COMPOUND SEMICONDUCTOR

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Main cover image: *Toyota's Prius is the best-known hybrid electric vehicle, but it could become even more efficient if SiC chips replace silicon in some functions. See p14. Credit: Toyota.*

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Editor Michael Hatcher
michael.hatcher@iop.org
Tel +44 117 930 1013. Fax +44 117 925 1942

Features editor Richard Stevenson
richard.stevenson@iop.org
Tel +44 117 930 1192

Reporter Andy Extance
andy.extance@iop.org
Tel +44 117 930 1007

Senior sales executive David Iddon
david.iddon@iop.org
Tel +44 117 930 1032. Fax +44 117 920 0977

Business development manager Rosemarie Guardino
Guardino@ioppubusa.com
Tel +1 215 627 0880. Fax +1 215 627 0879

Sales executive Paul Russo
russo@ioppubusa.com
Tel +1 215 627 0880

Circulation manager Claire Webber
claire.webber@iop.org
Tel +44 117 930 1165. Fax +44 117 920 0984

Publisher Michael Hatcher
Production Louise Unwin
Ad production Mark Trimnell
Art director Andrew Giaquinto
Technical illustrator Alison Tovey

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IOP Publishing

Is it GaN time yet?

One of the inevitable challenges with a monthly magazine is that of the printing deadline. I'm writing this just a day before we send the issue to be produced, which also happens to be the eve of the annual International Microwave Symposium (IMS) in Atlanta. But the logistics of the printing process and our worldwide circulation means that you will inevitably be reading it after the event has taken place.

So any predictions about developments at this key meeting for the wireless industry are likely to invite egg onto face. Here goes: I reckon that GaN-based RF devices will make a bit of an impact this time round.

Touted as a key technology for third-generation cellular base stations for many years now, GaN has hardly made a dent in the hegemony of high-power silicon LDMOS and, to a lesser extent, GaAs PHEMTs. However, in the run-up to IMS 2008, also known as MTT-S, there were signs that we could be nearing a turning point for GaN microelectronics. TriQuint Semiconductor was expected to make some important announcements, while Cree released the world's first GaN MMIC amplifiers and a new GaN foundry service. Might we also see details of real system integration of these high-tech, but expensive, devices? By now you will know.

> "I reckon that GaN-based RF devices will make a bit of an impact this time round."

The issue of cost has been a crucial element in the failure of GaN to penetrate the cellular business. But it isn't the only factor – the wireless industry is conservative and displacing an incumbent technology that works pretty well with an unproved alternative is never going to be a compelling argument without a massive performance increase to justify the technology switch. GaN protagonists have failed to convince thus far.

However, with developments like Cree's new foundry service, and the research by IMEC and Aixtron suggesting that GaN and silicon could be compatible on a wafer diameter as large as 8 inches (p5), device costs should drop considerably. Add to that the major efforts to deploy new protocols like WiMAX and cellular long-term evolution, where there is no incumbent technology, and wide-bandgap semiconductor technology suddenly doesn't find itself at such a major disadvantage.

I guess I'll find out whether that is beginning to stack up soon.

Michael Hatcher *Editor*

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EPITAXY

GaN looks good on 8 inch silicon wafer

Researchers from IMEC and Aixtron have produced the first crack-free nitride film on a 200 mm silicon substrate.

The work, demonstrated in Aixtron's application laboratory using a "CRIUS" close-coupled showerhead tool for MOCVD adapted for the larger material, suggests that GaN-based power devices could be made in volume on a low-cost silicon substrate.

With native nitride substrates remaining unavailable or prohibitively expensive, engineers have to make do with SiC, sapphire or silicon substrates, none of which is ideal for the task.

SiC wafers provide a good lattice match with GaN but are very expensive to produce. Sapphire is cheaper, but its lattice mismatch with nitrides means that crystal defects are a huge problem. Silicon is much cheaper than both, but it poses thermal and lattice mismatch issues when combined with the wide-bandgap semiconductor.

Over the past few years the IMEC team has shown that the production of GaN on large-area silicon could be viable: first with 100, then 150 and now 200 mm wafer fabrication. Marianne Germain, who manages IMEC's efficient power program, said: "Bringing GaN devices to a [price] level acceptable for most applications requires a drastic reduction in the cost of this technology."

"Only silicon is viable for mass applications," she told *Compound Semiconductor*.

Growth business: this 200 mm silicon wafer is the largest to feature a smooth AlGaN/GaN film.

IMEC

Crucial to the latest work is the availability of 200 mm (111) crystal orientation silicon substrates, custom-made by wafer specialist MEMC Electronic Materials. This is not the standard (001) silicon material used in CMOS and memory applications, but Germain believes that it will not prove to be a hindrance to low-cost production.

The team began the deposition of a standard layer stack with AlN epitaxy directly onto the silicon, followed by an AlGaN buffer layer and a 1 µm thick GaN top layer. Next came a 20 nm AlGaN layer, before the structure was capped with 2 nm of GaN.

The resulting epiwafer showed excellent thickness uniformity and, says Germain, good crystalline quality, as measured by high-resolution X-ray diffraction.

One problem that still remains is the substantial bowing effect that is caused by the large silicon wafer. This is in the range of 100 µm, but Germain believes that an optimized buffer layer will reduce the degree of bowing drastically. A new *in situ* thermal profiling tool developed with collaborators at Aixtron is also helping to produce more uniform wafers, while MOCVD-grown SiN passivation layers play an important role in stabilizing the layer structure and allowing low sheet resistivity.

The IMEC team has also now fabricated power devices on smaller substrates. "For 4 and 6 inch wafers, the bow is well under control," said Germain. At the moment, the maximum breakdown voltage limit for devices made on 4 inch (111) silicon stands at 600 V. Germain is aiming to push up this figure by increasing the layer thickness.

With the work impressing delegates at the recent IC-MOVPE Conference in Metz, France, Germain is confident that her approach will ultimately prove successful in the commercial arena. "This confirms the importance of the GaN-on-silicon approach using MOCVD," she said. "I think that this approach will be the only one in the industry used for power switching applications."

Germain estimates that the technique will become commercialized in about three years. IMEC is also developing GaN-on-silicon HEMTs for RFIC applications, and it has a project working on optoelectronics – with the aim of improving internal quantum efficiencies in green LEDs made on a 4 inch silicon platform.

WIRELESS COMMUNICATIONS

Shift to 700 MHz spectrum needs GaAs linearity

GaAs chip makers should benefit from the newly available 700 MHz spectrum in the US when analog TV broadcasts are dropped in early 2009 and the band becomes available for wireless applications, believe Avago Technologies and Strategy Analytics.

Now that the dust has settled from the US auction of this spectrum, the winning wireless communications companies say that these airwaves will be used for long-term evolution (LTE) cellular services. The efforts to bring the 4G standard online are being led by Verizon, which is expected to deploy the first LTE networks, and AT&T.

Although lower than the frequencies currently used in 3G communications, LTE will help to ensure that GaAs remains dominant in 700 MHz RF power amplifiers (PAs).

"Where the focus is on data and LTE, then linearity requirements will ensure that GaAs remains the primary technology for handset front-ends," said Asif Anwar, the director of Strategy Analytics' GaAs and compound semiconductor program.

"The fact that 700 MHz looks like it will be used for LTE argues for the use of GaAs rather than silicon," agreed William Mueller, manager of RF chip manufacturer Avago Technologies' wireless semiconductor division. Mueller and Anwar agree that products look set to be physically released for use in the former analog TV spectrum by 2010.

As well as the tough linearity requirements, Mueller says that design and performance expectations for LTE will call on PAs to be very small and efficient, and to operate within tight current and temperature limits. He highlights that, although it is reputed for its excellent radio signal propagation properties, the 700 MHz spectrum's bandwidth constraints mean that some services will still need to operate at higher frequencies. This will limit the overall demand for 700 MHz products.

Anwar says that Avago and all of the major GaAs PA suppliers are readily able to address the 700 MHz spectrum. "We may also see a challenge from Mitsubishi Electric, which is looking to expand beyond its Asian market base into North America and Europe," remarked the analyst.

MOBILE HANDSETS

Blackberries bear fruit for Skyworks

Shares in Skyworks Solutions reached a four-year high of just over $11 in mid-June, thanks partly to growing sales of Blackberry smartphones and increased penetration of applications outside mobile handsets.

Part of the recent burst of growth in sales and profitability at the Woburn, MA, manufacturer of GaAs chips has resulted from its acquisition of Freescale's handset power amplifier (PA) business in late 2007. PAs feature heavily in Blackberry smartphones made by Research in Motion, and they highlight how Skyworks' handset business is diverging into two distinct categories.

At the top end of the market, each phone might contain up to $6 worth of Skyworks components. The company is already shipping in volume to each of the top-five phone manufacturers.

Crucially, Skyworks has now agreed a deal with key handset chip supplier Qualcomm, marking the first time that it has worked directly with the semiconductor giant on platforms for next-generation handset designs. Skyworks will provide Qualcomm with several new front-end RF architectures, including a 4 × 4 mm PA operating at 450 MHz, which ought to keep it at the forefront in advanced handsets.

RESEARCH IN MOTION

The acquisition of Freescale's handset power amplifier business in late 2007 has increased Skyworks' penetration in Blackberry smartphones.

Meanwhile, the market for low-end handsets in developing economies is growing rapidly, with phone manufacturers like Nokia hoping to drive the cost of its products further down. Counter intuitively, company CEO David Aldrich says that the market for low-end handsets is now becoming "less commoditized".

The reason for this is an increased use of system-on-chip architectures in these types of handset. This means that there is an increasing need for higher performance from the phone's PA, switch and filter components, says Aldrich.

Skyworks has capitalized on this and is supplying its "Intera" products to sit alongside the "LoCosto" SoC platforms provided by Texas Instruments for cheaper handsets.

Demand for its GaAs chips has reached the point where Skyworks has enlisted the services of Taiwanese foundry WIN Semiconductors to extend its manufacturing capability. The move comes not long after Skyworks inked an extension to its agreement with epitaxy partner Kopin. WIN, which already runs two 6 inch fabs, says that it too is expanding, having just purchased land earmarked for a third wafer fab.

For Skyworks, WIN is mostly focused on manufacturing GaAs PHEMTs, although the relationship is expected to extend to other types of device as the US company looks to diversify further outside its traditional handset domain. Femtocells represent one new market (p7) and the company is also supporting 802.11n wireless LAN applications through its partnerships with Broadcom and Atheros.

MERGERS AND ACQUISITIONS

TriQuint completes WJ deal and closes gap on rivals

Californian RF device firm WJ Communications is now formally a part of TriQuint Semiconductor, as consolidation in the GaAs industry continues to reduce the number of companies vying for slots in wireless communications products.

The deal, valued at $72 million, saw 132 WJ staff join TriQuint, while it adds significantly to the set of RF devices that TriQuint can supply for wireless applications.

Already strong in high-power amplifier, low-noise amplifier, and surface and bulk acoustic-wave (SAW and BAW) filter components, the WJ acquisition adds expertise in mixer, variable amplifier and relatively low-power amplifier technologies.

Commenting on the completion of the deal in a prepared statement for the company, TriQuint's vice-president of networks, Brian Balut, said: "WJ's gain block portfolio complements our base station line-up with very little overlap."

"For example, there are three functionally related areas in a base-station RF amplifier circuit comprise predriver, driver and output stages. WJ's lower-power, high-voltage HBT products are well suited as predrivers and drivers, while our high-power devices serve the driver and output stages."

WJ has also enjoyed initial success in the emerging Chinese market for third-generation wireless communications, which is based on the local TD-SCDMA protocol. The company became a fabless operation relatively recently and works with the Californian foundry Global Communication Semiconductors (GCS).

Although TriQuint operates two GaAs fabs of its own, these are currently running near to ideal capacity, so GCS will continue to manufacture the former WJ products for the foreseeable future.

Meanwhile, Strategy Analytics says that TriQuint made up ground on RFMD and Skyworks last year. As cellphone power amplifier (PA) makers enjoyed industry-wide sales increases in 2007, TriQuint trumped the rest of the field by gaining nearly 5% of market share.

According to the company's market analyst review of the global PA market, 2007 was a "banner year" in which total sales grew by 12.6% overall to reach $1.94 billion. Approximately 90% of this market value was accounted for by GaAs PAs.

"RF Micro Devices and Skyworks slipped slightly in market share in cellular PAs in 2007," said the report's author, Chris Taylor. "Much of this went to TriQuint, which moved ahead of Renesas as the third-ranked supplier in terms of revenue on the strength of its broad line of compact PAs, PA switches and PA-duplexer-filter modules."

MARKETS

Femtocells shape up for GaAs

Skyworks is supplying Samsung with four types of component for use in the Korean firm's femtocells, including the wideband-CDMA SKY77410 PA.

New reports conclude that the market for femtocells – tiny base stations that provide broadband cellular connectivity in the home or office – is set to boom. The emerging market is expected to explode over the next five years, providing a key new application for power amplifier (PA) components, and a likely boost for makers of GaAs devices.

Reports from ABI Research, In-Stat and Wintergreen Research all predict a sharp increase in deployments of femtocells, with accompanying demand for the various semiconductor components that they require. The transmitters are seen by some as the best solution to providing reliable broadband cellular connectivity inside homes and offices.

As anybody living in a house with thick stone walls will attest, indoor cellular reception can be very variable. That's because the signals being transmitted between a cellular handset and a remote base station are absorbed to varying degrees depending on the specific location of the two.

For conventional mobile services, like voice calls and simple messaging, that isn't a problem, but with demand for data-hungry services increasing, broadband coverage needs to be less patchy and more reliable.

It seems that some network operators have concluded that the most cost-effective way of ensuring coverage is for customers who want broadband cellular access to deploy femtocells in their homes and workplaces.

The US company Wintergreen Research issued a report forecasting that global shipments of the tiny base stations, which today stand at virtually zero, will grow to nearly 48 million in 2012 as the predicted cost of the cells drops to just $100. In its less bullish report, In-Stat predicts 31 million unit shipments of femtocells and related picocells and microcells by the same year.

"One barrier to roll-out is the need to reduce the cost per unit of the hardware," states the Wintergreen report. "Initially it may be that operators provide femtocells to customers as part of a service plan."

In another report, Stuart Carlaw from ABI Research predicts that the market for semiconductors used in femtocell applications will grow from less than $72 million in 2008 to nearly $2 billion by 2013.

As always, that market will be dominated by silicon devices, but femtocells will also require PAs operating at cellular frequencies – an application dominated by GaAs at the handset level, but by silicon LDMOS in conventional base stations.

Femtocell signals are designed to operate over a short range, so the high power of silicon LDMOS technologies is not a prerequisite, suggesting that incumbent handset PA suppliers, such as RF Micro Devices and Skyworks Solutions, may actually be at an advantage.

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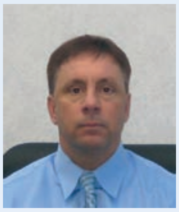
...Cree sampling for WiMAX

Chip maker Cree has released two GaN HEMT transistors for use in WiMAX applications covering the 4.9–5.8 GHz frequency band, as well as the first GaN MMIC amplifiers and a new GaN foundry service. The new transistors, designated CGH55015F and CGH55030F, are the first GaN HEMTs to be released that are specified to operate at up to 5.8 GHz for the 4G wireless protocol.

...Plextek targets X-band

UK-based electronics and communications design consultancy Plextek has designed 2 W and 4 W X-band power amplifier MMICs for a domestic electronics component supplier. Significantly, the MMICs are not subject to ITAR export restrictions because the fabrication, design and supply is undertaken by non-US companies. Both of the MMICs cover 8–12 GHz.



SEMICONDUCTOR MATERIALS

SAFC scales up its precursor delivery

Metalorganics supplier SAFC Hitech is making a departure into selling industrial-scale vapor distribution systems, in response to growing demand from compound semiconductor manufacturers.

SAFC launched its EpiVapor system on June 2 to coincide with the International Conference of Metalorganic Vapor Phase Epitaxy in Metz, France, to highlight the benefits over traditional small-scale reagent bubblers to the III-V audience.

"The purpose of this equipment is to make the process of delivery into the reactor chamber cheaper," said Peter Heys, SAFC Hitech's research and development director.

EpiVapor pumps chemicals from a dedicated storage cabinet – designed specifically to handle pyrophoric materials – outside a semiconductor fab's cleanroom, through a series of temperature-controlled pipes.

These pipes run into bubblers linked to deposition tools, refilling them automatically when deemed necessary by the integrated EpiSensor capacitance-detection system. The set-up can be used to feed up to eight reactors, using hydrogen or another inert carrier gas to ensure reagent stability.

As an intermediate option for increasing the precursor delivery scale that does not demand full industrial automation, SAFC is bringing a 13 kg bubbler to market. According to Heys, current bubblers create a huge expense from lost output because reactors are shut down when they are replenished.

"The amount of money that's spent on downtime is hundreds and thousands of dollars per hour," he said. "The EpiVapor system reduces the amount of downtime in the fab. Instead of having to change every 500 g or 1 kg as a bubbler empties of material, it will only have to be changed after 25 kg."

The EpiVapor system is primarily targeted towards ALD and MOCVD, and it could be used in a wide range of applications, including solar cells and memory. However, high-volume industrialization of the LED industry is the principal driving force behind its development, making it particularly well suited for use with trimethylgallium and trimethylaluminum.

"The wafer fab area of these customers has increased and therefore it has demanded an improved method of delivery to keep the rate of production of LEDs going," Heys said. "The design is based on these customers' comments and demands, and the feeling that we pick up through the marketplace."

SAPPHIRE SUBSTRATES

Chinese group to buy Honeywell's sapphire

Industrial giant China Silian Instruments Group is set to buy Honeywell's sapphire business and launch a bid to become a vertically integrated LED manufacturer.

The 45 workers at Honeywell's Victoria, Canada, site are due to transfer to Silian on July 26. The deal includes Honeywell's sapphire substrate, window, dome and custom sapphire fabrication business.

Silian believes that this move is a big coup for its fledgling LED business. It says that the international sapphire wafer market is seriously short on supply, especially for large and high-quality substrates.

Xiaobo Xiang, Silian's chairman, points out that making sapphire wafers will allow the company to play a pivotal role in the global LED industry. He adds confidently that the high-quality core technology that his company is set to acquire will break through the supply bottleneck.

The Silian Group operates in a diverse range of industries, focusing on industrial automation control systems. It plans to supplement the Canadian business by building a larger-scale sapphire manufacturing facility in Chongqing, to serve Asian markets.

Beyond that, the Chinese group will set up a 0.66 km^2 LED industrial park in the Caijia industrial zone. Construction will begin in 2008 and production in 2012.

OSRAM OS

Chips made by Osram Opto Semiconductors were a hit at the 2008 Society for Information Display (SID) Symposium, which was held in Las Vegas, Nevada, in late May. They featured in this curved 42 inch display as well as a 70 inch Sony TV and a 103 inch prototype.

The German firm also launched its RGB MicrosideLED, in which Osram claims an industry-leading high-efficiency green chip that delivers 1000 mcd at 20 A. That comes at a power efficiency of 50 lm/W from a square 0.3 mm long chip and integrates into an overall package measuring only 5.0 × 1.4 × 0.6 mm.

"The MicrosideLED is very, very thin," said Osram's manager for LCD backlighting, Winfried Schwedler. "There is no other design with this great green in such a thin package right now." He adds that while he was at SID, a "very big" LCD producer said that the package could provide a breakthrough in mobile handset applications.

Schwedler says that uptake from consumer electronics companies could see MicrosideLED being manufactured in volumes of tens of millions of units within six months.

VENTURE FUNDING

CrystalQ secures sapphire funds

CrystalQ, the Dutch supplier of sapphire substrates, has secured venture funding that it will use to start producing its own crystals, rather than cutting and polishing externally sourced material.

"We are going to use the money to invest in equipment for crystal growth because that is where we see the bottleneck," said Joris Barendregt, general manager of CrystalQ. "We believe that there will be huge pressure on the sapphire market. There is a very high barrier for entry."

Barandregt told *Compound Semiconductor* that part of the funding will buy equipment from Russian suppliers, and will develop an in-house crystal growth process.

Led by Sustainable Energy Technology Fund, EPT/Benno Wiersma and E2 Cleantech, the latest funding round was accompanied by an investment incentive. If and when CrystalQ proves that it can produce bulk crystal sapphire, additional multimillion euro funding will allow a production scale-up. "It is important to show that we can produce, that we have the knowledge and process under control," Barandregt said.

He says that if CrystalQ can achieve this goal, LED and radio-frequency chip-manufacturing companies are ready to follow with large purchases.

The company has already built some relationships by selling the equivalent of 50,000 2 inch wafers annually, which it slices and smooths with a proprietary polishing technique. However, CrystalQ focuses on larger-diameter substrates and its crystal growth development will concentrate initially on 6 inch sapphire wafers.

SOLID-STATE LIGHTING

Toshiba challenges 100 W bulb brightness

Next month, Toshiba Lighting and Technology (TLT) Corporation will release a series of LED-based downlights that boast a brightness equivalent to that of a conventional 100 W incandescent bulb.

Due to launch on August 1, there are eight different models in the "E-CORE100" range. They are said to deliver up to 920 lm in total light output at a maximum efficacy of 65 lm/W. Having previously launched 40 and 60 W equivalents, the Toshiba subsidiary claims that its E-CORE100 will be the brightest LED lamps on the market.

However, that 920 lm figure only applies to one of the models, which has a color temperature of 5000 K – similar to that of a cool-white fluorescent lamp. What's more, the lamps do not come cheap. TLT quotes a list price of ¥38,000 ($360) for the 5000 K lamp, excluding tax.

Other lamps in the new range include two warm-white sources with a color temperature of 2800 K – a good match to regular incandescent bulbs – optimized for either power efficiency or color rendering, depending on the customer's preference.

Despite the high price of its new lamps, TLT is anticipating strong demand and is aiming to sell 60,000 units per year.

AUDI

Audi says that 54 LEDs feature in its first all-solid-state headlamp, released in late May as an upgrade option for its R8 sports car. It quotes a price of €3590 ($5550).

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...Sony returns to LEDs

New BRAVIA TVs from Sony are to feature LED backlights for the first time. Its 8-series 55 and 46 inch models both use red, green and blue emitters.

...Showa Denko in production

Japanese chip maker Showa Denko has started shipping red LEDs with a claimed record efficiency of 80 lm/W. Improved electrode design and chip-surface treatment are said to be behind the 40% increase in performance.

SOLAR POWER

Compound cells double electricity yield

Compound semiconductor cells have helped a solar installation in Seville, Spain, to claim a record conversion efficiency of sunlight into alternating current. In May, German firm Concentrix Solar measured a figure of 23% under normal operating conditions as its 5.6 kW concentrator photovoltaic (CPV) system fed energy into the utility grid.

The record system exploited improved CPV modules, in which sunlight is focused onto GaAs-based solar cells to generate a DC output. The system's inverter converts this into the AC form that is required by the grid. Concentrix emphasized the importance of this stage in the overall efficiency of the set-up.

"We are overjoyed that we have succeeded in even exceeding the projected values", said Concentrix's CEO, Hansjörg Lerchenmüller. He says that the overall system produced almost exactly double the electricity yield of conventional photovoltaic power systems. "Typical daily average AC system efficiency is in the region of 22%," he said.


CONCENTRIX SOLAR

Photovoltaic concentrator systems like these from Concentrix are increasingly being seen in Spain.

Lerchenmüller says that typical silicon photovoltaic modules only deliver 13.5% conversion efficiencies, even before losses in the system are taken into account: "You lose 4 or 5% in the inverter and you lose 8 or 9% due to temperature effects, so without even considering other losses you are down to 11.7% [with silicon]."

Further improvements to the CPV system efficiency should follow with the introduction of an inverter based on SiC semiconductor components, which the record-breaking system does not yet use.

Lerchenmüller's excitement looks excusable, with a pivotal 100 kW system that uses the record-breaking technology at the ISFOC project in Castilla-La Mancha "ready to be connected to the grid". Overall, Concentrix will contribute 500 kW to this 3 MW project.

The company will soon start production at its system plant in Freiburg, which has an annual capacity of 25 MW. The systems will be sold by Concentrix Iberia, a collaboration between Concentrix and Abengoa Solar. Abengoa operates and builds photovoltaic systems in a portfolio that it says runs to hundreds of megawatts across Europe, northern Africa and North America.

Although deployments like ISFOC will take up a proportion of its production, Concentrix is doing brisk business in CPV systems sales. At the CPV Today summit in early April, Lerchenmüller said that even with the new plant coming online, Concentrix's capacity for 2008 is already fully booked.

In early June he added that the company is still receiving lots of requests: "Spain and Italy are in front, but there is a strong interest from the US too."

FIBER-OPTIC COMPONENTS

Finisar and Optium aim for top

By Pauline Rigby and Michael Hatcher

Consolidation in the optical components industry moved up a gear in mid-May with the news that Finisar and Optium had reached a definitive agreement to merge in an all-stock transaction worth approximately $212 million.

The deal calls for each Optium share to be exchanged for 6.262 Finisar shares. On completion, which is expected in the third quarter of 2008, Finisar and Optium shareholders will own approximately 65 and 35% of the combined company, respectively.

According to the two companies, the merger will create the world's largest supplier of optical components, modules and subsystems for the fiber-optic communications industry – overtaking the current number one player, JDSU.

The deal will be welcome relief to the telecoms industry. The sheer number of optical components suppliers has created a cut-throat market environment where vendors are forced to compete on price, sometimes cutting their own throats in the process.

What's more, the two vendors appear to have broken down the usual barriers to consolidation – overlapping product lines, poor profitability and a lack of shared interests – to create an attractive deal for investors.

Finisar, which unlike Optium manufactures its own III-V devices, currently occupies the number-two position in terms of market share, while Optium is the number-10 supplier. Combining the revenues of the two component vendors gives total annualized revenues of around $612 million. JDSU's revenues, calculated in the same way, are $544 million.

With the fiber-optic industry rebounding strongly on demand for additional bandwidth, both Finisar and Optium announced record revenues in their latest financial quarters. Optium's sales rocketed by 30% year on year and more than 10% sequentially to $45 million, while Finisar's jumped by 25% year-on-year to $121 million.

For Finisar and Optium, the deal will create scale, not just in revenues but also in the range of their product portfolio.

Finisar sells primarily into enterprise and storage networking markets, while Optium's main customers are in the telecoms space with a smaller percentage in cable TV, although Jerry Rawls, Finisar's chair, admits that there is some overlap in 10 Gbit/s pluggable modules.

Finisar recently took an equity stake in reconfigurable optical add-drop multiplexer (ROADM) start-up Nistica, but Rawls doesn't see any conflict with Optium's home-grown ROADM products. "The major product from Optium is high port-count, while Nistica's is an edge device."

Once the deal is ratified, the Finisar name will survive and the combined company will continue to trade on the Nasdaq stock market under the symbol FNSR.

Rawls will remain as the executive chairman of Finisar's board, while Optium's chairman and CEO Eitan Gertel will become president and CEO of the new combined company.

Pauline Rigby is editor of fibresystems.org.

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...'Missing link' from CIP

CIP Technologies, the UK photonics foundry based in Ipswich, has released what is believed to be the first commercial reflective electroabsorption modulator. The InP-based device is said to provide a simple way of linking radio antennae to high-speed optical cable, thereby extending the coverage of high-data-rate wireless technologies.

...Cool vision

InGaAs sensor specialist Princeton Lightwave and Nextreme Thermal Solutions are to jointly develop a short-wave infrared focal-plane sensor featuring very efficient thermoelectric cooling to reduce thermally generated noise. The two companies will integrate thin-film thermoelectric coolers with focal-plane arrays to improve night-vision equipment.

...Nakamura award

Shuji Nakamura, GaN optoelectronics pioneer and director of UC Santa Barbara's Solid-State Lighting and Energy Center, has won the 2008 Prince of Asturias Award for Technical and Scientific Research.

BOOKHAM

Couder turns the tables at Bookham

Despite burning its way through hundreds of millions of dollars over the past 20 years, InP and GaAs chip maker Bookham is still in business. Remarkably, it now looks like it will be generating cash by the end of 2008. **Michael Hatcher** asks CEO **Alain Couder** how he has turned around the company's fortunes.

BOOKHAM

Alain Couder: CV highlights

August 2007: Joins Bookham as CEO.
March 2005: President and CEO of Solid Information Technology Inc, a supplier of database solutions.
May 2004: Advisor for Sofinnova Ventures.
April 2003: President and CEO of Confluent Software, Inc.
August 2002: President and CEO of IP Dynamics, Inc.
Feb 2000 – May 2002: COO of Agilent Technologies.
1998–1999: Chairman and CEO of Packard Bell NEC, Inc.
1991–1999: Chief operating officer of Groupe Bull.
1970–1984: IBM, rose from research scientist to engineering lead, codeveloping IBM's first RISC microprocessor.

What have you brought to Bookham?
I think I bring experience in turning companies around. The difficult part is not so much cutting costs, but building a growth path after that. And building a management team that can do it.

In terms of the semiconductor industry, as an engineer I started out doing chip design. And later on I was chief operating officer at Agilent Technologies [now Avago]. So I have been involved with very dense, high-performance large-scale integration, and telecoms and optical technologies.

I have a pretty good understanding of the market, as well as management experience. But this is not enough – even if you are the boss, you do not change the culture of a 2000-person company overnight. I really liked the people I met here – like Jim Haynes and Adrian Meldrum – and I thought that we could work well together. That's an important element of success, to be in a team that can work together and with minimal politics at the executive level.

Bookham has never been a profitable chip maker – how can you achieve that?
There are two pillars to a strong company. One is innovation and the other is customer relationships. I believe that, from an intellectual property standpoint, we have excellent engineers who can innovate. But we just need to make sure that they are focused on a few projects, so that we don't spread our resources too thin. Although I wasn't there, from what I have seen this has probably happened in the past. There were several areas that we had to discontinue because we had no chance of becoming a leader in that field.

With customer relationships you need to be perceived as easy to do business with and better than your competition. You need to enter into a business relationship with them because they want to make money and you want to make money – you can't always be in a price war, it just doesn't work. In order to get there you need to be reducing your costs, but still make sure that you achieve the right margin.

This was the challenge that we had with recent new products. They didn't have the correct bill of materials to be priced at the right point for the market. So we worked with our customers on what the right price was and then we put in place a cost-reduction program. One example was with the tunable [laser], which is now a high-growth product in telecom. With that in place we are quite confident that we can start generating cash before the end of the year.

How much more do you need to improve margins?
We are doing a little bit of additional cost cutting, by moving our San Jose manufacturing to Shenzhen and by aligning our research and development resources around the world better, but without cutting them. I want to keep research and development spending at 13% of revenue, so this is more of a redeployment of resources than an actual cost cut.

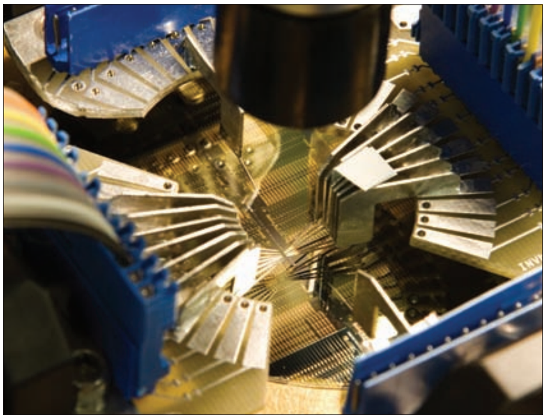
Because of the improvement in our bill of materials and efficiency, plus the additional restructuring, between now and the end of the year we will save about $5–6 million per quarter.

Then we will be making money, but we won't stop there. The next step is to continue to grow the top line, and I think that we're on track to do that year after year. We are growing between 20 and 30% [per annum] right now and I think that we clearly have an objective to have a gross margin in the range of 25–30%, with a 10% operating margin. We have tax credits in the UK and US, so we probably won't be paying taxes for a few years. This could make us an attractive company from an earnings point of view.

Bookham has raised and burned through a lot of cash in the past. Will you need to raise any more?
No. This is why we have been putting all the focus on cash. The number-one priority now, and for several months, has been cash. I'm not saying that by the end of the year we will be profitable, but the objective is to start generating cash by then.

We have about $50 million cash [on our balance sheet] and moving forward we are not going to use much of that. I'm not saying that we will never again raise money from an external source, but for organic growth, no – we have the cash we need. It is incredible that you can raise cash for 20 years and not make money, but this is the way it has been.

When I joined there was a lot of doubt about the future of Bookham and whether we would still be around. I think that this has totally changed. When I



BOOKHAM

On-wafer testing of ILMZ chips being developed at Bookham. An engineer by training, Couder plans to maintain a high level of R&D spending to ensure innovation at the chip level.

meet with investors now, I get a lot of questions but I don't think that there is any doubt that we will be one of the important players in the game.

Has pricing pressure eased in response to industry consolidation?

Price pressure is there, and will continue to be there. I've been in the semiconductor industry before and I don't see any reason why Moore's law will not apply to the optical components industry too. So it's not price pressure: it's more prices declining over time with better technology.

If you look at it as Moore's law, rather than price pressure, you make different decisions. You decide that you have no choice but to invest in innovations in such a way that the price can decline. This takes us back to one of the major strategic decisions that Bookham has made: that the breakthroughs in cost reduction have to come from the chip level. It is by integrating more functions in one chip that we will get the costs down. I think that having control of the InP fab in Caswell and having a very experienced R&D team working on these matters makes a difference.

For GaAs lasers the price per watt of output is declining very much along the lines of Moore's law as well. It's the same thing.

How will industry consolidation in optical components affect Bookham?

Bookham's chip technology is the cornerstone of future growth, but it does position us in telecom. We are not in data communications and we are not in access networks – we are focused on long-haul and metro, and in that area we have been successful.

But we think that to be competitive in the amplifier space we need reconfigurable optical add/drop multiplexer technology, so we will find a way to get that. We are strong at the chip level – that's our core competence. We will complement that with partnerships and we are working on technology acquisitions.

At the same time, consolidation in the industry is clearly there, and Avanex and Bookham were talking 18 months ago. If the opportunity arises, and makes sense for our shareholders, we might do it. But we have to be aware that mergers between similar-sized companies are difficult. In high-tech, my experience is that the probability of success is not very high.

What kind of chip technologies are you spending money to develop?

There is some money in the UK for InP: we have a 40 Gbit/s prototype that we are showing customers, which has more than one function on the chip. In Zurich we are working on improving the price per watt. We entered the submarine pump business two years ago and we are deploying in volume to Tyco. We also have design wins with a couple more customers and next year we should start shipping in volume to them as well. So we are putting in money to ensure that we continue to improve these products.

It is very clear that the backbone networks are out of bandwidth. Now that the world economy is increasingly global, the backbone between continents is critical. And the only technology to increase the bandwidth on backbone between continents is optical submarine cable. Right now I think that the industry is deploying as much cable as it can.

However, in pump lasers the number of competitors has shrunk dramatically. We are down to competition with just JDSU and 3S Photonics. So with that consolidation we can really invest for the future and increase the power and stability of our product. This is an area where we can make money.

What is Bookham's most important product?

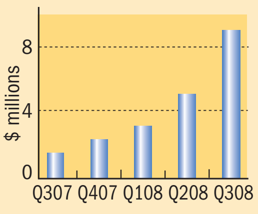
Oh, it is clearly our tunable laser – that is growing very fast. We are capacity limited for the June quarter, and we are investing in a significant increase in capacity for the next and following quarters. In the March quarter our sequential growth was 75% for tunable lasers. In the June quarter it will be less, but we should resume this kind of growth in the September and December quarters.

But we were not optimistic enough in our forecast and we have changed it to make sure that it does not happen again in the future. The limitation was due to slow testing capability – testing a tunable product is a lot more complex than a fixed-wavelength laser because you have to check all of the wavelengths.

We are winning the designs almost all of the time because of a combination of performance, cost and quality. There have been some rumors in the industry that we have been dumping prices to gain market share, but I don't think we did that. We maybe did some forward pricing but that's all.

You came in to turn the company around. When will you have achieved that?

The next milestone is clearly generating cash, but this only has value if you can maintain growth momentum. You can't get there out of breath, because if you are you cannot run any more. [Generating cash] is the next milestone, but it is not the end. The target is to get to a cost structure that can generate a 10% operating margin. We have growth momentum, but our fab is not full and nor is Shenzhen. I believe that we will be able to get there in a reasonable amount of time and that we are starting to make it a great company. Profitable growth – that's the only game in town.



Sales of tunable lasers are one of the main reasons behind Bookham's recent financial turnaround, and demand is currently outstripping supply.

"When I joined there was a lot of doubt about the future of Bookham...this has totally changed."

SiC BJTs promise to cut th

Getting SiC transistors into hybrid electric vehicles is a win–win scenario. It will open up a large and lucrative market for the wide-bandgap semiconductor, while squeezing a few more miles per gallon out of the automobile, according to **Martin Domeij** and **Muhammad Nawaz** from TranSiC.

Oil prices are rocketing. Black gold shot past $100 a barrel this spring, and many speculate that it could hit twice this figure by the end of the decade. This may be great news for oil traders, but for the rest of us it will just mean higher prices at the pump.

Against this backdrop, alternative vehicle fuels look more attractive. One option is biofuels, such as ethanol, which have been touted as promising alternatives to oil. However, closer inspection reveals the folly of going down this route. Fuel manufacture comes at the expense of global crop production, and this can't be the right thing to do when many of the world's poor have barely enough food to eat.

On a personal level, it is possible to minimize the effects of higher gas prices – and simultaneously reduce your carbon footprint – by switching to a more efficient automobile. This might mean the purchase of a small diesel, but more radical alternatives also exist. Although fuel-cell cars will probably be far too expensive for the foreseeable future, it is possible to go out today and buy competitively priced hybrid electric vehicles (HEVs) from the likes of Honda, Toyota and Lexus.

HEVs deliver more miles per gallon by using an intelligent control system to link a combustion engine with an electric motor. Combustion engine efficiency increases, which slashes fuel consumption by up to 50%. Further improvements are possible, thanks to plug-in HEVs. Charging from the grid cuts airborne pollutants and could deliver an incredibly low carbon footprint if the primary energy source is renewable.

Although HEVs are enjoying some commercial success, further improvements will spur sales. Alongside better batteries, one area neding attention is the power electronic system that drives the motor. This features silicon PN diodes and insulated gate bipolar transistors (IGBTs) to convert the DC source from the battery to an AC form that can power the motor. The systems in today's HEVs are too bulky, so a slimmed-down version would free up space and boost automobile efficiency.

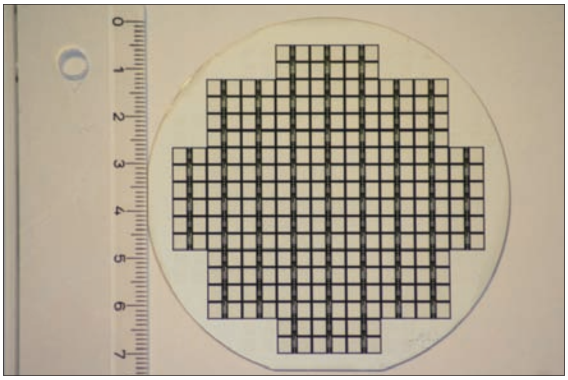
A big impact could be made by eliminating the separate water-cooling system currently needed for the power electronics, which maintains the temperature of silicon devices at less than 150 °C and allows these components to operate reliably. Replacing the silicon chips with SiC equivalents would make this water-cooling system redundant because the combustion engine's system could be used instead.

A switch to SiC would involve the deployment of SiC Schottky diodes and transistors in the boost converter, the DC/AC inverter and the step-down (buck) converter. The boost converter's job is to up-convert the voltage from the DC battery to around 400 V DC. This output is fed into the DC/AC converter. A three-phase AC output from this module produces variable amplitude and frequency that can control the speed of the electrical motor. Step-down converters are also required to transform the high input voltage into lower ones that are suitable for other electronics in the car.

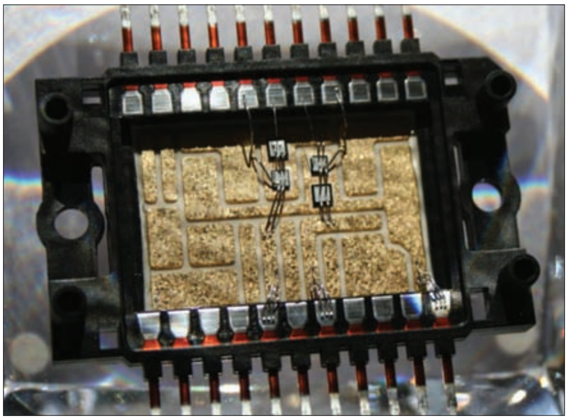
The transistor's role is that of a switch, which can block high voltages in its off state and conduct high currents with low-power losses in its on state. The current alternates between the transistor and a diode that protects the transistor from inductive voltage overshoots. Both of these SiC chips can operate at temperatures well beyond 300 °C, and the maximum operating temperature tends to be limited by their packaging technology. Thanks to the wider bandgap, these devices also enjoy lower conduction and

e cost of greener driving

TOYOTA



TRANSIC



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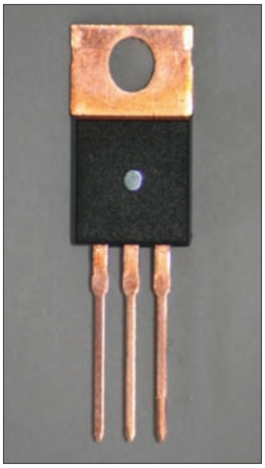


TRANSIC

The Toyota Prius is a hybrid electric vehicle that uses a battery to provide some of the energy needed to power it (far left). Silicon transistors and diodes are currently employed to convert the DC output from the battery into an AC form. However, SiC equivalents would be a better option because they require far less cooling and could eliminate one of the water-based cooling systems. TranSiC has launched bipolar junction transistors for this application. These are grown on 3 inch wafers (top left). They are available on ceramic direct copper bonded substrates (bottom left) and in TO-220 packages (above).

switching power losses than silicon equivalents.

In the past, poor-quality substrates have prevented SiC power devices from fulfilling their promise. Micropipes were the major killer, but they have been eliminated in 100 mm and smaller substrates. Cree has also reduced the density of basal plane dislocations, which will aid device performance by enabling manufacture of reliable, large-area chips.

The breakthroughs in substrate quality have opened the door to the manufacture of high-quality, large-area power devices. SiC Schottky diode chips with 1200 V, 50 A ratings are available from a handful of manufacturers, and the race is on to produce and market SiC power transistors that can deliver all of the benefits associated with this material.

SiC developers have already demonstrated several species of SiC power transistor, including MOSFETs, junction field effect transistors (JFETs), bipolar junction transistors (BJTs) and IGBTs.

The JFET is the most developed technology. This transistor, which is manufactured by SiCED and SemiSouth Laboratories, delivers fast switching and benefits from a low on-resistance. However, the device is normally on, which raises concerns about reliability for HEV applications due to the risk of a driver supply voltage failure.

The MOSFETs that are being developed by SiCED and Cree are another option. However, the channel mobilities in this type of transistor are relatively low, and there are question marks over oxide reliability and threshold voltage stability.

Cree has also been looking at IGBTs. However, this transistor suffers from high on-state losses owing to an additional 3 V forward voltage drop resulting from a PN junction. The IGBT is better suited to high-voltage applications of more than 5 kV, such as the motors in trains and high-voltage DC power transmission.

This leaves the BJT, which is a very promising device for HEV deployment, thanks to its fast switching speeds and low power losses. At TranSiC – which is based in Kista, Sweden, and is a spin-out from KTH Royal Institute of Technology – we have been developing this device since 2005 through funding from Volvo Technology Transfer, Midroc New Technology, the Swedish Energy Agency and the Swedish Governmental Agency for Innovation Systems.

Cree and United Silicon Carbide are also developing the SiC BJT, but we are the first to market following our product launches in May. We now offer two

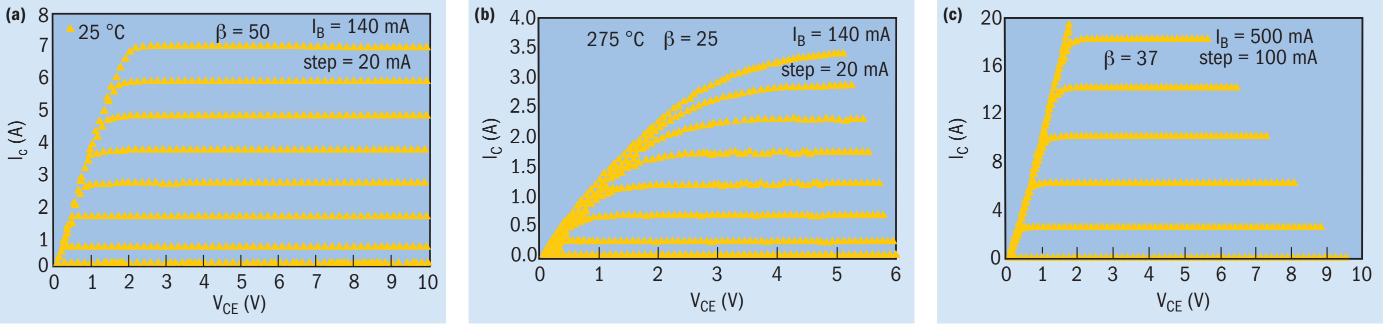
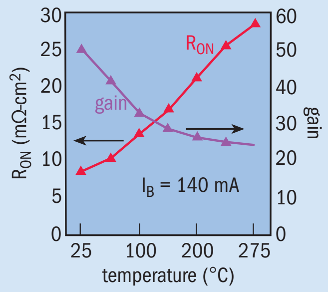
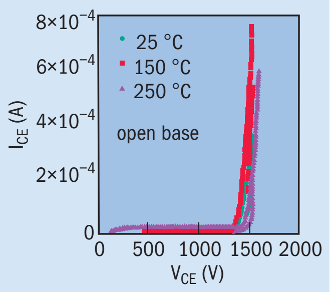


Fig. 1. TranSiC's 6 A **(a, b)** and 20 A **(c)** bipolar junction transistors have a collector-emitter saturation voltage that is 70% lower than that of their silicon equivalents.





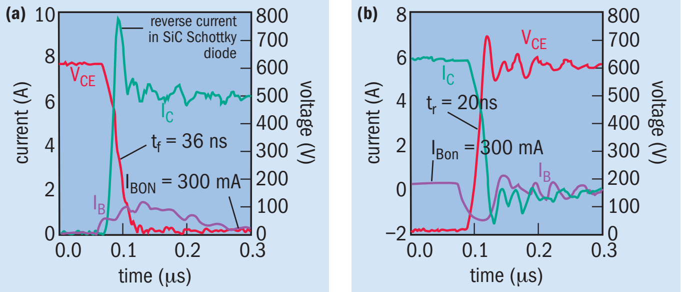


Fig. 2. (left) Decreases in gain at higher temperatures are accompanied by an increase in on-resistance, which ultimately leads to stable parallel connection of several transistor chips. **Fig. 3.** (center left) TranSiC's 1200 V bipolar junction transistors have a breakdown voltage of 1500 V over the temperature range 25–200 °C, which makes them strong candidates in hard-switching applications, such as motor drives. **Fig. 4.** (center right and right) The bipolar junction transistor's fast rise and fall times make it a strong candidate for deployment in the boost converters of hybrid electric vehicles, which have switching speeds of around 100 kHz.

forms of 1200 V BJTs – 6 and 20 A versions, which have active areas of 3.4 and 8.4 mm^2, respectively. Customers can build their own modules by purchasing our single dies, buy our TO-220 packaged BJTs, or purchase BJTs mounted and wire-bonded onto a ceramic direct copper bonded substrate.

Our devices are manufactured on high-quality 3 inch SiC in the Electrum Laboratory, which is owned by KTH. A vertical NPN structure is employed, with dry etching used to create the emitter and base regions. Ion implantation forms low-resistance ohmic contacts with the base, along with high-voltage junction termination. The surface is passivated by thermal oxidation of the etched SiC. This also cuts defect concentrations at the surface and boosts current gain through a reduction in surface recombination. Pads with two metal layers are added over the active region for the bond wires.

Our BJTs produce low-conduction power losses because the collector-emitter voltages (V_{CESAT}) at a collector current density of 100 A/cm^2 are just 0.8–0.85 V (figure 1). In comparison, silicon IGBTs have a V_{CESAT} of at least 2.5 V. This is significant because it slashes the conduction power chip losses by 70% (assuming that both types of chip are the same size) and cuts the chip's cooling demands.

Higher operating temperatures increase the on-resistance of SiC BJTs and reduce the current gain (figure 2). This is beneficial because it enables current sharing and ultimately the stable parallel connection of several transistor chips.

Our 1200 V BJT chips also have a wider reverse bias safe operating area than their silicon equivalents – the breakdown voltage is 1500 V across a wide temperature range (figure 3). This characteristic is a plus point for hard-switching application in motor-drive systems, where there are rapid changes from high currents to high blocking voltages.

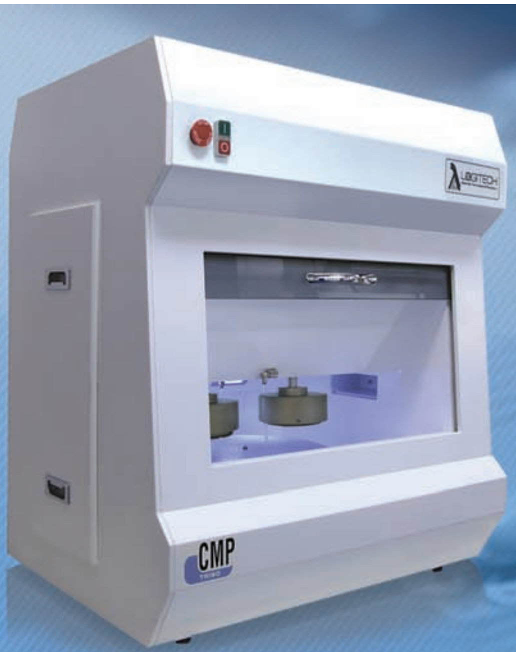
Our BJTs can meet the requirements for fast switching at low power losses in the boost converter, thanks to minimal storage of charge and a high current gain (figure 4). They are capable of switching speeds of 100 kHz at DC voltages of 600–800 V, which are typically used for a 1200 V transistor.

We have demonstrated our BJT's ruggedness with 550 °C I-V tests that house our chip in a special high-temperature package. Its short-circuit capability was verified at room temperature by a 10 μs wide turn-on pulse with a very small series resistance at a V_{CE} of 600 V, followed by successful turn-off. This implies that our device is unlikely to fail in motor-drive systems that have a mistimed transistor turn-on.

We are now scaling up production to 100 mm wafers to increase production capacity and reduce die-fabrication costs. Other targets on our agenda include a BJT gain of 100, which will reduce the current required to maintain the device's on state. Ongoing activities include further fast turn-off tests at high voltages, and efforts to cut the on-resistance and associated on-state power losses. The latter goal will be realized through optimization of the junction-termination technology, which will permit an increase in collector doping. All of these advances will make our BJTs even more appealing for both the HEV market and niche applications, such as high-temperature electronics. ●

About the authors

Martin Domeij (left) is CTO and co-founder of TranSiC. He has been working on the design and characterization of SiC and silicon power devices for the last 14 years and is still active in the SiC device research group at KTH Royal Institute of Technology. **Muhammad Nawaz** (right) is vice-president of test and quality at TranSiC. He has 15 years of experience in the design, modeling, processing and characterization of semiconductor devices and circuits, and has previously worked at Infineon, Ericsson and Chalmers University of Technology in Sweden.


CMP

HOGEN H Series Hydrogen Generation System
HOGEN S Series Hydrogen Generator

DARPA rattles up a half century

DARPA's funding has made a staggering contribution to the compound semiconductor community. Novel materials and devices have flowed forth from its programs and opened up lucrative markets for military and commercial applications. **Richard Stevenson** looks back at the agency's first 50 years.

It's hard to imagine where we would be without the US Defense Advanced Research Projects Agency (DARPA). Decades of funding haven't just helped to create a sizable military market for III-V chips: they have revolutionized manufacturing efficiencies and improved the performance of many compound semiconductor devices for commercial applications. These include the famous GaAs Microwave and Millimeter-Wave Monolithic Integrated Circuits (MIMIC) program, which led to multibillion dollar sales for RF Micro Devices and Skyworks Solutions.

DARPA, formerly known as ARPA, didn't support the compounds when it was formed in 1958. However, it wasn't long before this agency recognized the superior electronic properties of GaAs over silicon, which couldn't produce a good solid-state device for microwave frequencies. In the early 1960s DARPA funded Calver Meads' development of the first GaAs FET at the California Institute of Technology, and by the end of the decade it was constructing its own Center for Materials Research (CMR) at Stanford University. This facility focused on the liquid-phase epitaxial growth of GaAs and the fabrication of microwave devices.

One of CMR's goals was to educate PhD candidates who would subsequently be involved in materials-related technology development issues facing government, industry and university labs. Some success came when two members of CMR – Al Joseph and Richard Eden – moved to Rockwell Science Center, where they continued to develop GaAs microwave devices. Internal funding for this project was under threat in the early 1970s, so they turned to DARPA for support and netted three years' worth of funding in 1973.

Eden believes that DARPA's funding throughout the 1970s helped to spur the development of the GaAs IC through long-term investments in materials and fabrication. "If you had told me [then] what would have been the real winner for GaAs IC technology – the cell-phone power amplifier – it would have been the last thing that I'd have guessed."

It wasn't long before the efforts on microwave devices were ditched at Rockwell in favor of ICs. Silicon-based efforts within the company were making circuits that could operate in the microwave region and required components employing logic functions. GaAs equivalents promised faster speeds, but the existing MESFETs were unsuitable for logic. "The standard deviation of pinch-off voltage was enormous, and if you wanted to make ICs from the devices, you would need a large voltage swing," recollected Eden.


US NAVY

DARPA sank $0.5 billion into its GaAs MIMIC program. Affordable front ends for weapons systems were the goal, and success ensured that GaAs is now the military's incumbent technology for this type of application. GaAs is employed in the US Navy's advanced medium range air-to-air missiles, which were taken on the aircraft carrier USS Nimitz during the war in Iraq.

Employing a radically different MESFET technology slashed the variations in pinch-off voltage. Out went the mesa-epitaxial process that provided device isolation by selective removal of active material, in came a simpler, cheaper ion-implantation approach. "We were able to drop the standard deviation of the pinch-off voltages by a factor of 20 or more, down to where they were comparable to silicon."

The team went back to DARPA and requested funding to develop large-scale integrated circuits

Table 1. A selection of current DARPA programs

Program	*Principal goal*
Compound semiconductor materials on silicon (COSMOS)	Aims to create a process for the fine-scale heterogeneous integration of CS devices with standard silicon CMOS
Efficient mid-infrared lasers (EMIL)	Targeting continuous-wave room temperature lasers operating in the range 3.8–4.8 μm
Sub-millimeter wave imaging focal-plane technology (SWIFT)	Aims to build an active imaging system operating at 340 GHz
Architecture for diode high-energy laser systems (ADHELS)	Seeks to develop diodes that have high-quality beams with low divergence and efficiencies of more than 60%

US NAVY

Radar systems, such as this X-band radar moored in Pearl Harbor, HI, have benefited from the GaAs components developed during the DARPA MIMIC program of the 1980s and 1990s.

with 1000 gates or more. DARPA's director, George Heilmeier, was interested, but was only willing to stump up the cash if the team could demonstrate a gate with a power dissipation of less than 1 mW.

In a bizarre twist, Eden and his colleague Bryant Welsh were taken off the project at that point and the responsibility was handed to more senior members of the microwave group. But this did not deter these two, who devoted their nights and weekends to Heilmeier's goal. They produced devices that were so small that they could fit into the saw kerf space between the die areas of the official GaAs IC mask set. "These were the only things that were measured," said Eden, "because we were able to get decent ring oscillator speeds out of devices with power dissipations of 0.5–1.0 mW per gate."

With Heilmeier's target reached, a $5.47 million effort followed, centering on an 8 × 8 bit parallel processor. Success came in September 1980, five months after the three-year deadline had expired.

Computing GaAs

DARPA's funding didn't just provide the military with cutting-edge technology. It also spawned two companies that built high-speed circuits for computational purposes – Gigabit Logic, which was co-founded by Eden in 1981, and Vitesse Semiconductor, which was started by Joseph in 1984.

Gigabit Logic also received help from DARPA. "When we started the company we had a desperate need for funding and validation from customers," explained Eden. DARPA and Westinghouse fulfilled this need by paying for studies on analog-to-digital converters and ICs.

This convinced venture capitalists to invest, but Gigabit was never a great commercial success. GaAs computer chips were deployed in the Cray 3, but this computer was never launched and when Cray's founder, Seymour Cray, lost his life in an automobile accident in 1996 the company lost interest in III-Vs. Vitesse fared better and it opened the world's first 6 inch GaAs wafer fab in 1998, but today it focuses on products for optical networks.

DARPA continued to fund GaAs development throughout the 1980s and 1990s, and between 1988 and 1995 it pumped $0.5 billion into the incredibly thorough MIMIC program. "The pull behind the program was the need to develop more affordable weapon-system front ends," explained Eliot Cohen, who was the manager for the vast majority of this program. He says that there was a general recognition that hybrid circuits – the common type of circuit for microwave and millimeter-wave frequencies at that time – were not doing their job. The effort was also expected to deliver key technologies for radar, communication and electronic countermeasure systems that would benefit all three military services.

Cohen says that there was none of the production capability that exists today when the MIMIC program began. "It was going to take a substantial amount of money to get to a point where you really had the capability to produce these devices affordably, in reasonable quantities and in high yield." Very little attention had been paid to statistical process control and the identification of yield inhibitors, while substantial improvements to material quality, packaging and computer-aided design were needed.

MMICs had been demonstrated before the program. However, none of the companies that made them could foresee the number of lucrative commercial applications that would result, which meant that they were unwilling to make the investments to develop the technology.

In fact, commercial applications were a prerequisite for financially viable production lines. "It was a win-win situation," said Cohen. "You needed the ICs for military applications, but commercial applications served a very useful purpose."

By the early 1990s, MMICs were starting to appear in neighborhood phones – cordless handsets with a limited transmission range. "Very quickly after that the prices dropped as chips became more available," said Cohen. "Then they started being used in wireless, which of course is the principal application today."

The other application that was very exciting at the time was collision-avoidance radar. Hughes Aircraft developed "Forewarn", a simple radar system to warn drivers when children walked in front of or behind school buses. Other applications also came to light as the program continued, such as commercial satellite communications.

The commercial markets created by the MIMIC

"I think that 20–30 years from now we will look at GaAs as a transitional material that led us to better materials".

Mark Rosker
Wide-bandgap semiconductors-RF applications program manager

program have left a wonderful legacy, but they should not obscure the significant gains to the military. “It really revolutionized the way people produce the front end of systems,” said Cohen. “I don’t think you’ll find many modern systems that use hybrid technology anymore.”

The MIMIC program’s success resulted from its thoroughness. All of the issues relating to GaAs circuit manufacture were addressed, including substrate and epilayer quality, computer-aided design, process control, and chip design and testing.

“I emphasized early on that people had to use manufacturing techniques that would result in an understanding of what were the yield inhibitors, the critical parameters to be monitored and so on,” explained Cohen. According to him, the other major contribution was the improvement in computer-aided design: “They started realizing that you could produce the same circuits in a much smaller area of GaAs.” Shrinking these circuits slashed production costs for military and commercial applications.

The GaAs MIMIC program also helped to establish MBE as a viable production technique for high-volume chip manufacture. Growers were producing 3 inch material with very good quality by the end of the first phase of the program.

Chip design also flourished. GaAs MESFET gate lengths were reduced from 0.5 to 0.25 µm in the first phase, while the second phase delivered improvements in HEMTs and HBT technologies. Processes for these transistors were not orientated to any specific application, and the development of more accurate transistor and matching circuit models, alongside greatly improved computer-aided design tools, made it possible to produce MMICs in foundries for various applications.

From GaAs to GaN

The vast improvements in chip manufacturing have not only positioned GaAs as an incumbent technology within the military. They have also provided the foundations for future DARPA efforts, such as the program entitled “Wide bandgap semiconductors – RF applications”, which started in mid 2002.

“Our program can’t compete in terms of its size to the MIMIC program,” admitted wide-bandgap program manager Mark Rosker. “But on the other hand, we’ve had the benefit of an awful lot of infrastructure that didn’t exist for the MIMIC program. Because we get the piggyback, it doesn’t require the same amount of resources.”

The motivation for developing GaN-based RFICs stems from the material’s very high levels of power density, in terms of W/mm. “Improvements in going from GaAs to GaN are not factors of 50% or even factors of two, but an order of magnitude,” said Rosker. This means that a smaller device can be used for the same RF power, which either improves efficiency or simplifies matching to other components, thanks to a wider frequency range.

Rosker believes that these advantages over GaAs will lead to the widespread deployment of GaN in various classes of radar, communication and imaging. “I can’t imagine why anyone would use GaAs if GaN was available, reliable and cost effective.” Penetrating commercial markets may not be so easy, however. GaN is a very promising material for base stations, but it is not clear whether it can unlock the stranglehold that GaAs has on the handset market.

The first 24 months of the wide-bandgap program focused on improving material quality. “We could have gone directly to making devices or MMICs, but we would never have solved some of the fundamental problems,” said Rosker. When the program began, SiC growth was plagued with defects, and it was difficult to control GaN-on-SiC growth.

Since early 2005 the program has been focusing on devices with contributions coming from three teams. Raytheon is leading an effort to build an 8–12 GHz transmit/receive module, TriQuint is heading a team with the goal of making a 2–20 GHz wideband amplifier and Northrop Grumman Space Technologies is in charge of a project to build an amplifier operating at more than 40 GHz.

Rosker is unable to provide details regarding recent successes, but he says that all of the partners have delivered remarkable levels of performance against difficult metrics. Most of this effort has focused on improving device reliability. “When we started you could literally watch a part on the bench degrade before your eyes,” explained Rosker. Accelerated projections of state-of-the-art devices are now showing mean times to failure of more than 10^5 hours.

The results that Rosker is getting are validating his views on GaN: “I think it will be a long time before a material really displaces GaN. I think that 20–30 years from now we will look at GaAs as a transitional material that led us to better materials, both in terms of bandgap and other things.” And that is the march of DARPA – continual development of novel materials for military use, which can spawn lucrative application in the commercial world. ●

NOKIA

DARPA’s GaAs MIMIC program helped to revolutionize the manufacture of these chips. Advances in computer-aided design, statistical process control, epiwafer quality and packaging helped to slash MMIC costs and spur their deployment in the nascent wireless handset business, which is now the primary market for the likes of RF Micro Devices and Skyworks.

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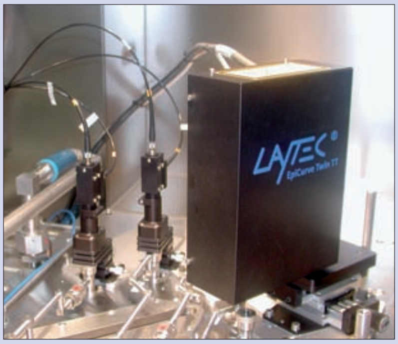

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WAFER DICING

Lasers make the grade at GaAs fabs

Despite some initial problems, the leading GaAs wafer fabs in the US are now reaping the advantages of a switch to laser dicing systems that are displacing scribe-and-break equipment. But those yet to change to the laser process can learn a lot from TriQuint Semiconductor's experiences both good and bad, discovers **Michael Hatcher**.

ALSI

The DCA 802 automatic laser dicing system from Advanced Laser Separation International has virtually cornered the market in GaAs wafer dicing by laser. The system is based on technology developed initially at Philips and shares certain aspects of design with ASML lithography systems.

Compound semiconductor manufacturers tend to keep their introductions of innovative processes and technologies well under wraps. After a while, and typically at the CS Mantech Conference, a few details might be revealed, but by then the process will probably have been qualified for at least a year.

At this year's Mantech, held in the north Chicago suburb of Wheeling, TriQuint Semiconductor revealed that it has been using lasers to dice its GaAs RFIC wafers for quite some time. In itself this revelation is not particularly surprising – the Oregon-based company and many of its competitors have spent the past couple of years implementing the technology in a bid to speed wafer throughput. Perhaps more of a surprise is TriQuint's acknowledgement of the problems that it encountered along the way.

Travis Abshere presented TriQuint's "lessons learned from laser dicing" paper at Mantech. Although the laser systems from Advanced Laser Separation International (ALSI) ultimately proved to be a great success, the development and qualification period had clearly not been plain sailing.

The primary motivation behind a move to laser dicing is to increase wafer throughput. The TriQuint team had calculated that a five-fold improvement over conventional diamond sawing would provide a compelling return on its investment. In addition to the faster processing, laser dicing offers a potential reduction in die size that effectively increases the capacity of each wafer, and of the wafer fab in general. Abshere described how the reduction in street widths (the gaps between adjacent devices on the wafer) from 50 to 25 µm, possible with laser equipment, would effectively yield an "extra" wafer from each batch that is processed.

Before evaluating the technique for production, Abshere and his colleagues had identified what they saw as being the most likely problems: damage to the dielectric material left in the "streets", changes in the appearance of the diced edge of the die, potential die-cracking, and so on.

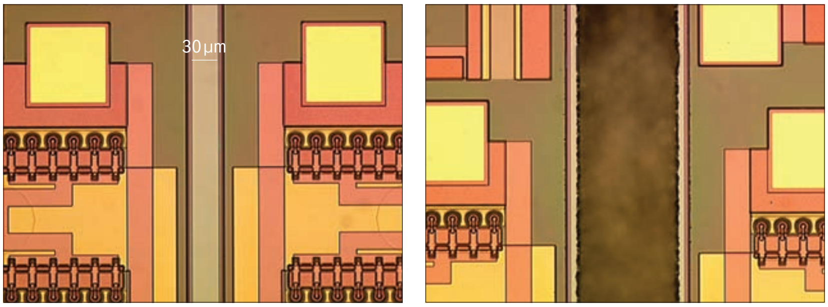
Yield drop

When TriQuint introduced laser dicing it saw a drop in yields. While that may not have been a surprise, the reason was unexpected – power amplifiers based on GaAs die were failing because of shorting caused by wire bonds. As it turned out, one of TriQuint's subcontract assemblers (SCAs) was using a process that caused these wires, which provide interchip bonding, to sag and short out on exposed metal "zippers" that form the edge of the die. "With laser-diced chips, the bond wire could sag to the point that it contacted the metal zipper, and cause a short," Abshere explained.

Normally these sagging bonds would not pose any problems because the same SiN coating that protects die from scratches would also protect the metal zippers. However, in developing the laser-dicing process it was found not only that the laser could damage the SiN that coated the die streets but also that this damage could extend beyond the metal zipper protection and into the die itself. To get round this, TriQuint removed SiN from the die streets selectively. However, the opening created by this extra step extended to the center of the metal zipper, ultimately exposing the metal to the drooping wire bond.

To solve the problem, TriQuint made two significant changes. First, it told the SCA to address the sagging bonds. Second, it made sure that the layer of SiN covered the metal zippers and extended a couple of microns into the die street for good measure.

Another technical problem arose because of the narrower cutting ability of the laser system compared



A 100 μm thick GaAs wafer with 30 μm dicing street (left) and the same wafer after dicing and stretching showing a 17 μm dicing width (right). TriQuint's early-adopter experiences ought to benefit companies yet to make the switch to laser-dicing of GaAs wafers. RF Micro Devices, another early adopter, is thought to have invested in ALSI machines for its high-volume GaAs fabs.

with the diamond saw. This narrower "kerf" means that completed wafers have to be more carefully handled to make sure that adjacent die do not rub up against each other and cause damage, and so-called "hoop rings" are needed to stretch the wafers and keep the die well separated. With diamond saws, the larger kerf means that this isn't a problem.

All three of TriQuint's SCAs had prior experience of using hoop rings, so they gave the green light to proceed. The only problem was that none of them had ever used hoop rings suitable for GaAs wafers before. So when the stretched wafers arrived, the hoops did not fit the saw frames being used and the SCAs could not pick die all of the way to the edge of the wafers.

Lesson two

"The lesson learned here is that complete samples need to be provided to SCAs sooner," said Abshere. "It turned out that none of the SCAs had actually used small rings with 6 inch wafers." The solution was simple enough: TriQuint switched to larger saw frames and hoop rings, but this increased the process cost and caused more delays.

The third problem revolved around die cracking, something that TriQuint had already flagged up as the major risk of a switch to the laser dicing approach. After introducing this new technique, the company began to see die cracks and a high failure rate on laser-diced devices. However, the problem was not quite the one that it had previously predicted.

TriQuint's original concern was that the shape of the "cuts" from the laser would cause cracks. So after consulting with ALSI and other GaAs manufacturers that were using laser dicing, it introduced an etch-cleaning step designed to strengthen the edges of the laser-processed die.

Things did not go quite according to plan, though. Although the etch clean worked on the top of the GaAs wafers, it did not strengthen the edges. The inevitable result was die cracking, and TriQuint had to stop all laser dicing until it could solve the problem.

"We had viewed the etch clean as an opportunity to avoid dealing with a protect-coat process rather than a critical change for avoiding weak die edges," Abshere admitted. After testing the die strength in collaboration with ALSI, the team concluded that the problem was largely a result of the etch clean equipment being used, and that the wafers ought to be stretched on a hoop ring prior to the etch step to ensure a good clean. Buying a tool with greater automation and using hoop rings allowed more room for the cleaning solvent to get in between individual die. This resulted in much stronger die edges, even compared with those produced using a diamond saw.

TriQuint is far from alone in its use of laser dicing. RF Micro Devices – the biggest volume manufacturer of GaAs RFICs – was probably the first to try out the technology and is thought by some in the industry to have as many as eight laser-dicing machines.

Another leading manufacturer has been using ALSI equipment in its wafer fab since summer 2007, following an extensive trial period. Like TriQuint, it is very happy with the results and intends to purchase further laser equipment for future manufacturing expansion. "We are using lasers for pretty much everything," said a source from the company, who wished to retain his anonymity and that of his employer. "To all intents and purposes it has eliminated the scribe-and-break process," he added.

This second company has not had problems with die cracking, and it is clear that, although it may have been slower on the uptake than its rivals, it has benefited from TriQuint's early-adopter experiences.

For the unnamed company, a five-fold increase in wafer throughput has meant that far fewer wafers have needed to be outsourced for processing. "Not only is laser dicing much faster; the yields are also as good as diamond saws," said the firm. For typical 6 inch wafers with an average die count, its two ALSI machines can each process around 600 wafers per week. "That is way more than is possible with a diamond saw," said the unnamed source. The real-world figure matches pretty well with ALSI's own claim that its tool processes a typical 6 inch wafer in around 10 minutes (equivalent to just over 1000 wafers per week in a fab running round the clock).

ALSI's seems to be the laser-dicing equipment of choice for GaAs fabs. Rene Hendriks, director of commerce at the Netherlands-based firm, told *Compound Semiconductor*: "We have installed our system at all major RFIC manufacturers in the US and Asia."

The technology was originally developed at Philips, and this pedigree has been an advantage. Users have been impressed by the company's approach – rather than adapting a conventional system by replacing the diamond saw with a high-power laser, ALSI developed an optimized laser-dicing system from scratch.

Hendriks explained: "The laser process is based on many relatively low-power individual beams, which minimizes the heat impact and damage to the wafers and adds to the overall productivity."

In the end, Abshere believes that it only took TriQuint a year to see a return on its investment in laser-dicing equipment, despite the unexpected problems that were encountered. For other GaAs fab managers, who can learn from the TriQuint experience, that period should be shorter and the business case appears pretty compelling, provided that they are able to work through any problems that do arise.

Further reading

T Abshere *et al.* 2008 *CS Mantech Digest* 69.

Interband cascade lasers shed their ultra-cool credentials

Diode lasers and their quantum cascade cousins struggle to reach some mid-infrared wavelengths needed for gas sensing and missile jamming, but put the two together and it's a different story, say **Chadwick Canedy**, **Igor Vurgaftman** and **Jerry Meyer** from the US Naval Research Laboratory.

US NAVY

A US F/A-18 "Hornet" fires flares during a training mission. The flares form part of the fighter aircraft's defense against surface-to-air and air-to-air infrared heat-seeking missile attacks. The flares aren't always a successful decoy, however, so the Navy is funding research into mid-infrared III-V laser diodes that could be used to jam the missile-guidance systems more effectively.

The US-led coalition's fight against terrorism and insurgents in Iraq and Afghanistan is aided by control of the skies. But this is under threat from shoulder-launched heat-seeking missiles that are made around the globe and are widely available.

These missiles can be prevented from hitting fighter jets by flares that divert them away from the aircraft's engine. However, this is not foolproof and the flares pose a risk of starting fires on the ground.

A more promising form of countermeasure is based on high-power mid-infrared lasers that can jam the guidance systems of heat-seeking missiles. Compact, low-cost sources needed for this form of defense are not available today, but excellent progress has been made through the development of novel interband cascade lasers (ICLs) by our team at the Naval Research Laboratory in Washington DC.

Improvements in infrared laser performance would also bring other benefits, like the detection of methane, ethane, hydrogen chloride, formaldehyde, hydrogen sulfide, nitrous oxide, and carbon monoxide and dioxide, which all have strong absorption lines between 3.3 and 4.6 µm. Methane is the primary component of natural gas, and a room-temperature laser with a narrow emission profile could provide the key component in a methane detector. Similar instruments could map out the distribution of this potent greenhouse gas in the Earth's atmosphere.

Making a suitable laser for gas sensing and infrared counter measures is not easy, however. Although solid-state parametric sources exist, their usefulness is limited by high cost. Lead salt IV–VI lasers also have their downsides, including a need for cryogenic cooling and output powers of less than 1 mW.

One alternative is III-V laser diodes, which are a multibillion-dollar business in the 0.8–1.6 µm spectral range. But it's very tricky to extend these lasers into the mid-infrared region of 3–5 µm. Carrier absorption losses scale as λ^2 to λ^3, and Auger non-radiative decay rates shoot up exponentially with increases in wavelength.

On top of this the GaSb-based material system that's needed for producing emission in this spectral region is relatively immature. Consequently, this type of laser has fallen short of what's needed for potential applications and the development of infrared sources has only come to the fore in the last decade.

Our recent success unites two different types of emitter: quantum cascade lasers (QCLs) and GaSb-based interband lasers. Neither of these can perform well in continuous-wave (CW) mode throughout the mid-infrared, but their marriage forms a hybrid design that can span the 3–4 µm range.

QCLs work best at 4.5–10 µm, although Manijeh Razeghi's group at Northwestern University, IL, has produced a 3.8 µm room-temperature laser. However, further improvements will be tough because there is a physical limit to the maximum barrier height that dictates the emission wavelength in a strain-balanced InGaAs/InAlAs/InP quantum well (QW).

GaSb-based interband lasers are now able to produce CW room-temperature lasing throughout the 2–3 µm band, thanks to highly strained InGaAsSb QWs. But extending this design much beyond 3 µm is problematic because the lasing wavelength is determined by the valence band offset that confines

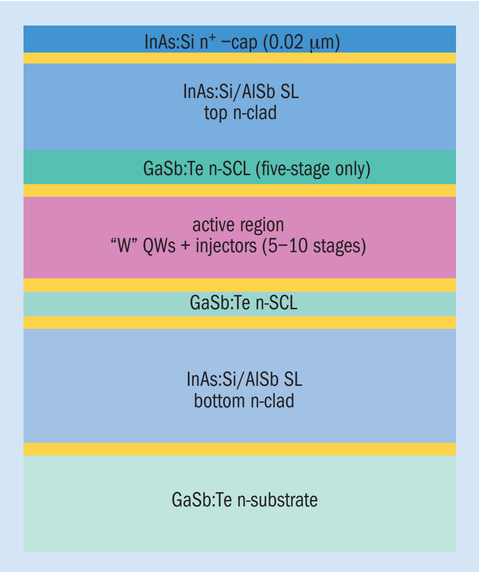
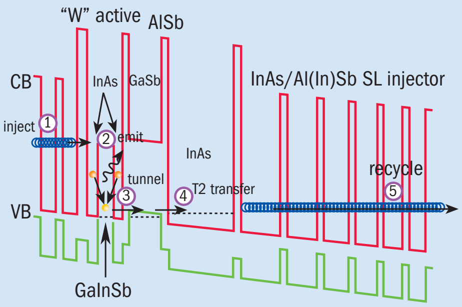


Fig. 1. The US Naval Research Laboratory team uses MBE to create the interband cascade laser structures on GaSb. Each active stage in the device is separated from its neighbor by a transition superlattice that smooths the abrupt shifts in conduction band offset.

How an ICL works



ICLs feature multiple active regions connected by superlattice injectors. The lasing process begins with the injection of electrons from the proceeding stage into the conduction band (CB) of the active region (1).

This active region has a type-II structure with a W-shaped CB profile. An electron is confined within the CB of the two InAs QWs, which surround a GaInSb QW whose valence band (VB) contains a hole. These two carriers interact to produce a photon via an interband optical transition (2). The electron transfers to the GaInSb VB during this process, which can tunnel to one or more adjacent GaSb hole QWs (3).

Thanks to the type-II energy overlap between InAs and GaSb, the electrons in the GaSb VB elastically scatter to CB states in the thick InAs QW that forms the first part of the next injector region (4). The electron then gathers energy as it propagates through an InAs/AlInSb superlattice with progressively decreasing QW thicknesses, before recycling into the next active region, where it emits an additional photon (5).

the holes in the active QWs.

Our ICLs, which are evolutions of Rui Yang's invention at the University of Toronto in 1995, produce lasing through interband optical transitions. This is the process found in other types of laser diode, but the crucial difference with an ICL is that it also employs multiple active stages cascaded in series (see box "How an ICL works").

Cascading means that several photons are emitted for each injected electron. This increases output power at the expense of an increased bias voltage, which is needed to activate all of the cascaded stages simultaneously. However, the positives outweigh the negatives because lower current densities for a given output power reduce the effects of parasitic ohmic and non-ohmic voltage drops.

We fabricate our ICLs by MBE growth on tellurium-doped GaSb substrates. Our design features an active region with 5–10 stages, which are clad with two n-type InAs/AlSb superlattices (figure 1).

Our first lasers, which we made in August 2005, shared two of the weaknesses of many early ICLs – high threshold current densities and a low temperature for CW output. However, the ICL community received a boost in 2006, thanks to the efforts of another team headed by Yang – by then working at the Jet Propulsion Laboratory, CA. The breakthrough was the fabrication of 12-stage, 3.3 µm ICLs with an operating temperature of 264 K. Close proximity to room-temperature operation is significant because it allows device cooling via a compact, energy-efficient thermoelectric cooler.

We followed this up with an ICL featuring five active stages that lased at up to 257 K. Using fewer stages failed to provide sufficient gain at high temperatures to overcome the structure's internal losses, and pulsed operation peaked at 295 K. However, we overcame this weakness with a new design that produced a 4.1 µm ICL operating at 288 K. Increases in high-temperature capability resulted from a doubling of the number of active stages to increase gain, improvements to the design of the band structure, lower Auger losses and a reduction in free carrier absorption.

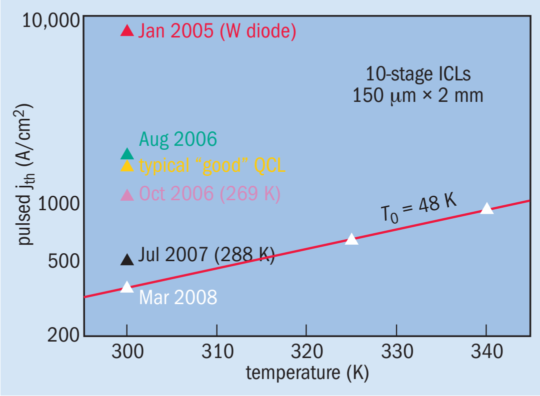
Our latest ICL designs feature an additional GaSb QW for hole confinement, which reduces electron tunneling leakage that would bypass the holes. The dimensions of this well must be carefully chosen to ensure a low hole density in the GaSb layer because this minimizes intervalence absorption – one of the primary sources of optical loss.

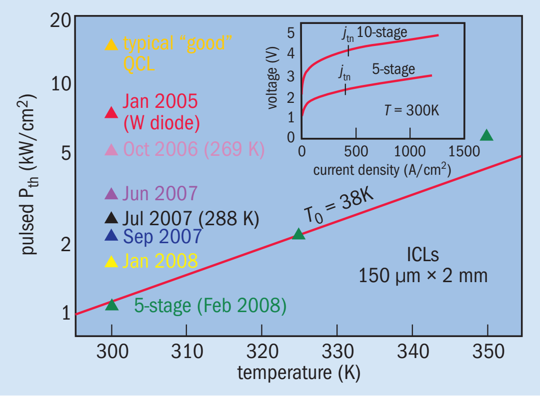
We have optimized the electron free-carrier absorption in the optical cladding layers, which is governed by the doping density. If doping is too low, this can lead to excessive series resistance; if it's too high laser thresholds and external efficiencies suffer.

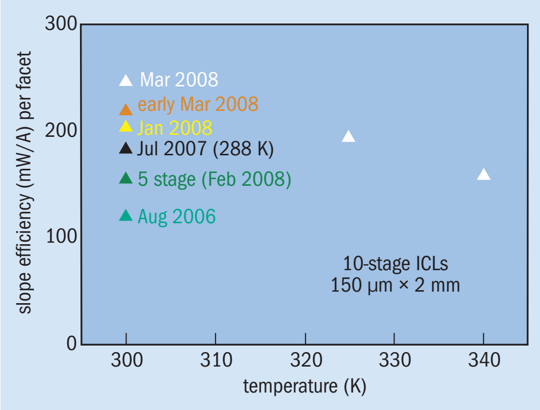
Auger recombination – a non-radiative process that involves the transfer of energy from electron-and-hole recombination to a third carrier – plagues the performances of all mid-infrared laser diodes and gets worse as you move farther into the infrared. We minimized this loss mechanism by optimizing the composition and thickness of the GaInSb QW that provides hole confinement, and we were able to produce 3–4 µm ICLs with room-temperature Auger coefficients of $3–4 \times 10^{-28}$ cm^6/s. Our low laser thresholds are a direct consequence of this low Auger coefficient – it is by far the lowest value for any III-V laser covering this wavelength range.

Our lasers have low threshold currents, such as

> "We have produced the first CW, room-temperature interband cascade lasers."







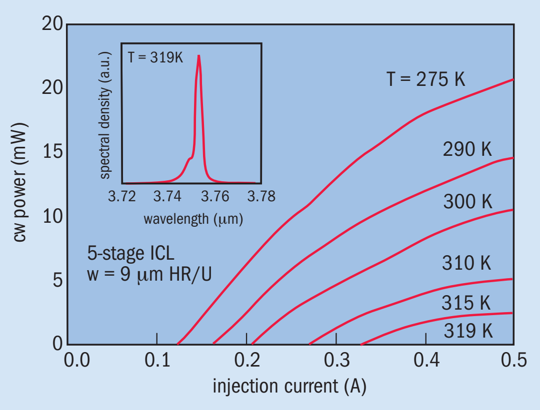


Fig. 2. (top left) The Naval Research Laboratory has steadily improved the threshold and efficiency of its interband cascade lasers (ICLs) during the last two years. Each entry represents the best result obtained up to that date, which denotes the month when the device was grown rather than tested. **Fig. 3.** (top right) ICLs now deliver far lower threshold power densities than QCLs and non-cascade W diodes. Pulsed input power densities reveal the heat-dissipation requirements for a laser. The latest five-stage devices have the smallest requirements, which make them the best candidates for room-temperature CW devices. **Fig. 4.** (bottom left) Pulsed threshold slope efficiencies have steadily improved over the last two years. **Fig. 5.** (bottom right) The Naval Research Laboratory's 9 µm wide-ridge waveguide ICL can operate at temperatures of up to 319 K. This is the highest operating temperature for any III-V laser emitting between 3.1 and 4.6 µm.

2.5 A/cm^2 at 78 K. When pulsed at 300 K this rose to 360–400 A/cm^2 (figure 2). Pulsed input power densities are lower than QCLs and W diodes (figure 3).

Recent efforts have focused on improvements in ICL efficiency, driven by reductions in internal optical losses. According to pulsed room-temperature slope efficiencies, our most recent device is twice as efficient as our best effort from 2006 (figure 4).

Reducing internal losses has a secondary benefit – less gain is needed, so we have been able to revert to cascading only five stages. We produced this type of ICL in March, which lased in pulsed mode at temperatures well beyond 300 K and had an efficiency of 160 mW/A. A big advantage of this design is that optical losses are actually lower than those for its 10-stage cousin, thanks to fewer net holes that contribute to unwanted intervalence processes.

To close in on the holy grail of ICLs that perform in CW at practical system temperatures, more attention was given to thermal management. Heat that must be dissipated to run these diodes is equivalent to the pulsed input power density (the product of threshold current density and applied bias) required for lasing (figure 3). Biasing the ICL is proportional to its number of stages, which makes our five-stage device the best for room-temperature CW lasing.

We have produced the first CW ICLs operating at room temperature by fabricating narrow-ridge waveguides into the five-stage design and adding a gold electroplated film for improved thermal dissipation when the laser is mounted epitaxial side up. Devices with 5, 9 and 11 µm ridges have delivered CW lasing up to 313, 319 and 317 K, and output powers of more than 10 mW at 300 K (figure 5).

These recent successes should pave the way for CW, room-temperature ICLs throughout the 3–4 µm band. Nothing should obstruct this advance because the threshold current densities are broadly similar across this spectral range. There is also good reason to believe that further improvements in device performance are possible because ICLs are still a relatively immature laser technology.

Our efforts are shifting to the development of packaged devices for real-world applications. We are aiming to equip products with robust, spectrally pure beams by incorporating features such as gratings based on distributed feedback or photonic crystals. Spectroscopy applications can be targeted with this type of design, but we will need to deliver far higher output powers for missile jamming. This could be realized through further reductions in the internal loss at high temperatures, optimization of narrow-ridge fabrication and better heat sinking. ●

Further reading

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About the authors

Chadwick Canedy (left; chad.canedy@nrl.navy.mil) grows ICLs, type-II antimonide detectors and other III-V heterostructures for the NRL team by MBE. As the team's lead optoelectronic device designer and simulator, **Igor Vurgaftman** (center; igor.vurgaftman@nrl.navy.mil) carries out theoretical research on infrared lasers, LEDs and detectors, dilute nitrides, plasmonic lasers, metamaterials, and other advanced technologies. **Jerry Meyer** (right; jerry.meyer@nrl.navy.mil) is the team leader and head of the NRL Quantum Optoelectronics section.

InP LASERS

VCSELs head farther into the infrared

Sometimes it's very difficult to take a successful device and replicate it in another materials system. The GaAs VCSEL is a case in point: although it has been a great commercial success, transferring the design to longer wavelengths has been fraught with difficulty. The main stumbling block is the design and fabrication of lattice-matched mirrors with sufficiently high reflectivity.

However, European institutions have been figuring out ways of getting round this problem, and at May's Indium Phosphide and Related Materials Conference in Versailles, France, several speakers outlined novel designs in the 1.5–2.3 µm range.

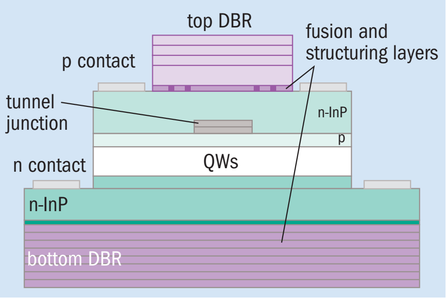
Alexander Mereuta from Ecole Polytechnique Fédérale de Lausanne described developments in 2 µm VCSELs made by wafer fusing. His group has previously used this approach to construct 1.3 and 1.55 µm equivalents, which are under commercialization at spin-off BeamExpress.

Mereuta's InP VCSEL is designed for sensing water and CO_2, which have absorption lines at 2003 and 2004 nm. According to him, distributed-feedback edge-emitting lasers could also be used for this application. However, these power-hungry devices suffer from mode-hopping when their wavelength is tuned, as well as a wider beam profile and a narrower tuning range.

An Aixtron MOCVD tool is used to grow the active region on an InP substrate and each of the two undoped GaAs/AlGaAs distributed Bragg reflectors (DBRs) on separate GaAs substrates. The structures are then fused together. This allows the independent optimization of the active region and the mirrors, and it circumvents problems associated with a monolithic design.

The active region contains InGaAs/InAlGaAs quantum wells that generate the lasing, top and bottom intracavity contacting layers, a reverse-biased junction for lateral current confinement, and a PN and tunnel junction for carrier injection (figure 1).

Chemical etching forms a 9 µm diameter tunnel junction that defines the device's electrical and optical aperture. An n-doped InP spacer layer on top of this structure provides a platform for a top intracavity contact and creates a PN blocking junction that surrounds the tunnel junction and promotes current flow through the aperture.



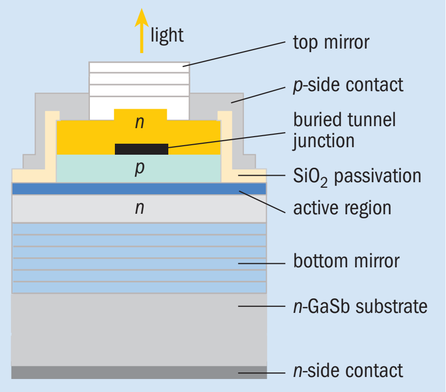


Fig. 1. (top) EPFL has extended its wafer-fusing technology from telecoms wavelengths to 2.0 µm, where it can be used to detect water and CO_2. **Fig. 2.** (bottom) Switching from InP-based VCSELs to those based on GaSb promises to push the emission wavelength to 3.0 µm. Researchers at the Walter Schottky Institute at the Technical University of München have already fabricated a 2.25 µm laser.

The researchers selected a quantum-well composition with a room-temperature peak photoluminescence of 1950 nm. This is short of the target wavelength, but it's a good choice. That's because device operation increases the cavity's temperature by 50 °C and brings the emission peak to the target operating wavelength of the laser.

This produced a 0.5 W continuous-wave laser with a side-mode suppression ratio in excess of 30 dB and a maximum operating temperature of 46 °C. Tuning rates of 0.31 nm/mA and 0.14 nm/°C enabled tuning from 2002 to 2007 nm and detection of water and CO_2 in air.

Gas sensing is also a target for Alexander Bachmann's team at the Walter Schottky Institute (WSI), Technical University of München, Germany. This team is developing GaSb VCSELs that can span 2.3–3.0 µm. This spectral range offers stronger gas-absorption lines, but it is out of reach for InP-based devices.

WSI produced its VCSEL by bonding a Si/SiO_2 dielectric DBR and an MBE-grown epitaxial structure that comprises a GaSb/AlAsSb DBR and an active region (figure 2). Again, a tunnel junction is included in the design to define the aperture size.

The team evaluated the device's performance after mounting the VCSEL onto a temperature-controlled copper stage. Its 5.5 µm diameter aperture laser operated up to a heat sink temperature of 55 °C and had a threshold voltage of 0.95 V. The relatively high voltage indicates that some series resistance is present, which could be caused by an unoptimized active region or a poor-quality epitaxial DBR.

Altering the pump current tunes the VCSEL from 2248 to 2256 nm at a rate of 0.87 nm/mA. The output is just 75 µW and efforts are under way to identify the cause of low power. Prime suspects are a mismatch of the gain spectrum to the cavity resonance and an active region of insufficient quality.

Bachmann revealed that the German electronics giant Siemens has used one of the lasers produced by WSI for gas sensing, and has detected carbon monoxide with a concentration of 57 ppm.

Future targets include improvements in current confinement and an extension of the emission wavelength to 2.5–3.0 µm.

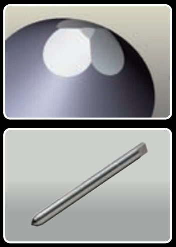
In another presentation from the same technical session, Jean-Philippe Tourrenc from the Photonics and Nanostructures Laboratory in Marcoussis, France, detailed the efforts of a partnership with the Alcatel-Thales III-V lab to develop vertical external cavity surface emitting lasers (VECSELs). Unlike VCSELs, this type of laser has a large gap between one of its mirrors and the active region, and it can produce much higher single-mode output powers, thanks to a larger spot size for the laser beam.

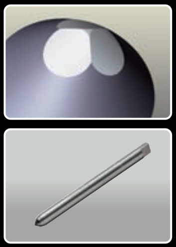
This French partnership has been developing a high-power 1.55 µm source for telecommunications, such as optical sampling and coherent communications. The output power of electrically pumped VECSELs is limited by the thermal conductivity of the materials, but the researchers have started to address this with a hybrid metal-dielectric mirror and a CVD diamond structure.

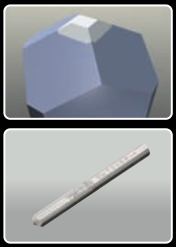
Their VECSEL featured an InGaAlAs quantum-well active region and a 15-pair GaAs/AlAs mirror. A dielectric stack formed the external mirror.

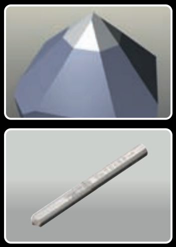
Tourrenc revealed that pumping the VECSEL optically with an 800 nm multi-watt laser produced an output of more than 120 mW. In comparison, an equivalent device built on SiC produced a thermally limited peak power of just 30 mW.

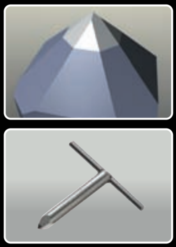
TECDIA's Scribing Tool Selection

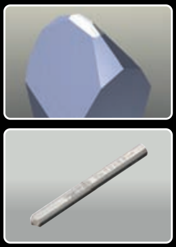

TD-3YGP
For LED sapphire wafer use


TD-3P
For mostly Inp wafer use

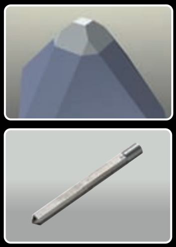

TD-4PB
For mostly silicon wafer use, toe-cut type


TD-420
Primarily for GaAs, glass wafer use, heel-cut type


TD-4L
For mostly silicon, GaAs, glass wafer use


TD-2P
Custom made, for all semiconductor wafer use


TD-8P
Custom made, for R&D use (both toe and heel cut type)


TD-8D
For mostly silicon, GaAs, glass wafer use

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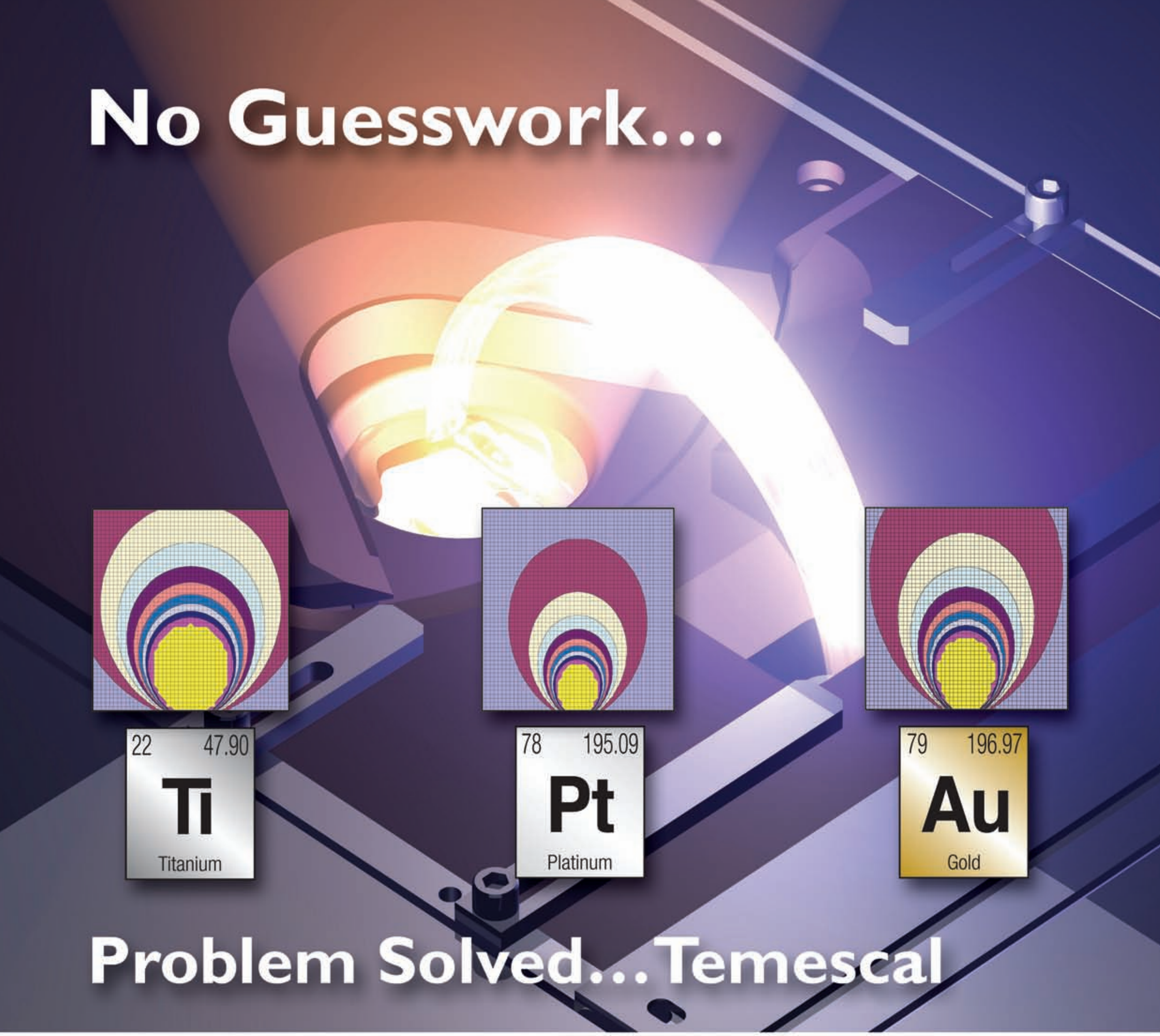
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