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Wide-bandgap semiconductors gear up for electric vehicles

Cree partners with ABB and ZF on automotive applications •
Emcore sells CATV production operation to China's Hytera



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p15 Cree and automotive supplier ZF are partnering on silicon carbide-based power inverters for electric vehicles.



p42 Osram's Firefly SFH 4030 and 4060 IR LEDs aim to prevent side effects of VR/AR by enabling eye-trackers that provide a targeted point of reference.



p74 Fraunhofer IAF claims to be first to manufacture AlScN by MOCVD, targeting power electronics based on AlScN transistors for industrial use.



Cover: Netherlands-based Nexperia, which makes discrete and MOSFET components and analog & logic ICs, has announced its entry into the GaN FET market with a 650V GaN-on-Si device targeted at high-volume EV, communication infrastructure and industrial sectors. **p20**

Silicon carbide adoption accelerates

As in the last few months, this issue again shows how silicon carbide (SiC) is increasingly being adopted for power electronics in automotive and industrial applications, with investment filtering through the supply chain.

In September, Cree Inc of Durham, NC, USA announced an expansion of its \$1bn Wolfspeed business' investment in both SiC materials and device manufacturing. The firm also partnered with UK automotive propulsion technology provider Delphi for its SiC MOSFETs to be used in 800V traction drive inverters (and subsequently DC/DC converters and chargers).

Now, in November, Cree said that it was intensifying its cooperation with Germany's ZF Friedrichshafen (one of the world's largest automotive suppliers) via a strategic partnership to create SiC-based power inverters for electric drivelines (for market availability by 2022) — see page 15. Separately, Cree has partnered with ABB's Power Grids business to jointly expand the rollout of silicon carbide in the power semiconductor market, incorporating the use of Wolfspeed SiC-based devices into ABB's product portfolio (enabling Cree to broaden its customer base while accelerating ABB's entry into the electric vehicle sector) — see page 14.

Cree has also announced the extension and expansion (doubling to over \$500m) of an existing multi-year agreement (signed just in January) to supply 150mm-diameter bare and epitaxial SiC wafers to Switzerland's STMicroelectronics (page 15). The firms say that the increased wafer supply enables them to address rapidly growing demand for silicon carbide power devices globally, particularly in automotive and industrial applications.

In parallel, in early December, ST itself completed its full acquisition of Sweden's Norstel, which makes 150mm SiC bare and epitaxial wafers (page 12), following its initial acquisition of a 55% stake in February. The total purchase price was \$137.5m. "This acquisition comes in addition to wafer supply agreements signed with third parties, with the overall goal to secure the required level of wafers to manufacture MOSFETs and diodes for the automotive and industrial customer programs that will ramp up over the next years," said president & CEO Jean-Marc Chery.

In late November, France-based substrate maker Soitec announced a joint program to combine its proprietary Smart Cut technology — used mainly for making silicon-on-insulator (SOI) products — with the process technology and equipment-making expertise of US-based Applied Materials to develop SiC substrate manufacturing (page 14). A pilot line at CEA-Leti in Grenoble, France should produce samples in second-half 2020.

Also, after launching its AIX G5 WW C chemical vapor deposition (CVD) system for high-volume production of SiC epiwafers at the International Conference on Silicon Carbide and Related Materials (ICSCRM 2019) at the beginning of October, in early November Germany's Aixtron said that it had installed a system at China-based pure-play SiC epiwafer foundry EpiWorld International, targeting the manufacturing of 600V, 1200V and 1700V power devices for automotive applications (see page 27).

A bump in the road is a drop in EV sales in China (contributing to Cree expecting Wolfspeed sales to be down 3–6% this quarter — see page 40). As well as being a short-term blip, increasing adoption elsewhere plus rapid displacement of silicon by SiC in power semiconductors should ensure continued growth.

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- feature articles (technology, markets, regional profiles);
- conference reports;
- event calendar and event previews;
- suppliers' directory.

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HBTs pHEMTs BiFET/BiHEMTs

GaN substrate market to grow at 10% CAGR to 2027

In terms of revenue, the global gallium nitride substrate market will expand at a compound annual growth rate (CAGR) of ~10% to \$225m in 2027, estimates a report by Transparency Market Research.

GaN substrates promise to dramatically enhance the performance, efficiency and ubiquity of sophisticated power management and control functions. If low-cost bulk GaN substrate is not available, GaN can be grown on other substrates such as sapphire, silicon carbide (SiC) or silicon. For better cost economics, GaN devices can be fabricated on large-diameter silicon substrates in existing silicon CMOS (complementary metal-oxide-semiconductor) fabs. GaN devices are gaining popularity due to various advantages that they offer including high breakdown voltage, high switching speed, high thermal conductivity and low on-resistance. This is expected to have a positive impact on the gallium nitride substrate market.

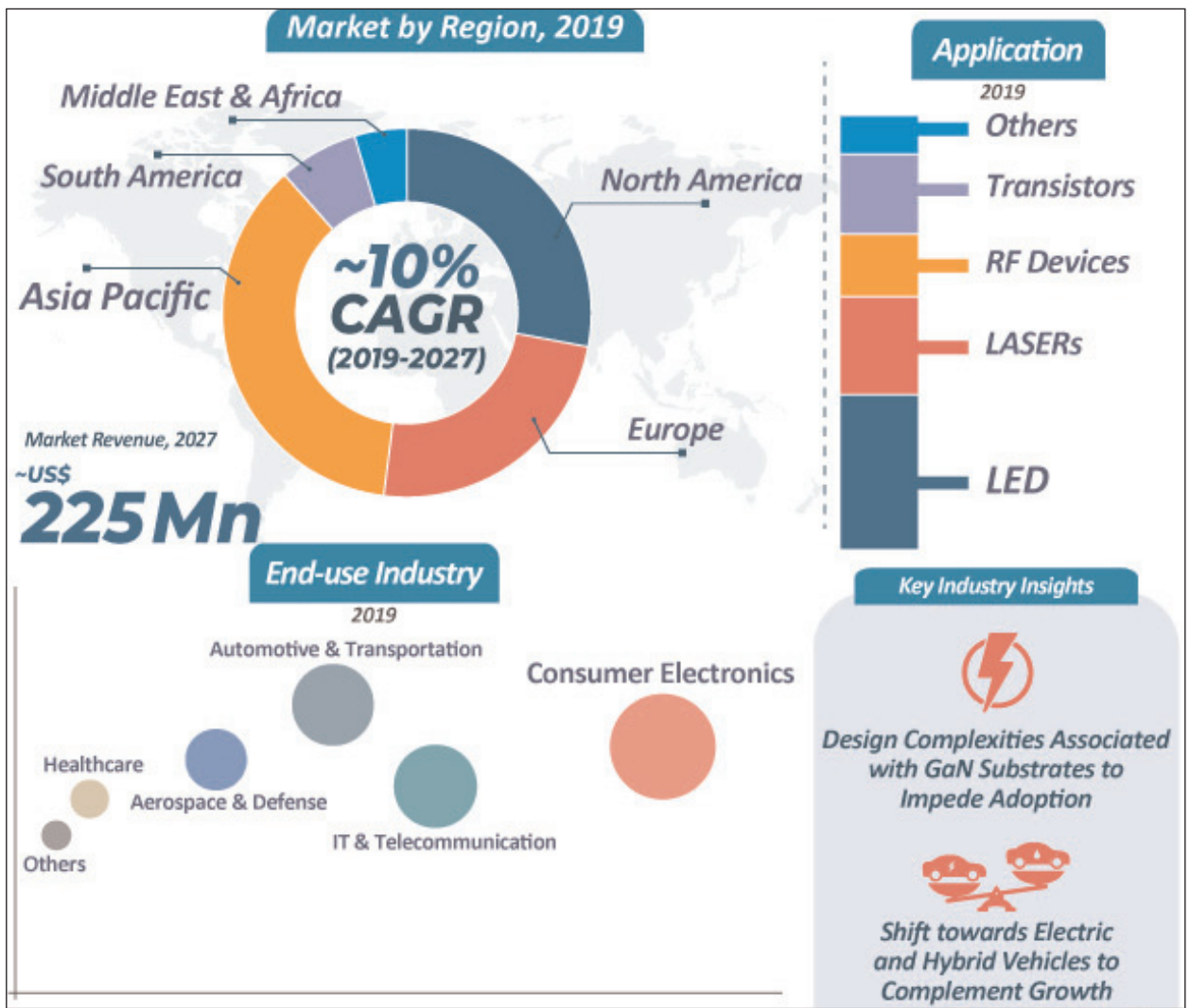
GaN substrates have evolved significantly since their introduction in the last few years ago. The growing use of GaN technology devices for high-frequency, high-voltage, and high-

temperature applications is expected to drive the global GaN substrate market during the forecast period. Increasing adoption of white-light LEDs is another factor boosting the GaN substrate market. GaN substrates are increasingly being used to make white-light LEDs, in addition to power devices, that exceed the performance of current devices, as they offer improved electric characteristics. Furthermore, rapid advances in GaN technology have

GaN substrate suppliers are expanding by forming strategic alliances with peers as well as various research institutions

led to the development of efficient GaN substrates with low defect density and free macro defect density. Hence, they can increasingly be used for realizing white-light LEDs. The increasing adoption of white-light LEDs is hence expected to drive growth of the GaN substrate market.

Asia-Pacific to remain dominant
Having accounted for a key share of the global GaN substrate market in 2018, the Asia-Pacific region is expected to continue to dominate between 2019 and 2027 due to the rising popularity of GaN devices for various applications in several end-use industries. China constituted a significant share of the Asia-Pacific market in 2018, and the country



Segmentation



will see large investments in R&D, targeted at innovating new technologies. Also, the region is home to prominent GaN technology companies that are engaged in R&D on innovative GaN solutions and their introduction to the marketplace.

North America has emerged as the second-largest market for GaN substrates. The region is expected to maintain a considerable share of the global market during the forecast period, due to the increasing adoption of GaN substrates for various applications such as white-light LEDs and the increasing adoption of electric vehicles. GaN-based

devices and GaN substrates can be employed in several applications in the automotive sector, such as LiDAR, 48V–12V power distribution, and high-intensity headlights. The region therefore presents significant opportunities for the GaN substrate market, the report reckons.

Europe is expected to be a lucrative market for GaN substrates throughout the forecast period due to the growing popularity of GaN devices and their rising use in the automotive industry in countries in Western Europe and Central Europe. The European market is anticipated to increase in the next few years

due to rapid industrialization in the region. Furthermore, key players are engaged in making technical advances in GaN technology to overcome the challenges associated with devices based on this technology.

Key players in the global GaN substrate market are displaying synergies through close cooperation and collaboration in sales, marketing and technical advances. GaN substrate suppliers are also expanding by forming strategic alliances with peers as well as various research institutions in order to establish themselves as players in the global market.

www.transparencymarketresearch.com

RF GaN market growth to accelerate to over \$1.7bn in 2023: SEDI, Wolfspeed and Qorvo to benefit

Revenue from RF gallium nitride (GaN)-enabled devices grew nearly 22% in 2018 and will accelerate, surpassing \$1.7bn in 2023, forecasts the Strategy Analytics Advanced Semiconductor Applications (ASA) report 'RF GaN Market Forecast: 2018 – 2023 (Data Tables)'. The drivers for this growth will be the continuing deployments of 4G and emerging 5G base-stations, along with a

variety of defense applications.

"Base stations represent the largest source of GaN revenue," notes Eric Higham, director of the Advanced Semiconductor Applications (ASA) service and the Advanced Defense Systems (ADS) service. "Trade tensions between the US and China remains a wildcard, but Sumitomo Electric Device Innovations and Wolfspeed will remain the dominant GaN suppliers

for base-station applications," he adds.

"The defense market, primarily radar and communications applications, is seeing strong growth from new systems and major platform upgrades. This is also providing fuel for the GaN growth engine and should bode well for companies like Qorvo and Wolfspeed," Higham concludes.

www.strategyanalytics.com

Qorvo's quarterly revenue well above guidance, driven by integration-related content gains in 5G Mobile Products Infrastructure & Defense Products to rebound in December quarter

For its fiscal second-quarter 2020 (ended 28 September 2019), Qorvo Inc of Greensboro, NC, USA (which provides core technologies and RF solutions for mobile, infrastructure and defense applications) has reported revenue of \$806.7m, down 8.8% on \$884.4m a year ago but up 4% on \$775.6m last quarter, and \$52m above the midpoint of the \$745–765m guidance. This was driven by stronger-than-forecasted Mobile Products revenue of \$623m, down 6.6% on \$667m a year ago but 12% up on \$556m last quarter.

In particular, revenue exceeded expectations at the three largest customers, including China's Huawei (about 5% of total revenue, rather than the 3–4%). "While staying completely consistent with export regulations, we're able to ship highly integrated modules across all frequency bands to Huawei's handset division," notes Eric Creviston, president of Qorvo's Mobile Products Group. "In China the dollar content for 5G phones is significantly increased over 4G phones," says president & CEO Bob Bruggeworth. "Integration was key and being able to integrate the components that are needed for 5G phones. We're taking some share there from discrete players. You're seeing the integration coming together in the 4G portion of a 5G phone, plus for 5G, and that's what's really driving," he adds.

"Leading Korea-based smartphone maker Samsung was a standout, as Qorvo secured new design wins and expanded its participation in their mass-market phones," notes Bruggeworth. "We got out of alignment with the product roadmap and their architecture for a cycle or two, but we're fully back in alignment across not only the flagship or marquee tier but also the mass tier of handsets there," says Creviston.

Infrastructure & Defense Products (IDP) revenue has fallen by 16% from \$218m both a year ago and

last quarter to \$184m, due mainly to the effects of export restrictions. Nevertheless, Qorvo has been able to ship some components into Huawei's infrastructure side, says Bruggeworth.

On a non-GAAP basis, gross margin was 46.5%, down from 47.7% a year ago but up from 46.2% last quarter and at the top end of the 46–46.5% guidance range. This was a result of better-than-expected manufacturing costs, partially offset by \$10m worth of excess inventory charges due to (i) some excess parts on older-generation handset products, (ii) a very isolated quality issue in the non-core market, and (iii) being unable to repurpose a portion of a customer-specific product.

Operating expenses have been cut further, from \$168.3m a year ago and \$167.9m last quarter to \$166.7m.

Despite being down on \$224.9m (\$1.75 per diluted share) a year ago, net income has grown further from \$165.3m (\$1.36 per diluted share) last quarter to \$181.2m (\$1.52 per diluted share, exceeding the \$1.30 guidance).

Cash flow from operations was \$173.4m and capital expenditure (CapEx) was \$38m, so free cash flow was \$135.4m (contributing to free cash flow for fiscal first-half 2020 of a record \$342m). "We expect to maintain strong free cash flow through the fiscal year," says chief financial officer Mark Murphy. During the quarter, Qorvo repurchased \$165m of its stock. Overall, cash and cash equivalents overall hence fell by \$42.8m, from \$629.6m to \$586.8m.

Over the past 12 months, Qorvo has deployed over \$500m with the purchases of two companies. In May, Qorvo completed the acquisition of Active-Semi International Inc of Dallas, TX, USA, a fabless supplier of programmable analog/mixed-signal power management integrated circuits (PMICs) and power application controllers (PACs).

Qorvo hence expanded its portfolio of integrated motor power management control solutions supporting brushless motor applications in white goods, power tools and other products. "Our power management solutions enable smaller, lighter devices that charge faster and operate longer with between charges," claims Bruggeworth. "On the design front, programmability enables our customers for lower product development costs and reduced time-to-market. We expect to leverage our scale to drive growth in power tools, light goods, industrial equipment and other product categories."

Also, after the quarter-end, Qorvo completed the acquisition of the remaining equity in Cavendish Kinetics for \$203m, adding RF MEMS capabilities and expanding its technology portfolio for switches, tuners and other product applications. "We intend to optimize and scale our RF MEMS technology for smartphones and ultimately apply to other growth segments," says Bruggeworth.

"Our technology investments, portfolio management and operational discipline continued to yield strong and consistent performance," he adds. "During the quarter, we successfully integrated our programmable power management products and technologies into IDP."

"Qorvo's broad portfolio of enabling technology, coupled with a robust supply chain and solid product execution, is allowing us to solve our customers' most challenging problems across all tiers of their portfolio," Bruggeworth says.

"In Mobile products, the trend toward integration is driving our industry, and integration is all the more important with the interaction of 5G," he notes. "Qorvo is securing significant content in 5G smartphones with our premium technologies and our highly integrated modules, enabling our customers to enhance system performance, overcome

design challenges and bring their smartphones to market faster than ever," Bruggeworth adds. Qorvo has correspondingly been selected by the top four China-based smartphone OEMs to supply low-, mid-high- and ultrahigh-band power amplifier duplexer (PAD) and other highly integrated solutions for their upcoming 5G smartphones. "Our wins are broad-based and our solutions are mated with all the major chipset providers including SLSI, Qualcomm, MediaTek and HiSilicon." In mobile Wi-Fi applications, Qorvo is ramping its recently launched Wi-Fi 6 front-end modules (FEMs) in support of multiple leading China-based smartphone OEMs.

"In IDP, our markets are supported by secular trends including the deployment of 5G, as well as the proliferation of IoT, the adoption of Wi-Fi 6 and the performance advantages of gallium nitride (GaN) technology in defense, broadband and massive MIMO base-station applications," says Bruggeworth.

"In Defense business, we are lead participant in a US government program to advance the state-of-the-art in RF integration packaging and test. We are also increasing our GaN opportunities with the US branch and we secured wins for our GaN amplifiers and integrated front-end modules for X-band and Ka-band defense radar and communications programs."

In Infrastructure, the 5G ramp is to be rolling out faster than the 4G ramp. Activity is primarily in the sub-6GHz frequencies, and Qorvo's GaN technology is increasingly the technology of choice, the firm claims.

During the quarter, Qorvo secured new GaN design wins for sub-6GHz massive MIMO deployments expected to span multiple years. China Unicom and China Telecom will share cell sites to accelerate 5G deployments. This will drive the need for broader-band and higher-power amplifiers, favoring Qorvo's GaN solutions, it is reckoned.

In IoT, ratification of Wi-Fi 6 is a catalyst for the industry, and design wins for Qorvo's Wi-Fi 6 solutions are building. The quarter saw the

launch of what is said to be the first Wi-Fi 6 dual-band front-end module and the first Wi-Fi 6 iFEM for CPE applications, expanding its Wi-Fi product portfolio for retail, enterprise and network operators.

In automotive, Qorvo began production shipments of its Wi-Fi FEMs supporting multiple automotive OEM platforms, and secured a design win to supply V2X coexistence 5.9GHz BAW filters to a top-tier automotive OEM for models shipping in calendar 2020.

Fiscal Q3/2020 (to end-December 2019) should see rises in revenue to \$840-860m and diluted earnings per share to \$1.67, reflecting continued robust mobile demand, aided by a rise in 5G handset volumes, and a return to sequential growth for IDP.

"For Mobile, we expect December-quarter sales to increase sequentially and return to growth year-over-year as 5G handset launches with our integrated solutions and a healthy channel support strong demand," says Murphy. This is despite overall smartphone units being down, and Huawei becoming a significantly smaller customer year-over-year, down to no more than 5% of total revenue per quarter in the fiscal second half (making less than 10% of sales for full-year fiscal 2020, compared with 15% for fiscal 2019).

"For IDP, we project December-quarter sales to increase [showing double-digit quarter-over-quarter growth] based on higher defense business volumes, the Wi-Fi 6 ramp, and broader 5G infrastructure customer demand," says Murphy. "While Qorvo's current near-term outlook is strong and channels are healthy, trade and other factors contributed challenges and uncertainty forecast in the outlook."

A more favorable product mix and lower inventory charges should drive gross margin up to about 48%.

However, due to the operating costs of recent acquisitions and increased product investment costs related to growth in 5G, operating expenses should rise in second half fiscal 2020 to \$175-180m per quarter.

Qorvo continues to project CapEx

below \$200m in full-year fiscal 2020 as it remains disciplined on adding capacity. "Spend remains weighted towards improving our bulk acoustic wave (BAW) filter and GaN capabilities," says Murphy.

"Qorvo is operating well as 5G, Wi-Fi, defense and other markets strengthen," says Murphy. "As a result of our market outlook, operating performance, free cash flow forecast and other factors, Qorvo's board of directors has authorized a new \$1bn share repurchase program."

For fiscal Q4/2020 (to end-March), Qorvo expects a seasonal drop in revenue of about 15% sequentially. However, while Mobile Products revenue should be down seasonally quarter-to-quarter, it should be up by double-digits year-on-year. IDP is expected to strengthen. "The restrictions on Huawei have definitely limited our ability to grow in the near-term. However, we hope to return to year-over-year growth in Q4," says James Klein, president of Qorvo's Infrastructure and Defense Products Group.

Gross margin is expected to fall by 100 base points or more sequentially, but that is a typical function of seasonal mix and the effects of fixed manufacturing costs on lower revenue. "We're still working to achieve 50% or more [longer term]," notes Murphy. "We expect volume growth, so we'd expect to see better utilization," he adds. "Next calendar year, we're also having a consolidation of our fabs... most notably Florida will be closed and those products rolled into Greensboro, so those cost effects will subside. Also over time, we would expect the mix at IDP to improve and be a larger part of Qorvo. We're doing a lot of product portfolio management as well. So that'll improve that mix and that's the purpose of our select and high-tech investments. Finally, we are operating as well as we ever have and that's allowing us to drive better productivity than we were even before and, to the extent we're doing above-inflation price erosion, that would be incremental benefit to gross margin."

www.qorvo.com

Skyworks' quarterly revenue rebounds by 8%, or 20% excluding export-restricted Huawei

Product ramps, content gains and expansion in customers, end markets and applications to drive further growth

For full-year fiscal 2019 (ended 27 September), Skyworks Solutions Inc of Woburn, MA, USA (which makes analog and mixed-signal semiconductors) has reported revenue of \$3.377bn, down 12.7% on fiscal 2018's \$3.868bn.

Fiscal fourth-quarter 2019 revenue was \$827.4m, down 17.9% on \$1008m a year ago (since revenue from Huawei — until recently the firm's second largest customer — was just \$10m) but up 8% on \$767m last quarter and \$2m above the midpoint of the \$815–835m guidance. Also, excluding Huawei, revenue rose 20% sequentially (one of Skyworks' strongest sequential growth rates).

On 15 May the US Department of Commerce's Bureau of Industry and Securities (BIS) added China-based smartphone and telecom network infrastructure maker Huawei to its 'Entity List' prohibiting the sale to Huawei of products covered by the Export Administration Regulations (EAR) without obtaining a license. Skyworks subsequently ceased all shipments to Huawei (which had contributed 12% of total revenue in fiscal first-half 2019).

By market sector, Mobile (Integrated Mobile Systems and Power Amplifiers) rebounded from 63% of total revenue last quarter to 67%. Broad Markets was about 33% of total revenue, still up on 28% a year ago but down from 37% last quarter. However, excluding Huawei it was up sequentially, as well as year-on-year by mid-single digits as a percentage. Senior VP & chief financial officer Kris Sennesael cites "multiple drivers... Wi-Fi 6 adoption, the 5G opportunity beyond the mobile phone, as well as some good traction in our audio play that we have as well".

Highlights during the quarter

included:

- powering Samsung's suite of 4G mobile devices and their first foldable 5G smartphone;
- enabling LG's V50ThinQ flagship 5G handset;
- accelerating the Sky5 portfolio ramp supporting multiple 5G launches;
- supporting leading infrastructure customers with 5G small-cell architectures;
- securing Wi-Fi 6 design wins in Netgear's Orbi and Nighthawk platforms;
- delivering LTE-powered IoT engines across Sierra Wireless' industrial gateways and transportation platforms;
- commencing volume production of high-performance mesh network connectivity modules for Amazon, Juniper and Ruckus;
- ramping fully integrated LTE solutions with major automotive manufacturers;
- shipping Zigbee ultra-low-power devices for a tier-one

Broad Markets was about 33% of total revenue, still up on 28% a year ago but down from 37% last quarter. However, excluding Huawei it was up sequentially, as well as year-on-year by mid-single digits as a percentage. Senior VP & chief financial officer Kris Sennesael cites "multiple drivers... Wi-Fi 6 adoption, the 5G opportunity beyond the mobile phone, as well as some good traction in our audio play that we have as well"

home security provider;

- expanding reach at Sonos, enabling its indoor/outdoor portable smart speakers; and
- introducing cognitive chipsets for ultra-low-latency, next-generation wireless gaming headsets.

On a non-GAAP basis, gross margin has fallen further, from 51.2% a year ago and 50.4% last quarter to 50.3%, reducing full-year gross margin from 51.1% to 50.6%.

Operating expenses were \$135m (16.3% of revenue), flattish through the March and June quarters.

Full-year net income has fallen from \$1323.4m (\$7.22 per diluted share) to \$1.1bn (\$6.17 per diluted share). Fourth-quarter net income was \$261.9m (\$1.52 per diluted share, above the \$1.50 guidance), down from \$349.7m (\$1.94 per diluted share) a year ago. However, this is up from \$233.6m (\$1.35 per diluted share) last quarter.

Cash flow from operations was \$417m for the quarter (almost doubling from \$209.3m last quarter) and \$1367.4bn for the full year (up 8.5% from \$1260.6m for fiscal 2018). Quarterly capital expenditure (CapEx) was \$84.4m (\$398.4m for the full year). Free cash flow was hence \$333m (free cash flow margin of 40%), contributing to \$969m for the full year (free cash flow margin of 29%, nearing the model target of 30%). Skyworks paid \$75m in dividends (making \$274m for the full year) and repurchased 1.9 million shares of common stock for \$146m (making \$658m for 8.9 million shares in the full year). So, in total, Skyworks has returned \$932m to shareholders through buybacks and dividends in full-year fiscal 2019 (just over 96% of free cash flow).

Overall, cash, cash equivalents and marketable securities have risen by \$112.1m from \$970.1m at

the end of last quarter to \$1082.2m. Skyworks has no debt.

"Skyworks delivered solid financial results in the fourth fiscal quarter, closing a year that saw extraordinary market volatility and change," says president & CEO Liam K. Griffin.

Skyworks' board of directors has since declared a cash dividend of \$0.44 per share of common stock (payable on 24 December, to stockholders of record at the close of business on 3 December).

"Looking ahead, we are well positioned to execute on our mission of delivering compelling 5G solutions across a growing and diverse suite of customers and markets," reckons Griffin. "Our systems-level approach, highlighted by our Sky5 platform, now includes strategic capabilities in BAW [bulk acoustic wave filters], Wi-Fi 6, MIMO and custom diversity

receive. Collectively, these solutions are unleashing the true potential of 5G — successfully providing a range of options to our customers while increasing the value and utility of each usage case. We are in the early innings of this substantial

Our systems-level approach, highlighted by our Sky5 platform, now includes strategic capabilities in BAW [bulk acoustic wave filters], Wi-Fi 6, MIMO and custom diversity receive. Collectively, these solutions are unleashing the true potential of 5G

technology inflection, as we translate these dynamics into sustainable growth and profitability," he adds.

"Strategic product ramps, content gains and an expanding footprint across a broad set of customers, end markets and applications are expected to drive sequential revenue and earnings growth in the December quarter," says Sennesael. Specifically, in fiscal first-quarter 2020, Skyworks expects revenue of \$870–890m (up 6.5%), gross margin roughly flat at about 50% (due to the lingering issues with Huawei business), operating expenses of \$132m (cut by \$7m year-on-year, to 15% of revenue, as Skyworks implements certain cost reductions), and diluted earnings per share hence up to \$1.65.

www.skyworksinc.com

Cardiff uses LEEM-MBE to observe metastability on gallium arsenide surfaces

Cardiff–ICS team to examine if phenomenon can be used to influence growth of device structures

Researchers at Cardiff University's School of Physics and Astronomy and the Institute for Compound Semiconductors say that they have, for the first time, spotted previously unseen 'instabilities' on the surface of gallium arsenide that have a tendency to appear and then disappear (K. Hannikainen et al, 'Surface Phase Metastability during Langmuir Evaporation', Phys. Rev. Lett. vol123, 186102).

Specifically, the team has directly imaged the spontaneous formation of metastable surface phase domains in the atomic structure of GaAs(001) during Langmuir evaporation. It is the first time that this phenomenon of metastability has been observed on GaAs surfaces.

These metastable phases transform to the thermodynamically stable parent phase, producing a dynamic phase coexistence with a temperature-dependent, time-averaged coverage. The measured

temperature dependence of the time-averaged coverage has been explain using Monte Carlo simulations to identify the key kinetic processes and investigate the interplay between phase metastability and evolving surface morphology.

"At the moment we do not know whether this phenomenon is affecting the growth of semiconductor device structures – this is what we need to study next," says co-author Dr Juan Pereiro Viterbo of the School of Physics and Astronomy. "If this phenomenon were to occur during the growth of semiconductor devices then this could have profound consequences," he adds.

"Ultimately these findings are helping us to better understand what is happening at the molecular scale, which will enable us to develop new materials and structures, reduce defects in existing compound semiconductor devices and therefore develop better electronics for our

communication systems, computers, phones, cars and more."

Key to the discovery was the availability of equipment with capabilities that do not exist anywhere else in the world, it is claimed. The labs at the School of Physics and Astronomy and the Institute for Compound Semiconductors have a low-energy electron microscope (LEEM) combined with a molecular beam epitaxy (MBE) system, which allows researchers to observe dynamic changes on the structure of materials while compound semiconductors are being fabricated. "Even though GaAs has been well studied, the use of low-energy electron microscopy in the growth process allows us to observe dynamic events that have never been seen before," says Viterbo.

<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.186102>
<https://leemlab.cf.ac.uk>

STMicroelectronics acquires remaining 45% stake in silicon carbide wafer maker Norstel

ST to continue growing both production of 150mm SiC wafers and R&D on 200mm production

STMicroelectronics of Geneva, Switzerland has completed its full acquisition of Norstel AB of Norrköping, Sweden, which was spun off from Linköping University in 2005 and develops and manufactures 150mm silicon carbide (SiC) bare and epitaxial wafers. ST exercised its option to acquire the remaining 45% stake, following the initial acquisition of a majority 55% stake announced in February. The total consideration for the acquisition of Norstel was \$137.5m, funded with available cash.

"At a time of constrained global capacity for silicon carbide, the full acquisition of Norstel will strengthen our internal SiC ecosystem: it will boost our flexibility, allow us to control better the improvement of yield and quality of the wafers, and support our long-term silicon carbide roadmap and business," says ST's president & CEO Jean-Marc Chery. "This acquisition comes in addition to wafer supply agreements signed with third parties, with the overall goal to secure the required level of

wafers to manufacture MOSFET and diodes for the automotive and industrial customer programs that will ramp up over the next years."

Norstel will be fully integrated into ST's global R&D and manufacturing operations. ST says that it will continue growing its activities covering both the production of 150mm bare and epitaxial silicon carbide wafers and R&D on 200mm production as well as, more broadly, on wide-bandgap materials.

www.norstel.com
www.st.com

SOI Industry Consortium honors pSemi's Jim Cable and Ningbo's Herb Huang for pioneering RF-SOI work

At its 2019 RF-SOI Workshop in Shanghai in September, the SOI Industry Consortium has awarded two pioneers of radio-frequency silicon-on-insulator technology (RF-SOI), namely Jim Cable (pictured on the left), chairman & chief technology officer of pSemi Corp of San Diego, CA, USA (a Murata Company) and Herb Huang, CEO & general manager of Ningbo Semiconductor International Corp (NSI) of Ningbo, China.

"Thanks in large part to the innovation, dedication and perseverance of men like Jim Cable and Herb Huang, RF technology based on SOI is now ubiquitous," commented SOI Industry Consortium chairman & executive director Carlos Mazure (on the right in the photo). "Jim Cable drove the development of SOI and RF switches that are now in every cellphone, and Herb Huang has been a key contributor to SOI technology and a champion of the SOI foundry ecosystem in China."

Cable joined pSemi (formerly Peregrine Semiconductor Corp) in



Jim Cable (left) with SOI Industry Consortium chairman Carlos Mazure.

1996 and held technical leadership roles before serving as CEO from 2002 to 2017. An early pioneer of SOI technology, he believed SOI would ultimately replace other technologies in the RF front end. Cable is a co-inventor on more than 70 semiconductor and technology patents, including breakthroughs in SOI-based processes for CMOS RF switch linearity and integration that are used by all smartphones today, and will become even more mission-critical in 5G and millimeter-wave markets, it is reckoned. He received his B.S. in physics

from UC Riverside and his master's degree and Ph.D. in electrical engineering from UCLA.

Huang is CEO of Ningbo Semiconductor International Corp (NSI) of Ningbo, China. A driver of the RF-SOI ecosystem in China, he spent much of his career at SMIC, the largest semiconductor foundry in mainland China. In 2016, SMIC created NSI as a joint venture subsidiary with China IC Investment Fund, Ningbo Economic Development Zone Industrial Investment Company Ltd and other IC investment funds. Under Huang's leadership, NSI optimized the process and model of a 0.13_μm RF-SOI technology platform transferred from SMIC. Now in mass production, the RF-SOI technology platform supports customers in IC design and product development for a new generations of radio communications. Huang holds both a Ph.D in Materials Science and Engineering and an MBA from the University of Minnesota.

www.soiconsortium.org
www.psemi.com

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Cree and ABB partner on silicon carbide for automotive and industrial applications

Cree to broaden customer base as ABB Power Grids business accelerates entry into EV sector

Cree Inc of Durham, NC, USA and ABB's Power Grids business have partnered to expand the rollout of silicon carbide (SiC) in the rapidly growing high-power semiconductor market. The agreement incorporates use of Cree's Wolfspeed SiC-based semiconductors into ABB's product portfolio, enabling Cree to broaden its customer base while accelerating ABB's entry into the fast-expanding electric vehicle (EV) sector.

Cree's products will be included as part of ABB's power semiconductor product portfolio, across power grids, train and traction, industrial

and e-mobility sectors. Specifically, Cree's SiC devices will be assembled into ABB power modules.

"Cree is committed to leading the global semiconductor market's transition to more energy-efficient, higher-performing silicon carbide-based solutions. ABB has a long-standing heritage as the world market leader in industrial power electrification solutions, so expanding our work with them will help increase the adoption of transformative and eco-friendly alternatives in the power and automotive sectors," comments Cree's CEO

Gregg Lowe. "Together, this partnership delivers Wolfspeed silicon carbide into new markets, such as power grids and high-speed trains for the continued advancement of the power, traction, industrial and EV markets," he adds.

"The partnership with Cree supports ABB's strategy in developing energy-efficient silicon carbide semiconductors in the automotive and industrial sectors," says Rainer Käsmaier, managing director of semiconductors at ABB's Power Grids business.

www.cree.com

Soitec and Applied Materials to jointly develop SiC engineered substrates using Smart Cut technology

Pilot line to be operating at Substrate Innovation Center at CEA-Leti by first-half 2020, for wafer samples in second-half 2020

Engineered substrate manufacturer Soitec of Bernin, near Grenoble, France has announced a joint development program with semiconductor equipment maker Applied Materials Inc of Santa Clara, CA, USA on silicon carbide substrates.

Demand for SiC-based chips has been rising, particularly in electric vehicles (EVs), telecoms and industrial applications. However, adoption has been limited due to challenges related to supply, yield and cost of silicon carbide substrates. Soitec says that it will be working with Applied Materials to develop substrates that can overcome these challenges.

The development program will combine Soitec's expertise in engineered substrates with that of Applied Materials in materials engineering solutions. Soitec will leverage its proprietary Smart Cut technology — currently in use for the manufacture of silicon-on-insulator (SOI)

products widely adopted by chip makers. Applied Materials will contribute process technology and equipment expertise.

Under the development program, the firms will install a silicon carbide engineered substrate pilot line at the Substrate Innovation Center located at micro/nanotechnology R&D center CEA-Leti in Grenoble, France. The line is expected to be operational by first-half 2020, with the goal of producing silicon carbide wafer samples using Soitec's Smart Cut technology in second-half 2020.

"Soitec's Smart Cut technology and 30 years of experience, together with Applied Materials' great leadership in materials engineering, can enable the development of a robust technology and boost the silicon carbide supply chain," believes Thomas Piliszczuk, executive VP of Strategic Office at Soitec.

"With its broad portfolio and deep expertise, Applied Materials is best positioned to help the power electronics industry overcome the toughest technology challenges," reckons Steve Ghanayem, senior VP of New Markets and Alliances at Applied Materials.

"Electric vehicles are a key focus for Audi. The future of mobility will be electric — based on technology innovations beginning at the semiconductor material and substrate level," comments Berthold Hellenenthal, head of Competence Center Electronics and Semiconductors and the Semiconductor Strategy at Audi AG. "Silicon carbide can enable higher power density and better efficiency semiconductors in electric vehicles. We are pleased to see Soitec and Applied Materials working together to advance this technology."

www.appliedmaterials.com

www.soitec.com

ZF and Cree partner on SiC-based power inverters for EVs

Cree Inc of Durham, NC, USA, which manufactures silicon carbide (SiC) and gallium nitride (GaN) wafers and devices, and ZF Friedrichshafen AG (one of the world's largest automotive suppliers, with 148,000 staff and annual sales of €36.9bn) are intensifying their existing cooperation by announcing a strategic partnership to create highly efficient electric drivelines.

"We're building on our cooperation with Cree using their Wolfspeed silicon carbide technology and are absolutely convinced that combining our strengths will further improve efficiency and competitive edge for our components and systems," says Jörg Grotendorst, head of the ZF E-Mobility Division.

In contrast to today's standard silicon technology, the future use of SiC-based power semiconductors



Jörg Grotendorst (head of ZF Division E-Mobility) and Cengiz Balkas (senior VP & general manager of Wolfspeed) signing the partnership (Photo: ZF).

should increase range for electric vehicles. Due to high battery costs, efficient electric drive represents enormous growth potential. In particular, silicon carbide technology — in conjunction with the 800V vehicle electrical system voltage — makes a significant contribution to further increasing efficiency.

"Partnering with a tier-one leading

global automotive supplier like ZF for the use of silicon carbide-based power inverters in next generation electric vehicles is indicative of the integral role silicon carbide plays in extending the capabilities of EVs everywhere," says Cree's CEO Gregg Lowe.

Cree's technology will initially be used to fulfill orders that ZF has already received for SiC-based electric drives from several leading global automakers. Through the partnership, ZF expects to make silicon carbide electric drivelines available to the market by 2022.

Since January 2016, ZF has bundled its electro-mobility activities in the E-Mobility Division headquartered in Schweinfurt, Germany (which has more than 9000 staff worldwide).

www.zf.com

www.cree.com

Cree and ST expand and extend silicon carbide wafer supply agreement

Doubling of value to \$500m addresses rapidly growing demand for SiC power devices, particularly in automotive and industrial applications

Cree Inc of Durham, NC, USA and STMicroelectronics of Geneva, Switzerland have announced the expansion and extension of an existing multi-year, long-term silicon carbide wafer supply agreement (signed in January) to more than \$500m.

The extended agreement is a doubling in value of the original agreement for the supply of Cree's 150mm-diameter silicon carbide bare and epitaxial wafers to ST over the next several years. The firms says that the increased wafer supply enables them to address the rapidly growing demand for silicon carbide power devices globally, particularly in automotive and industrial applications.

"Expanding our long-term wafer supply agreement with Cree will increase the flexibility of our global

silicon carbide substrate supply," says STMicroelectronics' president & CEO Jean-Marc Chery. "It will further contribute to securing the required volume of substrate we need to manufacture our silicon carbide-based products as we ramp up production over the next years for the increasing number of programs won at automotive and industrial customers," he adds.

"Silicon carbide delivers performance enhancements that are critical to electric vehicles (EVs) and a host of next-generation industrial solutions for solar, energy storage and uninterruptible power systems (UPS)," says Cree's CEO Gregg Lowe. "Cree remains committed to leading the semiconductor industry's transition from silicon to silicon carbide, and the extension of the agreement with ST ensures we are able to

meet the accelerating, global demand for this solution across a diverse range of applications while accelerating the market."

Cree notes that the adoption of silicon carbide-based power solutions is rapidly growing across the automotive market as the industry seeks to accelerate its move from internal combustion engines to electric vehicles, enabling greater system efficiencies that result in electric cars with longer range and faster charging, while reducing cost, lowering weight and conserving space. In the industrial market, silicon carbide modules enable smaller, lighter and more cost-effective inverters, converting energy more efficiently, the firm adds.

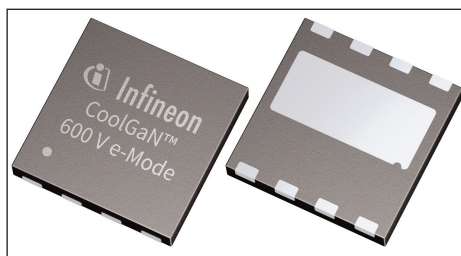
www.st.com

www.cree.com

Infinion adds 400V & 600V devices to CoolGaN portfolio

Infinion Technologies AG of Munich, Germany has broadened its CoolGaN series with two new devices. The CoolGaN 400V device (IGT40R070D1 E8220) is tailored for premium HiFi audio systems where end users demand every detail of their high-resolution sound tracks. These have conventionally been addressed by bulky linear or tube amplifiers. Instead, audio designers can use the CoolGaN 400V switch as the class D output stage. The CoolGaN 600V industrial-grade device (IGLD60R190D1) enables performance and cost optimization for low- and mid-power applications, such as in the area of low-power SMPS and telecom rectifiers. Every product in the CoolGaN family meets JEDEC standards.

Infinion says that the CoolGaN 400V switch enables smoother



switching and more linear class D output stage by offering low/linear Coss, zero Qrr, and normally-off switch. Suitable class D audio amplifiers offer 0% distortion and 100% efficiency. What impairs the linearity and power loss is highly dependent on the switching characteristics of the device. Infineon says that CoolGaN introduces zero reverse recovery charge in the body diode and very small, linear input and output capacitances. The benefit to the end users is more natural and wider soundstage audio.

To further simplify the design, Infineon pairs the CoolGaN 400V device in an HSOF-8-3 (TO-lead-less) package with a popular class D controller (IRS20957STRPBF) in an evaluation board.

The CoolGaN 600V portfolio is now also extended with a new 190mΩ, industrial-grade high-electron-mobility transistor (HEMT), developed to fit any consumer and industrial application on an optimized cost with the aim to lower the technology entry barrier. Easy design-in is supported with a standardized DFN 8x8 packaging and the matching driver ICs from the GaN EiceDRIVER series.

CoolGaN 400V (IGT40R070D1 E8220) and 600V (IGLD60R190D1) devices can be ordered now. The evaluation board EVAL_AUDAMP24 will be available for order in February.

www.infineon.com/gan

Transphorm ships over half a million GaN power devices for multi-kW-class applications

Transphorm Inc of Goleta, near Santa Barbara, CA, USA — which designs and manufactures JEDEC- and AEC-Q101-qualified 650V GaN field-effect transistors (FETs) — says it has shipped more than 500,000 high-voltage GaN FETs.

Customers in the broad industrial, infrastructure & IT and PC gaming markets have publicly announced in-production devices built with Transphorm's GaN technology, illustrating the rising confidence in GaN solutions, says the firm.

In fact, industry analyst firm IHS Markit Technology (now a part of Informa Tech) forecasts that total GaN power discrete, module and system IC revenue will reach \$1.2bn by 2028 ('SiC & GaN Power Semiconductors Report', May 2019). About \$750m of that (almost two-thirds of the total market) will be driven by high-voltage GaN solutions.

"We came to market with the most robust, two-chip normally-off device at a time when the industry

was more familiar with single-chip normally-off silicon MOSFETs," says Transphorm's co-founder & chief operating officer Primit Parikh. "As proven by our public momentum and also that of other reputable manufacturers like Power Integrations in the consumer adapter space, the two-chip normally-off GaN solution is the most practical high-voltage GaN FET design today," he adds. "In fact, it's this design that enables Transphorm's GaN to deliver high performance with strong robustness, which has led to more than 5 billion hours (with <2 FIT) of field reliability data to date."

Transphorm says that its adoption continues to be driven largely by the quality and reliability (Q+R) of its products, which is backed by its robust normally-off GaN platform, strong control of its epitaxial process, and manufacturing capability — positioned to meet the volume and quality requirements of various cross-industry markets from con-

sumer adapters to automotive.

"Following our success in the core higher-power markets targeted by GaN, we're also working with customers in fast-growing markets that are underserved by silicon such as consumer adapters and set-top boxes," says Philip Zuk, VP of worldwide technical marketing & North American sales. "Consider that the majority of products we've shipped to date were targeted for higher-power applications. Those 500,000-plus 650V FETs equate to more than 4 million lower-power (sub-100W) FETs, demonstrating our volume production capabilities."

A year ago, Transphorm released the first complete set of validation data for high-voltage GaN power semiconductors. The firm has now formally released its latest field reliability data. With more than 5 billion hours in the field, Transphorm's GaN technology currently has a <2.0 FIT rate at <19.8 PPM per year.

www.transphormusa.com

IGaN and RAM partner on commercializing GaN-on-Si whole-body monitoring quantum sensor Applications beyond healthcare also targeted

Singapore-based technology providers RAM Group (which has developed multi-parametric, single-point bio-electro-mechanical quantum sensor technology) and IGSS GaN Pte Ltd (IGaN) — which supplies proprietary 8" gallium nitride on silicon (GaN-on-Si) epitaxial wafer fabrication services for both power and radio frequency (RF) devices — have announced what is claimed to be the first clinically validated quantum device sensor (QDS) providing non-invasive, continuous whole-body organ system monitoring.

Targeted at an array of healthcare applications and wearables, QDS integrates a proprietary Artificial General Intelligence (AGI) engine to produce data sets with the potential to aid immediate and hyper-accurate diagnosis of diseases or disorders in the heart, lungs and other organs.

"Powered by AGI that operates 70% faster than AI in neural net analysis, the QDS addresses the need for a small, ultra-low power, non-invasive sensor that can simultaneously and continuously detect minute changes in electrical fields

within the human body," says RAM Group's CEO & founder Ayal Ram. "It fundamentally transforms the way critical illnesses and disease states are detected, diagnosed and understood sooner with less stress and cost," he adds.

"We are excited to bring to this partnership IGaN's in-depth know-how in cost-competitive commercializing and accelerating time-to-market of GaN-on-Si based technologies," says Raj Kumar, founder & group CEO of IGSS Ventures Pte Ltd (of which IGaN is a subsidiary). "Successful clinical trialling and QDS' market-readiness is a case in point for the advanced capabilities of niche semiconductors like GaN-on-Si, particularly as a superior replacement for silicon chips," he adds. "With RAM Group we can, together, enable the adoption of GaN-on-Si sensor-based applications beyond healthcare to further drive Singapore's potential as a global innovation hub in emerging semiconductor applications."

www.igssgan.com

www.ram.group

Qorvo recognized by Raytheon for excellence in defense & aerospace

Qorvo Inc of Greensboro, NC, USA (which provides core technologies and RF solutions for mobile, infrastructure and defense applications) has been recognized with Raytheon's 2019 EPIC Supplier Excellence Award for excellence in performance, innovation and collaboration for one or more Raytheon businesses. Only the highest-performing suppliers are recognized with this honor.

"Qorvo's ongoing partnership and continued recognition by Raytheon highlights our commitment to quality and continuous improvement,"

says James Klein, president of Qorvo's Infrastructure and Defense Products (IDP).

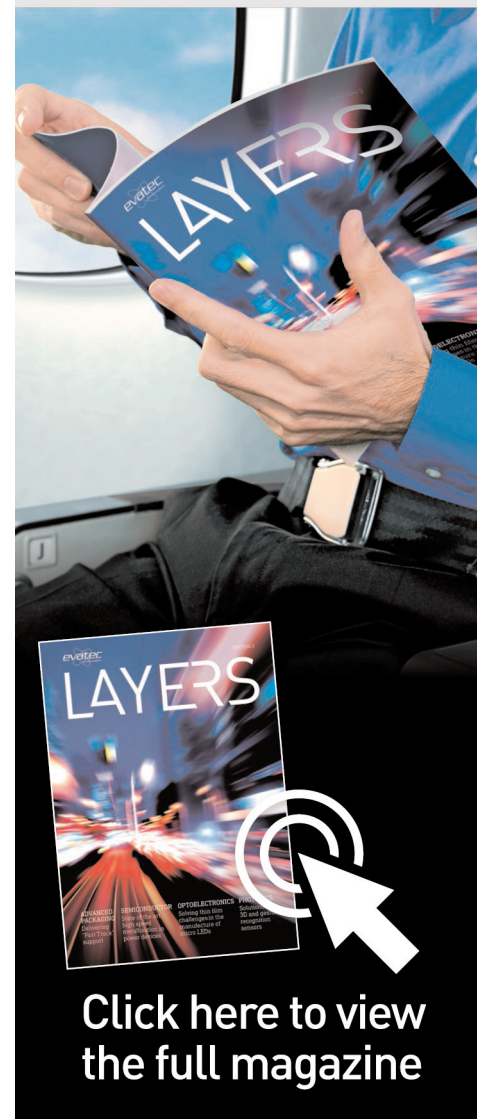
Qorvo products are at the core of many radar, space, communications and electronic warfare (EW) systems. Using gallium nitride (GaN), gallium arsenide (GaAs), surface acoustic wave (SAW) and bulk acoustic wave (BAW) technologies, Qorvo supplies RF system solutions for Raytheon's defense products.

www.raytheon.com

www.qorvo.com/defense



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GaN Systems receives ISO 9001:2015 certification

GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications) has received International Organization for Standardization (ISO) 9001:2015 certification for the design and manufacture of power semiconductor products.

Both its Canadian headquarters and Taiwanese operations facilities received ISO certification from the British Standards Institute (BSI, the world's first national standards body and one of the largest). GaN Systems says that certification represents third-party validation of

its commitment to providing high-quality products and services that align with the standards of excellence required by major multi-national customers.

The ISO 9000 family of standards is designed to ensure that GaN Systems meets the needs of customers and other stakeholders via its quality management systems (QMS) while meeting and exceeding qualification requirements for its Joint Electron Device Engineering Council (JEDEC) and Automotive Electronics Council (AEC-Q101) qualified GaN power transistor products.

ISO 9001 is considered the leading

standard for quality management systems and performance worldwide. ISO 9001:2015 is the most recent version, with significant enhancements since the last ISO 9001:2008 update.

"The ISO 9001:2015 revision demands a higher degree of leadership and management commitment than the previous standards," says GaN Systems' CEO Jim Witham. "This commitment is consistent with our mission to be the place designers can go to realize all the system benefits of GaN in their power conversion applications," he adds.

www.gansystems.com

GaN Systems Cup competition winners honored at China Power Supply Society awards ceremony

At an awards ceremony on 3 November at the China Power Supply Society Conference (CPSSC), GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications) — alongside the China Power Supply Society (CPSS), China Power Society Science Popularization Committee, and Tsinghua University — has announced the winners of the fifth annual 'GaN Systems Cup' design competition.

The contest challenges top engineering teams from China's leading universities to design new or improved power electronics systems using GaN power transistors from design to build that meets specified requirements. This year's challenge was to develop a high-efficiency, high-power-density AC/DC power supply for data-center server power applications with GaN Systems' 650V power transistors. The design had to meet several requirements: 400W-rated output power, 220V_{AC} input voltage range/48V_{DC} output voltage, and 94% efficiency at 50% load



and greater than 3W/cm³ power density.

Forty teams participated in the first round of the competition, 30 teams moved on to the second round, and 12 participated in the final competition. Five engineering teams were awarded for their GaN-based inverter designs. Cash awards of 20,000 yuan, 10,000 yuan and 5,000 yuan were given to the top, first and second winning teams:

Top winner:

● Zhejiang University

First:

● Huazhong University of Science and Technology

● North China University of Technology

Second:

● Nanjing University of Aeronautics and Astronautics

● Heilongjiang University of Science and Technology.

Honorable mentions go to: Chongqing University of Technology, Hangzhou University of Electronic Science and Technology, Harbin Institute of Technology, Kunming University of Science and Technology, Shanghai Maritime University, Tsinghua University, and Yanshan University.

The top winning team from Zhejiang University designed a solution that had a 3.76W/cm³ power density with 93.8% efficiency. Designs were judged on meeting the design criteria, functionality during the test day, ingenuity, and quality of presentation.

"The 'GaN Systems Cup' continues to provide engineering students practical experience leveraging the benefits of GaN to address today's high-efficiency, high-power needs," says Paul Wiener, VP strategic marketing at GaN Systems.

www.cpss.org.cn

GaN Systems and ON Semiconductor make available high-speed half-bridge evaluation board

GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications) and ON Semiconductor of Phoenix, AZ, USA – which supplies power management, analog, sensors, logic, timing, connectivity, discrete, system-on-chip (SoC) and custom devices – have announced the availability of a high-speed, half-bridge GaN daughter board using GaN Systems' 650V, 30A GaN E-HEMTs and ON Semiconductor's NCP51820 high-speed gate driver evaluation board.

The evaluation board has been developed for existing and new PCB designs and allows designers to evaluate GaN in existing half-bridge or full-bridge power supplies. The kit has a reduced component count in an ultra-small 25mm x 25mm layout, minimizing PCB board space. Features, which include 1+MHz operation and a 200V/ns CMTI rating, provide increased power density and improved performance with fast-switching GaN power transistors.

With benefits said to include significant reductions in power losses, weight, size (up to 80% in layout size) and system costs (up to 60% BOM cost savings), suitable applications include AC-DC adapters, data-center power supplies,

photovoltaic (PV) inverters, energy storage systems, and bridgeless totem pole topologies. The solution is one of many upcoming GaN-based power system solutions that both companies are developing.

"The expansion of the GaN components ecosystem – including driver ICs such as our NCP51820 – removes design barriers and takes advantage of the numerous benefits that GaN E-HEMTs provide," says ON Semiconductor's director of marketing Ryan Zahn. "With rising interest and adoption of GaN, we look forward to continued collaboration with GaN Systems in supporting and meeting the new power requirements taking place across many industries," he adds.

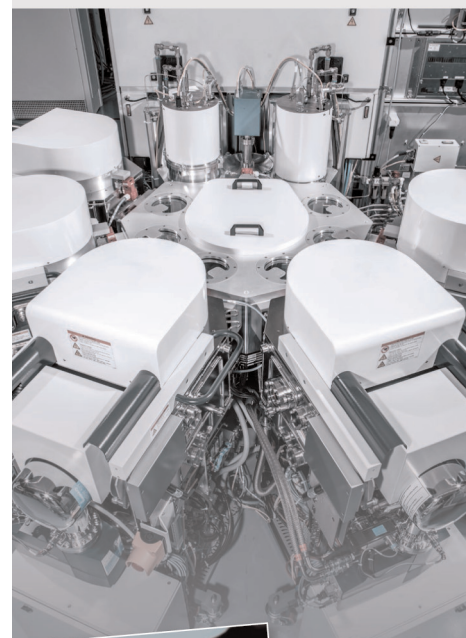
"The new evaluation board developed in collaboration with ON Semiconductor makes it easier and more cost effective to design with GaN – opening the door for smaller, lighter and more efficient power converters," says Charles Bailley, senior director, Worldwide Business Development at GaN Systems. "This collaboration signals the innovation not only happening with end-products designed with GaN but in components, design tools and reference designs that optimize the use of GaN."

www.gansystems.com

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Nexperia enters gallium nitride FET market

650V GaN-on-silicon device targeted at high-volume EV, communication infrastructure and industrial sectors

Nexperia BV of Nijmegen, Netherlands, which manufactures discrete and MOSFET components and analog & logic ICs, has announced its entry into the gallium nitride (GaN) field-effect transistor (FET) market with the introduction of the 650V GAN063-650WSA, which has a gate-source voltage (V_{GS}) of $\pm 20V$, a temperature range of $-55^{\circ}C$ to $+175^{\circ}C$, a low on-resistance ($R_{DS(on)}$) of down to $60m\Omega$, and fast switching to offer very high efficiency.

In April 2018, Cree Inc of Durham, NC, USA signed a non-exclusive, worldwide, royalty-bearing patent license agreement that provided Nexperia with access to its GaN power device patent portfolio, addressing device structures, materials and processing improvements, and packaging technology.

Nexperia is targeting high-performance application segments



including hybrid and all-electric vehicles (xEV), data centers, telecom infrastructure, industrial automation and high-end power supplies. The firm says that its GaN-on-silicon process is robust and mature with proven quality and reliability, and that it is highly scalable as wafers can be processed in existing silicon fabrication facilities. Also, the device is available in the industry-standard TO-247, allowing the benefit of GaN's performance in a familiar package.

"This is a strategic move for

Nexperia into the high-voltage area, and we can now deliver technology suitable for xEV power semiconductor applications," says Toni Versluijs, general manager of Nexperia MOS Business Group. "Our GaN is a technology that is ready for volume production, and with scalability to meet high-volume applications," he adds. "The automotive sector is a key focus for Nexperia and one which is forecast to grow significantly for two decades as electric vehicles replace those powered by traditional internal combustion engines as the preferred means of personal and public transport."

The GAN063-650WSA GaN FET is the first in a portfolio of GaN devices that Nexperia is developing to address the automotive, communication infrastructure and industrial markets.

www.nexperia.com

Power Integrations delivers millionth InnoSwitch3 IC

Power Integrations of San Jose, CA, USA, which provides high-voltage integrated circuits for energy-efficient power conversion, has delivered its one-millionth InnoSwitch3 switcher IC featuring its PowiGaN gallium nitride technology.

CEO Balu Balakrishnan presented the millionth GaN-based IC to Steven Yang, CEO of Anker Innovations in an event at the latter's Shenzhen headquarters. Anker is a manufacturer of chargers and adapters, supplying retailers worldwide with powerful, compact USB PD adapters and a range of chargers and adapters for laptops, smart mobile devices, set-top boxes, displays, appliances, networking gear and gaming products.

InnoSwitch3 offline CV/CC flyback switcher ICs with PowiGaN technology are up to 95% efficient across the load range. The very low



switching and conduction losses of PowiGaN's primary switch allows the delivery of as much as 100W from a space-saving InSOP 24D surface-mount package in enclosed adapter applications without requiring a heat-sink. Quasi-resonant InnoSwitch3-CP, InnoSwitch3-EP and InnoSwitch3-Pro ICs combine the primary power switch, primary and secondary control with a safety isolated high-speed link (FluxLink)

in between, as well as the secondary SR driver and feedback circuits in a single surface-mount package. Power Integrations says that the switching performance of PowiGaN technology results in substantially higher efficiency, enabling very compact adapter designs.

"Anker is a world leader in compact charger design, and was the first high-volume customer for InnoSwitch3 products with PowiGaN," says Balakrishnan, who thanks Yang for his "critical contribution to the first successful mass-market deployment of high-voltage GaN technology."

"By using PowiGaN-based InnoSwitch3 ICs we are able to offer USB PD chargers that are compact, lightweight and capable of delivering high power output," comments Yang.

www.power.com

US Army and Rice University target diamond materials as ultrawide-bandgap successor to GaN in improved RF electronics

Facility to be built at Rice for growing ultrapure diamond films and heterostructures for RF electronic prototypes

The US Army has signed a five-year, \$30m cooperative agreement with Rice University to conduct research in next-generation networks and advanced materials. The research aims to deliver advanced intelligence, surveillance and reconnaissance capabilities to the army.

The team comprises personnel from the Army Research Laboratory (ARL) and Rice University, and will focus on next-generation wireless networks and radio frequency (RF) electronics.

"Our relationship with Rice is setting the stage for bringing new, disruptive research technologies, transformative research, to the army so that it can increase its capabilities in the future," says ARL Army Combat Capabilities Development Command director Phil Perconti.

The partnership dates back to April, when commanding general US Army Futures Command general John Murray visited Rice University to explore partnership opportunities to drive army modernization.

The ARL-Rice diamond materials team is jointly led by Rice University's Department of Materials Science and NanoEngineering (MSNE) chairperson Pulickel Ajayan and ARL Electronics and RF Division branch chief Tony Ivanov, and also includes MSNE faculty member Robert Vajtai. The team is focused on developing an ultrawide-bandgap successor to gallium nitride (GaN) to deliver improvements in RF electronics. Rice University stated that enhancements in RF hardware could also help



Researchers will work to develop ultrawide-bandgap diamond semiconductors for use in high-performance RF electronics and power electronics. Credit: Brandon Martin/Rice University.

efforts to improve the process of setting up and managing wireless networks.

One of the priorities is to build a facility at the university for 'growing ultrapure diamond films and heterostructures of diamond and other materials that can be used in RF electronic prototypes'.

The networking team is working on building distributed, self-aware networks capable of detecting attacks and protecting themselves by adaption or stealth.

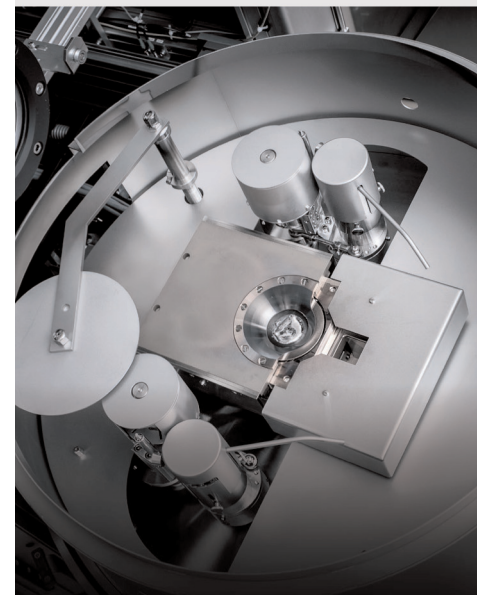
"We want to deliver the capability of quickly deploying secure, robust army communications networks wherever and whenever they're needed," says ARL South regional director Heidi Maupin. "The technology needed for that will benefit the world by transforming the economics of rural broadband, reducing response times to natural disasters, opening new opportunities for online education and more."

<https://msne.rice.edu>
www.arl.army.mil



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SweGaN, IEMN and Linköping University unveil Transmorphic Heteroepitaxy GaN-on-SiC growth process for power devices

New hybrid GaN-on-SiC material targets power savings in electric vehicles and charging stations as well as solar inverters

A project funded by the EU's Horizon 2020 research and innovation program has contributed to custom gallium nitride on silicon carbide (GaN-on-SiC) epitaxial wafer manufacturer SweGaN AB of Linköping, Sweden collaborating with Linköping University and Institut d'Electronique, de Microélectronique et de Nanotechnologie IEMN-CNRS (a French research group dedicated to high-power devices) to develop the new epitaxial growth mechanism Transmorphic Heteroepitaxy for producing next-generation GaN-on-SiC power devices ('Transmorphic Epitaxial Growth of AlN Nucleation Layers on SiC Substrates for High-Breakdown Thin GaN Transistors', Applied Physics Letters, vol115, no22, 25 November 2019).

Specifically, SweGaN collaborated with the scientists in electron microscopy and modeling at Linköping University and senior researchers at IEMN to explore the nature of the new epitaxial growth mechanism and the potential of SweGaN's QuanFINE hybrid GaN-SiC heterostructures for high-power device applications (joining to the firm's existing product portfolio for RF components and devices).

"Not only is this a high-impact innovation, but it comes together

with a scientific discovery of a novel epitaxial growth mechanism, which we coin transmorphic," says the paper's co-author Lars Hultman, professor at Linköping University and member of the Royal Swedish Academy of Sciences.

"This breakthrough could significantly reduce the power loss for high-power devices, which would truly manifest the superiority of GaN power devices over silicon super-junction power devices and silicon carbide MOSFETs for 650V-rated devices," says chief technology officer Jr-Tai Chen.

The new results show Transmorphic Heteroepitaxy growth where less than 1nm-thick atomic interlayers with ordered vacancies are created to sufficiently accommodate the lattice mismatch at the interface between the first epilayer and the substrate.

SweGaN highlights the following:

- The new growth mechanism suppresses the formation of structural defects in the beginning of the epitaxy, which enables grain-boundary-free aluminium nitride (AlN) nucleation layers and subsequent high-quality buffer-free GaN-based heterostructures to be realized on SiC substrates.

- A GaN high-electron-mobility transistor (HEMT) heterostructure with a total thickness of less than 300nm grown by the transmorphic epitaxial scheme on a semi-insulating SiC substrate shows a lateral critical breakdown field of $\sim 2\text{MV/cm}$ and a vertical breakdown voltage of $\geq 3\text{kV}$ (measured by senior researchers at IEMN).

- The critical breakdown field is nearly three times higher than that of GaN-on-Si epiwafers grown by the conventional thick-buffer approach. So, the device's ON-resistance has the potential to be lower by more than one order of magnitude than the value achievable currently, according to Baliga's figure of merit (BFOM).

"With these new results, SweGaN will now extend the focus of its QuanFINE technology to include the global power market in addition to RF devices, particularly in Asia showing the most hunger for new-generation GaN power devices," says Chen. "We anticipate releasing more new findings on the performance of QuanFINE based power devices in the near future."

www.swegan.se

www.liu.se/en

www.iemn.fr

AKHAN gains US and Japan patents for n-type diamond

AKHAN Semiconductor Inc of Gurnee, IL, USA — which specializes in the fabrication and application of lab-grown, electronics-grade diamond as functional semiconductors — has been issued patents by both the US Patent and Trademark Office (USPTO) and Japan Patent Office (JPO) covering its n-type diamond semiconductor system and diamond-based multi-layer anti-reflective coating systems (key in military &

aerospace sensor and detector applications, amongst others).

AKHAN says that patents 6580644 in Japan and 10,422,928 & 10,410,860 in the USA are key additions to its Miraj Diamond intellectual property portfolio, and are claimed to enable breakthrough performance in semiconductor devices as well as new capabilities in optical sensing, detecting and transmission. Through integration

of high-quality diamond in semiconductor electronics applications and multi-layer materials, the systems allow for next-generation electronics performance and optical components with ultra-hardness, scratch-resistance, high thermal conductivity, hydrophobicity, chemical and biological inertness, and with high transmittance at a variety of critical angles, it is claimed.

www.akhansemi.com

UIUC reports thermal conductivity dependence on dislocation density of various GaN materials

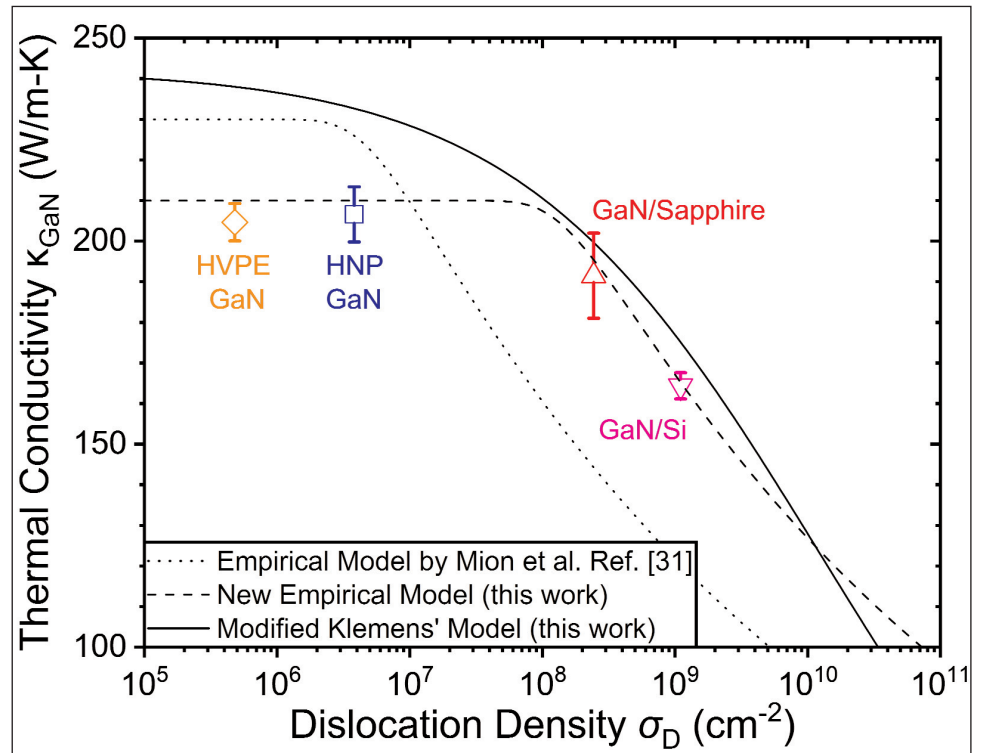
Work targets thermal management of GaN-based devices grown on foreign substrates with high dislocation densities

Gallium nitride (GaN) materials are critical for energy conversion, communications and sensing but, despite material advantages, existing mainstream GaN photonic and electronic devices are limited by the thermal heat extraction, and one of the biggest challenges in GaN devices (including RF transistors and LEDs) is heat extraction.

A research team at the University of Illinois at Urbana-Champaign (UIUC) led by professor Can Bayram has now reported what is claimed to be the first systematic study of the thermal conductivity of GaN materials with various dislocation densities, including hydride vapor phase epitaxy (HVPE)-grown GaN, high nitride pressure (HNP)-grown GaN, and metal-organic chemical vapor deposition (MOCVD)-grown GaN on sapphire (GaN/sapphire) and GaN on silicon (111) (GaN/Si) — see K. Park and C. Bayram, 'Impact of dislocations on the thermal conductivity of gallium nitride studied by time-domain thermoreflectance', *J. Appl. Phys.* 126, 185103 (2019).

GaN thermal conductivities (κ_{GaN}) of HVPE GaN, HNP GaN and MOCVD-grown GaN/sapphire and GaN/Si are measured as 204.7(± 4.6), 206.6(± 6.8), 191.5(± 10.5) and 164.4(± 3.2)W/m.K, respectively, using time-domain thermoreflectance (TDTR). Dislocation densities (σ_D) of HVPE GaN, HNP GaN, GaN/sapphire, and GaN/Si are measured as $4.80(\pm 0.42) \times 10^5$, $3.81(\pm 0.08) \times 10^6$, $2.43(\pm 0.20) \times 10^8$ and $1.10(\pm 0.10) \times 10^9 \text{ cm}^{-2}$, respectively, using cathodoluminescence and XRD. Impurity concentrations of Si, H, C and O are measured by secondary-ion mass spectroscopy (SIMS) to complement the analysis.

Using the experimental data, the team proposes a new empirical



Effect on thermal conductivity of dislocation density in various GaN materials. κ_{GaN} of HVPE GaN, HNP GaN, GaN/sapphire and GaN/Si as a function of σ_D (open symbols). Empirical model by Mion et al [*Appl. Phys. Lett.* 89, 092123 (2006)], $\kappa_{\text{GaN}} = 230 \tanh^{0.12}(5 \times 10^6 / \sigma_D)$ (dotted line), new empirical model, $\kappa_{\text{GaN}} = 210 \tanh^{0.12}(1.5 \times 10^8 / \sigma_D)$ (dashed line, University of Illinois work), and modified Klemens' model (solid line, University of Illinois work) are plotted together for comparison.

model to describe how thermal conductivity of GaN is affected by dislocation density, specifically $\kappa_{\text{GaN}} = 210 \tanh^{0.12}(1.5 \times 10^8 / \sigma_D)$. They also propose a modification in Klemens' model, where dislocation-induced scattering strength is increased, to explain the experimental rate of

Their empirical expression provides a means to estimate the thermal conductivity of hetero-epitaxially grown GaN samples indirectly by determining the dislocation density

decrease in thermal conductivity with increasing dislocation density.

Their empirical expression provides a means to estimate the thermal conductivity of hetero-epitaxially grown GaN samples indirectly by determining the dislocation density which is, in many cases, simpler than directly measuring the thermal conductivity.

The team reckons that the work provides key design guidelines for the thermal management of GaN-based devices, typically grown on foreign substrates with high dislocation densities.

<https://icorlab.ece.illinois.edu>
<https://aip.scitation.org/doi/full/10.1063/1.5126970>

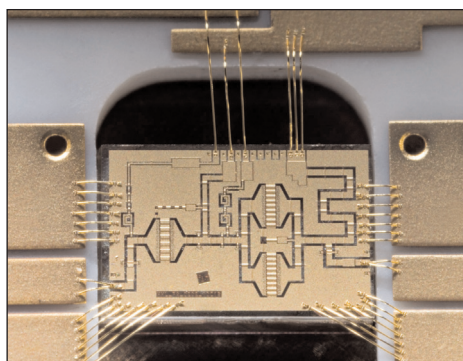
FBH-led project ‘power transistors based on AlN (ForMikro-LeitBAN)’ launched

Millimeter-wave and power electronic devices to be developed on free-standing aluminium nitride substrates

Coordinated by the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) of Berlin, Germany, the joint project ‘power transistors based on AlN (ForMikro-LeitBAN)’ aims to develop highly efficient power semiconductors that can pave the way for a wide range of novel applications — from e-mobility to artificial intelligence.

Smart energy supply, electro-mobility, broadband communication systems and artificial intelligence (AI) are driving constant growth in the number of interacting and interconnected systems. However, with the growing number of systems and increasing data traffic, primary energy consumption is also rising. Electrical energy must be converted at all times to be usable by the various systems, which is why the need for electrical conversion is also increasing. In Europe alone, it is estimated that more than 3TeraWatt-hours of energy (the amount of electricity produced by a medium-sized coal-fired power plant) are lost by energy conversion each year. Efficient energy conversion is therefore key for applications like AI and Industry 4.0 (representing the fourth industrial revolution based on digitization processes in manufacturing). The prerequisite for this are efficiently switching power semiconductors that enable high power density. Used to a large extent, this would result in noticeable energy savings and make a relevant contribution to CO₂ reduction.

The project aims to develop aluminium nitride semiconductor material for this task, to test it with suitable devices and to qualify it for future applications in systems. Until 2023, the project will be funded with €3.3m by Germany’s Federal Ministry of Education and Research (BMBF) within the program ForMikro (Forschung für neue Mikroelektronik).



Gallium nitride amplifier from an earlier FBH project. In the ForMikro-LeitBAN project, the technology for millimeter waves is to be transferred to AlN. (© FBH/schurian.com)

Aluminum nitride — starting material with potential

The efficiency of systems is limited by static and dynamic power losses of semiconductors, determined by the respective material. It is becoming increasingly difficult to increase the efficiency of electrical converters and power amplifiers with conventional silicon-based power components. New semiconductor materials with improved properties must therefore be investigated and brought to market maturity, says FBH. The project partners aim to use aluminum nitride (AlN), which has so far been little studied for electronic applications but offers up to 10,000 times less conduction losses than silicon devices. It is also characterized by very high breakdown strength and thermal conductivity — ideal prerequisites for power semiconductors with high energy density and efficiency. Free-standing insulating AlN wafers are to be used and qualified as the substrate. Compared to AlN epitaxy on foreign substrates such as silicon carbide (SiC), the dislocation density can be reduced by five orders of magnitude. This offers the potential for fast and efficient switching devices while maintaining high reliability.

Full process chain – from crystal growth to system demonstrators

From a conceptual point of view, the novel AlN components are based on well-researched GaN technology. A new aspect is the transition from conventional foreign substrates such as silicon carbide, sapphire or silicon to free-standing AlN substrates. ForMikro-LeitBAN is researching the development of such AlN wafers and testing them in a tailor-made device process. Test systems for millimeter-wave applications and for power electronic energy converters qualify the new highly efficient AlN devices for applications in corresponding systems.

ForMikro-LeitBAN involves the following partners, which collectively span the entire value chain (from AlN wafers to both millimeter-wave and power electronic systems):

- Ferdinand-Braun-Institut (FBH): AlN device design and development;
- Fraunhofer IISB, Erlangen (IISB): AlN crystal growth, wafer manufacturing;
- TU Bergakademie-Freiberg (IAP): Process module development, analytics;
- Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU): material analysis;
- Brandenburgische Technische Universität Cottbus-Senftenberg (BTU): AlN millimetre-wave systems;
- Technische Universität Berlin (TUB): AlN power electronic systems.

The technology will also be prepared for transfer of into an industrial environment. The consortium’s work is hence being supported by an industrial advisory board comprising Infineon for power electronics, UMS for millimetre-wave technology and III/V-Reclaim for the recycling of AlN wafers. A respective follow-up project is also planned.

www.elektronikforschung.de/projekte/formikro-leitban

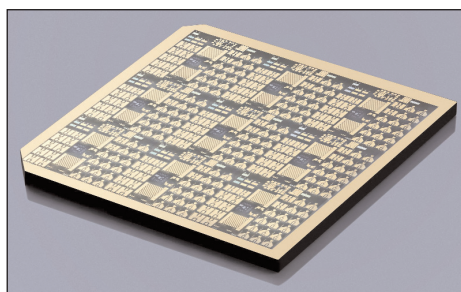
Germany-funded 'ForMikro-GoNext' project investigating vertical gallium oxide devices for power electronics

Leibniz-IKZ, FBH, University of Bremen, ABB Power Grids Switzerland and Aixtron partner on four-year, €2m β -Ga₂O₃ project

In the project 'ForMikro-GoNext' — funded by Germany's Federal Ministry of Education and Research (BMBF) with €2m over 4 years — the Leibniz-Institut für Kristallzüchtung (IKZ), the Ferdinand-Braun-Institut Leibniz-Institut für Höchstfrequenztechnik (FBH), the University of Bremen and industrial partners ABB Power Grids Switzerland Ltd and Aixtron SE are investigating beta-gallium oxide (β -Ga₂O₃) using a new vertical device architectures to exploit its properties for transistors more effectively.

Wide-bandgap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) offer a higher electrical breakdown field strength than silicon, allowing fabrication of components in much smaller and more compact dimensions. β -Ga₂O₃ has a breakdown field strength twice that of SiC and GaN and thus offers the potential to further increase power converter efficiency. High voltages can be switched with significantly smaller semiconductor drift regions — the basis for more compact systems. In addition, transistors based on β -Ga₂O₃ are characterized by a low on-resistance at a given breakdown voltage and faster switching transients, which leads to lower power losses. Due to these properties, β -Ga₂O₃ has the best prerequisites to become the high-performance material for next-generation power applications, it is thought.

So far, lateral Ga₂O₃ devices have been investigated. In this configuration, voltage is switched across the device surface, making large chip size areas combined with complex isolation techniques necessary for high voltages. ForMikro-GoNext targets vertical device structures to



Ga₂O₃ chip with lateral transistor and measurement structures, fabricated at FBH by projection lithography. GoNext targets vertical devices.

more efficiently utilize the high electrical breakdown field strength of β -Ga₂O₃. Better exploitation of the chip size also opens the potential of upscaling device geometries towards technically relevant very high current switching. Development of these transistors requires a synchronized process chain from crystal growth, epitaxy and device processing to characterization, which is completely covered within the project.

By focusing the expertise of the Leibniz Institutes IKZ (β -Ga₂O₃ crystal growth, epitaxy and material characterization) and FBH (device design, manufacturing and testing) the aim is to efficiently transfer the results of basic research into application- and industry-oriented research.

The Institute for Electrical Drives, Power Electronics and Devices (IALB) at the University of Bremen provides qualified assessment of the application potential of the new devices with its power electronic characterization capabilities. Reliability tests will provide information about the stability of the Ga₂O₃ transistors.

The project will be supported by industrial partners Aixtron (epitaxy) and ABB Power Grids Switzerland Ltd (design and testing of devices).

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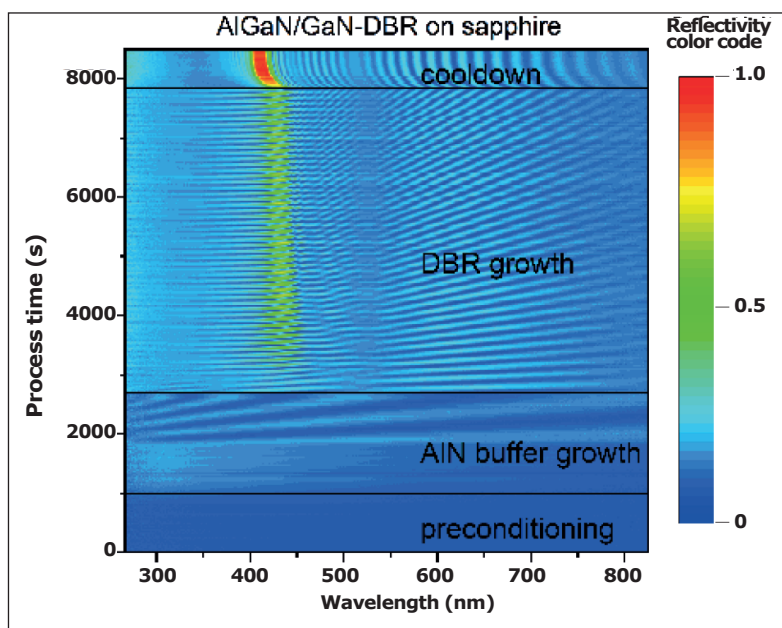
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LayTec adds UV-capable model to EpiTT VCSEL family

LayTec AG of Berlin, Germany has added to its EpiTT VCSEL (vertical-cavity surface-emitting laser) family of in-situ metrology instruments by launching the new EpiTT VCSEL UV, which combines spectral sensing of UV-vis (ultraviolet-visible) reflectance (300–800nm) with the capabilities of the EpiTT regarding wafer temperature sensing and high-accuracy multi-wavelength growth rate measurements.

Professor Andrei Vescan and his team at Germany's RWTH Aachen University are using the new metrology tool to accelerate their projects for gallium nitride (GaN)-based optoelectronic device growth. The Figure shows the spectral in-situ



Spectral reflectance signature of an AlGaIn/GaN DBR during growth in Aixtron AIX200 RF/S reactor. The DBR stop-band is clearly seen at $\lambda=420\text{nm}$ (growth) and 405nm after cooldown. www.laytec.de

reflectance signature of an AlGaIn/GaN distributed Bragg reflector (DBR) as it is used in a novel type of GaN-based modulator device combining epitaxial III-N bottom DBRs with dielectric top DBRs.

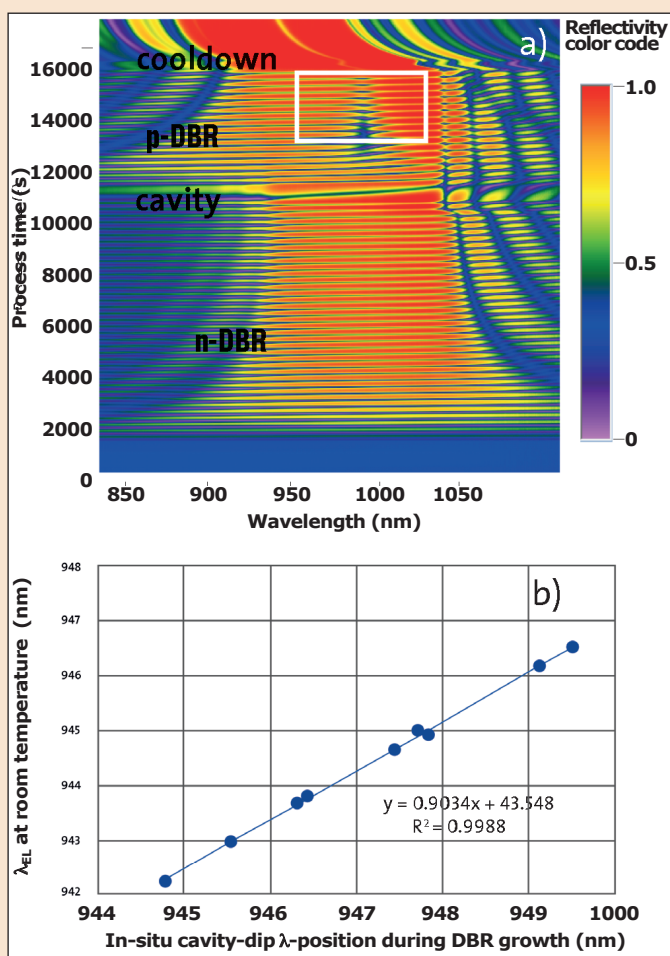
The project 'Next-Generation LED' (13N14223/13N14224) has been funded by Germany's Federal Ministry of Education and Research (BMBF).

Algorithms for better in-situ prediction of VCSEL emission wavelength

The target specifications for VCSEL emission wavelengths currently lie within the $\pm 0.5\text{nm}$ accuracy range. So, for yield prediction based on spectral in-situ sensing, an even better wavelength accuracy is needed, notes LayTec.

The firm has hence recently developed advanced algorithms for dynamic cavity-dip analysis during p-DBR (distributed Bragg reflector) growth that take into account the specifics of wafer rotation in planetary reactors and apply advanced filtering and averaging procedures. The resulting $\pm 0.2\text{nm}$ accuracy in in-situ measurement of high-temperature cavity-dip positions during the final periods of the p-DBR allows for highly precise prediction of the VCSEL emission wavelength, says LayTec.

In the Figure, part (a) gives an example in-situ reflectance color plot with the cavity-dip clearly visible during p-DBR growth. Part (b) shows more results from this VCSEL run: $R^2=0.999$ correlation between the in-situ measured cavity-dip position during the final



(a) Reflectance color plot, as measured during epitaxy, for a 940nm VCSEL. The white square marks the in-situ cavity-dip region during p-DBR growth. (b) The correlation between the in-situ cavity-dip position and the room-temperature EL emission wavelength.

emission wavelength as measured by electro-luminescence at room temperature after the run. A deeper insight into the origin of the wavelength distribution can be gained by correlation of these high-accuracy cavity-dip positions with wafer temperatures and satellite numbers.

10 periods of the p-DBR and the

www.laytec.de/VCSEL

China's EpiWorld expands SiC epi foundry with new Aixtron AIX G5 WW C high-volume deposition system

Deposition equipment maker Aixtron SE of Herzogenrath, near Aachen, Germany says that in third-quarter 2019 it shipped and installed an AIX G5 WW C high-volume manufacturing system to pure-play silicon carbide (SiC) epitaxial wafer foundry EpiWorld International Co Ltd in Xiamen, China (a privately owned joint venture with investors in the USA, Japan and China) for the further development of SiC epiwafers (used mainly for manufacturing power devices for automotive applications).

Based on Aixtron's production-proven, fully automated Planetary Reactor platform, the AIX G5 WW C MOCVD system is said to have the largest batch capacity and highest throughput in the industry. Offering

flexible 6" or 4" configurations, the design is targeted at squeezing production costs to a minimum while maintaining excellent production quality.

EpiWorld aims to further expand its production capacity to meet increasing customer demand. The firm has already completed production lines for 4" and 6" SiC epiwafers for 600V, 1200V and 1700V power devices.

"In recent years, we have been qualified as a leading supplier of SiC epitaxy wafers by device manufacturers in the automotive and various other sectors. Therefore, we have a strong footprint in one of the most challenging industries. We had so far served over 100 customers around the world," says EpiWorld's general manager Dr Gan

Feng. "With this new addition, our annual capacity will be increased to 60,000 wafers in 2019. Our recently completed phase I expansion of an 18,000m² new facility is designed to provide manufacturing space for an annual capacity of up to 400,000 wafers," he adds.

"We are delighted to cooperate with one of the leading epitaxy foundries to accelerate the further commercialization of silicon carbide," comments Aixtron's president Dr Felix Grawert. "Silicon carbide will support the development of numerous high-end power electronics applications, meaning that we are paving the way for megatrends such as e-mobility or renewable energy."

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AXT's Q3 revenue hit by China-related absence of expected data-center and PON market growth

InP and GaAs demand expected to bounce back in 2020

For third-quarter 2019, AXT Inc of Fremont, CA, USA — which manufactures gallium arsenide (GaAs), indium phosphide (InP) and germanium (Ge) substrates and raw materials — has reported revenue of \$19.8m, down 20.2% on \$24.8m last quarter and 30.8% on \$28.6m a year ago, and below the original guidance of \$24.5–26m. “2019 has proven to be a challenging year, given the turbulent geographical, geopolitical and global economic conditions,” comments CEO Dr Morris Young.

Of total revenue, the proportion from the Asia-Pacific region fell from 75% last quarter to 66%, while Europe rose from 19% to 25% and North America from 6% to 9%. Just one customer reached 10% of revenue and the top five comprised about 40% (down from 48% last quarter, showing diversification of the customer base).

Each product category was lower than expected, indicating broad-based market declines.

Revenue from substrate sales was \$16m, down 22.3% on \$20.6m last quarter and 29.8% on \$22.8m a year ago. “Results in Q2 were strengthened by the completion of a large order from a telecommunication customer in Asia that we did not expect to repeat in second-half 2019,” notes Young. “Coming into Q3, our customers in data-center and PON [passive optical network] markets were predicting an improvement in the demand environment which would have resulted in renewed growth in demand for our substrates. However, this improvement in the demand environment did not materialize. Data-center was particularly soft compared to expectations, which may be a result of US-China trade tensions,” he adds. “Ultimately, our indium phosphide substrate revenue for data-center and PON remained fairly steady sequentially in Q3, but

we were not able to make up for the absence of the telecommunication order that we had in Q2.”

In GaAs, LEDs and lasers have been slow to recover from the downward trend of recent quarters. “LED is particularly impacted by the slowdown in China,” says Young. “Automotive applications have been particularly hard hit and continued to be weak in Q3,” he adds. “Wireless applications are holding steady at their reduced rates.”

Germanium substrate sales fell by about 8% from last quarter due to the softer demand environment.

“The sluggishness in the substrate market appears to have a negative ripple effect on the raw material companies that we consolidate,” says Young. Revenue from raw material joint ventures was \$3.9m, down 7.1% on \$4.2m last quarter and 32.8% on \$5.8m a year ago (although, as of this year, AXT is consolidating only two companies into its results, rather than three last year).

Due mainly to the lower volumes and changes in product mix (specifically the lower InP business), gross margin has fallen further, from 37.1% a year ago and 34.3% last quarter to 29%.

Operating expenses were \$6.2m, roughly level with \$6.2m last quarter and \$6.3m a year ago.

Net loss was \$0.9m (\$0.02 per diluted share), compared with net income of \$1.5m (\$0.04 per diluted share) last quarter and \$3.9m (\$0.10 per diluted share) a year ago.

Depreciation and amortization was steady at \$1.3m. Capital expenditure (CapEx) was \$4.6m (reduced from \$5.5m last quarter). Accounts receivables (net of reserves) fell

from \$18.2m to \$17.4m.

During the quarter, cash, cash equivalents and investments rose from \$37.5m to \$38.5m. The firm also has a \$10m line of credit with Wells Fargo Bank (which it has not utilized) and in Q3 it established a bank loan of about \$5.8m in China.

Net inventory fell from \$50.3m to \$49.1m (47% in raw materials, 46% in work in progress, and only 7% in finished goods). “Reduction in inventory has been a focus for us in 2019,” notes chief financial officer Gary Fischer.

“The demand environment remains challenging and is not expected to improve in Q4,” says Fischer. For fourth-quarter 2019, AXT expects roughly flat revenue of \$19.5–20.5m, and increased loss per diluted share of \$0.06–0.08.

GaAs revenue should be a little stronger in Q4 than in Q3. “The LED market is coming back,” notes Young. However, germanium substrate sales are expected to remain soft (while excess inventory at certain customers is digested) and InP should fall again.

“Despite these near-term challenges in environment, we remain optimistic about underlying large-scale technology trends that build the demand for our products,” says Young. “We do expect indium phosphide to bounce back,” he adds.

“The data-center upgrade cycle is well underway to accommodate massive growth in bandwidth requirements at hyperscale and large enterprise data centers. We believe that the silicon photonics market will continue to grow, driven by the technology transition to 100G and beyond to 400G,” continues Young. “Related to the data-center upgrade is the nascent 5G infrastructure roll out and the continued build out and upgrade of passive optical networks worldwide. The increase in video streaming, new services enabled by 5G, and

In GaAs, LEDs and lasers have been slow to recover. LED is particularly impacted by the slowdown in China

strong growth in data-intensive cloud-based services will continue to drive increasing demand for optical components that will require InP substrates," he adds.

"The gallium arsenide market holds significant opportunities," believes Young. "Our traditional applications will recover in 2020, so that we see great promise in applications such as power lasers for industrial welding and cutting, VCSELs for a variety of customers, industrial and automotive applications, and micro-LEDs, which use gallium arsenide for the red portion of the red-green-blue light spectrum," he adds.

"In the meantime, we are taking the opportunity to effectively execute our relocation [from Beijing]," says Young. In Q4/2019, AXT expects to spend about \$5m on the relocation of its manufacturing facilities, in line with its expectation for full-year 2019 of about \$21m.

"After a lengthy process, we have reached a significant milestone in completing the necessary permitting requirements for both our Dingxing and Chaozhou locations. In addition, we now have sufficient capacity outlying in both facilities to

be able to handle large-volume production," he adds.

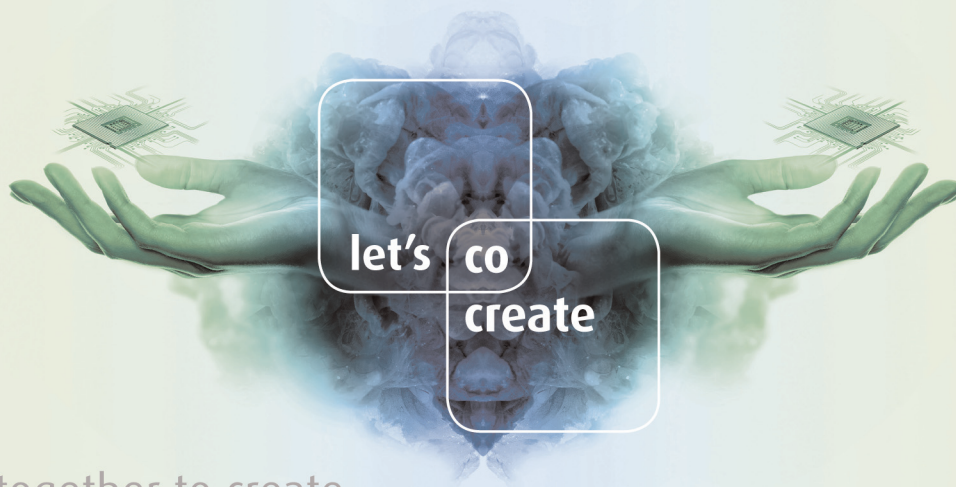
Chaozhou (which is mostly crystal growth facilities) has been ramping up very rapidly so that most of AXT's output crystal can come from there. The Dingxing

GaAs applications will recover in 2020... we see great promise in applications such as power lasers for industrial welding and cutting, VCSELs for a variety of customers, industrial and automotive applications, and micro-LEDs

wafer processing facility is now providing up to 20% of customer demand so, in the next quarter or two, AXT is going to start to qualify major customer requirements from there. "I definitely expect two major customers to complete the shift of taking products from the new Dingxing facility by the end of Q1/2020," states Young.

"We have also placed significant focus on the recruitment, training and relocation of our employees," continues Young. "We are encouraged by the quality of talent we are being able to attract and retain and believe we now have all the essential components in place to meaningfully ramp up production in both locations [Dingxing and Chaozhou] over the coming quarters. As such, we are prepared for renewed growth when the demand environment improves as expected in 2020," concludes Young.

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IQE cuts 2019 revenue guidance from £140–160m to £136–142m due to inventory reductions by US RF chip customers

Return to growth beyond Q1/2020 to be driven by content gains in 3D sensing, GaN demand in 5G infrastructure, and expanding Asian markets as supply chains localize

In a trading update for full-year 2019, epiwafer foundry & substrate maker IQE plc of Cardiff, Wales, UK has reduced its revenue guidance from £140–160m (given in June) to £136–142m, including a foreign exchange (forex) tailwind of £3m. This is down on 2018's £156.3m.

A mid-single-digit adjusted operating loss is now expected, resulting from revenue being below the previous guidance range, additional one-off commissioning costs at the firm's new foundry in Newport, general diseconomies of scale associated with operating at low volume in some sites and the inclusion of losses for Singapore-based CSDC (formerly a joint venture, but now a 100% subsidiary since October).

In the Wireless business, there have been continued low volumes of orders and reductions in inventory by IQE's major RF chip customers in the USA, offset to some extent by a "promising" increase in production for Asian supply chains. IQE has qualified three tools (with two more in the process of qualifying) with a major Taiwanese foundry. The firm adds that it continues to make good progress on new product development in RF filters and switches for 5G.

In Photonics, consistently strong

3D sensing volumes with IQE's largest vertical-cavity surface-emitting laser (VCSEL) customer have been achieved in second-half 2019, underlining what IQE claims is its lead position for epiwafers in this supply chain. The firm says that it continues to make good progress on a significant number of Android-related supply chains, including two recently announced production qualifications. The market for indium phosphide (InP) lasers for datacom/telecom applications has remained weak but shows signs of growth for 2020, particularly in Asian markets.

The infrastructure phase of IQE's capacity expansion was completed in first-half 2019, so since June the firm has taken steps to reduce costs and capital expenditure. Capex will be towards the bottom end of the prior guidance of £30–40m, and the net debt position at year end is expected to be £15–20m, against increased debt facilities of £57m announced in June.

The outlook for 2020 includes a seasonally weak first quarter and continued supply chain transitions in the wireless market. Beyond Q1, IQE is cautiously optimistic about a return to growth, driven by expected content gains in an

expanding market for 3D sensing, demand for gallium nitride (GaN) to meet accelerating 5G infrastructure deployments, and expanding Asian market opportunities for both Photonics and Wireless products as supply chains continue to localize. IQE hence expects total revenue to return to moderate growth in 2020.

"IQE has experienced very challenging market conditions in 2019," notes CEO Dr Drew Nelson. "Shortfalls in revenue relate predominantly to two major customers, with whom IQE is confident it has not lost share and who remain very well positioned for returns to growth in 2020. Indeed, the company remains well positioned to capitalize on an expanding future compound semiconductor market opportunity driven by the macro trends of 5G and connected devices," he believes. "To fully realise this opportunity, the recently announced Executive Management Board is already making good progress in driving the company's approach to increasing profitability, with specific responsibilities assigned for programs on operational execution, new technology introduction, revenue expansion through customer proximity and diversification, and strong cost management."

www.iqep.com

IQE wins 2019 Raytheon Premier Supplier Excellence Award

IQE has been awarded a 2019 Raytheon Supplier Excellence Award.

As part of the Raytheon Supplier Excellence Program, suppliers are awarded for their outstanding performance, contributions and support to programs across one or more Raytheon businesses. This year, Raytheon has recognized IQE

with a Premier Supplier Excellence Award for its outstanding achievement. Premier awards are given to suppliers who have demonstrated premier achievement for Raytheon in business management, technology, partnership or affordability. Only the highest achieving suppliers are awarded the honor.

"It is a great honor to receive the 2019 Premier Supplier Excellence Award from Raytheon, a highly respected global technology leader," comments Dr Wayne Johnson, IQE's executive VP of Wireless & Emerging Products. "This award recognizes the strong partnership that IQE has demonstrated to Raytheon."

IQE's CEO Nelson receives Bessemer Society's Lifetime Fellowship Award

At a dinner at the City of London Club on 20 November, Dr Drew Nelson (co-founder & CEO of epiwafer foundry and substrate maker IQE plc of Cardiff, Wales, UK) received the Lifetime Fellowship Award of the Bessemer Society from professor Sir Colin Humphreys, director of the Cambridge Centre for Gallium Nitride and director of research in the Department of Materials Science and Metallurgy at University of Cambridge.

Named after steel-making pioneer Sir Henry Bessemer, the Bessemer Society was founded in 2015 to provide a mutual support network for entrepreneurs who lead high-tech companies that depend on manufacturing, enabling them to meet and share information on the basis of mutual trust.

The Lifetime Fellowship Award is presented each year to an entrepreneur who has shown the qualities that reflect the ethos of the Bessemer Society: ambition, perseverance, technical acumen, social purpose, and leadership.

Following a PhD in Semiconductor Physics, Nelson joined BT Research



Drew Nelson.

Laboratories in 1981, leading the group responsible for the development of optoelectronic devices for fiber-optic communications. He co-founded EPI (Epitaxial Products International) in Cardiff in 1988, which in 1999 merged with Pennsylvania-based Quantum Epitaxial Designs (QED) to become IQE, when he was appointed CEO.

Since then IQE has grown to become the leading global supplier of epiwafers for compound semiconductor chips, operating manufacturing plants in the UK, USA and Asia. More recently it has established an additional foundry in Newport, in what is becoming a 'Compound Semiconductor Valley' in South Wales, where Nelson has encouraged linkages between companies in the local value chain and universities under the CS Connected initiative.

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Riber's growth in Systems and Services revenues offsets 91% drop for Evaporators

Full-year growth expected in both revenue and operating income

For third-quarter 2019, Riber S.A. of Bezons, France — which manufactures molecular beam epitaxy (MBE) systems as well as evaporation sources and effusion cells — has reported revenue of €6.8m, down on €7.2m last quarter but up 39% on €4.9m a year ago.

However, for the nine months to end-September, revenue is still down 4% year-on-year from €21.6m to €20.7m.

Specifically, Evaporators sales dropped by 91%, from €10.6m to €1m, following completion of the previous investment cycle for organic light-emitting diode (OLED) screen production equipment.

However, the contraction in the Evaporators business linked to the general economic environment has been offset by the development of Systems and Services activities.

Systems sales grew by 136%, from €5.4m to €12.8m, aided by the positive market environment for production MBE, with the delivery of six systems (including five production units) compared with five (including just two production units) in the first nine months of 2018.

Services & Accessories revenue for grew further, by 23% from €5.6m to €6.9m

Correspondingly, segmenting total revenue by geographic region, just 32% came from Asia (down from 59% in the first nine months of 2018), 44% came from Europe (up from 32%) and 24% came from North America (up from just 9%).

The order book at the end of September was €26.4m, down 15% on €31m a year previously. However, this was largely due to Evaporators

orders dropping from €3.8m to zero. Services & Accessories orders fell by 8% from €6.6m to €6.1m. Systems orders fell by just 1% from €20.6m to €20.4m, comprising 12 systems (six production and six research), with six system (including two production units) scheduled for delivery during fourth-quarter 2019.

In view of these factors, for full-year 2019 Riber expects year-on-year growth in both revenue and operating income.

Riber concludes that, in a globally positive environment for the compound semiconductor market, it is moving forward with its development strategy, consolidating its market shares, expanding its portfolio of technologies and clients, and supporting the development of its service activities.

University of Bremen orders Riber Compact 21 MBE system for nanophotonic research

Riber has received an order from Germany's University of Bremen for a Compact 21 research MBE

machine, to be delivered in 2020, for use in preparing and analyzing hybrid nanostructures. The system

is intended to produce nanophotonic components.

www.riber.com

Riber receives multi-million euro MBE system order from ZSW for research on CIGS PV

Riber has received an order worth several million euros from the ZSW (Zentrum für Sonnenenergie- und Wasserstoff-Forschung — or Center for Solar Energy and Hydrogen Research — Baden-Württemberg) in Stuttgart, Germany.

As a research institute conducting research and development in photovoltaics, renewable energy

sources, battery and fuel cell technologies, ZSW spans the entire industrial value chain, from material research, prototype development and production processes to application systems.

The automated platform that Riber will deliver in 2020 consists of two clustered 4" MBE 412 systems. Combined with other deposition

technologies, it will be used to produce copper indium gallium diselenide (CIGS) thin-film solar cells.

In CIGS-based thin-film photovoltaics, ZSW aims to boost the solar energy conversion efficiency above 25%, beyond the 22.6% achieved by ZSW in 2016.

www.zsw-bw.de

Order from Asia for MBE 6000 multi-wafer production system

Riber says that an Asian industrial company has ordered a third MBE 6000 machine.

Scheduled for delivery in 2020, the high-performance multi-wafer system is intended for the produc-

tion of electronic and optoelectronic devices.

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Veeco's revenue rebounds in Q3/2019 as 300mm GaN MOCVD cluster system accepted for pilot production

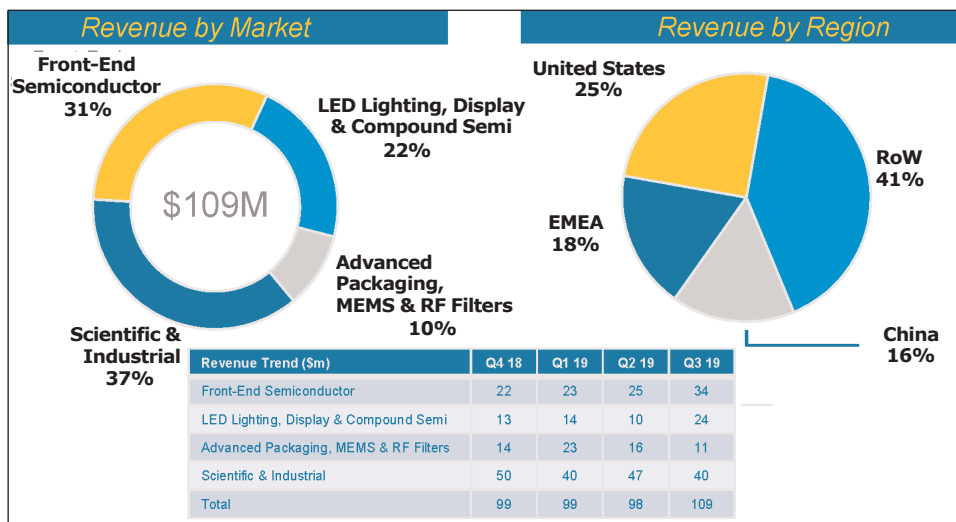
Firm re-enters profit; OpEx to be cut by \$4m per quarter by Q3/2020

For third-quarter 2019, epitaxial deposition and process equipment maker Veeco Instruments Inc of Plainview, NY, USA has reported revenue of \$109m, down 14% on \$126.8m a year ago but up 11.5% on \$97.8m last quarter and above the midpoint of the \$95–115m guidance range.

The LED Lighting, Display & Compound Semiconductor segment — which includes photonics, 5G RF, power devices and advanced display applications — contributed \$24m (22% of overall revenue), more than doubling from just \$10m last quarter, including service and upgrades for LED customers and shipment of Veeco's first 300mm fully automated single-wafer gallium nitride (GaN) metal-organic chemical vapor deposition (MOCVD) cluster system to a "leading-edge semiconductor fab" for a pilot-production environment (after completing development during the quarter). "We recently obtained acceptance from our customer on this tool," notes CEO Bill Miller.

The Front-End Semiconductor segment (formerly part of the Scientific & Industrial segment, before the May 2017 acquisition of lithography, laser-processing and inspection system maker Ultratech Inc of San Jose, CA, USA) contributed \$34m (31% of total revenue), up 36% on \$25m last quarter, driven by shipment of Veeco's second production extreme ultraviolet (EUV) mask blank system as well as sales of multiple laser spike annealing (LSA) systems. Also, shipments to data storage customers remained solid as they continued to invest in technology and capacity.

The Advanced Packaging, MEMS & RF Filter segment — including lithography and Precision Surface Processing (PSP) systems sold to integrated device manufacturers (IDMs) and outsourced assembly & test firms (OSATs) for Advanced



Packaging in automotive, memory and other areas — contributed \$11m (10% of overall revenue), falling 31% from \$16m last quarter, reflecting continued market softness.

The Scientific & Industrial segment fell back by 15% from \$47m last quarter to \$40m (37% of total revenue), including ion beam system shipments to data storage customers as well as sales of ion beam sputtering systems to high-end optical coating customers.

By region, the rest of the world (RoW, including Japan, Taiwan, Korea and Southeast Asia) was 41% of overall revenue (driven by the EUV mask blank system sale, LSA product sales and data storage products). The USA contributed 25% of overall revenue (including sales to the data storage market) and Europe, the Middle-East & Africa (EMEA) was 18% (driven by sales to Scientific & Industrial customers). China was 16% of overall revenue (driven by LSA product shipments to foundries).

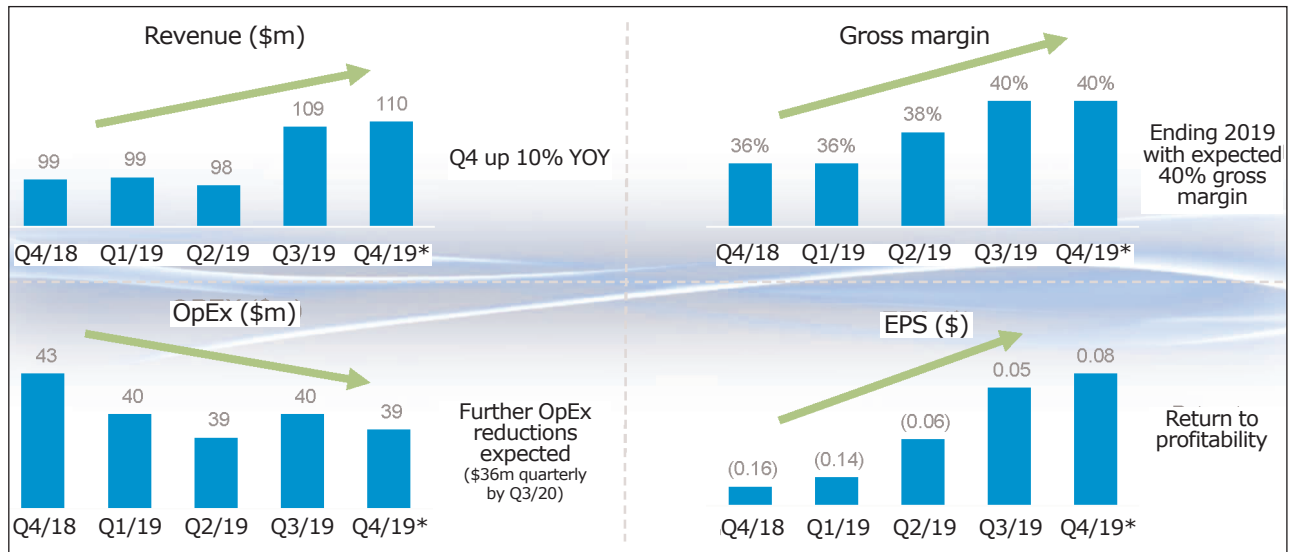
On a non-GAAP basis, gross margin was 40.3%, up from 37.8% last quarter and 38.2% a year ago, and above the guidance of 37–39%, driven by improved product mix, higher volume and well managed expenses. Operating expenditure (OpEx) was \$40m, above the expected \$39m and \$38.5m last quarter

but cut from \$40.4m a year ago.

"The company returned to profitability on a non-GAAP basis," says Miller. Net income was \$2.6m (\$0.05 per diluted share), down from \$5.3m (\$0.11 per diluted share) a year ago but recovering from a net loss of \$3m (\$0.06 per diluted share) last quarter, and above the midpoint of the guidance range between a loss of \$5m (–\$0.10 per diluted share) and a profit of \$4m (+\$0.10 per diluted share).

Compared with cash inflow from operations of \$14m last quarter, cash outflow from operations was –\$15m. This was due to biannual interest payment on the firm's debt and an increase of about \$10m in contract assets on the balance sheet (a tool was shipped to a Japanese customer, recorded as per US SEC revenue-recognition rules, but — following the Japanese business practice — to be invoiced only after the tool has been received, installed and then accepted). Accounts receivable have hence risen from \$59m to \$73m. Accounts payable has risen from \$22m to \$35m. Inventory has been reduced from \$140m to \$135m. "We have made progress reducing overall inventory, however a portion of the inventory is slow moving, which is related to the LED

business and certain other products,” notes chief operating officer & chief financial officer Sam Maheshwari. “We believe the slow moving inventory is no more than \$25m, and we are



pursuing steps to sell this.” Capital expenditure (CapEx) has more than halved from \$4.3m last quarter was \$1.7m.

Overall, cash and short-term investments hence fell during the quarter by \$15m from \$247m to \$232m (of which \$42m is held off-shore). Long-term debt has risen slightly from \$294m to \$297m, representing the carrying value of \$345m in convertible notes.

Order bookings were \$115m, up on \$100m a year ago and rebounding by 47% on \$78.2m last quarter, driven by strength in both data storage and EUV mask blank markets.

Quarter-end backlog rose from \$274m last quarter to \$279m, driven by the ‘very strong’ Front-End Semi and Scientific & Industrial (data storage) segments, as Advanced Packaging is weak (driven largely by the smartphone unit-related softness) and the Lighting, Display & Compound Semi segment is also “somewhat on the weak side” (while Veeco tries to penetrate opportunities in power semiconductors as well as in VCSELs and certain other arsenide-phosphide applications including edge-emitting lasers and photonics-related applications).

For fourth-quarter 2019, Veeco expects revenue of \$100–120m and gross margin of 39–41%. OpEx should be cut back to about \$39m. Net earnings should range between a loss of \$2m (\$0.03 per share) and a profit of \$8m (\$0.18 per share).

“Based on our current visibility we see Q1/2020 trending similar to Q4/2019 [regarding revenue and gross margin],” says Maheshwari.

Miller says that the transformation of Veeco will be completed in two phases: returning the company to profitability and driving growth.

“Phase 1 — returning the company to profitability — is well underway and includes our MOCVD shift from the commodity-led markets to photonics and emerging applications, making general infrastructure reductions, and rationalizing our product lines by re-prioritizing R&D expenditures. On our last earnings call, we alluded to slow moving inventory. We also mentioned reducing expenses to improve profitability. We made progress in both areas,” Miller says.

Veeco continues to take action to reduce infrastructure costs as well as rationalize ongoing investments in certain product lines. “We have been working on a number of products and product development efforts. So there is a little bit of facilities- and administrative-oriented signing and optimization that we are going to be working through,” says Maheshwari. “But a larger portion of the reduction is going to come from the R&D line. And that is really driven by optimizing and reducing consultants, contractors and project material related spending as a number of our products are getting towards the late stages in terms of their

development cycles.” The target is to eliminate about \$16m from the current run rate on an annualized basis, or about \$4m per quarter. So, at current revenue levels, Operating expenditure is expected to decline towards the target of \$36m per quarter by third-quarter 2020.

“Phase 2 — driving growth — is in the early stages,” says Miller. “We’re taking steps to grow our existing Front-End Semi advanced packaging and data storage markets. In addition, we are investing in new applications such as EUV mass blank production and compound semi applications with our MOCVD products,” he adds.

Last quarter Veeco announced the shipment of a beta version of its improved arsenide-phosphide MOCVD system, optimized for photonics applications including VCSELs, edge-emitting lasers, mini- and micro-LEDs and red/orange/yellow LEDs. “We are on target to receive customer acceptance in the next few quarters,” notes Miller. “We have been working closely with other customers as well to place another evaluation tool for VCSELs. When this market begins to grow, we hope to be well positioned and gain market share,” he adds.

“When we complete our transformation we will be a leaner and real focused company on the path to growth,” Miller concludes.

www.veeco.com

DISCO improves throughput and communication support for semi-automatic dicing saws

Tokyo-based DISCO Corp — which makes manufacturing equipment including chemical mechanical polishing (CMP) systems and laser-based ingot slicing equipment and processes for silicon carbide (SiC) — has developed the DAD3351 semi-automatic dicing saw for 200mm-diameter wafers, a model with 5% greater unit per hour (UPH) throughput and 10% smaller footprint. Additionally, the DAD3361 and DAD3431 models have also been developed. All will go on sales release in January, alongside the existing model DAD3350.

With the development of the three new models, DISCO has also completed a transition for all nine semi-automatic dicing saw models, with improved productivity and communication support in all models.

Model change for all semi-automatic dicing saws

For mass production, multiple units must be installed and simultaneously operated in parallel due to the time needed to process difficult-to-cut materials such as glass and ceramics used for sensors and passive components. Many production sites therefore adopt manual dicing saws with simple functions, and a small group of operators control them. However, communication functions were limited in existing models, making it difficult to control them centrally. There was therefore demand for communication support enabling timely control of multiple

dicing saws, says DISCO. A model transition was hence undertaken for all nine existing semi-automatic dicing saw models.

DAD3351 product features

The existing DAD3350 semi-automatic dicing saw is a best-selling model that flexibly supports a wide range of workpieces and has been delivered to many companies worldwide, says DISCO. The newly developed DAD3351 has inherited its features, with a high-rigidity bridge-type frame for the spindle axis (which can withstand high-load processing) and high extensibility to support various options and user-specified specifications. Accompanying the model change carried out for all nine semi-automatic dicing saws, the following features have been improved.

- UPH increased by 5% — By increasing the X-axis speed from 600mm/s to 1000mm/s and the Y-axis speed from 200mm/s to 400mm/s (through an improvement in motor performance) and by optimizing the parameters, UPH has been improved by 5% compared with the DAD3350.
- Small footprint — The footprint has been reduced by 10% (to 880mm x 1000mm = 0.88m²) compared with the DAD3350 (900mm x 1050mm = 0.95m²). Major components of model change
- Enhanced communication support and software support functions through installation of a

new type of PC — supports the SECS/GEM SEMI Equipment Communications Standard and Generic Model for Communication and Control of Manufacturing Equipment (optional); — supports a communication network that enables batch control of multiple items of equipment.

- Productivity improvement through installation of a new type of non-contact setup — reduces the time necessary to complete measurement of blade height against the processing chuck table's upper surface by 74%; — improves processing quality through a stable cut depth for the workpiece by increasing measurement accuracy.
- Control performance improvement for X-, Y- and Z-axis — possible to control the processing axis precisely through the adoption of servo motors for each axis and high-speed communication support; — improves processing quality by achieving a stable cut depth for the workpiece through high-precision height control.
- Innovation of standard software — adopts Windows 10 as the operating system (OS); — improves user-interface of the standard software.

The DAD324, DAD3351, and DAD3651 are on show at SEMICON Japan in Tokyo (11–13 December) www.disco.co.jp

GTAT achieves ISO-9001:2015 certification

GT Advanced Technologies (GTAT) of Hudson, NH, USA — which produces silicon carbide (SiC) material and crystal growth equipment — has achieved ISO-9001:2015 certification through auditors TÜV Rheinland of North America, a third-party testing, inspection and certification firm.

“Obtaining ISO certification is one of many milestones that we have been able to achieve very rapidly,”

says GTAT's CEO Greg Knight. “In less than a year, we equipped our facility, reached volume production, and achieved ISO certification.”

SiC is the preferred substrate for power electronics in applications like electric vehicles. GTAT's CrystX SiC is sold to industry partners who produce sliced and polished wafers.

GTAT says its rapid growth reflects accelerating demand from power

electronics semiconductor makers. “Our focus has been to rapidly scale production and achieve the necessary quality certifications so that growing markets can take advantage of what we produce,” says Knight. In August, GTAT signed a long-term supply agreement with Taiwan-based GlobalWafers Co (GWC) for its CrystX silicon carbide.

www.gtat.com

Merger of Nanometrics and Rudolph completed, forming Onto Innovation

Onto Innovation Inc has announced the completion on 25 October of the merger (agreed in June) between process control metrology and software analytics provider Nanometrics Inc of Milpitas, CA, USA and Rudolph Technologies Inc of Wilmington, MA, USA (which makes lithography equipment, process control systems and process control software for semiconductor and advanced packaging device makers).

Headquartered in Wilmington, Onto Innovation is expected to be the fourth largest semiconductor capital equipment supplier by revenue in the USA and a top 15 semiconductor equipment company worldwide (based on Gartner's most recent wafer fab equipment market share report, released in April).

Shares of Nanometrics common stock (which were traded on Nasdaq under the ticker 'NANO') have begun trading on the New York Stock Exchange under the ticker 'ONTO'. Rudolph shares ceased trading on the New York Stock Exchange on 25 October and have converted into 0.8042 shares of Onto Innovation common stock for each Rudolph share.

Board of directors

Onto Innovation says that its new

board of directors consists of 12 members with a deep understanding of Nanometrics' and Rudolph's businesses, a diverse mix of background, skills and experience, and a track record of driving long-term shareholder value. Drawn equally from Nanometrics and Rudolph, they are:

- Christopher A. Seams – chairman, former CEO, Deca Technologies;
- Michael P. Plisinski – CEO, former CEO of Rudolph Technologies;
- Jeffrey A. Aukerman – former partner at Deloitte & Touche LLP;
- Leo Berlinghieri – former CEO & president of MKS Instruments;
- Edward J. Brown Jr – former CEO of Cymer Light Source;
- Vita Cassese – CEO, Mardon Management Advisors;
- Robert G. Deuster – former CEO, Collectors Universe;
- David B. Miller – former President, DuPont Electronics & Communications;
- Bruce C. Rhine – former CEO, Accent Optical Technologies;
- Timothy J. Stultz – former CEO & president, Nanometrics;
- Christine A. Tsingos – former executive VP & CFO, Bio-Rad Laboratories;
- John R. Whitten – former CFO & treasurer, Applied Industrial

Technologies.

Structure and leadership

The Onto management team will be led by Mike Plisinski, CEO, and Steven Roth, CFO. The new organization, like the board, is a combination of Nanometrics and Rudolph executives that will manage the firm's product lines and corporate functions. The center for metrology innovation will be located in Milpitas, CA, with the inspection innovation center remaining in Bloomington, MN. Software and lithography innovation centers will remain in Wilmington, MA.

"We have created a powerful new choice for customers seeking advanced process control solutions across the semiconductor value chain," believes Plisinski. "Our customers are under increasing pressure to improve device performance, reduce costs and improve product cycle times. To meet these demands they seek collaborative partners with whom they can work to solve a broader suite of challenges," he adds. "Onto Innovation will leverage core competencies in software and optics to provide leading-edge products in inspection, metrology, lithography and enterprise process control."

www.ontoinnovation.com

www.nanometrics.com

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SETi gains permanent injunction against Bolb and Q-Egg

Sensor Electronics Technology Inc (SETi) of Columbia, SC, USA — a division of South Korean LED maker Seoul Semiconductor and UV LED product maker Seoul Viosys Co Ltd (SVC) that manufactures UV-A, UV-B and UV-C deep-ultraviolet LEDs (emitting at wavelengths shorter than 340nm) — has obtained a permanent injunction in a patent infringement lawsuit against US-based Bolb Inc and Quantum Egg Inc (Q-Egg).

The California Northern District federal court issued a permanent injunction against the sales of an accused UV LED sterilizer device, as well as any colorable variations. The court will therefore prohibit the sale of similar products if they prove to be mere colorable variations of the accused products.

The asserted patents cover fundamental UV LED technology, encompassing UV LED sterilizer structures and drivers, chip fabrication, and epitaxial layer growth.

Bolb is a UV LED company co-founded by former SETi employees,

and Q-Egg was the distributor of the accused UV LED sterilizer device.

After expanding into a range of fields (including air and water purification devices, as well as medical and bio devices for skin care), the UV LED market value will grow to \$1.2bn in 2022, according to a report last year by LEDinside.

SETi has also collaborated with Seoul Viosys, resulting in the development of Violeds technology for UV LED-based disinfection, deodorization, phototherapy and curing. Violeds technology has been used by the US National Aeronautics and Space Administration (NASA) aboard the International Space Station (ISS). SETi also supplies UV LED products to the USA's largest heating and cooling manufacturing brand. This product has been recognized by customers for its high performance in sterilizing various bacteria that live inside air-conditioning equipment and preventing it from spreading inside a home office during operation.

"It is difficult to survive on a long-term basis in the UV LED industry without a strong foundation in intellectual property and technology expertise, something that SETi and SVC have gained thanks to their extensive investment in research and development," says SETi's chief executive officer Chae Hon Kim.

"SETi believes in furthering a market of fair competition and investment in intellectual property. We believe that this rewards research and development, allowing entrepreneurs and small businesses to have their hard work recognized in the marketplace," he adds.

"As a UV LED pioneer developing commercialized UV LED for the first time in the world, we plan to make our products available at even more competitive pricing to encourage the distribution of our green technology products in the market," Kim concludes.

www.seoulviosys.com
www.s-et.com

AquiSense's PearlAqua Micro first UV-C LED product certified to NSF/ANSI 55-2019 Standard

Nikkiso Group company AquiSense Technologies LLC of Erlanger, KY, USA (which designs and manufactures water, air and surface disinfection systems based on UV-C LEDs) has claimed the first NSF Component Certification to the newly updated NSF/ANSI 55-2019 Standard for its PearlAqua Micro range, certified by NSF International in compliance with the new NSF/ANSI 55 Standard for Material Safety and Structural Integrity.

With tens of thousands of units shipped this year, the PearlAqua Micro is claimed to be the smallest UV-C LED water treatment system. Manufactured to ISO-9001:2015 quality standards, the range includes five discrete model sizes offering flow rates of up to 8lpm



The PearlAqua Micro. The range is designed to

be integrated at the point of use and offers 12VDC or 24VDC input voltage, automatic on/off control, multiple sensing/alarm options, and customizable housing options.

The NSF/ANSI 55-2019 Standard has recently been updated to address the unique technical differences of LED technology compared with traditional mercury gas-discharge

and third-party validation disinfection performance of up to 6-log (99.9999%) pathogen reduction.

lamp technology. Following very soon will be microbiological performance certification by NSF. This will provide additional verification to the already completed third-party microbiological validation completed on the PearlAqua Micro range, showing supplemental bacterial treatment of drinking water supplies. This provides a strong final barrier and 'last-mile' protection to many applications.

"Prior to September 2019, there was no specific standard for LED technology in water treatment applications," notes CEO Oliver Lawal. "Our team has worked for years supporting NSF International to ensure the new 55 Standard is robust and future-proof," he adds.

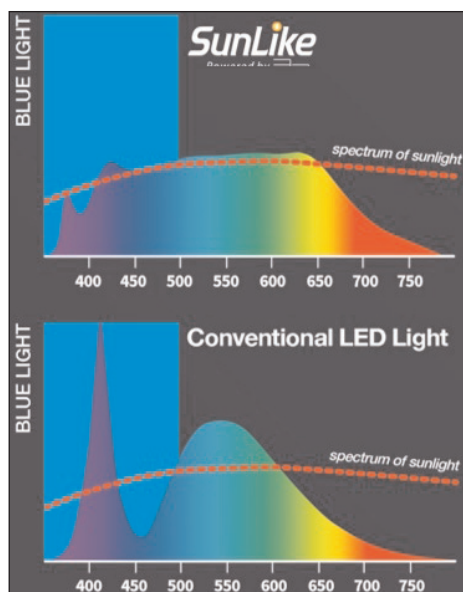
www.aquisense.com

Seoul Semiconductor's SunLike Series natural-spectrum LEDs adopted by lighting brand REMEZ

South Korean LED maker Seoul Semiconductor Co Ltd says that its SunLike Series natural-spectrum LEDs have been adopted for lighting brand 'REMEZ' by RemiLicht GmbH for the Russian lighting market. The LED light bulbs feature a human-centric lighting design enabled by the SunLike Series LEDs.

The SunLike Series LEDs adopted by RemiLicht (for LED light bulbs for residential lighting and desk lamps) achieved warm-white (3000K) and cold-white (5700K) correlated color temperatures (CCTs), optimized to natural light spectra by reaching lower blue light peak similar to sunlight's spectral curve in order to reduce scattered reflection and glare common in conventional LEDs.

Seoul says that its SunLike Series natural-spectrum LEDs have been identified as a key light source for promoting human well-being, based on the results of a recent comprehensive sleep study conducted by professor Christian Cajochen and his team at the University of Basel in Switzerland ('Effect of Daylight LED on Visual Comfort, Melatonin, Mood, Waking Performance, and Sleep', Journal of Lighting and Research Technology, on 24 March). "We have evidence that a daylight [natural spectrum] LED solution has beneficial effects on visual comfort, daytime alertness, mood, and sleep intensity in



healthy volunteers," Cajochen says.

Light sources with SunLike Series LEDs are said to more accurately show the color of objects as they would appear in natural sunlight. Optimized to natural light spectra and color rendering index of CRI-97 (close to the CRI-100 of sunlight, and higher than the CRI-80 of conventional LEDs), it is claimed that SunLike Series LEDs deliver significant benefits in vivid color, contrast detail, and quality of light consistency.

"We have sought LED light sources to replicate the qualities of natural sunlight for indoor environments to deliver beneficial effects on eye comfort and human health," says RemiLicht's CEO Igor Remez. "We were able to create LED light

bulbs for human-centric lighting with Seoul Semiconductor's innovative SunLike Series LEDs, which will deliver healthy light that were not possible to achieve using conventional LED technology," he adds.

"Even if different sources of white light look identical to the naked eye, they may contain different levels of the crucial wavelength in the blue spectrum that triggers the body's hormonal response," says Carlo Romiti, Europe sales VP at Seoul Semiconductor. "A truly human-centric lighting source must not only closely match the spectrum of natural sunlight but it also must have the correct level of blue-wavelength light for the time of day," he adds. "Our SunLike Series LEDs enable truly human-centric lighting design that closely matches the spectrum of natural sunlight. It has also achieved the highest level of eye safety certification from the International Commission on Illumination as an RG-1 level light source with no photo-biological risks."

Seoul Semiconductor developed SunLike Series natural-spectrum LEDs in collaboration with Toshiba Materials' TRI-R spectrum technology in 2017 as the first LED light source to closely match the spectrum of natural sunlight.

www.remezlight.com/en

www.seoulsemicon.com/en/technology/Sunlike

SunLike Series LEDs adopted by WALTRON for aquarium lighting

Seoul Semiconductor says that its SunLike Series natural-spectrum LEDs have also been adopted by WALTRON of Lower Saxony, Germany for its daytime Pendix aquarium lighting solutions.

Indoor aquaria are full of colorful corals, fish, and water plants living in an ecosystem similar to nature. Direct sunlight is typically avoided in these spaces in order to limit the reproduction of algae and keep

water from becoming turbid and harming the ecological balance of the aquarium system. Lighting solutions hence play a key role in maintaining growth without disturbing the ecological cycle.

Pendix is a matrix LED module with nine different color temperatures and has a customized spectral lighting design that closely matches the spectrum of natural sunlight enabled by SunLike Series LEDs.

Different light colors such as white, blue and red can be combined in the module to provide the optimal lighting solution for both saltwater aquaria and freshwater aquaria.

"SunLike Series natural spectrum LEDs as healthy light sources will offer the considerable benefits for better growth of fishes and plants in aquaria," says Carlo Romiti, Europe sales VP.

www.daytime.de/led-systeme-pendix

Cree's LED revenue down 22% year-on-year due to soft market and China trade and tariff concerns

Customers cautious as trade concerns linger, 5G rollout is delayed and China electric vehicle sales are down

For its fiscal first-quarter 2020 (ended 29 September 2019), Cree Inc of Durham, NC, USA has reported revenue of \$242.8m, down 3% on \$251.2m last quarter and 11% on \$274.2m a year ago, after excluding (as discontinued operations) the Lighting Products business unit (LED lighting fixtures, lamps and corporate lighting for commercial, industrial and consumer applications), which Cree sold on 13 May to IDEAL Industries Inc of Sycamore, IL, USA.

The drop in continuing business was because LED Products revenue of \$115.1m (47.4% of total revenue) was down 22% on \$146.8m (54% of total revenue) a year ago due to soft market conditions and the ongoing trade and tariff concerns with China. However, this is down only 1.6% on \$117m last quarter (better than the expected 2–4% decline) and an increase from 46.6% of total revenue.

Revenue for Cree's Wolfspeed silicon carbide (SiC) materials, power and gallium nitride (GaN) RF device business was \$127.7m (52.6% of total revenue), up fractionally on \$127.4m (46% of total revenue) a year ago, but down 5% on \$134.2m (53.4% of total revenue) last quarter, as Cree continues to see softness in China related to the change in electric vehicle (EV) subsidies earlier this year. "This marks the third consecutive month of weaker automotive sales trends in China," notes chief financial officer Neill Reynold. "In our RF business, in addition to Huawei, we are seeing some push outs and delays in purchasing activity as it relates to the rollout of 5G networks," he adds.

On a non-GAAP basis, gross margin has fallen further, from 37% a year ago and 36.6% last quarter to 31% (although this exceeds the expected

30.8%). By sector, Wolf-speed gross margin was 46.3%, down from 47.4% a year ago and falling back from 50.2% last quarter, impacted by customer mix related to the Huawei ban. LED gross margin has fallen further, from 28% a year ago and 24.1% last quarter to 19.2%, due mainly to lower factory utilization, but exceeding the expected 17.5%, driven by improved customer mix and cost execution.

Operating expenses (OpEx) were \$84m (34.6% of revenue), up from \$82m (32.6% of revenue) last quarter and above the \$83m target.

Compared with net income of \$23.2m

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(\$0.23 per diluted share) a year ago and \$11.5m (\$0.11 per diluted share) last quarter, net loss from continuing operations was \$3.6m (\$0.03 per diluted share), but this was better than the midpoint of the targeted range of \$3–7m (\$0.03–0.07 per diluted share) due to the better-than-expected gross margin in the LED business.

Cash from operations was an outflow of –\$20m. Capital expenditure (CapEx) was \$43m (up from \$37m last quarter) as Cree continues to invest for growth to expand capacity in its Wolfspeed business. Free cash outflow was hence –\$63m (up from \$34.5m).

During the quarter, cash and short-term investments fell back from \$1051m to \$994m. Cree has zero balance on its line of credit and convertible debt with a face value of \$575m.

"Cree's strategic transformation remains on track. We continue to see strong momentum and growing interest in our silicon carbide and GaN technologies," says CEO Gregg Lowe. "We delivered results that met or exceeded the upper end of the ranges we set for revenue, gross margin and EPS," he adds.

"We continue to confront some headwinds related to geopolitical and macroeconomic issues, and we don't expect this to change in the near term," says Lowe. "Customers are being more cautious as trade concerns linger, the rollout of 5G is delayed and EV sales in China are down," he adds.

For its fiscal second-quarter 2020, Cree targets revenue of \$234–240m. "LED revenue is expected to be flat on a sequential basis, as we don't see any material change in the LED market outlook," says Reynold. Wolfspeed revenue is expected to be down 3–6% sequentially as Cree continues to deal with the impact

(on RF business) of the Huawei ban and softness in 5G network spending and (on the Power business) of lower EV sales in China. "We continue to comply with US federal law as it relates to Huawei and we have applied for licenses from the government to potentially resume certain shipments to our customer, but we are still awaiting a response," says Reynold.

Gross margin is targeted to be about 30%. This includes LED gross margin of 19.5–20.5%, up modestly on a sequential basis. Wolfspeed gross margin are expected to be down about 400 basis points sequentially to 41–44%, driven by lower factory utilization to manage short-term inventories, a significant scrap event, and lower-than-expected yields as Cree ramps its 150mm SiC MOSFET product. "As we significantly increased our capacity, we are bound to face some manufacturing challenges," says Lowe. "We had a significant scrap event and overall lower yields on our 150mm ramp in our Durham fab, impacting our gross margin in the near term. We have a clear understanding of the issue, and are implementing improvements as we speak and expect to resolve these issues and get the yield back to target in short order," he adds. "Utilization effect should reverse when volumes recover, and we have plans in place to improve the 150mm MOSFET yields," says Reynold. "However, it will take one to two quarters for margins to improve once volumes increase and improvements are implemented on 150mm MOSFET yields," he adds.

OpEx should rise slightly sequentially in fiscal Q2/2020, to about \$85m, as Cree continues to invest for growth in the Wolfspeed business and align its LED cost structure to the current environment.

Net loss is expected to be \$8–12m (\$0.07–0.11 per diluted share), impacted by about \$0.02 due to the ongoing impact of the tariffs.

For fiscal 2020, Cree continues to target capital investment of about

\$200m. "Capital allocation priorities remain focused on expanding capacity in our Wolfspeed business to support anticipated demand," says Reynold.

"We are continuing with our efforts to increase the availability of silicon carbide as customers look to leverage the benefits of our [Wolfspeed] silicon carbide and GaN solutions to drive innovation," says Lowe.

In May, Cree started a significant, multi-year factory optimization plan, to be anchored by an automated 200mm silicon carbide wafer fabrication facility, which in September it announced would be built in Marcy, NY (Mohawk Valley), complementing the 'mega materials' factory expansion underway at its US campus headquarters in Durham (forming a 'silicon carbide corridor' on the East Coast

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of the USA).

"The mega materials factory expansion has been ongoing for some time, as we have installed new crystal growers, shifted more LED growers to Wolfspeed, and drove improved productivity across the entire fleet of growers," notes Lowe. "While we are at the early stages of the creation of the Mohawk Valley fab, the teams have already shifted the prep work into high gear and we expect the work on the site to begin soon," he adds.

"Just two weeks after we announced our partnership in New York, we successfully ran our first silicon carbide test wafers at State University of New York (SUNY) Albany. The prototype line in Albany was part of the overall incentive package and allows us to de-risk the start-up of a new fab," Lowe continues. "This is a very capital-efficient way to build two high-quality modern facilities to support the growing demand we expect from the automotive, communications infrastructure and industrial segments."

Also, in September Cree announced a partnership for automotive propulsion technology provider Delphi Technologies to use Wolfspeed SiC-based MOSFETs in their 800V inverter for EVs, with production beginning in 2022. "The auto industry represents one of the most significant multi-year opportunities for silicon carbide, and this partnership is a strong endorsement for Cree in the device area," says Lowe.

"Beyond electric vehicles, the benefits of silicon carbide carry over to other end markets including telecom, infrastructure, solar, industrial and other applications," he adds. "Across our end markets, Cree is engaging with innovative companies who are running up against the limitations of silicon to help them break through and deliver the promise of their next-generation applications, and our leadership and expertise positions us well with many of these innovators."

www.cree.com

Osram adds 850 & 940nm Firefly SFH 4030 and 4060 IR LEDs to improve VR & AR eye-tracking systems

Osram Opto Semiconductors GmbH of Regensburg, Germany says that its new Firefly SFH 4030 and SFH 4060 infrared LEDs aim to help prevent the side effects of both virtual reality (VR) and augmented reality (AR) — whereby some users are developing feelings of discomfort and dizziness when the virtual and real perceptions do not match — by enabling state-of-the-art eye-tracking solutions that provide a targeted point of reference, allowing users to safely immerse in other worlds.

Eye-tracking systems register the user's viewing angle and the movements of their eyes. They illuminate the eyes with infrared light and register the reflections with a camera sensor. Software then determines the exact position of the eyes



and the viewing direction of the user to derive relevant information for the imaging elements of the system.

Depending on the requirements of the target application, the 850nm-wavelength SFH 4060 benefits from the high sensitivity of the sensors in this wavelength range, whereas the 940nm-wavelength SFH 4030 avoids the disturbing 'red glow' effect where users see a red light.

The SFH 4030 and SFH 4060 feature compact dimensions of only 1.0mm x 0.325mm. Due to their low height of just 0.55mm, the side-emitting components can be easily installed, says Osram. A special feature is the black cap, which makes the two IREDS 'invisible' when installed.

"Eye-tracking offers a very intuitive way of human-machine interaction for AR and VR applications, including displaying important information about the focused object," says product manager Bianka Schnabel. "With the IREDS' two wavelength options and black package, we are broadening the options for our customers, and at the same time, making system integration easier."

www.osram-os.com

Lumileds' new LUXEON CX Plus CoBs boost intensity of chip-on-board LEDs for spotlights and downlights

Lumileds LLC of San Jose, CA, USA has introduced three lines of CoB (chip-on-board) LEDs, the LUXEON CX Plus CoB (Gen 2), LUXEON CX Plus CoB – High Density and LUXEON CX Plus CoB – High Density (Below BBL), as drop-in upgrades for both Lumileds and competing arrays. The second-generation arrays feature a 14% flux improvement on the previous generation. Delivered in a range of light-emitting surfaces (LES of 4.5mm, 6mm, 12mm and 14mm) and correlated color temperatures (CCTs of 2700–5000K), the Gen 2 arrays provide luminous efficiency of more than 140lm/W at 3000K 80CRI or 122lm/W at 3000K 90CRI.

The High Density version of the LUXEON CX Plus CoB provides what is claimed to be industry-leading punch (center-beam candle power) and is available in either on-BBL (blackbody locus) coordinates for halogen-like illumination or below-



BBL for ceramic metal halide-like illumination. The LUXEON CX Plus CoB – High Density provides flux of up to 1150lm at 3000K 90CRI from the smallest LES of 4.5mm. Flux is 10% more than competing CoBs at 6mm and 9mm LES. Offered in

three LES (4.5mm, 6mm and 9mm) on 13.35mm x 13.35mm substrate, the arrays cover a range of color temperatures (2700K to 5000K) with a minimum of 80CRI or 90CRI and color control within 3- or 2-step MacAdam ellipse. For the below-BBL versions, color temperature range is 2700–4000K at a minimum of 95CRI with color control within 3-step or 2-step MacAdam ellipse. "The below-blackbody option is perfect for illuminating artwork, for instance, because the highest color fidelity combines with slightly more saturated colors," says LUXEON CoB product manager LP Liew.

All LUXEON arrays utilize a metal core PCB substrate that is more resistant to cracking during luminaire assembly. The low resistance of the MCPCB also provides superior removal of heat from the LED, leading to smaller heatsinks and more compact luminaires, says Lumileds.

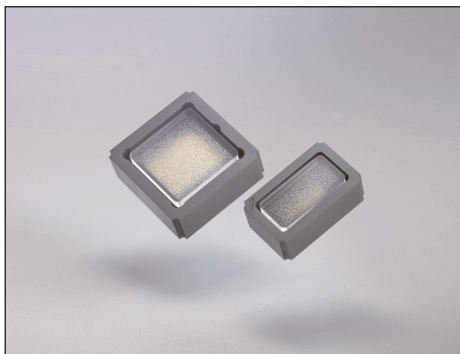
www.lumileds.com

TRUMPF delivers billionth VCSEL to ST for smartphones

TRUMPF GmbH of Ditzingen, near Stuttgart, Germany says that in the autumn it delivered the 1 billionth vertical-cavity surface-emitting laser (VCSEL) to its sensor-manufacturing European partner STMicroelectronics, for use in its time-of-flight product families.

The VCSEL is a fundamental component of sensors that feature prominently in smartphones to improve the camera autofocus, enable face recognition to unlock the device's display, and switch off the display when the user raises the smartphone to their ear when taking a call. TRUMPF's VCSEL technology is now installed in more than 150 smartphones from a wide range of leading OEMs.

TRUMPF develops and produces its VCSEL technology at Photonic Components, a business field located at its Ulm site. VCSEL technology complements TRUMPF's wide-ranging laser product and



TRUMPF's VCSELs, used in sensors in smartphones.

technology portfolio.

"We have been working successfully with STMicroelectronics since 2012 and intend to deepen this relationship to unlock the great potential for growth in many consumer electronics segments," says Joseph Pankert, managing director in charge of the VCSEL line of business. "We also see strong growth potential for our VCSELs in other markets including higher-resolution

time-of-flight cameras. These cameras flood an object or a room with infrared light, measure the round-trip travel time or the phase shift of the emitted light, and calculate three-dimensional models based on this data," he adds. "VCSELs are used not only in the consumer industry, but also in data transmission, industrial robots and autonomous vehicles."

"ST's time-of-flight product families have been widely adopted by leading smartphone OEMs, with more than 150 phone models already using our technology," says Eric Aussedat, STMicroelectronics' executive VP & general manager of its Imaging sub-group. "Building on this success, we look forward to further co-work with TRUMPF to address the exciting and rapidly growing 3D and depth sensing markets."

www.trumpf.com/en_GB/products/vcsel-solutions-photodiodes

Scottish Enterprise-funded MIRAGE project helps secure CST Global access to global FTTH, sensing, imaging and telecoms markets

III-V optoelectronic foundry Compound Semiconductor Technologies Global Ltd (CST Global) of Glasgow, Scotland, UK (a subsidiary of Sweden's Sivers IMA Holdings AB) says that the Scottish Enterprise government-funded MIRAGE project – which has now completed, after starting in 2015 – has helped it to develop mid-infrared laser chips for applications in global fiber-to-the-home (FTTH), sensing, imaging, telecoms and data-center markets.

The first project of its kind in Scotland, MIRAGE was delivered by a collaboration of four SME companies: CST Global, Cascade Technologies, Gas Sensing Solutions and Amethyst Research. The project fund of £6.35m was managed through Scottish Enterprise

and is expected to add £56m of cumulative growth to the Scottish economy and create 41 new jobs.

"The cutting-edge laser technology developed for MIRAGE is applicable to a wide range of massive-growth markets," says Thomas Slight, project lead and research engineer at CST Global. "FTTH connectivity for cable television and the Internet is just one, but data-center connectivity, autonomous vehicles and many other industrial, defense and healthcare applications have been enabled," he adds.

New commercial and residential buildings requiring direct FTTH connections for Internet and TV is a rapidly growing market, particularly in China, where CST Global already has a sales presence. According to

a report from the Asia Video Industry Association (AVIA), the number of pay TV subscribers is expected to rise to 353 million by 2022.

"The MIRAGE project gave us access to the expertise and materials required to compete in these markets," says Thomas. "Not only has it allowed CST Global to develop a new chip at the forefront of the global sensors and imaging systems sector, but it has also helped to create a globally competitive supply chain in Scotland," he adds. "We have successfully manufactured competitive lasers in high volumes and yields that meet the required ITU standards. This has created six highly skilled new roles at CST Global alone, adding to our team of specialist engineers."

www.cstglobal.uk

Lumerical's photonic inverse design cuts CompoundTek's silicon photonics grating coupler footprint by 20x

Singapore-based silicon photonic (SiPh) foundry services provider CompoundTek Pte Ltd has announced the tapeout of a reduced-footprint grating coupler for photonic I/O. The grating couplers were designed and optimized using photonic inverse design (PID) in conjunction with the FDTD (finite-difference time domain) nanophotonic simulator of photonic simulation software provider Lumerical Inc of Vancouver, British Columbia, Canada. Lumerical's PID capability enables photonic designers to rapidly develop entirely new functionality with improved performance, reduced footprint and more robust manufacturability.

"With this successful tapeout in partnership with Lumerical, customers will be able to access Lumerical's PID solution with confidence when taping-out to CompoundTek in the future," says CompoundTek's chief operating officer KS Ang. "The integration into our design flow, design partners and open SiPh manufacturing platform ecosystem will accelerate the adoption of SiPh solutions for various applications ranging from datacom transceivers, smart sensor, bio-medical, automotive LiDAR, quantum computing and artificial intelligence," he adds.

The SiPh grating coupler is a key functional block for photonic I/O, enabling light to be coupled from fiber into and out of a photonic integrated circuit (PIC). Unlike end-fire edge couplers, grating couplers can be located anywhere on chip, enabling additional applications



such as sense and test. With this flexibility comes the requirement for reduced footprint while maintaining high coupling efficiency. However, with over 100 design parameters, grating couplers are geometrically complex, rendering traditional optimization techniques impractical. Lumerical's PID technology enables designers to automatically and reliably generate optimal grating couplers with hundreds of free parameters. As testimony to its effectiveness, CompoundTek's SiPh new grating couplers have been reduced in size by 20x and promise improved coupling efficiency.

"These new grating couplers will enable our customers to create improved commercial designs with higher yields and faster time to market," says Lumerical's chief technical officer James Pond. "PID's powerful optimization algorithms leverage adjoint sensitivity analysis to explore design spaces that are impractical by other means," he adds. "Coupled with Lumerical's industry-leading FDTD solver, PID enables designers to efficiently explore and optimise designs with hundreds or more design parameters. In contrast, traditional design approaches are limited to a small

number of established device designs, exploring much smaller parameter spaces, typically fewer than ten parameters."

CompoundTek says that its SiPh multi-project wafer (MPW) platform offers a highly flexible solution for PIC developers requiring rapid design and manufacture, necessitating multiple variants of the new grating couplers. New capabilities introduced with Lumerical's 2020a release allow PID to run efficiently on HPC resources, and include job checkpointing, support for Amazon Linux, and online self activation for FDTD Burst Packs (see www.lumerical.com/products/fdtd/#HPCFDTDB) Other notable PID features such as global optimization allow designers to efficiently explore a broad design space and co-optimize for process and packaging variation for the creation of robust designs. Rapidly scaling up with Lumerical's HPC cloud deployment reduced the design cycle for the optimized grating couplers for all eight variants to under two weeks.

The Python-based open source PID implementation is packaged together with Lumerical FDTD for ease of deployment. Alternatively, the original source code is freely available on GitHub at <https://github.com/chriskeraly/lumopt>. To help new users get started with PID, examples are included in Lumerical's application gallery to speed designers' time to implementation.

<https://compoundtek.com>
www.lumerical.com/products/aapi

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www.semiconductor-today.com

Keysight, FormFactor and CompoundTek jointly develop on-wafer testing for integrated photonics

Keysight Technologies Inc of Santa Rosa, CA, USA, FormFactor Inc of Livermore, CA, USA (which provides test & measurement technologies along the full IC life cycle — from characterization, modeling, reliability and design de-bug to qualification and production test) and Singapore-based silicon photonic (SiPh) foundry services provider CompoundTek Pte Ltd have joined forces to accelerate integrated photonics (silicon photonics) innovations.

While photonics integrated circuits (PICs) offer an alternative to the limitations of traditional data-center networking, they also introduce new design and test challenges for component and device makers. The adoption of PICs is primarily dependent on an industrial ecosystem consisting of new foundries, commercial modeling tools and photonic test capabilities.

Keysight, FormFactor and CompoundTek have jointly developed a photonics on-wafer testing solution that delivers what is claimed to be industry-first capabilities including automated alignment, simultaneous optical-optical and optical-electrical device tests.

To be offered by CompoundTek, the joint solution includes:

- the FormFactor CM300xi-SiPh, with automated wafer-level photonics positioning combined with Keysight's industry-standard IL/PDL engines and N7700A Photonics Application Suite (PAS),

to support wavelength repeatability of $\pm 1.5\text{pm}$ at two-way sweeps up to 200nm/s within 1240–1650nm to ensure accuracy and repeatability from O-band to L-band;

- Keysight's N4373E 67GHz Lightwave Component Analyzer, which delivers what is claimed to be unprecedented bandwidth for both optical receiver testing and optical transmitter testing with guaranteed specifications for electro-optical S-parameter measurements for device traceability;
- Keysight's PathWave software platform, which provides a consistent user experience, common data formats and control interfaces;
- FormFactor's SiPh software, which enables automated calibrations and alignments and simplifies integration with Keysight's PathWave software platform, as well as optical instrumentation, to ensure ease of use.

Silicon photonics also delivers benefits for industrial segments such as intra-data-center communication and data-center interconnects (DCI), telecom, 5G and automotive connectivity, high-performance computing (HPC), light detection & ranging (LiDAR), as well as sensing and medical applications.

"Innovation in optics is critical to connect the world and help the industry to monetize 5G, as well as data-center and telecom services," says Dr Joachim Peerlings, Keysight's VP of Network and Data Center Solutions. "Advancing in speed as

well as power and cost efficiency requires a tightly connected ecosystem to jointly solve the challenges ahead."

CompoundTek plans to establish a silicon photonics testing services hub in Singapore. "With added on-wafer level, automated silicon photonics optical/electrical/RF testing with this solution, customers will be able to limit packaging costs to avoid module-packaging-level testing turn-around time losses," says chief operating officer, K.S. Ang. "This test solution complements our current services in mass-production volume with fast cycle-time, offered alongside world-class commercial foundry capabilities that accelerate time-to-market to achieve customers' commercialization goals," he adds.

"FormFactor's industry-leading silicon photonics wafer test capability allows our customers to obtain repeatable, consistent results with unsurpassed throughput," claims Claus Dietrich, VP & general manager of the Systems business unit at FormFactor. "The system's automated and high-speed calibration and optical alignment, as well as precision measurement capability in collaboration with Keysight, enable CompoundTek to offer customers faster time to market."

<https://compoundtek.com>
www.formfactor.com/product/probe-systems/300-mm-systems/cm300xi-siph
www.keysight.com

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POET completes sale of DenseLight subsidiary

POET Technologies Inc of Toronto, Ontario, Canada and San Jose, CA, USA — a designer and manufacturer of optoelectronic devices, including light sources, passive waveguides and photonic integrated circuits (PIC) — has completed the sale of its Singapore-based subsidiary DenseLight Semiconductors Pte Ltd to DenseLight Semiconductor Technology (Shanghai) Ltd (a special-purpose company organized by China Prosper Group on behalf of a consortium of investors).

POET's shareholders approved the sale with 99% of votes submitted at a Special Meeting on 24 October.

The first tranche payment of US\$8m were received on 8 November in return for which POET initiated the transfer of 30% of DenseLight shares to the buyer. The remaining 70% were placed in escrow, to be released upon receipt of the remaining two payments of US\$13m and US\$5m (which are expected to be made on or before 31 December 2019 and 31 May 2020, respectively).

POET says that, as a result of completing the sale, it is no longer responsible for DenseLight's expenses, enabling further execution on POET's objective to operate according to a 'fab-light' strategy.

Concurrent with the closing, POET repaid in full its loan to Espresso Capital and other parties as well as discharged all associated security interests in POET's assets (which are no longer subject to any material liens or encumbrances).

www.poet-technologies.com

Cardiff University's Qiang Li wins UK EPSRC's New Investigator Award

The New Investigator Award of the UK Engineering and Physical Sciences Research Council (EPSRC) has gone to Dr Qiang Li, a lecturer in Advanced Materials and Devices in the Sêr Cymru Research Group of Cardiff University's School of Physics and Astronomy.

Working with partners IQE plc, Rockley Photonics Ltd and the University of Macau in the project 'Tunnel epitaxy: building a buffer-less III-V-on-insulator (XOI) platform for on-chip light sources' (EP/T01105X/1, funded with £282,062 from 1 November 2019 to 31 October 2021), principal investigator Li's research aims to develop an epitaxial crystal growth process to enable the direct integration of III-V on insulator (XOI) structures on silicon wafers.

By taking advantage of the crystallographic geography and selective area growth in confined spaces (using a process pioneered by Li), the project aims to achieve dislocation-free micro-sized thin films on insulators without needing to designs complex intervening buffer layers.

It is believed that efficient optical interconnects can be achieved through the direct growth of compound semiconductor devices on a mature silicon platform,



Dr Qiang Li.

producing cheaper, faster chips. Until now, it has been necessary to introduce buffers between the two materials, but this lengthens the manufacturing processes and brings challenges in combining different device components. A buffer-less platform can potentially support integration of III-V compound semiconductors with silicon waveguides and open up opportunities in silicon photonics.

"Compound semiconductors already complement silicon in many niche applications like 3D sensing and wireless communications," says Li. "Through this project, we aim to explore a more creative approach to combine their unique physical properties with the silicon manufacturing platform." As a proof-of-concept demonstration, micro-disk lasers will be fabricated to validate the optical quality of the III-V structures and highlight its potential for photonics integration.

"Dr Li is a very talented young researcher with an international network," comments professor Diana Huffaker, Sêr Cymru Chair in Advanced Engineering and Materials.

"He was headhunted to bring the III-V/Si epitaxy capability into the Ser Cymru Research Group," she adds. "The EPSRC Award will serve as a foundation for him to launch his successful career at Cardiff."

Competitively awarded by the EPSRC, New Investigator Awards are granted to support and develop the research careers of talented individuals who hold an academic lectureship position but have not previously led a research group. The award gives them an opportunity to manage a grant, establish and lead their own research team and assert their research independence. It should enable Li to recruit a postdoctoral researcher, develop an internationally competitive research program at Cardiff and build wider collaborations within the UK semiconductor community.

"It is an ambitious endeavour to develop this method to a point that allows the creation of useful integrated indium phosphide (InP) photonics on silicon," commented the EPSRC on granting the award. "The proposal is highly relevant to Manufacturing the Future [an EPSRC's funding theme spanning 271 grants totaling £354m], and offers significant opportunities for the compound semiconductor cluster in Cardiff."

www.cardiff.ac.uk

POET cuts losses, despite sales falling in Q3/2019 due to weaker industry-wide demand

For third-quarter 2019, POET Technologies Inc of Toronto, Ontario, Canada and San Jose, CA, USA — a designer and manufacturer of optoelectronic devices, including light sources, passive waveguides and photonic integrated circuits (PIC) for the sensing and datacom markets — has reported revenue of US\$1.183m, up on US\$0.907m a year ago but down on US\$1.358m last quarter. The sequential decline was due to a slowing of device sales from Singapore-based subsidiary Denselight Semiconductor Pte Ltd resulting from weaker industry-wide demand.

Results include Denselight as a discontinued operation, after a definitive agreement was signed on 20 August for its sale (which was finalized on 8 November). All financial data hence represent the combined results from both continuing and discontinued operations.

Gross margin was 71%, up only slightly from 70% last quarter but improving substantially on 59% a year ago, due to the higher proportion of non-recurring engineering (NRE) in the revenue mix. Net loss was cut from US\$4.939m (\$0.02 per share) a year ago and US\$3.8m (\$0.01 per share) last

quarter to US\$2.944m (\$0.01 per share). During Q3, the fifth and final tranche of convertible debenture private placement was closed for gross proceeds of US\$137,000 (C\$182,000), bringing the total capital raised through convertible debentures to US\$3.7m (C\$5m).

POET will continue reporting revenues consolidated with Denselight through 8 November, since the bulk of its R&D, production and sales activities were conducted there. With the sale now completed, Denselight is expected to remain a key development partner and supplier to POET.

POET appoints Vivek Rajgarhia as president, while CEO Suresh Venkatesan adds chairman role

POET has appointed industry veteran Vivek Rajgarhia as president & general manager, while its CEO Dr Suresh Venkatesan has added the role of chairman. David Lazovsky, who has been executive chairman since early 2017, resigned as executive chair but will continue as a director on the board. Existing director Peter Charbonneau becomes lead independent director.

The changes in the senior management organization came ahead of the closing of the sale of Singapore-based wafer fabrication subsidiary Denselight Semiconductors.

Rajgarhia was most recently senior VP & general manager of the Lightwave business unit of MACOM, which he joined through the acquisition of Optomai Inc (where he was co-founder & CEO), representing MACOM's initial entry into the optical business. He was then instrumental in identifying and leading several strategic acquisitions to build an extensive portfolio of optical and photonic businesses, which formed MACOM's Lightwave business unit.

Rajgarhia has held senior management positions in his 30 years in the optical communications

industry. He was director of sales & marketing (Asia) for Lucent Technologies' (now Nokia) optical components, where he started its Asia business; VP of product marketing & business development for OpNext (formerly Hitachi's Fiber Optics Division), where he was part of the team to spin off the optical business from Hitachi; director of product management & marketing for JDS Uniphase (now Viavi), and VP of global sales for GigOptix.

Rajgarhia has also been an entrepreneur, founding two optical companies, and has held international assignments in Hong Kong, Germany and India. He has a Bachelor of Engineering (Electrical) degree from Stevens Institute of Technology in New Jersey.

"This appointment represents a powerful partnering of two senior executives from the photonics and semiconductor industries," says Lazovsky. "Together, these two executives combine extraordinary careers with unparalleled business, market and product development experience. Suresh and Vivek bring together the ideal combination of strategic, technical and operational

execution expertise in photonics and semiconductors that will position the company well to capitalize on the disruptive potential of the POET Optical Interposer platform," he reckons.

After resigning from his position as executive chairman, Lazovsky will be joining Khosla Ventures in Menlo Park, where he has been appointed venture partner. "We want to thank Dave for his tireless work on business strategy and strategic partnership initiatives that he has led since 2017 as executive chairman," says Venkatesan. "We will be able to continue to tap his considerable talents while he remains on the board," he adds. "In concert with the governance requirements of the TSXV, we are also pleased that the board has elected Peter Charbonneau from among its members as lead independent director. Peter has led the reviews of the charters and operation of the board and each of its committees. We appreciate his efforts to modernize and update these important governance rules." Charbonneau was first elected to POET's board in March 2018.

Emcore sells CATV production assets to Shenzhen-based Hytera for \$5.5m

Transfer to EMS model eliminates exposure to China tariffs

Emcore Corp of Alhambra, CA, USA — which provides indium phosphide (InP)-based optical chips, components, subsystems and systems for the broadband and specialty fiber-optics markets — has announced the sale of its cable TV (CATV) production equipment and transfer of its CATV manufacturing operations from its Beijing facility to Hytera Communications (Hong Kong) Co Ltd and Shenzhen Hytera Communications Co Ltd. The sale price for the equipment is about \$5.5m and is expected to be received beginning in the December 2019 quarter and continuing over the ten months through the September 2020 quarter. Hytera will use the equipment to manufacture CATV components and subsystems from its facility in Southeast Asia.

In its fiscal third-quarter 2019 earnings call, Emcore discussed plans to take four actions to improve profitability and cash flow while

eliminating exposure to tariffs associated with the import of products manufactured in China. With the execution of this agreement and subsequent production transfer to Hytera, Emcore will complete the first of these actions — streamlining operations and moving to a variable-cost model in its CATV product lines. Additionally, Emcore completed two other actions in the quarter by reducing the size of its CATV team and reducing the capacity of its wafer fab to one shift.

These actions incurred one-time costs of \$0.4m in the quarter to end-September and are expected to result in annual cash savings of about \$3m beginning in the December 2019 quarter. These operational changes in CATV also fulfill a strategic objective of positioning the CATV product lines to generate positive cash flow to help fund Emcore's other growth areas in Aerospace and Defense.

"We've been working to transition to a true EMS (electronics manufacturing services) model for our cable TV products since 2015 when we launched the automation initiatives in our Beijing facility," says president & CEO Jeffrey Rittichier. "Insertion of automation into Beijing dramatically improved yields and reduced cycle times, clearing the way for the final move to an EMS model," he adds.

"Hytera has been with us during our entire transformation, and this agreement with them finalizes the realization of our strategy... We are looking forward to many years of success together. Along with our other improvements in operational efficiencies, we expect this agreement to enable Emcore to steadily improve gross margins over the coming quarters," Rittichier concludes.

www.emcore.com

www.hytera.com

II-VI wins Hisense awards for Core Supplier and Outstanding Quality

At a supplier event hosted by China's Hisense, engineered materials and optoelectronic component maker II-VI Inc of Saxonburg, PA, USA has been presented with two Core Supplier and Outstanding Quality awards by Hisense Broadband's chairman Weiping Huang.

The awards are in recognition of II-VI's high-speed vertical-cavity surface-emitting lasers (VCSELs) for short-reach datacom transceivers and active optical cables (AOCs), as well as microfilters and assemblies for long-reach datacom transceivers. Hisense recognized II-VI for supporting its ability to meet the sustained demand for its datacom products, which is driven by the global buildout of the cloud

infrastructure, particularly in China where the hyperscale datacenter footprint is growing rapidly.

"We are very proud to receive our third award from Hisense in three years, in recognition of our ability to be a reliable partner and scalable supplier of high-speed VCSEL devices," says Dr Karlheinz Gulden, VP, Laser Devices and Systems business unit. "We look forward to expanding our strong relationship with Hisense now that II-VI offers one of the most complete portfolios of optoelectronics in the industry, based on world-class gallium arsenide and indium phosphide technology platforms, which will enable datacenter upgrades to 200G and 400G," he adds.

The award is "a strong testament to our micro-optics technology platform differentiated by its very low-loss performance, especially compared with other alternatives in silicon photonics," says Dr Guanglong Yu, VP, Advanced Optics business unit. "Our precision thin-film coatings technology platform has long proven its low-cost and high-volume capabilities, with hundreds of millions of filters deployed in fiber-to-the-home networks worldwide," he adds. "Enabled by high-volume automated assembly manufacturing, it is again the technology of choice for wavelength multiplexing and demultiplexing in long-reach Ethernet transceivers."

www.ii-vi.com



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NeoPhotonics' 13% revenue growth in Q3 drives return to profit, despite US export restrictions on Huawei

Growth driven by strong end-customer demand in Western metro and data-center interconnect markets, 400G-and-faster products, and strength in China

For third-quarter 2019, NeoPhotonics Corp of San Jose, CA, USA (a vertically integrated designer and manufacturer of hybrid photonic integrated optoelectronic modules and subsystems for high-speed communications) has reported revenue of \$92.4m, up 13% on \$81.7m both last quarter and a year ago (and near the top end of the \$87–93m guidance range).

"We achieved strong results, driven by increased partnerships with the leaders in the industry, strong end-customer demand in Western metro and data-center interconnect (DCI) markets, our continued leadership and progress on 400G-and-faster solutions, and strength in China," says chairman, CEO & president Tim Jenks.

Driven by the firm's leading coherent products, revenue for High-Speed Products (for data rates of 100G-and-above) has grown by 25% year-on-year, rising from 84% of total revenue a year ago and 89% last quarter to 92%.

Compared with last quarter (as a proportion of total revenue), shipments to the Americas have risen slightly from 24% to 25%, the rest of the world (RoW) has fallen from 28% to 27%, and China remained flat at 48%.

NeoPhotonics had two 10% customers, one of which was Huawei Technologies. "Huawei has been the largest systems supplier in our industry for several years and, as a result, has also been NeoPhotonics' largest customer," notes Jenks. Despite being down from 46% in 2018, Huawei actually rebounded slightly from 36% of total revenue last quarter to 37%, all from products that are not subject to US Export Administration Regulations (EAR). "We have weathered the headwinds of Huawei Technologies'

inclusion [as of 21 May] on the US Department of Commerce's Bureau of Industry and Security (BIS) 'Entities List' thus far and we remain committed to complying with US EAR," he adds.

"Despite the trade tensions, we believe the macro trends of the industry favor our core capabilities of delivering the highest-performance products for the most demanding applications," says Jenks.

The next four customers again showed strong performance, contributing 48% of revenue. "Our business has continued on a strong footing with our leading Western customers, especially those serving DCI and metro markets," says Jenks.

On a non-GAAP basis, gross margin has risen further, from 24% a year ago and 25.6% last quarter to 29% (at the upper end of the 25–29% guidance range). Within this, product margins were about 34%, up from 32% both last quarter and a year ago, due to good execution and continued cost reductions. Other cost of sales charges of about 5 points consisted of about 4 points of under-utilization charges in the firm's laser fabs and factories impacted by the US Export Administration Regulations, and just under 1 point of tariff charges on products shipping from the firm's US fabs into China.

Operating expenditure (OpEx) has risen slightly, from \$22.1m both a year ago and last quarter to \$22.3m, although this represents a cut from 27.1% of revenue to 24.2% of revenue.

"Solid execution, strong customer demand, and cost reduction combined for a profitable quarter," says Jenks. "While we continue to monitor the evolving status of US-China trade and the global macroeconomic environment, we have made

the changes necessary to drive a profitable second half of 2019," reckons senior VP, finance & chief financial officer Beth Eby.

Appreciation of the US dollar relative to the Chinese Yuan (the functional currency of the firm's China operations) yielded a foreign exchange gain of about \$2.6m, driven by revaluation of the China balance sheet items to the end-of-quarter exchange rate. "We view this as temporary good news that will reverse as the Chinese Yuan appreciates," notes Eby.

Net income was hence \$5.4m (\$0.11 per diluted share — \$0.04 from after-tax FX gain and \$0.07 from ongoing business — at the high end of the forecasted range of between a \$0.03 loss and a \$0.07 profit). This compares with a loss of \$1.2m (\$0.03 per diluted share) last quarter and \$2.1m (\$0.05 per diluted share) a year ago.

Cash generated from operations was \$9m (up from just \$0.7m last quarter). Free cash flow was about \$7m (up from \$0.3m). Net inventory was \$49m (66 days), roughly flat with last quarter despite the 13% higher revenue, as operational efficiency continues to improve. During the quarter, cash and cash equivalents, short-term investments and restricted cash hence rose by \$6m to \$80m.

"Demand signals from our global customers remain positive. In China, we see signals that most products are selling through to end customers, as evidenced by tender activity," says Eby. "Looking forward, we believe certain key customers in China and in the West have a desire to build additional inventory to deal with surges and/or to mitigate their perceived supply chain risks. This is reflected in our outlook," she adds. ➔

► For fourth-quarter 2019, NeoPhotonics expects revenue to grow to \$94–100m. Gross margin should be 28–32%. “We expect margins to grow with cost reductions, offset by the initial impact of annual price negotiations,” says Eby. “With profitability, operating expenses increase slightly on an increase in variable compensation,” she adds. OpEx should hence rise to \$23m. Diluted earnings per share are expected to be \$0.04–0.14.

At the European Conference on Optical Communications (ECOC 2019) in Dublin, Ireland (23–25 September), NeoPhotonics made several announcements related to increasing data-carrying capacity of optical fiber networks in both telecom and data-center applications. “Our solutions include our C++ laser, modulator and receiver. These products have expanded spectral bandwidth ranges to support the full Super C-band, which is 50% more than the standard network configuration. These are industry-leading solutions, which allow customers to significantly expand bandwidth and data-carrying capacity of their existing and new

fiber installations,” says Jenks.

“Further, we announced initial shipment of new arrayed waveguide grating (AWG) multiplexers and de-multiplexers for high-capacity, high-baud-rate, coherent transmission systems. Based on NeoPhotonics high-volume, high-reliability planar lightwave circuit (PLC) platform, these new AWGs have broad and flat filter response functions over the pass-band to support new coherent systems operating from 60Gbaud to 128Gbaud. These support both current state-of-the-art networks and the next generation at 600G, 800G and higher capacities on a single wavelength with customized channel spacings,” he adds.

“Inside the data center, we announced general availability of our non-hermetic 30–40mW DFB laser sources for silicon photonics 100G-per-wavelength FR and DR reach transceivers. Silicon photonics transceivers require a separate laser to supply light powerful enough to overcome intrinsic losses. NeoPhotonics family of high-power DFB lasers are

designed to efficiently couple to the SiPho modulator chip and do not require hermetic packaging making them an ideal choice for next-generation transceiver modules. Moreover, these capabilities open some adjacent market opportunities for our high-speed technologies over the long term.”

“The fundamental driver of our coherent business is the continued deployment of 100G-and-above coherent ports, which have been growing at 20% or more each year. We expect this to continue for the next several years. We anticipate that 400G will continue to ship while our 600G products ramp through this year and next, and will soon include 400ZR rollouts,” continues Jenks.

“Beyond 2020, we expect that 400ZR, 600G and 800G will coexist, and we will be engaged in each of these. These approaches all require best-in-class component performance and are well aligned with our advanced technologies, high-speed capabilities and strong presence in high-speed component platforms.”

www.neophotonics.com

Lumentum divests lithium niobate-based product lines in Italy to China's AFR

Lumentum ramping down LiNbO₃ operations in San Donato as it focuses on InP PIC-based components and modules

China-based Advanced Fiber Resources (Zhuhai) Ltd (AFR), a provider of passive optical components (mainly for industrial laser, telecom, data center, fiber sensing, biomedical and academic research fields), has agreed to acquire the assets associated with certain lithium niobate (LiNbO₃)-based optical component product lines developed and manufactured in San Donato, Italy by Lumentum Holdings Inc of Milpitas, CA, USA, which makes photonics products for optical networking and lasers for industrial and consumer markets.

“Lumentum’s telecom transmission product strategy is now

focused on indium phosphide (InP) photonic integrated circuit (PIC)-based components and modules, and we planned to ramp down lithium niobate operations in San Donato,” notes Beck Mason, Lumentum’s senior VP & general manager, Telecom Transmission.

“AFR is excited to expand its market opportunities and capabilities to include lithium niobate-based products for the communications and sensing markets,” says AFR’s chairman & CEO X.L. Wang. “With our strengths in cost-effective high-volume manufacturing, we are well positioned to address customer needs for lithium niobate products

in our addressable markets,” he believes. Incorporated in 2000, AFR has more than 1000 staff and manufactures products (including high-power and polarization maintaining components) in its 360,000ft² facilities in Zhuhai and Shenzhen.

Subject to certain customary closing conditions, the transaction is expected to close early in Lumentum’s fiscal third-quarter 2020. The product lines in the proposed transaction are part of the discontinued Telecom and Datacom product lines that Lumentum previously discussed on its fiscal first-quarter 2020 earnings call on 31 October.

www.lumentum.com

First Solar's sales fall 6.5% in Q3 to \$547m due to lower systems revenue from US project sales

Full-year guidance raised for gross margin and operating income as expectations are cut for production start-up expenses

For third-quarter 2019, First Solar Inc of Tempe, AZ, USA — which makes thin-film photovoltaic modules based on cadmium telluride (CdTe) as well as providing engineering, procurement & construction (EPC) services — has reported net sales of \$547m, down 6.5% on \$585m last quarter and 19% on \$676m a year ago, due primarily to lower systems revenue from project sales in the USA, offset partially by higher module sales volume.

Net income per share was \$0.29, down from \$0.54 per share a year ago but an improvement on a loss per share of \$0.18 last quarter.

During the quarter, cash, restricted cash and marketable

securities fell from \$2.1bn to \$1.6bn (including net cash falling from \$1.7bn to \$1.2bn), due mainly to higher expenditure for the development and construction of project assets and continued capital investment in Series 6 manufacturing capacity.

"We're pleased with the ongoing progress of our Series 6 technology platform," comments CEO Mark Widmar. "Capacity utilization, throughput and yield continue to improve, resulting in record Series 6 production of approximately 1GW in the quarter."

With year-to-date net bookings rising during Q3/2019 by 1.1GW_{DC} to 5.4GW_{DC}, First Solar has main-

tained its full-year 2019 guidance for shipments of 5.4–5.6GW, revenue of \$3.5–3.7bn, earnings per share of \$2.25–2.75, net cash balance of \$1.7–1.9bn and capital expenditure of \$650–750m. However, it has increased its guidance for gross margin from 18.5–19.5% to 19–20% (despite expected ramp costs rising from \$60–70m to \$70–80m) and for operating income from \$290–340m to \$320–370m, as expected operating expenses are reduced from \$360–380m to \$350–370m (including production start-up expenses falling from \$55–65m to \$40–50m).

www.firstsolar.com

DESRI acquires Cove Mountain photovoltaic projects in Utah, doubling its First Solar-developed portfolio to over 360MW

First Solar says that D. E. Shaw Renewable Investments (DESRI) is the acquirer of the Cove Mountain and Cove Mountain 2 projects in Iron County, Utah. The acquisition of the two projects, the sales of which were previously disclosed by First Solar and which total 180MW_{AC} in capacity, nearly doubles DESRI's portfolio of First Solar-developed projects to over 360MW_{AC}.

Both under construction with completion expected in the second and fourth quarters of 2020, Cove Mountain and Cove Mountain 2 have long-term power purchase agreements (PPAs) with PacifiCorp on behalf of Facebook, providing Facebook's data-center operations with new solar resources. DESRI has previously acquired four First Solar projects in California: the 100MW_{AC} Willow Springs Solar Project in Kern County; the 40MW_{AC} Cuyama Solar Project in Santa Barbara County; the 31MW_{AC} Portal Ridge Solar Project

in Los Angeles County; and the 11MW_{AC} Rancho Seco Solar Project in Sacramento County.

"Cove Mountain 1 and 2 are powered by one of the most financeable and reliable photovoltaic technologies available today, and are underpinned by long-term PPAs to support the renewable energy and carbon reduction goals of one of the best-recognized names in technology," comments DESRI's CEO Bryan Martin. "While these projects further solidify the longstanding partnership between our companies, they also demonstrate the value that First Solar is able to deliver by developing and operating world-class solar assets."

Once commissioned, both projects will be operated by First Solar Energy Services which, with over 10GW under management, is reckoned to be the most experienced operations & maintenance (O&M) service provider for large-scale solar power plants.

Both projects will be powered by First Solar's Series 6 modules. Produced in just 3.5 hours using fully integrated manufacturing processes, each large-format Series 6 module leverages First Solar's proprietary thin-film technology, retaining the performance and reliability of earlier-generation modules. The carbon footprint that is reckoned to be up to six times lower than crystalline silicon PV panels that are manufactured using conventional, energy-intensive production methods.

First Solar is expanding its manufacturing capacity to meet demand for Series 6 modules, with its second facility in the USA — representing nearly \$1bn in cumulative investment — expected to start production in early 2020. Once operational, the new facility in Perrysburg, Ohio, will take the firm's total Series 6 manufacturing capacity to 5.4GW per year, making First Solar the USA's largest solar manufacturer.

Solar Frontier and Triumph sign MoU for feasibility study on developing CIS-based building-integrated PV for China

Tokyo-based Solar Frontier — the largest manufacturer of CIS (copper indium selenium) thin-film photovoltaic (PV) solar modules — has signed a memorandum of understanding (MoU) with China National Building Material Group subsidiary Triumph Science and Technology Group (a multi-func-

tional platform for the management, industrialization, financing, investment and acquisition of high-end technology) for a joint feasibility study.

Together with Solar Frontier's parent company Idemitsu Kosan, Triumph Science and Technology Group and Solar Frontier will look

into developing building-integrated photovoltaics (BIPV) using CIS thin-film technology, with the aim of expanding photovoltaic power generation in China.

Developments from the feasibility study will be announced depending on the results of the joint initiative.

www.solar-frontier.com

Midsummer Solar Roof installed power boosted by 6% per unit area; extra staff recruited to meet demand

Midsummer AB of Järfälla, Sweden — a provider of turnkey production lines as well as flexible, lightweight copper indium gallium diselenide (CIGS) thin-film solar panels for building-integrated photovoltaics (BIPV) — says that, by increasing the radius of its rounded solar cells from 90mm to 100mm, power has been boosted by 6% per unit area, offering installed power of 100W/m² integrated on the Midsummer Solar Roof.

Where traditional solar panels with their fragile and heavy silicon-based solar cells with glass and aluminum frames stand out from the roofs, Midsummer's cadmium-free thin-film solar panels are only 2mm thick, very flexible and durable. These are integrated with the firm's own folded metal roofs, which can be connected to chimneys, skylights, covers and valleys, and are also fit to walk on. The metal roofs are

custom-made to optimally match the solar module and maximize the total installed power, yielding a neat, discreet and efficient solar cell roof that is also maintenance-free, says Midsummer.

Demand is such that existing production is sold out until March 2020. To meet the demand for Midsummer Solar Roofs, additional staff are now being recruited.

www.midsummer.se

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22	2483	25.4mm	Undoped
500	444	50.8mm	P
267	446	50.8mm	N

Indium phosphide template for laser and silicon-on-insulator integration

Researchers combine wafer bonding and direct epitaxy on silicon approaches to reduce threading dislocation density by two orders of magnitude.

Hewlett Packard Labs (HP) and University of California Santa Barbara (UCSB) in the USA have reported on their work on integrating 1.3 μm -wavelength III-V laser diodes on a silicon (Si) platform [Yingtao Hu et al, *Light: Science & Applications*, vol8, p93, 2019]. The HP/UCSB method (Figure 1) combines the two usual approaches to integration of the III-V devices on silicon — direct wafer bonding and direct epitaxy on silicon — by transferring an indium phosphide (InP) layer to a silicon-on-insulator (SOI) substrate, forming a growth surface for subsequent metal-organic chemical vapor deposition (MOCVD).

Direct epitaxy suffers from performance and lifetime degradation due to defect generation from lattice and thermal expansion mismatching between III-V compound semiconductors and silicon. Threading dislocations typically reach densities of the order $10^8/\text{cm}^2$. The attractions of direct epitaxy over wafer bonding include the less expensive substrate cost and economies of scale from the use of large-diameter wafers.

The aim is the integration of electronics with a complete photonics platform on silicon, from light generation, transmission through waveguides and fibers, and detection. Apart from light generation, transmission and detection can be efficiently accomplished using silicon-based systems. "Silicon photonics is becoming a mainstream data-transmission solution for next-generation data centers, high-performance computers, and many emerging applications," the researchers comment.

Adding efficient III-V light generation should enable a wide range of new and old electronic, photonic and micro-electro-mechanical system (MEMS) applications, by supplying light sources, amplifiers, modulators and detectors on a single chip with close proximity and low coupling loss.

The researchers foresee the ability to integrate lasers, amplifiers, modulators and photodetectors onto the bonding plus epitaxy integration platform, using multiple selective regrowth steps. The team also suggests that the source InP growth substrate could be used multiple

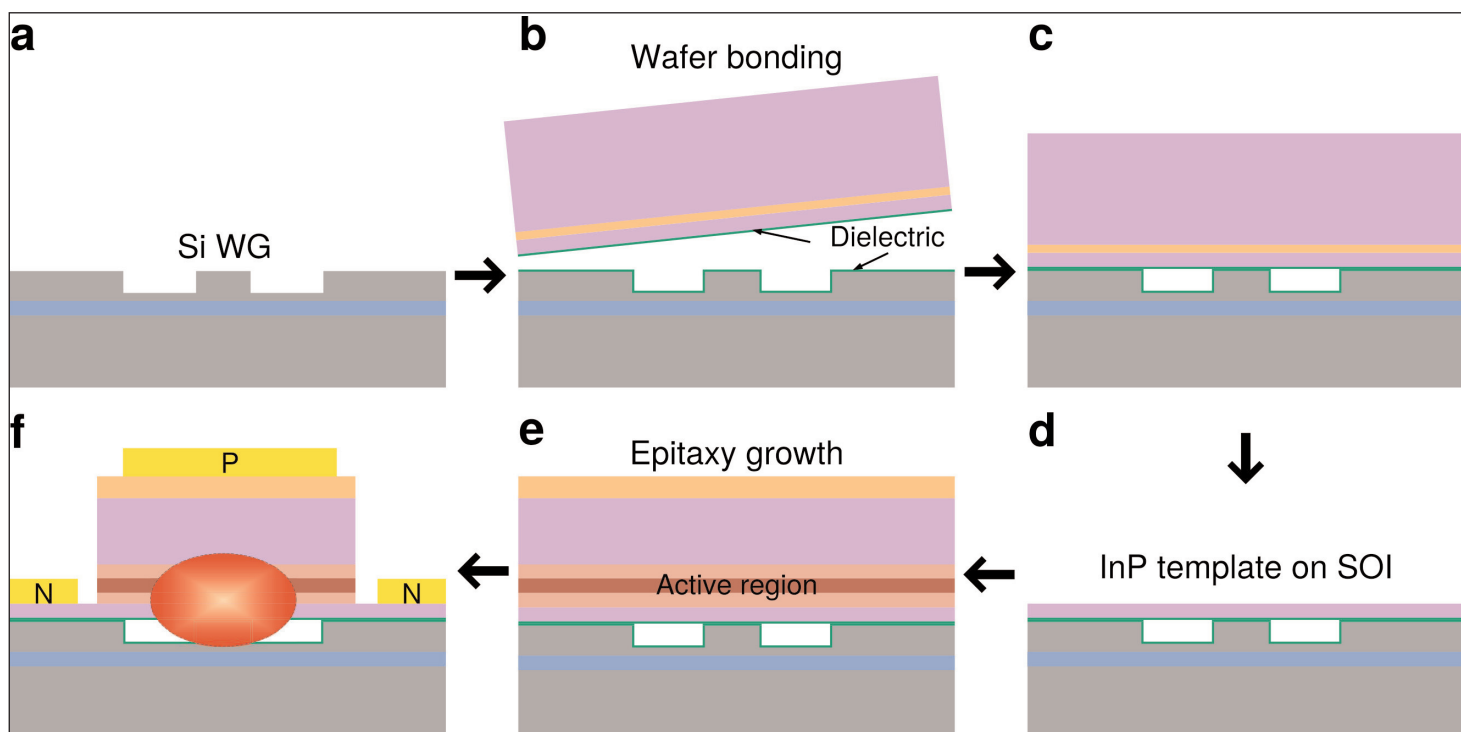


Figure 1. Schematic of III-V/Si integration.

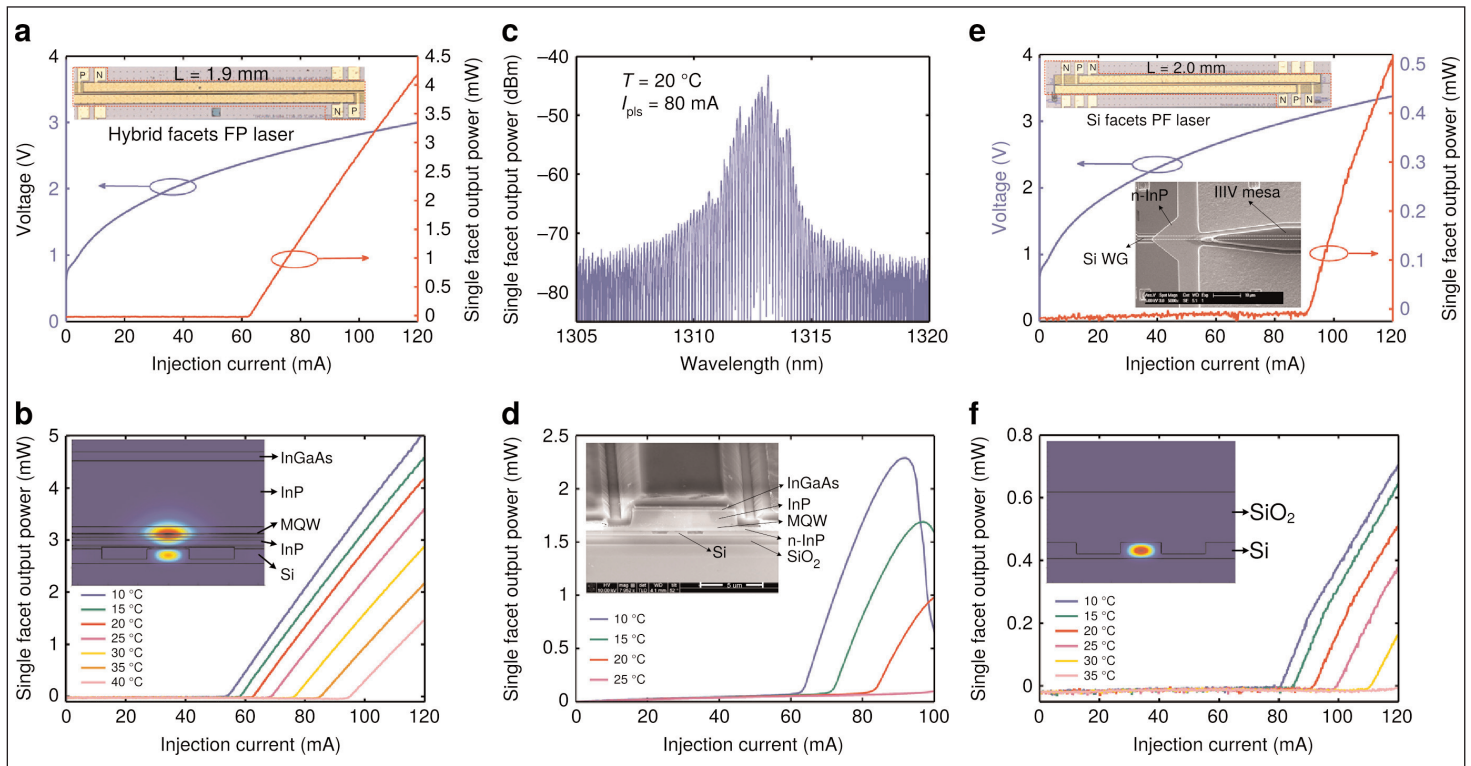


Figure 2. (a) Room-temperature pulsed voltage and light output power against current (inset: microscope image). (b) Pulsed light output versus current up to 40°C (inset simulated mode profile at facets). (c) Device spectrum. (d) Continuous-wave light output power versus current up to 20°C (inset: scanning electron micrograph (SEM) of hybrid facet). (e) Room-temperature pulsed performance with silicon waveguide at laser facet (inset: microscope image of device and SEM of taper). (f) Pulsed light output versus current up to 35°C (inset: simulated mode profile at facets).

times to transfer template layers to a number of SOI platforms, reducing material costs.

The 4-inch SOI substrate with 350nm Si top layer and 1µm buried oxide was prepared with waveguides and out-gassing structures etched into the silicon layer (Figure 1). The 150nm-thick n-InP template layer was applied from a 2-inch wafer that included the growth substrate and 200nm InGaAs etch-stop layer.

The template was wafer bonded to the silicon with an intermediate 7nm atomic layer deposition (ALD) silicon dioxide dielectric layer on both sides of the bond. The researchers used a cleaved quarter patterned SOI wafer. The InP template wafer was also quartered. The bonding was strengthened by a 300°C annealing step. The InP growth substrate and InGaAs etch stop were then removed. Presumably, in future multiple-use contexts, the growth substrate would be removed by some non-destructive process such as laser lift-off or ion-implantation (e.g. Soitec's smartcut process) rather than the destructive mechanical polishing/grinding and wet etching, as here.

The InP template layer was found to be strained due to thermal expansion mismatch between it and the underlying silicon. The strain was found to be ~1250-parts-per-million compressive in x-ray analysis.

MOCVD at 600°C on the n-InP template resulted in a ~2µm vertical p-i-n epitaxial structure for standard

laser diode fabrication. The target wavelength for emission from the 102nm six-period indium gallium arsenide phosphide (InGaAsP) multiple quantum well (MQW) active region was 1.31µm. The MQW was grown on a 50nm separate-confinement heterostructure (SCH) layer on the 150nm n-InP template. Following on from the MQW were 150nm SCH, 1.5µm p-InP cladding, and 200nm p-InGaAs contact.

The bonded structure avoided the usual lattice and charge-polarity mismatches between silicon and III-V materials. This meant that thick buffer layer transitions from silicon to the III-V layer was not required. In addition, the laser structure was much closer to the underlying silicon waveguide systems, so that coupling into the silicon photonics waveguide platform should become much easier.

The researchers quantified the threading dislocation (TD) density at $9.4 \times 10^4/\text{cm}^2$, using electron-channeling contrast imaging on $100 \times 14.5 \mu\text{m} \times 14.5 \mu\text{m}$ fields, resulting in the detection of 20 TDs. The team points out that this is only one order of magnitude higher than for material grown on native InP substrates, and two orders of magnitude lower than for "state-of-the-art conventional monolithic growth [on Si] with a thick buffer layer". Further analysis found some small areas of higher TD density, which the researchers blame on bonding voids or included dirt particles. ▶

Photoluminescence (PL) produced using a 780nm pump laser showed 2.53x the intensity of a sample grown on native InP. The researchers attribute the increase to strong reflection of the pump light from the underlying silicon and buried-oxide layers, creating a cavity effect. In both cases, the upper contact and cladding layers were removed.

The position of the PL peak for the sample on silicon was also shifted to a shorter wavelength of 1288.0nm, compared with 1305.5nm on native InP. The full-width at half maximum (FWHM) was also narrower in the bonded sample — 41.1meV, compared with 61.9meV on native InP.

The team explains: “The residual thermal strain in the MQWs of the bonded substrate sample likely caused the differences in the PL profile and wavelength. In addition, a slight difference in the growth temperature on the top surface of the bonded substrate and on the InP substrate due to the difference in their thermal conductivity could cause composition changes, thus leading to PL shifts. Nevertheless, the epitaxy quality on the bonded substrate is comparable with that on

the InP substrate.”

Fabry-Perot ridge-laser bars on silicon with a 1.9mm-long cavity (Figure 2) had a threshold current of 61.8mA (813A/cm²). The 4µm-wide p-channel was defined using proton implantation, followed by etching of an 8µm-wide mesa. The device surfaces also were passivated with 800nm of silicon dioxide.

At 120mA injection, the output power from a single facet was 4.2mW. The slope efficiency was 0.14W/A. These measurements were made at 20°C room temperature with 0.5µs current pulses at 0.25% duty cycle. Continuous-wave operation increased the threshold to around 80mA due to self-heating effects. The peak wavelength was at 1313nm.

The researchers report some processing problems such as a 10x higher zinc doping concentration in the p-InP cladding than intended. This caused light absorption that reduced efficiency. The p-contact metal process was also less than ideal and, along with a ‘problematic’ wet etch, increased electrical resistance. ■

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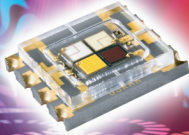


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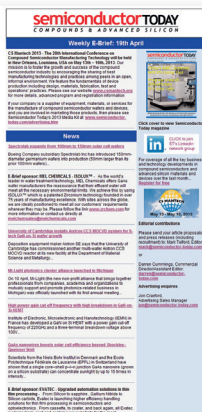


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Aluminium gallium nitride enables deep ultraviolet laser diodes

Mike Cooke reports on recent achievements of electrically- and optically-pumped devices, along with some developments in material processing.

Aluminium gallium nitride (AlGaN) is the key semiconductor alloy material in the present development of deep ultraviolet (UV) laser diodes (LDs) in the sub-300nm wavelength range. The first reports of working devices opens the way to new applications.

AlGaN alloys are wide-bandgap materials with potential for deep-UV light emission and for electronics that can sustain high electric fields and voltages before breakdown. The bandgap ranges from $\sim 3.4\text{eV}$ (GaN) up to around $\sim 6.2\text{eV}$ (AlN). These energy gaps correspond to photons with wavelengths from 365nm to 200nm, respectively.

The very short 100–280nm wavelengths of deep ultraviolet UV-C are able to disrupt biochemicals such as DNA, with the potential for disinfection, sterilization and water purification of bacterial and viral pathogens. UV-C emitting devices could also have a wide range of other, sometimes overlapping, applications: biochemical sensing/detection, small-particle detection, communications, optical storage, spectral analysis, medical treatment, and surface monitoring.

Here we look at the reports of UV-C laser diodes and optically pumped systems, along with some developments in AlGaN processing that could enable further UV-C laser diode progress.

Deep-UV laser diode

Researchers from Japan and the USA claim the shortest wavelength so far reported for current-injection laser diodes [Ziyi Zhang et al, Appl. Phys. Express, vol12, p124003, 2019]. The emission wavelength of 271.8nm places it in the UV-C range. Previous UV laser diode reports have been restricted to the 315–400nm UV-A field.

Asahi Kasei Corp and Nagoya University in Japan and Crystal IS in the USA collaborated on the device, which used low-dislocation-density AlN substrates to grow layers of AlGaN. Most reported short-wavelength laser diodes use silicon carbide, sapphire or free-

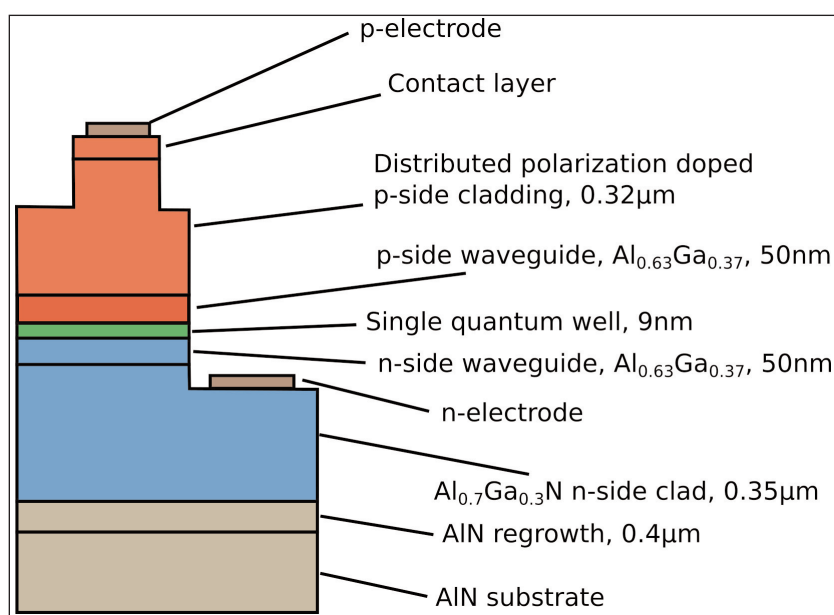


Figure 1. Schematic of fabricated UV-C laser diode structure.

standing gallium nitride.

The team used an unintentionally doped distributed polarization-induced doping cladding layer on the p-side, aiming for low internal loss, high hole conductivity and high hole injection. The usual magnesium doping of AlGaN has very poor performance in terms of generating mobile holes. Further, the use of ionized impurities creates scattering centers for light and charged carriers, which adversely impact performance.

The researchers grew the laser diode structure (Figure 1) on 2inch-diameter (0001) AlN substrates using metal-organic chemical vapor deposition (MOCVD). The dislocation density in the single-crystal substrate from Crystal IS was in the range 10^3 – $10^4/\text{cm}^2$. The 9nm light-emitting single quantum well (QW) was designed to emit 270nm-wavelength UV-C light.

The 0.32µm distributed polarization doped (DPD) p-side cladding consisted of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ graded from 100% to 70% Al content. The grading effects a charge polarization gradient that generates and conducts mobile holes. The p-contact region consisted of magnesium-doped AlGaN further graded down to

pure GaN. The n-side of the device was doped with silicon using an impurity concentration of more than $1 \times 10^{19}/\text{cm}^3$ in both contact and cladding layers. The epitaxial layers were strained pseudomorphically with the underlying AlN substrate.

Laser diode devices were fabricated with $4\mu\text{m}$ -wide ridge waveguides. The ridge etch exposed the n-contact layer on which vanadium-based metal was deposited. Silicon dioxide passivation was applied before the n-contact metal. The p-contact and other wiring and probe pads consisted of nickel/gold metal.

The fabricated laser diodes were cleaved along the $\langle 11\bar{2}0 \rangle$ direction into $400\mu\text{m}$ -long cavities. The resulting $(1\bar{1}00)$ -plane facets were coated with five dielectric layer pairs consisting of hafnium dioxide and silicon dioxide. The reflectivity of the coatings were more than 90%, according to the researchers. The high reflectivity was a key factor in reducing threshold current.

The laser diodes were tested under pulsed operation with 50ns width and 0.01% duty cycle. The light output power increased non-linearly at around 0.4A injection, $25\text{kA}/\text{cm}^2$ density relative to the p-electrode area. Above this threshold a sharp spectral peak emerged around 271.8nm wavelength. The threshold occurred with a forward voltage of 13.8V.

The optical polarization of the emission was transverse electric (TE): while the transverse magnetic (TM) component had a constant 11nm full-width at half maximum (FWHM) between 0.2A and 0.5A, the TE values were 6.6nm and 0.41nm, respectively (Figure 2).

The researchers attributed the 'remarkably low' threshold voltage of 13.8V to the DPD structure giving a flat valence-band profile on the p-side, allowing injection of the holes without a barrier. They also speculate that the high-Al-content material on the p-side of the waveguide layer created an electron-blocking barrier in the conduction band.

The team comments: "The pseudomorphic growth of the whole structure, including the DPD on the single-crystal AlN substrate, maximized the polarization-induced charge to achieve high hole conductivity, considering that relaxation of the graded structure can also hinder polarization doping."

One problem was found in the MOCVD growth process: convex, hexagonal pyramid-shaped hillocks on the surface with a density of $6 \times 10^3/\text{cm}^2$. The hillocks seemed to contribute an additional emission peak around 278nm wavelength. In devices that included one of these hillocks, lasing was not achieved.

Based on transmission electron microscope analysis, the researchers believe that the hillocks originate from pre-existing threading dislocations in the AlN substrate. Threading dislocations offer non-radiative routes to carrier recombination and can adversely affect current flow patterns.

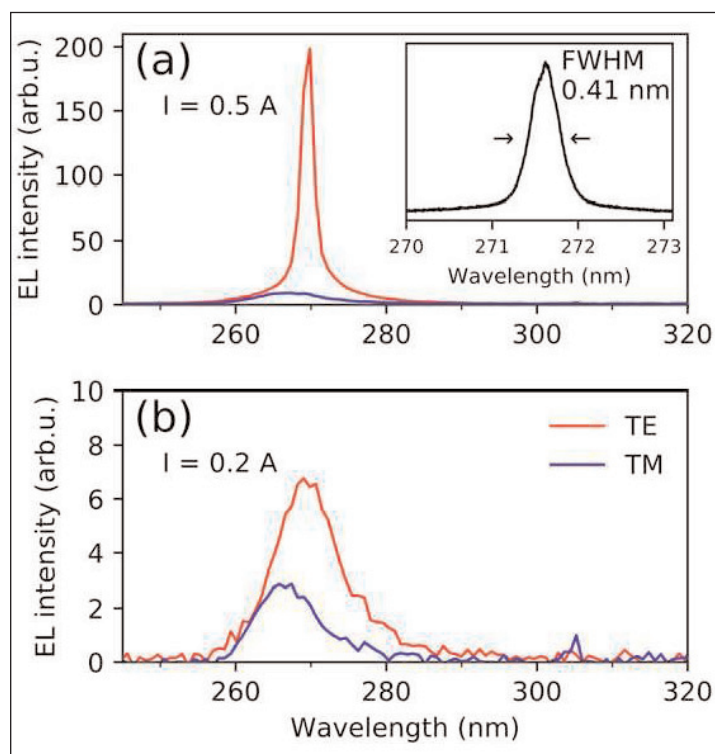


Figure 2. Edge-emission spectra with TE and TM polarization at (a) 0.5A and (b) 0.2A forward current. Inset in (a) shows spectrum of TE mode at 0.5A with highest wavelength resolution.

For lasing, the hillocks also affect the optical structure, scattering light out of the waveguide mode. "A high-quality AlN substrate with low dislocation density appears to be fundamental to the development of a UV-C LD," the team concludes.

Optically pumped lasing

Researchers in China shortly before presented a deep-UV (DUV) 249nm optically pumped III-nitride laser structure based on gallium nitride rather than the more usual wider-bandgap AlGaIn QWs [Maocheng Shan et al, ACS Photonics, vol6, p2387, 2019]. The very short wavelength of 249nm was enabled by the extreme confinement of very thin GaN wells in thin AlN barriers. The corresponding photon energy was 5.0eV, a couple of eV higher than the $\sim 3.4\text{eV}$ bandgap of bulk GaN.

The team from Huazhong University of Science and Technology in China, Saudi Arabia's King Abdullah University of Science and Technology (KAUST) and Ningbo Institute of Materials Technology and Engineering in China reports that previously only spontaneous emission has been achieved in GaN/AlN multiple quantum well (MQW) systems.

Among the problems for AlGaIn DUV lasers are strong quantum-confined Stark effects (QCSEs) arising from electric fields, based in ionic charge polarization, that pull electrons away from holes, inhibiting recombination into photons. Also, high-Al-content AlGaIn tends to emit radiation optically polarized in a TM mode, which

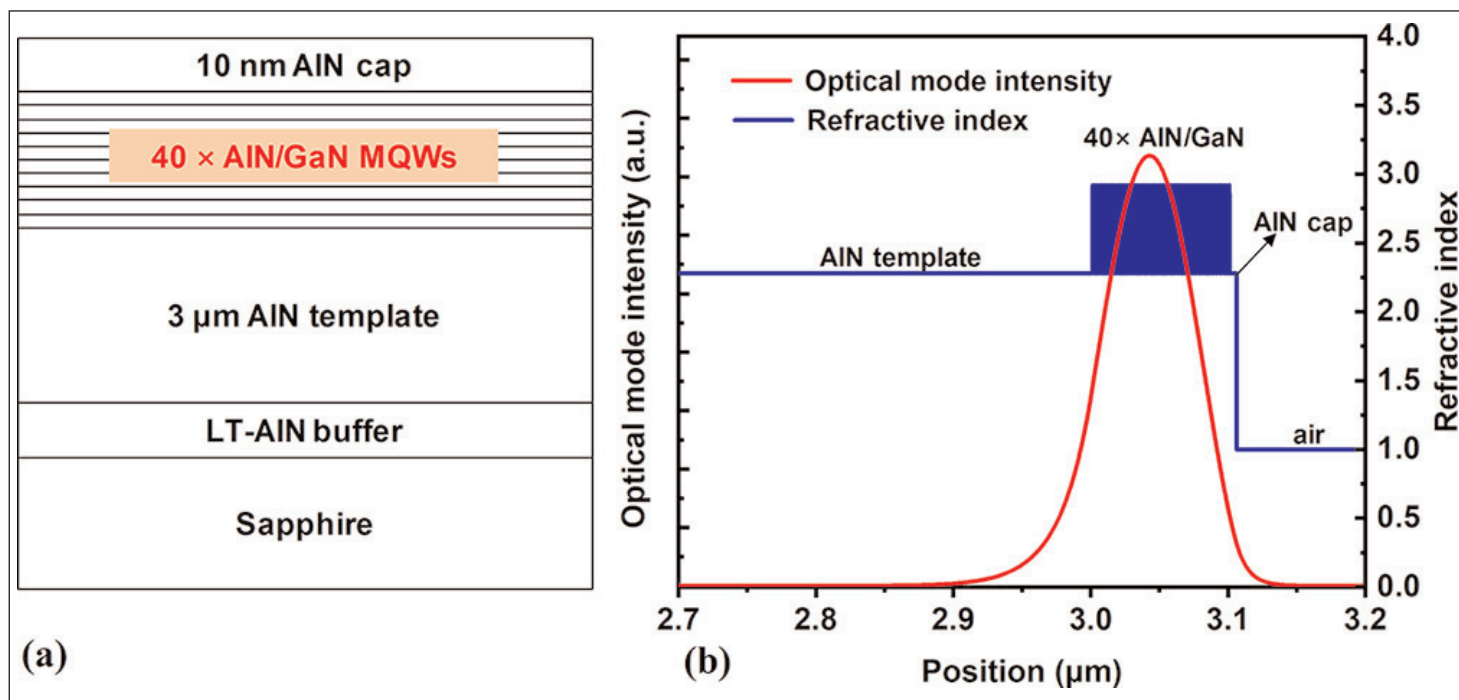


Figure 3. (a) Schematic diagram of AlN/GaN MQW DUV laser grown on sapphire substrate; (b) simulated optical mode profile and refractive index distribution.

is more difficult to use efficiently in light-emitting diode and edge-emitting laser structures.

MOCVD on two-inch c-plane sapphire resulted in an AlN/GaN MQW laser structure (Figure 3). The 750°C low-temperature (LT) AlN buffer was 15nm thick. The 3μm AlN template layer was grown at 1230°C. X-ray rocking curve analysis suggested that the AlN template was of higher crystalline quality than previously used for AlGaIn DUV laser structures.

A somewhat lower growth temperature of 1040°C was chosen for the MQW to ensure high-quality wells, avoiding evaporation of the more volatile GaN material. The GaN wells were designed to be 4 monolayers (MLs) thick, while the AlN barriers were 6MLs. In metric measurements, according to x-ray analysis, the wells and barriers were 1.0nm and 1.5nm thick, respectively.

The similarity of the QW and barrier (QB) thicknesses was expected to lead to a higher refractive index, compared with the usual situation with significantly thicker barriers. The researchers explain the use of 40 wells as being “due to comprehensive considerations of the lateral optical confinement, penetration depth of the excitation laser beam, gain medium volume, strain relaxation, and material and interface quality.”

The final 10nm AlN cap was to provide surface passivation. The team says that ideally the top AlN layer would be thicker to provide a more symmetric waveguide effect coupled with the underlying AlN template. The reason for the thinness was to enable pumping from a 193nm argon fluoride (ArF) excimer laser with minimal absorption losses.

Optical simulations of the structure suggested a 35.4% confinement factor. The researchers explain:

“The large factor was partially attributed to the use of high-index GaN QWs and large MQW pair number of 40. Also, it is partially caused by the comparable thicknesses between the GaN QWs and the AlN QBs, resulting in a larger average index.”

The material was prepared into 1mm-long cavity laser bars by thinning the sapphire substrate, and laser scribing and cleaving. No optical coating was applied to the facet.

The laser pump was pulsed at 50Hz with 5ns duration. The emission peak was at 249nm with little shift between spontaneous and lasing operation (Figure 4). The researchers attribute this to a minimal QCSE, resulting from the thinness of the GaN QWs.

The team puts the lasing threshold at 190kW/cm² pumping power density. The researchers report that this is comparable to AlGaIn-based DUV laser structures on sapphire or AlN substrates. “Such a threshold can be mostly attributed to the high material and interface quality, large quantum and optical confinement, and smooth cleaved facet,” they write.

As the system passed through the laser threshold, the linewidth reduced from 8nm to 0.2nm FWHM. Above and below threshold the degree of optical polarization was 0.92 and 0.48, respectively. The polarization here was the ratio of the TE intensity excess over the TM to the total intensity (that is, $(I_{TE}-I_{TM})/(I_{TE}+I_{TM})$).

The researchers explain the favoring of TE polarization: “The TE dominance is caused by the topmost position of the heavy hole (HH) band of GaN and thereby the optical transition between the conduction band and the HH band.”

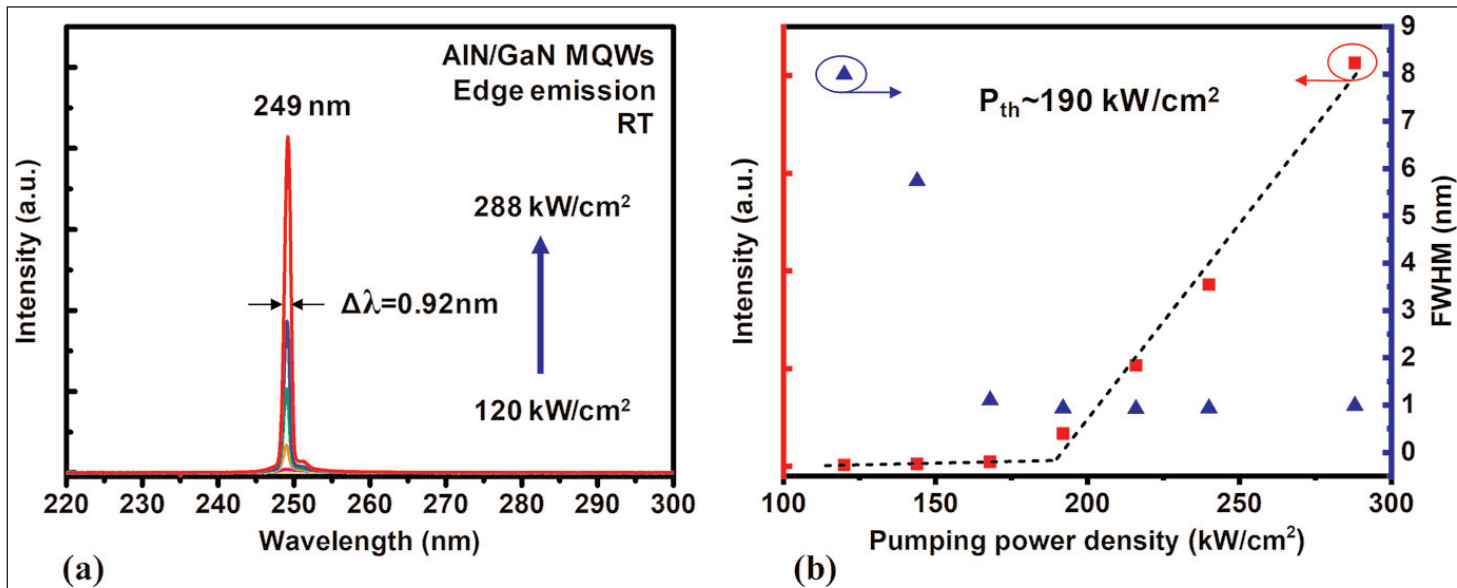


Figure 4. (a) Laser emission spectra and (b) peak intensity and line width of spectra as function of pumping power density.

The even greater favoring of TE emission above laser threshold is attributed to a large TE-to-TM gain ratio in stimulated operation.

Electrochemical membrane release

Moving on to AlGaN processing technology advances, researchers from Sweden and Germany have been developing electrochemical etching as a means to create thin-film AlGaN optoelectronic and power-electronic devices [Michael A. Bergmann et al, Appl. Phys. Lett., vol115, p182103, 2019].

The researchers from Chalmers University of Technology in Sweden, Technische Universität Berlin in Germany and KTH Royal Institute of Technology in Sweden comment: "Heterogeneously integrated AlGaN epitaxial layers will be essential for future optical and electrical devices like thin-film flip-chip UV light-emitting diodes, UV vertical-cavity surface-emitting lasers, and high-electron-mobility transistors on efficient heat sinks."

Releasing the AlGaN layers from the epitaxial growth substrate would enable vertical cavities with dielectric applied to both sides of a membrane. However, present methods for releasing AlGaN such as laser lift-off tend to damage the material, reducing performance in the final device.

The researchers first grew a $2 \times 10^{18} / \text{cm}^3$ silicon-doped $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ layer on c-plane sapphire with an AlN template layer using a close-coupled showerhead MOCVD reactor (Figure 5). The n-type conductivity from the silicon doping ensured current spreading for uniform electrochemical etching.

The current-spreading layer was followed by a 225nm $0.5 \times 10^{18} / \text{cm}^3$ lightly silicon-doped $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ etch-stop layer. The sacrificial layer for membrane release was 130nm $2 \times 10^{19} / \text{cm}^3$ heavily Si-doped $\text{Al}_x\text{Ga}_{1-x}\text{N}$. The membrane layer was 580nm (1900nm for $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ sacrificial layer sample) unintentionally doped $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$.

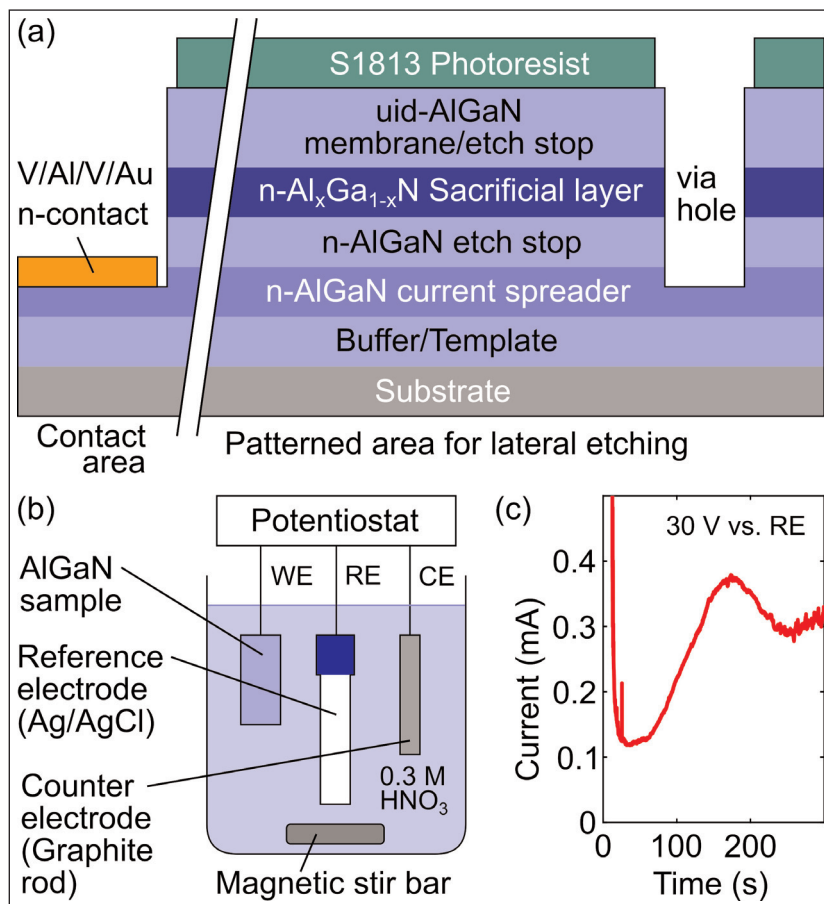


Figure 5. (a) AlGaN sample structure, (b) three-electrode setup for electrochemical etching, and (c) etching current versus time for etching $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ sacrificial layer at 30V.

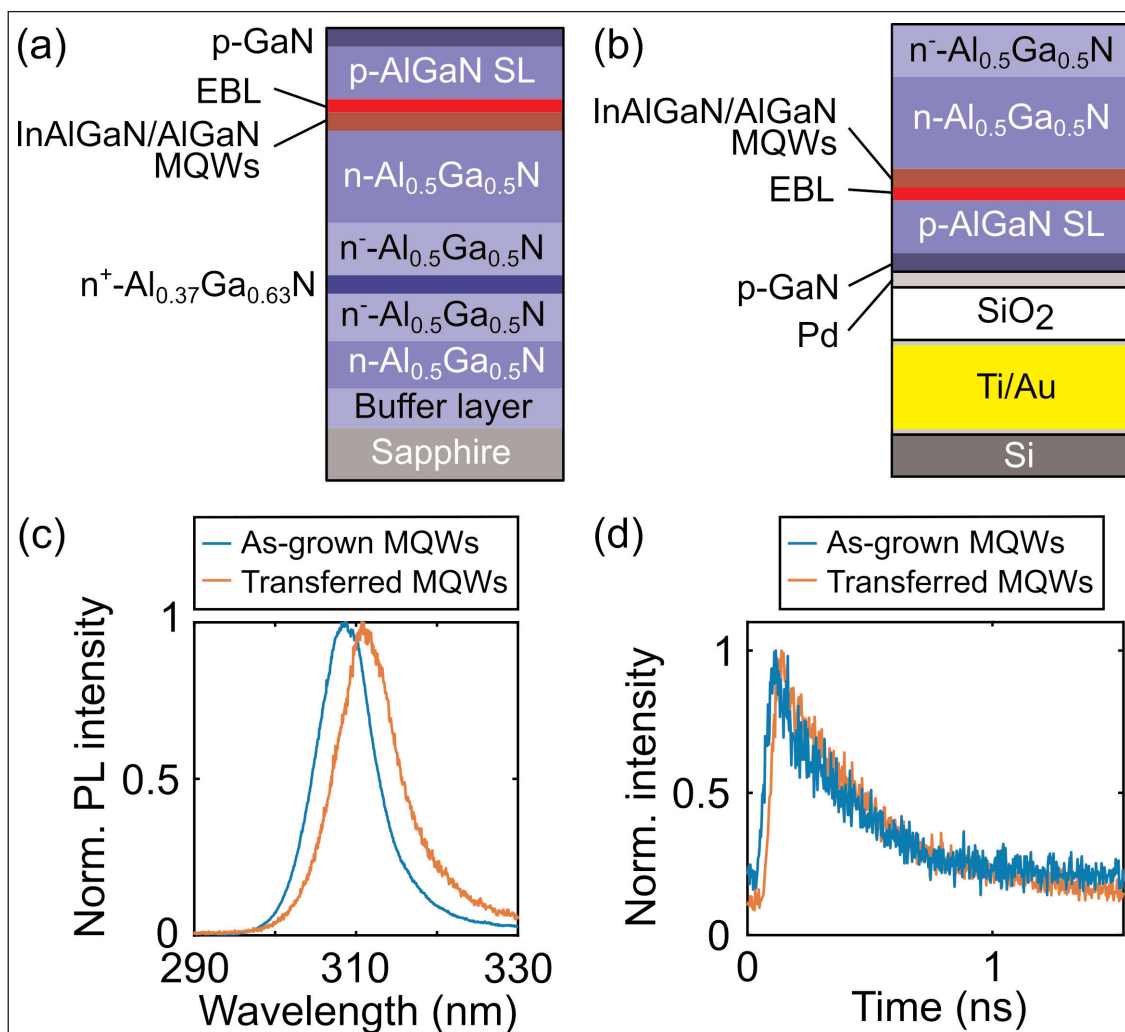


Figure 6. (a) As-grown MQW sample structure, (b) transferred structure, (c) PL spectrum of as-grown MQW probed from Ga-polar side and transferred structure probed from etched N-polar side, and (d) time-resolved PL of structures.

X-ray analysis showed that the $\text{Al}_{0.5}\text{Ga}_{0.5}\text{:Si}$ was 'pseudomorphic' — i.e. strained — on all sacrificial layer compositions.

The electrochemical etching was enabled by dry reactive-ion etching $10\mu\text{m}$ -diameter via holes in a 7×9 $400\mu\text{m}$ -pitch array to expose the sacrificial layer. The etched holes reached down to the current-spreading layer. The electrochemical contact with the current-spreading layer was made through an electron-beam-evaporated and annealed vanadium/aluminium/vanadium/gold metal stack. The top-side of the membrane was protected from etching damage with a $1.3\mu\text{m}$ photoresist layer.

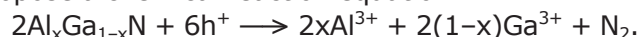
The electrochemical etch used three electrodes in 0.3M nitric acid electrolyte, which was constantly stirred with a magnetic bar. The AlGaN 'working electrode' was kept at a constant positive potential relative to the silver/silver chloride (Ag/AgCl) 'reference electrode'. Control of the process was through a graphite rod 'counter electrode', which allowed the current flow to vary in the low-milliamp range. The samples were $5\text{mm}\times 10\text{mm}$.

The electrochemical etch was found to proceed isotropically around the etch holes, creating an air gap between the substrate and membrane. Eventually the etch fronts merged. With an $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ sacrificial layer, an etch potential of 30V resulted in smooth surfaces on the upper and lower etch-stop layers. At the lower potential of 25V some residues were left on the etch-stop layers. Even lower potentials of 20V and 15V resulted in increasingly porous sacrificial layers.

The researchers attribute the etching to the generation of holes at the AlGaN/electrolyte interface from Zener tunneling or avalanche breakdown in a depletion region.

"These holes oxidize AlGaN at the interface, and the oxidized material can be dissolved by

the electrolyte," the team explains. The researchers propose a chemical reaction equation:



Atomic force microscopy on the etched surface of a membrane transferred to a silicon carrier had 3.5nm root-mean-square (RMS) roughness on a $1\mu\text{m}\times 1\mu\text{m}$ area. The sacrificial layer used for the electrochemical etch was $\text{Al}_{0.27}\text{Ga}_{0.73}\text{N}$.

A MQW structure was grown on a 130nm $\text{Al}_{0.37}\text{Ga}_{0.63}\text{N}$ sacrificial layer to show that the electrochemical etch could be used without affecting device performance (Figure 6). The $2\times 10^{18}/\text{cm}^3$ silicon-doped $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ 4mm -thick underlayer was relaxed. The sacrificial layer aluminium content was chosen to be transparent for photoluminescence (PL) analysis but low enough to contrast with surrounding layers.

The MQWs were indium aluminium gallium nitride with 21% Al content. The three wells were 2nm thick, separated by 5nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ barriers. The magnesium-doped p-type layers were an $\text{Al}_{0.75}\text{Ga}_{0.25}\text{N}$ electron-blocking layer, an AlGaN superlattice (SL), and a 20nm p-GaN cap layer.

The material was prepared for electrochemical etching by dry reactive-ion etching circular mesas. Palladium was deposited on the p-GaN cap. The mesas were partially covered with 1 μm sputtered silicon dioxide (SiO_2) to prevent parasitic etching during the electrochemical process. Finally, a titanium/gold bond pad was deposited on the palladium.

The electrochemical etch potential was 25V. The released structures were transferred to silicon carriers with titanium/gold bonding layer using a 300 $^\circ\text{C}$ thermos-compression process.

The PL analysis showed a small red-shift after transfer. The researchers report "This shift of 2nm could be caused by small local variations in the Al composition and thickness over the sample, residual strain in the epitaxy, and process induced strain."

Time-resolved measurements before and after transfer showed the same PL decay rate of 340ps. The team concludes: "This confirms that the electrochemical etching and transfer process do not influence the quality of the QWs and, hence, are an appropriate process for fabrication of devices based on free-standing membranes."

Metal-organic growth on silicon carbide

University of California Santa Barbara (UCSB) in the USA has improved MOCVD AlN growth on silicon carbide (SiC) with a view to AlGaIn DUV light-emitting diode and optoelectronics fabrication [Christian J. Zollner et al, Appl. Phys. Lett., vol115, p161101, 2019].

The work was aimed at providing crack-free AlN templates for AlGaIn growth with low threading dislocation density without using costly and time-consuming approaches such as pulsed lateral overgrowth or growing very thick (>10 μm) buffer layers.

The researchers comment: "Combining overall improvements in AlN MOCVD techniques, improved SiC wafer quality, and growth-mode control concepts demonstrated in MBE, we find that MOCVD growth of AlN/SiC is a viable route to high-quality UV-LED template layers."

The team also points out that there are highly selective dry etch techniques for efficient SiC substrate removal, raising the prospect of high-efficiency DUV-LED fabrication. Such removal would be necessary since SiC is highly absorbing of these high-energy DUV photons. In fact, SiC becomes absorbing around 380nm.

Although AlN can be grown on much lower-cost sapphire, which is transparent to DUV, the advantage of SiC is that it is a much better match in terms of crystal structure. The researchers also point out that "there is no risk of inadvertent nitrogen-polar growth on the substrate's Si-face." At present, deep-UV LEDs exhibit low wall-plug efficiency due to a number of factors, one of which is the presence of threading dislocations.

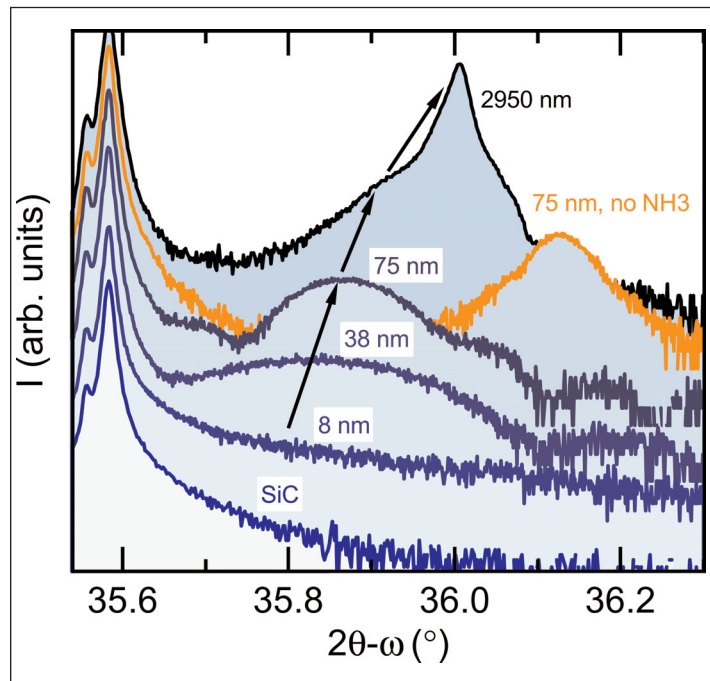


Figure 7. Symmetric triple-axis $2\theta-\theta$ x-ray diffraction scans of AlN/SiC films, with SiC double-peak (blue) for reference. Growth sequence with (black) and without (orange) ammonia pretreatment compared up to 75nm, along with full 2.95 μm AlN thickness template (black). Logarithmic intensity scale.

A 250nm AlN initiation layer was grown at 1200 $^\circ\text{C}$, followed by 2.7 μm AlN at 1400 $^\circ\text{C}$. The growth rates were 1.5 $\text{\AA}/\text{s}$ and 6 $\text{\AA}/\text{s}$, respectively. The two-step process targeted reduced numbers of threading dislocations and a smoother surface.

The 4H SiC substrates came from two suppliers. The 'sample A' substrate was mechanically polished with polishing marks obscuring the atomic steps typically produced during the crystal growth process. In 'Sample B', which had a smoother surface from chemical-mechanical planarization (CMP), these steps were visible in terraced surface structures. Samples A and B were 250 μm and 500 μm thick, respectively.

AlN films grown on sample B were found to have reduced tensile stress and less cracking. "The marked reduction in tension when switching to smooth substrates suggests that small island size is a primary driver of stress generation on rough substrates," the team comments.

A 10 minute ammonia pretreatment of sample B at 1400 $^\circ\text{C}$ for 10 minutes changed the slight tensile stress to strong compression with a value of -1.1GPa. The surface was also crack-free up to a 5 μm scale. X-ray rocking curves also showed reduced FWHM diffraction peaks, suggesting higher film quality (Figure 7).

One effect of the pre-treatment was to increase the spacing of the atomic steps from 165nm to 330nm.

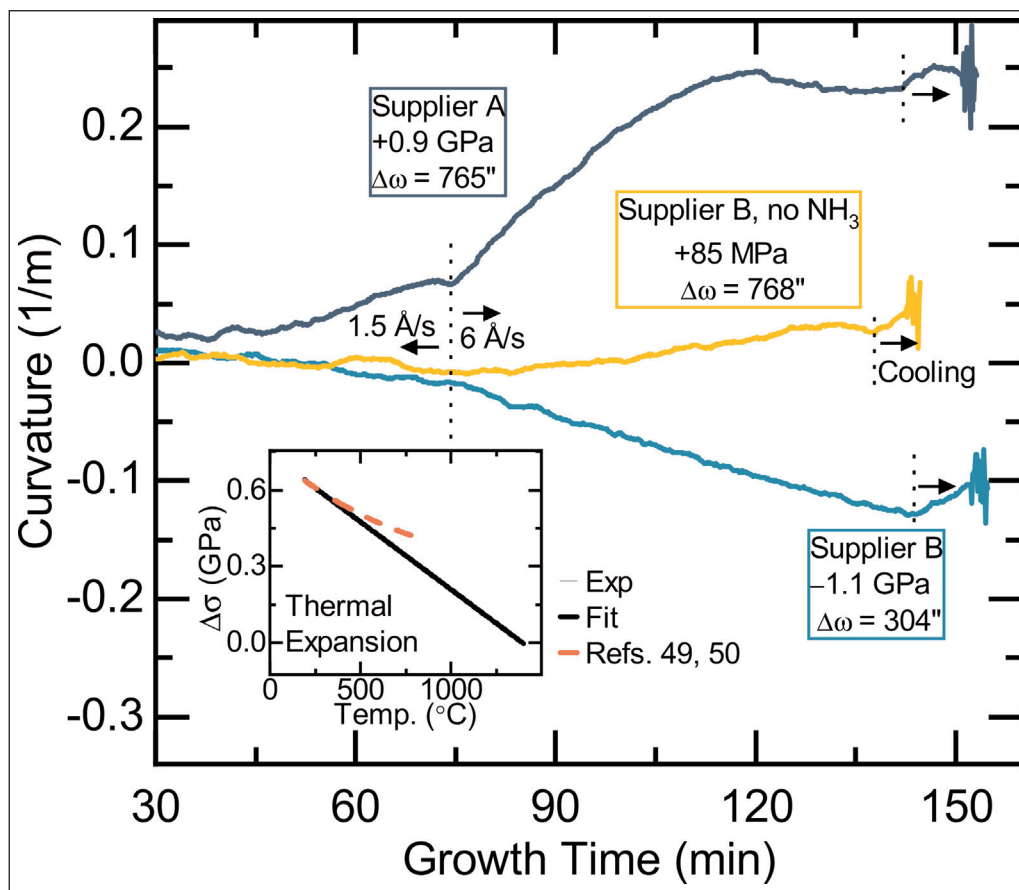


Figure 8. In situ curvature of AlN template on three substrate types: rough SiC with ammonia pre-treatment (top, tensile), smooth substrate (middle, weakly tensile), and smooth substrate with ammonia treatment (bottom, highly compressive). Growth stress and 2θ FWHM, $\Delta\omega$, listed. Inset: thermal expansion mismatch stress: data (gray) compared with literature models (red, dashed) and linear least squares fit (black, solid).

coefficient mismatch in sample B of $1.13 \times 10^{-6}/^{\circ}\text{C}$, which resulted in a slight increase in lattice mismatch of 0.15% at 1375°C . A thick AlN layer is fully relaxed at its growth temperature, but on cooling to room temperature develops tensile stress of $\sim 700\text{MPa}$ that can lead to cracking.

The shorter step distance in the initial surface has been found to increase threading dislocation density and to create lattice stacking mismatch problems.

Laser monitoring of the substrate curvature during growth (Figure 8) suggested a thermal expansion

Plan-view transmission electron microscopy gave a threading dislocation density value of $2.4 \times 10^8/\text{cm}^2$. ■

The author Mike Cooke has worked as a semiconductor and advanced technology journalist since 1997.

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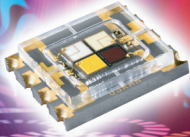


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InGaN surface-emitting superluminescent LEDs

Researchers claim record high light output power of 2.2W in pulsed operations.

Ireland's Tyndall National Institute claims a record high 2.2W for output power from indium gallium nitride (InGaN) superluminescent light-emitting diodes (SLEDs) [R. Cahill et al, Appl. Phys. Lett., vol115, p171102, 2019]. The researchers used slanted facets to direct the amplified spontaneous emission (ASE) through the GaN substrate with very low feedback, avoiding laser action. The team also claims that their device is the first surface-emitting structure, since previous reports used edge-emitting geometries.

The team comments: "The surface emitting structure provides potential for integration of further functionality onto the back side of the device, increasing its potential for fiber-based systems and displays." Other potential uses include high-resolution optical coherence tomography, compact image projectors and smart solid-state lighting.

SLEDs combine the operating principles of LEDs and laser diodes. Lasers generally use Fabry-Perot reflecting structures to feedback light and boost stimulated emission. SLEDs use stimulated emission in a one-pass structure to amplify spontaneously generated photons. The light from SLEDs benefits from features such as high power output and high directionality. A number of strategies are used to suppress feedback, such as absorbing facets or bent cavities.

Cap	p ⁺ -GaN
Cladding	500nm p-AlGaN
Cladding	100nm p-GaN
Electron blocking	Mg-doped Al _{0.2} Ga _{0.8} N
Quantum wells	2xInGaN in GaN barriers
Cladding	1μm n-AlGaN
Substrate	n-GaN

Figure 1. Epitaxial structure.

The Tyndall InGaN material heterostructure was grown on n-GaN substrates using metal-organic vapor phase epitaxy (Figure 1). The fabricated device (Figure 2) consisted of a 3μm-wide waveguide with 1mm gain length. The etched end facets of the waveguide were angled at 45° to form turning mirrors, directing the emitted radiation through the substrate. The back-side of the GaN substrate was polished to minimize scattering of the radiation. A further measure to reduce feedback and increase light extraction was to apply a silicon dioxide anti-reflective layer to the substrate surface.

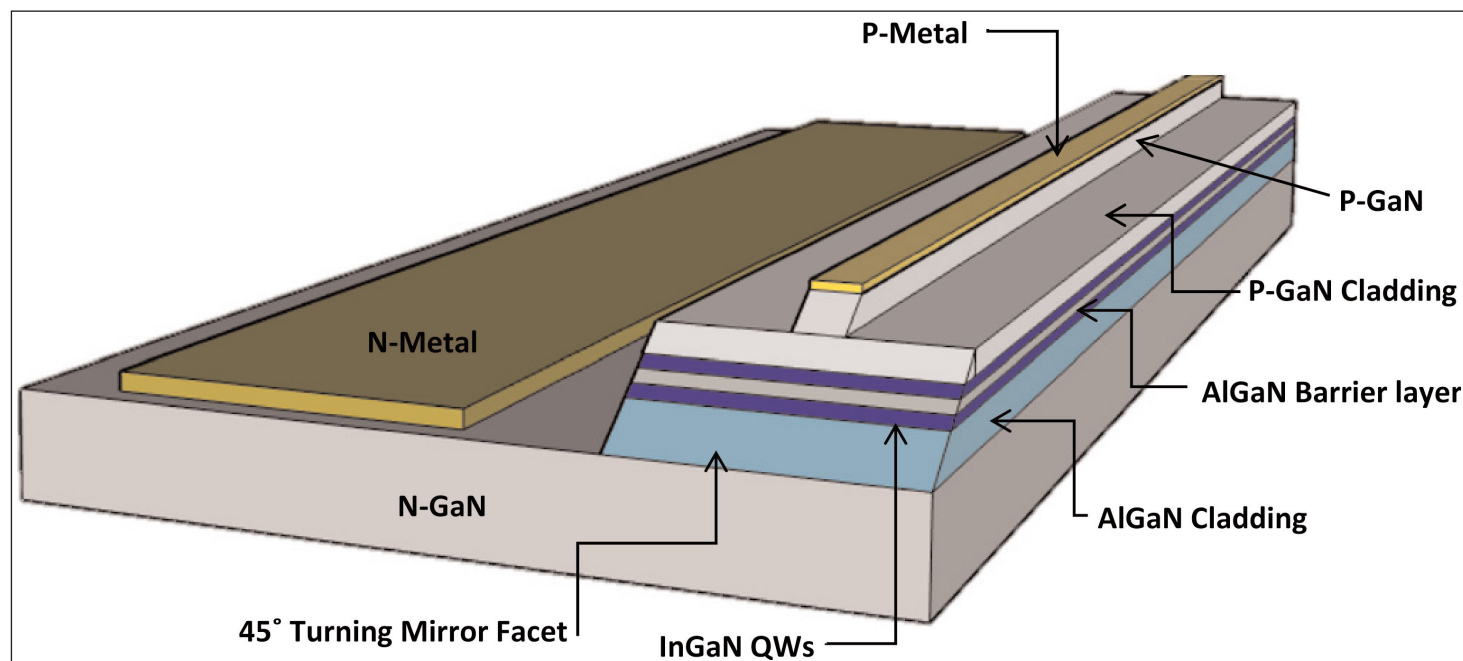


Figure 2. Schematic of blue surface-emitting LED.

The device was operated with 220ns pulses and 1% duty cycle (Figure 3). The maximum output power of 2.2W was achieved at 1.5A injection (50kA/cm² density). The forward voltage was between 6V and 7V. The external quantum efficiency at the maximum power was 49%. The peak wavelength occurred at 416nm. The researchers comment: "The devices were not observed to degrade under these conditions, testament to the quality of the low-defect-density substrate."

Theoretical analysis using a standard gain model suggested that higher powers could be achieved in future. "The peak optical powers provided by this device are far higher than has been previously reported," the team writes. The group attributes the high power to the technique for avoiding feedback: directing the radiation through the substrate, rather than using absorbing back facets, for example.

The onset of amplified spontaneous emission occurs for an injection current of about 300mA. At lower current the full-width at half maximum (FWHM) was around 26nm in wavelength. This decreased to the order of 6nm (corresponding to a 41meV energy spread) above 300mA. FWHM values for InGaN lasers tend to be less than 1nm.

The anti-reflective coating was found to suppress parasitic lasing. In devices without such coating, evi-

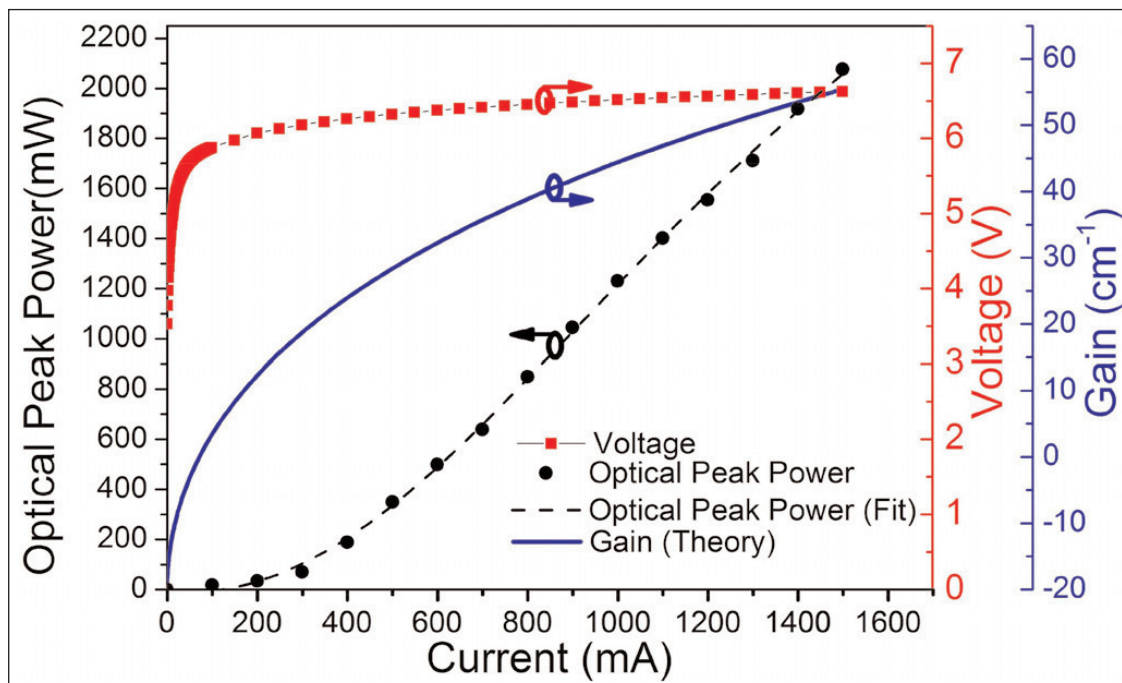


Figure 3. Light-current-voltage and gain characteristics of blue SLED under pulsed operation.

dence of laser action occurred above 700mA injection.

Analysis of spontaneous emission from the top side of the device suggested active-region heating of the order of 110K between 300mA and 1.5A injection. Also, the study suggested that the carrier temperature increased by about 100K between threshold and maximum power.

Increasing the pulse duration up to 1500ns reduced the output power (~20%) and increased the peak wavelength slightly, indicating the effects of junction heating on the device. The researchers hope that improved thermal management measurements could lead to longer pulse lengths or even continuous-wave operation at higher currents. ■

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Boost to magnesium doping of GaN on freestanding substrates

Researchers find higher free hole concentrations for a given doping level, compared with material grown on sapphire.

Japan's National Institute for Materials Science (NIMS) has found that magnesium doping of gallium nitride (GaN:Mg) is far more effective in material grown homoepitaxially on freestanding substrates as opposed to GaN/sapphire templates [Liwen Sang et al, *Appl. Phys. Lett.*, vol115, p172103, 2019].

The researchers point to the reduction of self-compensation as the basis for the enhanced doping performance. Self-compensation occurs where acceptor states are neutralized by the generation of parasitic deep-donor non-radiative recombination centers (NRCs). Also, the reduced numbers of threading dislocations in material grown on freestanding substrates is thought to reduce Mg diffusion effects that adversely affect doping performance.

Freestanding substrates can have threading dislocation densities as low as $10^4/\text{cm}^2$, some three orders of magnitude lower than for GaN/sapphire templates. Of course, freestanding substrates are significantly more expensive than the templates, but the development of potential application opportunities and substrate production technology should encourage economies of scale in future.

The enhanced GaN:Mg on freestanding substrates was found to have five to ten times the free hole density, implying higher conductivity. In addition, one would expect higher mobility if lower magnesium concentration can be used due to reduced impurity scattering.

Another potential use of p-GaN is as a current-blocking layer in vertical metal-oxide-semiconductor field-effect transistors (MOSFETs) and current-aperture vertical electron transistors

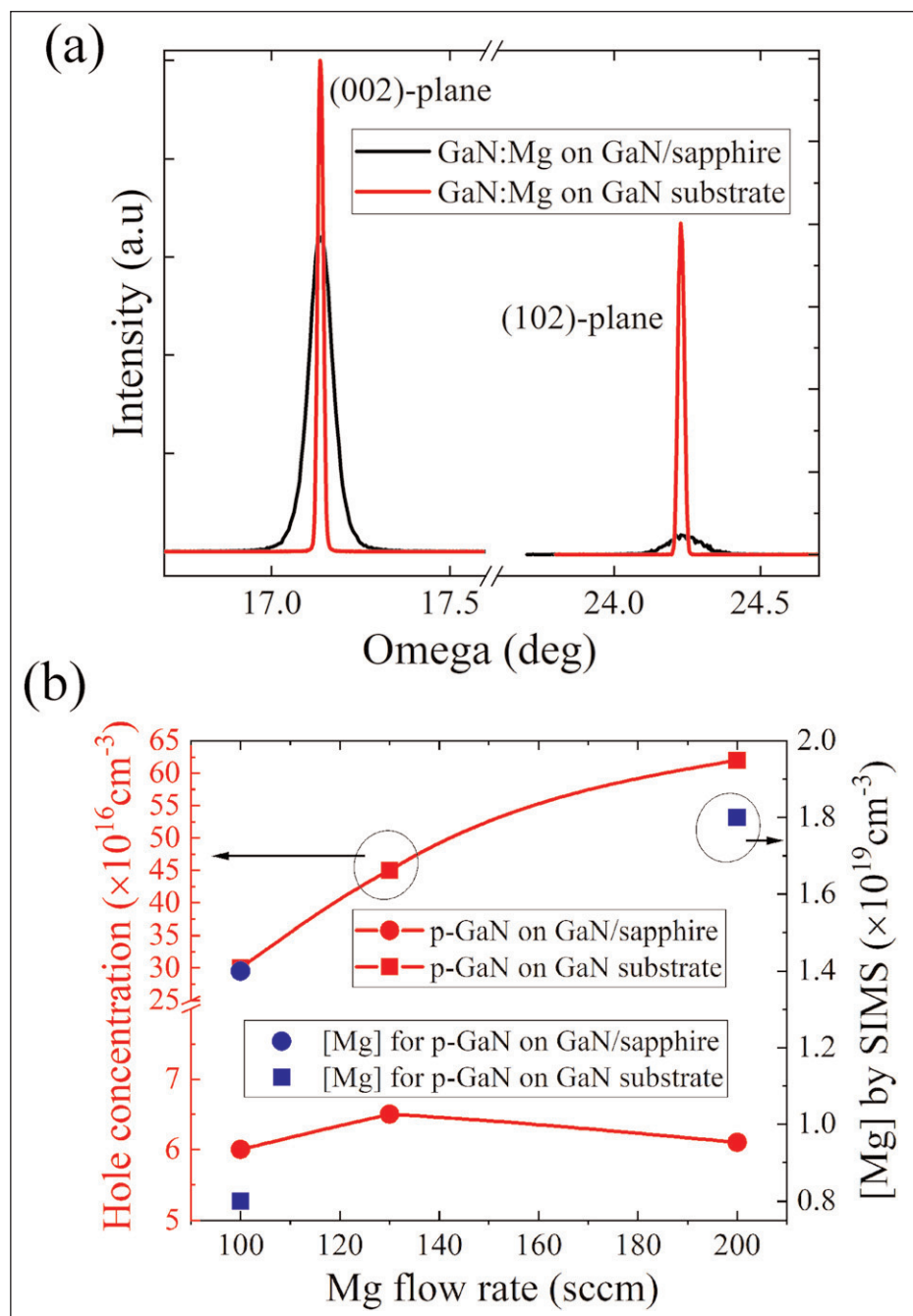


Figure 1. (a) XRD omega rocking curves of (002)- and (102)-plane reflection for homoepitaxial and heteroepitaxial GaN:Mg films. (b) Free hole concentration and [Mg] values for homoepitaxial and heteroepitaxial GaN:Mg films.

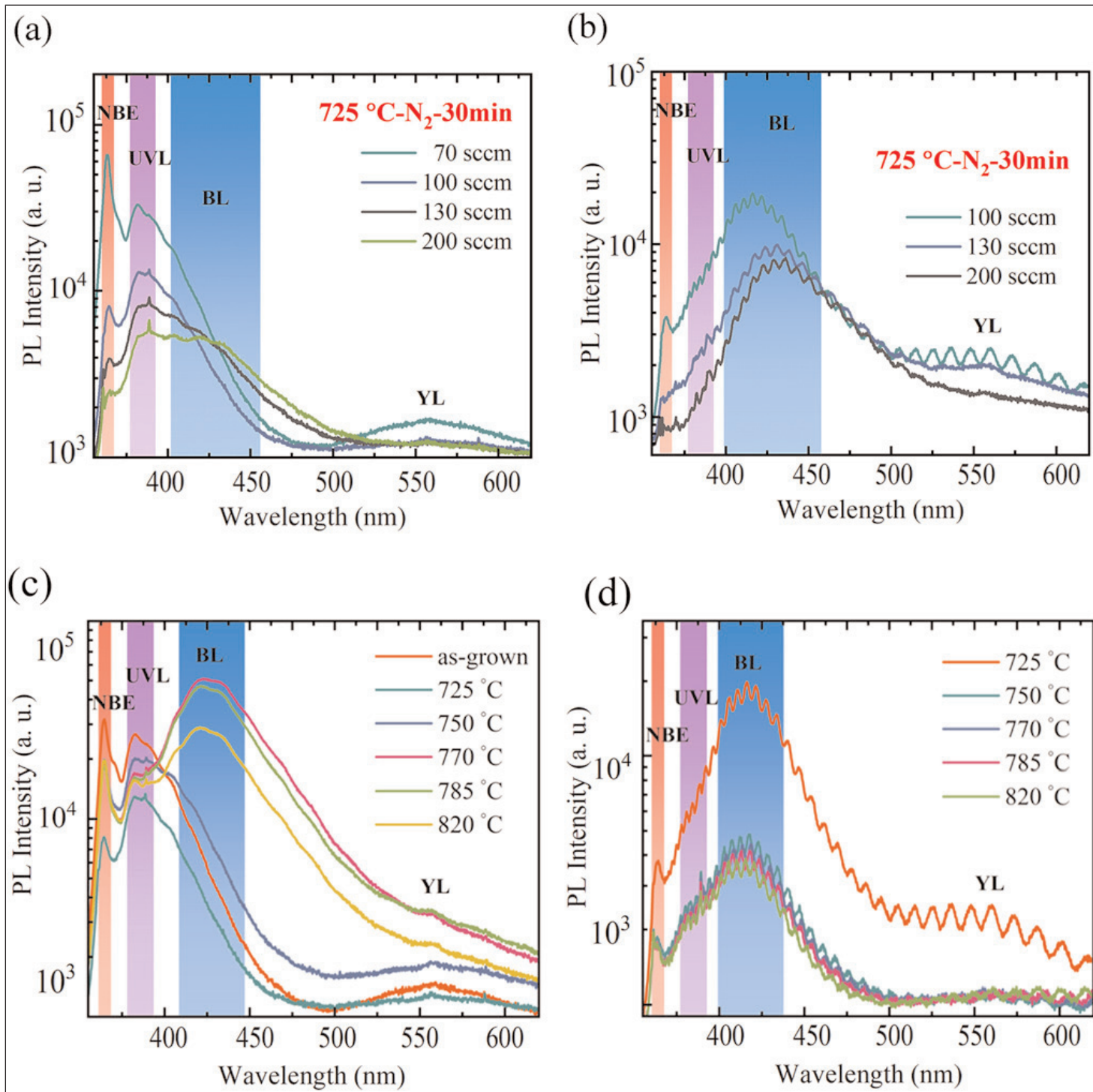


Figure 2. PL spectra of p-GaN films grown on (a) GaN substrates and (b) GaN/sapphire templates activated at 725°C in N_2 with different Mg doping concentrations. (c) and (d) PL spectra of homoepitaxial and heteroepitaxial GaN:Mg films activated at varying temperatures, respectively.

(CAVETs). The creation of p-GaN:Mg during epitaxial growth is preferred over ion implantation. The latter process suffers from excessive out-diffusion of the dopants during thermal anneal processes.

Metal-organic chemical vapor deposition (MOCVD) was used to grow $1\mu\text{m}$ Mg-doped GaN on c-plane n^+ -GaN freestanding substrates with $4 \times 10^6/\text{cm}^2$ threading dislocation density. The growth temperature was 1000°C and bis(methylcyclopentadienyl) magnesium was the precursor for the doping. The Mg-doped

layer was grown on an undoped $2\mu\text{m}$ GaN buffer with $5 \times 10^{15}/\text{cm}^3$ free electron density. The Mg doping was activated with 30-minute annealing at 725 – 820°C .

One effect of using GaN substrates was narrow peaks in x-ray diffraction (XRD) rocking curves (Figure 1): 68arcsec full-width at half maximum (FWHM) for the (002) plane and 95arcsec for (102). These values correspond to a threading dislocation density of $7 \times 10^6/\text{cm}^2$. The same growth process, but using GaN/sapphire templates, led to FWHM values of

280arcsec and 491arcsec for the (002) and (102) planes, respectively. The estimated threading dislocation density in this case was $6 \times 10^9/\text{cm}^2$, almost three orders of magnitude higher than for the GaN:Mg on freestanding substrate.

Hall measurements with lightly doped GaN on GaN/sapphire template with $1.4 \times 10^{19}/\text{cm}^3$ {Mg} concentration gave a $6 \times 10^{16}/\text{cm}^2$ free hole density. Homoepitaxy on freestanding GaN increased the free hole concentration five-fold to $3 \times 10^{17}/\text{cm}^3$ with a reduced {Mg} of $8 \times 10^{18}/\text{cm}^3$. The higher Mg incorporation on sapphire was attributed to a higher density of edge-type dislocations.

Heavier Mg-doping resulted in free hole concentrations of $6.0 \times 10^{17}/\text{cm}^3$ on freestanding substrate ($1.8 \times 10^{19}/\text{cm}^3$ Mg concentration). This was ten times the $6.1 \times 10^{16}/\text{cm}^3$ on sapphire for the same Mg flow. The team comments: "The marked enhancement of the doping efficiency is attributed to the suppression of the Mg-related self-compensation centers or non-radiative recombination centers benefitting from the greatly reduced dislocation density."

The researchers also found that the relation between photoluminescence (PL) spectral structure and p-type conductivity in GaN:Mg was different on freestanding GaN substrates, compared with heteroepitaxy on sapphire (Figure 2).

With heteroepitaxial GaN:Mg a blue-band luminescence (BL, $\sim 2.9\text{eV}$) is associated with onset of p-conductivity. This luminescence is generally attributed to deep donor-acceptor pair (DAP) recombination.

By contrast the NIMS researchers found that ultraviolet luminescence (UVL, $\sim 3.26\text{eV}$) was the signal for homoepitaxial GaN:Mg on freestanding GaN to be

p-type conducting. These emissions were attributed to free electron or shallow donor recombination with acceptor levels.

The PL spectra also include near-band-edge (NBE) emissions and yellow luminescence (YL). The YL emissions are attributed to electron transitions into deep acceptor levels associated with carbon atoms on nitrogen sites.

The homoepitaxial GaN:Mg had increased ultraviolet luminescence with increased activation anneal temperatures up to 750°C , but then BL emissions started appearing, indicating reduced effectiveness. The higher activation temperatures also resulted in increased surface roughness measured using atomic force microscopy: 0.81nm root mean square at 770°C , compared with 0.25nm at 725°C .

The NIMS team comments: "The rough morphology deteriorates the luminescence behaviors, which is related to the increased thermal emission of electrons from donor levels to the conduction band and their recapture by the non-radiative recombination centers on the rougher surface. The electrical current of Ohmic contacts is reduced when the activation temperature is higher than 750°C ."

X-ray photoelectron spectra (XPS) indicated that homoepitaxy also improved the uniformity of surface states, avoiding regions with excess Mg-Ga-O. Such excess Mg-Ga-O inhibits abrupt interfaces when growing aluminium oxide dielectric. Abrupt interfaces are desired for metal-oxide-semiconductor structures in vertical field-effect transistors with high mobility and stable positive threshold voltages. ■

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High-carrier-density two-dimensional hole gas in strained gallium nitride

Development of p-channel transistors could enable high-voltage circuits using more power-efficient complementary combination with n-channel devices.

Cornell University in the USA reports a high-conductivity two-dimensional hole gas (2DHG) in gallium nitride (GaN) that could enable high-voltage circuits using more power-efficient complementary combinations of n- and p-channel transistors [Reet Chaudhuri et al, Science, vol365, p1454, 2019].

Since the work described in the Science paper, Chaudhuri and fellow researcher Samuel James Bader have realized what is described in a press release as “some of the most efficient p-type GaN transistors in a collaborative project with Intel”.

Combining the p-type transistors with more conventional and developed n-type devices could lead to a range of opportunities in high-power switching, 5G cellular technology and energy-efficient electronics, including phone and laptop chargers, using more

complex circuitry.

Another co-senior author, Huili Grace Xing, comments: “It’s very difficult to simultaneously achieve n-type and p-type in a wide-bandgap semiconductor. Right now, silicon carbide is the only other one that has both besides GaN. But the mobile electrons in silicon carbide are more sluggish than those in GaN. Using these complementary operations enabled by both n-type and p-type devices, much more energy-efficient architecture can be built.”

“Silicon is very good at switching off and on and controlling electrical energy flow, but when you take it to high voltages it doesn’t operate very well because silicon has a weak electric strength, whereas GaN can sustain much higher electric fields,” adds co-senior author Debdeep Jena. “If you’re doing very large

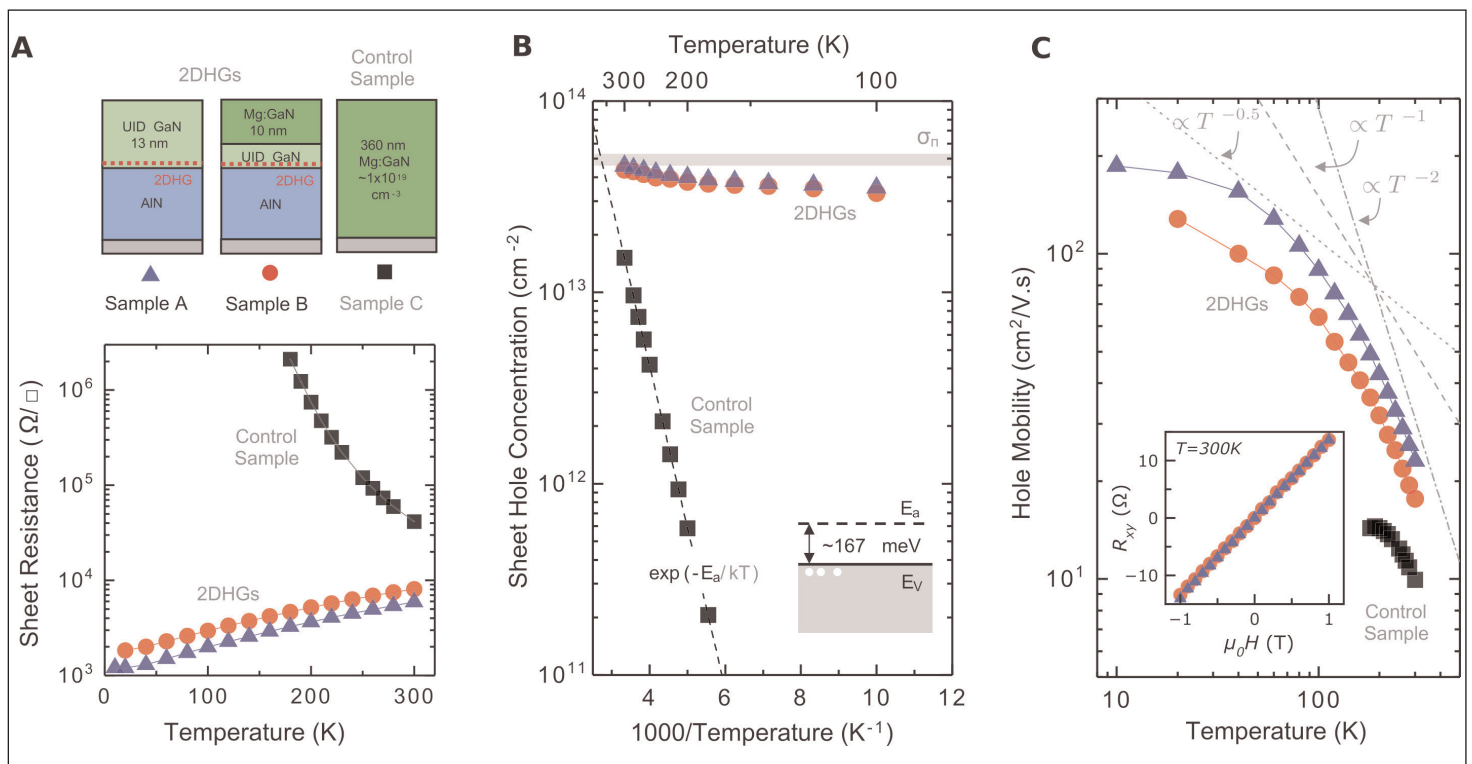


Figure 1. Magneto-transport measurements between 300K and 10K with applied field of 1 Tesla (1T): (A) sheet resistance with schematics of samples; (B) sheet hole concentration, with inset scheme of activation/acceptor level energy (E_a) above valence band edge (E_v); and (C) hole mobility, with inset Hall coefficient (R_{xy}) versus magnetic field (μ_{0H}) at room temperature.

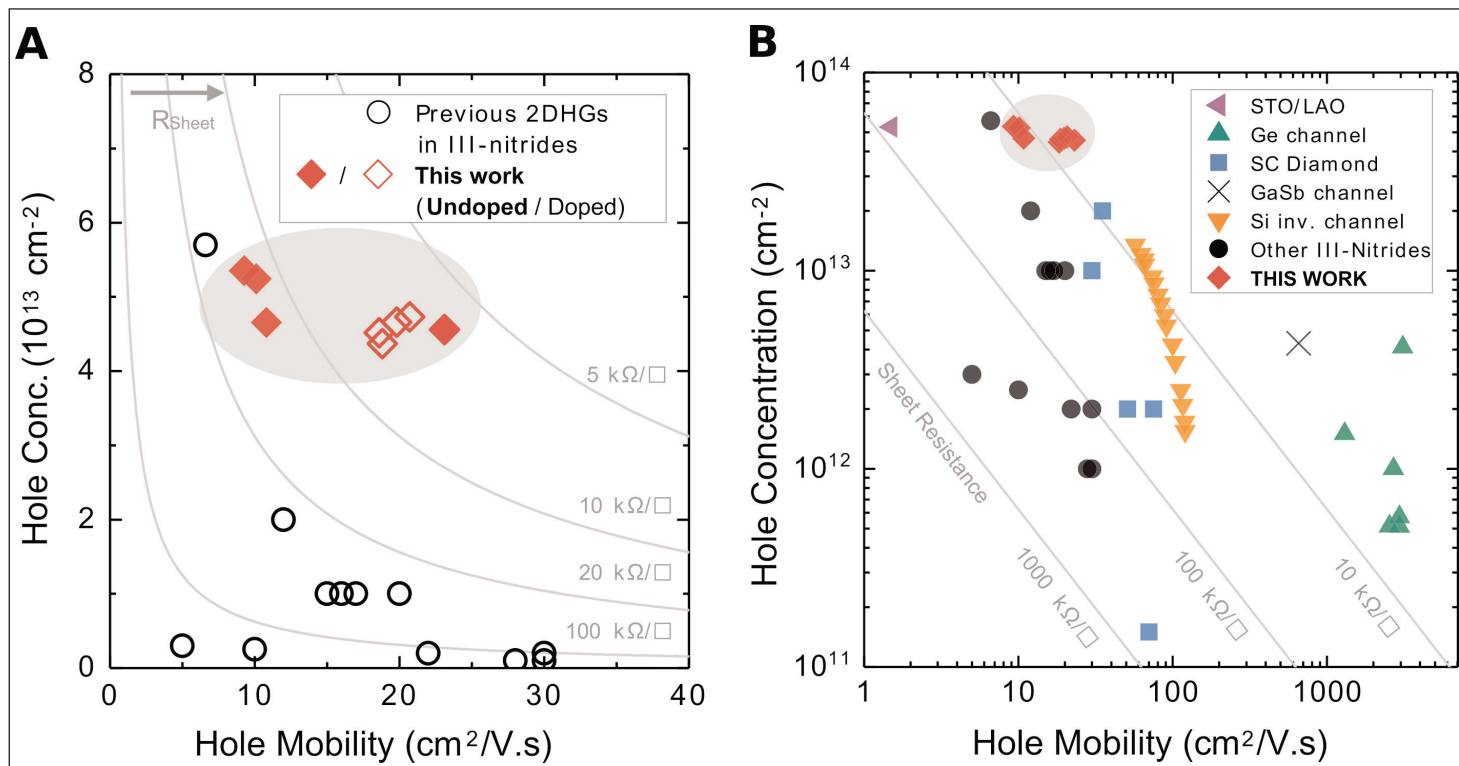


Figure 2. Comparisons with other reported 2DHGs: (A) in III-nitrides; (B) other semiconductor material systems — strontium titanium oxide/lanthanum aluminium oxide (STO/LAO), germanium (Ge), silicon inversion (Si inv.), gallium antimonide (GaSb), semiconducting (SC) diamond.

amounts of energy conversion, then wide-bandgap semiconductors such as GaN and silicon carbide are the solutions.”

Cornell’s 2DHG depends on similar principles to the more usual 2D electron gas (2DEG) when aluminium gallium nitride (AlGaN) is grown on GaN. Such 2DEGs are the basis for high-frequency, high-power and/or high-voltage n-channel transistors being developed for wireless network power amplifiers, power switching, and other applications.

The 2DEG results from the broken inversion symmetry of the III-nitride lattice structure with the bonds between the atoms being strongly ionic — i.e. the charge density tends around the Ga and Al metal ions to be positive, and around the N atoms negative. There are both spontaneous and strain-dependent (‘piezoelectric’) charge polarizations. Within homogeneous regions, the net charge is zero, but at interfaces between different material compositions an interface charge develops that is due to the difference in charge polarization on each side. The charge in the case of AlGaN/GaN induces a 2DEG nearby, mostly in the GaN buffer.

The Cornell strategy for its 2DHG was to grow a thin strained-layer of GaN pseudomorphically on a thick relaxed AlN buffer. This reverses the situation for the conventional 2DEG where the AlGaN is a thin layer on a relaxed GaN buffer.

The contrast of charge polarization at the strained GaN on AlN was expected to create a negative interface

charge of order $5 \times 10^{13}/\text{cm}^2$, inducing a compensating 2DHG nearby. The valence band offset between the materials should push the 2DHG to mainly reside in the strained GaN layer.

The experimental samples were produced using plasma-assisted molecular beam epitaxy (PAMBE) on sapphire. X-ray analysis suggested that the GaN layer was compressively strained 2.4%.

In addition to the main 13nm/400nm GaN/AlN sample A, the researchers also produced variations for comparison: sample B with magnesium-doped p-GaN replacing the top 10nm of the GaN layer, and sample C with a thick magnesium-doped GaN layer directly on the sapphire substrate. Sample B was designed “to lock the Fermi level to valence band edge separation, screening the 2DHG from variations of the surface potential”; sample C was intended as a control comparison with conventional acceptor doping.

The temperature dependence of the resistivity of the control sample C, with higher values at low temperature, suggested an activation energy of $\sim 170 \text{ meV}$ for the acceptor doping (Figure 1). The increased resistance was almost entirely related to the reduction in thermally excited holes, the researchers explain.

The team adds: “We observed a dramatically different behavior for the undoped heterostructure sample A and the Mg-doped heterostructure B. They showed metallic behavior, with the resistivity decreasing with decreasing temperature, which is a signature of a degenerate 2D hole gas.”

At a typical room temperature of 300K, the resistivity of sample A was $6.0\text{k}\Omega/\text{square}$, while B's value came in at $8.0\text{k}\Omega/\text{square}$. The corresponding low-temperature values were $1\text{k}\Omega/\text{square}$ (10K) and $2\text{k}\Omega/\text{square}$ (20K). The hole densities in the 2DHG were considered to be relatively temperature independent. The reductions in resistivity thus suggest increases in mobility at low temperature.

The areal hole concentration of the 10nm p-GaN layer in sample B was around $5 \times 10^{12}/\text{cm}^2$, an order of magnitude lower than the expected 2DHG density. Hall measurements gave mobility values of $25\text{cm}^2/\text{V-s}$ and $20\text{cm}^2/\text{V-s}$ at room temperature for samples A and B, respectively. At very low temperature, the mobility increased to $190\text{cm}^2/\text{V-s}$ for sample A at 10K, and $120\text{cm}^2/\text{V-s}$ for sample B at 20K.

The researchers comment: "The variation of the measured 2D hole gas mobility with temperature is expected to be strongly influenced by acoustic phonon scattering, in addition to the polar optical phonon scattering that dominates in most polar compound semiconductors."

The undoped sample A mobility was not saturated at 10K and the researchers suggest that values of $200\text{cm}^2/\text{V-s}$ could be reached. This would allow the use of magneto-transport studies for detailed probing of

the GaN valence band.

Two-dimensional holes gases were observed in a number of heterostructures similar to the main samples A and B presented in the paper. The team reports: "The 2DHG densities of $\sim 5 \times 10^{13}/\text{cm}^2$ measured in this work are near the expected polarization difference and much higher than previously reported 2DHG densities in nitride semiconductors [Figure 2]."

The 2DHG concentration also beats the values in other semiconductor systems. At the same time, compared with narrower-bandgap semiconductors, the III-nitride 'light' and 'heavy' holes tend to have higher effective masses, reducing mobility. "However, a large bandgap means that the high 2D hole gas densities can be modulated effectively with a gate through field effect because the semiconductor intrinsically is capable of sustaining much larger electric fields," the team writes.

The polarization-based doping effect has another advantage — uniformity down to the atomic scale in contrast to the fluctuations of dopant concentration in the more usual magnesium-doped p-GaN. ■

<https://doi.org/10.1126/science.aau8623>

www.newswise.com/articles/discovery-in-gallium-nitride-a-key-enabler-of-energy-efficient-electronics

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Fraunhofer IAF claims first MOCVD production of AlScN layers for transistors

An MOCVD reactor has been modified for scandium precursor.

The Fraunhofer Institute for Applied Solid State Physics (IAF) in Freiburg, Germany claims to be first to manufacture aluminium scandium nitride (AlScN) by metal-organic chemical vapor deposition (MOCVD), taking a step towards its goal of developing power electronics based on AlScN transistors for industrial applications.

Transistors based on AlScN are promising for various industrial applications such as data transfer, satellite communication, radar systems and autonomous driving, especially since existing devices based on silicon are reaching their physical limit in these applications. One reason for this is the size of silicon devices, which cannot be reduced further according to existing research.

High-electron-mobility transistors (HEMTs) far surpass the possibilities of silicon devices due to the materials on which they are based. AlScN has exceptional properties, allowing higher carrier concentrations than other materials. In the future, significantly more powerful and efficient HEMTs will be realized based on AlScN, reckons Fraunhofer IAF.

Previous manufacturing processes failed due to quality and productivity

The production of AlScN involves fundamental challenges. The state-of-the-art production process grows AlScN layers via sputtering. Unfortunately, the quality of these layers is insufficient for electronic applications such as light-emitting diodes (LEDs) and high-power transistors. An alternative method is to produce AlScN via molecular beam epitaxy (MBE), with which large amounts of scandium can be incorporated in the compound. The quality is also sufficient for the production of microelectronic devices. However, the procedure is complex and the productivity too low for industrial-scale productions.

Metal-organic chemical vapor deposition promises industrial-grade production

The production of AlScN by MOCVD promises not only the necessary quality but also sufficient productivity for industrial applications. "We knew that previous



The research group of Stefano Leone (bottom right) together with the MOCVD system, modified for AlScN growth.

attempts by other scientists to produce gallium scandium nitride via MOCVD had failed," says group leader Dr Stefano Leone. "We also know that many scientists all over the world are working to develop AlScN transistors, but no one before us has succeeded in doing it by using MOCVD, even though it is a very promising



Fraunhofer IAF's MOCVD system has been modified to enable the growth of AlScN with sufficient quality and productivity for industry.

approach for industry," he adds.

During the MOCVD, gases are guided across a heated wafer. Through the heat exposure distinct molecules are released from the gas and integrated into the crystalline structure of the wafer. The crystal structure can be precisely adjusted by regulating the gas flow, temperature and pressure. Furthermore, the quick change of gas allows growth of different material layers on top of each other.

MOCVD reactor modified for scandium precursor

The challenge for researchers at Fraunhofer IAF is that there was no gas source for scandium. The precursors for scandium are very large and difficult to bring into the gas phase. "We studied the best possible precursor for scandium and planned adjustments of our MOCVD reactor for the necessary procedure," says Leone. "We did a lot of research and had numerous discussions until we developed a setup that we are now even patenting. We have now succeeded in growing AlScN layers via MOCVD with a very high crystal quality and the right amount of scandium in order to develop the next generation of power transistors," he adds. The MOCVD system at Fraunhofer IAF has been modified by the research group to enable a high-quality and reproducible AlScN production process.

First MOCVD-grown AlScN layers for transistors

After successful deposition of AlScN in the MOCVD system, the first AlScN layers for transistors were produced. The layers have already yielded promising



The AlScN layers have very high crystal quality and the right amount of scandium, with which the researchers want to develop the next generation of electronic power transistors.

results, with sheet resistance of $\sim 200\Omega/\text{sq.}$, mobility of $\sim 600\text{cm}^2/\text{Vs}$ and charge carrier density of $\sim 4.0 \times 10^{13}\text{cm}^{-2}$.

The current goal of the researchers is to reduce the sheet resistance and to further increase the mobility and material quality. This should improve the performance of future transistors, so Fraunhofer IAF aims to take a significant step towards its goal of providing AlScN HEMTs for industrial power electronic applications. ■

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SiC 600V transistors comparable to silicon

High-frequency figures of merit surpass those of Infineon's commercially available 600V P7 silicon CoolMOS technology, according to researchers.

North Carolina State University in the USA has implemented its 4H-polytype silicon carbide (SiC) inversion-channel power metal-oxide-semiconductor field-effect transistor (MOSFET) technology on a 6-inch foundry process, achieving 600V high-voltage rating and 15V gate drive [Aditi Agarwal, Kijeong Han and B. Jayant Baliga, IEEE Electron Device Letters, vol40, issue 11 (November 2019), p1792]. The 15V gate-drive value makes the technology compatible with insulated-gate bipolar transistor (IGBT) circuitry.

The team reports: "The high-frequency figures-of-merit (HF-FOMs) of the SiC MOSFETs with 27nm gate oxide were found to surpass that of commercially available 600V P7 Si CoolMOS products for the first time." Up to now, SiC-based devices have found it difficult to beat the performance of 600V-rated silicon products, inhibiting adoption of the technology.

The inversion-channel devices (Figure 1) were manufactured at a commercial foundry facility run by X-Fab on 6-inch SiC wafers. The gate oxide thickness (T_{ox}) was 27nm; the channel was 0.5 μ m long. The fabrication of the drift region used NCSU's trade-marked PRESiCE process. The gate oxide was created through thermal oxidation at 1175°C for 150 minutes. A comparison device with 55nm oxide used a 300-minute oxidation process. The resulting device active area was 0.045cm².

Simulations of the structure suggested that the peak field in the off-state would be in the middle of the JFET region. The peak field in the gate oxide with 600V drain bias was 3.2MV/cm (2.8MV/cm for 55nm-thick oxide). A value of 4MV/cm is considered to be the threshold where block-state operation becomes unreliable.

In the on-state, with 15V on the gate, the simulated peak oxide field was 5.6MV/cm (3.6MV/cm for 55nm). The researchers believe this large on-field is acceptable, "because an oxide electric field of 6MV/cm at 175°C will result in stable on-state operation for 1000 years."

For the fabricated devices, the threshold voltages for 1mA current with 0.1V drain bias were 1.9V and 3.56V for the 27nm and 55nm oxides, respectively. The corresponding transconductances at 10A/20V drain current/voltage were 8.5S and 5.5S. The higher transconductance for the 27nm-oxide transistor should enable faster switching.

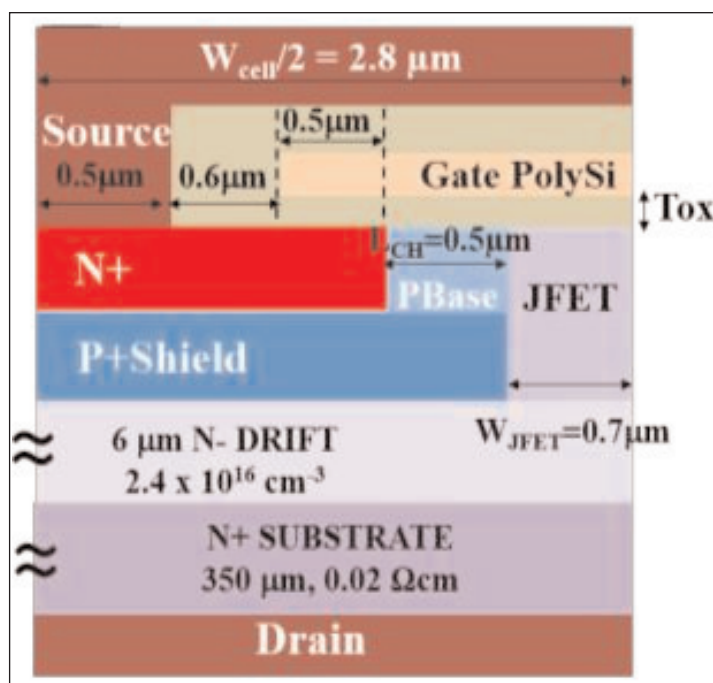


Figure 1. Schematic cross section for fabricated linear cell MOSFET devices.

Comparing the on-resistance at gate potentials of 15V and 20V for the 27nm- and 55nm-oxide MOSFETs, respectively, showed a 1.7x smaller value in the 27nm case. The effective channel-inversion mobilities in the two cases were similar, of the order 15cm²/V-s, so the lower on-resistance was the result of the normal field from the gate creating a higher carrier density in the channel in the 27nm case.

The specific on-resistance with the gate potential in the 10–15V range for the 27nm is similar to that for 55nm-MOSFET in the 20–25V range. The team comments: "Reducing the gate drive voltage to the 10–15V range with the 27nm gate oxide thickness allows the use of widely available 15V gate drivers previously developed for Si IGBTs."

The blocking voltage (BV) for 100 μ A leakage current ($I_{leakage}$) was 846V for 27nm oxide, greater than that the 703V value for 55nm. "We believe that this is due to a combination of increased field-plate effect, or differences in drift region doping and/or thickness for the two wafers," the researchers write.

Statistically analyzing the performance variation across the wafers, the leakage current was in the nA

range at 600V drain bias (Figure 2). The specific on-resistance of the 27nm-oxide MOSFETs was just over half that of the 55nm version. The breakdown voltage for all the 27nm devices was well above 600V.

The researchers report: "The $R_{on,sp}$ mean and best value of 3.77 and 3.28mΩ-cm² for the 27nm devices are smaller than that reported in previous papers for inversion-mode devices with linear cell topology." They add: "The measured mean and standard deviation numbers for $R_{on,sp}$, BV and $I_{leakage}$ demonstrate that the PRESiCE non-self-aligned foundry process is robust even for 27nm gate oxide MOSFETs."

The thinner oxide also benefits a number of FOMs with respect to the various parasitic capacitances and related charge storage, One HF-FOM, the product of on-resistance and reverse-transfer capacitance ($R_{on} \times C_{rss}$), was 1.7x lower in the 27nm-oxide MOSFET, compared with the 55nm version. Another HF-FOM, the product of Ron and the gate-drain charge (Q_{gd}), was 1.6x lower. The ratio of input capacitance to reverse-transfer capacitance (C_{iss}/C_{rss}) was improved by 1.5x: 185 for 27nm, and 120 for 55nm gate oxide.

The 934mΩ-nC $R_{on} \times Q_{gd}$ for the 27nm gate oxide device compares favorably with the 1160mΩ-nC value for the commercial Infineon's CoolMOS silicon product (IPW60R180P7). Rohm's R6020JNZ4 SiC MOSFET only manages 3060mΩ-nC. On the other hand, the 834mΩ-pF $R_{on} \times C_{rss}$ FOM average for the 27nm-oxide device is somewhat higher than the 725mΩ-pF and 720mΩ-pF values for the commercial Si and SiC products, respectively. The best RonxCrсс for the 27nm-oxide MOSFETs was in fact lower at 646mΩ-pF, so process optimization holds out the hope for consistent improvement over the commercial CoolMOS device.

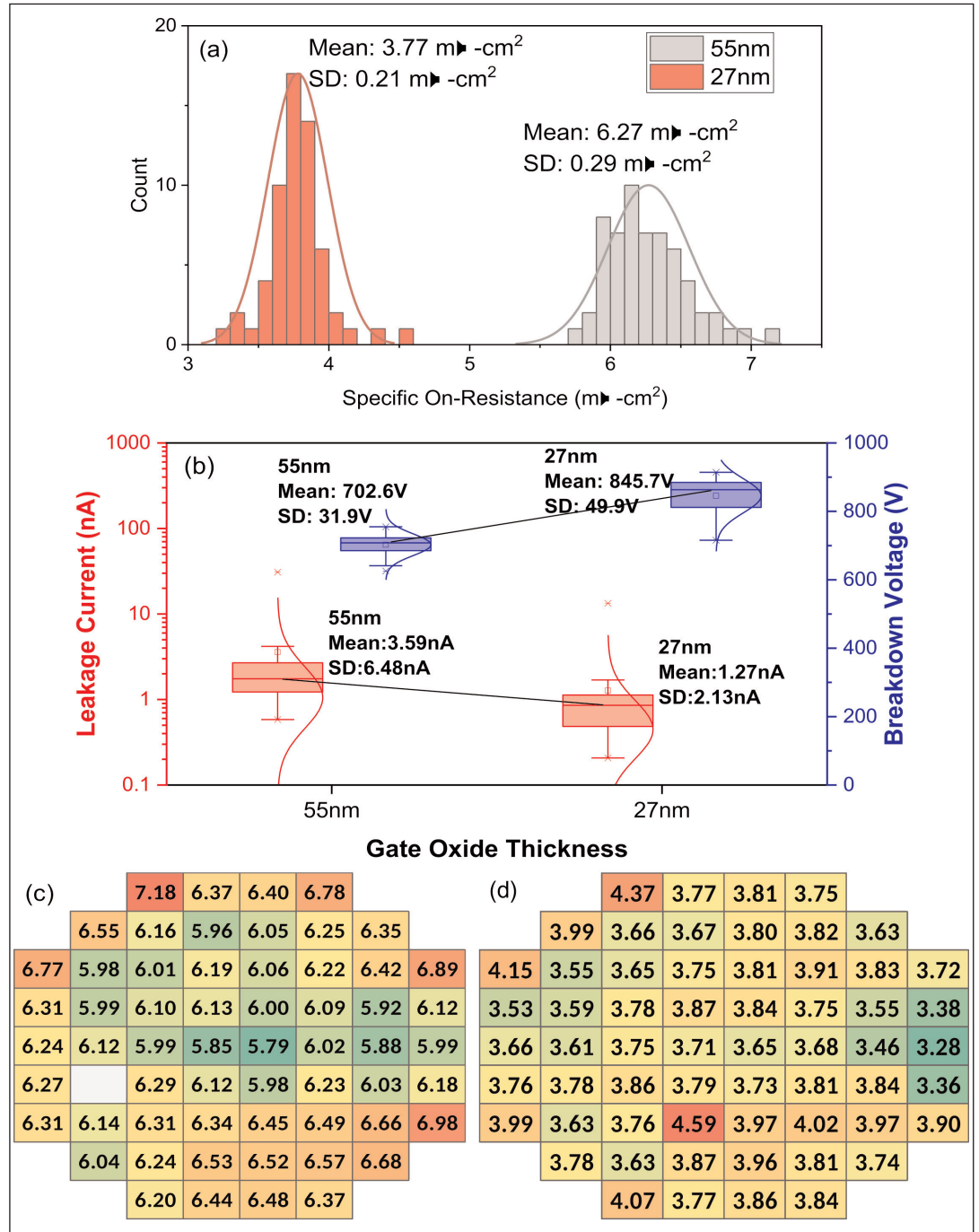


Figure 2. (a) Statistical distributions of $R_{on,sp}$ for 55nm and 27nm gate oxide MOSFETs at 20V and 15V gate potential, respectively; (b) box plots of leakage current (red) at 600V and BV (blue) at 100μA; (c) wafer-map of $R_{on,sp}$ for 55nm device at 20V gate voltage and 10A drain current, and (d) for 27nm device at 15V gate and the same drain current.

The team comments: "The average and best FOM [$R_{on} \times Q_{gd}$] for the 27nm gate oxide device are 1.24Ω and 1.43Ω better than the Si P7 CoolMOS product, and its $R_{on,sp}$ is 2.5Ω smaller. This demonstrates for the first time that 600V SiC power MOSFETs can be manufactured with superior performance compared to Si CoolMOS products, opening up new market opportunities for SiC technology." ■

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 Finedon Road Industrial Estate,
 Wellingborough,
 Northants NN8 4PE,
 UK

Tel: +44 1933 220626
 Fax: +44 1933 227814

www.MCP-group.com

Umicore Indium Products

50 Simms Avenue,
 Providence, RI 02902,
 USA

Tel: +1 401 456 0800
 Fax: +1 401 421 2419

www.thinfilmpducts.umicore.com

United Mineral & Chemical Corp

1100 Valley Brook Avenue,
 Lyndhurst, NJ 07071,
 USA

Tel: +1 201 507 3300
 Fax: +1 201 507 1506

www.umccorp.com

2 Bulk crystal growth equipment

MR Semicon Inc

PO Box 91687,
 Albuquerque,
 NM 87199-1687,
 USA

Tel: +1 505 899 8183
 Fax: +1 505 899 8172

www.mrsemicon.com

3 Substrates

AXT Inc

4281 Technology Drive,
 Fremont,
 CA 94538,
 USA

Tel: +1 510 438 4700
 Fax: +1 510 683 5901

www.axt.com

Supplies GaAs, InP, and Ge wafers using VGF technology with manufacturing facilities in Beijing and five joint ventures in China producing raw materials, including Ga, As, Ge, pBN, B₂O₃.



CrystAI-N GmbH

Dr.-Mack-Straße 77,
 D-90762
 Fürth,
 Germany

Tel: +49 (0)911 650 78 650 90
 Fax: +49 (0)911 650 78 650 93
 E-mail: info@crystal-n.com

www.crystal-n.com

Crystal IS Inc

70 Cohoes Avenue
 Green Island, NY 12183, USA

Tel: +1 518 271 7375
 Fax: +1 518 271 7394

www.crystal-is.com

Freiberger Compound Materials

Am Junger Loewe Schacht 5,
 Freiberg, 09599, Germany

Tel: +49 3731 280 0
 Fax: +49 3731 280 106

www.fcm-germany.com

Kyma Technologies Inc

8829 Midway West Road,
 Raleigh, NC, USA

Tel: +1 919 789 8880
 Fax: +1 919 789 8881

www.kymatech.com

MARUWA CO LTD

3-83, Minamihonjigahara-cho,
Owariasahi, Aichi 488-0044,
Japan

Tel: +81 572 52 2317

[www.maruwa-g.com/e/
products/ceramic](http://www.maruwa-g.com/e/products/ceramic)

sp3 Diamond Technologies

2220 Martin Avenue,
Santa Clara, CA 95050,
USA

Tel: +1 877 773 9940

Fax: +1 408 492 0633

www.sp3inc.com

**Sumitomo Electric
Semiconductor Materials Inc**

7230 NW Evergreen Parkway,
Hillsboro, OR 97124,
USA

Tel: +1 503 693 3100 x207

Fax: +1 503 693 8275

www.sesmi.com

III/V-Reclaim

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84568 Pleiskirchen,
Germany

Tel: +49 8728 911 093

Fax: +49 8728 911 156

www.35reclaim.de

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handled. The firm offers single-side
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B-2250 Olen,
Belgium

Tel: +32-14 24 53 67

Fax: +32-14 24 58 00

www.substrates.umicore.com

Wafer World Inc

1100 Technology Place, Suite 104,
West Palm Beach,
FL 33407,
USA

Tel: +1-561-842-4441

Fax: +1-561-842-2677

E-mail: sales@waferworld.com

www.waferworld.com

4 Epiwafer foundry**Spire Semiconductor LLC**

25 Sagamore Park Drive,
Hudson, NH 03051,
USA

Tel: +1 603 595 8900

Fax: +1 603 595 0975

www.spirecorp.com

Albemarle Cambridge Chemical Ltd

Unit 5 Chesterton Mills,
French's Road,
Cambridge CB4 3NP,
UK

Tel: +44 (0)1223 352244

Fax: +44 (0)1223 352444

www.camchem.co.uk

Intelligent Epitaxy Technology Inc

1250 E Collins Blvd,
Richardson,
TX 75081-2401,
USA

Tel: +1 972 234 0068

Fax: +1 972 234 0069

www.intelliepi.com

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Villejust, 91971 Courtabouef,
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Tel: +33 (0)1 69 31 61 30

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**5 Deposition
materials****Akzo Nobel
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Metalorganics**

www.akzonobel.com/hpmo

Asia Pacific:

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China

Tel: +86 21 2216 3600

Fax: +86 21 3360 7739

metalorganicsAP@akzonobel.com

Americas:

AkzoNobel Functional Chemicals,
Chicago,
USA

Tel: +31 800 828 7929 (US only)

Tel: +1 312 544 7000

Fax: +1 312 544 7188

metalorganicsNA@akzonobel.com

Europe, Middle East and Africa:

AkzoNobel Functional Chemicals,
Amersfoort,
The Netherlands

Tel: +31 33 467 6656

Fax: +31 33 467 6101

metalorganicsEU@akzonobel.com

Cambridge Chemical Company Ltd

Unit 5 Chesterton Mills,
French's Road,
Cambridge CB4 3NP,
UK

Tel: +44 (0)1223 352244

Fax: +44 (0)1223 352444

www.camchem.co.uk

Dow Electronic Materials

60 Willow Street,
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USA

Tel: +1 978 557 1700

Fax: +1 978 557 1701

www.metalorganics.com

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Newark, CA 94560,
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www.mathesontrigas.com

Mining & Chemical Products Ltd

(see section 1 for full contact details)

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www.praxair.com/electronics

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www.safchitech.com

Materion Advanced Materials Group

2978 Main Street,
Buffalo, NY 14214,
USA
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Fax: +1 716 833 2926
www.williams-adv.com

6 Deposition equipment

AIXTRON SE

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www.evatecnet.com

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www.svta.com

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7 Wafer processing materials

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www.airproducts.com/compound

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MA 02464, USA
Tel: +1 617 965 5511
Fax: +1 617 965 5818
www.microchem.com

Praxair Electronics

(see section 5 for full contact details)

8 Wafer processing equipment

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DI Erich Thallner Strasse 1,
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Austria
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Fax: +43 7712 5311 4600
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www.logitech.uk.com

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(see section 6 for full contact details)

SAMCO International Inc

532 Weddell Drive,
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USA
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Fax: +1 408 734 0961
www.samcointl.com

SPTS Technology Ltd

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UK
Tel: +44 (0)1633 414000
Fax: +44 (0)1633 414141
www.spts.com

SUSS MicroTec AG

Schleißheimer Strasse 90,
85748 Garching,
Germany
Tel: +49 89 32007 0
Fax: +49 89 32007 162
www.suss.com

Veeco Instruments Inc

(see section 6 for full contact details)

9 Materials & metals

Goodfellow Cambridge Ltd

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Cambridgeshire PE29 6WR,
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Fax: +44 (0) 1480 424900
www.goodfellow.com



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Air Products and Chemicals Inc

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Cambridge Fluid Systems

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Cambridge CB3 8SQ,
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Tel: +44 (0)1954 786800
Fax: +44 (0)1954 786818
www.cambridge-fluid.com

CS CLEAN SOLUTIONS AG

Fraunhoferstrasse 4,
Ismaning, 85737,
Germany
Tel: +49 89 96 24000
Fax: +49 89 96 2400122
www.csclean.com

SAES Pure Gas Inc

4175 Santa Fe Road,
San Luis Obispo,
CA 93401,
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Tel: +1 805 541 9299
Fax: +1 805 541 9399
www.saesgetters.com

11 Process monitoring and control

Conax Technologies

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Tel: +1 734 426 7977
Fax: +1 734 426 7955
www.k-space.com

KLA-Tencor

One Technology Dr,
1-2221I, Milpitas,
CA 95035,
USA
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Fax: +1 408 875 4144
www.kla-tencor.com

LayTec AG

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Fax: +49 7723 9197 22
www.wepcontrol.com

12 Inspection equipment

Bruker AXS GmbH

Oestliche Rheinbrueckenstrasse 49,
Karlsruhe, 76187,
Germany
Tel: +49 (0)721 595 2888
Fax: +49 (0)721 595 4587
www.bruker-axs.de

13 Characterization equipment

J.A. Woollam Co. Inc.

645 M Street Suite 102,
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Tel: +1 402 477 7501
Fax: +1 402 477 8214
www.jawoollam.com

Lake Shore Cryotronics Inc

575 McCorkle Boulevard,
Westerville, OH 43082, USA
Tel: +1 614 891 2244
Fax: +1 614 818 1600
www.lakeshore.com

14 Chip test equipment

Keithley Instruments Inc

28775 Aurora Road,
Cleveland, OH 44139, USA
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Fax: +1 440.248.6168
www.keithley.com

15 Assembly/packaging materials

ePAK International Inc

4926 Spicewood Springs Road,
Austin, TX 78759,
USA
Tel: +1 512 231 8083
Fax: +1 512 231 8183
www.epak.com

Gel-Pak

31398 Huntwood Avenue,
Hayward, CA 94544, USA
Tel: +1 510 576 2220
Fax: +1 510 576 2282
www.gelpak.com

Wafer World Inc

(see section 3 for full contact details)

Materion Advanced Materials Group

2978 Main Street,
Buffalo, NY 14214,
USA
Tel: +1 716 837 1000
Fax: +1 716 833 2926
www.williams-adv.com

16 Assembly/packaging equipment

Ismeca Europe Semiconductor SA

Helvetie 283, La Chaux-de-Fonds,
2301, Switzerland
Tel: +41 329257111
Fax: +41 329257115
www.ismeca.com

Kulicke & Soffa Industries

1005 Virginia Drive,
Fort Washington, PA 19034,
USA
Tel: +1 215 784 6000
Fax: +1 215 784 6001
www.kns.com

Palomar Technologies Inc

2728 Loker Avenue West,
Carlsbad, CA 92010,
USA
Tel: +1 760 931 3600
Fax: +1 760 931 5191
www.PalomarTechnologies.com

TECDIA Inc

2700 Augustine Drive, Suite 110,
Santa Clara, CA 95054,
USA
Tel: +1 408 748 0100
Fax: +1 408 748 0111
www.tecdia.com

17 Assembly/packaging foundry

Quik-Pak

10987 Via Frontera,
San Diego, CA 92127,
USA
Tel: +1 858 674 4676
Fax: +1 8586 74 4681
www.quikicpak.com

18 Chip foundry

Compound Semiconductor Technologies Ltd

Block 7, Kelvin Campus,
West of Scotland, Glasgow,
Scotland G20 0TH,
UK
Tel: +44 141 579 3000
Fax: +44 141 579 3040
www.compoundsemi.co.uk

United Monolithic Semiconductors

Route departementale 128,
BP46, Orsay, 91401,
France
Tel: +33 1 69 33 04 72
Fax: +33 169 33 02 92
www.ums-gaas.com

19 Facility equipment

MEI, LLC

3474 18th Avenue SE,
Albany, OR 97322-7014,
USA
Tel: +1 541 917 3626
Fax: +1 541 917 3623
www.marlerenterprises.net

20 Facility consumables

W.L. Gore & Associates

401 Airport Rd, Elkton,
MD 21921-4236,
USA
Tel: +1 410 392 4440
Fax: +1 410 506 8749
www.gore.com

21 Computer hardware & software

Ansoft Corp

4 Station Square,
Suite 200,
Pittsburgh, PA 15219,
USA
Tel: +1 412 261 3200
Fax: +1 412 471 9427
www.ansoft.com

Crosslight Software Inc

121-3989 Henning Dr.,
Burnaby, BC, V5C 6P8,
Canada
Tel: +1 604 320 1704
Fax: +1 604 320 1734
www.crosslight.com

Semiconductor Technology Research Inc

10404 Patterson Ave.,
Suite 108, Richmond, VA 23238,
USA
Tel: +1 804 740 8314
Fax: +1 804 740 3814
www.semitech.us

22 Used equipment

Class One Equipment Inc

5302 Snapfinger Woods Drive,
Decatur, GA 30035,
USA
Tel: +1 770 808 8708
Fax: +1 770 808 8308
www.ClassOneEquipment.com

23 Services

Henry Butcher International

Brownlow House, 50-51
High Holborn, London WC1V 6EG,
UK

Tel: +44 (0)20 7405 8411
 Fax: +44 (0)20 7405 9772
www.henrybutcher.com

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 Stuttgart, Germany
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 Fax: +49 711 8804 1950
www.mw-zander.com

24 Consulting

Fishbone Consulting SARL
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78460 Choisel,
 France
 Tel: + 33 (0)1 30 47 29 03
 E-mail: jean-luc.ledys@neuf.fr

25 Resources

Al Shultz Advertising Marketing for Advanced Technology Companies

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 7140 San Jose, CA 95126,
 USA
 Tel: +1 408 289 9555
www.alshultz.com

SEMI Global Headquarters

3081 Zanker Road,
 San Jose,
 CA 95134,
 USA
 Tel: +1 408 943 6900
 Fax: +1 408 428 9600
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SEMICON Japan 2019

Tokyo Big Sight, Tokyo, Japan

E-mail: semicon@sakurain.co.jp

www.semiconjapan.org/en

11–14 December 2019

2019 IEEE 50th IEEE Semiconductor Interface Specialists Conference (SISC)

Bahia Resort Hotel, San Diego, CA, USA

E-mail: wzhu@ieeesisc.org

www.ieeesisc.org

28–30 January 2020

OPTRO 2020 (9th International Symposium on Optronics in Defence Security)

Paris, France

E-mail: optro2020.exhibition@3af.fr

www.optro2020.com

30 January 2020

EPIC Roundtable on Quantum Optronics at OPTRO

Paris, France

E-mail: neringa.norbutaite@epic-assoc.com

www.epic-assoc.com/

epic-roundtable-on-quantum-optronics-at-optro

1–6 February 2020

Photonics West 2020

The Moscone Center, San Francisco, CA, USA

E-mail: customerservice@spie.org

https://spie.org/conferences-and-exhibitions/photonics-west

2–6 February 2020

IEEE International Solid- State Circuits Conference (ISSCC 2020)

San Francisco, CA, USA

E-mail: Issccinfo@yesevents.com

www.isscc.org

3 February 2020

EPIC World Photonics Technology Summit

St. Regis San Francisco Hotel, San Francisco, CA, USA

E-mail: neringa.norbutaite@epic-assoc.com

www.epic-assoc.com/epic-world-photonics-technology-summit-2020

5–7 February 2020

SEMICON Korea 2020

COEX Convention & Exhibition Center, Seoul, South Korea

E-mail: semiconkorea@semi.org

www.semiconkorea.org/en

11–13 February 2020

Strategies in Light

San Diego Convention Center, San Diego, CA, USA

E-mail: SIL@american-tradeshow.com

www.strategiesinlight.com

8–12 March 2020

OFC: The Optical Networking and Communication Conference & Exhibition

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12–14 March 2020**International Conference on Nano Research and Development (ICNRD-2020) – Breakthrough and Innovation in Nano Science and Technology**

Grand Copthorne Waterfront Hotel, Singapore

E-mail: laura@icnrd.com**www.istci.org/ICNRD2020/Program.asp****15–19 March 2020****IEEE Applied Power Electronics Conference and Exposition (APEC 2020)**Ernest N. Morial Convention Center,
New Orleans, LA, USA**E-mail:** apec@apec-conf.org**www.apec-conf.org****15–17 April 2020****EPIC Annual General Meeting 2020**

Radisson Blu Hotel Lietuva, Vilnius, Lithuania

E-mail: neringa.norbutaite@epic-assoc.com**www.epic-assoc.com/epic-annual-general-meeting-2020****21–23 April 2020****24th Annual Components for Military & Space Electronics Conference & Exhibition (CMSE 2020)**

Four Points by Sheraton (LAX), Los Angeles, CA, USA

E-mail: info@tjgreenllc.com**www.tjgreenllc.com/cmse****26–29 April 2020****2nd International Conference on UV LED Technologies & Applications (ICULTA 2020)**

MELIÄ Hotel, Berlin, Germany

E-mail: contact@icultra.com**www.ICULTA.com****4–6 May 2020****16th International Conference on Concentrator Photovoltaic Systems (CPV-16)**

Golden, near Denver, CO, USA

E-mail: info@cpv-16.org**www.cpv-16.org****7–8 May 2020****EPIC Meeting on Nanophotonics for Communication, Sensing and Data Processing at Nanoscribe**

Karlsruhe, Germany

E-mail: neringa.norbutaite@epic-assoc.com**www.epic-assoc.com/epic-events****10–15 May 2020****2020 Conference on Lasers & Electro-Optics (CLEO)**

San Jose Convention Center, San Jose, CA, USA

E-mail: CLEO@compusystems.com**www.cleoconference.org****11–14 May 2020****CS MANTECH: 2020 International Conference on Compound Semiconductor Manufacturing Technology**

JW Marriott Starr Pass, Tucson, AZ, USA

E-mail: registration@csmantech.org**www.csmantech.org****17–21 May 2020****32nd International Symposium on Power Semiconductor Devices and ICs (ISPSD 2020)**

Hofburg Palace, Vienna, Austria

E-mail: ispsd2020@guarant.cz**www.ispsd2020.com****22–25 July 2020****International Congress on Advanced Materials Sciences & Engineering (AMSE-2020)**

Vienna, Austria

E-mail: eve@istci.org**www.istci.org/amse2020****23–27 August 2020****SPIE Optics + Photonics 2020**

San Diego Convention Center, San Diego, CA, USA

Abstract deadline: 12 February 2020

E-mail: customerservice@spie.org**https://spie.org/Optics_Photonics****23–28 August 2020****International Workshop on Nitride Semiconductors (IWN 2020)**

Maritim Hotel Berlin, Germany

E-mail: iwn2020@conventus.de**www.iwn2020.org****23–28 August 2020****9th International Conference on Optical, Optoelectronic and Photonic Materials and Applications (ICOOPMA)**

University of Pardubice, Czech Republic

E-mail: info@icoopma.com**www.icoopma.com****7–11 September 2020****22nd European Conference on Power Electronics and Applications (EPE 2020 ECCE Europe)**

Lyon, France

www.epe2020.com



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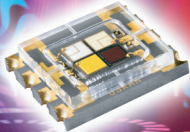


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