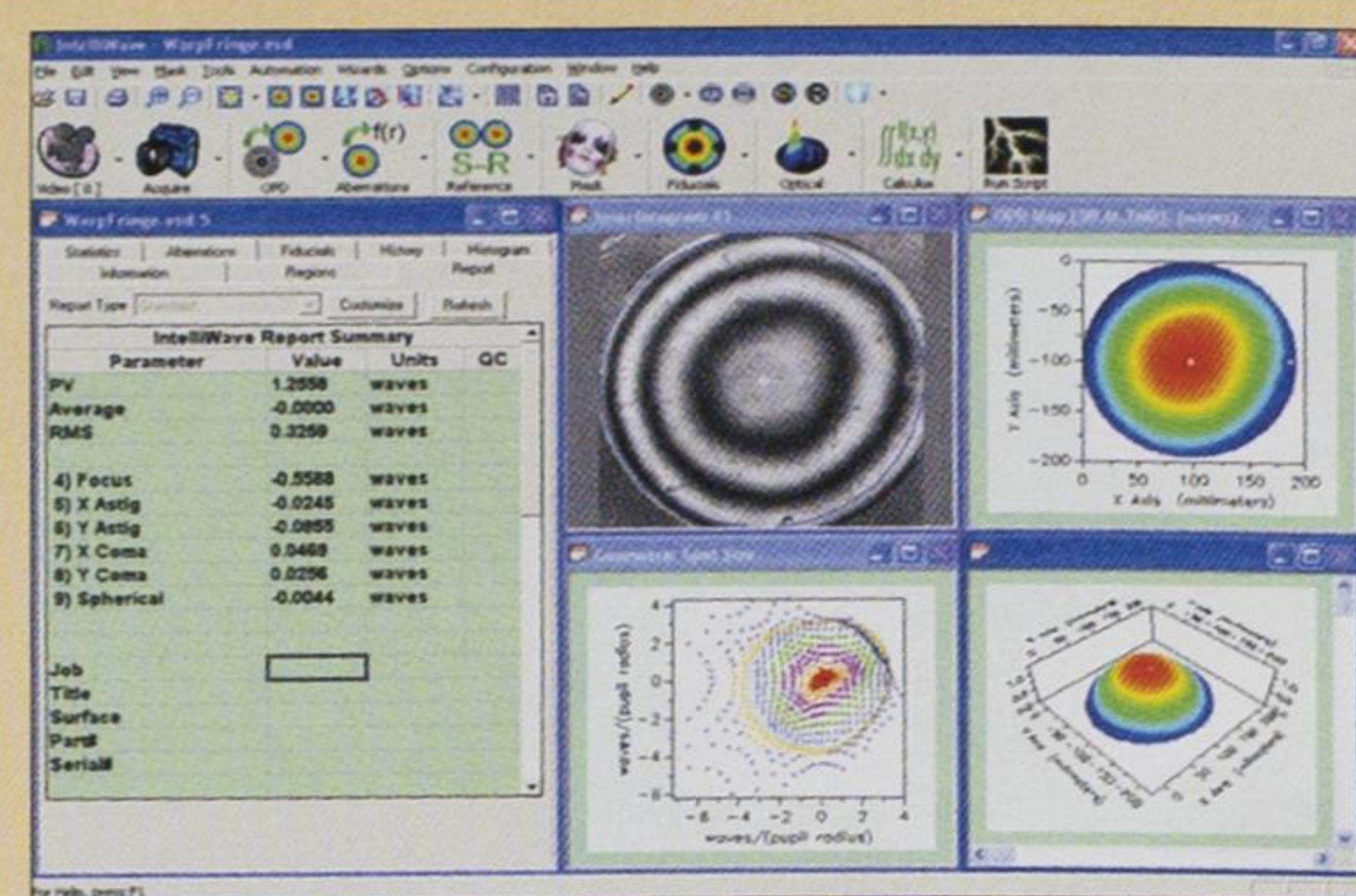
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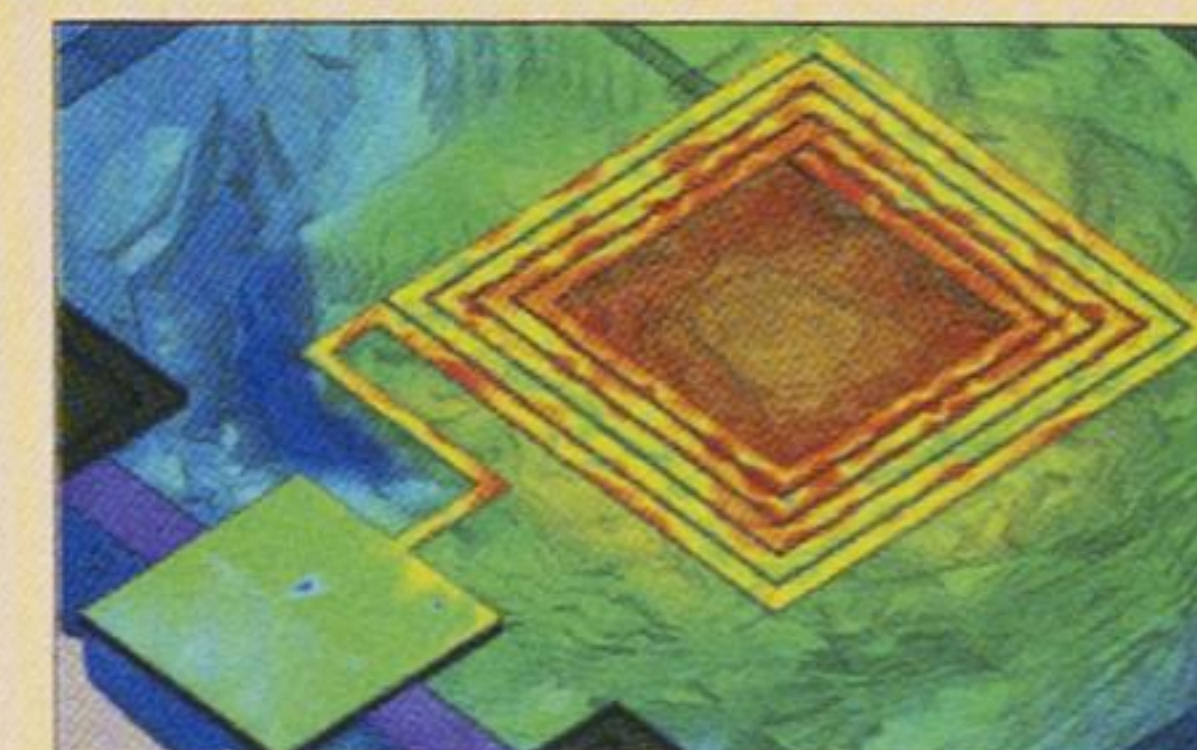


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Dedicated software uncovers failings in communication circuits

Many MMIC and RFIC designers are still using primitive modeling techniques that ignore image noise and non-linear effects. Because these omissions can postpone product launches and hit sales, argues **Chris Paris**, designers should use dedicated software that can expose circuits' weaknesses.

Wireless communications technology serving commercial and defense markets is evolving at a rapid pace. The changes are putting pressure on MMIC and RFIC designers to deliver products with higher data rates and discover the "killer applications" for cellular, satellite communications, wireless LAN (WLAN), software radio, and WiMAX markets. For success, products must hit the market ahead of the competition, as the typical lifetime for consumer electronics is only two to three years and a six-month delay can mean a wasted opportunity. Consequently, engineers need to gain a detailed understanding of the RF system fast.

Clinging to the abacus

Unfortunately the electronic design automation (EDA) tools at the system level are inferior to those at the digital and circuit level and have fallen behind the needs of the designer. Engineers are instead relying on spreadsheets, the computational equivalent of the abacus, for a first-hand analysis of system-level performance.

This modern abacus is an effective computational tool but it fails to deliver an in-depth analysis of the RF link performance. This lack of precision means that several cycles of design iterations and breadboard tests are required to hit the desired specifications, which slows the product release and impacts on a company's sales. However, this weakness is not to be interpreted as a criticism of designers who use spreadsheets as their first pass design tool of choice, but a reflection of the paucity of alternative software available over the past 20 years of the wireless revolution.

Another weakness of spreadsheet-based analysis tools is that they eat into the time engineers spend developing communications technology because months are lost to perfecting spreadsheet macros. These are often optimized for a specific structure, which means that time is also required to develop more spreadsheets for analyzing new structures. The personalized nature of these spreadsheets is also problematic. If they are passed on to another engineer the recipient can be unaware of idiosyncrasies and caveats contained within the tool, and this can lead to erroneous specifications.

On top of all these flaws, most spreadsheets suffer from one fundamental failing: incorrect calculations of the noise that determines the RF link quality in components such as receivers. This error arises because the



The lifetime of wireless products is typically only a few years so it is essential to release them quickly, which means swift development and circuit testing. Many of today's designers are working with spreadsheets that slow this design cycle, but improvements can be made by switching to targeted software that accelerates this process through more accurate modeling of the circuit performance.

calculations for the cascaded noise figure (NF) – the noise that results from a string of RF components connected to form a circuit – use a formula that ignores image noise (see box "What is image noise?"). In addition, spreadsheets often omit factors such as phase noise and impedance mismatch between components.

These oversights produce ballpark results of typical cascaded values and a superficial view of RF link performance. Although this can be addressed by manipulating the spreadsheet to account for the missing features, it requires expert knowledge and precious time.

We believe that a more effective approach to ana-

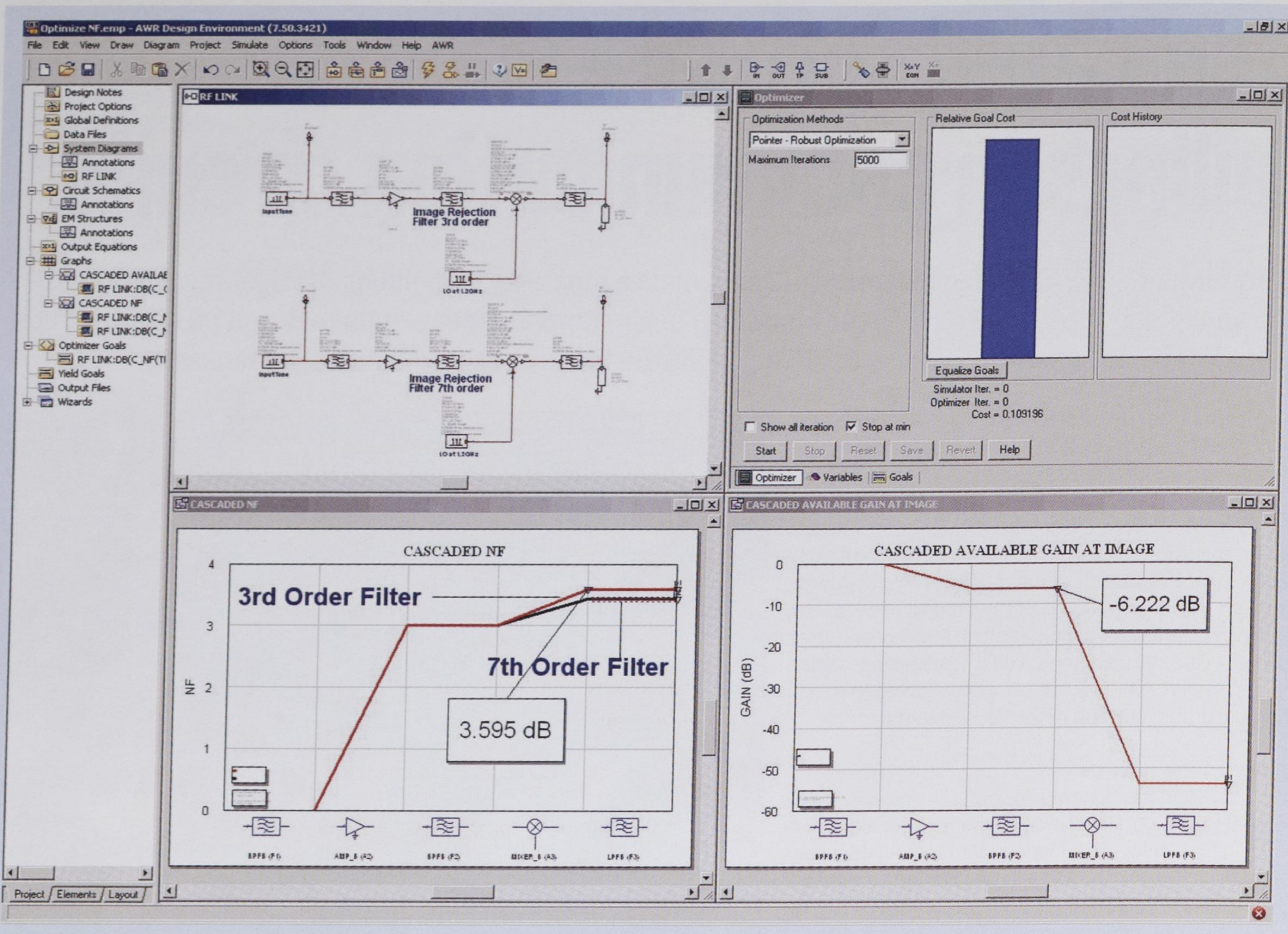


Fig. 1. This screenshot shows the RF Budget Analysis tool from Applied Wave Research's Visual System Simulator. The software is being used to compare two typical circuits for MMIC front end receiver links (top left) that are distinguished by third-order and seventh-order image noise rejection filters. Calculations of the cascaded noise figure and the available gain are shown in the bottom parts of this image. Values for the adjacent channel power ratio, error vector magnitude and bit error rate can also be calculated.

lyzing wireless circuit performance involves using Applied Wave Research's RF Budget Analysis tool, which was released in September 2006. This software, which can run on a standard PC and is part of Applied Wave Research's updated Visual System Simulator (VSS) RF Analysis (RFA) tool, enables designers to make traditional RF cascaded measurements along a communication link of properties such as gain, noise figure and third-order intercept, inclusive of image noise. With this tool MMIC and RFIC designers can also explore the interactions of components within the radio design at the system level before individual components are connected together at the circuit level.

Some of the benefits of our software, which can reduce design cycle times and accelerate product launches, are illustrated in a comparison between two typical MMIC front end receiver links (see figure 1 for a screenshot of our software that compares the two scenarios). These circuits, which can be evaluated in a matter of seconds, feature two different image noise rejection filter in links that also contain a bandpass filter, low-noise amplifier (LNA), quadrature mixer, low

What is image noise?

Image noise is a consequence of the nature of simple analog multipliers or mixers that do not preserve polarity. This noise is seen in a typical "down-conversion" process, which produces the signal at the center frequency from the difference between the mixer's local oscillator frequency and the input frequency. This center frequency also features a contribution from a higher frequency, referred to as the image frequency, which produces a signal at the center frequency when down-converted. Not accounting properly for image frequency can lead to incorrect values for the RF link quality. The amount of image noise that is added is dependent on how much of the image frequency band is present at the input of the mixer and its effects can be reduced with image noise rejection filters.

pass filter and a 50 Ω terminating load.

The seventh-order image noise rejection filter produces an RF link with a 3.4 dB NF, 0.2 dB lower than that using a third-order filter. However, it has the

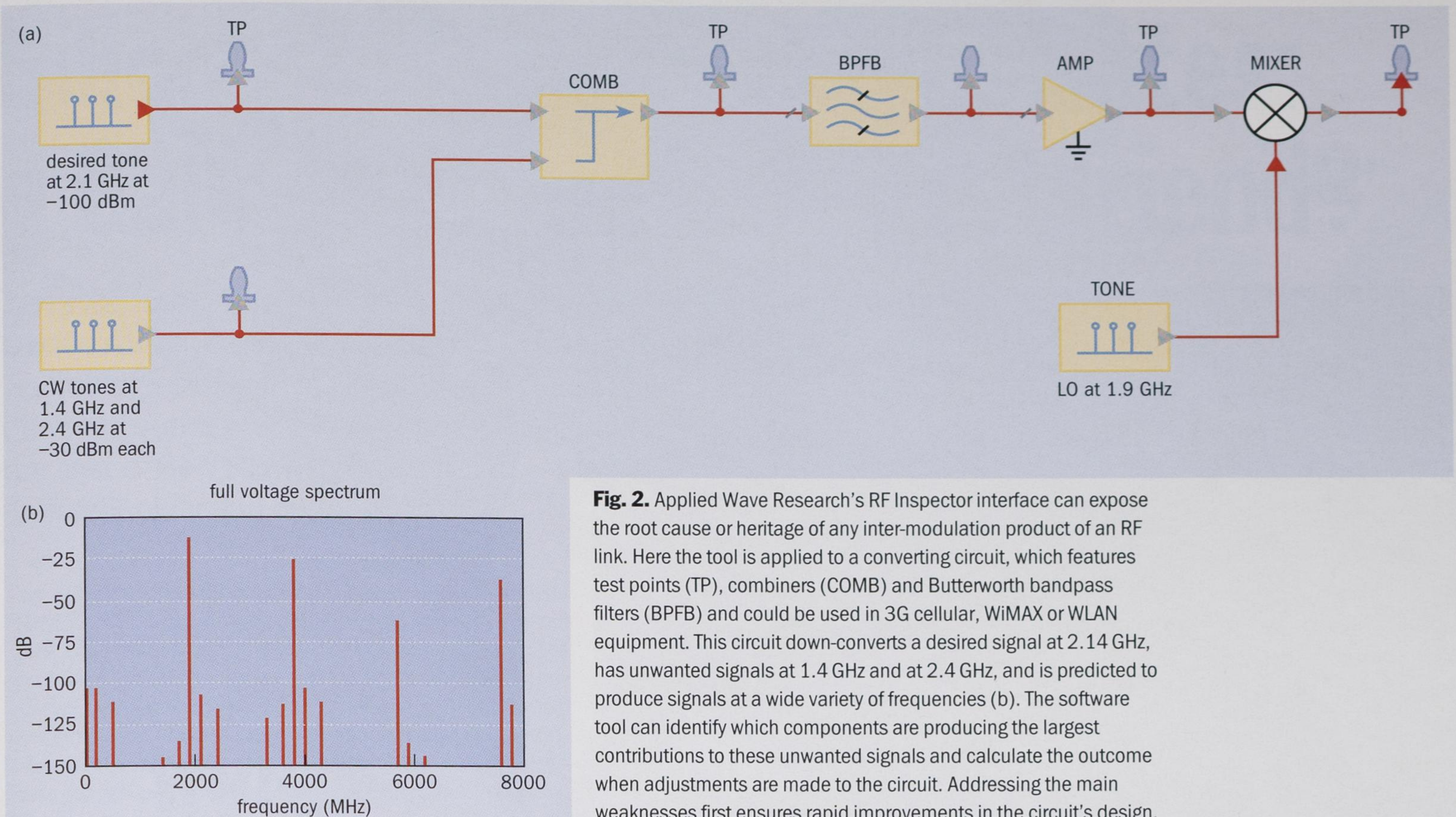


Fig. 2. Applied Wave Research's RF Inspector interface can expose the root cause or heritage of any inter-modulation product of an RF link. Here the tool is applied to a converting circuit, which features test points (TP), combiners (COMB) and Butterworth bandpass filters (BPFB) and could be used in 3G cellular, WiMAX or WLAN equipment. This circuit down-converts a desired signal at 2.14 GHz, has unwanted signals at 1.4 GHz and at 2.4 GHz, and is predicted to produce signals at a wide variety of frequencies (b). The software tool can identify which components are producing the largest contributions to these unwanted signals and calculate the outcome when adjustments are made to the circuit. Addressing the main weaknesses first ensures rapid improvements in the circuit's design.

penalty of a higher component cost and a similar performance at a lower price might be produced with a third-order filter and an LNA with less noise.

Both of these scenarios can be evaluated within a few minutes with our software that can also provide a yield analysis and keep track of changes in other figures of merit – for example, the available cascaded gain at the image frequency changed from -6.22 dB to -32.9 dB by switching from a seventh order to a third-order filter. This example demonstrates some of the benefits of commercial system simulation tools, which can account for real world circuit interactions and make it easy for a designer to perform trade-off studies.

Another component of the VSS RFA package is the RF Inspector technology tool, a new frequency-domain simulation tool that helps to determine the causes of any inter-modulation product in an RF link. This tool, which is based on a new set of algorithms, takes into account the effects of conversions, harmonics and intermodulation, and includes thermal and phase noise. The tool can identify contributions from

every component in the circuit to unwanted signals, which allows designers to tackle the most significant problems first.

The advantages of this tool are demonstrated by examining a circuit that could feature in 3G cellular, WiMAX or WLAN applications, which down-converts a desired signal at 2.1 GHz to an intermediate frequency (see figure 2a). This circuit is subjected to two unwanted signals at 1.4 GHz and 2.4 GHz that cause interference and can replicate undesired signals generated by other applications. Our RF Inspector evaluates the effects of these unwanted signals and reveals the repercussions of improper filtering before down-conversion. Placing a marker over a particular tone of interest shows the associated power level and signal heritage at that frequency.

The tool can monitor the full frequency spectrum, the spectrum of only the signal, the phase noise of the RF link or just the effects of the thermal noise (see figure 2b). The data can also be replicated as a table that uses flags of different colors to identify the desired signal, inter-modulation and distortion products.

We believe that the ability to expose the weaknesses in circuits with the RF Inspector, combined with the circuit performance analysis offered by our RF budget analysis, enables circuit designers to create and verify the initial specifications of a wireless design and identify potential pitfalls at an early stage of the design process. This will ultimately shorten the design cycle and boost company revenue by increasing the pace at which products are brought to market.



About the author

Chris Paris (cparis@appwave.com) is director of European operations at Applied Wave Research. He thanks Joel Kirshman, product manager for AWR system analysis tools, for his technical contributions.

“Our RF Inspector reveals the repercussions of improper filtering before down-conversion.”

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Silicon-on-diamond substrates: a GaN HEMT maker's best friend?

Jerry Zimmer, Gerry Chandler and Dwain Aidala from sp3 Diamond Technologies describe how silicon-on-diamond substrates are able to reduce the cost of GaN HEMTs and improve their reliability and output power.

The substrate is the Achilles' heel of today's GaN HEMTs. The high power densities promised by these devices, which are 10 times greater than their GaAs cousins, expose the wafer's poor heat handling capabilities, while the typical substrate sizes impact on economies of scale. These drawbacks limit the potential performance of the devices and hinder their deployment in cell phone base stations and other forms of wireless communications.

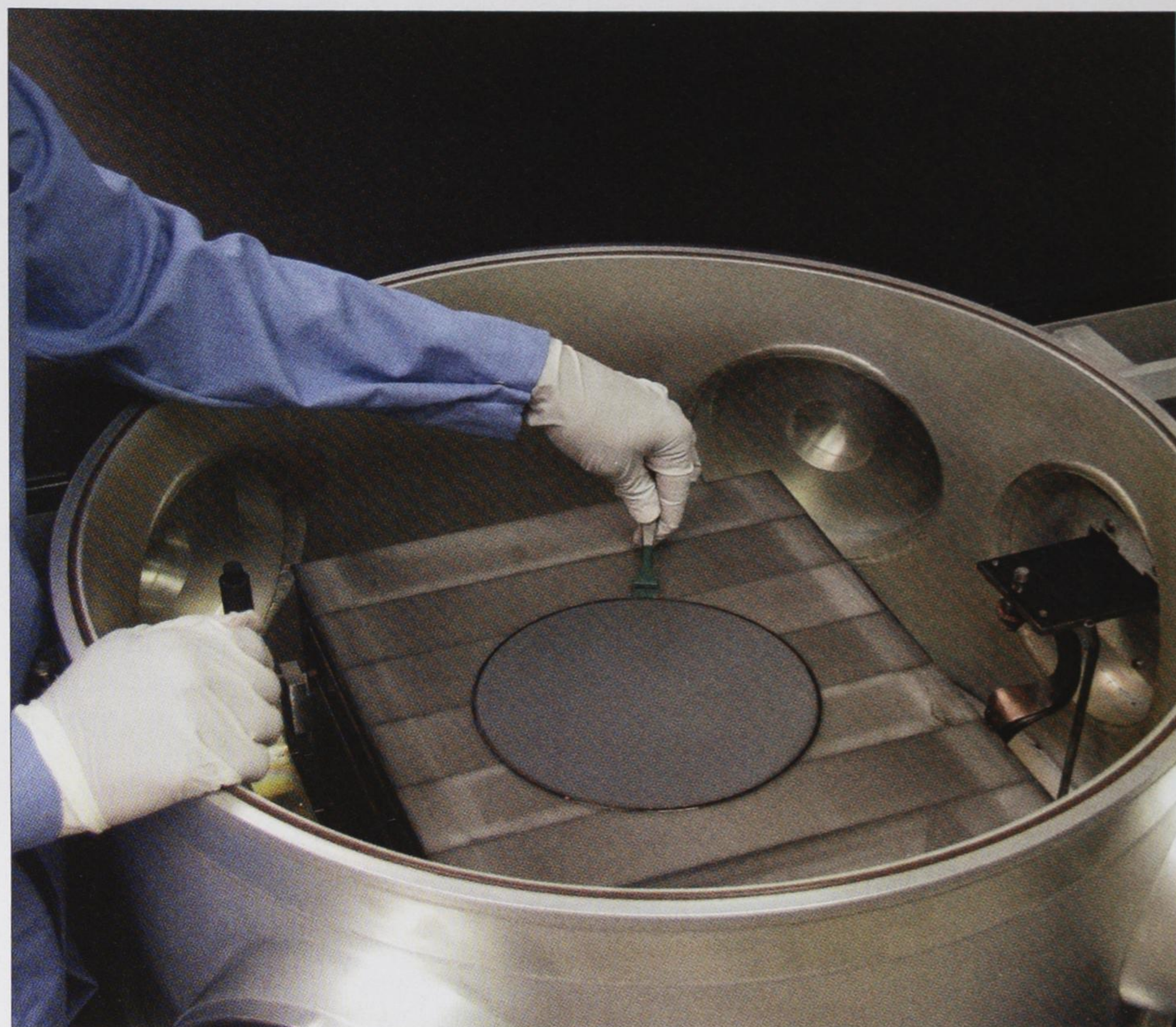
The development of substrates for these RF devices has a checkered history. GaN is the ideal platform from a growth perspective because it produces very low defect density epilayers. However, this type of substrate is not used because it is too expensive, difficult to make and limited to a few centimeters in diameter. GaN HEMT developers instead turn to other platforms for GaN epitaxy, including sapphire, AlN, SiC and several silicon-based wafers. They are much cheaper to produce, but aside from the various silicon types, are limited to sizes of 100 mm or less.

Unfortunately, silicon's larger wafer sizes are balanced out by a low thermal conductivity that keeps device performance within limits (see table 1). Poor thermal management caps the transistor's maximum output power and reduces the device's lifetime through high operating temperatures.

Hybrid structures

However, it is possible to combine the attributes of silicon's larger diameters and higher thermal conductivities by employing a multi-layer substrate. At sp3 Diamond Technologies, based in Santa Clara, CA, we have produced silicon-on-diamond (SOD) substrates that can be used for GaN growth and feature an integrated thermal spreading layer of diamond (see figure 1).

These hybrid structures have a one-to-several-microns-thick silicon layer on top of a diamond layer that is tens of microns thick. Both of these layers, which are grown on a silicon substrate by CVD, have thicknesses that are fine-tuned to specific applications.



sp3 Diamond Technologies of Santa Clara, CA, has developed silicon-on-diamond substrates with diameters ranging in size from 50 to 300 mm that are produced with chemical vapor deposition.

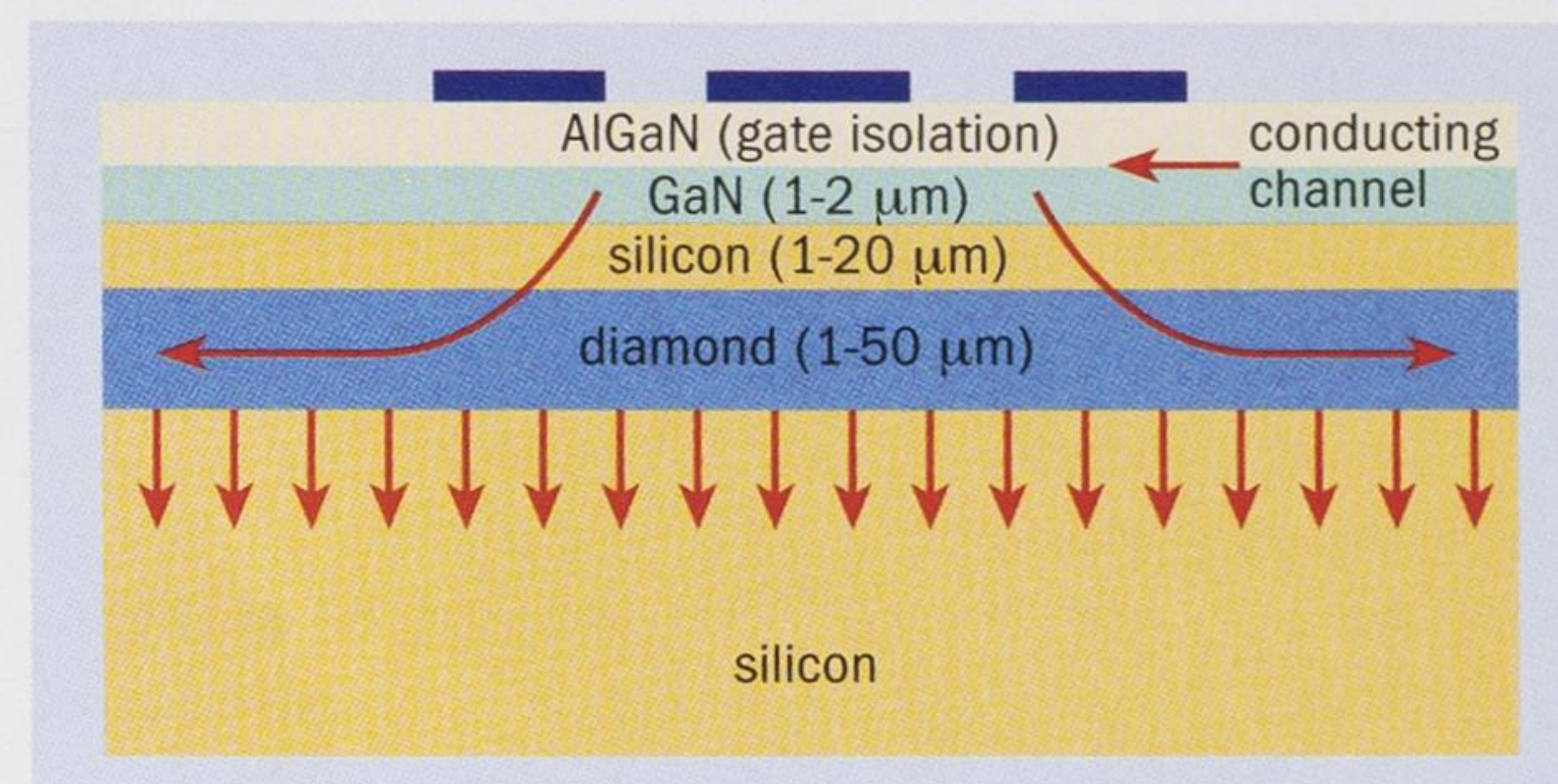


Fig. 1. sp3 Diamond Technologies' substrates have a much higher thermal conductivity than any of today's commercially available substrates, and that can increase the lifetime of GaN HEMTs through reductions in operating temperature.

Table 1. Thermal conductivities of substrates

Substrate	Thermal conductivity (W/cm-K)
Diamond	10.0
Sapphire	1.7
GaN	1.3
AlN	1.7
SiC	4.9
Silicon	1.5

Table 2. Simulated performance of GaN HEMTs on silicon, silicon-on-diamond and sapphire

Substrate	Thermal conductivity (W/cm-K)	Device temperature (K)	Channel current density (A/cm ²)	Channel current improvement (%)	Drain current (mA)	Drain current improvement (%)
Silicon	0.984	380	7×10^6	3	441	4
SOD	0.984/10*	300	8.7×10^6	28	604	43
Sapphire	1.7	379	7×10^6	3	425	0

Calculations from the Naval Postgraduate School predict that the higher thermal conductivity of silicon-on-diamond (SOD) substrates leads to a lower transistor operating temperature and an increase in the device's channel current density. The thermal conductivity used for the silicon substrate in this table is not the value used in Table 1, but is taken from a particular product specification. Results on SiC substrates, which are not shown in the table, are used as the base line for calculating the current density improvement. * The thermal conductivity of SOD substrates is a combination of silicon and diamond, which have values of 0.984 and 10 respectively.

The silicon wafer also serves as a handle for processing and it can be either thinned or completely removed before packaging. The addition of diamond boosts the thermal handling properties of the wafer. At this thickness the SOD wafer's thermal conductivity is influenced by the grain size, and is 2–3 times greater than copper and 4–5 times higher than SiC.

Our SOD substrates – which are manufactured with a hot filament CVD process in sizes of 50 to 300 mm and can be doped with boron – could increase the output power of HEMTs from the current typical value of 6 W/mm to more than 15 W/mm. This increase in performance results from a cooler channel temperature that reduces the device's running temperature and boosts transistor lifetime by several orders of magnitude. This improvement will also lead to an increase in the reliability of systems using these devices.

The performance gains produced by this type of substrate are illustrated by simulations from the Naval Postgraduate School in Monterey, CA, that compare AlGaIn/GaN HEMTs on sapphire, silicon and SOD substrates. This approach, which uses commercial software to model the device with a matrix-mesh of thousands of grid points, can simulate transport properties using differential equations derived from Maxwell's equations. A lattice heat flow equation is also included in the calculations, which break down the HEMT into nine regions, such as the oxide region, an AlGaIn layer and different electrical contacts. Electrical results from a two-dimensional model produced similar predictions to a three-dimensional one, but with greater speed. The results from this simpler model are shown in table 2.

Combating hot spots

These calculations reveal that switching from SiC to the SOD platform should boost HEMT current density by 28%. Drain current would be increased by 43%, while maintaining an overall transistor temperature of 300 K. This operating temperature, which is 80 K lower than that for GaN HEMTs built on either sapphire and silicon, boosts device lifetime. Calculations, which rely on the activation energy associated with the materials in the epilayers, predict that the reduction in electromigration within the device could increase the transistor lifetime by a factor of between 16 and 1700.

SOD wafers are also better at addressing issues associated with non-uniform heat generation across the chip – a common characteristic of many devices.

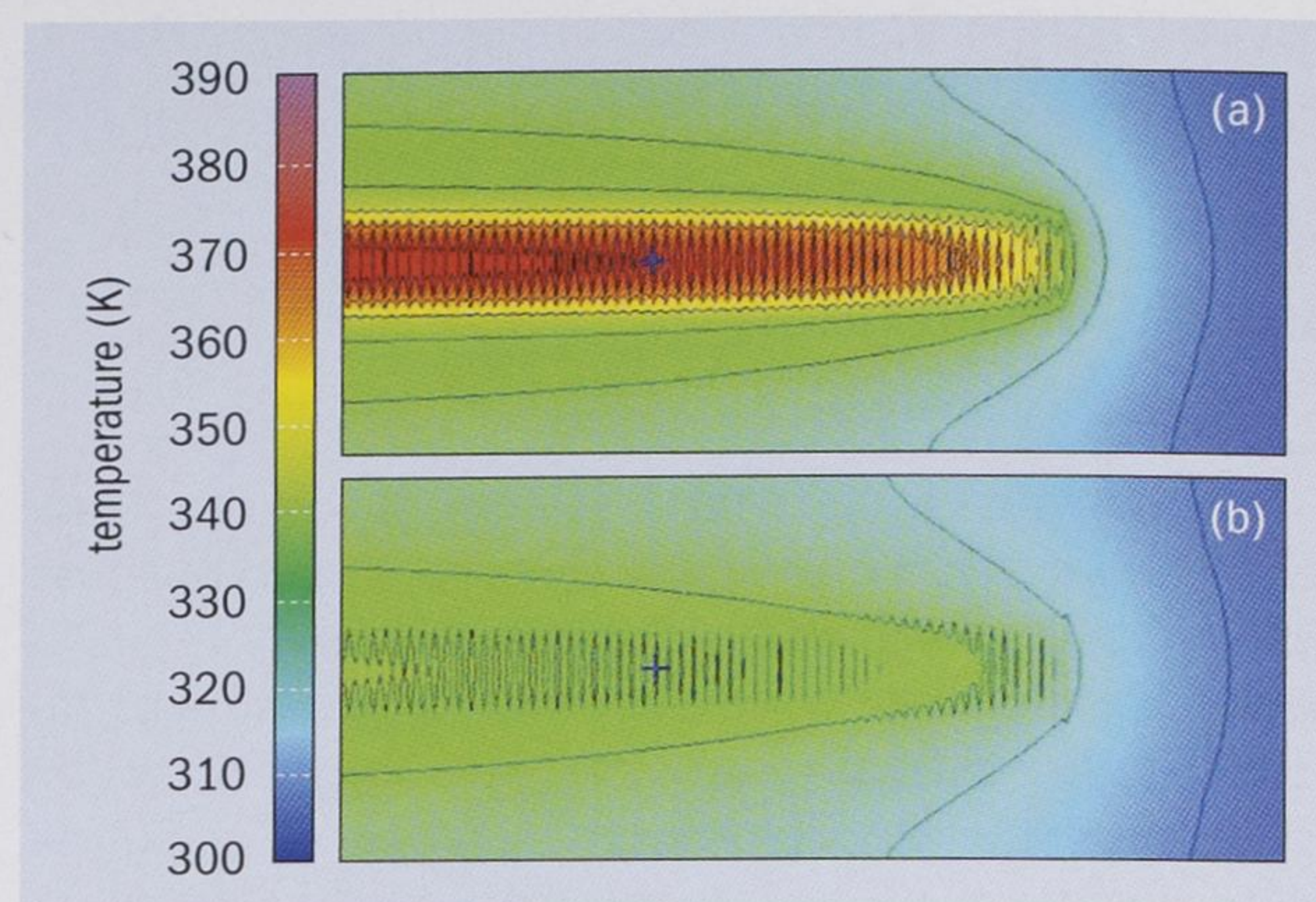


Fig. 2. Nitronex's calculations demonstrate the reduction in operating temperature of multi-gate RF power transistors when a 150 μm-thick silicon substrate (a) is replaced with a SOD wafer incorporating a 20 μm-thick diamond layer (b).

The problem arises because GaN is unable to effectively remove the heat generated during device operation. Heat spreaders can be attached directly to the device to distribute heat away from the hot spots to colder regions of the chip. However, heat still has to be extracted through the substrate's entire thickness before it can be quenched by a heat spreader or a heat sink.

A more effective solution is to place the heat spreader as close as possible to the heat generating areas. Our SOD wafers do just this because they contain a heat-spreading diamond layer that is within a few microns of the chip's surface.

“Switching from silicon to SOD substrates could lower the LED's operational temperature, increase its stability and lead to reduced color variations with device aging.”

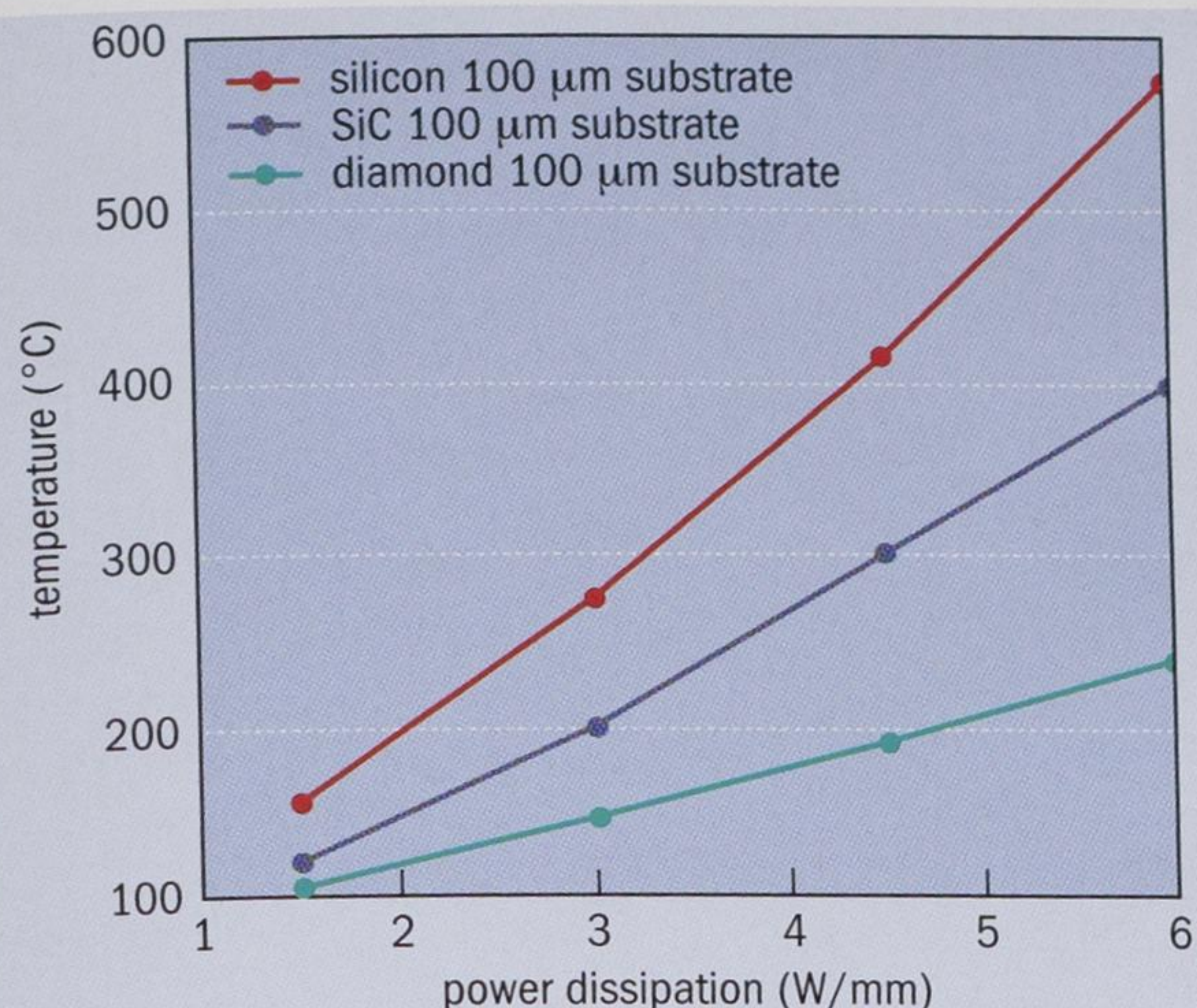


Fig. 3. Simulations by TriQuint Semiconductor demonstrate that the advantages of silicon-on-diamond can become more significant as the output power of GaN HEMTs increases.

This diamond layer reduces the local junction temperature and equalizes the temperature across an entire chip at the device junction level. The improvements in temperature uniformity are predicted by calculations from Nitronex, which compare multi-gate RF power transistors on a standard silicon substrates and a SOD platform (see figure 2). The Rayleigh, NC, firm is working with us as part of a \$0.75 million contract from the

Missile Defense Agency to build active devices on SOD.

The advantages of SOD substrates over those manufactured from silicon and SiC for a range of output powers are also illustrated by calculations carried out by TriQuint (see figure 3). These simulations take a very conservative approach by using a thermal conductivity for diamond of only 6 W/cm-K and may underestimate the true advantage of SOD. Even so, the predicted improvements are dramatic.

Making the switch

Although we expect GaN HEMTs to benefit most from SOD, we believe that our hybrid substrates with tailored silicon and diamond layer thicknesses could also aid optoelectronic devices. For example, there were reports late last year that Shimei Semiconductor, a start-up company based in Kyoto, Japan, is developing a blue LED using GaN-on-silicon epitaxy. Switching from silicon to SOD substrates could not only reduce the device's operational temperature, it could also increase its temperature stability and lead to lower variations in color of LEDs with device aging. The advantages could also be felt in more exotic devices, such as GaN-based VCSELs, by increasing the emitter's output power. In fact, we believe that in the future all high-performance efficient devices will require the use of a heat spreading material like diamond in very close proximity to the junction. ●



About the authors

Dwain Aidala (left) is president and COO of sp3 Diamond Technologies. Before joining the company in 2005 he held executive management positions at C Speed Corporation, Mitsubishi Electronics and NEC. **Jerry Zimmer** (middle) is CTO and co-founder of sp3, and leads the firm's technology and product development programs. He has previously held engineering and management positions at Silicon Valley Group, AMD, and Raytheon. **Gerry Chandler** (right) is sp3's senior process engineer and has experience as a co-founder of a silicon-on-insulator company.

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DEVICE PROCESSING

Printing technique integrates materials

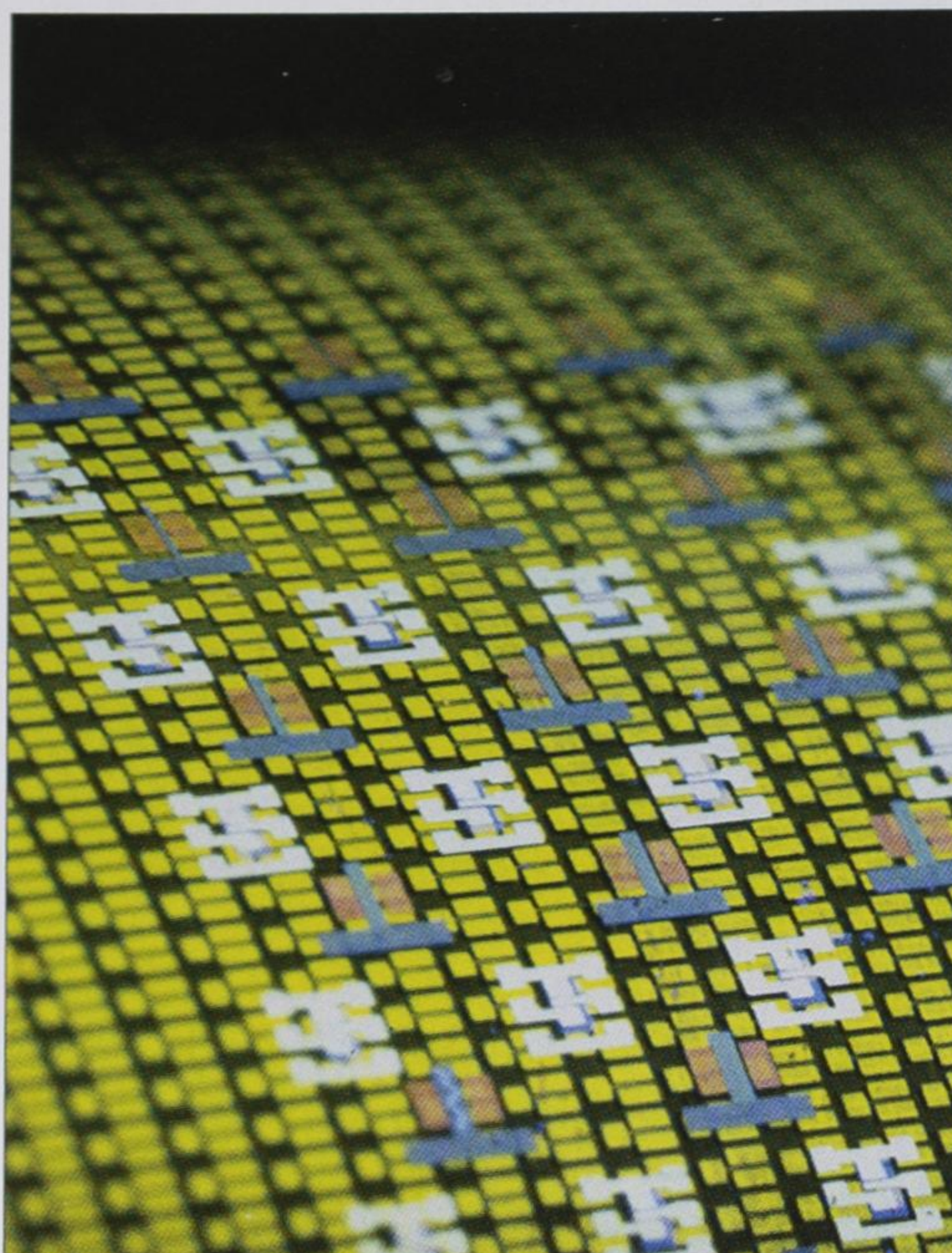
A printing technique that combines HEMTs, MOSFETs and thin film transistors made from nanowires and nanotubes has been developed by scientists from the University of Illinois, Urbana-Champaign.

The process, which can also be used to integrate other dissimilar materials, is claimed to be capable of producing a variety of unusual electronic systems that would be impossible to make with other methods like MOCVD and MBE.

The researchers' multi-device structures are formed by first producing semiconductor nanomaterials, such as single wall nanotubes (SWNTs), GaN nanobars and silicon wires, on separate substrates.

Material from these substrates is then transferred using stamp-based printing onto a device substrate, such as a sheet of polyimide. This sheet has a thin, spin-cast layer of a liquid prepolymer, such as polyamic acid, which adheres to the polyimide and embeds the printed material once it is cured.

Further processing steps include deposition and patterning of gate dielectrics, electrodes and interconnects. Once this is carried out another spin-coated polymer interlayer is added and a second circuit featuring a different material.



Printing combines silicon MOSFETs, single-wall carbon nanotube thin film transistors and GaN HEMTs on a flexible polyimide substrate. The gold contact pads on the silicon devices are spaced 100 μm apart.

With this approach, the researchers produced a circuit on polyimide with a bottom layer of GaN HEMTs, followed by layers of SWNT thin-film transistors (TFTs) and silicon MOSFETs. These devices have similar characteristics to those fabricated on the source wafers and repeated bending of the substrate produces no major change in their properties.

The flexible substrates make these devices suitable for applications such as wearable electronics and flexible displays. "The plastics that we make are lightweight and mechanically tough", said the team leader, John Rogers. "A disadvantage is poor thermal properties, but that doesn't matter for many applications."

Rogers says that the team is now working on printed photodiodes, solar cells and LEDs, and that it will report results later this year. Commercial applications are also being explored through the recent launch of a start-up company, Semprius, which is looking at flexible displays, large-area solar cells, curved focal plane arrays and structural health monitors for aerospace applications.



Journal reference

J Rogers et al. 2006 *Science* **314** 1754.

INP OPTOELECTRONICS

Dashes beat dots for high-power laser

Boon Ooi and his team from Lehigh University claim to have built the first high-power broadband semiconductor laser operating at 1.6 μm .

The InP-based laser, which was produced in collaboration with IQE, Pennsylvania, and the Army Research Laboratory, Maryland, features InAs quantum dashes, which are elongated quantum dots. The device has a center wavelength of 1.64 μm , a 76 nm wavelength range and delivers 0.4 W at room temperature.

"Compared with conventional InGaAsP

quantum-well lasers emitting at 1.55 μm , Lehigh's quantum-dash laser displays significantly broader linewidth at comparable output power," explained Ooi.

The US Army is interested in using these eye-safe sources for range-finding and burst illumination imaging – a technique that involves probing objects with short laser pulses and detecting the reflection using time-gated electronics.

The quantum dot lasers, which potentially cover 1.3 to 2.0 μm , could also be used in spectrometers to identify common gases by their absorption spectra. Dentistry could also benefit, as these emitters could allow deeper images of gum tissue and enamel produced by optical coherence tomography.

IQE engineers grew the devices by MBE on (100) InP substrates. They formed InAs dashes using a Stranski-Krastanow growth mode and embedded in them InAlGaAs quantum wells.

Ooi says that quantum dashes are used in the active region, rather than dots, because it is easier to produce high gain active material in the required size distribution that is needed for broadband emission. Devices based on chirped quantum-dot layers can also suffer from photon re-absorption, which significantly reduces efficiency.

The team's goal is to develop a broadband semiconductor laser that covers both C-band (1525–1565 nm) and L-band (1565–1625 nm) for optical telecommunication, sensing and tomography applications.

PHOTODETECTORS

AlN stretches out photodetection range

Researchers at the Kansas State University and its spin-off firm III-N Technology claim to have extended the operating range of AlGaIn-based photodetectors. The partnership's AlN device has a cut-off wavelength of 207 nm, which is 22 nm shorter than the pre-

vious best result that was produced by Bilkent University, Turkey.

The result is of interest to NASA, which is supporting the team's research, because it is keen to develop compact solid-state detectors that can operate in the extreme ultraviolet spectral range for applications in astrophysics.

The Defense Advanced Research Projects Agency is also funding the university's research efforts to develop ultraviolet avalanche photodiodes (APDs) for bio-agent detection and non-line-of-sight optical communications.

MOCVD-grown AlN detectors had a peak response at 200 nm, a dark current of 100 fA at a 200 V bias voltage and a responsivity that typically increases from 0.1 to 0.4 A/W as the bias voltage is increased from 0 to 100 V.

The team will continue to improve the quality of its AlN epilayers, and try to fabricate Schottky diode photodetectors and APDs based upon AlN epilayers and AlGaIn alloys.



Journal reference

J Li et al. 2006 *Appl. Phys. Lett.* **89** 213510.

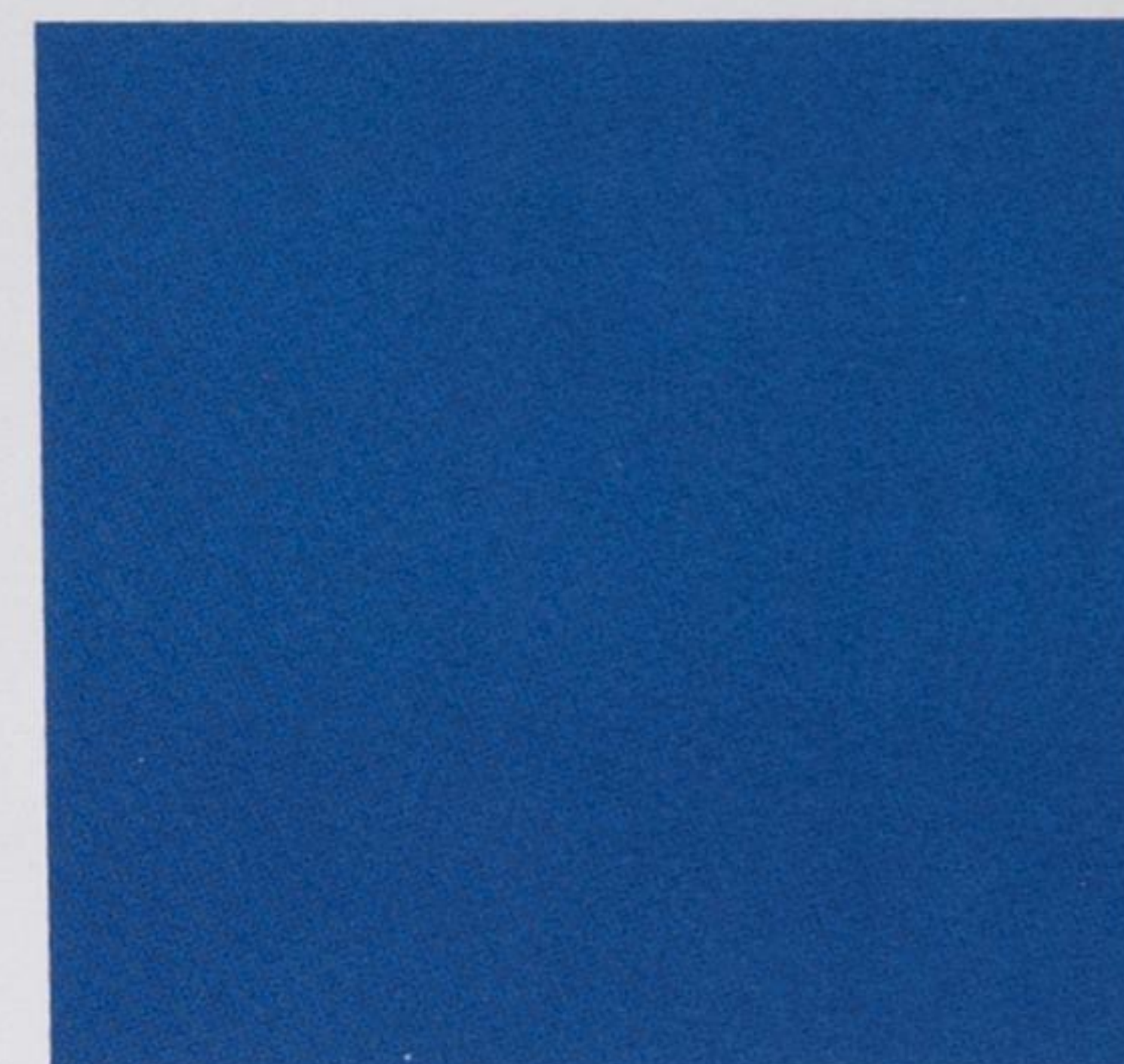
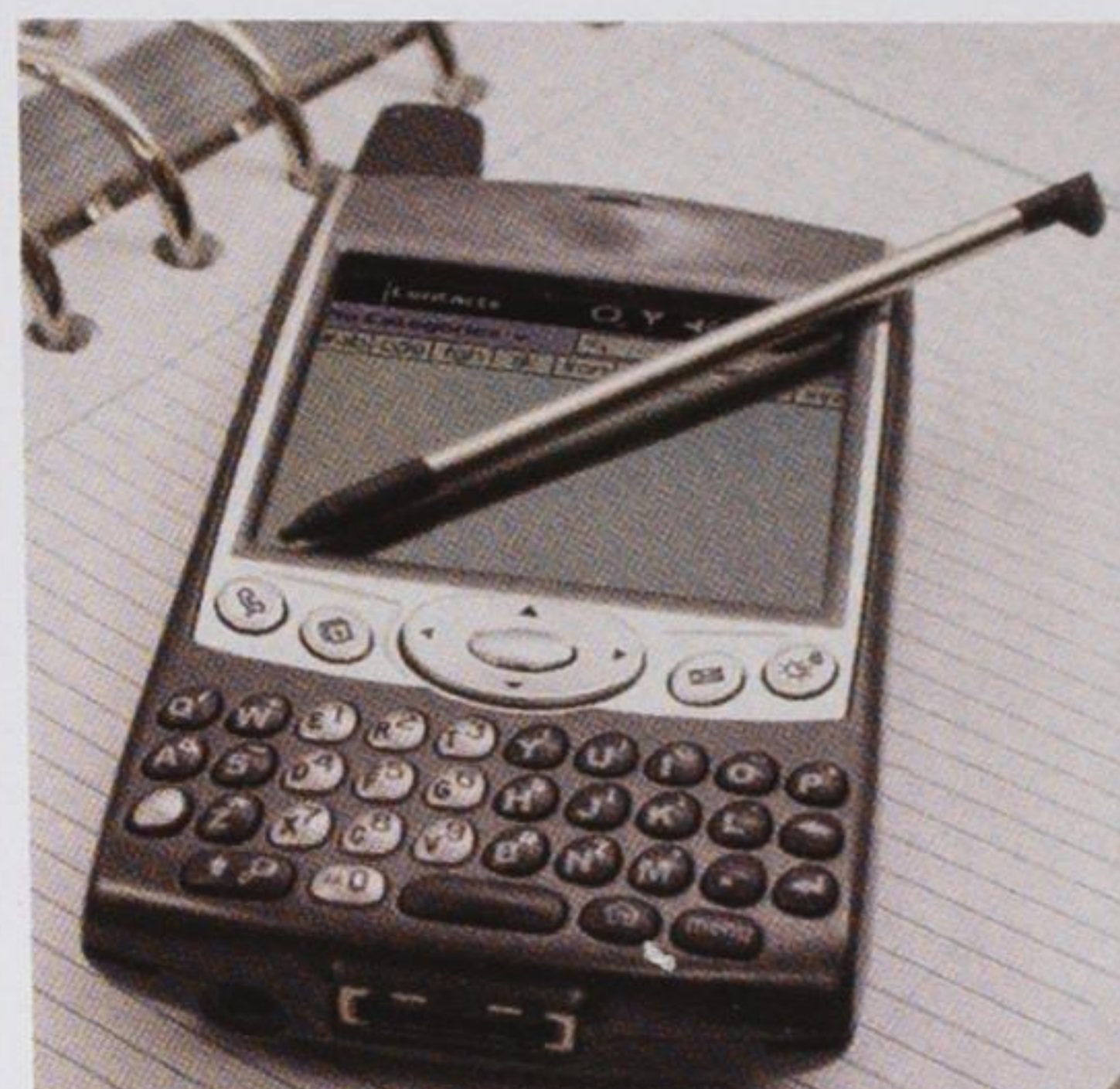


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