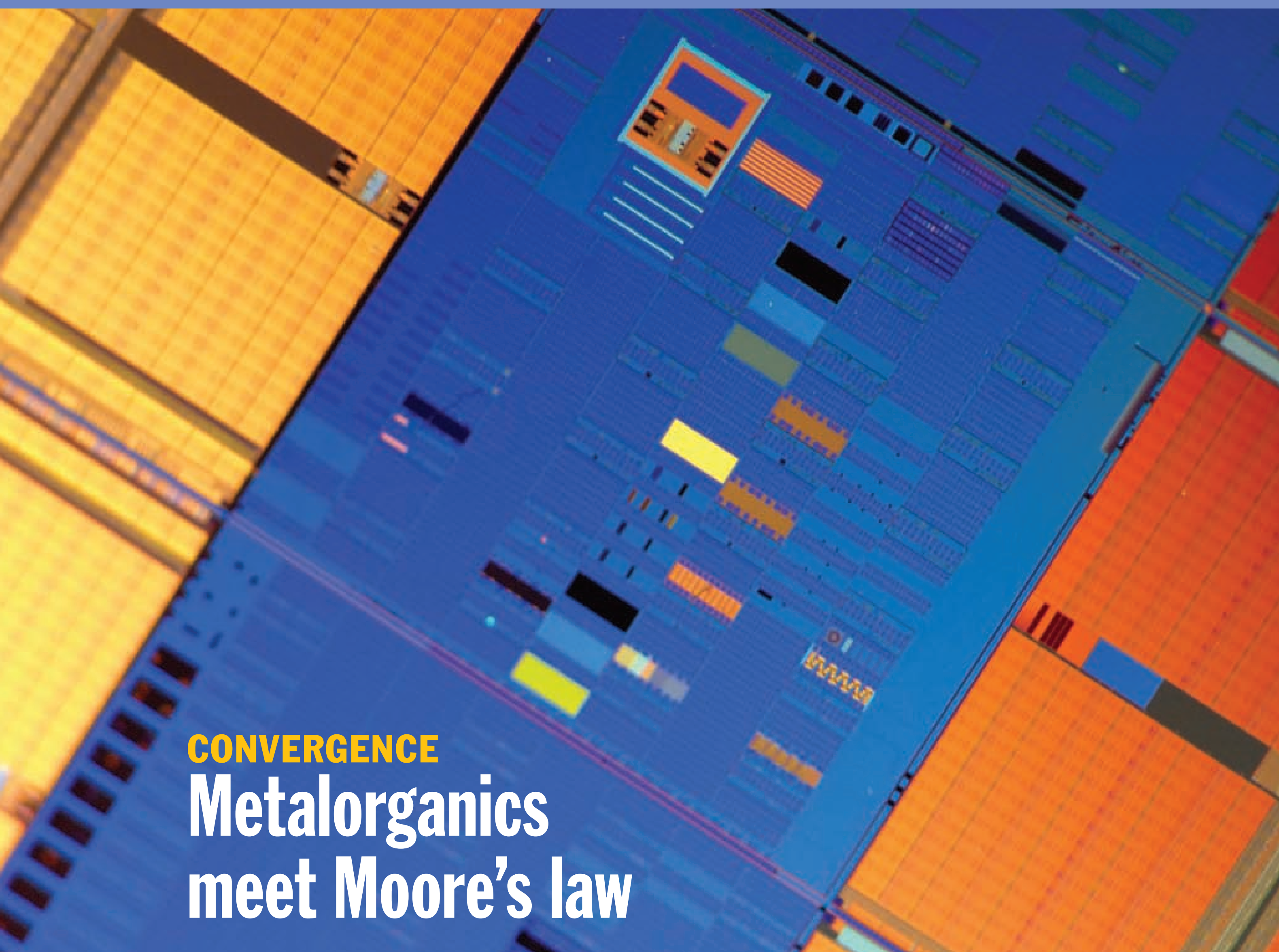
COMPOUND SEMICONDUCTOR

August 2007 Volume 13 Number 7

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY



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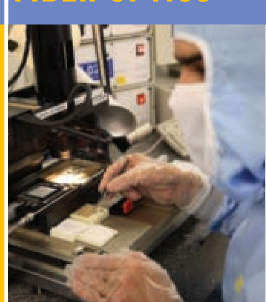

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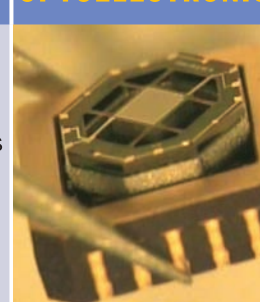

One lump or two?

High-performance VCSELs are the key to atomic clocks the size of a sugar cube. p14

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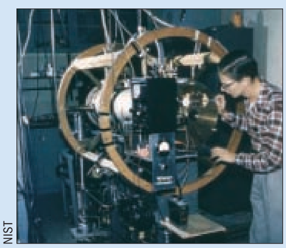

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Time machine
Over the last 40 years atomic clocks have been drastically reduced in size – and they are about to become smaller still. p14

Main cover image: *Intel's Penryn processors, fabricated using metalorganic chemicals and deposition techniques initially developed for the III-V industry, are about to enter mass production. This image shows a close-up of a test wafer for memory applications. See p12. Credit: Intel.*

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IOP Publishing

Europe's new entrepreneurs

It's been a good few months for two of Europe's technologists-turned-entrepreneurs. Barry Leese, who set up Epichem some 24 years ago, is reaping the benefit of its February takeover by the chemicals giant Sigma-Aldrich, and is now president of its SAFC Hitech subsidiary. Meanwhile, IQE's Drew Nelson was honored by Jemi UK (the Joint Equipment and Materials Initiative), receiving the organization's award for services to the semiconductor industry at the recent S2K conference in Cardiff.

Truth be told, though, entrepreneurship is one area where Europe does tend to lag the US, and, aside from some notable exceptions like these, the pioneering force has been a little thin on the ground in recent years. But, in a flurry of developments, the spirit of entrepreneurship appears to be flowing through Europe again – appropriately enough, in new ventures located close to the Seine, the Thames and the Clyde.

> "The spirit of entrepreneurship is flowing through Europe again."

In Paris, Ommic is beginning a new chapter in its history after major shareholder Philips' predictable withdrawal from the GaAs scene (aided and abetted by a partial management buy-out). Fellow Parisian 3S Photonics, now free from the ties of Avanex and previous owner Alcatel-Lucent, also has high hopes. Serial entrepreneur Alexandre Krivine has taken the plunge as CEO there.

Over to the UK and, on the banks of the Thames at leafy Richmond, the solar start-up Quantasol has sprung into life under the direction of CEO Kevin Arthur – armed with novel quantum-well technology developed a few miles downstream at Imperial College. A few hundred miles north, Nick Wood is heading up XanIC, which has emerged from Glasgow's ultrafast systems group, and planning to exploit its leading-edge GaAs HEMT technology for high-frequency security applications.

Marc Rocchi, the Ommic CEO, says that Europe needs a more entrepreneurial attitude to succeed in the compound semiconductor business. Already, it would seem, something is stirring.

As Rocchi insists, there's no reason why Europe should be a minnow in this business. With the changes at Ommic, he's in a position to help make sure of that himself. So good luck to him, Krivine, Wood and Arthur – and to everybody else looking to make their mark in Europe. In the future, we look forward to seeing some of those new names in lights too.

Michael Hatcher *Editor*

Advertisers' Index

FOUNDRIES

Ommic team steps out of Philips' shadow

By Michael Hatcher

Philips has sold its controlling stake in the French GaAs and InP foundry Ommic in a management-assisted buy-out led by new investor Financière Victoire.

The deal, in which Ommic's senior managers took a very active role and a stake in the company, follows Philips' spin-off of its silicon business (now known as NXP Semiconductors) in September 2006.

And although Financière Victoire may not be a familiar name as far as high-technology investments are concerned, Ommic CEO Marc Rocchi is excited about the firm's future. "The investors were totally convinced, and we now plan to really grow the company," he said.

III-V RF device manufacturing had long since ceased to be a core part of Philips' wider strategic plan, so the sell-off came as little surprise. The Dutch electronics giant no longer requires any of the chips made by Ommic, although it has chosen to retain a small share in the foundry.

Clearly now feeling much more in control of Ommic's destiny, Rocchi said: "There is no reason why Europe should be a dwarf in the compound semiconductor business." He feels that the continent's two major III-V microelectronics fabs – Filtronic and United Monolithic Semiconductors (UMS) – both have problems, albeit for different reasons.

Filtronic, set to be hit by a rapid slackening in demand for its GaAs PHEMT switches, is making big cuts and may even sell its fab, while Rocchi views UMS as a captive operation, restricted by its EADS Deutschland/Thales ownership. Industry sources also say that UMS has been capacity-limited recently, and forced to offload some manufacturing requirements to alternative foundries.

"Europe needs a more entrepreneurial attitude," Rocchi continued, saying that Ommic is now free to concentrate on precise, high-value niche applications. "We're not so concerned with volume – [but] we are very concerned with profit. Small can be beautiful."

One of those niche areas that is growing fast at the moment is for 60 GHz E/D-mode PHEMTs, which are increasingly used in phase shifters and phase attenuators for defense applications such as smart antennae and radar systems used in weather reporting. Rocchi cites Ommic's foundry offering in this sector as world-leading.

Ommic also offers high-indium-content metamorphic GaAs HEMT processing for microwave applications such as security screening equipment, power PHEMTs and more. Its manufacturing service stretches all the way from epitaxy through to final end-user qualification – something that the company has dubbed its "fab+" service.

The company has been working on niche power-switching GaN applications, details of which should become clearer over the next few months. Understandably excited about the opportunity for growth, the CEO concluded: "It's a big success for the management here. This deal can only be positive."

PHOTOVOLTAICS

WIN prepares for solar-cell market entry

Taiwan-based GaAs foundry WIN Semiconductors is diversifying into multi-junction solar-cell production.

The company, which owns a 6 inch fab in Kuei Shan Hsiang with a capacity of 75,000 wafers per year, has previously concentrated on RFIC applications and offered HBT, PHEMT and metamorphic HEMT processes.

Now, it has ordered a production MOCVD tool from German equipment-vendor Aixtron as part of its new venture into terrestrial applications of triple-junction cells grown on germanium wafers. At the moment, however, WIN is saying little except that it is concentrating on facility installation.

The AIX 2600G3 IC tool it has ordered is typically designed to handle either 12 × 4 inch or 7 × 6 inch wafer configurations. Production-scale solar-cell epitaxy is usually based on 4 inch germanium material.

Although US solar-cell manufacturers Emcore and Spectrolab lead the market in terms of volume production and photoelectric conversion efficiencies, it appears that the sector will become much more crowded in the near future.

Aside from WIN, the Spanish solar system company Isofoton is rumored to be investing heavily in epitaxy equipment, while the Japanese firm Sharp may also move into the compound semiconductor space. And the Imperial College, London, spin-off Quantasol recently raised seed funding to support its bid to commercialize strain-balanced multi-junction cells (see p10).

WIN said of the equipment purchase: "The major players in the solar-cell epitaxy market in Europe are successfully using the Aixtron MOCVD systems. We are convinced of their track record, and are confident that the new system will clear the way for our success."

Aixtron is keen not to hype up the emerging photovoltaics sector, although it seems inevitable that others will try to capitalize on the potential of multi-junction cells in the drive towards "clean" energy production.

APPLE

Skyworks Solutions is supplying chips for Apple's much-vaunted iPhone. Semiconductor Insights confirmed that its dissection of the $600 gadget revealed the Woburn, MA, company's SKY77340-13 power amplifier (PA) module as one of the key components in the handset.

The quad-band GSM/EDGE module contains two HBT PA blocks fabricated onto InGaP die. "Apple's decision to use Skyworks is a material technology endorsement that should be acknowledged by investors," wrote Stifel Nicholas' analyst Cody Acree.

Having shipped 3 million units for the iPhone launch, Apple is hoping to sell 10 million this year.

WAFER FABS

Anadigics breaks new ground in China

Civic representatives in Kunshan, China, have staged colorful celebrations at the ground-breaking ceremony for Anadigics' new GaAs fab in the city. Anadigics' current estimates suggest that construction will be completed in the first half of 2008, with operations set to begin later the same year.

"Whereas the expansion will enable us to meet our future growth needs it also demonstrates our commitment to the communications market in China as well as the larger Asia-Pacific region," said Bami Bastani, CEO of the New Jersey based company.

The ground breaking was performed by Anadigics' managers, plus local dignitaries and politicians from Beijing – something that illustrates Anadigics' importance as the flagship in Kunshan's New and Hi-tech Industrial Development zone.

"The addition of the commercial 6 inch GaAs wafer fab to the development not only shows our ever-growing interest in the semiconductor industry but marks a historical first for the city of Kunshan and the country of China," said the city's vice-mayor Feng-Quan Zhu.

ANADIGICS

Foundation for growth: Anadigics CTO Charles Huang, CEO Bami Bastani and local Mayor Aiguo Guan were among the dignitaries at the ground-breaking ceremony for Anadigics' GaAs wafer-processing fab in Kunshan.

START-UP VENTURE

Glasgow spin-out has metamorphic focus

An investment of up to £0.4 million ($0.8 million) will help a new company called XanIC commercialize metamorphic GaAs HEMT (MHEMT) technology developed in Scotland.

High-frequency, low-noise amplifiers (LNAs) based on the advanced structures are set to be used in new airport-security scanner equipment, aircraft-landing systems and high-speed data communications.

The investment comes from IP Group and Scottish Equity Partners, and XanIC will use a semiconductor process developed by Iain Thayne and colleagues at the University of Glasgow's James Watt Nanofabrication Centre.

The first MHEMT-based product will be a 94 GHz LNA, which has applications in security scanner systems such as millimeter-wave imagers.

These kinds of systems can detect a wide range of materials, including plastics, that conventional X-ray scanners are unable to pick up and are expected to be widely deployed in airports in the future.

Thayne says that the MHEMT structures offer the high-frequency performance of InP-based devices, coupled with the much simpler fabrication of a GaAs platform.

In the epitaxial design of GaAs MHEMTs, layers of InAlAs and InGaAs are deposited and this extra indium content leads to higher electron mobilities that, in turn, translates to higher-frequency operation.

US companies like Northrop Grumman and HRL have developed similar high-performance components but systems integrators in Europe have expressed a preference for a European supplier, which XanIC will now be looking to exploit.

A critical advantage that the company has is the availability of a large-area electron-beam lithography tool at the James Watt Nanofabrication Centre. Using this and other equipment including MBE, the Glasgow team has developed a 50 nm gate-length process and record-breaking transistor characteristics.

In the first instance, prototypes and devices for sampling will be fabricated using the Centre's tools, although that manufacturing strategy may change if high volumes of components are required.

PRODUCT DEVELOPMENT

Fujitsu unveils longest-lasting GaN HEMTs

Fujitsu claims to have made GaN HEMTs that will operate for 100 years at 200 °C, opening the way for the devices to be used in increasingly demanding applications.

Results initially presented at the 2007 IEEE MTT-S International Microwave Symposium in Hawaii suggest that the devices are, in Fujitsu's words, "the most reliable in the world". The Japanese IT and communications company is the first to achieve the million-hour record with a 50 V drain voltage by pinch-off testing, the most demanding reliability test.

Fujitsu says planned applications for its ultra-reliable HEMTs include satellite communications, cellular base stations and WiMAX, and other wireless technologies.

Delivery of the reliability record hinged upon Fujitsu's investigations of the relationship between the gate-leakage current, crystal quality and device structure.

Researchers then grew a device using Fujitsu's proprietary n-type GaN cap layer and higher-quality materials.

CHIP MANUFACTURING

RF Micro ends Filtronic's contract

Filtronic has lost its leading GaAs PHEMT switch customer, the giant US power amplifier (PA) manufacturer RF Micro Devices (RFMD). In response, the UK company will downsize its fab operations with the loss of 115 jobs, while it is now actively looking to sell the compound semiconductor business.

In a brief statement, Filtronic, whose 6 inch facility represents the UK's only major GaAs fab, said: "Our predominant customer has now advised us that its requirement for switches from Filtronic will cease in September because of [its] decision to in-source all production."

"This will result in a substantial reduction in the level of activity for our business. The board has therefore decided to reduce the size of the compound semiconductor business accordingly."

In 2005, Filtronic significantly ramped GaAs PHEMT production after signing a major supply deal with RFMD. However, it had struggled to expand its customer base significantly beyond that, and in recent months it was forced into a costly scaling back of capacity expansion plans.

Filtronic representatives had indicated previously that RFMD was the largest of only a handful of customers that it was providing with GaAs PHEMT switches. Merchant production of PHEMTs was said to amount to approximately half of the division's revenues.

However, there is some suggestion that Filtronic has been able to expand that customer base recently, and that it had prepared itself for what some had seen as the inevitable loss of the RFMD business. Focusing on niche markets outside the cell-phone handset sector should enable Filtronic to sell chips at a much healthier margin.

GaAs wafer production at the firm's Newton Aycliffe facility also supports Filtronic's own broadband point-to-point and defense businesses.

In its most recent financial presentation, Filtronic said that its compound semiconductor business accounted for just over £15 million ($30 million) in revenue in the first half of fiscal year 2007, out of total sales of £35.8 million.

Losing the RFMD account would appear to blow a huge hole in those finances, leaving a major question mark over the future viability of the company. "The board is considering a full range of possibilities for the ongoing operation, including sale," was Filtronic's ominous-sounding conclusion.

WIDE-BANDGAP MATERIALS

New CEO oversees Norstel expansion

SiC materials company Norstel has appointed a new CEO and chairman, in a management shake-up designed to make the company a leader in the wafer-supply industry.

Iain Jackson, a 25 year veteran of the semiconductor industry, has been appointed CEO, as the Swedish substrate maker looks to ramp up its output. "We are seeking to scale in two directions," explained Jackson. "In product diversity at the same time as capacity, giving us the ability to become a high-volume manufacturing facility."

Norstel is hoping to broaden its 2 and 3 inch semi-insulating and nitrogen-doped 4H SiC wafers, made by its proprietary high-temperature CVD growth method, to 4 inches by 2009. The development will exploit the benefits of a long-term, multimillion-dollar SiC gem supply deal, says Jackson.

"I'm convinced, and I think Norstel is convinced, that the SiC industry can offer end-product features that are sufficiently differentiated to carve out a unique market space in both the high-frequency segments and the power segments, in addition to our gemstone customer," Jackson said.

Jackson, who previously had worked for ASIC pioneer LSI in management positions ranging from fab operations to marketing, replaces Norstel's founder Asko Vehanen, who becomes a director of the company.

Hasse Johansson, group vice-president for research and development at heavy-transport-vehicle maker Scania, becomes Norstel's new chairman. Former chairman Jörgen Bladh retains his seat as a director in the amicable reshuffle. Bladh said: "The ramp up of our silicon carbide manufacturing is proceeding well and these appointments position us perfectly for the next stage of Norstel's development."

Norstel is also developing growth processes in collaboration with the Institute of Advanced Industrial Science and Technology (AIST) of Tsukuba, Japan. The Energy Technology Research Institute at AIST works on improving SiC quality and has developed and optimized sublimation methods that are suitable for 4 inch diameter material growth.

DISPUTE

Epistar cranks chip development to beat ITC ban

By Andy Extance

Epistar says that its new Phoenix and Aquarius product lines will bypass the US International Trade Commission (ITC) import ban on its LEDs – just as Philips Lumileds begins enforcing the ruling.

In early July, the companies' ongoing patent dispute over AlGaInP chips seemed to have entered its final phase, as Lumileds informed customers using Epistar's infringing LEDs that they could be held responsible for infringing patent rights.

Epistar then introduced the Phoenix and Aquarius AlGaInP LEDs, which are specifically designed to circumvent the ITC's ban. "In light of the ITC's ruling, we accelerated our development program and are now manufacturing Phoenix and Aquarius in volume," said Epistar president B J Lee. "Those products remove entirely the feature that Lumileds claims is the basis for its patent, and also provide significantly improved performance over the previous designs."

Although the Taiwanese LED maker has prioritized the development of the new product lines, it must convince US customs that the Phoenix and Aquarius are not subject to the ITC ruling, although Epistar says it "expects a favorable determination shortly".

Lumileds is also seeking damages for Epistar's infringement of its 5,008,718 patent, although Epistar is again confident of a ruling in its favor.

Lumileds is skeptical about Epistar's capacity to move beyond the technology used in the infringing LEDs.

"During the ITC investigation Epistar was required to disclose all of its currently available AlGaInP LED products and its "next-generation" products, and these were all found to infringe the 718 patent," it said. While Lumileds said Epistar would be unable to suddenly devise a non-infringing alternative, Epistar maintains that this is exactly what it has done.

NEW PRODUCTS

Avago and Osram aim at automotive lighting

Semiconductor-maker Avago Technologies has introduced a range of new AlInGaP-based LEDs designed for automotive lighting applications.

The robust single-chip designs of surface-mounted red, amber and orange emitters are tailored to tolerate harsh conditions and to produce a narrow viewing angle useful for turn signals and center-height mounted stop-lights.

Avago says that the new product line, known as the HSMx-A46x series, has two significant advantages. One is that the LEDs can be soldered easily using conventional surface-mount techniques, thus keeping production costs low.

The LEDs are also very moisture-resistant and can be kept in the open air for up to four weeks after being removed from their sealed packages. As well as the automotive industry, Avago is aiming the LEDs at applications in signal lighting.

Meanwhile, Avago's German rival Osram Opto Semiconductors claims to have dramatically improved the brightness of its white chips that are designed for use in car headlights.

With LED-based headlights only just becoming a commercial reality, this application is seen as a major opportunity for GaN chip manufacturers over the next few years. Osram, whose "Ostar" LEDs have been certified for automotive use, claims that its new five-chip design delivers a typical brightness of 500 lm at a drive current of 700 mA and a color temperature of 6000 K.

KENNDEY AND VIOLICH ARCHITECTURE

LEDs and thin-film solar cells are being used to provide light in remote Mexican communities, in place of traditional but hazardous technologies like kerosene lamps.

"The idea is breathtakingly simple, taking a textile to combine a flexible solar source and semiconductor technologies," said Sheila Kennedy of the Boston-based Portable Light Project, whose pilot scheme has been operating in the Sierra Madre, Mexico, for the past year.

A portable LED light consists of a kit containing solar cells combined with batteries and two 40 lm Luxeon HB-LEDs, which produce approximately 100 lm of light.

Kennedy is now seeking makers of ultraviolet LEDs to provide chips for similar systems to sterilize water for drinking, and is urging *Compound Semiconductor* readers involved in the LED business to get in touch if they can help. Visit http://www.portablelight.org/ for more details.

SOLID-STATE LIGHTING

Big guns release new white chips

Major LED chip makers have released a raft of new, more efficient white LEDs in various cool-white and warm-white formats, for applications ranging from lighting in parking lots, to reading lamps and aircraft cabins.

Cree has released a cool-white version of its XLamp LED range that delivers a minimum luminous flux of 100 lm at 350 mA. Based around a 1 mm × 1 mm XR-E high-brightness GaN chip, the new XLamp is available in production quantities with a lead time of 6–12 weeks, depending on the volumes required.

The Durham, North Carolina, firm stressed the importance of the manufacturing breakthrough: "This is an announcement of volume availability, not a research and development result or availability of a few parts," said Norbert Hiller, Cree's general manager for lighting LEDs.

According to Cree, the 100 lm XLamp is available in cool-white tones (between 5000 and 10,000 K) and is suitable for outdoor area illumination like streetlights, tunnels and parking lots, as well as in portable applications such as torches.

Cree did not indicate whether a warm-white equivalent that would be more suited to interior lighting applications was in the pipeline, however.

Shortly afterwards, Philips Lumileds unveiled improved cool-white "Rebel" LEDs. The latest versions in the product family now offer a minimum flux level of 100 lm at 350 mA, matching Cree's high-end offering.

Hot on the heels of the Cree and Philips Lumileds products, San Jose firm Avago Technologies and Japan-based Toyoda Gosei also released new white LEDs for lighting applications.

Avago's 1 W warm-white "Moonstone" emitters are said to deliver a minimum luminous flux of 50 lm at a 350 mA drive current, and the company is aiming the devices at applications including reading lights, garden lamps and architectural illumination.

Like its latest AlInGaP LEDs, Avago's warm-white product range has been designed for ease-of-manufacture and durability. Featuring an exposed pad design said to provide low thermal resistance between the chip junction and circuit board, the LEDs are able to withstand high operating temperatures and drive currents, says the firm.

Encapsulated in a silicone compound to aid UV light and heat resistance, the Moonstone LEDs can deliver up to 56 lm over a 110° viewing angle.

While Cree and Lumileds can boast slightly higher brightnesses with their warm-white XLamp and Rebel products, Avago says that the Moonstone LEDs are priced at only $2.50 when ordered in bulk quantities.

Whereas Avago is targeting applications in and around the home, Toyoda Gosei's new white emitters are aimed squarely at the market for aircraft lighting.

The Japanese firm says that its "Aerospace White" mid-power surface-mount LEDs will make problems with binning a thing of the past. Emitting a color temperature of 4200 K, the InGaN chips are designed to withstand electrostatic discharge voltages of 2 kV. With a typical luminous flux of 20 lm at 200 mA, Toyoda says that the LEDs are suitable for overhead and galley lighting in the cabin, and flight deck instrumentation.

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...China deal

Johnson Matthey has sold two bulk hydrogen purifiers to LED companies in China. Shanghai Blue Light Technology Company has purchased a GPT-30 bulk hydrogen purifier for use in making GaN epitaxial wafers and chips, and HC Semitek, an LED epitaxial wafer producer, has bought a GPT-20 bulk purifier.

"China's compound semiconductor market is one of the fastest growing in Asia," said Sean Peng, Asian sales manager for gas purification at the company.

...Radical wafer solution

A low-temperature radical activation wafer bonding technique is challenging direct bonding, and proving useful for HB-LED heat sinks and reflectors. Applied Microengineering Limited extracts radicals from argon, oxygen or nitrogen gas plasmas onto the wafer, activating the surface for bonding at room temperature to 300 °C, instead of the 1000 °C process required for direct wafer bonding that can cause problems because of differing thermal expansion coefficients.

GAN LASERS

PS3 is now in full production, says Sony

This year's increases in GaN-based blue semiconductor laser manufacturing capacity are making Sony confident of meeting its PlayStation3 sales targets, with the company expecting to ship 11 million consoles in the 12 months to April 2008.

Sony now makes 1.7 million blue lasers per month, sufficient production for its console commitments and plenty of Blu-ray players besides.

"Production problems have now ceased, we're in full production as far as PlayStation3 is concerned and there's a steady chain of supply in North America, Japan and Europe," said a spokesperson for the computer entertainment division of the Japanese corporation.

In its annual report, Sony said it sold 5.5 million PlayStation3 units in the fiscal year ended March 31 2007, despite having faced production yield problems for its blue semiconductor lasers that feature inside each machine.

Sony is convinced that the PlayStation3 will eventually match the wild success of the PlayStation2, discounting competition from other console makers as a factor.

"We're aiming towards a much broader lifestyle for home-entertainment enthusiasts, that's one of the reasons the PlayStation2 went on to sell over 115 million units worldwide," said a spokesperson.

In its annual report Sony says it expects to establish the same successful business model with the PlayStation3 that it achieved with the PlayStation2. "Ultimately it will come down to content," explained the company's spokesperson.

"What it offers for its price is exceptional value for money – a quarter of the cost of a PC of similar capability and about the same as a commercial Blu-ray player."

● Strategy Analytics says that the market for GaN-based laser diodes will grow rapidly from just $34 million in 2006, to exceed $1 billion by 2011. Unusually, the price of these lasers is expected to trend upwards as higher-power devices begin to dominate the niche sector after 2009.

At the moment, GaN laser manufacture remains dominated by Nichia, said report author Asif Anwar, who estimates that the Japanese company controls 80% of the market. Sony is the number two producer, holding 10–15%, added the analyst.

Anwar believes that Nichia's stranglehold on intellectual property relating to the design and manufacture of the chips is now loosening, with most of the major Japanese electronics companies having turned to a form of GaN substrate developed by Sumitomo Electric Industries on which to grow laser structures.

"There's no point having a 2 inch substrate which only costs $20 but can only get a 30% yield. It makes more sense to have a more expensive substrate that you can get higher yield and better quality from," Anwar said.

OPTICAL COMMUNICATIONS

LED transceivers bring plastic fiber home

Visible-spectrum data transmission is now simpler, thanks to Optolock, Firecomms' plugless rival to copper, conventional fiber-optics and wireless systems for short-range network applications.

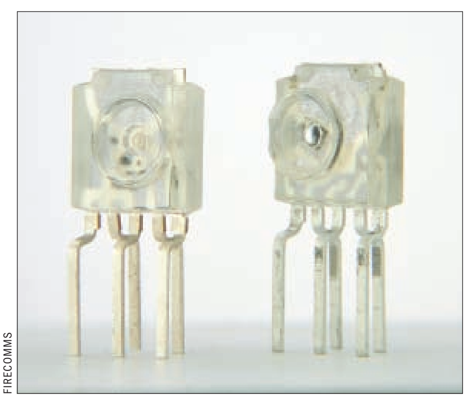
The Cork, Ireland, based company is licensing the plastic optical fiber (POF) technology to Taiwanese connector and cable assembly firm Comoss, in a deal that includes the sale of 650 nm resonant-cavity LED (RC-LED) transceivers.

A second deal replaces all existing transceivers with Firecomms' technology in the renowned interconnect-maker Molex's small multimedia interface.

"We estimate that there's several hundred million euros of transceiver business staring us in the face right now", said Firecomms' CEO Declan O'Mahoney, "and there's a growing market for fast ethernet and long-distance fiber."

Light from a red-emitting AlGaInP/GaAs RC-LED, transmitted down an easily cut plastic fiber, is safer and more straightforward to handle than the infrared laser emission that is typically used in glass fiber.

Also, unlike copper, it can't be shorted out, electrocute anyone or damage the boxes it goes into – all of which allows the direct attachment of the plastic fiber into the transceiver used in Optolock.



FIRECOMMS

Fired up: plastic optical networks employing 635 nm resonant-cavity LEDs based on GaAs structures are starting to rival conventional copper and wireless systems for high-speed, short-range applications.

"This technology is enabling us to do this with 100 or 200 Mbits/s networks," said O'Mahoney. "It completely simplifies fiber-optic communications – it's really a home do-it-yourself solution, if you like."

Firecomms is confident in its ability to meet the supply needs of the new deals as its devices are made by "state of the art epitaxy and fabrication vendors", with packaging and testing performed in Asia.

"We're not at all capacity restrained – we use some of the biggest vendors in the world. We're a fabless company, so we've got ample capacity," said O'Mahoney.

"We're operating in very low-cost, high-end environments in facilities where they're making hundreds of millions of emitter devices a month."

The current transceiver deals use the same RC-LED technology that Firecomms has exploited in the automotive industry, but the benefits are still being realized in other plastic fiber networks operating up to and over 100 Mbit/s.

"650 nm is one of the sweet spots for plastic fiber," said Mahoney. "Up until the creation of RC-LEDs, plastic fiber wasn't being driven at its optimum speeds."

As well as predicting strong sales for its existing products, Firecomms is optimistic about how its ongoing research efforts, with its Cork neighbor the Tyndall Institute, will push POF into the future.

"We've got major research and development going on at the moment into the development of our VCSELs," O'Mahoney added. "Firecomms is the only company in the world making visible VCSELs right now. This thing is capable of doing 3.2, 3.5 Gbit s^{-1} over plastic fiber, which obviously just drives it to completely new heights."

PHOTOVOLTAICS

UK venture plants £1.35 m seed

University spin-off Quantasol has entered the compound-semiconductor solar-cell business, currently led by Emcore and Spectrolab, with a kick-start of £1.35 million ($2.7 million) in seed funding. The money will be used to develop the Richmond, UK, company's quantum-well photovoltaic (QWPV) technology.

"Our unique strain-balanced quantum-well technology enables us to extend the spectral range of a single-junction cell and optimize a tandem cell without introducing any dislocations," said Keith Barnham of Imperial College, London, founder and director of Quantasol.

"We have fewer tunnel junctions than the Emcore or Spectrolab triple-junction cells, giving better device yield, enhanced lifetime and the ability to optimize for the spectral output of a particular concentrator system," explained Barnham.

GaAs-based solar cells currently hold the energy-conversion efficiency record of 27.8% for single-junction devices, and Barnham says that Quantasol's initial devices are already close to this figure, achieving 27% at 320-fold concentration.

Wafer epitaxy and cell fabrication are currently outsourced to UK-based partners, says the company's CEO, Kevin Arthur, with the aim of prototyping single-junction and tandem cells for three or four lead customers. By combining Quantasol's high-efficiency QWPV cells with low-cost, high-concentration systems from its partners, Barnham anticipates a cost-effective final solar solution.

Quantasol was formed in 2006, based on research by Barnham, with Massimo Mazzer of the National Research Council of Italy and John Roberts at the University of Sheffield.

The £1.35 million seed deal included contributions by spin-out incubator funds from Imperial and Sheffield, and investment groups Numis Securities, Netscientific and Low Carbon Accelerator.

Barnham and Mazzer have advocated the use of solar as a preferable energy source compared with revamping end-of-life nuclear energy plants. Commenting in the British political magazine, the *New Statesman*, Barnham and Mazzer wrote, "If the UK implemented similar policies on photovoltaics to Germany, then by 2020 photovoltaics would have installed as much power as the current nuclear contribution."

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...New CEO for Bookham

Alain Couder has been appointed as the new man in charge at InP laser and optical module manufacturer Bookham. Couder joins the company from database specialist Solid Information Technology, and has previously held a number of positions at other software firms. Interim CEO Peter Bordui, who took over after Giorgio Anania's sharp exit earlier this year, will remain as chairman of the San Jose-headquartered chip manufacturer. Couder says that Bookham is "poised to achieve profitable growth", a financial status that has eluded the company since its move into compound semiconductors.

...Emcore set to add again

Demand for concentrator photovoltaic (CPV) systems in Europe's sunniest locations will drive a further increase in multi-junction cell manufacturing capacity at Emcore next year.

With 70–75 MW of annual cell-manufacturing capacity already in place at its Albuquerque MOCVD facility, the company is at an advanced stage of negotiations with energy providers in Spain, Greece and Italy over the provision of high-efficiency systems.

And, although most providers in the US are lagging behind the southern Europeans in terms of their acceptance of the technology, Emcore says that it is now engaged with around a dozen US-based energy companies.

...Single-photon GaN

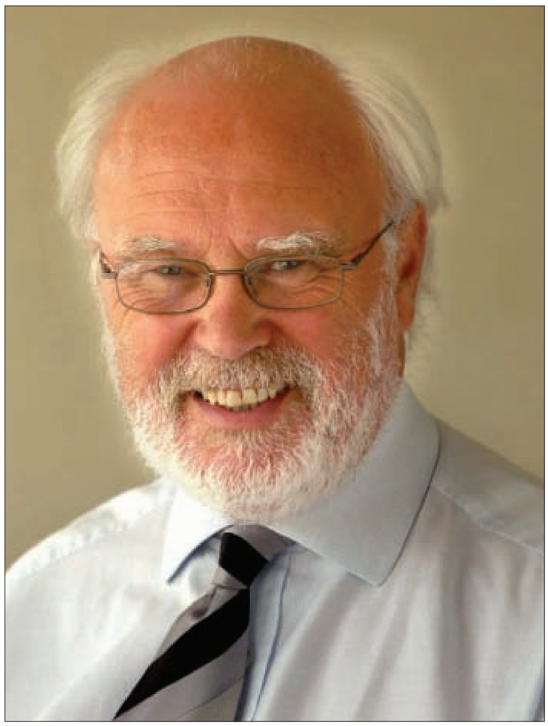
A collaboration between researchers at Cambridge, Oxford and Sheffield universities has produced the world's first single-photon source of blue light. Speaking at the UK Compound Semiconductor conference in Sheffield on July 4, Rachel Oliver of the Cambridge group said that the GaN device emitted at approximately 435 nm.

Rather than covert communications, the GaN emitter is intended to improve the sensitivity of fast detection equipment used in scientific research.

CONVERGENCE

Epichem finds the right chemistry with global giant Sigma-Aldrich

When a major global corporate swallows up a specialist company, things don't always go according to plan. But Epichem co-founder Barry Leese tells **Michael Hatcher** that joining forces with the chemicals giant Sigma-Aldrich has enabled the UK metalorganics supplier access to the fast-growing market for advanced silicon devices.



SAFC

All smiles: Now the president of SAFC Hitech, Epichem founder Barry Leese says that hooking up with Sigma-Aldrich will allow the merged operation to scale up production of exotic precursor materials for the silicon semiconductor market far more quickly.

Chemistry has always been a fundamental part of the compound semiconductor industry, and volatile metalorganics a cornerstone of the MOCVD production process. But, for the silicon industry, the idea of developing new materials to keep pace with Moore's law is still a relatively new one.

Epichem's February 2007 merger with Sigma-Aldrich's fine chemicals (SAFC) division, now establishing itself under the SAFC Hitech brand, has highlighted the new importance of the relationship between chemistry and mainstream semiconductor processing. And it has brought into even sharper focus the concept of "convergence" – where the often disparate silicon and compound semiconductor industries benefit from shared ideas relating to materials, processing and devices.

Founded by Barry Leese and Graham Williams in 1983, Epichem's initial focus was on silane, but, over the intervening 24 years, the UK company has become far better known for its expertise in metalorganics, the often nasty materials like trimethylgallium, as well as group V precursors phosphine and arsine. Because of the materials-driven nature of the compound semiconductor industry, where fine-tuning the proportions of different elements in epilayer structures is critical to LED or laser-diode design, the relationship between the metalorganic suppliers, the epitaxy equipment vendors and the device manufacturers has been very close and highly collaborative.

"The way that we developed Epichem in the first place was to have very close collaborations," explained Leese. "In the UK at first, with the likes of British Telecom to develop visible lasers. And the only way that we could develop the right chemicals, with the right purity, was to work with them to grow the layers, and then get their feedback."

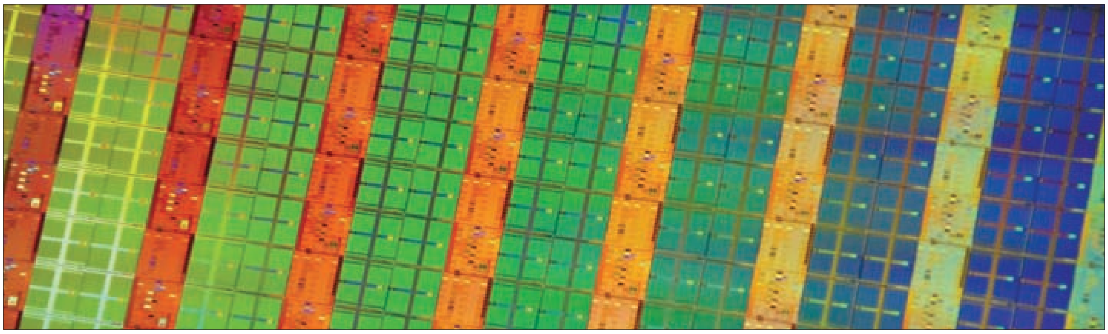
In silicon, things have traditionally been different. The development of faster transistors and higher-density memories has relied on physical processes, typically by scaling device features to smaller and smaller sizes. "For years, the silicon industry hadn't had to worry about [materials], because it had been able to shrink using lithography," explained Leese.

But in recent years, with the major silicon players anticipating the problem of leakage associated with extremely thin layers of silicon dioxide used in the gate oxide, that emphasis is changing. Intel is preparing to ramp production of its 45 nm node Penryn processors, and IBM and Texas Instruments are following suit with similar processes. The acquisition of Epichem by SAFC and the merged entity's targeting of mainstream semiconductors is a clear sign that the silicon industry is becoming materials-driven.

Despite its great success in high-brightness LEDs, where it is a key supplier, Epichem by itself simply wouldn't have been able to service the needs of a company like Intel. "When you move from III-V to mainstream silicon, the scale of the operation just goes up – the volumes, the levels of service that are needed. These are nice things, but they are really demanding," said Leese.

The key materials that the silicon giants want, and want in large volumes, are precursors of high-k dielectrics and the metals that are needed in new transistor gate structures. A lot of the detail, particularly on the metal gate composition that sits on top of the gate oxide, remains a closely guarded secret. But metals like aluminum, hafnium and barium are key, and they are grown using epitaxy-like techniques including atomic layer deposition. This means that volatile sources of the metals are needed, and points inevitably to metalorganics.

Following the post-bubble dip in the III-V business, Epichem decided to put much of its develop-



INTEL

Intel is set to begin production of hafnium-containing Penryn transistors before the end of 2007, while IBM and Texas Instruments say that they will implement high-k gate stacks at a later date. Texas Instruments is to use chemical vapor deposition to grow HfSiON.

mental resources into the high-k dielectric area, in the process attracting investment funds from no less than Intel Capital. It now lists nine different hafnium metalorganics, including hafnium tetrachloride, among its products, as well as six tantalum precursors and various others for zirconium, niobium and more. In fact, it seems that almost the entire range of transition-metal elements is covered.

Prior to SAFC's intervention, the problem Epichem faced was one of scale. As Leese says, the company was of a size commensurate with the LED business, not the silicon industry. SAFC's motivation, largely stemming from a desire to change the wider perception of Sigma-Aldrich as a supplier of specialist molecules to research chemists, was one of diversification from the life sciences. Allied to that was a realization that the silicon industry suddenly needed specialist chemicals, and needed them in bulk quantities.

Geoff Irvine is the director of commercial development at SAFC Hitech, the business unit that Epichem is now at the heart of. "To do what the [silicon] industry is clearly needing – because they're looking everywhere for the solutions and not finding them – you need to be working in a very collaborative way, which is what Epichem built its reputation on in the early years.

"They [Epichem] had established themselves, had credibility in the marketplace, had the early-stage customers; but they had no commercialization pathway for these materials, or the financial fortitude to really put the sort of thing in place that you need for this industry."

Armed with a PhD in organometallic chemistry from the University of Auckland, perhaps it is no surprise that Irvine clearly saw the potential that Epichem had, and what it lacked. That's when an acquisition started to make a lot of sense. Coupled with SAFC's highly developed manufacturing footprint, which uses 36 production facilities all around the world and shares them between different parts of the business to reduce overhead costs, Epichem could maintain its collaborative, customer focus and scale up too. "It really was a 'marriage made in heaven', when you look at the deal logic," Irvine said.

The scale of the silicon semiconductor materials market as it moves into the high-k era and beyond is clearly the major reason why SAFC decided to buy Epichem, but Irvine is quick to dispel any suggestion that the compounds sector is an afterthought: "It's a combination of both, because it provides us with access to a new market that's growing very, very strongly, especially in HB-LEDs."

"We're going to continue to invest in that area to sustain growth. Now we're all in a [world] where energy costs are soaring and people are looking for efficiency, so it makes sense to stay in that area. Even within our own Hitech business, it stands to reason that you don't want to be a pure-play – you benefit internally and in the marketplace by participating in aligned industry segments."

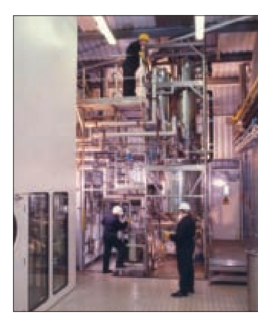
That sounds like a clear indication that semiconductor industry "convergence" is becoming a reality. Prior to the SAFC deal, Epichem's annual sales revenues of $40 million were dominated by demand from the LED market – demand that is sure to grow with the burgeoning desire to use solid-state sources in backlights, automobiles and general lighting. But with the growth curve for silicon applications only just taking off, Irvine and Leese are in no doubt about how that sales split will change.

"From what we can see, the DRAM people have been the ones who have taken on board the new technologies [and materials] quickest, whereas the microprocessor people are much more conservative, but that's now coming through," said Irvine. "[Silicon's] got to be bigger in the end, because it's just a much bigger market. And it's going to shift the SAFC Hitech revenue balance that way."

As the co-founder of Epichem, you might think that Leese has concerns about the business losing some of its identity after being "swallowed whole" by a global firm of the magnitude of Sigma-Aldrich, with its 7600 employees and annual sales close on $2 billion. Not a bit of it: "The combination will enable the Epichem approach to happen more elegantly and more quickly than we could have done as an independent firm," Leese said.

"They didn't want to pull us apart, and I'm the president of SAFC Hitech. We can scale up much quicker, and with extra resources we can go into other areas that we were really unable to as Epichem, like solar cells. We're not allowing the larger corporation to change us."

Maintaining customer focus while servicing huge clients and overseeing major production scale-up is the challenge for Leese now, but it seems that the move towards convergence is benefiting him and his new colleagues already.



Traditionally focused on precursor materials for III-V applications like high-brightness LEDs, most of SAFC Hitech's operation currently involves manufacturing materials like trimethylgallium.

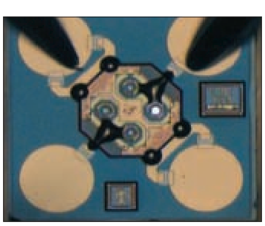
Atomic clocks throw down th

Miniature atomic clocks offer a small but valuable market for VCSEL manufacturers that are able to build single-mode lasers with a low threshold current and very precise emission wavelengths, according to **Darwin Serkland** from Sandia National Labs and **Robert Lutwak** from Symmetricom.

Atomic clocks provide accurate timing signals, which are required in a variety of applications from telecommunication networks to the global positioning system (GPS). In 1964 Hewlett-Packard introduced its "portable" model 5060A cesium-beam frequency standard that weighed 30 kg and consumed 40 W. During the subsequent 40 years, manufacturers have substantially reduced the size of atomic clocks – Symmetricom's X72 rubidium clock has a volume of just 122 cm^3. However power consumption has decreased only modestly – the X72 still consumes 10 W.

In order to achieve atomic-timing accuracy in portable applications that can run for 24 hours on a small battery, the US Defense Advanced Research Projects Agency (DARPA) launched the chip-scale atomic clock (CSAC) program in 2002. Its five-year goal is to produce a 1 cm^3 atomic clock consuming 30 mW or less.

With the CSAC project now in its fifth year and several competing teams (NIST, Symmetricom/Draper/Sandia, Rockwell/Agilent, Honeywell and Sarnoff/Princeton) succeeding well beyond initial expectations, attention is turning to commercialization of the technology and potential applications. Ultimately, widespread deployment of CSAC technology will depend on the final product performance specifications and cost, but here we will consider a few application possibilities.



A VCSEL chip (0.25 mm^2) as used in a prototype chip-scale atomic clock . Only one of the four VCSELs on this chip is needed, and only two of the four VCSELs are electrically connected to the round bond pads. The common cathode is connected to the other two bond pads.

Market opportunities for miniature clocks

Potential CSAC applications include ad-hoc mobile communication networks that could self-assemble among a group of people, each carrying their own atomic clock for precise synchronization. CSAC-enhanced GPS receivers could lock to satellites much more rapidly, allowing for faster acquisition of precise positioning information. Finally, if CSACs could be mass produced using batch fabrication techniques, the unit cost could potentially fall to the point where CSACs could replace ovenized crystal oscillators in a large number of precision timing applications.

DARPA's mid-term three-year power goal of 200 mW, while less aggressive than the ultimate 30 mW goal, still represents a fifty-fold reduction in power consumption relative to current commercial atomic clocks. The team comprised of Symmetricom, the Charles Stark Draper Laboratory and Sandia National Laboratories has recently reported (see Lutwak *et al* 2007 in Further reading) a pre-production build of 10 miniature atomic clocks that meet the mid-term power goal, consuming only 125 mW each. This pre-production build represents a first step toward commercialization, allowing us to determine the manufacturability, unit-to-unit variation and long-term aging effects of this new generation of atomic clocks.

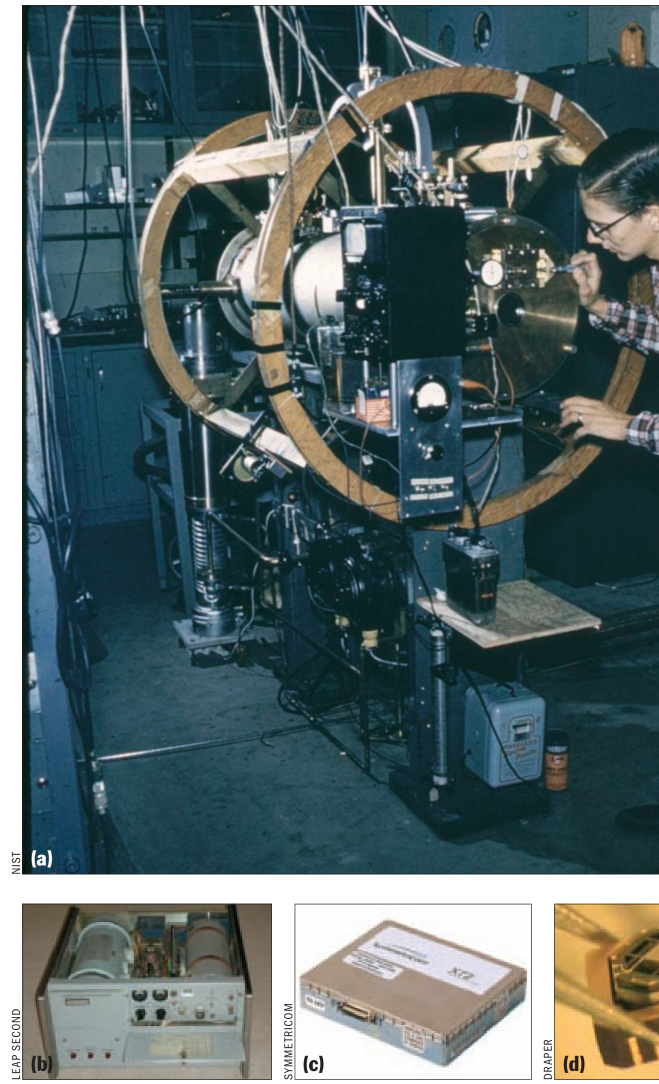
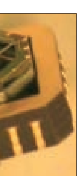


Fig. 1. Atomic clock evolution has improved portability: **(a)** NIST's first ces standard named NBS-1 from 1952; **(b)** Hewlett-Packard's 5060A, which w 30 kg, from 1964; **(c)** Symmetricom's model X72 rubidium oscillator; **(d)** D MEMS physics package used in prototype CSACs.

e gauntlet to VCSEL makers



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Switching from lamps to VCSELs

VCSELs are a key enabling component for the hundredfold reduction of size and power realized in the chip-scale atomic clock. However, fully exploiting the power savings allowed by VCSEL technology requires the use of new techniques for atomic interrogation.

Figure 2b shows a block diagram of a conventional atomic clock, which does not use a VCSEL. The resonance cell contains the ^{87}Rb isotope, which has a ground state that is split into two sublevels, labeled *a* and *b*, separated by 6.8 GHz due to the hyperfine interaction between the nuclear and electronic spins (see figure 2a).

Conventional rubidium clocks exploit a coincidence of nature, using ^{85}Rb vapor to filter light emitted by an ^{87}Rb gas discharge lamp, so that only light at the frequency f_{ad} reaches the cell. This depopulates level *a* and reduces absorption of f_{ad} photons. When an RF cavity containing an ^{87}Rb vapor cell is excited at exactly the 6.8 GHz HFS frequency, as shown in figure 2b, the atoms return from level *b* back to *a*, increasing the absorption of f_{ad} light. Locking the RF frequency to the photocurrent dip at 6.8 GHz produces a precisely known frequency – the clock frequency, from which other practical frequencies, such as 10 MHz, can be derived.

Coherent population trapping (CPT) offers an alternative interrogation method that does not require an RF cavity around the alkali gas (either rubidium or cesium) cell. Figure 3a shows the relevant energy levels of a cesium atom. Similar to rubidium, the ground state of cesium is also split into two sublevels, labeled *a* and *b*, which have a hyperfine splitting of 9.2 GHz. In fact, the internationally accepted definition of the second is the time equal to exactly 9,192,631,770 oscillation periods of the cesium hyperfine frequency.

The name "coherent population trapping" refers to the fact that a fraction of the cesium atoms become "trapped" in a coherent superposition of the ground states *a* and *b*, and do not absorb light due to destructive interference between the *ac* and *bc* transitions. CPT requires the simultaneous application of coherent optical frequencies f_{ac} and f_{bc}, which can be achieved by modulating a single VCSEL at 4.6 GHz. This produces frequency modulation (FM) sidebands at ±4.6 GHz from the carrier optical frequency of 335 THz (894 nm).

Figure 3b shows the required elements of a CPT atomic clock: a 4.6 GHz microwave oscillator with approximately −10 dBm of power, a VCSEL with adequate FM sensitivity at 4.6 GHz, a quarter-wave plate (QWP) to create a pure circular polarization state, a cesium cell heated to approximately 85 °C, and a low-frequency photodiode to measure transmission of the VCSEL light. Locking the 4.6 GHz microwave frequency to obtain maximum photocurrent yields the desired clock frequency, from which a standard frequency of 10 MHz may be synthesized.

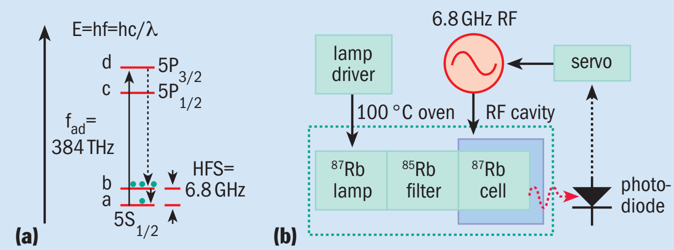

Fig. 2. Conventional atomic clock. **(a)** Rubidium energy levels, showing the 6.8 GHz hyperfine splitting. **(b)** Conventional rubidium vapor clock architecture, including an ^{87}Rb lamp, RF cavity, an ^{85}Rb filter, a photodiode and an oven.

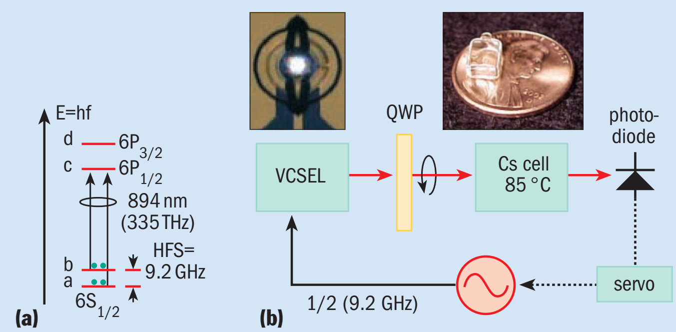

Fig. 3. Coherent population trapping (CPT) atomic clock. **(a)** Cesium energy levels, showing the 9.2 GHz hyperfine splitting. **(b)** CPT clock architecture, using an FM-modulated VCSEL, a QWP and a small heated cesium vapor cell.

Achieving the ambitious CSAC objectives of reducing the size and power of atomic clocks by two orders of magnitude demands innovation, both in the fundamental approach to atomic interrogation (see box "Switching from lamps to VCSELs") as well as in the materials and fabrication processes of the physics package assembly. Replacing the conventional RF discharge lamp with a VCSEL cuts the power required to drive the light source from several watts to several milliwatts. Incorporating the VCSEL and a photodiode with a MEMS-fabricated vapor cell permits a reduction in the size and mass of the resonance cell and consequently the necessary heater power. Figure 1d shows a MEMS physics package, developed by our colleagues at the Charles Stark Draper Laboratory, that requires only 10 mW to heat a tiny cesium vapor cell to 85 °C.

While functional CSACs have been demonstrated in the laboratory, commercialization of the technology requires development of production processes for several key components, including high-performance VCSELs and MEMS-fabricated physics packages.

The performance of the VCSEL component

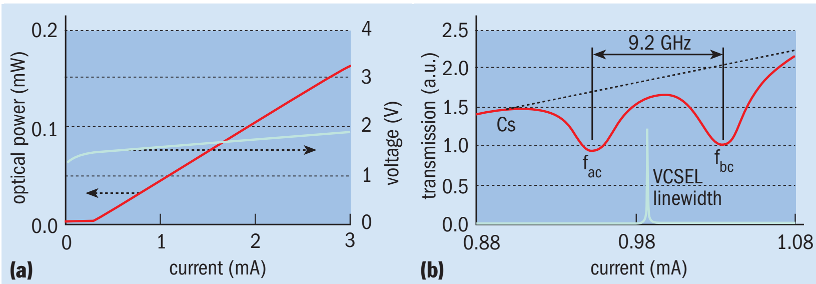

Fig. 4. (a) Single-mode VCSELs with threshold currents below 0.5 mA are needed to produce low-power atomic clocks. The laser is normally operated at 0.5 mA above threshold. **(b)** Ramping the injection current of an unmodulated VCSEL tunes its wavelength across the two hyperfine absorption lines. For comparison, the measured VCSEL linewidth of 50 MHz is shown on the same scale.

Table 1. Atomic clock properties

Parameter	*Rubidium*	*Cesium*	*Units*
Clock frequency	6.8	9.2	GHz
Wavelength (D1)	795.0	894.6	nm
Wavelength (D2)	780.2	852.4	nm
Cell temperature	100.0	85.0	°C

Table 2. VCSEL requirements for CSACs

Parameter	*Minimum*	*Maximum*	*Units*
Threshold current		0.5	mA
Optical power	20	40	μW
Linewidth		75	MHz
RF modulation power		−10	dBm
Transverse modes		−10	dBc
Polarization modes		−10	dBc
Relative intensity noise at 30 μW		−130	dB/Hz
Mean time to failure	100,000		hours

directly influences the performance, power consumption and reliability of the CSAC. Unfortunately, the VCSELs used today for data communication are inadequate for use in CSACs that are based on coherent population trapping. VCSELs for these clocks must emit in a single polarization state, operate in a single transverse mode, be tuned exactly to a particular resonance wavelength of the atomic vapor (typically rubidium or cesium) and remain stable at this wavelength and polarization for the life of the CSAC. They must have a low threshold current and high modulation bandwidth to reduce power consumption. Finally, because the noise properties of the VCSEL directly impact the stability of the atomic clock, they must exhibit unusually high spectral purity (narrow linewidth).

Wavelength requirements

Table 1 shows the available optical resonance wavelengths, ranging from 780 to 895 nm, and microwave clock frequencies for rubidium and cesium atomic clocks. D1 wavelengths yield higher signal-to-noise ratios and are preferable to D2 wavelengths.

VCSELs can reach rubidium wavelengths using AlGaAs quantum wells, and cesium wavelengths using InGaAs quantum wells. However, these lasers must also operate at a single frequency that is tunable to exactly the D1 or D2 wavelength at a specified operating temperature. For example, if the VCSEL operating temperature is constrained to 85 °C ± 5 °C, then the wavelength is constrained to ±0.3 nm. This immediately reduces yield to at most 20% for an epitaxial growth uniformity of 3 nm (0.35%) across a 75 mm diameter GaAs wafer.

Table 2 lists most of the important VCSEL requirements for use in CSACs. To minimize DC power consumption and overhead heat dissipation, a threshold current below 0.5 mA is desired (see figure 4a). The VCSEL, which is typically operated at 0.5 mA above this threshold, should provide an optical power in the cesium cell between 20 and 40 μW, to maximize the clock signal-to-noise ratio and minimize light-induced frequency shifts. Importantly, the VCSEL linewidth should be at most 75 MHz, so that it is much narrower than the pressure-broadened cesium absorption linewidths (see figure 4b). These requirements in threshold current and linewidth can be met simultaneously by increasing the top distributed Bragg reflector reflectivity from 99.6% for a typical data communication VCSEL, to 99.9% for a CSAC VCSEL.

Modulation requirements

The VCSELs used in CSACs must also be frequency modulated at half of the clock frequency using enough RF power to put most of the optical power into the two sidebands at ±4.6 GHz (modulation index M = 1.8). Ideally, the required RF power to produce sufficient modulation is less than –10 dBm to minimize power consumption.

The VCSEL also needs to operate in a single transverse and linear polarization mode, because other modes are detuned from resonance and will simply add partition noise. Finally, the VCSEL should operate for a lifetime of 10 years (90,000 hours) at an operating temperature of approximately 85 °C.

It is a significant challenge to manufacture VCSELs that meet all of these requirements simultaneously with a yield of 10% or more. Fortunately, in the near-term, atomic-clock customers can probably afford to pay ten times more for their VCSELs than the going rate for standard data communication VCSELs that dominate the market today. ●

Further reading

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www.symmetricom.com (search for white papers)


About the authors
Darwin Serkland (**dkserkl@sandia.gov**) (left) is a principal member of technical staff at Sandia National Laboratories, Albuquerque, NM. He leads a team developing surface-normal optoelectronic devices including VCSELs, photodiodes, and electro-absorption modulators.
Robert Lutwak (**rlutwak@symmetricom.com**) (right) is a senior scientist at Symmetricom's Technology Realization Center in Beverly, MA, and is a principal investigator on the DARPA-sponsored CSAC program.
The CSAC work has also been supported by Sandia, a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SUBMARINE LASERS

3S Photonics goes back to its roots

At one corner of the Alcatel-Lucent campus on the outskirts of Paris, change is in the air. Surrounded by farmers tending their crops, 3S Photonics is determined to dominate the resurgent market for submarine optical communication components. **Andy Extance** reports from rustic Nozay.

Visiting 3S Photonics' site on the outskirts of Paris, it's easy to wonder if you've come to the right place. Driving through the rural French villages, fields and market gardens, it's hard to believe they call it the "Optics Valley". Then, when the extensive Alcatel-Lucent site draws into view at Nozay, few employees are certain where to find the single 3S building hidden in the sprawl of its historical founder.

3S Photonics is the company emerging from the sale of Avanex's foundry and laser business to French entrepreneur Alexandre Krivine. The new company is pushing aggressively for profitability in the first year of business, a major departure from the captive but loss-making role it played for Avanex. The opportunity to achieve that goal arises partly from the newfound freedom to sell products to all transponder and transceiver makers, including Avanex's competitors.

Beyond this, Krivine is very clear in stating the key application that will move 3S's finances into the black. "Submarine. I have no doubt. This is the key growth market, the submarine market, and we are one of only two suppliers in the world."

Krivine's bold statement is backed up by 3S's chief operating officer, Didier Sauvage: "Today there are only two players, JDSU and us. Bookham has announced some [product] introductions, but it is not yet a player. Commercially speaking, for the moment, we are the top player. We know through the meetings that we have with customers like Alcatel-Lucent, NEC, Fujitsu and Tyco, that the architecture we have is really working effectively. We are in a very strong position at this point."

3S originates from Alcatel Optronics, whose GaAs and InP fabs employed 400 people at the height of the internet boom. The consolidated fab at the Nozay site now employs 110 people, although the new company also inherits a partnership with the Thai packaging firm Fabrinet, which has 250 employees dedicated to 3S. Many staff at 3S date back to the establishment of Alcatel Optronics and would be forgiven for touting the potential of submarine lasers simply because they want to relive their former glory. Sauvage explains, however, that the time is right for a resurgence in this area, not just because it's what he and his colleagues know, but because of what 3S's customers say.

"If you look at the cycle, you had a huge investment in the year 2000 in the Atlantic side. For the moment there is no further investment there. Most of the investment is in the Pacific side, with 40,000–60,000 km of new links per year for the next three years. There are also submarine links between India and Singapore. In 2009–2010 Europe and the Atlantic will come back. This is clearly the message we are getting from customers like NEC and Alcatel-Lucent."

In Krivine, 3S has a CEO who calls himself a serial entrepreneur. 3S is the fourth company he has founded, having sold his previous ventures to a variety of communication stalwarts, including Alcatel. His vision for 3S holds true to his background, looking beyond the submarine business to help 3S introduce breakthrough technologies in the longer term.


3S PHOTONICS

Precision fabrication is performed in 3S' InP and GaAs facility, which is essential for producing reliable submarine lasers.

Krivine's strategy is concentrated on increasing product sales, so much so that he is contemplating pulling 3S out of foundry service work. Instead, he feels the company needs different products to guarantee its future, but they have to be the right ones.

"We need to target new markets," said Krivine, "but of course we don't have much venture money, so we want to be sure that what we are doing is good, is market directed. We are looking toward the industrial laser market, defense and the medical market too."

To help it select new markets accurately, 3S has created a dedicated scientific advisory council gathered from French academic institutions and government centers, including the president of SFO, the French optics society.

The willingness of the academic community to help 3S is an example of the goodwill the company has gained by returning to French ownership and the potential of these relationships. Another illustration came when one representative of the national defense research body declared himself "touched" at the company's launch, a widely echoed feeling that is helping 3S to enter markets previously closed to Avanex.

"Now we're French, it's much easier with the defense department," said Krivine, who will work to bring the company's wider operations closer to home.

"We really want to develop the number of employees in Europe. We're trying to reduce the number of employees who are in Asia. We have started a program with the government and we'll focus on that."

"I'm happy to have the opportunity to bring something back to France, and, to be blunt, keep this in the country, rather than have the technology go abroad."

Agilent proves that defects kill HBTs

Dislocations are the root cause of infant HBT failure, says Agilent, and reducing their density is the only way to achieve higher levels of integration with excellent reliability. **Richard Stevenson** investigates.

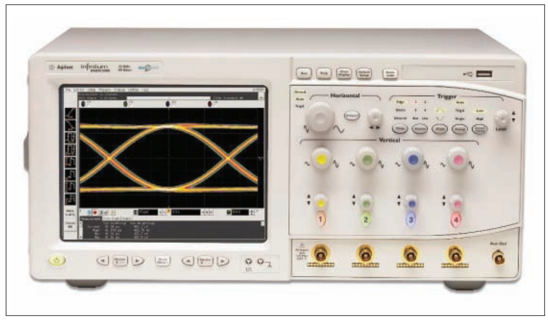
It's easy to ignore very small changes in device performance, or dismiss them as irrelevant. But figuring out exactly what these fluctuations mean can pay dividends – in Agilent's case, it enabled the company to discover the early failure mode for HBTs. What's more, this type of failure could impact the reliability of HBTs in the power amplifiers of cell-phone handsets.

"In a fairly large circuit, a selectable divider with nearly 200 transistors, we noticed a 2% drift in supply current over a typical lifetime," explained Thomas Low, senior R&D engineer at Agilent's Santa Rosa site. "Initially, this power-supply drift seemed a trivial thing and it only happened on a small fraction of IC parts, maybe 1 in 50, so many of us would have preferred to ignore it. But one of our product engineers, Kevin Alt, decided to dig deeper and realized that the reason the supply current was drifting was that the current gains in random individual transistors in the current mirror circuit were dying." This scenario posed the obvious question: why are a very small proportion of the HBTs failing at an early stage, while the others are unaffected?

This is not just an academic question for Agilent because it manufactures electronic test instruments, such as oscilloscopes, sources, and network and spectrum analyzers, containing hundreds or even thousands of GaAs HBTs shared among many ICs. "If you randomly toss a small population of transistors into these circuits and say that these HBTs will have their current gains die in a short time, then that's a very bleak prediction," explained Low.

These concerns drove Agilent to try to understand the reason for the infant current-gain failure in a small proportion of HBTs. Its investigative team stripped down and examined HBTs that had failed with various techniques, such as scanning electron microscopy and transmission electron microscopy. The result of this failure analysis was null, according to Low. Researchers did manage to find some process-induced defects, which Low describes as "warts", on metal lines and in passivation dielectrics but there was no significant correlation of these defects with HBT failures.

However, success eventually followed by employing a highly parallel method for reliability testing that was developed by Low's colleague, Bob Yeats. The traditional reliability-testing method, high-temperature operating-life testing cannot detect infant failures because the sample size is too small, typically being limited to less than 100 HBTs. In contrast, Yeats' technique can measure between 12,800 and 100,000 HBTs per wafer (see box "Parallel approach to HBT reliability testing", p20), which is a large enough sample size to detect the small infant-mortality rates associated with these devices.



Agilent makes GaInP/GaAs HBT ICs at its Santa Rosa, CA, fab for a range of test and measurement products, such as oscilloscopes. Fabricated from epiwafers grown at MicroLink Devices, these chips have boosted the performance of many instruments that were previously employing silicon technology.

Agilent's researchers discovered that the probability per HBT of infant failure (P_{qf}) is proportional to the etch pitch density (EPD) of the underlying GaAs substrate (see figure 1, p20). In fact, these two quantities are related by the equation $P_{qf} = A_{eb} \times EPD$, which implies that the size of the emitter area directly governs the likelihood of a HBT suffering from early current-gain failure. Put another way, this data suggests that any HBT emitter-base junction that is pierced by a threading dislocation from the substrate will fail by current gain far sooner than its dislocation-free companions.

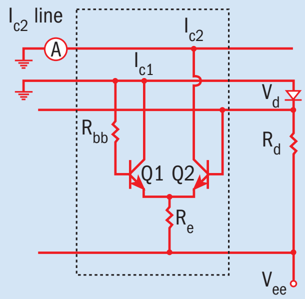
The above equation produces a good line through the data, but the data points show significant scatter (see figure 1). "There are at least two components to the vertical scatter," explained Low. "One is the intermittent presence of additional defects, from the epi and/or process, that cause infant failures – which are mechanisms that are currently unidentified. Another component is sampling error. If you only detect five failed HBTs within the sample tested on a given wafer, then there is a square-root-of-five uncertainty in the actual HBT failure rate for that wafer." For a fixed sample size, this effect will produce more scatter in the data at low EPDs. According to Low, there is also a horizontal scatter which results from uncertainty in the actual dislocation density, due to EPD counting errors. This scatter is larger at higher EPDs, where separation between

The discovery of the cause of infant failure in HBTs by Thomas Low and colleagues at Agilent won this year's best paper award at CS Mantech. The other authors on this paper, "The role of substrate dislocations in causing infant failures in high-complexity InGaP/GaAs HBT ICs", were K W Alt, R E Yeats, C P Hutchinson, D K Kuhn, M Iwamoto, M E Adamski, R L Shimon, T E Shirley, M Bonse, F G Kellert, D C D'Avanzo, A Wibowo, S Hassler, N Pan, G Hillier, H Badawi, M Young and W Lui.

Parallel approach to HBT reliability testing

Yeats' reliability testing method can probe many devices in parallel and can be used to analyze failures that only occur in a very small proportion of devices.

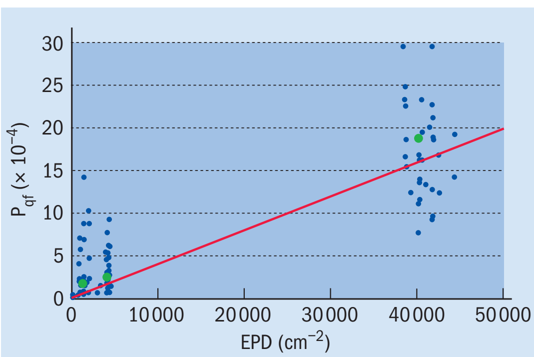
The technique involves a medium-scale integration circuit with a basic test cell featuring two transistors, a Schottky diode, and resistors (see figure). The cell is repeated 50 times in a single array and twice on a chip measuring 1540 µm × 790 µm, so that 200 HBTs are under stress.



These HBTs, referred to as Q1, are paired with a normally off HBT, Q2 (a condition produced by biasing the Q2 transistor base at a voltage more negative than the Q1 base using the Schottky diode and resistor).

When a Q1 HBT's current gain falls below 30, which is about one-third of its initial value, base current I_{b1} increases and the voltages V_{b1} and V_{e1} fall due to the additional voltage drop across R_{bb}. This turns the Q2 HBT on, which conducts a current of around 1 mA and exposes this particular Q1's failure.

Using this approach, MSI circuits were evaluated after stressing them for 168 hours using a junction current of 0.6 mA µm^{2} and an ambient temperature of 165 °C, which resulted in a device junction temperature of 230 °C. As the probability of infant failure varied between 1 in 1000 and 1 in 100,000, many HBTs per wafer had to be assessed. Typically 12,800 HBTs were tested per wafer, but occasionally 100,000 HBTs were analyzed.



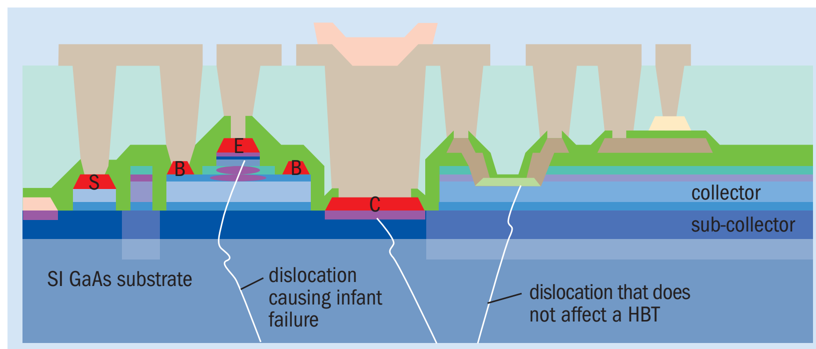


Fig. 1. The probability of infant current-gain failure is proportional to the EPD of the GaAs substrates (the green circles show the median at different substrate EPDs). The substrates with the higher EPDs were made by the LEC technique and those with lower densities were produced by the VGF approach. AXT optimized its VGF process by reducing the thermal gradients in the growth chamber. It has already cut its EPD for 3 inch semi-insulating GaAs from 2500 cm^{-2} to 1000 cm^{-2} and it is now setting itself a goal of 500 cm^{-2} or less. **Fig. 2.** Agilent believes that the root cause of infant failure is a form of recombination-enhanced defect generation, which is initiated by a dislocation at the base-emitter junction. If the dislocations do not pass through the base-emitter junction then they cannot cause infant failure.

etch pits becomes comparable to their size.

By fabricating reliability-test circuits on epi material grown on N+ GaAs substrates, Agilent confirmed its belief that dislocations are the primary cause of HBT infant failure. This type of substrate is not suitable for making working RF devices. However, it can be used for DC reliability tests, and it has a dislocation density that's much lower than even the very best semi-insulating substrates, with an EPD of less than 100 cm^{-2}. "We tested 100,000 transistors per wafer on three of these N+ wafers and we saw a total of three HBTs fail," remarked Low. The conclusion was that the additional tenfold reduction in dislocation density produced a similar fall in the infant failure rate.

Agilent believes that any further reductions in HBT infant mortality will only come through additional improvements in substrate EPD. The company is already specifying that AXT's incoming substrates must have an EPD of less than 1,200 cm^{-2} and it hopes that its recent published findings will encourage GaAs substrate suppliers to develop even lower EPD substrates.

The high number of HBTs in each Agilent chip could fool HBT power-amplifier (PA) manufacturers into thinking that their products are immune to the EPD problem, but this would be a mistake. That's because it is the total emitter area that actually matters. At *Compound Semiconductor* we note that the emitter area for a typical cell-phone PA is even larger than Agilent's largest circuit so, at a given EPD, the predicted infant-failure rate of PA circuits is even worse. Simple calculations show that a typical GSM-output stage alone. which has a total emitter area of 4×10^{-5} cm^{-2}, will have a probability of infant current-gain failure of 83% for a typical liquid-encapsulated Czochralski (LEC) substrate (EPD = 45,000 cm^{-2}) and 15% for typical vertical-gradient freeze (VGF) substrate (EPD = 4000 cm^{-2}). These are startling figures that could motivate many HBT cell-phone PA manufacturers, who consume a much larger volume of material than Agilent, to also beat the drum for lower EPD GaAs substrates.

The high failure rate also begs the question: why are so many handsets still working? The most likely answer is that the HBTs in the cell phone slowly degrade, rather than suddenly failing. If the output power from the PA continuously and linearly degrades over time, then the bias-control circuitry will adjust accordingly. Since the PA monitors the transmit power, the PA bias will increase. This reduces the battery lifetime, which is annoying to the user. However, it does not stop the handset from operating, at least not immediately.

Agilent has also tried to establish the nature of the infant failure of the HBT and to see whether it differs from the wear-out failure. Infrared images of the test chip allowed the failed HBT to be identified by its lack of electroluminescence (see figure 3). This failed transistor was interrogated with various DC tests. The I(V) characteristics were generally similar to those of HBTs that had failed by the more common wear-out mode, but there was a difference in the time dependence of the base current. "The non-dislocation-driven wear-out mode has a base current versus time that is constant for some long period, and then, bam, over 10 hours it increases radically," Low explained. "But with the dislocation-driven failure mode, the base current versus time is rock-solid linear. It linearly increases as long as you keep stressing it, even well into beta [current-gain] failure" said Low.

According to him, the gradual increase in base current versus time for infant failures has an important practical implication for circuit reliability. Circuits which can operate with low current gain, such as emitter-coupl ed logic ICs, will continue to function for significantly longer under a given bias stress than circuits that are more sensitive to the current gain, like certain amplifiers and other analog circuits.

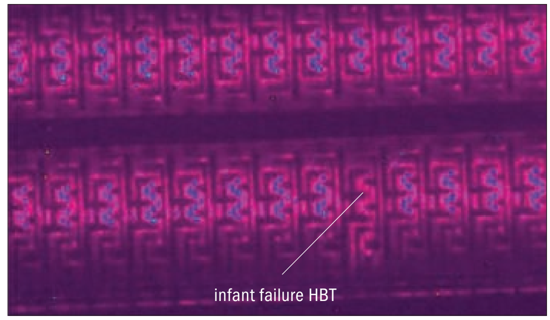


Fig. 3. GaAs HBTs behave like 870 nm LEDs. Infrared images can detect a reduction in emission intensity and pinpoint a HBT that has suffered from infant current-gain failure.

Low believes that Agilent's research effort has been very thorough. "At this point we have only to specify and verify the lowest possible EPDs". However, he does not see this as a triumph but rather as a restriction. "The lowest substrate EPDs available to us today come from AXT and have a value of less than 1200 cm^{-2}. These defects affect yield and restrict the maximum level of integration of our circuits." And the only way out of this predicament, says Low, is for substrate suppliers to develop GaAs material with much lower EPD than that available today.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Kyma looks to scale HVPE approach

Currently producing 2 inch GaN substrates from a native seed, Kyma Technologies' crystal process will be scaled up to 4 inches by the end of the decade, report **Keith Gurnett** and **Tom Adams**.

GaN devices are enjoying great commercial success, but their performance is still held back by the foreign substrates that are generally used as a basis for their manufacture. Switching to high-quality GaN substrates would cure this problem, but making this form of substrate is not easy. Because of GaN's high melting point (~2500 °C) and the incredible chemical stability of nitrogen gas, conventional liquid approaches such as those used for silicon and GaAs, where an ingot is pulled directly from a crystal melt, have only brought limited success. The GaN crystals produced by this method do have an excellent crystalline quality, but they are far too small for manufacturing purposes.

The lack of progress has spurred the development of alternative approaches to form GaN substrates. These have been led by HVPE-based techniques, which use hydrogen chloride gas to transport gallium to a growing crystal, where it reacts with ammonia to form GaN. This approach has enabled several manufacturers to make various forms of GaN substrate, including Kyma Technologies in the US and various companies in Japan (see box, p24, "Japan's GaN development").

Kyma, which is based in Raleigh, NC, uses the approach nearest to silicon-like growing of GaN crystals. Starting with a GaN seed, the company currently grows crystals that are up to 1 cm thick and up to 2 inches in diameter. The 1 cm thick wafer can then be sliced into a dozen or so 500 µm thick substrates. This makes Kyma the only manufacturer of native GaN.

The technique is able to address the problem of defect density, which plagues the deposition of GaN onto foreign substrates and is usually in the 10^8–10^9 cm^{-2} range. With Kyma's method, defect densities are below 5×10^6 cm^{-2} and are uniformly distributed across the wafer. Kyma's native approach is one of four related HVPE-based methods for producing GaN substrates, but it is the only method that involves growth onto a GaN seed crystal as opposed to a foreign platform (see figure 1 for an overview of all four methods).

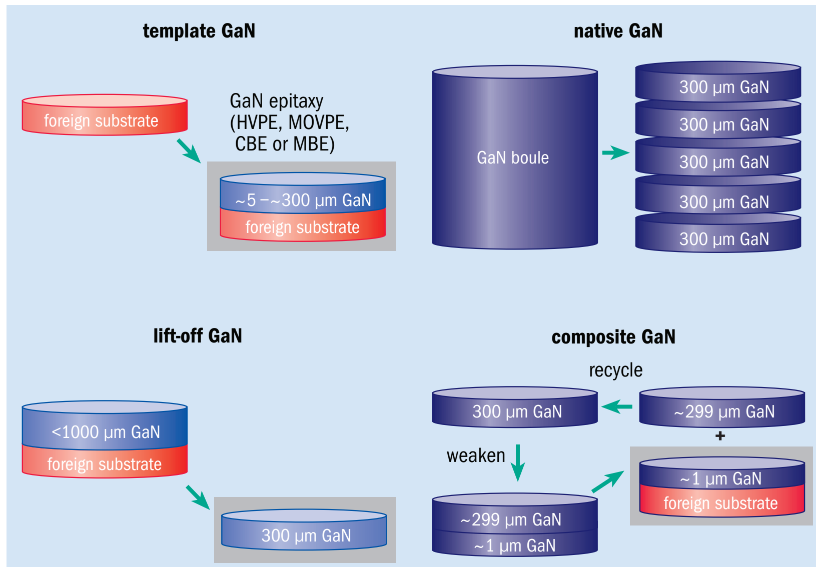

Fig. 1. HVPE-based methods can be used to produce four different types of GaN substrate. Template GaN **(a)** products consist of a GaN film grown onto a foreign substrate. Native GaN **(b)**, which is made by Kyma, involves forming a substrate from a GaN boule. The lift-off GaN **(c)** approach begins with growth of 1 µm or more of GaN onto a foreign platform. GaN is then removed, thinned and polished to form a free-standing substrate. Thin GaN films can also be attached to foreign substrates, such a polycrystalline AlN, to form composite GaN **(d)**.

Competing HVPE-based techniques

One common method for making GaN substrates is known as "lift-off GaN", in which a free-standing substrate is made by lifting-off a single GaN epilayer, less than 1 mm thick, after it has been grown on a foreign platform, such as sapphire. Lift-off GaN can differ from native GaN in three ways, says Keith Evans, Kyma's CEO. The manufacturing costs for this approach can be higher due to a greater number of complex steps taken per substrate. Average dislocation densities for lift-off GaN are also generally higher, unless additional processes such as epitaxial layer overgrowth (ELOG) are used, which add to the cost. And the use of additional processes or pre-growth patterning can also cause a large lateral, sometimes periodic, variation in dislocation density, which hinders subsequent device production.

A second alternative to native GaN production is known as template GaN. This method, which is also used by Kyma for some of its other products, again involves growing an epitaxial layer that is typically 5–300 µm thick on foreign materials such as SiC or sapphire. Unlike the lift-off approach, the GaN layer is left on the host material. Again, ELOG can be used to cut the average dislocation density, but with the same drawback of a surface of alternating high and low dislocation density regions.

The other option for producing GaN substrates involves bonding a thin layer of GaN onto a carrier that offers specific benefits. This produces "composite GaN" substrates, for example bonding

"There is a very strong dislocation-density dependence of the thermal conductivity."
Keith Evans
Kyma Technologies

Japan's GaN development

Japan is a hotbed for GaN substrate production, with companies such as Mitsubishi Chemical Corporation, Sumitomo Electric Industries Ltd and Hitachi Cable manufacturing GaN substrates for GaN-based laser and LED applications. All of these companies are using a HVPE approach with a variety of substrates, before removing the GaN layers. Recent announcements from Sumitomo Electric suggest that they lead the industry in terms of production quantities and material quality for laser production. The company is producing over a thousand 2 inch GaN wafers per month and it has developed an "advanced deep" growth process that enables a dislocation density in regions (stripes) of the substrate of 10^5 cm^{-2} or less.

Growth engineers in Japan also formed a Solvothermal Crystal Growth Research Alliance in 2004 that is pursuing the ammonothermal (solvothermal) growth of GaN. Among the alliance partners are Mitsubishi Chemical Corporation, Tokyo Dempa Co Ltd, The Japan Steel Works Ltd, Nippon Kasei Chemical Co Ltd, and Furuya Metal Co. Using technology originally developed for the growth of 3 inch (0001) ZnO crystals, the team grows GaN from a supercritical ammonia solution containing mineralizers, which increase the solubility of GaN in this environment.

The current development process is limited by a slow growth rate, but the approach holds promise because it offers potentially lower production costs through the use of larger-scale growth systems and cheaper processes.

GaN to diamond to enhance thermal dissipation (see *Compound Semiconductor* January/February 2007, p29), or to polycrystalline AlN to achieve a good match of thermal expansion coefficients. With this technique the quality of the GaN matches its original manufacturing approach, which could be native, lift-off or template in origin.

Dislocations and thermal conductivity

The density of the dislocations in the GaN material also influences thermal conductivity. For GaN grown on non-native substrates, says Evans, the widespread supposition is that the epilayers have an inherently low thermal conductivity. "What we have demonstrated unequivocally in the last two years in partnership with North Carolina State University (NCSU) is a very strong dislocation-density dependence of the thermal conductivity."

According to him, it's common to hear GaN thermal conductivity values of 1.0–1.1 $W\,m^{-1}\,K^{-1}$ when GaN is deposited on a foreign substrate such as SiC. But with Kyma's native substrates that are sliced from a GaN boule, NCSU researchers measured 2.3 $W\,m^{-1}\,K^{-1}$. "Below about 10^7 dislocations per square centimeter, thermal conductivity is routinely 2.3 ± 0.1 $W\,m^{-1}\,K^{-1}$. As you go to higher dislocation densities, it drops. As a result, the buffer layer and active regions of GaN structures grown on foreign substrates can be a thermal bottleneck during device operation." Evans thinks that Kyma's native GaN thermal conductivity figure will go even higher as substrate quality continues to improve, which could ultimately boost device performance.

GaN substrate size is another matter of great interest to customers. Kyma currently produces template GaN substrates with diameters of 2 inches, 3 inches and 4 inches. Diameters of native GaN are smaller. "We have shipped 2 inch (conductive only) GaN in the past, but we decided that was a mistake. So we stopped that in 2005 and focused instead on quality. Our quality is now under control and we are focused on increasing size and reducing cost," explained Evans. Until recently, Kyma shipped 1 cm^2 GaN substrates, but moved recently to 18 mm × 18 mm substrates and has just begun to offer 25 mm × 25 mm material.

The company projects that the first shipments of 2 inch circular native GaN will be late in 2007, with 3 inch and 4 inch equivalents to follow in mid-2009 and mid-2010, respectively. However, the forecasts are "based on confidential assumptions about profitability and additional financial support," said Evans.

Market opportunities

The blue laser diode is today's only commercial device produced in volume on free-standing GaN. However, Kyma is working towards the widespread insertion of native GaN across all such applications. "Our materials have been demonstrated in high-performance LEDs, laser diodes, UV detectors, RF FETs and Schottky diode electronic switches. Our primary remaining opportunities are to improve the size and reduce the cost."

The demonstrations that Evans is referring to include collaboration with the US Naval Research Laboratory to improve the reliability of high-power radio-frequency transistors based on both conventional and novel FET designs. Initial materials and device results are described as encouraging, and very good device results are claimed for frequencies up to the X-band. MBE-grown AlGaN/GaN HEMTs on Kyma's semi-insulating 18 mm × 18 mm native GaN substrates have produced breakdown voltages of up to 200 V and output-power densities of 5.1 $W\,mm^{-1}$ at 4 GHz. This output delivers a power-added efficiency of 46% at a gain of 13.6 dB.

On the optoelectronics side, Kyma's native GaN substrates have been used to build avalanche photodiodes (APDs) by Russell Dupuis' team from Georgia Institute of Technology, GA. The detector produced the highest optical gain yet seen in a GaN APD, delivering a maximum optical gain of more than 1000 when illuminated by 360 nm radiation. At 50 μm in diameter, the APD also had the largest

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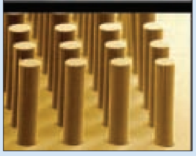

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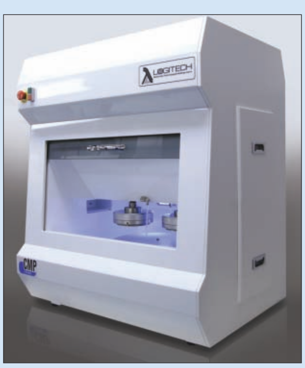

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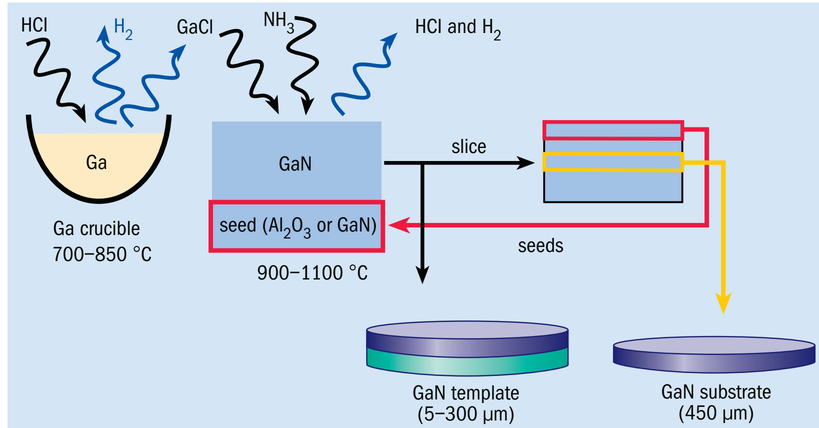

Fig. 2. Kyma's high-purity polycrystalline GaN can be used as the target in pulsed laser deposition and other sputtering processes, and as the feedstock for ammonothermal growth. **Fig. 3.** Kyma's HVPE process produces GaN films by reacting gaseous NH_3 and GaCl (formed by the reaction of a gallium melt and HCl gas) at the surface of a sapphire or GaN seed crystal. This technique can form GaN templates on sapphire and GaN boules, which can be sliced into substrates.

area yet reported for any III-N APDs.

Kyma's material has also been used by researchers at Auburn and Furman Universities to produce "visible-blind" ultraviolet detectors with a ultraviolet/visible contrast of over one million. The Schottky-type detectors produce a dark current of just 0.56 pA at –10 V, which was partly attributed to the low dislocation density of the substrate.

In addition, Christian Wetzel's team at the Rensselaer Polytechnic Institute in Troy, NY, has fabricated InGaN/GaN LEDs on Kyma's native GaN and compared them with devices grown on sapphire. Atomic force microscopy measurements revealed that the threading dislocation densities of the LEDs grown on native GaN were typically $2–5 \times 10^8$ cm^{-2}, but on sapphire this figure increased to 2×10^9 cm^{-2}.

The superior material quality improved device results. The native GaN LED, which had peak emission at 440 nm, produced 7 mW at 0.5 A in an experiment that coupled the emission from the backside of the device into an optical fiber. In comparison, the sapphire-based LED – which had a shorter peak-emission wavelength of 420 nm thanks to reduced indium incorporation in the quantum wells – produced an output at least an order of magnitude lower. In addition, the sapphire LED could only handle currents up to 80 mA, while the native GaN LED could operate at up to 600 mA.

Despite these encouraging results, there is much debate over when native GaN substrates will become important to the LED market. Some believe the transition is imminent and others suggest that a 2010 time frame is more likely. At the moment free-standing GaN is too expensive for the commercial LED market, says Evans, even though this sector really needs GaN substrates. "There's a catch-22 here: the GaN prices are going to come down as the volume goes up – the volume associated with their sales. But the sales won't go up until a volume application such as LEDs starts to get traction."

However, in Japan it appears that this traction is just starting to kick in, with Panasonic sampling LEDs produced on an undisclosed form of GaN substrate. The company is claiming that its 460 nm emitting blue chips are 50% more efficient than sapphire-based LEDs and produce a total radiative flux of 355 mW when driven at 350 mA. This translates to an external quantum efficiency of 38%.

After HVPE?

Kyma believes that its current HVPE process has the edge in achieving thickness, lowering dislocation density and increasing thermal conductivity, but the company is also looking at other crystal-growth methods.

The International Workshop on Nitride Semiconductors held in Kyoto, Japan, in the fall of 2006 highlighted the widespread interest and activity in investigating select high-pressure solution methods for bulk growth of GaN crystals. Historically, Evans says, these more conventional approaches have only had limited success, in part because of the very high temperature and pressures that are required. But Evans thinks that with more support, the technical problems can be solved.

"The Institute of High Pressure Physics of the Polish Academy of Sciences has led the way in terms of crystalline perfection, but they've been limited in terms of crystal size and so they continue to look at how that might be turned into a manufacturable process. And there are teams making strong efforts in Japan [at the Institute of Multidisciplinary Research for Advanced Materials at Sendai], Germany [at the University of Erlangen] and elsewhere, working hard to develop both high- and low-pressure liquid techniques with full-scale commercialization as the ultimate goal." ●

Further reading:

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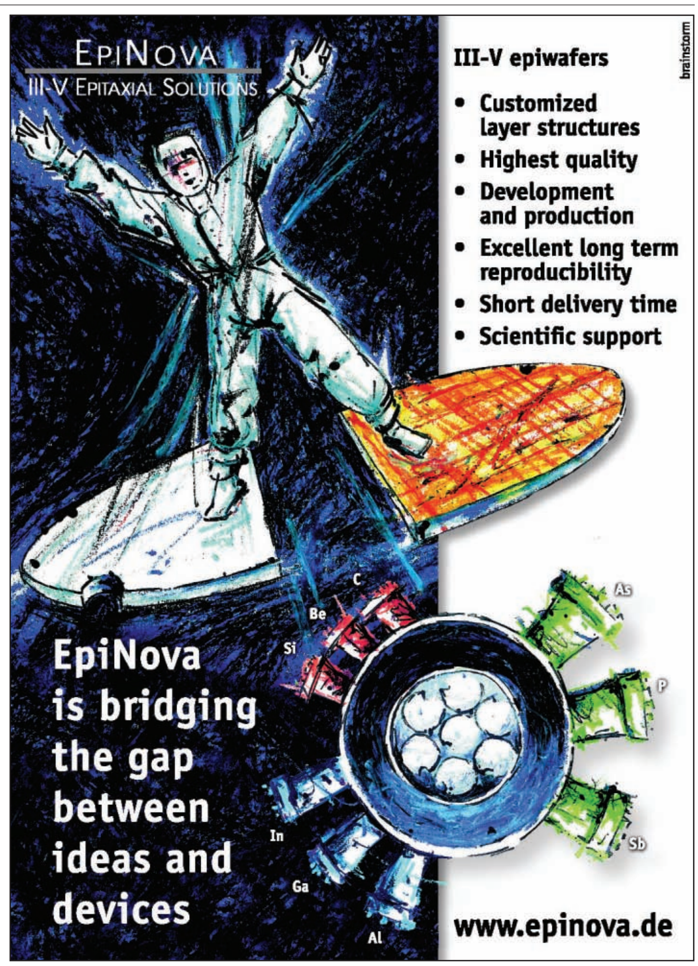

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BULK MATERIAL

Polycrystalline GaN cuts crystal defects

Researchers from the University of California, Santa Barbara (USCB), have slashed the defect density of GaN material grown by the ammonothermal method by three orders of magnitude to $10^6\,cm^{-2}$.

The improvement could cut the production cost of GaN substrates due to more efficient use of the starting materials, and resulted from switching the gallium source from metallic gallium to polycrystalline GaN.

The team, which includes James Speck and Shuji Nakamura, grew its material on a single-crystal GaN seed using supercritical ammonia made from 100 g of polycrystalline GaN and 3.9 mol% of sodium amide.

Fifty days of growth in a pressure vessel containing the seed crystal in the bottom half, heated to 700 °C, and polycrystalline GaN in the top half at 506 °C, produced the crystal shown in the figure. The thickness of the additional growth in the +*c* (Ga-polar), –*c* (N-polar) and non-polar *m* directions is 40, 180 and 300 µm, respectively.

USCB scientists have produced crystalline GaN films on a 5x5 mm HVPE-grown seed crystal that has threading dislocation densities as low as $10^6\,cm^{-2}$. The process promises lower costs than the HVPE technique used for making GaN substrates today.

Tunneling electron microscopy images of the brown crystal revealed that threading dislocation densities on the gallium and nitrogen faces were less than 10^6 and $10^7\,cm^{-2}$, respectively. Meanwhile, acid etching followed by inspection with a scanning electron microscope, determined an etch pit density of $3 \times 10^6\,cm^{-2}$ for the gallium face and $7 \times 10^4\,cm^{-2}$ for the nitrogen face.

Although the crystal took nearly two months to grow by this method, UCSB researcher Tadao Hashimoto says that the technique is suitable for commercial manufacturing. According to him the approach is very similar to the process used to grow artificial quartz, in which hundreds of crystals can be made at the same time.

"Tokya Denpa, a Japanese company growing ZnO with a hydrothermal method, uses 90 days of growth for commercial ZnO wafers," explains Hashimoto, who believes that the same business model can be applied to manufacturing GaN substrates.

Journal reference
T Hashimoto *et al.* 2007 *Jap. J. Appl. Phys.* **46** L525.

POWER TRANSISTORS

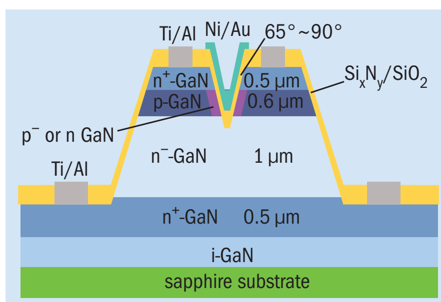
GaN MOSFETs shoot past SiC transistors

A Japanese partnership between Rohm and Ritsumeikan University claims that its vertical GaN MOSFETs can deliver better performance than SiC equivalents.

The team's transistors, which could be used for power-switching applications, have a channel mobility of $133\,cm^2\,V^{-1}\,s^{-1}$ and an on-voltage of 5.1 V.

Rohm's Horoaki Otake told *Compound Semiconductor* that three advancements have led to the improvement: a new design that does not require implantation; surface stabilization through the use of a SiN/SiO_2 bi-layer gate; and a trench gate structure.

The vertical MOSFET was grown by MOCVD on sapphire substrates (see figure). Dry etching of the GaN epilayer formed the trench structures for the vertical gate, before the SiN and SiN/SiO_2 layers were added by plasma-assisted sputtering.



The GaN MOSFET is grown on sapphire and features a silicon-doped layer, a drift layer, a magnesium-doped channel and a silicon-doped contact.

DC tests on the MOSFET revealed that the drain current was more than 20 mA/mm at a drain-source voltage of 1 V. The transistor's breakdown voltage when the gate was added to the device was not reported in the paper, but Otake says that it is "sufficiently high".

The leakage current is described as extremely low at a drain-source voltage of 5 V, but relatively large when several tens of volts were applied. The researchers put this down to the high density of threading dislocations that results from growth on sapphire. This problem can be overcome by switching to a bulk GaN substrate, according to the researchers, who will publish results using this platform.

Journal reference
H Otake *et al.* 2007 *Jap. J. Appl. Phys.* **46** L599.

LOGIC

InP shows promise for future CMOS circuits

IBM's TJ Watson Research Center, its Zürich Research Laboratory and Princeton University have built enhancement-mode buried-channel InGaAs/InAlAs MOSFETs on InP that feature a HfO_2 dielectric.

The team says that the devices – which display good saturation, low leakage and an on-off ratio of 10^4 – are being evaluated for future CMOS technology nodes and show a promising path to realizing scalable III-V channel MOSFETs.

The differences between the latest device and an InGaAs buried-channel MOSFET reported by the team last year are the removal of doping in the channel region, the omission of an InP layer and a thinner InAlAs barrier.

The upshot of this is much better gate control, says IBM's Yanning Sun. This control arises from the reduced effective oxide thickness of the InAlAs barrier compared with previous designs. In addition, the new structure is more suitable for vertical scaling as it doesn't have a δ-doped region. If δ-doping is used, the doped region and channel must be separated by at least 2 nm.

Sun says that the team plans to continue to improve the III-V MOSFET performance by optimizing the device structure, the gate dielectric and the interface properties.

"Down the road, we also need to look at manufacturing issues of III-V devices and the integration with existing silicon devices and infrastructure," she added.

Journal reference
Y Sun *et al.* 2007 *IEEE Electron Device Lett.* **28** 473.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