

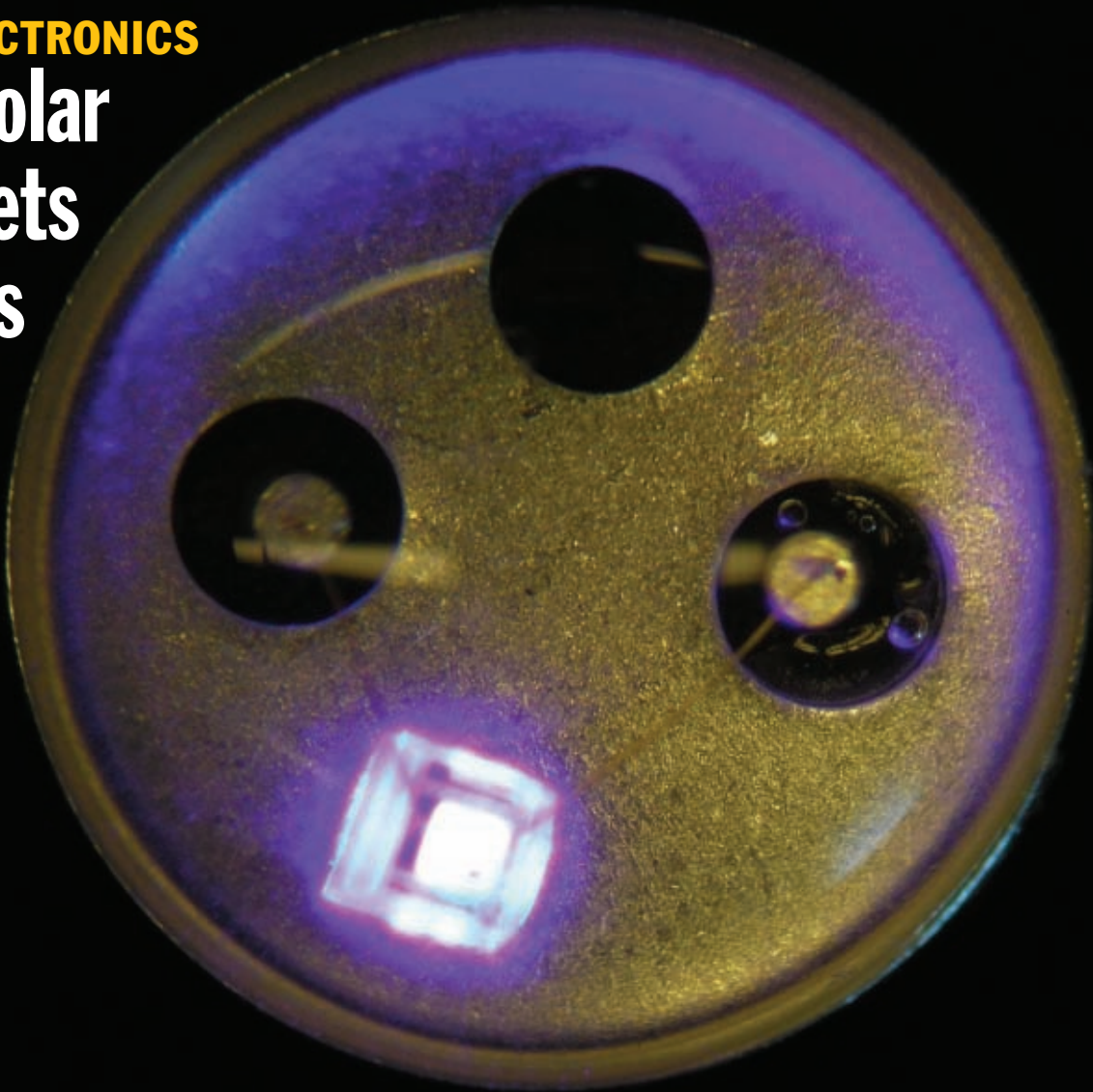
# COMPOUND SEMICONDUCTOR

June 2007 Volume 13 Number 5

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

## OPTOELECTRONICS

# Non-polar GaN gets into its stride



## SUPPLIERS GUIDE

### Materials and equipment for LED chip makers p24

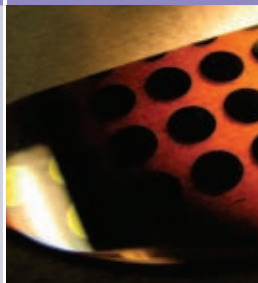
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LED chip manufacturers need lighting specialists to design more efficient fixtures. p14

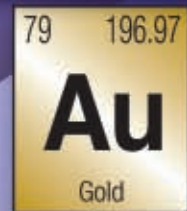
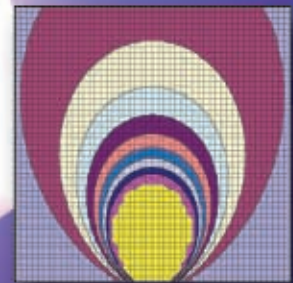
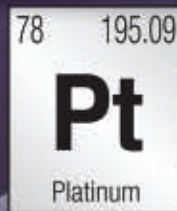
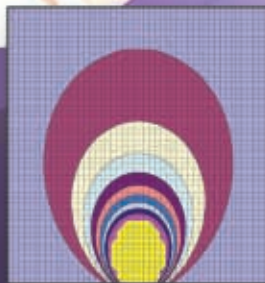
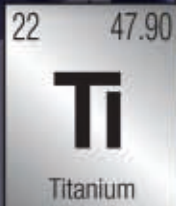
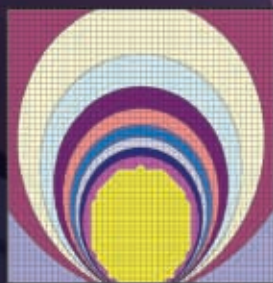
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### Green machine

How solar energy and GaP could turn carbon dioxide into fuel. p10

# No Guesswork...



## Problem Solved... Temescal



### Experts in Metallization

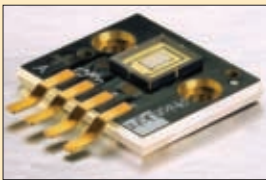
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Samsung has released a range of new televisions that are illuminated by the Phlatlight 120 chipset. **p8**

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- 14** **Behind the Headlines Poor fixtures threaten to jeopardize the illumination potential of LEDs:** LED manufacturers are running massive marketing campaigns to woo the illumination market with brighter, lower cost chips. But this will be in vain if their customers continue to design inefficient fixtures, reports Richard Stevenson.

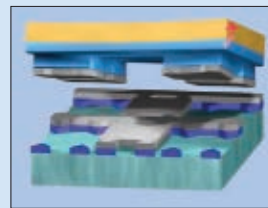


### Bright lights

Many available fixtures are inefficient, but LED Lighting Fixtures' recent design produces 650lm at 11 W. **p14**

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### Printing chiplets

Sempruis' printing process enables efficient and accurate transfer of chiplets. **p16**

- 21** **Non-polar GaN reaches tipping point:** Non-polar light-emitting devices based on GaN have huge potential, but chip performance has been limited. However, this is starting to change, say Steve DenBaars, Shuji Nakamura and Jim Speck, who have made non-polar LEDs with an efficiency of up to 45%.

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**Main cover image:** The UCSB team's prototype LED package, containing a non-polar InGaN chip operating at higher powers, and with a higher efficiency, than any other LEDs in the 400nm wavelength range. See p5, p21. Credit: MSchmidt, UCSB.

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# IOP Publishing

# Nakamura team sees the light



If the compound semiconductor community drew up a list of its cult heroes, Shuji Nakamura would be right up there. The intrepid researcher's rise from obscurity to notoriety is charted in Bob Johnstone's new book *Brilliant!* – as much a biography of compound semiconductor LEDs as it is of the man himself.

Nakamura's work throughout the 1990s, while he was at Nichia, is the stuff of legend but, since switching to the University of California at Santa Barbara (UCSB) seven years ago, he has hit the headlines more for his court battles against his former employers than for his science. Far less has been written about the drive to develop non-polar GaN-based LEDs that promise to raise the performance bar of blue and white LEDs further still – until now, it seems.

That non-polar work has now passed a critical milestone: Nakamura, along with UCSB colleagues such as Steve DenBaars and Jim Speck, appears to have cracked a key problem. They have made devices that maintain very high efficiency at high drive currents – suggesting that powerful non-polar white LEDs are now within reach.

Compared with the seminal breakthroughs of the early 1990s, however, one stark difference shines out. Teamwork. No longer the lone, maverick researcher, Nakamura is now surrounded by like-minded scientists and engineers in California.

Another key part of that team should not be overlooked – substrate developer Mitsubishi Chemical. Without the high-quality non-polar substrates to work from, Nakamura and his co-workers would have had little hope of making the progress that they themselves detail on p21 of this issue.

One of the key challenges now is to scale those substrates up from the size of a postage stamp to production-worthy wafers. That is something that would also be brilliant.

## Michael Hatcher Editor

*Published by Prometheus Books, Brilliant! charts Shuji Nakamura's development of GaN-based LEDs and lasers at Nichia, and the subsequent legal battles with his former employers following a move to UCSB. Bob Johnstone relates the complex, intriguing tale with characteristic verve.*

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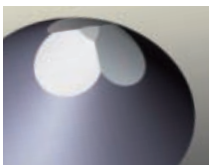
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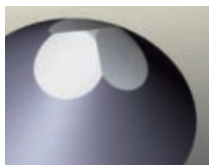
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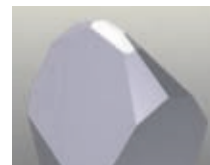
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## GaAs ICs

# GaAs industry gets back into balance

By Michael Hatcher in Austin, Texas

Global supply and demand of GaAs ICs has returned to equilibrium after several years of overcapacity. That's according to TriQuint Semiconductor CEO Ralph Quinsey, who opened mid-May's CS Mantech conference in Austin with a "state of the industry" address.

"Clearly, we have turned the corner," said Quinsey. "The year 2006 will be remembered as a transition year for the compound semiconductor industry. This was the first year in many where worldwide GaAs supply and demand came back into balance."

According to both Quinsey and Filtronic's Wolfgang Bösch, the global demand for GaAs ICs rose sharply to around 75% of total available capacity in 2006. Only 50% of global capacity, which is estimated at just

over 800,000 6 inch GaAs wafer equivalents, was required in the previous year.

The extra demand for GaAs was stimulated by the more complex RF requirements of multi-mode and multi-band cell-phone handsets. Quinsey expects between 150 million and 170 million of these handsets to sell in 2007, meaning that demand for GaAs will remain well matched to the available supply.

He added that for a brief period in 2006 the GaAs industry became supply-constrained, after several years of overcapacity. That said, Quinsey believes that there will be few major capacity build-outs in the near future, despite Anadigics' recent decision to build a 6 inch-wafer processing fab in China.

While the top three GaAs suppliers – RF Micro Devices, Skyworks and TriQuint

– now control half of the industry's capacity, mid-tier suppliers may be under pressure to choose between consolidation and integration into a vertical business model to survive. Mid-tier foundry consolidation may also emerge to support a more widespread shift to fabless business models, Quinsey added.

Quinsey's analysis could signal the end of a price war between the top suppliers of GaAs products, although this situation may not prevail for very long.

GaAs wafer vendors in Austin indicated a recent softness in sales, which was considered to be largely seasonal and partly due to problems at Motorola, although all expected demand to pick up strongly later in the year. Many of the equipment vendors present said that 2006 had been their strongest year since 2000.

## OPTOELECTRONICS

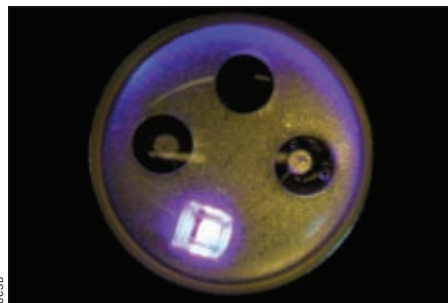
## Massive power boost for non-polar GaN LEDs

Researchers working on non-polar GaN at the University of California, Santa Barbara (UCSB), have fabricated an LED with the highest efficiency and output power ever reported for the 400 nm range.

The team, which includes Shuji Nakamura, produced an InGaN multi-quantum-well structure with an output power of 28 mW and a peak wavelength of 402 nm when driven at 20 mA – equivalent to an external quantum efficiency (EQE) of 45.4% (2007 *Phys. Stat. Sol. (RRL)* 1 125).

Crucially, that impressive conversion efficiency was maintained at much higher currents, with the device emitting 250 mW when driven at 200 mA. Previous efforts have shown promise, but this new result represents a huge increase in output power.

Commenting on the latest UCSB results in an article co-authored by Ulrich Schwarz,



**Blue breakthrough:** the UCSB/Mitsubishi Chemical team had previously made high-efficiency LEDs based on non-polar GaN, but the latest device maintains the same conversion efficiency at a much higher output power – crucial for high-brightness applications.

GaN expert Michael Kneissl from the Technical University of Berlin said, "The achieved external quantum efficiency is

clearly a remarkable result."

"Most important, only a small drop of the EQE over the current-density range from 1 A/cm<sup>2</sup> to 350 A/cm<sup>2</sup> is observed."

Much of this latest hike in performance is attributable to the development of improved *m*-plane GaN substrates supplied by the Japanese firm Mitsubishi Chemical. The base material was sliced from conventional *c*-plane GaN grown using hydride VPE.

However, one key issue that remains to be solved before non-polar GaN can be commercialized is the size of these substrates. Currently, they measure only about one square centimeter, whereas 50 mm diameter material would typically be required in a commercial setting

● See feature article "Non-polar GaN reaches tipping point", written by the UCSB team, on p21 of this issue.

## COMPANY FINANCES

## Record sales reflect healthy industry

Two of the biggest names in compound semiconductors racked up record sales figures in their latest financial quarters.

GaAs IC manufacturer RF Micro Devices enjoyed a vintage fiscal year, with annual

revenues breaching the \$1 billion mark for the first time. The annual net profit of \$83.4 m was a huge increase on the \$16.3 m posted in the previous year, and also represented the US company's best-ever.

Meanwhile, the German deposition equipment specialist Aixtron earned revenue of €63.8 m (\$86.3 m) in the first quarter of 2007, its highest-ever quarterly figure, and double the €32 m posted in the same period

of the previous year.

The MOCVD reactor vendor also turned a quarterly net profit of €7.6 m, more than the €5.9 m total profit that it made in the whole of fiscal 2006. Aixtron also exceeded €40 m in orders for the fourth quarter in succession, 73% of which comprised compound semiconductor equipment bookings.

● See "Portfolio" on p12 for a round-up of company finances.

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## GaAs ICs

# New customer benefits TriQuint

RF chip manufacturer TriQuint has begun shipments of approximately one million CDMA transmit power amplifier modules for a major new customer.

President and CEO of the Hillsboro, Oregon, company Ralph Quinsey announced, "I am very happy to report that we are supplying production volume transmit modules for four of the top five handset manufacturers. With this, we are now shipping handset modules to the top three handset suppliers."

The recent iSuppli worldwide ranking named the top five mobile phone suppliers, in descending order as: Nokia, Motorola, Samsung, Sony Ericsson and LG.

CFO Stephanie Welty confirmed that Motorola and Samsung remained TriQuint's most important customers, together contributing over 30% of total revenues in the latest quarter.

The new order was a key feature of the company's first financial quarter of 2007,

in which it reported a net profit of \$6.4 m, up from \$5.8 m in the previous quarter, and achieved a record number of new designs being taken up by its handset customers.

TriQuint posted revenues of \$110.6 m for the quarter, roughly in line with the previous quarter's figure of \$114.3 m, and up 26% from the \$87.9 m recorded one year ago. Networks business compensated for low orders from Motorola, with wireless LAN, base stations and VSAT amplifier products making contributions that exceeded expectations. TriQuint's military market performance was also better than anticipated due to strong sales in satellite products.

Despite the positive figures, the company predicts flat revenue and profit for the next quarter. TriQuint expects Motorola's continued troubles, and the costs of moving to an inventory system where it retains ownership of stock held by its customers, to balance out the gains made by its growing business.

## POWER AMPLIFIERS

# IBM threatens GaAs

by Andy Exrance

Information technology giant IBM is bringing "through-silicon vias" (TSVs), and the "breakthrough chip-stacking" they allow, into production to extend its silicon based systems' capabilities beyond current expected limits.

TSVs enable a wide range of performance improvements, but IBM states that the first applications will be in wireless communications chips for power amplification in wireless LAN and handsets, and that GaAs applications will be targeted.

The new chips are already running on IBM's manufacturing lines and the company intends to provide samples later this year, with full production at three plants in New York State and Vermont scheduled for 2008.

The concept enables chips to be stacked one top of another, rather than side by side. This eliminates the need for long metal wires and shortens the distance that information needs to travel by a factor of a thousand.

IBM generates the vias by etching through wafers and filling the resulting gaps with metal, a technique that can also create a hundred times more information pathways. In wireless communications technology, the through-silicon via replaces wire bonds that are less efficient at transferring signals off the chip.



ANADIGICS

Korean handset maker LG is receiving production volumes of Anadigics' dual-band power amplifier (PA) modules for its metallic "Shine" range of mobile phones and for its VX9400 handset, which is designed for mobile television applications.

Both phones feature Anadigics' compact AWT6310R modules, which LG says take up less space than competing technologies. Anadigics uses its trademarked "InGaP-plus" BiFET technology in the CDMA modules, combining transistor functions onto a single die to take up 25% less board space than two individual PAs.

Anadigics also bucked the usual first quarter downturn by adding a modest 2% sequential growth to the strong revenues delivered at the end of 2006. Revenue and loss in the first quarter of 2007 were \$49.6 and \$1.2 million respectively, compared with \$48.5 and \$0.1 million in the previous three months.



## STRATEGY

# RFMD eyes long-term evolution

by Andy Extance

US power amplifier (PA) powerhouse RF Micro Devices (RFMD) expects that, although production of WiMAX base stations and handset modules is already gathering pace, volumes will be eclipsed by the so-called "UTRAN LTE" (long-term evolution of the 3G UMTS protocol), which will be seen in handsets from 2009.

Nokia has now announced plans to bring WiMAX handsets to market in 2008, while Samsung and Motorola are also developing phones for the US carrier Sprint, forcing PA makers to sit up and pay attention to the emerging protocol.

But RFMD's own analysis predicts that the wireless industry will make only 13.5 million WiMAX enabled handsets annually by 2011, in comparison to 63.5 million handsets for LTE.

"RFMD isn't taking any sides on WiMAX," said Alastair Upton, the Greensboro, NC, company's managing director of strategic marketing. "According to the company's modeling, LTE is going to be a much bigger 4G system overall."

The brief history of WiMAX – short for worldwide interoperability for microwave access – has shown it to be a notable and controversial technology, with debates on the

topic finding global powers such as Intel and the Organisation for Economic Co-operation and Development (OECD) putting forward differing opinions about its usefulness.

OECD is interested in WiMAX's potential to bring the internet to less developed countries, but skeptical about the costs involved. Intel has been banging the WiMAX drum since 2005, touting its power to overturn the status quo in wireless communications.

While some companies, like RFMD's rival Anadigics, have shared that vision from the start, RFMD's backing for WiMAX has been less obvious.

"Motorola and Samsung are developing WiMAX-enabled handsets for Sprint," Upton said. "These are the kind of companies that RFMD would normally be working with, so although I can't say anything specific, there is good motivation for us to make PAs for WiMAX."

In their recent investor call, RFMD's senior managers did highlight the importance of the WiMAX infrastructure market to the company, particularly with relation to its emerging set of wide-bandgap transistor technologies based on GaN.

But, on the handset side, the question of who is supplying Nokia's PAs for WiMAX, remains open to speculation.



## From our web pages...

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### ... Flying without fab

Hittite Microwave continues to thrive on its fabless status, recording first quarter 2007 revenues 30% higher than the previous year and 2.6% higher than the closing quarter of 2006. The chip designer made a quarterly profit of \$12m, down \$0.1m sequentially.

### ...BiFET delays hit AXT

AXT saw its revenue decline sequentially and dip below prior guidance to \$12.5m in the first fiscal quarter of 2007. The company said that the lower-than-expected sales resulted mainly from delays to the qualification of its GaAs material for use in BiFET chips. Sales of 6inch GaAs wafers dropped from \$4.9m in the closing quarter of 2006 to \$3.3m during the latest period, suggesting a wider slowdown. Despite the delays, AXT still posted a net profit of \$1.3m, thanks largely to improving sales of germanium wafers and raw materials.

### ...Skyworks gets pay-back

Chip and component maker Skyworks delivered profit of \$12.2m in the first three months of 2007, a giant step up from the \$0.9m recorded for the same period in 2006. Overall sales for the two periods were similar, with higher profitability resulting from Skyworks' departure from the non-GaAs baseband market.

### ...EpiWorks expansion targets BiFETS

EpiWorks Inc of Illinois, US, has completed the initial phase of its expansion of 6inch HBT epiwafer production capacity. New MOCVD systems, installed in summer 2006, have increased the capacity at the company's Champaign production facility to 50,000 wafers per year, a figure expected to double again by 2009. As well as conventional HBTs and PHEMTs, the extra capacity will be used to make integrated BiFET materials.



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## APPLICATIONS

# PhlatLight shines on new Samsung TVs

By Michael Hatcher

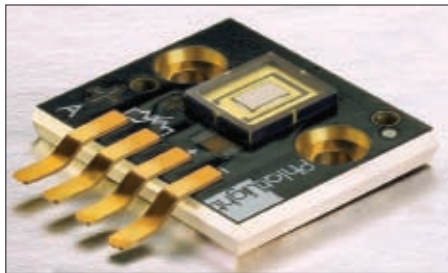
Consumer electronics colossus Samsung has released six new rear-projection televisions that are illuminated with red, green and blue LEDs made by the US chip firm Luminus Devices.

The 50 inch, 56 inch and 61 inch televisions are in US stores now and, unlike previous attempts by Sony to introduce LED backlights into televisions, Samsung appears to be having great success with the technology.

The Korean company, which is ranked number one in world market share for television sales by analysts at DisplaySearch, has plans to introduce LED lighting into all of its large-area display screens. It says that the first of its LED-based televisions, launched last year, were so well received that it decided to expand the range for 2007.

Whereas Sony's LED-based Qualia televisions were extremely costly, Samsung's are much more affordable at around \$2500.

LED chips improve on-screen color reproduction compared with traditional lighting technologies, largely because of the extra brightness provided in the red part of the spectrum. Combined with digital light processor chipsets from Texas Instruments, the PhlatLight chips produce sequential



**Samsung's choice:** The PhlatLight 120 chipsets from Luminus Devices now feature in a range of large televisions sold by the Korean electronics company.

red, blue and green light at a cycle rate of 2.9kHz – 48 times faster than conventional television frame rates.

The LEDs used in the PhlatLight chipsets incorporate textured patterns that increase light extraction efficiency. Luminus manufactures the chipsets at its facility in Boston, close to the Massachusetts Institute of Technology (MIT) where the approach was pioneered.

The new Samsung televisions feature the PT120 LED chipset, which has an emitting area of 12mm<sup>2</sup>. The red chip emits 660 lumens, the green 1550 lumens and the blue 250 lumens.

Because they emit such bright light, the

photonic lattice chips cut down the overall complexity of more conventional LED backlighting systems, which require hundreds of individual emitters to illuminate a large screen.

Although Luminus has not revealed too many details about its technology, early structures developed at MIT were based on GaAs substrates and featured six-period GaAs/Al<sub>x</sub>O<sub>y</sub> distributed Bragg reflectors.

The top of those structures featured a photonic crystal, which sat on top of an InGaP cladding layer and an InGaAs quantum-well layer. The novel design, says Luminus, yields both high extraction efficiency and a collimated beam of light, which helps with device packaging and backlight design.

Luminus has also been sampling a higher-power chipset, the PT180, which emits a total of 2600 lumens and features four chip die per color.

Having made good penetration in the rear-projection television space, the company is now planning to attack the much bigger market for liquid-crystal display televisions. Working with optics specialist Global Lighting Technologies, Luminus is developing backlight units for 46 inch and 52 inch LCD televisions at the moment.

## CHIP MANUFACTURING

## Osram plans new plant

Europe's top LED chip maker, Osram Opto Semiconductors, is building an additional plant to meet booming demand. The Munich-based firm will also expand existing assembly plants at its Penang, Malaysia, and Regensburg, Germany, sites.

The new chip factory will be built at its site in Penang, where Osram OS has operated since 1999. A spokesperson for Osram said that the chip production line would be focused on back-end processing, with the epitaxy stage remaining in Regensburg.

The company told *Compound Semiconductor*: "The new line will produce chips based on ThinGaN and SiC material for high-power appliances in applications such as LCD backlighting, general illumination and automotive lighting."

Rather than being built specifically to house new technologies, the facilities are required to meet the growing demand for existing LED-based lighting products, according to Ruediger Müller, CEO of Osram OS.

## DISPUTE

## Epistar to appeal patent ruling

The US International Trade Commission (USITC) has ruled that certain LED chips made by the Taiwanese firm Epistar infringe a Philips Lumileds patent.

The "final determination" from the USITC includes a limited exclusion order that will prohibit imports of the specified LED chips, packaged devices and arrays of packaged LEDs into the US – although not complete systems featuring the chips.

While Lumileds has declared itself "satisfied" with the ruling, Epistar says that it plans to appeal against the USITC findings.

Since late 2005, Lumileds and Epistar have been locked in a battle over the intellectual property in three US patents relating to AlInGaP LED chip manufacturing processes, including wafer bonding and the use of a transparent semiconductor window layer within the chip structures.

According to Epistar, the USITC has reversed its initial ruling in the case, by

finding that Epistar's optical-mirror adhesion, glue-bond and metal-bond LEDs infringed two claims in US patent 5,008,718, but did not infringe two patents covering wafer bonding.

"We are obviously disappointed with the decision of the USITC," said Epistar president BJ Lee. "In reaching this decision, Epistar believes that the USITC has interpreted these patents erroneously, to grant exclusive rights to Lumileds to technology that it did not invent and has never used. For this reason, Epistar is considering an appeal."

The next stage of the litigation process will involve a US presidential review, after which the limited exclusion order on Epistar products will become final. This process is expected to take 60 days.

Lumileds has also filed a court action against Epistar in northern California, under which it is seeking both damages and an injunction.

## SOLID-STATE LIGHTING

## Cree positive despite low sales

At the recent Lightfair show in New York, a key event for the lighting industry, chip-manufacturer Cree highlighted the growing number of companies that are using its LEDs in streetlights and down lights.

Streetlights from five companies, including Stanley, Ledlight Group and BetaLED, were on show at Cree's booth, alongside down lights from Renaissance Lighting, Panasonic and LED Lighting Fixtures.

Meanwhile CEO Chuck Swoboda, addressing the Piper Jaffray investment conference held in New York the same week as Lightfair, said that the "solid-state lighting revolution" had already begun, highlighting early installations in pools, spas and commercial buildings.

Prior to that, Cree had filed a \$21.1 million net profit for its third quarter 2007 results, although \$20.9 million of that came from interest credits and tax benefits, masking an operating income of only \$0.2 million.

Swoboda said that the company was in a strong position particularly after comple-

ting the purchase of the Hong Kong-based LED producer COTCO. Despite its positive outlook, the company still faces significant challenges. Its fab-utilization rates remain low, with 4 inch wafer capacity underexploited, and LED prices are under continued downward pressure. Swoboda maintains that Cree will be the first LED company to migrate to volume production on a 4 inch wafer platform, however.

"We're managing an incredible amount of product ramp-ups in the near term," Swoboda explained, "so those margins are about getting those products through the learning curve, getting us stabilized and getting the volumes to the level where we can drive cost reductions."

For the first time, HB-LEDs made up over 50% of the LEDs sold by the company, which helped Cree achieve its first increase in average LED selling price for more than a year. To help continue this trend, Cree is targeting double-digit growth in the XLamp product range over the coming year.



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## ...Veeco's MOCVD sales burst

Ed Braun the outgoing CEO of semiconductor manufacturing equipment vendor Veeco Instruments singled out strong sales of its latest MOCVD systems as the critical reason for the company's improving finances. Traditional applications of HB-LEDs, including signage and automotive lamps, were behind the strong performance, as Veeco posted total sales of \$99.2 m and a net profit of \$0.3 m in its first quarter. Combined revenue of \$21 m from sales of systems for HB-LED and RFIC manufacturing (including MOCVD and MBE equipment) in the quarter that ended on March 31 represented a 39% increase on the equivalent period last year.

The company's MOCVD order book paints an even rosier picture: "Orders were up 60% year-over-year, as we continue to experience positive customer acceptance for our new K-series MOCVD systems," Braun said.

## ...Apple to use LEDs in Mac displays

Apple CEO Steve Jobs has responded to criticism from environmental pressure group Greenpeace with a pledge to use LED technology in backlights for its Mac computers.

"Apple plans to reduce and eventually eliminate the use of mercury by transitioning to LED backlighting for all displays when technically and economically feasible," said Jobs in an open letter. The first Macs with LED backlights are scheduled for launch this year.

## ...Patent clash over laser scribes

New Wave Research has begun legal proceedings in Taipei against Laser Solutions of Kyoto, in the belief that its patent covering sapphire-substrate scribing with UV lasers has been infringed. The initial injunction prevented Laser Solutions manufacturing or selling its RPYULAS MP-T1 030 and MPT-2030 equipment, with reference to New Wave's Taiwanese patent, No. 194157, covering the US company's scribing procedure and system.

## ...Rohm's tiny chips

Rohm claims that its new line of PicoLED ultra-compact chips operate at double the efficiency of conventional 1 mA emitters. At 1 mA drive current, the yellow-colored PicoLED delivers a brightness of 7.5 mcd. This brightness drops off to 2.1 mcd for yellow-green emitters and 3.5 mcd for red chips.

Some gems  
need a little  
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## SOLAR CELLS

# Terrestrial demand drives Emcore ramp

Solar cell and fiber-optic component maker Emcore is adding significantly to its chip manufacturing capacity to meet increasing demand for terrestrial solar-power systems featuring high-performance compound semiconductors.

During an investor conference call to discuss its recent financial performance, company CEO Reuben Richards said that two more production MOCVD systems would be added at Emcore's chip fab in Albuquerque, New Mexico, this year.

Back-end wafer-processing equipment, including evaporators and photolithography systems to make the GaAs/GaInP/Ge cells, will also be purchased in a capacity expansion estimated to cost between \$6m and \$7m.

Richards and Emcore president Hong

Hou explained why the extra equipment was needed when they detailed the extent of future orders for solar systems: Emcore has three key design wins that, collectively, could be worth over \$300m. These include a three-year contract with WorldWater & Power, a company in which Emcore owns a considerable stake. This deal is valued at \$100m.

This year, Emcore will deliver cells capable of producing 1.5MW for that project, followed by 10MW in 2008 and 15MW in 2009. The cost of those concentrator solar systems is estimated at between \$4 and \$5 per watt – considerably less than the cost of a comparable system featuring silicon cells.

Emcore also has a contract with a Spanish energy supplier that is valued at more than \$100m over the next five years. More

recently, it has struck a deal with a customer in Asia. Although this third contract is at a very early phase and will be worth only \$1.5m to Emcore this year, Richards said that this could become a long-term deal worth in excess of \$100m.

With an annual solar-cell capacity of only 50MW using the five production MOCVD systems already in place at Albuquerque currently, the magnitude of these contracts clearly make it necessary for Emcore to increase its solar cell output.

● Emcore has also won a high-profile contract to supply NASA's Jet Propulsion Laboratory (JPL) with solar panels for JPL's Mars cruise stage spacecraft. The spacecraft will carry the Mars Science Laboratory rover to the red planet, in a mission that is expected to launch in late 2009.

## RESEARCH

## GaP solar cell transforms carbon dioxide into fuel

A research group at the University of California, San Diego (UCSD), has shown how compound semiconductor solar cells can convert atmospheric carbon dioxide into carbon monoxide – a useful gas for industrial chemists and, potentially, a fuel.

Cliff Kubiak and graduate student Aaron Sathrum used p-type GaP and GaAsP to harness enough energy from sunlight to split carbon dioxide molecules via an electrochemical reaction. The semiconductor material behaves like an electrode and, in conjunction with two thin layers of chemical catalysts, produces both carbon monoxide and oxygen through electrolysis.

Although the work is at a very early stage, it could result in a simple way to simultaneously reduce the atmospheric concentration of carbon dioxide and produce a useful gas for detergent and plastics manufacturing.

Sathrum explained why the group chose GaP for its experiment: "First, p-GaP has a large bandgap of 2.26eV, which can generate a sufficiently large photovoltage for splitting carbon dioxide.

"Second – and a critical point for conversion efficiency – the energetic positions of the valence and conduction bands [in GaP] are very close to the electrochemical potentials for the two half-reactions required for splitting carbon dioxide."

The team used commercially available



**Green machine:** using sunlight, chemical catalysts and commercial 2 inch GaP material, the UCSD team showed that carbon dioxide can be turned into a much more useful gas, carbon monoxide.

2 inch GaP wafer material to fabricate the electrode. Sathrum says that although multi-junction solar cells could provide higher photovoltaic conversion efficiency, it is more important that the energy levels in the semiconductor are well-matched to the energy required to split carbon dioxide molecules.

"The bandgap of the materials used in multi-junction solar cells is smaller and may not be able to provide a high enough internal potential to drive the splitting reactions," Sathrum explained.

While the increasing level of atmospheric carbon dioxide has become the *cause célèbre* of the current environmental agenda, one problem for the UCSD team is that the concentration of the greenhouse gas remains vanishingly low at under 0.3%.

This means that converting large quantities of carbon dioxide into more useful chemicals will be challenging. On top of that, the cost of p-type GaP remains quite high, and the fabrication of reliable electrical contacts is something of a black art, says Sathrum.

## GaN LASERS

# Sony accelerates chip production

Sony says that it has increased its monthly capacity of GaN-based blue semiconductor lasers to 1.7 m.

The Japanese electronics giant, whose subsidiary Sony Shiroishi Semiconductor manufactures the chips, has just released two versions of a high-power GaN laser that emits 170 mW at 405 nm.

Those MOCVD-produced lasers will cost up to ¥5000 (\$42) and Sony will follow up their release in June with a couple of cheaper low-power lasers, for playback-only applications, costing around \$8 each. Then, in November this year, Sony will release a pair of 240 mW lasers also priced at up to ¥5000.

Rivals Sharp and Nichia have already revealed details of their own high-power GaN laser developments, with Nichia set to mass-produce a 250 mW laser in early 2008.

"There has been a rapid increase in blue-violet laser diode demand," Sony said. "To meet this demand, [we have] already installed front-end wafer-processing equipment capable of producing 5 m [playback only] blue-violet laser diodes."

Sony will increase its back-end assembly capacity at the Shiroishi fab when there is sufficient demand to justify such a move.

Compound semiconductor laser-chip fabrication at the Shiroishi subsidiary has now

surpassed 2bn units since the first such device rolled off of its production line in 1986. It took until 2001 before the facility passed the 1 bn laser mark, but the popularity of DVD players and recorders since then has driven chip fabrication to the 2 bn milestone in less than half that time.

GaN-based blue laser diodes only represent a tiny fraction of that total so far, but Sony is expecting a rapid acceleration in market demand over the coming five years.

The Japanese company's internal survey of the sector suggests that the entire laser-diode market consumed 1.1 bn chips in 2006, and that production will reach 1.4 bn chips in 2010.

Demand for Blu-ray disc and high-definition DVD recorders, as well as high-end games consoles, will ensure that GaN lasers are a major component of that market growth, believes Sony. Its internal figures suggest that unit shipments of blue laser diodes will grow from just 6 m in 2006 to about 26 m this year, and on to 110 m in 2010.

Sony reckons that it has a global market share, in terms of laser diodes shipped, of just over 25%, with 650 nm emitters, which are used in DVD recorders, representing the biggest single application.

## SUBSTRATES

## Hitachi confirms GaN wafer progress

By Andy Extance

Hitachi Cable Ltd, the materials-focused subsidiary of the well-known Japanese group, has produced 3 inch diameter GaN substrates, an innovation that promises high-quality GaN materials for making cheaper, higher-performance optoelectronics, in particular GaN-based laser diodes.

The enlargement relies upon the group's void-assisted separation technology. In this technique, a thin GaN layer is grown on a sapphire-base substrate. A metal, such as titanium, is then deposited over the thin GaN layer.

By heating this intermediate stage in a gas mixture containing hydrogen, the GaN decomposes forming voids at the interface with the metal layer. A thicker GaN layer can then be deposited on top of the metal via HVPE deposition. The voids act as a cushion to lower stress caused by differences in

lattice constant, improving crystal quality as well as lowering defect density and warping effects in the thicker GaN layer.

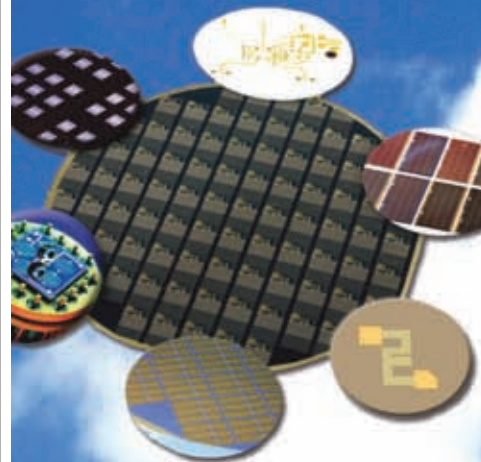
As the procedure's name suggests, the low mechanical strength of the void layer also allows straightforward removal of the freestanding, large-diameter GaN wafers.

A company spokesman also highlighted the crucial role played by Hitachi Cable's in-house developed high-throughput HVPE deposition techniques.

Despite the company's willingness to publicize this advance, it was less forthcoming regarding plans for commercialization, commenting, "At this moment this is still in the investigational stage, details have not yet been decided."

When asked about using these techniques to make 4 inch substrates, a representative said, "We do not have any specific plans, but we would like to start our development after looking deeply at customers' needs." Hitachi Cable's researchers are, however, due to present details of their work on substrates at the 49th Electronic Materials Conference in Indiana in late June.

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## SHARE-PRICE SURVEY

# Yoyo stocks give investors a rough ride

In a bad year for compound semiconductor chip stocks in general, more than half of our portfolio of prominent companies have shed an alarming third of their value. But, reports **Michael Hatcher**, it wasn't all doom and gloom – and, for a change, the star performer this year was an epitaxial equipment vendor, Germany's Aixtron.

## Compound semiconductor share-price leaderboard

Rank	Company	Ticker	Share value May 9, 2006 (\$)	Share value May 2, 2007 (\$)	% appreciation (May 06–May 07)
1	Aixtron (Frankfurt)	AIX	3.46	6.12	76.88
2	Anadigics	ANAD	9.06	10.59	16.89
3	Hittite	HITT	37.95	43.68	15.10
<b>4</b>	<b>NASDAQ composite</b>	<b>Index</b>	<b>2337.83</b>	<b>2531.53</b>	<b>8.29</b>
5	Skyworks	SWKS	6.96	6.85	-1.58
6	IQE	IQE	16.08	15.75	-2.05
7	Triquint	TQNT	5.47	5.13	-6.22
8	AXT	AXTI	4.25	3.90	-8.24
9	Avanex*	AVNX	2.36	1.70	-27.97
10	OCPI	OCPI	2.19	1.50	-31.51
11	RFMD	RFMD	9.07	6.18	-31.86
12	Finisar	FNSR	5.25	3.56	-32.19
13	Veeco	VECO	27.29	18.37	-32.69
14	Riber (Paris)	RIB	2.60	1.66	-36.15
15	Filtronic (London)	FLTC	205.00	130.00	-36.59
16	Endwave	ENWV	16.10	10.14	-37.02
17	Kopin	KOPN	5.50	3.41	-38.00
18	Cree	CREE	31.12	19.16	-38.43
19	JDSU**	JDSU	3.41	2.0275	-40.54
20	Bookham	BKHM	4.83	2.18	-54.87
21	Emcore	EMKR	12.39	4.96	-59.97

\*has now divested chip operations; \*\*after accounting for 8:1 reverse stock split

What a difference a year makes – in our June 2006 survey, the stock prices of almost every single publicly owned company involved in compound semiconductors was on a high. Eleven out of our 20 performers had more than doubled in value in the preceding 12 months. Since then, the situation has nearly reversed, with only three of those 20 firms registering any kind of gain over the past year.

Our comparison may be a little bit unfair – mid-2006 turned out to be the point at which many of the rallying tech stocks peaked.

But such are the risks of playing the stock market. The bemusing paradox is that, while stock prices have been on the slide, market conditions and individual company performances have undoubtedly improved over the past year, with many posting record-breaking figures. Why is this? The problem is one of perceived risk, and at the moment there seem to be a number of risk factors associated – however loosely – with compound semiconductor stocks.

That negative sentiment does not seem to have spread across all technology stocks, however, with significant gains in the past year for key companies like Nokia, Intel, HP and IBM. Meanwhile, an underperforming Motorola has bombed, which would have impacted on many of the US GaAs manufacturers.

But, just because a company has a healthy top and bottom-line financial performance and exposure to the biggest clients in its market, it does not necessarily make for a good short-term investment.

RF Micro Devices is a prime example. The biggest GaAs chip manufacturer in the world for RF applications – bar none – RFMD has just enjoyed a record-breaking year in which it not only posted revenues of over \$1 billion for the first time, but also registered a best-ever net profit of \$83.4 million (see figure on p13). Market analyst Strategy Analytics reckons that the Greensboro-based firm is further tightening its already strong grip on the power amplifier business. So, what's not to like about RFMD?

The share price: down 32% in the past year. And that's in a record-breaking year. Even taking into account, as noted above, that our May 2006 baseline could be somewhat anomalous, the past year has seen minimal gain. But look back over the past two years, and between May 2005 and May 2007 RFMD's stock actually notched up a very healthy increase of 64%.

The more recent dip in RFMD's stock price seems to be rooted in a number of factors. Of the major phone manufacturers, Nokia and Samsung seem to be firing on all cylinders, but Motorola's well-publicized problems have clogged up the sales channel and resulted in a build-up of inventory. Combine that with a general concern over future consumer spending patterns, as well as a school of thought suggesting that RFMD will have to face growing competition from suppliers of single-chip transceivers, and perhaps a drag on its shares is not such a great surprise.

But still, here's the rub: how do you go about investing in stock like RFMD? We know that it's a well-run, innovative, market-leading company, performing at the top of its game. But its stock price is about as predictable as British weather.

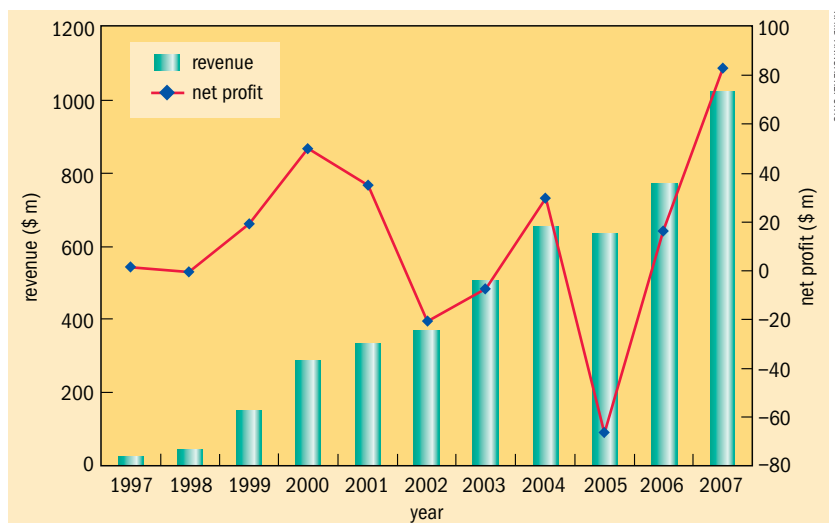
### Takeover talk

One compound semiconductor company's stock price has outperformed the rest of our portfolio by a huge margin over the past year, however – the value of German MOCVD equipment vendor Aixtron has rocketed by almost 80% from May 2006 to May 2007.

How much of that increase is due to business conditions and performance, and how much is due to takeover speculation is difficult to tell. Aixtron's share value spiked in mid-April when seemingly unfounded rumors of a potential takeover bid took hold on the Frankfurt stock exchange. What actually seems to have happened is that Aixtron's rising share price crossed an arbitrary threshold that gave the company a higher profile among the investor community, and combined with a more general increase in merger and acquisition activity in Germany to fuel a further surge.

Undeniably, market conditions have been good for both Aixtron and its chief MOCVD equipment rival, Veeco Instruments. Both companies are racking up big sales figures and filling their order books as LED producers upgrade their chip manufacturing capacities. Aixtron has just posted best-ever quarterly revenues of €63.8 million (\$86.3 million), double the figure seen in the previous year, and a very healthy profit of €7.6 million. While Veeco's share price has not followed the same trajectory as Aixtron's, its combined orders for MOCVD and MBE equipment now represent the US company's single largest market sector for the first time since it acquired Emcore's TurboDisc division.

Emcore itself has endured a torrid year on the stock market. That's despite what appears to have been a thoroughly successful re-focusing of the company over the past year. Now very much aligned with the photovoltaics and fiber-optic sectors, from chip production through to systems, Emcore was one of our top performers in last year's survey. But it spiralled



**On the up:** RFMD's fiscal 2007 resulted in record figures for total revenue and net profit – although Motorola's problems dragged down the RFIC manufacturer's share price.

down from a long-time high of more than \$12 back in May 2006 to around \$5 over the past year, during which time it was also hurt by an investigation into backdating of stock options. That investigation hasn't just affected Emcore's reputation – a historical review of those awards also cost the company \$2 million in the latest quarter.

LED manufacturer Cree also continues to have a tough time on the stock market, with its value having slumped 20% over the past two years. The Durham-based company is also in the middle of a strategic transformation, but seems to be suffering from serious competition in the HB-LED space. Cree is keenly promoting the solid-state lighting "revolution", which CEO Chuck Swoboda described at the recent Piper Jaffray Semiconductor and Communications conference in New York as "really starting to happen". Investors don't seem to be quite convinced of that just yet, but the company's acquisition of COTCO should be a big help – giving Cree exposure to the Chinese market, which is far more tuned in to the advantages of LED-based lighting than the US.

Back at the top of our leaderboard, there's no doubt about which company has been the most consistent stock-market performer over the past two years. Anadigics' value has admittedly slipped back a little since hitting a long-time high of nearly \$14 in recent months, but is still trading at more than six times its May 2005 level. Although the company is yet to register a really significant net profit, it seems to have plenty of good will among the investor community and is seen as a good long-term bet. Recent design wins at LG also seem to have gone down well.

So, given the extremely volatile nature of these compound semiconductor stocks, this seems to be how we should best view these companies – as long-term bets. Any firm that differentiates itself with a new, potentially disruptive technology is seen as a risky investment in the financial community. And speculating on compound semiconductor stocks is clearly not a vocation for the faint-hearted.



**Michael Hatcher** does not own or intend to purchase any of the stocks in this article.



## WHITE LEDS

# Poor fixtures threaten to jeopardize the illumination potential of LEDs

LED manufacturers are running massive marketing campaigns to woo the illumination market with brighter, lower-cost chips. But this will be in vain if their customers continue to design inefficient fixtures, reports **Richard Stevenson**.



## LED-chip efficacy

improvements are trickling into commercially available products. However, these improvements are often being wasted through inefficient lighting fixtures, which often throw away more than half of the emitted light. A few companies, such as LED Lighting Fixtures do have more efficient designs, however.

You're probably used to hearing that general illumination is going to be the next big thing for the LED. Manufacturers rarely talk about anything else, and have even conducted surveys to show that people feel safer in LED-lit parking lots. Researchers are using the illumination market to attach greater importance to their breakthroughs in chip performance, and market analysts are championing it as the key sector for LED growth over the next decade.

Strategies Unlimited market analyst Bob Steele, for example, is predicting that over the next five years LED sales to the illumination market will grow at a compound annual rate of 38%. This will propel the value of the sector, which already includes hundreds of fixture and luminaire companies throughout the globe, from \$205 million in 2006 to \$1 billion in 2011. These five years will also see a decline in the proportion of sales of red, green and blue LEDs, which are often used to illuminate the outside of buildings, and a growth in the white emitters that could replace conventional bulbs. White LEDs will account for some 60% of this illumination market by 2011.

These predictions, combined with the enthusiasm of the high-brightness LED makers and favorable legislation that could outlaw sales of incandescent bulbs in some parts of the world in the coming years, make it is easy to conclude that success in the general illumination market is nothing other than a formality. However, when you take a closer look at what is actually happening a different picture begins to emerge. The position of LEDs in the markets with the greatest potential is relatively weak, and many fixtures are failing to deliver the degree of efficacy promised by LED-based lighting.

As Steele points out, the current sales growth in the illumination market has not come from the replace-

ment of light bulbs in homes or offices. Instead, it has actually resulted from increased sales of LEDs in dozens of smaller and less lucrative markets, of which architectural lighting is the largest. What has driven the market up until now is the functionality associated with these devices, says Steele, such as the colors and the opportunity to adjust the color. "Efficiency has not been the driver because, until quite recently, LEDs have not been so efficient that it stands out. If you were looking for efficiency you would use fluorescent bulbs, compact fluorescents or ceramic metal halides." The choice of colors and the low temperature of the light source has brought notable successes in lighting cosmetics counters and jewelers, where the LED illumination gives the gems an attractive sparkle. Another major triumph is the illumination of refrigeration display cases at Walmart, which is thanks to the relatively high efficiency of the devices at colder temperatures.

But getting a foothold into the residential lighting market is a different proposition, with the new construction market offering the best prospect for growth. However, even displacing the incumbent technology in new-builds is not easy, according to Steele. "New technology comes along that's more expensive and potentially better. But thousands – perhaps tens of thousands – of lighting designers and fixture companies around the world have built up an infrastructure to support incandescents and fluorescent lamps. That infrastructure does not just go away."

Steele also points out that changes in the lighting industry occur slowly, which hinders rapid adoption of any new technology. Although there is already tremendous interest in LED technology, sales of these products to lighting fixture companies amount to only a very small percentage of overall sales.



**First round results from the DoE's solid-state lighting test program**

Type of luminaire	Manufacturer published LED luminous efficacy (lm/W)	Measured luminaire efficacy (lm/W)	Fixture efficiency (%)	Light output (lm)	Color-correlated temperature (K)	Color-rendering index
CPTP 06-01 Down light	40	12.8	32.0	193	3012	70
CPTP 06-02 Under cabinet	55	16.1	29.3	166	3483	78.2
CPTP 06-03 Down light	45	19.4	43.1	298	2724	67.3
CPTP 06-04 Task light	36	11.6	32.2	114	6392	76
CPTP 06-05 Outdoor area	24	23.9	99.6	2638	4661	20
CPTP 06-06A Surface mount	55	23.5	42.7	960	3405	75
CPTP 06-06B Surface mount	55	23.8	43.3	967	3414	75

**Measurements from the US Department of Energy** commercial-product testing program reveal that many fixtures are limiting the efficacy of LED-based luminaires.

More worrying is the potential long-term damage that could result from sales of poorly designed, inefficient fixtures. "The LED makers are doing an excellent job of pushing the technology and it's likely that we'll see a 100 lm/W device on the market this year," said Steele. "But the fixture guys are not taking advantage of the efficiencies that are being given to them. This is a major problem in the solid-state lighting industry, dealing with propagating the skills that can produce efficient fixtures."

This stark warning from Steele is backed by a report from the US Department of Energy's (DoE) solid-state lighting commercial-product testing program, which was published this March. The DoE detailed the results of efficacy tests on various LED-based luminaires (see table for a selection of the results) and concluded that some products on the market today provide less light output than traditional sources and most have efficacies that are lower than those implied by the product's literature.

According to the report, the shortfall in performance arises because several product manufacturers take the LED efficacy figure and assign it to the lamp. This is misleading because many of the fixtures produce an efficacy that is only a third of that of the LED. Unfortunately, this inaccuracy regarding the product's efficacy is widespread – only one of the six luminaires assessed in the DoE report came with accurate values for its overall output and efficacy.

Buying something that fails to live up to its specifications is never going to win customer satisfaction. "Not only is the efficiency low," lamented Steele, "but it is so much lower than what is claimed. And when the claims of efficiency are not supported by the actual results, there's going to be a credibility problem. If the lighting industry gets disillusioned, that could set things back for years."

Steele believes that the low efficiency of many fixtures results from a lack of specific and necessary skills within the workforce of many companies. "We know from our surveys that most of the traditional lighting companies – even the largest ones – don't have in-house skills and people with the skill sets to do efficient fixture design with LEDs." The skills shortage, which should be resolved over time, is partly due to a lack of familiarity with the electrical systems used to power the LEDs and the techniques needed for thermal management and optical design. "But when we see products with poor efficiencies coming out of the

smaller companies that understand LEDs, and how to use them, then that's a little bit daunting."

Not knowing how to install and use an LED lighting fixture can also shorten the diode's lifetime through poor thermal management and excessive drive currents. In addition, any failures in the fixture cannot be fixed by replacing a cheap bulb. Instead, repairs may involve replacing an entire light engine, an expensive procedure that can include fitting a new thermal management system and new optics.

These daunting issues facing LED fixtures may be casting a black cloud over the industry, but there is a silver lining in the form of a handful of fixture companies that are developing efficient products. This small list includes LED Lighting Fixtures (LLF), which was co-founded by former Cree CEO, president and chairman Neal Hunter. He shares Steele's concerns and believes that over-zealous marketing is producing misleading numbers, saying that there is no long-term benefit from releasing unreliable products or "tricked" numbers. These unrepresentatively high performance numbers can be generated by measuring the LED instantaneously, when it is not in thermal equilibrium, and by using low drive currents that produce higher device efficiencies.

LLF recently released a 6 inch downlighter that produces 650 lm at 11 W wall-plug power. The impressive lumens per watt figure of the lamp, which has a price tag below \$75, has been verified by a third-party lighting lab at thermal equilibrium and demonstrates the benefit of good design that can produce a fixture efficiency of over 90%.

Steele adds that an optical design house that he visited recently is producing designs with optical efficiencies of 95%. This confirms that high-efficiency LED fixtures are possible and that the LED lighting industry is not condemned to the same path as the fiber-optic lighting sector, which failed to live up to its expectations 10–15 years ago. However, with the exception of large, vertically integrated companies such as Osram and Philips, successful market penetration is not solely in the hands of the chip makers. Although lower chip costs and better lumen efficiency will help to increase sales in the lighting market, using fixtures that can make the best use of the light from the LED is probably more important, and forging relationships with the companies who can facilitate this could hold the key to success in general illumination.

**"The fixture guys are not taking advantage of the efficiencies that are being given to them."**

**Bob Steele**  
Strategies Unlimited

# Printing cuts the cost of uni

Semprius is refining and scaling a versatile printing process for uniting III-Vs with silicon. The technique will cut the cost of photovoltaics and RF and broadband sources, say **Kyle Benkendorfer, Etienne Menard** and **Joseph Carr**.

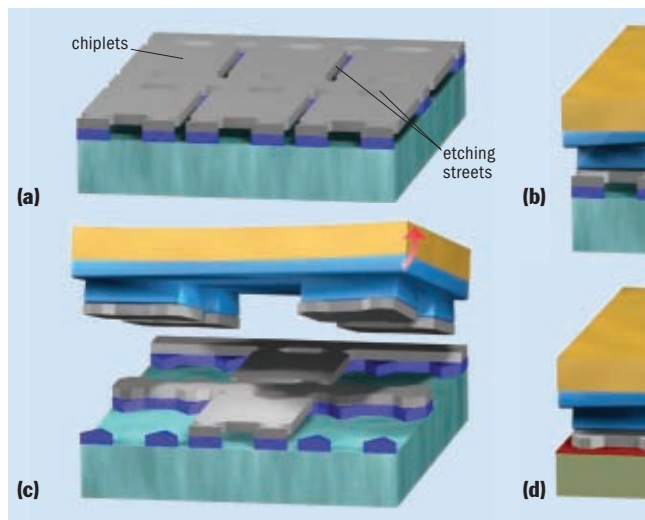
A lot of time has been devoted to the tricky problem of combining the best attributes of compound semiconductors, like high mobility and a direct bandgap, with the low-cost, mature manufacturing processes of silicon CMOS. The efforts have brought success at the research level, but in many cases commercialization is still a distant dream.

One technique that does promise near-term commercialization, however, is a simple, scalable process for the heterogeneous integration of III-Vs and silicon. This process was invented at the University of Illinois, Urbana-Champaign, by John Rogers and his team. The technique, which can create unique architectures that will ultimately produce new high-performance, low-cost RF and broadband devices and high-spectral-response photovoltaics, is being licensed by us at Semprius, a spin-out based in Durham, NC (see box “The Semprius story so far” for more details about the company). We plan to refine this process for volume production and ultimately commercialize the technology over the next few years.

Our technology centers on a printing technique for transferring sub-millimeter sized, sub-micron thick “chipllets” – which could include individual compound semiconductor transistors or small circuits – from one substrate to another (see figure 1). With an elastomeric stamp, arrays of chipllets can be transferred from donor to acceptor substrates in a single process.

The process begins by bringing a stamp into intimate contact with chipllets formed at the surface of compound semiconductor wafers (see figure 1 (b)). This stamp is then peeled back at a rate that removes the microstructures efficiently from the donor substrate, while maintaining their order and alignment (see figure 1 (c)). These chipllets are then printed onto the target substrate, which has been coated with an ultrathin film adhesive, and the stamp is peeled back ensuring full transfer of the microstructures.

Before this process can begin, the chipllet’s dimensions are defined with a “delineation” process. This step involves using an etchant to produce streets around the chipllets and remove a release layer. The undercutting process can be applied to GaAs wafers with AIAs release layers and to GaN films grown on silicon (111) substrates – an orientation that is



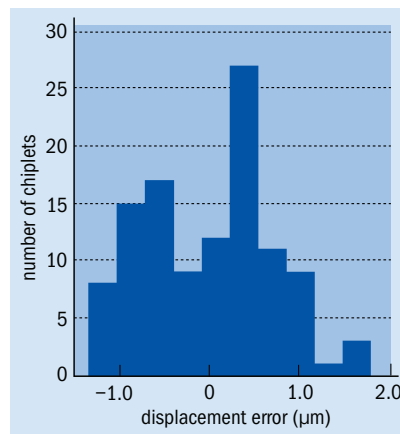
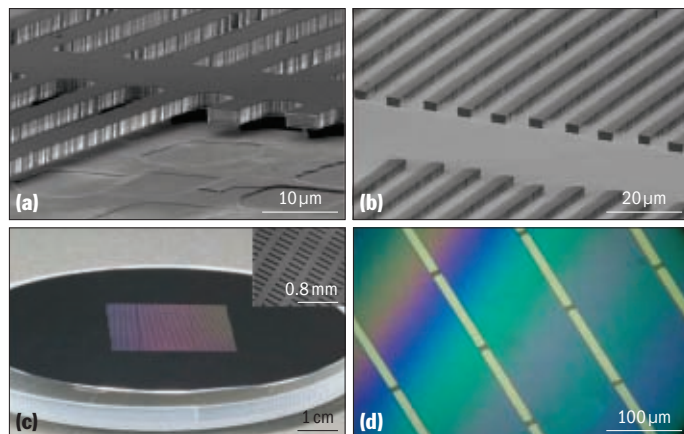
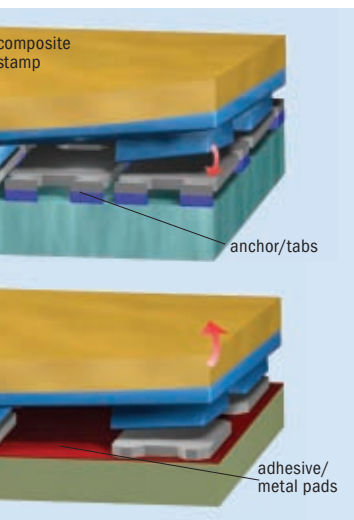
**Fig. 1.** The semiconductor printing process developed by John Rogers’ team: preparation of microstructures on conventional semiconductor wafers (a). A stamp (b), before it is quickly peeled away to leave the microstructures transferred to the target substrate and printed onto this platform, which can

suitable for GaN growth, but not CMOS processing. When the underlying silicon is etched, “microbridges” are formed that hold the chipllets in place before they are transferred to CMOS-compatible silicon (100) (see figure 2 (b)).

Our printing process has already printed single-crystal silicon, GaN and GaAs chipllets with thicknesses of 50nm–100µm and lateral dimensions ranging from 300nm to a few millimeters. Examples include a 30mm×38mm array of 24,000 silicon microstructures on a 100mm GaAs wafer, which was produced with a process yield – including micro-machining, pick up and release – of 95% (see figure 2 (c) and (d)). A reverse approach is possible, involving the printing of GaAs ribbons onto a silicon surface. We have successfully created many other structures with this approach, including silicon MOSFETs and GaN MESFETs arrays, circuits featuring ring oscillators, differential amplifiers, logic gates, diodes and resistors – which have been interconnected to the underlying substrate using evaporated metal lines formed over the device’s edge.

Our work has not been limited to the transfer of chipllets onto silicon and GaAs substrates: we have also developed this technique for transfer onto flexible plastics. On these platforms we have proven that printing does not dramatically alter device performance. Silicon chips on polyimide show mobilities of over 400cm<sup>2</sup>/Vs and on/off ratios of over 10<sup>6</sup>, and GaAs transistors on polyethylene terephthalate produce typical I-V characteristics.

# Printing III-Vs with silicon CMOS



**Fig. 2.** (left) Printing can be used to transfer under-etched GaN ribbons from a Nitronex GaN-on-silicon (111) wafer **(a)** to a target silicon (100) wafer **(b)**. The microstructures are perfectly aligned after the wet release process, because their ends are tethered to the source wafer. The process can also produce a 30 mm × 38 mm array of 24,000 silicon microstructures on a 100 mm GaAs wafer **(c)**. GaAs ribbons printed on a glass substrate are shown in **(d)**. High-resolution scanning electron microscopy images suggest that fewer than 100 microstructures are missing from this array. **Fig. 3.** (right) Our prototype dry transfer printing tool fitted with a thin 24 mm × 24 mm composite transfer stamp produces deviations from perfect placement of typically only ±1 μm, which are caused by the tool and local distortions. This histogram was produced by processing 112 images captured with the tool's built-in CCD camera.

the University of Illinois begins with the composite stamp is then laminated against the stamp **(c)**. The stamp is then coated with an adhesive layer **(d)**.

## The Semprius story so far

Semprius was founded in January 2005 with seed investment from Illinois Ventures. An additional \$4.1 million of series A funding was secured this April for product and business development from Illinois Ventures, Arch Venture Partners and Intersouth Partners.

The start-up currently employs five people, and expects its workforce to double by 2008. It is headed by CEO Joseph Carr, who has a strong pedigree in leading materials technology companies.

He was previously CEO of QD Vision and prior to that he worked



**Semprius** has built an automated printing tool for volume production.

for Osram Opto Semiconductors (OOS), where he held the roles of CEO of OSS Inc and general manager of the business unit for

organic LED displays. He has over 20 years of experience working for the Dow Chemical Company.

Carr has also provided consultancy services to several start-ups and currently serves on the board of directors of several companies.

Another member of the Semprius team is Kyle Benkendorfer, senior director of business development, who has also been a consultant to several start-ups. Benkendorfer has over 23 years of experience in bringing early stage research to market

through his role as a technical and commercial manager at Dow Chemical. He has commercialized new semiconductor packaging materials in Japan, Korea, Taiwan, Singapore and the US; new polyurethane materials in Australia and New Zealand; spin-on dielectrics in North America and Europe; and light emitting polymers for use in organic LED displays in Japan and Taiwan.

A third key member of the Semprius' team is Etienne Menard, who is co-inventor of much of the company's technology

A key feature of our printing approach is the isolation of demanding fabrication processes to specific mother substrates. This means that different optimized and tailor-made processes can be applied to the compound semiconductor chiplets and the receiving CMOS silicon wafer in the most efficient and affordable way. Complications from incompatible or inefficient processes are avoided.

The transfer printing step also delivers two major benefits: massively parallel transfer of chiplets and "geometric magnification." Depending on the

specific circuit configuration, each transfer step can print between hundreds and tens of thousands of chiplets simultaneously, which cuts costs and boosts manufacturing throughput. By designing the silicone stamp pad to pick up only one of every "n" chiplets, the printed substrate can also be populated over a larger area using a less dense array. On return to the source, the stamp can be indexed over one chiplet and the process repeated, thereby ensuring a very efficient use of the chiplets.

Another advantage of our process is that it can

## Rival approaches to integration

Many different commercial approaches have been developed to unite silicon and III-Vs.

The most straightforward option involves integrating various functions into sophisticated silicon or strained silicon chips, an approach referred to as “system-on-a-chip”. This route benefits from standard manufacturing processes, but employs more complex designs to improve the circuit’s performance. Companies can then use their existing manufacturing toolkit while dramatically increasing performance, but they have to accept a moderate rise in costs due to increased chip complexity.

Improvements in silicon technology are

increasing the popularity of this approach, but performance is still overshadowed by that of compound semiconductors.

An alternative and common approach involves the direct growth of III-Vs onto silicon. To ensure good-quality material, a lattice mismatch of less than 2% is required between the epitaxial film and the underlying substrate, which rules out the growth of GaAs-on-silicon.

Recently, several research groups have attempted to bridge or mute this mismatch by inserting a crystalline amorphous transition layer between the substrate and the device that has an intermediate lattice constant. Intel, Motorola and Philips have

all independently had success with this approach, but they say that commercial applications could be decades away.

The third popular route to heterogeneous integration is wafer-to-wafer or die-to-wafer bonding. Compound die or wafers are bonded to a silicon substrate processed with a receptor core, before the surplus base of the die or wafer is ground or etched away. This leaves the compound semiconductor circuitry intact within the silicon circuit.

This approach is used commercially, but suffers from the drawbacks of limited flexibility and high costs that are caused by significant material wastage during the process.

affordably handle and print chiplets with lateral dimensions of just 10  $\mu\text{m}$ , whereas traditional methods typically struggle to handle die with sides below 100  $\mu\text{m}$ . The etching step is also cheaper than dicing-based methods, which waste more material and produce less devices per wafer.

### Printing challenges

The primary challenge is to place the chiplets with enough accuracy. The elastomeric stamps used to do this are made by casting and curing a 1 cm thick piece of silicone rubber against a master substrate. They are capable of replicating the master’s nanometer-scale patterns, so long as the stamp is made from a low-modulus silicone such as polydimethylsiloxane. However, single-layer stamps built with this soft material are prone to deformation during printing, which limits their use to coarse placement. Fortunately, this weakness can be addressed with advanced composite stamps that have low coefficients of thermal expansion, high in-plane mechanical rigidity and environmental stability, and a placement accuracy of less than  $\pm 2 \mu\text{m}$  (see figure 3).

The printing technique must also be compatible with the brittle chiplets. This brittleness stems from the fully fabricated chip’s structure, which has several dielectric and metal layers on top of the thin epitaxial layer. These additional layers have a built-in strain that causes the ultrathin chiplets to bow after the wet-etching undercut process. However, this bowing can be avoided by optimizing the shape of the micro-bridge structures, so that they maintain the chiplet’s flatness when they are attached to the wafer. Alternatively, the chiplet’s mechanical stress can be offset with strain-balanced passivation layers.

Ours is not the only technique under commercial development for marrying silicon’s cost and processing advantages with high-performance compound semiconductors. However, we believe that our approach has greater flexibility than alternative methods, which require improvements to silicon’s performance, techniques to grow III-Vs directly

onto silicon and wafer-to-wafer technologies (see box “Rival approaches to integration”).

One market that could benefit from our approach to circuit production is GaAs power-module manufacture. Discussions with several component makers and cost models produced by an industry expert have revealed that our printing approach could lead to cost savings through more effective use of GaAs and silicon. These savings result from using GaAs to make the transistors and the silicon CMOS substrate to form other components in the circuit, such as resistors and capacitors. This cuts the compound semiconductor real estate for each power-amplifier module and enables the costs of these units to approach CMOS silicon levels.

We are also targeting high-efficiency, high-spectral-response photovoltaics. Printing techniques can cut the production costs for these devices because an optimized combination of different materials can be brought together that offers high performance at low cost. Our process also offers further savings through wafer reprocessing, because our street etch process only removes a few microns of material.

We are now working to scale up a robust printing process to address both of these markets, and also markets involving active matrix display backplanes, large-area sensor arrays, such as X-ray detectors, and flexible electronics, such as smart packaging and RFID tags. We are also developing partnerships with companies that are expert in certain target markets and we are keen to engage more partners. We expect that our technology will be commercialized in the next few years. ●

### Further reading

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### About the authors

**Joseph Carr** is Semprius’ CEO (right), **Kyle**

**Benkendorfer** (kyle. benkendorfer@semprius.com)

is the company’s senior director of business development (left), and

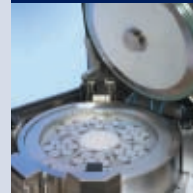
**Etienne Menard** (middle) is a founding scientist at Semprius who co-invented a large proportion of the company’s technology. The authors thank all the researchers in John Rogers group who prepared the GaAs and GaN heterogeneously integrated substrates.

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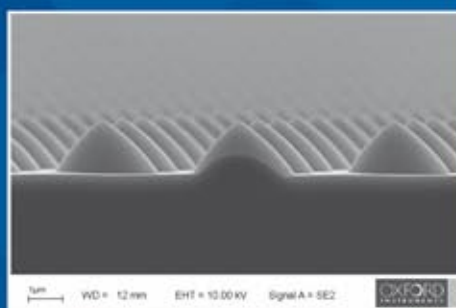
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# Non-polar GaN reaches tipping point

Non-polar light-emitting devices based on GaN have huge potential, but chip performance has been limited. However, this is starting to change, say **Steve DenBaars**, **Shuji Nakamura** and **Jim Speck**, who have made non-polar LEDs with an efficiency of up to 45% and some of the first non-polar lasers.

GaN-based light emitters have made a great commercial impact. The LEDs have backlit billions of mobile phones and illuminated numerous buildings, and are starting to replace the cathode-ray tubes in televisions. Meanwhile, the lasers are beginning to find their feet as key components in the next generation of DVD machines and gaming consoles.

However, despite their tremendous success, these devices have a fundamental flaw – an internal electric field that restricts laser and LED performance. The devices are produced by growing GaN along the *c*-axis of the wurtzite crystal, leading to spontaneous and piezoelectric polarization within the heterostructure, which causes the electric field. This field pulls apart electrons and holes, so that they are spatially separated within the quantum well. The result is a reduction in recombination rate and light emission, possibly combined with a decrease in internal quantum efficiency. The internal field also means that the emission wavelength shifts with drive current. This can limit the use of GaN devices in certain applications, such as those that involve the precise mixing of red, green and blue light to produce white illumination.

To overcome these issues, the scientific community has been developing structures grown on non-polar planes, such as the *m*-plane and the *a*-plane, which are free from polarization-related internal electric fields (see figure 1, p22). This began with hetero-epitaxial growth of GaN on foreign substrates. Unfortunately, these films were plagued with a high density of stacking faults (SFs) and threading dislocations (TDs), which impaired device performance. TDs, for example, act as non-radiative recombination centers, which quench luminescence and limit output power.

Defects are what hampered the performance of the first *m*-plane LED, which was fabricated by our group in 2004 at the Solid State Lighting and Display Center at the University of California, Santa Barbara (UCSB). Many of these defects would have originated in the HVPE-grown free-standing *m*-plane GaN substrate, which had a TD density of  $4 \times 10^9 \text{ cm}^{-2}$  and a SF density of  $1 \times 10^5 \text{ cm}^{-1}$ . This 450nm LED produced just 0.24mW at an external quantum efficiency (EQE) of 0.43%, when driven at 20mA.

Higher outputs from non-polar LEDs were reported last year by researchers at Rohm Corporation, Japan, which is a partner of ours. This team fabricated an LED on a dislocation-free *m*-plane

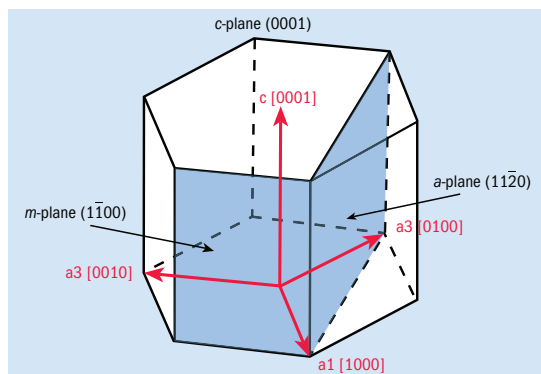


**Unlocking the potential of non-polar devices** could deliver a hike in GaN LED performance and make these emitters a more attractive option for general illumination purposes.

GaN free-standing substrate that operated at the slightly shorter wavelength of 435 nm. It delivered 1.79 mW and an EQE of 3.1% at 20 mA. But even with this improvement, the efficiency of the GaN non-polar LED still trailed that of its conventional *c*-plane cousin by an order of magnitude.

Recently, however, there has been a tremendous hike in non-polar LED performance. Our devices, fabricated at the end of 2006, have an EQE in excess of 40% and our very latest emitters can deliver an efficiency of up to 46% (see figure 2, p22). The significant jump in efficiency has been driven by improvements in the quality of bulk *m*-plane GaN substrates. The latest LEDs were fabricated on Mitsubishi Chemical Company's free-standing bulk *m*-plane GaN substrate, which was produced using chemical and mechanical surface treatments on the exposed surface. Transmission electron microscopy images indicated that these substrates were free of dislocations, and placed an upper limit on the dislocation density of  $10^6 \text{ cm}^{-2}$ .

With these superior substrates our LED's output at 20 mA has rocketed to 28 mW, with an EQE of 45%, according to room-temperature DC measurements taken using an integrating sphere (see figure 3, p22, for device details). The EQE peaks at a drive current 10 mA (see figure 4, p23), and slightly decreases at higher currents, which is likely to be due to device



**Fig. 1.** Today's commercial LEDs and lasers are built by growing epitaxial layers on the *c*-plane of GaN, which limits device performance due to the presence of strong internal electric fields. Switching growth to the *m*-plane creates devices that are free from these fields, and could lead to more efficient emitters.

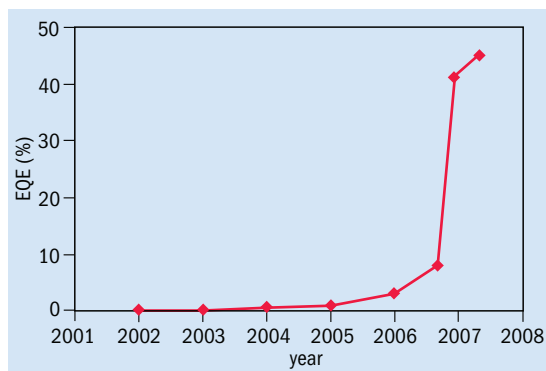
heating. The fairly flat response of the EQE over this current range is probably related to the absence of polarization-related electric fields in these structures, but it might also be a consequence of the relatively short wavelength (407 nm) of these emitters.

Laser diodes produced on *m*-plane GaN have the potential to share many of the attributes enjoyed by their LEDs equivalents. They could also benefit from higher gain, due to the structure's unbalanced biaxial stress and the absence of parasitic waveguides that disturb the beam profile. The lack of strong internal fields within the device also allows thicker InGaN quantum wells to be included in the design, which can provide effective waveguiding of the laser's transverse optical mode.

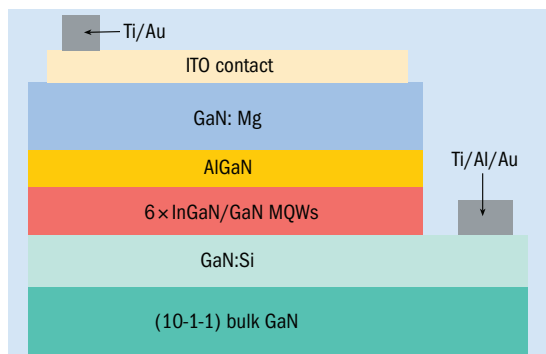
In this year's February 27 issue of the *Japanese Journal of Applied Physics*, our group and Rohm independently announced the fabrication of the first non-polar GaN laser. Our initial device was a broad-area gain-guided laser that was driven in pulsed mode and had a threshold-current density of  $7.5 \text{ kA cm}^{-2}$ . In comparison, Rohm's device had an index-guided ridge geometry and operated in the preferred, continuous-wave mode. The maximum output power for this device was 10 mW, and current densities were as low as  $4.0 \text{ kA cm}^{-2}$ . Both of the devices were fabricated by MOCVD on Mitsubishi's high-quality low-defect-density GaN substrates, which were undoubtedly critical to these breakthroughs.

### Cladding ditched

More recently, we have started to investigate the performance of non-polar *m*-plane InGaN/GaN laser diodes that do not contain AlGaIn cladding layers, which have the potential to operate at lower threshold-current densities. The removal of the AlGaIn layer – needed for optical-mode confinement in conventional structures – frees the laser from the severe constraints associated with *c*-plane device growth due to tensile strain in the AlGaIn layers. The device can then be grown and fabricated in a similar way to the InGaN/GaN LEDs, which



**Fig. 2.** The performance of UCSB's LEDs have rocketed, thanks to improvements in the quality of *m*-plane material.



**Fig. 3.** UCSB's latest LEDs have a wider multiple-quantum-well (MQW) region than conventional *c*-plane devices, which boosts their efficiency. The devices feature a 10 nm thick undoped AlGaIn electron-blocking layer on top of the p-type barrier and a 160 nm p-GaN layer. The LEDs, which are a conventional  $300 \times 300 \mu\text{m}^2$  design with a U-shaped n-contact and an indium tin oxide (ITO) contact layer, were grown by atmospheric pressure MOCVD using temperatures of 875–1185 °C. After fabrication, the devices were diced and packaged using standard die and wire bonding techniques, and then molded with epoxy.

ultimately offers a more straightforward method for the manufacture of GaN laser diodes.

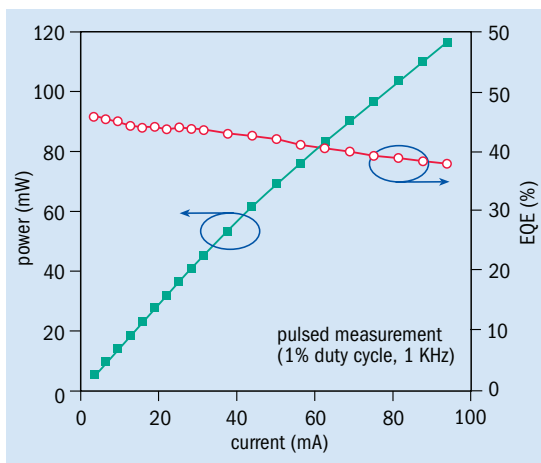
To compare the performance of this design with that featuring cladding layers, we have produced three different broad-area lasers with growth conditions similar to those used for *c*-plane LEDs. Each of these lasers, which share the same basic structure (see figure 5), were fabricated by using lithographic patterning to define a thin metal stripe that provides a current injection area of  $15 \times 1000 \mu\text{m}^2$ . Reactive ion etching defined the mesa and laser facet; a current blocking layer was added by patterning a  $\text{SiO}_2$  film; and n-metal contacts and p-metal contact pads were formed by evaporation.

The first device that was built for comparison has a structure similar to a traditional *c*-plane GaN-based laser diode and has AlGaIn/GaN superlattice waveguide cladding layers on either side of the active region. However, this active region contains thicker quantum wells and features five 8 nm InGaIn wells separated by 8 nm GaN barriers. This design produced a laser threshold voltage of 11.7 V

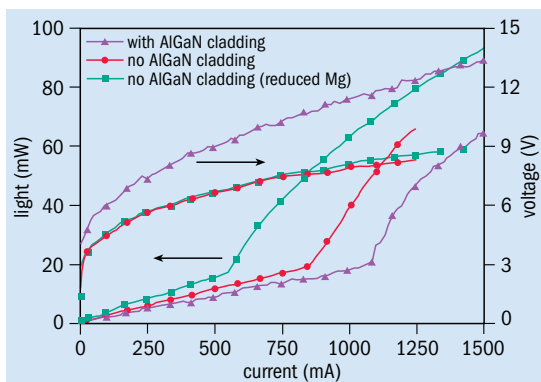


**UCSB's first broad-area laser** was announced this February. The initial device had a threshold-current density of  $7.2 \text{ kA cm}^{-2}$ , but improvements to the design have already lowered this key figure of merit to  $2.3 \text{ kA cm}^{-2}$ .





**Fig. 4.** Non-polar LEDs show less of a decline in efficiency at higher drive currents than their conventional cousins.



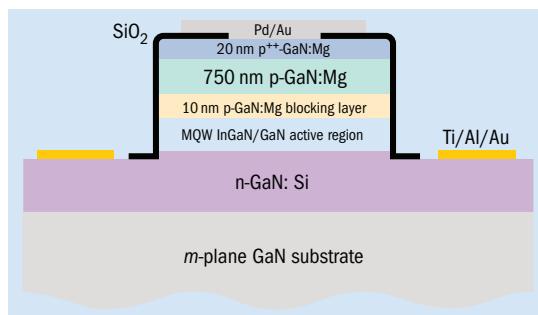
**Fig. 6.** Removing the AlGaN cladding layers from the laser has cut the threshold-current density by a factor of three and reduced the emitter's threshold voltage.

and a threshold-current density of  $7.2 \text{ kA cm}^{-2}$ , which is a slight improvement on our earlier design (see figure 6).

The second device differs in only one aspect from the first – the lack of an AlGaN waveguide cladding layer. This change reduces the operating voltage to 7.6 V and cuts the threshold current to  $5.6 \text{ kA cm}^{-2}$ .

Our final design also omits the AlGaN cladding layer. It differs from the second design by featuring a reduced magnesium concentration in the p-type GaN and a new active region, which consists of three 13 nm thick InGaN quantum wells separated by 8 nm GaN barriers. The result cut the threshold voltage to 6.7 V and the current density to  $3.7 \text{ kA cm}^{-2}$ . The 411.3 nm lasing peak from this device has a full-width half-maximum of less than 0.5 nm, making it suitable for optical recording.

The lasing characteristics of the unclad devices – which we believe are the first GaN-based laser diodes that do not contain AlGaN cladding layers – are particularly encouraging because they feature uncoated etched facets, rather than cleaved facets. We used ion-beam etching to create smooth, vertical facets and further improve the laser performance. This has reduced the threshold density of our



**Fig. 5.** The three different laser designs produced by UCSB feature the following layers: a silicon-doped GaN layer, which was grown on the free-standing *m*-plane substrate without using a low-temperature nucleation layer; a five-period undoped-InGaN/GaN multiple-quantum-well active region with 8 nm quantum wells and 8 nm barriers; a 10 nm thick magnesium-doped AlGaN electron-blocking layer, which is the only aluminum-containing layer in the structure; a 750 nm thick magnesium-doped p-type GaN layer; and a 20 nm magnesium-doped p-type GaN contact layer. The AlGaN cladding layer is not included in this structure.

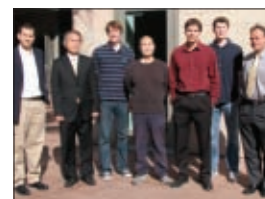
broad-area lasers to  $2.3 \text{ kA cm}^{-2}$  using processing steps that deliver a very high yield.

We believe that the threshold current can be further reduced by introducing a ridge-waveguide structure and by optimizing the magnesium-doping levels. When we built a laser that combined the active region of the third device with the magnesium-doping levels used in the first two designs, we produced an emitter with a performance similar to that of the second device. This implied that the laser's performance is predominantly governed by the magnesium-doping level, which impacts optical absorption losses and is not strongly influenced by the quantum-well design. Since this magnesium doping has not been optimized, further improvements in diode performance are highly likely.

Our improvements to the performance of non-polar LEDs, which are mainly thanks to significant gains in *m*-plane material quality, means that these non-polar devices now match their conventional cousins. We anticipate further refinements in substrate quality, alongside improvements in device optimization, which will propel these emitters and their laser diode equivalents to higher performance levels, and ultimately increase deployment of GaN devices.

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**Steve DenBaars** is a professor of materials and electrical & computer engineering at UCSB, and the Mitsubishi Chemical Professor in Solid State Lighting and Display. **Shuji Nakamura** was the 2005 winner of the Millennium Technology Prize and is a professor of materials and the Cree Professor in Solid State Lighting and Display. **Jim Speck** is professor and chair of the materials department, UCSB. The scientists that make up UCSB's non-polar laser and LED team are (from left to right) Speck, Nakamura, Danny Fazzell, KC Kim, Matt Schmidt, R Farrell, and DenBaars. All authors acknowledge the support of the SSLDC, the supply of substrates from Mitsubishi Chemical and the NICP/JST exploratory research for advanced technology

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## SUBSTRATES

# Developers seek new nitride platform

With no immediate bulk GaN on the commercial horizon, engineers have started to look beyond silicon and SiC to composite materials and metals as a platform for nitride growth.

**Richard Stevenson** investigates.

If our community was granted a single wish, it would probably ask for an affordable, large-size bulk GaN substrate. That's because today's GaN substrates are small and pricey, which is limiting the development of every nitride device. The difficulties associated with producing GaN bulk material have driven many firms to pioneer alternative platforms for nitride growth.

One company that has been pursuing this route for the best part of a decade is French epiwafers specialist Picogiga, a division of Soitec. "We are the only company in the world that can provide GaN HEMT epiwafers on three different substrates," explained Picogiga's chief operating officer Jean-Luc Ledys.

The first wide-bandgap product launched by Picogiga was a GaN-on-SiC epiwafer. This offers great performance, but at a high price due to the costs associated with using single-crystal SiC. To offer a cheaper option, the company then added GaN-on-silicon epiwafers, which are suitable for less demanding applications due to their poorer thermal management characteristics. A third solution to nitride growth has also been added more recently, silicon-on-polycrystalline-SiC (SopSiC), which combines an intermediate price with power-handling characteristics similar to crystalline SiC.

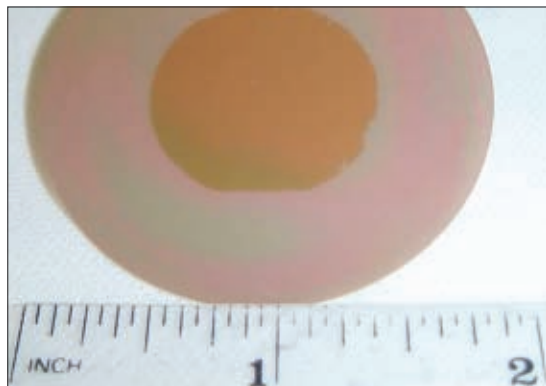
"SopSiC is a thin silicon layer, bonded and transferred onto polycrystalline SiC," explained Ledys. The widely available polycrystalline SiC base was chosen because it's 10–20% of the cost of its crystalline brother, it is compatible with the company's MBE processes, it is widely available and it can be produced in sizes of up to 12 inches.

Ledys believes this platform is ideal for producing high-voltage Schottky diodes for rectification because devices built on silicon are limited to 250 V. "[The alternatives are silicon] bipolar devices, which are not very efficient, or SiC devices, which are very, very expensive."

The Smart Cut technology that holds the key to SopSiC production has also been used to fabricate SiC-on-insulator (SiCOI) material. The company first produced 2 inch SiCOI substrates several years ago, but since then they have put development on the back burner. "SiCOI does not give either us or our customers a good solution in terms of supplier, because we have to rely on SiC vendors. This does not help to expand the source supply chain," explained Ledys.

Picogiga is also developing GaNOI material. This could be used for microelectronic applications, but the company sees it primarily as a potential platform for homo-epitaxial growth of high-brightness white LEDs. "There is a serious bottleneck – similar to SiC – because very few people can grow bulk GaN," admitted Ledys. "However, we are ready to put in more effort and even look at growing GaN ourselves."

Wafer bonding is also at the heart of Aonex Technologies' prototype substrates, which feature thin



Aonex's wafer development has involved refining the transfer of 1 inch GaN layers onto 2 inch polycrystalline AlN substrates.

layers of either sapphire or GaN attached to polycrystalline AlN, a relatively low-cost material with comparable power-handling capabilities to GaN.

"For technology and market reasons we're focusing on the GaN-on-AlN right now," revealed the California start-up's co-founder James Zahler. This composite could produce material with an epitaxial quality equivalent to that produced by growth on single-crystal GaN, but at lower cost, making it ideal for lasers and high-performance LEDs.

Zahler regards the sapphire-on-AlN composites as a second, more affordable platform for vertical LEDs. According to him, these wafers enable LED production with a flip-chip technique that is much simpler than laser lift-off, which is normally used to separate sapphire from the nitride epilayers. In addition, the wafer is less prone to bowing and warping during growth, thanks to a closer match between the thermal expansion coefficients of the nitride epilayers and the underlying AlN.

Another candidate for nitride growth is metallic substrates, which are being developed at the Naval Research Laboratory in Washington, DC. "Metallic substrates are attractive to us because they have an ohmic contact and very good thermal conductivity," explained team-member James Freitas.

Nitride films grown on TiC have a similar quality, in terms of morphology and electrical properties, to those obtained on sapphire and SiC. The electrical properties of TiC show great promise for producing LED and laser structures, which would benefit from excellent carrier injection. However, the defect densities in the nitride epilayers are currently too high. Commercialization of this potential substrate would also require an increase in size from the 5 mm × 5 mm pieces used by Freitas to standard manufacturing sizes. "Unfortunately, there is not a lot of interest in single-crystal TiC material," said Freitas, but if this technology was pursued, it might offer yet another solution to the awkward problem of nitride growth.

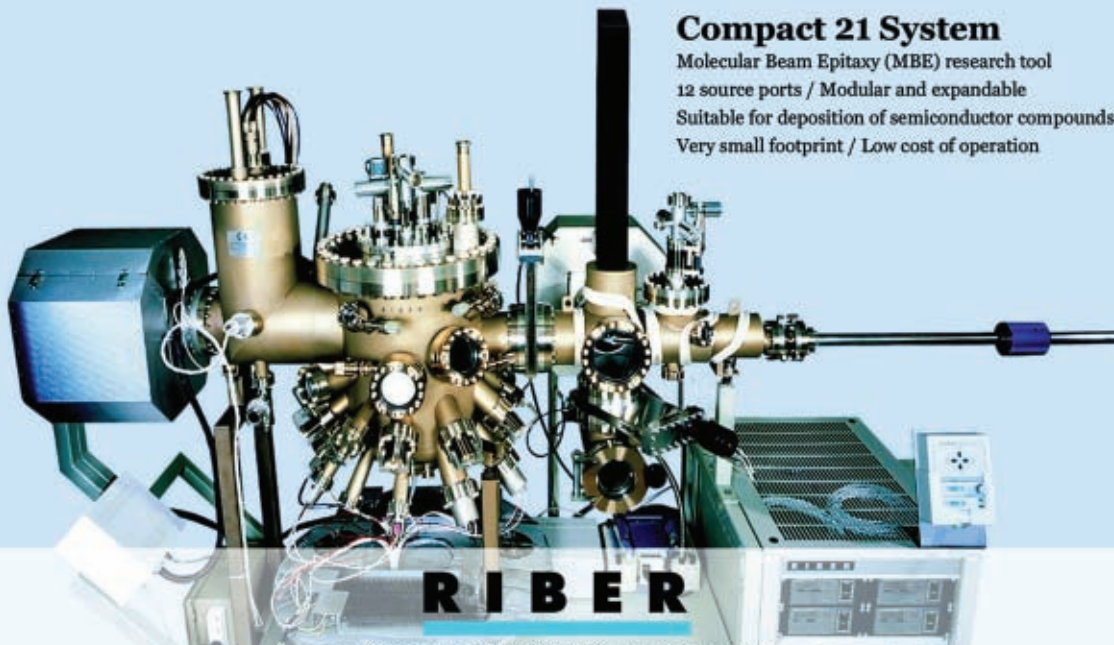
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# SHEDS leaves high-power legacy

Innovations emerging from the super-high-efficiency diode sources program haven't just boosted the efficiency of hero devices, says Alfalight's **Rob Williamson**, they have also had the knock-on effect of driving up the performance of commercial products across the board.

For the past two decades solid-state lasers have primarily been flash-lamp pumped devices with typical wall-plug efficiencies of less than 1%. This started to change a few years ago, following the advent of reliable, high-power diode lasers with wall-plug efficiencies approaching 8–10%. Unfortunately, this efficiency is still far too low for many military defense applications, which require portability, battery operation and scaling to multiple kilowatts. Although systems that were once relegated to large optical benches are now being flown in airplanes, carried by soldiers or mounted in Humvees, these lasers are a significant drain on turbines, batteries and engines. In fact, in some cases the carrying vehicle is custom-designed to incorporate the laser.

Initiatives such as the recently completed multi-million dollar super-high efficiency diode sources (SHEDS) program, which was run by Defense Advanced Research Projects Agency (DARPA), have laid the groundwork for building highly efficient 100kW laser-based defense weapons. This work has also assisted the development of a range of mobile defense applications – including laser interferometric detection and ranging, targeting and imaging – and aided commercial laser systems, which benefit from lower power consumption, a smaller factory-floor footprint and portability.

Before the three-year SHEDS program began in late 2003, the state-of-the-art emitters operating in the wavelength range 800–980nm were InGaAs/GaAs devices delivering efficiencies of up to 45%. The spatial beam quality of high-power laser diodes is insufficient for cutting metal or for long-distance propagation, so these devices are used to pump another laser cavity that produces a far less divergent beam, usually rare-earth-doped crystals such as Yb:glass or Nd:YAG. This conversion process was typically 25% efficient (in YAG) at converting pump light into a high-spatial-quality output beam. If a 100kW diode-pumped solid-state laser system was built using this technology, it would dissipate 700kW of heat and consume nearly 800kW of electricity. Addressing these cooling and electrical power needs would require two tractor-trailers, which is too great a burden for a tactically usable weapon system.

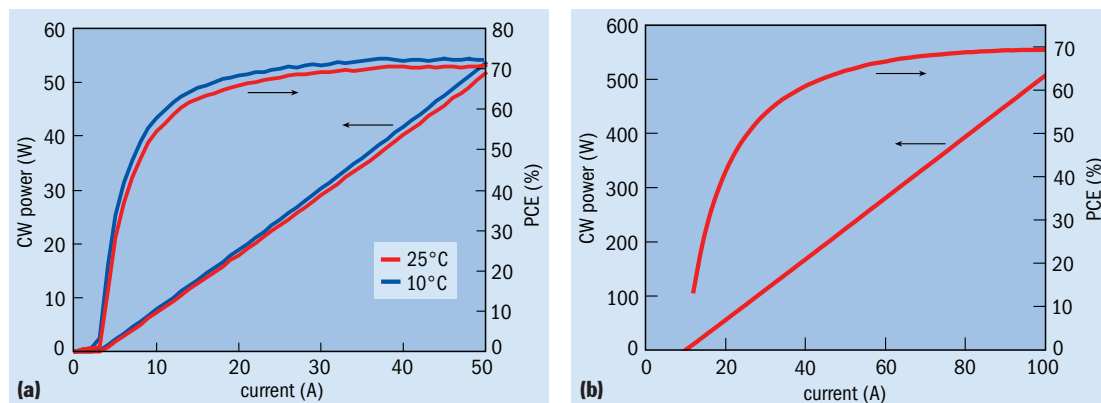
To make portable laser-based weapons viable, DARPA launched the SHEDS program to drive efficiency improvements in room-temperature laser diode bars operating at 976nm, which is a key



**The SHEDS program** aimed to assist the development of defense applications, which require portability, battery operation and scaling, by boosting laser diode efficiency to 80%.

absorption line in ytterbium-doped gain material. A target of 65% power conversion efficiency (PCE) was set for the program's midpoint, and an 80% goal for its completion. Hitting the 80% diode goal and improving solid-state laser efficiency could ultimately cut the weight of the laser weapon's thermal management system from 15,000 kg to around 1,000 kg. Alongside this principal target, the SHEDS program laid down other requirements to ensure that these devices were suitable for laser weapons. These included power density of at least 500 W/cm<sup>2</sup> per diode bar, a spectral linewidth of below 2 nm, a spread in peak emission wavelength across a bar of less than 1 nm, and a "wavelength stabilization" target that would prevent drifts in emission wavelength with temperature.

The targets laid out in the SHEDS program have been chased by the laser-diode manufacturers Alfalight, JDSU and nLight, which were supported by teams at the University of Central Florida, Caltech and the National Institute of Standards and Technology (NIST). The chip makers have made progress by introducing fundamental changes to the device's design; the university teams have provided solid-state laser modeling and external wavelength-control gratings; and NIST has provided objective, standardized measurement of device performance. With this approach, all three manufacturers have produced



**Fig. 1.** Alfalight's results from the SHEDS program include a 50 W diode laser bar **(a)** and a 500 W bar array stack **(b)** operating at 976 nm with PCEs of 73% (10 °C) and 69.3% (25 °C) respectively. NIST calibrated **(a)** or measured **(b)** device performance.

976 nm emitters that exceeded the 65% milestone, although none have hit the final 80% target.

At Alfalight, our efforts ultimately produced a diode bar with a peak PCE of 73% that delivered 50 W at 10 °C, and a 500 W bar stack built from five 1 cm arrays, which had a maximum, NIST-certified array PCE of 69.3% at 25 °C (see figure 1).

During the course of the SHEDS program we improved the efficiency of our diodes by over 20% by identifying and addressing the various loss mechanisms present in traditional quantum-well diode lasers. These efficiency-limiting losses occur during the transport of electrons and holes from their respective contacts to the active region, and also during the recombination process. The losses include: contact resistance at the metal–semiconductor interface; Joule heating in the bulk semiconductor material, which is caused by the diode's effective series resistance; series ohmic resistance of contacts; heating of the crystal lattice as energetic carriers cross heterojunctions between high and low bandgap material; carrier leakage, caused by electrons that do not combine with holes to form photons in the laser cavity; scattering or absorption of the photons out of the laser; and non-radiative losses, including the current consumed to achieve population inversion.

We tackled these loss mechanisms with a new laser design that featured compositional grading of the interfaces in the quantum well to reduce band alignment losses; a judicious choice of material to provide additional optical and electrical carrier confinement; and doping changes that reduced the contact resistance. Our device's scattering and absorption losses were also reduced through the introduction of tighter manufacturing tolerances for several growth and lithographic processes.

With these changes, all the major loss mechanisms were reduced, aside from the below-threshold mechanisms (see figure 2). However, the increase from this particular mechanism is something of an anomaly, as its actual value was unchanged and its rise is only a comparative one, which resulted from a decline in the contribution from other losses.

Although all of the participants in the SHEDS program produced outstanding results, the room-temperature 80% PCE target remains elusive and invites the question of whether this goal can ever be met. The answer is “yes, but...” because significant development is still required. Until now, progress has been made by attacking the losses inherent to traditional quantum-well devices – any more “belt tightening” will squeeze out only small improvements.

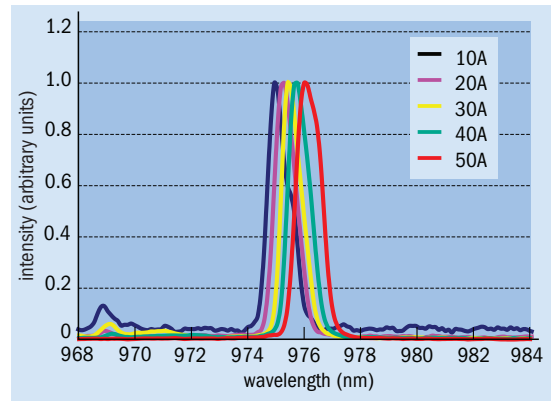
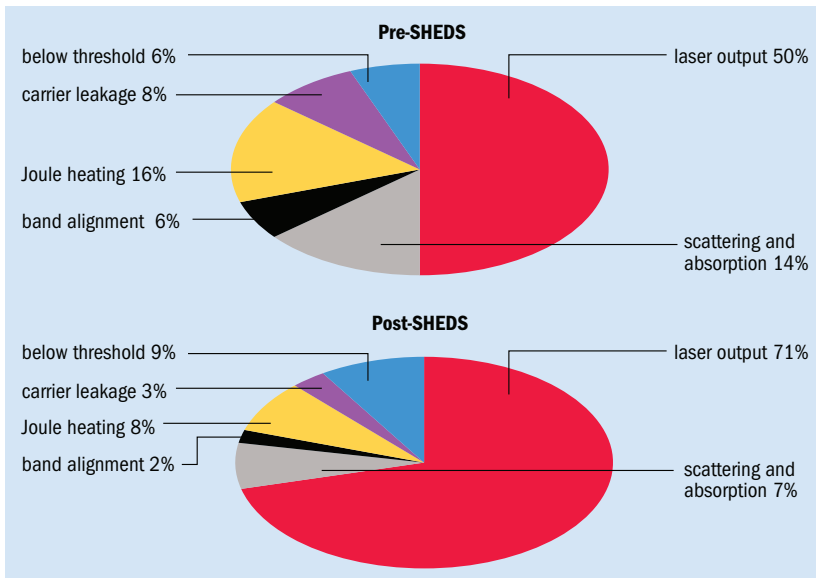
Additional gains will instead have to come from more radical designs such as those using an alternative gain medium, which targets below-threshold losses by introducing fundamental changes to the quantum well. The quantum dot and (110)-plane growth approaches explored in the SHEDS program show promise, but it takes time to optimize the growth conditions of these new structures. Until this is done, it will not be possible to manufacture low-loss devices in this fashion. Encouragingly, some true quantum-dot-confined commercial devices do exist today, but output powers and efficiencies are low and it will require significant effort to develop multi-watt diode lasers with this technology.

#### Indirect beneficiaries

The benefits of the SHEDS program have already expanded beyond laboratory results to enable efficiency hikes in commercial laser-diode products. In the real world, device lifetimes are critical and lasers must have proven reliability to win sales, including figures of merit such as characteristic temperatures  $T_0$  and  $T_1$ , mean-time-to-failure and lifetime models. The higher output powers bring a new set of challenges that influence packaging, choice of substrates, attachment technologies, interconnects, exterior packages and cooling methodologies. Volume manufacturing also requires an understanding of the acceptable tolerances for growth, device processing and testing. To address all these production issues and transform a lab device into a commercial product with a proven lifetime can take at least a year.

At Alfalight, the SHEDS program results have already been translated into commercial products.

The benefits of the SHEDS program have already expanded to include efficiency hikes in commercial laser-diode products.



**Fig. 2.** (left) Alfalight has substantially reduced the loss mechanisms from several sources during the SHEDS program.

**Fig. 3.** (above) Wavelength stabilization technology has reduced wavelength shifts to  $0.07 \text{ nm}/^\circ\text{C}$  ( $0.02 \text{ nm}/\text{W}$ ) while maintaining a PCE of 58%, making these devices ideal for pumping the narrow atomic absorption lines of solid-state, fiber and alkali lasers.

The first stage in achieving this was to incorporate some of the lessons learnt during the project by tightening manufacturing tolerances on existing designs. The second, to realize truly improved PCE levels, required introducing entirely new laser structures and the associated qualifications and life-time test. New commercial high-power laser products are generally delivering a PCE in excess of 50%, and some commercial offerings are even approaching 65% in a single-emitter package format.

The improved efficiency has increased the output powers of both single emitters and bar arrays. It also enables the use of brighter pump sources (watts per emitter or ex-fiber) which are the key to making cost-effective fiber lasers and to boosting the power of compact kilowatt-class diode-pumped solid-state lasers.

### Spectral brightness

Our efforts, and those of other SHEDS program participants, are now focused on extending the efficiency gains achieved at 976 nm to other important pump wavelengths, including 808 nm, 885 nm and 915 nm. The principles for reducing various loss mechanisms at these additional wavelengths are the same, although implementation requires different material systems and quantum-well structures.

We have also made our lasers more suitable for efficient pumping of the narrow absorption lines of rare-earth-doped gain crystals and gain fibers by reducing the emitter's spectral width and its wavelength shift with temperature. This is important for building solid-state lasers, as pump power that falls outside the absorption range of the gain crystal is wasted and actually becomes an additional source of laser system inefficiency.

During the program, the diode bar's output wavelength was controlled with a carefully aligned external grating. This approach can be costly and cumbersome, especially when it is applied to multi-

bar stacks and arrays. At Alfalight, with support from the Air Force Research Laboratory, we have now developed an integrated solution that involves adding a semiconductor grating during wafer processing. After both the quantum well and waveguide-index cap are grown, a holographic grating is lithographically exposed across the entire wafer, before it is etched and regrown. The semiconductor grating, which is far outside the laser active region, narrows and stabilizes the shift in output wavelength with temperature and only results in an efficiency loss of around 3–5%.

This monolithically integrated wavelength-stabilization technology has produced passively cooled 976 nm laser bars with 50 W outputs that deliver a record PCE of 58% at  $25^\circ\text{C}$  (see figure 3). The bar has an overall spectral width of less than 1 nm and a wavelength shift with temperature of only  $0.07 \text{ nm}/^\circ\text{C}$ , which is a fivefold reduction over traditional pump diodes. Reduced temperature dependence also eases the demands on the system cooling required to maintain pump wavelength over a system's typical range of operating temperatures and output powers.

Although all these improvements will help towards the eventual realization of a laser-based weapon, there is still work to do. The industry is now much closer to the 80% SHEDS target following the hikes in efficiency delivered by all three diode manufacturers, but further improvements will not be easy as they will require radical changes to the device structure.

Users of high-power laser diodes already benefit from the techniques developed in the SHEDS program through the boost in laser efficiency in commercial products. As these techniques permeate to other types of semiconductor laser this may lead to additional laser products with SHEDS-like efficiencies, including surface emitting designs and quantum-dot devices.



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## HVPE

# Hybrid reactor speeds up AlN growth

A Japanese partnership claims that the higher temperature capability of its hybrid HVPE reactor enables an increase in the growth rate used to produce high-quality material.

The faster growth rate produced by the partnership between Tokuyama Corporation and Tokyo University of Agriculture and Technology has resulted from the use of a modified HVPE reactor that is capable of higher growth temperatures.

Fabrication at these high growth rates is commercially important because it promises increased throughput of crystalline AlN, which cannot be made by traditional methods. Free-standing AlN substrates are already in demand for the production of deep ultraviolet emitters and high-power electronic devices.

The team's free-standing wafer was grown at 1230 °C in a hybrid HVPE tool that comprises an atmospheric pressure hot-wall quartz reactor, an electric furnace and an additional resistance-heating susceptor.

The only other report of producing a



**A modified HVPE reactor** can increase the growth rate for producing high-quality films.

free-standing AlN substrate using silicon involved a reactor temperature that was limited to growth temperatures below 1200 °C to prevent thermal deformation of quartz glass. At this lower temperature, lower growth rates are needed to produce AlN with the equivalent crystal quality.

To produce the (0001) AlN substrate, the researchers placed a 5 mm × 5 mm piece of silicon with a chemically cleaned surface into the modified HVPE reactor and deposited an AlN nucleation layer at 1140 °C. The

temperature was then increased to 1230 °C, before a 112 μm thick film was added. Chemical etching then separated the AlN layer from the silicon platform.

The resulting AlN film is quite uniform, say the researchers, with a smooth surface which is free of cracks but has a few pits.

The average dislocation density for the film's surface is  $3 \times 10^9 \text{ cm}^{-2}$ . This figure is higher than that for AlN substrates prepared by growth on SiC. "However, the ease of removal of the silicon substrate and the reproducibility of AlN substrate preparation are very attractive," remarked team-member Yoshinao Kumagai.

Kumagai says that the defect density of the free-standing AlN substrates needs to be reduced to  $10^6 \text{ cm}^{-2}$  for commercial device fabrication, a goal that the team is working towards through process optimization.



#### Journal reference

YKumagai *et al.* 2007 *Jap. J. Appl. Phys.* **46** L389.

## SOLAR CELLS

# Strain-balanced cell promises multi-junction boost

Taiwanese researchers at National Cheng Kung University and the Institute of Nuclear Energy Research have built a strain-balanced GaAsN/InGaAs solar cell that could boost the performance of multi-junction devices.

These improvements would result from stronger absorption at longer wavelengths, which could be produced by inserting the strain-balanced cell between GaAs and germanium layers in traditional triple-junction GaInP/GaAs/germanium structures.

The team's single-junction cell, which was grown by low-pressure MOCVD, has an active area of 0.25 cm<sup>2</sup> and features InGaAs layers with a 15% indium composition. This produces an absorption edge at 1.2 eV, a peak efficiency of over 60%, a total power conversion efficiency of 4.3% and a short-circuit current density of 20.9 mA cm<sup>-2</sup>.

The rival candidate for providing absorption at these wavelengths is InGaNaAs, which yields cells with comparable efficiency. However, the current density in the strain-

balanced device is much higher, according to Yan-Kuin Su, making the Taiwanese team's structure more suitable for incorporation in multi-junction cells.

The researchers now intend to prove their claim by building a multi-junction cell that incorporates strain-balanced GaAsN/InGaAs.



#### Journal reference

P-HWu *et al.* 2007 *Semicond. Sci. Technol.* **22** 549.

## PROCESSING

# Patterned epiwafer improves quality

Epitaxy on a patterned GaN epiwafer can reduce the vertical threading dislocations in the active regions of III-N devices, according to researchers from a US collaboration led by the Naval Research Laboratory in Washington, DC.

Using a process that involved conventional GaN growth on an *a*-plane sapphire substrate, followed by SiO<sub>2</sub> sputtering, a selective oxide lift-off technique and subsequent

GaN growth, the engineers produced a 3 μm thick film with reduced strain and a surface dislocation density of just  $6 \times 10^8 \text{ cm}^{-2}$ .

"We feel this approach is a better utilization of wafer area than the widely applied lateral epitaxial overgrowth technique," remarked team-member Charles Eddy. According to him, the packing density of the growth regions, which currently occupy about half of the wafer's total surface area, can be increased to reduce any "wasted" space between the confined epitaxy openings.

The researchers have also used their growth technique to fabricate an unpassivated p-GaN/n-Al<sub>0.2</sub>Ga<sub>0.8</sub>N heterojunction diode

for ultraviolet detector applications, which had reverse leakage current of  $1 \times 10^7 \text{ A cm}^{-2}$ . Eddy says that this is an improvement of at least two orders of magnitude over similar devices grown directly on sapphire.

He adds that the confined epitaxy technique is well-suited to making ultraviolet emitters, vertical transistors such as BJTs, and distributed power devices that are formed by combining a collection of smaller devices.



#### Journal reference

CEddy *et al.* 2007 *Appl. Phys. Lett.* **90** 162101.



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