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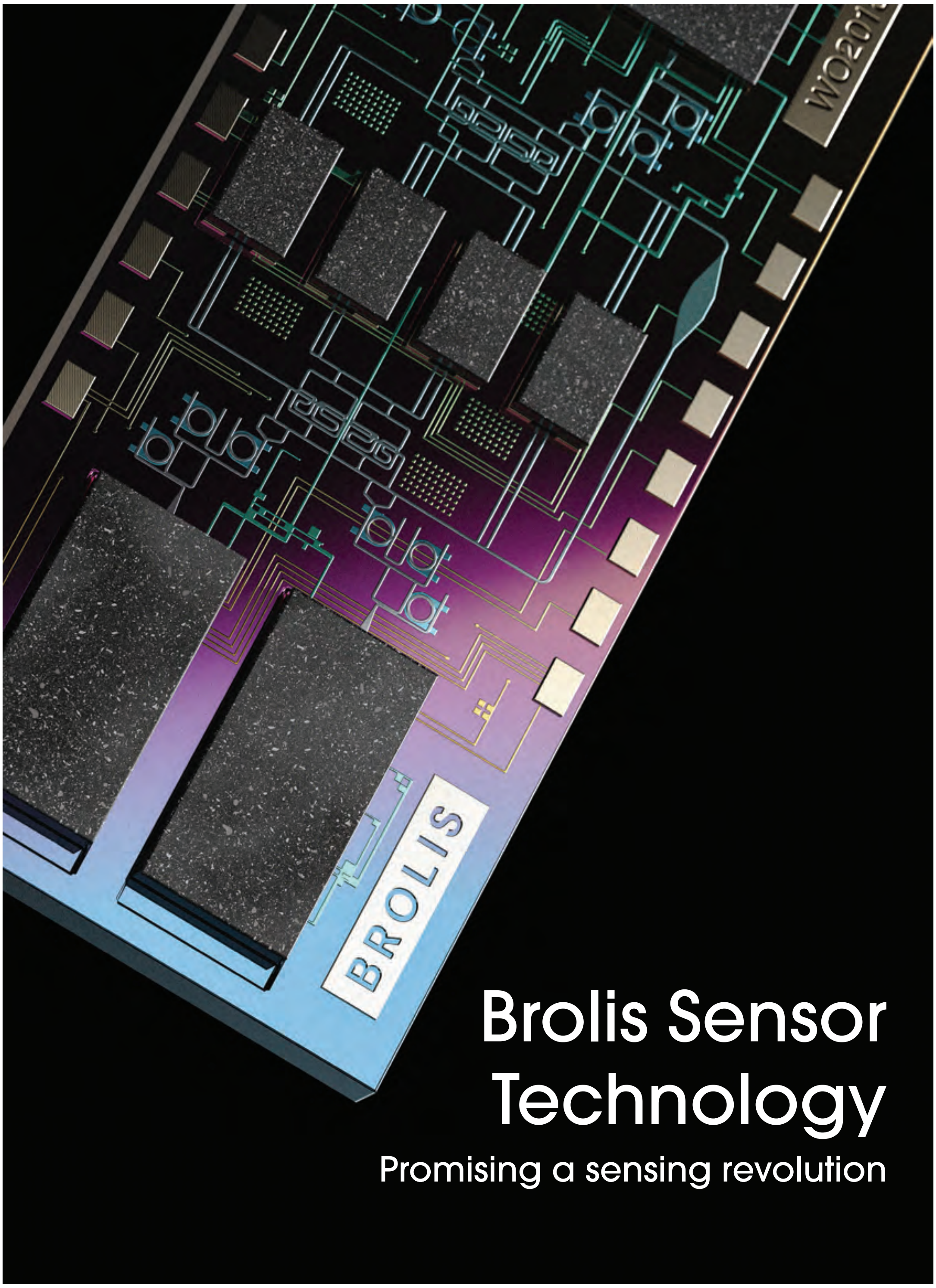
IEDM outlines how to give 5G better GaN

Striving for success in silicon photonics

Nano-porous GaN enhances microLEDs

Taking on tubes with high-voltage HEMTs

Targetting telecoms with nanowire lasers



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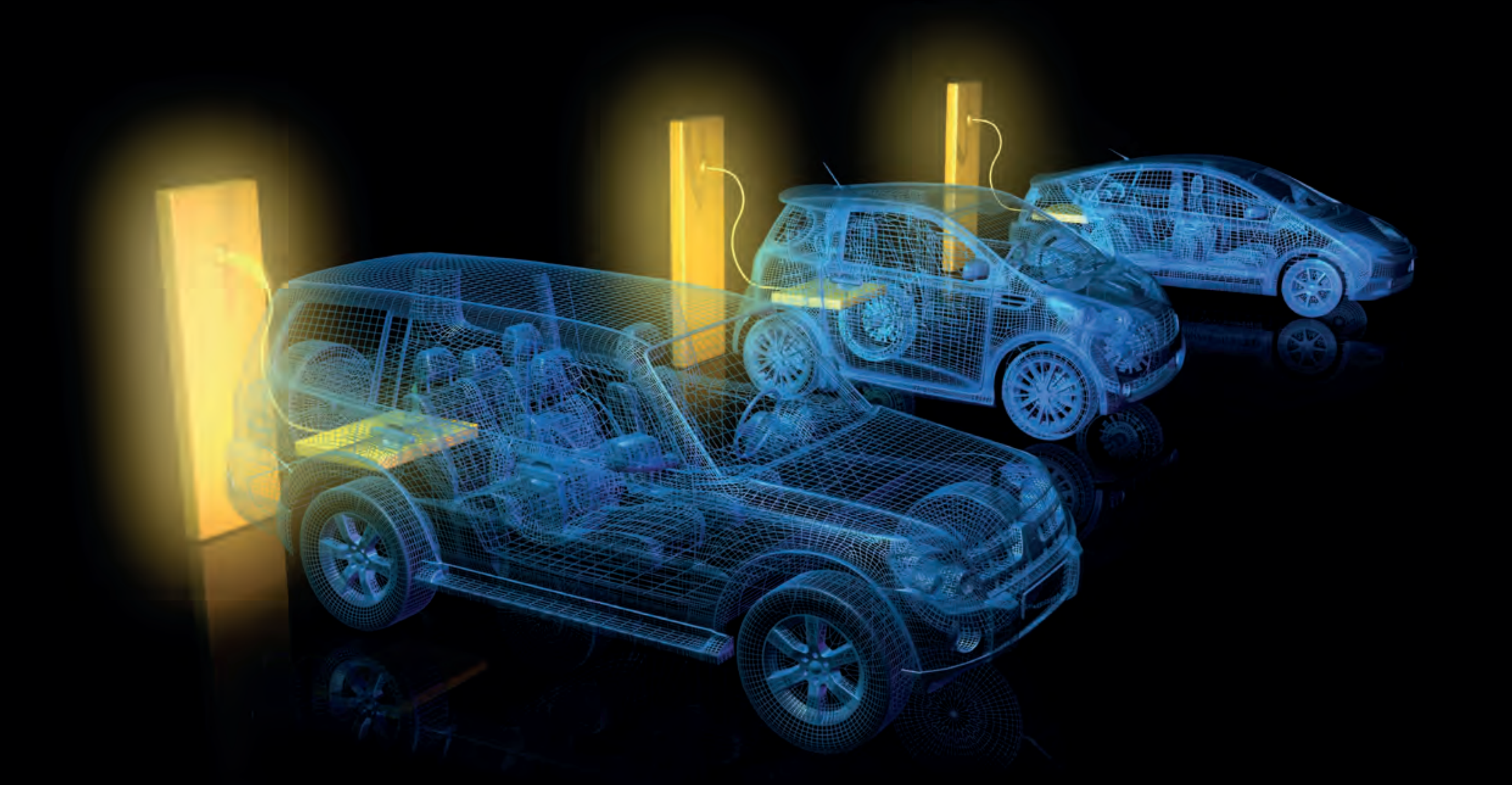



AIXTRON
AIXTRON

Viewpoint

By Dr Richard Stevenson, Editor

Planning ahead

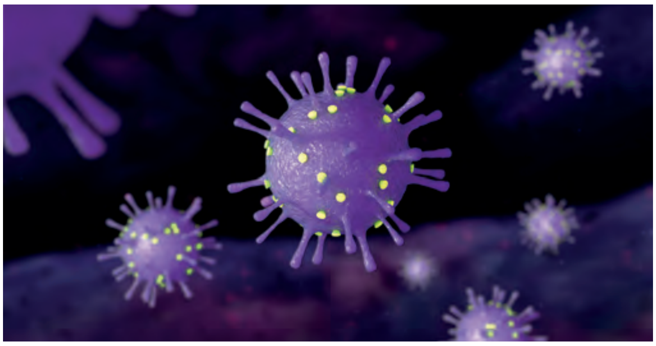
MAKING PLANS comes easily at the beginning of every new year. There is a fresh start, a blank new calendar, and it's only natural to wonder what we should aim to achieve, and how best to fill our time.

Now caught up in a pandemic, planning can take a back seat. After all, when travel is discouraged, there may seem little point compiling a list of conferences to attend, or deciding when we might visit a company that we are collborating with. But there is no reason to get caught up in too much negative thinking. Vaccinations are now rolling out, and when spring turns to summer we will edge closer to normality.

Although 2020 has been a very tough year for most of us, the pandemic has not hit our industry that hard – and in some cases it even provided a silver lining to some very grey clouds.

To discover those sectors boosted by the virus, and those that took a minor hit or continued along an existing trajectory, I spoke to Yole Développement. Initially focusing on SiC, over the last decade this market analyst has expanded its activities, and now covers all the majors sectors within the compound semiconductor industry.

It's of no surprise that sales of the UVC LED have blossomed over the last few months. If a bacteria-killing source can't prosper in a pandemic, it's never going to succeed. What's encouraging, through, is that the analysts at Yole are predicting that this market will continue to thrive well after the vaccination programme is over, with sales climbing from just over $300 million in 2020 to $2.5 billion in 2025.



Far harder to foresee has been the positive impact of the pandemic on SiC power devices. A significant chunk of sales of this class of chip come from the electric vehicle sector, which forms a small but growing part of the automotive industry that has suffered from falling sales, now that many of us no longer have a daily commute. Governments from all around the world have been stepping in to support the car market, providing incentives for us to go out and buy an electric vehicle. According to Yole, by 2025, electric vehicles will account for more than 60 percent of a SiC market that will have mushroomed from below $1 billion this year to more than $2.5 billion come 2025.

As you may expect, not all sectors have blossomed during the pandemic. But which ones have suffered the most? If you are curious, turn to page 40 to find out.

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VOLUME 27 ISSUE I 2021

CONTENTS

16 COVER STORY

GaSb-based chips promise a sensing revolution

Compact spectroscopic infrared sensors could aid healthcare, farmers, and sportsman

24 **Giving 5G better GaN**

Helping advance the GaN HEMT, researchers are developing processes for manufacturing complex millimetre-wave circuits, getting to the bottom of substrates losses and non-linearities, and speeding *p*-type devices

29 SPECIAL REPORT

The revival of Japan's semiconductor industry and its role in Industry 4.0

Special 6 page supplement

36 **Nano-porous GaN enhances microLEDs**

Inserting quantum dots in nanopores creates efficient, reliable microLEDs

40 **Covid-19 delivers a mixed blessing**

The pandemic is behind soaring sales in some sectors of the compound semiconductor industry, while others take a hit or continue along an existing trajectory

46 **Targeting telecoms with nanowires**

Nanowire lasers could provide the telecom industry with a widely tuneable source that is easy to integrate with silicon photonics

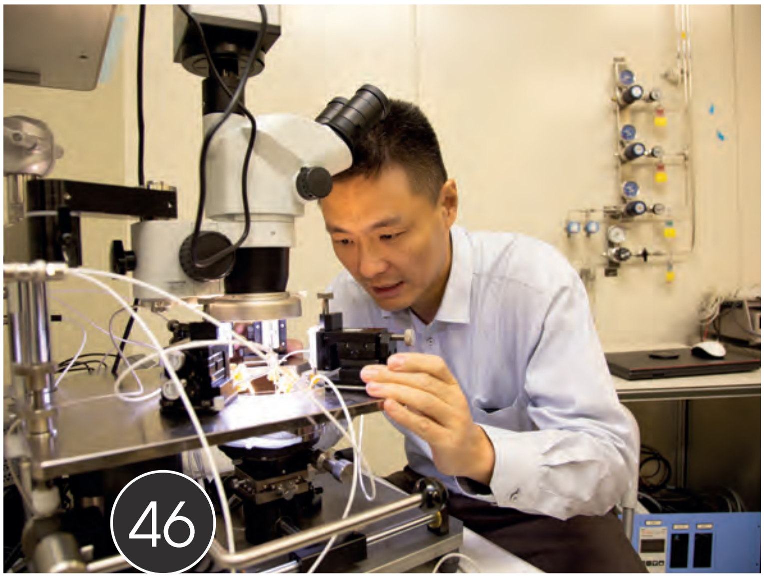
52 **Disrupting the tubes market with high-voltage GaN HEMTs**

GaN HEMTs operating at voltages of up to 150 V outperform vacuum tubes by combining high performance with greater reliability, longer lifetime and lower operating costs

60 PRODUCT SHOWCASE

BENEQ ALD enables next-generations of power devices

Driven by fast-growing demand in electric vehicles, consumer electronics and renewable electricity modern power devices are evolving rapidly in terms of materials as well as design and process technologies



news

06 Aledia makes first nanowire microLEDs

07 Testing the D-band for 6G and car radar

08 Tower to create integrated laser-on-silicon process

09 LEDs to reach $15.7 billion yearly revenue in 2021

10 STMicroelectronics introduces MasterGaN2

11 Price hike for LEDs due to growth in demand

12 Ams introduces VCSEL infrared emitter family

13 Violeds can kill 99 percent of Covid in under a second

news analysis

14 **Rockley Photonics: Bold plans in tough times**
How an up and coming silicon photonics start-up plans to take on a soon-to-be multi-billion dollar industry

research review

56 **Turbo-charging the channel of the GaN MOSFET**
Exposure to a nitrogen plasma enhances field-effect mobility in GaN vertical-channel MOSFETs

57 **Quashing interface states in SiC MOSFETs**
To trim channel resistance, the production of SiC MOSFETs should include etching with hydrogen gas, deposition of silicon dioxide by CVD, and a nitridation process

58 **Uncovering degradation mechanisms in green LEDs**
Intentional degradation induces the introduction of interstitial indium in the quantum wells

Aledia makes first nanowire microLEDs

ALEDIA, a French startup pioneering a disruptive technology for microLED displays, claims that it has manufactured the world's first microLED chips produced on 300 mm silicon wafers.

The company, which developed its breakthrough technology on 200 mm silicon wafers over the past eight years, will produce the chips on both 200 mm and 300 mm wafers. The larger wafers provide better economic payoff and cost-effective integration with smaller-node electronics, which are only available on 300 mm silicon wafers. Aledia was spun out of CEA-Leti, a French research institute pioneering micro- and nano-technologies, in 2012, and the work on 300 mm wafers has been performed by joint Aledia and CEA-Leti teams.

"We believe producing microLEDs on large-area 300 mm silicon wafers is a world's first, and opens this technology to huge potential-volume-manufacturing capabilities," said Giorgio Anania, Aledia CEO and cofounder.

"The larger size allows 60-100 smartphone displays to be made on a single 300 mm wafer, versus approximately four-to-six using the present LED industry-standard, 4 inch sapphire substrate. Thanks to Aledia's unique nanowire LED technology (3D LED), this can be done with commercially available processes and equipment, since it uses standard-thickness silicon wafers."

Traditional planar, 2D microLEDs are produced by depositing flat layers of GaN crystal on sapphire wafers of 100-150 mm diameter, with the majority of production today being on 100 mm wafers.

Aledia's microLED technology grows GaN nanowires (GaN crystals of sub-micron diameter) on top of large-area silicon (called 3D). This 3D nanowire technology does not create any of the stresses seen on 2D chips, which build up as the wafer size is increased, and so allows the use of very large-size wafers. In addition, this silicon-based technology allows production in conventional silicon foundries, which can be ramped up to high-volume production with extremely high yield.

"We are very pleased to have helped Aledia push forward the state of the art of 3D LED manufacturing using our 300 mm silicon processing line. We believe large-area silicon wafers are the best manufacturing platform in the world today for displays, and give big advantages in manufacturability," said Emmanuel

Sabonnadière, CEO of CEA-Leti. "3D nanowire microLEDs have the potential to make serious penetration into large display markets. CEA-Leti is very active today in supporting the display industry's transition to microLED technology."

"We believe the use of large-area silicon wafers and microelectronics foundries are the only way to deliver the huge volumes demanded by end-user markets," Anania said.

"For example, if only the large-screen TVs of 60 inch in diagonal and larger transitioned to silicon nanowire technology to obtain better image quality and lower manufacturing costs, this would require 24 million 300 mm wafers per year, volumes that can only be delivered by the silicon industry and supply chains. Smartphones, laptops and tablets would be on top of that."

JePPIX opens InP pilot line services

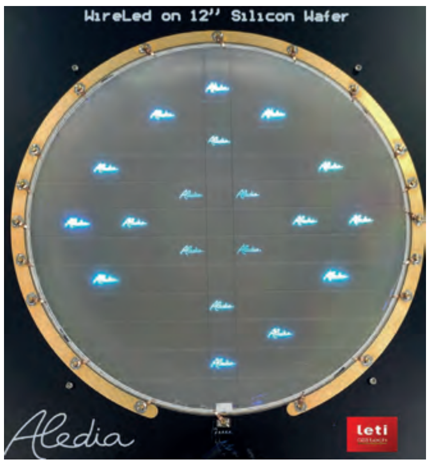
JePPIX PiLOT LINE has launched its design and manufacturing services for InP photonic integrated circuit (PIC) production. The JePPIX Pilot Line offers commercial InP PIC production based on mature process design kits (PDKs), that are embedded in industry-standard design environments.

The JePPIX Pilot Line provides a single point of contact for all the services needed for InP PIC product qualification, including: functional PIC modelling with manufacturing tolerances, design for test, design for manufacturing, and automated die testing with customizable scripting and test services.

JePPIX brings together the European PIC supply chain as a coherent force to advance and promote PIC technology. It promotes and facilitatse an open-access, horizontal and generic foundry model that keeps pace with the market, bringing in new users, enabling specialisation, and facilitating the supply chain needed for new sectors.

To accelerate the use of InP PICs, the European Union's Horizon 2020 research and innovation programme has supported the pilot line through the InPulse project that has received funding under grant agreement No 871345 (www.photonics21.org).

InP PICs offer the benefits of being small in size, low in weight, and having a low power consumption. Moreover, the possibility to integrate lasers, detectors, interferometers, photodetectors, modulators, filters, waveguides and other (electro-)optical technologies all on a single chip has a huge impact on material resources needed, circuit level reproducibility and the overall cost of the system.



Testing the D-band for 6G and car radar

WIRELESS comms test expert Rohde & Schwarz, in collaboration with the research facility IHP GmbH (Innovations for High Performance Microelectronics), has performed the industry's first full 2D/3D antenna characterisation of transceiver modules operating in the D-Band.

The D-Band, ranging from 110 GHz to 170 GHz, is a candidate for beyond 5G and 6G mobile communications as well as for future automotive radar applications. But D-band antenna systems and RF transceiver modules share features that make their testing a challenge. Their wide frequency range, a greater number of antenna elements and the lack of conventional external RF connectors demands testing over-the-air in a shielded environment.

Rohde & Schwarz and IHP have transferred their current 5G test methods to the sub-THz range. The test setup consists of the R&S ATS1000 antenna test system, the R&S ZNA43 vector network analyzer and the R&S AMS32 antenna measurement software from Rohde & Schwarz.

The R&S ATS1000 antenna test system is a compact and mobile shielded chamber solution for OTA and antenna measurements, ideal for 5G millimetre-wave applications. To cover the D-Band frequencies, extensions from Radiometer Physics GmbH, a Rohde & Schwarz company, are used in the setup, which allow direct frequency conversion at the probe in both transmit and receive directions. No mechanical modifications or additional RF cabling to the antenna test system is necessary.

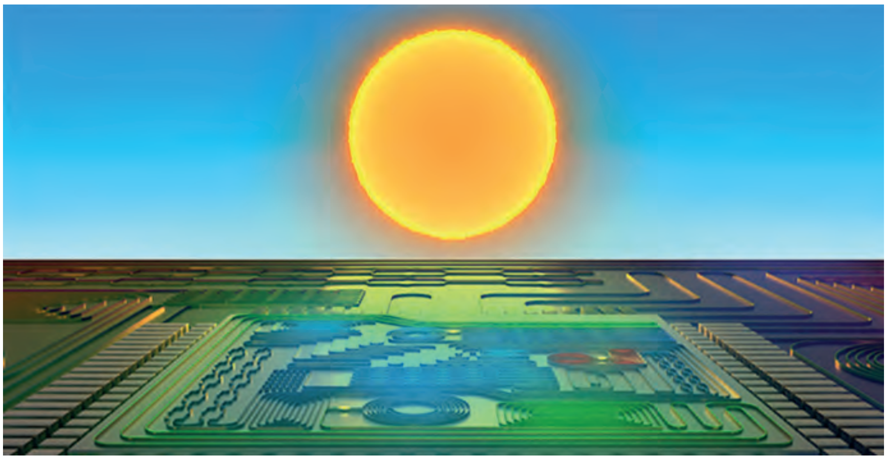
The setup can measure the amplitude and phase coherent response of a device under test (DUT) radiating in the D-Band. Fully automated 3D-pattern measurements including post-processing can be performed in short time thanks to the R&S AMS32 software options for nearfield to farfield transformation and the highly accurate precision positioner.

IHP provided four different DUTs, based on the same D-Band radar transceiver chipset but with different antenna structures, including on-chip single and stacked patches with air trenches and an on-chip antenna array. The over-the-air characterisation verified the wider bandwidth provided by the stacked patches than that by the single patch.

The performance of the various DUTs was characterised by spherical measurements, using two different setups. By comparing the different DUT designs based on the obtained measurement data, researchers of IHP were able to analyse the effect of the finite on-board reflector area on the radar sensor field-of-view.

Gerhard Kahmen, managing director of IHP, says: "The Rohde & Schwarz OTA test system, extended to D-Band, provides an excellent way to characterise radiation patterns of the complex antenna structures, realised in our D-Band radar chips, in a time efficient and precise way."

Tower to create integrated laser-on-silicon process



ANALOGUE SEMICONDUCTOR foundry Tower Semiconductor has announced that it is participating in the LUMOS program, with partial support from DARPA, to create a semiconductor foundry integrated-laser-on-silicon photonics process.

This process will combine high-performance III-V laser diodes with Tower's PH18 production silicon photonics platform. Multi-project wafer runs will be coordinated with the new process, when ready. The initial versions of the process development kit are expected in 2021 and will include laser and amplifier blocks.

The benefits of laser integration on silicon include an increase in the density of lasers, a reduction of coupling losses between the laser and the photonics, a reduction in components required and a much-simplified packaging scheme.

When combined with Tower's passive and active silicon photonics elements – such as silicon and SiN waveguides, Mach-Zehnder modulators, and germanium photodiodes – the co-integration will enable new products unavailable today from a volume semiconductor or photonics foundry.

The advanced process will be part of DARPA's Lasers for Universal Microscale Optical Systems (LUMOS) program, which aims to bring high-performance lasers to advanced photonics platforms, addressing commercial and defence applications.

Cree announces SiC power module portfolio

CREE has announced the launch of its Wolfspeed WolfPACK power modules, extending its range of solutions and ushering in a new era of performance for a diverse range of industrial power markets, including electric vehicle fast charging, renewable energy and energy storage, and industrial power applications.

Using 1200 V Wolfspeed MOSFET technology, the new modules deliver maximum efficiency in easy-to-use packages that allow designers to significantly increase efficiency and performance with smaller, more scalable power systems.

The new SiC modules maximise power density while simplifying designs in a standard form factor to significantly accelerate the production and rollout of next-generation technology for a wide range of rapidly growing industrial markets, including off-board charging and solar energy solutions.

The offering bridges the gap between single die discrete components and high-ampacity module solutions, giving today's design engineers a wide breadth of portfolio options for design requirements using Wolfspeed SiC.

"The introduction of the Wolfspeed WolfPACK power modules extends our power portfolio to cover the broad spectrum of high-voltage power applications, which will help an array of high-growth industries transform as the global transition from silicon to SiC continues to accelerate," said Jay Cameron, senior vice president and general manager, Wolfspeed Power.

"Maximising power density while minimising design complexity is essential for engineers working in the mid-power range, and the new modules simplify layouts to help accelerate production of EV fast charging and solar infrastructures."

The modules are available in half-bridge and six-pack configurations with a variety of on-resistance options.

LEDs to reach $15.7 billion yearly revenue in 2021

THE Covid-19 pandemic has had a substantial impact on the LED industry in 2020, resulting in a considerable drop in market demand and a projected yearly revenue of merely $15.1 billion, a 10 percent decrease YoY, according to TrendForce's latest investigations.

Although the YoY decline in 2020 represents a magnitude of historic proportions, as Covid vaccines become more widely available in 2021, long-term pent-up market demand will likely rebound from rock-bottom levels, resulting in a forecasted yearly revenue of $15.7 billion for the global LED industry this year, a 3.8 percent increase YoY.

TrendForce indicates that, due to the wide variety of LED applications, the degree of recovery in each application-specific industry varies as well. With regards to traditional backlighting applications, demand for consumer electronics, such as tablets and notebook computers, has skyrocketed on the back of the 'new normal' brought about by the pandemic, which involves the proliferation of working from home and distance education. Given the resultant high demand for display panels, LED backlighting suppliers have seen remarkable performances across the board this year.

However, in light of the possibility that most consumers have already purchased the needed electronics products ahead of time in 2020, TrendForce therefore holds a conservative attitude towards whether the strong market demand in 2020 will persist in 2021.
On the other hand, with regards to the long-anticipated miniLED backlights, various new products are expected to be released in 2021, spearheaded by major brands including Apple and Samsung. As such, miniLED backlighting demand will see a substantial growth, with a forecasted $131 million in yearly revenue for 2021, a 900 percent YoY increase.

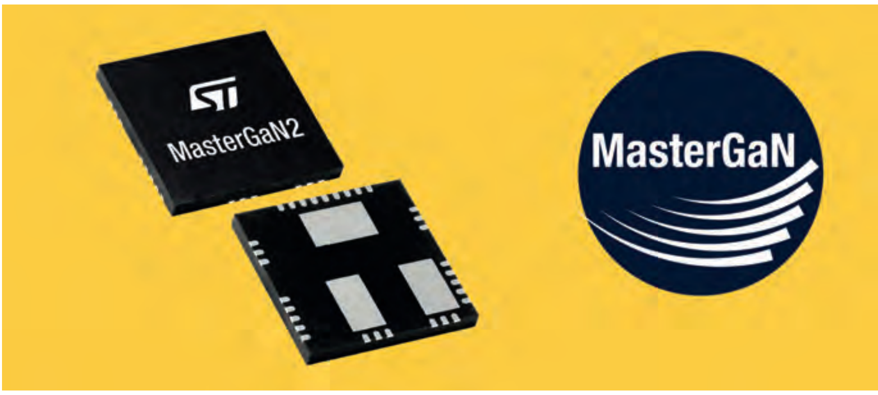
With regards to display applications, LED displays are primarily used within the commercial space. Similar to general lighting applications, the cutbacks in live performances this year caused a corresponding 9.3 percent YoY decrease in LED display revenue.

However, looking ahead to 2021, TrendForce expects LED display revenue to return to the pre-pandemic level of about $1.48 billion due to the gradual recovery of live performances and the rising demand for high-resolution, small-pixel-pitch LED displays.

With regards to general-use lighting, LED lighting applications have suffered massive declines due to the pandemic's impacts. As commercial activities dwindled this year, the declines in commercial lighting and outdoor landscape lighting have been the most noticeable among various LED lighting applications.

Conversely, the gradual legalization of marijuana and the pandemic-generated skyrocketing market for medical and recreational marijuana in North America have galvanized a substantial increase in horticultural LED demand.

STMicroelectronics introduces MasterGaN2



BUILDING upon the advantages of STMicroelectronics' MasterGaN platform, MasterGaN2 is the first in the new family to contain two asymmetric GaN transistors, delivering an integrated GaN solution suited to soft-switching and active-rectification converter topologies.

The 650 V normally-off GaN transistors have on-resistances of 150 mΩ and 225 mΩ. Each is combined with an optimised gate driver, making GaN technology as easy to use as ordinary silicon devices.

By combining advanced integration with GaN's inherent performance advantages, MasterGaN2 further extends the efficiency gains, size reduction, and weight savings of topologies such as active clamp flyback.

The MasterGaN power system-in-package (SiP) family combines the two GaN HEMTs and associated high-voltage gate drivers in the same package with all necessary protection mechanisms built-in. The designer can easily connect external devices including Hall sensors and a controller such as a DSP, FPGA, or microcontroller directly to the MasterGaN device. The inputs are compatible with logic signals from 3.3 V to 15 V, which helps simplify the circuit design and bill of materials, permits a smaller footprint, and streamlines assembly. This integration helps raise the power density of adapters and fast chargers.

GaN technology is driving the evolution toward fast USB-PD adapters and smartphone chargers. ST's MasterGaN devices enable these to become up to 80 percent smaller and 70 percent lighter, while charging three times faster compared with ordinary silicon-based solutions.

The built-in protection comprises low-side and high-side under-voltage lockout, gate-driver interlocks, a dedicated shutdown pin, and over-temperature protection. The 9 mm x 9 mm x 1 mm GQFN package is optimised for high-voltage applications, having over 2 mm creepage distance between high-voltage and low-voltage pads.

MasterGaN2 is in production now, priced from $6.50 for orders of 1000 pieces.

Osram presents its first UVC LED

OSRAM OPTO SEMICONDUCTORS has announced the Oslon UV 3636, the first product in an upcoming range of UVC LEDs for disinfection applications.

Irradiation with UVC light causes chemical bonds in the RNA or DNA helix of the pathogens to break down. As a result, they are no longer able to multiply and are thus rendered harmless.

A major advantage of modern, LED-based UV-C solutions is the compact size of the light sources. Thanks to their space-saving dimensions, the LEDs can be installed easily on the final application for direct interaction with the substance being sanitized such as: significantly reducing germs in faucets and disinfecting the air in air-conditioning systems before it is blown into car interiors.

The direct integration of the light sources also has the advantage of ensuring that the high-energy, short-wave UVC light does not reach the surrounding area, and therefore, does not pose a risk to people. In addition, unlike conventional lighting technologies, LEDs are very robust and insensitive to external shocks.

The Oslon UV 3636, Osram's first UVC LED, is available in a low- and a mid-power version and features compact dimensions of 3.6 mm x 3.6 mm. With a wavelength of 275 nm, both versions are ideal for disinfection applications. The low-power version achieves 4.5 mW at 30 mA. The mid-power version impresses with 42 mW at 350 mA.

"Thanks to their compact footprint and different optical power classes, UVC LEDs enable completely new designs and applications," explains Christian Leirer, product manager for UVC at Osram Opto Semiconductors. "The Oslon UV 3636 is the first product in a series of innovations from Osram Opto Semiconductors in the UVC range. A high-power UVC LED will be launched in early 2021."

Price hike for LEDs due to growth in demand

WHILE MAJOR OEMs such as Apple and Samsung prepare to release their new notebook computers, tablets, and TVs that are fully equipped with miniLED backlights this year, various companies in the LED supply chain began procuring miniLED chips ahead of time in 4Q20, leading to an explosive demand growth for these chips. This in turn has crowded out the LED suppliers' production capacities for other mainstream LED chips, according to TrendForce's latest investigations.

Given this structure-wide shortage of LED chips, certain LED chip suppliers have been raising the quotes on chips supplied to non-core clients and chips with relatively low gross margins. This price hike is estimated at about 5-10 percent.

TrendForce further indicates that companies in the downstream LED supply chain have started to aggressively procure components in order to mitigate the impending price hike on raw materials and shortage of components due to manufacturers' tight production capacities after the Chinese New Year. However, products of certain serial numbers or specifications are already in shortage at the moment, therefore prompting these downstream companies to raise quotes first for small- and medium-size clients who place relatively low-volume orders. As for tier-one clients who have relatively higher bargaining power, should they reject such a price hike, they would then need to wait for more than two months in lead times, which is significantly longer than the average of two weeks.

Epistar is currently shipping about 150,000 pcs of miniLED wafers (4-inch equivalent) per month. As miniLED chips yield far higher gross margins than traditional LEDs, Epistar has reallocated some of its production capacities for the latter, less profitable products to miniLED chip manufacturing instead. On the other hand, San'an and HC SemiTek are directly benefitting from Epistar's order transfers. In addition to persistently growing demand for traditional LED backlights and RGB LED chips for video walls, San'an and HC SemiTek are also shipping several tens of thousands of miniLED wafers per month (4-inch equivalent) owing to skyrocketing miniLED demand.

Worth mentioning is the fact that HC SemiTek's product strategy of focusing on LED chips for display applications is paying off noticeably. By leveraging its competitive advantage of highly cost-effective products, HC SemiTek's capacity utilization rates have been fully loaded for two consecutive quarters since 3Q20. On the other hand, about 400,000 pcs in PSS production capacity was suspended last month due to the fire at GAPSS' fab. This incident led to a 5-10 percent price hike in key upstream LED chip materials including

sapphire wafers and PSS, likely to further exacerbate the price hike and shortage of LED chips.

TrendForce believes that the structural shortage taking place in the LED industry, which led to a price hike for LED chips, can primarily be attributed to the that fact the industry underestimated the production capacity needed for key parts of the supply chain during the infancy of pandemic-related emerging applications, in addition to the corresponding production capacity squeeze, although these issues are expected to be resolved within half a year. As well, the downturn experienced by the LED industry within the past few years led to a clearance of excess capacities and subsequently a highly concentrated supply of key materials in the upstream LED supply chain, including sapphire wafers and PSS. As a result, the suppliers of these key materials now enjoy increased bargaining power in price negotiations.

Ams introduces VCSEL infrared emitter family

AMS has introduced a family of infrared VCSEL flood illuminators that help industrial manufacturers to develop new and innovative applications for robots, cobots, autonomous guided vehicles, and smart devices which perform 2D and 3D optical sensing.

With everything including VCSEL and diffuser managed in-house by Ams for tight quality control and supply chain management on key components, the new EGA2000 flood illuminators provide a uniform, tightly controlled and high-output power illumination. This is essential for evolving applications using ranging, object detection and face recognition that use 2D and even the more sophisticated 3D sensing techniques based on time-of-flight or stereo vision.

The implementation of 3D sensing was pioneered in mobile phones, where it is used for secure face recognition. It is now emerging in the industrial mass market as a successful technique for applications such a object dimension detection in robotics; 3D mapping of the environment supporting the operation of autonomous guided vehicles (AGVs), including automatic vacuum cleaners and lawnmowers; face recognition in industrial systems; and night vision cameras.

Markus Luidolt, senior marketing director for 3D Sensing Modules and Solutions at Ams, said: "The rate of innovation in markets such as logistics and warehousing, home and building automation, and Industry 4.0 is remarkable. A mass market is emerging for new product categories such as home cleaning robots, cobots to assist human factory operators, and AGVs to replace conventional forklift trucks in warehouses."

He added: "The superior optical performance of the EGA2000 family and the range of options which it provides will help industrial companies to achieve more reliable ranging and depth mapping, speeding the go-to-market with fewer design iterations and less system debugging. Furthermore, to support customers' R&D investments in industrial products serving a wide range of challenging applications, the EGA product family is designed for long-term availability."

The optical performance of the EGA2000 flood illuminators is said to be a feature of the integrated Ams IR emitter architecture. Matching the micro-optics to suit the characteristics of the VCSEL emitter, the EGA2000 illuminators produce a uniform beam, which has a homogeneous rectangular profile. This tightly controlled illumination profile and field-of-illumination match the field-of-view of the IR image sensors used in 2D and 3D ranging and detection systems, thus increasing the strength and integrity of the reflected optical signal.

The EGA2000 family of illuminators offers two wavelength options: 850 nm for systems requiring maximum sensitivity and 940 nm for easier compliance with eye safety regulations. Good rejection of sunlight interference also makes the 940 nm illuminators suitable for use outdoors. Each wavelength option is also available in one of three beam configurations.

The EGA2000 flood illuminators are now available for sampling targeting mass production by Q2 2021.

Osram and Chronoptics work together on 3D camera

OSRAM OPTO SEMICONDUCTORS and New Zealand-based Chronoptics are cooperating on a 3D time-of-flight (ToF) camera kit based on Chronoptics' patented depth processing algorithms alongside Osram's infrared VCSEL technologies.

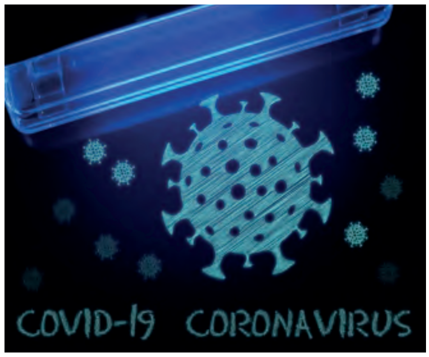
The Chronoptics KEA 3D ToF camera system will be used for industrial, consumer as well as automotive use cases. With its small dimensions of 100 mm x 40 mm x 35 mm, the camera is designed for an operating distance between 0.2 m to 15 m and has an ambient light immunity of up to 120,000 lux.

Osram's Bidos P2433Q VCSEL has been chosen due to its compact form factor, its high performance with regards to power output and module efficiencies of 38 percent today and upcoming modules with up to 50 percent, as well as its high-volume manufacturing package concept.

"During the project we really enjoyed the close technical support and intense exchange on the project with our partners at Osram," explains Richard Conroy, CEO and founder of Chronoptics. "We simplify the design and integration of 3D camera solutions into tomorrow's intelligent products for our partners, leveraging our patented depth processing and deep ToF

expertise. Our KEA ToF camera, powered by Osram's leading VCSEL illumination, is available to accelerate your product development."

Violeds can kill 99 percent of Covid in under a second



UV LED technology firms Sensor Electronic Technology, Inc (SETi) and Seoul Viosys, subsidiaries of Seoul Semiconductor, have announced that their Violeds technology can quickly and effectively kill 99.437 percent of SARS-CoV-2 in less than one second.

The testing was conducted in December 2020 through KR Biotech, a South Korea-based research institute specialising in sterilisation testing of the new coronavirus.

Results demonstrate that Violeds UV LED technology could be an effective method to disinfect airborne viruses, water systems, as well as areas where Covid-19 patients were housed, including hospital rooms.

After exposing SARS-CoV-2 to the Violeds UV LED module for one, three, and five seconds respectively, the research team observed the inactivation rate of virus particles at 99.437 percent in one second.

Violeds can replace of conventional UV lamps that contain mercury, a toxic element which is released when UV lamps are broken. Because of their short lifespan of around 5,000 hours, conventional UV lamps require frequent replacement. UV LED technology has advantages in both cost and safety with a long life of up to 50,000 hours, which is more than ten times the life of conventional mercury lamps.

UV LED technology is rapidly replacing the $70 million UV mercury lamp market due to technology advancements including miniaturisation to less than 1mm^2 as well as improved efficiency. As UV LED technology is adopted by new industries for bio-healthcare and virus disinfection, the global market for UV LEDs is expected to grow to $2.8 billion in 2025, according to Yole Développement, a leading compound semiconductor market research company.

“The Covid-19 pandemic and the accompanying risk of virus variants continue. Despite vaccination with influenza vaccines, flu deaths in the US average more than 10,000 per year. As hundreds of millions of people around the world are exposed to various infectious diseases, prevention through disinfection is now an essential method for reducing infections”, said an official at Seoul Viosys.

They added: “Due to the hazards of chemical disinfection methods, professionally designed UV LED disinfection systems represent a safer solution and may be the world standard in the future.”

Rockley Photonics: Bold plans in tough times

How an up and coming silicon photonics start-up plans to take on a soon-to-be multi-billion dollar industry

BY REBECCA POOL

BACK IN 2020, UK-based Rockley Photonics won $50 million in investment funds to grow its silicon photonics manufacturing technology, crucial for integrating III-V materials to silicon photonic integrated circuits. Investments now total more than $225 million, with the platform ready to take on large-volume production of high-density photonics circuits, including optical fibre and datacentre communication transceivers.

As chief executive, Andrew Rickman, says: "The latest funds are testament to the strength of our technology... We're on track for the big wave of 400G transceivers and believe we'll be in a pre-eminent position for the further wave of 800G transceivers for data centres."

The timing of the funding isn't surprising. Over the next few years, the global silicon photonics market is expected to mushroom, with analysts unanimous that this sector will be worth at least $3 billion come 2025 to 2027.

US-based Research and Markets predicts a mighty $3.77 billion by 2027, Global Market Insights, US, forecasts $3 billion by 2026, while Yole Développement of France, reckons the silicon photonic transceiver industry will be worth $3.6 billion come 2025. Today's market comes in at around $800 million.

Growth looks set to be largely fuelled by increasing demand for high-speed broadband services and deployment of 5G technologies and data centres worldwide, including developing nations, with applications such as LiDAR also emerging in the automotive sector. And like its competitors, Cisco, Intel, Macom, Mellanox, Neophotonics and more, Rockley Photonics is intent on capturing market share here.

However, Rickman and recently appointed chief commercial officer, Vafa Jamali, also believe the healthcare and wellness sector holds huge promise, with the company developing optical sensing chipsets for handheld and wearable devices.

Jamali spent more than 25 years working in the medical device industry, most recently at US-Ireland based Medtronic, and reckons that while home health has been an emerging trend for some time, the pandemic has accelerated demand.

"So many people now want to have a lab on their wrist [that provides] accurate and meaningful measurements that they can trust," he says. "This market is enormous and is growing at up to a 10 percent CAGR – I think there's a great opportunity to disrupt with a better technology, and we reckon we have something that can do this."

"So that's my thesis for coming to Rockley after 28 years in medical devices," he adds. "There's nobody that aggressively addresses this market [with non-invasive devices], I am excited."

Rickman is equally bullish, and highlights how wearables and smartphones are addressing a $45 billion market right now. "In our journey of 30 years in silicon photonics, we're always looking out for that massive opportunity, and we know that anything that really gets driven by an economy of scale is in a consumer market," he says. "So we saw this opportunity in devices for health and wellness – we believe that this is by far the single biggest opportunity in the field of silicon photonics."

Winning formula

But how does Rockley Photonics intend to compete with industry players such as Cisco and Intel? Rickman is no stranger to tech giants.

Cisco and Intel each invested $10 million in Bookham Technology, the silicon photonics components business he founded back in 1988. Meanwhile, the company he chaired from 2008, Kotura, was acquired by Israeli-American computer networking multinational, Mellanox Technologies, for its 100G photonic ICs in 2013.

Since launching Rockley Photonics, in 2013, Rickman has asserted that the company's 'third generation' silicon photonic platform is very different to the technology he helped to pioneer, and is offered, by rival firms. While most existing technologies integrate photonic structures with CMOS on a semiconductor chip, Rickman describes Rockley's silicon photonic process as 'engineered from the ground-up and optimised for photonics and not electronics'. And the platform still runs in large-scale silicon foundries.

According to the chief executive, difficulties arise when using a CMOS approach to integrate photonics structures at sub-micron dimensions as the wavelength of the photon is of the order of a micron. Rockley's platform counters this in a number of ways, including the use of multi-micron waveguides that lead to lower waveguide losses and more consistent performance.

The platform also: eliminates the need for active precision fibre alignment, a key stumbling block in the manufacture of transceivers; efficiently integrates III-Vs; removes expensive specialised processing techniques; and can pack a large number of components at high density. Indeed, in 2018, Rockley demonstrated how its technology could cost-effectively make high-density optoASICs for datacentre switching.

China links

But beyond the different platform approach, Rockley also hopes to have an edge on its competitors by having a foot in the Chinese market with its joint venture with optical fibre and cable provider, Hengtong Optic-Electric. The partners are manufacturing 400G optical transceiver modules based on Rockley's silicon photonics technology.

"We also realised that to be competitive we needed to take a vertically integrated approach to the market, and the Hengtong joint venture enables this," points out Rickman. "So we're now ramping up and shipping chips to our customers."

Indeed, the timing looks right and the market is growing. The silicon photonics industry has already shipped millions of units of optical transceivers, and beyond Hengtong, other China-based companies have entered the market.

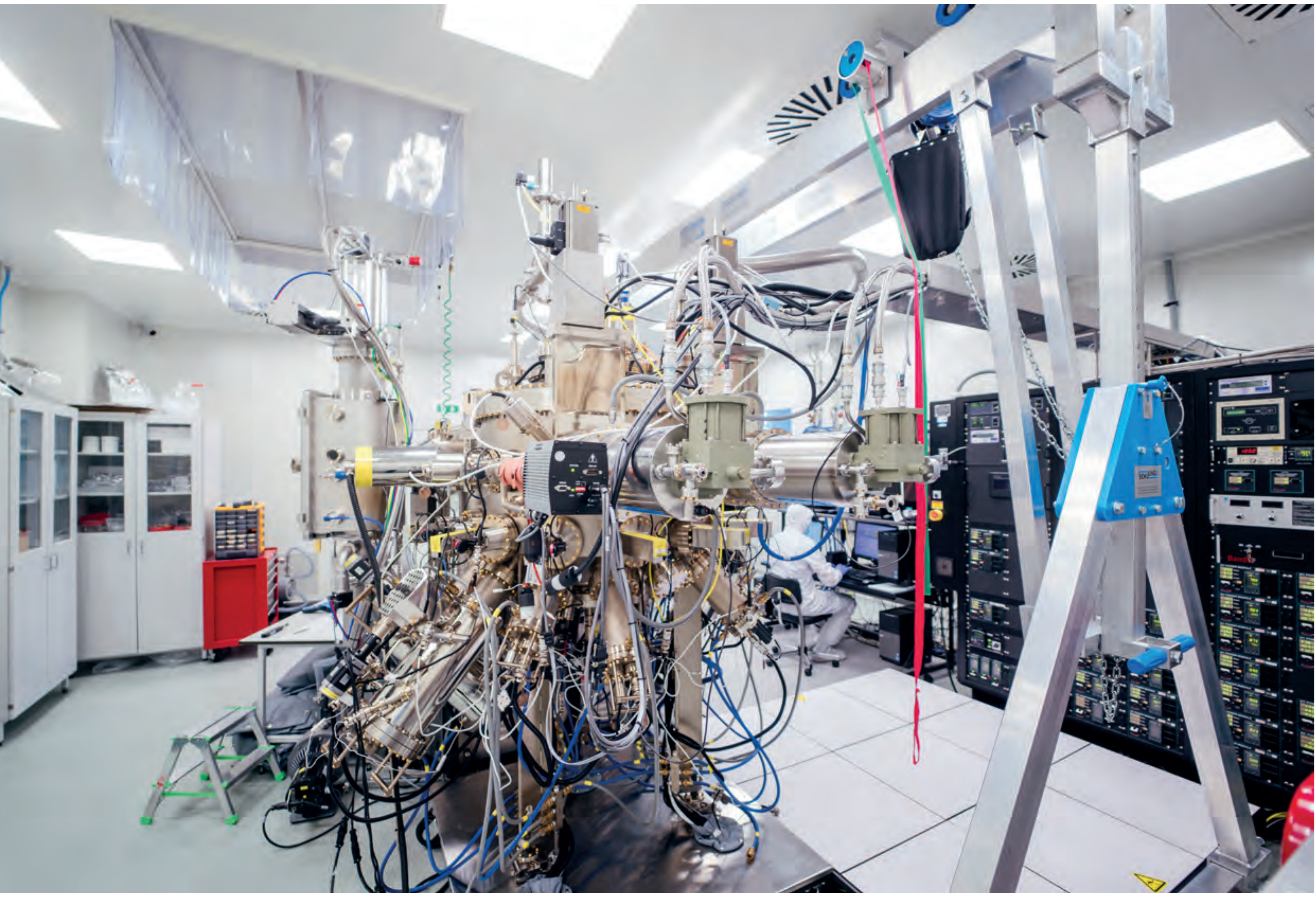
For example, Chinese cloud computing business, Alibaba Cloud, teamed up with US-based and Nokia-owned silicon photonics developer Elenion Technologies to manufacture a 400G optical transceiver. And China-based optoelectronics device provider, Broadex Technologies, has also joined forces with German start-up Sicoya, which manufactures silicon photonics transceiver chips.

Rickman is excited. From word go, Rockley has been working closely with large silicon and III-V materials foundries, as well as packaging facilities, preparing for the all-important ramp to large-volume manufacture.

"We believe that we now have the lowest cost technology and the lowest cost business structure to address a market of a particular time, including this extraordinary opportunity in health and wellness," he says. "Next year is going to be all about ramping up production and from there on in we expect volumes to grow significantly."

Rockley Photonics chief commercial officer, Vafa Jamali.

Andrew Rickman: Founder, Chairman & CEO of Rockley Photonics



GaSb-based chips promise a sensing revolution

Compact spectroscopic infrared sensors could aid healthcare, farmers, and sportsman

BY KRISTIJONAS VIZBARAS FROM BROLIS SENSOR TECHNOLOGY

Think of infrared chips and you'll probably think of InP. That's because this material and its related alloys have had tremendous success in this spectral domain, providing countless lasers and detectors for long-distance optical communication.

But InP can only get you so far. While it's the number one choice in the near-infrared, if you want to go further in that direction while retaining inter-band transitions, you'll need to consider another class of material. And providing the best choice is the GaSb system, which is paving the way towards an optical sensing revolution.

Merits of GaSb and its related alloys include an accessible spectral range spanning 1.5 μm to 4 μm – this is rich in strong, specific combinations of fundamental absorption bands associated with

Technology	Spectral region	Spectral region of optimal performance	Typical input power for 1 mm cavity, RT	Efficiency (> 2 µm)	Typical CW Operation temperature	SOI integration compatible*	Reference(s)
InP type-I	1.3 – 2.3	1.3 – 1.7	~ 100 mW	<10 %	RT and above	Yes	[1, 2]
GaSb type-I	1.5 – 3.5	1.7 - 2.7	< 30 mW	10 – 30 %	RT and above	Yes	[1, 2, 3, 4]
InP type-II	2 – 4	Insufficient data	1 W – 2 W	< 1 %	Below 0° C	Yes	[1, 2]
GaSb ICL	2 – 6	3 – 4	~ 100 mW – 2 W	~ 10 %	around RT	Yes	[2, 5]
InP QCL	3 – 20	4 - 12	0.5 – 5 W	< 10 %	RT	Yes	[2, 5, 6, 7]
OPO	2 – 5	2- 5	500 – 1000 W	< 1%	RT	No	[2]

Table I. Comparing different technologies for infrared lasers underscores the merits of GaSb. [1] R. Wang *et al*. Sensors **17** 1788 (2017) [2] S. Sprengel *et al*. Semicond. Sci. Technol. **31** 113005 (2016) [3] K. Vizbaras *et al*. Proc. Of SPIE **8277** 82771B, (2012) [4] K. Vizbaras *et al*. Appl. Phys. Lett. **107** 011103 (2015) [5] A. Spott *et al*. IEEE Photonics Conference 2017, October 10, 2017 [6] M. Razeghi *et al*. Optics Express **23** 8462 (2015) [7] M. Vitiello *et al*. Optics Express **23** 5167 (2015)

molecular rotational-vibrational transitions (see Table 1 for comparison). In addition, this material system enables high-volume, scalable manufacturing of efficient light sources and detectors that operate at room-temperature and can be integrated with SOI-based PICs.

There are numerous opportunities associated with spectroscopy in the 1.5 µm to 2.5 µm range. Within this band are absorption lines for lactates, ethanol, glucose, urea and other important bio-molecules. As infrared light penetrates through the skin, this enables non-invasive monitoring, aiding the health sector, improving training for sportsman, and helping to prevent alcohol-related accidents in the factory and on the road. More details on all these opportunities, along with those related to farming and plastic recycling, follow on from an introduction to spectroscopy based on GaSb devices.

Evaluating emission

For the GaSb material system – just as is the case for InP and its related materials – various options are available for generating laser emission. The most common is to use a type I quantum well, but for longer wavelengths interband cascade transitions may be needed. The pros and cons of these approaches, alongside alternative material systems, are outlined in Table 1.

Glance at this table and it is clear why the antimonide-based materials system is preferred, and why type-I technology is the best choice for high-volume applications that benefit from low energy consumption. Strengths include a mature design, high gain that results from the largest possible overlap between electron and hole wave-functions, and direct wafer-level testing of key electrical, optical and structural parameters – they include current-voltage characteristics, electroluminescence, and high-resolution X-ray diffraction spectra that offer an insight into strain, composition, and layer thickness. Having the opportunity to scrutinise a wafer before it is taped-in to make a device provides reliable early control of manufacturing yield, and allows pre-selection of wafers meeting the requirements to allow further processing.

Like other forms of type I quantum-well laser, to adjust the emission wavelength of that based on GaSb involves altering the composition of the quantum well and barrier layers and the thickness of the well. As a typical GaSb-based laser has no more than three quantum wells, most material in the epitaxial structure is in the form of the bulk layer, a situation that simplifies the epitaxial process and makes it less sensitive to deviations during production.

For high-volume production of infrared and telecom-wavelength optoelectronic devices based on GaAs and InP, the most common substrate size is

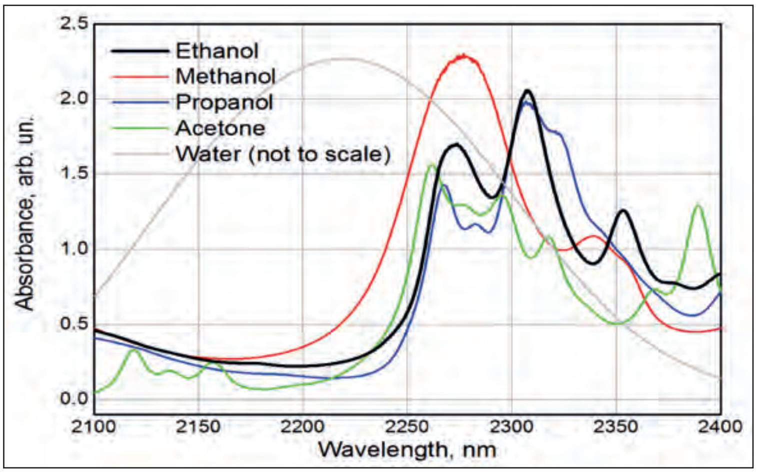


Figure 1. Infrared spectroscopy can identify ethanol, methanol, propanol and acetone by their unique absorbance spectra. The light grey line shows superimposed water transmission spectra.

Technology	Typical materials	Spectral coverage, µm	Pros	Cons	References
Type-I QW	InP**, GaSb	1.5 – 3.7	• Semiconductor technology; • Bulk layers mainly, • Easy on-wafer testing; • High manufacturability • Low input power devices	• InP performance drops rapidly at wavelengths > 1.7 micron • GaSb is limited to MBE technology only • GaSb performance drops at wavelengths > 2.5 microns	[1, 2, 4, 5, 6]
Type-II QW	InP	2 - 4	• Semiconductor technology • Bulk layers mainly • Easy on wafer testing • MOCVD compatible	• Extremely sensitive to thickness deviations • Low manufacturability • Current performance data limited • Operating below RT, very low output powers	[3,4]
ICL	GaSb	2 - 6	• Semiconductor technology • On wafer testing feasible but with limitations • Good performance around 3.3 micron • NRL willing to license the patent	• Superlattice based – huge amount of interfaces • Thickness deviation sensitive • Surface passivation needed • Low manufacturability • NRL holds the patent to this technology • Performance below or beyond 3.3-3.4-micron range limited	[4, 6]
QCL	InP	3 - 16	• Semiconductor technology • MBE & MOCVD compatible • Very wide wavelength design range	• Extreme number of interfaces – epi wafer growth complex • No on-wafer testing • Manufacturability low at high volumes • Wavelengths < 4 microns difficult with good performance • High-voltage, high power consumption	[4, 7, 8]
OPO	Other	2 - 5	• Single device for entire spectrum	• Solid-state laser technology • Not-compact • Not scalable • No integration with SOI • High power consumption	[9]

Table II. There are various of light source technology for accessing wavelengths beyond telecom. [1] K. Vizbaras *et al*. Appl. Phys. Lett. **107** 011103 (2015) [2] R. Wang *et al*. Opt. Express. **24** 28977 (2016) [3] R. Wang *et al*. Sensors **17** 1788 2017 [4] S. Sprengel *et al*. Semicond. Sci. Technol. **31** 113005 (2016) [5] K. Vizbaras *et al*. Proc. Of SPIE 8277 82771B (2012) [6] A. Spott *et al.* IEEE Photonics Conference 2017, October 10, 2017 [7] M. Razeghi *et al.* Optics Express **23** 8462 (2015) [8] M. Vitiello *et al*. Optics Express **23** 5167 (2015) [9] Cobolt Odin TM, IPG CLT-SF lasers (http://www.ipgphotonics.com/en/products/lasers/mid-ir-hybrid-lasers/1-8-3-4-micron/cl-sf-and-clt-sf-0-2-10-w http://www.coboltlasers.com/wp-content/uploads/2014/11/D0348-B_Datasheet-Cobolt-Odin-Series.pdf).

3-inch. However, recent developments in datacom technology, primarily the roll-out of low-cost VCSELs, has led to an increase in the use of 6-inch GaAs substrates.

Production of GaSb laser diodes tends to involves 3-inch or 4-inch wafers, but it is rumoured that 6-inch device-grade GaSb wafers are already available for testing. They are often loaded into multi-wafer MBE chambers, typically with a configuration of 7 x 3-inch, 5 x 3-inch or 4 x 4-inch. Epiwafer throughput and quality continues to increase, thanks to the efforts of manufacturers of substrates and growth tools. In the last few years, substrate manufacturers such as Wafer Technology have matured GaSb substrate technology up to 6-inch diameter; and MBE tool manufacturers, such as the US company Veeco and the French firm Riber, have made considerable improvements, introducing new component designs and chamber geometries. These refinements enable increases in group-III flux uniformity and temporal stability, crucial for multi-wafer growth of very thick heterostructures.

By working closely with MBE tool manufacturers, over the last eight years our team at Brolis has developed tremendous expertise and technology for multi-wafer, large-scale production of GaSb-based optoelectronic devices. Our first major milestone came in 2016, when we demonstrated the world's first widely-swept hybrid GaSb/SOI laser. Since then we have made

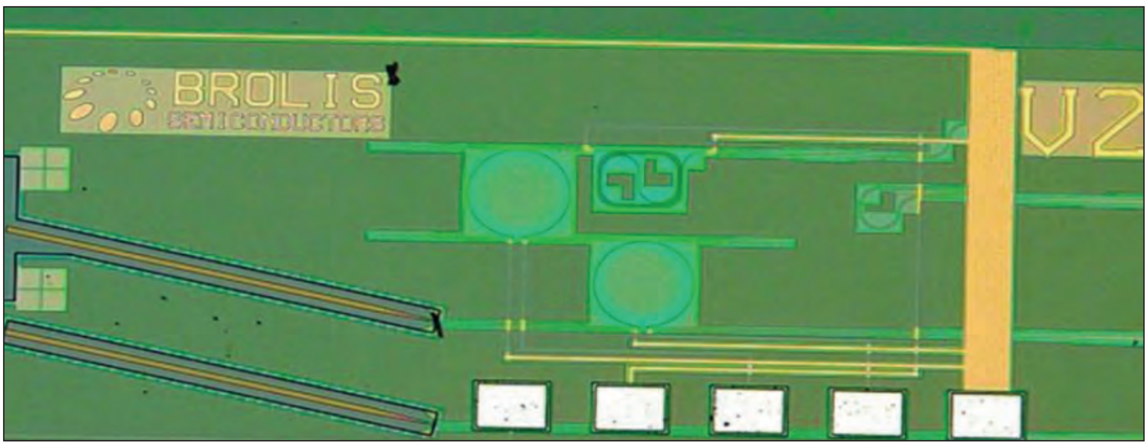


Figure 2.
The SOI part of Brolis' widely-swept GaSb/SOI hybrid laser. Two coupled micro-rings are clearly visible.

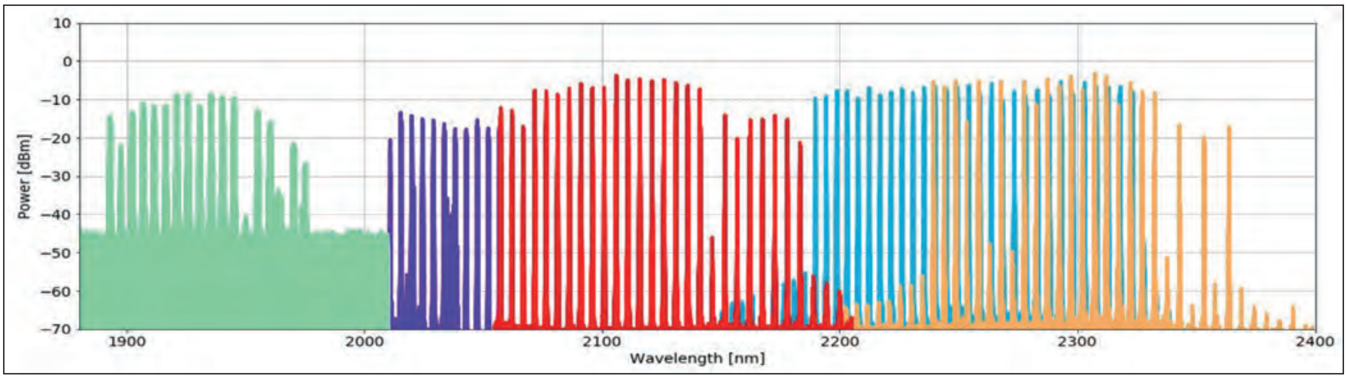


Figure 3. Superimposed spectra show that four widely-swept GaSb/SOI lasers can cover the spectral range from 1900 nm to 2400 nm. Devices exhibit continuous-wave lasing with output powers of around 1 mW. As tuning involved only tuning a single micro-ring, spectral separation is defined by the free spectral range of a ring (several nm).

considerable progress in integrating GaSb type-I light emitters with SOI PICs.

Our latest success is the fabrication of a GaSb-based monolithic laser spectrometer, based on four ultra-widely swept hybrid lasers and photodetectors. Lying at the heart of this spectrometer are four single-mode lasers, each with a side-mode suppression ratio exceeding 20 dB. These lasers are combined with two coupled micro-ring resonators with slightly different diameters, realised in an SOI circuit. By turning to the Vernier effect, we are able to electrothermally sweep the laser's wavelength at a rate of up to 1 kHz. Each laser offers 120 nm of tuning, and by shifting the gain peak for each GaSb light source, we realise a combined tuning range of over 400 nm (see Figure 2).

If we thermally tune just one of the micro-rings, this leads to spectral hopping across the free spectral range of the ring – the mode hops are typically 4-5 nm. By tuning both micro-rings in a coordinated manner, we realise virtually quazi-continuous tuning across the entire spectral range (see Figures 3 and 4).

As one may expect, our first hybrid sensor looked a little 'clumsy', as is often the case for new devices (see Figure 5 (a)). But it is functional, thanks to successful integration of four GaSb-based photodetectors, one GaSb-based light emitter and an external SOI cavity. Subsequent miniaturisation of this spectroscopic sensor is in progress (see Figures 5 (b) – 5 (c)), and it includes already 2-4 GaSb gain-chips, butt-coupled to the SOI and 4 GaSb control detectors flip-chipped on the SOI. The experimental tuning range (wavelength map) of one such hybrid device's one channel is shown in Figure 3. In the long run, the technology should enable a footprint of just 2 x 3 x 1 mm, which is fully compatible with all current consumer and industrial platforms. Current sensor evaluation boards for internal use are shown in Figure 5 (c).

With our current state-of-the art GaSb/SOI technology, we use four lasers with output powers of around 0.25 - 1 mW to sweep across 480 nm. For this uncooled

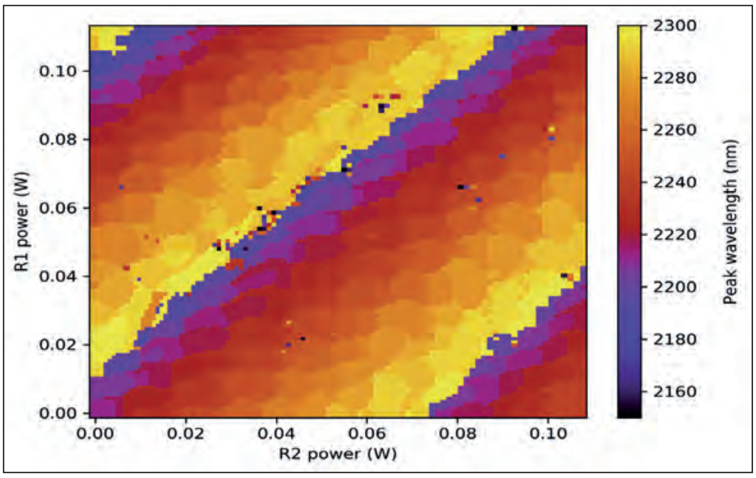


Figure 4. The peak wavelength of Brolis' single widely-swept laser, when both micro-rings are electrothermally tuned in a specific manner. Continuous spectral coverage is clearly visible.

technology, key figures of merit are a responsivity of 1.5 A/W, a detectivity of 2-3 x 10^{10} cm $Hz^{0.5}$ W^{-1}, and a noise-equivalent power of 2 x 10^{-12} W $Hz^{-0.5}$. These figures prove that our technology delivers sufficient performance for a plurality of applications – from fluid to gas analysis by tuneable laser absorption spectroscopy. What's more, the best is still to come, as we continue improving the light source, detector and hybrid integration technology.

Multiple markets

The most famous application for spectroscopic sensing is measuring levels of glucose, an insight helping those with diabetes to monitor their condition. Realising this technology is not easy, because sensing glucose comes from measurements made on skin – that is, the tissue matrix – and this has great variability, both from person-to-person and from day-to-day. When those challenges are overcome, there is still the issue that glucose monitoring demands a highly regulated environment. Even if a technology is ready that addresses all these concerns, it could take up to a decade to enter the market.

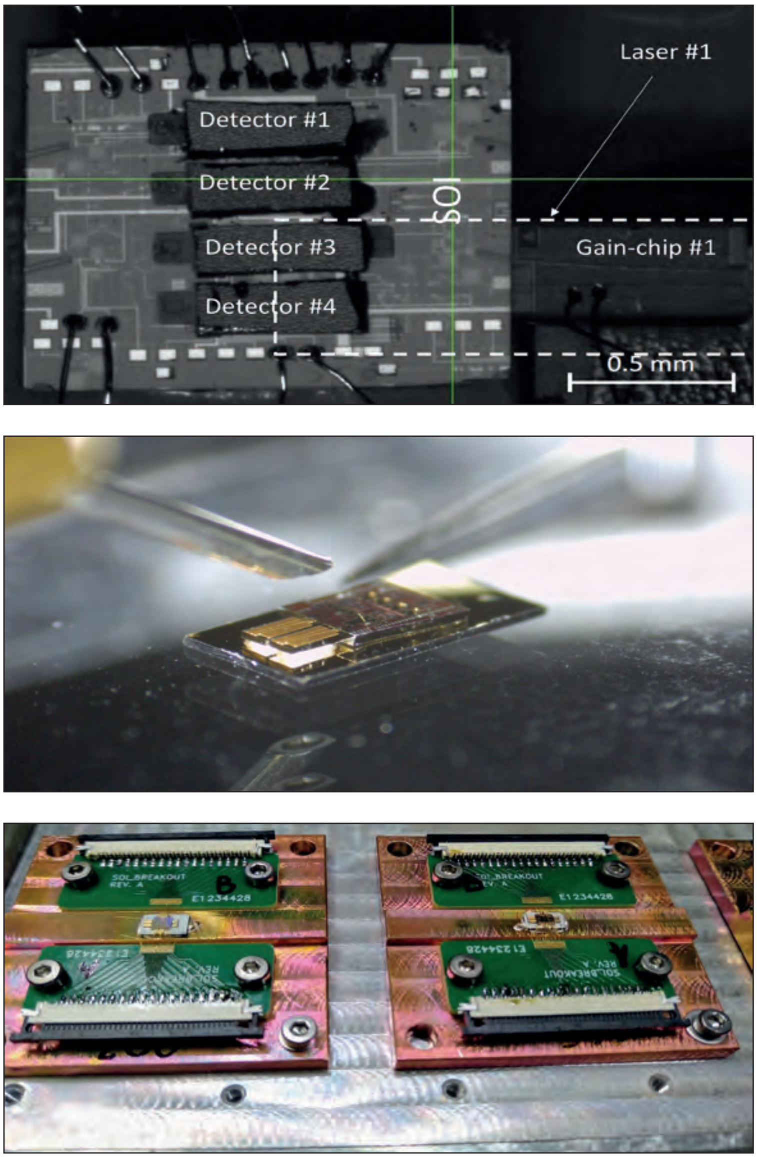


Figure 5. (top) Brolis first integrated GaSb/SOI sensor, based on four widely-swept lasers, has been produced in-house. On the lower right of the GaSb gain chip, the coupled to SOI external cavity is visible, along with: the four GaSb-based photodetectors flip-chipped on the SOI for wavelength control; output power monitoring (centre): and three additional ports for gain-chip coupling (the sides).(middle) Snapshot of current hybrid integration process – two GaSb gain chips butt-coupled to the SOI are visible. The automated hybrid integration robot is Brolis in-house designed and built. (bottom) Assembled BROLIS sensor demonstrators for evaluation boards (currently for in-house testing only). All four gain-chips, butt-coupled to the SOI are visible.

A related field for transdermal spectroscopic sensors is monitoring lactates. One benefit of keeping track of lactate concentration in human blood is that a rise in value provides an early predictor of sepsis, which is responsible for one in five hospital deaths worldwide.

In addition, as lactates are a biomarker for anaerobic performance and fatigue, they are of great importance in endurance and power sports. It would be a dream-come-true for many professional athletes, coaches and amateur-sportsmen to monitor lactate dynamics during exercise. This real-time insight would allow sportsman to precisely adjust training loads, avoid overtraining and injury and increase performance. If a spectroscopic sensor is in an integrated chip form, it can be incorporated into a wearable device form factor and target the consumer segment.

Another important molecule to consider is ethanol, key to measuring alcohol levels in the blood steam. It is possible to determine levels of ethanol by measuring the reflection spectrum through the skin (see Figure 6). This technique could curb accidents, due to the threat of exposing either drinking and driving, or drinking and working. In addition, it could help everyone to take more personal responsibility, by making self-monitoring available. It is far better to know that you have drunk too much to be safe to work or drive, than to be caught ‘in the act’, possibly after a fatality.

Uptake of a personal alcohol-monitoring system could be very high if such a device could be integrated in a wearable form or added to a wearable/smartwatch platform. Another option, available in the age of the IoT, is to integrate a sensor with a critical piece of machinery, such as a car or industrial tool. This could prevent intoxicated drivers from starting their cars, and operators under the influence of alcohol from using machinery.

Like the measurements of other molecules trans-dermally, it is a challenge to determine levels of ethanol. Success requires a long, expensive research and development effort, so it will be at least three-to-five years before a sensor will enter the market.

Before our GaSb-based technology makes an impact in complex transdermal sensing, we expect it to be deployed in hand-held fluid spectroscopic sensing. In the brewing industry it is crucial to determine precisely the ethanol content, and be able to distinguish between different alcohols and control their presence during the process. It is easy to add spectroscopic

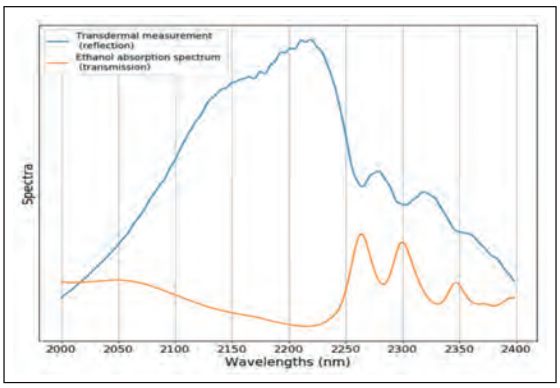


Figure 6. Transdermal optical signal of a tissue matrix containing ethanol, measured in reflection geometry (blue line) and ethanol absorption spectrum (orange). Characteristic ethanol absorption dips are clearly visible in the transdermal signal.

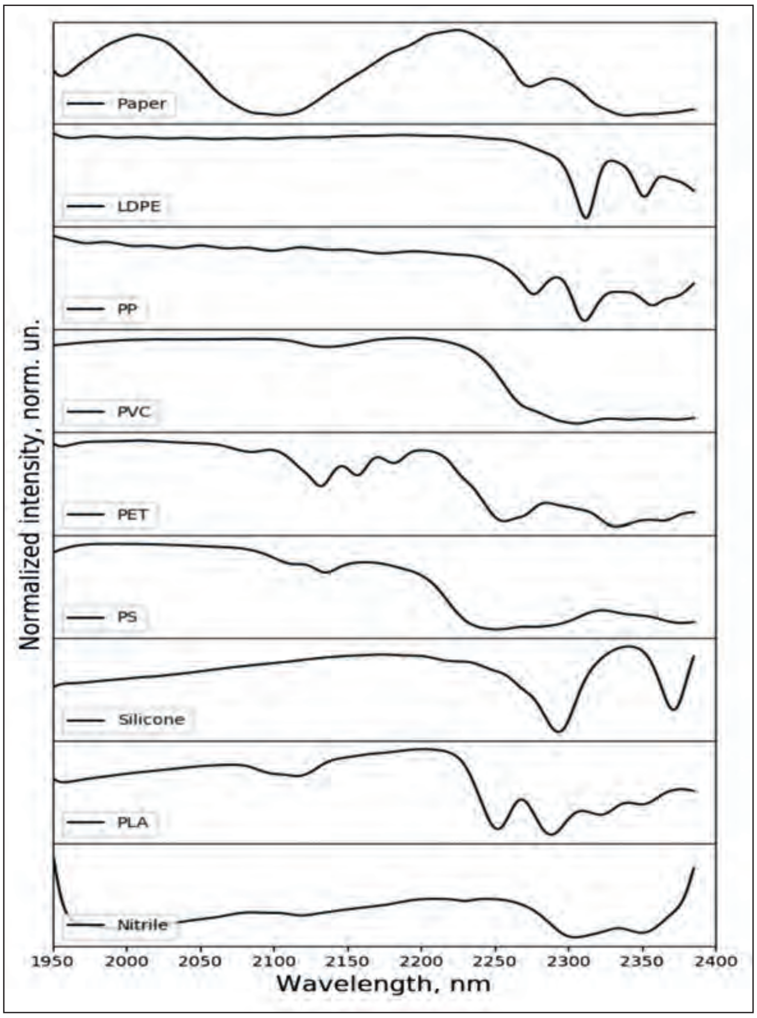


Figure 7. Sorting different types of plastic can draw on the transmission spectra of different materials.

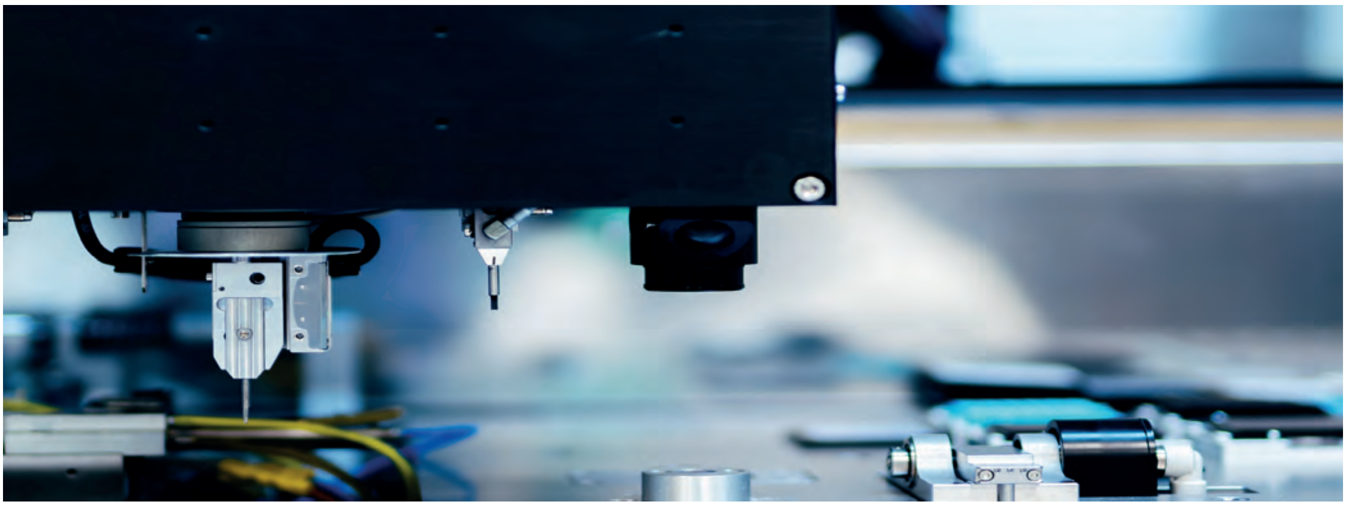
sensors to existing industrial machinery, and to use a hand held spectrometer for home or small-scale brewing.

A related opportunity is the deployment of an ethanol content sensor in a fuel or another fluid matrix. This sensor could be handheld, or incorporated into existing industrial machinery.

Yet another potential application for GaSb-based sensors is the sorting of plastics, for recycling or other purposes. Different plastics can be identified by strong, clearly distinguishable features in the spectral range spanning 1.5 μm to 2.5 μm (see Figure 7). A laser spectrometer based on our technology offers a more affordable, compact alternative to the current solution, an expensive short-wave infrared camera.

Potentially lucrative opportunities for spectroscopic sensing also exist in the agricultural sector. This technology can identify milk constituents, such as fats, proteins, and urea, because they have significant absorption features between 1.5 μm and 2.5 μm. There is much merit in monitoring milk content in real-time and tracking trends in individual cows and their herds. If farmers monitor and record milk fat, milk protein, somatic cell count and urea content, they can adjust nutrition and get an early warning of incoming mastitis. Armed with this insight, they can take preventative action, rather than eventually prescribing antibiotics and removing the cow from milk production. With our technology, it should be easy to incorporate sensing hardware into most existing milking machinery.

The examples that we have listed here are just a fraction of those that exist for fluid, solid-state and gas sensing. The key point is that our current spectroscopic sensor – that is, our laser-spectrometer that combines widely-swept hybrid GaSb/SOI lasers with an uncooled GaSb-based detector on a single chip – is a powerful, generic piece of hardware that can address niche market segments and be scaled to serve consumer applications.



Giving 5G better GaN

Helping advance the GaN HEMT, researchers are developing processes for manufacturing complex millimetre-wave circuits, getting to the bottom of substrates losses and non-linearities, and speeding *p*-type devices

BY RICHARD STEVENSON

RECENTLY, FOR MANY OF US, our mobile has been anything but. Instead, it has sat at home, providing connectivity through our WiFi as we hunker down through wave after wave of the pandemic.

But this time will pass. As the vaccine rolls out, we will return to the outside world and once again rely on networks of base stations to upload web-pages to our phones, and stream music and video. There will be delays in the data at times, and our initial frustration may turn to a desire to see a greater roll-out of a 5G network, to convince us that now is the time to upgrade to a cutting-edge phone.

For 5G infrastructure, GaN is the key material for 5G. When it is used to make solid-state amplifiers, rather than other materials such as silicon and GaAs, it enables higher powers, a high efficiency, and a higher power density. As GaN devices can be built on silicon, high-volume, low-cost production in 300 mm foundries is possible. What's more, the silicon foundation provides an opportunity to integrate this technology with silicon CMOS. It is a marriage that could aid the development of complex circuits, such as those involving beam-forming and phased-antenna arrays, that are part of the 5G roadmap.

While GaN is by no means the finished article, its weaknesses are being addressed, with significant progress reported at the most recent International Electron Devices Meeting (IEDM), held on-line in late 2020. At that virtual gathering, one imec-led team detailed a 200 mm process for making millimetre-wave GaN on-silicon HEMTs that incorporate three copper layers, another imec-led collaboration reported the results of investigations into substrate RF losses and non-linearities; and a team led by engineers at Cornell University claimed to have obliterated the gigahertz barrier for a *p*-type GaN HEMT.

Millimetre-wave process

The roll-out of 5G will come in two parts. We are already seeing the introduction of a sub-6 GHz infrastructure that will lead to a slight increase in data rates compared with 4G. Following on, and offering a breath-taking hike in download and upload speeds, will come millimetre-wave connectivity.

At IEDM 2019, a team from imec reported the results for RF GaN-on-silicon HEMTs produced with an aluminium-based back-end-of-line process suitable for making sub-6 GHz devices on 200 mm silicon.

"This is probably a technology of choice for sub-6 GHz applications," claimed Bertrand Parvais, who this December unveiled the latest advances in an on-line talk and accompanying paper. Recent progress

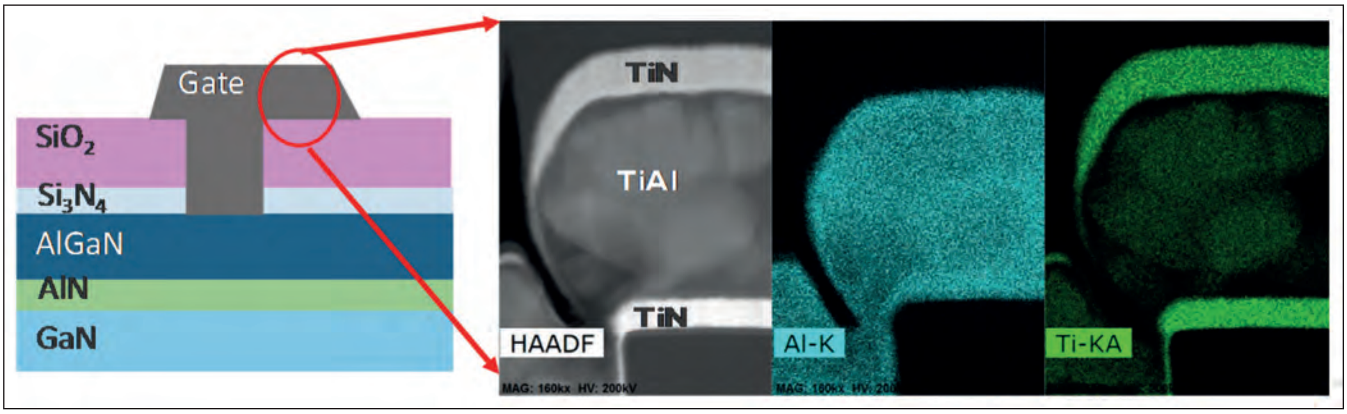


Figure 1. Images obtained with high-angle angular dark-field transmission electron microscopy show that the layer of titanium in the metal stack has reacted with AlCu to form TiAl. As TiAl leads to an increase in sheet resistance, titanium has been removed from the metal stack used to make millimetre-wave HEMTs.

has created a second-generation technology, suitable for millimetre-wave circuit operation.

"To achieve this goal, gate lengths have to be scaled down using a 193 nm lithography," said Parvais. "Furthermore, multi-finger transistors need to be enabled, and this is possible through three layers of copper backend."

As well as scaling device dimensions and switching from an aluminium back-end-of-line process to one involving three layers of copper, Parvais and co-workers slashed the gate leakage current in their HEMTs, and trimmed the contact and gate resistance.

For the sub-6 GHz technology reported in 2019, imec's engineers deposited TiN by PVD to form Schottky gates. This led to high-leakage currents, which would exceed the breakdown criteria of 1 mA mm^{-1} under an off-state bias for gate lengths of 320 nm and below.

To ensure an acceptable gate leakage for a gate length of just 110 nm, which is the dimension employed for millimetre-wave circuits, Parvais and colleagues switched to an ion-metal plasma process for the addition of TiN. This move slashed the leakage current by two orders of magnitude, a breakthrough attributed to the 0.2 eV increase in the work function of TiN.

Shrinking HEMT dimensions can also cause the contact resistance to hamper RF performance. Preventing this from happening, the imec team cut the contact resistance from around 0.3 Ω mm to below 0.15 Ω mm by improving the process for the AlGaN barrier etch and the post-etch clean.

A low gate resistance is key to realising a high maximum-oscillation frequency, essential for millimetre-wave amplification. Accomplishing this with a lift-off process involving a thick gold layer is easy, but that's not an option, explained Parvais: "In order to ensure CMOS compatibility, lift-off is prohibited, and a gate first approach is adopted in order to avoid any possible degradation during the ohmic contact formation."

The team from imec deposited a metal stack, before defining the dimensions of the contact with a subtractive process involving lithography and etching. Initially, the stack included a layer of AlCu, sandwiched between titanium. However, intermixing created TiAl (see Figure 1), which has a higher sheet resistance than AlCu. So Parvais and co-workers moved to a titanium-free process that trimmed sheet resistance from 0.55 Ω/square to 0.2 Ω/square. This refinement also increased the maximum oscillation frequency by more than 30 percent.

Fabrication of 110 nm-gate-length HEMTs involved 193 nm lithography and a standard CMOS copper damascene-based process (for more details, see Figure 2).

Measurements on an 8-finger device with a gate length of 110 nm and a total width of 200 mm revealed a drain current of 1.2 A mm^{-1} at a gate bias of 2 V, and a typical peak conductance of 430 mS mm^{-1}, produced at a drain-source voltage of 4 V. Corresponding values for the cut-off frequency and maximum oscillation frequency were 56 GHz and 135 GHz, respectively.

Large signal characterisation at 28 GHz using HEMTs with a gate length of 200 nm revealed a power-added efficiency of 42 percent at an output power of 17.5 dBm.

Parvais admitted that the cut-off frequency of imec's HEMT is lower than would be expected for a transistor with a 110 nm gate length. He attributed the shortfall to an issue associated with the patterning of the ohmic layer. Simulations suggest that by addressing this, the cut-off frequency should increase to 80 GHz, along with increases in the maximum oscillation frequency and the power-added efficiency.

RF losses and linearity

One of the weaknesses of the pairing of GaN devices and the silicon foundation is that the finite resistivity of the substrate limits the performance of the transistor, as well as the passives, leading to poor isolation. Employing high-resistivity silicon can help to address this, but the substrate is compromised, with studies showing that losses increase after MOCVD of the

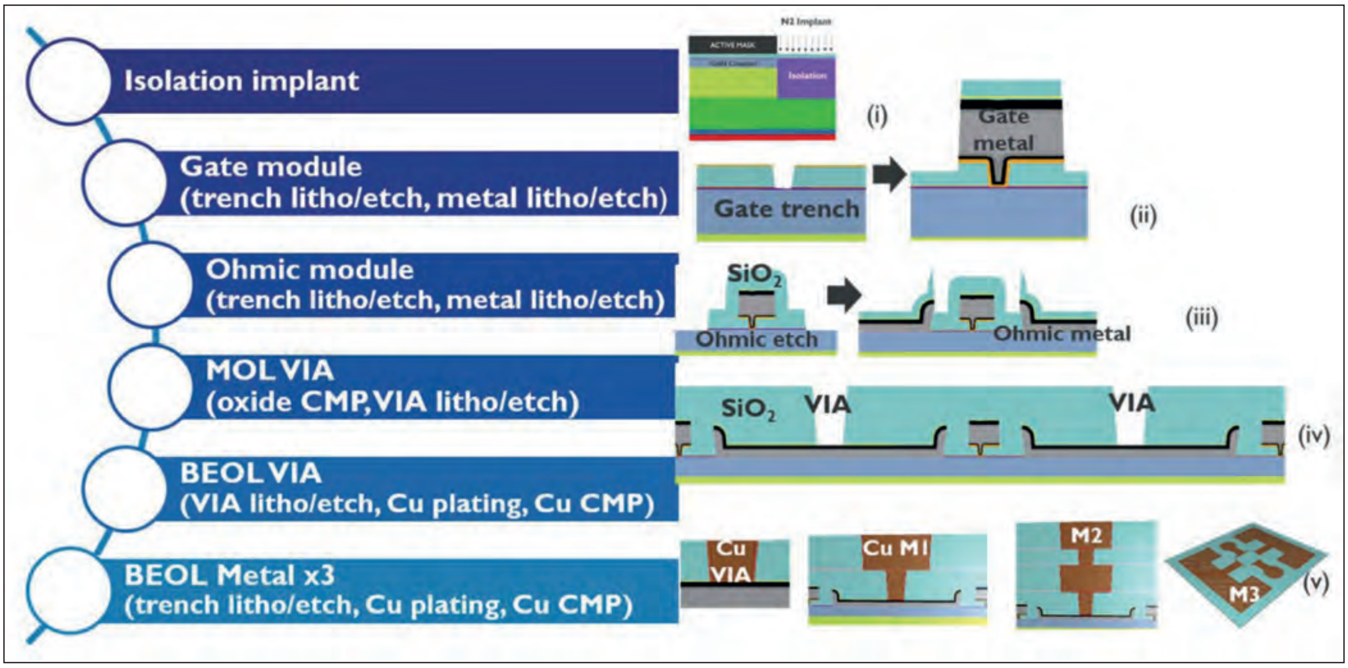


Figure 2. Imec's approach for producing millimetre-wave devices with a three-level copper back-end-of-line process begins with the deposition of a SiO layer and isolation by a nitrogen implant (i). Etching a trench in SiO creates a gate opening (ii), before a further layer of SiO is added, followed by an etch of the source/drain ohmic regions and metallisation, patterning and anneal (iii). The middle-of-line (MOL) includes deposition and planarization of SiO (iv). Vias are then added, by etching the ohmic and gate metals, prior to filling with copper and subsequent chemical mechanical polishing. The M1 dielectric is deposited and patterned, before a copper fill and chemical mechanical polishing. This via and metal process is repeated twice to form the three-copper-layer architecture.

HEMT epilayers. Concerns have been directed at: an inversion layer formed at the interface of silicon and the AlN nucleation layer; the creation of S-O-N complexes near the top of the silicon substrate; and diffusion of aluminium and gallium atoms into the substrate, occurring during epitaxy.

What's been lacking has been a detailed study of substrate losses and non-linearities for GaN-on-silicon HEMTs that considers both epitaxy and fabrication. But that's now been addressed, thanks to a team lead by researchers from imec that has considered the impact of material growth and key processing steps

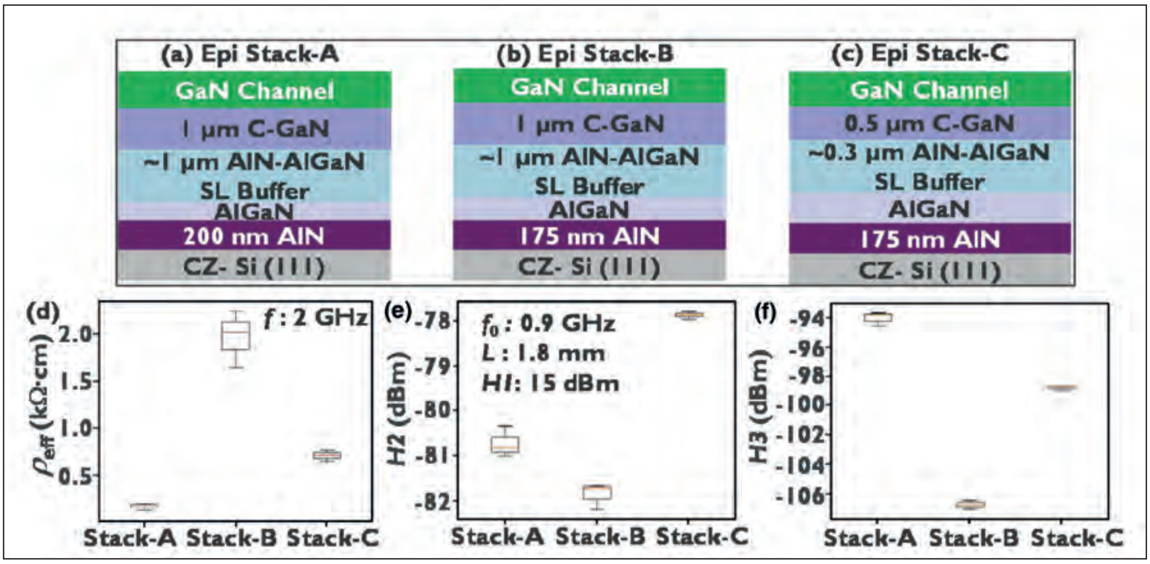


Figure 3. A team from imec considered how the changes to the epitaxial design of the GaN HEMT ((a) to (c)) impact effective resistivity (d) and second- and third-harmonic power ((e) and (f), respectively). The effective resistivity is determined from co-planar waveguides with a centre conductor width of 75 μm and a slot width of 50 μm. Values for the second (H2) and third (H3) harmonic power are measured at a fundamental frequency of 0.9 GHz, and a H1 of 15 dBm, for 1.8 mm-long lines.

on RF losses and linearity associated with substrates used to make GaN-on-silicon HEMTs.

Team spokesman, Sachin Yadav, explained that he and his co-workers used Czochralski silicon for their work, because this is the only substrate available up to 300 mm in diameter. On these boron-doped substrates, which are 1.15 mm-thick, they added a stack of nitride layers by MOCVD to investigate the formation of a parasitic channel, caused by back diffusion of aluminium and gallium atoms during the growth. This diffusion created a *p*-type layer.

Two figures-of-merit were used to evaluate the different growth processes and structures. The effective resistivity of the substrate provided a yardstick that is independent of metallic losses, while the second harmonic power, determined for a fundamental tone at 0.9 GHz, offered an insight into non-linearity. Both values were extracted from small- and large-signal measurements on 1.8 mm lines.

Of the three structures grown by the team (see Figure 3), the one with the highest resistivity and greatest non-linearity exhibited the strongest in-diffusion of aluminium and gallium atoms.

One option for providing DC isolation, to make CMOS-compatible GaN HEMTs, is nitrogen implantation. "Our understanding is that implants creates traps inside the nitride layers, which remotely modulate the conductivity of the parasitic surface conduction layer, and hence change the losses," explained Yadav.

To evaluate the impact of nitrogen implantation, Yadav and co-workers investigated the changes in effective resistivity and second-harmonic power resulting from implants with energies of 75 keV, 150 keV and 375 keV. Any implantation diminished effective resistivity, while the combination of a 75 keV and a 150 keV implant produced the best linearity.

A downside of the silicon substrate grown by the Czochralski process is that it contains interstitial oxygen impurities, stemming from the dissolution of the silicon oxide crucible. If processing steps increase the temperature of this substrate to the range 350°C to 500°C, the interstitial impurities tend to form clusters, which act as electrically active thermal double donors. Such temperatures are common for the fabrication of GaN HEMTs, as they occur during III-V epitaxy, dielectric deposition and ohmic anneals.

Regarding the latter, the formation of low-resistance contacts with a CMOS-compatible process requires rapid thermal annealing between 500°C and 600°C. Yadav and co-workers have considered the impact of this process, finding that a 90 s anneal in nitrogen gas at between 400°C and 600°C degraded effective resistivity. For a high-resistivity silicon substrate with an effective resistivity of 3-6 kΩ cm and an unspecified level of interstitial oxygen, this resistivity

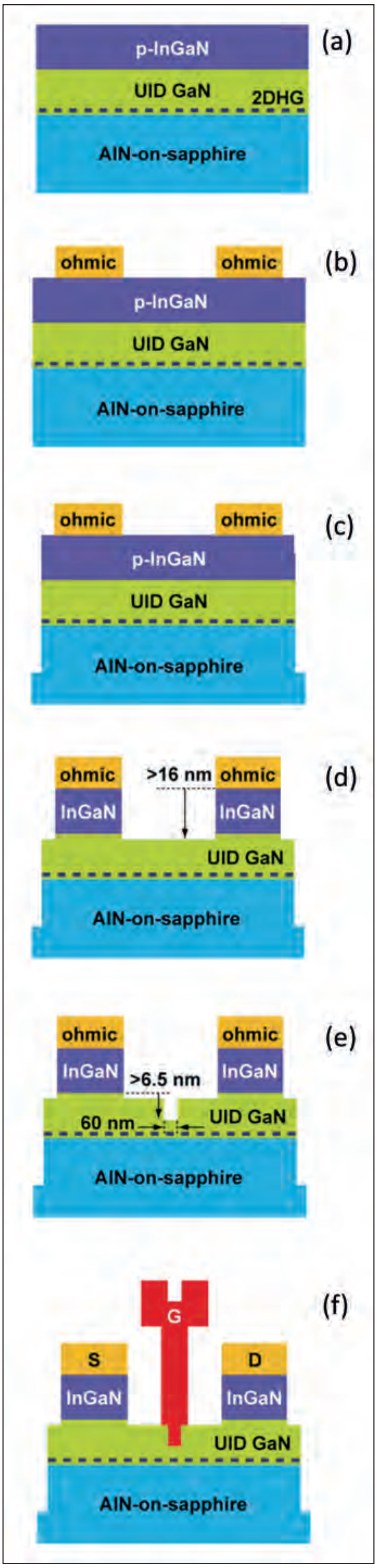


Figure 4. Researchers from Cornell and Intel have smashed the gigahertz barrier for *p*-channel HEMTs with a device with a gate length of just 120 nm. Fabrication of these transistors began with MBE-growth of a GaN/AlN heterostructure with a magnesium-doped $In_{0.05}Ga_{0.95}N$ layer (a). The addition of non-alloyed Pd/Au/Ni ohmics came next (b), followed by a chlorine-based inductively coupled plasma etch for mesa isolation (c), the first recess etch step for removing *p*-type InGaN (d), a second recess etch with electron-beam lithography to thin the gate-channel distance (e), and the addition of a Mo/Au Schottky T-gate.

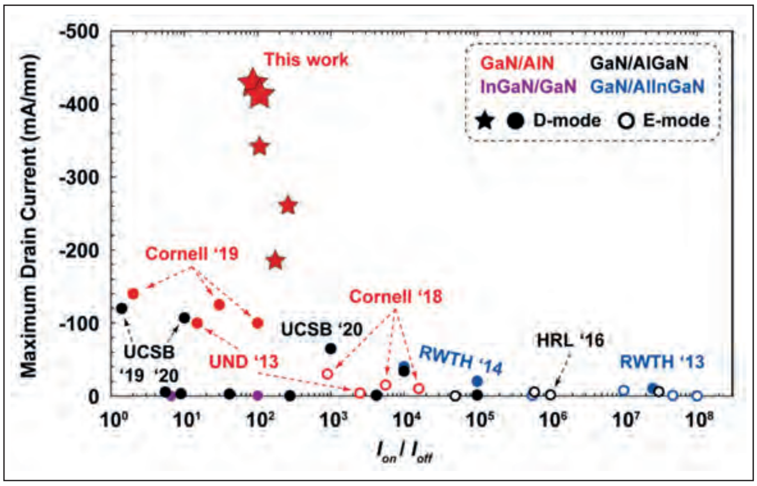


Figure 5. A partnership between engineers at Cornell and Intel has propelled the drain current for *p*-channel HEMTs to a new high. Success results from scaling device dimensions and trimming the contact resistance.

exhibited a monotonic reduction with annealing temperature. In contrast, for substrates with effective resistivities of 7.5 kΩ cm and 4.3 kΩ cm and interstitial oxygen levels of 3.8 ppma and 3 ppma, respectively, degradation did not depend on temperature.

Yadav and co-workers have benchmarked their results, considering values for effective resistivity and second-harmonic power. "Our results compare well with many high-res SOI substrate technologies, but still lag the most advanced, trap-rich SOI samples. Further substrate improvements are needed to match that performance."

Accelerating *p*-channel HEMTs

Due to challenges associated with *p*-type doping of GaN, the performance of this class of HEMT has lagged its more common *n*-type counterpart. If this weakness could be addressed, it would aid development of: wideband amplifiers that handle active loads; the powering of digital-to-analogue converters; and the construction of digital power amplifiers, as this would ease impedance matching and power combining.

Making massive strides towards closing that gap are Kazuki Nomoto and colleagues from Cornell University, working in partnership with researchers from Intel. Prior to their work, *p*-channel GaN HEMTs had a cut-off frequency and maximum oscillation frequency of no more than hundreds of megahertz – now these devices can reach values of around 20 GHz. In addition, the drain current has hit a new high, realising more than 420 mA mm^{-1} at room temperature. Critical to success on both fronts is the substantial shrinking of device dimensions.

HEMTs were fabricated from GaN/AlN epiwafers, formed by taking Al-polar AlN-on-sapphire templates, loading them into an MBE chamber, and depositing a 500 nm-thick layer of AlN, followed by a 15 nm-thick undoped GaN layer, and a 15 nm-thick heavily doped InGaN layer. This structure forms a two-dimensional hole gas at the GaN/AlN interface, confined in the GaN layer by a valence band offset and a high polarisation field. Devices with a gate length of just 120 nm were formed by mesa isolation, followed by processes including etching and lithography (see Figure 4 for details of the process).

Measurements of the contact resistance showed that this plummets from around 9 Ω mm to below 1 Ω mm when the current exceeds 100 mA mm^{-1}. According to the team, the latter value for the contact resistance is amongst the lowest reported for *p*-channel HEMTs, and contributes to the high-performance of these devices.

The saturated on-current hit 428 mA/mm at room temperature, for a *p*-channel HEMT with a source-drain distance of 680 nm. This value breaks new ground for this class of device (see Figure 5).

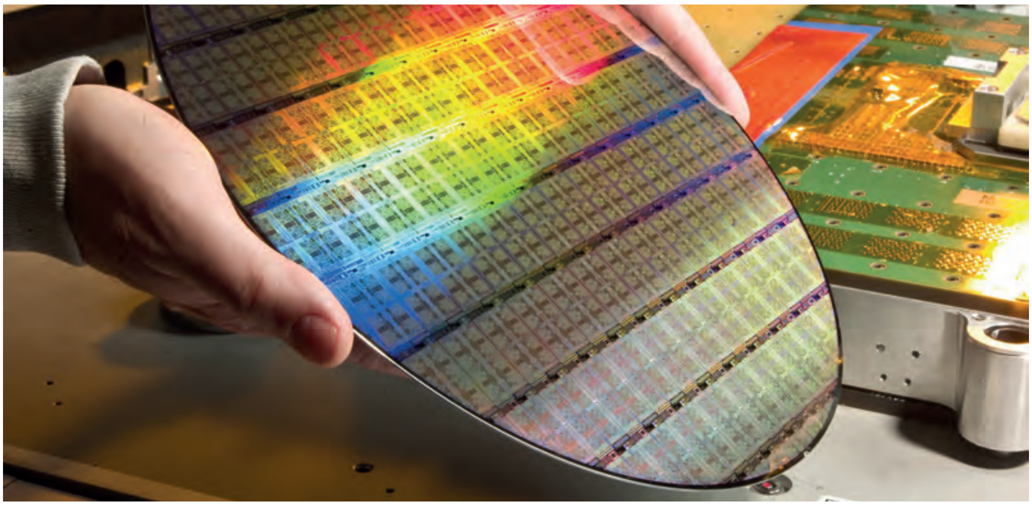
Even higher values were recorded at cryogenic temperatures. "The on-current almost achieved 1 Amp-per-millimetre at 77 Kelvin," revealed Nomoto.

High-frequency measurements – involving de-embedding parasitics by using an open structure on the same chip as the *p*-channel HEMTs – led to values for the cut-off frequency and maximum oscillation frequency of 19.7 GHz and 23.3 GHz, respectively. Compared with conventional HEMTs, source and contact resistances were an order of magnitude higher. Trimming these resistances should lead to even higher frequencies.

The recent breakthroughs made by this team and those led by researchers at imec show that there is much more to come from the GaN transistor. Further advances are sure to be announced at this year's IEDM, which will hopefully be held in person rather than on-line.

The saturated on-current hit 428 mA/mm at room temperature, for a p-channel HEMT with a source-drain distance of 680 nm. This value breaks new ground for this class of device.

The revival of Japan's semiconductor industry and its role in Industry 4.0



"While Japan has lost its leading market share in terms of semiconductor manufacturing since the 1990s, its dominance in the fields of material science and manufacturing machinery will ensure it continues to play an essential role in the semiconductor supply chain, and hence in the development of Industry 4.0 technologies."

With the emergence of new technologies such as 5G/6G broadband, Big Data, IoT, cloud computing, advanced robotics and automation, the world is witnessing the dawn of a new era hailed as the fourth industrial revolution, or Industry 4.0. The advent of these new technologies has breathed new life into the semiconductor industry, pushing the market towards new innovations and developments following years of stagnation.

In IoT, for example, there is an ever-increasing demand for advanced manufacturing technologies such as MEMS and NEMS for sensor devices, as well as application specific microcontrollers (MCUs) and flexible System on Chip (SoC)-type designs. Smart devices, smart cars, smart phones and smart cities will all require ever-more powerful, high-performing and smaller semiconductors, chips and components; while the incredible strides being made in advanced robotics and automation, cloud computing and Big Data analytics would not be possible without the latest high-speed processing semiconductor chips. It's fair to say then that semiconductors essentially serve as the building blocks of Industry 4.0.

Meanwhile, ultra-high-speed internet (now 5G and later 6G), the web which essentially ties all these Industry 4.0 technologies togethers, has also driven unprecedented demand for Memory, Power and AI semiconductors. As such, analysts at consultancy firm Frost & Sullivan have forecasted that the market for 5G AI, memory, and PA semiconductors will grow from $536.9 million in 2019 to $15.03 billion by 2025, translating to a staggering 74.3% CAGR.

"The AI processor market for 5G applications is rapidly growing, specifically in edge devices. They are expected to play a significant role in various devices, including edge servers and autonomous cars," said Prabhu Karunakaran, Test & Measurement Industry Analyst at Frost & Sullivan.

"Memory integrated circuits (ICs) supporting 5G end-user markets will be the highest contributors. Power amplifier IC is estimated to have generated larger revenue due to multiple 5G deployments, with revenue from the infrastructure segment. Additionally, AI is in the infancy stage and is expected to grow significantly in the next five years."

So what does this all mean for Japan?

As one of the world's technology leaders, Japan has naturally positioned itself at the forefront of this new Industry 4.0 era and is ready to serve the companies advancing these new technologies both at home and abroad.

In fact the birth of this new era could not have come at a more apt moment for Japanese manufacturing, which has been undergoing somewhat of a renaissance over the past few years in the face of increasing competition from regional competitors such as China and South Korea in recent decades.

This includes Japan's once-flailing semiconductor industry, which has witnessed a long-needed revival driven by the nation's SME manufacturers that are developing the next generation materials and manufacturing equipment for the latest semiconductors, wafers, microchips, MEMs, NEMs and sensors. While Japan has lost its leading market share in terms of semiconductor manufacturing since the 1990s, its dominance in the fields of material science and manufacturing machinery will ensure it continues to play an essential role in the semiconductor supply chain, and hence in the development of Industry 4.0 technologies.

Thanks largely to these SME equipment makers, Japan maintains a 35% share of the global market for semiconductor equipment while at the same time the Nippon nation has managed to maintain a 30% share of the global passive components market and represents around 17% of the world's total installed semiconductor manufacturing plant capacity.

Meanwhile, Japanese manufacturers have maintained their leading position in key material markets both for front-end and back-end processes, including silicon and compound semiconductor wafers, photomasks and photoresists, as well as bonding wires, lead frames and mold compounds, with experts estimating that Japan supplies around 40% of globally consumed semiconductor materials.

As ardent proponents of *Monozukuri* (the Japanese philosophy of manufacturing craftsmanship), Japan's SMEs involved in semiconductor materials and equipment will play a vital role in the advancement of Industry 4.0 – by leveraging on their technological and innovative capabilities to supply the highest-quality products to clients across the globe.

Regional Director: Fernando Llaryora
Editorial Director: Antoine Azoulay
Journalist: Sasha Lauture
Market Analyst: Islene Davila

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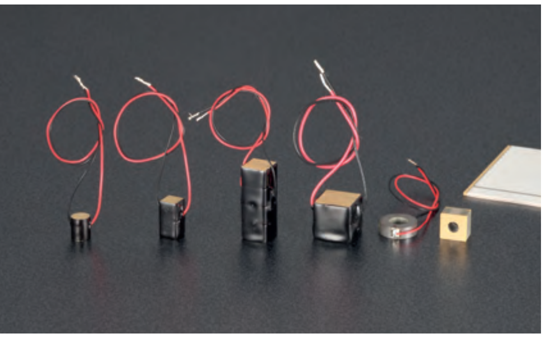
Fuji Ceramics: state-of-the-art piezoceramics for the semiconductor industry

ULTRASONIC TRANSDUCER (BLT) FOR MACHINE PROCESSING
Ultrasonic vibrator with ring-shaped piezoceramics elements between metal blocks. Used for ultrasonic welding/bonding. Fuji Ceramics supplies both BLT and piezoceramic elements.



MULTI-LAYER PIEZO ACTUATOR (MLA)
In comparison with electromagnetic actuators, MLA is quick in response, perfect for precision positioning with its high resolution, and has no electromagnetic noise. It is used for driving valves of mass-flow controllers.

PIEZO SENSOR
Piezo accelerometer is used to detect the shock and vibration of the measured object, as well as for monitoring machine operation. The Acoustic Emission (AE) sensor is used for diagnostics in manufacturing facilities and can detect the elastic waves generated when a solid is distorted.

Piezoelectric ceramics, which can convert mechanical effects into electric signals or vice-versa, play an essential role in manufacturing. As they are widely used in several high-tech industries, including semiconductors, electronics, automotives, telecommunications and medical devices, demand and applications for piezoelectric ceramic technology will continue to expand over the coming years.

For over 40 years, Fuji Ceramics Corporation has supported industrial development as a leading developer of piezoelectric ceramic technology and independent ceramics manufacturer. Now, at the dawn of a new era defined by Industry 4.0 technologies, Fuji Ceramics will continue to make major contributions to industry, such as through the provision of advanced sensor technology for the manufacture of semiconductors, electronic vehicles, artificial intelligence and medical devices.

While competition has grown in the piezoelectric ceramics market in recent years, Fuji Ceramics continues to set itself apart from its competitors by offering high-quality products and flexible solutions tailormade to respond to the needs of its customers.

> “Our strength lies in our ability to flexibly realize our customer’s requests with our integrated system, from the materials level all the way to the finished product.”
>
> **YUTAKA SEIJI, CEO of Fuji Ceramics**

“Even as competition intensifies with foreign manufacturers, our quality has earned high praise, and we have provided our reliable technical strength in a variety of fields to all manners of top-level clients in Japan and abroad,” says CEO, Yutaka Seiji. “Our strength lies in our ability to flexibly respond to our customer’s requests with our integrated system, from the raw materials all the way to the finished product.”

When it comes to the semiconductor industry, Fuji Ceramics has four main products: BLTs for processing machines and circular elements for BLTs; stacked piezoelectric actuators for valve opening and closing; piezoelectric elements for flow measurement; and piezoelectric sensors.

Piezoceramic devices are used in the semiconductor industry for ultrasonic processing and ultrasonic cleaning. Depending on the purpose and application, piezoceramic elements come in a wide range of specifications, and Fuji Ceramics can flexibly respond to requests for small custom orders. “In addition to piezoelectric elements, we also manufacture and sell ultrasonic transducers (BLTs) in which piezoelectric elements are embedded, which are used in various ultrasonic processing machines and ultrasonic cleaning machines in a wide range of industries including the semiconductor industry,” adds Mr. Seiji.

One specific example of a piezoceramic device in the semiconductor industry is a mass flow controller for fluid flow measurement and control. The basic structure consists of a control circuit; a bypass of the fluid movement path; a flow sensor; and a flow control valve. “The piezoceramic element is used for the flow sensor and flow control valve; while the single plate element is used for the flow sensor and the stacked element for the actuator (valve opening/closing),” explains Mr. Seiji, whose company offers a range of these devices that are tried and trusted by semiconductor manufacturers.

Fuji Ceramics’ piezoelectric sensors, such as AE sensors and acceleration sensors, also have applications in the manufacturing process for semiconductors. “The AE sensor is used for diagnostics and proactive monitoring of manufacturing equipment, while the acceleration sensor is used to monitor the operation and status of manufacturing equipment, contributing to equipment maintenance, production yield and efficiency,” adds Mr. Seiji.

“In general, piezoelectric elements are not directly related to semiconductor manufacturing, but they can be used indirectly as sensors and actuators to provide intelligent assistance to workers and act as a component of the realization of Industry 4.0 concepts such as manufacturing process interoperability, information transparency, and technical assistance.”

FUJI CERAMICS CORPORATION
www.fujicera.co.jp/en/

Miyatsu: experts in dry striping equipment for the front-end semiconductor manufacturing industry

■ Miyatsu offers a full range of total engineering services, from providing semiconductor and electrical manufacturing equipment to supplying necessary parts for maintenance and operation.

Monozukuri, the age-old philosophy behind Japan's world-renowned craftsmanship, was made famous by the nation's automotive and industrial giants like Toyota and Mitsubishi. Dedicated to quality, craftsmanship and the constant pursuit of innovation, agile and tech-savvy Japanese SMEs in the semiconductor industry like Miyatsu are also purveyors of *monozukuri*, bringing the concept to new heights to build new technologies and products for the fourth industrial revolution (or Industry 4.0) era.

> "Our business exists to provide technological advancement and innovation to satisfy client demands."
>
> **CHIHARU MIYATA, CEO of Miyatsu**

No longer the world's number one manufacturer of semiconductors, Japan has lost a significant amount of market share in the past 20 years with the emergence of new global competitors. But Miyatsu's president, Chiharu Miyata, believes that Japanese SMEs can catapult Japan into a leading position in the Industry 4.0 era by developing equipment and materials for the latest technologies such as IoT, 5G, and artificial intelligence (AI).

Offering a full range of total engineering services, from providing semiconductor and electrical manufacturing equipment to supplying necessary parts for maintenance and operation, *monozukuri*-focused Miyatsu aims to take its bespoke solutions to a wider global customer base.

"Key materials and technology for semiconductor manufacturing equipment are very important elements for the Japanese company. The industry will mark history with the introduction of Industry 4.0, 5G, and the emergence of IoT networks. This brings a very beneficial opportunity for market players, especially SMEs and I believe that SMEs will continue to keep their position in the market among tight competition," says Mr. Miyata.

"We are very much engaged in the *monozukuri* mindset – the Japanese mindset of craftsmanship. In the digital era, things are changing rapidly, but we have kept this mindset and our core values are to improve productivity, service, and high quality for our clients. We can continue to penetrate the global market further by continuing our long history in providing our advanced products defined by competitive cost, high quality and excellent delivery times."

As Miyatsu looks to further penetrate the global market, the company holds several competitive advantages. First is its experience in serving the needs of high-demanding Japanese electronics giants such as Mitsubishi and Omron, for whom Miyatsu develops hardware design to rudder design for control units used for various process control equipment. "Our machines are dedicated to the legacy process. We manufacture 6-inch and 8-inch dry striping systems which are mainly used for sensors and power devices and we are targeting to serve both the domestic and overseas markets. We have the advantages of supplying these manufactured products to big companies from our networks," adds Mr. Miyata.

MIYATSU
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MG6500R: 6-inch batch Dry Striping (Ashing) System

MG8500R: 8-inch batch Dry Striping (Ashing) System

MG200: 8-inch Single Wafer Dry Striping (Ashing) System

Secondly, Miyatsu also boasts a fully integrated in-house production system that allows it to develop tailormade solutions to meet each customer's specific requirements. The company provides total process solutions, from specification development to mass production through its highly cost-efficient production system.

"In addition, our experiences of making a plasma system as a subcontractor are significant to helping us to develop our competitive advantages. We are currently in an independent position which also brings a huge opportunity for us to compete in the global market," explains Mr. Miyata. "Moreover, we can create an advantage in our OEM business sector, where we can provide our products at a good cost, high quality, and exact delivery time to the global supply chain system."

Moving forward, with the emergence of Industry 4.0 technologies, Miyatsu aims to focus on providing sensors, memory devices and other equipment for companies involved in AI, IoT and Big Data, drawing on its 60-year experience of meeting the demands of an ever-changing market with state-of-the-art solutions.

Leader Roundtable

	What is the role today of Japanese enterprises in the international supply chain of the semiconductor industry?	How do you envision the future of Japan's semiconductor industry?
 **YUTAKA SEIJI,** CEO of Fuji Ceramics	Enterprises in the US, Europe, and Japan are playing a central role in supplying semiconductor manufacturing equipment to the international market, and we face a kaleidoscopic change in technology. The role of SMEs in the semiconductor industry is to swiftly and efficiently deliver the products based on the information from the customers.	We are about to enter the true era of Big Data, and we envisage that IoT, AI, and 5G will bring exploding growth to Japan's semiconductor industry in the near future. Along with that, the demand for data processing components such as SoC and data storage components such as memory will dramatically increase in every market segment.
 **SATOSHI SAWAMURA,** President of ROHM Co., Ltd.	With the emergence of IoT, digitalization, and innovative solutions in various applications, we expect the demand for our products to witness significant growth, especially in the automotive and industrial segments. In the automotive market, the use of our products is expanding thanks to ADAS technology and EV adoption.	The IT industry is inexorably approaching maturity. The recent surge in orders for semiconductor production equipment may lead people to imagine that the good times are about to return. But unless the electronic device industry finds new growth vectors, the future won't be bright.
 **SHUNPEI YAMAZAKI,** President of Semiconductor Energy Laboratory Co., Ltd.	In the context of our company, SEL is developing next-generation material technology for semiconductors that can replace the 'complimentary metal-oxide semiconductors' that are ubiquitous in digital electronics. SEL's R&D efforts have focused on using ceramic materials to make crystalline oxide semiconductors, devices which can significantly reduce energy consumption.	Looking to the future from our perspective, SEL is developing applications that utilize the extremely low off-state current and AI hardware to produce a novel lithium-ion secondary battery control system using OSFETs (BTOS). We are also working on further improvement in lithium-ion battery performance and have patented technology that promises to reduce battery size, increase capacity, and improve rapid charge and discharge characteristics.

TESEC Corporation: the global benchmark in semiconductor testing

■ TESEC provides market-leading integrated test systems in response to the latest industry demands.

High-quality manufacturing is based around high-quality testing – which is why discerning semiconductor manufacturers from around the globe depend on the high-performing testing equipment from TESEC Corporation.

TESEC has long been recognized as "the Benchmark in Discrete Component Testing". Today, in addition to discrete device testing systems, MAP (Matrix Alley Package) handlers, MEMS handlers, and wafer parallel testers have become mainstay products of the company.

"Many of our competitors do not have the resources to develop both handlers and testers, and must focus on one or the other," says president, Kenji Tanaka. "We however can effectively produce both which allows our tester and handler engineers to provide market leading integrated test systems."

As the company has grown in tandem with the semiconductor industry, key to its success has been its ability to respond to the latest market demands. Now, at a time when market trends such as the electrification of automobiles, miniaturization and automation have prompted demand for smaller and higher-performing semiconductors, TESEC has enhanced its portfolio of high-value-added testers.

KENJI TANAKA,
President of Tesec

"In the semiconductor industry, where technological innovation is becoming fierce, our basic policy is to promptly develop products that accurately meet a wide range of customer demands. We are advancing product development that will be the core of our future business ," says Mr. Tanaka.

"In order to secure our competitive advantage in the next-generation of semiconductor testing equipment, we are promoting equipment for compound semiconductors to pioneering companies, and we will take the lead in ascertaining the characteristics of various new materials."

Die Sorter, TESEC

Discrete Device Test System, TESEC

Film Frame Strip Handler, TESEC

http://en.tesec.co.jp/

Hemmi: collaboration is key in semiconductor market

■ Not long ago, well-established Hemmi Slide Rule Co. made the decision to collaborate with a domestic competitor to safeguard the success of its company in a fiercely cut-throat semiconductor marketplace. It hasn't looked back, and is now looking for international partners too.

Challenged with an increasingly competitive global market, Japanese semiconductor firms still hold an important part in the semiconductor supply chain today, supplying one-third of the world's semiconductor manufacturing equipment and 40% of total materials.

Established in 1895, Hemmi Slide Rule Co. is a prime example of the long-established and universally respected Japanese semiconductor industry. "The first question that Japanese manufacturers should be asking themselves in this tough market is how can each company take steps in order to remain relevant," says company president, Takeshi Okura.

TAKESHI OKURA,
President & CEO, HEMMI Slide Rule Co., Ltd.

"Our idea was not to focus on the competitiveness of the product, but rather to focus on the competitiveness of our corporation in order to survive. And so, three years ago we came to the stage where we finally found a reliable partner here in Japan, who is now utilizing our manufacturing experience and equipment to make an end product under their brand."

The product – a chemical vapor deposition (CVD) system which produces high quality, high-performance materials for use in the semiconductor industry – has been developed alongside its domestic partner and since become a huge success.

With this success, Mr. Okura says Hemmi is open to further partnerships, potentially further afield than Japan, in order to capitalize on the manufacturing industry's increasingly fruitful culture for collaboration and knowledge sharing.

"The reason we are open to an overseas partner is that it helps to enhance the level of competitiveness which is growing even here in the domestic market," he explains. "We are looking for an international partner company with whom to create a relationship based on mutual trust."

Fluid control devices

CVD

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ATE SERVICE: the leading semiconductor testing and inspection services provider going above and beyond

■ "Having been in the industry for a very long time, we have built the solid trust of our clients and networks, especially with European and American companies," says ATE president, Rocky Kobayashi.

For almost three decades, Japanese firm ATE Service has earned a solid reputation in the niche field of semiconductor testing, supplying state-of-the-art testing and inspection equipment to high-demanding clients in the semiconductor, electronics and automotive industries.

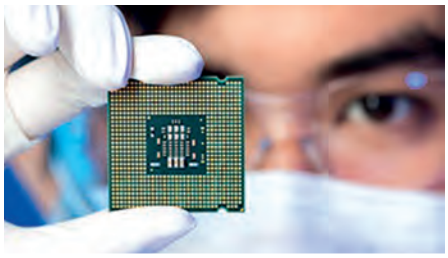
ROCKY KOBAYASHI,
President & CEO, ATE Service

Drawing on the technology and knowledge accumulated since its establishment, ATE goes beyond the role of a mere manufacturer, offering its clients a full suite of solutions and after-sales services, including technical training on how to best use its equipment.

"Our company is quite different from manufacturers and distributors, as we approach our clients about what kind of tools they need, and what kind of problems are occurring, and then we look for ways to help them," says president, Rocky Kobayashi.

"We search for the products the clients need, and if there are no such products that fit the requirements, we develop new solutions for them on our own. This is why our business style is unique and how we gain the trust of our clients."

Indeed, working closely with clients and developing solutions in response to their needs has been key to ATE's success. So too has the company's ability to keep up with global trends and technological advancements, thus ensuring that its equipment is best suited for the testing of the latest semiconductors deployed in emerging fields, such as smart cars, electronic vehicles and autonomous vehicles. ATE's IDDX monitors, for example, are used to test components for Toyota, Nissan, and Honda; while chips tested using its modelling systems are deployed in Toshiba's semi-automatic driving system, Visconti.



System LSI Testing Service

"Car components and sensors need to reach a certain level of high reliability, especially if you are supplying them to Japanese tier 1 companies, such as Toyota, Nissan, and Honda. The challenge for us is to keep costs down and lead times short while improving the quality of the testing," says Mr. Kobayashi, who believes the company, which recently struck up a partnership with Tesla, is well-placed to support American and European companies with subsidiaries in Asia.

ATE service
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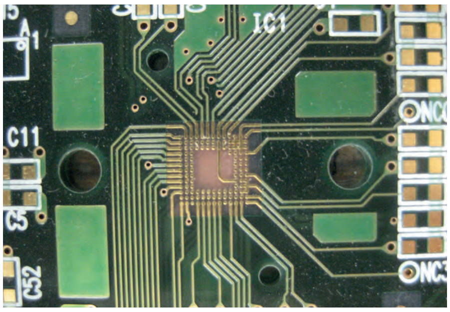
K2P: The shortest delivery times for high-quality rigid and flexible printed circuit boards

■ Thanks to its integrated production model, K2P can manufacture high-quality PCBs much faster than its competitors.



Rigid PCB

The 1980s and 90s represented the glory days for Japan's semiconductor industry, which, at the time, ranked number one in the world, accounting for about half of the world's production. But as the 2000s approached, Japan's once-mighty semiconductor industry saw its leading position fall quite quickly, mainly due to the rise of regional competitors who could offer products at a cheaper price. Another factor in this decline was Japan's slow adaptation to emerging trends such as mobile semiconductors.

However, the recent emergence of a new era defined by technologies such as automation, 5G/6G internet, Big Data and robotics, has spurred somewhat of a renaissance for Japan's semiconductor industry. While Japan knows it cannot compete with some regional competitors when it comes to price and scale, Japanese semiconductor manufacturers have underscored their high-quality products – the result of a strict adherence to the long-standing ideals of Japanese *monozukuri* craftsmanship – as the crucial factor that sets them apart.

"K2P can give a speedy response to the customer's needs with high-quality PCBs."

RYUICHI KAWASAKA, CEO of K2P

Producing such high-quality bodes well for Japanese manufacturers when it comes to meeting the strenuous demands triggered by the latest technological trends – for example in the automotive industry with the shift to smart cars, electric vehicles and autonomous driving technology. For example, Japanese SMEs like K2P – which develops printed circuit boards (PCBs), including the normal rigid boards, flexible boards, build-up boards and special boards – has found a place for itself in the provision of high-quality PCBs for autonomous driving technology as well as for high-frequency antenna for 5G.

"K2P believes that the strength of Japanese companies is the reliability of high-quality service, as we know that we are handicapped by the higher operating cost when compared to other countries," says company president and CEO, Ryuichi Kawasaka. "Countries like Korea and China are growing rapidly, however, Japanese industries can play along and compete in this industry with the quality of service, technological advancement, and speed of services offered to clients. And these factors are ensuring Japan's leadership in the global market."

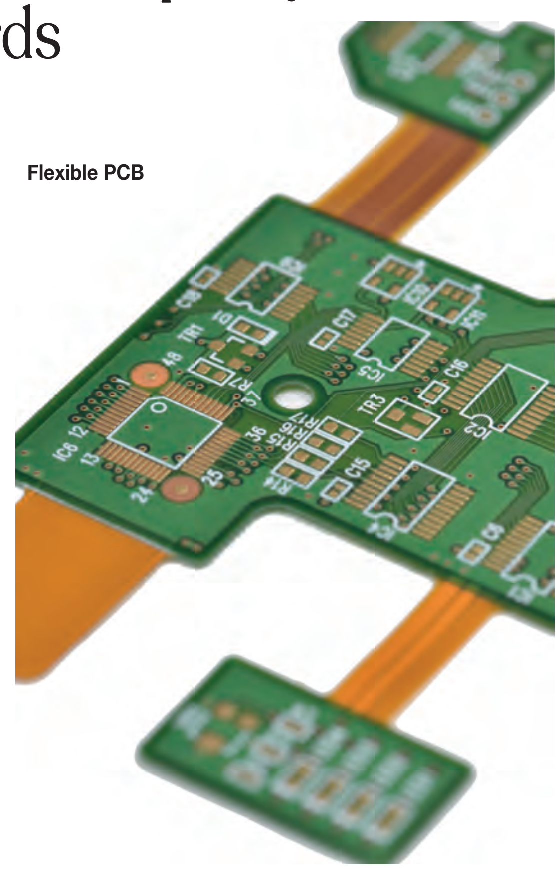
Indeed, high-quality and fast lead times are exactly what differentiates K2P from its competitors, and are the direct result of the company's fully integrated production model, which ensures all steps of the production process are completed in-house.

"This supply chain system is very efficient, with no loss of time from transport. As a result, K2P can give a speedy response to the customer's needs with high-quality PCBs. It takes roughly four days for other companies in the manufacturing process of PCB, however, K2P takes only two days, as no outsourcing process is needed," explains Mr. Kawasaka. "Furthermore, we can maintain close quality control with all the steps and components needed during the manufacturing processes."

Amid the emergence of these fourth industrial revolution technologies, demands for increasingly smaller and high-performing semiconductor components and PCBs continues to grow – which represents the major challenge for manufacturers across the globe. However it is a challenge that Japanese companies like K2P are facing head on as the nation's semiconductor industry looks to position itself at the forefront of these latest technologies – sparking a return to the glory days once again.

Of course, developing the latest PCB technology generally requires the latest equipment, which does not come cheaply for SME manufacturers like K2P. As such, the company is facing up to the challenge by focusing on investing in its highly capable and skilled workforce, rather than in expensive new production equipment.

Flexible PCB



"Many semiconductor manufacturers are faced with the challenge of making everything smaller mounted on a higher density. Miniaturization has been the recent global trend and it requires modern technology equipment. However, K2P makes up for its lack of modern technology equipment by giving proper training to our people," adds Mr. Kawasaka.

Through this, Mr. Kawasaka stresses that high-quality products can be produced for K2P's clients without the need for expensive modern equipment. "Taking an example of the process of etching in creating mini-mate boards, we train our employees to be able to use the accurate amount of concentration with precise ratio and temperature to provide the exact condition in creating these boards. By doing so, we believe that we can overcome our weaknesses and compete with many other major companies that have a high budget for investing in the technologies."

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Nano-porous GaN enhances microLEDs

Inserting quantum dots in nanopores creates efficient, reliable microLEDs

BY JIE SONG AND CHEN CHEN FROM SAPHLUX

DISPLAYS MADE from microLEDs are attracting tremendous attention due to their long lifetime, high brightness and excellent efficiency. Helping to put them in the spotlight are some of the biggest tech companies in the world, such as Apple and Samsung, which are developing this form of display using mass-transfer or nanoprint technology.

Despite years of intense development, several key technical issues are still hampering the key ingredient, the miniaturised LED. Those emitting in the red are plagued by a low efficiency and a thermal droop, limiting the performance of the display; it is challenging to fabricate devices with a pitch below 10 μm, a requirement for microdisplays for augmented reality and mixed reality; as the size of the LED reduces, bin sorting gets harder and more costly; and of greatest concern of all, production costs are high.

Helping to address all these issues are colour-converted microLEDs, which use a chip emitting in the ultraviolet or blue part of the spectrum to pump quantum dots. Devices that operate in this manner have many unique properties, including a high quantum yield, a size-dependent emission wavelength, a narrow emission linewidth, and a short luminescent lifetime. What's more, by using patterning and spin-coating to add quantum dots to the substrate, this class of LED can serve a broad range of applications.

One option for fabricating quantum-dot-based, colour-converting microLEDs with a high light-conversion efficiency is to coat a chip with a thick film populated by quantum dots. But this is not ideal, becuase the addition of traditional quantum dots can cause light extraction and reliability issues.

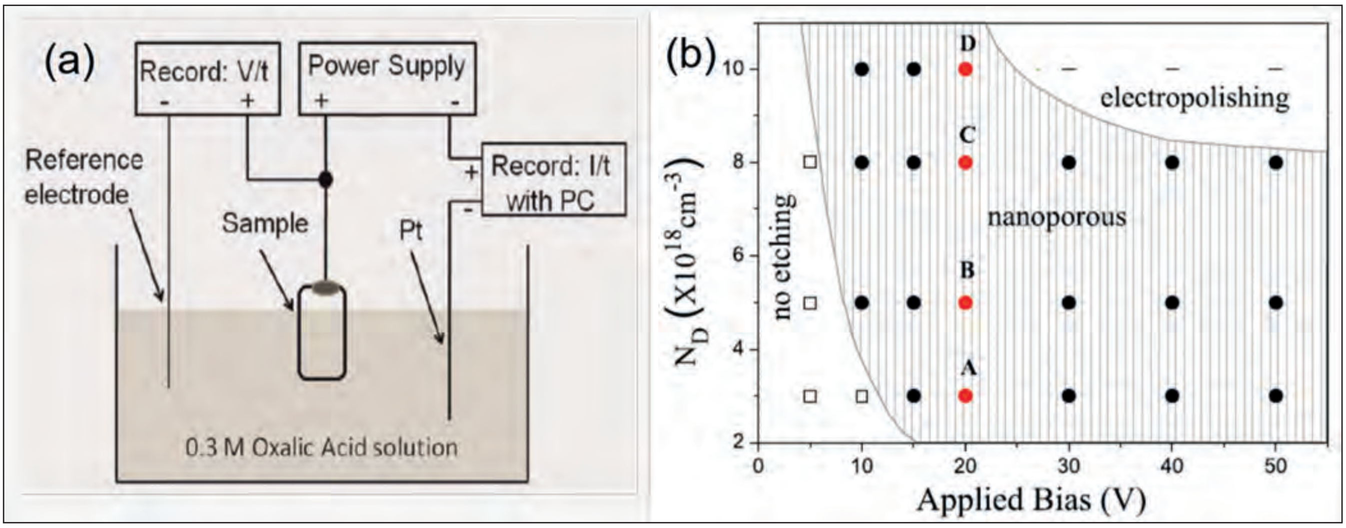

Figure 1. (a) An electrochemical etching process produces nano-porous GaN. (b) A phase diagram of the GaN electrochemical etching process shows how the etching characteristics are related to silicon doping in GaN and the applied bias.

To address these issues, our team from Saphlux of Branford, Connecticut, has developed a nano-pore technology that allows quantum dots to be embedded in microLEDs. This results in devices that are very efficient, reliable, and low in cost.

Nano-porous GaN

We create nanoscale pores in our LEDs by dipping the material in an acidic solution and applying a bias, which drives electro-chemical etching of *n*-type GaN (see Figure 1 (a)). By varying either the applied bias voltage or the silicon doping concentration in GaN, we are capable of producing dramatic changes in electro-chemical etching behaviour. If we apply a low bias voltage to GaN with a low silicon-doping concentration there is no etching; and if we use a high bias voltage or a high silicon-doping concentration, we etch GaN completely away (this is called electropolishing). To form nano-porous GaN we chart a course between these extremes, selecting an appropriate bias voltage and silicon doping concentration.

Imaging our nano-porous GaN with a scanning electron microscope allows us to evaluate the impact of the silicon doping concentration and the applied bias voltage on our material's morphology (see Figure 2). Microscopy reveals that by adjusting the etching voltage, we change both the porosity and the size of the nanopores.

Simulations suggest that the incorporation of nanopores into our LEDs can lead to a tremendous

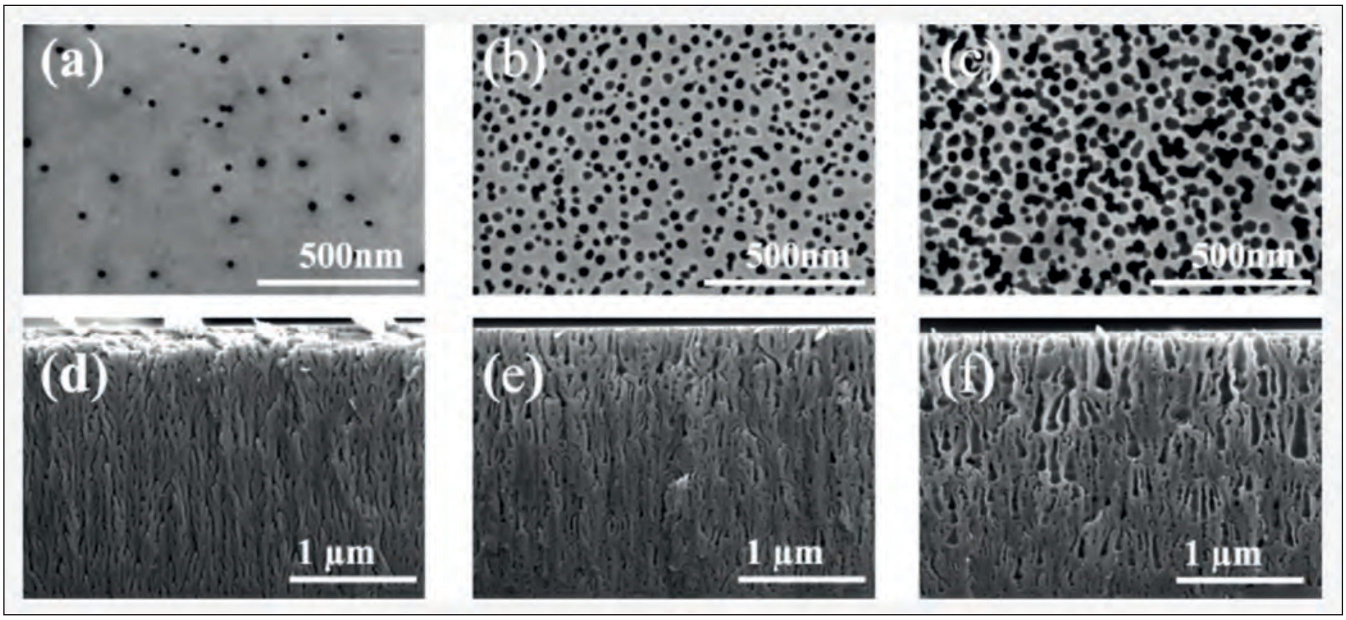

Figure 2. (a-c) Top-view and (d-f) cross-sectional scanning-electron microscopy images of nano-porous GaN with different porosity etched at different bias voltages. Reprinted with the permission of the American Society Chemistry.

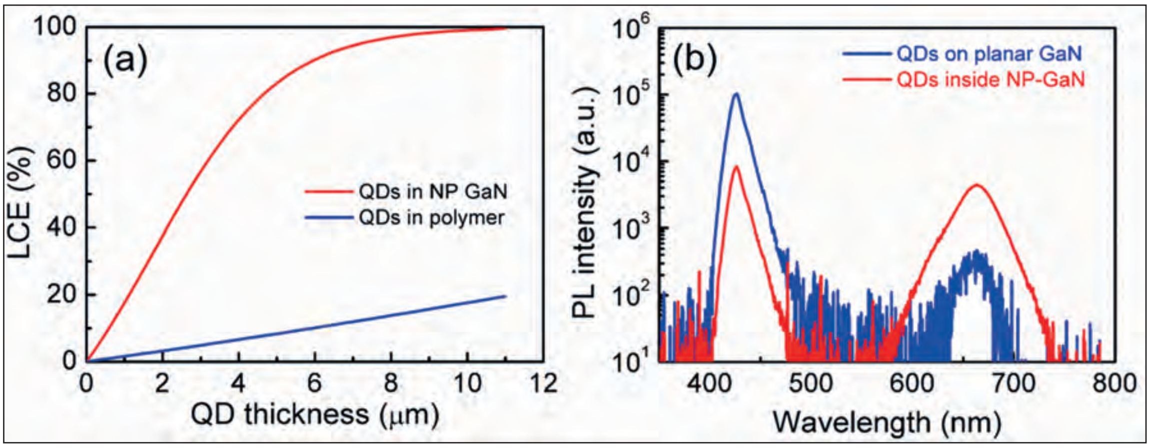

Figure 3. (a) Simulated results for the light-conversion efficiency (LCE) of quantum dots (QDs) loaded in polymer and nano-porous GaN, respectively. The same concentration of dots is used in both samples. (b) Photo-luminescence spectra of red QDs on planar GaN and nano-porous GaN, respectively.

increase in device efficiency. For planar quantum dots in a polymer film, light-conversion efficiency increases linearly with increases in the thickness of the quantum dot layer to a maximum of only 20 percent – that's for a 10 μm-thick quantum-dot layer (see Figure 3(a)). In stark contrast, when dots fill the nanopores, light-conversion efficiency exceeds 80 percent, for a film thickness of just 5 μm.

Measurements support these simulations. We have obtained photoluminescence spectra of red-emitting quantum dots loaded on planar GaN and compared these results with those for dots added to nano-porous GaN by spin coating. Using a 420 nm blue LED to pump these samples, we observed a weak red peak at 650 nm from the red-emitting dots loaded on planar GaN (see Figure 3 (a)). When the dots were placed inside nano-porous GaN, the photoluminescence intensity climbed by almost two orders of magnitude, while that of the blue excitation peak fell by a similar factor. Based on the photoluminescence spectra, we calculated a light-conversion efficiency of 91 percent for the red-emitting quantum dots in nano-porous GaN.

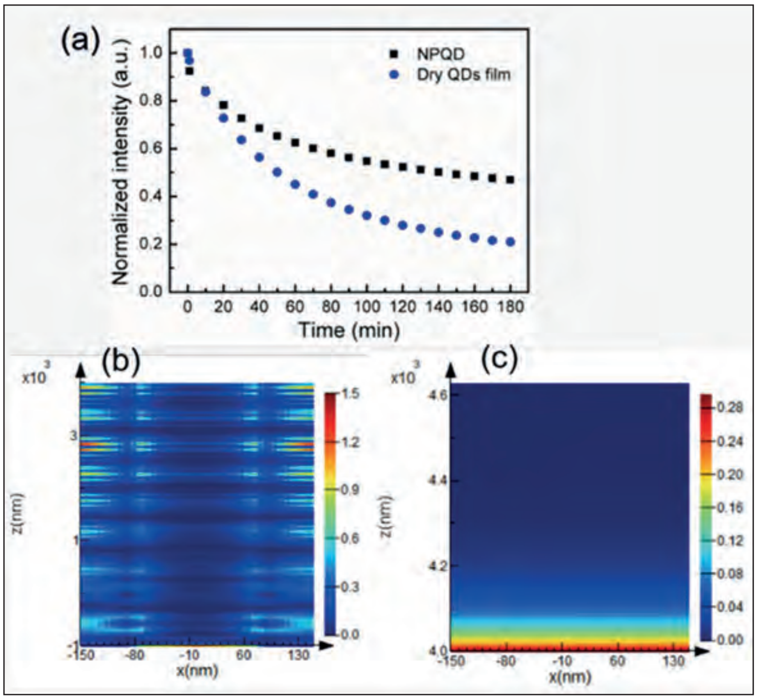

Figure 4. (a) Comparison of the normalized power intensity of red emission from a red nano-porous quantum-dot sample and a quantum-dot film on a GaN-on-sapphire wafer. Both samples were subjected to 3 hours of excitation with a 420 nm blue laser. (b) Simulated mapping results of blue light absorption by nano-porous GaN. (c) Simulated mapping results of blue light absorption by a nano-porous film.

Benefits of the nano-porous structure are not limited to greater efficiency. Reliability also increases, as demonstrated by our optical excitation measurements at a high power density. When we pumped the planar samples with a 420 nm blue laser at an optical power density of about 25 W cm^{-2}, the normalized intensity of red emission fell to just 20 percent of its initial value after 3 hours of excitation. In comparison, when dots were housed in the nano-pores, identical excitation conditions led to a 55 percent reduction in intensity compared with the initial value.

We have turned to simulations to understand why the nanopores enhance reliability. These calculations suggest that the maximum power intensity absorbed by the dots in nano-porous GaN is 0.05, compared with 0.39 for the quantum dot film (see Figures 4 (b) and 4 (c)). This hike by a factor of almost 8 in absorption is behind the far longer lifetime for the dots when they are deployed in nano-porous GaN, rather than used in a planar film.

Dots for displays

Producing our displays involves forming nano-porous blue-emitting LEDs, before putting some of them aside and coating others with either red-emitting or green-emitting dots (see Figure 5). We bond exposed nano-porous GaN to a current driver panel, before loading red- and green-emitting dots onto different zones. If the zones are free from dots, they emit blue light; and if they are loaded with dots, they produce red or green emission through colour-conversion.

Using this approach we have demonstrated a microLED array with dimensions of 36 μm by 36 μm. This features an optical filter that blocks the blue backlight in red and green sub-pixels. By combining many microLEDs, we have made a display with our company logo (see Figure 6(b)).

We are now fabricating nano-porous GaN microLED arrays with customized pixel sizes to suit the needs of our customers. Many applications offer broad market prospects, including wearable devices, vehicle displays, smartphones, and various forms of augmented and virtual reality.

In addition to these efforts, we have fabricated red miniLEDs. Again, they operate by using nano-porous GaN to convert blue emission to red. We have demonstrated a range of devices, with sizes of 250 × 750 μm², 150 × 500 μm², and 100 × 150 μm² (see Figure 7 for images of these LEDs). According to our measurement, we have achieved more than 97 percent of converted red colour purity.

These devices, like their smaller siblings, show much promise. They are well-positioned to drive the manufacture of displays made from tiny, efficient, reliable LEDs that are low in cost and will help this market to blossom.

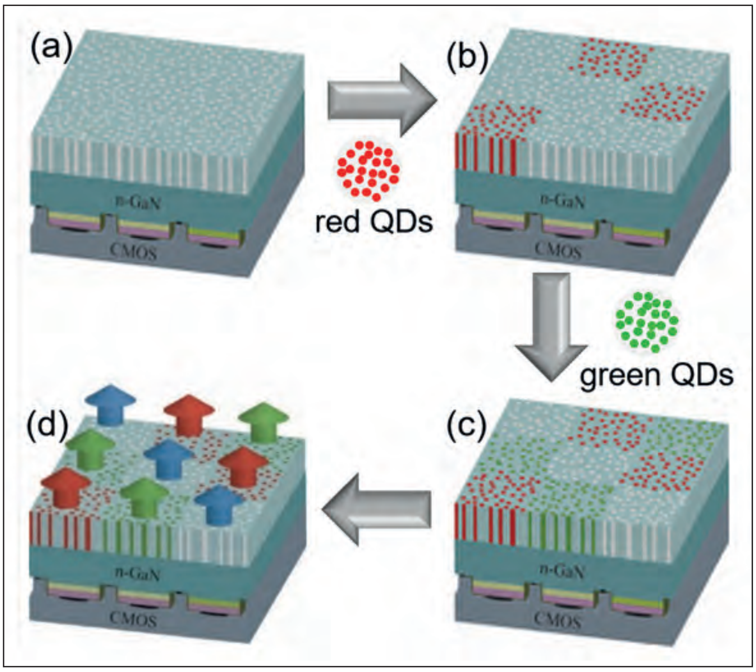

Figure 5. Saphlux's approach to making monolithic RGB microLEDs. (a) A vertical blue LED with exposed nano-porous GaN is bonded to a current-driver panel. (b) Red quantum dots are selectively loaded into red zones. (c) Green quantum dots are selectively loaded into green zones. (d) Red, green and blue light emitted from red quantum dot zones, green quantum dots zones, and zones without any quantum dots, respectively.

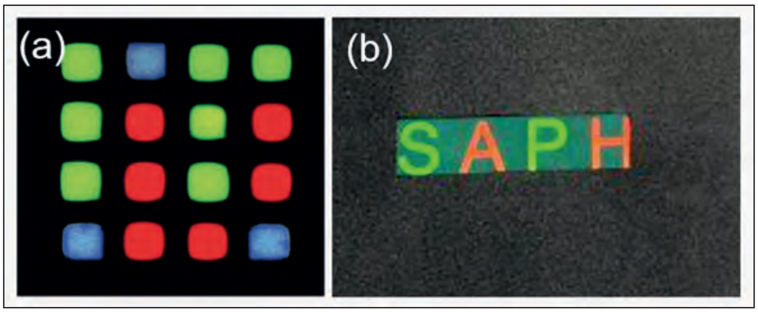

Figure 6. (a) Saphlux RGB monolithic microLEDs excited by a blue LED source from the backside. (b) A picture of the company logo "SAPHLUX" fabricated by red and green nano-porous quantum-dot microLEDs.

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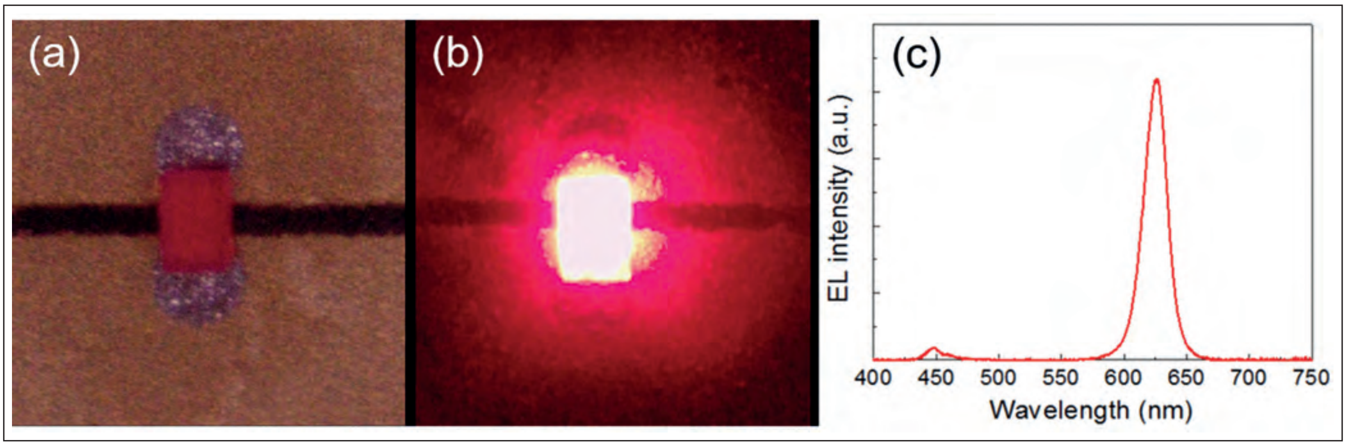
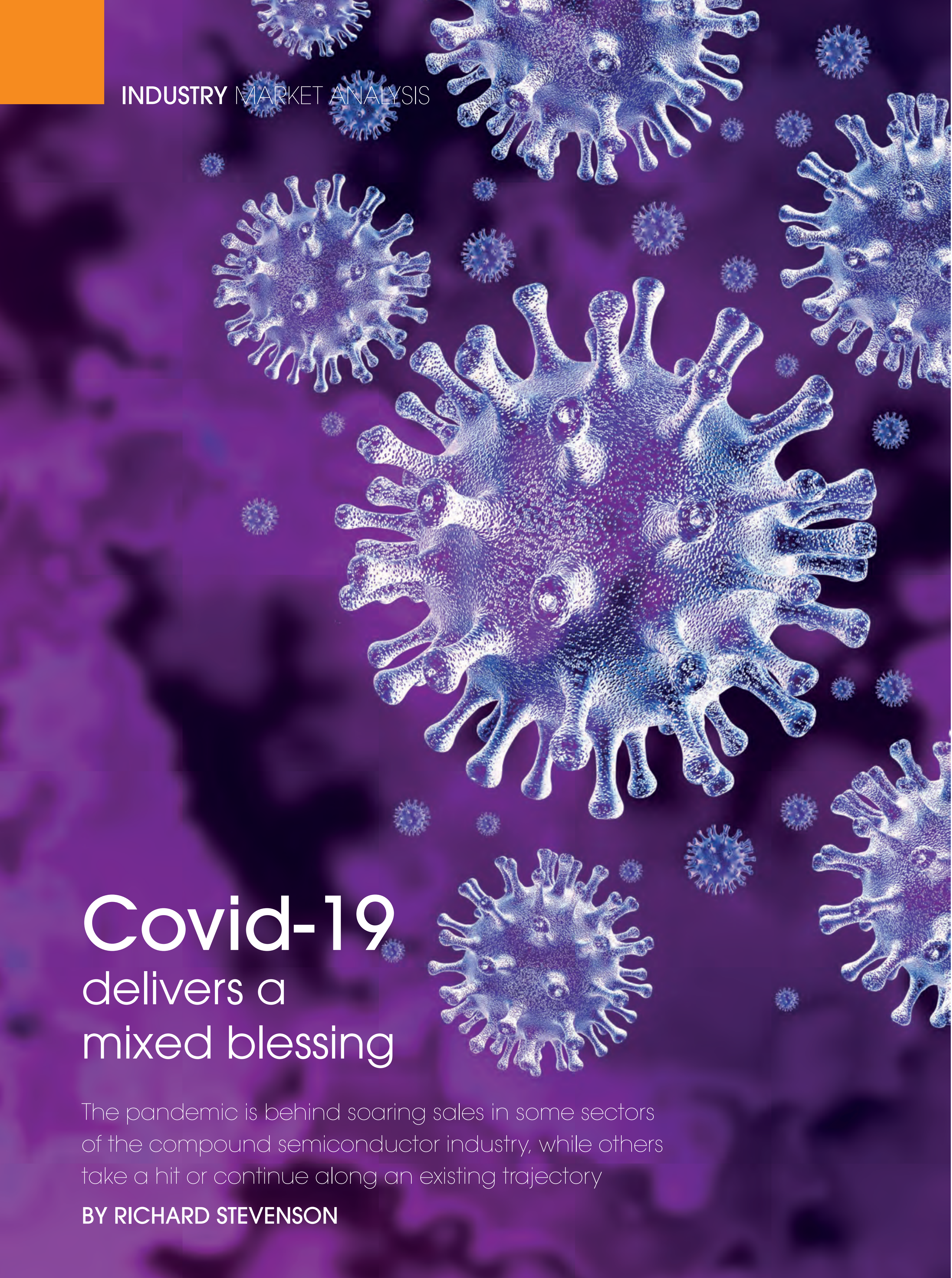


Figure 7. Photos of 100 × 150 μm² red nano-porous quantum dot miniLED mounted on a PCB board (a) and lit-up at an injection current of 1 mA (b). (c) Spectrum of a red nano-porous quantum dot LED shown in (b). Testing the reliability of the red nano-porous quantum-dot miniLED revealed acceptable results at 30 W cm^{-2}. This power density is more than sufficient for most microLED applications.



Covid-19 delivers a mixed blessing

The pandemic is behind soaring sales in some sectors of the compound semiconductor industry, while others take a hit or continue along an existing trajectory

BY RICHARD STEVENSON

WE HAVE ALL SUFFERED from the pandemic on a personal level. Loved ones have been lost, many of us have had to stay at home for weeks on end, and life is not nearly as much fun as it used to be.

However, when it comes to business, it is a very different state of affairs, as we are not all sharing in the pain. While millions have been made redundant and countless more had their pay packet cut, some have benefitted from Covid-19. It is well publicised that Jeff Bezos, the owner of Amazon, has nearly doubled his wealth, and some of the providers and distributors of PPE equipment have lined their pockets by applying extortionate margins. Many others have also done well, growing their investments and swelling their pension funds, thanks to soaring share prices of some companies.

But what about the compound semiconductor industry? Is it a winner, a loser, or a bit of both?

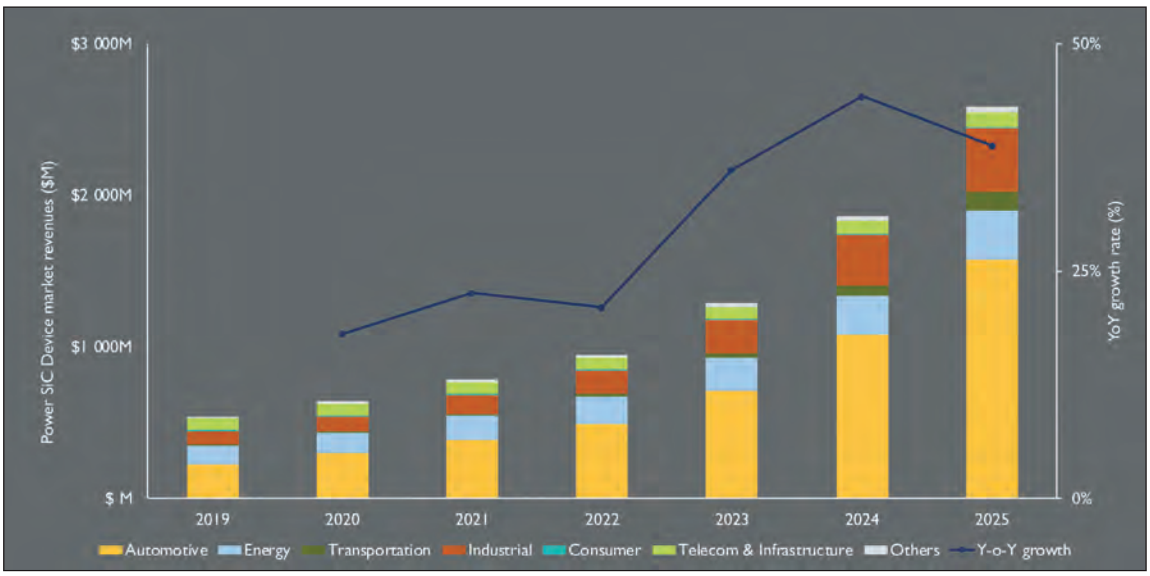
For any manufacturer, the outcome is always influenced by two critical factors. One is the ability to churn out product. Is there a reliable supply of materials? And is the production facility able to run at high capacity? Succeeding on this front is no guarantee of making a profit, however, as financial success also hinges on having strong demand for what is being produced.

Like makers of any class of goods, production facilities within the compound semiconductor industry have suffered from logistical issues, while manufacturing efficiency has been pegged back by the introduction of new practices to minimise transmission of Covid-19. The good news, though, is that the disruption from the pandemic has been fairly minor – it is certainly less than that within the automotive industry, which, for example, saw Tesla's plants in Shanghai and California shut for a couple of months. Helping chipmakers has been the backing of governments, who are keen to maintain economic activity and view semiconductor production as a critical activity.

Sales of SiC are growing fast, thanks to deployment of these devices in the Tesla 3, X and S models.

Within the semiconductor industry, companies have taken broadly similar approaches. Two big European players, ST Microelectronics and Infineon, have scaled back production at times – but by not shutting, they have been able to quickly return to normal levels of production. It's a similar story for the two biggest players in the GaAs RF industry, Qorvo and Skyworks. The latter briefly shut its facility in Mexico, before coming back very quickly, while Qorvo didn't stop, with the US Government viewing this chipmaker as an essential business.

When it comes to demand, the picture is more complex across the compound semiconductor industry. To understand the impact of the coronavirus, one needs to consider consequences sector by sector. That requires expertise in all areas, from LEDs to lasers, power electronics and RF. Offering such a comprehensive coverage is Yole Développement,



Increasing sales of SiC power devices are being driven by the electric vehicle industry. Source: Compound Semiconductor Quarterly Market Monitor, Q4, 2020. Module II, Yole Développement

Commoditisation of the LED has led to razor-thin margins in the big, established markets of general illumination and backlighting screens. Horticultural lighting, requiring fine-tuning of the emission wavelengths to accelerate plant growth, offers a more lucrative opportunity.

which has a team of market analysts covering all the critical bases. They reveal that the consequences of Covid-19 are incredibly varied. The pandemic has had little impact on some sectors, with changes driven by other factors; but this infectious disease is also behind some phenomenal successes and depressed sales.

Covid's silver linings…

One market that has enjoyed a very positive impact from the pandemic is that of LEDs emitting in the UVC domain – that is, wavelengths of 280 nm and below. For more than a decade, UV LEDs have been championed as a great source for disinfection, and this year they have attracted tremendous publicity, as they have been shown to kill Covid-19 bacteria.

Pars Mukish, Buisness Unit Manager, Solid-State Lighting and Display, told *Compound Semiconductor* that he is expecting the UVC LED market to have nearly doubled between 2019 and 2020, climbing from $144 million to $308 million. From this year onwards, growth will slow, to a still very healthy compound annual growth rate of 52 percent through to 2025. By then the sector will be worth $2.5 billion.

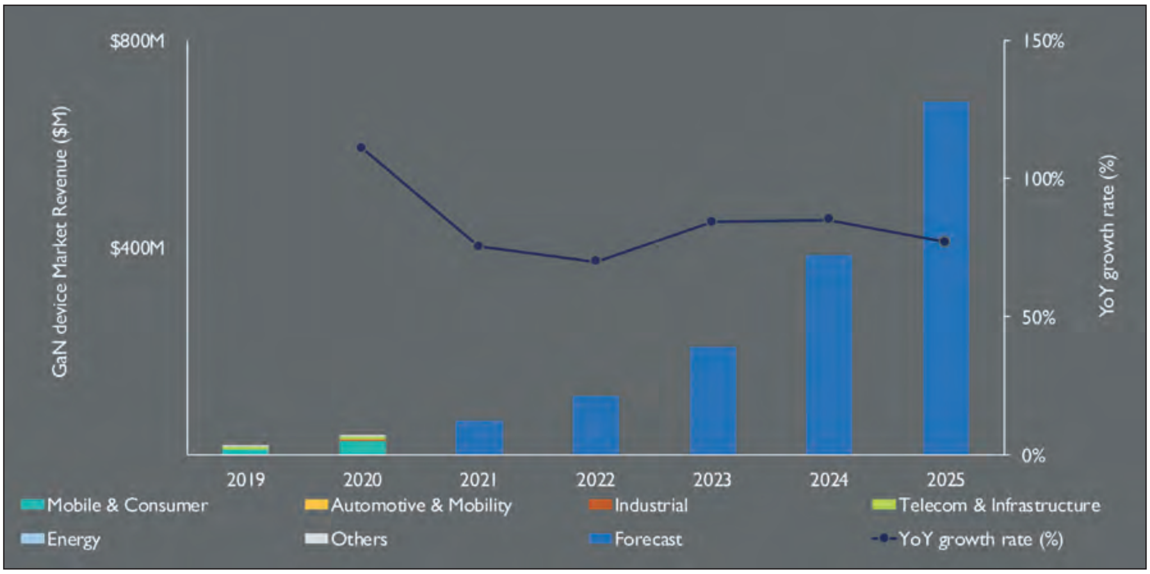
"Those figures take into account the development of a vaccine," says Mukish, who explains that the epidemic has provided a tremendous spark for the UVC LED industry. Last year's jump in sales came on the back of steady progress throughout the last decade, with improvements including a staggering reduction in the cost-per-Watt – this tumbled from nearly $100 per milliwatt in 2015 to around just $1 per milliwatt by the end of last year.

Lamps based on the UVC LED are also undergoing a rapid rise in sales. Offering one perspective on this is global lighting manufacturer Signify, formerly Philips lighting. It stated that it expected global revenue for UV lamps to grew by 73 percent between 2019 and 2020. In line with this trend, last June it announced an eight-fold increase in production capacity.

Note that the UVA LED industry, which provides sources for curing adhesives, is not on the same trajectory. Mukish explains that as UVC LEDs emit at wavelengths only a little shorter than their visible counterparts, makers of blue LEDs have flooded this market, driving down prices. Note that those chipmakers are not able to move further in this direction and target the UVC LED, because it has a markedly different, more complex architecture.

One would expect the makers of InP edge-emitting lasers used in metro and long-haul networks, along

Despite a substantial fall in handset shipments in the first half of 2020, revenue for GaAs die continues to climb, thanks to the rollout of 5G and a move to the Wi-Fi 6 standard. Source: Compound Semiconductor Quarterly Market Monitor, Q4, 2020. Module II, Yole Développement.



Revenue for the GaN power device market is taking off, thanks to the rapid growth of 65 W fast chargers incorporating this technology. Source: Compound Semiconductor Quarterly Market Monitor, Q4, 2020. Module I, Yole Développement.

with the manufacturers of GaAs VCSELs that are employed in data centres, to have benefitted from the epidemic. With internet traffic reaching a new high, now that many of us spend much of our working day on video calls, there is much demand to increase network capacity. However, Mukish believes that this pressure will not have an immediate impact. Instead, it will take time to strengthen infrastructure, which will help to accelerate the digitalisation of our world.

What may raise a few eyebrows is the positive impact that Covid is having on the SiC power market. After all, the outbreak of this virus chocked car sales. However, the response from governments all around the world has been to try and support this industry by helping speed its electrification – China has plans to extend subsidies for this sector to 2022, while citizens of Germany, France, Spain and the UK are being offered financial incentives to go out and buy electric vehicles. This is great news for the SiC sector. Sales to the electric vehicle industry are forecast to grow and account for 60 percent of the SiC market by 2025, according to Yole.

Yole's Ezgi Dogmus, Team Lead Analyst, Compound Semiconductors and Emerging Substrates, says that the deployment of SiC in electric vehicles has started with high-end cars, such as those made by Tesla. Elon Musk's company deploys this material in its Model 3, S and X. "We are aware of other OEMs that are coming with SiC adoption this year," adds Dogmus.

When Tesla adopted SiC in its vehicles a few years' ago, the corresponding hike in orders for power devices led to concerns over SiC substrate supply. Leading chipmakers ensured that they would not miss out by negotiating supply contracts with the biggest producer of SiC substrates, Wolfspeed. Since then supply concerns have fallen, according to Dogmus, who says that the market is now benefiting from the entry and expansion of numerous suppliers. In China, firms such as TankeBlue and SICC have big expansion plans.

As well as the increase in the number of producers of SiC substrates, chipmakers are benefitting from the introduction of SiC boules on the market, provided by US firm GTAT. Dogmus says that GTAT established a partnership with ON Semiconductor, and has more recently entered into another with Infineon. "This is an interesting approach for companies who have internal SiC wafering facility, which can help them to grow and produce their own wafers, and also reduce their SiC dependence on other external factors."

...and grey clouds

Within the automotive industry, investment in electrification has come at the expense of LiDAR. There have been delays in projects associated with this technology, which involves laser chips. "When you take a look at the LiDAR market it's quite huge, and there are not so many automotive brands that are implementing it yet," says Mukish. The long-term future is promising, with Yole predicting that the LiDAR market will grow from $1.6 billion in 2019 to $3.8 billion in 2025.

The smartphone market has suffered from shuttered stops, travel restrictions and a tightening of belts. Global shipments for 2020 were down compared with 2019, particularly in the first two quarters.

For makers of VCSELs, a fall in smartphone sales is only part of the problem. There has also been a shift from using a pair of front-facing VCSELs in facial recognition systems, to a single world-facing emitter for photography or augmented reality. "There will be a direct impact on the volume of VCSELs and the revenue," says Mukish, adding that Yole has revised down its forecast accordingly. However, despite this headwind, the VCSEL market is still expected climb at a compound annual growth rate of 18.4 percent until 2025, to total $2.7 billion.

Dominating VCSEL sales is Lumentum, which sources its epiwafers from IQE. Lumentum enjoyed a 49 percent share of the market in 2019, aided by contracts with Apple, which has generated the highest volume for VCSELs for 3D sensing. However, Apple is diversifying its supply, with a significant and growing number of VCSELs coming from II-VI, thanks to its acquisition of Finisar in late 2019.

Despite a reduction in smartphone shipments in 2020, revenue for GaAs microelectronics increased year-on-year, according to Yole's Poshun Chiu, a Technology and Market Analyst, Compound Semiconductors and Emerging Substrates. He argues that this rise in global sales is due to the need for the latest phones to incorporate power amplifiers for both 5G and also the new Wi-Fi protocol, Wi-Fi 6, which offers GaAs a chance of taking market share away from the likes of silicon, SOI and germanium technologies. Going hand-in-hand with the higher revenues are increases in the volume of both GaAs chips and their associated epiwafers.

"5G and Wi-Fi 6 – the new connectivity is a big selling point – are driving the replacement of the new phones for consumers," says Chiu, pointing out that many OEMs have recently released models featuring these technologies. Looking further ahead, 5G phones will start to include amplifiers operating in the millimetre-wave, potentially increasing volumes for GaAs microelectronic devices.

Yole's last forecast for the visible LED market came out in 2019, when analysts predicted sales of $17.4 billion for that year and a modest compound annual growth rate out to 2024 of 5 percent. Some of its most recent analysis, however, suggest that the pandemic has taken its toll on this sector – declines in commercial lighting, outdoor landscape lighting, and outdoor displays have outweighed gains in sales for backlighting TVs, tablets and laptops. Total revenue is tipped to fall by around 8 percent between 2019 and 2020, before showing a slight increase in 2021.

Even before the pandemic, the visible LED market was in the doldrums, according to Mukish. "General lighting, initially the killer application for the LED, ended up being a bloodbath after the entry of Taiwanese and Chinese players that created a situation of overcapacity and strong price pressure." It is this state of affairs, rather than any consequence of Covid, that led Cree/Wolfspeed to sell off the LED-based parts of its business, and focus on RF and power electronics.

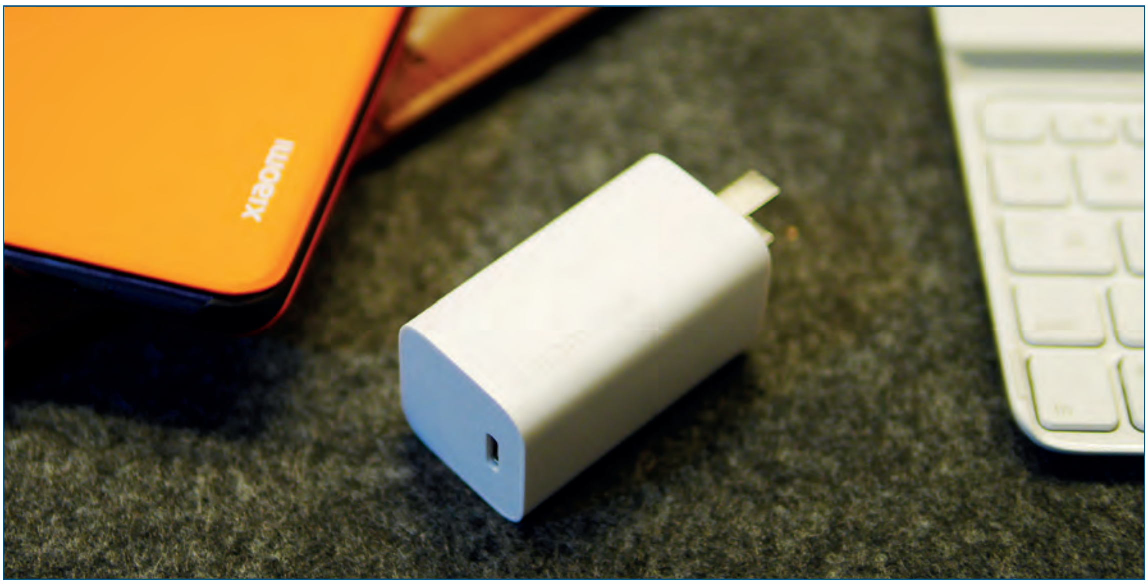
Commoditisation of the LED industry is not going to be accelerated by the pandemic. "It's already commoditised," argues Mukish, who believes the pandemic could drive further consolidation of this industry.

To secure better margins, some of today's leading LED manufacturers are targeting two niche areas: exterior automotive lighting and horticulture.

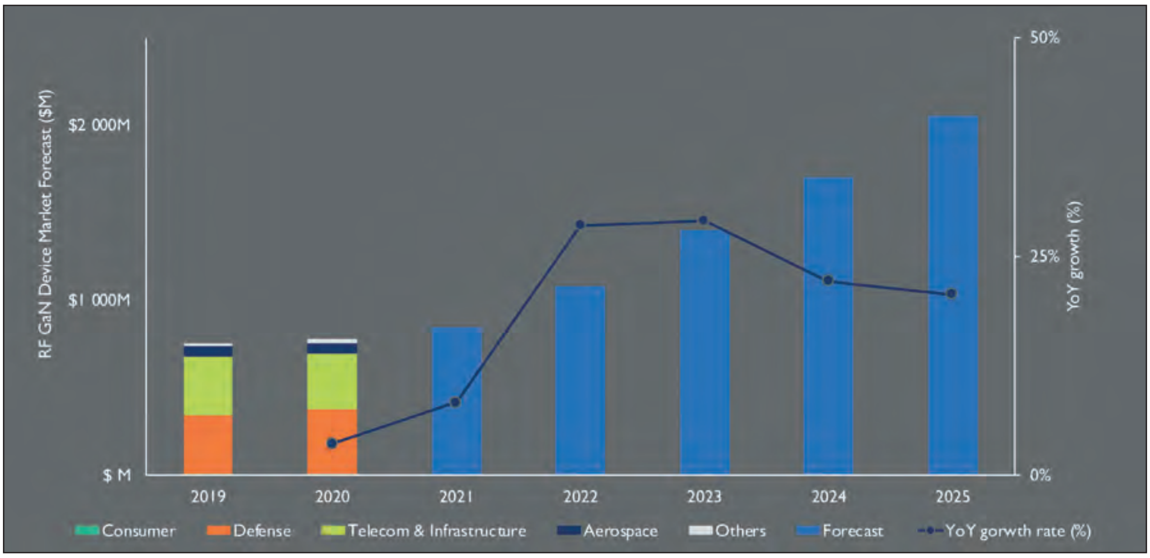
LED-based headlamps continue to evolve, now offering an opportunity for carmakers to enhance their brand by making it instantly recognisable day and night. One of the latest advancements is to combine brand-specific lighting with a camera, to create a smart headlamp offering controllability, such as the direction of the beam.

"Only a few companies can supply those kinds of device, mostly for headlamps, because this is where you require really high power, and really high power-density devices, which means expertise in thermal management and so on," explains Mukish. He says that Osram is the key supplier for automotive lighting, a niche that also brings in revenue for Lumileds.

The latter is a key player in horticultural lighting, where success hinges on fine-tuning emission wavelengths rather than optimising power density. Scientists are just starting to discover the optimal spectra for accelerating growth of specific plants, fruit and vegetables.



65 W fast chargers based on GaN devices are driving rapid growth in the GaN power electronic market.



Tensions between the US and China are impeding the growth of the GaN RF market. Source: Compound Semiconductor Quarterly Market Monitor, Q4, 2020. Module II, Yole Développement.

Independent success

One rapidly growing market that is not deriving any benefit from the epidemic is GaN power electronics. Chips are being deployed in fast chargers for mobile phones. Sales are ramping so fast that the GaN power market almost doubled between 2019 and 2020.

Yole's Ahmed Ben Slimane, Technology and Market Analyst, Compound Semiconductor and Emerging Substrates, told *Compound Semiconductor* that sales of GaN power devices began to take off in late 2019, when Reno's Ace Oppo Phone started to be dispatched with an accompanying 65 W GaN charger.

"We have identified two main companies that have targeted this consumer market: Power Integration and Navitas," says Ben Slimane. "They both have products and design wins with different Chinese OEMs, and other OEMs." Due to this activity, several models of smartphone now come with a GaN charger.

Rapidly growing markets always attract competition. Ben Slimane says that Transphorm, GaN Systems and Innoscience have all released impressive performance figures for their products that will help them to enter the GaN fast-charger market, which is also going to be targeted by big IDMs, such as STMicroelectronics and Texas Instruments.

Like the power GaN market, that for microLEDs has not been impacted by Covid-19. For microLEDs, that's because the market is emerging. It did reach an important milestone last year, with the release of the first commercial product.

According to Mukish, the next steps for this sector are further development of the technology, and the release of a "real" consumer product. "I say a real consumer product, because when you take a look at the product from Samsung, it's a luxury TV with a price tag of nearly $150,000," explains Mukish. While such an expensive item is out of the reach of most of us, prices may not need to tumble as much as one might expect before a trickle of sales begin, thanks to the emergence of a luxury, high-end TV market.

Trade wars

For the makers of RF GaN devices, the two largest markets are defence and telecom infrastructure. RF GaN is already established in wireless infrastructure, having been used in 4G LTE base stations. GaN is the preferred technology for Huawei, which is deploying 5G infrastructure in China, and for European rivals Nokia and Ericsson.

According to Ben Slimane, the pandemic has not had a big impact on the RF GaN market for 5G. What has held back sales is an ongoing trade war between the US and China, with Huawei impacted severely by restrictions, which have also dragged down revenue for Skyworks and Qorvo.

"2021 will be an important year to watch," says Ben Slimane. "There will be a new presidency, and this might bring a new strategy with China."

With Joe Biden at the healm, there will also be a dramatic shift in the position of the US towards climate change, possibly providing another boost to the makers of electric vehicles and those in this supply chain. Another big change this year will be the wide roll-out of an effective vaccine, which will help to ensure smooth running of all compound semiconductor fabs. As the analysis by Yole shows, our industry has not taken any major blows from the pandemic, and a trajectory of long-term growth looks set to continue throughout this decade.

Targeting telecoms with nanowires

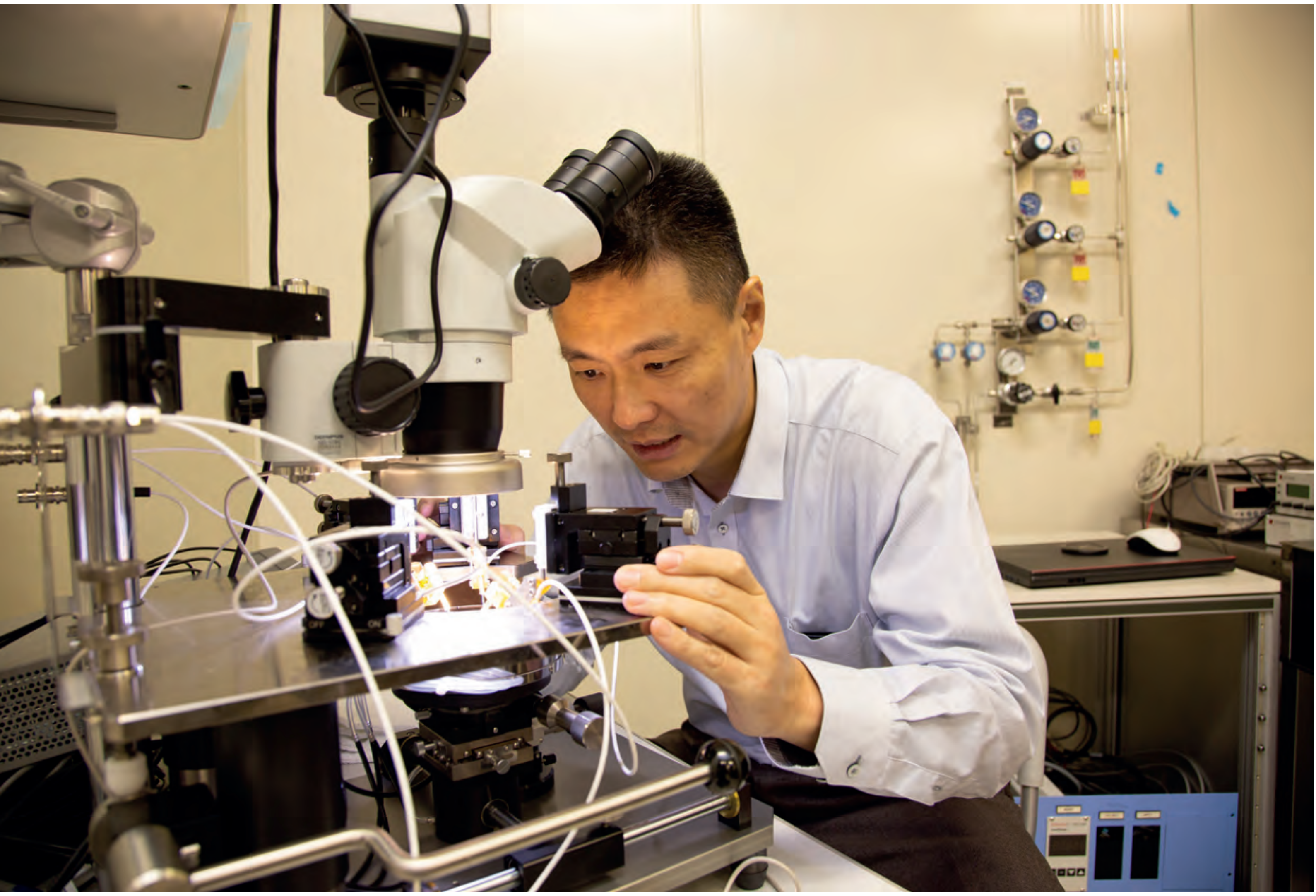
Nanowire lasers could provide the telecom industry with a widely tuneable source that is easy to integrate with silicon photonics

BY GUOQIANG ZHANG FROM NTT CORPORATION

ALMOST ALL DEVICES produced by our industry are formed from compound semiconductor heterostructures. By controlling the composition, doping and thickness of every layer within an epitaxial structure, we are able to produce a wide range of devices with excellent characteristics.

One such device is the edge-emitting InP-based laser. Generating sales of billions of dollars, this class of laser, which operates in the spectral domain spanning 1.2 μm to 1.6 μm, is a key ingredient in optical communication networks.

To produce these telecom lasers, engineers load InP substrates into MOCVD reactors and deposit an epitaxial stack containing layers of InP and InGaAs(P). It is a material combination that has its pros and cons – by adjusting the composition, the designer can adjust the wavelength of the laser's emission, targeting absorption minima in optical fibres; but



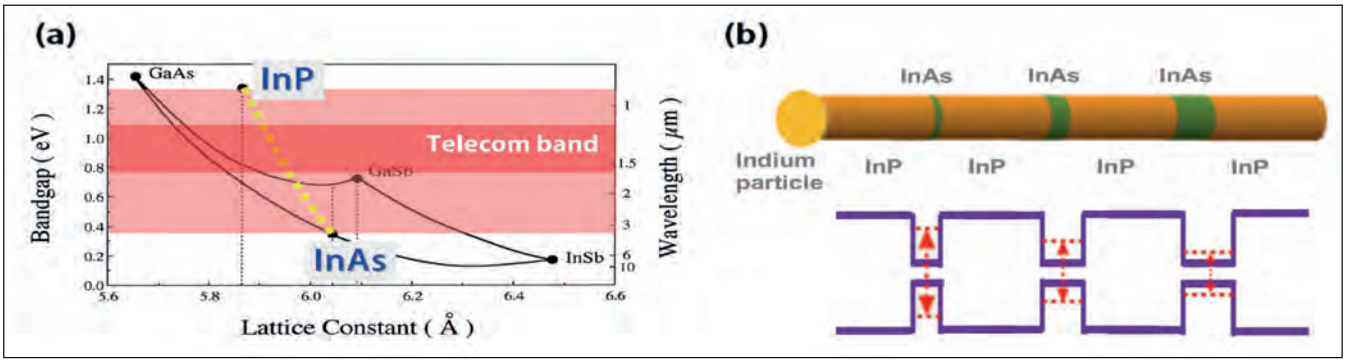


Figure 1. (a) Bandgap and lattice constant of III-V compound semiconductors. InP/InAs can cover a wide spectral range, including the telecom band. (b) Lattice-matching constraints are far less severe in InP/InAs heterostructure nanowires connected by a single indium particle, than in conventional heterostructures. In these nanowires, the quantum confinement effect along the axial direction allows the real bandgap of the InAs layer to be modulated by the thickness.

there are mismatches in lattice and thermal expansion coefficient between InP and its related alloys, and this hampers further integration into functional systems and platforms.

At NTT, Japan, we are developing a technology that is not held back by these issues. To break the shackles we are heading in a new dimension – rather than working with planar material, we adopt a nanowire structure that is far better at accommodating strain. This opens up new opportunities for heterostructures and functional devices.

By targeting the 1.2 μm to 1.6 μm domain with our nanowire lasers, as well as providing potential sources for data transmission through fibre, we have the opportunity to turn to mature silicon photonics platforms for integration – that's because silicon is transparent at telecom wavelengths.

We form our telecom-band single-nanowire lasers from InP/InAs quantum heterostructure nanowires. The pairing of InP and InAs can create quantum heterostructures with a wide spectral range that includes the telecom band, thanks to a substantial quantum confinement in an InAs quantum disc along the axial direction (see Figure 1).

Mastering mismatch

In planar structures, growing InAs layers on InP tends to result in a high density of dislocations in the InAs active layers, due to significant lattice mismatch – it is 3.1 percent (see Figures 2 (a)-(c)). This mismatch makes it extremely challenging to form dislocation-free InAs active layers with excellent optical properties.

It's a very different state of affairs with the nanowire structure. Due to its nanoscale diameter, its crystalline lattice can be deformed laterally, relaxing the strain induced by lattice mismatch (see Figure 2 (d)). A dislocation-free active region results, with the nanowire heterostructure enduring strain caused by the large lattice mismatch. The most common approach for nanowire synthesis is bottom-up, vapour-liquid-solid growth. It offers high controllability regarding composition, doping, the heterostructure architecture and diameter (see Figure 3).

Researchers have used gold-particle-catalysed vapour-liquid-solid growth to fabricate various

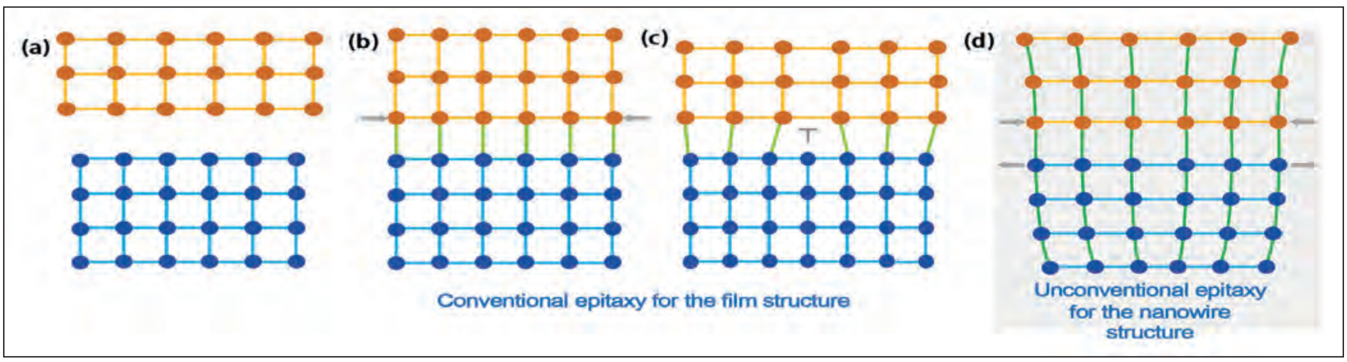


Figure 2. Strain relaxation for crystal materials with lattice mismatch varies between conventional heterostructures and nanowires. (a) Lattices of crystalline materials before epitaxy. (b) Coherent growth by elastic deformation of the epi-layer lattice. (c) Incoherent growth (strain relaxation by mismatch dislocations). (d) Coherent growth by elastic deformation of both lattices. In contrast to the film structure, the lattice in the nanowire structure can deform much more along the radial direction because of its microscale or nanoscale diameter. Thanks to this, nanowires can endure higher strain induced by lattice mismatch.

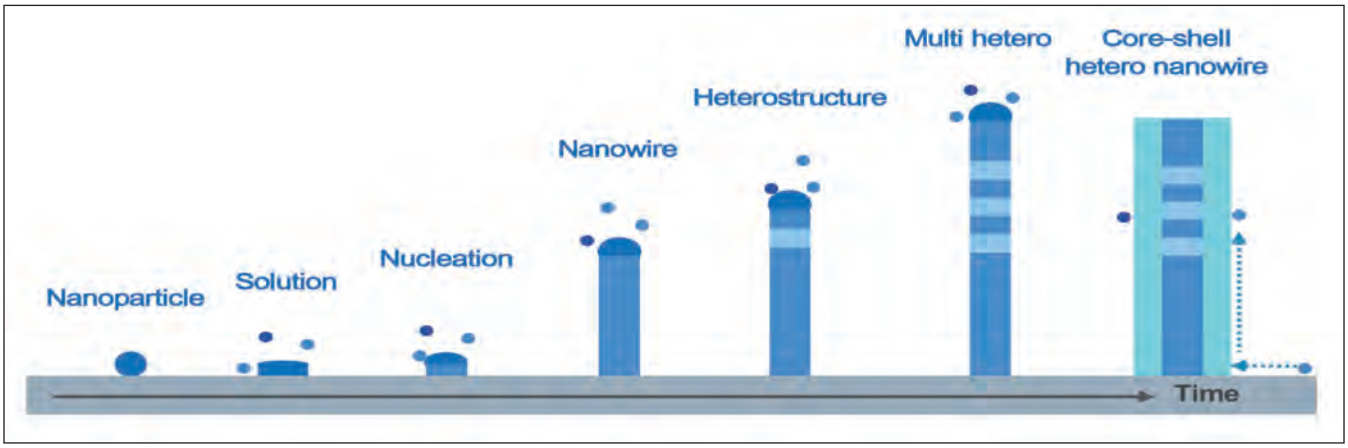


Figure 3. Schematic diagram of the vapour-liquid-solid growth mode. InAs and InP nanowires can be grown by the self-catalysed vapour-liquid-solid mode using indium particles.

nanowires, including those based on GaAs and InP. Using gold is not ideal, because it is incompatible with the mainstream CMOS process and consequently hinders integration of optically active III-V nanowires with silicon technology. Far better alternatives for producing compound semiconductor nanowires by the vapour-liquid-solid growth approach are particle catalysts based on either group III or V elements – and out of these two the former is more suitable.

We have established a growth technology for making InP/InAs heterostructure nanowires by the self-catalysed vapour-liquid-solid mode. This approach provides high controllability, allowing us to insert multiple InAs quantum discs that emit in the telecommunication domain into our InP nanowires (see Figure 4).

The high quality of our structures is evident in high-angle annular dark-field scanning transmission electron microscopy, which reveals the multiple quantum disc layers along the [011] direction (see Figure 4 (c)). Our structures result from a vapour-liquid-solid growth mode that is dominant along the axial direction. Thanks to the low growth temperature, negligible growth occurs in the radial direction via

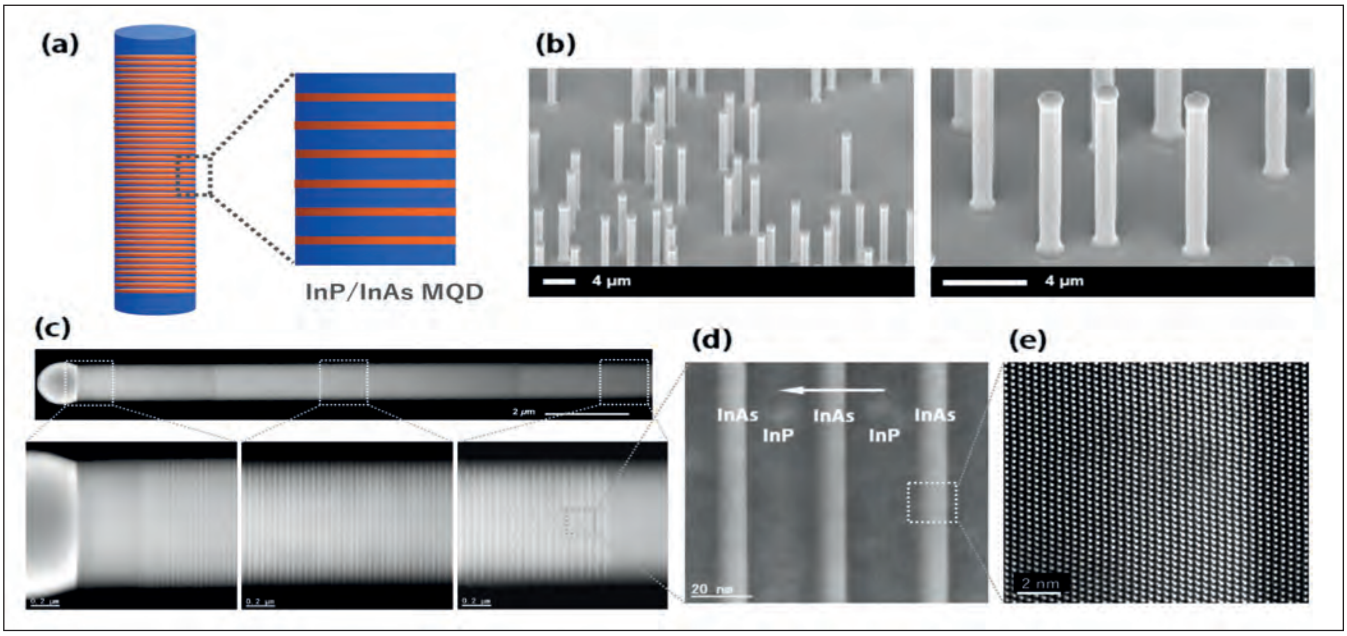


Figure 4. InP/InAs multi-quantum-disc (MQD) nanowires. (a) Schematic diagram of a MQD heterostructure nanowire and a magnified view of the heterostructure highlighting the InP/InAs MQD structure. The InAs layer is indicated in red. (b) Scanning electron microscopy images (tilt: 38°) of InP/InAs MQD nanowires grown on an InP (111)B substrate. (c) High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images of an InP/InAs MQD nanowire taken along the [011] zone axis. The nanowire contains 400 units of InP/InAs heterostructure. ((d) and (e)) Aberration-corrected HAADF-STEM images of InP/InAs heterostructures taken along the [011] zone axis. The horizontal white arrow indicates the growth direction. The thicknesses of the InAs layer and the InP barrier layer are 9.0±1 nm and 25.6±1 nm, respectively.

the conventional film growth mode – this is the uncatalyzed mode. With all these factors at play, there is high growth controllability, ensuring homogeneity of the gain medium throughout the entire multiple quantum disc region.

Imaging our nanowires with a high-resolution scanning tunnelling electron microscope allows us to directly visualize the stacking of the InP/InAs heterostructure and the interface traits (see Figures 4 (d) and (e)). These images highlight a dislocation-free InAs/InP interface, despite the 3.1 percent lattice mismatch between InP and InAs. When InAs is grown on InP, the interface is atomically abrupt (see Figure 4(c)); and when InP is added on InAs, a gradient layer results, due to the strong reservoir effect of arsenic in indium catalyst particles. Due to coherent interfaces within the InP/InAs multiple quantum disc structure, there is relatively high strain, stemming from the lattice mismatch. As the InP layers are much thicker than the InAs discs, there is compressive strain in the latter.

Creating cavities

We turned to micro-photoluminescence to characterise the optical properties of our nanowires. When they are mechanically dispersed onto foreign substrates, we can remove the indium particles at their tips to create a (111)-facet mirror – and thus a Fabry-Pérot cavity. This structure has intrinsic Fabry-Pérot resonance modes with a sufficiently large mode index in a wide diameter range.

Optically pumping our nanowires leads to lasing behaviour. Measuring the photoluminescence of numerous individual nanowires reveals a broad spontaneous emission spectrum, with a peak wavelength around 1.57 μm to 1.59 μm. When pumped with an excitation power of 2.15 mJ cm^{-2}, a spike centred at 1573 nm appears. Plotting the light input-output curve by varying the excitation power uncovers a strong transition from spontaneous to stimulated emission.

One of the merits of our nanowire lasers is that their wavelength can be tuned over a wide range, such as the entire telecom band. By tuning the thickness of single InAs quantum discs over a wide range, we are able to modulate the photon emission energy. To adjust the thickness of our discs, we vary the flow rate of the source materials (see Figure 6). Based on the results realised by this approach, our nanowires promise to provide modulation of the lasing wavelength over a broad range. We can stretch as far as 2.6 μm into the infrared by forming pure InAs nanowires with a wurtzite crystalline structure (note that there are no quantum confinement effects in these structures).

So far, we have described optically pumped devices. However, many applications, including photonic integration, demand current-injection light emitters. It is incredibly challenging to realise current-injection lasing from single nanowires, because making a direct electrical contact to them deteriorates light confinement. However, we have taken important steps towards this goal, demonstrating LEDs with *p-i-n*-structured nanowires that emit in the telecom range. Fabrication of these current-injection emitters began with the growth of an InP/InAs *p-i-n* structure, using the self-catalysed vapour-liquid-solid mode. Growth on InP (111)B substrates enabled vertically aligned nanowires (see Figure 7). They feature an InAs active layer as thin as around 9 nm. As that's significantly below the Bohr radius of bulk crystalline InAs, which is around 34 nm, this ensures quantum confinement along the axial direction.

To form our novel LEDs, we began by embedding these nanowires in transparent insulating benzocyclobutene. Subsequent reactive-ion etching then removed this organic from the surface, exposed the nanowire tips, and ultimately paved the way to adding electrical contacts. Depositing AuZn metal

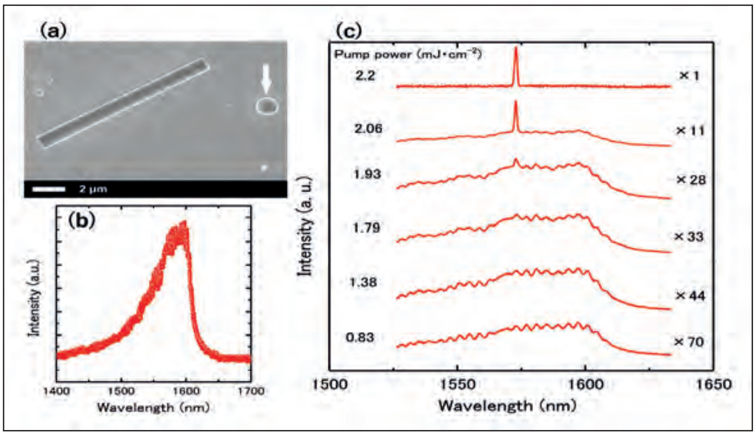


Figure 5. (a) Scanning electron microscopy image of a nanowire mechanically dispersed onto a gold-film-covered SiO_2-on-silicon substrate. The white arrow indicates a removed indium particle. (b) Photoluminescence spectrum of a single nanowire under a pump laser power of 0.83 mJ cm^{-2}. (c) Photoluminescence spectra of the nanowire with increasing pump power, revealing spectral narrowing.

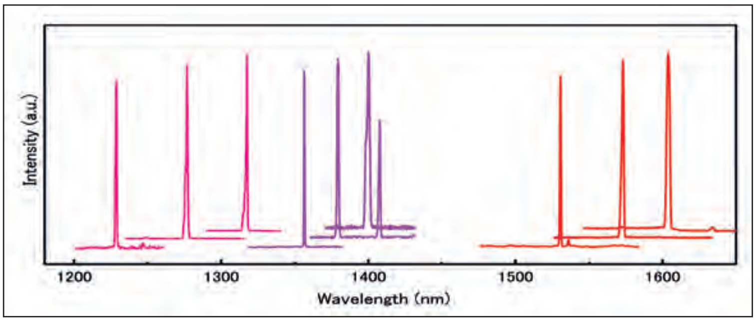


Figure 6. Nanowires allow a tuning of the laser wavelength range in the telecom band. Spectra are offset for clarity. The laser wavelength is modulated by the growth parameters, such as flow rates of the metal-organic sources. Thus a broad wavelength range is covered in the whole telecom band, including the two technologically important telecom-band windows centred around 1.3 μm and 1.55 μm.

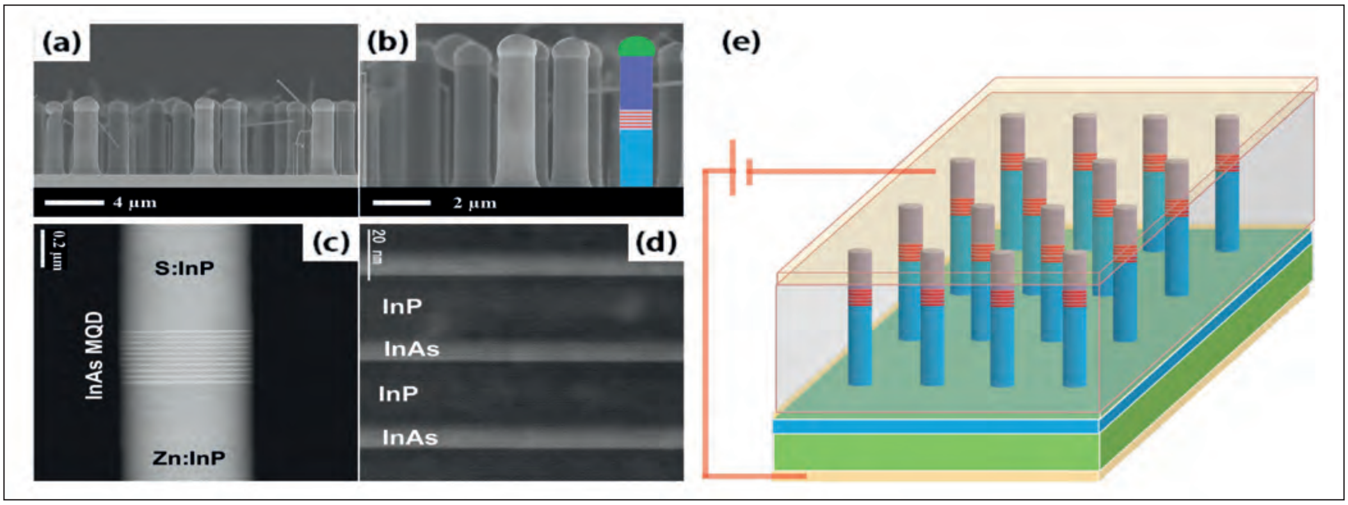


Figure 7. Morphological and structural analysis of InP/InAs heterostructure nanowires. (a) and (b) Cross-sectional scanning electron microscopy images of InP/InAs nanowires. The inset shows the *p-i-n* structure of these nanowires. (c) and (d), high-angle annular dark-field scanning transmission electron microscopy images of the multi-quantum-disc (MQD) active region between zinc-doped and sulphur-doped InP segments. The MQD active region consisting of 10 InAs quantum discs. (e) A diagram of the nanowire LED device. (Figure reprinted with permission from IOP publishing).

onto the *p*-InP substrate and indium-tin-oxide onto the *n*-InP nanowire segment created electrical contacts for this device.

We have investigated the optoelectronic characteristics of our nanowire LEDs. The current-voltage (I-V) behaviour mirrors that of conventional LEDs (see Figure 8). To observe the electroluminescence of single nanowires, we carried out micro-electroluminescence measurements at room temperature. One can see the luminescence from nanowires within an area of just 380 μm by 475 μm (see Figure 8 (c)). In general, a single bright spot corresponds to a single nanowire LED. As we increased the bias, more and more nanowires exhibited a continuously increasing electroluminescence intensity.

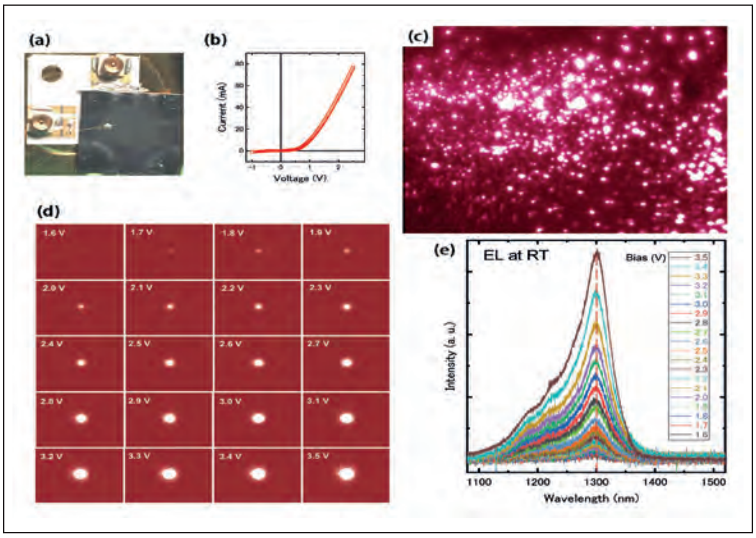


Figure 8. Electrical performance of a nanowire LED at room temperature. (a) The nanowire sample is fixed to a white ceramic substrate with metallic electrodes. The black-colour area is the nanowire LED device (10 μm ×10 μm). (b) A typical current-voltage curve for a nanowire LED. (c) An electroluminescence image taken by an infrared camera under an LED bias of 2.5 V. (d) Electroluminescence images of a single luminescent nanowire with increasing bias (step: 0.1 V). The area of each image is 24 μm × 36 μm. (e) The electroluminescence spectra of the nanowire shown in (d) with increasing bias (step: 0.1 V). The spectra show a constant peak at 1300 ± 5 nm, corresponding to the O-band of telecom-band range. (Figure reprinted with permission from IOP publishing).

Critical to the development of high-performance optoelectronic devices is tunability of the electroluminescence wavelength. Our multiple quantum disc active region allows us to modulate the photon emission energy by adjusting the thickness of single InAs quantum discs – this alters the quantum confinement along the axial direction. Thanks to the high degree of control provided by vapour-liquid-solid synthesis, we are able to precisely define the thickness of each InAs quantum disc, and thus tune the electroluminescence in the O and E bands of the telecom range.

Our progress to date has hinged on overcoming the lattice-match limitation of conventional heterostructures. By turning to bottom-up growth via vapour-liquid-solid synthesis, we have produced optically pumped nanowire lasers and LED-based variants emitting in the telecom band. Our progress will open up new opportunities for novel functional devices and different forms of integration.

Further reading

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Disrupting the tubes market with high-voltage GaN HEMTs

GaN HEMTs operating at voltages of up to 150 V outperform vacuum tubes by combining high performance with greater reliability, longer lifetime and lower operating costs

BY GABRIELE FORMICONE, JEFF BURGER, JAMES CUSTER AND JOHN WALKER FROM INTEGRA TECHNOLOGIES

INVENTED PREDOMINANTLY in the first half of the twentieth century, vacuum electron devices (VEDs) have a long history as a critical component enabling satellite communications, radar systems, high-energy particle accelerators, and other applications requiring high output power, wide operating bandwidth and high efficiency. VEDs include traveling-wave tubes and klystrons.

While VEDs are an accepted technology, they suffer from multiple weaknesses, many of which can be addressed by semiconductor-based solid-state amplifiers, which have become the mainstream technology in the lower power, lower frequency VED market. Semiconductor-based solutions deliver longer lifetime, superior ruggedness, and higher reliability, and reduce overall system size, weight, and costs. Yet despite all this success, solid-state sources have yet to penetrate the high end of the market for high power, multi-kilowatt applications.

Modernization of high-power RF communication and data transmission systems will push the requirements of what traditional VEDs can deliver. In addition, system architects are demanding more efficient power sources to meet green requirements while driving down operating costs over the system life. Thanks to the pioneering work of our team at Integra Technologies Inc., a market leader in RF and microwave high power devices, we have achieved a breakthrough by pushing the operating voltage for this class of device to a new high, raising the bar for high efficiency GaN-on-SiC technology. These efforts draw on our long heritage of silicon bipolar and GaN/SiC RF high power expertise at 28 V and 50 V, with our latest success representing yet another milestone in our advancements in green technology, which date back to 2013. The ground-breaking progress that we have made enables high-voltage GaN/SiC-based HEMTs to offer a compelling commercial alternative to the VED.

The foundation for our advanced R&D activity is our portfolio of proprietary epitaxial structures. They are specifically developed for high-power RF applications, and benefit from decades of refinement, realised through close collaborations with our high-power customers.

Leveraging this field-proven IP, we have developed new epitaxial structures specifically designed for high-voltage operation. In addition to this advance, we have introduced and then patented innovated circuit and thermal management techniques specifically for high power operation. Benefiting from all this progress, our devices can now operate at voltages of up to 150 V, resulting in a dramatic improvement in output characteristics.

Our latest generation of high-voltage GaN/SiC devices, which produce pulsed power densities up to more than 20 W/mm, enables the production of solid-state devices with an output power of several kilowatts. Critical to the performance of the next high-power-generation green platforms, our HEMTs deliver sufficient gain, efficiency, and reliability to enable these systems to fulfil their performance targets. Our devices are manufactured in a mainstream wafer fabrication foundry, using commercially available, production-ready materials.

Increasing power and dynamic range

At last year's International Microwave Symposium, our company demonstrated the incredibly high output powers that can be produced by RF GaN/SiC transistors operating at elevated voltages of between 100 V and 150 V. We reported 2 x 50 mm gate periphery die yielding 1.2 kW when operating in CW mode at 100 V, and producing 2.3 kW when driven at 145 V using 100 μs-wide pulses and a 5 percent duty cycle. Plots of power gain and drain efficiency versus output power for these devices, which have a drain efficiency of 80 percent when operating in both modes, are shown in Figure 1. Two key features of this amplifier's design are harmonic tuning, used to realise high efficiency, and patented thermal enhancement techniques that help mitigate heat dissipation in such high-power density transistors. We have designed the devices and circuits to operate at 400.8 MHz. This is the frequency employed in today's largest particle accelerators, and also a frequency of interest for long-range, early-warning radar systems.

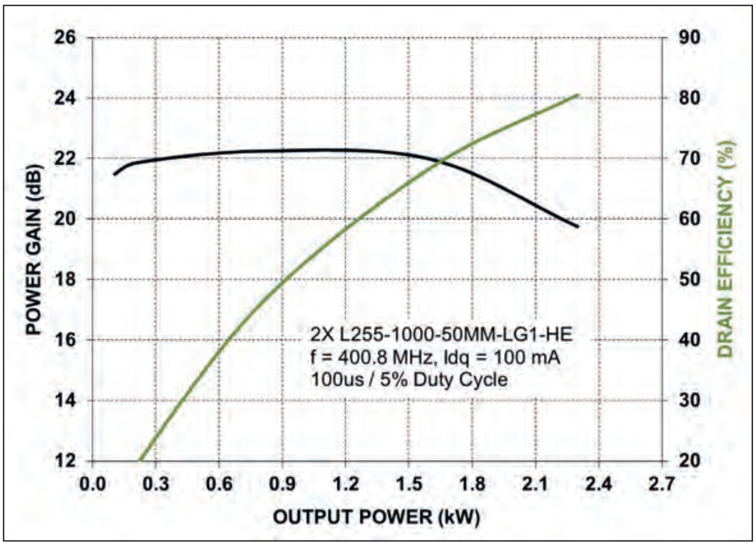


Figure 1. Measured RF power gain and drain efficiency versus output power at 145 V bias and 400.8 MHz. Quiescent current is 100 mA. 6 Ω series gate resistors help to stabilise the transistor with 20 dB gain at 2 dB compression and 2.3 kW saturated power. Drain efficiency peaks at 80 percent. In CW operation at 100 V bias, saturated power is 1.2 kW with the same 80 percent peak drain efficiency.

Our technology enables a single transistor to produce a CW power level of 2 kW and a pulsed output of 4 kW at an efficiency greater than 70 percent. With this level of performance, megawatt power levels can be realised with fewer combiners and lower related losses. By comparison, off-the-shelf 50 V RF technology would require massive power combiners

Our technology enables a single transistor to produce a CW power level of 2 kW and a pulsed output of 4 kW at an efficiency greater than 70 percent. With this level of performance, megawatt power levels can be realised with fewer combiners and lower related losses

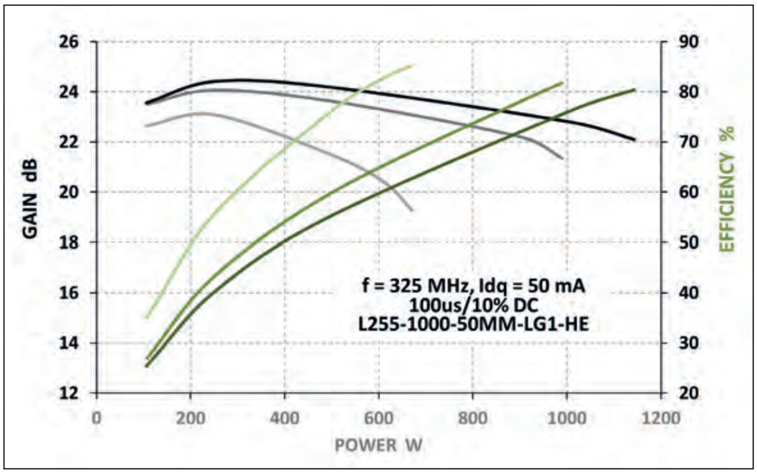


Figure 2. Measured RF power gain and drain efficiency versus output power for a 50 mm die with a signal of 100 µs pulse width and 10 percent duty cycle at 325 MHz. The device is characterized at 100 V, 125 V and 145 V DC bias demonstrating a 3 dB power dynamic range. By reducing operating bias to 50 V a 6 dB dynamic range is achieved.

to achieve similar performance, degrading system efficiency, while increasing the complexity of heat extraction. We also showcased the design flexibility of this technology by increasing the operating voltage to 150 V at the 2020 European Microwave Week. In this forum, we reported a single 50 mm gate periphery die that produced a 3 dB power dynamic range when modulating its operating bias from 100 V to 125 V and then on to 145 V (see Figure 2).

This amplifier's devices and circuits are designed to operate at 325 MHz, targeting large particle accelerators. Our single semiconductor die delivers a 1.1 kW peak power at 145 V with 80 percent peak efficiency. The peak power decreases by about 3 dB at 100 V bias.

Going to even lower voltages can offer additional benefits. When we dial back the bias to 50 V, peak power can be modulated by around 6 dB while still preserving 80 percent peak efficiency; and we can realise additional dB of dynamic range by reducing the operating bias towards 28 V or 32 V. We have obtained similar results, also announced at European Microwave Week, with a power amplifier designed to operate at 650 MHz.

Such a great dynamic range is a key enabler in high-power RF systems. It allows multi-use or functionality, and it also enables older systems to be upgraded to combine legacy performance with additional state-of-the-art capabilities. For the high-power devices we reported at the most recent International Microwave Symposium and European Microwave Week, the peak channel temperature is only around 150 °C. Such low temperatures are realised from proprietary techniques that enhance heat flow from the hottest spots of the active region.

Our R&D activities have extended to considering the bandwidth associated with the higher power densities and higher load impedances at 100 V and 150 V. Power-over-bandwidth is a 'hot button' in several applications, with requirements that may be strictly application-specific and not discussed in the public domain. What we can say, nonetheless, is that broadband high-power applications are destined to reap huge benefits from our 100 – 150 V amplifier technology.

System-level benefits

As mentioned earlier in this article, the higher voltage GaN transistors can achieve power densities of more than 20 W/mm, thus allowing for reduced circuit complexity for the same relative power level. As an example, two 1 kW transistors running at 50 V could be replaced by a single 2 kW transistor operating at 100 V. This eliminates one transistor and the combining structure required for the lower voltage solution.

Another advantage of a higher voltage is evident in a simple load-line analysis. While a 50 V device will provide a 25 W output power with just a 50 Ω load, a 100 V device will provide four times this power.

For broadband applications, higher voltage GaN HEMTs can also be an advantage, considering that the device impedances increase with higher voltage operation and the capacitance-per-Watt are reduced. Lower voltage solutions require larger impedance transformations to achieve bandwidth, while a higher voltage solution can eliminate these transformers or reduce transformation ratios and their complexity. When utilizing 100 V GaN, the matching structure size can be reduced by a factor of two or more by removing transformers over a 50 V GaN solution for the same RF output power.

There is no doubt that much is to be gained from increasing the operating voltage of the GaN HEMT. There are benefits for the device itself, including an increase in output power, plus plenty of advantages at the circuit and system level. Our company is in talks with several VED's users to commercialize our high-voltage GaN/SiC green technology.

Further reading

G. Formicone et al. "A 2.3 kW 80% Efficiency Single GaN Transistor Amplifier for 400.8 MHz Particle Accelerators and UHF Radar Systems", IEEE-MTTS International Microwave Symposium, 2020.

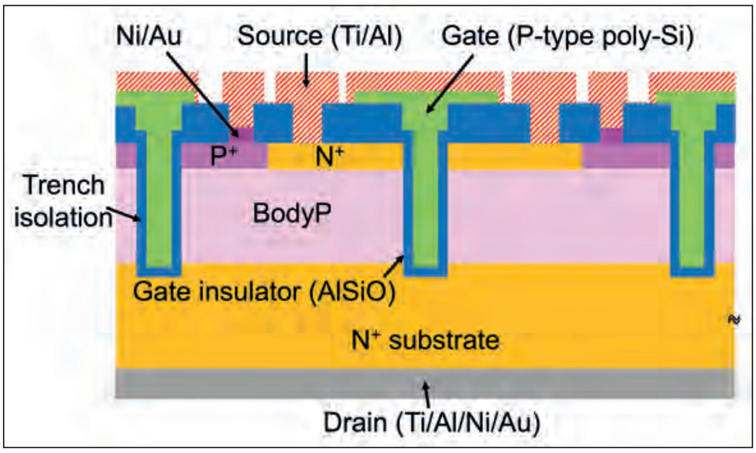
G. Formicone et al. "A GaN/SiC UHF PA for Particle Accelerators with 100-145V Quasi-Static Drain Modulation," European Microwave Week, 2020.

G. Formicone et al. "Targeting radar with 150 V RF GaN HEMTs" Compound Semiconductor magazine, March 2016.

Turbo-charging the channel of the GaN MOSFET

Exposure to a nitrogen plasma enhances field-effect mobility in GaN vertical-channel MOSFETs

ENGINEERS at Nagoya University, Japan, are claiming to have broken new ground by unveiling a simple process to improve the channel of a GaN trench MOSFET. Their effort will help to advance the capability of the GaN trench MOSFET, which has the upper hand over other classes of GaN transistor in realising a lower specific on-resistance, thanks to a narrower cell pitch that results from the use of a vertical channel.



Engineers at Nagoya University, Japan, have increased the mobility of the channel in vertical GaN MOSFETs by turning to an *in-situ* nitrogen plasma treatment in an atomic layer deposition chamber.

The team from Nagoya University have increased channel mobility in the GaN trench MOSFET with a two-step process that involves an *in-situ* nitrogen plasma treatment in an atomic layer deposition (ALD) chamber, followed by deposition of a gate insulator GaN channel. "Any special equipment or extensive process is not necessary," points out team spokesman Takashi Ishida.

A high channel mobility results from the compensation of nitrogen vacancies within a device – this is said to be a ground-breaking accomplishment. The reduction in vacancies combats Coulomb scattering, which is known to inhibit channel mobility.

Merits of the nitrogen plasma process are underscored by electrical measurements on a portfolio vertical trench MOSFETs, which have been formed with different treatments to the sidewalls.

Fabrication of the MOSFETs began by loading an *n*-type GaN substrate into an MOCVD chamber and depositing a 2 μm-thick *p*-type body layer, followed by a 100 nm-thick *p*-type contact. To aid analysis of channel properties, the team omitted the drift layer, as this allowed them to exclude drift resistance.

The next steps in the fabrication process involved activation of *p*-type layers by high-temperature annealing, the addition of a 500 nm-thick SiO_2 mask and selective etching of the *p*-type contact layer. Deposition of a 200 nm-thick *n*-type source layer over the whole surface followed, prior to selective etching with tetramethylammonium hydroxide (TMAH).

Ishida and co-workers used sputtering, rather than ion implantation, to create dopants in the *n*-type source layer. They took this approach because sputtering does not require high-temperature annealing at 1000 °C, a step that could introduce defects in the *p*-type body layer where the channel is formed. Note that defects in this region could also result from ion implantation.

To form the trench structure, the team employed multi-step bias etching. After this, they subjected the structure to a 30 minute nitrogen plasma treatment in an ALD chamber, using an output power of 300 W and argon and nitrogen flows of 130 sccm and 20 sccm, respectively.

Final steps for device fabrication involved ALD and annealing of a 35 nm-thick layer of $Al_{0.78}Si_{0.22}O$ that formed the gate oxide, and then the addition of a poly-silicon gate electrode and metal stacks to create source, drain and *p*-type body contacts.

Secondary ion mass spectrometry revealed that silicon did not diffuse into the *p*-type body layer. Magnesium diffusion into the *n*-type source did occur, but levels were more than three orders of magnitude lower than that for the silicon dopant, so had negligible impact. Electrical measurements determined that plasma treatment led to an increase in field-effect mobility from 30 $cm^2 V^{-1} s^{-1}$ to 47 $cm^2 V^{-1} s^{-1}$, leading the team to conclude that plasma treatment is effective at improving the channel properties of vertical trench GaN MOSFETs.

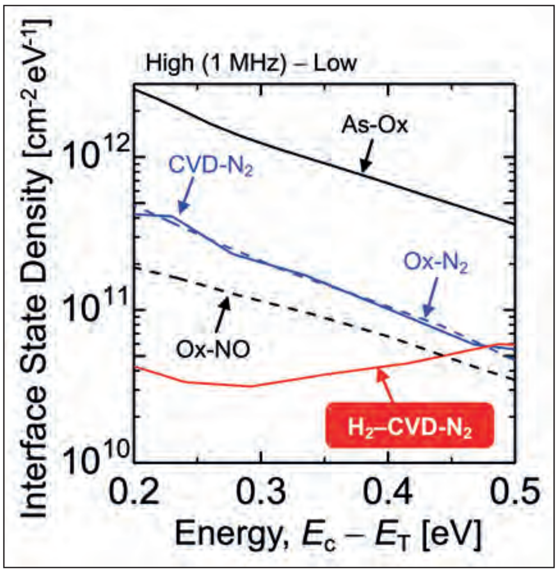
The engineers are now making a vertical trench GaN MOSFET with a drift layer. According to Ishida, as it is important to also realise a desired breakdown voltage, in parallel the team are developing an edge-termination structure.

Reference

T. Ishida *et al*. Appl. Phys. Express **13** 124003 (2020)

Quashing interface states in SiC MOSFETs

To trim channel resistance, the production of SiC MOSFETs should include etching with hydrogen gas, deposition of silicon dioxide by CVD, and a nitridation process



Interface defects in MOSFETs fall by the combination of H_2 gas etching, SiO_2 deposition and nitridation ("H_2-CVD-N_2"). The un-annealed sample, labelled "As-Ox", suffers from a large frequency dispersion. Reduced dispersion came from the processes: "CVD-N_2", which involved SiO_2 deposition and a N_2 gas anneal; "Ox-N_2", a combination of dry oxidation and a N_2 gas anneal; and "OX-NO", which involves dry oxidation and NO annealing at 1250 °C.

THE SiC MOSFET, widely viewed as the best commercial device for fast switching at high voltages, is compromised by a high channel resistance that stems from a high density of interface states.

But this weakness can be overcome, thanks to a novel three-step process that has recently been developed by a team from Kyoto University, Japan.

Using techniques such as secondary ion mass spectrometry and deep-level transient spectroscopy, the researchers found that defects are generated near the SiC-SiO_2 interface during thermal oxidation, the standard process used to make the gate oxide of a SiC MOSFET. To quash these defects, they have developed a process that involves etching SiC with hydrogen gas before depositing a SiO_2 film by plasma-enhanced CVD and using nitridation with N_2 gas to passivate defects at the SiC-SiO_2 interface.

Spokesman for the team, Tsunenobu Kimoto, points out that he and his colleagues are by no means the first to create the SiO_2 film by deposition, rather than thermal oxidation. Up until now, though, deposition processes proved unsatisfactory, due to defects generated during sacrificial oxidation that are located up to 5 nm below the surface. "We solved this problem by appropriate hydrogen etching before silicon dioxide deposition," explains Kimoto.

Another recent approach for forming a high-quality SiC MOS interface involves the use of supercritical CO_2 (see *Compound Semiconductor*, Nov & Dec 2020, p. 66). However, according to Kimoto, this alternative fails to deliver a significant reduction in defect density, while their approach reduces this by a factor of 30 to 50.

The process developed by engineers at Kyoto University will aid designers of SiC MOSFETs, because it increases the range of dimensions that can be used for this class of transistor. By reducing resistance through a lowering of the interface states, it is possible to employ shorter channels while avoiding short-channel effects, such as a decreasing threshold voltage and a degradation in sub-threshold slope that leads to the need for larger switching voltages. When SiC MOSFETs are made with conventional processes, short-channel effects start encroaching at channel lengths below 1 μm.

To investigate the impact of interface states on different processes used to add and treat the SiO_2 film, Kimoto and co-workers fabricated a portfolio MOS capacitors on *n*-type 4H-SiC (0001) epilayers. As part of this study, they investigated whether the benefits of the nitridation process were simply due to the high temperature employed – it takes place at 1400 °C – or resulted from the use of N_2 gas. To test the latter, the team compared results with those associated with a similar process involving argon. The engineers also fabricated MOS capacitors by dry oxidation to aid comparison.

Values for the density of interface state for MOS capacitors produced with various processes are shown in the figure (see above). The lowest dispersion came from H_2 gas etching, followed by SiO_2 deposition and nitridation ("H_2-CVD-N_2").

Kimoto and colleagues are now using their process to produce and evaluate SiC MOSFETs. Initial results are encouraging, with channel mobility increasing from 38 $cm^2 V^{-1} s^{-1}$ to 85 $cm^2 V^{-1} s^{-1}$. Dielectric breakdown characteristics of the gate oxide and the threshold-voltage stability are said to be "very good".

The team intends to make additional refinements to its process. "[We] would like to show a high channel mobility over 100 $cm^2 V^{-1} s^{-1}$ in *n*-channel 4H-SiC(0001) MOSFETs," says Kimoto.

Reference
K. Tachiki *et al*. Appl. Phys. Express 13 121002 (2020)

Uncovering degradation mechanisms in green LEDs

Intentional degradation induces the introduction of interstitial indium in the quantum wells

RESEARCHERS IN CHINA are claiming to have shed new light on changes that occur within a green-emitting GaN LED as it degrades.

The experimental and theoretical study conducted by the team from Shaanxi University of Science and Technology and Taiyuan University of Technology concluded that degradation resulted in red-shifted LEDs with a reduced luminous efficiency. These changes were attributed to three factors: decreased bandgap, caused by relaxation of the InGaN quantum well; increased defect density, due to the introduction of interstitial atoms; and increased InGaN quantum well thickness.

LEDs employed in the investigation were fabricated in-house. The devices, grown in an Aixtron MOCVD reactor on 2-inch *c*-plane sapphire substrates, featured nine 15.6 nm-thick $In_{0.28}Ga_{0.72}N$ quantum wells separated by 3.1 nm-thick GaN quantum barriers. LEDs subjected to degradation were heated to 460K for 3 hours.

Degradation of green LEDs produces a small shift in wavelength and a reduction in efficiency.

High-resolution X-ray diffraction curves for pristine and degraded LEDs revealed satellite peaks up to the fifth order, indicating "acceptable" crystalline quality for the wells and the interface quality. Curve fitting suggested a thickness period of 18.5 nm, a value in good agreement with device design. A slight widening of the first diffraction peak for the annealed LED indicates that the high-temperature, degradation-inducing step led to a reduction in the quality of the crystalline material and the interface.

All these conjectures are confirmed with scanning tunnelling electron microscopy high-angle annular dark field images that identify atomic columns of InGa and gallium. These images reveal that after annealing, InGa and gallium atomic columns become indistinct, reflecting a deterioration in the quality of the crystal and the interface.

An additional insight provided by these images is the change in the thickness of the layers within the active region. Degradation induced an increase in the thickness of 11 atomic layers in the InGaN quantum well from 285 nm to 308 nm in the [0002] direction, and an increase from 2.85 nm to 308 nm in the $[10\bar{1}0]$ direction. For the GaN barrier, a far smaller change took place, with the thickness of 28 atomic layers in the barrier increasing from 8.17 nm to 8.19 nm in both the [0002] and $[10\bar{1}0]$ directions. Another finding from these dark-field images is that annealing created additional atomic columns. Based on this observation, and the others obtained with this imaging technique, the team concluded that the introduction of interstitial atoms is behind the increase in thickness of the InGaN wells.

According to the researchers, elevating the temperature of the LED to 460K resulted in intense atomic lattice vibrations that caused the indium atoms to migrate from their normal lattice position to interstitial sites. Electroluminescence measurements determined that annealing at 460K led to a 1.6 nm red-shift in peak emission from 519.9 nm to 521.5 nm, and a fall in integrated intensity by 32.8 percent. The annealed device produces stronger luminescence at 650 nm, a peak associated with impurities and defects. When LEDs have a higher density of defects, luminescence is known to fall, due to increases in both defect-related Shockley-Read-Hall recombination and Auger recombination.

To gain greater insight into how the emission characteristics of the quantum well are influenced by gallium interstitial atoms, and gallium and nitrogen vacancies, the team turned to density functional theory based on first principles calculations. This theoretical study revealed that the red-shift of the LED and its decline in efficiency resulted from: a decreased bandgap, due to relaxation in the InGaN well; and a hike in defect density, due to the introduction of interstitial indium atoms within the active region.

Reference

Q. Liu *et al.* Appl. Phys. Lett **117** 212103 (2020)

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Beneq Transform™ cluster tool is a fully automated, in-vacuum cassette-to-cassette ALD manufacturing solution

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Beneq Transform™ platform overview

single wafer automation. The configuration is highly flexible and scalable and can be adapted to various R&D and manufacturing requirements for wafer sizes from 3'' up to 8''," says Dr. Patrick Rabinzohn, Business Executive, Semiconductor ALD Business Line.
The Beneq Transform™ can be configured with or retrofitted with Beneq single wafer thermal and/or plasma as well as batch ALD process modules. Its proprietary preheating module nearly eliminates heating related waiting time, boosting productivity to a whole new level. In addition, the mainframe accommodates an optical aligner, and can be equipped with optional integrated Brooks TopCooler™ cool-down unit, and internal wafer buffer. The Beneq Transform™ is fully compliant with ultra-clean requirements, SECS/GEM communication and SEMI S2 and S8 standards certified.

Designed with versatility at heart

Beneq Transform™ can be used to deposit a wide range of oxides, including Al_2O_3, HfO_2, Ta_2O_5, TiO_2 and SiO_2 using thermal single wafer or batch ALD, and nitrides such as AlN, Si_3N_4 using plasma enhanced ALD. In addition to oxides, thermal batch processing up to 25 wafers for nitrides such as AlN and TiN requiring high processing temperatures is supported. Beneq Transform™ is the leading choice for all More-than-Moore applications. It is configured to have the smallest footprint and lowest cost-of-ownership for any of the very diverse process capabilities x capacity requirements of the MtM market segments shown below.

Beneq Transform™ tool is fully upgradable in the field from 3" to 8'' wafer processing. For both the single wafer / plasma enhanced ALD process module and the thermal batch ALD process module, a simple process kit change needs to be done.

Additionally, Beneq single wafer process module comes with high degree of built-in processing versatility, which is particularly beneficial in processing sensitive materials such as SiC, GaN, GaAs, and InP. Firstly, the plasma ALD module can be used for efficient *in-situ* surface pre-clean/nitridation, which is crucial for eliminating surface states associated with non-stoichiometric oxides. A further benefit is the capability of sequencing of plasma/thermal nitrides and thermal/plasma Oxide processes in the same chamber either as bi-layer or as laminates/mixtures, without the need to transfer the wafer from a nitride chamber to an oxide chamber. A further processing option is the possibility to switch the plasma enhanced ALD module to thermal ALD processing only, by a simple change kit.

In a nutshell from single wafer and batch process modules to single wafer sequential and parallel processing versatility is at the heart of BENEQ Transform™.

About Beneq

Beneq is the home of ALD, offering a wide portfolio of equipment products and development services. Today Beneq leads the market with innovative solutions for advanced R&D (TFS 200, R2), flexible high-volume manufacturing (BENEQ Transform™), ultra-fast high precision spatial ALD coatings (C2R), roll-to-roll thin film coating of continuous webs (WCS 600), and specialized batch production for thicker film stacks (P400, P800). Headquartered in Espoo, Finland Beneq is dedicated to making ALD technology accessible for researchers and enabling technology mega trends through engineered ALD materials solutions.

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Market segments	High-k & MIM(/MIS)	Surface passivation	Nucleation & seed, Barrier/Seed	Chemical barrier	Encapsulation (« Moisture barrier »)
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RF filters		✓	✓	✓	✓
RF IC's	✓	✓			✓
MEMS	✓	✓		✓	✓
Image sensors		✓	✓		✓
III-V Photonics Mini/Micro-LED		✓			✓

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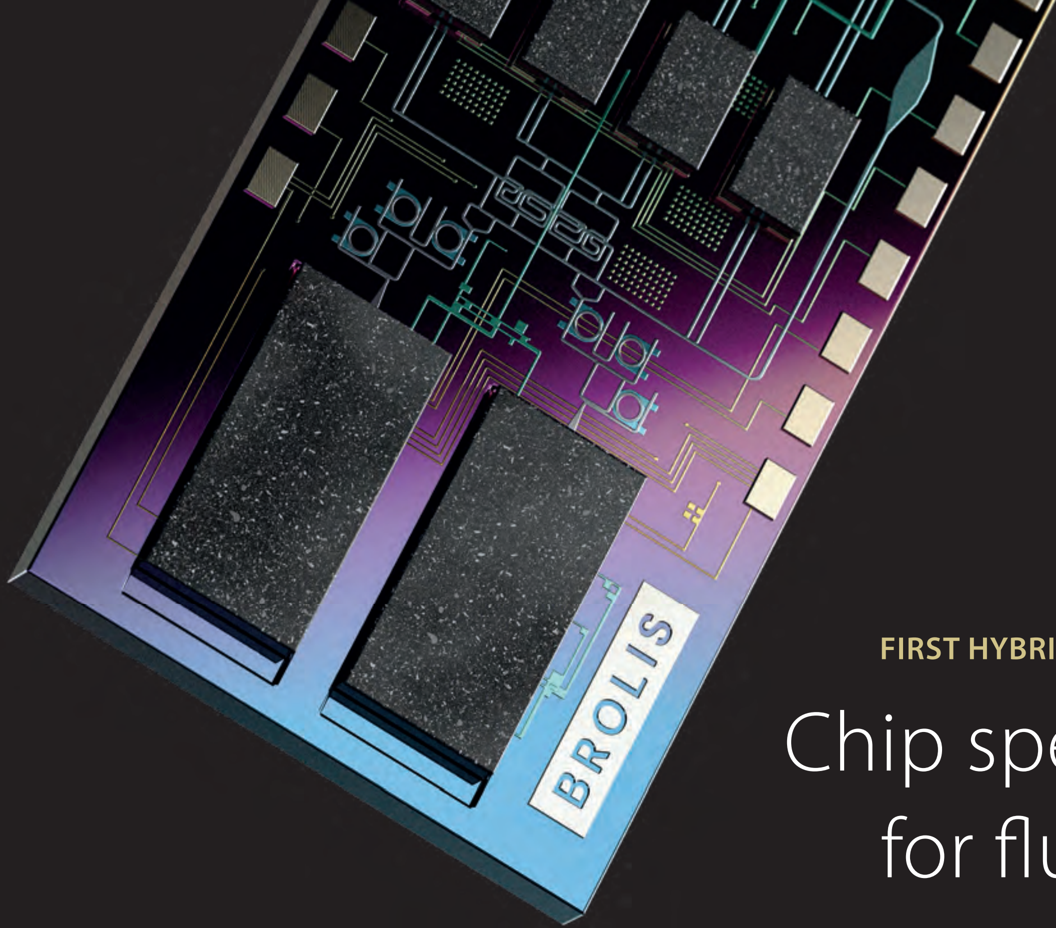

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