COMPOUND SEMICONDUCTOR

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

PLASMA POLISH

A PROVEN SOLUTION

VOLUME 29 ISSUE IX 2023

AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

COMPOUNDSEMICONDUCTOR.NET

INSIDE

News, Analysis, Features, Editorial View, Research Review and much more

Low-temperature epitaxy of AlN

Record electron and hole concentrations could unleash a new generation of higher performing devices

Extending the reach of the VCSELs

Single-mode VCSEL with a double aperture can transmit data at nearly 100 Gbit/s over kilometre-length links

Gaining avalanche capability

Pairing Ga_2O_3 with NiO produces robust power electronics that can withstand common faults in harsh environments

VIEWPOINT

By Richard Stevenson, Editor

Uncovering new paths for growth

OUR INDUSTRY places much emphasis on increasing the bang-per-buck of compound semiconductor devices.

Fortunately, there are numerous levers that we can pull to progress this key metric. Gains can come through: the introduction of new tools that boost throughput, and ultimately lower cost; the introduction of superior production processes that increase yield; and a switch to superior device architectures that enhance chip performance.

It is well known that optimising the growth process is crucial to maximising the performance of any device. To this end, process engineers make many fine adjustments, including those to growth rates, growth temperatures and the flows of various sources.

None of these tweaks are radical. They involve making the best of what's there, rather than asking this far more taxing question: Is the growth process actually the best one for this device?

In this issue we include two accounts of research teams that have asked themselves this crucial question and concluded that in order to try and make substantial progress, there's a need to venture beyond the established epitaxial technique.

For many years, the most prominent material within our industry has been GaN, which is behind substantial sales in LEDs, lasers, and power and RF transistors. Its higher bandgap sibling, AlN, is yet to fulfil its potential, but has much promise for the production of even-more-efficient transistors and powerful, deep-UV LEDs. However, fulfilling this potential is far from easy. Along with considerable challenges in producing a native substrate, there's the major flaw of the lack of substantial doping, particularly *p*-type doping.

Addressing this challenge is Alan Dolittle's team from Georgia Institute of Technology. This group had developed a low-temperature variant of MBE known as metal-modulated epitaxy. Using shutters that ensure epitaxial growth almost always occurs in metal-rich conditions, they have realised breakthrough levels of *p*-type and *n*-type doping in AlN (see p 40 for details), thereby providing a great foundation for improving AlN-based devices.

When it comes to solar cells, those made from III-Vs are already delivering a level of performance far beyond that provided by other materials. But the problem is cost. Whether devices are grown by MBE or MOCVD, the expense associated with epitaxy is so high that it limits the deployment of these high-efficiency cells to spaced-based applications, such as powering satellites.

Offering a breakthrough is a team from the US National Renewable Energy Lab. They are pioneering a dynamic form of HVPE that involves moving wafers between chambers rather than switching gases within a single chamber. While there is a compromise in device performance, it's small and diminishing, with single-junction GaAs-based cells now realising efficiencies of 27 percent.

That success – and the triumph of Doolittle and his co-workers – stems from exceptional innovation. Rather than making minor adjustments to epitaxial growth, they have gone back to the drawing board to deliver results that are revolutionary.

CONTENTS

VOL. 29 ISSUE IX 2023

NEWS ANALYSIS

RESEARCH REVIEW

NEWS

Editor Richard Stevenson
richardstevenson@angelbc.com
+44 (0)1291 629640

News Editor Christine Evans-Pughe
christine.evans-pughe@angelbc.com

Design & Production Manager
Mitch Gaynor
mitch.gaynor@angelbc.com
+44 (0)1923 690214

Director of Logistics Sharon Cowley
sharon.cowley@angelbc.com
+44 (0)1923 690200

Senior Sales Executive
Jacob Caulfield
jacob.caulfield@angelbc.com
+44 (0)2476 718979

Marketing & Logistics Executive
Eve O'Sullivan
+44 (0)2476 823 123
eve.osullivan@angelbc.com

Circulation
Scott Adams
scott.adams@angelbc.com

Publisher Jackie Cannon
jackie.cannon@angelbc.com
+44 (0)1923 690205

USA Representatives
Brun Media
Janice Jenkins
jjenkins@brunmedia.com
+1 724-929-3550

Tom Brun
tbrun@brunmedia.com
+1 724 539-2404

Chief Executive Officer
Sukhi Bhadal
sukhi.bhadal@angelbc.com
+44 (0)2476 718970

Chief Technical Officer
Scott Adams
scott.adams@angelbc.com
+44 (0)2476 718970

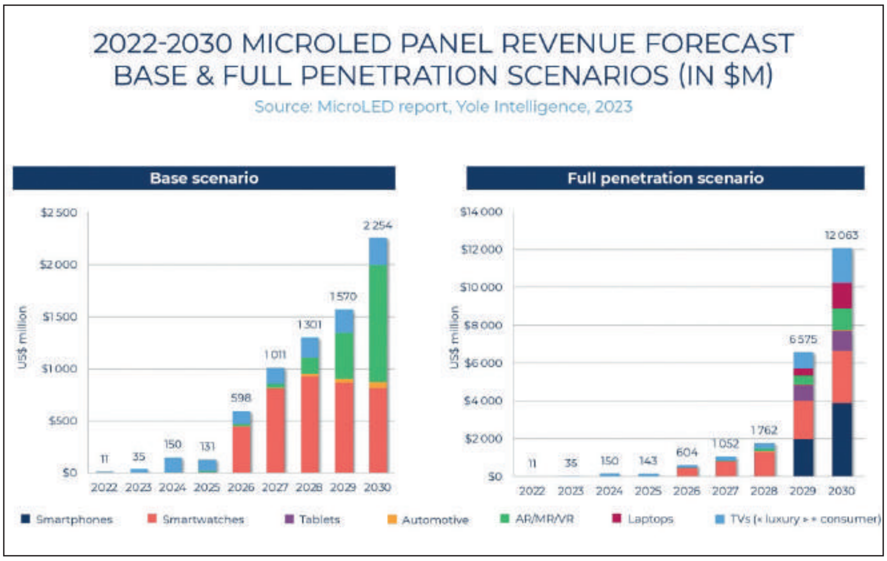
Directors
Jackie Cannon, Sharon Cowley

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

Compound Semiconductor is published nine times a year on a controlled circulation basis. Non-qualifying individuals can subscribe at: £105.00 per annum (UK), €158 per annum (Europe), $198 per annum (air mail) (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 2023. 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 9 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.Airfreight and mailing in the USA by agent named World Container INC 150-15, 183rd St, Jamaica, NY 11413, USA. Periodicals Postage Paid at Brooklyn, NY 11256. POSTMASTER: Send address changes to Compound Semiconductor, Air Business Ltd, c/o World Container INC 150-15, 183rd St, Jamaica, NY 11413, USA. We strive for accuracy in all we publish; readers and contributors are encouraged to contact us if they recognise an error or omission. Once a magazine edition is published [online, in print or both], we do not update previously published articles to align old company names, branding, marketing efforts, taglines, mission statements or other promotional verbiage, images, or logos to newly created or updated names, images, typographic renderings, logos (or similar) when such references/images were accurately stated, rendered or displayed at the time of the original publication. When companies change their names or the images/text used to represent the company, we invite organizations to provide Angel Business Communications with a news release detailing their new business objectives and/or other changes that could impact how customers/prospects might recognise the company, contact the organisation, or engage with them for future commercial enterprise. Printed by: The Manson Group. ISSN 1096-598X (Print) ISSN 2042-7328 (Online) © Copyright 2023.

Where are we with microLEDs?

Success may hinge on disruptive architectural changes like silicon-CMOS microdrivers, says Yole


2022-2030 MICROLED PANEL REVENUE FORECAST
BASE & FULL PENETRATION SCENARIOS (IN $M)

Source: MicroLED report, Yole Intelligence, 2023

OPTIMISM surrounding microLED technology in 2017, with expectations of commercialisation by 2020-2021, has given way to a more extended timeline, according to Yole Intelligence.

Meaningful production volumes are now predicted to be achievable in the next two to three years, with widespread consumer adoption potentially taking five to ten years.

Eric Virey, senior market and technology analyst at Yole Intelligence says: "While the industry has seen substantial investment with over $11.5 billion spent by 2023, including $8.8 billion for R&D and startup funding and $2.7 billion for pilot lines and manufacturing preparations, the path to success has been marked by ups and downs, often due to challenges in achieving high-yield, low-cost, high-volume production."

He adds: "Cost models struggle to demonstrate that microLEDs can match OLED prices, and even if they do, the differentiation will be small, particularly in competitive markets like smartphones."

Yole says that the urgency for microLED technology to succeed has grown as OLED technology continues to advance. With cost unlikely to be an element of differentiation, to establish itself as a strong alternative to OLED, the microLED must deliver clear performances and functionality advantages. This includes higher brightness, colour depth, stability, modular displays etc.

MicroLED's success may hinge on disruptive architectural changes like silicon-CMOS microdrivers, which have the potential to enable advanced features like memory-in-pixel or integrated sensors, and significantly reduced power consumption. Microdrivers also have the potential to transform the display industry into a full semiconductor industry.

Raphaël Mermet-Lyaudoz, technology and market analyst, for displays at Yole Intelligence, says: "However, such changes may be driven by industry outsiders and require further optimisation to compete with traditional TFT architectures. In this evolving landscape, companies like Apple, with their hybrid microdriver + TFT approach, and innovators like X-Display, VueReal, Aledia, Sapien Semiconductors, Lextar and others are vying for a competitive edge, but pricing challenges persist, particularly for those outside of the largest players with silicon-CMOS foundry access."

Comprehensive supply chain management poses challenges. Few are likely to achieve full vertical integration, opting for sourcing chip-on-wafer or chip-on-chip from LED manufacturers, according to Yole.

Beyond corporate competition, it's an ecosystem competition, particularly evident in China and Taiwan. Taiwan's ecosystem covers all aspects of microLED development and manufacturing, marked by the formation of a domestic microLED alliance in April 2023. China's display and LED industries are fostering domestic tool makers for mass transfer, testing, and repair.

Korea lacks well-established ecosystems and clear alliances within the supply chain, but LG and Samsung leverage their influence over domestic equipment players to drive microLED tool and process development.

Comprehensive supply chain management poses challenges. Few are likely to achieve full vertical integration, opting for sourcing chip-on-wafer or chip-on-chip from LED manufacturers, according to Yole.

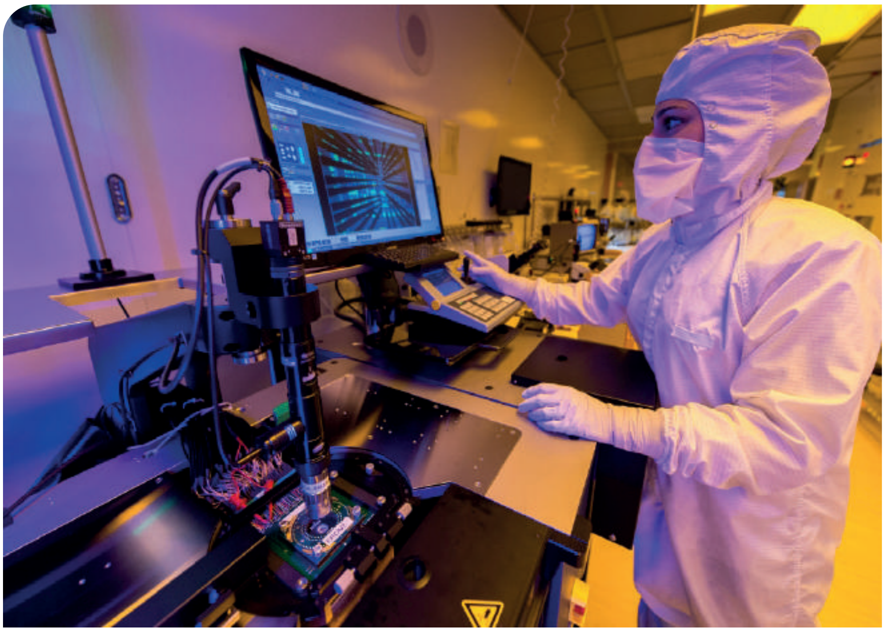
Raytheon/DARPA project to use GaN and diamond

$15 million THREADS project will employ diamond and GaN to increase RF sensor capabilities

RAYTHEON has been awarded a four-year, $15 million contract from DARPA to increase the electronic capability of radio frequency sensors with high-power-density GaN transistors. The improved transistors will have 16 times higher output power than traditional GaN with no increase in operating temperature.

This new prototyping work is being performed under DARPA's Technologies for Heat Removal in Electronics at the Device Scale programme, known as THREADS.

"Our engineers have unlocked a new way to produce GaN, where thermal management is no longer a limiting factor," said Colin Whelan, president of Advanced Technology at Raytheon. "These new system architectures will result in sensors with enhanced range."



Raytheon is partnering with the Naval Research Laboratory, Stanford University and Diamond Foundry to grow diamond, the world's best thermal conductor, for integration with military-grade GaN transistors and circuits. Cornell University, Michigan State University, the University of Maryland and Penn State University are also providing technology and performance analysis.

Raytheon's GaN chips are currently used in defence systems like the Patriot, LTAMDS/GhostEye family of radars, APG-79(v)4 and SPY-6 family of radars.

Oki develops GaN lift off/bonding technology

JAPANESE FIRM Oki, in collaboration with Shin-Etsu Chemical, has announced the successful development of a technology that uses Oki's CFB (crystal film bonding) technology to lift off only the GaN functional layer from Shin-Etsu Chemical's QST (Qromis Substrate Technology) and bond it to a different material substrate.

The companies say this technology enables the vertical conduction of GaN and is expected to contribute to the realisation and commercialisation of vertical GaN power devices capable of controlling large currents. The coefficient of thermal expansion of Shin-Etsu Chemical's QST substrate is equivalent to that of GaN. This means it can suppress warpage and cracking. It also enables the crystal growth of thick GaN films with high breakdown voltages even on wafers larger than 200 mm, enabling the production of wafers with larger diameters.

Oki's CFB technology can lift off only the GaN functional layer from the QST substrate while maintaining high device characteristics.

The insulating buffer layer required for GaN crystal growth can be removed and bonded to various substrates via metal electrodes that allow ohmic contacts.

Bonding of these functional layers to a conductive substrate with high heat dissipation will enable both high heat dissipation and vertical conductivity, according to Oki.

In the future, the two companies aim to develop vertical GaN power devices through Shin-Etsu Chemical's provision of QST substrates or GaN grown QST substrates to companies manufacturing GaN devices, and Oki's provision of CFB technology through partnering and licensing. Oki also hopes to use CFB technology to provide added value to semiconductor devices that go beyond the framework of single materials.

Vishay to acquire Nexperia's Newport wafer fab

$177 million cash deal will accelerate Vishay's SiC production plans and secure the future of UK's largest wafer fab

US-BASED Vishay Intertechnology will acquire Nexperia's Newport wafer fabrication facility, a 200 mm fab in South Wales, UK, that mainly supplies automotive markets.

The $177 million cash acquisition of UK's largest semiconductor manufacturing site brings together Vishay's capacity expansion plans for automotive and industrial customers, and meets the UK's strategic goal of improved supply chain resilience.

In addition to expanding capacity, Vishay says it intends to collaborate with the Compound Semiconductor Cluster in South Wales to develop the semiconductor industry in the UK, including university and community partners in the UK and particularly South Wales.

"Under new leadership in early 2023, Vishay set an ambitious goal of investing approximately $1.2 billion in capacity over a three-year period in order to position the company to seize the opportunities created by the megatrends of e-mobility and sustainability needed for a net zero economy, " said Joel Smejkal, president and CEO of Vishay.

"While this transaction is supplemental to our capex investment strategy, adding Newport Wafer Fab to our manufacturing footprint will be instrumental to achieving our goal of expanding capacity for our customers and to accelerating our SiC strategy," said Joel Smejkal, president and CEO of Vishay.

By agreeing to acquire Newport Wafer Fab, Vishay says its aim is to safeguard the positions of the skilled and dedicated employees and to invest the necessary capital to set up production for SiC trench MOSFETs and diodes. "With its solid balance sheet and ample liquidity, Vishay will immediately bring stability and its reliable cash flow generation to ensure the facility becomes a fully operational and profitable fab" added Smejkal.

Marc Zandman, executive chairman of the board, Vishay said, "Vishay's Board made a critical decision last year to pivot the company toward profitable growth under new leadership, leveraging the company's solid cash flow generation, sound operational capabilities and broad product portfolio.

Zandman added: "A key element of this strategic shift is the investment in technologies and incremental capacity to position Vishay to capitalise on the megatrends in e-mobility and sustainability. Acquiring Newport Wafer Fab demonstrates Vishay's commitment to executing this strategic shift, and to realising improved returns for our stockholders."

Toni Versluijs, country manager, Nexperia UK, stated: "Nexperia would have preferred to continue the long-term strategy it implemented when it acquired the investment-starved fab in 2021 and provided for massive investments in equipment and personnel. However, these investment plans have been cut short by the unexpected and wrongful divestment order made by the UK Government in November 2022.

"The UK Government's order, in combination with a weakness in the global semiconductor market, recently led us to announce the intention to reduce the number of employees at the site by at least 100. The site needs clarity about its future to avoid further losses, and today's announcement provides this. Of all options, this agreement with Vishay is the most viable one to secure the future of the site as Vishay – like Nexperia – has a solid customer base for the fab's capabilities."

Versluijs added: "For the site, Vishay's commitment to further make the Newport Wafer Fab a success story is encouraging. Nexperia's position with regards to the UK Government's order remains unchanged."

The closing of Newport wafer fab transaction is subject to UK government review, the purchase rights of a third party, and customary closing conditions, and is expected to occur in the first quarter of 2024.

Element Six joins US DoD LADDIS programme

CVD diamond maker to work with Raytheon and Bristol University towards a new generation of military grade RF and power devices

ELEMENT SIX (E6), a CVD diamond manufacturer and part of the De Beers Group, has been selected for the LADDIS (Large Area Device-quality Diamond Substrates) programme, set up by the United States Defense Advanced Research Projects Agency (DARPA).

LADDIS aims to develop new ways of fabricating device-quality diamond substrates for applications that include RF and power electronics for operating in harsh military environments.

E6 will use its expertise to develop large-area, single-crystal diamond substrates to produce substrates measuring 50 mm in diameter. It will work with Raytheon, which makes high-power GaN RF devices for defence applications, and Martin Kuball, professor of Physics at the University of Bristol, who has pioneered the thermal characterisation techniques that can be used to assess the produced material of the group's synthesis work.

Diamond-based semiconductors have the potential for unprecedented power density, speed, and performance; however, there is a lack of industrial-size single crystal diamond wafers that are needed to commercialise these 'super-devices'. By working with its network of partners as part of the LADDIS project, E6 will aim to overcome these challenges.

E6 first developed electronic grade CVD diamond as an integral part of the European Council for Nuclear Research (CERN) Large Hadron Collider monitoring systems, used in the experiments that enabled the discovery of the Higgs Boson. In addition, by combining this electronic grade intrinsic diamond with solving the challenge to achieve high boron doping (more than 5 x 10^{20} cm^{-3}), E6 in collaborated with ABB, demonstrating diamond Schottky diodes with a blocking voltage of more than 4 keV.

Since then, E6 has invested in the development and manufacturing of single-crystal diamond and has registered over 2,000 patents in 40 countries. In addition to its facility in Santa Clara, California, US, E6 has also built and commissioned what was believed to be the world's largest operating single-crystal diamond factory, in Portland, Oregon, US.

Daniel Twitchen, chief technologist at E6 said: "Element Six has a 20-year track record of introducing disruptive single-crystal diamond-enabled solutions to the market, helping to unlock a range of new applications in sensing, optics and semiconductors. We are looking forward to leveraging our expertise, alongside Raytheon and E6's long-term academic partner, professor Martin Kuball, to further develop this world-leading diamond semiconductor technology."

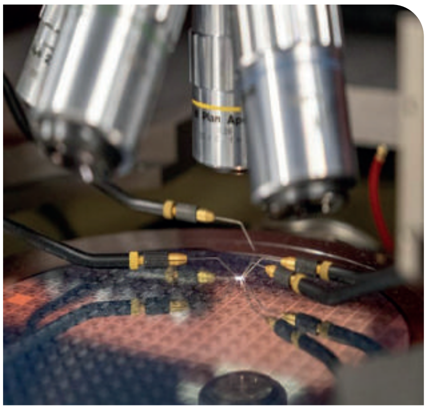
E6 has already demonstrated the successful and scaled synthesis of polycrystalline diamond with diameters greater than 100 mm. These are already being adopted in passive thermal management applications of high-power density silicon and GaN semiconductor devices, used for example in satellite communications, electronic warfare and telecommunication infrastructures.

Vermont Tech Hub to focus on GaN

Consortium led by the University of Vermont and including GlobalFoundries designated one of 31 Tech Hubs by the US Department of Commerce

A CONSORTIUM led by the University of Vermont (UVM) and including GlobalFoundries and the state of Vermont has been designated as one of 31 Tech Hubs by the US Department of Commerce's Economic Development Administration, unlocking the opportunity for up to $75 milion in federal grant funding to further research in GaN semiconductor technology.

The goal of the Vermont Tech Hub is to build and sustain a successful ecosystem for advancing GaN and other semiconductor innovations, and in the process, to grow the economy and economic vitality of the region and the state.



"GlobalFoundries looks forward to deepening our partnership with UVM, working together to realise the full potential of high-volume manufacturing of GaN on silicon chips, and to driving US leadership in this emerging technology," said Ken McAvey, VP and general manager of GlobalFoundries Vermont. "The CHIPS and Science Act has proven to be a successful catalyst for renewed enthusiasm, collaboration and investment in US semiconductor manufacturing, and the Tech Program will be a critical vehicle for advancing new technologies through development and into the marketplace."

The estimated global demand for GaN and related semiconductor solutions is growing, and the technology invites significant potential uses and offers advantages over current semiconductor technology – it adds speed, power, and efficiency. GaN has the potential for many applications, including high-frequency radio communications, power electronics, automotive electronics, aerospace applications, high-performance medical imaging equipment, and consumer electronics.

The CHIPS and Science Act signed into law in August 2022 authorised $10 billion in funding for the Tech Hubs Program. EDA has received $500 million – or 5 percent – of the authorixed dollar amount and has designated 31 Tech Hubs and awarded 29 Strategy Development Grants.

At its core, the Tech Hubs Program is an economic development initiative designed to drive technology- and innovation-centric growth by strengthening a region's capacity to manufacture, commercialise, and deploy critical technologies.

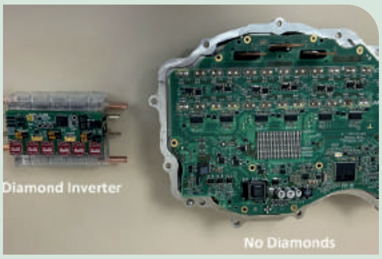
The consortium's regional vision is focused on the tech ecosystem that will emerge with the next generation of high-power, high-speed chips based on GaN. The northeast region has the partnerships, technology leaders, and research capacity to become a global leader in this technology.

The Tech Hub designation comes on the heels of the launch of UVM's new Device Characterization Lab, a partnership with GlobalFoundries with funding from the US Department of Education aimed at driving semiconductor research and preparing students for key roles within the field.

Diamond Foundry shrinks EV inverters

DIAMOND FOUNDRY has created a 250 W electric vehicle (EV) inverter based on its diamond wafer technology, with a power electronics unit six times smaller than that of a Tesla 3.

The company, which has its HQ in California, says the solution also delivers power more efficiently, thanks to a smart design enabled by diamond wafers in composition with established SiC dies.



Overall, the new 250 W DF Perseus inverter use 18 SiC chips, occupies a volume of 0.46 litres and has a power density of 500 kW/l. In comparison, a Tesla 3 inverter has 96 SiC chips, occupies 28 litres, and has a power density of 9 kW/l.

Power semiconductor design is driven by thermal conductivity and electrical conductivity. The thermal path has always been a challenge.

To add to the problem, power semiconductors need to be isolated because of the high voltages – and voltage isolation barriers have poor thermal conductivity.

The company says that advent of cost efficient diamond wafers overcomes these issues by enabling extreme thermal performance plus extreme electrical insulation.

Aixtron tool helps BelGaN expand GaN business

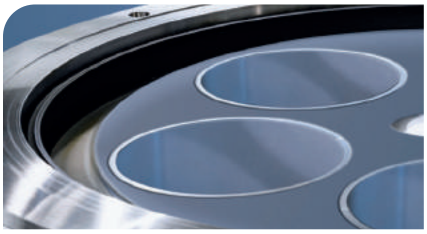
European semiconductor foundry invests in G10-GaN MOCVD system to expand business

EUROPEAN semiconductor foundry BelGaN will be using Aixtron's new G10-GaN MOCVD tool to expand its business into the growing GaN market.

Starting with an 8 x 150 mm configuration, the system will be delivered to the BelGaN production site in Oudenaarde, Belgium, before the end of 2023 and will in the future migrate to 5 x 200 mm.

BelGaN, a GaN automotive-qualified semiconductor open foundry, recently announced the production start of its first-generation 650 V eGaN technology. The Gen1 platform is designed for the requirements of energy-efficient applications for sustainability and carbon neutrality, according to Aixtron.

The G10-GaN will be used to further extend the range of power chips with voltage ratings from 40 V to 1200 V, using GaN-on-silicon, GaN on SOI, and novel GaN-on-engineered substrates. It will be applied both on lateral as well as vertical power-GaN products, with a focus on high performance, automotive quality and reliability, high yield, and low costs.



GaN epitaxy using MOCVD is a critical process in any power-GaN technology, both to innovate device architectures, boost performance, yield, and quality, and to cut down the cost of GaN products, according to Marnix Tack, CTO and VP business development of BelGaN. "We have been impressed by the high levels of productivity, uniformity, and low cost of ownership of Aixtron's new G10 platform," he said.

The new G10-GaN builds on the fundamentals of Aixtron's current tool the G5+ C, while delivering twice the productivity per cleanroom area. The G10-GaN also guarantees the highest throughput per m^2/cleanroom, and with its full automation end-to-end, it is the only MOCVD system fully designed for silicon fabs, says Aixtron.

Nexperia and Mitsubishi announce SiC partnership

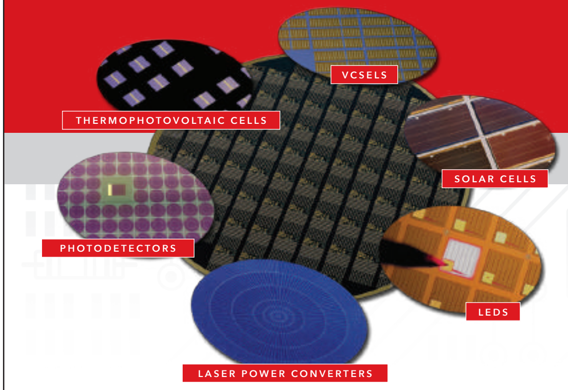
NEXPERIA has entered into a strategic partnership with Mitsubishi Electric to jointly develop SiC MOSFETs.

"This mutually beneficial strategic partnership with Mitsubishi Electric represents a significant stride in Nexperia's SiC journey," said Mark Roeloffzen, SVP and general manager of Bipolar Discretes at Nexperia.

Mitsubishi Electric has a track record as a supplier of SiC devices and modules. These devices are employed in Japan's acclaimed high-speed Shinkansen trains. Nexperia has silicon and wide bandgap devices. It also has expertise in discrete device products and packaging.

According to Roeloffzen, the collaboration will "generate positive synergies between both companies – ultimately enabling our customers to deliver highly energy efficient products in the industrial, automotive or consumer markets they serve."

Masayoshi Takemi, executive officer and group president for semiconductors and devices at Mitsubishi, said: "We are delighted to have reached an agreement on a partnership for joint development that leverages the semiconductor technologies of both companies."



DOE provides $42 million to update US power grid

Funding for 15 R&D projects aims to bolster efficiency and prevent power outages

THE US Department of Energy (DoE) has announced $42 million for 15 projects across 11 states to improve the reliability, resiliency and flexibility of the domestic power grid through the development of next-generation semiconductor technologies.

Funded through DoE's *Unlocking Lasting Transformative Resiliency Advances by Faster Actuation of power Semiconductor Technologies* (ULTRAFAST) programme, the technologies being developed would enable more effective control of grid power flow and better protection of critical infrastructure assets.

"Modernising our nation's aging power grid is critical to strengthening our national and energy security, and absolutely essential to reaching President Biden's ambitious goal of a net-zero economy by 2050," said US Secretary of Energy Jennifer Granholm.

Managed by DoE's Advanced Research Projects Agency-Energy (ARPA-E), selected projects include:

NextWatt (Hoffman Estates, IL) will develop an ultrawide-bandgap optical triggered device that addresses the need for fast protection for solid-state transformers, a promising technology for revolutionising substations and renewable energy systems. (Award amount: $2,268,750)

GaNify (State College, PA) will develop an optically isolated, power-integrated building block that would enable enhanced control of power electronics converters for a more efficient and reliable grid. (Award amount: $3,060,000)

Georgia Institute of Technology will develop a novel semiconductor switching device from III-Nitride material to improve grid control, resilience, and reliability. (Award amount: $2,700,000)

Great Lakes Crystal Technologies (East Lansing, MI) will develop a diamond semiconductor transistor to support the control infrastructure needed for an energy grid with more distributed generation sources and more variable loads. (Award amount: $2,301,538)

Lawrence Livermore National Laboratory will develop an optically-controlled semiconductor transistor to enable future grid control systems to accommodate higher voltage and current than state-of-the-art devices. (Award amount: $3,000,000)

Opcondys (Manteca, CA) will develop a light-controlled grid protection device to suppress destructive, sudden transient surges on the grid such as those caused by lightning and electromagnetic pulses. (Award amount: $3,178,977)

RTX Technology Research Center (East Hartford, CT) will develop semiconductor switching modules that are triggered by wireless radio frequency signals, reducing losses and improving control of power electronics converters for the grid and other applications. (Award amount: $2,500,000)

Sandia National Laboratories will develop a novel solid-state surge arrester that would protect the grid from very fast electromagnetic pulses that threaten the grid's reliability and performance. (Award amount: $2,560,000)

Texas Tech University will develop a photoconductive semiconductor switching device from advanced ultrawide-bandgap materials that would enable improved control of the grid. (Award amount: $3,070,735)

University of Arkansas will develop a heterogeneously integrated high-power semiconductor module for applications in the electric power grid and electrified transportation. (Award amount: $2,931,177)

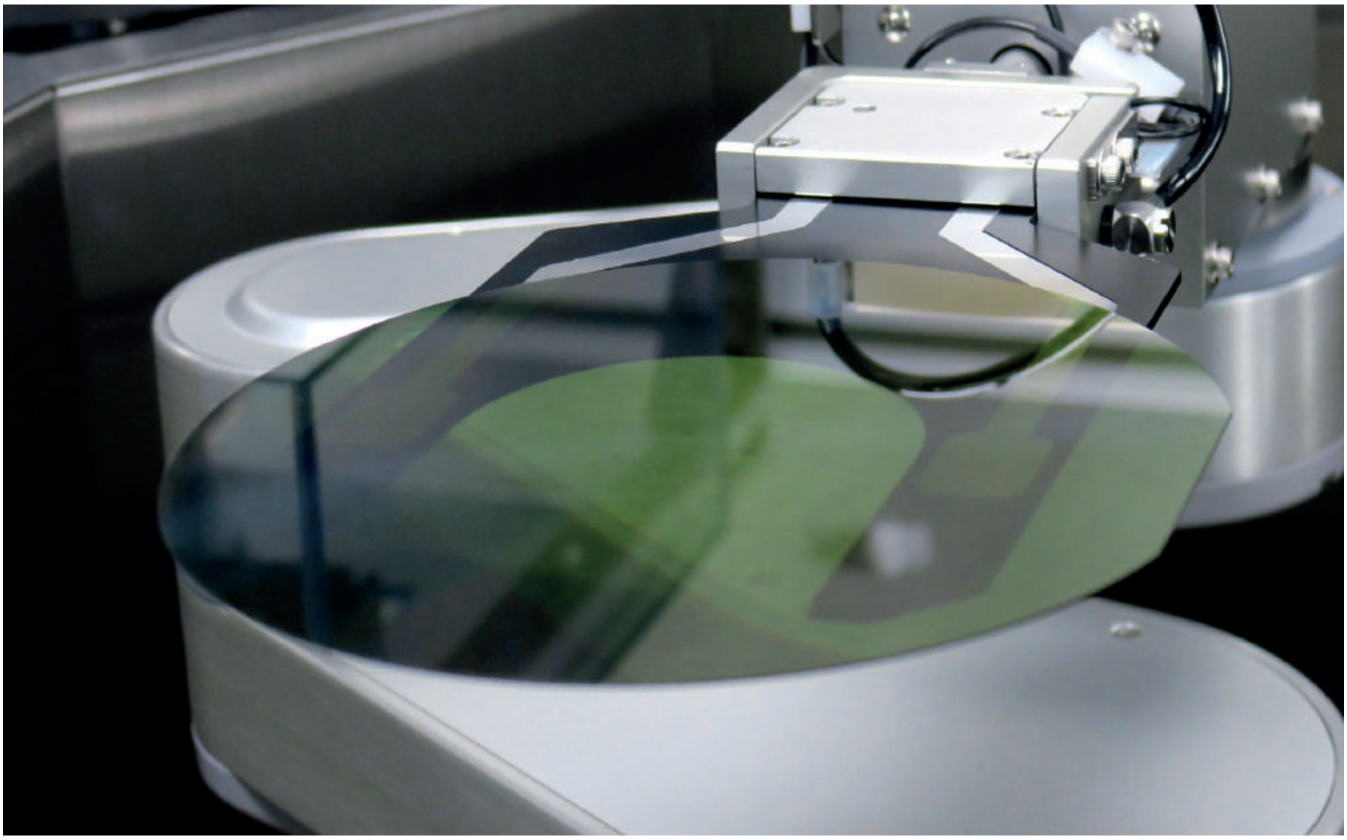
University of California, Santa Barbara, will develop ultrawide-bandgap switching devices that would achieve higher voltages and speeds than the state-of-the-art, enabling more sophisticated control methods for the grid. (Award amount: $3,122,356)

University of Illinois at Urbana-Champaign will develop optically triggered diamond semiconductor switching devices to enable revolutionary breakthroughs in electricity grid protection. (Award amount: $2,982,311)

University of Pennsylvania will develop an integrated module featuring wide-bandgap power devices with optical control and sensing to improve electric grid control, resilience, and reliability. (Award amount: $2,240,309)

University of Wisconsin-Madison will develop an optically triggered semiconductor switching device to cut power losses and increase performance compared with current technologies. (Award amount: $2,990,321)

University of Tennessee, Knoxville, will develop scalable, light-triggered semiconductor switching modules with integrated sensing for protection of the grid and other power distribution systems. (Award amount: $2,759,821)



A Coherent plan for SiC

Backed by substantial investment from two of the biggest names in power electronics, Coherent has a well-devised plan for expanding the quality and quantity of its SiC portfolio

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

DRIVEN ON by lucrative opportunities in the burgeoning electric vehicles market, many makers of SiC materials and devices are establishing substantial expansion plans. Just this year Wolfspeed announced its intention to build the world's largest SiC fab in Germany, only to be eclipsed this summer, when Infineon boasted a similar claim for its new SiC facility, to be constructed in Malaysia. And this October Coherent has been grabbing the headlines by creating a subsidiary devoted to SiC.

Supported by investment from Denso and Mitsubishi Electric that totals $1 billion – a transaction scheduled for completion in the first quarter of 2024 – efforts to create this subsidiary are already underway. In exchange for these two substantial cash injections, each $500 million, the Japanese firms will each receive a 12.5 percent non-controlling ownership interest, as well as long-term supply agreements that support their SiC activity. Coherent will ship SiC substrates, both 150 mm and 200 mm, to Mitsubishi Electric and Denso.

Heading up the new subsidiary is Sohail Khan, Coherent's executive VP, Wide-Bandgap Electronics Technologies. Khan is definitely delighted with this *modus operandi*.

"You always want to have the leading system companies as your lead customers," remarks Khan, who points out that Denso is a leading tier-one supplier to the automotive industry and Mitsubishi Electric is a leading provider of industrial and automotive power systems.

Coherent, which has its II-VI heritage to thank for its SiC prowess, could have turned to a number of different options for funding the growth of its new subsidiary.

Some may see investment from other firms as questionable – but not Khan, who argues that it's an asset. "Our view was that when you have ownership, you have the right interest and motivation. I would go as far as saying not all money is the same."

➤ Top: 150 mm substrates on a robotic arm.

Note, though, that Khan is not advocating that any partner will be beneficial. “It is important to have the partners who have validated your technology, have used your technology, and have the confidence in your technology and capability.”

He adds that for the relationship to blossom, a partner also needs assurance that they will be supplied with high-quality products, in volume, at a competitive price.

Confident of meeting all these requirements, the Coherent subsidiary will benefit from getting “maximum learning”. The leadership at II-VI always considered this as a vital pillar to market success, and this philosophy still lies at the centre of Coherent and its subsidiary.

Another benefit of working with Mitsubishi Electric and Denso is that it allows Khan and his team to get much closer to the end suppliers to the market. “That’s absolutely critical,” argues Khan.

The insights gained from the new venture will help to continually refine the production processes of this vertically integrated Coherent subsidiary, which as well as making substrates and epiwafers is expanding into devices and modules.

Open to all

Khan is very keen to point out that the subsidiary is not just there to serve Mitsubishi and Denso. “I want to emphasise that we are not going to be a captive supplier. It is just an investment from these companies into the silicon carbide business.”

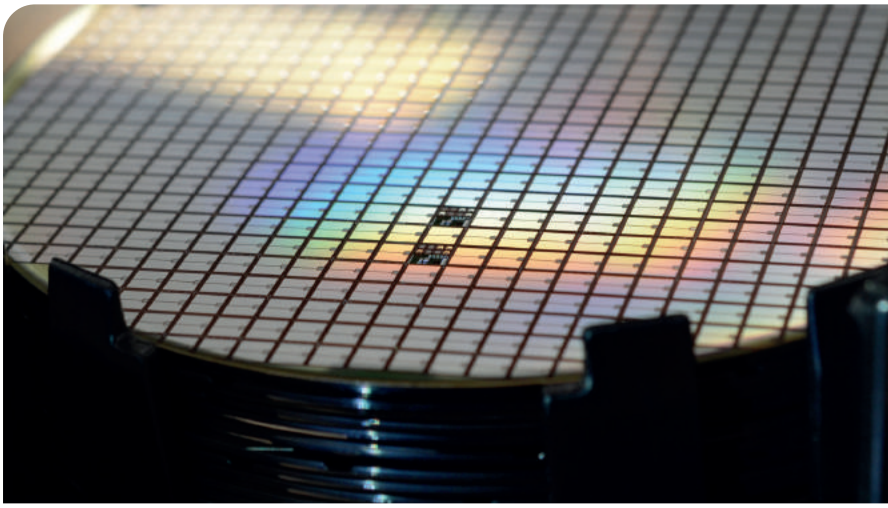
He adds: “The idea is to be a merchant player, learning from other customers and providing our products at every level.” The Coherent subsidiary will engage with some companies at the substrate and epiwafer level, and others at the device or module level.

Khan is responsible for around 650 staff in the US, spread over a number of facilities. In addition, there is a site in Fuzhou, China, that provides contract manufacturing.

Investment in the Coherent subsidiary will increase capacity and support growth. Capital and operational expenditure will follow, ranging from the installation of additional furnaces and epi-reactors to improved R&D capabilities that support the development of devices and module designs.

Substrates produced by the subsidiary are already available in 150 mm and 200 mm diameters. According to Khan, lines for processing the larger size are now being brought up, with tools undergoing qualification. However, this will take time – and Khan expects it will be 2025 before 200 mm is the dominant diameter for substrate shipments.

Through the licensing of General Electric’s SiC MOSFET technology, Coherent has been qualifying 1200 V and 1700 V devices that meet the Automotive Electronics Council AEC-Q101 standard.



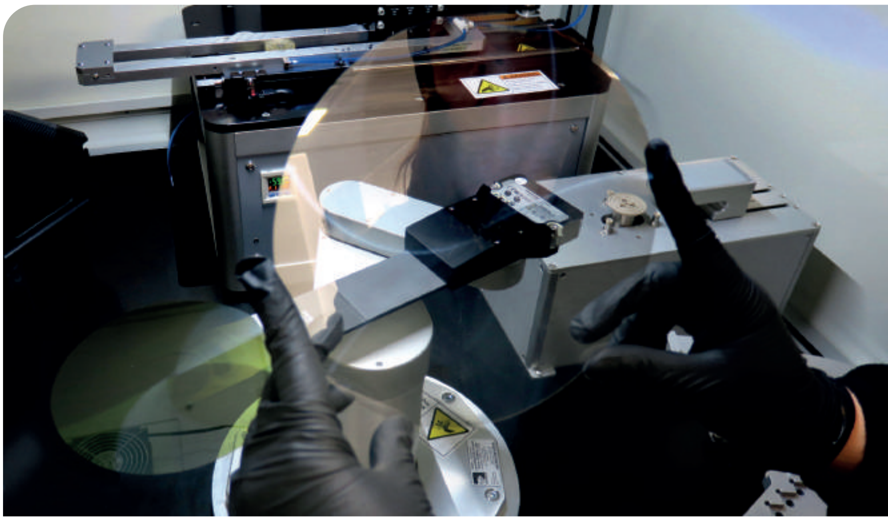
➤ 150 mm wafer populated with SiC devices.

“If you look at the power market, they guarantee 175 degrees C,” says Khan. “We guarantee 200 degrees C operation. Our devices are very rugged and go through extensive tests on reliability.” These MOSFETs are now being sampled at pre-production levels.

The degree of success that will come from Coherent’s SiC subsidiary will be disclosed in quarterly results. Khan is confident of rising sales in a global market now worth around $3 billion, and forecast to generate revenue of more than $20 billion by the end of the decade.

It is possible that sales may even outstrip this figure, suggests Khan, arguing that once newer technologies prove themselves, they always replace the incumbents. “No one has a crystal ball, but we have seen predictions anywhere from 30 percent to 80 percent penetration of [silicon carbide] in EVs.”

Should deployment veers towards the upper end, the Coherent subsidiary will enjoy tremendous success, along with its two Japanese investors.



➤ 200 mm substrate.

Slashing solar cell costs

A dynamic variant of HVPE promises to provide a continuous growth process that allows III-V solar cell production costs to tumble without compromising performance

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

IF THE ONLY METRIC that really mattered for the solar cell were its performance, III-Vs would utterly dominate this market. But cost is paramount, accounting for the widespread deployment of silicon panels.

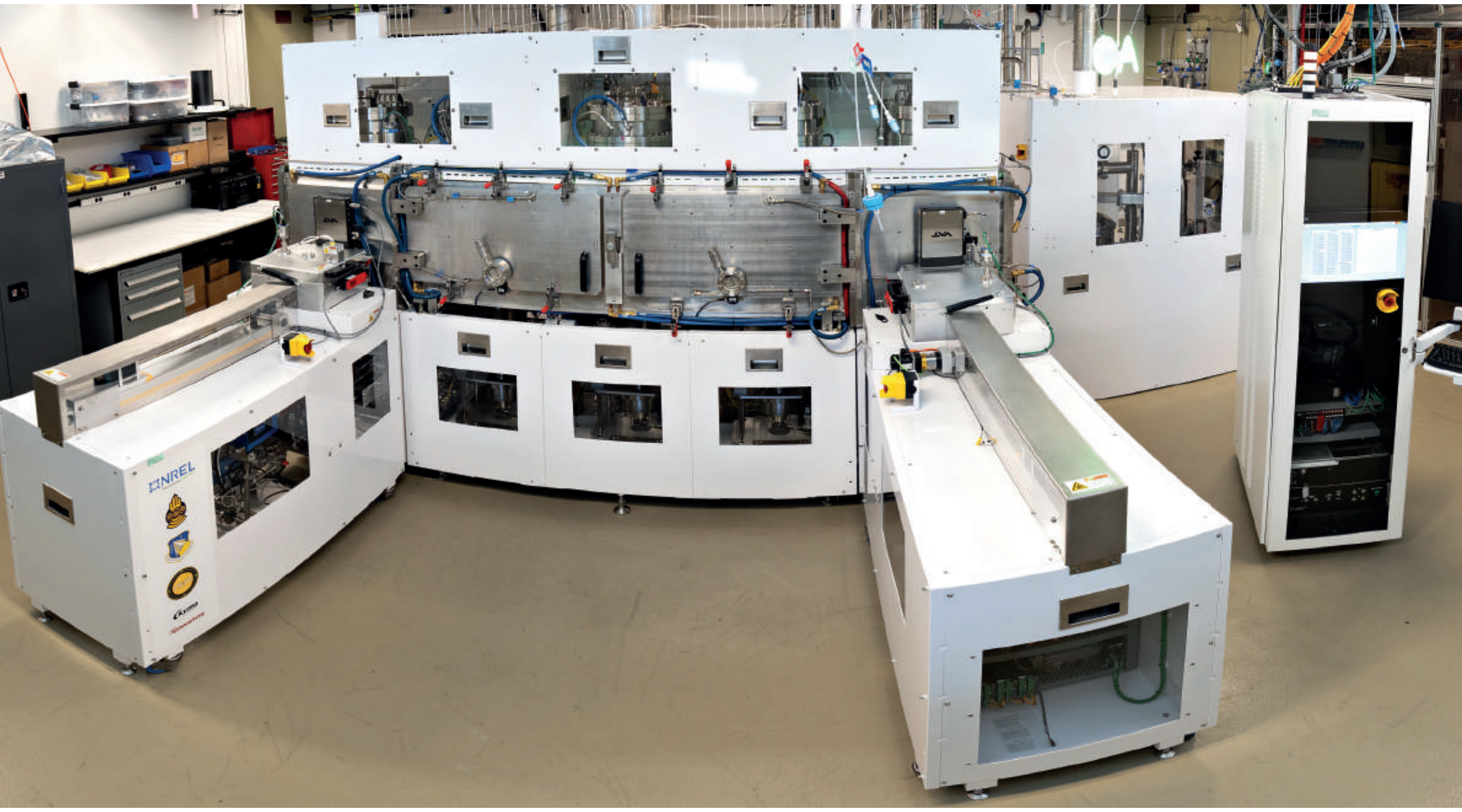
A primary cause of the high cost of III-V solar cells is the epitaxial process. Growth is relatively slow, using a batch approach that is inefficient, with time lost to loading and unloading wafers into a reactor that has to be heated and cooled.

Addressing all of these weaknesses is a team from the National Renewable Energy Laboratory (NREL) in Golden, CO, that is pioneering a novel approach to epitaxial growth that is referred to as dynamic HVPE.

One major asset of this particular technology is a growth rate that is typically an order of magnitude faster than that of the established epitaxial technologies for making solar cells, such as MOCVD. What's more, this approach opens the door to moving away from batch processing.

What's crucial is that all these advantages are realised while still allowing III-V cells to deliver a level of efficiency way beyond what's possible with other material systems. The performance of solar cells grown by dynamic HVPE has been steadily increasing, and recently the team from NREL reported a single-junction cell with efficiency of 27 percent.

That's still a little shy of the best ever performance of any single-junction cell, a record held by the now defunct Alta Devices, which announced a new benchmark of 29.1 percent efficiency in 2018.



➤ NREL's pilot system will help to drive development of dynamic HVPE on an industrial scale.

However, that record-breaking cell is thought to include optical structures to boost photon recycling and ultimately increase output voltage, according to Kevin Schulte from NREL. He has little doubt that without these valuable, performance-boosting optical technologies, which are not deployed on the NREL cells, the efficiency gap resulting from different growth technologies would be smaller.

The 27 percent efficient cells produced by the team from Colorado were made using a growth rate of 60 µm/hr, which is still well below the upper limit of what is possible. "We've grown solar cells up to 300 microns an hour without seeing significant degradation," says Schulte.

To produce their single-heterojunction cells, Schulte and co-workers shuffle wafers between the two chambers of their research reactor. While growth is taking place in one chamber, gas flows are switched in other chamber to prepare for deposition of the subsequent epilayer.

It is a *modus operandi* that provides a stepping stone towards the team's grand vision of a linear reactor, containing multiple chambers that each provide the growth of a single layer. In this instance, as every layer requires a different thickness, the growth rate would vary from chamber to chamber.

In addition to the cost savings that come from higher growth rates and the more time-efficient approach associated with dynamic HVPE, there are financial benefits resulting from the use of different precursors. MOCVD demands pricey metal-organic compounds, while HVPE involves the use of precursors formed from reactions between metallic elements and anhydrous HCl. "The precursors are thought to be about an order of magnitude cheaper," says Schulte.

Producers of III-V solar cells that adopt dynamic HVPE will probably begin by targeting the satellite market, which is able to sustain relatively high costs. Success there would enable an increase in production volumes, helping drive down manufacturing costs that would then allow device makers to pursue terrestrial opportunities, such as providing portable power or generating electricity in space-constrained environments.

Schulte is sceptical when it comes to whether a fall in the cost of III-V devices could ignite a resurgence in interest in concentrating photovoltaics. While lower-cost cells would increase the competitiveness of this technology, gains are marginal, as the price of the system is governed by other components, such as the optics and solar tracking systems.

"The problem is that silicon just got so cheap, so fast," reasons Schulte, who points out that CPV has now missed out on many years of cost reduction that come from fierce competition in high-volume markets.

In addition to the cost savings that come from higher growth rates and the more time-efficient approach associated with dynamic HVPE, there are financial benefits resulting from the use of different precursors.

Modelling insights

To speed their development of high-efficiency, single-junction cells, Schulte and his colleagues turned to a freeware package called ASFORS-HET, previously available online and managed by the Helmholtz Centre, Berlin.

"It's a device physics simulator developed for silicon solar cells, but the fundamentals are the same for III-Vs," says Schulte.

The package, which can produce current-voltage curves for different cells in a minute or so, enabled the team to hone its device design over several months. In particular, the researchers were able to fine tune the composition, thickness and doping of the emitter layer in their heterojunction structure.

While it would also have been possible to optimise the heterojunction cell with a purely experimental approach, this would have typically required ten or so calibration runs for each device. Due to this, many hundred runs would have been needed to reach the same conclusion, a considerable outlay in both time and money.

Schulte and his colleagues have also produced a two-junction cell with an efficiency of 28 percent. He says that even higher values should be possible, pointing out that a team in Japan has used HVPE to produce a III-V device with an efficiency of 28.3 percent. "Given enough time to optimise our tandem structure, I think we could get 30 percent or more."

That's not the primary focus for the team, however. Instead, efforts are directed at making larger-area devices, and trying to validate dynamic HVPE at what is approaching an industrial scale. Helping succeed on this front is the installation of a pilot system in Colorado. This new tool arrived earlier this year, and the start-up phase is well underway.

Hopefully next year Schulte and his co-workers will be sharing device data from this tool. Success with that larger scale dynamic HVPE reactor would help to strengthen the case that this growth technology can produce efficient III-V cells in volume, and could ultimately help to drive the expansion of market opportunities for this device.

Accelerating sales with the automobile

While it's easy to be dazzled by ramping sales of SiC power devices for electric vehicles, today the revenue for LEDs in the automotive sector is far higher, and continuing to climb

BY ANIKET ROY FROM STRATVIEW RESEARCH

IN THIS EVER-MOVING WORLD, where an average adult in a developed nation spends more than ten hours a week inside their four-wheeled luxury, cars are no longer just a way of transit. Instead, after the home and the office, they are slowly becoming the third space for many. Since for most households a personal vehicle isn't something to change every year, buyers are tending to exercise a fairly high degree of selectivity.

Prior to the turn of the millennium, most car buyers adopted a fairly utilitarian sentiment. Now, though, the factors at play are more complex, incorporating elevated expectations, in terms of both features and aesthetics.

While the goal of every buyer is still to select the best combination of features and aesthetics within their price range, research shows that buying decisions are more influenced by aesthetics than features. Due to this, car makers are loading their models with sleek designs, luxurious interiors, premium wheels, and whatnot.

Among the checklist of factors that make a vehicle attractive is 'lighting'. This makes a significant contribution to the interior and exterior aesthetics of any vehicle.

Automobiles have been produced since the 1880s. Over the intervening years they have been fitted with a number of different lighting technologies, including: the acetylene lamps, introduced around 1908; semi-sealed beam incandescent bulbs, coming in during the 1920s; sealed beam headlamps, pioneered in the 1940s; halogen lamps, introduced in the 1960s; and high-intensity discharge lamps, an innovation from early 1990s.

More recently, LEDs have started to dominate; a technology that is still evolving.

Initially, LEDs were deployed in the likes of brake lights or trunk lights. Tracing the introduction of these solid-state sources back to a single model is far from easy, but it is widely accepted that the first significant application of the LED in the automotive world came in the form of the Daytime Running Light assembly, incorporated in the Audi A8 in 2004.

This high-end manufacturer is also responsible for another important milestone, having introduced the first full LED headlight in 2007, fitted to the R8. Since then LEDs have rapidly penetrated the automotive lighting industry.

Longer and brighter

The success of LEDs stems from its superior performance. Compared to its predecessors, the halogen and the high-intensity discharge lamp, the LED is at least 50 percent more efficient and lasts far longer, having a lifetime of 45,000 hours or more. That's around 40 times longer than a halogen lamp, and typically 8-15 times longer than a high-intensity discharge lamp.

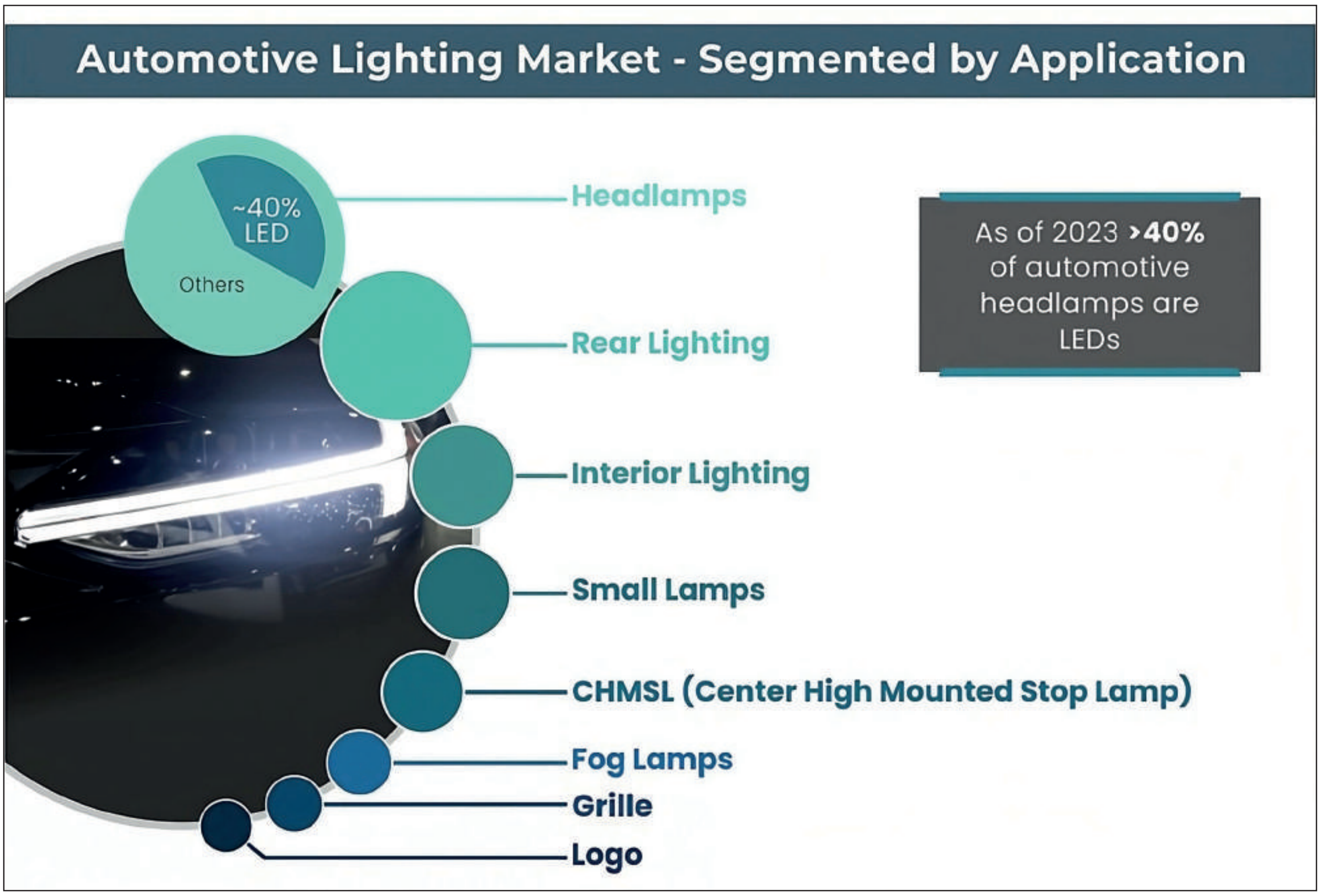
The main downside of the LED-based headlight is its high cost – it can be $500 or more for a single LED headlight. Yet despite this, LEDs are preferred to halogen and high-intensity discharge lamps on the grounds of practicality since the need to replace an LED might never arise, thanks to its long lifespan and its immunity to physical damage.

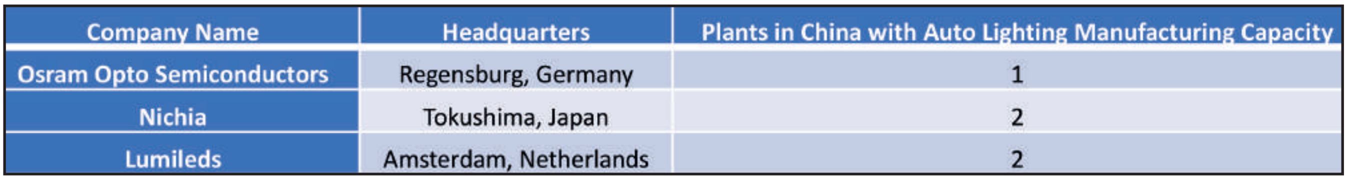
Another strength of the LED is its superior flexibility, in terms of both application and installation. For instance, in both exterior and interior applications, LEDs can be used in the form of 'strips', due to their compact nature. This feature is nearly impossible to realise with halogen and high-intensity discharge lamps.

Today, there isn't any segment of automotive lighting where LEDs haven't marked their presence – and for some segments, this presence is expected to turn into complete dominance within the next decade.

According to our company, Stratview Research, if we roughly classify the lighting applications in automobiles as follows – headlamps, rear lighting, interior lighting, small lamps, centre high-mounted stop lamps, fog lamps, grille lights and logos – then more than 60 percent of the automotive lighting market can be accredited to just headlamps. That's a substantial change, as the share of LEDs in the automotive headlamps market used to be around just 15 percent half a decade ago.

Another way to evaluate the success of the LED headlamp is to consider its penetration into the global automotive headlights market. Against this metric, this year LED headlights will account for more than 40 percent of the global automotive





Company Name	Headquarters	Plants in China with Auto Lighting Manufacturing Capacity
Osram Opto Semiconductors	Regensburg, Germany	1
Nichia	Tokushima, Japan	2
Lumileds	Amsterdam, Netherlands	2

headlights market. The key enabler behind such success is the ease with which LEDs can be programmed for adaptive headlights. While halogens can achieve some degree of adaptability, LEDs can change their direction and intensity more quickly, and also provide more options in terms of achievable colour temperatures.

Adaptive lighting is not just limited to headlamps. This feature is also favoured in interiors, with a survey conducted by DTS involving 900 US car owners finding that more than a third of them want their vehicles to automatically change the lighting and temperature when they enter their car. This level of personalised experience with lighting is easiest to realise with LEDs. Due to the increasing demand for such features, we expect LEDs to completely replace halogens in automotive interiors in the 2030-35 timeframe.

As the one-stop solution for energy efficiency, longevity and controllability, while delivering all desired lighting characteristics, LEDs are in an enviable position to shine in the automotive lighting market over the coming years. With this industry's transition towards energy-efficient and highly customisable lightings now well underway, even back in 2022 the automotive LED market was valued at $5.2 billion. Growth is forecast to outpace that of the automotive industry, driven by increasing penetration in existing lighting segments. By 2027 the automotive LED market is predicted to have climbed to $6.9 billion.

Regional oddities

One of the quirks of the automotive LED market is that while China and the US are entrenched as the biggest manufacturers of automobiles, none of the top three players in the automotive LED lighting space are based in either of these countries. Our research has determined that the biggest player in the automotive LED market is Osram Opto Semiconductors. Nichia and Lumileds are in second and third spot, respectively. Between them, these three have captured more than 50 percent of the automotive LED market.

It's interesting to note that this trio have all expanded their manufacturing capabilities to China, to address the needs of the world's biggest manufacturer of automobiles (see Table 1).

The road ahead

Further development of LED technology for automotive lighting will be driven by the need to realise more energy-efficient lighting and to develop 'intelligent' lighting systems.

From an innovation perspective, many players are focusing on increasing the numbers of pixels or chips via LED matrices. Companies like Osram have developed systems with around 25,000 pixels in a single monolithic microLED chip array, and some experts are predicting that the number of pixels could quadruple by 2028. Based on the current pace of development, it appears it's not that challenging to achieve that count by as early as 2025, but it's hard to know for sure.

What is beyond doubt is that the continuous advancement in LED technology within the automotive lighting industry is certain to lead to even more energy-efficient, versatile, and visually appealing lighting solutions.

Strengthening the case for Plasma Polish

Three pioneering metrology techniques confirm that the Plasma Polish production process eradicates subsurface damage in SiC substrates while improving crystal quality

BY GRANT BALDWIN AND JAMES SAGAR, OXFORD INSTRUMENTS PLC

BACK IN SEPTEMBER 2022 at the International Conference for Silicon Carbide and Related Materials (ICSCRM), held in Davos, Oxford Instruments, launched Plasma Polish. Originally conceived as either a replacement or a complementary process to a chemical mechanical polish (CMP), this alternative plasma-based process has been attracting significant interest from leading substrate manufacturers and vertically integrated device manufacturers. Wafers that have undergone Plasma Polish during processing into diodes and MOSFETs have a performance that's in line with industry standard CMP, according to full wafer electrical measurements and yield results (see Figure 1).

The non-contact, dry Plasma Polish process has several key benefits including lower cost, a reduced environmental impact and the ability to remove subsurface damage.

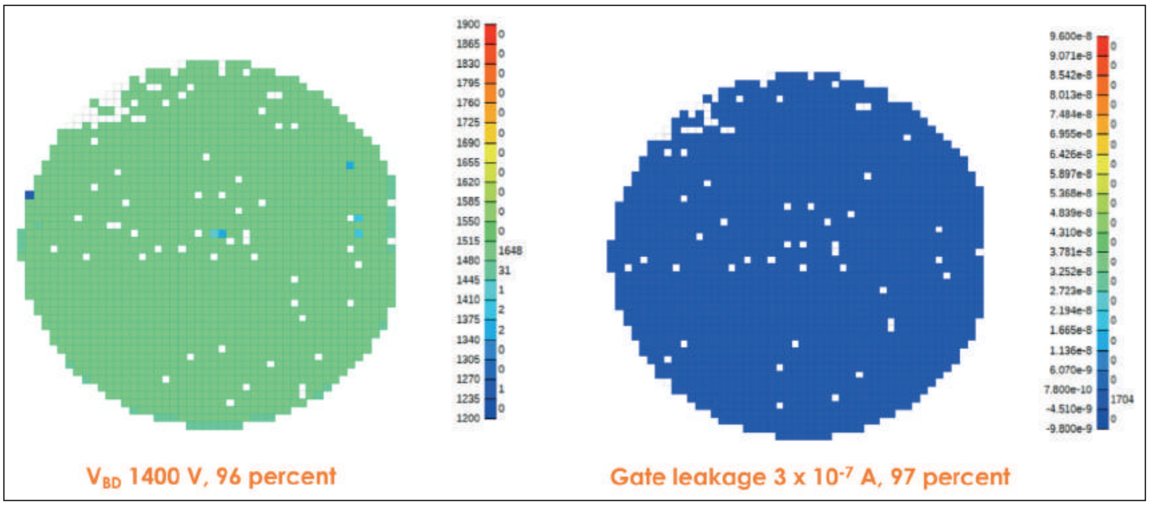
Plasma Polish requires low levels of consumables and creates no toxic slurry, leading to an operating cost reduction of up to 85 percent, resulting from the removal of these process requirements and their associated costs. The absence of the slurry also means that there are no disposal issues and removes the significant water use typically associated with CMP, making Plasma Polish better for the environment. Plasma Polish uses industry standard non-toxic process gasses, making it unproblematic to install in production facilities.

The third benefit, subsurface damage removal, is unique to Plasma Polish. This great strength, discussed in more detail on pages 23 to 25, comes without having to make any changes to either upstream or subsequent processes.

Assessing crystal quality

We originally conceived of Plasma Polish as a technique for preparing SiC substrates for the subsequent growth of epitaxial layers. However, following significant market engagement, including demonstrations on customer material, more and more opportunities are emerging where Plasma Polish provides a solution to surface and subsurface damage.

At this year's ICSCRM, held in Sorrento, Italy, we presented data that confirms that Plasma Polish



➤ Figure 1. Plasma Polish achieves a high yield on full-wafer device tests.

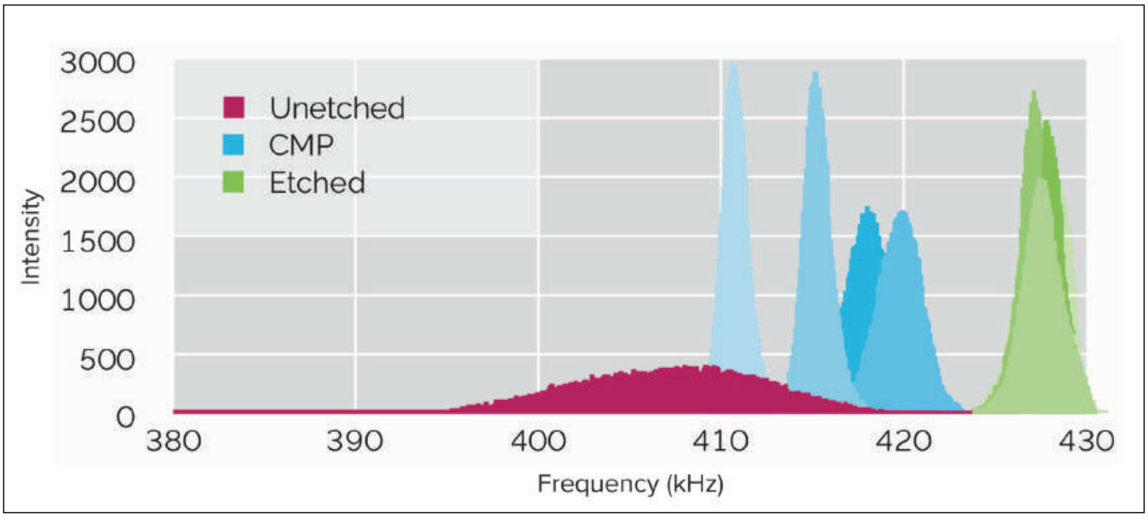
removes subsurface damage. To prove this is the case, we developed breakthrough characterisation techniques by harnessing expertise from many parts of our business. Our validation of the subsurface damage removal capabilities of Plasma Polish comes from three metrology and crystal analysis techniques: contact-resonance atomic force microscopy; electron back-scatter diffraction, which is an electron microscopy-based analytical tool; and Raman microscopy.

Before setting out into the insights provided by these techniques, we'll briefly explain how and why Plasma Polish works. It's a technique that employs physical and chemical mechanisms able to access and remove subsurface damage, with the extent of this benefit dependent on the chamber design, its configuration and the process recipe. Wafers are processed in a reactor chamber on a radio-frequency-biased wafer stage at a low pressure – this enables the acceleration of the chemically reactive plasma gas onto the wafer surface. As any damaged or defective crystal is inherently weakly bonded, this unique form of plasma etch removes poor-quality material far faster than good-quality, strongly bonded crystal. Consequently, all that remains after a Plasma Polish is higher quality material exhibiting excellent crystallography. In stark contrast, while CMP provides planarisation (flattening), it fails to remove damaged material at a higher rate than good-quality crystal.

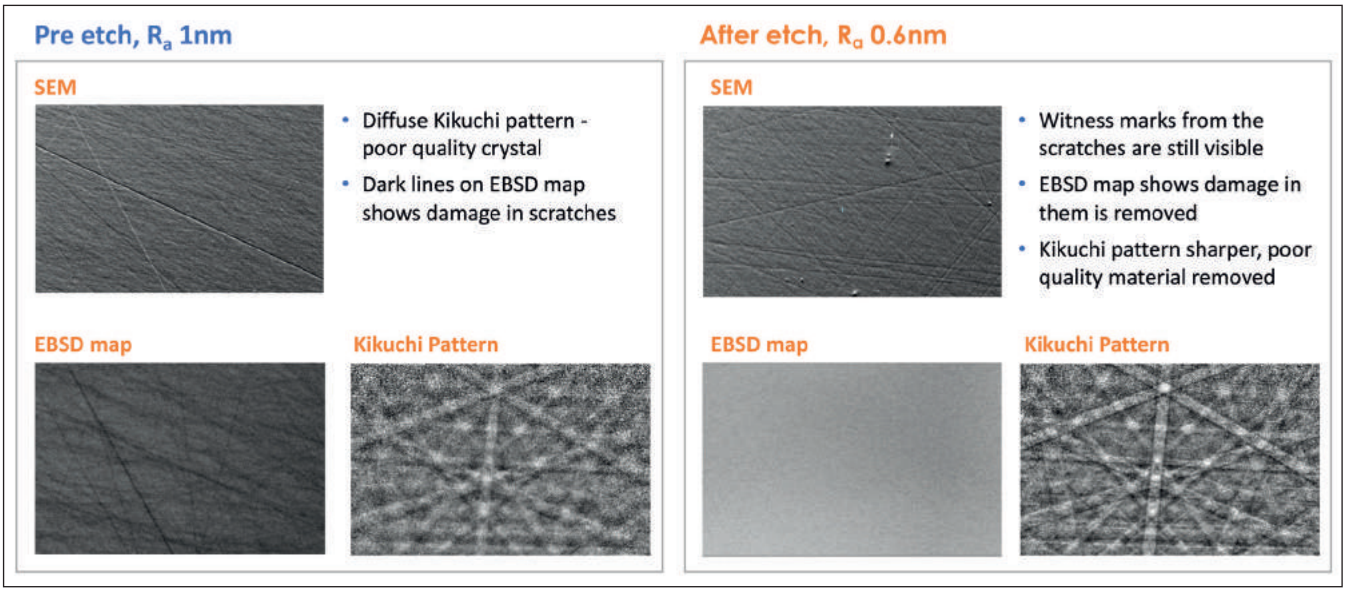
To assess the crystal quality of SiC processed by Plasma Polish, we have turned to a variant of atomic force microscopy known as contact resonance. With this technique, we have mapped the sample surface with a cantilevered stylus that spot-measures the resonant frequency. From this it is possible to obtain a measure of crystal quality as a function of material stiffness, with sharper peaks at higher frequencies equating to higher quality.

We have used contact-resonance atomic force microscopy to compare the crystal quality of incoming unprocessed material and that processed by Plasma Polish. Incoming unprocessed material has a very broad peak at the lowest average frequency, indicating neither good crystal quality nor homogeneity (see the red curve in Figure 2).

To compare SiC processed by CMP and Plasma Polish, we performed four measurements on each wafer: one treated with CMP (Blue), and one treated with Plasma Polish (green). As the blue peaks are



➤ Figure 2. Contact-resonance atomic force microscopy of four unprocessed points of a CMP substrate (blue) and four points of a Plasma Polished substrate (green).



➤ Figure 3. Electron back scatter diffraction (EBSD) images of pre-Plasma Polish and post-Plasma Polish Etch.

narrower than the red, we have concluded that CMP produces an improvement in quality compared with the incoming substrate. However, the four blue peaks are at markedly different frequencies, indicating variation. Meanwhile, the four narrow green peaks have significant overlap, indicating that Plasma Polish improves crystal quality and homogeneity.

The second technique that we have employed, electron back-scatter diffraction, characterises crystallinity and type at a depth of up to a few tens of nanometres. With this form of diffraction, we have produced two images of interest: a Kikuchi pattern at each imaged pixel; and a pattern quality map, revealing the quality of the pattern at each pixel.

For Kikuchi patterns, quality is defined by the sharpness of the diffraction pattern. If it is sharp, this indicates high crystal structure conformality; and if it is diffuse or blurry, it is evidence of either poor structure conformality or more than one SiC polytype. When electron back-scatter diffraction is used, a featureless pattern quality map with a bright colour indicates a high-quality, uniform surface.

When using a scanning electron microscope (SEM) to scrutinise pre-etch samples and those having undergone Plasma Polish, we obtained images that are actually very comparable, mostly showing topography (see Figure 3). This indicates that metrology techniques with more structural specificity are needed to offer greater insight into what is happening at the subsurface. Electron back-scatter diffraction meets this requirement, providing a true assessment of subsurface crystal conformality and polytype purity. Using this technique to study a pre-etched sample yields a pattern quality map with dark lines associated with damaged or amorphous crystal. Once Plasma Polish is applied, electron back-scatter diffraction creates a featureless pattern quality map, indicating improved crystal conformality and purity. The Kikuchi pattern is sharper and of higher quality, thanks to removal of damaged material by Plasma Polish.

Raman microscopy is the third and final SiC substrate characterisation technique we have utilised to assess crystal quality. This form of microscopy, which is incredibly sensitive to local chemical bonds, can penetrate

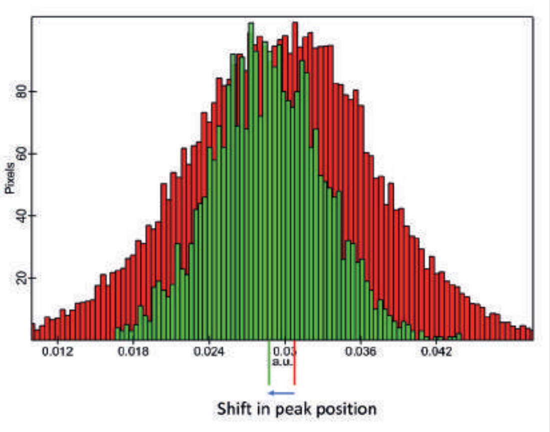
➤ Oxford Instruments multi-chamber production cluster to around 2 μm, thereby enabling the gathering of information from deeper in the crystal. By comparing specific Raman peaks in a spectrum, we are able to assess types of order and disorder. This is accomplished by determining an intensity ratio for two peaks: one peak corresponding to the 4H polytype of SiC, and the other corresponding to disordered Si-C.

We have produced histograms of measured peak ratios after acquiring Raman spectra across a whole SiC wafer (see Figure 4, which has red and green bars for measurements of unetched and Plasma Polish wafers, respectively). The green peak is narrower than its red counterpart and it is closer to the ideal ratio of zero. Based on these observations, we can conclude that Plasma Polish results in a superior crystal uniformity and a higher concentration of 4H SiC, the critical polytype for device production.

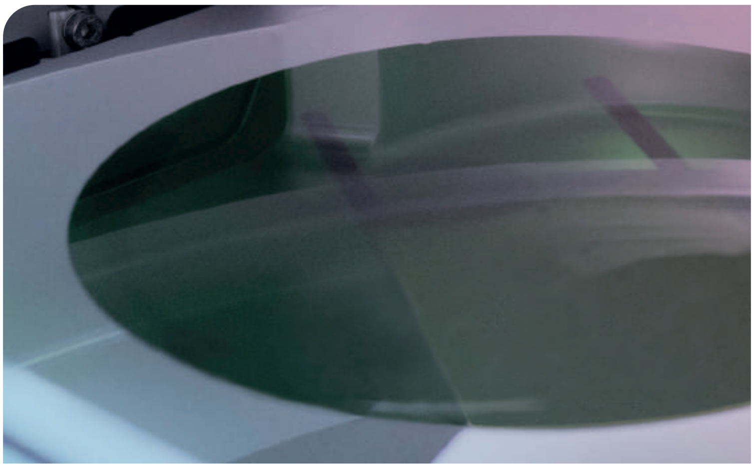
Additional opportunities

As well as replacing CMP, Plasma Polish can work alongside while offering a drastically lower operating cost, no toxic consumable usage or disposal, and a proven capability to remove subsurface damage and increase crystal quality. So, given all these great attributes, how can this advanced solution to preparing SiC substrates for epitaxial growth move forward? Well, there are limitless applications for dry Plasma Polish, where a traditional wet polish process is either not possible, or at least suboptimal. For example, Plasma Polish can rectify substrate bow/warp, optimise device process integration by swapping out wet cleans for dry polishes, reclaim substrates, maintain crystal quality on thicker epilayers for high-voltage devices, improve repeatability with integrated automatic endpoint process control and enable thinner substrates – note that all these opportunities apply equally for 150 mm and 200 mm material, thanks to the innate scalability of our process.

Our Plasma Polish technology forms part of a strong offering to producers of wide bandgap power devices. For the makers of high-end GaN devices, we have an established market-leading atomic layer etch capability to address shallow etch, surface smoothing, and defect reduction challenges. Now there is significant interest to apply this technology to address issues specific to SiC power device manufacture. For GaN MISHEMTs, we offer atomic layer etch with our Etchpoint technology, in collaboration with LayTec AG. This technology, installed at key Japanese GaN device manufacturers, enables partial AlGaN recess etches with a critical target depth to an unparelled accuracy of ±0.5 nm, for next generation E-mode device functionality. Our other production solution is for GaN HEMT manufacture. The production qualified technology offers high etch rate with repeatable Etchpoint automated switchover to atomic layer etch soft-landing to protect the device-critical underlying layers. In addition, we offer a high-quality GaN atomic layer deposition process with interface optimisation pre-treatment to reduce and remove native oxides and infill nitrogen vacancies. This is qualified and in high-volume production at leading device manufacturers in Japan and the US.

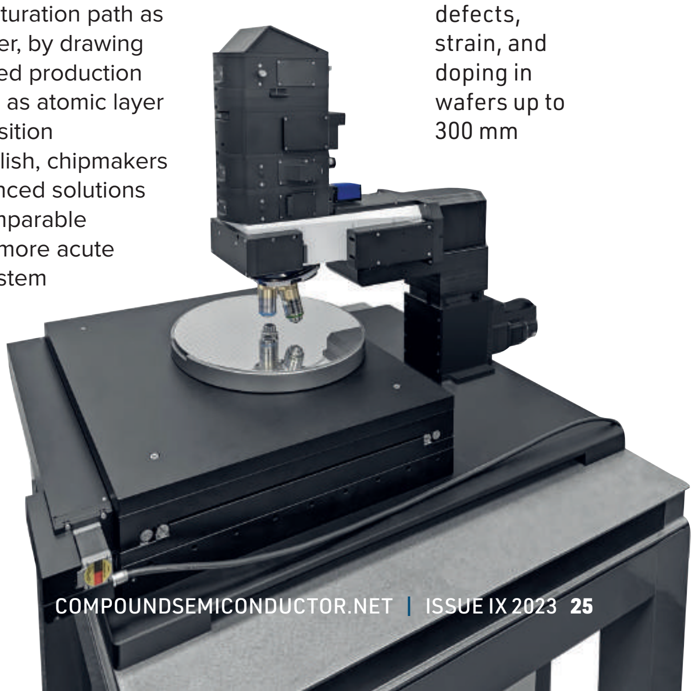


➤ Figure 4. Histogram of SiC peak positions from 2,000 Raman spectra of pre-Plasma Polish (red) and post-Plasma Polish (green).



➤ Successful transfer of 150 mm process to 200 mm wafers

There's no doubt that SiC substrate and device production will follow the same lengthy technology maturation path as silicon. However, by drawing on our advanced production solutions, such as atomic layer etch and deposition and Plasma Polish, chipmakers will have advanced solutions to address comparable but inherently more acute problems that stem from the significant differences in the cost and the properties of these two materials.



➤ alpha300 Raman microscope for characterising chemical composition, crystallinity, defects, strain, and doping in wafers up to 300 mm

➤ With a racing car at its stand, Infinera grabbed plenty of attention at ECOC 2023, held at the Scottish Exhibition Centre, Glasgow, from 1-5 October.

Optical communications: Supporting colossal growth with superior lasers

As lasers with traditional architectures are helping to deliver ever higher data rates, newer designs with even more impressive characteristics are promising to gain traction

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

THERE ARE TIMES when anecdotal evidence obscures the big picture. That, though, is rarely the case. Take the youth of today – they have little interest in watching TV, but when the mood takes them they devour hour-after-hour of video clips on their devices. So, based on this observation, it is anything but surprising when market analysts forecast that the global transfer of data is on a continuous rise that shows no sign of abating.

Supporting the watching habits of the young, as well as the lives of all of us, is a rather complex infrastructure that enables the transmission of an astonishing level of data, involving systems working in both the RF and the optical domain. The capability of both is on the rise. For the RF, there's the roll-out of 5G, while capacity of optical communication is increasing through the combination of sources with faster data rates and the laying of more fibre.

Like many of its predecessors, at this year's European Conference on Optical Communication (ECOC) many speakers described efforts to hike data rates with optical technologies. This included the use of more sophisticated modulation schemes for propagating light through an optical fibre – a collaboration between researchers in Japan and Europe unveiled communication at an eye-watering 22.9 Pbit/s by extreme space-wavelength multiplexing – as well as increases in the modulation rate of many forms of laser. And in addition to the traditional approach to data transfer, involving optical fibre, a number of forms of free-space communication were discussed. They included transmission of data from Earth to satellites with 100 W sources emitting at around 1.55 μm, the use of blue and green lasers for underwater communication, and turning to light for the final link in homes and offices. Note that in many applications, one of the key benefits of switching from the RF to the optical is the far higher bandwidth.

At the heart of all these forms of optical communication is the laser. In some cases, this device is directly modulated to deliver the data, and at other times it's combined with some form of modulator.

Those attending ECOC 2023 got to hear a great deal about this vital source of light. In the Market Focus session, held in the exhibition hall, volumes of various forms of laser used in optical communication were discussed by Julie Eng, CTO of Coherent; and Gunter Larish, Product Manager Datacom at Trumpf, spoke about VCSELs for interconnects at more than 100 Gbit/s. Meanwhile, in the conference sessions, Chang Ge from Tokyo University of Technology claimed a record-breaking speed for 1060 nm VCSELs with a metal aperture; and Takuro Fujii from NTT Device Technology Labs, Japan, outlined efforts at developing a directly modulated membrane laser array on silicon. Another novel laser taking prominence at ECOC was the PCSEL, short for the photonic crystal surface emitting laser. Its trailblazer, Vector Photonics, discussed the capabilities of this source in the Market Focus session, the conference, and an off-site meeting held at the company's headquarters – this is just a short drive from the Scottish Exhibition Centre, the location for this year's ECOC.

A Coherent overview

One of the biggest suppliers of lasers to the optical communications market is Coherent. Speaking on its behalf, Eng explained that sales of transceivers are undergoing tremendous growth, while life cycles are typically just 2-3 years. More than half of the products sold today are operating at 200 Gbit/s or more, a sector that will be worth $10 billion by 2028.

The Coherent CTO also offered an insight into the types of materials that dominate, and where they are used. She explained that InP dominates optical communications, accounting for around three-quarters of the market. Of the remainder, GaAs has the largest share, with silicon photonics responsible for just a few percent.

➤ Speaking in the Market Focus session, Coherent's CEO Julie Eng gave an excellent overview of the deployment of various forms of laser in optical communications.

According to Eng, GaAs lasers, in the form of the VCSEL, are widely used in short-reach links of less than 100 m. Meanwhile, technologies based on InP and silicon photonics are deployed for transmission over 500 m to 10 km, and also at more than 10 km, where narrow laser linewidths are needed.

Eng remarked that the GaAs VCSEL is only capable of low powers, but at low cost, and its sales will benefit from the rise in AI and machine learning. Modulation speeds for this class of VCSEL are increasing, with 1 x 4 and 1 x 8 arrays providing 400 Gbit/s and 800 Gbit/s sources. There is now much interest in a 200 Gbit/s VCSEL. "We and the rest of the industry will be working on that," added Eng.

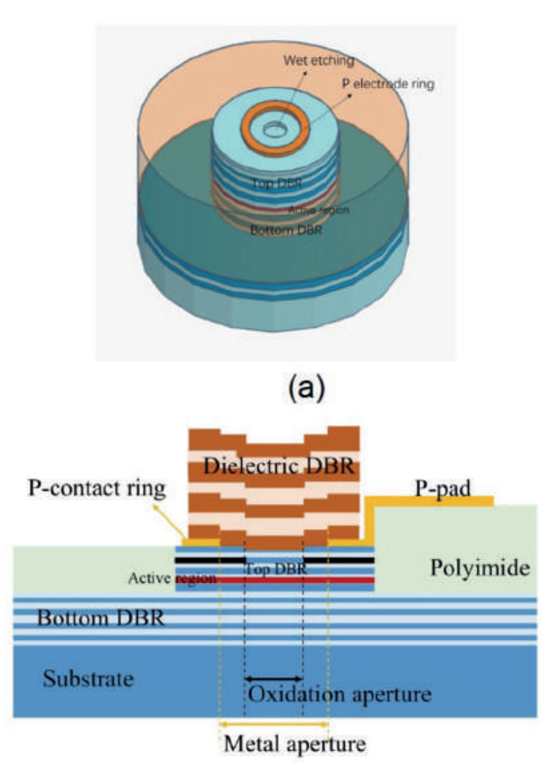
For silicon photonics, which offers modulation and routing, there's a need to combine this chip with a high-power InP laser. Options include 100 mW uncooled and 200 mW cooled sources, according to Eng.

Similar capabilities may be provided with electro-modulated lasers, produced using monolithic integration. Coherent has demonstrated 200 Gbit/s per lane, using a source with 7 dBm (5 mW) of power that's claimed to be suitable for transmitting data over distances from 500 m to a few kilometres.

For longer distances, Eng advocates combining an InP laser emitting in CW with a Mach-Zehnder modulator, a pairing that offers 200 Gbit/s per lane. She encouraged delegates to go to a live demo of this at the Coherent booth, where data transfer took place over 6 km of fibre.

VCSEL virtues

VCSELs are now a high-volume product, with billions shipped every year, partly due to their incorporation in cell phones. The performance of this class of laser continues to advance, with the VCSELs of tomorrow expected to combine an increased channel capacity



➤ Figure 1. The metal aperture VCSELs with surface relief, produced by the University of Tokyo and Ambition Photonics, are capable of record-breaking data rates.

with reduced power consumption and enhanced functionality, according to Larish.

The spokesman for Trumpf told those attending the Market Focus session that his company has been developing VCSELs for many years, and is currently working on increasing the spectral range of this device beyond 850 nm to 880 nm, 910 nm, 940 nm, 980 nm and 1060 nm, for sources operating at 100 Gbit/s. Larish added that the company is already shipping VCSELs with data rates of up to 56 Gbit/s.

Significant progress in combining higher speeds with longer wavelengths, which increase the transmission distance and minimise dispersion, was claimed by Ge, who has been working with colleagues at the University of Tokyo and Ambition Photonics. This team has been advancing VCSELs with a metal aperture, a design that is said to increase bandwidth and improve temperature stability (see Figure 1).

The devices made by Ge and colleagues were fabricated using a surface relief process, involving shallow wet etching to a depth of 30 nm. The team applied this approach to 3-inch epiwafers featuring four InGaAs quantum wells, and top and bottom distributed Bragg reflectors (DBRs) formed with six and 30 mirror pairs, respectively. Confinement of the optical modes is realised with an oxide aperture, typically 5 μm in diameter, and a ring-shaped *p*-contact metal with a diameter of 5 μm, grown on the top DBR. A five pair dielectric is deposited on top of this, and a thick layer of polyimide inserted under the *p*-type pad to reduce parasitic capacitance and increase the modulation bandwidth.

This design provides enhancement of the bandwidth while controlling the transverse mode. Benefits come from the shorter resonance wavelength in the surface relief region, compared with the un-etched region, that allow the optical field to laterally spread into the oxidised region and reflect at the metal-aperture boundary.

Driven at 6 mA, these VCSELs produce a single-mode power of more than 2.5 mW. The divergence angle is 13 degrees, which is "almost the diffraction limit", said Ge.

She shared the results of small signal characterisation at drive currents of 6 mA to 8 mA. "The record modulation bandwidth of over 31 GHz at a bias current of 8 mA was obtained for 1060 nm single-mode VCSELs, thanks to the coupled cavity effects" claimed Ge.

When coupling the emission from the VCSEL into a 2 km length of fibre with a small diameter, modulation bandwidth increased to 35 GHz, thanks to pulse compression. The product of the data rate and the link length is 450 Gbit/s km, claimed to be the highest value ever reported for a VCSEL. "Recently, we demonstrated the record baud rate of over 128 Gbit/s over 2 km fibre transmission with non-linear DSP operation," added Ge.

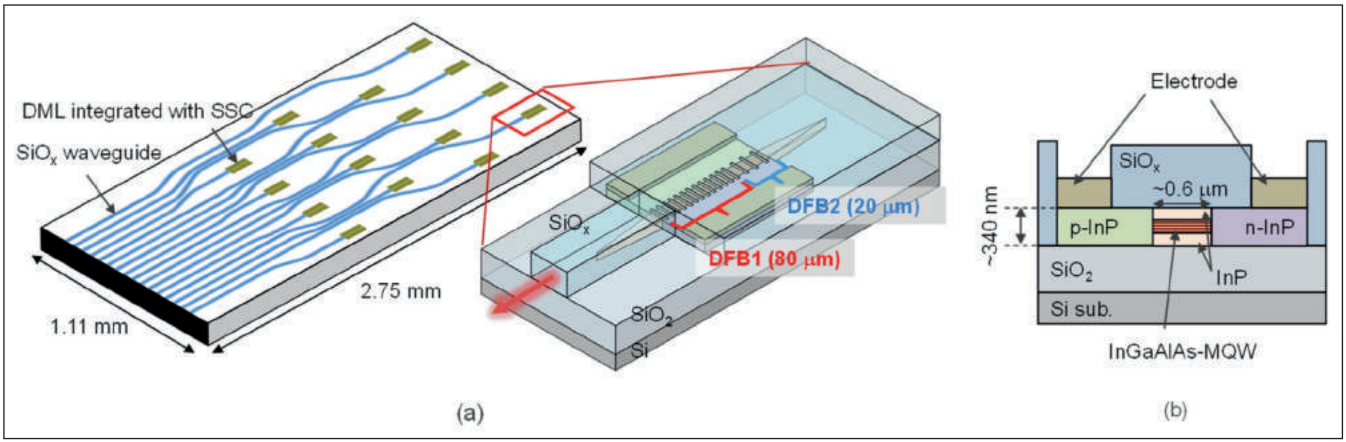
Frugal membranes

As well as helping to meet the demand to transmit ever more data, the lasers of tomorrow need to set a new benchmark for efficiency, to prevent the internet from accounting for an increasingly large carbon footprint. Discussing this matter, NTT researcher Fujii began his presentation by remarking that between 1 and 2 percent of global electrical consumption is associated with the data centre. Note that his company is targeting carbon neutrality for data centres by 2030.

To help produce more frugal data centres, Fujii and his research group have identified three objectives for next-generation devices. These aims, which encompass the need for greater efficiency and include other important requirements, are: a low power consumption, realised with a directly modulated laser with a low active volume; a low assembly cost, aided by the uptake of photonic integrated circuits produced using silicon process technologies; and a small footprint, due to the limited space for components.

"To meet these requirements, we are developing a membrane directly modulated laser on silicon," explained Fujii. "The device consists of a membrane structured laser, together with a spot size converter, so that efficiency coupling to the fibre is achieved."

He emphasised that one of the key features of this device is the thinness of the membrane structure – it is around just 350 nm thick (see Figure 2 for details



➤ Figure. 2. The array of 16 InP membrane lasers by NTT Device Technology Labs has been developed with the aim of reducing the power consumed by data centres.

of the device architecture). This InP-based structure is sandwiched between low-refractive-index SiO_2 materials, leading to a high optical and carrier confinement that helps to reduce the device's power consumption. Above the active region is a grating that ensures single-mode operation with a short cavity, another asset for trimming power consumption.

"Since we fabricate these lasers on silicon, the process can be scalable and we can use large silicon wafers to fabricate these lasers," said Fujii. He added that in future, they could integrate several passive silicon photonic devices with their lasers. Fabrication of the membrane lasers begins by growing an InP-based heterostructure, plus an etch-stop layer, on an InP substrate that is subsequently bonded to a SiO_2-on-silicon wafer.

The InP substrate is then removed, before defining a mesa strip and forming a buried heterostructure with the regrowth of InP. *n*-type and *p*-type doping layers are then defined by thermal diffusion of zinc and ion implantation of silicon. Fabrication is completed with the formation of an InP taper by etching, and the addition of a spot-size converter, created by deposition and etching of SiO_2.

"The key point of our fabrication procedure is to carry out epitaxial growth after heterogeneous integration," explained Fujii. "Why do we use such a unique fabrication procedure? It's because it makes it possible to easily align the devices to the silicon photonic devices in the future."

One downside of membrane lasers is the thermal strain between the InP-based and the silicon-based

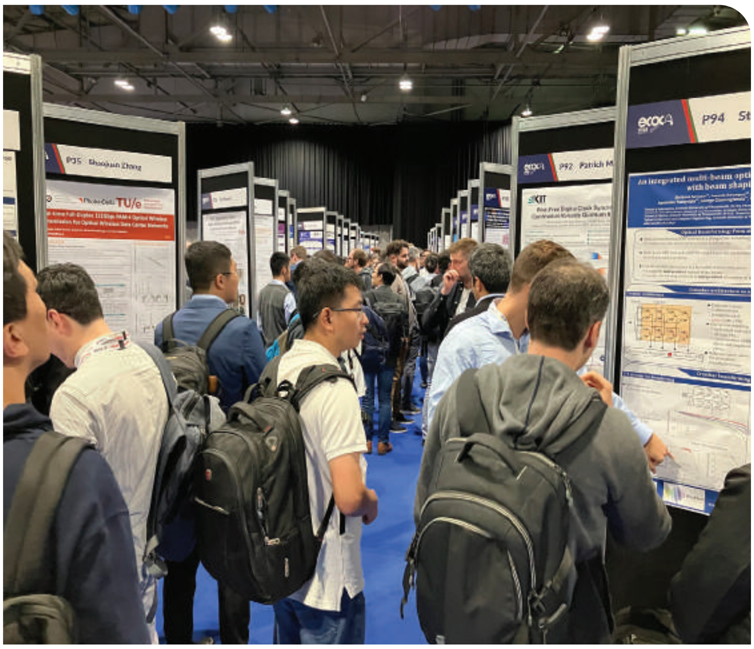


Image credit: Sarah Sennett

structures, due to differences in the coefficients of thermal expansion and the high temperatures required for MOCVD growth. Consequently, to supress thermal degradation, the InP-based heterostructure must be no more than 430 nm-thick, a value described as the critical thickness. NTT have used their technology to develop a number of different devices, including lasers, modulators and photo-detectors. At this year's ECOC, Fuji described the fabrication of a 16 channel directly modulated laser array, featuring 100 µm cavities and a low-loss spot-size converter.

One of the advances in this latest array, compared with previous devices, is the introduction of a non-alloy contact. This enables a smaller differential resistance and better uniformity.

Image credit: Ian Arthur Photography

To characterise the array, Fujii and co-workers applied an RF probe and coupled the output from the laser to a high-numerical aperture fibre using index-matching oil. They found that the lasers produced single-mode emission, and had a threshold current below 1.3 mA and a maximum output power of more than 1 mW. Wavelength variability for the lasers is less than ± 0.2 nm.

The team realised a date rate of 56 Gbit/s at both room temperature and 50 °C when transmitting over 2 km of fibre using 28 GBaud PAM 4 with a 9-tap simple linear equaliser. The transmission had an associated bandwidth density of 807 Gbit/s/mm and an energy cost of 0.65 pJ/bit. Encouragingly, the engineers found no electrical crosstalk between the channels when using a multi-channel RF probe.

Higher data rates were realised by turning to 56 GBaud PAM. This enabled transmission over 2 km of fibre at 112 Gbit/s at room temperature, but required an increase in the number of taps.

"We've also confirmed all 16 channel eye-diagrams, with a received output power of about 0 dB m," said Fujji, who added that the bandwidth density and energy cost associated with this transmission were 1.6 Gbit/s/mm and 0.33 pJ/bit.

The power of the PCSEL

The capabilities of the PCSEL were championed at Vector's headquarters by its Sales and Marketing Director, Euan Livingston. He explained that the Scottish start-up is on a mission to commercialise 2D PCSELs (see Figure 3), which offer a level of functionality that is not possible with other lasers. The PCSEL combines surface emission with high speed, high power and a low cost.

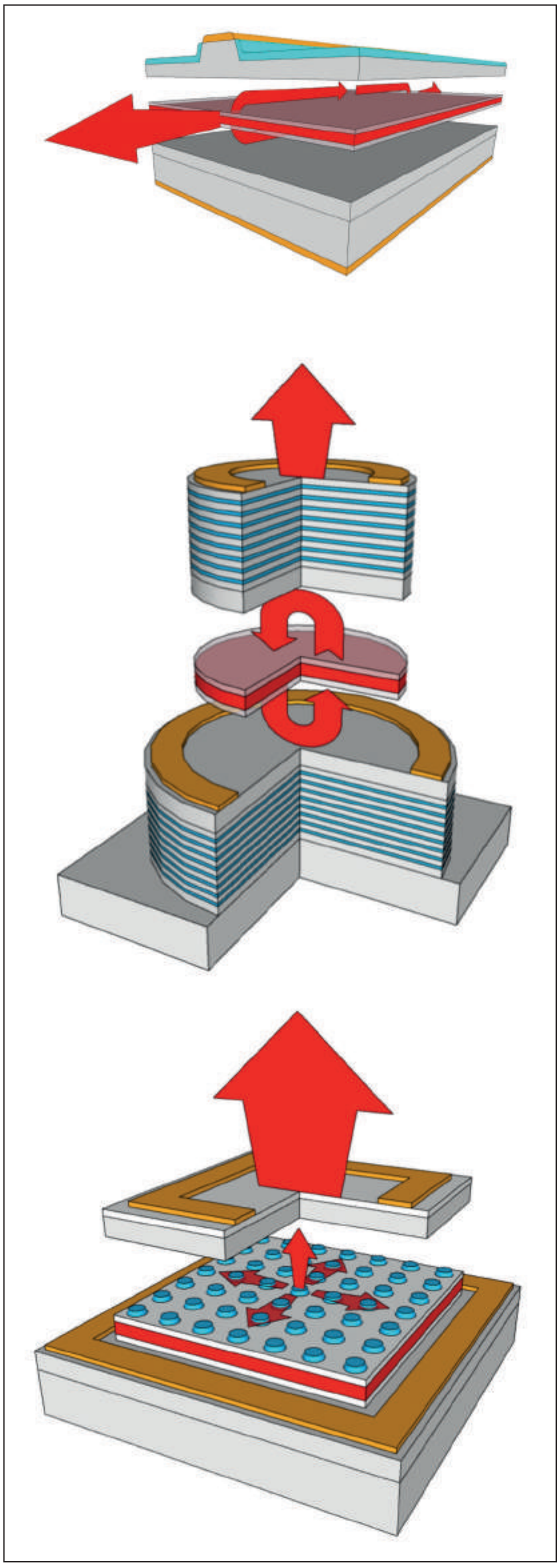
Another great attribute of the PCSEL is its capability to emit an incredibly broad range of wavelengths. Any material that offers optical gain can be used to make a PCSEL. Vector has demonstrated devices with emission from 739 nm to almost 5 µm, using a a design with a quantum cascade laser structure to reach far into the infra-red.

Vector is a fabless company that will draw on a scalable supply chain to ramp up volumes of its devices. For the development of the VCSEL, the company has been well served by Scotland's photonic cluster, which generates annual sales totalling $1.25 billion. Livingston feels that such success fails to get the recognition it deserves, arguing that more attention is given to photonics revenues for Wales, even though that is notably smaller.

During its initial PCSEL development, Vector has been using a local supply chain, with all its partners within 25 miles of its facilities. That's a tremendous benefit, argues Livingston, because if issues arise, engineers can visit production sites, help to identify any problems and support the solutions.

For prototyping, Vector has worked with: III-V Epi, to supply the epiwafers; Kelvin Nanotechnology, a provider of front-end processing; Helia Photonics, which supplies back-end-of-line services; and packaging expert Alter Technology. As volumes increase to tens of wafers per month, Vector may need to introduce new partners.

The timing of Vector's launch was far from ideal, with the company formed on 13 March 2020, just days before the UK went into lockdown. This led to efforts to secure funding through on-line meetings, an approach that hampers efforts to build a rapport, but did not prevent Vector from raising significant investment. Innovate UK has provided financial support every year, with an initial investment of £2 million followed by £0.7 million in 2021, £2 million in 2022, and another £1 million in 2023. Alongside this £5.7 million, another £4.1 million has been raised from private equity. The company is now in the process of trying to secure additional investment, designed to support the company through to the end of 2024.



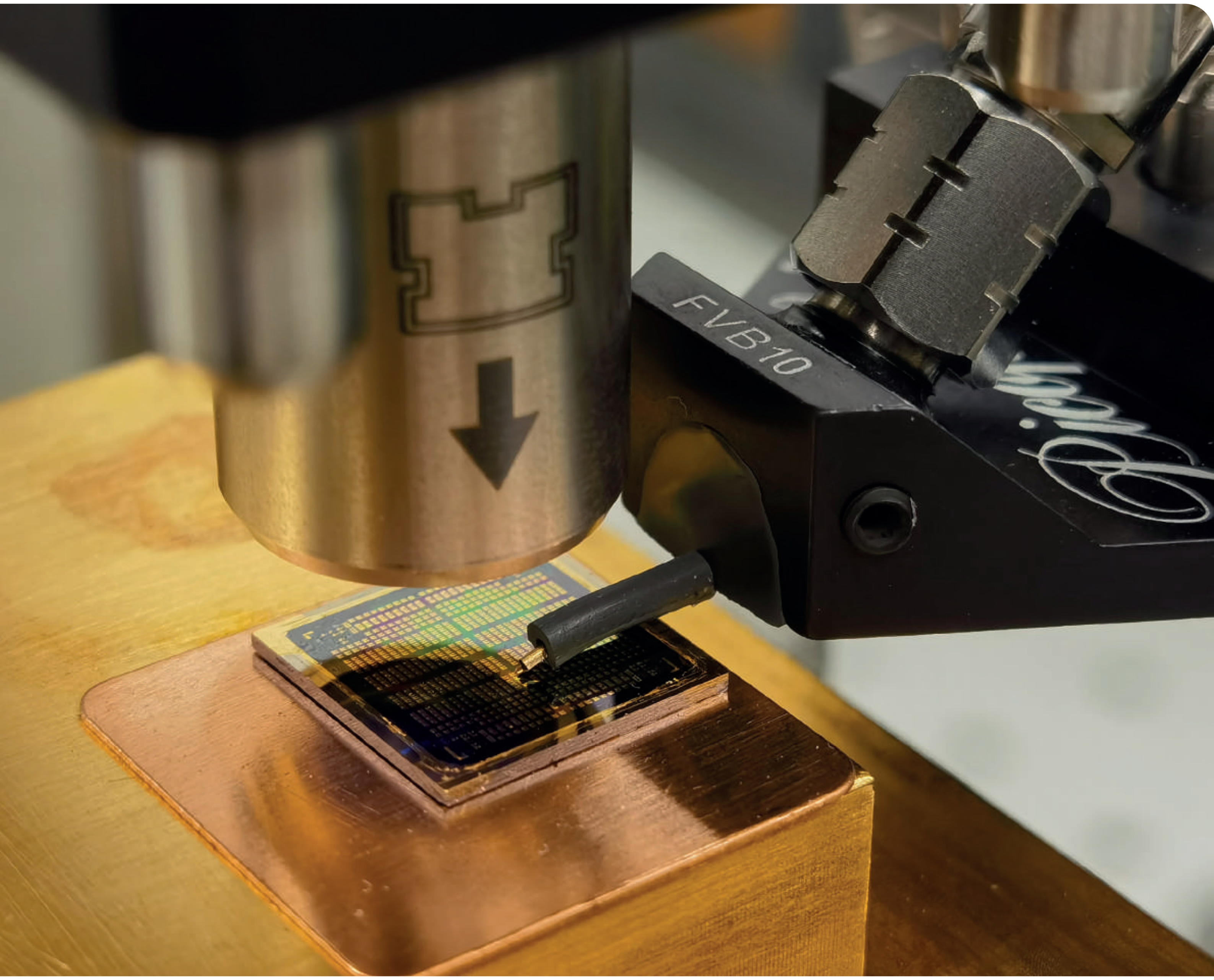
➤ Figure 3. The two most common forms of the laser are the edge-emitter (top) and the VCSEL (middle). Vector Photonics is on a mission to commercialise the Photonic Crystal Surface Emitting Laser (PCSEL), which combines surface emission with high speed, high power and a low cost.

One of the big challenges facing Livingston and his fellow executives is determining which sector to pursue with their PCSELs. This class of laser is a promising alternative for deployment in many applications, and it could be used in cars, phones, computers, the internet and 3D printing. Vector's leaders considered the opportunity associated with lidar, but found that the market for lasers was only worth $100 million, so looked elsewhere.

Now they expect the communication sector to provide the opportunity to ramp production and revenue, with the PCSEL supporting data rates of 800 Gbit/s and 1600 Gbit/s. Vector has identified 15 customers operating in this sector with very similar requirements. According to Livingston, the DFB lasers that serve in this application are limited to output powers of 100 mW or so, while the PCSEL can go far higher.

As well as evaluating and refining prototypes and evaluating market opportunities, Livingston and his colleagues are devoting much effort to securing their intellectual property, with meetings with patent lawyers on a weekly basis. Despite the high cost, Vector is filing patents. Initially they are filed in the UK, before the US, Europe and Japan.

The need to protect IP on a global scale reflects the worlwide production of III-V lasers, a device well represented at ECOC. There continues to be much progress in both the manufacture and development of these vital light sources for optical communication, with breakthroughs sure to feature at next year's meeting, the fiftieth conference in this series, which will be held in Frankfurt from 22 to 26 September.



Extending the reach of high-speed VCSELs

Single-mode oxide-VCSELs incorporating a double aperture can transmit data at nearly 100 Gbit/s over 1 km links

BY HAONAN WU, DUFEI WU AND MILTON FENG FROM UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN AND XIN YU FROM FOXCONN INTERCONNECT TECHNOLOGY

TODAY the VCSEL is probably best known for its widespread use as a proximity sensor in smartphones. But its first high-volume market is datacoms, a sector that continues to provide substantial sales to many makers of this class of laser.

For more than twenty years ultra-low-power, oxide-confined VCSELs, which use an oxide aperture to confine the emission, have provided a cost-effective and scalable solution to short-reach optical interconnects in data centers. Supporting links of no more than 100 m or so, these devices combine low-power consumption with a compact form factor and high-speed data transfer. It's a set of attributes that assist in the efficient operation of data centre networks.

Unfortunately, conventional multi-mode oxide VCSEL cannot be deployed to transmit data over longer lengths of fibre. Due to differential modal delay and chromatic dispersion in multi-mode fibre, the multi-mode nature of the emission makes this device unsuitable for optical data transmission over distances of several hundred metres or more. Transmission over such distances is needed, for example, to connect one hub to another.

One option for extending transmission is to turn to a single-mode VCSEL. Using this approach, a team from Chalmers University of Technology, Sweden, reported 20 Gbit/s non-return-to-zero data transmission for link lengths of up to 2 km. However, that group's approach to realising single-mode emission involved scaling the oxide-aperture. This has downsides, including a compromised reliability and a thermally limited laser operating current at a high modulation bandwidth.

What's clear is that there's a need to develop high-performance, single-mode VCSELs, as they are a vital ingredient to trimming the cost of emerging technologies, such as 5G networks, where high-speed and low-latency data transmission is critical for wireless backhaul and fronthaul connections. Success on this front would also create sources with a circular beam profile that are compatible with standard single-mode optical fibre. Such interoperability simplifies the integration of single-mode VCSELs into existing long-distance optical communication networks, making them a practical, cost-efficient choice for network upgrades and expansions.

A novel design

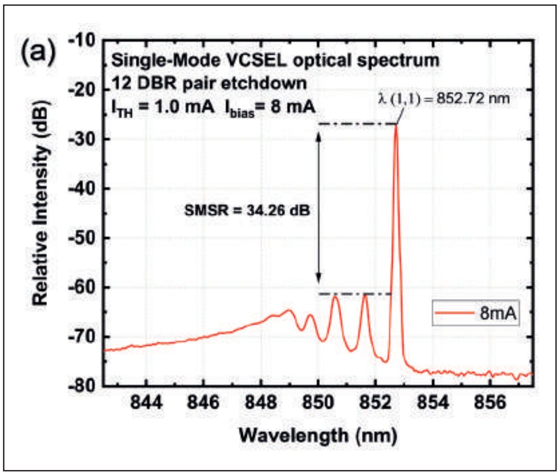
Breaking new ground on this front is a form of VCSEL with an innovative integrated-mode-select-filter, a design pioneered by our collaboration between the University of Illinois at Urbana-Champaign and sponsored by Foxconn Interconnect Technology.

In terms of fabrication, a key difference between our design and that of a conventional VCSEL is that ours requires a two-step oxidation process to form the top and bottom oxide apertures (see Figure 1, which provides a cross-sectional view of the device). Aside from that, our design is similar to that of a conventional oxide-VCSEL – it features a half-wavelength cavity, a *p*-doped distributed Bragg reflector mesa, an electrical current/optical confinement oxide layer, and contact metals.

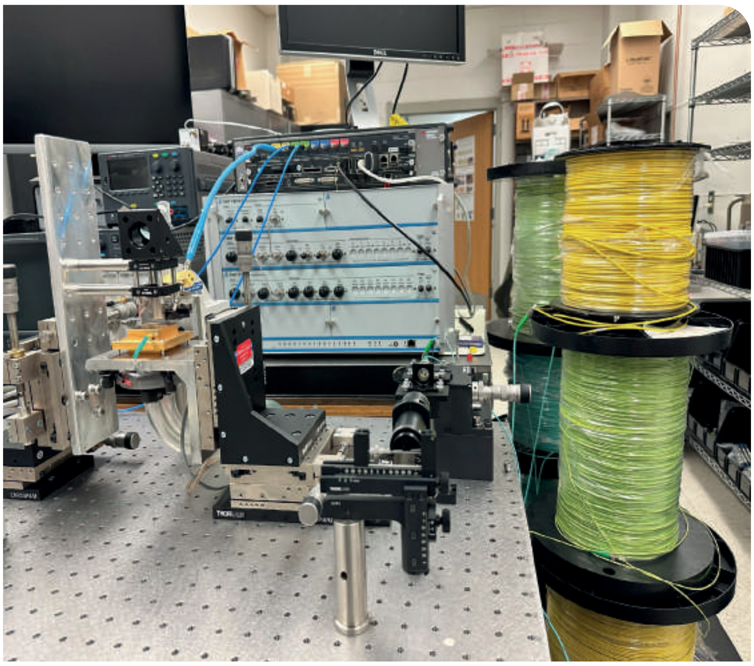
To create the top oxide aperture, we oxidise multiple *p*-type pairs in the distributed Bragg reflector. This is followed by the formation of the integrated-mode-select-filter mesa, which is around 6 μm in diameter, and defined by a calibrated, chlorine-based dry etch using reactive ions and an inductively coupled plasma. By fine-tuning the composition of the dry etching gas, adjusting the plasma pressure, and optimising the ratio of reactive ion etch to the power of the inductively coupled plasma, we realise precise control over the sidewall of the mesa. This enables us to produce smooth sidewalls that maintain a 90-degree orientation relative to the *p*-type distributed Bragg reflector mesa. Note that due to difficulty in controlling the oxidation rate of this mesa, it is essential to have precise dry-etching process control, as this is key to defining the top oxide aperture size. Another key to a high yield across the entire sample is accurate control of the top and bottom oxide aperture ratio.

➤ Figure 1. Cross-section view of the integrated-mode-select-filter (IMSF) mesa structure and bottom oxide aperture of the fabricated single-mode VCSEL. The single transverse-mode operation is achieved with an optimised top and bottom aperture ratio and IMSF height. The scanning electron microscopy image is the fabricated device sliced by the focused ion beam.

Thanks to the unique mesa structure in our novel VCSEL, this design favours the lasing condition of the fundamental mode (or the LP_{01} mode, if we approximate the VCSEL cavity as a cylindrical waveguide). In the weakly guided core/cladding waveguide, the fundamental mode peaks in the centre of the waveguide, while the higher-order modes are concentrated near the periphery. As a result, the small top aperture reduces the quality factor of higher-order modes, thereby altering the



➤ Figure 2. Measured optical spectrum of the single-mode VCSEL. The side-mode suppression ratio exceeds 34 dB.



VCSEL free-space optical coupling setup for long-distance optical fiber data transmission measurement.

modal characteristics and ensuring that only the fundamental mode is favoured.

We have undertaken DC characterisation of our integrated-mode-select-filter VCSELs at room temperature, using fibre-optic coupling with a ball lens (see Figure 2 for the typical measured optical spectrum). We have found that the fibre-coupled optical power of our lasers ranges from 1.3 mW to 1.6 mW at 8 mA, and the threshold current varies from 0.8 mA to 1.0 mA among all measured devices. All the VCSELs we have characterised exhibit single-mode operation with a fundamental mode wavelength near 852 nm, and have a single-mode-suppression-ratio exceeding 34 dB at 8 mA, satisfying the specifications of the IEEE 802.3 standard.

To evaluate the variations from one device to another, we have mapped our single-mode VCSELs driven at 8 mA, considering a single quadrant on the 1.2 cm x 1.2 cm sample (see Figure 3 (a), which includes green labels on this map that signify those devices that underwent rigorous examination). We are encouraged by finding that all our devices demonstrate single-mode operation up to thermal rollover.

We have subjected these devices to rigorous testing under different conditions, spanning room temperature to 70 °C and using fibre spool lengths from back-to-back to 2 km. Notably, throughout these examinations, we did not uncover any sign of optical power decline or any shift in the lasing threshold.

Cranking up the speed

Back in 2021, using an early generation of our novel VCSELs, we reported a record speed performance of 38 Gbit/s over 1 km of single-mode fibre, for error-free optical data transmission using a non-return-to-zero configuration. To realise even higher speeds, we can switch to advanced modulation schemes, thanks to the single-mode output of our devices.

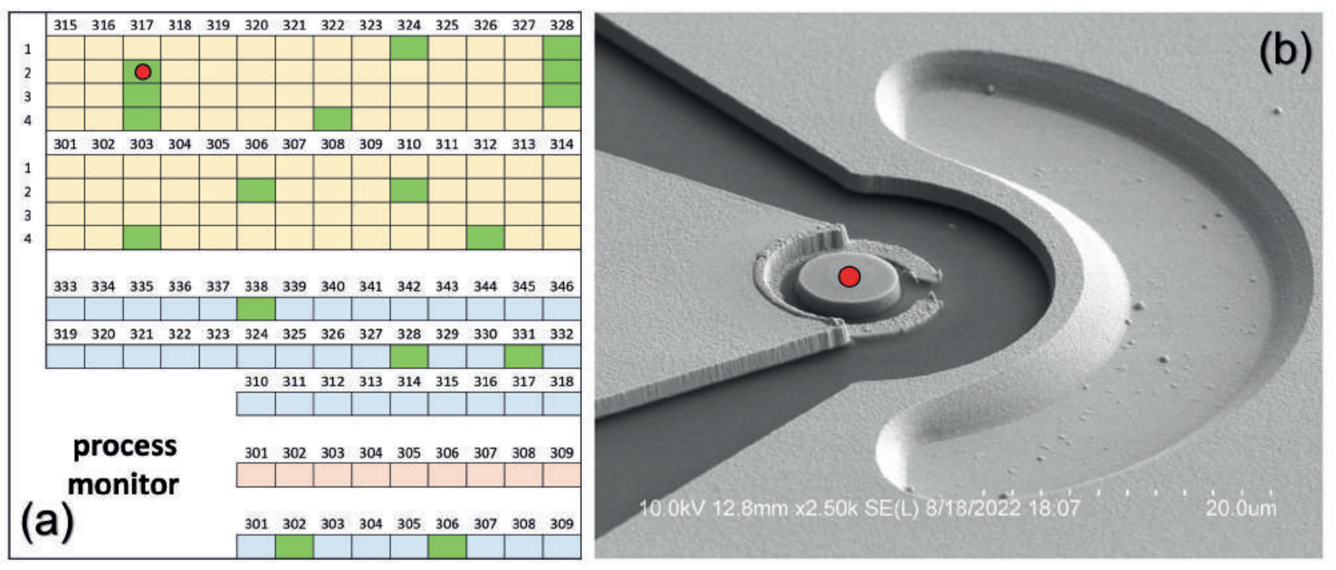
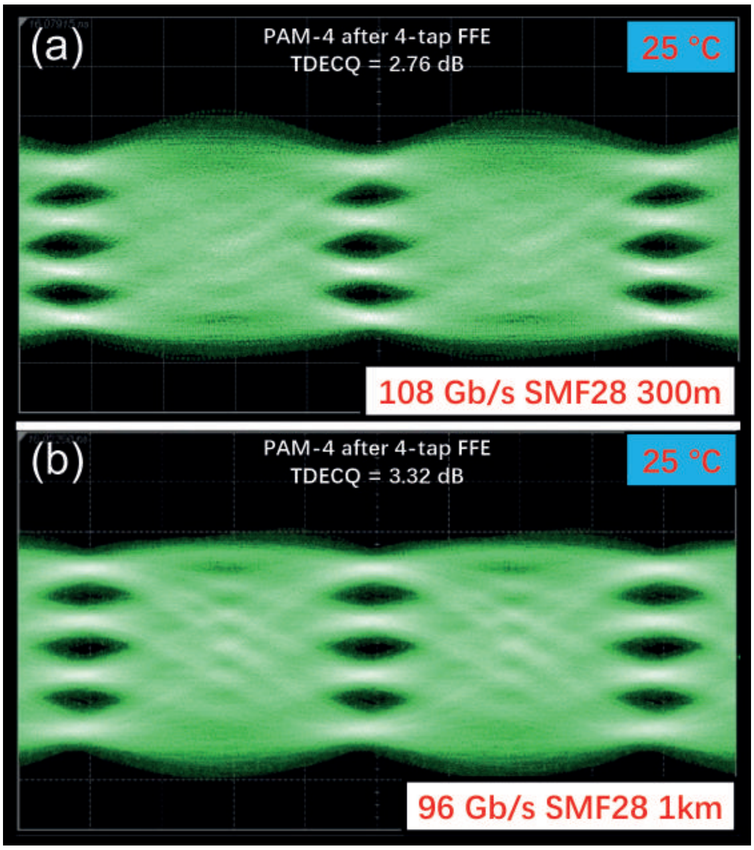


Figure 3. (a) The single-mode VCSEL testing map of one quadrant on a 1.2 x 1.2 cm^2 sample. All tested VCSELs are labelled green, showing single-mode operation with a side-mode suppression ratio of more than 34 dB. The red dot labelled single-mode VCSEL under test for both DC and PAM-4 data transmission. (b) The scanning electron microscopy top-view image of the single-mode VCSEL under test, providing clear visualisations of the integrated-mode-select-filter mesa structure, the top *p*-contact, and the coplanar waveguide used in the high-speed VCSEL layout. The red dot shows the device location on the wafer map.


CS INTERNATIONAL CONFERENCE
ANGELTECH



➤ Figure 4. Single-mode VCSEL PAM-4 eye diagrams at (a) 108 Gbit/s (300 m SMF-28) and (b) 96 Gbit/s (1 km SMF-28) with a standard 4-tap feed-forward equalizer. The device under test was supplied with 7 mA DC current via SHF BT65R bias tee and directly modulated by the grey-coded PRBS13 (PRBS13Q) data pattern, which is generated by the Keysight 120 GSa/s M8194A arbitrary waveform generator. All eye diagrams are un-averaged, and the transmitter dispersion eye closure quadrature (TDECQ) value is calculated based on the PRBS13Q pattern. The TDECQ values were calculated assuming a target symbol error rate of 4.8 x 10^{-4}.

One common advanced modulation scheme is Pulse Amplitude Modulation-4. Due to the rapid expansion of cloud services and data centres, this form of modulation has been standardised for 400 Gbit/s Ethernet in the IEEE Standard 802.3. Using Pulse Amplitude Modulation-4, last year we reported 96 Gbit/s data transmission over 1 km of fibre at room temperature.

We have measured room-temperature eye diagrams with this form of modulation, which enables data rates as high as 108 Gbit/s (see Figure 4 for details).

Given concerns related to carbon footprints, another key metric is energy per bit consumption. For 330 m and 1 km links, this is calculated to be 175.1 fJ per bit and 196.9 fJ per bit, respectively.

The very promising performance of our directly-modulated single-mode VCSELs makes them compelling candidates for playing a vital role in optical fiber communication, especially in scenarios where production scalability, low manufacturing cost, high-speed and long-distance are essential. Their performance advantages and low cost make them strong contenders for deployment in 400 GBase-DR4 optical links in data centers. We will contiunue to refine their characteristics, with efforts directed at optimising device topology, so this will ensure an even higher reliability and intrinsic device bandwidth for data rates beyond 120 Gbit/s per lane.

We acknowledge the sponsorship of CNICE on the single-mode VCSEL research project by Foxconn Interconnect Technology, a leading interconnect company led by Mr. Sidney Lu, UIUC's distinguished alumni. The authors would also like to thank Dr. Mike Gerhold for ARO support for Microcavity Laser Design and PAM-4 Test under. No. W911NF-22-1-0046.

FURTHER READING

➤ R. Safaisini *et al*. "20 Gbit/s data transmission over 2 km multimode fibre using 850 nm mode filter VCSEL," Electron Lett. **50** 40 (2014)

➤ J. Qiu *et al*. "Advanced Single-Mode 850 nm VCSELs for Record NRZ and PAM-4 Data Rate on SMF-28 Fiber up to 1 km," in Optical Fiber Communication Conference, 2021

➤ M. Feng *et al*. "Related U.S. Application Data (60) Provisional application No. 62 / 744," 2017

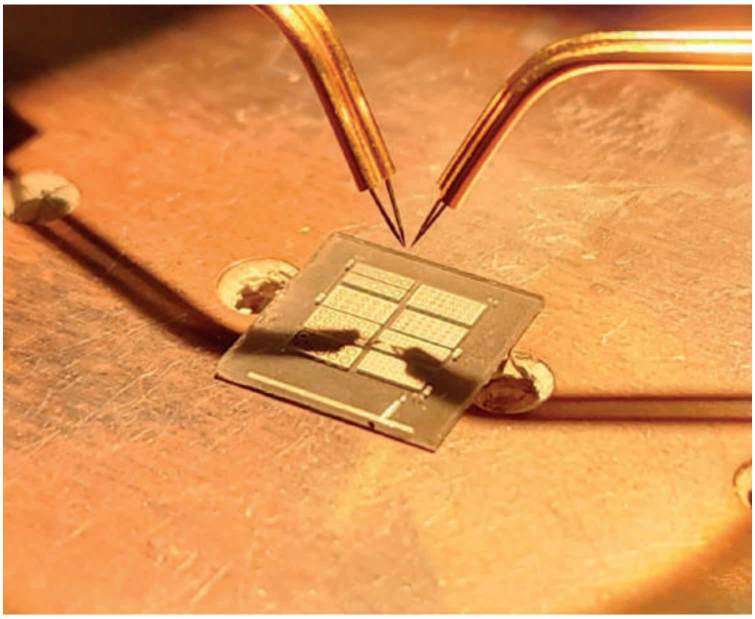
➤ J. Qiu et al. "85°C Operation of Single-Mode 850 nm VCSELs for High Speed Error-Free Transmission up to 1 km in OM4 Fiber," in Optical Fiber Communication Conference, 2019

➤ J. Qiu *et al*. "50 Gb/s VCSELs with an Integrated Mode-Selected Filter for Extending OM4 Transmission up to 1 km and 70°C," in Optical Fiber Communication Conference

➤ D. Wu *et al*. "Single-mode 850nm VCSELs Demonstrate 96 Gb/s PAM-4 OM4 Fiber Link for Extended Reach to 1km," in Optical Fiber Communication Conference, 2022

By delivering record electron and hole concentrations in AlN, low-temperature epitaxy promises to unleash a new generation of extreme bandgap devices

BY CHRISTOPHER MATTHEWS, HABIB AHMAD, KEISUKE MOTOKI, SANGHO LEE, AHELI GHOSH, EMILY MARSHALL, AMANDA TANG AND W. ALAN DOOLITTLE FROM GEORGIA INSTITUTE OF TECHNOLOGY



AlN: Opening doors with low-temperature epitaxy

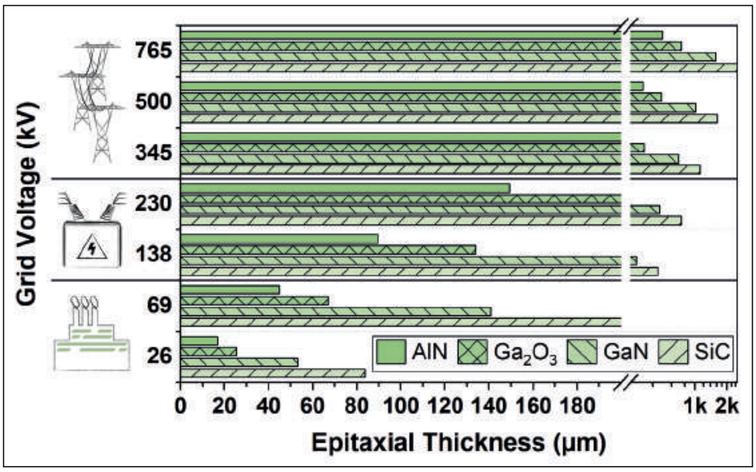
UNFORTUNATELY, today's materials are not going to meet tomorrow's needs. That's not to say that GaN and SiC have not had substantial success – they are transforming power electronics and making solid-state lighting a reality. However, these wide bandgap materials have limitations when employed for high-power diodes and transistors for grid-scale electronics and electric vehicles, and they cannot be used to make ultraviolet emitters for sterilisation and lithography.

Offering much promise on all these fronts are a number of materials with even wider band gaps that have been attracting increasing attention in recent years. They include Ga_2O_3, diamond, and very recently, AlN.

For all of these materials, progress at the device level is far from easy. Ga_2O_3 has a number of great attributes, including a bandgap of 4.9 eV, a high critical electric field and compatibility with inexpensive bulk growth methods. But there are weaknesses: devices are limited to those that are unipolar, due to only *n*-type doping; and recent results have highlighted the low thermal conductivity of this oxide, hindering its applicability to power electronics.

Offering an even higher bandgap of 5.5 eV is diamond, which benefits from a high thermal conductivity and other favourable material properties. However, despite impressive recent substrate advances, diamond is difficult to dope and expensive to produce. This material is also hampered by its indirect band gap, making it unsuitable for optoelectronic applications, which have been a major leveraging factor for driving early investment and research in other semiconductors, such as GaN.

AlN has also garnered interest, thanks to its direct bandgap of 6.1 eV, its high critical electric field of 15.4 V/cm, its high thermal conductivity of 319 W/mK, and its compatibility with the established III-nitride infrastructure. However, doping AlN is challenging.



➤ Figure 1. Minimum required device thickness versus grid voltage for various points along the power transmission grid, assuming the theoretical critical electric field limits (taken from J. Y. Tsao *et al*. Adv. Electron. Mater. **4** 1600501 (2018)). Thicknesses below 200 μm are considered reasonable for semiconductor devices. For higher voltage transmission applications, every material requires an unreasonably high device thickness. However, AlN is the only material compatible with substation-level applications at both 230 kV and 138 kV. While multiple materials can hold off lower voltages, AlN devices require the least material, which makes them a comparatively economical choice.

Prior to 2020, reported carrier concentrations were limited to around 10^{10} cm^{-3} for holes and 10^{15} cm^{-3} for electrons.

Our team at Georgia Institute of Technology has smashed through this ceiling with metal-modulated epitaxy (MME), a low-temperature variant of MBE. Using MME, we have realised *p*- and *n*-type doping in AlN with beryllium and silicon dopants, respectively, obtaining carrier concentrations greatly exceeding previously reported values – they are well above 10^{18} cm^{-3}. Read on to discover how low-temperature MME enabled this success.

Epitaxial considerations

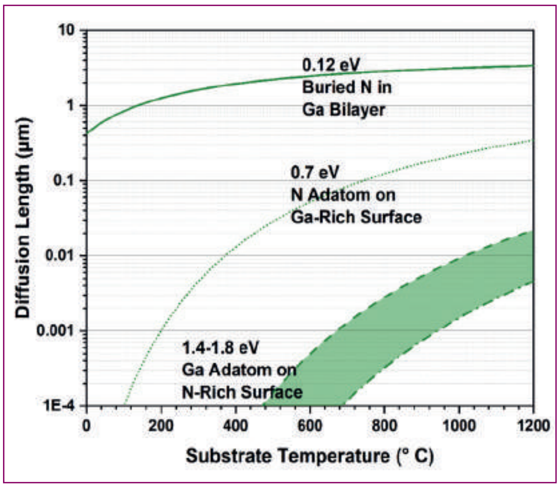
In III-nitride semiconductors, the doping efficacy is largely influenced by the concentration of unintentional point defects. They include: contaminant atoms, typically oxygen, carbon, and hydrogen; cation vacancies; N-vacancies (V_{Al} and V_N for AlN); and reconfigurable defects, such as the DX-centre. Thus, it is of utmost importance to limit the incorporation of undesired impurities and the formation of vacancies, especially when trying to dope notoriously insulating materials, such as AlN.

These impurities, arising from various sources, are dependent on the growth technique. For oxygen and carbon contamination, two competing thermal mechanisms are at play. Higher temperatures increase the extent of the degassing of these elements from structural components within a growth chamber, but this is somewhat counterbalanced by a simultaneous decrease in their sticking coefficient on a semiconductor surface. To limit the incorporation of oxygen and carbon in thin films, growth is typically conducted at diametric temperatures – that is, as low or as high as possible.

For III-nitride epitaxy, the formation of vacancies is often thought to be related solely to the III/V (or V/III) ratio, with V_{Al} occurring for N-rich growth and V_N occurring for metal-rich growth, with the majority flux used to replace atoms lost to desorption. More generally, the concentration of vacancies is related exponentially to the temperature, so one useful strategy to reduce the vacancy concentration is to dramatically reduce the temperature.

One example of the diametric approach is MOCVD. This epitaxial growth technique employs high temperatures and thermodynamically produces high concentrations of V_N. However, kinetically, the massive V/III ratio that's used in MOCVD replaces these V_N as they are produced.

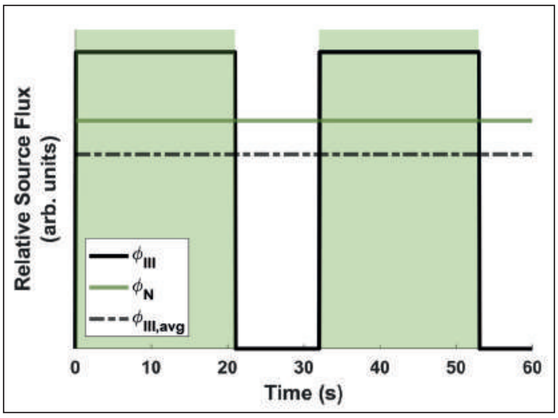
The opposite approach, involving low temperature methods, never creates the enormous surface concentrations of vacancies by removing the thermodynamic driving force. Due to this, even excessive aluminium-rich III/V ratios lead to a low concentration of V_N, regardless of the flux that's used. In most cases, the epitaxy of compound semiconductor layers is conducted near the highest temperature possible for that material, typically helping to promote the growth of smooth films. For the III-nitrides, this approach has been pursued to optimise films that are grown under nitrogen-rich growth conditions. However, there is a dramatic shift in physics for metal-rich growth that's been overlooked. Essentially, high temperatures are needed in the nitrogen-rich regime to overcome large surface binding energy barriers and promote long-range adatom hopping, critical for the formation of smooth films. These barriers are much lower when adatoms exist on a metal-rich surface, ensuring that a similar degree of diffusion is possible at much lower temperatures.



➤ Figure 2. Representative calculations of the hoping rates and surface diffusion lengths as a function of various atomic diffusion pathway barriers. Nitrogen in a gallium bilayer has a diffusion length on the order of one micron, even at low growth temperatures.

It is easy to see these factors at play when comparing the diffusion lengths of the limiting reactants in GaN growth on different GaN surface terminations. For N-terminated (or dry) GaN surfaces, the diffusion barrier for gallium is between 1.4 eV and 1.8 eV. In comparison, the barrier is only 0.7 eV for nitrogen diffusion on a gallium terminated surface, and it is as low as just 0.12 eV for surfaces covered in a bilayer of gallium. Due to these variations, adatom surface diffusion lengths are significantly higher for metal-rich growth, exceeding 3 µm, compared with lengths for nitrogen-rich growth, even at much lower temperatures.

Based on this observation, reconsidering the use of high growth temperatures is worthwhile. After all, high quality III-nitride films can be realised at low growth temperatures using metal-rich conditions, while high growth temperatures have several downsides: there is an increase in impurity generation due to outgassing of structural components; greater thermal expansion takes place, introducing unwanted strain; and doping can be impaired.

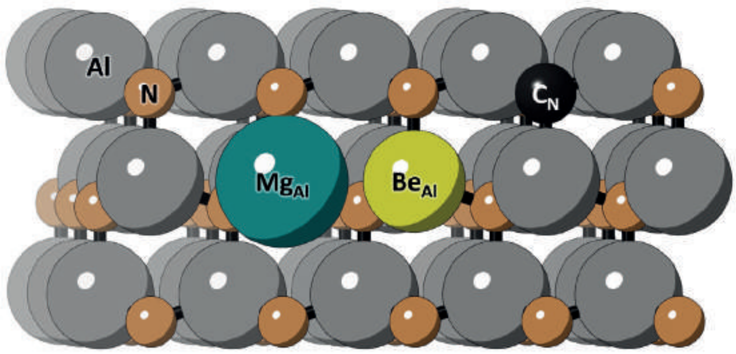


➤ Figure 3. Typical flux profiles as a function of time in metal-modulated epitaxy. Instantaneous metal flux (ϕ_{III}) is higher than the nitrogen flux (ϕ_N), ensuring that growth occurs in metal rich conditions. The time-averaged metal flux ($\phi_{III,avg}$) is lower than (ϕ_N), eliminating droplet build-up.

Unfortunately, it's not as easy as simply lowering the growth temperature and using exclusively metal-rich conditions. If that approach is adopted, it leads to an excess droplet build-up of metal, and ultimately has adverse effects on III-nitride film quality. What's needed is a modulated growth technique, alternating between metal- and nitrogen-rich growth conditions. Typically implemented as a variation of MBE, this approach takes advantage of the benefits of metal-rich growth and limits the accumulation of excess metal.

Chief among these modified growth methods is MME. With this form of epitaxy, the MBE metal flux is in excess of the nitrogen flux by between 30 percent and 200 percent. A key part of the process is physically shuttering the metal sources, undertaken in a manner that ensures that the time-averaged growth conditions are nitrogen-rich through periodic removal of all metal accumulation (see Figure 3). When the metal shutters are opened, the surface is quickly terminated by a metal adlayer. Accumulation continues until the metal shutters are closed, at which point the metal adlayer is consumed by the continuous supply of active nitrogen. Once the metal adlayer is fully depleted, the film briefly stops growing until the metal shutters are re-opened and the cycle repeats. However, since the growth reaction only depends on the amount of adsorbed metal on the surface, rather than the metal flux, growth (almost) always occurs in metal-rich conditions.

➤ Figure 4. Positions of and relative size (to scale) of magnesium, beryllium, and carbon acceptors in AlN.



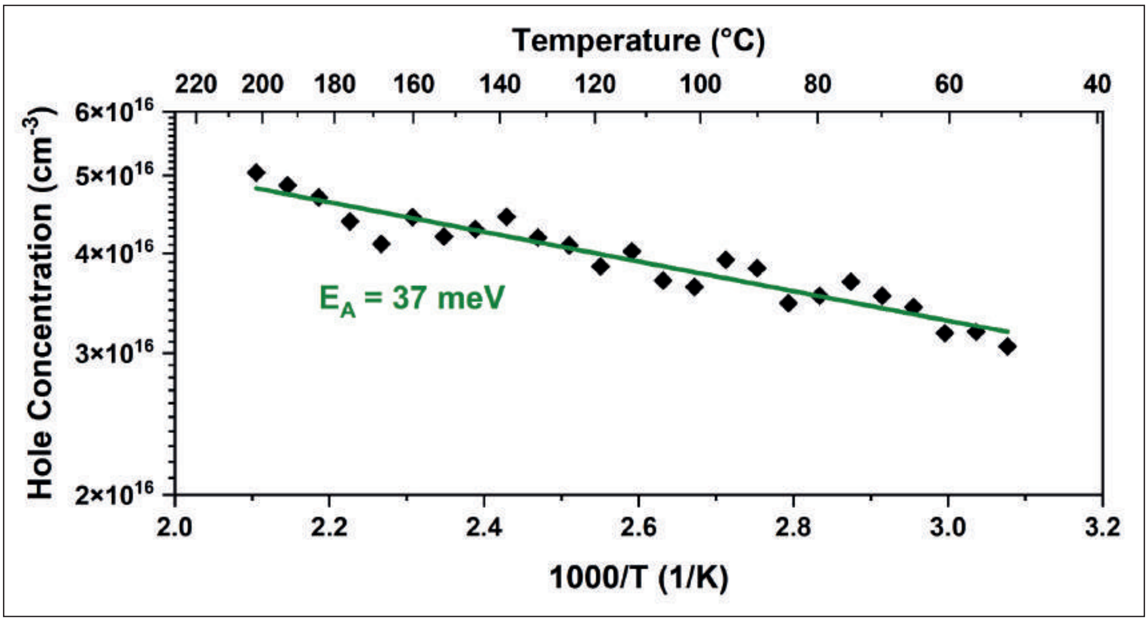
Our group developed MME in 2007. Since then, we have used this form of epitaxy to deliver a number of impressive results in the III-nitrides, including: growth rates of nearly 10 µm/hr; single-phase ternary III-nitrides, without phase separation, throughout the miscibility gap of InGaN and at technically relevant compositions in the miscibility gap of AlInN; high *n*-type doping, with electron concentrations in GaN above 10^{20} cm^{-3}; extremely high *p*-type doping, with hole concentrations in GaN above 6×10^{19} cm^{-3}; and tunnel junctions in GaN with extremely low voltage drops (0.14 V), and in AlGaN alloys with up to 60 percent aluminium. Note that all this success has come without compromising film quality. Typical MME-grown films produce excellent X-ray diffraction figures-of-merit – that is, the rocking curve line widths match the substrate – alongside smooth surfaces, with a root-mean-square roughness below 1 nm, as has been demonstrated in multiple devices.

Initially our results, especially the doping successes, were fairly controversial, due to their incompatibility with the understanding of III-nitrides grown by traditional methods. For instance, prior theory and experimental results found that magnesium had a deep acceptor activation energy in GaN, limiting hole concentrations, but we found shallow acceptor activation in MME-grown films. This finding came as a surprise. Upon further inspection we realised that theoretical reports tend to only consider doping at levels close to the equilibrium solubility limit of the dopant impurities, a restriction that results in deep, isolated acceptor states in the band gap. With MME, growth is kinetically limited, allowing for deviations from equilibrium conditions, specifically hyper-doping beyond solubility limits. One consequence is that dopants can be forced into films at higher concentrations than the equilibrium solubility limit – and when the concentration is particularly high, the Bohr orbitals of these dopants start to overlap, creating a dopant band. For the magnesium dopant in GaN, formation of the acceptor band reduces the effective activation energies from around 210 meV to 50 meV. This leads to hole concentrations of nearly 1×10^{20} cm^{-3}.

Following on from this work, we found an acceptor band in AlGaN with an aluminium composition of up to 60 percent. This observation provided the basis for investigating doped AlN.

Producing *p*-type...

We considered three potential dopants for *p*-type AlN: two of them were cation-substituted magnesium (Mg_{Al}) and beryllium (Be_{Al}), and the other was anion-substituted carbon (C_N). Magnesium is the natural first choice, due to its use as the primary *p*-type dopant for GaN. However, the highest



➤ Figure 5. Temperature dependent Hall measurements of *p*-AlN showing an activation energy of 37 meV. Jeff Lindemuth from Lake Shore Cryotronics, Inc. is thanked for performing this measurement.

reported hole concentrations in magnesium-doped AlN are less than 10^{10} cm^{-3}. According to theoretical studies, magnesium behaves as a deep acceptor with an activation energy of 510-630 meV. While it is possible that this dopant could form a magnesium acceptor band, that's unlikely. There is a reduced solubility of magnesium in AlN, coming from a large atomic radius mismatch between aluminium (118 pm) and magnesium (145 pm), as shown in Figure 4. It's also worth noting that there are reports of a reduced efficacy of magnesium-doping on hole generation as the aluminium-content in AlGaN is increased, and thus, the average cation size is decreased.

Carbon is a similarly unrealistic dopant, but for different reasons. While there is a report of limited, surface-level *p*-type conduction in carbon-doped AlN, this candidate for doping is yet to provide substantial bulk hole concentrations in AlN and it is commonly understood to be a compensating impurity in AlN. Another major concern is that the carbon concentrations in MOCVD-grown III-nitrides are inconsistent from run-to-run, due to carbon in the metal-organic sources. The likelihood is that this unwanted variation would make carbon doping difficult to control.

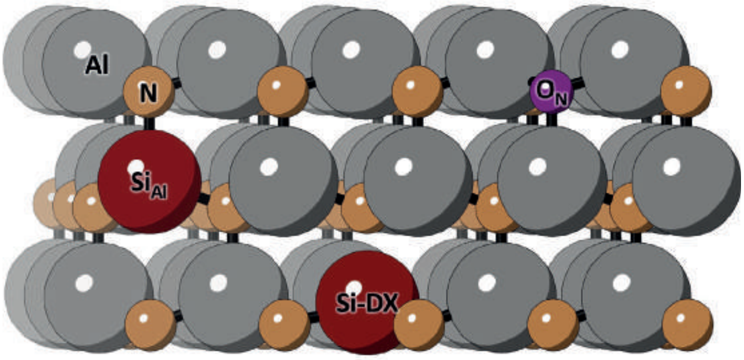
That leaves beryllium as the most promising *p*-type dopant. While it's also predicted to be a deep acceptor, having an activation energy of 220-340 meV, it does not suffer from the same issues as carbon and magnesium. Unlike magnesium, there's a fairly small atomic radius mismatch, because the radius for beryllium is 112 pm (see Figure 4). Due to this, there is the promise that the high solubility of beryllium in AlN enables acceptor band formation. Our recent studies support this possibility, with investigations determining a room-temperature hole concentration of 4.4 x 10^{18} cm^{-3} in beryllium-doped AlN, along with an effective activation energy of 37 meV (see Figure 5).

Based on work from the Nobel Prize-winning condensed matter physicist Sir Neville Mott, in partnership with W.D. Twose, it is possible to estimate the critical dopant concentration at which an energy band begins to form. For beryllium in AlN, the beryllium concentration in AlN could be predicted to be a staggering 4 x 10^{21} cm^{-3}, equating to roughly 4 percent of the atomic density of AlN.

Why so high a value? It's because the calculation assumes that the valence band structure of AlN is similar to other III-nitrides – and that's not actually the case. For AlN, the split-off band has greater curvature and is closer in energy to the conduction band than the heavy- and light-hole bands. Due to this, the lowest-energy holes in AlN have a much lower effective mass than those in the other III-nitrides. Once this is accounted for, the critical dopant concentration for acceptor band formation is amended to just 1.2 x 10^{18} cm^{-3}. It's a value that agrees with experimental evidence, which indicates that *p*-type conduction is only measurable for beryllium concentrations beyond the high 10^{17} cm^{-3} range, where sufficient holes exist to allow respectable contacts.

Despite our successes, there are still challenges with beryllium-doping in AlN, primarily associated with the growth temperature. Our biggest temperature-dependent concern is that beryllium has an intermediate vapour pressure, so it is very easily desorbed, even at relatively low growth

> Armed with the capability to produce reasonably high hole and electron concentrations in AlN by MME, we have demonstrated rectification in a *p-i-n* diode



➤ Figure 6. Positions of and relative size (to scale) of silicon and oxygen donors in AlN, as well as the compensating silicon DX-centre configurations.

temperatures of just over 750 °C. Due to this, growing beryllium-doped AlN at high temperatures results in reduced beryllium incorporation and thus a reduced hole concentration. Cranking up the beryllium flux is not an option, as too much beryllium desorption in the growth chamber can result in beryllium runaway, making the chamber itself an uncontrollable source of beryllium.

Another important consideration when doping AlN with beryllium is to limit the number of compensating defects that may arise in the film, such as V_N and oxygen – the latter is particularly attracted to aluminium and beryllium, and may form O_N and Be-O defect complexes. As discussed previously, it is possible to limit V_N defects by appropriately tuning MME growth conditions, and to reduce the generation rate of oxygen by growing at low temperatures where metal components do not outgas.

One other issue that arises with beryllium is that due to its small size – it is slightly smaller than the aluminium cations – it can physically reconfigure in the lattice, transforming from a Be_{Al} acceptor to a compensating beryllium interstitial. As this reconfiguration is more likely to occur in films grown at high temperatures, due to thermal expansion, this is yet another reason why it is vital to grow *p*-type AlN at low temperatures.

... and *n*-type material

For *n*-type AlN, potential dopants are anion-substituted oxygen (O_N) and cation-substituted silicon (Si_{Al}), as shown in Figure 6. However, we can quickly rule out oxygen, as it only generates shallow donors in AlN when it is combined with significant aluminium-vacancy concentrations to form negatively-charged defect complexes, and that limits its usefulness.

Fortunately, silicon doping has been slightly more straightforward, enabling bulk electron concentrations of 6×10^{18} cm^{-3}, which represents nearly a 3000-fold improvement over the previous state of the art. While silicon has a much lower vapour pressure than beryllium, and thus will not desorb at typical III-nitride growth temperatures, it appears that the low growth temperatures for MME still play a crucial role, with silicon doping benefiting from low temperature, metal-rich growth conditions. The major complication associated with silicon doping of AlN is the silicon-DX centre, which forms during the breaking of the *c*-axis bond between a Si_{Al} atom and its neighbouring nitrogen atom. Like with beryllium doping, higher growth temperatures are undesirable, as they can result is greater thermal expansion and promote an undesirable lattice reconfiguration. Furthermore, the presence of V_{Al} defects can 'soften' the lattice, making it easier for these types of DX-centres to form. To combat this, the approach we have already discussed – the use of metal-rich growth – can dramatically lower the likelihood of V_{Al} formation.

So far, the most common approach to trying to dope AlN has been via MOCVD, which requires high growth temperatures and nitrogen-rich growth conditions. Both are impediments to realising a high efficacy for silicon doping. An additional impediment is the compensating nature of carbon, which is inevitable in MOCVD-grown films. With all these factors at play, maybe it's not surprising that we have been able to exceed the previous state of the art in *n*-type AlN by such a large margin.

Developing devices

Armed with the capability to produce reasonably high hole and electron concentrations in AlN by MME, we have demonstrated rectification in a *p-i-n* diode. Our preliminary diodes show six orders of magnitude of rectification, an ideal turn on voltage at nearly 6 V, and a current density of up to 2.8 A cm^{-2}.

The performance of these devices is dominated by a high series resistance in forward bias, probably originating from contact issues to the etched *n*-type surface of these quasi-vertical diodes that need to be addressed. Our initial theories for the high contact resistance include a fundamental issue when contacting a 6.1 eV band gap material with metals whose work functions are limited to 2.8 eV to 5.8 eV, and damage to the *n*-AlN film from non-optimised plasma etching.

We have carried out temperature-dependent current-voltage characterisation of these diodes, which revealed a thermally activated process at voltages above turn-on. For voltages below turn-on, the current is independent of temperature, suggesting contacts are dominated by tunnelling rather than traditional ohmic conduction. We need to undertake further investigation of our diodes, so that we can determine the physical processes that dictate the electrical characteristics of AlN diodes. Such efforts must include investigations to establish better contact solutions, which will remove one complication when analysing the current-voltage curves and enable higher current devices.

There is no doubt that low-temperature epitaxy plays

CS ROUNDTABLE

Connecting Leaders & Experts in the Compound Semiconductor Field

Not every discussion is a **heated debate...**

- Based around a hot topic for your company, this 60-minute recorded, moderated ZOOM roundtable would be a platform for debate and discussion
- Moderated by an editor, Richard Stevenson, this can include 3 speakers
- Questions prepared and shared in advance
- There would be an opportunity to view and edit out any unflattering bloopers

This event would be publicised for 4 weeks through all our mediums including:

- A banner on the Compound Semiconductor homepage for 8 weeks
- 4x weekly dedicated HTMLs
- 4x news pieces which would also appear on the weekly e-newsletters
- Promoted through our social media platforms for 8 weeks (pre and post event)
- Available as an on-demand asset through all mediums
- All registered attendees' details would be made available to you

Cost: €5995

ANGEL

a vital role in realising highly *p*- and *n*-doped AlN and AlN diodes. The low temperatures allow beryllium and silicon dopants to incorporate into AlN films without reconfiguring into compensating centres. This limits the creation of compensating vacancies in AlN, and reduces the levels of compensating impurities, such as carbon and oxygen, that outgas from structural components in a growth chamber.

Thanks to the large diffusion lengths of adatoms on metal-rich surfaces, metal-rich vacuum processes can be conducted at these low temperatures without sacrificing the structural quality of these films. By avoiding the complications that arise from dopant desorption, beryllium incorporates into AlN films at high enough concentrations to form an acceptor band, greatly reducing the effective activation energy and improving the viability of *p*-type AlN. Another benefit of this material combination is that due to the unique valence band structure for AlN, the impurity band forms at much lower beryllium concentrations than in GaN, giving rise to the promise of much higher hole mobilities.

Measurements on our MME-grown films of *p*- and *n*-type AlN reveal carrier concentrations of 4.4 x 10^{18} cm^{-3} and 6 x 10^{18} cm^{-3} and resistivities of 0.045 Ω cm and 0.02 Ω cm, respectively. We have also recorded a hole mobility for AlN that is ten times higher than that for GaN at the same carrier concentration, suggesting AlN may offer more promise for *p*-type devices. While much work is still needed, there are encouraging signs that AlN offers the solution to the search for a material that will handle future performance needs in electronics and optoelectronics.

FURTHER READING

- J. Y. Tsao *et al*. "Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges" Adv. Electron. Mater. **4** 1600501 (2018)
- M. A. Khan *et al*. "III–Nitride UV Devices" Jpn. J. Appl. Phys. **44** 7191 (2005)
- C. Stampfl *et al*. "Theoretical Investigation of Native Defects, Impurities, and Complexes in Aluminum Nitride" Phys. Rev. B **65** 155212 (2002)
- J. L. Lyons *et al*. "Effects of Hole Localization on Limiting P-Type Conductivity in Oxide and Nitride Semiconductors" J. Appl. Phys. **115** 012014 (2014)
- G. A. Slack *et al.* "Some Effects of Oxygen Impurities on AlN and GaN, Journal of Crystal Growth" **246** 287 (2002)
- W. A. Doolittle *et al.* "Prospectives for AlN Electronics and Optoelectronics and the Important Role of Alternative Synthesis" Appl. Phys. Lett. **123** 070501 (2023).
- H. Ahmad *et al*. "Realization of Homojunction PN AlN Diodes" J. Appl. Phys. **131** 175701 (2022)
- H. Ahmad *et al.* "Comprehensive Analysis of Metal Modulated Epitaxial GaN" ACS Appl. Mater. Interfaces **12** 37693 (2020)
- Y. Taniyasu *et al.* "An Aluminium Nitride Light-Emitting Diode with a Wavelength of 210 Nanometres" Nature **441** 7091 (2006)
- T. Ive *et al.* "Controlled N-Type Doping of AlN:Si Films Grown on 6H-SiC(0001) by Plasma Assisted Molecular Beam Epitaxy" Appl. Phys. Lett. **86** 024106 (2005)
- P. Bagheri *et al.* "Doping and Compensation in Heavily Mg Doped Al-Rich AlGaN Films" Appl. Phys. Lett. **120** 082102 (2022)

semi™

Connecting Semiconductors and Electronics

About SEMI:
SEMI connects more than 2,500 member companies and 1.3 million professionals worldwide to advance the technology and business of electronics design and manufacturing. The breadth and depth of our events, programs and services help members accelerate innovation and collaboration on the toughest challenges to growth.

SMART MANUFACTURING

SMART MOBILITY

SMART MEDTECH

SMART DATA-AI

WORKFORCE DEVELOPMENT

Global ADVOCACY

Sustainability

MIT MARKET INTELLIGENCE TEAM

1000+ **STANDARDS**

THOUGHT LEADERSHIP

SEMICON

TECH COMMUNITIES

SEMI UNIVERSITY

Cyber Security

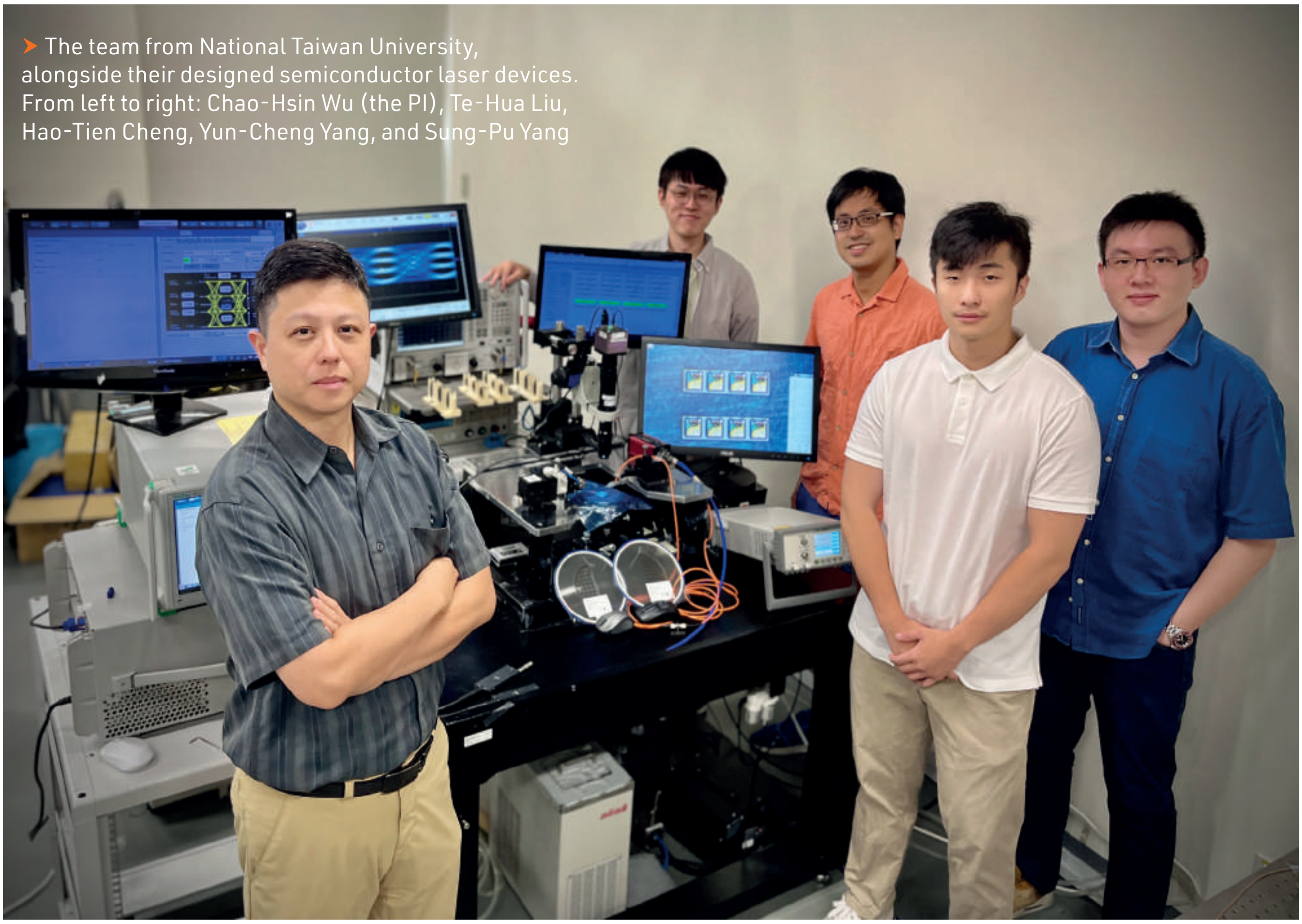
ESDA Electronic System Design *Alliance*

FlexTech

FOA Fab Owners Alliance

MEMS & SENSORS INDUSTRY GROUP®

SOI Industry Consortium



➤ The team from National Taiwan University, alongside their designed semiconductor laser devices. From left to right: Chao-Hsin Wu (the PI), Te-Hua Liu, Hao-Tien Cheng, Yun-Cheng Yang, and Sung-Pu Yang

Elevating ethernet networks with distributed-feedback lasers

Directly modulate AlInGaAs distributed-feedback lasers provide a low-cost, high-speed source for tomorrow's Ethernet

BY TE-HUA LIU, SUNG-PU YANG, HAO-TIEN CHENG, YUN-CHENG YANG AND CHAO-HSIN WU FROM NATIONAL TAIWAN UNIVERSITY

THE SEMICONDUCTOR LASER has come an awfully long way since its invention in the 1960s by groups at General Electric and IBM. Amongst the many successes of this seminal invention, now a cornerstone of modern technology, is the evolution of today's optical communication. Serving in diverse domains, from data centres to lidar, this efficient light source is facilitating advances in Ethernet networks, 5G communication, and AI infrastructures. Its users are demanding faster speeds and lower power consumption, driving improvements to its performance.

In the dynamic field of optical communication, manufacturers of lasers are striving to meet future demands. A ubiquitous component in this market is the optical transceiver, key to data transmission and reception. Utilising fibre optic technology, optical transceivers adeptly transform electrical impulses to optical signals and vice versa. In the 5G era, their role is indispensable, especially in front-haul and back-haul connections. Data from 2022 reveals the 25 Gbit/s transceiver's dominance, accounting for over 30 percent of the optical communication market's revenue. With the evolution of Ethernet, suppliers are pressed to address growing data traffic, prompting innovations in transmission speeds.

To support an increase in data traffic, driven by the increasing use of smartphones and cloud computing, there has been an introduction of 100 Gigabit Ethernet (100 GbE). Here, the emphasis is on transceivers that transmit data over long distances, maintaining network stability. However, increasing the transmission distance is far from trivial, due to chromatic dispersion within the optical fibre.

One solution is to use lasers that emit in a spectral window centred around 1.31 μm, a domain that ensures low chromatic dispersion. To produce a narrow emission profile, such lasers incorporate an intra-cavity grating structure. Operating at 25 Gbit/s and using four wavelength channels, these sources are apt for mid-to-long-range communication.

The ever increasing demand for data is driving advances in transceiver capability, with industry migrating towards 100 GbE and 400 GbE systems, succeeding the current 10 GbE and 25 GbE models. Discussions surrounding standardised transmission rates continue, and potential 400 GbE configurations include 16 x 25 Gbit/s, 8 x 50 Gbit/s, and 4 x 100 Gbit/s.

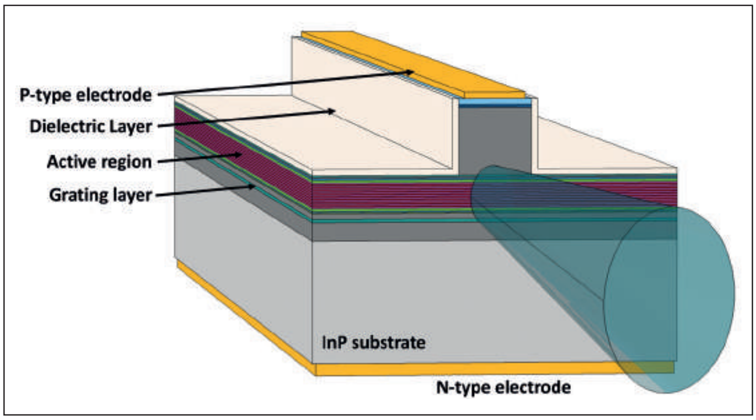
What's clear is that network operators can either increase their capacity or reduce their channel count by turning to transceivers that operate at faster data rates. The two standout laser designs that could be deployed in these transceivers are external-modulation lasers and direct-modulation lasers. There is a transmission prowess that comes from external modulation, associated with data transmission over long distances, but this comes with a higher purchase price. As well as lower cost, the direct modulation laser is compact and efficient, making it the top choice for multi-channel integration.

Directly modulated lasers

The merits of the directly modulated distributed feedback laser have motivated our team at National Taiwan University to improve this device while drawing on our robust domestic supply chain. We have made a strategic choice to employ AlGaInAs as the foundational material, due to its pronounced conduction band offset. It's a selection that ensures that the carriers remain within the laser diode's active region, preserving optoelectronic integrity, even under strenuous conditions such as elevated temperatures or currents.

Our architecture incorporates a ridge waveguide structure. Using this design, we sidestep additional regrowth procedures during manufacturing, thereby gaining on two fronts: we bring down production costs, and we improve device reliability.

Crafted on an *n*-type doped InP substrate with the assistance of MOCVD technology, our laser has an AlGaInAs active zone surrounded by a separate confinement heterostructure. This technology features a meticulously designed grating, formed from alternating layers of InGaAsP and InP, and a cavity precisely engineered at 150 μm (see Figure 1). To optimise resonance, we apply anti-reflective and high-reflectivity thin films to the front and rear facets, respectively.

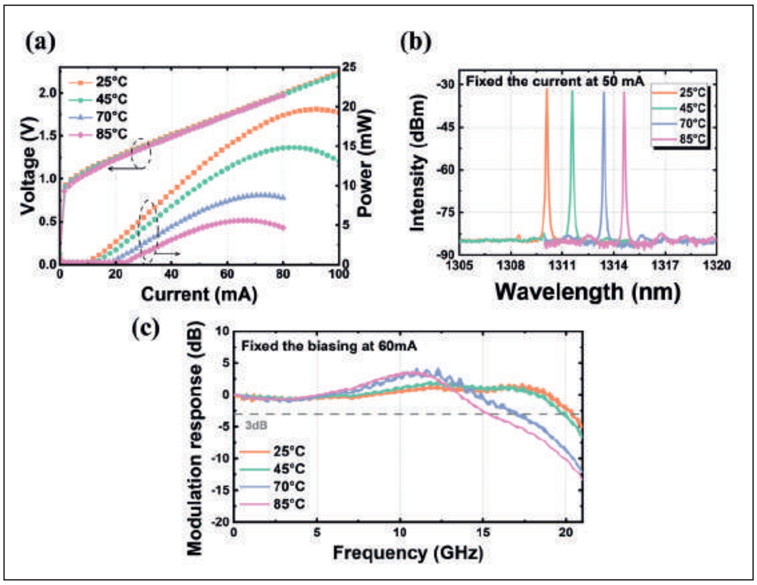


➤ Figure 1. An illustration of the 1.31 μm directly modulated AlGaInAs-based ridge-waveguide distributed-feedback laser.

During the transceiver's operation, its internal module temperature escalates. It's important that when this happens, the laser upholds its peak optical power and maintains its wavelength uniformity and adequate modulation frequency. All these factors are instrumental in determining the transceiver's efficacy.

To thoroughly gauge our laser's attributes, we have carried out DC and microwave evaluations. These investigations reveal that our AlGaInAs-based ridge-waveguide laser consistently performs across an extensive temperature spectrum (see Figure 2, which shows temperature-variant tests that evaluate optical power, spectral attributes and electro-optical responses). What stands out is the spectrum's minimal drift – there's just a 4.5 nm wavelength deviation between ambient temperature and 85 °C.

We are particularly encouraged that even within this temperature bracket, the disparity in intensity between the primary mode and its adjacent



➤ Figure 2(a). Light-current-voltage (L-I-V) characteristics of a 1.31 μm directly modulated AlGaInAs-based ridge-waveguide distributed-feedback laser across a wide temperature range of 25-85 °C (b). Characteristics of optical spectra at different temperatures for laser operation at 50 mA (d). Electro/optical (E/O) response of the laser operated at 60 mA across 25–85 °C.

side mode is always greater than 50 dB. This asset highlights our laser's superior single-mode characteristics. For long-haul transceivers covering expanses of several kilometres, this attribute is incredibly valuable, as any deviation towards multi-mode behaviour threatens to heighten transmission discrepancies. The steadiness of the optical mode and its wavelength are paramount for optimal functionality of laser diodes within optical transceivers.

Electro-optical microwave tests determine a 3 dB frequency around 21 GHz at 25 °C for our laser. This device retains a frequency above 15 GHz, even when the temperature reaches 85 °C. Delving into the electro-optical response metrics reveals that our laser exhibits performance capabilities beyond 30 Gbit/s at 25 °C and remains robust, delivering above 20 Gbit/s at 85 °C.

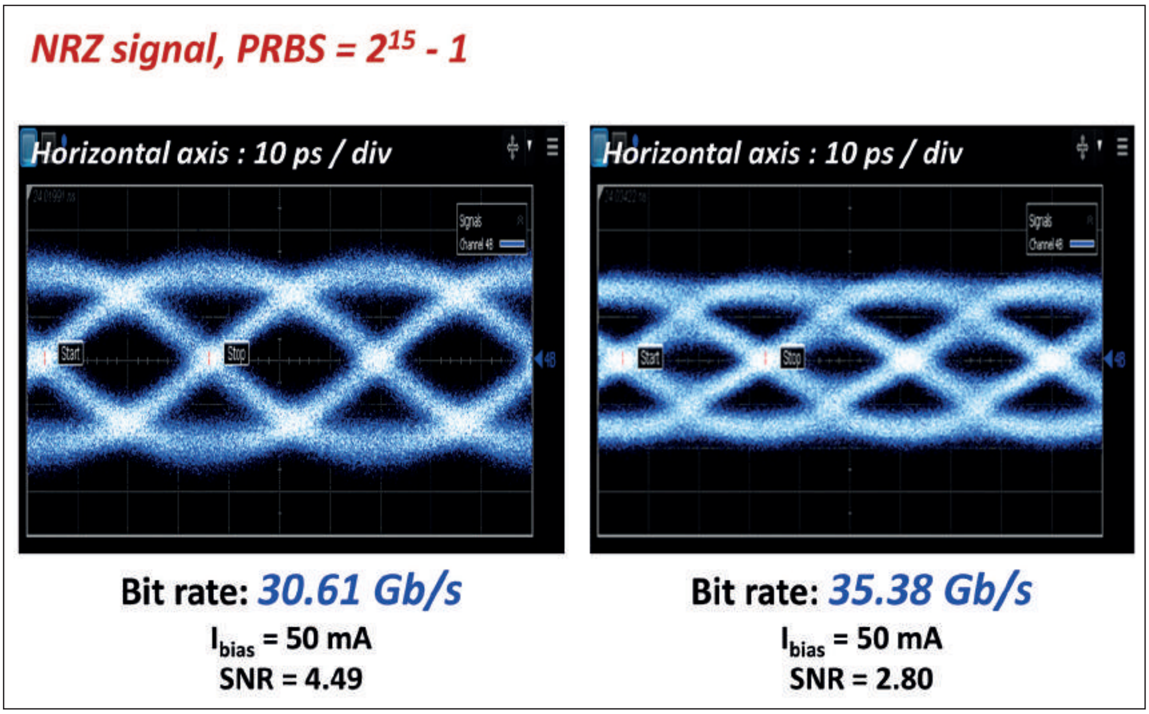
Our assessments, visually represented with eye diagrams (see Figure 3), indicate that our distributed feedback laser is adept at realising data transmission speeds surpassing 35 Gbit/s while operating in a Non-Return-to-Zero (NRZ) mode with a signal sequence of 2^{15}-1. Notably, this transmission efficacy is attained without the need for specialised techniques, such as pre-emphasis or equalisation. Our illustrative eye diagrams underscore our laser's promising potential, hinting at its capability to facilitate 100 GbE and 400 GbE transceivers when integrated across multiple channels.

By capitalising on the outstanding DC and high-frequency transmission capabilities of our laser, even at increased temperatures, there is the promise that we might be able to produce ridge-waveguide distributed-feedback lasers that are free from active cooling. Success in this regard would pave the way for a reduction in power consumption and curtail costs associated with thermoelectric cooling components inside transceivers.

Driving commercialisation

Our successful development of AlGaInAs-based ridge-waveguide distributed-feedback lasers offers another route to advancing data transmission, and making global information networks faster and more reliable. Since the inception of semiconductor lasers, every generation of scientists and engineers has contributed to the evolution of this technology. The emergence of our AlGaInAs-based laser brings new prospects for high-speed optical communication. Superior characteristics – including stable light output under varying temperature conditions, a single-mode spectrum, high-frequency capability, and flexibility for multi-channel integration – position this device as an exceptional candidate for high-capacity Ethernet networks.

Now more than 60 years since their invention, semiconductor lasers have permeated various corners of modern life. Whether in sensing or communication applications, their significance is unquestionable. Given the diverse array of applications, system providers expect prompt responses from laser suppliers. So, to address this urgent need, our team has established a technology start-up, LiVe Optronics Co., Ltd. We anticipate that through this venture we will translate years of research experience into tangible products, rapidly designing semiconductor lasers for customer systems and producing devices through international collaboration. Through LiVe Optronics, we also expect to foster more collaborative relationships and accelerate the development of semiconductor lasers.



➤ Figure 3. Eye diagrams of a 1.31 μm directly modulated AlGaInAs-based ridge-waveguide distributed-feedback laser at room temperature, showcasing 35 Gbit/s and 30 Gbit/s data rates under a modulating signal of 2^{15}-1 NRZ pattern.

Giving gallium oxide avalanche capability

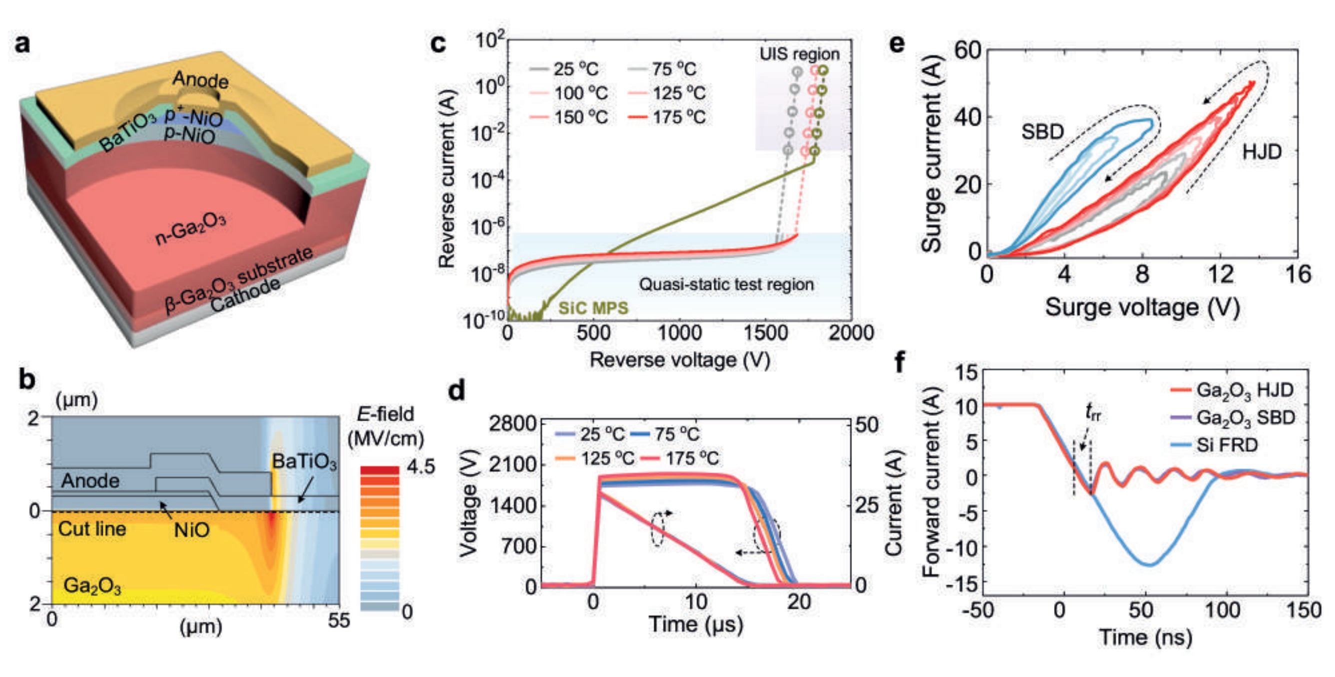
Pairing Ga_2O_3 with NiO produces robust power electronics for harsh environments

BY FENGZHOU AND JIANDONG YE FROM NANJING UNIVERSITY AND YUHAO ZHANG FROM VIRGINIA TECH

ADVANCED POWER DEVICES are essential building blocks for high-efficiency energy conversion in a number of applications, including electric vehicles, data centers, electric grids and renewable energy processing. To reach higher levels of performance with these devices, the ultimate driving force is the selection of the semiconductor material. The last decade has witnessed the success of wide bandgap semiconductors, such as GaN and SiC. Compared to silicon, these alternatives have raised the bar. But even more impressive devices are now on the horizon, drawing on the superior strengths of ultrawide bandgap semiconductors, such as Ga_2O_3, diamond and AlN.

Regardless of the material used, the primary function of the power device is to operate as a switch between a high blocking voltage and a high conduction current. Due to this requirement, the ability to handle overvoltage and overcurrent events is indispensable for any power device. Armed with that attribute, power devices can temporarily survive common faults in power systems – they could be short circuits, excessive loads, or arc/ground faults – before protection circuitry intervenes.

Traditionally, avalanche and surge current capabilities have been realised with homogenous *p-n* junctions. However, this architecture has proven



➤ Figure 1. (a) Three-dimensional illustration of a fabricated NiO/Ga$_2$O$_3$ hetero-junction diode. (b) Simulated in-plane electric-field contour of devices with the BaTiO$_3$ dielectric layer. (c) Temperature-dependent reverse current-voltage characteristics of the hetero-junction diode. (d) Typical temperature-dependent unclamped inductive switching voltage and current waveforms for Ga$_2$O$_3$ hetero-junction diodes at an inductance of 1 mH. (e) Surge current-voltage locus of the hetero-junction diode and the reference Ga$_2$O$_3$ Sckottky barrier diode. (f) Reverse recovery characteristics of the Ga$_2$O$_3$ hetero-junction diode, the reference Ga$_2$O$_3$ Sckottky barrier diode, and a commercial silicon fast-recovery diode.

elusive in power devices based on ultrawide bandgap semiconductors, because it is incredibly challenging to realise bipolar doping, a requirement for making homogenous junctions.

One way to tackle this challenge is turn to the hetero-integration of foreign *p*-type oxides, such as NiO, which can be paired with *n*-type Ga$_2$O$_3$. It's an approach that has been adopted by those of us at Nanjing University. Back in 2020, we broke new ground with the first double-layered *p*-NiO/*n*-Ga$_2$O$_3$ heterojunction power rectifier. It's an innovation that enhanced the reverse blocking capability up to 1.86 kV and ensured stable operation at temperatures as high as 440 K. We then built on that success, producing β-Ga$_2$O$_3$-based bipolar power devices that combine a high current output with a fast reverse recovery and nanosecond switching. It's a foundation that has put us in a great position to address the most critical avalanche and surge robustness challenges in Ga$_2$O$_3$ devices.

For that most recent challenge, we have joined forces with Yuhao Zhang's team at Virginia Tech. It's a collaboration that has borne much fruit, realising an exceptional level of avalanche and surge current robustness in NiO/Ga$_2$O$_3$ *p-n* heterojunctions through innovative device design and circuit evaluations.

Architectures for avalanche

For power devices, it is crucial to manage electric field crowding and prevent premature breakdown. Working together, our partnership has addressed this matter by developing an etching-free edge termination technology, featuring a small-angle bevelled double-layered NiO junction termination extension (see Figure 1 (a)). We use an amorphous BaTiO$_3$ layer with an ultra-high dielectric to conformally cover the NiO junction termination extension structure in a consistent manner. Introducing this ultra-high dielectric ensures a nearly uniform electric field at the NiO/Ga$_2$O$_3$ junction, and ultimately enables a uniform and robust avalanche (see Figure 1 (b)). For circuit tests, we house a large-area (3 mm by 3 mm) NiO/Ga$_2$O$_3$ *p-n* heterojunction device in a TO-220 package.

Power devices with avalanche capability can withstand overvoltage stresses. Such devices are able to accommodate high avalanche current at the avalanche breakdown voltage, and dissipate excessive energy in circuits. The proven capability of our NiO/Ga$_2$O$_3$ heterojunction devices comes from rigorous testing, using both quasi-static current-voltage sweeps and dynamic unclamped inductive-switching circuit tests. These investigations reveal that the avalanche breakdown voltage increases with temperature (see Figure 1 (c)), with a positive temperature coefficient of 1 V/°C – that's a typical manifestation of device avalanche. According to unclamped inductive-switching circuit testing, our device produces textbook-like avalanche waveforms (see Figure 1 (d)). What's more, the temperature coefficient of the avalanche breakdown voltage extracted from unclamped inductive-switching waveforms is identical to that extracted from current-voltage characteristics.

We have provided additional validation of our device's robust avalanche capacity with 1 million cycles of repetitive avalanche tests. This confirms that compared with traditional homogenous *p-n* junctions, our ultra-wide bandgap heterojunctions offer superior performance and robustness for power applications.

In addition to this avalanche capability, our NiO/Ga_2O_3 heterojunction demonstrates exceptional surge current capability, withstanding over 50 A of surge current. In stark contrast to the Schottky barrier diode, the surge current waveforms of our heterojunction device exhibit an anticlockwise locus signature, which signifies negative temperature coefficients for the differential on-resistance (see Figure 1 (e)). Surprisingly, the 1200 V reverse recovery time of our heterojunction device is at the nanosecond level (Figure 1 (f)) – that's similar to the unipolar Ga_2O_3 Schottky barrier diode, and far faster than the bipolar silicon fast-recovery diode. Based on these results, it appears that our NiO/Ga_2O_3 heterojunction can deliver a simultaneous reduction in conduction loss and switching loss, compared with conventional bipolar devices.

Operating under extreme conditions

Thanks to our breakthroughs in avalanche and surge operation, we have been able to delve into the details of fundamental carrier dynamics in these ultra-wide bandgap semiconductor heterojunctions under extreme conditions. This includes high electric fields, high current densities, high temperatures, and non-equilibrium dynamic conditions.

The realisation of avalanche behaviour hinges on impact ionisation and multiplication occurring at the junction, as well as the efficient removal of non-equilibrium carriers that result from impact ionisation. As illustrated in Figure 2 (a), once impact ionisation is initiated in the *n*-type Ga_2O_3 drift layer, the strong electric field sweeps electrons and holes produced by this interaction to the cathode and heterojunction, respectively. Due to the staggered

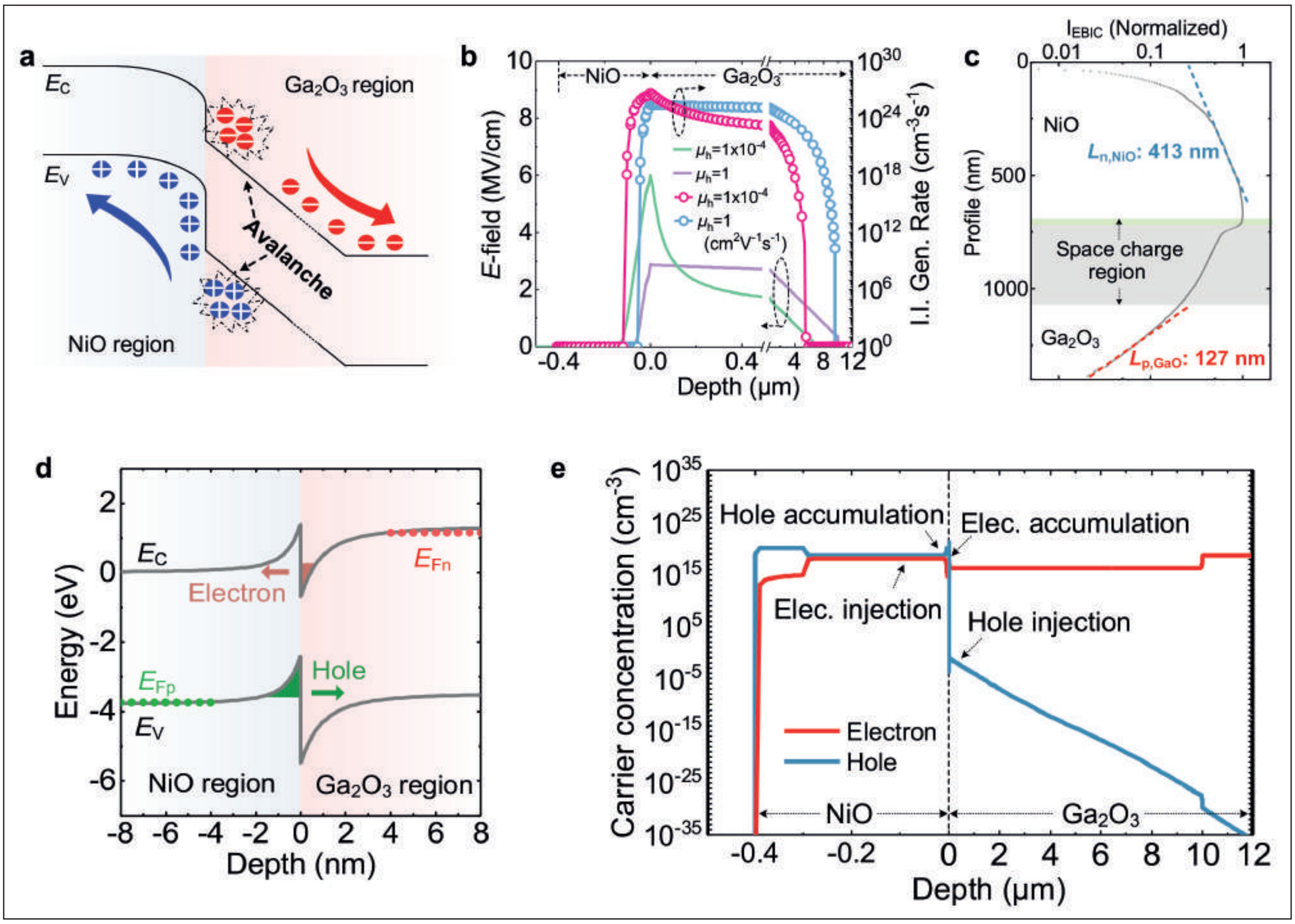
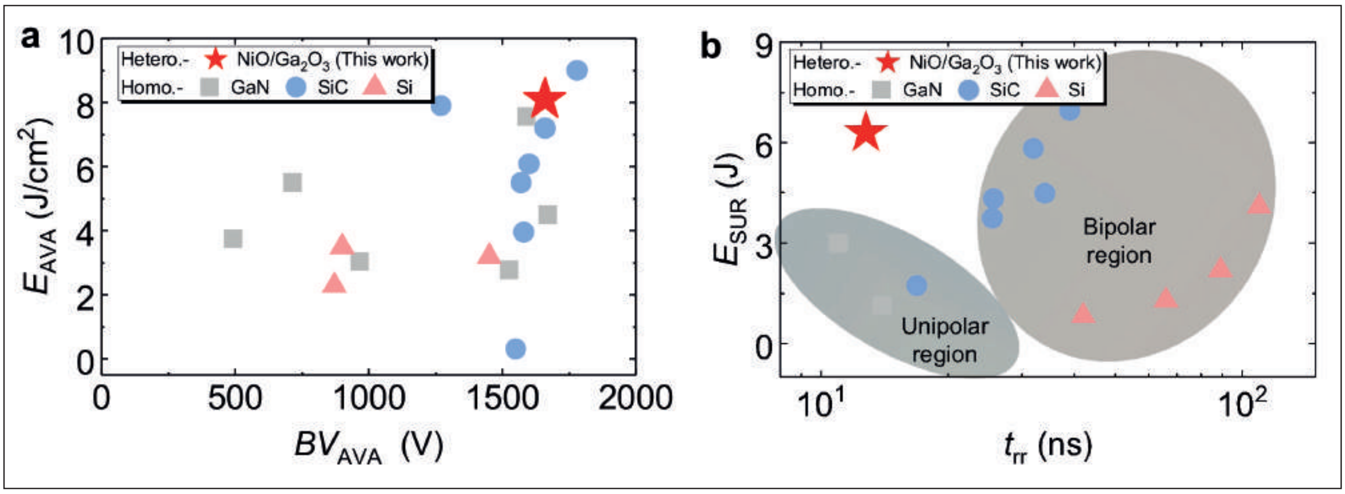


Figure 2. (a) Illustration of the band diagram and carrier transport dynamics under the avalanche condition. (b) Simulated profiles of the electron and hole concentration, electric field and generation rate in the hetero-junction diode under two different hole mobilities, at an avalanche current of 30 A. (c) Electron-beam-induced current profile of a NiO/Ga_2O_3 heterojunction to determine the minority carrier diffusion lengths. (d) Illustration of the carrier transport dynamics under the high forward current. (e) Simulated distribution of minority carriers on both sides of the hetero-junction diode at a forward voltage of 6 V.


PIC INTERNATIONAL CONFERENCE



➤ Figure 3. (a) Electric field at avalanche versus avalance blocking voltage benchmark and (b) surge energy versus reverse recovery time (t_{rr}) benchmark, all for reported Ga_2O_3, GaN, SiC, and silicon power diodes.

band structure, the NiO/Ga_2O_3 heterojunction produces no barriers to hole transport.

We have simulated the behaviour of our devices. These calculations suggest that holes produced by impact ionisation in Ga_2O_3 are exempt from controversial self-trapping, and drift with considerable mobility – it is this that enables a high avalanche current. The dynamic avalanche characteristics also allow us to extract a full set of electron and hole impact ionisation coefficients in Ga2O3, which is important for developing solar-blind avalanche photodetectors that could serve in numerous applications.

Yet another advantage of the robust surge capability of the NiO/Ga_2O_3 heterojunction is that it sheds new light on minority carrier (hole) transport in Ga_2O_3, which remains controversial and largely unexplored.

Our efforts on this front, in partnership with researchers at the Australian National University, have involved imaging the minority carrier dynamics in NiO/Ga_2O_3 heterojunction diodes with a microscopic electron-beam-induced current (see Figure 2 (c)). This technique unveiled asymmetric minority carrier lifetimes for electrons in *p*-NiO and holes in Ga_2O_3 of 124.0 ns and 6.2ns, respectively. Based on these values, we expect bipolar conductivity modulation to occur predominantly in NiO at high forward bias, primarily through electron tunnelling injection (this is illustrated in Figure 2 (d) and 2 (e)). When this device is being switched off, depletion mainly occurs in the lightly-doped Ga_2O_3. As minimal minority carriers need to be recombined in *p*-NiO for switching to occur, this has an insignificant impact on device reverse recovery.

Benchmarking

Our NiO/Ga_2O_3 heterojunction sets new performance benchmarks by combining low on-resistance with high current capacity and a high blocking voltage. As summarised in Figure 3 (a), surge current and surge energy capacities surpass those of silicon devices, and are comparable to the best reported performances for SiC and GaN devices. It's important to note that our heterojunction overcomes the fundamental trade-off between robustness and switching speed in conventional homojunctions (see Figure 3 (b)), clearing a path to advancing ultra-wide bandgap devices in power applications.

As well as the opportunities in power electronics, our innovative ultra-wide bandgap heterojunction architecture that features avalanche ruggedness has great potential for realising ultra-low noise avalanche photodetectors in the deep-ultraviolet spectral range. Such devices are expected to break through the fundamental trade-off between responsivity and response speed, a triumph that promises to have far-reaching implications in the fields of optoelectronics and photonics.

FURTHER READING

➤ H. Gong *et al*. "A 1.86-kV double-layered NiO/β-Ga_2O_3 vertical *p-n* heterojunction diode," Appl. Phys. Lett. **117** 022104 (2020)

➤ F. Zhou *et al*. "1.95-kV Beveled-Mesa NiO/β-Ga_2O_3 Heterojunction Diode With 98.5% Conversion Efficiency and Over Million-Times Overvoltage Ruggedness," IEEE Trans. Power Electron. **37** 1223 (2022)

➤ Y. Qin *et al*. "Recent progress of Ga_2O_3 power technology: large-area devices, packaging and applications," Jpn. J. Appl. Phys. **62** SF0801 (2023)

➤ F. Zhou *et al*. "An avalanche-and-surge robust ultrawide-bandgap heterojunction for power electronics," Nat. Commun. **14** 4459 (2023)

➤ J. Kozak *et al*. "Stability, Reliability, and Robustness of GaN Power Devices: A Review," IEEE Trans. Power Electron. **38** 8442 (2023)


ANGELTECH
PE INTERNATIONAL CONFERENCE
DIAMOND SPONSOR
SCREEN

Advancing communication in the deep UV

Deep-UV LEDs lie at the heart of a network providing 10 Mbit/s connectivity between multiple users

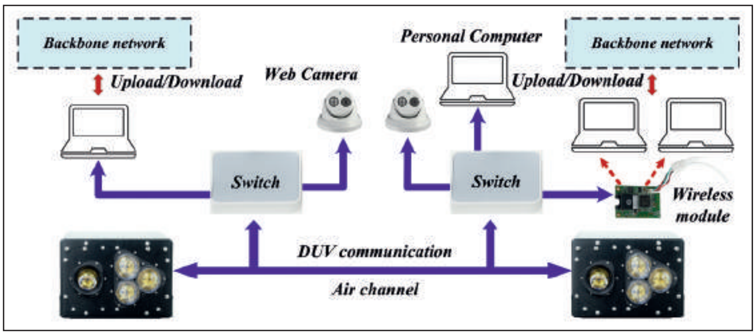
USING LIGHT in the deep UV for optical wireless communication has much appeal: thanks to its invisible character, security is high; due to strong filtering by the atmosphere, the source benefits from a low background noise; and absorption of light is not as severe as in the infra-red, aiding the transmission distance.

Driven on by all these strengths, there has been much interest in deep-UV communication over the last few decades. Up until recently, progress in emitters and detectors has helped to advance the progress of offline deep-UV light communication systems – and now a team from China is claiming to have taken the technology into a new era, with the first communication system operating in this spectral range that offers multiple services for all users.

The team making this claim – they are from Nanjing University of Posts and Telecommunications and Suzhou Lighting Chip Monolithic Optoelectronics Technology – have proposed, manufactured and characterised a solar-blind full-duplex light communication system employing LEDs emitting at 275 nm for the light source.

This effort, featuring the demonstration of real-time video communication in sunlight, has established a deep-UV communication network that contains an integrated wireless module, and provides access for users within a 46 m^2 area.

Spokesman for the researchers, Yonglin Wang, who works for both Nanjing University of Posts and Telecommunications and Suzhou Lighting Chip Monolithic Optoelectronics Technology, believes that one of the highlights of this work is solar-noise-free transmission at 10 Mbit/s under sunlight. According to him, another asset is the use of TCP/IP, which provides prerequisites for networking.



➤ The architecture of the deep-UV network.

Wang and co-workers have expertise in deep-UV LED technology, having developed a vertical AlGaN-based deep-UV LED emitting at 272 nm in 2022. However, for this latest work they employ commercial devices, constructing three transmitter units, each with four LEDs.

“This design significantly increases the emitted optical power at the transmitter, thus improving the point-to-point transmission distance between two deep-UV transceivers,” argues Wang.

The deep-UV LEDs employed by the team, which use a thin-film flip-chip architecture to trim the forward voltage and increase light extraction, are attached to a solder pad on a printed circuit board. Driven at 24 V, these units, formed from four LEDs in series, produce an output power of 34 mW. The dominant emission wavelength is 275 nm, and the full-width at half maximum associated with this peak is just 10 nm.

To transmit data, a transistor-transistor logic signal that’s modulated by an on-off-keying modem is applied to the deep-UV LEDs.

Detection of the transmitted signals is realised with a Hamamatsu S14124-20 avalanche photodiode. This has a quantum efficiency of 87 percent at 266 nm.

Wang and co-workers have determined that the maximum transmission rate for this real-time full-duplex communication system is 10 Mbit/s. When they realised this rate in a solar-blind experiment on an open balcony at an altitude of 82 m, they determined bi-directional packet loss rates of 1.28 percent and 1.58 percent.

One of the team’s next goals is to tackle another big issue in deep-UV light communication: combining high speeds with long distances. “In our future work, a photo-multiplier tube will be used as the core receive device to significantly increase the transmission distance,” remarks Wang.

Another problem that they are planning to address is the difficulty of alignment associated with moving wireless optical communications. According to Wang, an automatic alignment feature will be introduced to enhance the practicality of the system.

A third direction for the engineers is combining their technology with other communication systems, such as underwater blue light communication technology. This will allow the team to establish a space-air-sea communication network.

REFERENCE

➤ Z. Qi *et al.* Appl. Phys. Lett. **123** 161109 (2023)

Dedicated webinars for the compound semiconductor industry

Using our 30+ years' experience in B2B vertical technical markets, and as the publisher of Compound Semiconductor portfolio, we offer effective webinars, webcasts and virtual events. We help you get your message, to your desired audience, by marketing to over 60,000 compound semiconductor professionals.

In addition to organising and managing your webinar, we can also market your webinar to our specialist databases.

In a dedicated 6 week program we will promote through our magazine, newsletters, LinkedIn group and website.

We can also provide the webinar moderator, from our team of highly respected editors.

Let our editors work with you and help you with the content.

Reach Educate Influence

- **Brand Awareness**
  Increase global awareness by running sponsored webinars, Zoom interviews and virtual events
- **Lead Generation**
  Generate and mature leads through the use of online events.
- **Thought Leadership**
  Become the voice of knowledge by generating compelling content via online events

---

CS COMPOUND SEMICONDUCTOR

Find out how Angel Webinars can help you organise and run a webinar within the compound semiconductor industry.
Contact: Jackie Cannon
jackie.cannon@angelbc.com
+44 (0)1923 690205

Realising vertical deep-UV lasers

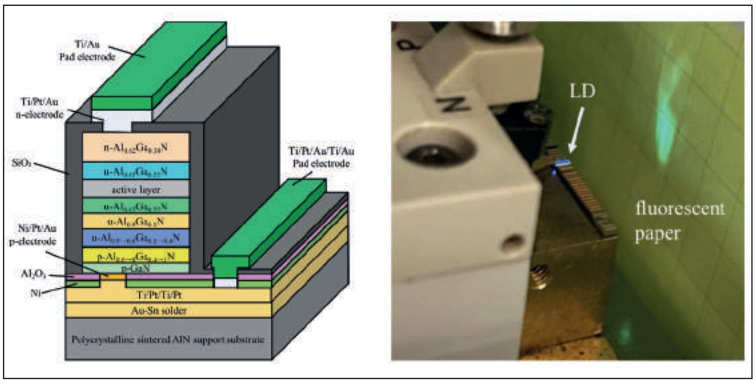
Deep-UV lasers with a vertical architecture have the potential to address issues associated with current injection

ENGINEERS from Japan are claiming to have broken new ground with a deep-UV semiconductor laser with a geometry that's vertical, rather than horizontal.

"This is an essential technology for increasing the optical output power in AlGaN-based deep-ultraviolet laser diodes," remarks team spokesman Motoaki Iwaya from Meijo University.

According to Iwaya, a major downside of the majority of AlGaN-based devices, which are grown on semi-insulating materials such as sapphire and AlN to ensure a high crystal quality, is their lateral device geometry that limits current flow. This restriction in carrier transport stems from difficulties in *p*-type doping that hamper the realisation of large *p*-type electrodes with uniform current conduction.

To overcome this bottleneck, the team from Meijo University, Ushio and Seishin Trading are pursuing a vertical device architecture. This geometry has already demonstrated success in InGaN-based visible LEDs and laser diodes.



➤ The emission pattern of the 298 nm laser can be seen with phosphor-coated paper.

For AlGaN-based vertical devices, there's a need to remove the insulating AlN or sapphire, a task that can be accomplished with either laser lift-off, electrochemical etching, or grinding and polishing.

Iwaya and co-workers employ a form of exfoliation based on laser lift-off to extract material with a size of around 1 cm^2. Efforts begin by growing the device structure on AlGaN templates with a foundation of AlN nanopillars that have been defined by nano-printing and inductively coupled plasma etching. This is an approach previously used by the team to fabricate AlGaN-based LEDs emitting in the UVB.

The laser structures are grown on 2-inch *c*-plane sapphire substrates with AlN nanopillars with a 400 nm terrace width that are 300 nm high and arranged in a triangular lattice pattern with a 1 μm pitch. On these pillars the engineers have used MOCVD to add a 5 μm-thick undoped $Al_{0.68}Ga_{0.32}N$ template, a 170 nm-thick undoped $Al_{0.5}Ga_{0.5}N$ layer designed for laser absorption in the lift-off process, and the device heterostructure (its details are provided in the figure).

Device fabrication continues with the cleaving of the epiwafer into 1 cm^2 squares, the addition of polycrystalline sintered AlN for structural support – bonded to the heterostructure using a Au-Sn solder – and laser lift off with a pulsed laser emitting at 257 nm and providing an optical density of 0.53 J cm^{-2}. Subsequent processing, including the addition of electrodes and scribing, creates lasers with cavity lengths between 500 nm and 1.2 μm.

Only around two-thirds of the lasers produced by the team have operated effectively, due to *p*-type electrode detachment. Iwaya and co-workers argue that yield loss comes from insufficient bonding strength with the support substrate, as well as substrate warpage during crystal growth and a sub-optimal selection of dielectric films and other components. Improving the selection of materials and processes should address these issues.

Using 50 ns pulses to drive lasers with a 1200 μm cavity length and a 5 μm aperture width produces an extremely sharp emission peak at 298.1 nm at a current density of 25 kA cm^{-2}. At higher current densities, multiple lasing peaks are produced, with output power increasing to several milliwatts.

The introduction of additional peaks does not surprise Iwaya. "The optical cavity is designed without considering transverse and longitudinal optical confinement, so the laser is oscillating in multimode." He says that modal confinement can be improved by adopting the cavity control techniques used for visible laser diodes.

One of the next goals for the team is to address the high operating voltage of the laser, which stems from the Schottky contact of the *n*-type electrode. "We aim to reduce the operating voltage by forming low-resistance ohmic *n*-type electrodes, and then to demonstrate the operation of a deep-ultraviolet laser diode with a watt-class optical output from a single chip by increasing the size of the device."

REFERENCE

➤ T. Nishibayashi *et al*. Appl. Phys Express **16** 104001 (2023)

Turning to tunnel-junctions for monolithic multi-colour microLED arrays

Tunnel-junctions address the challenge of producing ohmic contacts on a plasma-etched *p*-type surface

DUE TO YIELD and throughput issues associated with the pick-and-place approaches that are being pursued to produce displays based on microLEDs, monolithic technology is attracting much interest.

On that front a collaboration between engineers at Meijo University and King Abdullah University of Science and Technology (KAUST) is making substantial progress – they are claiming to have produced the first red, green and blue (RGB) monolithic microLED arrays that are GaN-based and connected via tunnel junctions.

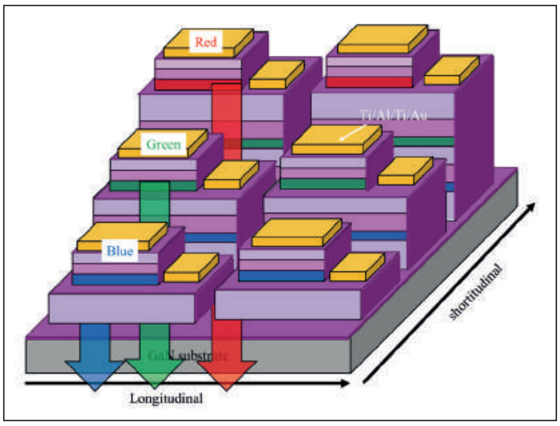
"We have also succeeded in minimising the voltage increase due to etching damage by using tunnel junctions," says team spokesman Motoaki Iwaya from Meijo University. "Such an approach is considered extremely effective in realising monolithic displays with microLEDs."

The engineers at Meijo University have produced an epistructure that includes a blue-emitting double-quantum-well region, followed by a tunnel junction, and then a green-emitting double-quantum-well region, also followed by a tunnel junction. After shipping this epistructure to KAUST, that team added a red-emitting structure, featuring a red single quantum well grown on top of a blue single quantum well to increase emission efficiency.

Several steps were employed to form microLED arrays with 330 pixels-per-inch from the epiwafer. Efforts began with the addition of ITO by sputtering, followed by inductively coupled plasma-reactive ion etching with chlorine gas to form a mesa structure. Subsequent annealing activated *p*-type GaN in the tunnel junctions, prior to passivation with a SiO_2 layer and the addition of *n*-type electrodes by electron-beam deposition.

The microLEDs produced by this process have a device size of 73 µm by 20 µm, and a mesa area of 35 µm by 15 µm. However, scaling to far smaller dimensions is possible, says Iwaya, who revealed that they have realised highly efficient luminescence from a square single element with sides of about 3 µm. Iwaya added that the team is yet to have the technology to implement 3 µm devices, but once they have a mounting technology available, they hope to demonstrate displays finer than 2000 ppi.

Driven at 50 mA, the blue, green and red microLEDs in the array produce emission with peaks at 486 nm, 514 nm and 604 nm. There is also an additional, weaker peak produced by the blue microLED at 380 nm, which could be eliminated by applying AlN cap layers and lowering the growth temperature of the *n*-type AlGaN layer to that of the active layer of the blue LED. Another concern is what is described as broad fringe emission from the red LED, occurring at around 450 nm, possibly resulting from non-optimal growth conditions.



➤ Thanks to incorporation of a tunnel-junction, a pair of *n*-type electrodes can drive red, green and blue microLEDs.

The turn-on voltages for the blue, green and red LEDs were 2.8 V, 3.2 V and 3.2 V. For the green and red LEDs these values are 0.5 V and 1 V higher than they would be for an ideal LED. The green microLED is thought to be held back by the anode forming an electrical barrier at the growth interface, while the red microLED may be impeded by a combination of a high contact resistance between *p*-type GaN and the electrode, and a small electrode area that increases contact resistance.

Optical measurements reveal that the intensity of emission from the green microLED is far higher than that from its blue and red siblings.

"For blue, it is possible to increase brightness by about one order of magnitude and control wavelengths if the effects of heat are suppressed," says Iwaya, who anticipates that improvements to the red microLED will be much harder to realise. He accepts that it will be a challenge to produce red microLEDs that emit higher luminance at longer wavelengths. "However, luminance is already about one order of magnitude higher than that of OLED, so I think it is possible to bring it to a practical level."

REFERENCE

➤ T. Saito *et. al.* Appl. Phys. Express **16** 084001 (2023)

INDUSTRY SERVICES DIRECTORY

agnitron technology
Tel: +1 952 937 7505
Email: sales@agnitron.com
www.agnitron.com

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

APPLIED ENERGY SYSTEMS
Tel: +001 610-647-8744
info@appliedenergysystems.com
www.appliedenergysystems.com

ARM PURIFICATION
BY APPLIED ENERGY SYSTEMS
Tel: 1 610-647-8744
purification@appliedenergysystems.com
www.armpurification.com

BRUKER
Tel: +44 (0)191 332 4700
Fax: +44 (0)191 332 4800
sales.semi@bruker.com
www.bruker.com

CVD Equipment Corporation
enabling tomorrow's technologies™
Tel No: +1 631 981 7081
Email: sales@cvdequipment.com
www.cvdequipment.com

ECM GREENTECH
GORDON BANISH
586-945-3606 | gordonbanish@ecm-usa.com
WAFER PROCESSING FURNACES
www.ecm-usa.com/greentech

Efab
Tel: +886 4 2534-7800
Fax: +886 4 2534-8869
Email: sales@efab.com.tw
www.efab.com.tw

evatec *process systems*
Tel: + 41 81 403 8000
Fax: + 41 81 403 8001
www.evatecnet.com

Freiberg Instruments Driven by Innovation
www.freiberginstruments.com

Greene Tweed
SEALS | CONNECTORS | COMPONENTS
gtweed.com

HAMAMATSU
PHOTON IS OUR BUSINESS
www.hamamatsu.com

H-SQUARE CORPORATION™
Tel: +1 408 982 9108
Email: info@h-square.com
www.h-square.com

HORIBA Scientific
Tel: +1 732 494 8660
joanne.lowy@horiba.com
www.horiba.com/scientific

HOSHINE
Tel: +86 186 1219 1616
fanxing@hsmmcs.com
www.hs-mmcs.com

III/V-Reclaim
Tel: +49 8728 911 093
Fax: +49 8728 911 156
Email: sales@35reclaim.com
www.35reclaim.com

kSA
k-Space Associates, Inc.
Email: requestinfo@k-space.com
www.k-space.com

SOCSIL Expert of N_2O plants
Linde Making our world more productive
Tel No: +36 20 9561 897
Email: linde.n2o@linde.com
www.n2o-plant.com

Masimo® semiconductor
Tel: +1 603 595 8900
Email: sales@masimosemi.com
www.masimosemiconductor.com

MBE KOMPONENTEN | DR. EBERL
Tel: +49 7033 6937-0
info@mbe-components.com
www.mbe-components.com

nel®
Tel: + 1 203 949 8697
Email: info@nelhydrogen.com
www.nelhydrogen.com

Experience the Power of **Connected Thinking**
onto innovation.
ontoinnovation.com | info@ontoinnovation.com

RIBER
www.riber.com

Sanan Integrated Circuit Co., Ltd.
Tel: +1 949 241 9501
Email: ray@sanan-ic.com
www.sanan-ic.com/en

TAIYO NIPPON SANSO

Tel: + 1 908-403-3304
Email: info@tnsc-innovation.com
www.tnsc-innovation.com

Temescal

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

Trymax®
PLASMA TECHNOLOGY SOLUTIONS

Tel: +31 24 350 0809
info@trymax-semiconductor.com
www.trymax-semiconductor.com

umicore

www.umicore.com

COMPOUND SEMICONDUCTOR
CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

To advertise here contact:
UK, Europe + RoW: Jacob Caulfield
T: +44 (0)2476 719979 E: jacob.caulfield@angelbc.com
USA: Janice Jenkins
T: +1 724 929 3550 E: jjenkins@brunmedia.com

vistec
Electron Beam

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

Showcase to the Compound Semiconductor industry for 12 months


COMPOUND SEMICONDUCTOR
CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

G10-AsP brings microLEDs to high-volume production

VOLUME 29 ISSUE I 2023 | AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION | COMPOUNDSEMICONDUCTOR.NET

INSIDE
News, Analysis, Features, Editorial View, Research Review and much more

GALLIUM NITRIDE POWERS AHEAD
Researchers at the International Electron Devices Meeting unveil record-breaking devices featuring superior architectures

VIABLE DIAMOND SUBSTRATES
Diamond is set to serve in more applications, thanks to a heteroepitaxial growth process for fabricating 2-inch substrates

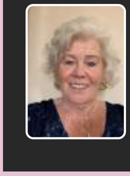
OPPORTUNITIES FOR THE VCSEL
Mirrors that incorporate porous layers of GaN will drive the commercialisation of blue and green VCSELs

COMPOUND SEMICONDUCTOR MAGAZINE is the primary information resource for professionals working with compound semiconductor materials and devices.

Each issue of the magazine is distributed in print and digitally to over 60,000 professionals worldwide. With the largest and most diverse global audience of qualified buyers served by any compound semiconductor focused magazine, secure a corporate partnership and buyers guide entry and receive 12 months of promotion and exposure to the compound semiconductor industry across the magazine portfolio including:

- 12 months of promotion in nine issues of the print and digital versions featuring your company logo and company details
- 12 months of promotion and exposure on the Compound Semiconductor website **compoundsemiconductor.net** featuring a Buyers Guide entry and hyperlinked company logo
- Sponsorship of one e-news alerts sent out to over 60,000 industry professionals with text and a standard web banner.

UK, Europe + Rest of the World
Jacob Caulfield
T: +44 (0)2476 719 979
E: jacob.caulfield@angelbc.com



USA:
Janice Jenkins
T: +1 724-929-355
E: jjenkins@brunmedia.com

WEBINARS

Specialists with 30 year+ pedigree and in-depth knowledge in overlapping sectors

COMPOUND SEMICONDUCTOR | SILICON SEMICONDUCTOR | POWER ELECTRONICS WORLD | PHOTONIC INTEGRATED CIRCUITS | SENSOR SOLUTIONS

Expertise: Moderators, Markets, 30 Years + Pedigree

Reach: Specialist vertical databases

Branding: Message delivery to high level influencers via various in house established magazines, websites, events and social media

For more information contact:
Jackie Cannon T: 01923 690205 E: jackie@angelwebinar.co.uk W: www.angelwebinar.co.uk
T: +44 (0)2476 718 970 E: info@angelbc.com W: www.angelbc.com

Angel
BUSINESS COMMUNICATIONS

Precise accuracy and low damage etching with surface smoothing

Excellent process etch uniformity for high performance p-GaN HEMTs and recessed gate MISHEMTs devices.

Remaining AlGaN thickness of 5 nm ±0.5 nm verified by TEM for 3 samples.