COMPOUND SEMICONDUCTOR

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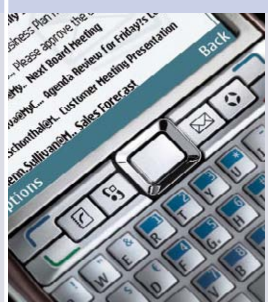

Spanish fever

GaAs grabs the attention as the mobile industry decends on Barcelona. p5

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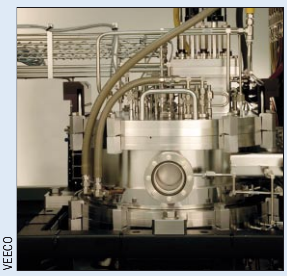
MOTOROLA

Sales success
Chipmaker TriQuint made a quarterly net profit of $6.4 million in the last quarter of 2006, thanks to its new focus on mobile handsets such as Motorola's MOTOKRZR K3. **p6**

TECHNOLOGY



VEECO

A new generation of reactors
Veeco's new reactors are easily upgradeable, so customers will be able to adapt their equipment as their requirements change. **p19**

Main cover image: *Philips Lumileds' Luxeon LED chips already illuminate architectural attractions such as the Clifton Suspension Bridge in Bristol, UK. The latest chip innovations should help Lumileds penetrate more markets, such as residential lighting. See p14. Credit: Martin Griffiths.*

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Perilous predictions

Writing in this column a few months back, I expressed a kind of national pride in the apparent renaissance of the UK's compound semiconductor industry. Well, that turned out to be a little bit presumptuous of me.

While the epiwafer foundry company IQE has continued to grow and now looks like a real global force, the news from the UK's two biggest III-V chip fabs has been disappointing to say the very least. Just last summer, Filtronic's GaAs fab in the north of England looked set for a massive expansion after the parent company sold off its wireless-infrastructure business unit to Powerwave Technologies in a deal worth $345 million.

That deal has since gone through, but after what appears to have been a huge misjudgment by Filtronic's management, plans to expand GaAs production have been largely shelved. The fact that the company has had to fork out an extraordinary £7 million ($13.6 million) simply on cancellation charges for equipment that it ordered mistakenly is nothing short of astonishing.

"Surely Filtronic's executives should be facing the chop"

Although it claims to have a number of volume customers, it seems likely that Filtronic has been unable to find any major foundry business aside from the PHEMT switch products that it manufactures for US giant RF Micro Devices. Thankfully, that deal does not appear to be in any jeopardy, despite RFMD's own GaAs capacity expansion. At the recent 3GSM World Congress in Barcelona, representatives from the US company confirmed that the supply deal with Filtronic remained a critical part of RFMD's future plans.

Meanwhile, Bookham's historic Caswell III-V fab in central England is set for more enforced changes, as the 2 inch InP line is finally closed down for good and employees are re-housed into fewer buildings in a bid to cut costs.

Time has also run out for Bookham CEO Giorgio Anania, who left the company on February 15 with immediate effect. While he can be credited with keeping Bookham going over such a difficult period, Anania's predictions of a profitable Bookham have never come close to fruition. Surely Filtronic's executives should also be facing the chop after making similarly gross miscalculations.

Michael Hatcher *Editor*

Advertisers' Index

Optoelectronic Device Yield

By Frank Burkeen

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

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

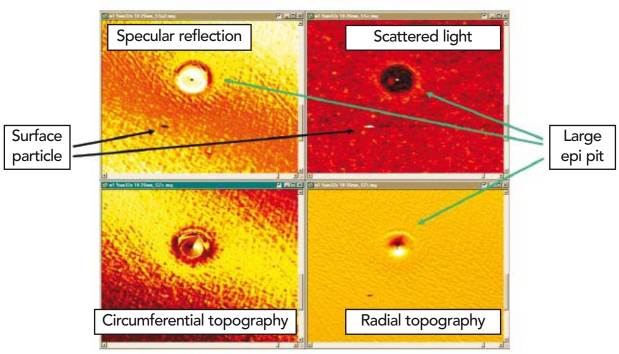

Figure 1: Defect images from four OSA signal types from a sapphire wafer with GaN epitaxial layers.

HB-LEDs

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

POWER DEVICES

Some SiC-based power device manufacturers rely on manual microscope inspection with the process being very time consuming and not capable of finding all critical defects. OSA can be used to detect and classify defects in SiC substrates and epi layers automatically. As an example, the surface of GaN HEMT wafer contains an AlN buffer layer, a GaN layer, and an AlNGaN surface layer grown on a SiC substrate. Inspection can be performed in various stages of the manufacturing process of these devices. Fig. 2 shows a micropipe defect and a crystal defect commonly called a triangle defect, which only appears in topography signals. Micropipes appear as elongated defects in OSA images, making them easy to detect and classify.

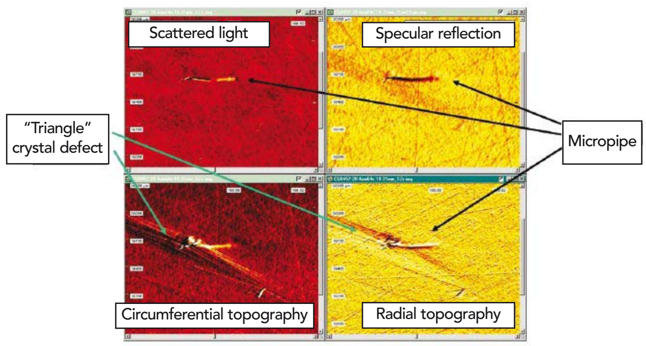

Figure 2: Defect images from four OSA signal types from a SiC wafer.

MICRODISPLAY

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

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

GaAs ICs

Chip makers focus on mobile strategies

By Michael Hatcher in Barcelona, Spain

As the global wireless communications industry descended on Barcelona in mid-February, leading GaAs chip manufacturers, including RF Micro Devices, Skyworks, TriQuint, Anadigics and Freescale, rolled out a welter of new chips, modules and strategies to meet the needs of mobile phone and wireless infrastructure companies.

Much of the talk among the estimated 55,000 delegates at the 3GSM World Congress was of the emergence of WiMAX and how it may or may not fit into the broadband wireless networks of the future. While many major global forces, such as Sprint, Intel, Motorola and Samsung, are putting their weight behind the protocol, other key players such as Vodafone believe that the technology is no real threat to the third-generation cellular networks on which they have spent billions.

Doubts over when and where WiMAX may end up being deployed are not much help to developers of GaAs-based RF devices. While Anadigics rolled out a new power amplifier for mobile WiMAX, all are taking an agnostic approach, saying that "the jury is still out". Something that all of the GaAs companies do agree on is that whichever wireless communication standards come to dominate the airwaves of the future, lots of GaAs chips will be required.

TriQuint's vice-president of handsets Tim Dunn says that with up to 11 individual frequency bands now requiring support, he is less concerned about the potential threat of CMOS-based power amplifiers than in previous years. "Wideband-CDMA and WiMAX require lots of RF content," said Dunn, adding that GaAs wafer volumes had more than doubled over the past two years as TriQuint has increased its focus on mobile handsets.

Advanced handsets, such as this new wideband-CDMA and Wi-Fi enabled E61i for business applications from Nokia, demand more complex RF technology and higher GaAs content than regular handsets.

The major challenge for GaAs chip makers right now is to meet the volume and performance requirements of wideband-CDMA. Now with more than 100 million subscribers (according to the latest figures from analysts at ABI Research), wideband-CDMA is the fastest-growing mobile handset technology, and it demands high-performance RF front-ends.

Skyworks' marketing director for mobile platforms Thomas Richter sees WiMAX as a technology that is still a long way off. In the shorter term, wideband-CDMA is his main focus. Richter says that a steady reduction in the size of the GaAs die used in front-end modules means that demand for GaAs material would only be strong enough to drive a slight increase in overall wafer volumes. "We have no major requirements to invest [in extra capacity]," he said.

For RFMD, the key trends are the uptake of wideband-CDMA, multi-region handsets and the integration of Wi-Fi capability into mobile phones. Duncan Pilgrim, who works in strategic marketing of cellular products at the US firm, estimates that around 17 million Wi-Fi-enabled handsets will ship globally in 2007, up from only 5 million in 2006. The extra complexity that this adds to the handset front-end means that more GaAs content is required in each phone.

Regarding WiMAX, Pilgrim said, "It is still extremely unclear what will happen." He added that RFMD was adopting a "wait-and-see attitude" and working on power amplifier products that may be required.

EPITAXY

Veeco CEO predicts 2007 boom in MOCVD market

With the company's sales of MOCVD equipment continuing to gather momentum, Veeco Instruments' chief executive officer Ed Braun says that the end of 2007 could mark a major scale-up in HB-LED chip capacity to meet anticipated demand from makers of large LCD screens.

Braun, who believes that the market opportunity for Veeco in the high-brightness LED business is still in its infancy, says that the company sold $89 million worth of MOCVD and MBE equipment during 2006, compared with $63 million in 2005.

The bulk of those sales came from makers of HB-LED chips based in Taiwan, Korea and China, and that trend is set to continue this year with the introduction of more large LCD screens featuring LED backlight units.

"Customers in Taiwan are buying two or three [MOCVD reactors] at a time to sample LEDs for LCD backlights," Braun told investors in a conference call to discuss the latest company results. "By the end of 2007, they are going to need 10 or 15 MOCVD tools at a time."

Although the market for large-size LED backlights in LCD monitors and TVs has yet to take off completely, big-name brands, such as Apple, Hewlett-Packard and Samsung in particular, have recently decided to design the technology into their notebook computer displays. TV applications, which require more LEDs and a higher-quality color reproduction, are expected to follow this trend from 2008 onwards.

Veeco anticipates that the need for new MOCVD tools to meet the growing demand for higher-quality chip production will help drive sales of epitaxy equipment to $115 million this year, and at a compound annual growth rate of nearly 30% thereafter.

WIDE-BANDGAP MATERIALS

RFMD wins order for GaN power amplifiers

A "top-tier" supplier of military equipment has placed the first purchase order with RF Micro Devices (RFMD) for its new range of GaN power amplifiers (PAs). The unspecified customer has ordered the chip manufacturer's RF3825 PAs, 15 W devices, which operate between 200 MHz and 1.9 GHz.

Based on a 3 inch GaN HEMT process and using SiC substrates, the new transistor technology offers a much broader bandwidth for wireless communications than GaAs or silicon LDMOS approaches. Material and device development has been funded largely by the US military community for applications such as long-distance radar and electronic-signal jamming.

RFMD believes that applications should spread beyond the military sphere to public mobile radio, WiMAX and wideband-CDMA infrastructure, and that the combined revenue opportunity presented by these markets is in the region of $1 billion.

Last year, RFMD switched part of its depreciated 4 inch GaAs manufacturing facility in Greensboro, NC, into a 3 inch GaN fab to support the new product roll-out. With more powerful products in the pipeline, including a 200 W GaN PA, the company is hoping that it can revolutionize wireless communications with GaN HEMTs in much the same way that it did with GaAs HBTs around 10 years ago.

POWER ELECTRONICS

Zero-micropipe wafers prompt Schottky ramp

SiC chip manufacturer Cree says that it is now shipping a high-power SiC Schottky rectifier that improves transmission efficiency across an electrical grid.

Rated at 50 A and 1200 V, the rectifier can be used in so-called inverter modules that convert the direct-current electricity generated by renewable sources (such as wind turbines and solar cells) into an alternating current. These inverters traditionally use silicon-based diodes, which operate at 90–96% efficiency. However, Cree says that this can be improved to up to 98% by using SiC-based devices instead.

If deployed widely over a power network, this slightly better performance has the potential to slash overall electricity transmission losses, creating a far more energy-efficient grid. Motor-drives and electric vehicles could also benefit from the SiC-based rectifiers, which have the added benefits of eliminating the need for "snubber" components, enabling cooler operating temperatures (because of their higher efficiency) and producing less electromagnetic interference than a silicon equivalent.

Thanks to recent advances in SiC material quality, the new rectifiers can deal with higher power levels than any products previously released by Cree. At 8.2 × 4 mm, the die-size is the largest in the SiC industry.

John Palmour, Cree's executive vice-president for advanced devices, says that the large-die rectifier is a direct result of improvements made within the past year: "Fundamental to these advances are very-low-defect density substrates, including zero-micropipe SiC substrates."

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Anadigics breaks even

Recovery continues at GaAs component maker Anadigics. The Warren, NJ, firm broke even on sales of $49.1 million in the final quarter of 2006, an increase of 10% on the previous quarter, and an increase of 48% compared with last year. The company is benefiting from increased sales of components for high-end mobile applications such as wideband-CDMA.

Streamlined Skyworks posts profit

GaAs chip and component manufacturer Skyworks Solutions posted sales of $196 million for the quarter ended December 29, 2006. The Woburn, MA, firm recently restructured to focus on analog and RF products. Skyworks also registered a net profit of $21.4 million – a new record – before taking into account restructuring and other one-time charges.

IXYS targets medical imaging

Microwave Technology (MwT), the GaAs manufacturing subsidiary of US-based IXYS Corporation, is releasing a line of high-performance pre-amplifiers ideal for use in magnetic resonance imaging (MRI) scanners. The low-noise amplifiers operate at between 43 and 27 MHz, and dissipate only half the heat of conventional pre-amps.

MOBILE HANDSETS

Samsung penetration boosts TriQuint's profit

Oregon-based TriQuint Semiconductor posted sales of $114.3 million in its final fiscal quarter of 2006, which ended on December 31. Not only did that represent an impressive 35% increase compared with the equivalent quarter in the previous year, but it also propelled the GaAs chip manufacturer to a quarterly net profit of $6.4 million.

The firm, which runs a 6 inch wafer fab in Hillsboro, OR, and a 4 inch facility in Richardson, TX, identified its increased focus on the mobile handset market as the key reason for its improved performance.


MOTOROLA

Designed in: some of Motorola's latest big-selling phones, such as the MOTOKRZR K3 pictured, now feature TriQuint's GaAs transistor technology.

CEO Ralph Quinsey said, "TriQuint's design-win success in 2006 placed us in approximately 97 new phone models, and we estimate [our] share in the handset market has grown to around 8–9%."

The market traction, which includes design wins at some of the world's top-ranking handset vendors, resulted in TriQuint shipping 43 million transmit modules during 2006 – compared with only 5 million the year before.

Tim Dunn, the vice-president of TriQuint's handset business unit, attributed much of the recent success to top customer Samsung. The Korean firm is using TriQuint products in many of its best-selling dual-band and quad-band GSM phones, while Motorola's popular RAZR phones also feature TriQuint components.

The company's technology portfolio is largely based on GaAs HBT and PHEMT transistors that are used in handset-switch and power-amplifier components. TriQuint has also developed a new flip-chip design for some of its latest products, which it intends to roll out across much of its portfolio.

For the full fiscal year, TriQuint sales just topped $400 million, and the company turned a pre-tax profit of $25.2 million. After accounting for stock-compensation expenses, that profit figure dropped to $22.4 million. In 2005, it had made a $7.8 million net loss on sales of only $295 million.

CHIP DEVELOPMENT

Lumileds brightens white LEDs

Breakthroughs in epitaxy, packaging, device physics and phosphors are behind a new record-breaking white-LED chip developed by Philips Lumileds.

The San Jose, CA, company reports that its 1 mm^2 power chip produced 136 lm when driven at 350 mA and 502 lm at 2 A. This equates to luminous efficacies of 115 lm/W at 350 mA and 61 lm/W at the higher drive current.

The high currents are significant – most recent claims of breakthroughs in LED efficacy have typically involved smaller, 20 mA chips. However, the larger "power" chips are the ones that will be required for important applications such as car headlights and general lighting in the home. These power chips tend to suffer from "efficacy droop" at a high drive current.

Another key aspect of the Lumileds claim is the color temperature of 4685 K. Relatively low for a high-efficacy LED chip, this figure indicates that the white color emitted is closer to the quality of light that is desirable inside the home.

In December, Korea's Seoul Semiconductor claimed to have developed a single-chip 100 lm/W white LED operating at 350 mA and delivering 240 lm. The first commercial versions of Seoul's chips produce a relatively harsh white light rated at 6500 K, although the company indicated to *Compound Semiconductor* that similar devices with color temperatures as low as 2800 K were also in development.

According to Lumileds, the first of its commercial products to incorporate some of the enhanced device designs will be released before the end of March 2007, with many others set to follow over the next 18 months.

● Lumileds now also claims to have solved the "efficacy droop" problem, although it provided no details about how this has been achieved. Lumileds did say that its new epitaxial technology will enable the first high-power LEDs that deliver 70 lm/W or more at drive currents of 1 A and above, and that it plans to introduce the technology into its Luxeon LEDs this year.

See Lumileds feature on page 14 of this issue for more details.

WAFER FABRICATION

Cree qualifies first 4 inch LED process

SiC and GaN chip manufacturer Cree says it has qualified 4 inch wafer processes for both LED and Schottky-diode fabrication for the first time. In an investor conference call to discuss its second-quarter 2007 results, Cree CEO Chuck Swoboda said the switch to the larger format would help with production yields of large-area die typically needed for very-high-brightness or "power" LED chips. This is because the "edge" effects that affect wafer yields become much less significant as the wafer manufacturing size is scaled up from 3 to 4 inches.

Cree plans to switch a small amount of its LED and Schottky-diode production to a 4 inch line in the current quarter. In the near term, however, Cree faces a greater challenge, as declining demand and selling prices hit both its revenue figures and, because of the resulting low fab use, its profitability.

For the three months leading up to December 24, 2006, Cree posted total sales of $88.8 million – down 16% compared with the same quarter in 2005. The main reason for this was a sharp slowdown in sales of the mid-brightness LED chips, which are typically used in the backlights of mobile-handset keypads. At $65.5 million, LED chip revenue dropped by more than 21% sequentially.

Although this application remains Cree's biggest sales driver, the Durham, NC, company is exposed to fluctuations in demand and the intense competition with LED manufacturers in Taiwan that has driven prices down in recent quarters.

Slack demand in the latest quarter meant that unit shipments of LED chips were down 15% sequentially. That lack of demand has also affected other suppliers and intensified the downward pressure on prices. The average selling price of Cree's LEDs dropped 28% over the past year.

As a result of the low demand, Cree has reduced its wafer-fab use, which has had a negative impact on its overall profit margins. "We slowed the factory down a lot," Swoboda admitted. Cree posted an operating profit of $3.1 million in the quarter; however, when its fab was much fuller a year ago, the equivalent figure was $26.5 million.

Although the move toward 4 inch wafer production will not help to improve fab use in the short term, the yield benefits of this switch for manufacturing powerful large-area chips should come to bear once new LED applications, such as LCD backlighting, automotive headlights and general lighting, begin to take off.

EPITAXY EQUIPMENT

Aixtron cashes in on Genesis Photonics' HB-LED project

Genesis Photonics, the Taiwanese LED epi-wafer and chip manufacturer, has ordered six more MOCVD reactors from Aixtron subsidiary Thomas Swan. Part of a long-term purchase agreement, the capacity expansion is evidence of a move by the company to target LCD backlighting applications for high-brightness LEDs.

Founded in 2002, and with more than 36,300 ft^2 of floor space, Genesis Photonics has been described as the fastest-growing LED manufacturer in Taiwan. "With this boost for our MOCVD production, Genesis will be in an excellent position to become one of the top suppliers for the LCD backlighting market," said CEO David Chung.

Display backlighting applications in handheld computers and mobile devices already represent around half of the total market for HB-LEDs. But, while unit shipments are continuing to grow quickly, selling prices of the chips are dropping just as rapidly, limiting the size of this application market to around $2 billion per year.

Meanwhile, HB-LED applications in much larger LCD display backlight units, such as notebook and desktop PCs, and high-definition televisions, are expected to grow strongly over the next five years.

Market reports from DisplaySearch and iSuppli both suggest that of the 450 million or so LCD panels expected to ship in 2009, around 2.5–3%, or 11–12 million, will feature backlight units based on HB-LEDs. *See market report on page 12 for more details.*

AUDI

Audi's R8 sports car and the new 2008 LS 600h L from luxury car maker Lexus will both contain headlights based on high-brightness LEDs when launched this year. Although LED-based headlights have been in development for many years, until now they have only been seen in concept cars or in the daytime running light function.

The new Lexus will employ HB-LEDs in the low-beam, while the Audi R8 will be the first production vehicle to feature semiconductor light sources in every headlight function when it is launched in late 2007. Audi will sell the LED headlight as an optional extra that aids night-time driving by providing a light source with a color temperature as close to daylight as possible. That, says the German company, will help to reduce driver fatigue.

Regulatory clearance for LED-based headlights has thus far only been gained in the US market. In Europe and Japan, these regulatory hurdles are expected to be cleared in 2008.

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Nichia upgrades UV LED portfolio

Nichia has released a 365 nm LED that it claims is the most powerful UV-emitting chip on the market. The device, which has a typical output of 250 mW and an emission profile similar to the "i-line" of a mercury lamp, is aimed at curing and photo-catalyst applications. The latest device complements Nichia's UV LED portfolio, which includes a 100 mW chip that emits at 365 nm.

LED rival to 65 W bulb

LED Lighting Fixtures (LLF) has launched what it describes as the first affordable lighting fixture powered by semiconductor emitters that is able to rival the output, appearance and lighting quality of a 65 W bulb. The recessed down light, which is the company's first product, uses Cree XR-E power chips to deliver around 650 lm from an electrical input power of only 10–12 W.

Vishay launches InGaN chips

Osram licensee Vishay Intertechnology, one of the world's biggest makers of discrete semiconductors, has launched a line of InGaN-on-sapphire white LEDs. The surface-mounted devices offer a light output of up to 355 mcd for a very low price, and are aimed at generic illumination applications.

FIBER-OPTIC COMPONENTS

CyOptics scores a $10 m home run with laser-chip business

CyOptics, an optoelectronic-chip foundry based in Lehigh Valley, PA, shipped more than 1 million InP-based lasers and photodiodes for fiber-to-the-home (FTTH) deployment in 2006.

The company says that use of the chips in gigabit passive optical networks (GPONs) is being driven by "explosive" demand from individual businesses and homes for these very-high-bandwidth connections.

The specific products made by CyOptics for the GPON applications include 1310 and 1490 nm distributed-feedback (DFB) lasers, and avalanche photodiodes, all of which are used in optical line terminals (OLTs) and optical networking units (ONUs).

According to market analysts Ovum-RHK, the rapid growth of this niche is set to continue. "GPON is the fastest-growing portion of the [wider] PON market now, and this rate will be sustained," explained Karen Liu, research director for components at the company. "Ovum expects both ONU and OLT shipments [for GPON] to more than double each year through 2011."

Ali Abouzari, vice-president of sales at CyOptics, told *Compound Semiconductor* that the company has a stranglehold on the market for GPON laser and detector chips, with a current estimated market share of more than 90%. He estimates that business from this particular application is worth more than $10 million annually.

CyOptics has enough capacity at its chip facility to meet current needs, but Abouzari says that there is still downward pressure on component prices as the volumes continue to increase. "Average selling prices are falling significantly," he said.

Japan and Korea are two of the biggest existing markets for FTTH deployments, but with carriers in the US such as Verizon now beginning to implement their plans for widespread FTTH deployment, CyOptics is in an excellent position to capitalize on an emerging domestic market.

COMPANY FINANCE

Abandoned acquisition costs Avanex $2 m

Although still making a hefty loss at the operating level, US optical-component and chip producer Avanex posted a big increase in sales revenue for its latest financial quarter. At $55.6 million, revenue for the three months that ended on December 31, 2006 came in 54% higher than the equivalent period of the previous year.

Despite the improving picture for revenue, Avanex still made a net loss of $8.6 million, according to the standard accounting treatment. But that figure was certainly not helped by a mysterious exceptional charge for $2.1 million listed in the report of the Fremont, CA, company.

In an entry buried deep in the company's statement of operations, Avanex revealed that its net loss for the latest quarter included these significant costs, and attributed them to "due-diligence expenses related to abandoned acquisition activity".

Exactly what aborted acquisition that cost refers to is not made clear, although in late 2006 rumors of a forthcoming merger between Avanex and Bookham, fellow chip-fab owner and San Jose neighbor, were rife. Whether or not the abandoned deal referred to Bookham, Avanex could have done without the extra expense. The company would have posted a net loss of $6.5 million if the acquisition had not been on the agenda.

On a more positive note, Avanex CEO Jo Major said that despite a short-term flattening of metro and long-haul markets for its optical components, the second half of 2007 should herald a return to growth.

With $37.4 million in cash reserves listed on its balance sheet, Avanex is taking measures to reduce its rate of cash burn, including making an attempt to improve manufacturing yields. In the last financial quarter, Avanex also cashed in some of its short-term investments to bolster its overall cash position.

● Avanex has released a new type of laser chip that is designed specifically to meet the needs for low-cost implementation of fiber-to-the-home services. The 1310 nm component is the first laser chip to integrate a spot-size converter with special features for automated alignment. This integration allows Avanex's customers to use low-cost passive assembly processes on their manufacturing lines.

UK WAFER FABS AND FOUNDRIES

Mixed fortunes for UK compound effort

Stock performance of UK compound semiconductor operations

Company	Ticker	Exchange	Feb 17, 2006	Feb 14, 2007	Year-on-year
Bookham	BKHM	NASDAQ	$7.32	$2.52	−66%
Filtronic	FTC	FTSE (London)	184.75 p	159.50 p	−14%
IQE	IQE	AIM (London)	11.00 p	18.50 p	+68%

LONDON STOCK EXCHANGE/YAHOO FINANCE

Although epiwafer foundry IQE is returning to financial health, the UK's two biggest compound semiconductor chip facilities are still struggling to make ends meet. **Michael Hatcher** evaluates their performance.

For a country that has such a strong tradition of innovation and some of the world's leading universities, commercial compound semiconductor facilities are thin on the ground in the UK.

Manufacturing is now largely banished to low-cost sites in the Far East, and the only major influences on the global III-V stage are the epiwafer foundry IQE and the chip fabs owned by Filtronic and Bookham, with Bookham based in California. These three are complemented by a smattering of equipment and materials firms like Oxford Instruments Plasma Technology and EpiChem (now owned by Sigma-Aldrich), and smaller fab operators such as the Centre for Integrated Photonics, Intense Photonics and CST Global.

For the publicly listed IQE, Bookham and Filtronic, the past couple of years have been tough. But trends in these three companies' individual share prices over the past year reveal a different story in each case. Things are looking up for IQE, but problems seem to be mounting for Bookham and Filtronic.

Investors have responded positively to IQE's global-expansion strategy. Since February 2006, the firm's stock price has risen steadily from 11 p (20 ¢), peaking at 20 p early this year, before settling back to just over 18.50 p at the time of writing – easily outperforming both the AIM index on which it is listed and the electronics sector.

In addition to acquiring Emcore's electronic materials division in New Jersey and Singapore's MBE Technology over the past year, IQE has steadied its core business, and demand across all sectors is looking strong. It now has a global presence and can multi-source certain products if required, and has access to some key new technologies – in particular GaN HEMT and BiFET epiwafers. In its latest trading update, IQE said that its future BiFET products should prove beneficial to sales revenue later this year.

Next to IQE, Filtronic's share-price performance has looked extremely volatile. Valued at £1.85 a year ago, the stock has endured a series of peaks and troughs in what has been a tumultuous 12 months for shareholders of the GaAs RF chipmaker.

Filtronic's stock price peaked at over £2.29 in early July 2006, shortly after executives revealed plans to sell off the largest part of the business – its wireless-infrastructure division. But that boost was short-lived, and the stock soon tumbled back below £1.80. After a late summer recovery, the sale of the infrastructure unit to US-based Powerwave appeared to spark another slump, and was followed by a change in CEO, as founder David Rhodes retired and CFO Charles Hindson moved into the corner office.

Since last summer, Filtronic has been forced to scale back its anticipated ramp of GaAs PHEMT switches because of a huge overestimate of demand. Unfortunately, that miscalculation has come at a big cost – Filtronic had already ordered lots of chip manufacturing equipment that it does not now need, resulting in contract-cancellation charges of £7 million.

Those charges knocked all the shine off of Filtronic's latest trading statement. For the six months leading up to November 30, 2006, the firm's compound semiconductor division enjoyed a strong increase in sales revenue to £15 million, compared with only £8.5 million for the same period in the previous year.

At first glance, the division's underlying operating loss also looked to be much improved – cut from nearly £5 million one year ago to just £1.5 million in the last six months. But when the equipment cancellation charges were added, that operating loss swelled to £8.5 million.

Filtronic still appears to be heavily reliant on RF Micro Devices (RFMD), which has significantly increased its own in-house production of PHEMT switches in recent months. The good news for Filtronic is that RFMD will continue to source PHEMTs from the UK foundry, as it works to keep up with strong demand from companies like Nokia.

However, Filtronic chairman John Poulter now says that lower-than-expected demand for its compound semiconductor devices will continue for the first half of 2007 at least, with no likely growth in revenue. "This is not an acceptable situation, and [the Filtronic board] will be pursuing further measures in the coming months," concluded Poulter.

While Filtronic executives will now be facing some tough choices, the company appears to be in better shape than Bookham. Bookham's latest trading update had a depressingly familiar ring to it, and recent cutbacks include the total shutdown of its 2 inch InP line in Caswell, and of development facilities in Ottawa. Company executives say that the cutbacks will save Bookham $6–7 million each quarter. While that estimate seems to bode well for Bookham, it still may not be enough to make the company profitable.

A year ago, Bookham's NASDAQ-listed stock price boomed suddenly to a long-time high of $9.50 on the back of a generally resurgent market for optical telecommunication components. But that price was short-lived, and the stock has mostly hovered between $2.00 and $4.00 since that time. Needham & Company is maintaining a "buy" rating on Bookham, although even it has become more pessimistic, reducing its target price from $6.00 to $4.00. Considering Bookham's apparent abandonment of a merger with Avanex, which could have created a stronger company, even a $4.00 stock price is now looking wishful.

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

LED BACKLIGHT UNITS

Backlight boom divides analyst opinion

Representing only a small niche in the market for large LCD displays, sales of LED-based backlight units will nevertheless grow rapidly between now and 2009. But the likely value of this emerging sector for LED manufacturers is a tough one to call. Michael Hatcher reviews the forecasts.

The backlight unit in large LCD screens (defined as more than 10 inches across the diagonal) is expected to be the next major application where high-brightness (HB) LEDs will take over from more traditional forms of illumination. Almost all of these large LCD screens are illuminated by cold-cathode fluorescent lamps (CCFLs), but using HB-LEDs should allow thinner, more energy-efficient TVs and monitors, with the added bonus of improved color reproduction. That's the theory, anyway.

Many makers of HB-LEDs are now scaling up production capacity in the belief that the emerging market will mimic that of small LCD screens. Driven largely by cellular handsets, small LCD screens became the first killer application of HB-LEDs, and now represent approximately half of the $4 billion annual market for such chips. With around 300 million large LCD screens now being manufactured every year, and the backlight unit accounting for up to one-third of the total component cost in larger displays, there is undoubtedly a major market opportunity staring makers of HB-LED chips and backlight units in the face.

So far, the switch from traditional technologies to LED backlighting has been very slow to take off. Only a handful of products – most of which are modestly sized handheld and notebook PC displays – feature LED backlight units. In fact, according to the latest report and forecast by market analyst DisplaySearch, only 1 million LED backlight units for large LCD screens are thought to have been sold in 2006 (0.4% of the 277 million estimated to have shipped in the year).

In what it describes as a "conservative" outlook, DisplaySearch says that shipments of LED backlight units for LCD televisions and PC monitors will triple to nearly 3 million in 2007 (see figure 1). But that fast-growing slice will still represent only 0.9% of the available market of more than 300 million LCD displays.

Steve Jurichich, DisplaySearch's director of display technology, estimates that shipments of LED backlight units will increase to 8 million in 2008 (2.1% penetration) and 12 million in 2009 (2.8%). Although this is undoubtedly rapid growth, it is nothing like the market penetration that LEDs have enjoyed in mobile-phone handsets over the past decade or so.

The simple reason for this, as always, can be reduced to cost and performance. Whereas just a few very cheap chips are enough to light up a mobile-handset screen, hundreds are needed to illuminate TVs of the size being purchased by today's consumers, and demands on the illumination quality are far more stringent than for a simple phone.

According to Jurichich, the key reason behind the relatively conservative DisplaySearch forecast for LED backlight penetration is that there is still a great deal of uncertainty over the merits of the new technology, when its cost to manufacturers of LCD TVs and monitors is taken into account. Part of the problem is that for TV applications, LED backlights have been incorporated primarily into very-high-end models – and without much success.

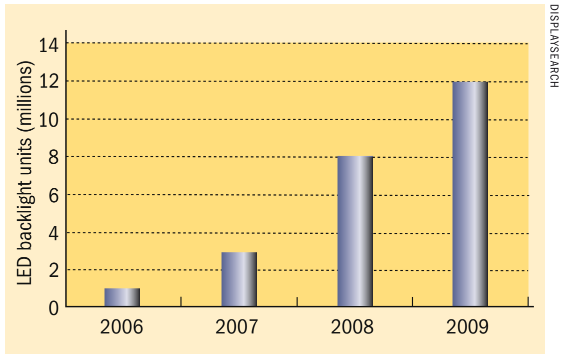


Fig. 1. As the cost–performance ratio of HB-LEDs continues to advance, so too does the market penetration of LED backlights. Last year, only 0.4% of large LCD panels featured LED backlights, but this is set to reach 2.8% (12 million units) in 2009.

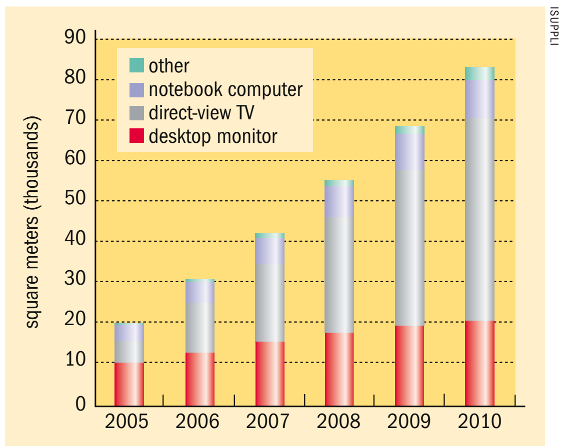


Fig. 2. As unit shipments of LCD panels increase to 500 million in 2010, TV applications will be the main growth driver for LED backlights, according to research by iSuppli. This is because the total area of LCD panels will be dominated by TVs, which are much larger than PC screens, and the number of LED chips required increases along with the area of the display.

Learning from Sony's mistakes

"The Sony experience has made [LCD TV makers] much more conservative," Jurichich said, referring to the Japanese company's failed attempt to lure early adopters to buy the $13,000 LED-backlit Qualia TV that it launched in 2004. "Those sets were ahead of the 'curve', and with 450 individual LEDs required in each backlight, they were also very expensive."

So, is rapid adoption likely? For that to be the case, the advantages of LEDs would have to be significant. In mobile handsets, two key factors that made LEDs the technology of choice were the desire of designers to make smaller, slimline phones; and the better light-conversion efficiency of semiconductor technology, which translated directly to a longer battery life. While notebooks and handheld PCs undoubtedly benefit from weighing less and having a longer battery life, these factors are of little use in large LCD screens. Desktop PC monitors and televisions are plugged into wall sockets rather than being battery-operated, and although LEDs might enable slightly thinner displays, the impact would be minimal compared with that created by HB-LEDs in mobiles.

Analysts at iSuppli are in the business of predicting the LED market, and they appear to be much more bullish on the opportunity emerging with large LCD backlights. Like DisplaySearch, iSuppli analyst Paul Semenza estimates that around 300 million large LCDs will ship this year, and that this will increase to around 500 million by 2010 – largely fueled by increased production of LCD TVs (see figure 2).

However, unlike DisplaySearch, Semenza also forecasts the likely value of the large LCD backlight market to LED chip manufacturers. He says that from a standing start in 2006, in which sales of LED backlight units were negligible, the market for LED chips used in large LCD applications will rise exponentially from around $100 million in 2007 to more than $1 billion in 2009.

This year looks like it may be a critical year, with the average selling price of LED backlight units expected to drop by one-third to $200. Even at this price, however, they would remain almost twice as expensive as the incumbent CCFLs.

The DisplaySearch report does not predict the effect large LCD backlights will have on the HB-LED market. This is because DisplaySearch's analysts feel that such a forecast would be reduced to guesswork, considering the number of variables to be factored in. For example, there are a huge number of backlight designs, including many that are custom-built. Larger screens would require brighter chips, with some using RGB sources and others using phosphor-based white LEDs, while the efficacy and price of the chips will continue to change on a regular basis over the next few years as processes and wafer yields are refined.

Market penetration

For LED manufacturers targeting large LCD backlight units, perhaps a more significant and reliable indicator is market penetration into the different LCD applications. The DisplaySearch and iSuppli reports broadly agree on the overall rate of penetration. For 2009, Jurichich from DisplaySearch suggested that 2.8% of all LCD screens will feature LED backlight units, while iSuppli's Semenza quotes 2.5%.

"The penetration is highest in very large (over 40 inch) TV panels: 13%," said Semenza. "But it is below 1% for standard notebooks and monitors. As the 40-plus inch panels will use many LEDs in each backlight unit, the LED value per panel will be $140 on average, compared with about $50 for notebook or monitor panels." Semenza added: "The significant uptick in LED value after 2009 reflects our assumption that penetration will increase significantly to 10% [overall] in 2011."

But, as Jurichich warns, CCFL makers are not standing by idly watching their products become obsolete. They are now developing improved color-rendering technology. "They have raised the bar," Jurichich said.

As a result, developers of LED backlights, which include the likes of Cree, Lumileds and Osram Opto Semiconductors, may have to concentrate on other advantages of solid-state technology. For example, LEDs do not require a large strike voltage to start up. This means that fewer capacitors are needed in the backlight unit.

Another advantage of RGB LEDs over CCFLs is that they can be switched very quickly, and synchronized to deliver a high-quality image without the need for a color filter.

In the longer term, this could be a decisive factor in favor of LEDs because the color filter is the second most expensive part of an LCD TV (after the backlight itself), accounting for 19% of the component costs in a typical 40 inch screen. Though it may be five years before this technology is fully developed, says Jurichich, this advantage could ultimately be the one that sparks widespread market penetration for LEDs.

What really matters

For now, though, the primary focus for LED and LED backlight manufacturers should be on improving the dollars-to-lumen ratio. For a 23 inch TV, a relatively modest improvement in LED efficacy to 60 lm/W would reduce the number of LEDs required in the backlight by around one-third, from 309 to 234. At that level, Jurichich says, the extra cost of the backlight would be much more acceptable to manufacturers and consumers alike.

At a glance: LED backlight units

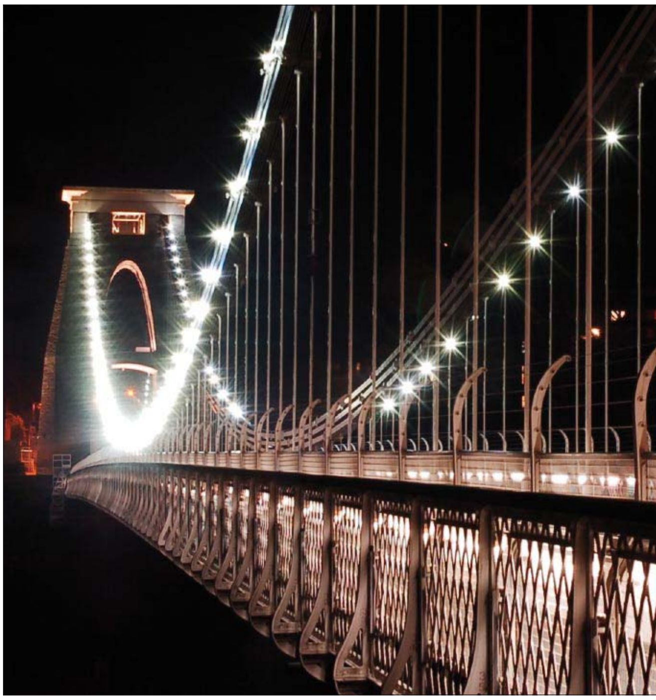
- LED backlights are useful in mobile applications because they drain much less battery power than traditional cold-cathode fluorescent lamp (CCFL) backlights, significantly extending the operating time of a notebook PC when it is used on a long flight, for example.
- Since 2005, notebook PC screens have used LED backlights, including Sony's 11 inch Vaio, Fujitsu-Siemens' 10.6 inch handheld, and Toshiba's Libretto – the first notebook to feature an LED backlight.
- In the TV market, the quality of the colors generated on screen is very important, which means that individual red, green and blue (RGB) emitters are preferable. But for notebook PCs, color rendering is much less of an issue and phosphor-based white emitters deliver adequate color for most applications.
- The color rendering of RGB LED backlights in TV applications is superior to CCFLs and particularly noticeable for red images. This is because the red light emitted by a CCFL is typically much weaker than the blue and green parts of its emission spectrum. However, CCFL makers are developing products with improved color rendering.
- LCD TVs will increasingly dominate the overall LCD market. This is primarily because TVs tend to be much larger than PC screens, and there is a clear trend toward consumers buying larger TVs – as a trip to an electronics store will confirm.
- The number of LED emitters required depends on the size of the LCD panel. iSuppli estimates that 50 phosphor-based white emitters are sufficient for a 17 inch notebook PC screen, but around 450 individual emitters (180 red and green; 90 blue) would be needed for a 46 inch LCD TV.

Further information

DisplaySearch's 832-slide *TFT LCD Materials Report* is available now. See **www.displaysearch.com** for details. iSuppli's Paul Semenza presented details of the company's HB-LED market forecast at Photonics West 2007, held in January.

Evolutionary new chip desig

Philips Lumileds has combined its thin-film structure with a flip-chip design. The result, say **Oleg Shchekin** and **Decai Sun**, is a highly efficient device for lighting applications that delivers a better performance than vertically injected LEDs.



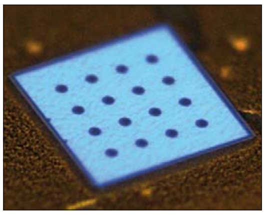
Philips Lumileds' Luxeon LED chips, which incorporate a flip-chip design, al such as the Clifton Suspension Bridge in Bristol, UK, completed in 1864. The a products will take the performance to a new level and help to initiate penetratio

The performance of commercial white-light LEDs has rocketed over the past few months. Competition has fueled the creation of novel device architectures with improved photon-extraction efficiencies, which have in turn increased the chip's brightness and output power. This has opened up the range of applications for these devices, and brought their characteristics more closely in line with the requirements for widespread deployment in solid-state lighting.

Among the many LEDs available today for these applications is an InGaN/GaN flip-chip (FC) design by Philips Lumileds, which features in our company's Luxeon products. We have now built on this success by uniting it with a thin-film (TF) structure to create a higher-performance thin-film flip-chip (TFFC) LED (see figure 1a).

This device combines the manufacturing merits of both approaches, and is produced by taking an FC-LED chip that has an anode and cathode on the same side and bonding it to a submount or package using gold interconnects (see figure 1b). An excimer laser removes the sapphire substrate before photo-electrical-chemical etching of the top GaN layer roughens the chip's surface with an ultraviolet lamp and a dilute potassium hydroxide solution. This texturing disrupts wave-guiding in the high refractive index epitaxial layers, increases light output and dramatically boosts the LED's external quantum efficiency.

The TFFC LED architecture produces excellent device characteristics. We show below that the output power, for example, is higher than that of vertically injected thin-film (VTF) chips (see figure 1c). This design was proposed more than a decade ago and has been implemented recently by several chip manufacturers.



Philips Lumileds' thin-film flip-chip LED technology will start appearing in Luxeon products during the spring.

The problems of vertical structures

The downsides of the VTF design are a consequence of its construction. It is usually produced by depositing a high-reflectivity metal contact onto the p-side of the epiwafer, and then bonding this structure to an intermediate conductive substrate to maintain device integrity throughout the remaining processing and packaging steps. Laser-assisted lift-off removes the sapphire before photoelectrical-chemical etching roughens the exposed GaN surface, and a mesh-like metallic n-contact is added that includes wire bonds.

The resulting structure has two major drawbacks compared with a TFFC design. The first is that the intermediate substrate increases the thermal resistance of the package. It has to be carefully chosen to match the thermal expansion coefficient of GaN, otherwise device failure can occur through thermal cycling. The other weakness of the VTF design is a lower light output. The patterned n-contact reduces the chip's effective emitting area, while the wire bonds obstruct light emission. These wire bonds are particularly irksome in the tightly packed chip arrays used in projection displays and some illumination systems, as they increase the distance from the surface of the LED to the primary optic. The greater distance either increases the size, weight and cost of the optic, or it decreases the system's efficiency (see figure 2). In contrast, our flip-chip architecture permits close packing of LEDs, as electrical connections are removed from the light path.

We have compared the performance of our TFFC LEDs with FC and VTF chips produced from the

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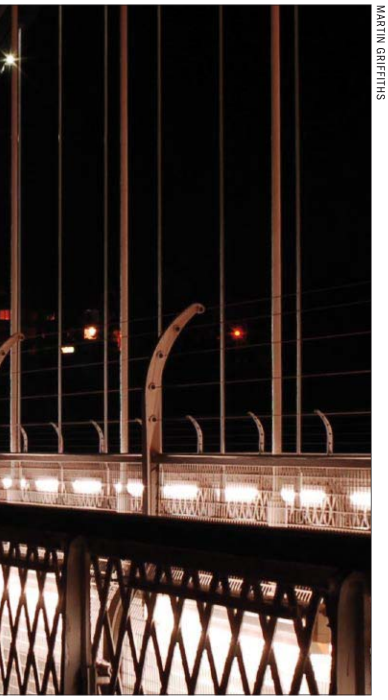

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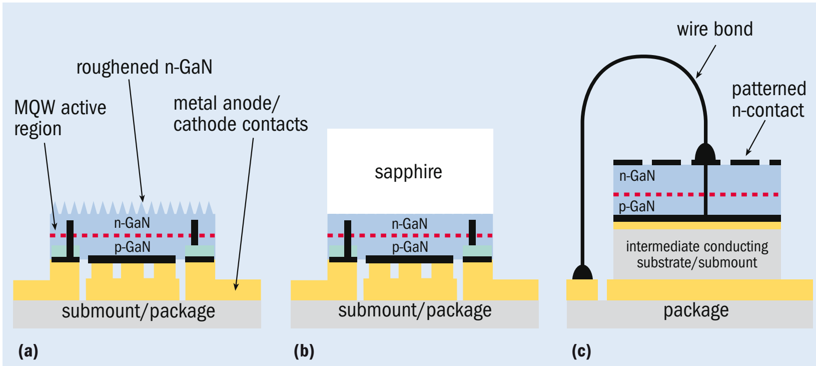


Fig. 1. Philips Lumileds has developed a thin-film flip-chip (TFFC) LED **(a)** that offers better performance than the flip-chip structures **(b)** currently employed in its Luxeon products. The TFFC LED also offers a higher light output and greater efficacies than vertical thin-film chips **(c)**.

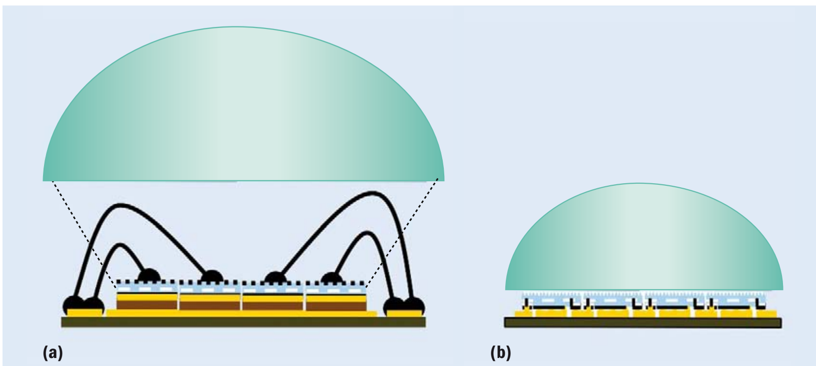


Fig. 2. LED arrays based on vertically injected thin-film (VTF) LEDs require a wire bond for each device **(a)**. These wires block some of the emitted light and force the primary optic that is used in projection displays and illumination systems away from the emitting surface of the LED. Greater light coupling efficiencies are produced with Philips Lumileds' VTTF design **(b)**, which eliminates the loss in light output caused by wires and reduces the distance to the primary optic.

same GaN-on-sapphire epiwafers. Measurements of the best encapsulated blue-emitting 1 mm × 1 mm chips for each type of device reveal that the TFFC structure produces the highest output as expected (see figure 3, p16). At a 1000 mA drive current, the output of the best performing TFFC LED is 46% higher than that of the FC device and 17% higher than the VTF chip.

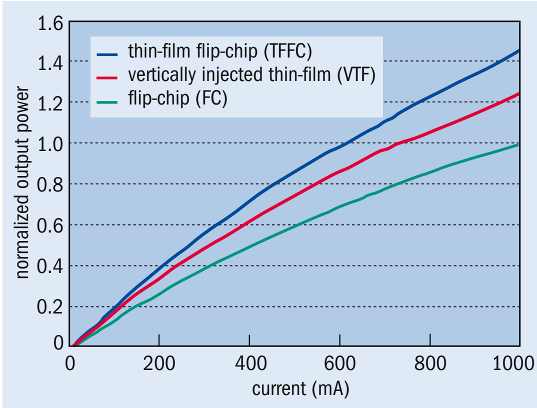
Patterning the top metal contact of the VTF device was not fully optimized in this demonstration, but it is impossible to boost the extraction efficiency and the high-current performance simultaneously. If the dimensions of the top contact are minimized for the greatest light extraction, current crowding increases, which cuts the electrical input power.

The efficacy and light output of our TFFC blue- and white-emitting LED chips at 25 °C and under direct-current conditions are shown in figures 4 and 5 (p16). The metallization and contact geometry of both devices have been optimized to provide a low dynamic resistance of 0.8 Ω at 350 mA and 0.4 Ω at 1000 mA.

Our 425 nm blue LED has a maximum external quantum efficiency (EQE) of 61% and a wall-plug efficiency (WPE) of 56%. At 350 mA the chip produces 566 mW at an EQE of 56% and a WPE of 44%, and at 2000 mA its output rises to nearly 2 W. This efficiency is among the highest ever reported for blue devices at these current densities.

The encapsulated white-light TFFC LED, which incorporates a YAG:Ce phosphor, has a peak luminous efficacy of 147 lm/W at 10 mA. At 350 mA it delivers 88 lm/W and at 1000 mA it produces 56 lm/W (see figure 5, p16). These efficacies are far higher than those produced by halogen sources, which typically emit 25 lm/W, and will enable manufacturers of lighting systems to deliver greater electrical efficiencies.

Luminance mapping across the surface of one of our non-encapsulated 1 mm × 1 mm white LED chips reveals a peak luminance of 58.8 Mnit (Mcd/m^2) and an average surface brightness of 50 Mnit (figure 6, p16). This brightness makes the chip a strong contender for projection displays and automotive headlights. The average brightness of LEDs, which is delivered at a luminous efficacy of 40 lm/W, is much higher than that of a halogen source (15–30 Mnit at ~30 lm/W) and not far behind the average effective brightness of high-intensity discharge lamps (60–80 Mnit at ~100 lm/W).



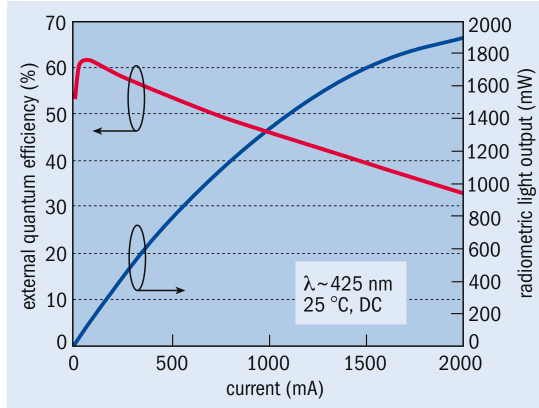
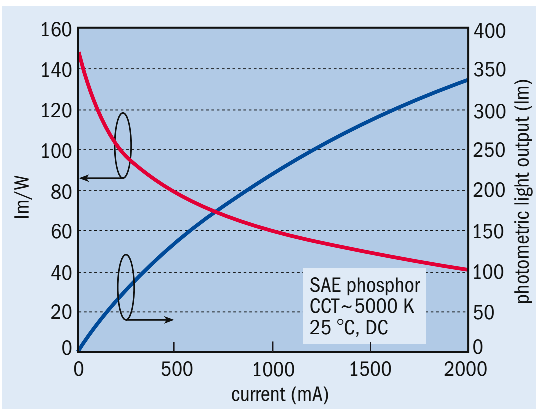


Fig. 3 (left). A split-wafer study of blue LEDs reveals that the TFFC design delivers a higher light output than VTF and FC equivalents at all drive currents up to 1 A. To ease comparison, light output has been normalized to that of an FC-LED at 1 A. The VTF-LED used in this test has a conventional design, with a reflective p-contact evaporated onto the p-doped side of the device and a GaAs intermediate substrate. Deposited aluminum forms the mesh-like n-contact and the wire-bond pads, and typically 50% of the top surface emits light. To minimize light occlusion effects, the resistivity of regions beneath the mesh contact has been increased with hydrogen-ion implantation. **Fig. 4 (right).** The encapsulated 425 nm blue TFFC LED can deliver a light output of almost 2 W at 2 A. The test was carried out under direct current conditions, with heatsinks used to maintain an operating temperature of 25 °C.



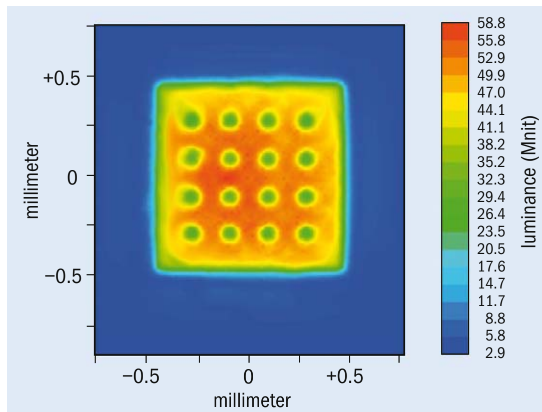


Fig. 5 (left). Coating the blue TFFC chip with a YAG:Ce phosphor produces a white-light device with a maximum efficacy of almost 150 lm/W. **Fig. 6 (right).** The surface of the non-encapsulated white LED chip has an average brightness of 50 Mnit at a 1 A drive current. In comparison, halogen sources and high-intensity discharge lamps produce 15–30 Mnit and 60–80 Mnit, respectively.

About the authors
Oleg Shchekin (left) is a staff scientist at Philips Lumileds Advanced Laboratories. **Decai Sun** (right) is a section manager in the R&D department of Philips Lumileds. Contributing authors from Philips Lumileds are: Henry Choy, Walter Daschner, John Epler, Mari Holcomb, Mike Krames, Ojin Kwon, Tal Margalith, Paul S Martin, Rajat Sharma, Dima Simonian, Dan Steigerwald, Charlene Sun, Melissa Taub and Ling Zhou.

Our devices also have a significant advantage over these two alternatives: a relatively uniform, tightly controlled emission surface. This eases the design of secondary optics and boosts utilization efficiency, advantages that are particularly attractive for automotive forward lighting. In fact, programs are now underway to install devices in production cars. Monochromatic LEDs, which have a very high surface brightness, are also reaching the point where they can compete directly with ultra-high-pressure projection bulbs because they do not require color filtering.

Reliability, another key parameter for commercial success, has been examined with in-house high-temperature reliability testing using direct current conditions and a 1 A drive current. Light output power drifted by at just a few percent during a 1000 h white-light LED chip test at 110 °C and a 7000 h blue-light device test at 85 °C.

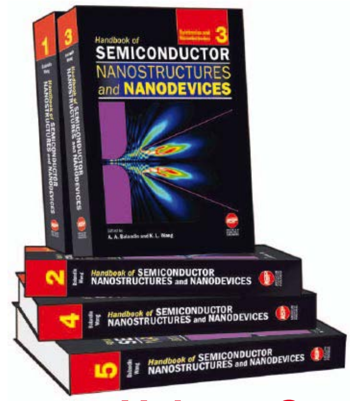
We have also combined this TFFC design with other technologies developed by Philips Lumileds to produce a 1 mm × 1 mm demonstration chip that delivers 115 lm/W at 350 mA, 61 lm/W at 2 A and a maximum light output of 502 lm. This LED has a correlated color temperature of 4685 K, which is lower than that of many chips produced by our competitors and closer to the wishes of our customers.

Product roll-out

The various technologies that feature in this record-breaking chip will be united in our products over the next 12–18 months. However, in the meantime customers will be able to purchase our first TFFC LEDs, which offer an unmatched combination of performance and versatility. These devices, which will be launched this spring, will deliver a reliable, high light output and brightness, and will be suitable for use in various lighting systems from projection to general lighting. We expect that this device platform will provide LED customers with a greater value than ever before, and establish a sound basis to proliferate solid-state lighting.

Handbook of

SEMICONDUCTOR NANOSTRUCTURES *and* NANODEVICES



Edited by **A. A. Balandin and K. L. Wang, USA**

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Volume 2: Nanofabrication and Nanoscale Characterization
Volume 3: Spintronics and Nanoelectronics
Volume 4: Nanophotonics and Optoelectronics
Volume 5: Nanodevices and Circuits

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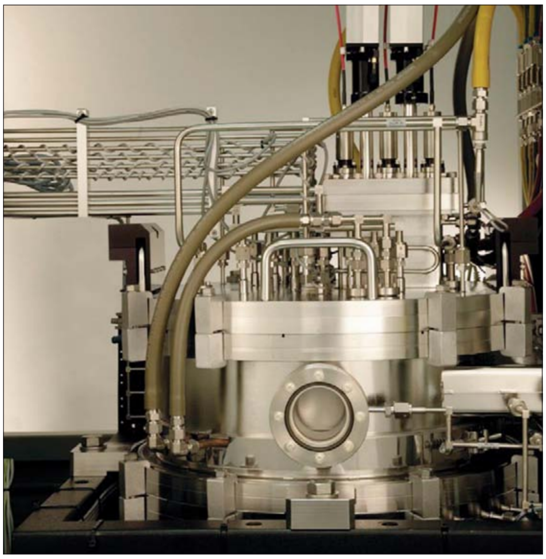
MOCVD REACTORS

Veeco puts faith in 'future-proof' tool

Richard Stevenson quizzes **Sudhakar Raman**, Veeco's vice-president of marketing for MOCVD operations, about the introduction of the company's K300 and K465 "future-proof" reactors for GaN LED production.



VEECO

Veeco says that customers with immediate capacity needs should buy the K300, then upgrade to the higher-capacity K465 when the larger machine becomes available later this year.

Chip manufacturers looking to purchase a reactor for making blue and white LEDs already have a lot of choice, including Veeco's GaNzilla II. Why do we need another generation of machines?
The fundamental reason is that as the LED market grows, volume is going up, so you have to come up with more productive tools that reduce the cost of ownership. Another reason is tighter technology specifications, such as higher brightness. Every time the LED cost-versus-brightness curve moves, we have to come out with a new version of MOCVD tools.

So what is different about the K300 and K465?
The key thing is the modular platform, which is upgradeable over multiple technologies and generations. The K300 is a bridge tool for people who need immediate capacity. It uses exactly the same process recipes as our previous GaNzilla II E300, but its design makes it easier to configure gases and materials.

Owners of the K300 will be able to upgrade to the K465 in six to nine months if they see the need for higher production, but people can also buy the K465 directly. In the K465 the biggest change is the reactor. We are going from a 21 × 2 inch wafer capacity [which is used in the GaNzilla II and K300] to a 45 × 2 inch capacity.

Is this larger capacity behind the claim that the K465 offers 50% more throughput than any other MOCVD tool currently available?
The K465 has two big advantages. The first one is wafer capacity, which is 8–40% higher than the nearest two competitors.

The second is unique to the Veeco platform. We have an automatic load-lock transfer mechanism that allows for continuous operation of the MOCVD system. While a platter of LEDs is being grown inside the reactor you load another wafer carrier in parallel into the vacuum load-lock. Normally after a run you let the reactor cool down before taking wafers out. But in our machine you don't need to cool it because it's under vacuum. Instead, the robot picks up the finished wafer carrier with 45 wafers, transfers it to a hub inside, and then takes the one that's loaded and puts it back in. It's all done within about 10 min, and without lowering the temperature.

Opening the reactor, lowering the temperature and then ramping up the temperature can take at least 1 h on other competitive tools. So for a typical 5 h LED process, you get an extra run each day. The combination of wafer capacity and more runs per day yields a huge number of LEDs. If you do the cost-of-ownership calculation, with yield [from different types of reactors] being equal, we offer at the very least a 50% advantage to the customer.

"We offer at the very least a 50% [cost-of-ownership] advantage to the customer."

Do you include gas and bubbler usage in this calculation?
Yes. The K-series reactor has several significant changes. The flow flange – through which the gas is injected from the top and circulated inside the reactor – has been completely redesigned. It cuts down the use of ammonia, one of the biggest costs for LED manufacture, by 25%. We were a little bit behind [the competition], but this has been narrowed significantly.

Why is upgradeability such a big deal?
It is very simple from a customer's perspective: they are protecting their initial capital investment, and can continue to extend their platform over multiple generations.

In addition, there is a point when the footprint becomes a major issue. You can't just keep adding equipment, because what are you going to do with the existing tool? They say: "I just bought a tool a year ago. Now you're coming in with a much better tool, and I've got to go and buy it. Why can't I balance my manufacturing line and upgrade this?"

Clearly there are benefits to customers. But is it a good strategy for equipment makers?
I know that some people think that it's going to cannibalize existing tool sales. But usually it doesn't. It actually protects and grows your market share in the long run.

Can we expect to hear about any other additions to the K-series in the next few months?
Probably not. We expect that this is going to be the major introduction on the GaN series for this year.

Product Showcase

Valved GaP Compound Source VGCS

Dr. Eberl MBE-Komponenten GmbH

The VGCS is a high purity Phosphorus (P_2) source for III/V MBE, which allows safe operation due to direct sublimation of P_2 from single crystal GaP(6N-7N). Only small amounts of white P are accumulated within the system, which is in contrast to elemental P sources. The source is equipped with a very reliable valve, which allows precise P_2-flux control. The VGCS has been readily approved in industrial applications. It is perfectly suited for applications in HEMTs, HBTs, GaAlInP laser diodes and other devices, which incorporate Phosphorus compounds. Injector length and flux distribution are easily adjusted to fit most MBE systems.

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Web: www.umccorp.com
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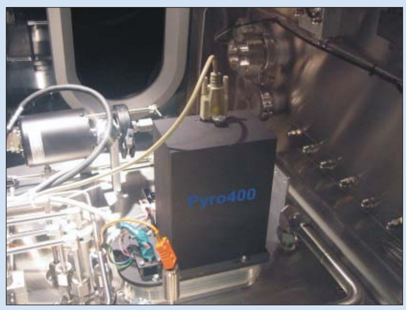
Pyrometry at 400 nm

LayTec GmbH

LayTec's new 400 nm pyrometer measures the real GaN and SiC surface temperature directly. Materials that are transparent at the usual wavelength of pyrometry (950 nm) like GaN and SiC have become visible now. Due to its high temperature resolution (better ±0.1 K) and time-resolution (better 20 ms), Pyro 400 provides insight into the surface temperature uniformity across the wafers in multi-wafer production MOCVD systems.



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Valved Sources for Corrosive Materials

Addon Creative Epitaxie

The VCOR source series permit high performances MBE growth of Sb, Te, Cd, CdTe and Mg containing materials. They use all new PBN reservoir/valve and vap-tube construction to prevent reaction between the reactive materials and the source parts and produce highly reproducible flux. They use a unique easy to refill design with a 720 g loading capacity. This is done in minutes to prevent oxidation of materials like Mg. The model shown on the picture comes in dedicated versions for all major MBE systems. This product features manual or remote control of the valve.

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Fabless model delivers high-speed tunable transmitter chip

Finally, tunable lasers are the way they are meant to be – smaller, faster, power-efficient and reliable, says Syntune's **Kevin Green**. This is accomplished with designs based on conventional lasers, an approach that has produced the first monolithic 10 Gbit/s tunable transmitter for optical networks.

Tunable lasers hold the key to improving the flexibility and agility of optical networks. By being able to select a particular wavelength within a communication band, users can carry fewer spares, while manufacturers can streamline operations by eliminating the need to fabricate, stock and maintain multiple devices. This will eliminate the need for 96 different lasers or line cards to cover the C-band (1525–1565 nm) using a 50 GHz spacing.

Wavelength-agile networks are also simplified with tunable lasers. Reconfigurable optical add–drop multiplexers (ROADMs) and wavelength-based routing will enable service providers to offer differentiated services, meet the ever-increasing demand for bandwidth and deliver all-optical networking.

Despite these advantages, tunable lasers have not dominated the market since their launch around 10 years ago, as early sales were hampered by the relatively poor performance of the device. However, the outlook is now brighter, and recently there has been a surge in shipments, according to market analysts such as RHK and Communications Industry Researchers. Last year saw shipments of 60,000 tunable lasers, and 50% of all newly deployed long-haul transmitters are using this format. This figure is expected to increase to 90% by the end of the decade. Tunable lasers are also starting to penetrate the metropolitan-area network segment and are expected to eventually account for over a third of all metro transmitters. With growth in both markets, shipments of this type of laser are expected to be between 100,000 and 120,000 for 2007, and increase at 64% year-on-year through 2010.

However, tunable lasers are a work in progress. While network operators recognize that these devices have reached an acceptable level of performance and reliability, costs and guarantee of supply are still a cause for concern. Many of today's designs rely on moving parts and multiple components, which require specialized, proprietary manufacturing techniques with costly alignment and low packaging yields. Such manufacturing constraints, combined with the relatively large designs, are hindering deployment. In particular, bulky tunable laser platforms are incompatible with 10 Gbit/s XFPs, the industry's most compact standardized transceiver platform.

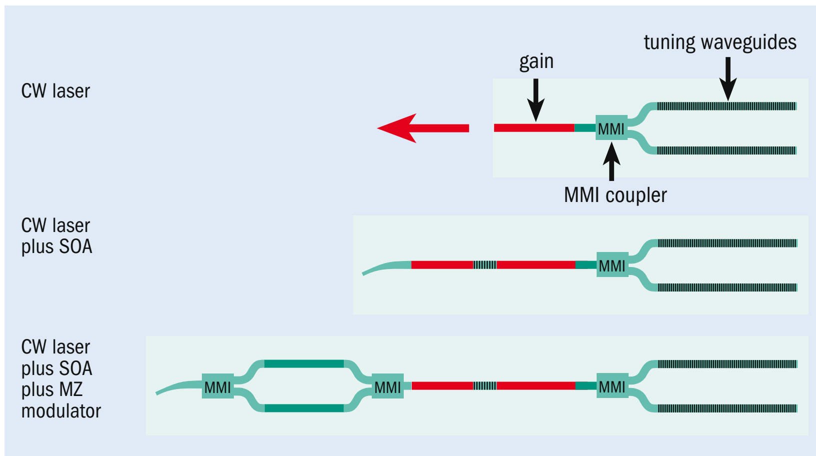


Fig. 1. Syntune's tunable design is based on a Y-branched laser. It is distinguished by its two grating reflectors appearing on the same side of the laser cavity, which improves the output power across all the channels. A Mach–Zehnder (MZ) modulator and semiconductor optical amplifier (SOA) can be added to this InP chip to form a tunable transmitter suitable for optical networks.

In short, the market is still looking for tunable lasers that cost no more than their fixed-wavelength cousins, but deliver the same performance, reliability, form factor and power consumption. At Syntune, which is based in Kista, Sweden, we have designed a new-generation laser that is a significant step in that direction – a practical, affordable tunable laser.

Competing designs

There has been, and still is, a wide variety of approaches to building tunable lasers. Each has its merits and drawbacks, but most are based on several discrete optical components, such as gain chips, tuning elements, lenses and mirrors, which are mounted and aligned together.

Intel, Paxera, which has recently been acquired by NeoPhotonics, and Pirelli all produce tunable lasers with an external cavity that requires the assembly of multiple discrete elements. Tight tolerances are implicit within these designs, as compo-

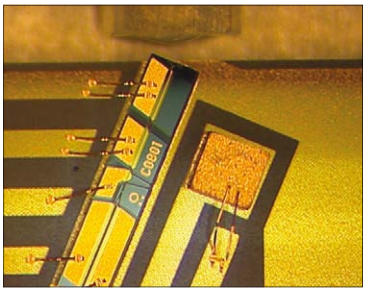


Fig. 2. Syntune's monolithically integrated laser chips are manufactured at foundries with conventional processes used to produce standard fixed-wavelength electroabsorption-modulated lasers.

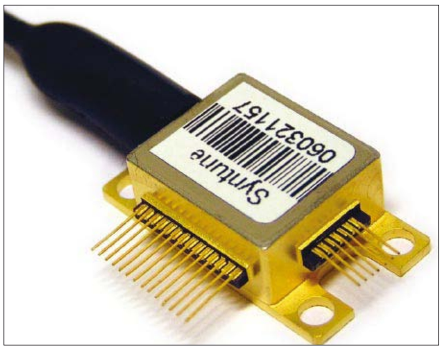


Fig. 3. Syntune's tunable 10 Gbit/s transmitter can fit in a mini-butterfly package and is suitable for small-form-factor transceivers and transponders.

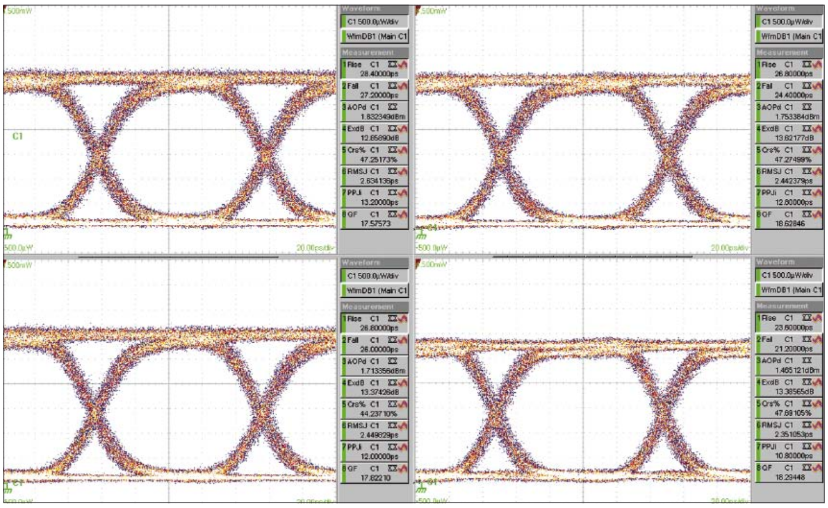


Fig. 4. The clarity of these diagrams from four different channels evenly spread across the C-band (191.50–196.25 THz) shows the capability of Syntune's 10 Gbit/s laser for serving optical networks.

nents have to be positioned at locations insensitive to mechanical vibration and flexing of the laser package. They also suffer from a larger "footprint" within the transmitter module than monolithically integrated chips.

Alternative approaches, such as that used by Santur, feature laser arrays, and use temperature tuning. However, this form of tuning is relatively slow and consumes a substantial portion of the power-dissipation budget of the module. It also places greater demands on the laser's reliability since the chip has to operate continuously at high temperatures to serve particular wavelength division multiplexing (WDM) channels.

The downside of discrete assembly

All these forms of discrete assembly not only increase the "part count" relative to monolithic designs, but can also require additional active optical-alignment steps during module assembly. Active alignments increase manufacturing costs, as they demand more skilled-operator time and more sophisticated robotics.

Full monolithic integration is clearly a more attractive approach, as it can minimize part count, lower power consumption and cut packaging costs by decreasing the number of time-consuming optical-alignment steps. Integrated tunable chips are also highly compact, which simplifies integration within transmitters and enables deployment in the smallest form-factor packages, namely XFP transceivers.

Unfortunately, most early attempts at monolithic InP integration were hampered by design compromises and manufacturing difficulties that produced low yields. Also, most approaches used proprietary processes and had to rely on supply from a unique fab.

For success, these proprietary processes must be replaced with standard ones so that the photonics industry can mature and replicate the silicon model. Design and manufacturing can then be decoupled, giving rise to fabless companies and outsourced manufacturing. This provides several well-known advantages, including more efficient use of the capital-intensive fab capacity, which ultimately lowers manufacturing costs, and the opportunity to move production from one fab to another, which simplifies second-sourcing and licensing of technology.

Syntune has implemented this model for its monolithic laser by using standard InP design methodologies and fabrication techniques. The result is a practical, affordable tunable laser chip that addresses the needs of network operators.

We are not the first company to have developed a monolithically integrated tunable laser chip, and we share the common approach, which features a combination of "comb" filters that have a series of high reflection spikes spaced approximately evenly in wavelength. Electrical injection current tuning selects a particular wavelength by bringing the reflection peak of one filter into alignment with that of another filter elsewhere in the chip. All other peaks are misaligned, and lasing occurs at a single frequency, a condition that is reinforced by the round-trip optical distance between the points of reflection equalling a whole number of wavelengths.

The conventional approach, which is used by JDSU, involves placing one filter at the back of the laser and another at the front (output) end. This has a downside: the variations in current needed to tune the front filter for the particular WDM channel alter the optical absorption. This produces variations in output power with wavelength, which has to be compensated with a semiconductor optical amplifier (SOA) that consumes part of the electrical power dissipation budget of the package.

This drawback can be offset by replacing the front comb filter with a more complex multi-electrode chirped front reflector, as has been demonstrated by Bookham. However, this has the downsides of more pins and more complicated tuning schemes. It also lengthens the time taken to identify the WDM channels for each chip.

Syntune has addressed these weaknesses by eliminating a tunable filter at the light-output end of the laser, and by using a modulated-grating, Y-branched architecture (see figure 1, p21). A simple static reflector is positioned at the front of the device and the two tunable filter sections at the back. The result is a tunable laser that delivers industry-leading power flatness over the tuning range.

We manufacture our device with conventional processes used for manufacturing standard fixed-wavelength electroabsorption modulated lasers (EMLs), which are also referred to as distributed feedback lasers with electroabsorption modulators (DFB-EAs). Hundreds of thousands of these fixed-wavelength lasers are manufactured every year.

Structurally, our tunable laser is similar to a normal distributed Bragg reflector (DBR) laser. However, it replaces the single grating reflector of the DBR with a parallel coupling of two reflectors that are combined using a multimode interference (MMI) coupler.

Simultaneous adjustment of both reflecting sections provides tuning of the lasing wavelength over the entire C-band at 50 GHz spacing, while maintaining a side-mode suppression exceeding 40 dB. Tuning is also fast, as switching from one frequency to another takes less than 50 ns, and it only requires relatively small currents that reduce any device heating.

Additional structures can be added to our design, such as SOAs, which can be placed in front of the gain section to amplify and further equalize power over the tuning range. In this case, the SOA does not have to provide extra gain to boost any low-power channels, so the chip can provide better operational efficiency than other approaches.

Output exceeds 40 mW at all wavelengths for this laser, which is packaged in a miniaturized DFB-style butterfly package with an internal wavelength locker. The output power coupled into the fiber is 13 dBm at all wavelengths (see figures 2 and 3).

We have added an on-chip Mach–Zehnder (MZ) modulator to our laser to produce the first commercially viable, completely monolithic 10 Gbit/s tunable transmitter (see figure 4). This can serve ultra-long-haul dispersion-managed fiber links of typically 1000 km, where it is essential to have “zero-chirp” (little or no transient optical frequency shift at the data-pulse rising and falling edges). A follow-on version of the transmitter will be built with negative chirp – a red shift on the data pulse’s rising edge and a blue shift on its falling edge. This is designed for metro applications, which require transmission over distances exceeding 80 km without dispersion compensation.

The advantages of our combined modulator and tunable transmitter on a single chip are obvious: reduced costs, a smaller size, fewer parts, lower power consumption and no alignment issues related to the assembly of discrete components. This will enable the deployment of tunable lasers in even the smallest form factors, such as XFPs, which cannot be addressed with other types of tunable laser that have a larger footprint.

The consistency of this transmitter’s performance from channel to channel is demonstrated by the similarities of the eye diagrams shown in figure 4. Output power averages 5 dBm, with only a 2.9 V drive required for each modulator arm. The high extinction ratio and low dispersion penalties needed for propagating long distances in optical fibers are demonstrated in figure 5.

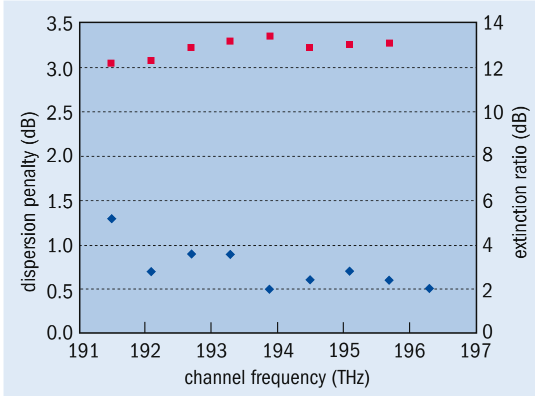


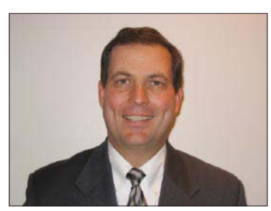
Fig. 5. The small dispersion penalties between −800 ps/nm and 800 ps/nm (blue diamonds) and the good values for the back-to-back extinction ratio at different channel frequencies (red squares) make Syntune’s transmitter appropriate for deployment in optical networks.

Our tunable laser has already been fabricated successfully in several different facilities, which demonstrates our ability to operate as a “fabless” company.

High-yield manufacturing

Our tunable lasers can be manufactured with high yields because they feature a few robust standard elements built with standard processes. Unlike silicon ICs, yield is only weakly dependent on chip size because only a very small portion of the chip is active. Instead, yield depends on processing quality and structural issues. Adding the modulator does not significantly reduce yield, as the DFB-EA processes used for the DBR structure also deliver a high-quality modulator, due to the similarity between the structures.

Our tunable laser has already been fabricated successfully in several different facilities, which demonstrates our ability to operate as a “fabless” company. Going forward, we are set to benefit from the freedom of designs and manufacturing techniques that do not require proprietary processes or unique fabrication equipment. This will allow us to build on the successful launch of the first 10 Gbit/s single-chip tunable transmitter, as it positions us to meet the rapidly growing customer demand for affordable, tunable lasers and transmitters. ●



About the author
Kevin Green (**kevin.green@syntune.com**) is Syntune’s vice-president of marketing and sales. He has more than 20 years’ experience marketing telecom devices.

Quantum dashes promise higher speeds for tomorrow's networks

France's Alcatel-Thales III–V Lab has built InAs quantum-dash lasers on InP substrates that share the attributes of quantum-dot lasers, but are easier to fabricate. **Béatrice Dagens**, **François Lelarge**, **Alain Accard** and **Guang-Hua Duan** explain their use in next-generation optical networks.

Lasers based on self-assembled nanostructures are attracting considerable attention owing to a range of favorable characteristics, such as low threshold current, high gain and good thermal stability. These advantages over quantum-well (QW) and bulk lasers have even led to the commercial launch by Innolume, formerly NL Semiconductor, of InAs-on-GaAs quantum-dot lasers emitting at 1.1–1.3 μm.

While Innolume's technology is based on quantum dots, there is also a growing interest in "quantum dashes", which are essentially elongated dots. These structures share many of the advantages of a dot, but offer an even higher gain that can improve laser efficiency. Like quantum-dots lasers, they can be mode-locked to produce short, high-bit-rate pulses with very low jitter. These characteristics make the dash-based lasers promising candidates for providing high-repetition-rate sources at bit-rates of 40 and 160 Gbit/s, the transmission speeds expected in tomorrow's networks. These properties also lead to an intrinsic "beating" emission at microwave frequencies. Thus quantum-dash lasers are also potential sources of microwaves in the 10–300 GHz range with very high spectral purity.

Quantum-dot and quantum-dash lasers based on the InAs/InP material system are of particular interest because they can be used for 1.5 μm transmission in the fiber-optic spectral window. However, fabricating dot-based lasers that emit at this wavelength is not easy. MOCVD is currently unproven for producing InAs quantum dots with high-quality cladding layers, while MBE on InP substrates with standard orientations tends to produce dashes rather than dots. This has led researchers either to investigate dash-based structures on (100) InP or produce dots on the (311) B surface.

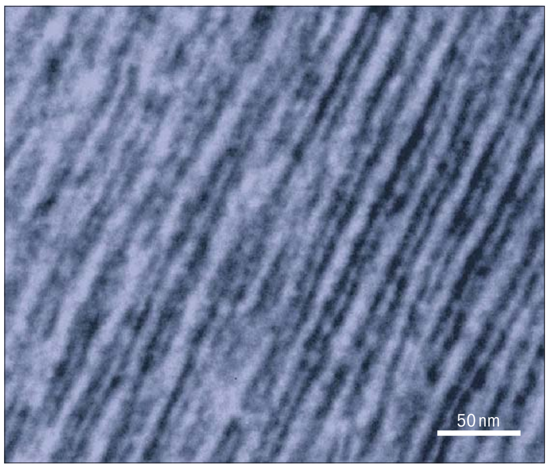


Fig. 1. A plan-view TEM image reveals the quantum-dash nanostructures at the top of a stack of six quantum-dash layers.

Building on standard substrates

At the Alcatel-Thales III–V Lab in Palaiseau, France, we are using MBE to produce dashes on (100) InP. This has the significant advantage of being compatible with existing standard fabrication processes for QW and bulk devices, including regrowth processes. This has enabled us to produce CW room-temperature lasers with quantum dashes in InGaAsP QWs and barriers. A group from Korea's Electronics and Telecommunication Research Institute and a research team at the University of Würzburg, Germany, have had similar success with InGaAlAs barriers.

Our Fabry–Pérot lasers offer a significant improvement over standard 1.55 μm aluminum-free lasers.

Our lasers are based on two designs that feature either dashes-in-a-barrier or dashes-in-a-well, and are produced by gas-source MBE on sulfur-doped substrates using the Stransky–Krastanow growth mode. Strain relaxation drives a 1 nm-thick InAs layer that has a 4% lattice mismatch with the underlying InGaAsP to form quantum-sized structures. In our case, this "self-organization" is highly sensitive to the surface anisotropy of InGaAsP, and dashes are formed along the [1–10] direction with a surface density of $1-4\times10^{10}\,cm^{-2}$. They are 15–20 nm wide and 40–300 nm long, depending on the growth

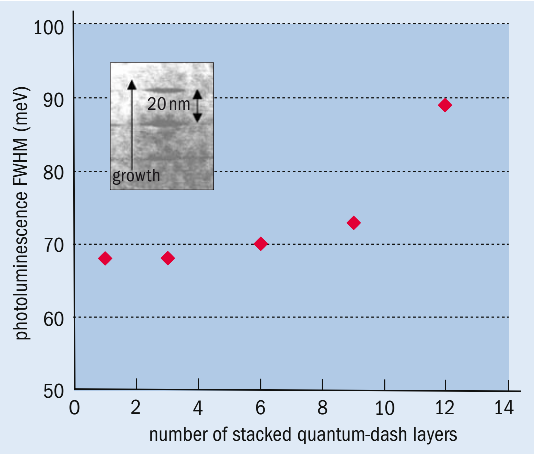


Fig. 2. Choosing appropriate growth conditions for individual layers can offset the change in the dimensions of the dashes as the stack gets thicker. With this approach, the broadening of photo-luminescence with increasing layer growth can be reduced, leading to epiwafers suitable for higher-performance lasers.

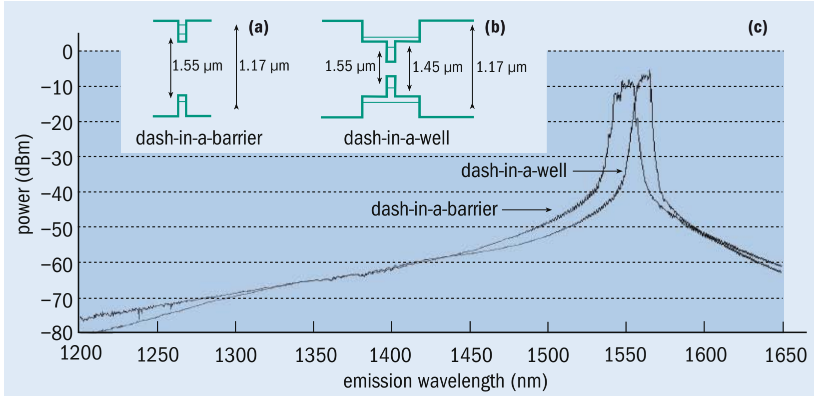


Fig. 3. The Alcatel-Thales Lab has produced lasers based on two different structures: dashes-in-a-barrier **(a)** and dashes-in-a-well **(b)**. The dashes-in-a-barrier structure sandwiches the InAs dashes between lattice-matched $Ga_{0.2}In_{0.8}As_{0.4}P_{0.6}$ 40 nm-thick barriers and 80 nm-thick separate-confinement heterostructure layers. The difference with the dashes-in-a well structure is that the dashes are embedded in 8 nm-thick lattice-matched GaInAsP quantum wells (QWs) that emit at 1.45 µm. The lasing spectra for both structures at an injection current of 75 mA – a figure which is nearly three times the threshold value – is shown in **(c)**.

conditions (see figure 1, p25). The dimensions of the dashes influence the laser's carrier-confinement properties and, ultimately, device performance.

One downside of making lasers from quantum-sized structures is their relatively small interaction with the optical modes of the device. Typically, just 0.15% of the power in the optical modes of the laser is actually confined in the quantum-dash layer – six times less than that for a QW layer. Consequently, to improve the modal gain, layers of quantum dashes are stacked close together between spacer layers. Unfortunately, this affects the dash density and dimensions, reduces modal gain at the lasing wavelength and hampers device performance (see figure 2). This shift is accentuated when the spacer layers are thinner than 60 nm.

Stack success

We have overcome this problem by tweaking the growth conditions for each dash layer to compensate for this wavelength shift. This has enabled us to stack up to 12 layers. The reproducibility of these layers can be judged by examining the full-width half-maximum (FWHM) of the photoluminescence emitted by this structure (see figure 2). This shows that uniformity between the quantum-dash layers is good enough for structures up to nine layers thick.

With this approach we have grown dashes-in-a-barrier and dashes-in-a-well structures targeting 1.5–1.6 µm emission (see figure 3). For initial analysis, we processed broad-area (BA) lasers that emit over a wide spectral range of 1250–1650 nm. Gain saturation, a problem that has plagued the InAs/GaAs system, is absent from these spectra. Threshold-current measurements reveal that the dashes-in-a-well structure provides better carrier injection – threshold-current density was 110 A/cm^2 per layer for this design, compared with 190 A/cm^2 per layer for the dashes-in-a-barrier laser. Internal quantum efficiency for a six-layer quantum-well-based design is 80%.

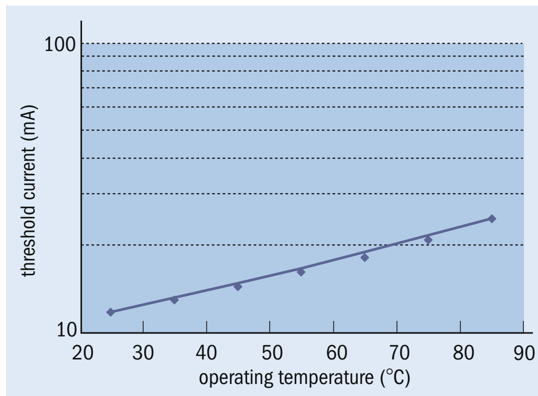


Fig. 4. The 1.55 µm Fabry–Pérot dashes-in-a-well laser performs better than standard aluminum-free lasers at the same wavelength. It has a ridge width of 1.5 µm, a cavity length of 600 µm and two cleaved, uncoated facets. The threshold current at 25 °C is 12 mA. The characteristic temperature, T_0, is 80 K for device operating temperatures of 25–85 °C.

We have assessed temperature performance by the conventional approach, determining the value of the "characteristic temperature" T_0, which is a well-known figure of merit. This figure is influenced by threshold-current stability and carrier confinement, and a higher value indicates that the laser can operate at higher temperatures. For a dashes-in-a-well system, T_0 can be increased by narrowing the width of the well, an approach that raises the energy of the well, and suppresses the electron flow from the dashes.

With this scheme, we have built devices with a T_0 of 100K for operating temperatures of 20–80 °C. This approach has also produced single-transverse-mode Fabry–Pérot lasers with a threshold current of just 12 mA at 25 °C (see figure 4) and

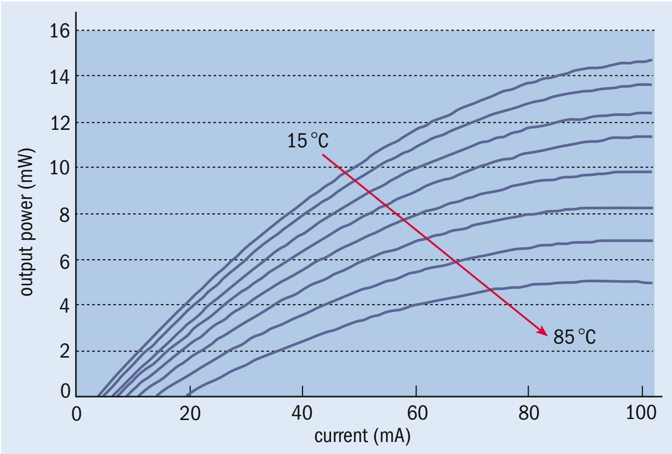


Fig. 5. Light output characteristics of a 205 µm-long buried-ridge-stripe distributed-feedback QD laser, with a high-reflection coating on the rear facet and a cleaved front facet is shown above for the 15–85 °C temperature range. At 25 °C, the threshold current is as low as 4.8 mA, while external efficiency reaches 0.3 mW/mA. Maximum output power exceeds 5 mW at 85 °C.

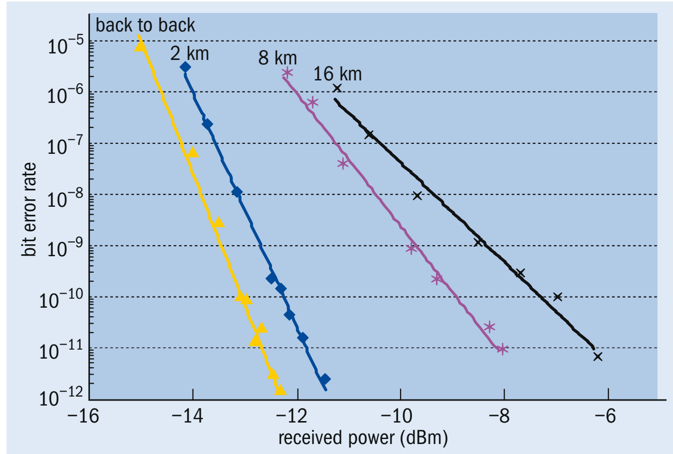


Fig. 6. Lasers featuring a dashes-in-a-well structure and distributed feedback can provide sources for 10 Gbit/s data transmission. The device was evaluated at 25 °C before and after transmission through 2, 8 and 16 km of standard fibers. "Non-return-to-zero" laser modulation at 10 Gbit/s was produced using a pseudo-random binary-sequence generator with $2^{31}-1$ long "words".

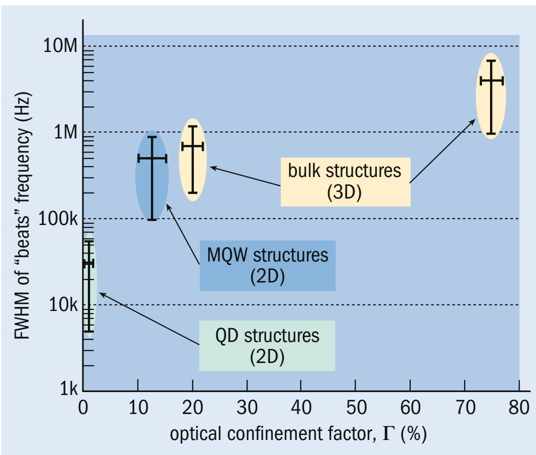


Fig. 7. The intrinsic beating-line widths of quantum-dot or -dash lasers have a very high spectral purity, with a typical FWHM of 15 kHz. This narrow line width makes the devices suitable for applications requiring microwave radiation of 10–300 GHz.

a T_0 of 80 K between 25 and 85 °C. This is a significant improvement in temperature performance over standard 1.55 µm aluminum-free multiple-quantum-well (multiple-QW) lasers.

We have developed these Fabry–Pérot lasers with buried-ridge-stripe (BRS) lasers. These were fabricated using standard processing steps established for InGaAsP multiple-QW lasers: plasma etching to form 1–2 µm-wide ridge waveguides; MOCVD regrowth to add the p-doped InP cladding layer and GaInAs contact layer; and proton implantation to define the current flow through the device. A distributed feedback (DFB) structure defined by electron-beam lithography was added for singlemode emission.

The devices that we have made include a 205 µm-long BRS laser that has a high-reflection-coated rear facet and DFB structure with six dashes-in-a-well layers. This device produces CW operation between 15 and 85 °C (see figure 5), and has a dominant lasing mode at 1512 nm with a side-mode suppression ratio (SMSR) of 45.5 dB. It is the first quantum-dash or quantum-dot laser to produce a floor-free bit-error-rate measurement when directly modulated for 10 Gbit/s transmission (see figure 6). The low error rates, which can be less than one part in 10^{11} for transmission down a 16 km length of fiber at a received power of –6 dBm, show the promise of quantum-dash lasers for telecom applications.

These lasers also have the potential to be used in microwave applications. Eighteen months ago we reported the demonstrated low-jitter, high-bit-rate short pulses using mode-locked 1.5 µm quantum-dot lasers and all-optical clock recovery. The intrinsic beating spectrum of a Fabry–Pérot quantum-dot laser has a typical FWHM of 15 kHz, compared with 1.5 MHz for a bulk DBR laser (see figure 7). Our quantum-dash lasers offer significant improvements over their bulk and QW-based predecessors, and we expect that they could deliver a superior performance at microwave frequencies.

We will direct future efforts at refining our control over the shape of these nanostructures. This will optimize the quantum-dash heterostructure design and boost the dynamic properties of the laser. We will also continue to develop quantum-dash-based mode-locked lasers for fiber-optic communications and millimeter-wave generation, and explore their excellent phase-noise and time-jitter characteristics. ●

Further reading

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About the authors

Béatrice Dagens (top left) is responsible for the development of modulated lasers and photonic integrated circuits. **François Lelarge** (top right) leads the MBE growth, with particular efforts directed at quantum-dash material. **Alain Accard** (bottom left) is responsible for laser development and fabrication. **Guang-Hua Duan** (bottom right) is the leader of the Lasers for Telecommunication Applications team. They acknowledge support from the European Union project ZODIAC and France's ROTOR project. They thank A Ramdane and B Lavigne for discussions, and G Patriarche for transmission-electron-microscope observations.

GAN LASERS

Rohm trumps UCSB's non-polar claim

The Solid State Lighting and Display Center at the University of California, Santa Barbara (UCSB) and Japanese chip maker Rohm have independently announced the fabrication of non-polar blue–violet GaN laser diodes.

The UCSB team, which is directed by GaN pioneers Shuji Nakamura, Steven DenBaars and James Speck, made the first claim for a non-polar GaN laser in a press release on January 29, 2007, which described a device that operates in pulsed mode.

Rohm responded three days later with a statement detailing its 404 nm laser that produces continuous emission. Further developments of both of these structures could ultimately improve the performance of high-density DVD players and recorders, as this type of laser is expected to deliver greater efficiencies and lifetimes than conventional GaN lasers built with polar material.

The UCSB press release includes few details about the device, but the team's results will be published in a forthcoming issue of the *Japanese Journal of Applied Physics*. However, DenBaars did reveal to *Compound Semiconductor* that the device is a broad-area (BA) 15 µm × 1000 µm laser with uncoated facets that produces up to 60 mW when driven at 1.1 A in pulsed mode (5 kHz repetition rate, 0.025% duty cycle).

UCSB

UCSB's first non-polar lasers use a broad-area design. The team plans to switch to a ridge-waveguide structure to reduce threshold current density.

The threshold current density of this laser is 4.6 kA/cm^{-2}, three times higher than Nichia's commercial, conventional GaN-on-sapphire lasers. However, DenBaars believes this current density can be reduced by switching to a ridge-waveguide design with high-reflection coatings.

In comparison, Rohm's 600 µm non-polar laser, which has a waveguide 1.5 µm wide, and a threshold current of 28 mA, delivers a continuous output of 10 mW at 55 mA. "The performance is already equivalent to, or higher than, that of [conventional] blue–violet laser diodes," the company stated.

Rohm plans to use its non-polar GaN technology to develop 532 nm green laser diodes. These can be combined with red and blue lasers to produce large high-definition displays with an excellent color gamut.

The company exhibited non-polar blue LEDs at last year's Combined Exhibition of Advanced Technologies in Japan, and manufactured green versions of the device on a trial basis. The green LEDs have an emission wavelength independent of injection current, which is one of the major benefits expected from non-polar devices.

GASB LASERS

Increased strain makes for more efficient lasers

Scientists from the State University of New York (SUNY) at Stony Brook have improved the efficiency of 1 W GaSb infrared laser diodes emitting at 2.4 µm by increasing the strain in the device's active region.

The gains in efficiency could aid military organizations, including the US Army and Air Force that funded this work, because it should lead to more efficient sources for 3.8 µm optically pumped lasers required for infrared countermeasures.

The improvements in performance, which cut threshold current by almost 50%, were created by increasing the strain in the 12 nm-thick InGaAsSb quantum wells to 1.6%.

Team-member George Belenky says that the strain engineering reduces the loss of holes out of the quantum wells through thermal excitation. According to him, Auger recombination, another mechanism that can limit device performance, is less of a concern at this wavelength.

The researchers produced their devices on tellurium-doped GaSb substrates with a Veeco GEN-930 solid-source MBE reactor. Lasers 1 mm long that have a 100 µm-wide oxide-confined gain-guided structure produced a CW output of 850 mW at 4 A, while 2 mm-long versions delivered 1.05 W at 6.2 A. Power-conversion efficiencies peaked at 15% and 17.5% for the 2 and 1 mm versions, respectively.

Belenky believes that heavily strained quantum-well structures could also enable the fabrication of several-hundred-milliwatt room-temperature lasers operating above 3 µm. Singlemode versions could serve remote and biological sensing applications.

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HEMTs

III-V on silicon reduces cost and boosts speed

A partnership between NTT, Japan, and the National Chiao Tung University (NCTU), Taiwan, has produced an AlGaSb/InAs HEMT structure on a silicon substrate with a mobility of 27,300 cm^2/Vs.

The researchers say that the structure could aid logic applications, which would benefit from the combination of the high mobility of the III-V structure and the low cost, hardness and large wafer sizes of the silicon platform.

The significant differences in both the lattice constant and the thermal expansion of the two different material systems were overcome with a complex buffer structure grown by CVD, MBE and MOCVD.

CVD produced 0.8 µm-thick layers of $Si_{0.1}Ge_{0.9}$ and $Si_{0.05}Ge_{0.95}$ and a 1 µm-thick layer of germanium on the silicon (100) substrate, which was off-cut by 6° in the [110] direction. A 1.5 µm GaAs film was then grown by MOCVD, before MBE was used to add the HEMT.

No cross-hatching was observed on the surface of the material. Transmission-electron-microscopy images showed sharp interfaces between the buffer layers, and a low defect density in the 15 nm-thick InAs channel layer. The surface roughness is less than 2 nm, according to atomic-force-microscopy images, and the sheet density of the HEMT structure is 3.04×10^{12} cm^{-2}.

Journal reference
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