



# COMPOUND SEMICONDUCTOR

Connecting the Compound Semiconductor Community

Volume 21 Issue 2 2015

@compoundsemi

www.compoundsemiconductor.net

Dismissing droop with novel diodes



Creating better white light sources



Building brighter infrared lasers



Making thinner GaN HEMTs



Targeting the terahertz transistor



## Ferrotec

### E-beam evaporators

inside **CS** COMPOUND SEMICONDUCTOR

News Review, News Analysis, Features, Research Review and much more.

Free Weekly E News round up , go to [www.compoundsemiconductor.net](http://www.compoundsemiconductor.net)

AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

# AIXTRON

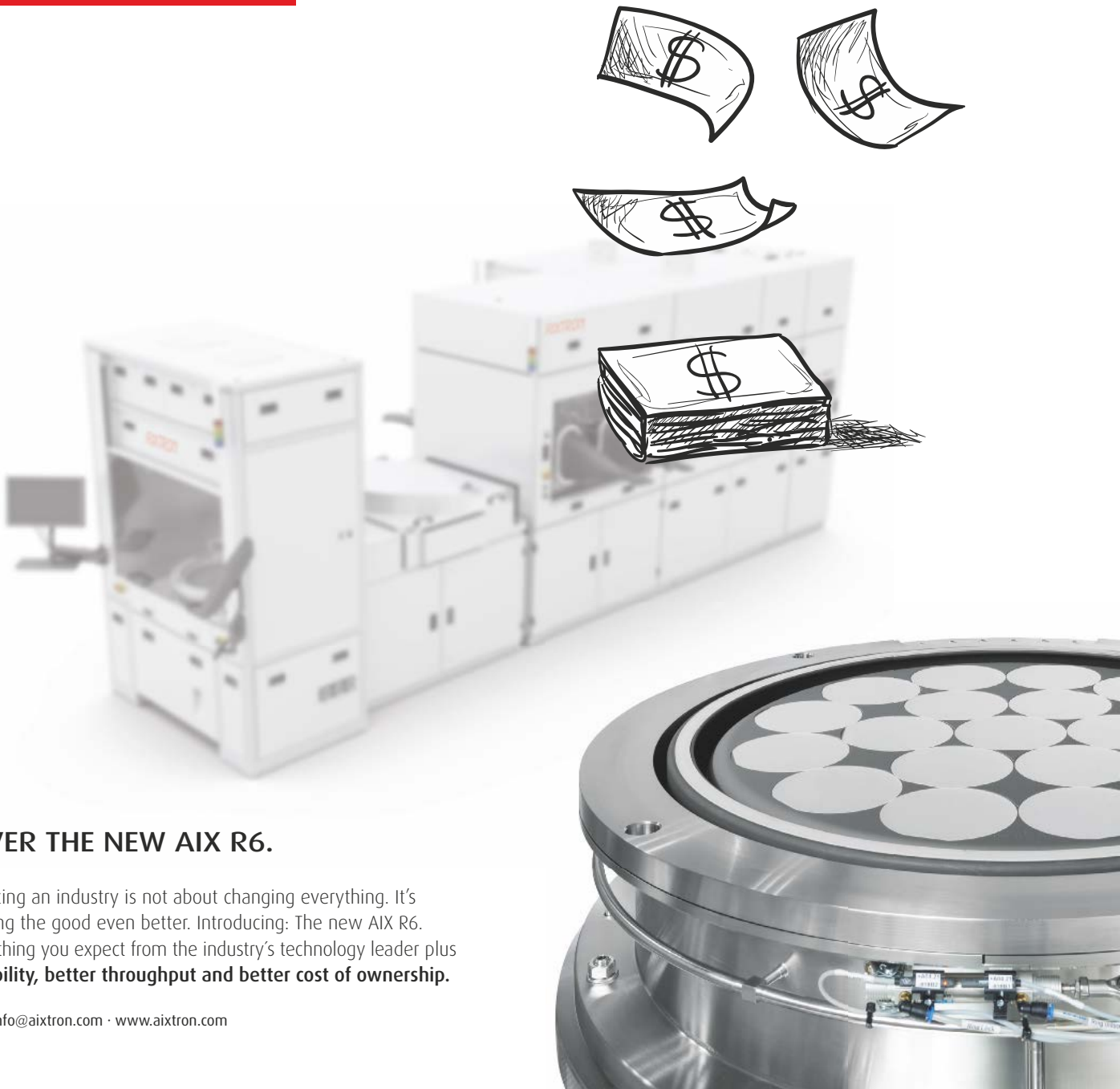
Our technology. Your future.

YOU THINK,

## AIXTRON SYSTEMS SHOULD OFFER YOU THE BEST COST OF OWNERSHIP.

WE THINK THAT TOO.

**THE NEW AIX R6.**



### DISCOVER THE NEW AIX R6.

Revolutionizing an industry is not about changing everything. It's about making the good even better. Introducing: The new AIX R6. It has everything you expect from the industry's technology leader plus **better usability, better throughput and better cost of ownership.**



# editorial view

by Dr Richard Stevenson, Editor

## Diminishing droop

THE PUBLIC want LED bulbs to be cheaper, brighter, and more efficient. And it would be possible to address all three in one fell swoop if you could eradicate droop, the decline in the light efficiency as the current through the chip is cranked up. After all, with a droop-busting LED, you could make a highly efficient bulb from fewer chips that are driven harder, creating a product that costs less while emitting more light.

The snag is that it is nigh on impossible to eliminate droop. But it is possible to either combat its impact, or, alternatively, to sidestep the problem by turning to another class of light emitter that is not plagued by this energy-sapping malady.

In this issue we highlight efforts in both these directions. Engineers at Sora are claiming to have set new benchmarks for wall-plug efficiency and extraction efficiency with a triangular-shaped flip-chip LED that has relatively little droop (see p.61); while a team from Unipress has taken a new tack, turning to a superluminescent diode (see p.30).

Soraa's chip is formed on a native substrate, which adds to the cost, but offers greater freedom in device design. This strategy



seems to pay off, with wall-plug efficiency still at 70 percent at a current density of 100 A cm<sup>-2</sup> – that's equivalent to 1000 mA through a chip with sides of 1 mm.

Even higher current densities are needed to get the superluminescent diode emitting, but when it starts producing photons, output goes up linearly with current.

This novel device can be thought of as half-laser, half LED. Feedback and waveguiding feature, but losses are much bigger than those in a laser, so emission is spontaneous and does not induce lasing.

Studies have shown that Auger is present in the superluminescent diode – at 100 A cm<sup>-2</sup> this would even overshadow all the other recombination mechanisms, were it not for stimulated emission. But thankfully this is a fast process, quashing droop at high current densities.

In terms of the public getting hold of droop-busting designs, Sora is clearly out in front. Its devices are already in bulbs, while the superluminescent diode is still in development. However, the latter has much to recommend it, including a much smaller chip size than an LED, and excellent light extraction.

<b>Editor</b> Richard Stevenson	richardstevenson@angelbc.com	+44 (0)1291 629640
<b>Contributing Editor</b> Rebecca Pool	editorial@rebeccapool.com	
<b>News Editor</b> Christine Evans-Pughe	chrise-p@dircon.co.uk	
<b>Publisher</b> Jackie Cannon	jackie.cannon@angelbc.com	+44 (0)1923 690205
<b>Senior Sales Executive</b> Robin Halder	robin.halder@angelbc.com	+44 (0)2476 718109
<b>Sales Manager</b> Shehzad Munshi	shehzad.munshi@angelbc.com	+44 (0)1923 690215
<b>USA Representatives</b> Tom Brun Brun Media	tbrun@brunmedia.com	+001 724 539-2404
Janice Jenkins	jjenkins@brunmedia.com	+001 724-929-3550
<b>Director of Logistics</b> Sharon Cowley	sharon.cowley@angelbc.com	+44 (0)1923 690200
<b>Design &amp; Production Manager</b> Mitch Gaynor	mitch.gaynor@angelbc.com	+44 (0)1923 690214
<b>Circulation Director</b> Jan Smoothy	jan.smoothy@angelbc.com	+44 (0)1923 690200

**Chief Operating Officer** Stephen Whitehurst stephen.whitehurst@angelbc.com +44 (0)2476 718970  
**Directors** Bill Dunlop Uprichard – CEO, Stephen Whitehurst – COO, Jan Smoothy – CFO, Jackie Cannon, Scott Adams, Sharon Cowley, Sukhi Bhadal, Jason Holloway.

**Published by** Angel Business Communications Ltd, Hannay House, 39 Clarendon Road, Watford, Herts WD17 1JA, UK. T: +44 (0)1923 690200 F: +44 (0)1923 690201 E: ask@angelbc.com

Angel Business Communications Ltd, Unit 6, Bow Court, Fletchworth Gate, Burnsall Road, Coventry CV5 6SP, UK. T: +44 (0)2476 718 970 F: +44 (0)2476 718 971 E: info@angelbc.com



Compound Semiconductor is published eight times a year on a controlled circulation basis. Non-qualifying individuals can subscribe at: £105.00/€158 pa (UK & Europe), £138.00 pa (air mail), \$198 pa (USA). Cover price £4.50. All information herein is believed to be correct at time of going to press. The publisher does not accept responsibility for any errors and omissions. The views expressed in this publication are not necessarily those of the publisher. Every effort has been made to obtain copyright permission for the material contained in this publication. Angel Business Communications Ltd will be happy to acknowledge any copyright oversights in a subsequent issue of the publication. Angel Business Communications Ltd © Copyright 2015. All rights reserved. Contents may not be reproduced in whole or part without the written consent of the publishers. The paper used within this magazine is produced by chain of custody certified manufacturers, guaranteeing sustainable sourcing. US mailing information: Compound Semiconductor, ISSN 1096-598X, is published 8 times a year, Jan/Feb, March, April/May, June, July, August/September, October, November/ December by Angel Business Communications Ltd, Unit 6, Bow Court, Fletchworth Gate, Burnsall Rd, Coventry CV5 6SP UK. The 2015 US annual subscription price is \$198. Airfreight and mailing in the USA by agent named Air Business Ltd, c/o Worldnet Shipping Inc., 156-15, 146th Avenue, 2nd Floor, Jamaica, NY 11434, USA. Periodicals postage paid at Jamaica NY 11431. US Postmaster: Send address changes to Compound Semiconductor, c/o Worldnet Shipping Inc., 156-15, 146th Avenue, 2nd Floor, Jamaica, NY 11434, USA. Printed by: Pensord Press. ISSN 1096-598X (Print) ISSN 2042-7328 (Online) © Copyright 2015.



# contents

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

Volume 21 Issue 2 2015

## features



# 24

### 24 The resurgence of electron beam evaporation

After decades of playing second fiddle to sputtering, electron beam evaporation now dominates, thanks to its capability to produce a vast range of high-quality films

### 30 Building brighter, more powerful lasers diodes

Laser diodes can be more powerful when they employ facets with equal reflectivity, and brighter when they feature an architecture that trims the number of lateral modes

### 36 Trimming the thickness of high-voltage GaN-on-silicon HEMTs

A high-quality AlN nucleation layer promises lower-cost, high-quality HEMTs

### 41 Targeting a terahertz transistor

Can terahertz HEMTs result from a switch from GaN to InN channels?

### 44 Strategies for creating efficient, beautiful whites

Many paths to optimal colour mixing will accelerate the adoption of solid-state lighting

### 48 Superluminescent diodes: A novel approach for droop-free solid-state lighting?

Superluminescent diodes marry the virtues of LEDs and laser diodes by offering droop-free emission from a high-quality beam that can deliver speckle-free projection

## news

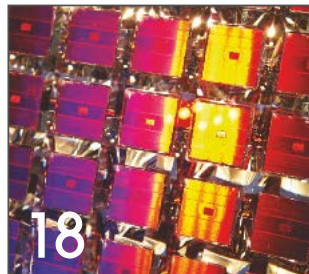
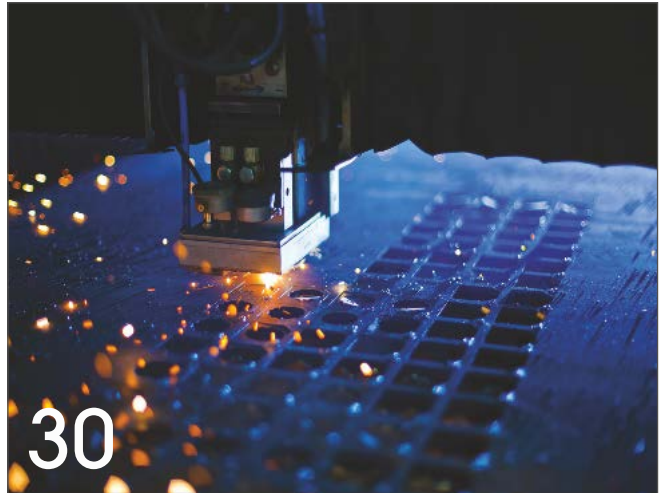
- 06 Toyota to road test SiC power semiconductors
- 08 Delta gets DOE grant to develop GaN-based charger for vehicles
- 09 Lux identifies strategies for success with GaN and SiC power electronics
- 10 RF GaN revenue to reach nearly \$560 million in 2019
- 12 Berkeley Lab shows new precision growth technique for GaN nanowires
- 13 EpiGaN appoints Markus Behet as CMO
- 14 ITC look at infringements of Cree LED patents
- 15 Sensor Electronic Technology appoints new president and CEO

## news analysis

- 16 Photonic ICs: reality check
- 18 Lights out for CPV?
- 20 Solar-Tectic on course for sapphire success
- 22 Photovoltaics: the future for GaN?

## research review

- 59 Hybrid growth promises better green lasers
- 60 InN looks to enhance nitride HEMTs
- 61 New highs for the LED



# Toyota to road test SiC power semiconductors

Using a 'Camry' hybrid prototype and a fuel cell bus, Toyota Motor Corporation will be road testing the performance of SiC power semiconductors. The company hopes this will lead to significant efficiency improvements in hybrids and other vehicles with electric powertrains.

At present, power semiconductors account for approximately 20 percent of a vehicle's total electrical losses, meaning that raising the efficiency of the power semiconductors is a promising way to increase powertrain efficiency. By comparison with existing silicon power semiconductors, the newly developed high quality SiC power semiconductors create less resistance when electricity flows through them. The technologies behind these SiC power semiconductors were developed jointly

by Toyota, Denso Corporation, and Toyota Central R&D Labs.

In the Camry hybrid prototype, Toyota is installing SiC transistors and diodes in the power control unit's (PCU) internal voltage step-up converter and the inverter that controls the motor. Data gathered will include PCU voltage and current as well as driving speeds, driving patterns, and conditions such as outside temperature.

By comparing this information with data from silicon semiconductors currently in use, Toyota will assess the improvement to efficiency achieved by the new SiC power semiconductors. Road testing of the Camry prototype will begin (primarily in Toyota City) in early March 2015, and will continue for about one year.



Similarly, on January 9, 2015, Toyota began collecting operating data from a fuel cell bus currently in regular commercial operation in Toyota City. The bus features SiC diodes in the fuel cell voltage step-up converter, which is used to control the voltage of electricity from the fuel cell stack.

Data from testing will be reflected in development, with the goal of putting the new SiC power semiconductors into practical use as soon as possible.

## LED market to grow at more than 30 percent in India until 2020

INDIA'S LED lighting market is currently at a nascent stage. Though the LED market is already growing at a robust pace over the last two to three years, the country offers huge growth potential, especially over the next five to ten years.

Increasing adoption of LED lighting is being witnessed across commercial and residential sectors, government projects, upcoming smart building projects, etc. According to a recently published report by TechSci Research 'India LED Lighting Market Forecast & Opportunities, 2020', the country's LED lighting market is projected to register a growth of over 32 percent during 2015-20.

Key factors that are expected to boost the market include declining LED prices coupled with favourable government initiatives to provide LED lights at subsidised cost and LED installation projects for streetlights.

In addition, growing awareness among consumers on account of awareness programs by manufacturers and regulatory bodies is expected to play a

vital role in shaping the country's LED market over the next five years.

"With manufacturing cost witnessing a decline every year and various government initiatives backing LED adoption, the LED lighting market in country is anticipated to grow robustly through 2020.

Moreover, rising consumer awareness about cost-effectiveness and eco-friendliness of LED lights would continue to drive volume sales from the residential and well as commercial sectors." said Karan Chechi, research director with TechSci Research, a research based global management consulting firm.

The report highlights that considering the growing adoption of LED lighting, various major players are planning to set up their manufacturing units in India in future.

Philips, Havells, Syska, Innovlite and GE are few of the leading players operating in the India's LED lighting market, however, various new entrants are expected in foray into the market in the coming years as well.

## SETi doubles efficiency of UVC LEDs

SENSOR Electronics Technology Inc., (SETi), a US company specialising in UV LED development and manufacturing, has announced it has shipping samples of its UVC LEDs with 2.5mW of optical power at 265nm to 280nm.

First launched in August 2013, the 3.5mm x 3.5mm ceramic SMD LEDs have evolved from 0.8mW of power at 20mA to 1.3mW in 2014 and now at 2.5mW, still at 20mA. This product is targeted at cost sensitive, high volume markets such as disinfection.

This announced increase in performance is part of SETi's performance roadmap that builds on developments made through the DARPA CMUVT program. Furthermore the performance represents a doubling of wall-plug efficiency (Pout/Pin) of 2.3 percent (EQE has been measured at 2.9 percent).

SETi continues to develop new epitaxial and chip fab processes along with novel packaging techniques. The 2.5mW UVC LEDs was exhibited at the SPIE Photonics West exhibition in San Francisco from February 10th - 12th.



*your*

# EPITAXIAL GROWTH

*partner*

InGaN InAlN AlGaN  
GaSb InSb InP InGaP  
InAlGaN GaAs AlGaAs

*Enabling advanced technologies*



- World leading technology
- Complete materials range
- MOCVD, MBE, CVD
- Advanced semiconductor wafer products
- Advanced R&D capabilities
- Multiple, manufacturing sites (Europe, Asia, USA)



[www.iqep.com](http://www.iqep.com)

# Delta gets DOE grant to develop GaN-based charger for vehicles

DELTA PRODUCTS CORPORATION (DPC), based in Fremont, CA, has announced its participation in a US Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) \$3.0 million award for the development of a high-efficiency, high-density, 6.6kW bidirectional on-board charger for plug-in Electric Vehicles (PEVs).

The on-board charger will use novel designs based on GaN power switches that target energy efficiency better than 95 percent and reduce volume and mass by 30 percent to 50 percent compared to today's technology.

The EERE research program will be a collaboration platform for industry and



academia. Delta, as a Tier-1 automotive supplier, will be partnering with FCA US LLC, a member of the Fiat Chrysler Automobiles NV (FCA) family of companies, Transphorm, a pioneering company in GaN power devices, and Virginia Tech's Center for Power Electronics Systems.

Products Corporation.

Delta has developed an energy-efficient solution for PEV on-board chargers, DC-DC converters, fast charger modules, battery disconnect units, and off-board charging station and site management systems.

'Delta is pleased to be working closely with EERE and our partners on this project to develop and commercialise the next generation of on-board EV chargers. The development of a smaller, lighter, less expensive and more efficient bidirectional on-board charger will be an enabling technology for affordable, fuel-efficient plug-in electric vehicles and vehicle-to-grid applications.' said M.S. Huang, president of Delta

## MBE GROWTH SPECIALISTS

Growth and device fabrication of arsenide/antimonide based III-V semiconductors notably:

- Narrow bandgap materials (InSb up to AlAs)
- Antimonide doping capability
- InGaAs/AlInAs structures lattice matched to InP substrates
- AlInGaAsSb lattice matched to InAs, GaSb or InP substrates
- Quantum dots/wells on GaAs substrates
- Antimonides on GaAs substrates using relaxed buffer layers

**Supplier of low volume wafer requirements.  
Research work enquiries welcome.**



Contact Tel - + 44 (0) 141 579 3020  
Email – [sales@quantumdevicesolutions.com](mailto:sales@quantumdevicesolutions.com)  
West of Scotland Science Park, Glasgow, G20 0SP

## New CS APP ready for Download NOW!

Continuing our aim of 'connecting the compound semiconductor industry', Compound Semiconductor has a Free app for Android, iPhone and iPad to allow you keep up to date wherever you are.

Available **FREE** from the App Store or Google Play, the app allows you to access:

- Latest Compound Semiconductor, CS China and CS Taiwan magazines
- Latest features
- Latest news and more...



For further information contact:  
[scott.adams@angelbc.com](mailto:scott.adams@angelbc.com)

[www.compoundsemiconductor.net](http://www.compoundsemiconductor.net)





# Lux identifies strategies for success with GaN and SiC power electronics

POWER ELECTRONICS based on GaN and SiC have the potential to significantly improve efficiency. But since these materials are higher-cost, companies need market-specific strategies in order to succeed as these new wide-bandgap (WBG) materials claim market share from silicon-based semiconductors, according to Lux Research.

Carmakers can succeed by playing the role of an 'integrator' by vertically integrating upstream in the value chain to power modules, while a GaN or SiC developer would do well to pursue a 'technology disruptor' strategy, offering core technology expertise to solar inverter makers and incumbent system integrators like ABB.

"Fast-growing markets like automotive and solar inverters are unforgiving when it comes to players without strong

business and strategy," said Pallavi Madakasira, Lux Research Analyst and the lead author of the report titled, 'Strategic Playbook for Power Electronics: Lessons from the IC Sector Evolution'.

"Start-ups trying to address these opportunities need to forge partnerships and collaborations - companies like Transphorm and GaN Systems that have done so are best-positioned for success," she added.

Lux Research analysts evaluated the value chain in GaN and SiC power electronics to identify strategies for the automotive and solar inverter market and came up with various findings.

One is that integrators face low risk. Carmakers could integrate upstream through acquisition to include power

modules and inverter/converter manufacturing. Such acquisitions will allow carmakers to own drivetrain design and lower overall costs.

Tech differentiation is also critical. A vertically integrated GaN/SiC device or module player is well-positioned in the solar value chain. The core technology differentiation that such a company offers will be critical for incumbent solar inverter makers like SMA and Fronius, and something system integrators like ABB do not have the competencies for. Finally, other players need to be nimble. Suppliers of substrates, packaging materials and thermal materials will need to customize. Staying nimble and planning for an increased number of specialised device makers in the power electronics value chain will be critical to their overall success.

## UV LED technology finds its path

NOW ESTABLISHED IN UV curing, UV LED technology will find growth opportunities in disinfection and purification and new applications by 2017/2018. Under its new technology and market analysis entitled "UV LED – Technology, Manufacturing and Application Trends", Yole Développement (Yole) the "More Than Moore" market research, technology and strategy consulting company, reviews and details the traditional UV lamp business and its current transition to UV LED technology.

Yole's report presents a comprehensive review of all UV lamp applications including a deep analysis of UV curing, UV purification and disinfection and analytical instruments. It highlights the UV LED working principle, market structure, UV LED market drivers and associated challenges and characteristics, the total accessible market for UV LEDs.

In this report, Yole's analysts also detail the market volume and size metrics for traditional UV lamps and UV LEDs over the period 2008-2019, with splits by application for each technology.



Thanks to their compactness and low cost of ownership, UV LED technology continues to make its way in the booming UV curing business, through replacement of incumbent technologies such as mercury lamps.

"Thanks to this an overall UV LED market that represented only ~\$20M in 2008 grew to ~\$90M in 2014, at a compound annual growth rate of 28.5%", explains Pars Mukish, Business Unit Manager,

LED activities at Yole. Such growth is likely to continue as LED-powered UV curing spreads across ink, adhesive and coating industries. And Pars Mukish from Yole, explains: "By 2017/2018, the UV LED market should also see part of its revenues coming from UVC disinfection and purification applications, for which device performance is not yet sufficient.

The UV LED business is therefore expected to grow from ~\$90M in 2014 to ~\$520M in 2019." This market's evaluation takes into account only standard applications, where UV LEDs replace UV lamps.

Pars Mukish adds: "The potential is even greater, if we consider UV LEDs' ability to enable new concepts in areas like general lighting, horticultural lighting, biomedical devices, and in fighting hospital-acquired infections (HAIs)".

Even this is just scratching the surface of UV LEDs' real potential. While the new applications do not yet have a strong impact on market size, Yole expects them to possibly count for nearly 10% of the total UV LED market size by 2019.

# RF GaN revenue to reach nearly \$560 million in 2019

ACCORDING to a new market research report GaN RF Market Update: 2014 - 2019 from Strategy Analytics, the market for RF GaN devices will reach nearly \$560 million by 2019, with a CAGR approaching 22 percent from 2014 to 2019."

After years of promise, but slow growth, the GaN RF market has finally taken off and it appears positioned for strong long-term growth. The defence industry has long been a supporter of GaN, providing the resources for GaN device, process and technology development for more than a decade. These applications continue to take advantage of the power and performance that GaN offers, but the adoption is changing slightly.

Land-based EW systems, with their high-power, wide bandwidth requirements and airborne radar systems that benefit from size and weight reductions appeared to be the best initial fit for GaN technology. These two applications were the early adopters of GaN, but usage has responded to a changing geo-political landscape. Initial land-based EW systems focused heavily on counter IED networks in asymmetric battlefield situations. With the reduction of US forces in Iraq and Afghanistan, this activity has decreased markedly. In addition, the anticipated uptake of GaN in AESA radar systems has been slow to materialize. Overall budget and program funding uncertainty has delayed and/or reduced the spending on new platforms and this is reducing the rate of GaN adoption in these applications. Despite a change in the anticipated usage scenarios, military applications continue to represent opportunities for GaN adoption. While growth rates for RF GaN devices in land-based EW and airborne radar systems have declined, they still represent the two largest sources of GaN revenue in military applications.

Tactical communications equipment will continue to benefit from the bandwidth and power capabilities of GaN and this segment will experience the fastest growth in device revenue. By 2019, this segment will account for the largest portion of the RF GaN defence revenue. The report speculates that AESA radar systems will move beyond fast jet

applications and experience increasing deployment in land and sea-based radar applications. This segment will be the second largest user of GaN RF devices by 2019. Shifting battle philosophies will position RF GaN device revenue in EW systems behind these other applications. "Applications for RF GaN devices are growing much more quickly than defence budgets," states Strategy Analytics analyst Asif Anwar. "We anticipate broad adoption of GaN RF devices in radar, communications and EW applications will fuel impressive revenue growth."

The biggest change in RF GaN usage comes from commercial applications. Previous research indicated that the commercial market for GaN-based RF devices was tantalizingly close to the tipping point for broad adoption. It now appears clear that the market has passed this point as evidenced by strong adoption in wireless and CATV/broadband infrastructure, along with the first reports of GaN usage in microwave/millimetre wave radios, VSAT and industrial applications. While CATV/broadband infrastructure was the first commercial application to use GaN widely for power amplifiers, wireless infrastructure applications have exploded in the past year or so. Initially relegated to low volume applications in the Asia-Pacific region, GaN-based power amplifiers have shown the right mix of production maturity and competitive pricing, coupled with performance advantages to capture a growing share of the new LTE wireless infrastructure deployments.

This segment of the commercial market has gotten a substantial boost from efforts in China to establish a nationwide LTE network. While GaN usage is still much smaller than LDMOS in these wireless infrastructure applications, the scope of the Chinese LTE deployment in 2014 was enough to make this the largest commercial segment.

The magnitude of RF GaN revenue in wireless infrastructure applications, coupled with adoption in a variety of other applications was enough to push the commercial segment to slightly more than half of the total revenue.

## STMicroelectronics extends SiC MOSFET family

STMICROELECTRONICS state their new SCT20N120 silicon-carbide power MOSFET brings advanced efficiency and reliability to a broader range of energy-conscious applications such as inverters for electric/hybrid vehicles, solar or wind power generation, high-efficiency drives, power supplies, and smart-grid equipment.

ST is among the few vendors developing the robust and efficient silicon-carbide power semiconductors. The 1200V SCT20N120 extends the family, with on-resistance  $R_{DS(ON)}$  better than 290mΩ all the way to the 200°C maximum operating junction temperature.



Switching performance is also consistent over temperature thanks to highly stable turn-off energy and gate charge. The resulting low conduction and switching losses, combined with ultra-low leakage current, simplify thermal management and maximize reliability.

In addition to their lower energy losses, ST's silicon-carbide MOSFETs permit switching frequencies up to three times higher than similar-rated silicon IGBTs allow. This enables designers to specify smaller external components and save size, weight, and bill-of-materials costs.

The SCT20N120's high-temperature capability helps to simplify cooling-system design in applications such as power modules for electric vehicles.

# CSindustry awards2015

## Winner announced at CS International

The CS Industry Awards recognise success and development along the entire value chain of the compound semiconductor industry from research to completed device, focusing on the people, processes and products that drive the industry forward. The CS Industry Awards will remind us what is good about the industry - the people who drive it with their technical expertise and customer orientated perspectives.

### The categories are:

#### SUBSTRATES & MATERIALS AWARD

**Cambridge Nanotherm Ltd**  
Nanotherm DM

**Crystal IS**  
Native AlN-based UVC LEDs

**Element Six**  
GaN-on-Diamond Wafers

#### DEVICE DESIGN & PACKAGING AWARD

**Cree, Inc**  
C2M0025120D

**M/A-COM Technology Solutions Inc**  
650 W Peak Power GaN on SiC Transistor

**Efficient Power Conversion (EPC)**  
GaN half-bridge transistor

#### R & D CHIP DEVELOPMENT AWARD

**DARPA**  
Terahertz Electronics program

**SemiLEDs Corporation**  
Enhanced FlipChip

**Soitec, CEA-Leti & Fraunhofer Institute for Solar Energy Systems**  
ISE Multi-Junction Solar Cell

#### INNOVATION AWARD

**Osram Opto Semiconductors**  
Displix Oval

**Veeco Instruments Inc**  
TurboDisc EPIK700 GaN MOCVD System

**Soraa Inc**  
GaN on GaN Gen3 LED

#### METROLOGY, TEST & MEASUREMENT AWARD

**Bruker Corporation**  
LumiMap Electroluminescence Tool

**LayTec AG**  
Pyro 400 Gen2

**KLA-Tencor Corporation**  
Candela CS920

#### Awards Sponsor



The winners will be announced and awards presented at an evening event, with 300 industry professionals, on March 11th 2015 at the CS International Conference, Frankfurt, Germany.

For more information: [www.csawards.net](http://www.csawards.net)



# Berkeley Lab shows new precision growth technique for GaN nanowires

IN A RECENT ISSUE of Nano Letters, scientists from the US Department of Energy's Lawrence Berkeley National Lab (Berkeley Lab) demonstrated a new growth technique for GaN nanowires that uses specially engineered catalysts. The catalysts, which are precursors to growing the nanowires, have given them more options in turning the colour of light-emitting nanowires.

The new approach could potentially be applied to a variety of materials and be used for making next-generation devices such as solar cells, LEDs, high power electronics and more, says Shaul Aloni, staff scientist at Berkeley Lab's Molecular Foundry, a DOE user facility, and lead author on the study.

Since the early 2000s, scientists have made steady progress in cultivating nanowires. Initially, early nanowire samples resembled "tangled noodles or wildfire-ravaged forests," according to the researchers. More recently, scientists have found various conditions lead to the growth of more orderly nanowire arrays. For instance, certain substrates on which the nanowires grow create conditions so that the nanowire growth orientation is dictated by the substrate's underlying crystal structure.

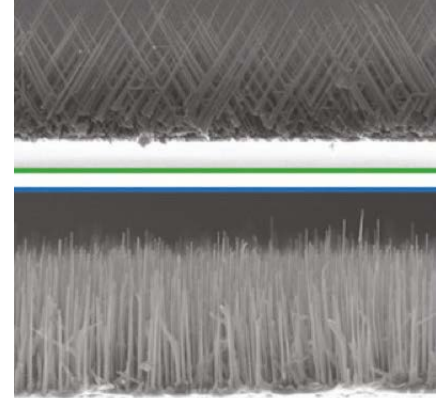
Unfortunately, this and other approaches haven't been fool proof and some nanowires still go rogue. Moreover, there is no simple way to grow different types of nanowires in the same environment and on the same substrate. This would be useful if you wanted to selectively

grow nanowires with different electronic or optical properties in the same batch, for example. "At the Molecular Foundry we are aiming to develop new strategies and add new tools to the bag of tricks used for nanomaterials synthesis," says Aloni. "For years we were searching for cleverer ways to grow nanostructures with different optical properties in identical growth conditions. Engineering the catalyst brings us closer to achieving this goal."

The researchers focused on nanowires made of GaN. In its bulk (non-nanoscale) form, GaN emits light in the blue or ultraviolet range. If indium atoms are added to it, the range can be extended to include red, essentially making it a broad-spectrum tunable light source in the visible range.

The problem is that adding indium atoms puts the crystal structure of GaN under stress, which leads to poorly performing devices. GaN nanowires, however, don't experience the same sort of crystal strain, so scientists hope to use them as tunable, broad-spectrum light sources. To achieve their control, the team focused on the catalysis which guide the nanowire growth. Normally, researchers use catalysts made of a single metal. The Berkeley team decided to use metallic mixtures of gold and nickel as catalysts.

In the study, the researchers found that the GaN nanowire growth orientation strongly depended on the relative concentration of nickel and gold within the catalyst. By altering



the concentrations in the alloy, the researchers could precisely manipulate, even on the same substrate in the same batch, the orientation of the nanowires. "No one had used bi-metallic catalysts to control growth direction before," says Teyve Kuykendall, scientist at Berkeley Lab's Molecular Foundry. Kuykendall says the mechanism driving the new growth process is not fully understood, but it involves the different tendencies of gold and nickel to align with various crystallographic surfaces at point where nanowires start to grow.

The researchers also showed that depending on the growth direction chosen, different optical properties were observed thanks to the crystal surfaces exposed at the surface of the nanowire. "One of the things that make nanostructures interesting, is that the surface plays a larger role in defining the material's properties," says Aloni. This leads to changes in optical properties not seen in larger-bulk materials, making them more useful.

## Rubicon's quarterly results up 11 percent

RUBICON TECHNOLOGY, a provider of sapphire substrates and products to the LED, semiconductor, and optical industries, last week reported financial results for its fourth quarter ended December 31, 2014.

The company reported Q4 revenue of \$8.9 million, an eleven percent increase over prior quarter revenue of \$8.0 million. Demand for the company's two-inch sapphire cores, primarily used in the mobile device market and the China LED

market, increased considerably in the period but was offset in part by lower revenue from four-inch cores sales.

Four-inch material is used almost exclusively in the LED market and fourth quarter demand was impacted by seasonality in the backlighting segment of the LED market. Revenue from 4 to 8 inch patterned sapphire substrates (PSS) and revenue from optical products also increased sequentially.

In addition to reporting fourth quarter results, the company provided information on key objectives for 2015. Those objectives include aggressively pursuing the potential of its PSS product, targeting high margin optical applications and driving down product costs. William Weissman, Rubicon's CEO, commented: "We are taking action to position Rubicon to drive strong margins when the market strengthens and also ensure that we are cash flow positive during downturns in the market."

# EpiGaN appoints Markus Behet as CMO

EPIGAN, a key global player in III/V materials technology, has appointed Markus Behet as Chief Marketing Officer for its GaN/Si and GaN/SiC epitaxy wafer product lines serving a host of innovative applications in the power switching and RF markets. In this newly created role, effective Feb 1, Markus Behet will lead the company's global commercial and marketing programs directly reporting to EpiGaN's CEO Marianne Germain.

The appointment of Markus Behet as EpiGaN's CMO signals a major strategic step for the company in the continuing expansion of its global marketing and sales activities in the rapidly proliferating GaN technology, which is continuously driven towards technology and process maturity by one of the world's leading GaN-on-Si wafer pioneers.

"EpiGaN is strongly committed to a leadership role in GaN-based wide-band-gap wafer technology as it enables a new generation of efficient power electronic devices and systems," EpiGaN CEO Marianne Germain said. "Markus' track record in global marketing and his deep III-V industry knowledge make him exceptionally well qualified for this newly created position. EpiGaN's strong science-based foundation and leading-edge GaN epitaxy wafer technology are tailored to support the sustainable growth of innovative product solutions for global power and RF device manufacturers."

"I am pleased and honoured to be able to contribute to EpiGaN's continued success," Markus Behet said. "EpiGaN is a true technology leader with a differentiating epitaxy approach. EpiGaN's GaN/Si and GaN/SiC wafer technologies will enable the power electronic industry to take the next step of innovation towards more efficient, higher performance and lower cost power devices and system solutions."

Markus joins EpiGaN from Dow Corning, where he held global market segment positions for their SiC and GaN/Si wafer business. Prior to this, he has worked for Triquint Semiconductor, Infineon Technologies and Siemens, where he was in charge of various key marketing, business development and sales positions for GaAs-based RF power and foundry business lines. Earlier, Markus was R&D manager at imec,

the world-renowned Belgian micro and nano-electronics research organization. Markus holds a PhD in semiconductor physics and electrical engineering from Aachen Technical University, Germany.

Wide band-gap GaN-based semiconductor devices offer superior performance vs. incumbent silicon or GaAs solutions in the realm of power switching and RF power applications. These properties make them ideally suited for highly efficient high-frequency and linear power electronic applications

in the consumer, transportation, energy and RF markets.

Integration of GaN device on Si substrates will leverage economies of scale and enable innovative solutions on low-cost, high-volume and large-diameter Si-processes.



## Pure SiC Perfection

Very close customer cooperation has given us a proven excellence in conductive and semi-insulating Silicon Carbide (SiC) substrates and epitaxial wafers. A flawless base for semiconductors in the power and RF electronic industries which results in high quality end products.

**Our promise to you: Pure – Clean – Quality**

**NORSTEL**★

For more information please contact [sales@norstel.com](mailto:sales@norstel.com), [www.norstel.com](http://www.norstel.com)

# ITC look at infringements of Cree LED patents

CREE has announced that the US International Trade Commission (ITC) has agreed to open an investigation into unfair trade practices by Feit Electric Company and its Asian supplier, Unity Opto Technology.

The investigation includes allegations of infringement of 8 Cree patents related to LED lighting and Feit's false and misleading advertising claims, including that certain of its products meet ENERGY STAR specifications. The decision to open an investigation comes after Cree filed a complaint on January 12, 2015, requesting an investigation by the ITC.

"We're pleased with the ITC's decision to open an investigation into this matter," said Chuck Swoboda, Cree Chairman and CEO.

"With nearly \$1 billion investment in developing the fundamental technology that underlies LED lighting adoption, it is our obligation to protect our intellectual property. Through their actions, Feit and Unity Opto are enjoying an unfair advantage in the market and discouraging the development of new products that benefit consumers."

The investigation is titled 'Certain Light-Emitting Diode Products and Components Thereof, ITC Inv. No. 337-TA-747'.

Cree has introduced a new addition to its CXA LED array family, CXA2 LED arrays, delivering up to 33 percent higher efficacy in the same form factors. Using elements of the Cree SC5 Technology Platform, this improvement in lumen density enables better performance and reduces system size and cost. The new chip-on-board (COB) LEDs allow lighting manufacturers to rapidly deliver more innovative solutions for applications such as track, downlight and outdoor lighting.

"We are working together with Cree to evaluate their latest COB technology," said Massimo Parravicini, R&D director of Reggiani Illuminazione. "I believe that the new CXA2 LED arrays, which deliver excellent performance in such small LES [light emitting surface], would be a great solution for the new generation of indoor luminaires we are currently developing." With the new CXA2 LED arrays, lighting manufacturers can achieve the same or better performance with a smaller LES compared to earlier products. For example, a 3800 lumen output from a

larger 19 mm LES LED can be replaced with a smaller 12 mm LES LED, resulting in up to 60 percent system cost savings from lower LED, mechanical and optic material costs.

"The new CXA2 LED arrays make it possible for lighting designers to radically reduce system costs in the next generation of industry-leading lighting products," said Dave Emerson, vice president and general manager for Cree LEDs. "By giving our customers innovative LED solutions instead of incremental LED improvements, we enable them to differentiate their products in the marketplace and deliver more value to their end customers."

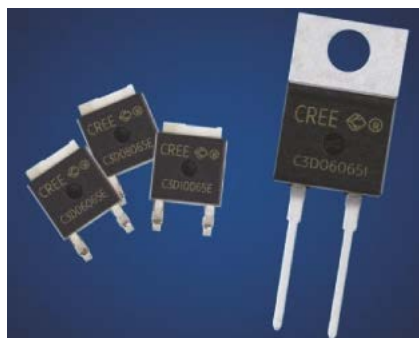
CXA2 LED arrays share the same physical design as earlier arrays, allowing lighting manufacturers to leverage the existing optical, mechanical and electrical design elements to accelerate time to market without additional cost.

LM-80 data is available for all CXA2 LED arrays for lighting manufacturers seeking ENERGY STAR qualification. The CXA2 LED arrays are also UL-recognised components and feature a level 4 rating.

## Cree adds 650V diodes to SiC Schottky portfolio

Cree, a pioneer in SiC power devices, has added four new 650V diodes to its SiC Schottky diode portfolio. Developed in response to the power supply industry's recent demand for components with a nominal voltage rating slightly higher than 600V, the new 650V Cree Z-Rec SiC Schottky diodes enable high efficiency power systems with improved reliability, simplicity, and total cost.

Key characteristics of the new diodes include: zero reverse recovery current, high frequency operation with low EMI, temperature-independent switching behavior, reduced heat sink requirements, and significantly higher surge and avalanche capabilities. They also exhibit higher efficiency than comparable silicon diodes, with essentially no switching losses, and a positive temperature coefficient on VF enables parallel devices without thermal runaway.



The new 650V 6A C3D06065E, 8A C3D08065E, and 10A C3D10065E Cree Z-Rec diodes are supplied in TO-252-2 (DPAK) packages with a smaller footprint than many of the comparable diodes currently on the market. The 650V devices are suitable for use in switch mode power supplies, power factor correction, and motor drives, among other applications. Additionally, these three diodes are automotive qualified to AEC-Q101, and are suitable for use in the power factor

correction and onboard power electronic conversion systems of hybrid and electric vehicles.

The fourth new 650V diode, Cree's 6A, 650V C3D06065I internally isolated Z-Rec Schottky diode is an alternative to full-pack diodes and a complement to the existing and extremely successful 8A C3D08065I and 10A C3D10065I. Featuring a TO-220 package with internal ceramic insulation - unique to Cree with regard to SiC Schottky diodes - that provides 2.5kV isolation, Cree's new 6A, 650V internally isolated diode also provides greater operating ranges and capabilities than comparable full-pack devices, including significantly higher maximum temperatures and greater power dissipation.

Additionally, by eliminating the need to insert an external isolating sheet between the diode and heat sink, this new diode eases design, reduces cost.



## Sensor Electronic Technology appoints new president and CEO

SENSOR ELECTRONICS TECHNOLOGY INC, SETi, a US company specialising in UV LED development and manufacturing, located in Columbia South Carolina, announced today that Emmanuel Lakios has joined the company as President and CEO.

Lakios joins SETi with 30 years of technology and business management experience. Prior to joining SETi he held positions as president and COO of Imago Scientific Instruments and 20 years at Veeco Instruments, where he held various senior management positions including president and general manager of process equipment and president of

field operations. In his new role, Emmanuel will build upon the existing technical excellence and organization and will coordinate all company activities. Emmanuel brings a strong track record in technology management, strategic market development, and operational performance. Lakios has over 30 years of experience in Semiconductor and equipment industry.

“SETi has a great opportunity for growth with its leading edge deep UV LED technology,” commented Lakios. “New applications for this class of LEDs emerge daily. Our mission is to maintain our technical leadership and product position, addressing the requirements of the marketplaces we serve”.

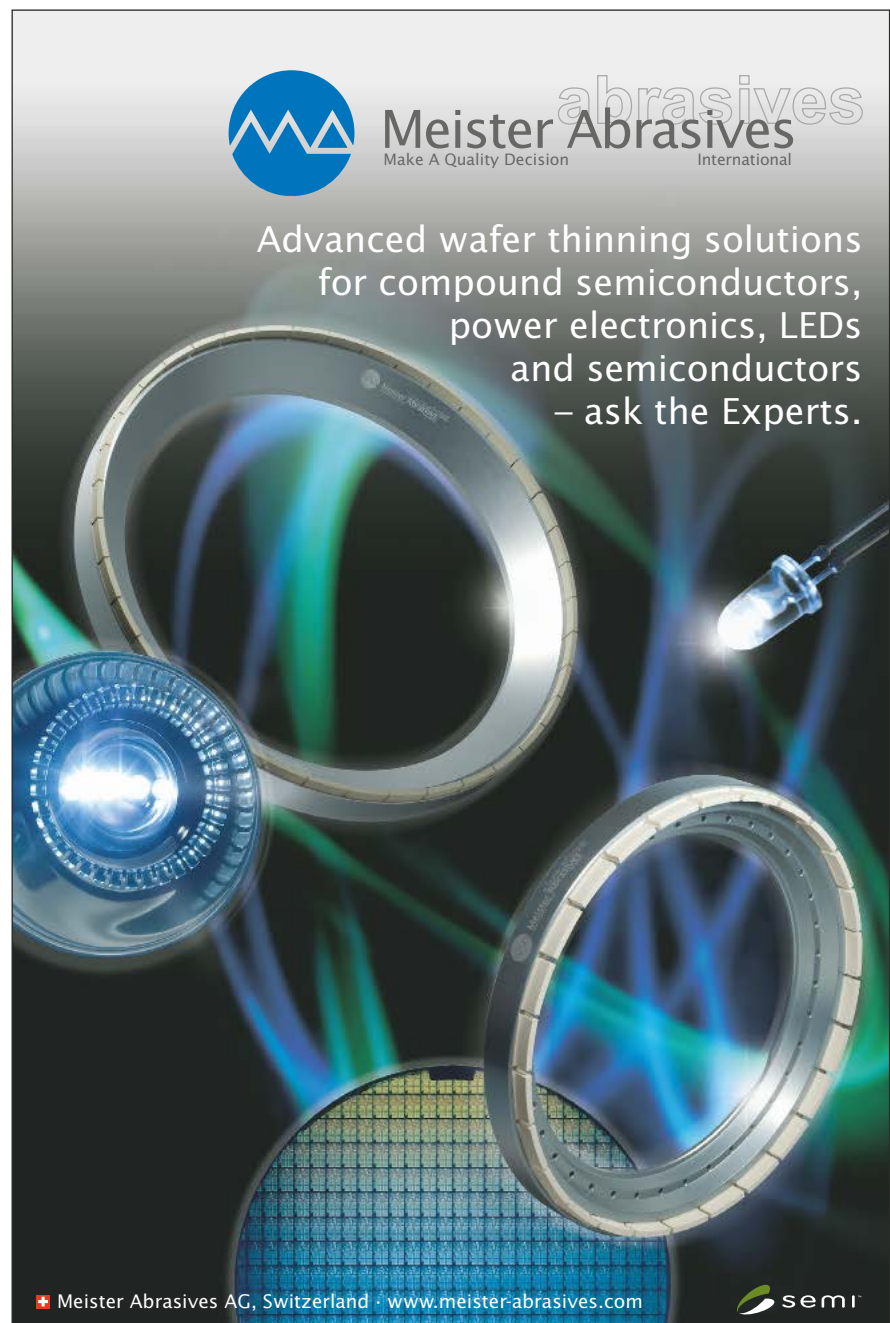
## Toshiba launches improved high-luminous efficacy white LEDs

TOSHIBA ELECTRONICS EUROPE has launched a new series of high power LEDs for use in a wide variety of residential, commercial and industrial lighting applications. The TL1L4 series offers better performance than the preceding TL1L3 series.

Toshiba state that the new TL1L4 series achieves a high luminous flux that surpasses 160lm at room temperature operation. Under conditions of  $T_a = 85$ , operating current can be driven to 1A and luminous flux is more than 60% greater than that offered by the preceding TL1L3 series. This contributes to improved luminous efficacy and lower power consumption for LED applications.

Available in nine-colour variations from 2700K to 6500K, the TL1L4 series utilises cost-effective GaN-on-Si wafer technology to create LEDs optimised for both output and energy efficiency. The devices are housed in a compact 3.5mm x 3.5mm lens package and rated to support an absolute maximum forward current of 1.5A max at  $T_a < 55$  and  $T_j < 150$ .

Hot binning tests for electrical and optical characteristics are conducted at 85 and  $I_F = 350\text{mA}$  that simulate real-life operating conditions. Mass production will commence imminently.



**Meister Abrasives**  
International  
Make A Quality Decision

Advanced wafer thinning solutions  
for compound semiconductors,  
power electronics, LEDs  
and semiconductors  
– ask the Experts.

Meister Abrasives AG, Switzerland · [www.meister-abrasives.com](http://www.meister-abrasives.com)

semi

# Photonic ICs: reality check

Will US plans to drive integrated photonics forward finally deliver real products for real applications? Rebecca Pool speaks to industry executive, Michael Lebby, to find out more.

LATE LAST YEAR, President Obama revealed his intention to form his sixth Institute of Manufacturing Innovation; an Integrated Photonics Institute for Manufacturing Innovation. Tasked with the key goal of developing cheap, high-volume manufacturing methods for complex photonics integrated circuits in just five years, Universities across California, New York, Florida and Pennsylvania have been rallying commercial support to establish industry-driven consortia.

With \$110 million government funds at stake, not to mention mandatory matching in-kind contributions from industry, and potential contributions from local government, competition has been fierce. Of the ten to twenty consortia that entered the first pre-proposal phase, only a maximum of four will be invited to submit a full proposal. These results are due at the end of this month, and a lone winner will follow.

"There is a shortlist process going on right now, but what is known is that three big consortia – from the Florida, New York and California areas – have emerged," explains Professor Michael Lebby from UK-based Glyndwr University, and President of US-based start-up OneChip Photonics and optoelectronics consultancy, Oculi.

"New York is using its big silicon fab at Albany as an anchor, Florida has a strong optics community and California has MOSIS, a successful silicon foundry service," he adds.

Crucially, as Lebby highlights, the states of these 'big three' have promised to provide funds. "We don't know how the Department of Defense will choose, but these three [consortia] have momentum," he says. "For example, California state has said it will match the federal money, so the proposal is already at \$220 million, and New York and Florida states are expected to match contributions too."

Lebby himself is a consultant for the Californian consortium, led by the Information Sciences Institute (ISI) at the University of Southern California (USC), alongside the Universities of California Berkeley (UCB), Los Angeles (UCLA), San Diego (UCSD), Arizona State University, University of New Mexico and Ohio State University.

As hinted, this consortium is emulating its program on MOSIS, California's cost-cutting integrated circuit foundry service, formed back in 1981.

MOSIS - Metal Oxide Silicon Implementation Service - is operated by the USC's ISI and was set up to reduce chip costs by integrating numerous IC



designs from different organisations onto a single wafer during fabrication. Designs are pooled into common lots and run through the fabrication process at foundries with the completed chips returned to customers.

Having prototyped more than 50,000 chip designs for private businesses, government agencies, research agencies and universities, this multi-project wafer approach has been very successful. And according to Lebby, this tactic will now be key to cutting integrated photonics technology costs.

"Whoever wins this competition is going to have to put a photonics MOSIS in place," he says. "Integrated photonics technology is very expensive to develop, so people are trying to apply the silicon industry's multi-wafer approach to the photonics industry."

As the industry executive highlights, MOSIS is a very successful silicon



brokering system, with its multi-part wafer tactic being applied across the silicon industry. "Having a III-V equivalent would be a very cool approach, and for California, this is certainly building on strengths, rather than starting from new," he adds.

But the notion of an integrated photonics foundry is hardly new. Thanks to more than a decade of European Commission funded programmes, organisations across Europe have been busy trialling lines. For example, Ghent University, Belgium, has been working with imec and CEA-LETI on a silicon photonics platform, while TU Berlin, Germany, and Leibniz-Institute IHP have established a silicon photonics opto-electronic IC pilot line.

And as Lebbby points out: "As a continent, Asia also funds infrastructure a lot more aggressively than the US. From a competitive standpoint with Europe and Asia, the US is behind."

What's more, for these nations, following a shared foundry model has been key to the successes. The manufacture of complex integrated photonics circuits isn't cheap and sharing resources to cut costs has been imperative.

"To do a good job in silicon photonics, and even InP, you need fifty to one hundred million dollars, how many companies can afford that?" asks Lebbby. "The [shared] foundry model means people can get integrated photonics at a lower cost structure. Europe already figured this out, Japan has figured this out and America has just figured this out."

For its part, the latest US programme now intends to develop an 'onshore' integrated photonics manufacturing line, in a bid to stem the steady stream of home-grown photonics technology to Asia-based nations. The initial platform will focus on photonic interconnects for data centres and the winning consortium

will home in on four key areas; RF photonics, optoelectronics sensing, digital communications, and packaging and assembly.

Crucially for the future of integrated photonics, other funding programmes, such as the EU's Horizon 2020, are already calling for integrated photonics lines to produce qualified products. And the US is following suit.

"Integrated photonics is now at a point where the [product] coming out of the foundry, pilot line needs to be used in real products by customers," he says. "US government wants industry to use these consortia to run a pilot line to get prototypes, this is important as the stuff coming out of any pilot line must be accepted by industry as a qualified product."

"Many want to see silicon photonics for real and a lot of money is being invested. There's a lot of hope out there," he adds.



# Lights out for CPV?

What does Soitec's decision to exit CPV mean for the rest of the industry?  
Rebecca Pool investigates.

AS THE DUST SETTLES on Soitec's recent decision to distance itself from concentrated photovoltaics and re-focus on electronic materials, industry players are mulling the impact on the costly world of CPV.

France-based Soitec, a consistent leader in CPV development, had set a record-breaking 46 percent solar cell efficiency and was one of the sector's highest hopes for mass commercialisation. Its 44 MW Touwsrivier project in South Africa was one of several big wins in recent years that fuelled analysts buoyant predictions of rapid market expansion through to 2020. But, as the price of rival silicon cells has plummeted, Soitec, and the industry, has struggled.

In April last year, Soitec revealed independent US energy company, Tenaska, had ditched plans to use

the CPV developer's technology at its planned 150 MW California PV power plant, choosing more conventional and cheaper PV modules instead. Then, come December, US utility San Diego Gas & Electric, which had agreed to buy the power generated at the California plant, terminated its business relationship with Soitec and shares sank to an all-time low.

The company's latest 'strategic re-focus' not only brings job cuts at Soitec's San Diego CPV module production plant, but sees industry analysts trimming CPV industry forecasts. Just days before Soitec's New Year bombshell, US-based industry analyst firm, IHS, predicted CPV would experience accelerated growth of 37 percent in 2015 bringing some 250 MW in new installations.

IHS solar research analyst, Karl Melkonyan, says the news shifts his

company's outlook back by around a year, as predictions had included many of Soitec's projects. But, crucially, he doesn't expect any significant long-term effects. "Of course this announcement negatively affects our projections, and perhaps investment will slow down," he says. "But CPV is an established technology and it doesn't mean we will see any mid- or long-term damage to the industry."

Pointing to very recent market developments, such as Portugal-based MagPower tying up with France-based Heliotrop to form a European CPV consortium, he says: "The CPV market is still in its early phases of growth, and the supplier base will continue to change over the next five years."

"This alliance between MagPower and Heliotrop is a good example of this, and





Left: Soitec achieved a module efficiency of 32.8 percent with its highly efficient multi-junction solar cells.

can help CPV technology find the path to a breakthrough,” he adds.

Indeed, Melkonyan cites MagPower as just one CPV developer to watch with others including China’s leading light, Suncore, Sempruis, US, and Spain-based Abengoa Solar.

“Progress will continue,” he says. “Sempruis is developing a new four-junction cell... Abengoa is ready to build a CPV plant. [The sector] is depending on good orders and investment, this will come with time.”

But what next for Soitec? Once industry has adjusted to the company’s re-focus, Melkonyan is hopeful, as he puts it: ‘a company with a large balance sheet’ will step in.

Pointing to partnerships between Middle East investors and CPV players, such as Enertech, Kuwait, and Morgan Solar, Canada, as well as Saudi-based KACST and Solar Junction, US, he says: “This is a good opportunity for, maybe an oil company, to either partner with Soitec or acquire [its assets].”

As he adds: “Soitec’s technology is established with competitive prices and good manufacturing... this could be an even better opportunity.”

For its part, Soitec hasn’t announced a firm plan of action. Following its initial cull of 100 employees at its manufacturing facility in San Diego, further cost-cutting and restructuring measures are expected. But in its last conference call, Soitec executives certainly emphasised that its solar cell technology is mature and ready for large-scale production, a fact that can only offer investor appeal. And with CPV installations in 14 countries, including the 44 MW Touwsrivier project, under development, it’s clearly not yet lights out for the company.

“Soitec’s solar [business] is still working, it hasn’t shut down,” asserts Melkonyan. “The company has reduced two to three of the production lines it had in the US and will complete remaining orders.”

“This is still a lot of installations compared to competitors, so the company must be looking for a good partnership with a larger business,” he adds.



Despite its re-focus, Soitec has installed more CPV modules than most.



# Solar-Tectic on course for sapphire success

As cheap sapphire glass production gathers pace, solar cell start-up, Solar-Tectic, has set its sights on photovoltaics, smartphone displays and more. Rebecca Pool reports.

IF SOLAR-TECTIC'S latest developments are anything to go by, 2015 should be a big year for the US-based solar cell start-up.

Plans to produce sapphire glass, consisting of a thin film of sapphire on MgO-buffered soda-lime glass, are well underway with smartphone covers clearly being the number one application.

What's more, company researchers have also deposited highly textured silicon films on the MgO/soda-lime glass substrate, opening the door to cheap fabrication of photovoltaics and more. And with the technology also being honed for LEDs, the future is looking bright.

Solar-Tectic was set up in 2010, to commercialise the thin film technology developed by the late Praveen Chaudhari, IBM



Left: Set to scale cheap sapphire glass production, Solar-Tectic will target solar cell, smartphone and LED applications.

materials physicist, Brookhaven National Laboratory director and 1995 US National Medal of Innovation and Technology winner.

As his son, Ashok Chaudhari, explains: “His idea for solar cells at the time was to deposit high quality but inexpensive thin films onto inexpensive substrates.”

“He wanted to deposit silicon onto a cheap substrate, with the trick being to deposit a thin film of sapphire onto glass,” adds Chaudhari. “If you could do this, then you have your crystalline substrate on which you can deposit silicon or another semiconductor film.”

Five years on and the ‘trick’ is being put into practice. Late last year, and working alongside colleagues from thin-film deposition system manufacturer, Blue Wave Semiconductors, US, the company received a US patent for its growth of single-crystal semiconductor films, on inexpensive substrates, including glass.

“Soda lime glass is very cheap and that makes a big difference,” says Chaudhari. “Other researchers hadn’t really thought about using this glass as it has a very low melting point. But we can deposit thin films onto this glass at much lower temperatures than other deposition processes.”

### Traditional science

Chaudhari’s success lies in the materials phenomenon, ‘eutectic melting’. When two elements, such as silicon and a metal, combine to form a superlattice, known as a eutectic system, the melting point of each is lowered.

At the so-called eutectic point, both elements within the superlattice will melt at the lowest possible melting temperature. However, fix the relative compositions of each as required, and your element of choice will still melt from the superlattice at a lower temperature than if in its pure form.

Chaudhari has harnessed this effect to develop his proprietary eutectic deposition method. Here, silicon films can be deposited from a metal-semiconductor system, such as an Al-Si eutectic melt, onto glass via an electron-beam evaporation system operating between temperatures of 300 to 600°C. These growth temperatures are higher than the materials systems’ eutectic point, but don’t melt the glass substrate.

As Chaudhari explains: “When depositing silicon from the eutectic melt, we keep the temperature constant, above the eutectic temperature, and increase the amount of silicon until heterogeneous nucleation takes place. This allows for large grained thin film deposition.”

So far the results are very promising. Initial X-ray diffraction of sapphire films, deposited via the electron-beam evaporation system onto the magnesium-buffered soda lime glass, reveals continuous highly textured  $\text{Al}_2\text{O}_3$ , crucial for smartphone cover applications. At the same time, similar analyses of silicon films,

deposited from an Al-Si eutectic melt, reveal a highly textured silicon film, ready for GaN deposition and, of course, LEDs.

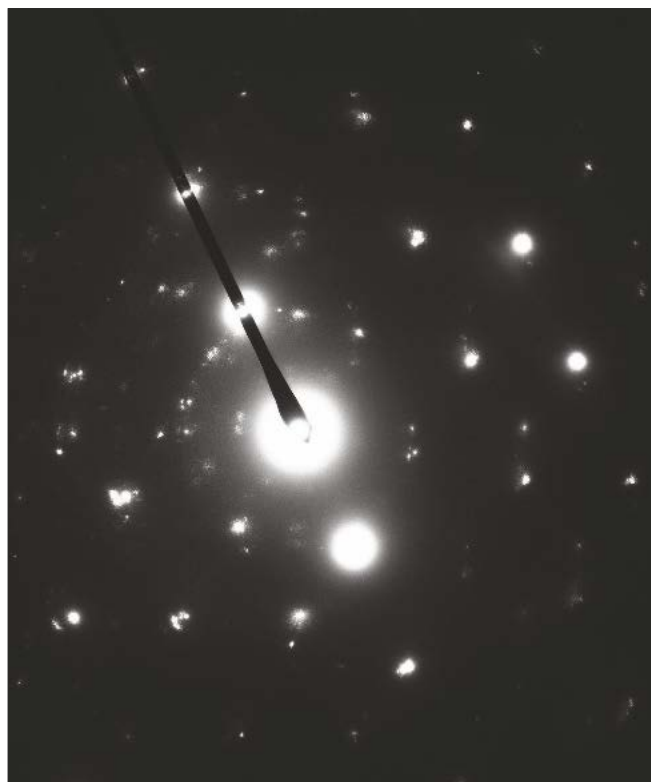
Chaudhari soon hopes to scale the process. Right now he and colleagues are working with small sample sizes, but in his words: “We don’t foresee any issues for scalability here.”

And crucially, the process is without a doubt relatively low-cost. As sapphire furnace maker and supplier of sapphire material for Apple’s smartphones, GT Advanced Technologies, files for bankruptcy, Chaudhari claims his deposition process is ‘many orders of magnitude cheaper’.

“It also consumes much less energy than the Apple-GTAT furnaces that heated sapphire to 2000 °C. We only heat to 550 °C and for a much shorter time,” he says.

“Our process is very traditional materials science, and why neither Apple nor GTAT took this route puzzles me,” he adds. “Apple is very cunning, but employees are primarily designers, not materials scientists, so maybe they just missed this traditional materials view.”

So where next for the start-up? According to Chaudhari, a next step is to deposit GaN on his highly textured silicon layers. In-house work starts soon, and companies are already contacting him to collaborate and develop the technology further. “We’re a start-up and a family-run business with a limited budget,” he says. “We’ve got great results with silicon so need a company to work with that can really take this forward.”



Transmission electron microscopy diffraction pattern of sapphire/MgO interface showing crystallinity of each. UV visible spectroscopy has also shown near perfect transparency of sapphire glass. [Chaudhari]

# Photovoltaics: the future for GaN?

Transphorm ramps up GaN-on-silicon device production as photovoltaic inverter markets drive growth. Rebecca Pool reports.

FOR GAN DEVICE MANUFACTURER, Transphorm, 2015 is already shaping up very nicely. Mass production of power devices kicked off at Fujitsu Semiconductor's CMOS-compatible 150 mm wafer fab in Fukushima in late January.

And now, Japan-based Yaskawa Electric has revealed it is using these very same GaN power modules in its PV inverters, currently under mass production for Japanese markets.

As Primit Parikh, president and co-founder of Transphorm tells *Compound Semiconductor*: "Fujitsu's fabrication line has been qualified for automotive-grade wafers in the past, and while our products have always been reliable, the scale of a large mass production foundry such as this is unmatched."

"Mass production here assures our customers they are getting the highest quality product at an affordable price, and they don't have to worry about scaling in the future," he adds.

Parikh will not be drawn into actual production numbers, but as he points out, Yaskawa intends to produce 34,000 systems every year, with each system containing several GaN devices and modules.

"Volumes are beginning to ramp and we are ready to supply and scale up," he says.

Surprisingly for Parikh, and many in the industry, the PV inverter market is proving to be very lucrative for GaN-based devices. The PV inverters market segment has already widely adopted SiC Schottky switching diodes from the likes of Cree, Infineon and Rohm.

And while industry pundits have speculated GaN transistors could make in-roads into this market, questions over qualification have been raised. Not any more, says Parikh.

"Traditionally, the photovoltaic industry has been associated with 25 years of reliability so many doubted the technology would be adopted here," he asserts.

But as the company co-founder points out, Transphorm has spent several years sampling and selling 600 V qualified devices to PV manufacturers, including Yaskawa and India-based Tata Power Solar, with real results.

"Our customers were not married to any technology so they looked at GaN devices from us and our competitors, as well as SiC devices from leading vendors," he explains. "They chose our

technology based on performance, cost and reliability. We beat SiC hands down."

Critically, for this industry, Transphorm's GaN-on-silicon diodes and transistors were JEDEC qualified in 2013 and the company has since demonstrated a high voltage off-state lifetime of more than 10 million hours, at 600 V, with these chips.

"This is a first for the GaN industry," highlights Parikh. "Cree has introduced the data for SiC MOSFETs and now we have done it for GaN. Nobody else in the wide bandgap industry has shown this true intrinsic lifetime via systematic reliability testing."

Cost-wise, Parikh points out that device to device, GaN-on-silicon is obviously more expensive than silicon, but adds: "SiC is even more expensive." And as he highlights, his company's GaN platform is diode-free as its GaN transistor serves the function of the anti-parallel or fly-back diode used in conventional approaches, bringing cost, space and energy savings.

"Instead of using two high performance components, such as a SiC MOSFET and SiC diode, the GaN customer can use just one," says Parikh. "So we deliver half the components, half the size and half the cost."





A big surprise: Transphorm's GaN power modules are being snapped up by photovoltaic manufacturers for use in inverters.

### Beyond PV

Packaging higher voltage semiconductors has also raised concerns across the industry. But again, Parikh highlights how his company has developed protective enclosures, such as its so-called Quiet Tab, based on standard packages, such as TO220, TO247 and PQFN, that 'work well'.

"New packaging will be important but we've patented some simple ways to use standard packaging in a configuration that allows high speed operation while

minimising the electrical parasitic effects," he says. "We don't have to wait for advanced packaging to be developed to take advantage of today's GaN products."

So where next for Transphorm? Parikh reckons the India-based PV inverter market is going to be huge for Transphorm but points out how the company's discrete and module products have also been designed into kW-class 99 percent Totem-Pole PFC circuits and multi-hundred Watt all-in-one computer compact power supplies.

Transphorm Japan is also collaborating with Japan-based auto-makers and OEMs on the use of GaN devices in electric vehicles. Key applications include inverters in drive trains as well as DC-to-DC converters in, for example, air conditioning units.

"Using GaN in these applications is more near-term than one would think," says Parikh. "I am hopeful for Transphorm and the entire GaN power industry that we will solve real problems and make a tangible dent to energy use."



# The resurgence of electron beam evaporation

After decades of playing second fiddle to sputtering in the silicon industry, electron beam evaporation now dominates in the compound semiconductor industry, thanks to its inherent advantage in the lift-off process

BY IMRAN AMIRANI FROM FERROTEC

EVERYBODY LIKES A COMEBACK STORY. It's uplifting to see an underdog claw out of the trenches, grow in strength, and eventually emerge victorious.

Head to the cinema, and you'll see plenty of films with this storyline. But the great comeback is not limited to the silver screen – sometimes it happens in real life, right within our own industry.

Take, for example, the fibre optic sector. Back in the late 1990s, stock prices in III-V companies operating in this realm reached astronomical valuation, as telecom firms from all over the world started to expand their network capacity to meet a projected surge in traffic. But that super-high level of growth failed to materialize, contributing instead to the 'dot.com' bust at the turn of the millennium. Fast forward to today, however, and business is booming again for the providers of optical components for communications, thanks to growing demand for more and faster data.

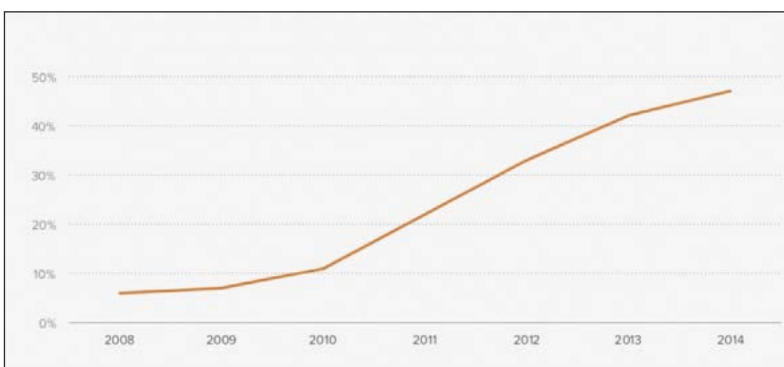
This is by no means the only comeback kid in our community. There is also the electron-beam

evaporation. Along with sputtering, it dominated the semiconductor industry in the 1960s and early 1970s, before the growth of microelectronics led to greater sales for sputtering tools for ever larger silicon wafers. Only in recent times has the situation reversed, with the electron-beam evaporator resuming its ascendancy, thanks to compound semiconductors capturing ever higher revenue from the soaring shipments of mobile devices. These devices feature compound semiconductor chips manufactured on production lines utilizing electron beam evaporators, which have superior uniformity and a lower cost-of-ownership than the other three established thin film deposition techniques (see panel 'Four options for metallization' for details of all techniques).

Of these four vacuum-based techniques for metal deposition, those that are best at serving the semiconductor industry are electron-beam evaporation and sputtering. They both have a long history, having been developed in the mid-nineteenth century. The roots of sputtering are found in the efforts of the Welshman Sir William Grove, who noticed deposits in the anode of a gaseous discharge, which was removed following a reversal of the polarity of the electrodes. Meanwhile, the beginnings of electron-beam evaporation can be seen in the work of English physicist Michael Faraday, who used a voltaic battery to deposit gold on a glass substrate, albeit with poor adhesion.

About a hundred years later, requirements of microelectronics drove the development of electron-beam systems for metallization. One of the pioneers was Temescal, and we remain a leading player in this field, owned by Ferrotec (USA) Corporation. We hold the original patent

Figure 1: The percentage share of mobile devices in the overall consumer electronics industry, reported by Evan, B (2014), *Mobile is Eating the World*



for 180° beam-deflection sources – that were widely used in early generations of electron-beam systems – and also 90° sources. Both approaches had a flaw, with wafers damaged by X-rays emitted with the beams. To address this, in 1972 we developed the patented 270°-deflection electron-beam source. This is now commercially adopted worldwide for electron-beam evaporation. However, at the time of its launch, sputtering was already viewed as the superior deposition process.

We moved with the times, and through Airco-Temescal we patented and developed apparatus using magnetron sputtering (see Figure 2). This technology held the upper hand due to its lower operating voltage and its simplicity in the use of masks for ensuring uniform film deposition. Note that in electron-beam systems, the multiple masks employed to achieve the best uniformity for each layer of a given metal stack are not stationary and generate particles during movement.

Sputtering also brought benefits in terms of versatility, as it can deposit complex films, such as refractory metal composites and metal nitrides. What's more, it can handle wafers with large diameters, including those up to 450 mm, and this gives it overwhelming advantages for the metallization of silicon devices.

However, electron-beam evaporation has never gone away, because it also has virtues. This deposition technique is isotropic and can limit unwanted sidewall coverage during the lift-off process. This step is widely used for producing compound semiconductor chips, and is generally preferred to the lift-off of a sputtered film with the assistance of CO<sub>2</sub> gas injection to break down the unavoidable sidewall coverage from sputtering. Electron-beam evaporation also offers significantly superior cost-of-ownership from its high-volume batch process, plus higher yield, thanks to elimination of the unwanted metal sidewall in the lift-off process.

It is these attributes that are behind the resurgence of the electron-beam evaporator, which has grown in sales as the manufacture of compound semiconductor chips has soared throughout the last decade. A hike in smartphone sales has been a key driver. Sales took off in 2007, with compound semiconductor fabs throughout the world experiencing a vast increase in demand for power amplifiers, filters and switches used in smart phones. Up until then, only the Blackberry made by Research In Motion offered enterprise email access through secure servers. It took 11 years for this company to gain 41 million

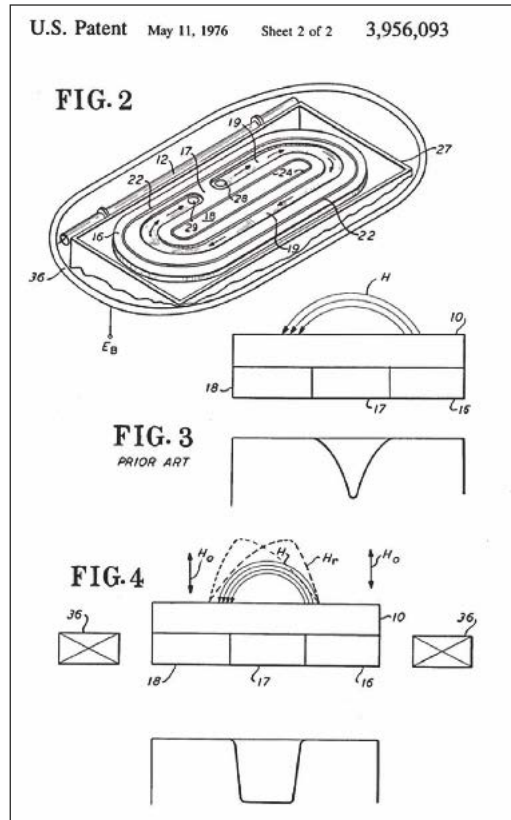


Figure 2: Airco-Temescal's Magnetron Sputtering patent.

subscribers, but it didn't stay at the top for long – Apple's iPhone took the market by storm, with annual sales hitting 40 million in just 11 quarters, due to a design delivering a previously unimagined level of productivity improvement. Google subsequently upped the ante, offering a free and open operating system for smart phones. This rapidly propelled Google's Android OS to leading position in 2010 (see Figure 3).

Around this time, the LED market underwent a revolution. It evolved from just illuminating

Figure 3: The ascension of the Google Android OS for smart phone, reported by Canalys (2011) Google's Android becomes the world's leading smartphone platform

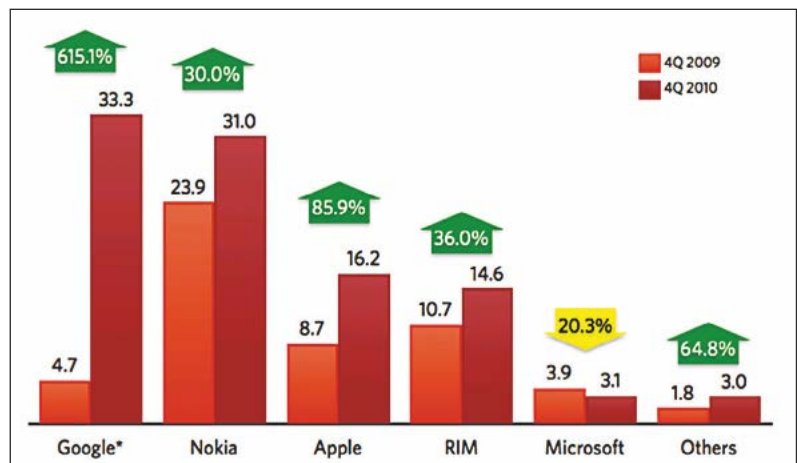
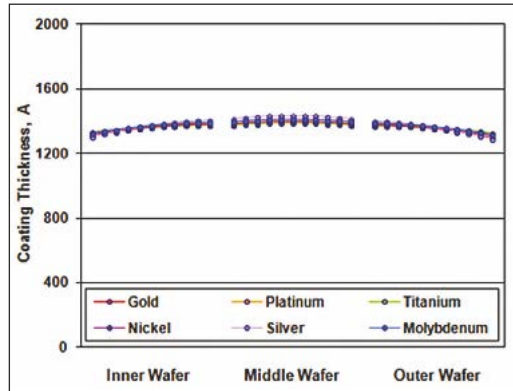


Figure 4: The thickness variation of common metals in a HULA evaporator is very small, even without any uniformity mask.



the screens and keypads in handsets to LCD backlighting and then general lighting. China has played a major role in the development of this industry, helping to fund the founding of its domestic LED chipmakers, and this has contributed to the rocketing demand for electron-beam evaporation equipment.

**Innovations in system design**

As stated previously, it is not easy to always realize a high level of thickness uniformity with electron-beam evaporation. This deposition technique can produce excellent thickness uniformity by positioning a single wafer optimally. But typically a multi-material-layer metal stack is deposited in a single-axis-of-rotation multi-wafer batch system; a high level of thickness uniformity could only be achieved with multiple masks, many of which must be movable. That is undesirable, because moving masks may generate particles.

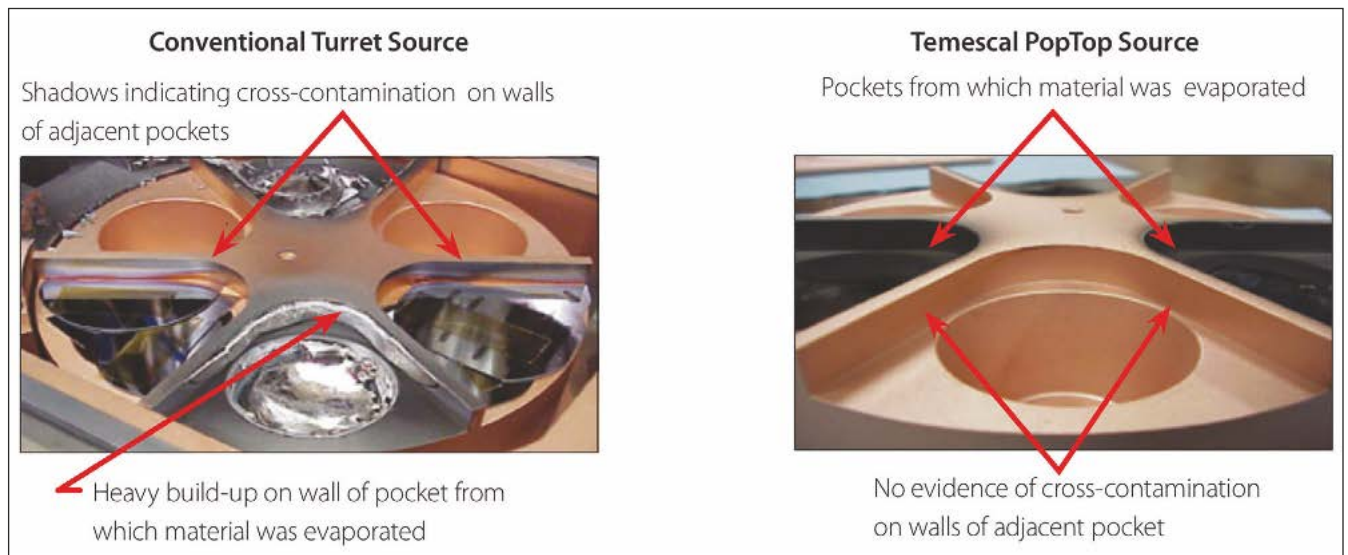
Uniformity masking is optional, however, with our patented High Uniformity Liftoff Assembly (HULA)

technology that generates no particles, thanks to a contactless magnetic drive. Highly uniform films result, due to the planetary configuration of the multi-dome assembly that provides time averaging on wafer residence across the product chamber. With this tool, nearly every evaporant can be deposited with a uniformity of less than 3 percent (see Figure 4), which is adequate for many applications – but even higher uniformities can be reached by adding a small mask. This inherently more uniform HULA evaporation also gives rise to saving in the purchasing cost of evaporants, because the material collection efficiency on wafers is 43 percent higher than that of traditional single-axis wafer carriers.

Efforts to improve uniformity are also aided by our extensive vapour cloud modelling. This has resulted in a rapid advance in the technology of the uniformity mask, cutting the time it takes to generate an optimized mask for any metal stack. This breakthrough, together with the combination of improved magnetic assembly for the electron-beam source, faster pumping speed and the isolation of the product chamber from the source chamber via load locking, trims the cost-of-ownership of our electron-beam system while increasing process stability and system reliability.

The next frontier for electron-beam evaporation is to drive down particle generation during evaporation. One of the causes is the spitting of gold, which is a function of the contamination introduced by adjacent sources in a conventional multi-pocket electron-gun or during the refinement process of gold. Temescal’s patented poptop technology virtually eliminates any cross contamination from adjacent pockets thus

Figure 5: The Temescal poptop source has advantages over a conventional turret source, including the elimination of cross-contamination.





maintaining the purity of gold (see Figure 5). The issue of contamination can also be mitigated by using Materion’s low-carbon gold. Moving mechanisms also generate particulates, which is why we have developed the contactless, magnetically driven wafer holder assembly (see Figure 6).

Another area where we have devoted much effort is in the mapping of the magnetic flux around the electron gun to produce an optimal beam shape. This has led to refinements in our capturing of secondary electrons, by upgrading the magnet material and magnetic assembly. By employing our patented placement of the magnet at the back of the electron-gun, we minimize the impact of secondary electrons on the photoresist.

**Emerging trends in copper, eutectic and ultra-thin films**

One way to cut chip costs in compound semiconductor fabs is to switch from precious metals, such as gold and platinum, to copper. This appears to be a good strategy – in a paper by Kezai Cheng from Skyworks, given at the 2009 CS Mantech conference, he noted that in addition to lower wafer cost, evaporated copper offers other technical advantages, such as lower resistivity and a reduced likelihood of spitting at high deposition rates.

Although the traditional method for depositing copper is electroplating, Cheng formed films with our electron-beam evaporator. In his paper, he offered three reasons for an evaporation and lift-off process: the existing tool set used for depositing the ohmic and the gate metal can be set up to run copper; the evaporated first interconnect layer of copper does not require additional wet steps of seed layer removal,

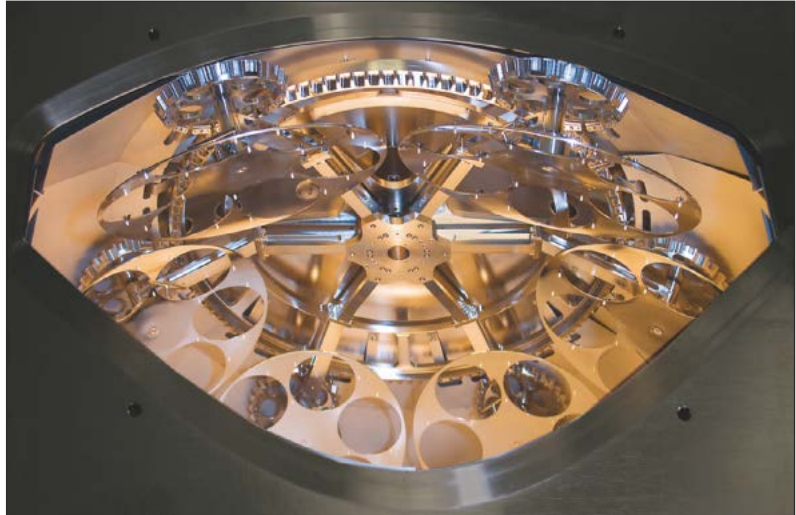


Figure 6. The HULA wafer holder assembly cuts particle generation, thanks to a magnetic drive system.

“

Another class of material used for both silicon and compound semiconductor manufacturing is the eutectic film. It is made from an homogeneous solid mix of atomic and/or chemical species that form a joint superlattice. Eutectics are employed in wire bonding, wafer bonding for die stacking, and hermetic encapsulation for wafer-level packaging.

”

whether it is de-plate or chemical etch; and copper can be evaporated at high rates with minimal risk of spitting. He concluded that throughput for the copper process using electron beam evaporation would be similar or higher than that by electroplating. Furthermore, for any given tool set, throughput with copper would be higher than that with gold.

Other groups have also succeeded in developing processes for copper interconnects and electrodes by electron-beam evaporation.

Research teams in Taiwan reported the forming of a 2 μm-thick copper interconnect for power HEMTs, and demonstrated a Pd/Ge/Au ohmic contact and a Ti/Pt/Cu seed layer of interconnect for a InGaP/GaAs HBT, using electron-beam evaporation. Another class of material used for both silicon and compound semiconductor manufacturing is the eutectic film. It is made from a homogeneous solid mix of atomic and/or chemical species that form a joint superlattice. Eutectics are employed in wire bonding, wafer bonding for die stacking, and hermetic encapsulation for wafer-level packaging.

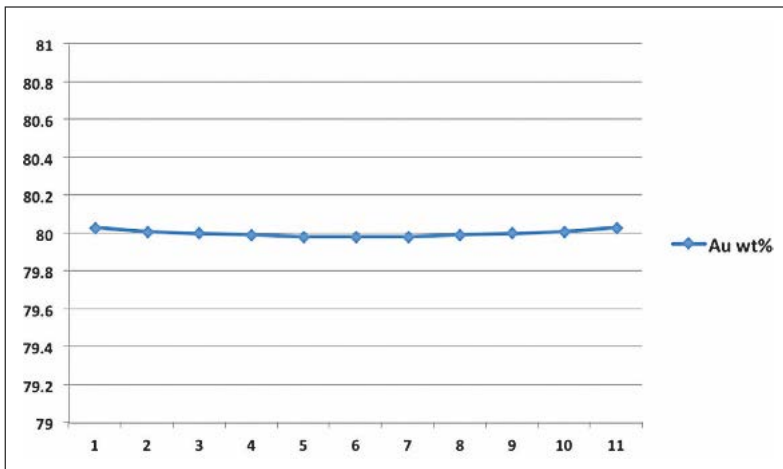
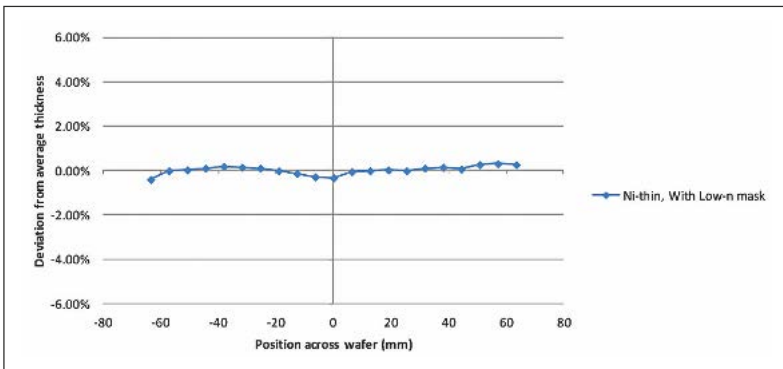


Figure 7: Control of AuSn eutectic composition in HULA across wafer without using any uniformity mask.



Ultra-thin Ni, Wafer-to-Wafer Uniformity		
	No Uniformity Mask	With Uniformity Mask
20 Å thick	0.54%	0.10%
50 Å thick	0.20%	
100 Å thick	0.10%	0.15%

Figure 8: An illustration on the thickness uniformity of ultra-thin films evaporated from a HULA evaporator, with and without a mask.

Ensuring a change from solid to liquid during the bonding process demands a specific compositional ratio of the constituent materials, with optimal soldering only occurring within a +/- 0.5 percent compositional window. Straying outside of this range is detrimental: Engineers from Materion have shown that a 0.75 percent shift in composition in a eutectic with 80 percent gold and 20 percent tin increases the melting temperature by 30 °C and degrades bonding quality.

If a eutectic film is formed by a magnetron sputtering system, its composition is governed by the deposition power and chamber pressure. This places stringent demands on the control of both the processing parameters and the composition of the sputtering target.

It is a different story with electron-beam evaporation. In this case, it is possible to evaporate each metal component of the eutectic film on the wafer sequentially, before they inter-diffuse naturally, without any annealing, to form the desired eutectic film. Since the thickness of each film can be precisely controlled with ease, control of the composition ratio is much tighter than that achieved by sputtering – HULA evaporators are capable of controlling the eutectic composition to +/- 0.2 percent (see Figure 7).

This type of evaporator is also inherently suited to the deposition of uniform, ultra-thin films. These are 50 Å or less films – making thickness control very challenging via sputtering – and they have been grown by our customers in the mobile device, hard disk drive, LED and power electronics industries (see Figure 8).

Capability of ultra-thin film growth is just one of the many reasons that we have highlighted for the resurgence of the electron-beam evaporator, which has an inherent advantage in the lift-off process widely used in the manufacture of compound semiconductor chips. The cost-of-ownership of evaporators can be very low, due to

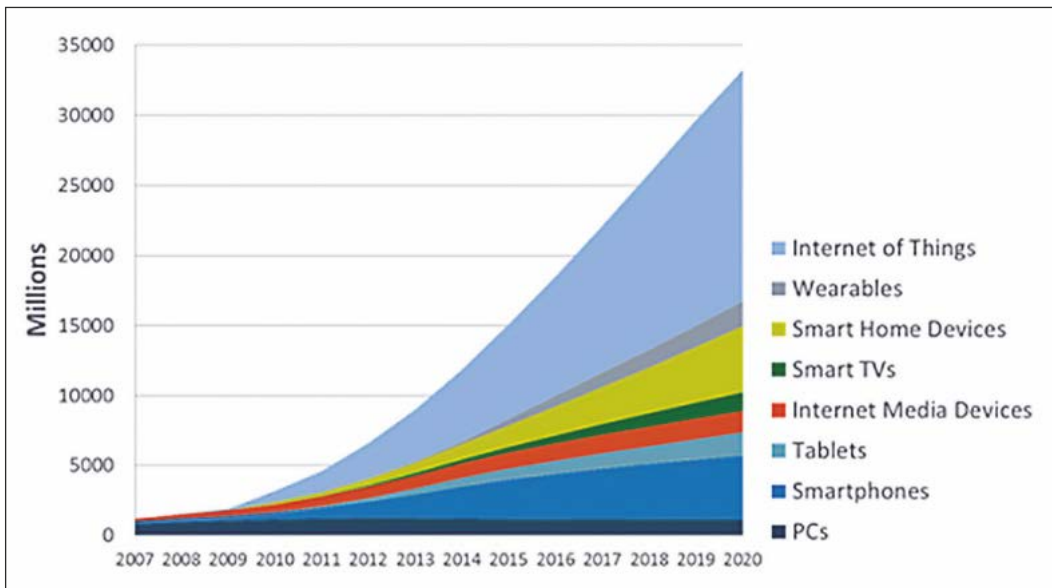


Figure 9: Strategy Analytics' projection on the wide adoption of connected devices.

parallel processing of many wafers, such as 42 6-inch wafers. This should help to trim the cost of connected devices which, according to Strategy Analytics (see Figure 9), could reach 33 billion units worldwide by 2020. To support the compound semiconductor industry for the competition in this booming market, we are addressing the new processing advances in copper, eutectic and ultra thin film deposition.

● The author would like to thank Gregg Wallace, Kuohsiung Li and Lyell Warren for their inputs on the development of this article.

**Further reading**

Duckham, A (2013). Developing a Fundamental Understanding of Gold Spitting During Evaporation. CS Mantech Conference.

Cheng, K. (2009). Copper Interconnect on GaAs pHEMT by Evaporation Process. CS Mantech Conference

Radulescu, F (2002). Introduction of Complete Sputtering Metallization in Conjunction with CO<sub>2</sub> Snow Lift-Off for High Volume GaAs Manufacturing. CS Mantech Conference .

Lichtenberger, H (2012). PVD Magnetron Sputtering Parameters and their Effect on the Composition of AuSn Solder . CS Mantech Conference .

Wallace, G. (2013). Electron-beam liftoff: Collection efficiency & paths to improvement. *Compound Semiconductor Magazine*, Volume 19 Number 2 p 29.

## Four options for metallisation

**METALLISATION** is a key process in the manufacture of compound semiconductor devices. It is used to form electrodes and interconnects, with up to 40 percent of the entire wafer covered by metals. The most common of these that are applied to compound semiconductor chips are gold, titanium, platinum, nickel, germanium and aluminium, and they may be added using one of four common techniques:

**Etching.** In this subtractive process, physical vapour deposition, in the form of electron-beam evaporation or sputtering, adds a metal or oxide film on to the substrate. This is patterned with a resist, before the unprotected material is removed with a dry or wet etch process.

**Electroplating.** A metal seed layer is first deposited via sputtering or electron-beam evaporation. After a photoresist is applied and developed, the wafer is electroplated before a chemical washing step removes the photoresist and the seed layer beneath it.

**Damascene:** In this additive process, patterns are etched into the dielectric substrate before a conductive metal is deposited onto the entire wafer. Chemical mechanical planarization removes any excess metal to leave inlaid metal in place on the wafer.

**Lift-Off:** Another additive process, this time involving the development of a sacrificial photoresist layer using a patterned mask. Evaporation or sputtering then adds a blanket coating of metal, before a lift-off wash removes material deposited on the photoresist. Metal that has been in direct contact with the wafer remains.

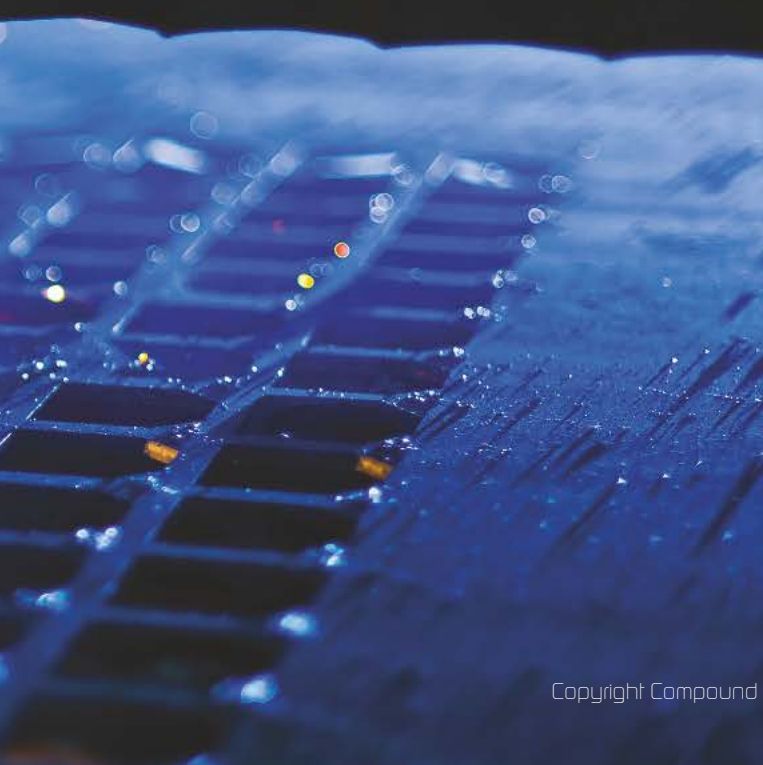


# Building brighter, more powerful lasers diodes

Laser diodes can be more powerful when they employ facets with equal reflectivity, and brighter when they features an architecture that trims the number of lateral modes

RICHARD STEVENSON REPORTS





THE GAAs-BASED LASER is one of the longest selling, most established products within our industry. Invented in 1962, it had its first 'killer application' in the late 1980s, when this infrared source started to read the binary data off of countless CDs. And more recently, further success has followed, with high-power versions of this chip cutting and drilling metals, and providing a pump source for various lasers.

Given this level of maturity, one might expect that today's improvements in performance are incremental. But judging by the papers on high-power near-infrared lasers at this year's Photonics West, that is certainly not the case. Significant advances in brightness, efficiency and output power have been reported by researchers from JDSU, nLight, FBH and Jenoptik, during a well-attended conference held in San Francisco from 7-12 February. These performance gains will help to improve the competitiveness of the high-power laser, while accelerating its sales as a capable alternative to the carbon dioxide laser, the traditional source for welding and cutting metals.

One of the biggest advances in laser output power has come from JDSU. At Photonics West 2015 a team of engineers announced that they had raised the bar for the output of broad-area lasers, with devices producing up to 33 W – it is claimed that typically output powers have been limited to 20-25 W.

This breakthrough in output power has come from what is described as an unfolded cavity. This is formed from two mirrors with low reflectivity, and it creates a source emitting a similar output power from both facets. With 10 percent reflectivity at the facets, output power is 29.5 W, and this rises to 33 W with a switch to 4 percent facet reflectivity.

Corresponding author of the paper, Abdullah Demir, explains that if this type of laser is to be used in commercial applications requiring a single-fibre output, there may need to be a combining of the beams, while accounting for spatial and polarization characteristics. However, this is not required in applications where power is the only criterion that matters, which makes this device particularly well suited to gesture recognition, heating and illumination.

Demir believes that the most important aspect of the recent work of him and his colleagues has been the revealing of the size of linear and non-linear power-limitation mechanisms for GaAs-based lasers. This has been uncovered through calculations and measurements of a standard cavity, which has one mirror with 100 percent reflectivity and another with

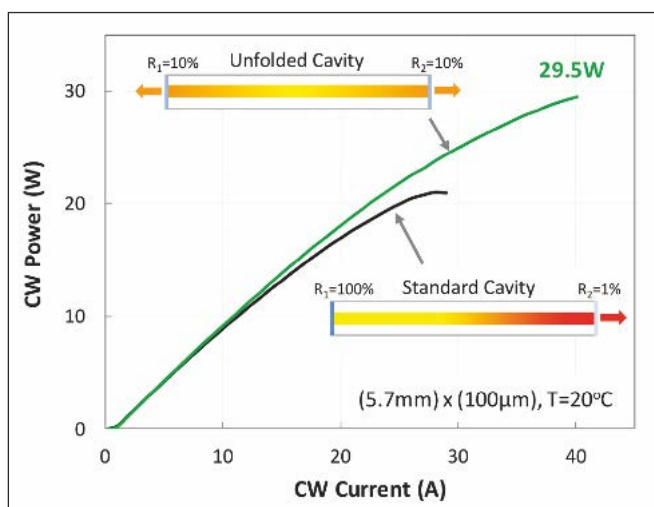
1 percent reflectivity, and an unfolded design with two mirrors with 10 percent reflectivity. The latter design produces very significant reductions in longitudinal spatial hole-burning and two-photon absorption.

The investigation by these researchers from Milpitas, California, determined that at an output of 20 W, the power penalty for two-photon absorption in a conventional design is four times that for an unfolded cavity with 10 percent reflectivity mirrors, and can hit 2.5 W. This non-linear process can occur when two photons are simultaneously absorbed by the waveguide to create free carriers. This causes losses increasing quadratically with photon density, while free carriers created by two-photon absorption can cause subsequent absorption losses increasing with the third power of photon density.

When it comes to longitudinal spatial hole-burning, it is calculated that a ten-fold reduction results from the switch to an unfolded cavity. However, the power penalty at 20 W for the conventional design is only around 1 W, so switching to an unfolded design potentially has its biggest impact on overall performance through a reduction in two-photon absorption.

Demir explains that longitudinal spatial hole-burning is caused by the inhomogeneous distribution of the carrier density, due to an inhomogeneous photon density distribution along the cavity. This effect is stronger in lasers with an asymmetric design, which explains why the unfolded design is less affected than the conventional equivalent.

Although the team's lasers are more powerful than conventional devices, calculations suggest even higher output powers should be possible, because the reductions in the power penalties associated with two-photon absorption and longitudinal spatial hole-burning are not as large as they could be.



Researchers at JDSU have increased the output from their laser by turning to an unfolded cavity that employs two mirrors with a facet reflectivity of 10 percent.

“We want to understand the reason for the gap between theory and experiment,” explains Demir, who will also be working with colleagues to develop more powerful designs with lower linear and non-linear losses.

### Boosting brightness

One of the goals of many manufacturers of laser diodes is to not only improve the power of lasers emitting at around 915 nm to 980 nm, but also their brightness, because this makes them more attractive for many applications: fibre laser pumping, materials processing, solid-state laser pumping, defence applications and consumer electronics manufacturing.

A key consideration in this quest for higher brightness and power is the divergence of the laser, which should be as small as possible. Laser diodes do not produce circular beams, with divergence depending on the geometry of the direction: in the vertical direction, which is also known as the fast-axis and is perpendicular to the plane of the substrate, the divergence is limited by diffraction; but in the lateral direction that is referred to as the slow axis, wider apertures deliver more power at the expense of greater divergence.

To improve the brightness along the slow axis, nLight of Vancouver, Washington, has developed a technology that breaks the traditional relationship between divergence and aperture width by trimming the number of allowed modes in the slow-axis direction.

“We have demonstrated the highest slow-axis brightness for a broad-area laser,” claims corresponding author Manoj Kanskar, who points out that a maximum brightness of 4.3 W/mm-mrad has been measured for one of the reduced-mode diode designs. “This is 48 percent higher compared to the brightest standard broad-area device we have produced in the past.”

Compared to the previous generation of laser, which did not feature a reduced-mode technology, the latest devices that sport a reduced mode technology can exhibit the same beam parameter product (the product of the aperture width of the beam and its divergence), while emitting up to 20 percent more power before roll-over. What’s more, they can deliver a higher electrical-to-optical conversion efficiency.

These attributes strengthen the case for using diodes, rather than bars, to couple to fibres. “We are able to extract more ex-facet power, as well as fit more power into a given fibre diameter, due to the fact that they are higher brightness, and there is no thermal crosstalk,” claims Kanskar. A lower part count for the same output power leads to a lowering of the dollars-per-Watt.

Engineers from nLight have placed 12 diodes into a package to create a source that, when driven at 17 A, produces up to 163 W of light that can be coupled into a fibre with a diameter of 105 µm and a numerical aperture of 0.15 (see Figure 2). “We are able to achieve this because we have reduced the slow-axis divergence by a factor of two compared to a standard broad-





Scientists at FBH have introduced a narrow stripe into their broad-area lasers to trim the number of lateral modes. This reduces the beam parameter product, making devices better suited to drilling holes in metals. Here a technician is preparing such high brilliance laser bars for facet passivation.

area laser,” says Kanskar.

Reliability tests on the reduced-mode lasers and the previous generation of devices suggest that the latest emitters are more reliable. Kanskar claims that this is to be expected, as the footprints of the reduced-mode lasers are larger, so they will have a lower thermal and series resistance.

### Shrinking stripes

Reducing the number of lateral modes has also held the key to the high performance of lasers fabricated by scientists from the Ferdinand Braun Institute in Leibniz, Berlin. By combining advanced epitaxial designs with facet passivation and 30  $\mu\text{m}$ -wide stripes that cut off higher order lateral modes, the team could produce diodes delivering more than 7 W at an efficiency in excess of 50 percent, while realising a beam parameter product of around 1.5 mm-mrad.

“For the first time, this corresponds to a higher brilliance than conventional single-mode lasers, which deliver around a Watt in 0.3 mm-rad” says lead author of the paper, Paul Crump. Brightness is also better, at 4.7 W  $\text{mm}^{-1} \text{rad}^{-1}$ , rather than around 3 W  $\text{mm}^{-1} \text{rad}^{-1}$ .

Reducing the lateral beam parameter product potentially allows laser diodes to directly access the majority of materials processing markets for the first time, the largest of which is deep metal cutting. “To cut deep holes, we require a high power density to be delivered within a narrow angle,” says Crump.

The scientists have also investigated a tapered laser. These novel emitters combine a single-mode region at the rear facet with a tapered amplifier, restricting the device to one lateral mode that should minimise the beam parameter product. Such a goal has been realised, with around 5 W delivered with a beam parameter product of around 1.5 mm-mrad, but this comes at the expense of inferior efficiency – it is around 40 percent. Other weaknesses of these tapered lasers are that they emit more than 1 W of stray light, and they operate with a complicated astigmatic beam.

Another approach that Crump and his co-workers have pursued to trimming the beam parameter product is to introduce lateral anti-guiding structures into broad-area lasers. These have paid dividends in prototype devices with 90  $\mu\text{m}$  stripes, where the beam parameter product has been cut from 4 mm-mrad to 3 mm-mrad without compromising efficiency.

“However, the devices with narrow stripes do not show comparable improvement in the beam parameter product, even though the number of guided modes is strongly reduced,” says Crump. “This indicates that there are other limits than simply the number of modes present.”

Designing devices that suppress factors known to limit the beam parameter product is one goal for the team. In addition, the scientists want to gain a better understanding of the remaining limits for the beam parameter product, as well as working to further increase efficiency and power.

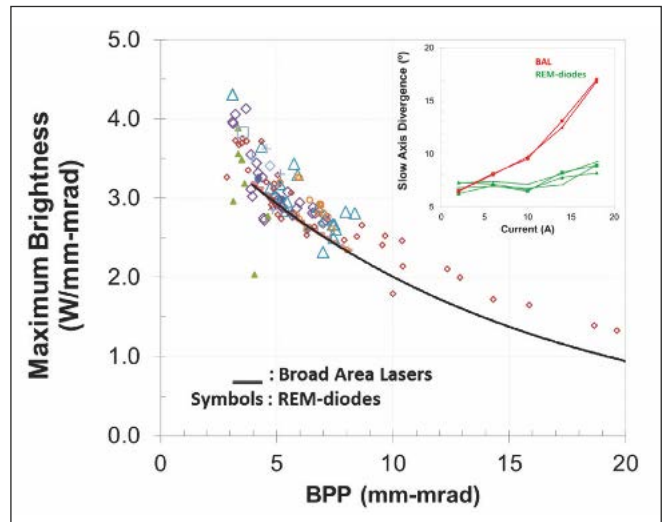
**Better bars**

At Jenoptik, researchers have been improving the performance of high-efficiency laser bars emitting in pulsed mode at around 880 nm and 940 nm. One of the highlights of these efforts are 1.5 mm-long bars emitting 1 kW at 880 nm with a fill factor factor – the ratio of pumped bar area to total bar area – of 75 percent. The same output was also possible from 940 nm, 4 mm-long bars with a fill-factor of 50 percent that were driven with far longer pulses.

Agnieszka Pietrzak, lead author of the paper, describes these results as “definitely very good and competitive”. However, she adds that record-breaking results are not the primary objective for the team: It is to build reliable, powerful devices meeting customer specifications.

The 1 kilowatt bars are still being developed, but at Photonics West the company did launch a lower power product: 500 W bars emitting at 880 nm. To do this, in the last 12 months engineers have increased the output power of 1.5 mm bars from 300 W up to a reliable 500 W. With a spectral width (95 percent power content) of 6 nm or less, and a slow-axis divergence of about 11 degrees, these lasers meet requirements for providing a pump source for Internal Fusion Energy Lasers.

Pietrzak will not discuss the technologies behind the improvements in performance in more detail than that provided in the paper. In that account, it is revealed that increases in carrier confinement and a reduction of the laser structure resistivity have boosted the output power of the devices, and that optical confinement in the lateral direction has been strengthened with an additional waveguiding along the electrical contact.



Engineers at nLight fabricated a range of reduced-mode laser diodes with beam parameter products in the range 915 nm to 980 nm. The solid curve represents the maximum brightness for a particular beam parameter product, while the symbols are the average values for various reduced-mode diodes that have been explored. The inset showcases the lower slow-axis divergence of the reduced mode (REM) diode compared to a broad area laser (BAL).

One of the next targets for the team is to improve the wall-plug efficiency of its 940 nm, 1 kW bars, for reliable operation. A higher efficiency, which will be targeted initially via an increase in fill-factor, trims the thermal load and should lead to a narrowing of spectral width and beam divergence.

Those attending Photonics West 2016 may get to hear whether the team from Jenoptik have succeeded in that endeavour, and whether the researchers at JDSU, nLight and FBI have also made further progress.

This conference has a great track record in highlighting the progress in high-power laser diodes, and judging from the latest presentations, there is still the opportunity to deliver significant improvements in the performance of these solid-state emitters.

“

One of the next targets for the team from Jenoptik is to improve the wall-plug efficiency of its 940 nm, 1 kW bars, for reliable operation. A higher efficiency, which will be targeted initially via an increase in fill-factor, trims the thermal load and should lead to a narrowing of spectral width and beam divergence.

”





CS CLEAN SYSTEMS®



**CLEAN-PROTECT**  
Emergency Gas Release Scrubber

**CLEANSORB**  
Pump Exhaust Dry Bed Scrubber

**CLEANVENT**  
Gas Supply Purge Gas Scrubber

### Exhaust Gas Abatement

Safe and eco-friendly solutions for GaAs Microelectronics, III-V CMOS, Optoelectronics and Lasers, SiC Epitaxy, Concentrating Photovoltaics

- ▶ Safe, dry chemical conversion of toxic gases to stable solids
- ▶ Proprietary CLEANSORB media
- ▶ No handling of toxic waste
- ▶ Practically maintenance-free
- ▶ Local refill service worldwide

- ▷ Over 25 years of experience
- ▷ More than 5,000 installations worldwide

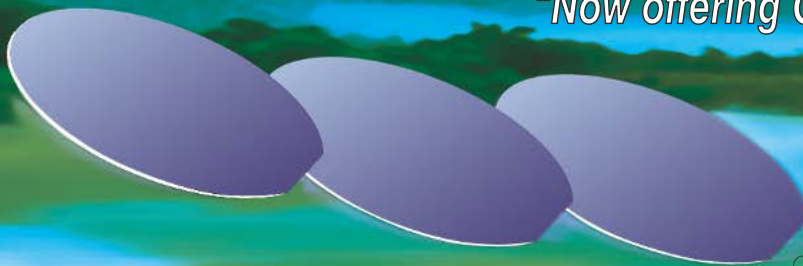
Find out more:

[www.cscleansystems.com](http://www.cscleansystems.com)

## III/V-Reclaim GaAs InP

*The most cost effective method to excellent quality.*

*"Now offering Germanium Reclaim"*



### III/V-Reclaim

Wald 10  
84568 Pleiskirchen / Germany  
Telefon: + (49) 8728-911093  
Telefax: + (49) 8728-911156  
E-Mail: [sales@35reclaim.com](mailto:sales@35reclaim.com)  
Internet: [www.35reclaim.com](http://www.35reclaim.com)

- We recycle your GaAs and InP wafer (all formats and sizes)
- One and double side polished wafer
- Best surface quality for direct use in Epitaxy
- Backside thinning of fully structured wafer
- Thin wafer (60 μm)
- Single wafer processing possible
- We buy used wafer and sell recycled wafer





Trimming the thickness of  
**high-voltage**  
**GaN-on-silicon HEMTs**

A high-quality AlN nucleation layer promises lower-cost, high-quality HEMTs

BY KAI CHENG FROM ENKRIS



Left: An Aixtron MOCVD tool used by engineers at Enkris to form GaN HEMT epiwafers with relatively thin buffer layers. Note that the company also uses an AMEC reactor for MOCVD growth.

The two leading forms of wide bandgap devices are those made from SiC and GaN. And compared to SiC, GaN has several key advantages: It allows the production of AlGaN/GaN HEMT structures with superior electrical conductivity and a more rugged gate dielectric, in the form of Si<sub>3</sub>N<sub>4</sub>, AlN or a combination of nitrides and high-κ dielectrics; and GaN can be grown hetero-epitaxially on silicon substrates with diameters of 150 mm and even 200 mm, enabling low chip production costs.

The promise of low-cost GaN-on-silicon electronics has already ignited tremendous interest within academia and industry, with efforts fueling an increase in epiwafer diameters from 2-inch to 200 mm. Successes with this platform include the release of commercial GaN-on-silicon devices with breakdown voltages of 30 V, 200 V and even 600 V, which have been brought to market by the likes of EPC, IR (now acquired by Infineon), Panasonic and Transphorm.

It appears that the sweet spot for these GaN-on silicon devices is at 600 V. That's because at 200 V and below, GaN offers only a minimal advantage over the silicon MOSFET, and at voltages of 1200 V or more, SiC is better at accommodating the higher power density.

If GaN-on-silicon devices are to dominate the market for 600 V products, their on-state and off-state characteristics need to be superior to those for silicon. This places an upper limit on the leakage current density at 600 V of less than 1 μA/mm, and ideally below 0.1 A/mm. One way to meet this requirement – which is far more stringent than that required by GaN RF transistors – is to increase the thickness of the buffer layer. This can also help to increase the breakdown voltage, with reports of buffer layers of more than 7 μm enabling breakdown voltages of 2000 V. This thickness is needed to meet the leakage requirements for 600 V devices with grounded silicon substrates, but the growth of thick films of GaN reduces the competitiveness of this product, by adding to the cost and the time taken to make it.

## Building better buffers

At Enkris Semiconductor of Suzhou Industrial Park, China, we have addressed this shortcoming, producing GaN HEMTs that meet the leakage current requirements while employing a far thinner buffer layer, thanks to an optimized AlN nucleation layer. This technology has allowed us to demonstrate GaN devices capable of handling more than 1600 V, using buffer layers with a thickness of less than 4 μm. It also holds the key to growth of flat, uniform, truly-crack-free epiwafers with diameters of up to 200 mm that can be used to fabricate high-voltage devices.

Producing crack-free wafers is far from easy, and even when this is accomplished, there can be a large concave wafer bow caused by the tremendous difference in the thermal expansion coefficients of GaN and silicon. The well-trodden path to avoiding this is to introduce compressive strain during high-temperature growth, so that it offsets the thermally induced tensile stress. Do this well, and it is possible to produce wafers with a bow below 50 μm, which is flat enough for processing in 150 mm or 200 mm CMOS-compatible lines.

However, even wafers meeting this criteria can have some major flaws. If the buffer layer has a thickness of 7 μm or

TODAY'S NEWS contains plenty of energy-related stories, including reports of efforts to increase efficiency. There are many ways to do this, including improving the insulation of homes and offices, sharing cars, and using products that consume less electricity.

Attempts to use electricity more efficiently can range from making refinements to the infrastructure of electrical grids to increasing the performance of electric vehicles and purchasing PCs with lower-loss power supplies. In all these cases and more, silicon transistors and diodes are directing and shaping electrical waveforms, with gains in efficiency possible by replacing them with those built from wide bandgap materials.

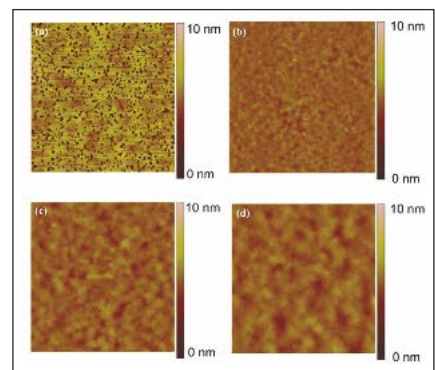


Figure 1. According to atomic force microscopy, the root mean square roughness of all the optimized AlN layers is less than 0.3 nm in 5×5 μm<sup>2</sup> area. Shown here are: (a) non-optimized AlN, (b) optimized AlN (50 nm), (c) optimized AlN (100 nm) and (d) optimized AlN (200 nm).

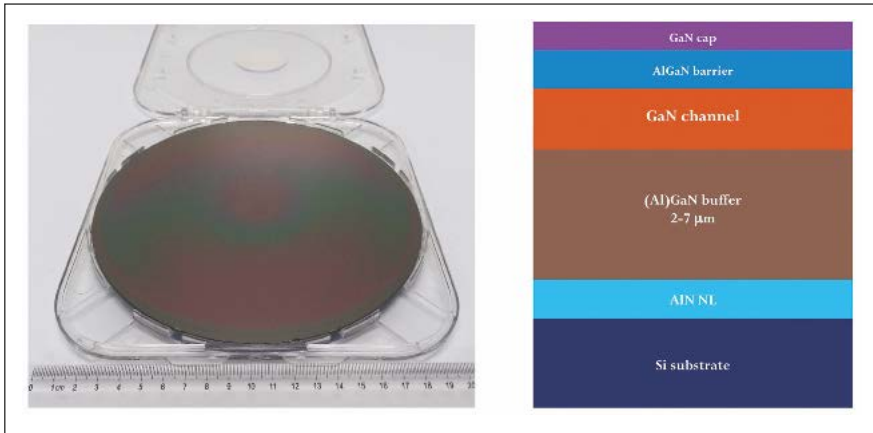


Figure 2. Enkris' 200 mm GaN-on-silicon wafers have a buffer that is 2 μm to 7 μm thick.

more to realize a high blocking voltage, then at the growth temperature convex bow in a 150 mm or 200 mm wafer may exceed 200 μm. This level of distortion is far from ideal, because it could lead to non-uniformities in properties such as total thickness, electron density, threshold voltage and breakdown behavior. Making matters worse, many large diameter epiwafers suffer from micro-cracks, pits and particles, and the devices that are made from them can be plagued by buffer leakage and current collapse. The upshot is pricey GaN epiwafers that hold back the penetration of this class of device into the power electronics market.

Our thinner buffer layer addresses these weaknesses and can yield devices that get closer to their theoretical potential – a critical electric field of more than 3 MV/cm. While values in the range 1.0-1.2 MV/cm are commonplace, we are able to reach more than 2 MV/cm.

The inferior critical electric field in conventional epiwafers accounts for the very thick buffers – 7 μm or more – that are employed in many 600 V devices. The root cause of this could be the nature of hetero-epitaxy, or the high density of defects in the layers, which can be a mixture of threading dislocations, surface cracks, pits, and micro-pits.

Pits are known to drive a hike in leakage current, drag down the critical electric field, and dramatically degrade the blocking properties of GaN-on-silicon devices. However, this imperfection makes little impact on devices made from our epiwafers, because they are relatively rare, thanks to optimization of the growth parameters of the AlN nucleation layer.

Growth of this layer is not just the first step in the growth of a GaN-on-silicon epitaxial structure – it is also the most critical step. This layer of AlN accomplishes a great deal by preventing a melt-back reaction, assisting subsequent GaN growth and cutting buffer leakage.

We have devoted a great deal of effort to optimizing the deposition of this layer, looking at the impact of different pre-treatments, pressures, temperatures and ammonia flows. This has enabled two-dimensional growth of atomically smooth AlN layers with thicknesses from 50 nm to 200 nm (see Figure 1 for atomic force microscopy images). These high-quality nucleation layers form a foundation for the growth of flat, crack-free epiwafers produced by careful stress management that consist of: a 100-200 nm-thick AlN nucleation layer, a 2-7 μm-thick AlGaIn buffer layer, a 150-300 nm-thick GaN channel, an Al(Ga)N barrier, and a GaN cap layer.

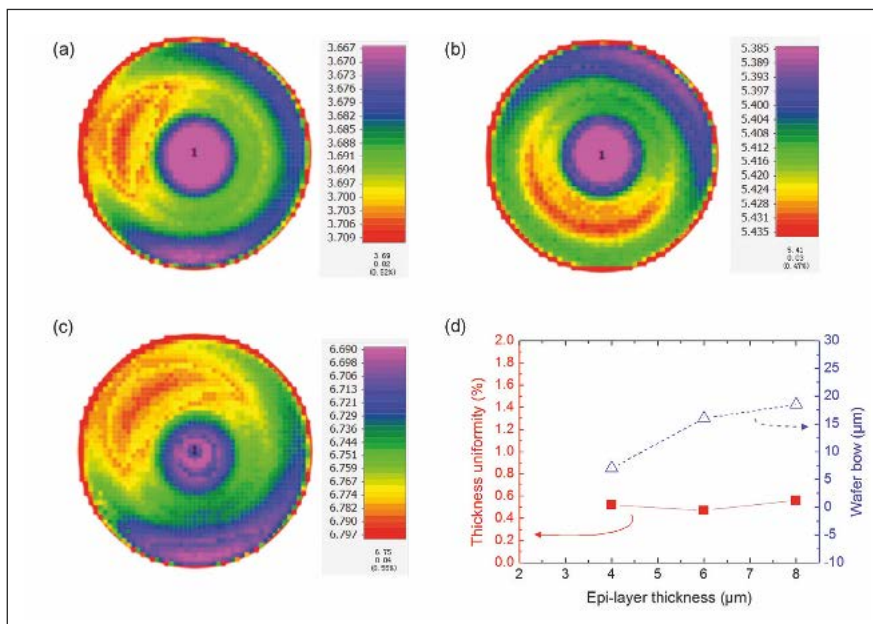


Figure 3. (a), (b) and (c): thickness mapping of 200 mm GaN-on-silicon wafers with varied buffer thicknesses; (d) thickness uniformity value and wafer bow of three wafers in (a), (b) and (c).

Stresses that arise during growth make it difficult to produce flat, uniform wafers – and the challenge gets even tougher for larger wafers. However, thanks to *in-situ* monitoring of wafer curvature, we are able to consistently produce 200 mm wafers with epilayers that are 4 μm to 7 μm thick and have a bow below 30 μm. According to thickness mapping based on white light interference, which is performed by a photoluminescence mapper from EtaMax, the thickness uniformity of these epiwafers is excellent (uniformity values are all below 0.6 percent without edge exclusion).

### Cutting cracks

Ideally, wafers should be completely free from cracks, because these are device killers. However, even if wafers have excellent strain balancing, there are always some cracks or micro-cracks caused by the large built-in stress. To prevent these cracks from having a



highly detrimental impact on yield, they should be restricted to within 2-3 mm of the wafer edge. This is not easy, however, and preventing crack generation across the wafer demands careful stress management and defect reduction. Defects such as particles or surface contamination are highly undesirable, because they can trigger micro-cracks.

We have found that by fine-tuning the grown-in stress generation process that takes place at a high temperature and the cooling procedure, we are able to limit crack-generation in our GaN-on-silicon wafers. They are inspected by a KLA-Tencor Candela CS920, with cracks only observed at the wafer edge, minimizing yield loss (see Figure 4). These findings are confirmed by inspection with an optical and an atomic force microscope. The latter, which failed to uncover any significant surface defects, determined a surface roughness of less than 0.3 nm (see Figure 5).

If GaN HEMTs are grown on sapphire or SiC, contactless eddy current mapping offers a straightforward way to determine sheet resistance. But when these high-voltage transistor structures are grown on silicon, no conventional in-line tool is available, due to widespread use of conductive silicon substrates. It is possible to turn to Hall measurements, but this is more suitable for small pieces of material, and mapping a whole wafer by this approach is tricky.

What's needed is a tool that can provide fast, reliable feedback of the electrical properties of a GaN-on-silicon HEMT – and we have worked with 4D of California to map capacitance-voltage characteristics across large GaN-on-silicon wafers. Scans show uniformities for the two-dimensional electron gas of 1.6 percent and 2.3 percent for 150 mm and 200 mm epiwafers, respectively, using an edge-exclusion zone of 10 mm.

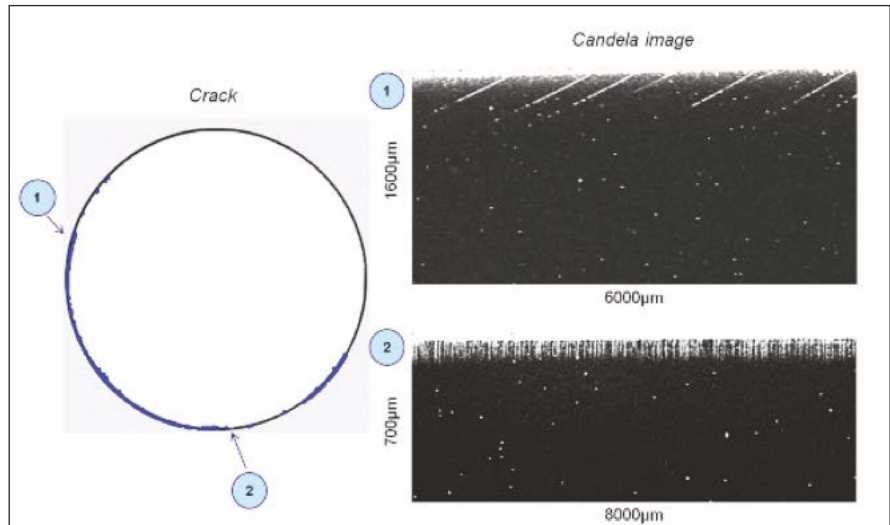


Figure 4. A KLA-Tencor Candela CS920 shows that the cracks across a 200 mm high-voltage GaN-on-silicon wafer are small and confined to the edge (no wafer edge exclusion)

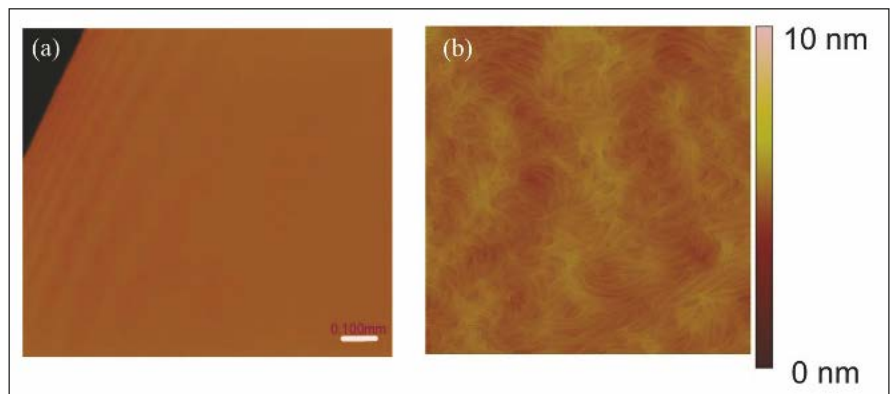


Figure 5. (a) An optical microscope image and (b) an atomic force microscopy image of the crack-free GaN-on-silicon wafer, which has a root-mean-square surface roughness of less than 0.3 nm in a  $5 \times 5 \mu\text{m}^2$  scan area.

Such high uniformity is essential for ensuring a small variation in the threshold voltage of devices.

Confirmation of these capacitance-voltage mapping results has come from Hall measurements on broken pieces of the 200 mm wafer. Agreement between the two techniques is seen in Hall

measurements, which reveal an electron mobility of around  $2000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  at an electron sheet concentration of  $9 \times 10^{12} \text{ cm}^{-2}$ . Sheet resistance in these AlGaIn/GaN HEMT structures is maintained below  $400 \Omega/\text{square}$ .

We have processed our 200 mm GaN-on-silicon wafer with a  $4 \mu\text{m}$ -thick buffer

If GaN HEMTs are grown on sapphire or SiC, contactless eddy current mapping offers a straightforward way to determine sheet resistance. But when these high-voltage transistor structures are grown on silicon, no conventional in-line tool is available, due to widespread use of conductive silicon substrates

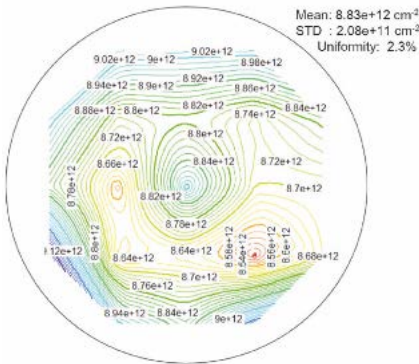


Figure 6. Enkris has worked with 4D on the development of a tool that can map the capacitance-voltage characteristics of a GaN-on-silicon epiwafer. Electron sheet concentration distributions have been recorded for an  $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$  HEMT on 200 mm silicon.

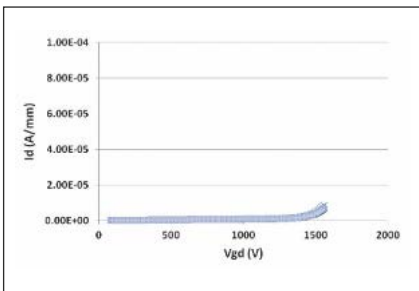


Figure 7. The leakage current of GaN HEMTs fabricated on 200 mm GaN-on-silicon wafers is low, thanks to the high quality of the AlN nucleation layer.

into devices with a 20 mm gate width. Device leakage is uniform and low across the entire wafer (see Figure 7), the vertical breakdown voltage exceeds 1000 V, and the three terminal breakdown voltage tops 1600 V. When the substrate is floating, leakage current is less than  $10 \mu\text{A}/\text{mm}$ , and when the silicon substrate is grounded, the leakage current density is below  $0.1 \mu\text{A}/\text{mm}$  at 600 V.

To verify the blocking properties of our GaN-on-silicon material, we prepared a new series of three samples on 150 mm silicon substrates. Vertical breakdown measurements on samples with buffer layers varying from  $2.8 \mu\text{m}$  to  $4.8 \mu\text{m}$  revealed an extremely low buffer leakage. Negative bias and positive bias have been applied to the top contact, and the results are slightly different (see Figure 8 a). Assuming a critical current of  $1 \mu\text{A}$ , the breakdown voltage of the samples increases linearly with the buffer

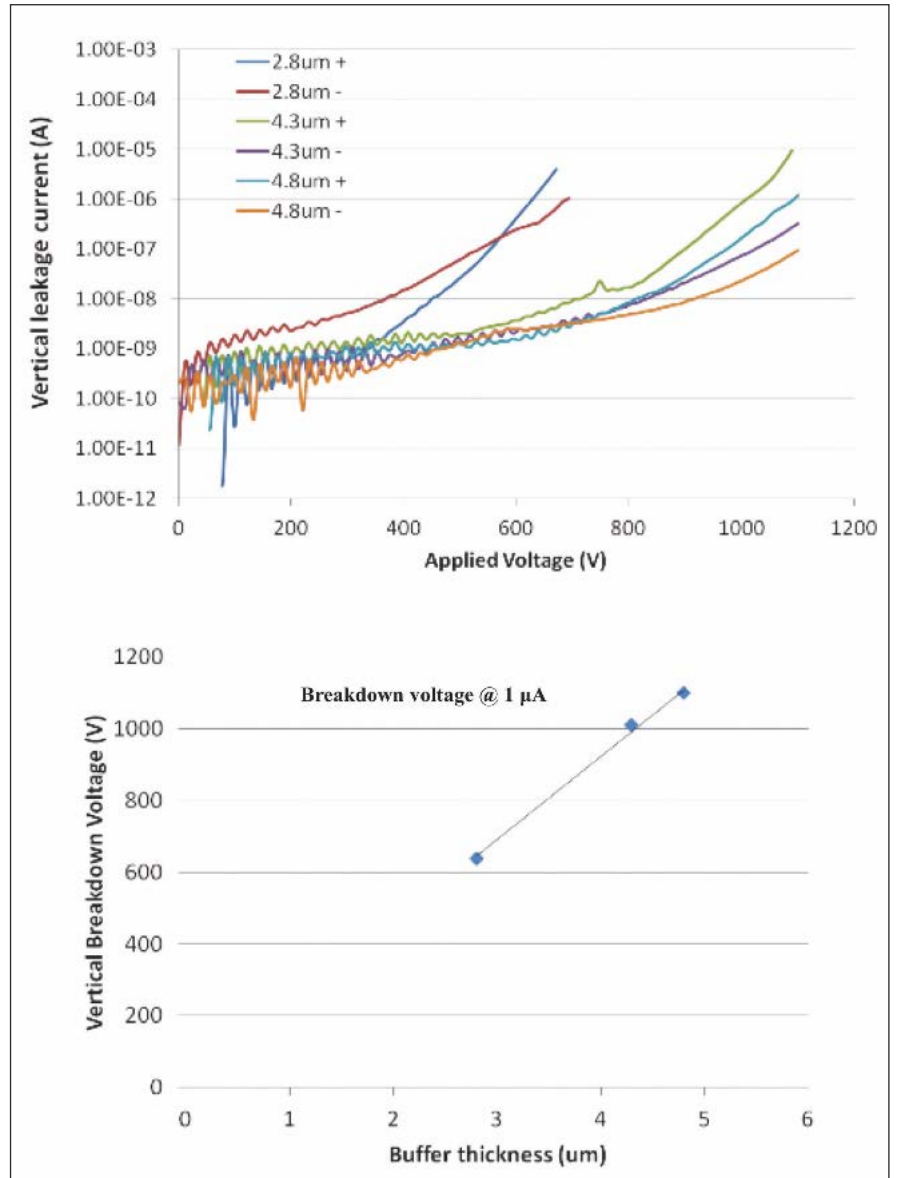


Figure 8. Vertical breakdown measurements of AlGaIn/GaN HEMT structures grown on 150 mm silicon indicate the high critical field strength in the GaN buffer layer.

thickness, and indicates that the critical electric field exceeds  $2 \text{ MV}/\text{cm}$  (see Figure 8 (b)).

This high critical field is highly valuable, because it simplifies growth, minimizes wafer bow and cuts epi-costs. And it may be possible to go to even higher fields in future, according to values for the theoretical maximum. If that were possible, even thinner buffers could be employed, reducing stress and possibly improving yield and reliability. The latter is sometimes a concern for device manufacturers, but if they work with growers, this should pave the way for mass production of GaN power devices.

**Further reading**

K. Cheng *et. al.* Jap. J. Appl. Phys. **47** 1553 (2008)  
 K. Cheng *et. al.* Appl. Phys. Express **5** 011002 (2012)  
 N. Ikeda *et. al.* Proc. of IEEE **98** 1151 (2010)  
 D. Marcon *et. al.* IEEE Trans. Semi. Manu. **26** 361 (2013)  
 T. Egawa *et. al.* IEDM 2012

# Targeting a terahertz transistor

Can terahertz HEMTs result from a switch from GaN to InN channels?

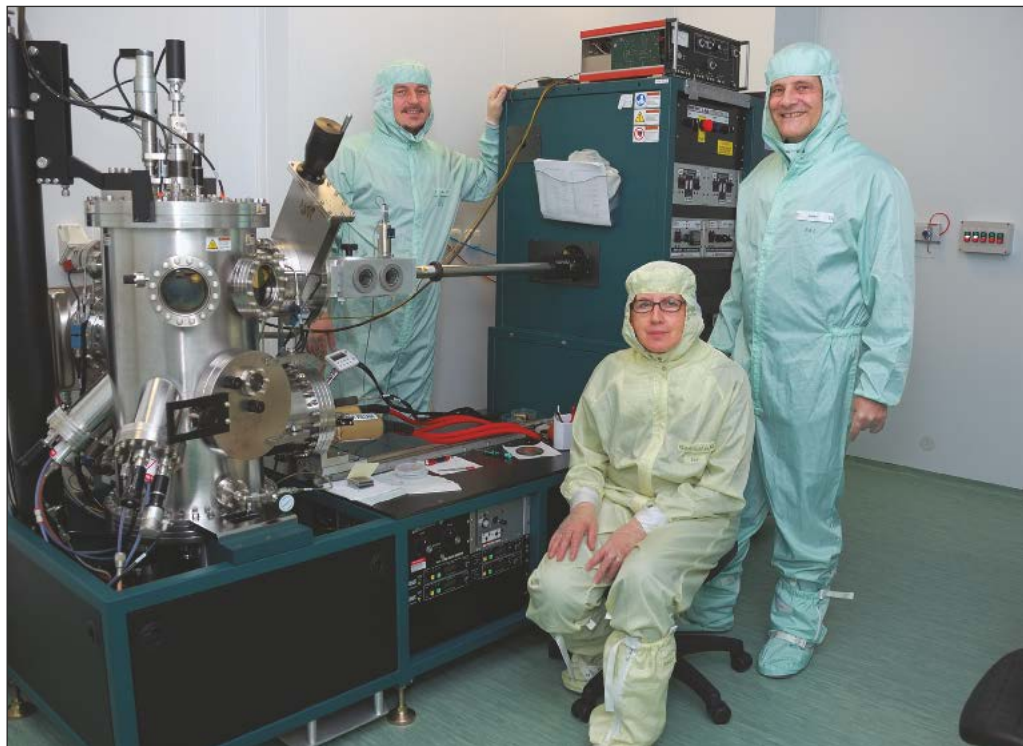
BY JÁN KUZMÍK FROM THE SLOVAK ACADEMY OF SCIENCES

A SPECTRAL FAMINE is looming at radio frequencies, due to exponential growth of wireless data transfer. However, at other slices of the electromagnetic spectrum an opportunity to feast is on offer, thanks to frequency bands that are largely untapped.

Terahertz frequencies represent one such opportunity, with progress pegged back by the difficulties of building sources operating in this domain. But if these challenges could be overcome, it would be great news for mankind. It could open the door to ultra-high speed circuits used for information and communication systems, including those operating wirelessly, as well as terahertz imaging systems and spectroscopy detection.

In recent times, researchers have taken two different tacks to reach the terahertz domain: going down in frequency for optical devices, and increasing the frequency for electronic devices. The optical approach involves semiconductor intersub-band sources, such as quantum cascade lasers (QCLs), while the leading electronic devices have been complex systems – for example, a Schottky contact diode with an integrated oscillator that may provide terahertz detection. All devices are based on electron-phonon interactions, with today's QCLs working mostly at low temperatures, limiting their deployment.

What's needed is a new approach that avoids temperature-related issues and is based solely on electron drift in high-power electronic devices. This is a goal that we are pursuing at the Slovak Academy of Sciences, where we have



The team from the Slovak Academy of Sciences expects that its biggest challenge related to processing will be fabricating a gate.

made some promising progress towards a novel HEMT featuring an InN channel.

A fundamental question that we have faced in our quest for higher speeds is this: What material shall I build my device from? One candidate is graphene, a material that has attracted a great deal of hype, in some cases for good reason. This atomic sheet of hexagonal carbon is blessed with an extremely high mobility, but it is a metallic system, so graphene transistors cannot be pinched off, limiting their use.

Transistors made from III-V channels don't suffer the same fate, which is why we have chosen them to pursue a terahertz transistor.

There are several options in this regard, and we have decided to focus our attention on III-N HEMTs, because they are known to have a higher critical breakdown field, greater robustness, higher current density and better thermal conductivity (when grown on SiC) than equivalents based on the InP and GaAs material systems.



This claim of superiority is based on the most mature form of the III-N HEMT, which is that featuring a GaN channel. And we hope that this position of superiority is maintained when a HEMT has an InN channel, which is the type of device we are developing.

We have selected InN because it sports the highest theoretical electron velocity of all commonly known semiconductors (see Figure 1). Consequently, HEMTs that are constructed with an InN channel have the best chance that nature can offer to excel in the field of ultra-high-frequency semiconductor electronics.

The operating speed of the HEMT also depends on the carrier transit time along the gate. Based on this, and the theoretical electron velocity, a switch from a GaN to an InN channel promises to increase the intrinsic current-gain cut-off frequency,  $f_T$ , by a factor of 2.5, which should take this transistor into the terahertz range.

Hitting such high frequencies will be helped by the low electron effective mass in InN. This offers the prospect for ballistic electron transport, which could propel the device to even higher speeds. However, despite all this promise, there are yet to be any demonstrations of microwave InN-channel HEMTs due to detrimental dislocations in InN layers.

These imperfections result from the significant difference in the lattice constants of InN and GaN. To try and avoid such issues, we are proposing an InN strained channel grown on an InAlN

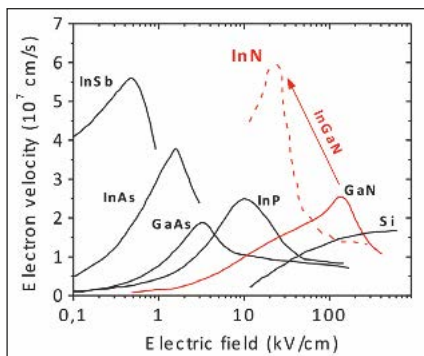


Figure 1. Electron velocity dependence on the electric field at room temperature in different semiconductors (taken from T. Palacios phys. stat. sol. (a) 206 1145 (2009)).

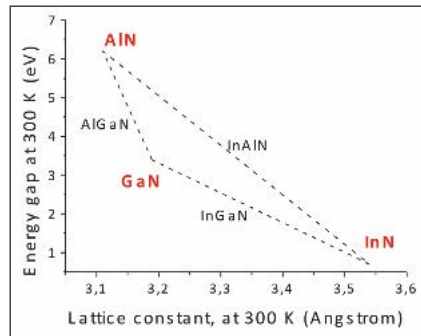


Figure 2. Energy gap dependence of III-Ns on the lattice constant.

buffer layer, with either indium or nitrogen polarity at the surface, or as a non-polar material. Thanks to the small difference in lattice constants of InN and indium-rich InAlN, it should be possible to perform coherent quantum well growth and ultimately create an InN-channel HEMT producing its theoretically predicted performance.

### Relaxing the buffer

The two most common designs of III-N HEMT feature a GaN channel and a barrier layer made from either AlGaIn or InAlN. The heterostructures for these devices are grown on a buffer layer, which is typically a semi-insulating GaN or an AlGaIn back barrier.

One peculiar property of the polar hetero-junctions made from the pairings of AlGaIn and GaN, or InAlN and GaN, is that they create a two-dimensional electron gas (2DEG) quantum well that is formed without intentional doping, due to the high spontaneous and piezoelectric polarization.

The piezoelectric polarization arises due to internal displacement of ion sublattices in the strained epitaxial layer, while spontaneous polarization results from a lack of inversion symmetry in the nitride crystal structure.

Growth conditions for these structures determine whether cation or anion bonds face the surface. The type of bond governs the polarization orientation – and it means that by reversing the polarity of the structure, it is possible to create a mirror-like scheme of the epi-layer stack without adjusting the density of the 2DEG.

Selecting the best layers in the heterostructure is not simply a matter of considering the lattice constant, as it is also important to take into account the relative bandgaps of the materials (see Figure 2).

Based on these considerations, we have chosen an indium-rich InAlN buffer layer, because it generates only a relatively weak compressive strain in the InN channel – to enable pseudomorphic growth of InN – and it has the highest energy gap difference compared to any other InAlGaIn combination. Our relaxed InAlN buffer layer with an indium molar fraction of 0.7-0.9 is used in conjunction with a thin GaN spacer between the InAlN barrier and InN channel. Calculations suggest that this should ensure excellent confinement of a high-density 2DEG in

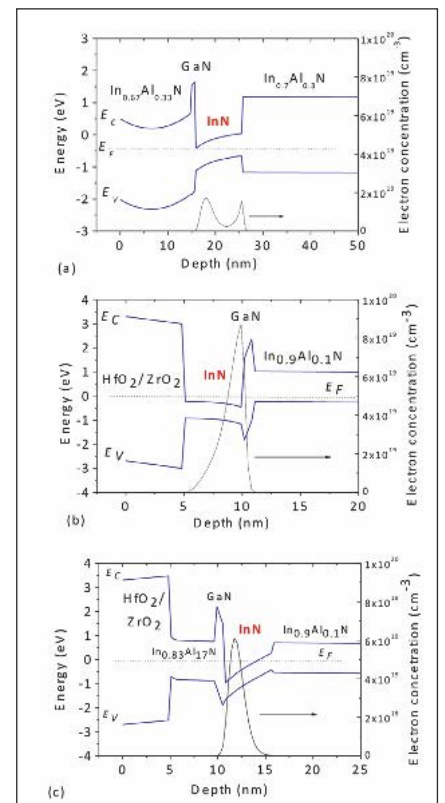
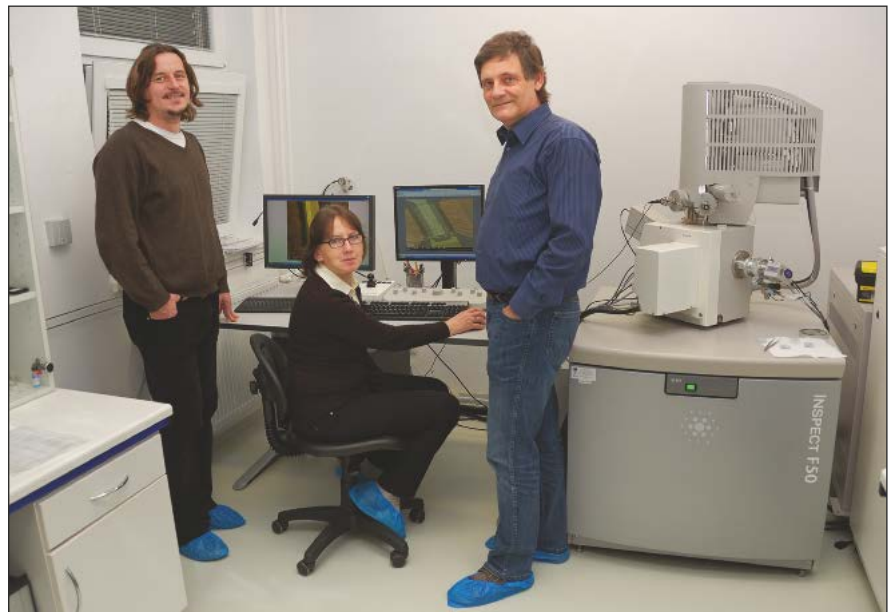


Figure 3. Calculated energy band profiles of normally-on InN-channel MOS HEMTs with (a) non-polar, (b) N-polarity, and (c) In-polarity orientation. For (a) the dielectric insulator is not shown and doping in the barrier is assumed to be  $10^{19} \text{ cm}^{-3}$ . Elsewhere the non-intentional doping is  $10^{15} \text{ cm}^{-3}$ . Calculated n2DEG = (a)  $0.6 \times 10^{13} \text{ cm}^{-2}$ , (b)  $1.6 \times 10^{13} \text{ cm}^{-2}$ , and (c)  $1.2 \times 10^{13} \text{ cm}^{-2}$ .

epi-structures for all polarity cases (see Figure 3 (a)-(c)).

This combination will hopefully unlock the door to the exploitation of an InN HEMT. When state-of-the-art InN material is grown on GaN – rather than the buffer we are proposing – it has high electron concentrations and, as a very thin (few nanometres thick) layer, it has a mobility that substantially lags that of theoretically predicted values. Our novel buffer and strained InN channel should lead to better HEMTs, by trimming the defect density in the quantum well and boosting mobility. To optimise this device, we will have to develop high-resistivity InAlN, which will involve exploring



A scanning electron microscope is a very useful tool for imaging the structure of HEMTs with sub-micron dimensions.

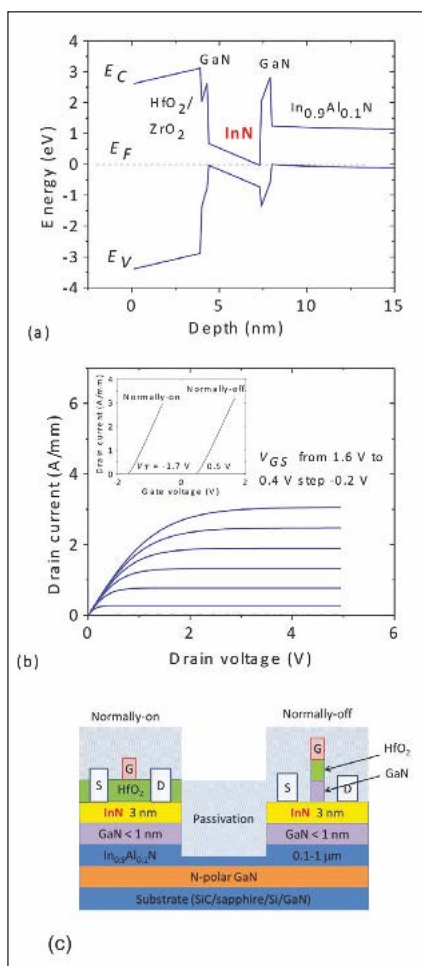


Figure 4. (a) The energy band diagram for an N-polar normally-off HEMT. (b) Calculated output and transfer characteristics of the proposed normally-off HEMT, together with the normally-on uncapped HEMT. (c) A novel technological approach enabling integration of both types of high-performance HEMTs.

various acceptor and/or deep level compensation mechanisms.

### Construction challenges

We expect our biggest challenge that is related to device processing will be fabricating a metal-oxide-semiconductor gate. Experiments on  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$ -based Schottky barrier contacts suggest that the barrier height is influenced by Fermi-level pinning. According to photoemission spectroscopy, however, for InAlN with an indium mole fraction of 0.6-0.8 there is no barrier, because the Fermi-level resides near to the conduction band. That means that we will probably turn to the dielectrics developed in the silicon CMOS industry, such as  $\text{ZrO}_2$  or  $\text{HfO}_2$ .

Another avenue that we will have to explore is that of the different polarity orientations of InN-channel heterostructures, which could lead to different growth sequences, different interfaces, and new trapping mechanisms. Our team has already shown that polarity can be used to design normally-off HEMTs, for N-polar HEMTs, where a thin GaN cap creates a negative polarisation charge that depletes the channel (see Figure 4(a)). This effort is helping to pave the way to beyond-CMOS logic ICs, because it allows integration with normally-on

HEMTs on identical substrates, thanks to highly selective etching of GaN over InN.

The realisation of ultra-fast logic and mixed-signal ICs based on InN HEMTs is clearly a long way off, but we have begun that journey. Achievements to date include the physical analysis of the concept; and practical breakthroughs, such as highly selective etching of GaN over InN, processing of MOS structures on (GaN)/InN, and the formation of the negative polarisation charge at the N-polar GaN/InN interface. If further progress is possible, then there might become a time when the InN HEMT lies at the heart of cutting edge technology deployed in circuits, imaging and communication in the terahertz domain.

### Further reading

- E. Dimakis *et al.* Appl. Phys. Lett. **97** 113520 (2005)
- J. Kuzmik *et al.* IEEE Trans. on El. Dev. **58** 720 (2011)
- J. Kuzmik Appl. Phys. Express **5** 044101 (2012)
- J. Kuzmik *et al.* Semicond. Sci. Technol. **29** 035015 (2014)
- K. Čičo *et al.* ASDAM 2014, Smolenice Castle, Slovakia, October 20-22, 2014

# Strategies for creating efficient, beautiful whites

Many paths to optimal colour mixing will accelerate the adoption of solid-state lighting

BY SERGEY KARPOV FROM THE STR GROUP (SOFT - IMPACT)

THERE IS MUCH TO LIKE about solid-state lighting: It trims global energy consumption, opens new lighting applications, and gives us a long-lasting light bulb that hits full brightness in an instant. However, penetration of this technology is not as fast as we would like, with adoption held back by high prices and an insufficient level of superiority over incumbent sources.

Many of the LED bulbs that are on sale today have at their heart a blue-emitting chip coated with one of more phosphors emitting at longer wavelengths. White light stems from colour-mixing, which can also be produced by combining either the output of blue, green and red LEDs; or the emission of a quartet of blue, green, amber and red devices. Whichever approach is taken, the designers of white-light sources

have to make two key decisions: how many, and what kind of individual emitters should be chosen to produce white light with desired properties; and what are the requirements for characteristics of the individual emitters. Getting the right answers demands careful optimization of light mixing, because it is not just a matter of optimizing the total emission spectrum produced by all the emitters – it also requires maximising the efficiency of electricity-to-light conversion of each individual device.

## LEDs and phosphors

Today's solid-state white light sources are based on III-nitride (III-N) LEDs, possibly combined with III-phosphide (III-P) cousins. Both of these forms of LED have a width and shape of the spectral emission that is normally asymmetric relative to the peak







wavelength (see Figure 1a and 1b), and one of their key figures of merit is the wall-plug efficiency, which is the efficiency of electricity-to-light conversion.

This efficiency depends on the current passing through the chip, and when it peaks, it is almost equal to the external quantum efficiency (essentially, this is the proportion of photons emitted for every electron and hole injected into the device).

Plotting the external quantum efficiency for a range of LEDs emitting at different wavelengths highlights a problem known as the 'green gap' (see Figure 1(c), which is based on the performance of a range of leading commercial LEDs from various chipmakers). The 'green gap' results from a lack of efficient LEDs emitting at 500-600 nm for reasons that are not yet completely understood, despite the practical importance of this issue.

Since the wall-plug efficiency of the LED varies with wavelength, calculations of the efficiency of a white-light source constructed from a collection of emitters of different colours requires a summing of individual contributions, and determining what the average of these is. Armed with this information, it is then possible to calculate the efficacy of the light source: It is the product of the wall-plug efficiency and a characteristic known as the luminous efficacy of radiation, which accounts for the spectral response of the human eye (see the panel "White light and its characteristics" for more details). Note that it is also possible to determine the efficiency of the light source when phosphors are used. To do this requires the inclusion of terms in the calculation that reflect the energy loss associated with the differences in excitation and emission wavelengths, and the quantum yield of the phosphor emission.

Whether phosphors are used or not, the aim of colour-mixing is to maximise the performance of the white-light source via judicious selection of the number of individual light emitters, their emission wavelengths, and the fraction of power that they contribute to the total emission spectrum. For specific lighting applications, the characteristic that is most frequently considered is the correlated colour temperature: For a warmer white, this value is lower; but if a harsher, more revealing white is preferred, a higher value is needed.

There are also other measures that reflect the quality of the light: The higher the colour rendering index, the better the colour rendition; the higher the luminous efficacy of radiation, the higher the total

emission spectrum and the luminous flux; and the higher the efficacy of the light source, the brighter it is.

The easiest, most frequently applied approach to building a better light source is to optimise simultaneously the colour-rendering index and the luminous efficiency of radiation. However, this approach only considers the emission spectrum of the light source, and it ignores the efficiencies of individual emitters. What's more, this approach is non-trivial, because it is not possible to independently optimise the colour-rendering index and the luminous efficiency of radiation, as they have to be traded against one another (see Figure 2). Due to this, the best result depends on the task facing the light source. If, for example, it is to be used to illuminate paintings, excellent colour rendition is the primary objective.

A different situation arises when the efficiencies of individual light emitters are taken into account. At the STR Group of St.Petersburg, Russia, we have taken this approach and discovered that the spectral dependencies of the emitter wall plug efficiencies have a crucial impact on the optimization results, making the choice of the white-light characteristics more evident and clear.

### Just LEDs...

When optimising the colour mixing of a white-light source made from LEDs emitting at different wavelengths, it is critical to account for individual efficiencies and use realistic emission spectra. We have done this, taking values from commercial LEDs, and our calculations have uncovered a distinct transition from optimal three- to four-LED operation at a colour-rendering index of about 92. However, even with three optimal LEDs, it is possible to hit a light source efficacy of 165-170 lm/W and a colour-rendering index of 87-91 at a colour-correlated temperature of 3000 K. Switching to four LEDs can lead to even higher values for the colour-rendering index, but the light source efficacy starts to drop off a cliff (see Figure 3 (b)). That's because the optimal wavelengths of two of the LEDs have to lie within the 'green gap', and this drags down the efficacy of the white-light source.

An important finding in our theoretical study is that the optimized LED peak wavelength shows only a very weak dependence on a particular colour-correlated temperature (Figure 3 (a)). This implies that a 'smart' white-light source can be constructed

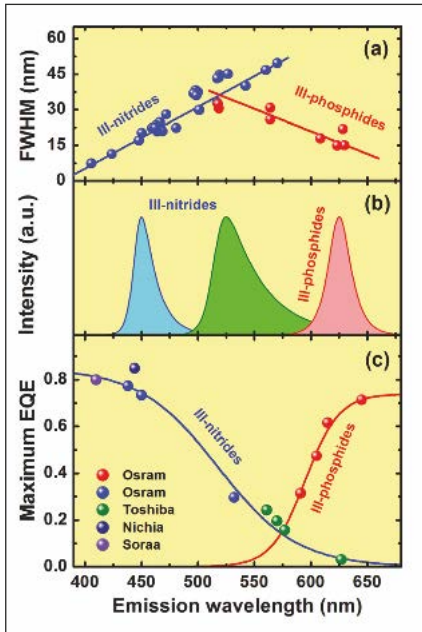


Figure 1. Calculations have considered commercial III-N and III-P LEDs, including values for: emission spectra (a), typical spectrum shapes (b), and maximum external quantum efficiency (EQE) (c). Note that the spectral width of III-N LEDs is greater for devices emitting at a longer wavelength.

that offers an adjustable colour-correlated temperature, which is selected by tuning the emission intensities of individual LEDs. For example, a combination of a 455 nm, a 532 nm and a 614 nm LED would allow the colour-correlated temperature to be varied from 2700 K to 8000 K while keeping the colour rendering index and the efficacy of the light source relatively stable (they range between 89-91 and 145-170 lm/W).

... or with phosphors

One common approach for sidestepping problems associated with the green gap is to use a phosphor emitting in the green-yellow. The wall-plug efficiency of the resulting chip can be higher than that of a direct green emitter – our calculations suggest that the pairing of a blue-emitting chip and a yellow YAG:Ce<sup>3+</sup> phosphor, which has a wide emission spectrum peaked at 570 nm, can spawn a device with a wall-plug efficiency of 55 percent. This is a few times higher than LEDs emitting in the green, and it allows the creation of a very high efficacy white-light sources based on two or three LEDs and a phosphor. However, compared to an LED-only approach, optimal wavelengths are generally dependent on the colour-correlated temperature (see Figures 4(a) and 5 (a)).

The combination of a nitride LED, a phosphide LED and a YAG phosphor can yield a warm source with an efficacy of 195-200 lm/W, a colour-rendering index exceeding 90, and a colour-correlated temperature of 2400-3000 K (see Figure 4(b)) – and even higher temperatures can be realised at the expense of efficacy. This kind of approach known as Brilliant Mix has already been adopted by Osram Opto Semiconductors, which in 2011 launched LEDs that produced an efficacy of 110 lm/W at a colour-rendering index of 90 under practical operation conditions.

We have found that turning from one nitride LED to two of them, while maintaining the phosphide LED and the phosphor, allows the fabrication of promising neutral white light sources with a colour-correlated temperature of 4000 K (see Figure 5 (b)). In this case, an efficacy of 185 lm/W is possible at an extremely high colour-rendering index of 96-98. Such high values can be realised because the optimal peak wavelengths of LEDs do not occupy the ‘green gap’.

What next?

To drive the development of white light sources that deliver a level of performance in this ballpark, the European Union has funded a Framework 7 programme NEWLED: Nanostructured Efficient White LEDs. This four year effort, which kicked off in late 2012 and is backed by € 11.8 million, is targeting the rather ambitious goal of white-light sources that combine an efficacy of 200 lm/W with a colour-rendering index in excess of 90.

Our calculations, which have been conducted within this project, offer routes to realising this goal. However, does this mean that the optimal ways for colour

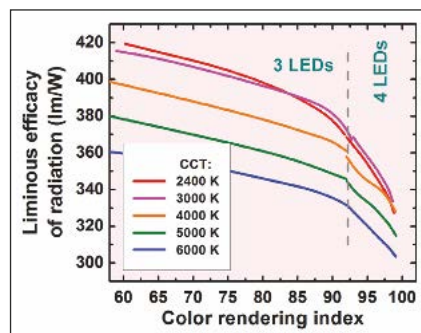


Figure 2. There is a trade-off between the maximum colour rendering index and luminous efficacy of radiation when optimizing the colour mixing in a white-light source comprising of two or three III-N and one III-P LEDs.

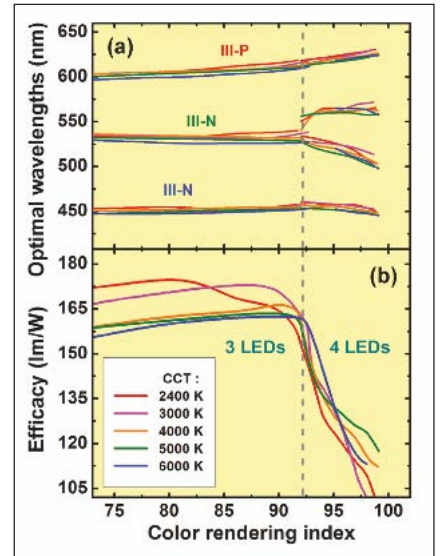


Figure 3. Optimal peak wavelengths of III-N and III-P LEDs (a) and maximum efficacy (b) for different colour rendering indexes of white-light sources comprising of LEDs only.

mixing are now determined, and there is no need for further refinement?

Well, yes and no – with the former answer reflecting the situation today, and the latter highlighting the need for further calculations to underpin longer-term efforts. It is worth noting that the results presented here draw on the performance for state-of-the-art LEDs and phosphors, and if improvements were made, particularly in relation to the green gap, the optimal approach for colour mixing would change.

We should also point out that our calculations are there to provide a benchmark, because they employ performance figures at drive currents too low for use in solid-state lighting. Given this, it would be both desirable and helpful to carry out calculations that indicate how to optimize colour mixing for LEDs at practical operating currents. On top of this, we would like to extend our study to include the stability of white light characteristics under variations of temperature and the total luminous flux of the light source. Such efforts might give additional insights into how to optimise colour mixing.

Even now, without these refinements, our insights into optimising colour mixing provide guidelines for how to develop high-performance white-light sources. And as more of these sources hit the markets, this will accelerate a lighting revolution.

White light and its characteristics

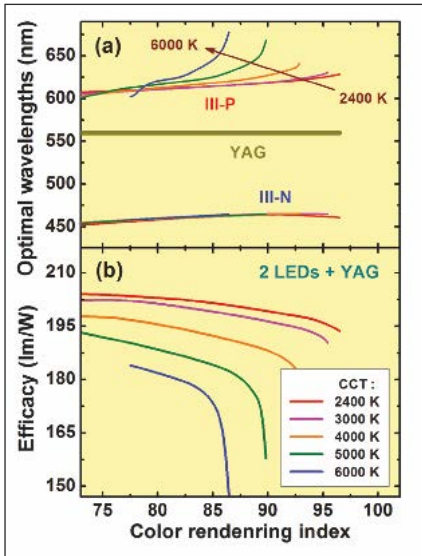


Figure 4 Optimal peak wavelengths of III-N and III-P LEDs (a) and maximum efficacy (b) for different colour rendering indexes of white-light sources comprising of two LEDs and a YAG:Ce<sup>3+</sup> phosphor.

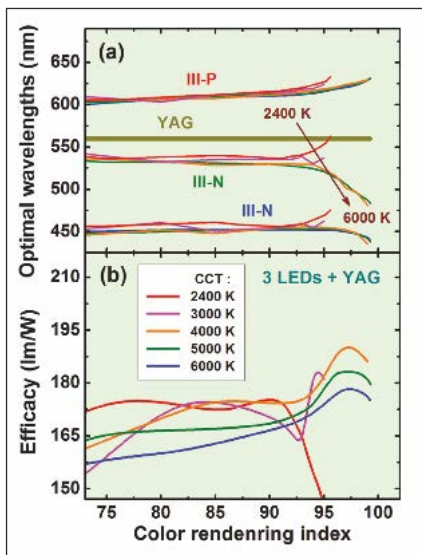


Figure 5 Optimal peak wavelengths of III-N and III-P LEDs (a) and maximum efficacy (b) for different colour rendering indexes of white-light sources comprising of three LEDs and a YAG:Ce<sup>3+</sup> phosphor.

Further reading

CIE. Publ. No 15.2, "Colorimetry. Official Recommendations of the International Commission on Illumination", Sec. Ed., Vienna, Central Bureau of the CIE (1986).  
 K. A. Bulashevich *et al.* Phys. Stat. Solidi A (2014) // DOI 10.1002/pssa.201431576.  
 A. Žukauskas *et al.* Appl. Phys. Lett. 80 (2014) 234.  
<http://www.newled-fp7.eu>

A WIDE VARIETY OF SPECTRA can form a light source that appears white to the human eye. To account for these differences, the nineteenth century physicist James Clarke Maxwell pioneered the use of three components to describe light, an approach that has subsequently been pursued by the International Commission on Illumination (see Figure 1).

One source of white light is a black body heated up to several thousand Kelvin. As this temperature varies, the chromatic co-ordinates shift, with a plot of chromatic co-ordinates at different temperatures tracing out a locus that nearly corresponds to white light (see Figure 1).

In practice, small deviations from this locus still produce light that appears white; and projections of the co-ordinates of these points onto the blackbody locus can provide a correlated colour temperature, which is one of the most important characteristics of white light.

Another important characteristic is the luminous efficacy of radiation, a measure that considers the sensitivity of the human eye (see Figure 2). This metric is equal to the total luminous flux measured in lumens and produced by a light source with a given spectrum and a total optical power of 1W.

Meanwhile, the colour-rendering index reveals the capability of a light source to reproduce properly the colours of illuminated objects. This index accounts for the differences between the chromatic coordinates of light reflected from a number of standard colour samples at their illuminating by the light source studied and by one or another standard illuminant.

The maximum value for the colour-rendering index is 100, and it drops by one for every chromatic coordinate difference obtained from the selected colour samples.

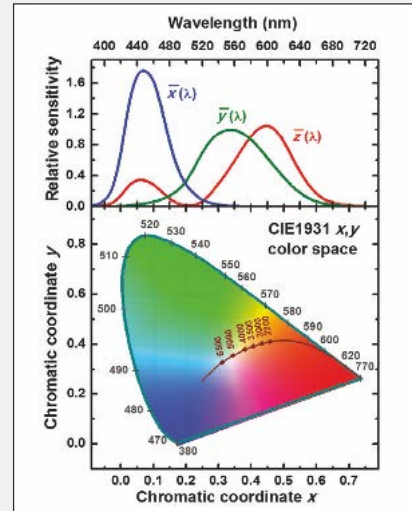


Figure 1. Three colour coordinates X, Y and Z, can be brought in by convolution of a light source emission spectrum  $S(\lambda)$  with three color matching functions  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$  and  $\bar{z}(\lambda)$ . Then the relative chromatic coordinates  $x = X/(X + Y + Z)$  and  $y = Y/(X + Y + Z)$  project the emission spectrum into the CIE1931 colour chart, represented by points in the (x, y) space. In this chart there are all the possible colours that can be met in practice. Note that the black-body radiation locus (dark-brown line) and points (diamonds) correspond to selected colour temperatures, and the (x, y)-colour space is confined by the pure-colour locus (dark-cyan line) with corresponding wavelengths indicated in nanometres.

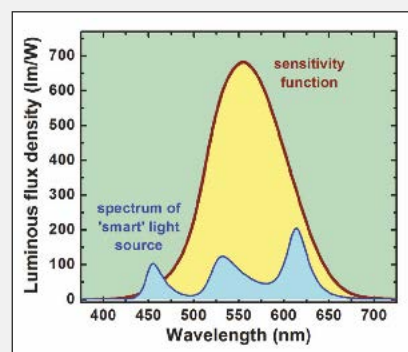


Figure 2. A sensitivity function for the human eye allows the calculation of luminous flux from a light source with a known spectrum and total spectrum of a 'smart' white-light source operating at a colour-correlated temperature of 3500 K.



# Superluminescent diodes

A novel approach for droop-free solid-state lighting?

Superluminescent diodes marry the virtues of LEDs and laser diodes by offering droop-free emission from a high-quality beam that can deliver speckle-free projection

BY ANNA KAFAR FROM UNIPRESS

ONE TREMENDOUS TALKING POINT of recent times has been the cause of droop, the decline in the efficiency of an LED as the current passing through it is cranked up. Getting to the bottom of this has been a goal for many researchers in industry and academia, who have hoped that by uncovering the cause of this mysterious malady, they will unlock the door to a generation of droop-free LEDs that will accelerate the adoption of solid-state lighting.

It did not take long for these investigators to realise that droop depends on the cube of carrier density. But it has taken far longer for them to come up with convincing evidence for its cause, which is non-radiative Auger recombination. Direct evidence only arrived in 2013, through a partnership between scientists at the University of California, Santa Barbara, and École Polytechnique, France (see *Compound Semiconductor* p.46 **8** (2013)).

Auger recombination is a material property, so suppressing droop is very difficult. However, it is possible to sidestep it, rather than address it head on, by turning to a droop-free light source: a laser diode. When this device is driven above its lasing threshold, its carrier density is constant, clamping droop-related recombination. Thanks to this, it can then operate with a high differential efficiency in a fashion described as droop free. For this reason, it has been recently proposed by scientists at Sandia National Laboratory that laser diodes, in partnership with phosphors, can be efficient sources of white light (the possibility of using such devices has been broadly discussed in the article "Solid-state lighting: Are laser diodes the logical successors to LEDs?" in *Compound Semiconductor* p.40 **8** (2013)).

The laser, however, does not have a monopoly on droop-free light emission – this accolade is shared by the superluminescent diode (SLD), a device that we have been developing and investigating at Unipress in Warsaw, Poland. This lesser-known light emitter combines many characteristics of LEDs and laser diodes, and can be viewed as an edge-emitter that is fabricated in a way very similar to that of the laser diode.

While it may look like a laser, the SLD is distinct, because it does not lase, due to far higher losses at the mirrors or at the end of the waveguide. This means that light is generated in a process of spontaneous emission, just like it is in an LED; although it is also amplified by stimulated emission in the waveguide, which is what happens in a laser.

The interplay of spontaneous and stimulated emission gives rise to a light-versus-current curve with an exponential region (see Figure 1 (a)). High mirror losses that are engineered by a specific device design prevent light from reflecting at both or one of the facets. This leads to a shape of emission spectrum resembling that of a laser diode below threshold (see Figure 1(b)). But the device can reach optical power comparable to laser diodes above threshold and, like a laser, it emits a high quality light beam.

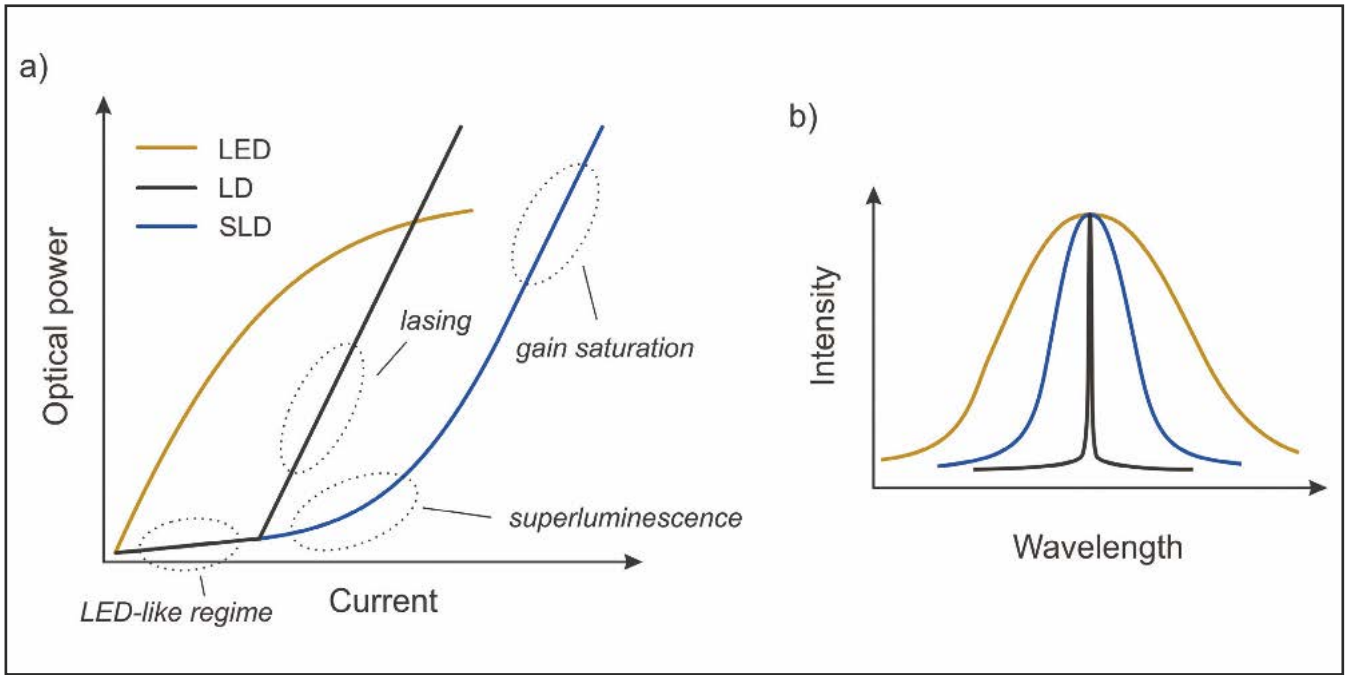


Figure 1. The output power profile of the superluminescent diode is similar to that of a laser, and it has a spectral profile resembling that of an LED.

Thanks to these attributes, arsenide and phosphide SLDs are already common light sources in applications such as optical coherence tomography and fibre-optic gyroscopes. And we believe that nitride SLDs, which are now less mature than their phosphide and arsenide cousins, can be used in the future in the same fields, as well as alternatives to laser diodes in droop-free light generation.

Turning to SLDs for lighting might raise a few eyebrows, because as these devices do not reach lasing threshold, one might expect that they are prone to droop, just like an LED. But our experience suggests otherwise. Our studies show that SLDs can easily emit high optical power at current densities three orders of magnitude beyond those associated with the peak quantum efficiency for an LED, which often occurs around  $10 \text{ A cm}^{-2}$ . At current densities of  $1000 \text{ A cm}^{-2}$  or more, droop would be expected to govern the light-current characteristics, but measurements show that's not the case, with the output

power steadily increasing with current. It is possible, therefore, that SLDs are even immune to droop.

Our development of SLDs has drawn on the efforts of others, including the pioneers of this device, who built the first emitters in the early 1970s using the arsenide material system. Nearly 40 years later, the SLD family expanded, with the first nitride SLDs emitting at around 420 nm emanating from the École Polytechnique Fédérale de Lausanne. Five years of intense study of SLDs followed, with many groups focusing their research on approaches for cavity suppression that could unlock the door to high-power devices spanning a wide range of emission wavelengths.

We started to develop SLDs in 2010, and the output of our latest violet devices is state-of-the-art at more than 200 mW. In comparison, the world record for blue-emitting variants, held by Osram, is above 100 mW. A reduction in output power at longer wavelengths is to be expected, and mirrors the behaviour of laser diodes. For both classes of device, when indium is added to push emission from the violet to the green, the strength of the built-in electric field increases, leading to reduced electron-hole overlap. A fall in gain results, lowering output power. But it is not all bad news for these SLDs that are following in the footsteps of the laser diodes, as many improvements to the latter can be applied to the former. Thanks to this, we believe that it should be possible to realise really fast developments in SLD performance.

### Mimicking laser manufacture

The fabrication of a nitride SLD is similar to the making of a laser, and begins by growing a separate confinement heterostructure on a GaN substrate. This is followed by the addition of waveguides and contacts. Performance of the device is governed by the cavity suppression mechanism, which can be realised by many means, including: the insertion of a waveguide that is tilted with respect to the facet, the addition of a high-quality anti-reflection coating, and the deployment of an absorbing region.



The superluminescent diode is not overwhelmed by droop, thanks to stimulated emission. Credit: S. Stańczyk, Unipress



Most of today's SLDs employ a tilted waveguide, which has an axis inclined to the cleavage planes (the future chip facets). With this design, light generated within the active area is guided towards the window while undergoing amplification, just as it would in a laser diode. However, light does not impinge on the facet perpendicularly. This means that a proportion of the light reflected back into the chip is directed outside the waveguide (see Figure 2(a)). Consequently, light does not oscillate between the facets, and no lasing takes place. Note that the light that is emitted out of the chip exits at an angle determined by the refractive index of the material in the laser, and the relative angles of the facet and waveguide.

One great strength of this design is that without substantial changes in standard laser diode fabrication, it is possible to reach an extremely low value of front facet reflectivity (below  $10^{-4}$ ) – this is highly desirable, as it quashes light oscillations. This low-reflectivity front facet can be combined with a rear facet with high reflectivity to form an SLD with double-pass amplification. When the SLD operates in this manner, the light initially travelling towards the rear facet is coupled back into the waveguide, creating an amplification path that is twice that of the length of the chip (see Figure 2 (b)).

Doubling the amplification path has a tremendous impact on output power, because intensity rises exponentially with path length. Creating a bend is the key to forming such devices, and in our case we use a 'j-shaped' waveguide. Further improvements in facet properties are possible with additional antireflection and high-reflection coatings, but care is required in order to preserve proper cavity suppression, and any increase in rear-facet reflectivity must go hand-in-hand with a trimming of front-facet reflectivity.

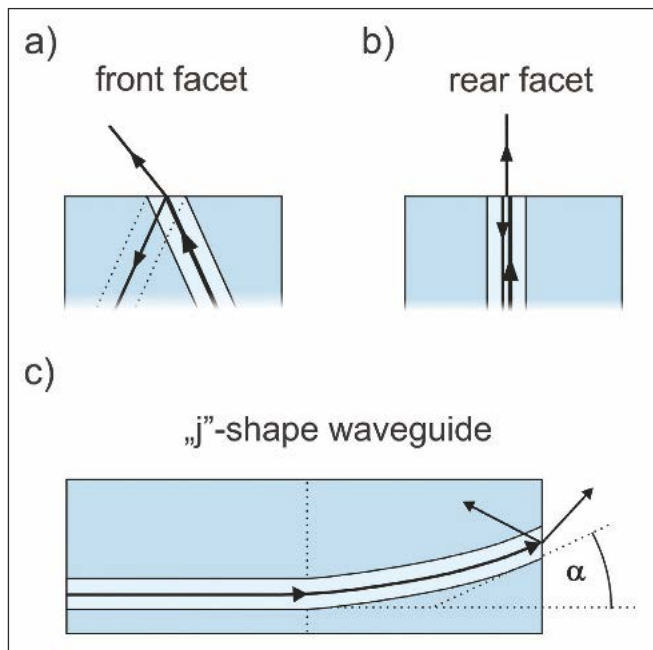


Figure 2. Superluminescent diodes feature a bend waveguide geometry. At the front facet a) light is reflected outside of the waveguide to prevent the device from lasing, whereas at the rear facet b) light is coupled back to the waveguide to lengthen the amplification path. The team at Unipress employ a "j"-shape design c), where half of the waveguide is straight, like it is in laser diodes.

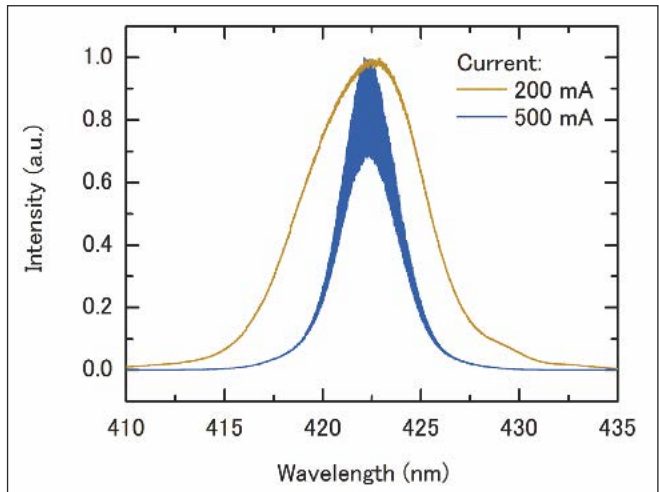


Figure 3. Emission spectra of a superluminescent diode measured close to the onset of amplified spontaneous emission (200 mA) and at high current (500 mA).

Although a front-facet reflectivity below  $10^{-4}$  can reduce light oscillations substantially, it cannot eliminate them. Any measurements on superluminescent diodes operating at a reasonable current will uncover modulations or ripples in the spectral output. These arise from the facets reflecting some light into the waveguide and are a sign of a high-loss Fabry-Pérot resonator. The depth of modulation increases with current until it reaches the full height of the spectrum, and then the device starts to lase (this is the limit of superluminescence).

During device optimisation, one of the biggest goals is to reduce the ripple depth as much as possible. In our case, because we employ a tilted waveguide design, this occurs through optimising the bend angle. Varying this angle produces a series of deep minima for front-facet reflectivity, and an optimised device geometry is realised from a minima associated with a very low reflectivity of the front facet.

### Combating droop

As a function of current, the efficiency profile of the SLD is vastly different from that of an LED. Instead of peaking at around  $10 \text{ A cm}^{-2}$ , it hits its peak performance at far higher current densities, where, surprisingly, droop does not appear to play a role. For a typical device, light output first increases exponentially with current, in agreement with theory, before entering a linear regime that is free from lasing (this is evident in measurements of emission spectra). What is particularly interesting is that a laser diode and SLD fabricated side-by-side produce the same slope efficiencies (see Figure 4), so it should be possible for an SLD to deliver the same output power as the laser, if it operates at a higher current.

The linear regime of the SLD is associated with the saturation of optical gain at high currents. To measure this gain, we have developed an approach that can compare amplified and spontaneous emission, and thus explicitly uncover the presence of gain saturation. This saturation is not that surprising, because our SLD operates at extremely high carrier densities. Unlike a laser, there is no clamping of the carrier density at threshold, and instead it climbs throughout the entire operating range. We have constructed a simple model for our SLD, drawing on the well-known ABC model used to explain LED behaviour. We

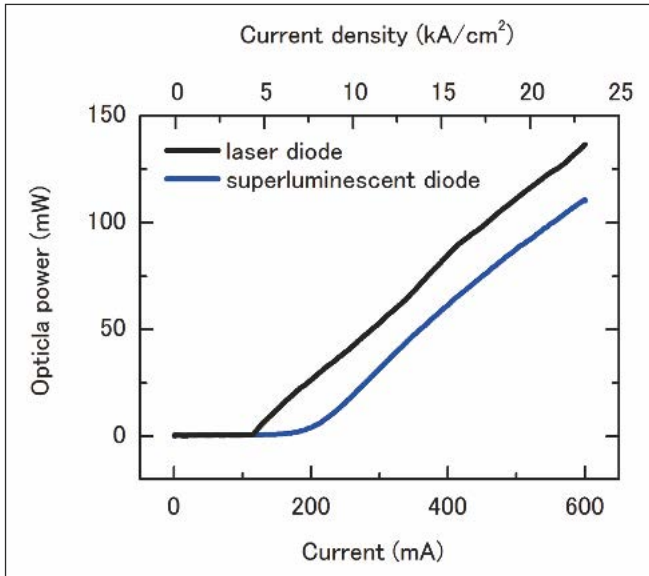


Figure 4. The waveguide geometry impacts the behaviour of the superluminescent diode, which has a spectra shown in Figure 3.

determined values for  $A$ ,  $B$  and  $C$  by fitting the spontaneous emission of the SLD, and the results of this suggest that for current densities in the linear regime, the gain value is so high that we approach its material limits (defined by Fermi-Dirac statistics), which we observe as saturation. On top of this, a high photon density can cause carriers to be ‘burned out’, if they are recombining quicker than the rate of new carrier supply. This situation also promotes gain saturation.

Our explanation thus far does not offer a clear answer to this question: Why can superluminescent diodes be immune to droop? To gain an insight into why this is the case, we calculated how Shockley-Read-Hall recombination, bimolecular recombination and Auger recombination depend on current density, using an ABC model.

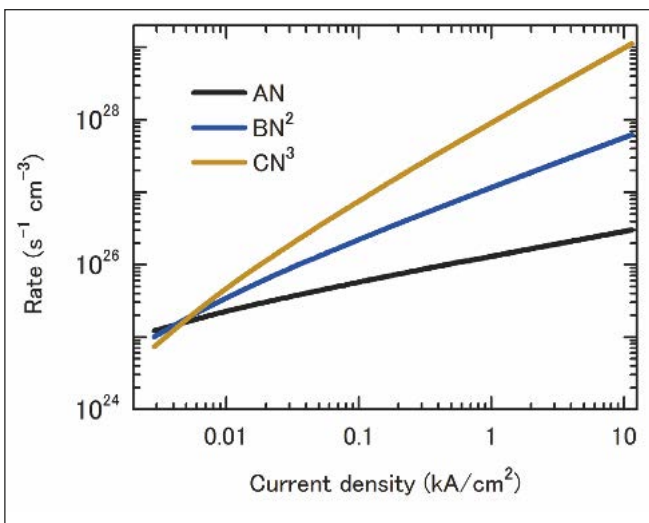
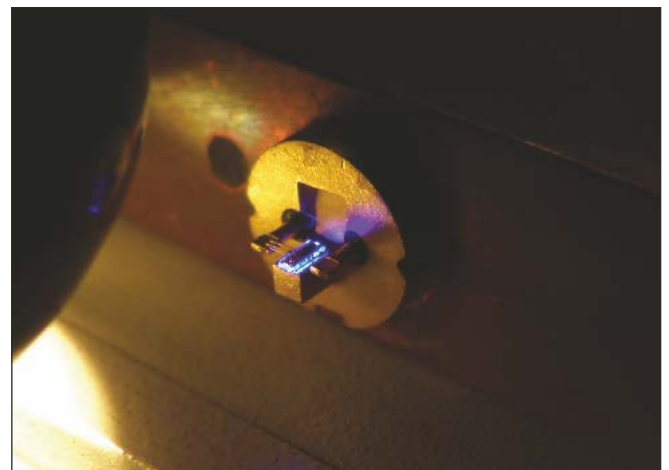


Figure 5. Comparing the rates of different recombination mechanisms using the ABC model and a fit of measured data suggests that Auger recombination strongly dominates in the operating regime of superluminescent diodes. However, this model ignores stimulated emission, which occurs at a rate that is far faster than Auger, and accounts for the majority of carriers.

This study shows that Auger recombination overshadows other mechanisms at rather low current densities, such as  $100 \text{ A cm}^{-2}$ . However, the key point is that there is another mechanism that we have ignored in our calculations – stimulated emission. This is a very fast process that is influenced by the photon density, and at high current densities this consumes carriers at a far higher rate than the Auger process. Consequently, droop is quashed at high current densities.

Virtues of the SLD over the LED are not restricted to immunity to droop, and include lower fabrication costs. This stems from the far smaller chip size, which is essential for cost-competitive nitride devices that are grown on native substrates. In addition, there is no need to devote time and effort to improving the extraction efficiency of the SLD (like in all edge emitters), while the high beam quality enables efficient fibre coupling and focusing.

What’s more, the SLDs have advantages over laser diodes for white-light generation. A lack of time coherence makes this source safer for general applications, and it should be possible to employ higher light intensity before damaging the phosphor.



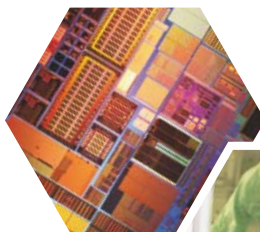
The superluminescent diode is much smaller than the LED, so material costs for this potential lighting source are lower. Credit: S. Sta czyk, Unipress

Note, also, that GaN SLDs are a perfect light source for pico-projectors. This form of display requires a high-quality light beam, and when a laser is employed, the image is compromised by speckle, an interference effect related to the high degree of time coherence of the source. SLDs have low time-coherence, and red, green and blue forms of this device promise to combine to form an excellent projector.

This is just one of many opportunities for the SLD. With a slope efficiency that matches that of the laser diode, it promises to increase in power, and serve multiple markets.

**Further reading**

- G. A. Alphonse Proc. SPIE 4648 125 (2002)
- E. Feltin *et. al.* Appl. Phys. Lett. 95 081107 (2009)
- A. Kafar *et. al.* Phys. Status Solidi A *early view available on-line*
- F. Kopp *et. al.* Jpn. J. Appl. Phys. 52 08JH07 (2013)



## Register Now for the Premier Microelectronics Manufacturing Event in Southeast Asia!

### ADVANCING SEMICONDUCTOR DEVELOPMENT THROUGH TECHNOLOGY INNOVATION AND DESIGN

Be a part of the inaugural SEMICON® Southeast Asia in Penang, Malaysia!

- *See products and engage technical experts* from more than 150 international companies
- *Access information and learn* about the latest developments and trends shaping the future of semiconductors, including IoT
- *Find solutions* to your critical manufacturing challenges from more than 150 companies and at technical sessions covering:
  - Assembly and Packaging
  - Yield Methodologies
  - Product and System Test
  - High-brightness LEDs
- *Engage technologists, researchers, executives, and peers*—find new partners, collaborate, and connect to more than 6,000 expected attendees

Register Early  
 for Your Chance  
 to Win Special  
 Lucky Draw  
 Prizes!

Register Now  
 and Save  
 on Programs!

Register before  
 March 20 and Save



[www.semiconsea.org](http://www.semiconsea.org)

Organized by



Supported by



Endorsed by



Sponsored by



Official Airline





Last few remaining seats



# 5<sup>th</sup> CS International Conference 2015

CS International 2015 will provide timely, comprehensive coverage of every important sector within the compound semiconductor industry.

The 5th CS International conference will be held at the Sheraton Frankfurt Airport Hotel, in Germany on Wednesday 11<sup>th</sup> & Thursday 12<sup>th</sup> March 2015. The conference will build on the success of its predecessors, with industry-leading insiders delivering more than 35 presentations spanning six sectors.

Please visit [www.cs-international.net](http://www.cs-international.net) for further information on this event.

**Book your place NOW**

Please visit [www.cs-international.net/register](http://www.cs-international.net/register) to secure your place

**TWO DAYS, SIX THEMES, OVER 35 INSPIRING PRESENTATIONS**

Six key themes lie at the heart of CS International 2015: solid-state lighting, power electronics, front-end mobiles, optoelectronics, III-V CMOS and RF electronics. Within each topic there is a key-note presentation from one of the most influential companies within each sector; one talk by a leading market analyst who will discuss trends within the industry and presentations by the leaders of firms developing cutting-edge technology in each field.















Connecting, informing and inspiring the compound semiconductor industry

*All speakers and presentations are subject to change.*

# 35+ presentations over two days covering six themes

## SOLID-STATE LIGHTING

Soaring sales of LED bulbs are creating a great opportunity for chipmakers. But what do companies need to do to stand out from the crowd and win substantial orders while maintaining healthy margins?

<b>KEYNOTE</b>		Opportunities for laser diodes in solid-state lighting <b>Jon Wierer - Principal Member of Technical Staff - Sandia National Laboratories</b>	
<b>ANALYST</b>		How will the solid-state lighting evolution unfold, and what will it mean for the LED chipmakers? <b>Will Rhodes - Research Manager - IHS Technology</b>	
<b>SPEAKER</b>		Commercialisation of GaN-on-silicon for LEDs <b>Keith Strickland - Innovations &amp; Technology Director - Plessey Semiconductors</b>	
<b>SPEAKER</b>		Increasing LED output with advanced plasma processing <b>Mark Dineen - Product Manager - Oxford Instruments Plc</b>	
<b>SPEAKER</b>		Yield optimisation of compound semiconductor processes through an effective metrology strategy <b>Torsten Stoll - Product &amp; Marketing Manager - Nanometrics Inc.</b>	
<b>SPEAKER</b>		Plasma dicing for III/V and thin wafers <b>Reinhard Windemuth - Sales Director ME Europe - Panasonic Factory Solutions</b>	

## OPTOELECTRONICS

Does the growth of the datacom market signal a long-awaited return to better times for the makers of optical components? Is CPV technology finally starting to gain a foothold in the solar industry?

<b>KEYNOTE</b>		Highest CPV cell and module efficiencies and CPV power plants <b>Rainer Krause - Director Smart Cell Development - Soitec</b>	
<b>ANALYST</b>		Where is the CPV industry heading, and what needs to happen to increase its market share? <b>Karl Melkonyan - Analyst Solar Research - IHS Technology</b>	
<b>SPEAKER</b>		Mid infrared LEDs enable portable, battery powered gas sensing <b>Des Gibson - CEO - Gas Sensing Solutions Ltd</b>	
<b>SPEAKER</b>		IC design for very high-speed optical communications – a holistic approach <b>The' Linh Nguyen - Senior Manager IC Development- Finisar Corporation</b>	
<b>SPEAKER</b>		UV LED - We are just scratching the surface of the technology's true potential <b>Pars Mukish - LED &amp; Sapphire Activities Leader - Yole Développement</b>	
<b>SPEAKER</b>		Unlocking opportunities for compound semiconductors with micro assembly <b>Chris Bower - CTO - X-Celeprint Ltd</b>	

**Delegate registration: [www.cs-international.net/register](http://www.cs-international.net/register)**

## III-V CMOS Sponsored by

By the end of this decade, it is said that silicon CMOS will have run out of steam. But what role will III-Vs have to play in the microprocessors of the future?

<b>KEYNOTE</b>		Heterogeneous integration of III-Vs and CMOS <b>Daniel Green - Program Manager - Defence Advanced Research Projects Agency</b>	
<b>ANALYST</b>		When will III-Vs make an impact in the silicon foundries? And will it last for long? <b>Mike Corbett - Managing Partner - Linx Consulting</b>	
<b>SPEAKER</b>		III-V FETs for future logic applications <b>Jesús A. del Alamo - Director of the Microsystems Technology Laboratories - MIT</b>	
<b>SPEAKER</b>		Opportunities and challenges of III-Vs in Si-based nanoelectronics industry <b>Matthias Passlack - R&amp;D Deputy Director Europe - Taiwan Semiconductor Manufacturing Company</b>	
<b>SPEAKER</b>		Advanced in-situ metrology for III-V on silicon technology <b>Kolja Haberland - CTO - LayTec AG</b>	
<b>SPEAKER</b>		Eliminating material borders for heterogeneous integration through new wafer bonding processes <b>Thomas Uhrmann - Head of Business Development - EV Group</b>	

## FRONT-END MOBILES

What's the biggest threat to revenues for GaAs power amplifiers? Is it the emergence of multi-band, multi-mode PAs built with this material, or the emergence of CMOS solutions?

<b>KEYNOTE</b>		The path to intelligent integration <b>Jim Cable - CEO, President and Chairman - Peregrine Semiconductor Corporation</b>	
<b>ANALYST</b>		Multi-mode, multi-band PAs: friend or foe to the compound semiconductor industry? <b>Eric Higham - Director - Advanced Semiconductor Applications - Strategy Analytics</b>	
<b>SPEAKER</b>		Improving system level integration and overall efficiency <b>Ed Anthony - VP Engineering - Skyworks Inc.</b>	
<b>SPEAKER</b>		LTE is driving complexity in smartphone design <b>Sean Riley - VP of Mobile Products - Qorvo</b>	

**CS** INTERNATIONAL  
CONFERENCE







Connecting, informing and inspiring the compound semiconductor industry

**Delegate registration: [www.cs-international.net/register](http://www.cs-international.net/register)**









## POWER ELECTRONICS

From a performance perspective, GaN and SiC are superior to silicon, but high prices are holding the materials back from displacing the incumbent silicon. How can this be addressed?

<b>KEYNOTE</b>		Ditching the package to drive down GaN transistor costs <b>Alex Lidow - CEO and Co-Founder - Efficient Power Conversion Corporation</b>	
<b>ANALYST</b>		When can WBG power electronics truly take off? <b>Pierric Gueguan- Senior Power Electronics Market Analyst - Yole Développement</b>	
<b>SPEAKER</b>		SiC technology in Power Electronics – A step change in value <b>Tang Yong Ang - VP Compound Semiconductors - Dow Corning Corporation</b>	
<b>SPEAKER</b>		High performance GaN-on-Si power epiwafers employing rare earth oxide buffer layers <b>Andrew Clark - VP Engineering - Translucent Inc.</b>	
<b>SPEAKER</b>		Automated defect monitoring strategy for surface and photoluminescence yield impacting defects <b>Brian Crawford - Director of Business Development - KLA-Tencor</b>	
<b>SPEAKER</b>		Driving down costs for next-generation PVD processes <b>Reinhard Benz - VP Sales and Marketing - Evatec Ltd</b>	
<b>SPEAKER</b>		Gallium nitride epitaxy on large area silicon substrates for power applications <b>Yoga Saripalli- Principle Engineer - GaN Epitaxy Group - imec</b>	
<b>SPEAKER</b>		Optimisation of III-V R&D and manufacturing using advanced analytical methods <b>Temel Buyuklimani - Senior Director, Quadropole SIMS Services - Evans Analytical Group</b>	
<b>SPEAKER</b>		Accelerating GaN power electronics devices using MOCVD technology <b>Sudhakar Raman - VP Marketing - Veeco Instruments</b>	
<b>SPEAKER</b>		Measurement solutions for high power SiC/GaN semiconductors <b>Stewart Wilson - European Business Manager - Keysight Technologies</b>	
<b>SPEAKER</b>		Cutting conversion losses with cost-efficient GaN-on-silicon <b>Marianne Germain- CEO - EPIGaN nv</b>	

## RF-ELECTRONICS

The potential of GaN in the RF arena has never been in doubt. But does it now satisfy all the requirements for deployment in the most taxing situations?

<b>KEYNOTE</b>		GaN for radar applications <b>Takahisa Kawai - General Manager - Sumitomo Electric Device Innovations, Inc.</b>	
<b>ANALYST</b>		The future for GaN, SiC, InP and GaAs in defence/military applications <b>Asif Anwar - Director - Strategy Analytics</b>	
<b>SPEAKER</b>		GaN for commercial RF applications enabled by the pure-play foundry model <b>Walter Wohlmuth - Associate VP Technology - WIN Semiconductors Corporation</b>	

## Event Sponsors

### Platinum



### Gold



### Exhibition



### Pen/USB Sponsor



### CS Industry Awards



### Theme Sponsor



### Delegate bag



### Lanyard



### Portfolio



### Supported by



Delegate registration: [www.cs-international.net](http://www.cs-international.net)

# Hybrid growth promises better green lasers

Growing the top part of the laser by MBE prevents degradation to the active region

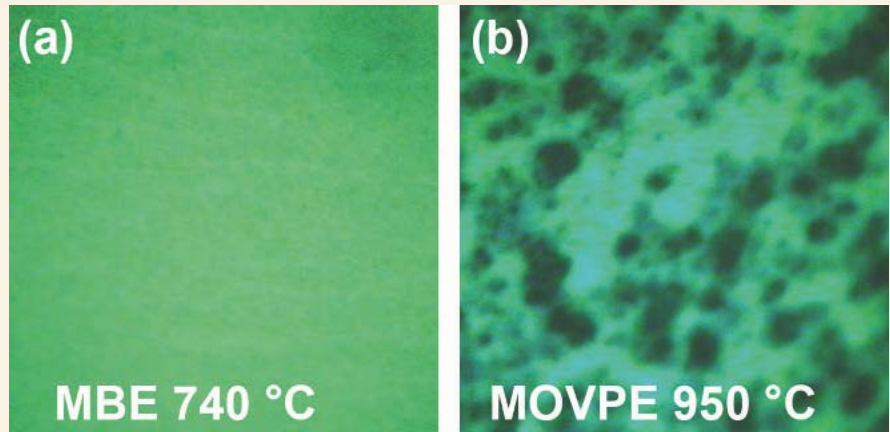
AN AWKWARD COMPROMISE lies at the heart of the growth of green laser epistuctures. If *p*-type layers are grown using optimum conditions, high temperatures of around 1050 °C deteriorate the quality of the quantum wells; but if the growth temperature is lowered, resistivity of the *p*-type layers increases, and optical quality of the cladding and waveguide can also decline.

To address these shortcomings, a team from Switzerland is pioneering a two-step process that involves the growth of the majority of the structure by MOCVD, before *p*-type layers are added by MBE. The *p*-type layers have state-of-the-art electrical characteristics, according to the team from EPFL, Novagan and Exalos. The researchers have used their hybrid growth approach to form 501 nm narrow ridge waveguide lasers with a threshold voltage of just 5.4 V.

Growth of these devices is by ammonia MBE, which is performed under nitrogen-rich conditions that are also associated with MOCVD. The team decided to use this approach, rather than plasma-assisted MBE, because the latter has a narrow growth window, making it demanding to produce high-quality material.

One of the challenges of plasma-MBE is that to ensure a smooth surface, a bilayer of gallium must be on the surface during growth. "If the growth conditions depart from that, either gallium droplets can form at the surface, or the growing surface experiences roughness," explains team member Marco Malinverni from EPFL.

He and his colleagues begin by fabricating green laser diodes by growing, by MOCVD, an *n*-type region and a three-period InGa<sub>0.06</sub>N quantum well on a freestanding GaN substrate. An ammonia atmosphere at 740 °C cleans the epiwafer, before MBE adds a 600 nm-thick magnesium-doped Al<sub>0.06</sub>Ga<sub>0.94</sub>N cladding layer and a heavily doped, 50 nm-thick GaN contact layer. According to secondary ion mass spectroscopy, the magnesium concentration in the top



A hybrid growth approach that involves deposition of the *n*-type region and active region by MOCVD, followed by MBE-growth of the *p*-type layers, leads to a more uniform fluorescence image (a) than that associated with growth of the entire structure by MOCVD (b).

cladding is  $5 \times 10^{18} \text{ cm}^{-3}$ , a value low enough to prevent high optical loss.

Before lasers were constructed, researchers compared the fluorescence of their structures with those formed via MOCVD of *p*-type layers at 950 °C. Fluorescence images of a 60 μm by 60 μm area of the laser grown by the conventional approach featured many black spots, indicative of limited radiative recombination, while highly uniform green luminescence emanated from the hybrid-growth structure.

Epiwafers were processed into 800 μm-long lasers featuring a 4 μm-wide ridge and, at each facet, distributed Bragg reflectors were formed from the pairing of SiO<sub>2</sub> and TiO<sub>2</sub>. Driven in pulsed mode (1 percent duty cycle and 1 μs pulses), light output for the 501 nm source hit 15 mW at 450 mA.

One major weakness of these lasers is that they cannot operate in continuous wave mode. Malinverni and his colleagues believe that this is due to deficiencies in the quality of the active region, and an injection efficiency of just 17 percent.

This very low value probably results from imperfections at the re-growth interface, an issue that the team has previously investigated with secondary ion mass

spectroscopy. Commenting on the previous study, Malinverni explained that they suspect contamination to have occurred during the cool down of the MOCVD reactor and the successive exposure to the atmosphere.

This finding does not imply, however, that hybrid growth cannot be used to manufacture high-quality green lasers. "In production, cluster tools and controlled-atmosphere boxes are frequently employed, and would prevent interface contamination," says Malinverni. "However, at present, MBE reactors are scarcely used in the GaN industry."

One goal for the team is to increase the injection efficiency of its lasers through improvements to the doping profile, junction location, and the quality of the active region. In addition, the researchers will investigate the origin of interface contamination, and then address this.

"We are confident that there is still room for big improvement in this technology," says Malinverni, who believes it could even help III-N lasers emitting beyond the green.

M. Malinverni *et al.*  
Appl. Phys. Express **8** 022105 (2015)



# InN looks to enhance nitride HEMTs

A high-mobility, single atomic layer of InN could improve the performance of nitride HEMTs

CALCULATIONS from the University of California, Santa Barbara, suggest that inserting a single atomic layer of InN into the heart of an AlGaIn/GaN HEMT improves device performance. According to Mao-sheng Miao and Chris Van de Walle, adding an ultra-thin InN layer increases the density, localisation and mobility of the two-dimensional electron gas, leading to significant performance improvements, such as superior switching.

These theorists decided to investigate this novel device because of the far higher electron mobility of InN than GaN.

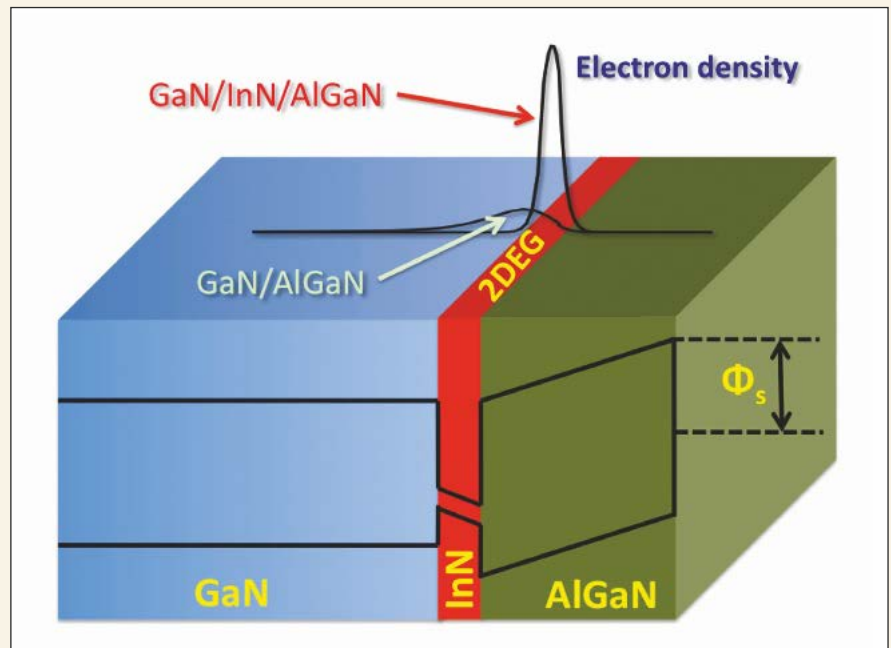
To evaluate the benefits of inserting a single layer of InN into a HEMT, the West-coast duo carried out first-principles electronic structure calculations with macroscopic device simulations based on Schrödinger-Poisson solvers.

Van de Walle explains that the Schrödinger-Poisson solvers enable the accessing of features such as the localisation of the two-dimensional electron gas.

“But first principles calculations are needed in order to obtain microscopic parameters, such as the effective mass of electrons in the InN layer.” They accomplished this with a form of density functional theory that employs an advanced hybrid functional and yields accurate results for the electronic structure.

“Such calculations are highly demanding, requiring up to twenty times more computing power than density functional calculations with traditional methods,” says Van de Walle. “They can only be run on supercomputers.”

One structure investigated by Miao and Van de Walle consists of 260 nm of GaN and 4 nm of  $\text{Al}_{0.34}\text{Ga}_{0.66}\text{N}$ , with a 0.36 nm-thick single atomic layer of InN inserted between. It is assumed that the InN is pseudomorphically grown on GaN, so it sustains a large compressive biaxial strain, accompanied by a corresponding relaxation of the lattice along the c-axis.



Inserting a single atomic layer of InN in an AlGaIn/GaN HEMT creates a highly localised two-dimensional electron gas. The surface barrier height is denoted by  $\Phi_s$ .

In contrast to a conventional GaN HEMT, where electron density is spread out over a width of at least 3 nm, the charge in the InN-containing structure is far more localised – it is spread over as little as 1 nm, judged by the value of the full-width at half maximum.

The nature of this electron gas has been investigated in more detail. Calculations suggest that for a fixed barrier height, the HEMT containing InN starts forming a two-dimensional electron gas at a smaller AlGaIn thickness, and its density is much higher. And if the AlGaIn thickness is held at 4 nm, the density of the two-dimensional electron gas is much higher when the atomic layer of InN is present, indicating that a transistor would be more sensitive to changes in gate voltage.

To switch off a HEMT, a negative voltage is applied that lowers the potential on the surface, and cuts charge transfer from surface states to the interface region.

Simulations by the team show that for a surface barrier height of up to 3.5 eV,

there will be a small residual two-dimensional electron gas at the interface of a conventional device; but for the variant with an ultra-thin InN layer, the density of the two-dimensional electron gas goes sharply to zero at a surface barrier height of just 3.0 eV.

Further calculations determined the in-plane effective mass of the electron, finding it to be 94 percent of that for the bulk, and more than 30 times less than that of GaN. This indicates the high mobility for electrons in the two-dimensional electron gas.

Proving the promise of these novel HEMTs requires their fabrication and testing. This might take place within the University – academic Stacey Keller, in the group headed by Umesh Mishra, has previously worked on InN/GaN heterostructures for potential use in HEMTs.

M. Miao *et al.* *Appl. Physics Express* **8** 024302 (2015)

# New highs for the LED

Soraa claims that its LEDs set new benchmarks for generating and extracting light

SORAA claims to have broken the record for LED wall-plug efficiency for high current densities and temperatures found within a lighting fixture.

The latest device has the 'triangular volumetric' design of its predecessors, but with the notable refinement of a flip-chip architecture that features both contacts on the same side of the device.

"We show that our improved design is superior across the line – extraction, epitaxy, electrical efficiency – and thus better demonstrates the extremely high potential of GaN-on-GaN technology," remarks Soraa's Christophe Hurni.

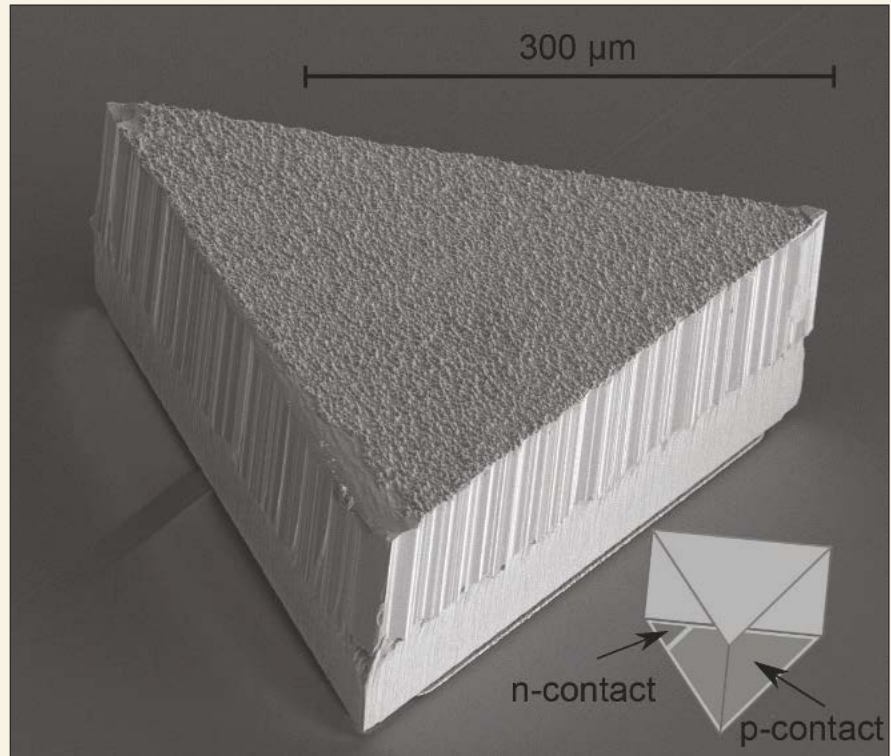
The West-coast outfit uses HVPE-grown GaN substrates as a foundation for its LEDs. According to Hurni, this platform provides many advantages over sapphire, silicon and SiC, including: better material quality, thanks to low-dislocation-density substrates; and better light extraction for high-power-density LEDs.

The latest triangular, volumetric LEDs emit at around 415 nm, have 400  $\mu\text{m}$ -long sides, and have *n*- and *p*-type contacts on the bottom of the structure. Wall plug efficiency peaks at 84 percent at 25 °C, and is 70 percent at 100 A  $\text{cm}^{-2}$  – and this level of performance is maintained at 85 °C.

Delivering high performance at this elevated temperature is crucial, argues Hurni. "Real-world lighting systems heat up during operation, and even with good heat-sinking, a junction temperature of 85 °C or above is common."

The team have evaluated all the factors that influence the wall-plug efficiency – it is the product of the package efficiency, extraction efficiency and internal quantum efficiency.

The packaged efficiency, which is the ratio of photons emitted by the chip to those escaping the test package, is 94 percent, according to ray-tracing software. The package has not been optimised for the die, but there is actually little benefit in doing so, according to Hurni: "In practice, package efficiency



A scanning electron microscope image of the triangular volumetric flip-chip device produced by Soraa. This LED has an extraction efficiency of 90 percent and a peak internal quantum efficiency of 95 percent.

only matters for phosphor-converted white light."

Efforts at Soraa have shown that extraction efficiency – the ratio of photons escaping the device to those radiated by the active region – is limited by thin-film LED architectures. A combination of surface roughness and chip shaping is able to increase the extraction efficiency of light of all trajectories, with advanced modelling by the team indicating an improvement of 10 percent over thin-film device structures. Comparisons of values from the light extraction model and experimental results on a series of chips suggest that the latest device has an extraction efficiency of 90 percent.

The third factor governing the wall-plug efficiency is the internal quantum efficiency, and this is influenced by defects, active region design, current-density-induced droop and thermal effects. Using a native substrate helps to

reduce some of these loss mechanisms, because the epilayers have fewer defects and there is greater freedom in the design of the structure.

Measurements indicate that the internal quantum efficiency peaks at 95 percent at 25 °C and 92 percent at 85 °C. Droop is very low, with the internal quantum efficiency still 85 percent at 85 °C and a current density of 100 A  $\text{cm}^{-2}$ , a value that is representative of realistic operating conditions.

The team has applied the well-known ABC model to plots of internal quantum efficiency as a function of current density. These simulations, which include phase-space filling effects, confirm the view held by those at Soraa that Auger scattering is the most plausible cause of droop.

C. Hurni et. al.  
Appl. Phys. Express **106** 031101 (2015)

# AIXTRON

Tel: +49 2407 9030 0  
 Fax: +49 2407 9030 40  
 Email: info@aixtron.com  
 www.aixtron.com

Non Contact Measurements  
 Resistance, Resistivity  
 Wafer Thickness



Tel: +49 (0)8122 86676  
 Fax: +49 (0)8122 86652  
 Email: info@kitec.de  
 www.kitec.de

# Temescal

Tel: +1 925 245 5817  
 Fax: +1 925 449 4096  
 Email: lwarren@ferrotec.com  
 www.temescal.net



Email: info@epigan.com  
 www.epigan.com



Tel. No.: +49 (0) 30 89 00 55 0  
 Fax No: +49 (0) 30 89 00 55 180  
 e-mail: info@laytec.de  
 website: www.laytec.de



Tel: +1 614 891 2244  
 Fax: +1 614 818 1600  
 Email: info@lakeshore.com  
 www.lakeshore.com

# HIDEN ANALYTICAL

Tel: +44 [0] 1925 445225  
 Fax: +44 [0] 1925 416518  
 Email: info@hiden.co.uk  
 www.hidenanalytical.com



The Business of Science®

Tel: +44 (0)1934 837000  
 Fax: +44 (0)1934 837001  
 Email: plasma.technology@oxinst.com  
 www.oxford-instruments.com



www.watlow.com



Tel: +41 52 304 22 00  
 Fax: +41 52 304 22 12  
 Email: info@meister-abrasives.ch  
 www.meister-abrasives.ch



semiconductor  
 Tel: +1 603 595 8900  
 Email: sales@masimo.com  
 www.masimosemi.com



Tel: +44 (0)1246 718 979  
 Fax: +44 (0)1246 718 971  
 Email: robin.halder@angelbc.com  
 www.compoundsemiconductor.net



Tel: +49 8728 911 093  
 Fax: +49 8728 911 156  
 Email: sales@35reclaim.com  
 www.35reclaim.de



Tel: +1 650-213-9311 Ext.229  
 Fax: +1 650-213-9511  
 Email: sales@translucentinc.com  
 www.translucentinc.com



Tel: +1 201 507 3300  
 Fax: +1 201 507 1506  
 Email: inquiry@umccorp.com  
 www.umccorp.com



Tel: +1 734-426-7977  
 e-mail: requestinfo@k-space.com  
 www.k-space.com



Tel: +49 33398 696592  
 Fax: +49 33398 696594  
 Email: jp@bachrc.de  
 www.bachrc.de



Tel: +1 512-385-4552  
 Fax: +1 512-385-4900  
 Email: r.andrade@nanomaster.com  
 www.nanomaster.com



Tel: +41 81 720 1080  
 Fax: 41 81 720 1161  
 www.evatecnet.com



Tel: +49 (0) 3641 79980  
 Fax: +49 (0) 3641 7998222  
 www.vistec-semi.com



Tel: +44 (0)1923 690 200  
 Fax: +44 (0)1923 690 201  
 Email: shehzad Munshi@angelbc.com  
 www.siliconsemiconductor.net



Tel: +49 721 50997-0  
 Fax: +49 721 50997-5654  
 Email: info@bruker-axs.de  
 www.bruker-axs.com



Tel: +44 (0)1389 875444  
 Fax: +44 (0)1389 890956  
 Email: info@logitech.uk.com  
 www.logitech.uk.com



Tel: 516-677-0200-1222  
 Fax: 516-714-1231  
 Email: jpina@veeco.com  
 www.veeco.com





Tel: +43 5672 600 2944  
Email: led@plansee.com  
www.plansee.com



Tel: +81 44 589 5894  
Fax: +81 44 541 1326  
Email: moreinfo@ntt-at.com  
www.ntt-at.com



DOWA ELECTRONICS MATERIALS CO., LTD.

Tel: +1-408-236-7560  
Email: asaharah@dicny.com  
www.dowa-electronic.co.jp



Tel No: +49 (89) 96 24 00-0  
Fax No: +49 (89) 96 24 00-122  
Email: sales@csclean.com  
www.cscleansystems.com



Tel. No: +82-62-602-7857  
Fax No: +82-62-972-0483  
www.hisolarled.co.kr  
e-mail: chonhh@hanmail.net  
e-mail: david@hisolarled.com



Tel: +7 812 601 06 05  
Email: sales@semiteq.ru  
www.semiteq.org



Tel: 800-762-3468  
www.durexindustries.com



Engineered Process Solutions

Tel: + (510) 384 1118  
Fax + (510) 887 0626  
Email mwise@mdcvacuum.com  
www.mdcvacuum.com



Tel: +86-592-7767288  
Email: sales@epiworld.com.cn  
www.epiworld.com.cn



ENABLING PHOTONIC TECHNOLOGIES

Tel: + (001) 407 422 3171  
Fax + (001) 407 648 5412  
Email orlandosales@gogchandhousego.com  
www.gogchandhousego.com



Tel: +44 (0)1246 718 979  
Fax +44 (0)1246 718 971  
Email: robin.halder@angelbc.com  
www.compoundsemiconductor.net



Tel: +49 (089) 45 49 43 - 0  
Fax: +49 (089) 45 49 43 - 11  
Email: info@instrumentsystems.com  
www.instrumentsystems.com

## Submit your Lab & Fab article

Research is the foundation for the growth of the compound semiconductor industry.

If you want to highlight the important breakthroughs that you make, submit your latest research stories to

[RichardStevenson@angelbc.com](mailto:RichardStevenson@angelbc.com)

It is imperative that Compound Semiconductor remains a timely resource for this industry, so we are only interested in highlighting very recent work reported in academic papers.

Therefore, please only consider writing a short piece highlighting your work if you have a journal paper that has been accepted and about to appear in press, or a paper that has been published within the last month.



[www.compoundsemiconductor.net](http://www.compoundsemiconductor.net)

Perfect  
layer  
deposition



# Beautifully Uniform Layers

We can do this all day!



Temescal UEFC-5700  
with Auratus Technology

In a glass or on a wafer, building perfect layers is an art. We've transformed near perfect uniformity into a science. Our Auratus™ deposition enhancement methodology eliminates the guesswork, harmonizing your process to the vapor cloud and enabling you to deliver better products. In less time. Using less material. So you'll have more money. Maybe enough to buy the next round.

Give us a shot. Find out how a Temescal system can bring near perfect uniformity to your lift-off metallization coating process.

To find out more, visit [www.temescal.net/auratus-shot](http://www.temescal.net/auratus-shot) or call 1-800-552-1215.

**Ferro Tec**