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Qorvo buys Custom MMIC & Decawave • Sheffield spins off EpiPix • Veeco launches Lumina As/P MOCVD platform

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Cover: At Photonics West Vixar has expanded its VCSEL chip portfolio by introducing a higher-power 10W 940nm-wavelength chip with greater efficiency, aimed at 3D sensing applications, and also launched its multi-junction VCSEL technology with a power conversion efficiency of 60% at 940nm. **p41**

editorial

Uncertainty through the supply chain

As of late February, daily new infections of Covid-19 coronavirus outside China have surpassed those inside China. Travel restrictions have curtailed industry events, while quarantines impact manufacturing in China and hence (through supply chains both upstream and downstream) elsewhere too.

On 12 February the GSMA cancelled the Mobile World Congress (MWC Barcelona, 24–27 February). On 24 February, Lighting + Building 2020 in Frankfurt, Germany (the world's largest trade fair for LED and solid-state lighting) was postponed from 8–13 March to second-half September, after Signify (formerly Philips Lighting) followed smaller exhibitors in withdrawing. On 27 February Silicon Valley-based Infinera withdrew from the Optical Networking and Communication conference (OFC) in San Diego 8–12 March.

Disruption to supply chains is affecting both component supply (e.g. of chips from South Korea into China) and end-product assembly (e.g. of Apple iPhones in China). The impact on production in China has been mitigated by the New Year holiday (before which inventories are stockpiled) as well as first quarters historically being weak for smartphone production. Nevertheless, the delayed return to work (until 10 February) has caused deliveries of components to be postponed, affecting smartphone assembly.

Due partly to this, TrendForce has lowered its forecast for global smartphone production in first-quarter 2020 to a 12% drop year-on-year (to 275 million units) — see page 6. Regarding the rapidly growing 5G smartphone sector, the coronavirus and economic slowdown will "put a cap on overall 5G demand this year," believes Strategy Analytics (page 7). "The COVID-19 outbreak is currently restricting smartphone production in Asia, disrupting supply chains, and deterring consumers from visiting retail stores to buy new 5G devices in some parts of China," says executive director Neil Mawston. "The first half of 2020 will be much weaker than expected for the 5G industry," he adds.

Manufacturers of the wireless RF components are hence being impacted. "We have reflected some added risk to our March-[quarter] guide including a wider range of outcomes," notes Mark Murphy, chief financial officer of US-based Qorvo (page 8). "Trade and other factors including potential demand and supply-chain effects related to the coronavirus concerns contributed to challenges and uncertainty forecast in the outlook," he adds.

Further up the supply chain, US-based MOCVD system maker Veeco has widened the low end of its Q1/2020 revenue guidance to accommodate "a significant level of uncertainty from coronavirus-related travel, restriction and factory shutdowns in China" (see page 28). US-headquartered substrate maker AXT (whose manufacturing facilities are in China) has widened its revenue guidance range from the usual ±$5m to ±$10m "as a precaution to allow for unanticipated effects in the supply chain," says CEO Morris Young (see page 26). "We are limited in the number of employees that are allowed to be in the factory on any given day… productivity may not be quite as high until the government-mandated restrictions are lifted."

TrendForce says that Q2/2020 smartphone production will depend on the status of outbreak control and the degree of supply chain recovery. In terms of yearly outlook, as long as the outbreak can be controlled and a basic level of demand can be supported by the overall global economy, TrendForce believes that most demand is deferred rather than eliminated. "We expect a strong bounce-back in the second half of the year if the coronavirus spread is brought under control," says Strategy Analytics' Mawston.

Mark Telford, Editor
mark@semiconductor-today.com

Mark Telford

semiconductorTODAY
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Editor
Mark Telford
Tel: +44 (0)1869 811 577
Cell: +44 (0)7944 455 602
Fax:+44 (0)1242 291 482
E-mail: mark@semiconductor-today.com

Commercial Director/Assistant Editor
Darren Cummings
Tel: +44 (0)121 288 0779
Cell:+44 (0)7990 623 395
Fax:+44 (0)1242 291 482
E-mail: darren@semiconductor-today.com

Advertisement Sales
Darren Cummings
Tel: +44 (0)121 288 0779
Cell:+44 (0)7990 623 395
Fax:+44 (0)1242 291 482
E-mail: darren@semiconductor-today.com

Original design Paul Johnson
www.higgs-boson.com

***Semiconductor Today* covers the R&D and manufacturing of compound semiconductor and advanced silicon materials and devices** (e.g. GaAs, InP and SiGe wafers, chips and modules for microelectronic and optoelectronic devices such as RFICs, lasers and LEDs in wireless and optical communications, etc).

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- event calendar and event previews;
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Q1 smartphone production forecast revised to 12% drop year-on-year due to coronavirus outbreak's impact on supply chain

Most demand deferred rather than eliminated

Market research firm TrendForce has lowered its forecast for global smartphone production in first-quarter 2020 to a 12% decline year-on-year, to 275 million units (a five-year low) due to several factors:

(1) the labor-intensive nature of the smartphone industry;
(2) China's delay in work resumption until 10 February and population movement control; and
(3) the reduction in the public's willingness to buy.

Delayed work resumption and uncertainties in employees' returns caused the monthly delivery of key components to be postponed, affecting the progress of smartphone production. Fortunately, first quarters have historically been weak seasons for smartphone production. Also, manufacturers typically maintain a healthy inventory before the Chinese New Year. Therefore, the outbreak was not expected to cause an immediate break in the supply chain after work resumed at smartphone assembly vendors' production bases on 10 February. Future developments depend on the work resumption status of upstream supply chains and the import/export of goods through customs, notes TrendForce. In particular, the shortage of active/passive components and camera modules, which began even before Chinese New Year, exacerbates the problem of smartphone component shortage because of their low inventory levels or labor-intensiveness.

Out of the top six smartphone brands globally, the main production base of market leader Samsung is in Vietnam. In addition, the Korean giant's smartphones account for only 2% of the domestic market in China. As a result, Samsung has suffered the least damage from the outbreak. However, because it sources some of its components from China, Samsung's Q1/2020 production forecast has been reduced by 3% compared to TrendForce's previous forecast, registering 71.5 million units.

Huawei, which ranks second in quarterly production volume, was placed on the US Department of Commerce's 'Entity List' and subsequently prevented from installing GMS on their newer models, lowering their overseas sales. Turning to a business model that focuses heavily on the Chinese market, Huawei sustained major losses from stagnant Chinese New Year sales numbers. Due to losses in both domestic and overseas markets, Huawei is now projected to produce 42.5 million units in Q1/2020, a 15% decrease from TrendForce's previous forecast.

Third-place Apple made arrangements for its employees to work from home in an effort to reduce risks of infection, but this has the side effect of slowing down the development of new iPhones in second-half 2020, with component certification coming to a near halt. In the short term, Apple faces uncertainties in its labor force's work resumption, and the supply of certain key components involved in the production of new iPhones cannot be properly delivered. These setbacks will directly affect the upcoming release of iPhone SE2 (also known as iPhone 9) and lower TrendForce's forecast of first-quarter 2020 iPhone production by about 10%, from 45.5 million to 41 million units.

The coronavirus outbreak has led to a weakened Q1/2020 smartphone production outlook. Q2 will depend on the status of outbreak control as well as the degree of supply chain recovery

Fourth-ranked Xiaomi relies primarily on online sales, with a relatively low market share in China (at about 9%). Compared to China's OPPO and Vivo, which have a domestically focused sales model, Xiaomi is not as affected by the outbreak. So, TrendForce is revising its Q1/2020 production forecast to 10% lower than its previous projection, to 2.47 million units (essentially unchanged from Q1/2019). Also, TrendForce is lowering Oppo and Vivo's production forecasts by 14% and 15%, to 2.4 million and 1.7 million units, respectively (ranking fifth and sixth globally in Q1/2020).

On the whole, the impact of the coronavirus outbreak has led to a weakened Q1/2020 smartphone production outlook, while Q2/2020 numbers will depend on the status of outbreak control as well as the degree of supply chain recovery, says TrendForce. In terms of yearly outlook, as long as the outbreak can be controlled and a basic level of demand can be supported by the overall global economy, TrendForce believes that most demand is deferred rather than eliminated and therefore the firm does not have an overly pessimistic outlook towards smartphone production in 2020.

www.trendforce.com

Global 5G smartphone shipments to grow tenfold to 199 million in 2020

Disruption from coronavirus and global economic slowdown to suppress sales in first-half 2020

Global 5G smartphone shipments will grow more than tenfold from 19 million units in 2019 to 199 million in 2020, according to the report 'Global Handset Sales for 88 Countries & 19 Technologies' from the Strategy Analytics Emerging Device Technologies (EDT) service.

"The 5G segment will be the fastest-growing part of the worldwide smartphone industry this year," says Ken Hyers, director at market research firm Strategy Analytics. "Consumers want faster 5G smartphones to surf richer content, such as video or games," he adds. The report forecasts that 5G penetration will rise from 1% of all smartphones shipped globally in 2019 to 15% of total in 2020, as non-5G smartphone shipments fall from 1394 million to 1165 million units, meaning that total smartphone shipments will fall from 1413 million units in 2019 to 1364 million in 2020.

"China, United States, South Korea, Japan and Germany are by far the largest 5G smartphone markets this year," notes associate director Ville-Petteri Ukonaho. "The big-five countries together will make up 9 in 10 of all 5G smartphones sold worldwide in 2020. However, other important regions, like India and Indonesia, are lagging way behind and will not be offering mass-market 5G for at least another year or two," he adds.

"The global 5G smartphone industry is growing quickly, but the ongoing coronavirus scare and subsequent economic slowdown will put a cap on overall 5G demand this year," cautions executive director Neil Mawston. "The COVID-19 outbreak is currently restricting smartphone production in Asia, disrupting supply chains, and deterring consumers from visiting retail stores to buy new 5G devices in some parts of China. The first half of 2020 will be much weaker than expected for the 5G industry, but we expect a strong bounce-back in the second half of the year if the coronavirus spread is brought under control."

www.strategyanalytics.com

Qorvo's quarterly revenue grows a greater-than-expected 7.7%, driven by 5G, Wi-Fi and Defense markets

Year-on-year growth to return for IDP, with Huawei loss countered by Wi-Fi 6 ramp-up plus low-power wireless and PMICs

For its fiscal third-quarter 2020 (ended 28 December 2019), Qorvo has reported revenue of $869.1m, up 4.4% on $832.3m a year ago and 7.7% on $806.7m last quarter (and above the $840-860m guidance), driven by strength in 5G, Wi-Fi and Defense end-markets.

Qorvo had two 10%-or-more customers, one of which was China-based Huawei Technologies Co Ltd, which (along with the other Asia-based handset makers) was stronger than expected (since Huawei is only expected to comprise 5% of total revenue across fiscal second-half 2020, after the firm was added last May to the US Department of Commerce's 'Entity List' prohibiting the sale of products covered by the Export Administration Regulations without obtaining an appropriate export license — this compares with Huawei contributing 15% of Qorvo's revenue in fiscal full-year 2019).

Specifically, by business segment, Mobile Products (MP) revenue was a stronger-than-expected $662m, up 6.3% on $623m last quarter and 10% on $602m a year ago. "We are offsetting year-over-year the decline that we've seen at Huawei," says president & CEO Bob Bruggeworth. "We are seeing broad-based strength related to 5G across Asian handset producers and, importantly, across all chipset producers," notes chief financial officer Mark Murphy. "The acceleration of 5G is driving demand for Qorvo's high-performance and highly integrated solutions," says Bruggeworth. "Carriers are bringing advanced 5G services across new frequency spectrum and that's driving greater complexity and enhanced designs as board space remains constrained. Qorvo is solving that complexity by integrating the industry's broadest portfolio of technologies and advancing the state-of-the-art and functional integration," he adds.

Infrastructure & Defense Products (IDP) revenue was $207m, down 11.7% on $230m a year ago due to the restrictions on exporting Infrastructure products to Huawei but up 12.5% on $184m last quarter due to strong Defense volumes. "Wi-Fi 6 is at the phase of deployments in base stations… we are starting ramps and starting to recover but, with the loss of Huawei, we are obviously still significantly off of our all-time highs in base stations," notes IDP president James Klein.

"In Mobile Products, 5G design wins are accelerating, and in IDP we are enjoying robust design-win momentum," notes Bruggeworth. "Both businesses are returning to growth year-over-year," he adds.

Mobile Products design wins

"We enjoyed significant [4G and 5G] design-win traction for our bulk acoustic wave [BAW]-based multiplexers across a range of band combinations including our hexaplexers and our recently launched micro BAW-based quadplexer. These multiplexers enable advanced carrier aggregation and they are critical to next-generation higher-data-rate applications," notes Bruggeworth.

"We also secured multiple design wins to supply low-, mid/high- and ultrahigh-band solutions for second-generation 5G smartphones. These are highly integrated and high-performance 4G/5G solutions enabling customers to reduce product footprint, enhance system performance and deliver products to the market even faster," he adds.

"Design wins for our ultrahigh-band front-end modules (FEMs) were broad based across customers and made with multiple 5G cellular chipsets. Qorvo's solutions deliver highly differentiated performance at higher frequencies as we expand our content in the next wave of 5G smartphones."

IDP design wins

In IDP, Qorvo's gallium nitride (GaN) customer engagements broadened as it ramped GaN high-power amplifiers and small-signal components at a third major OEM in support of 5G massive MIMO deployments. The firm also began volume shipments of BAW filters to a top-tier infrastructure OEM supporting China Mobile's 5G small-cell deployment. In addition, Qorvo launched a high-power gallium arsenide (GaAs) FEM addressing the more demanding performance requirements of second-generation 5G millimeter-wave base stations.

"In our Connectivity business, we enjoyed a rebound in demand driven by Wi-Fi 6 and supported by recently released GaAs and BAW processes," says Bruggeworth. Demand for the firm's newest Wi-Fi 6 FEMs was broad based, securing new design wins and increased shipments across CPE, retail and mobile applications.

"For the Connected Home, we began sampling the industry's first radio solution combining a Zigbee, Thread and Bluetooth Low Energy system-on-chip (SoC) with a Wi-Fi 6 FEM to enable next-generation distributed Wi-Fi networks," claims Bruggeworth.

For the connected car, Qorvo sampled a complete V2X front-end solution, featuring its recently released 5.9GHz Wi-Fi coexistence BAW filter, to multiple automotive OEMs and tier-one suppliers.

"Finally, we continue to expand our customer base in the programmable power management end-market, shipping power management ICs into data-center solid-state drives for two of the top three storage providers," says Bruggeworth.

On a non-GAAP basis, gross margin was 49.3%, down slightly on 49.5% a year ago but up from 46.5% last quarter (and above the 48% guidance) due to better-than-expected manufacturing costs and a favorable product mix.

Operating expenses have risen further, from $150.5m a year ago and $166.7m last quarter to $175.6m (due mainly to a sequential rise in R&D expenses of over $7m), although this is at the low-end of the $175–180m guidance range.

Net income is down on $234.1m ($1.85 per diluted share) a year ago but up from $181.2m ($1.52 per diluted share) last quarter to $220.8m (a record $1.86 per diluted share, $0.19 over the $1.67 guidance).

Operating c ash flow has risen from $173.4m last quarter to $300.8m. Meanwhile, capital expenditure (CapEx) has been increased only slightly from $38m to $40.7m. Free cash flow was hence $260.1m (almost doubling from $135.4m), or record free cash flow margin of nearly 30% of revenue (contributing to free cash flow of over $600m for the first nine months of fiscal 2020, exceeding any prior full fiscal year — in the last 12 months, free cash flow was $754m and the firm repurchased $689m of shares, so over 90% was returned to shareholders).

During the quarter, Qorvo spent $125m in repurchasing stock, but it raised funds by completing an opportunistic $200m add-on to its $350m of 2029 unsecured notes issued early in the quarter.

Qorvo also completed the purchase of the remaining equity in RF MEMS antenna tuning technology provider Cavendish Kinetics Inc of San Jose, CA, USA, strengthening its technology portfolio for switches, tuners and other products.

Overall, cash and cash equivalents overall hence rose from $586.8m to $1097.7m.

"Following the quarter end, we signed definitive agreements to acquire two companies that we have been evaluating for extended periods," notes Murphy, namely:

- Custom MMIC of Westford, MA, USA, expanding Qorvo's portfolio of high-performance GaAs and GaN monolithic microwave integrated circuits for defense and aerospace applications (a 'bolt-on' to IDP's core Defense business).
- Decawave Ltd of Dublin, Ireland, a pioneer in ultra-wideband (UWB) technology and a leading supplier of UWB solutions for mobile, automotive and IoT applications (opening up access to a large new and rapidly growing wireless market for ultra-accurate, ultra-secure short-range location solutions).

"With both companies, there is excellent strategic alignment and cultural fit," comments Murphy. The combined purchase value of these two acquisitions is about $500m (over three quarters of which is for Decawave), which will be funded from existing cash on hand. "Our guidance assumes both transactions close in February, and the financial impact slightly dilutive to earnings in the near-term is reflected in our March guidance," he adds.

For fiscal fourth-quarter 2020 (to end-March), Qorvo expects revenue to fall by about 5.6% sequentially to $800-840m, although this is less than the previously forecasted seasonal drop of about 15%, and would be well up on $680.9m a year previously. Specifically, due to "the strength of our broad technology portfolio and strong underlying trends in our end-markets", year-on-year growth will continue for Mobile Products and return for IDP (although, considering the loss of one of its top customers Huawei just a few quarters ago, IDP's growth will be relatively small, aided by high single-digit growth due to Wi-Fi rebounding with the ramp-up of Wi-Fi 6 plus double-digit growth for low-power wireless and power management integrated circuits). Sequentially, Mobile Product revenue is expected to fall, but by less than the normal seasonality due to continued robust mobile 5G demand. IDP revenue should rise again sequentially due to sustained strength in Defense, the ramp-up of Wi-Fi 6, and broader 5G infrastructure customer demand, offsetting some of the normal seasonality (which is typically between flat and up only slightly). The Custom MMIC acquisition should contribute just $3m for the part quarter (and about $5m per full quarter in the near-term).

Gross margin will be about 48.5%, down sequentially by about 100 basis point (typical, due to the effect of seasonal product mix and the effects of fixed manufacturing costs on lower revenue). Operating expenses are projected to rise to $185m due to higher personnel cost (including payroll effects) and incremental cost associated with the acquired businesses. Diluted earnings per share should fall to $1.55.

"While Qorvo's current near-term outlook is strong and channels are healthy, trade and other factors including potential demand and supply-chain effects related to the coronavirus concerns contributed to challenges and uncertainty forecast in the outlook," cautions Murphy.

"Qorvo's December-quarter results and March-quarter guidance reflect strength in our end markets of 5G, Wi-Fi and Defense and continued strong operating performance," comments Murphy. "On capital expenditures, we project less than $190m this fiscal year and remain highly disciplined on adding capacity," he adds.

"Given our operating results and capital management, we now forecast free cash flow for the full fiscal year of over $700m." Compared with the target of 30% set some time ago, full-year free cash flow margin should be "closer to 22%, but we continue to see the ability to expand free cash flow margins," Murphy says. "We are pursuing a model in investing in a way to achieve stronger and more sustainable free cash flow generation over time, and that comes from investing in the right technologies, of which you see some of that in the acquisitions we announced today. It's selecting the right products and having a rigorous portfolio management process, which we have executed on."

"We are still not at the utilization levels that we had hoped this year. ►

The infrastructure market softness has impacted us in a couple areas in the network, particularly Texas GaAs, GaN in Oregon," says Murphy. "In the December quarter, we had period cost in Florida [due to the phased closure of the fab in Apopka, as surface acoustic wave (SAW) filter production was consolidated to Greensboro]... Those do drop off in March. But we still have some period cost associated with Farmers Branch [the BAW filter fab in Texas, which was idled in early 2019 rather than being moved from start-up to production] and some small period costs elsewhere... Over time, we expect IDP to improve as a percent of the overall mix," he adds.

"We have a number of levers to expand margins. We are focused on spending capital only when we need to and then driving free cash flow growth, which allows us to make prudent investments either for accretion or technologies," explains Murphy.

Regarding the coronavirus, Murphy comments: "To-date, we've seen no material impact to our supply chain or demand signals. However, the situation is evolving. So, we have reflected some added risk to our March guide including a wider range of outcomes. Likewise we are thinking about potential effects into the June quarter and, even though our channels are lean, we are concerned about how this plays out."

In the June quarter, revenue is expected to fall to $750–800m (roughly level with $775.6m a year previously. "We tend to go down from our March to June on gross margins," adds Murphy. So, gross margin is expected to range between a low 47% to a high 47%.

www.qorvo.com

Qorvo completes acquisition of Custom MMIC

President & CTO joins Qorvo as director of engineering for IDP

Qorvo has completed its acquisition (announced at the end of January) of Custom MMIC of Westford, MA, USA, a supplier of gallium arsenide (GaAs) and gallium nitride (GaN) monolithic microwave integrated circuits for defense, aerospace and commercial applications.

Custom MMIC was founded in 2006 and has extensive experience developing MMICs at frequencies up to 70GHz. The firm provides Qorvo with small-signal mmWave expertise and a portfolio of over 180 standard products including low-noise amplifiers (LNAs), mixers, attenuators, phase shifters and switches. President & chief technology officer Paul Blount joins Qorvo as a director of engineering for Infrastructure & Defense Products.

As part of Qorvo's Infrastructure & Defense Products (IDP) business, the Custom MMIC team will continue to expand its millimetre-wave (mmWave) capabilities for products used in defense phased-array and active electronically scanned array (AESA) radars, electronic warfare (EW), satellite communications, wireless backhaul and microwave test equipment.

"Custom MMIC's best-in-class die and packaged components augment our power amplifiers to enable multi-chip modules for a broad range of defense, aerospace and commercial applications," comments IDP president James Klein. "We look forward to building on Custom MMIC's reputation as an outstanding strategic supplier to leading defense prime customers, as we expand our mmWave capabilities and product offerings for defense and commercial markets, including 5G."

www.custommmic.com

Qorvo launches highest-performance wideband GaN power amplifier for mission-critical defense applications

Qorvo has introduced what it claims is the highest-performance wideband power amplifier (PA).

Designed for electronic warfare, radar and test instrumentation applications, the TGA2962 (available now as a die to qualified customers) is fabricated using Qorvo's GaN QGaN15 process technology, and provides 10W of RF power over the 2–20GHz frequency range, 13dB large-signal gain and 20–35% power-added efficiency (PAE). This combination delivers the flexibility that system designers need to improve system performance and reliability while reducing component count, footprint and cost, reckons the firm.

"Qorvo has taken a significant step forward in the wideband space with the TGA2962, enhancing not just frequency range but every other performance aspect," says Roger Hall, general manager of Qorvo's High Performance Solutions business. "No other company offers a single PA with this output power, bandwidth, power-added-efficiency and large-signal gain," he claims.

In addition, improved component integration — and use of a smaller driver amplifier enabled by the 13dB large-signal gain — result in a smaller device, benefitting programs that require size, weight, power and cost (SWAP-C) improvements.

"The defense market, primarily radar and communications applications, is seeing strong growth from new systems and major platform upgrades," comments Eric Higham, director of the Advanced Semiconductor Applications service and the Advanced Defense Systems service for market research firm Strategy Analytics. "This is also providing fuel for the GaN growth engine and should bode well for companies like Qorvo."

www.qorvo.com/products/p/TGA2962

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Skyworks' quarterly revenue grows a more-than-expected 8% sequentially to $896m

Design wins for 5G mobile ramp plus increasing growth for infrastructure to drive recovery in margins

For fiscal first-quarter 2020 (ended 27 December 2019), Skyworks Solutions Inc of Woburn, MA, USA (which manufactures analog and mixed-signal semiconductors) has reported revenue of $896.1m. This is down 7.8% on $972m a year ago. However, this is impacted by the US Department of Commerce's Bureau of Industry and Securities (BIS) on 15 May adding China-based smartphone and telecom network infrastructure maker Huawei Technologies Co Ltd to its 'Entity List' prohibiting the sale to Huawei of products covered by the Export Administration Regulations (EAR) without obtaining an appropriate license. (Huawei had been Skyworks' second largest customer, contributing 12% of total revenue in fiscal first-half 2019, but was just $10m last quarter.)

Despite this, fiscal first-quarter 2020 revenue is up 8% on $827.4m last quarter, driven by the launch of flagship phones and early success of the Sky5 product portfolio as new 5G phones start ramping globally.

"Skyworks exceeded December-quarter expectations [of $870–890m] driven by global demand for our high-performance connectivity engines," notes president & CEO Liam K. Griffin. Although revenue from Huawei was "a little bit better than we expected… we are de-risking exposure to Huawei," he adds.

By market sector, Mobile (Integrated Mobile Systems and Power Amplifiers) rebounded further, from 67% of total revenue last quarter to 73% (although the December quarter is typically a very strong quarter for Mobile, with a lot of business with Skyworks' large customer plus the ramp of 5G phones). Broad Markets was down further, from 33% of total revenue last quarter to 27%. Broad Markets revenue was up by mid-single digits on a percentage basis, both sequentially and (if you exclude Huawei) year-on-year. "We have some Huawei infrastructure business that was part of Broad Markets," notes chief financial officer Kris Sennesael. "Due to the ban we lost most or almost all of that," he adds.

"Leveraging decades of experience, manufacturing scale and vertical integration capabilities, our highly advanced Sky5 platform is fueling market adoption of 5G across a broadening set of end markets and customers," says Griffin. "With an expansive suite of applications — from smartphones to wireless infrastructure, industrial robotics, autonomous vehicles, smart homes and virtual assistants — our solutions provide the critical connection, ensuring peak performance for 5G and IoT usage cases," he adds.

On a non-GAAP basis, gross margin has fallen further, from 51% a year ago and 50.3% last quarter to 50.1%, but this is slightly above the expected 50%.

Operating expenses have been cut further, from $135m (16.3% of revenue) last quarter to $134m (15% of revenue), down 4% from $139m a year ago as the firm continued to manage OpEx while making the necessary investments to accelerate future growth of the business.

Net income was $288.8m ($1.68 per diluted share), down from $324.6m ($1.83 per diluted share) a year ago but up from $261.9m ($1.52 per diluted share) last quarter (and better than the $1.65 guidance).

Operating cash flow was $398m. Capital expenditure (CapEx) was $111m. Free cash flow was therefore $287m (margin of 32%). Skyworks paid $75m in dividends and repurchased 742,000 shares of common stock for a total of $74m. (During the last 12 months, Skyworks has returned 87% of free cash flow back to shareholders through a combination of dividends and its share-buyback program.) During the quarter, cash and investments hence rose from $1.082bn to $1.229bn. The firm has no debt.

"Through crisp operational execution and a strong business model, we are translating these results into long-term shareholder value," says Griffin.

Skyworks' board of directors has declared a cash dividend of $0.44 per share of common stock, payable on 3 March, to stockholders of record at the close of business on 11 February.

"The expanding product pipeline at Skyworks is clearly generating strong design-win momentum across both Mobile and Broad Market segments," notes Griffin.

"In our Mobile business, traction in 5G is gaining strength with our Sky5 platform powering launches at Oppo, Vivo, Xiaomi and Samsung. Our baseband-agnostic solutions offer interoperability and are being deployed across leading chipset suppliers, including MediaTek, Samsung and Qualcomm," he adds. "With our expanding filter capabilities in TC-SAW [thermally compensated surface acoustic wave] and BAW [bulk acoustic wave], we help our customers navigate complex challenges while extending our reach across a broader spectrum of 4G and 5G bands."

In Broad Markets, at January's Consumer Electronics Show (CES 2020) in Las Vegas, Skyworks announced a unique set of 5G-enabled solutions, including Massive MIMO IoT, a suite of connected home devices and high-fidelity smart audio products. Specifically, it is powering rapidly emerging IoT applications with cellular-based platforms certified by KDDI, NTT DoCoMo, SoftBank and Verizon. "We're driving growth with the launch of our Wi-Fi 6 platforms, expanding our customer reach with industry leaders including AT&T, Cisco, Netgear, ARRIS and Aruba," notes Griffin.

In infrastructure, Skyworks is leveraging its capabilities in silicon germanium (SiGe), silicon-on-insulator (SOI), gallium arsenide (GaAs), bulk acoustic wave and ceramic filters while powering 5G Massive MIMO and small-cell base-station design wins. "In addition, we are gaining momentum in automotive, enabling new wins with leaders like Continental, Nissan and Renault along with industrial players including Honeywell, Bosch and GE… These were not customers two or three years ago," notes Griffin.

Specifically, during the quarter, Skyworks:

- advanced automotive content via the SkyOne, Wi-Fi 6 and V2X portfolio;
- extended its position in high-speed 802.11ax access points with advanced 2.4GHz and 5GHz front-end modules (FEMs);
- introduced Bluetooth Low Energy modules for Proctor & Gamble's infant monitoring system;
- leveraged Zigbee, Thread and Bluetooth Low Energy architectures for extended-range smart gas meter applications;
- began volume production of Wi-Fi 6 connectivity engines for ZTE and Belkin/Linksys;
- supported GoPro's next-generation wearable, waterproof action camera with GPS technology; and
- shipped LoRa devices powering premium home security platforms.

"Early momentum from the initial launch of 5G [Sky5 solutions] as we ramp design wins in our Mobile business, matched with solid traction in Broad Markets, are driving better-than-seasonal performance in the March quarter [which is typically a stronger quarter for Broad Markets]," says Sennesael.

For fiscal second-quarter of 2020 (to end March), Skyworks expects revenue of $800-820m, flat year-on-year (although, excluding Huawei, this would be up mid-teens as a percentage, with mid-single-digit growth in Broad Markets including infrastructure). Despite the normal seasonal decline in revenue, gross margin should be up to 50–50.5%. With operating expenses of about $135m, diluted earnings per share should fall to $1.46.

For fiscal second-half 2020, Skyworks expects further stronger growth in Broad Markets (including infrastructure) both sequentially and year-on-year (again, excluding Huawei). Driven by infrastructure total gross margin should improve.

"We are driving operational efficiencies and bringing high-added-value products to the market that will drive the gross margins towards our long-term target of 53% and our operating margins approaching 40%," reckons Sennesael. "OpEx is running on or about 15% [of revenue]… We can do a little bit better there so you get to an operating margin that approaches 40%. At the same time, we're very much focused on driving free cash flow [margin] at 30% or slightly above 30%," he adds.

"We will continue to invest in the business. One of our strengths is our operational footprint with our gallium arsenide fabs, our filter operation as well as our back-end operation. We continue to expand the capacity in those fabs and we continue to develop new technology, package technologies and filter technologies," says Sennesael. "That of course requires sufficient CapEx support. CapEx is running on or about 10% of revenue."

www.skyworksinc.com

Skyworks working with Wi-Fi Alliance to develop Wi-Fi 6E products for 5.925–7.125GHz range

Skyworks is supporting next-generation wireless technologies set forth by Wi-Fi Alliance and developing advanced connectivity solutions designed to meet future requirements. As well as offering a family of solutions that address all existing Wi-Fi standards, Skyworks is working in Wi-Fi Alliance to develop its Wi-Fi 6E products that operate in the 5.925–7.125GHz frequency range.

As a result of increasing demand for high-data applications such as streaming media/TV/audio, social media and smart home devices, there has been an initiative to open up additional frequency bands to complement the existing 2.4 and 5GHz bands. This new spectrum is expected to be made available by regulators around the world and it represents an opportunity to deliver the benefits of Wi-Fi 6 coupled with increased bandwidth available in the new 6GHz band.

"The 6GHz band addresses the growing need for Wi-Fi spectrum capacity to ensure users continue to experience reliable and seamless connectivity," says Wi-Fi Alliance's senior VP of marketing Kevin Robinson. "We are glad to see Wi-Fi Alliance members working closely in Wi-Fi Allianceto ensure that new products meet high standards for interoperability and security," he adds.

"Skyworks is leveraging our expertise to produce connectivity solutions that address the insatiable demand for more data and the ever-evolving needs of the market," says Dave Stasey, general manager of diversified analog solutions.

Skyworks' Wi-Fi connectivity modules facilitate Wi-Fi functionality with what is said to be best-in-class linearity and performance in the smallest footprint available. The solutions expedite time-to-market by incorporating the functionality to deliver maximum performance and contain a logarithmic power detector to support wide dynamic ranges, low power consumption and improved thermal management.

Anokiwave expands in San Diego to larger offices and new millimeter-wave lab

Anokiwave Inc of San Diego, CA, USA — which provides highly integrated silicon core chips and III-V front-end integrated circuits for millimeter-wave (mmW) markets and active antenna-based solutions — has expanded its San Diego operations to a new facility that will triple its floor space and lab capabilities to meet its growing needs. The location will increase the capabilities of its design center by providing a mmW laboratory for all mmW active antenna and IC design and test, and room to double its local workforce.

The move to Sorrento Towers South, in San Diego's tech hub Sorrento Mesa, was completed in early February. The expansion is driven by the firm's rapid growth in recent years, addressing technologies critical to 5G and other advanced wireless communications markets. The move follows Anokiwave's expansion of its design center in Billerica, MA and establishment of a new office in Taiwan. The firm aims to further expand its footprint with additional offices elsewhere for engineering and customer support.

To fully characterize the performance of Anokiwave's products in specific customer environments, the new facilities will house a mmW laboratory incorporating an anechoic chamber for the development of phased-array antennas for 5G, satellite communications and radar applications operating up to 50GHz. The lab enables complex antennas and components to be exhaustively tested and evaluated in conformance with exacting customer requirements in all operating modes.

"Last year we celebrated 20 years of being in business and doubled our space in Massachusetts. Now the expansion in San Diego just marks the steep growth trajectory that Anokiwave is on," says founder & chief technology officer Nitin Jain. "Anokiwave continues to push the bounds of mmW innovation and enable mmW active antennas at a commercial scale for 5G, SATCOM and radar markets. This new facility and a larger team will allow us to serve the market at a much broader scale and in more impactful ways than ever before," he believes.

Sorrento Towers South also allows the company to meet a key corporate goal to operate in an environmentally sustainable manner. The building is being re-certified as a LEED (Leadership in Energy and Environmental Design) facility and incorporates forward-thinking practices such as water efficiency standards, waste and e-waste recycling and green construction.

Anokiwave named Hot Tech Innovator by ABI Research

Anokiwave has been named a hot tech innovator by global technology market advisory firm ABI Research in its 2019 QTR 4 report 'Hot Tech Innovators' for Cellular and 5G Antenna Technologies.

Advances in phased-array antennas for use at mmW frequencies are essential for the rollout of new 5G, cellular and other applications. In naming Anokiwave as a Hot Tech Innovator in this area, ABI said that the firm's pioneering hybrid beamforming technology not only enables the development of high-performance antennas, it also provides the additional benefits of low cost, low complexity and ease of reconfigurability for even the largest designs.

"There has been a huge amount of R&D investment in antennas for 5G and cellular applications in recent years, and in the US this work is largely being carried out by smaller, fast-growing companies and startups, not by large, established infrastructure players," notes Dimitris Mavrakis, research director at ABI. "Anokiwave is at the forefront of this trend. Its unique hybrid beamforming technology allows numerous digital beams to form within analog, hard-coded beams, combining advantages from both domains," he adds. "Proof of the value of this approach is that the company is already shipping its advanced chipsets to tier-one OEMs, and they are already in the market for mmW base stations and customer premises equipment (CPE)."

Anokiwave recently celebrated the 20th anniversary of its founding, and in that time has shipped millions of silicon-based mmW ICs for RF front ends and control of active antennas for 5G, radar and SatCom applications. The firm offers a full lineup of silicon mmW beamformer ICs and silicon up- and down-converter ICs, which enable intelligent, scalable antenna arrays that can be configured for different power levels and frequency bands. The flexibility to optimize an array for different use cases is important because needs vary among 5G applications.

"Customers come to us because of our mature technologies, unparalleled systems-level knowledge of mmW applications, and the many advantages of silicon-based ICs, which range from the ease of porting circuit designs across frequency bands to silicon's superior integration capabilities," said Shmuel Ravid, Anokiwave Chief Engineer. "We're proud to be acknowledged as a technology leader by ABI Research, and see it as a validation of the ideas and hard work put forth by our employees day in and day out over many years."

www.abiresearch.com
www.anokiwave.com

Altum RF certified to ISO 9001 for evaluation of quality management system

Altum RF of Eindhoven, Netherlands (a start-up that designs high-performance millimeter-wave to digital solutions for next-generation markets and applications) has been certified (by TÜV Nederland, part of the international TÜV NORD GROUP) to the ISO 9001:2015 standard for its quality management system, demonstrating the firm's focus on the quality, reliability and performance of its design and development of semiconductor products.

Altum RF has strategic partnerships and office locations that span the globe to support its growing product portfolio. "We are committed to achieving and maintaining high quality standards and certifications to become a leading supplier in the RF and microwave industry," says CEO Greg Baker.

Founded in 2018, Altum RF's engineers are employing decades of modeling expertise and system applications knowledge to develop products for commercial and industrial applications based on proven technologies like gallium arsenide (GaAs), gallium nitride (GaN), silicon germanium (SiGe) or RF CMOS for commercial and industrial applications. Working with both customers and global partners on technical support and customer service, the firm says it can significantly shorten product development cycles by managing the entire supply chain from design to packaging, testing and qualification. Applications span telecom, 5G, Satcom, radar sensors, test & measurement, aerospace & defense and industrial, scientific & medical (ISM) applications. Altum RF adds that it has strategic roadmaps to rapidly expand its product portfolio.

www.altumrf.com

Filtronic launches new-gen Morpheus II E-band transceiver modules, enabling 10Gbps mmWave backhaul for 5G

Filtronic Ltd of Leeds, UK, which designs and manufactures RF, microwave and millimeter-wave (mmWave) products for the wireless telecoms, mission-critical communications and defence applications markets, has launched Morpheus II, its new generation of mmWave transceiver modules for E-band (71–76GHz and 81–86GHz) applications in carrier-grade mobile backhaul.

Morpheus II is based on Filtronic's proven E-band transceiver platform, of which over 36,000 units have already been shipped and deployed worldwide. Each fully integrated Morpheus II transceiver module contains all the transmit and receive functions necessary for the RF section of an E-band radio link, and provides a simple connection to a high-data-rate full-duplex modem. They are designed for easy incorporation into outdoor units, giving original equipment manufacturers (OEMs) the advantage of rapid time-to-market while requiring minimal engineering resource, says Filtronic.

Demand for E-band mmWave radio links is growing rapidly, as they can provide high-capacity and high-data-rate XHaul for the latest 5G networks that are being rolled out globally. In 2018 E-band accounted for 7% of wireless links, and is forecast to continue with year-on-year growth rates of around 36%, according to Dell'Oro Group.

Standard modules have a linear transmitter power control range of −4dBm to +16dBm, with an output third order intermodulation product (IP3) of typically up to +34dBm at the top end of the range. An enhanced power option, extending the control range up to +25dBm, is also available. With a low phase noise of −112dBc/Hz at 1MHz, the transceiver modules support a channel bandwidth in excess of 2GHz. They have demonstrated system performance at data rates of 10Gb/s with spectrally efficient 256QAM, and are capable of supporting even higher-order modulation schemes. The internal low-phase-noise voltage-controlled oscillators (VCOs) can be adjusted-via an SPI interface in 31.25MHz steps, to support ECC/ITU channel arrangements.

A single transmit/receive interface is provided by the integrated diplexer, which connects directly to an external antenna via a standard WR12 interface. The interface between the Morpheus II E-band module and the customer modem is via a single 50-way connector that supplies all communication between the module and the modem, as well as DC power, baseband data and control signals.

With a footprint of 90mm x 80mm and weighing only 110g, the Morpheus II transceiver modules are 20% smaller and 50% lighter than the existing Orpheus models, with which they retain interface compatibility.

"Morpheus II transceiver modules are 100% calibrated and tested, and are based on a platform that has extensive field-proven performance," says Dan Rhodes, director of business development – mmWave technology at Filtronic. "Their compact form factor makes them suitable for use in all types of mmWave XHaul applications, and their readily reconfigurable architecture also provides the ideal basis from which to develop systems for application in high-throughput satellites and High Altitude Pseudo-Satellites (HAPS)," he adds.

www.filtronic.com

ST and TSMC collaborate to accelerate market adoption of GaN-based products

Power GaN discretes and GaN ICs to target industrial and automotive power conversion

STMicroelectronics of Geneva, Switzerland and Taiwan Semiconductor Manufacturing Corporation (TMSC, the world's biggest silicon wafer foundry) are collaborating to accelerate the development of gallium nitride process technology and the supply of both discrete and integrated GaN devices to market. Through this collaboration, ST's GaN products will be manufactured using TSMC's GaN process technology.

Specifically, power GaN and GaN IC technology-based products will enable ST to provide solutions for medium- and high-power applications with better efficiency compared to silicon technologies on the same topologies, including automotive converters and chargers for hybrid and electric vehicles. They will also help to accelerate the megatrend of the electrification of consumer and commercial vehicles, says ST.

"As a leader in both wide-bandgap semiconductor technology and in power semiconductors for the demanding automotive and industrial markets, ST sees significant opportunity in accelerating the development and delivery of GaN process technology and bringing power GaN and GaN IC products to the market," says Marco Monti, president of STMicroelectronics' Automotive and Discrete Group. "TSMC is a trusted foundry partner that can uniquely meet the challenging reliability and roadmap evolution requirements of ST's target customers," he comments. "This cooperation complements our existing activities on power GaN undertaken at our site in Tours, France and with CEA-Leti. GaN represents the next major innovation in power and smart power electronics, as well as in process technology," adds Monti.

This cooperation complements our existing activities on power GaN undertaken at our site in Tours, France and with CEA-Leti

"We look forward to collaborating with ST and bring the applications of GaN power-electronics to industrial and automotive power conversion," says TSMC's VP of business development Dr Kevin Zhang. "TSMC's leading GaN manufacturing expertise, combined with STMicroelectronics' product design and automotive-grade qualification capabilities, will deliver great energy-efficiency improvement for industrial and automotive power conversion applications."

ST expects the delivery of first samples of power GaN discrete devices to its key customers later this year, followed by GaN IC products within a few months.

www.tsmc.com
www.st.com

SemiQ launches 650V, 1200V and 1700V silicon carbide Schottky diode family

SemiQ (previously Global Power Technologies Group) of Lake Forest, CA, USA — which manufacturing SiC components and SiC epiwafers for the development of low-cost, high-frequency, high-temperature and high-efficiency power semiconductor devices — has announced the release to production of its new family of third-generation silicon carbide (SiC) diodes, featuring blocking voltages of 650V, 1200V and 1700V with forward-current starting at 8A up to 50A per chip. Packages include TO-220-2L, TO-220-3L, TO-247-2L, TO-247-3L, SOT-227, TO-263 as well as bare die.

The Gen-3 products represent an improvement in reliability, device ruggedness, surge current capability, and moisture resistance, says the firm. Extensive qualification testing includes over 8 million device hours of high-temperature reverse bias (HTRB) and humidity testing with bias (H3TRB). All packaged devices are 100% tested for unclamped inductive load. Also, SemiQ provides a robust and reliable, redundant supply chain, including at least three suppliers of SiC substrates, at least four suppliers of SiC epitaxy, two qualified SiC wafer fabs, and multiple sources for high-volume packaging and testing.

SemiQ is an integrated development and manufacturing company that grows its own SiC epitaxy and is assembling a redundant supply chain with multiple substrate suppliers, multiple epitaxial suppliers, two wafer fabrication facilities, and multiple packaging and testing facilities.

The firm's product line includes SiC power discretes (diodes and MOSFETs), silicon (Si) and SiC power modules, SiC wafers and die, and SiC epiwafers. It also offers custom semiconductor module design for power system engineers needing modules that accommodate challenging customer-driven power conversion designs and applications.

www.SemiQ.com

Infineon launches CoolSiC MOSFET 650V family, extending reliability and performance to more applications

Infineon Technologies AG of Munich, Germany has expanded its silicon carbide (SiC) product portfolio with 650V devices. The firm says that, with the newly launched CoolSiC MOSFETs, it is addressing the growing demand for energy efficiency, power density and robustness in a wide range of applications, including server, telecom and industrial switched-mode power supplies (SMPS), solar energy systems, energy storage and battery formation, uninterruptible power system (UPS), motor drives and electric vehicle (EV) charging.

"With this launch, Infineon complements its broad silicon-, silicon carbide (SiC)- and gallium nitride (GaN)-based power semiconductor portfolio in the 600V/650V power domain," says Steffen Metzger, senior director High Voltage Conversion at Infineon's Power Management & Multimarket Division. "It underlines our unique position in the market, being the only manufacturer with such a broad offering for all three power technologies," he claims. "Additionally, the new CoolSiC family supports our claim to be the number-one supplier of SiC MOSFET switches for industrial purposes."

The CoolSiC MOSFET 650V devices are rated from 27mΩ to 107mΩ, available in classic TO-247 3-pin as well as TO-247 4-pin packages, allowing even lower switching losses. As for all previous CoolSiC MOSFET products, the new family of 650V devices is based on Infineon's trench semiconductor technology. Maximizing the strong physical characteristics of SiC, this ensures that the devices offer superior reliability, best-in-class switching and conduction losses, it is claimed. Additionally, they feature the highest transconductance level (gain), threshold voltage (V_{th}) of 4V and short-circuit robustness, the firm adds. Trench technology hence allows for the lowest losses in application and highest reliability in operation — without any compromise, it is claimed.

Infineon says that, compared with other silicon and silicon carbide solutions on the market, its 650V CoolSiC MOSFETs offer benefits such as switching efficiency at higher frequencies and outstanding reliability. Due to the very low on-state resistance ($R_{DS(on)}$) dependency on temperature, they feature what is reckoned to be excellent thermal behavior. The devices include robust and stable body diodes, retaining a very low level of reverse recovery charge (Q_{rr}), about 80% less compared with the best superjunction CoolMOS MOSFET. The commutation-robustness helps to achieve an overall system efficiency of 98%, for example through the usage of continuous conduction mode totem-pole power factor correction (PFC).

To ease the application design using 650V CoolSiC MOSFETs and to ensure high-performance operation of the devices, Infineon offers dedicated 1-channel and 2-channel galvanically isolated EiceDRIVER gate-driver ICs. Combining CoolSiC switches and dedicated gate-driver ICs, this helps to lower system costs as well as total cost of ownership and enables energy-efficiency gains. The CoolSiC MOSFETs also work seamlessly with other ICs from Infineon's EiceDRIVER gate-driver family.

The CoolSiC MOSFET 650V family comprises eight variants (which can be ordered now) housed in two through-hole TO-247 packages. Three dedicated gate-driver ICs will be available from March.

www.infineon.com/coolsic-mosfet-discretes

Transphorm's high-voltage GaN power on show at APEC

In booth #1514 at the Applied Power Electronics Conference (APEC 2020) in New Orleans (15–19 March), Transphorm Inc of Goleta, near Santa Barbara, CA, USA — which designs and manufactures JEDEC- and AEC-Q101-qualified 650V and 900V gallium nitride (GaN) field-effect transistors (FETs) — is showcasing end products from over five markets that leverage the inherent benefits offered by its GaN, including increased power density and power efficiency as well as lower overall system costs, often achieved within the same or better thermal performance range than comparative silicon-based products, it is claimed.

The customers behind the end products are using Transphorm's GaN in a wide variety of power ranges. Information gathered from their design experiences — coupled with the company's technological vision — has led to Transphorm's latest innovation, the Gen IV GaN platform.

APEC attendees will be able to view Transphorm's new GaN devices for power electronics, plus new design tools and resources for simplifying GaN power system development.

Transphorm says that its market traction to date is driven by its focus on four key areas:

- Reliability: First JEDEC- and AEC-qualified GaN power FETs that also offer less than four defective parts per million (DPPM) based on more than 5 billion field hours.
- Designability: GaN offered in standard device packages that use well-known design-in and thermal management techniques.
- Drivability: GaN FETs that require minimal external circuitry and drive like silicon.
- Reproducibility: GaN manufacturing process that offers silicon-like fab yields capable of high-volume scalability.

Transphorm's team members will address these four key areas as they present six related topics during APEC's educational, industry and technical sessions:

- Full Technology Validation of 600V+ GaN Power Devices — from Device Structure, Performance and Reliability, to Application Economics, User Satisfaction and ppm Field Failure Rate.
- Advances Through Innovation: Transphorm Changes the Game with Gen-IV 650V GaN Platform.
- Portable Power for the People: Inergy Realizes its Vision with Transphorm GaN.
- GaN FETs Enable High Frequency Dual Active Bridge Converters for Bi-Directional Battery Chargers.
- Best Practices Using Voltage Acceleration for Reliability Testing of High Voltage GaN.
- No Digital Control Experience Needed: Bridgeless Totem Pole PFC GaN Designs Made Simple

www.apec-conf.org
www.transphormusa.com

Navitas' 65W GaNFast charger power ICs used by Xiaomi

Navitas Semiconductor Inc of El Segundo, CA, USA says that its GaNFast charging technology has been adopted by China's Xiaomi for its flagship Mi 10 PRO smartphone.

Founded in 2014, Navitas introduced what it claimed to be the first commercial gallium nitride power ICs. Its proprietary 'AllGaN' process design kit monolithically integrates GaN power field-effect transistors (FETs) with GaN power, analog and logic circuits, enabling faster charging, higher power density and greater energy savings for mobile, consumer, enterprise, eMobility and new energy markets.

Since GaNFast power ICs can operate up to 100x faster than earlier silicon power chips, it takes only 45 minutes to charge the Mi 10 PRO from 0 to 100%, says Navitas.

GaN enables very small charger size and high charging efficiency. "The 65W GaN charger is only half the size of the 65W traditional charger that comes as standard with our Xiaomi 10 PRO," notes Xiaomi's chairman & CEO Jun Lei.

Xiaomi's 65W GaN charger uses Navitas' NV6115 and NV6117 GaNFast power ICs, which are optimized for high-frequency, soft-switching topologies. Monolithic integration of FETs, drivers and logic delivers a very small, fast, easy-to-use 'digital-in, power-out' high-performance power conversion module. Using GaNFast, Xiaomi's 65W GaN charger is only 56.3mm x 30.8mm x 30.8mm (53cc), which is half the size of standard adapters.

Xiaomi invested earlier in Navitas to lay the groundwork for this cooperation. Xiaomi's strategy is to establish upstream and downstream partnerships in the industry chain through capital investment, while taking into account the dual benefits of investment and business. Navitas has hence been able to broaden its sales channels.

"I am very pleased to see Xiaomi's open attitude towards new materials and new technologies," comments Navitas' CEO Gene Sheridan. "From the start, Navitas has focused on the technology application and innovation of GaN materials. GaNFast power ICs are monolithic integration of FET, drive and logic and achieve extremely small application size and high efficiency. For manufacturers who want to lead with technology, GaNFast enables high performance and drives product differentiation," he adds.

"The battery capacity of smartphones, tablets and laptops is increasing, while consumers are eager to have a faster-charging experience," says Yingjie Zha, general manager of Navitas Semiconductor China. "GaNFast technology brings the industry a small, efficient charger that can quickly charge electronic products such as mobile phones and laptops."

www.navitassemi.com

TMD invests in GaN power amplifier maker Diamond Microwave

Strategic investment builds on collaboration on solid-state microwave products for aerospace & defence systems

Diamond Microwave Ltd (DML) of Shipley, UK says that it has a new shareholder in the form of TMD Technologies Ltd of Hayes, West London, which designs and manufactures transmitters, amplifiers, microwave power modules (MPMs), high-voltage power supplies, microwave tubes and transponders for radar, EW and communications applications.

Diamond Microwave is described as a pioneer in the development and manufacture of compact GaN-based microwave high-power solid-state power amplifiers (SSPA) for the radar, electronic warfare (EW), communications and aerospace sectors, with chip and wire GaN technology that is particularly suited to such demanding applications where their power-to-volume performance is said to be a capability differentiator.

The investment from TMD is "a welcome step in enhancing our existing relationship and further developing our joint interests in world-class amplifier products," says DML's CEO Dr Richard Lang. TMD brings "the possibility of new channels through which to develop and exploit our solid-state power amplifier technology," he adds.

"We have been collaborating with Diamond Microwave for several years and are very pleased with this latest development, which is a logical step forward in our business relationship," comments TMD's group CEO Dave Brown. "Their specialized technological expertise has proved particularly successful across the aerospace and defence industries and complements our current technologies targeted at this market sector," he adds. "We are looking forward to increased involvement with this forward-looking company."

www.tmd.co.uk

www.diamondmic.com

Comtech PST receives $3.1m contract for GaN-based high-power amplifier systems

Comtech Telecommunications Corp says that in fiscal second-quarter 2020 its subsidiary Comtech PST Corp of Melville, NY, USA, which is part of Comtech's Government Solutions segment, received a $3.1m contract for high-power amplifier systems from a major domestic prime contractor.

The amplifiers, which use gallium nitride (GaN) transistor technology, are key transmit elements in a data communication system. They are in addition to an installed base of Comtech solid-state high-power RF amplifiers previously delivered to this customer.

"This follow-on order continues to demonstrate our leadership position in providing high-power communications technology and the ongoing demand for our solid-state high-power amplifiers that are utilized by major OEMs in both domestic and international markets," says Comtech Telecommunications' chairman & CEO Fred Kornberg.

www.comtechpst.com

Teledyne e2v HiRel and GaN Systems unveil high-reliability 100V GaN power HEMT

Teledyne e2v HiRel of Milpitas, CA, USA (part of the Teledyne Defense Electronics Group that provides solutions, sub-systems and components to the space, transportation, defense and industrial markets) is launching a ruggedized 100V/90A gallium nitride power high-electron-mobility transistor (HEMT) based on technology from GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of GaN-based power switching semiconductors for power conversion and control).

The TDG100E90 GaN power HEMT is available with a bottom-side-cooled package for all applications requiring extremely high reliability, in particular space and military. Joining the 650V, 60A TDG650E60 (launched last December) it provides a lower step-down voltage in high-reliability power circuitry.

GaN devices have revolutionized power conversion in other industries and are now available in radiation-tolerant, plastic-encapsulated packaging that has undergone stringent reliability and electrical testing to ensure mission-critical success. The new TDG100E90 GaN HEMT delivers the efficiency, size and power-density benefits required in demanding HiRel power applications.

Teledyne e2v HiRel says that, for all product lines, it performs demanding qualification and testing tailored to high-reliability applications. This includes sulfuric test, high-altitude simulation, dynamic burn-in, step stress up to 175°C ambient, testing at 9V gate voltage, and full temperature testing.

This new addition to Teledyne's GaN power HEMT family has an extremely small form factor and leverages GaN Systems' patented Island Technology, which is a scalable, vertical charge dissipating system that gives the power transistor ultra-low thermal losses, high power density, no-charge storage, and very high switching speeds.

Compared with silicon MOSFETs, the GaN-based TDG100E90 HEMT significantly reduces losses and electro-magnetic interference (EMI) due to no reverse recovery characteristics. To reduce drain–source on-resistance ($R_{DS(on)}$) or increase the load current, the TDG100E90 can support parallel driving configuration. The use of high-performance GaN*PX* packaging allows very high-frequency switching, extremely low inductance, and excellent thermal characteristics, enabling the size and weight of power electronics to be greatly reduced, claims GaN Systems.

"Teledyne e2v HiRel is pleased to be working with GaN Systems on solutions for the most demanding requirements in key applications for avionics, radar, satcom, space and more," comments Mont Taylor, Teledyne e2v HiRel's VP of business development. "In addition to the currently released TDG650E60 650V GaN HEMT, the TDG100E90 complements our portfolio with a lower-voltage, higher-current option, providing GaN flexibility and choices to the HiRel power design community."

www.e2v.com/products/semiconductors/power-solutions
www.gansystems.com

GaN Systems' power transistors used in Siemens' new low-voltage Simatic Micro-Drive product line

Siemens is integrating part of its Simatic Micro-Drive product line with GaN Systems' power semiconductors.

"The Simatic Micro-Drive is an extremely versatile, seamless and safety-integrated servo drive system that covers a wide range of applications in the extra-low-voltage range for EC motors from 24V to 48V," says Christian Neugebauer, Simatic Micro-Drive product manager, at Siemens. "With the GaN Systems devices, we are now able to increase the efficiency of the drives," he adds. "With GaN, Siemens can switch to a higher frequency, thereby enabling a faster motor response time compared with high-voltage drive systems."

Recently, Siemens entered the low-voltage drive market with the creation of its new Simatic Micro-Drive safety and extra-low-voltage family. The integrated Simatic Micro-Drive system comes in two different housing sizes for motor outputs of 100W to 1000W. The fundamental building block is the GaN power transistors made by GaN Systems. This 4-quadrant drive system can be used either with the integrated brake chopper on a power supply or directly in battery operation.

The servo drive system is suited to a wide range of diverse applications in moving, processing and positioning such as conveyor systems and stacker cranes, positioning of individual or multiple coordinated axes, shuttles for storage and retrieval machines or warehousing systems, automatic guided vehicles (AGVs) and medical technology.

"Many industrial customers have leveraged the benefits of GaN in their production products," notes GaN Systems' CEO Jim Witham. "We have designed and tested the high quality and performance requirements needed to earn the confidence in GaN technology required by our customers and are thrilled to see that the efforts that Siemens and GaN Systems have invested are now being realized."

www.news.siemens.com/global/en/products/drives/sinamics/servo-drive-system-simatic-micro-drive.html

US Marine Corps orders additional Northrop Grumman AN/TPS-80 radar systems

Northrop Grumman Corp has received an order from the US Marine Corps for two additional AN/TPS-80 Ground/Air Task-Oriented Radar (G/ATOR) systems as part of the full-rate production Lot 2 award received in December. This order completes the planned Lot 2 procurement for a total of eight systems for the Marine Corps.

"We are continuing to provide an advanced, multi-mission capability that meets the evolving needs of our customers," says Mike Meaney, vice president, land and maritime sensors, Northrop Grumman. "This order also enables us to keep the G/ATOR production pipeline full in anticipation for a Lot 3 award next year." The Marine Corps awarded Northrop Grumman a $958m full-rate production contract for 30 of the gallium nitride (GaN)-based G/ATOR systems in June 2019.

The AN/TPS-80 G/ATOR is an active electronically scanned array (AESA) multi-mission radar that leverages GaN to provide comprehensive real time, full-sector, 360° situational awareness against a broad array of threats.

www.northropgrumman.com

AKHAN issued US patent for fabricating monolithically integrated diamond semiconductors

AKHAN Semiconductor Inc of Gurnee, IL, USA — which was founded in 2013 and specializes in the fabrication and application of lab-grown, electronics-grade diamond as functional semiconductors — has been issued a patent by the United States Patent Office (USPTO) covering its new and improved system and method for fabricating monolithically integrated diamond semiconductors.

US patent 10,546,749 B2 is a key addition to AKHAN's Miraj Diamond intellectual property portfolio. It is the firm's seventh patent issued in the USA and is generally related to semiconductor fabrication methods, and more particularly to a method of fabricating diamond semiconductors.

Diamond possess favorable theoretical semiconductor performance characteristics, but practical diamond-based semiconductor device applications remain limited because of difficulties associated with fabricating quality n-type layers in diamond. AKHAN says that its latest patent covers the steps of seeding the surface of a substrate material, forming a diamond layer on the surface of the substrate material, and forming a semiconductor layer within the diamond layer, wherein the diamond semiconductor of the layer has n-type donor atoms and a diamond lattice.

"Through this new and improved system, we are able to more efficiently develop lab-grown diamond technology that performs exceptionally better than the market-leading materials commonly used today," claims founder & CEO Adam Khan.

www.akhansemi.com

LPE's PE108 8-inch SiC epi reactor undergoing preliminary tests, while power semiconductors drive 6-inch PE106 orders

LPE SpA of Milan, Italy, which designs and makes epitaxial reactors for power electronics applications, says that purchase orders for its PE106 silicon carbide (SiC) epitaxy reactor are maintaining strong momentum in the growing SiC market.

The firm also confirms that its new PE108 — the first 8" silicon carbide single-wafer epitaxial reactor — is undergoing preliminary tests. Shipments to various countries are expected to be made during 2020.

As silicon carbide epitaxy quality is becoming increasingly challenging, the PE108 has been designed to meet customers demand in terms of performance, throughput and cost. The PE108 is a fully automated cassette-to-cassette tool, maintaining full compatibility with existing 150mm substrates.

Founded in 1972 LPE introduced the first epi reactor capable of growing very thick epitaxial layers, and the firm has subsequently contributed to the European semiconductor industry's development of discrete power semiconductor device production. Today, more than 400 silicon reaction chambers are in operation, and nearly 30 silicon carbide reactors have been sold, to a worldwide customer base via a global sales & service organization.

LPE says that 20 years ago it identified silicon carbide as the material bound to play a key role in power applications. The silicon carbide device market is expected to grow to several billion dollars by 2030. The firm's existing SiC product range includes PE106 and 106A single-wafer reactor technology which, with multiple gas injection, ensures what is claimed to be matchless epi quality, combined with the most space-efficient design.

LPE says that it supports customers in the development of epi processes for power application, is partner in several European Union (EU)-funded R&D projects, and works closely with several European universities on processes and materials for power electronics.

www.lpe-epi.com

STAr acquires Accel-RF to expand scope of reliability test

STAr extends from DC-AC into RF, addressing 5G, LiDAR, photonics and radar applications

Reliability test system and probe card supplier STAr Technologies of Hsinchu City, Taiwan has acquired Accel-RF Instruments Corp of San Diego, CA, USA (which produces turn-key reliability and performance characterization test systems for compound semiconductors).

Established in 2000, STAr provides intellectual property, software, hardware, consumables, service and expertise to the semiconductor industry, spanning parametric electrical test (E-test), wafer-level and package-level reliability (WLR & PLR), mixed-signal tests, assembly & packaging services, probe cards, load boards, test interfaces and sockets.

The acquisition enhances STAr's reliability test offerings by adding Accel-RF's high-temperature RF and high-voltage switching reliability test systems for compound semiconductors, such as gallium nitride (GaN) and silicon carbide (SiC).

Founded in 2003, with cumulative experience based on decades of microwave circuit design, RF component reliability testing and comprehensive reliability test methodology development, Accel-RF has helped to facilitate industry adoption of compound semiconductor transistors and MMICs into space, military and commercial wireless markets. It has supplied reliability test systems to top-tier semiconductor and aerospace defense users throughout the USA, Europe and Asia. Accel-RF claims to be the only provider of fully integrated, scalable, turnkey systems that provide dynamic, multi-dimensional, RF, DC and temperature tests on one platform through a graphical user interface, in a small footprint.

"As a member of STAr's global connection, Accel-RF will solidify our commitment to providing a far-reaching and strong technical expertise to the compound semiconductor reliability community," says Accel-RF's CEO Roland Shaw. "We look forward to a collaborative future with STAr Technologies in pursuit of advanced test solutions that will reinforce our longstanding position as a leading RF and power semiconductor reliability test innovator," he adds.

"Acquisition of Accel-RF is another step towards strengthening our presence in wireless industry markets including RF through millimeter-wave applications," says STAr Technologies' CEO Dr Choon-Leong Lou. "Combination of STAr Technologies expertise in DC-AC and now extending into RF with Accel-RF, creates a formidable platform for addressing rapidly growing applications such as 5G, LiDAR, photonics and advanced radar systems," he reckons.

www.accelrf.com
www.star-quest.com

Meaglow receives order for 50th hollow-cathode gas plasma source

Hollow cathodes are best known for their application as sputter sources, but Meaglow Ltd of Thunder Bay, Ontario, Canada, which produces migration-enhanced afterglow epitaxy equipment and molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) accessories, has created an increasingly successful range of gas plasma sources for application in plasma-enhanced atomic layer deposition (PE-ALD) and plasma-enhanced chemical vapour deposition (PE-CVD). In the past, thin non-oxide films grown by PE-ALD had suffered from severe oxygen contamination problems.

Meaglow says that these problems are largely solved by its hollow cathodes, which have other advantages of high radical flux, low ion damage, and scalability. The firm has made several large-area sources. The new order involving the 50th plasma source is for three 4”-diameter sources and an 8”-diameter source for the OEM Okyay Tech, which will use the sources in some of their upcoming ALD equipment builds. Meaglow has also built 12”-diameter sources for other customers.

“Meaglow’s designs represent the first successful, widespread application of hollow-cathode gas sources for thin-film deposition,” claims chief scientist Dr Scott Butcher. “Past designs struggled with uniform plasma distribution, a problem which Meaglow has overcome.” Butcher’s early exposure to radio-frequency hollow-cathode technology, back in the 1990s, was a good fit for solving some of the problems faced by PE-ALD customers, reckons Meaglow. The firm’s technology can now be found in ten countries, and customers have published over 40 related journal papers.

www.meaglow.com
www.okyaytechald.com

AXT's Q4 revenue down 17% year-on-year, driven by drop in GaAs and Ge substrate sales

Indium phosphide surpasses gallium arsenide in full-year 2019, but GaAs and Ge to return to growth for 2020

For full-year 2019, AXT Inc of Fremont, CA, USA — which makes gallium arsenide (GaAs), indium phosphide (InP) and germanium (Ge) substrates and raw materials — has reported revenue of $83.3m, down 18.7% on 2018's $102.4m. Raw materials business declined by about $6m, mostly due to the changes in ownership positions in Q1/2019 that resulted in consolidating just two of the joint venture raw material companies in revenue results in 2019 (compared with three in 2018). The balance of the decline came from GaAs and Ge wafer substrate sales. "In gallium arsenide, our business weathered a difficult year in 2019," comments CEO Morris Young. "In germanium substrate, coming off a strong year in 2018 our sales took a meaningful step back in 2019. It is in a softer demand environment, particularly in China," he adds.

Fourth-quarter 2019 revenue was $18.4m, down 7% on $19.8m last quarter and 17% on $22.2m a year ago. Of total revenue, the proportion from the Asia-Pacific region actually rebounded slightly from 66% last quarter to 68% and North America rose further from 9% to 10%, while Europe fell from 25% to 22%. Two customer reached 10% of revenue and the top five comprised about 42%.

"Q4 capped off a turbulent year in the geopolitical and macroeconomic climate in which we weathered one of the most difficult demand environments in recent memory," notes Young. "Overall, this had a negative impact throughout the year on key applications and certain customers within AXT's gallium arsenide and germanium businesses, making up the majority of our year-over-year revenue decline," he adds. "The global demand environment in key [GaAs] applications such as LED lighting, automotive lighting, and other high-performance applications was challenging. There were certain customers who were predicting a pick up in Q4, but it did not materialize. Wireless applications were also down from the prior year."

"Despite these more challenging conditions, our indium phosphide business exceeded our expectations in Q4, and finished 2019 with modest growth over the prior year. In fact, 2019 was the first year in our history that total indium phosphide revenue surpassed total gallium arsenide revenue," says Young. "The substrate market demonstrates the gathering momentum in the trend driving indium phosphide demand. These trends such as data-center connectivity, 5G telecoms and optical network expansions are powerful and substantial and they are developing as we see."

Full-year gross margin has fallen from 36.2% in 2018 to 29.8% for 2019. Quarterly gross margin was 21%, down from 29% last quarter. Of the 8% decline, about half (about 4%) was due to lower gross margins on each of AXT's two consolidated raw material revenue (1.5%) and adjustments in excess and obsolete inventory (2.2%). The other 4% of the decline was due to a decline in manufacturing efficiencies and yields mainly associated with two new products – 6-inch InP substrates and a new 6-inch Ge product configuration for a large customer – addressing new market opportunities for AXT. "We view this decline in efficiency as temporary," says VP & chief financial officer Gary Fischer. "Larger-diameter substrates are inherently more challenging, where we are already taking steps to refine the processes and expect to show improvement [in manufacturing yields and efficiencies] in the coming quarters. "

Operating expenses were $6.7m, up from $6.2m last quarter as a result of end-of-year bonuses for employees at raw material joint ventures JinMei and BoYu that are part of AXT's supply chain. However, full-year OpEx rose only slightly, from $24.9m in 2018 to $25.1m for 2019.

Net loss was $2m ($0.05 per share), up from $0.9m ($0.02 per share) last quarter and $1.1m ($0.03 per share) a year ago. Consequently, full-year 2019 saw a net loss of $2.6m ($0.07 per share), compared with net income of $9.7m ($0.24 per diluted share) in 2018.

During the quarter, depreciation and amortization grew to $5.5m. Capital expenditure (CapEx) was increased to just over $7m. Accounts receivables (net of reserves) have risen from $17.4m to $19m.

Cash, cash equivalents and investments have hence fallen to $36.3m, down from $38.5m at the end of Q3/2019 but only $39.4m at the end of 2018. So, net cash burn in 2019 was only $3.1m (even though AXT spent almost $21m in 2019 on the relocation its GaAs crystal growth and wafer processing facilities from Beijing to Chaozhou and Dingxing, respectively). This includes a bank loan of about $5.8m in China, secured in Q3/2019. AXT also has a line of credit at Wells Fargo Bank that it has not utilized.

Despite rising slightly by $81,000 to $49.2m in Q4, net inventory has still been cut by $9.4m from $58.6m at the end of 2018. Of this reduction, $5.8m was a result of no longer consolidating Jia (one of AXT's raw material supply chain companies) and $3.6m was a result of operations and a focus on reducing inventory (near to the target of $1m per quarter during the year —

a "good result", given the lower revenue). End-of-year inventory consisted of about 42% in raw materials, 51% in work in progress (WiP) and only 7% in finished goods.

"As we move into 2020, AXT is poised for growth and improvement in our financial results," believes Young. "Our indium phosphide business is healthy, with exciting applications contributing today, and new ones on the horizon. Our gallium arsenide and germanium businesses are also well positioned to benefit from a recovery."

"During Q4 we met a major milestone by completing the relocation of our all GaAs crystal growth to Chaozhou, which opens many new doors for AXT. This facility was designed and built by us from the ground up and is optimized for innovation and best-practice manufacturing," notes Young. "Q1/2020 also marks other important milestone in our relocation of our GaAs wafer processing [to Dingxing]. We are making good progress with several customers regarding site qualification and results thus far have been positive, with final signing off expected later this quarter. We also expect to be able to drive additional customer qualification in the coming months. This will open the door to incremental business opportunities from new and returning customers," Young believes.

For first-quarter 2020, AXT expects revenue to rise to $18.5–20.5m. This is a wider-than-normal guidance range as a precaution to allow for unanticipated effects in the supply chain from the coronavirus. "All three of our facilities are in operation and have strong local management teams providing oversight," notes Young. "We continue to be able to meet customer requirements and have the benefit of inventory and manufacturing redundancies between our locations, should the need arise."

"In Q1 our indium phosphide revenue is off to a good start. Sales in the quarter will include a mix of applications including data-center, PON [passive optical networks] and 5G telecoms," says Young". Our customer relationships remain strong and we hope we can build upon our customer list more this year."

OpEx will likely be cut slightly to $6.4–6.5m in Q1 — despite increases in other general & administrative (G&A) areas such as insurance, payroll taxes and legal expenses — as customers transition to the new facility and some of the duplicative expenses continue to diminish. Loss per share should be $0.03–0.06.

"We expect to show incremental improvement in our gross margin, and we'll be focused throughout the year on improving our manufacturing efficiencies across all of our product lines," says Fischer.

"The biggest challenge we face currently [regarding the coronavirus] is the travel restrictions, both to and from China, and also within China," says Young. "These restrictions make it more difficult for our leadership to address certain issues that benefit from the hands-on problem solving, such as manufacturing efficiency, and yield for the launch of our larger-diameter substrate. As a result, we expect the rate of improvement may be a bit slower than it would under normal circumstances. We are also limited in the number of employees that are allowed to be in the factory on any given day. As such, productivity may not be quite as high until the government-mandated restrictions are lifted," he adds.

"As we move into 2020, the satellite solar cell market [for AXT's germanium substrates] is poised for improvement. With a number of satellite launches expected to increase worldwide, we expect we will participate in that improvement," says Young. "As we talked to our customers over the last several quarters about their current and future requirement, we came to believe that our ability to offer a new configuration of our 6-inch germanium wafers can open up new alternatives for AXT. It is a natural expansion of our current capability and will allow us to support our high-volume demand," he adds. "We are highly focused on driving manufacturing efficiency with this larger-diameter product and believe that we will be able to bring the gross margin up to a more normalized level in the coming quarters."

"While gallium arsenide had a difficult year in 2019 it is poised for renewed growth in year 2020 and beyond," believes Young. "This is likely to be driven by recovery in our traditional applications of high-performance LEDs used for example in automobile lighting and lasers as well as a number of new and promising applications, such as mini- and micro-LEDs, laser-based sensing and, over time, 5G wireless. We're excited to be able to open the doors with our new facilities at a time when gallium arsenide is experiencing its next leap of innovation, new applications and expansion."

AXT expects to spend about $5m in CapEx for gallium arsenide in 2020 and is considering additional investments in indium phosphide. "There are significant new trends visible on the horizon involving InP-based sensors for new applications in healthcare, automotive and more. Collectively, these applications position indium phosphide as one of the most important material of this new decade," says Young. "We are setting the pace in our market for technical innovation and we are expanding facilities and additional equipment. That will allow us to keep pace with the market demand," he believes.

"We are also bringing to market larger-diameter indium phosphide substrates. This is a capability that most current and potential new customers are asking for," Young adds. "This new capability will be essential to emerging large-volume applications for indium phosphide. It will also provide new barriers to entry for substrate manufacturers looking to move into this space."

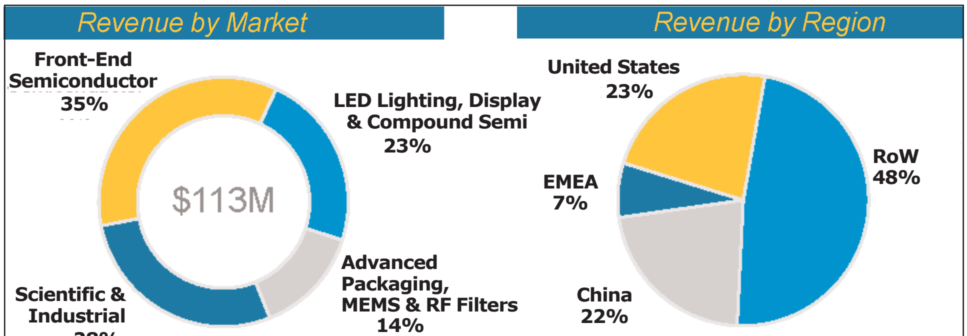
www.axt.com

Veeco's revenue rebounds in Q4, as cost cutting yields a second quarter of profit

Return to profitability with positive EPS in Q3 and Q4

Epitaxial deposition and process equipment maker Veeco Instruments Inc of Plainview, NY, USA has reported full-year revenue of $419.3m for 2019, down 22.6% on $542.1m for 2018.

However, quarterly revenue recovered in Q4/2019 to $113.2m, up 3.9% on $109m in Q3 and 14.3% on $99m a year ago (and above the midpoint of the $100–120m guidance), with strong revenue in the Front-end Semiconductor and Data Storage market segments.



Revenue Trend ($m)	Q4 18	Q1 19	Q2 19	Q3 19	Q4 19
Front-End Semiconductor	22	23	25	34	39
Advanced Packaging, MEMS & RF Filters	14	23	16	11	16
LED Lighting, Display & Compound Semi	13	14	10	24	26
Scientific & Industrial	50	40	47	40	32
Total	99	99	98	109	113

The Front-end Semiconductor segment (formerly part of the Scientific & Industrial segment, before the 2017 acquisition of lithography, laser-processing and inspection system maker Ultratech) contributed $39m (35% of total revenue), up 14.7% on $34m last quarter and 77% on $22m a year ago, driven by shipments of multiple ion beam deposition systems (for EUV mask blank customers) and laser spike annealing (LSA) systems (for leading-edge technology nodes). Full-year revenue has almost doubled from 2018's $63m to $120m in 2019 (rising from 12% to 29% of total revenue).

The Scientific & Industrial segment contributed $32m (28% of total revenue), down 20% on $40m last quarter and 36% on $50m a year ago. Nevertheless, full-year revenue has grown from 2018's $139m to $160m in 2019 (rising from 25% to 38% of total revenue), with shipments of ion beam systems to data storage customers remaining solid.

The LED Lighting, Display & Compound Semiconductor segment — which includes photonics, 5G RF, power devices and advanced display applications — contributed $26m (23% of total revenue), up 8.3% on $24m last quarter and doubling from $13m a year ago, boosted by multiple wet etch & clean system shipments to RF device makers for 5G-related power amplifiers plus the sale of slow-moving LED-related inventory. Full-year revenue has dropped from 2018's $250m to just $73m in 2019 (falling from 46% to just 17% of total revenue).

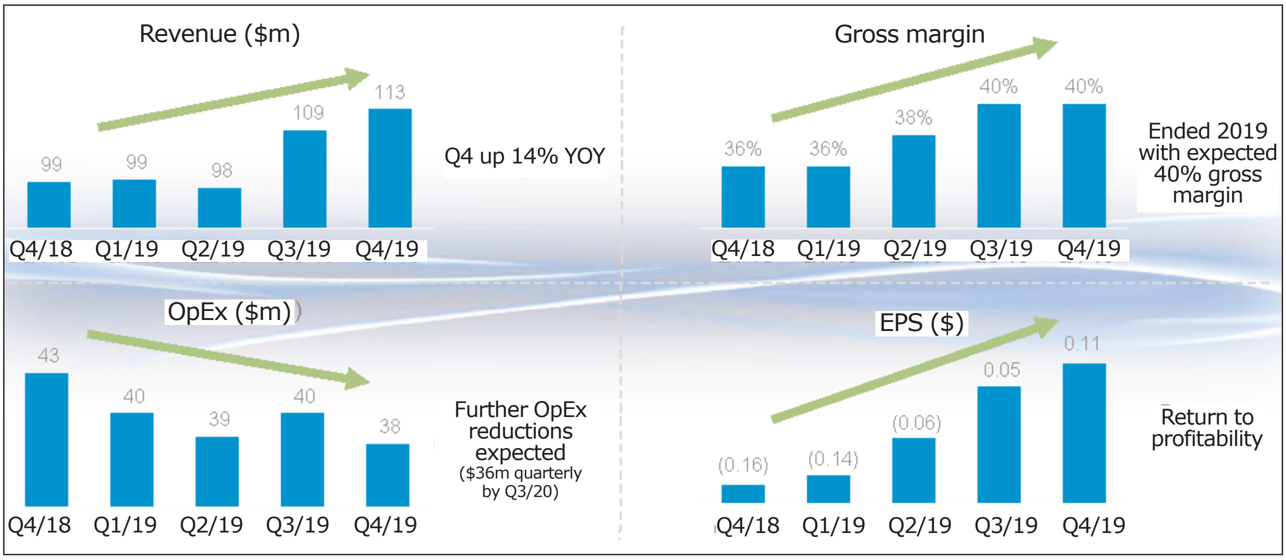
The Advanced Packaging, MEMS & RF Filter segment — including lithography and Precision Surface Processing (PSP) systems sold to integrated device manufacturers (IDMs) and outsourced assembly & test firms (OSATs) for Advanced Packaging in automotive, memory and other areas — contributed $16m (14% of total revenue), up 45% on $11m last quarter but only 14.3% on $14m a year ago, reflecting the softness in the lithography sector of the advanced packaging market that's lasted for well over a year. Full-year revenue has dropped from 2018's $91m to $67m in 2019 (falling slightly from 17% to 16% of total revenue).

By region, the rest of the world (RoW, which includes Japan, Taiwan, Korea and Southeast Asia) comprised 48% of overall revenue (up from 41% last quarter), driven by EUV mask blank and LSA systems. The USA contributed 23% (down from 25%), which included sales to the data storage market. China comprised 22% of overall revenue (up from 16%), mainly from multiple wet etch and clean systems. Europe, the Middle East & Africa (EMEA) contributed 7% of revenue (down from 18%).

On a non-GAAP basis, full-year gross margin has risen from 36.6% for 2018 to 38.5% for 2019, benefitting from improving product mix and volume increases. Q4/2019 gross margin was 40.2%, up from 36% a year ago albeit down slightly from 40.3% last quarter. "Selling off a portion of our slow-moving inventory, there was a slightly negative impact on gross margin [of 1–2 percentage points]," notes chief financial officer John Kiernan.

Operating expenses (OpEx) have been cut further, from $42.6m a year ago and $40m last quarter to $38m in Q4/2019, favorable to the forecasted $39m (contributing to full-year operating OpEx being cut from $175.2m in 2018 to $156.5m for 2019). "We are beginning to see the impact of the infrastructure cost reductions ahead of our target plan," says Kiernan.

Full-year net income has gone from a profit of $14.2m ($0.30 per diluted share) for 2018 to a loss of $1.3m ($0.03 per diluted share) for 2019. However, quarterly net income was a profit of $5.4m ($0.11 per diluted share), almost doubling from $2.6m ($0.05 per diluted share) last quarter and compared with a loss of $7.5m ($0.16 per diluted share) a year ago.



"We returned to non-GAAP profitability by posting two consecutive quarters of positive EPS in Q3 and Q4 of 2019," says CEO Bill Miller. "We executed well on the first phase of our transformation in 2019 by improving gross margins and reducing expenses, leading to a return to profitability in the second half of the year," he adds.

"During this transformational year, where we lost over $100m of commodity LED revenue, we were able to generate $5m in operating income," notes Miller. "Our 13% second-half revenue growth over first half exceeded our 10% outlook," he adds.

Veeco's transformation (begun last year) is in two phases: (1) returning the company to profitability and (2) driving growth. "The first phase, returning the company to profitability, is well underway and includes reducing costs and de-levering the company," says Miller. "As part of the de-levering process, we eliminated the chief operating officer role when Sam Maheshwari announced his resignation from the company last December. I promoted John Kiernan to the position of senior VP, chief financial officer as of the beginning of the year. John has been at Veeco for 25 years," he adds.

"Throughout the year, as part of our de-layering, we eliminated over 30% of vice-president-level and above positions, while trimming approximately 7% of our individual contributor positions. This was an intentional approach to our infrastructure reduction and preserves our ability to execute," states Miller.

"We also reorganized along product lines with a central R&D organization, which enables us to better allocate our R&D spend to our highest-priority project across the company. This allows us to improve our customer focus and operational efficiency," he adds.

"In addition to prioritizing R&D spend on projects with highest financial and strategic importance to the company, we are evaluating our existing product portfolio on a similar set of criteria. In our financials is an asset held for sale, which is an indication of our intent to divest a certain non-core product line."

Due to earnings in the quarter plus a $7m reduction in working capital, cash flow from operations was +$16m in Q4/2019, compared with outflow of –$15m in Q3. Capital expenditure (CapEx) was $2.7m (contributing to $10.9m for the year). Cash and short-term investments hence rose from $232m to $245m. Long-term debt was recorded at $300m, representing the carrying value of $345m in convertible notes.

During Q4/2019, accounts receivable fell from $73m to $45.7m, due to the timing of customer payments, resulting in days of sales outstanding (DSO) falling from 60 to 36 days (lower than the historical average). Accounts payable was reduced from $35m to $21m, resulting in days payables outstanding (DPO) being cut from 47 to 28 days. Inventory has been cut further, from $156.3m at the end of 2018 and $135m at the end of Q3/2019 to $133m at the end of 2019 (reducing the days of inventory from 185 to 177 days during Q4/2019). "We made progress selling slow-moving inventory in Q4 [selling off about $5m of the $25m inventory categorized as slow-moving], which has been a focus of ours for some time," says Kiernan.

Order bookings were $110m in Q4/2019, down 4.3% on $115m last quarter, contributing to quarter-end order backlog falling from $279m to $268m.

For first-quarter 2020, Veeco expects revenue of $95–120m. "There is still a significant level of uncertainty from coronavirus-related travel, restriction and factory shutdowns in China," notes Kiernan. "Accordingly, we have widened the low end of our guidance range to accommodate this." Gross margin should be 39–41%. OpEx is expect to be cut further, to $37m. Net income should be steady, at $0–11m ($0.00–0.22 per share).

"We do expect to continue to sell off the slow moving inventory in 2020 [given order activity in this area], which may provide gross margin headwinds. However, we are still targeting 40% gross margin or better going forward," says Kiernan.

"Based on our current visibility, we see Q2 revenue trending similar to or slightly higher than Q1. This Q2 outlook does not incorporate any potential coronavirus impact, which is unknown at this time," Kiernan continues. "Additionally, we are ahead of plan with OpEx reduction and reiterate that, at current revenue level, we expect non-GAAP OpEx to decline toward our target of $36m per quarter by Q3." This compares with $49m in Q3/2017, with most of the reduction coming in sales, general & administrative (SG&A) expenditure, rather than R&D spending.

"As we enter 2020, we are focused on optimizing our product portfolio, extending our core technologies into new markets, and further increasing our profitability," says Miller. "We are positioning the company for long-term growth in the Front-end Semiconductor, Advanced Packaging and Compound Semiconductor markets by executing on our product roadmaps," he adds.

"For 2019, our priorities were to innovate, penetrate markets and improve profitability," recalls Miller. "Regarding our market penetration objective, we had mixed results. We enjoyed great success in the EUV mask blank market, with our ion beam deposition systems. We have promising traction at very advanced nodes with our laser annealing product at two semiconductor industry leaders. In advanced packaging, we are still experiencing soft market conditions for lithography products. In the photonics market, we are disappointed with weak market condition for VCSELs."

"Regarding our innovation objective, we executed very well," says Miller. "We shipped multiple ion beam deposition systems for EUV mask blank production. We optimized our MOCVD platform for photonics applications and shipped our first beta system to a premier compound semi customer. We developed a 300mm single-wafer fully automated MOCVD cluster tool and shipped, with acceptance, to a major front-end semiconductor fab. We updated our advanced packaging lithography product to improve its performance and we made major enhancements to our laser annealing product to improve our competitiveness at the next nodes."

On 4 February Veeco launched the Lumina arsenide phosphide (As/P) MOCVD platform for photonics applications. "The Lumina system [beta tool] is currently being evaluated by a leader in photonics, and we are achieving excellent feedback [for not only VCSEL stacks but also other photonics applications]… Also, we're sharing our VCSEL and micro-LED data with several of the important end-customers and they've been impressed with their results as well," says Miller. "Additionally, during the quarter [Q4/2019], we received a purchase order from a second customer… our understanding is that it's for VCSEL applications."

Veeco launches Lumina As/P MOCVD platform

TurboDisc-based system targets high-volume manufacturing of VCSELs, edge-emitting lasers and mini/micro-LEDs

Veeco has launched the Lumina metal-organic chemical vapor deposition (MOCVD) platform, which incorporates the proprietary TurboDisc reactor technology for what is said to be outstanding film uniformity, yield and device performance for a variety of photonics applications. The new MOCVD platform, including the Lumina R480 and Lumina R480S models, will accelerate the production of vertical-cavity surface-emitting laser (VCSEL), edge-emitting laser (EEL) and mini/micro-LED devices.

In response to strong consumer demand for arsenic phosphide (As/P) MOCVD technology, the Lumina platform targets a new generation of high-efficiency photonics devices including VCSELs used in 3D sensing, autonomous driving and high-speed data communication. The Lumina platform is also designed for mini- and micro-LED production for advanced displays found in next-generation 4K and 8K TVs, smartphones and wearable devices, as well as EEL devices used for optical communications and silicon photonics applications.

"Leading photonics manufacturers are currently seeing the benefits of our Lumina MOCVD system and are validating its impact in the manufacturing of high-volume photonics devices," says Gerry Blumenstock, senior VP, product line management. "With its proven design, technology and performance, Lumina provides exciting opportunities for the next generation of photonics devices," he believes.

The Lumina R480 and R480S systems are based on Veeco's MOCVD TurboDisc technology which features high uniformity and low defectivity over long campaigns for high yield and flexibility. In addition, the firm's proprietary technology drives uniform thermal control for what is claimed to be excellent thickness and compositional uniformity. Providing a seamless wafer size transition, the system is capable of depositing high-quality As/P epitaxial layers on wafers up to 6-inches in diameter. The R480 and R480S systems allow users to customize their systems for maximum value, says Veeco.

www.veeco.com

Riber grows annual revenue by 7% to another record of €33.4m in 2019, driven by 31% growth in Q4

More than doubling of MBE system revenue offsets cyclical contraction in evaporator sales for OLED displays

For fourth-quarter 2019, Riber S.A. of Bezons, France — which manufactures molecular beam epitaxy (MBE) systems as well as evaporation sources and effusion cells — has reported revenue of €12.7m, almost doubling from €6.8m last quarter and up 31% on €9.7m a year ago.

Annual revenue has grown for a fourth consecutive year, up 7% on 2018's €31.3m to a new record of €33.4m for 2019. Asia contributed 52% of revenue (rebounding from 43% in 2018), Europe 32% (falling back from 49%) and North America 16% (up from 8%).

This was despite revenue for Evaporators (cells and sources) shrinking significantly, from €11.6m in 2018 to just €1m in 2019, due to the end of the previous investment cycle for organic light-emitting diode (OLED) display production equipment in 2018.

Revenue for Services & Accessories also fell, but by just 7% from €10.1m to €9.4m, due to a billing delayed over to 2020.

In contrast, revenue for Systems more than doubled to €23m (12 systems: seven production units and five research units), up 140% on 2018's €9.6m (just six systems: three production units and three research units).

The success with MBE systems linked to 5G wireless development is offsetting the temporary lack of investment in the OLED display industry, notes Riber.

The order book shrank by just 4% from €29.9m at the end of 2018 to €28.7m at the end of 2019. This is due largely to Systems order falling by 2%, from €22.3m to €21.8m (including 12 MBE systems deliverable in 2020, of which five are production machines), while orders for Evaporators fell from €0.8m to zero. In contrast, Services & Accessories orders rose slightly, by 1%, from €6.8m to €6.9m, which also does not include the major order from Asia for the OLED screen industry (announced on 20 January).

Riber says that this offers a good level of visibility for business in 2020, supported by the positive outlook for new orders in a general environment that is favorable for the semiconductor market. Riber hence plans to grow its revenue in 2020.

www.riber.com

Sheffield Quantum Centre launched to develop computing, communication, sensing and imaging technologies

New research centre to include £2.1m Quantum Technology Capital equipment capable of growing state-of-the-art semiconductor materials

A new research center targeting computing, communication, sensing and imaging technologies has been launched by the University of Sheffield.

Officially opened by alumnus Lord Jim O'Neill (chair of Chatham House, Royal Institute of International Affairs), the Sheffield Quantum Centre is bringing together more than 70 of the university's leading scientists and engineers to develop new quantum technologies, which it is reckoned could lead to the development of more secure communications technologies and computers that can solve problems far beyond the capabilities of existing computers. The UK government has invested in quantum research as part of a national program and has committed £1bn in funding over 10 years.

Led by the University's Department of Physics and Astronomy, Department of Electronic and Electrical Engineering and Department of Computer Science, the Sheffield Quantum Centre will join a group of northern universities that are playing a significant role in the development of quantum technologies.

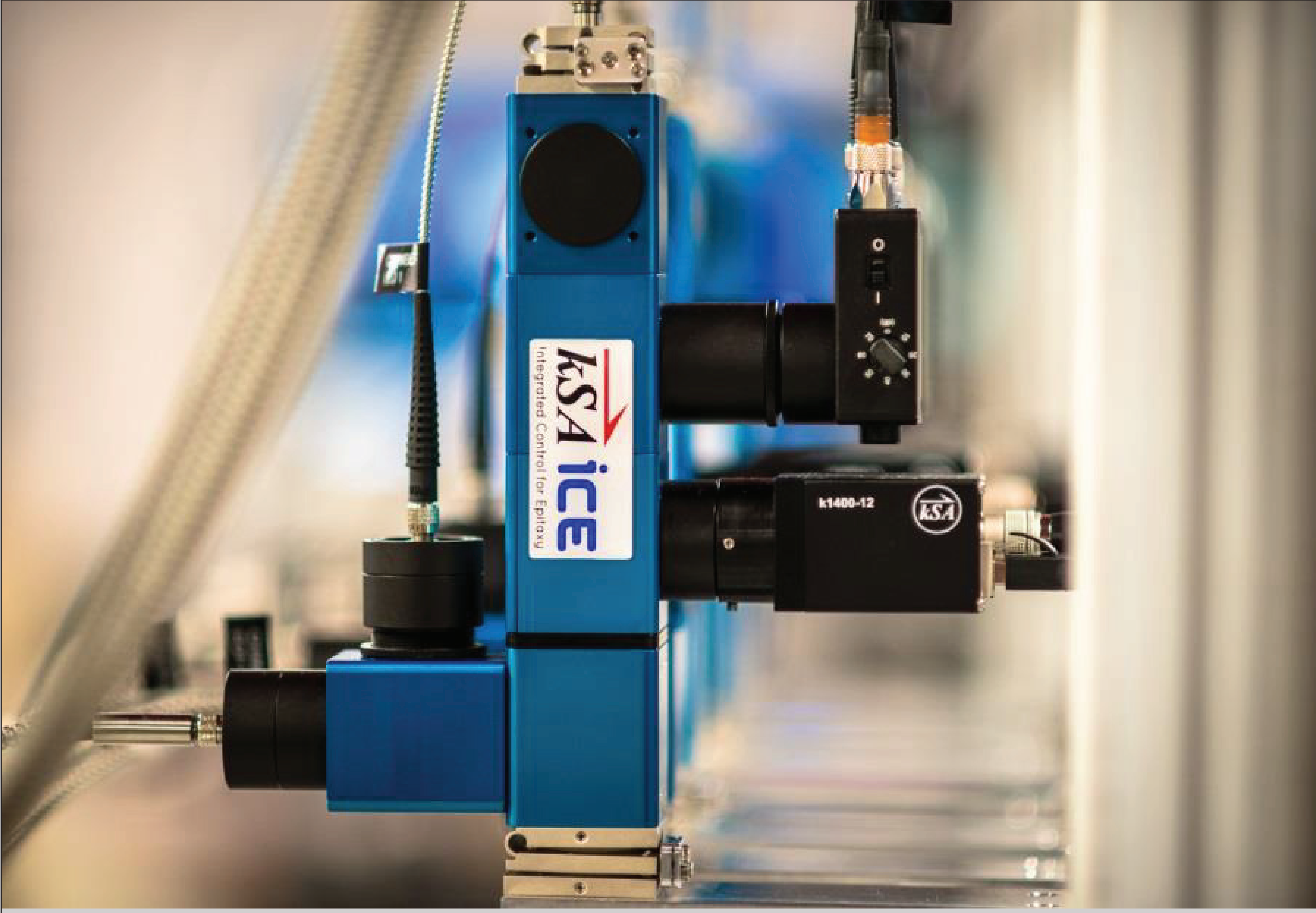
The University of Sheffield has a presence in quantum research, with capabilities in crystal growth, nanometer-scale device fabrication and device physics research. A spin-out company has already been formed to help commercialize research, with another in preparation.

"The University of Sheffield already has very considerable strengths in the highly topical area of quantum science and technology," says professor Maurice Skolnick, director of the Sheffield Quantum Centre. "I have strong expectation that the newly formed center will bring together these diverse strengths to maximise their impact, both internally and more widely across UK universities and funding bodies."

During the opening ceremony, the Sheffield Quantum Centre also launched its new £2.1m Quantum Technology Capital equipment. Funded by the UK's Engineering and Physical Sciences Research Council (EPSRC), the equipment comprises a molecular beam epitaxy (MBE) cluster tool designed to grow very high-quality semiconductor wafers. The semiconductor materials also have many new quantum applications that researchers are focused on developing.

"The University of Sheffield has a 40-year history of pioneering developments in semiconductor science and technology and is host to the National Epitaxy Facility," notes professor Jon Heffernan of the Department of Electronic and Electrical Engineering. "With the addition of this new quantum technologies equipment I am confident our new research center will lead to many new and exciting technological opportunities that can exploit the strange but powerful concepts from quantum science."

https://quantum.shef.ac.uk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Palomar moves to new global HQ, expanding to 110,000ft² of manufacturing and contract assembly labs

Photonics and microelectronic device assembly & packaging equipment maker Palomar Technologies Inc of Carlsbad, CA, USA says that, to meet growing customer demand for its solutions around the world, it has moved to a new global headquarters (at 6305 El Camino Real, Carlsbad, CA 92009) and expanded its facilities to over 110,000ft^2.

"Since acquiring SST International (renamed to SST Vacuum Reflow Systems) in 2015, our global business has rapidly developed with a new customer base, and these new facilities make it possible for Palomar to meet the growing global demand for our entire product line," says Bruce Hueners, CEO & president for Palomar Technologies and SST Vacuum Reflow Systems. "Additionally, our Innovation Center, which specializes in contract assembly and process development, has grown substantially and these new facilities will provide a top-notch laboratory, precision manufacturing, and training facilities."

Palomar has its roots in the aerospace & defense industry, with its origins as a technology division within Hughes Aircraft. Over the 40+ years of supporting the semiconductor and photonics industries, the firm has expanded beyond its traditional segments across automotive (LiDAR and power modules), medical semiconductor/biophotonics, microwave, RF/wireless, 5G, datacom, telecom, industrial and a few niche markets. Palomar says it is in the unique position to work with customers from start-up/prototype all the way to volume production, as it is a logical transition for the customer to move through Palomar Innovation Centers to purchase their own Palomar equipment line.

The new facilities complement the expansion in 2019 of the firm's contract manufacturing facilities in Singapore, as well as collaborating with the Electronics and Photonics Innovation Center (EPIC) in Paignton (Torbay) in the UK to open a demonstration/prototyping lab to serve its growing European customer base.

By moving into its new corporate headquarters, Palomar is expanding manufacturing, engineering laboratories, class ISO Class 6 & 7 (Fed STD Class 1000-10,000) cleanroom/laboratory and production laboratories, along with contract manufacturing/process development (Innovation Center) and office space. Additionally, the new building includes a dedicated training facility.

www.palomartechnologies.com

University of Sheffield spins off EpiPix to develop and commercialize micro-LED technology

Micro-display applications target smart devices, AR, VR, 3D sensing and Li-Fi communications

The UK's University of Sheffield has officially launched the spin-off firm EpiPix Ltd, which is developing and commercializing micro-LED technology for photonics applications such as micro-displays for portable smart devices, augmented reality (AR), virtual reality (VR), 3D sensing and visible light communications (VLC/Li-Fi).

Underpinned by research from professor Tao Wang and his team at the Department of Electronic and Electrical Engineering, the firm is collaborating with global corporations on next-generation micro-LED product development.

The pre-production technology has already been demonstrated for multi-colour micro-LED arrays on single wafers with high light efficiency and uniformity, the university says. EpiPix is developing robust micro-LED epitaxial wafers and product solutions for red, green and blue wavelengths with micro-LED pixel size ranging from 30μm down to 10μm, and has the company demonstrated prototypes with a diameter of less than 5μm.

EpiPix operates as a commercially driven technology center with worldwide exclusive commercial rights to all the micro-LED intellectual property that has been licensed by the company from the university.

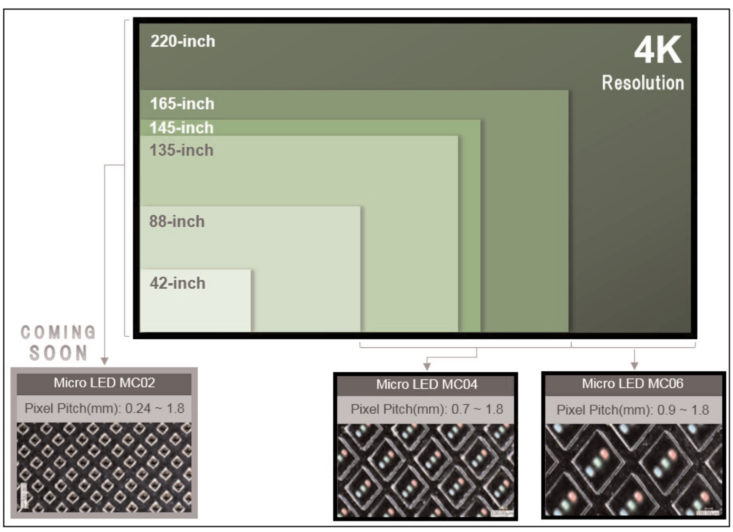
"This is an exciting opportunity, and great timing in the micro-LED markets, for turning excellent science into profitable micro-LED products," reckons EpiPix's CEO & director Dennis Camilleri. "We are already engaged with industry customers to ensure that EpiPix aligns with their short-term product requirements and future technology roadmaps," Camilleri adds.

www.sheffield.ac.uk/eee

Seoul Viosys and Seoul Semiconductor showcase single-pixel RGB 'Micro Clean LED' enabling 42–220-inch 4K-resolution TV displays

South Korean LED manufacturer Seoul Semiconductor Co Ltd and its ultraviolet (UV) LED product manufacturing subsidiary Seoul Viosys have showcased Micro Clean LED, a single-pixel RGB micro-LED technology that enables the design of 4K-resolution TVs with 42" to 220" displays. Unveiled at the Consumer Electronics Show (CES 2020) in Las Vegas in early January, the Micro Clean LEDs are now ready for mass production.

Combining technology capabilities from Seoul Viosys — epitaxial growth of red, green and blue LED chips as well as proprietary mass transfer technology for single-pixel RGB μ-level chips — and Seoul Semiconductor — optimized surface-mount technology (SMT) to increase production capacity, and tiling technology for substrate connectivity — enables the production of customized display screen sizes.



Targeting the $100bn display market, micro-LEDs are said to deliver superior color rendering and optimal off-angle viewing compared with conventional LED/LCD technology. Also, unlike with organic light-emitting diodes (OLEDs), μLEDs offer 1000x faster response time and up to a 30% reduction in internal/external power consumption, as well as infinite contrast range. In addition, display panels made with μLEDs can be combined into larger displays. This modular approach means that display manufacturers can easily customize the size of their screens.

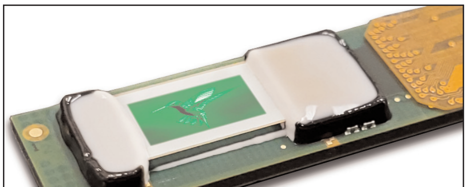
"The Micro Clean LED technology resolves several challenges in the manufacturing of μLEDs, which will bring cost reductions by combining three (RGB) LEDs in a single-pixel package, including transfer technology, consistent color mixing, and the ability to control individual color and light intensity," says Seoul Viosys' CEO Young Joo Lee.

www.seoulviosys.com

Compound Photonics and Plessey produce first 0.26-inch fully addressable integrated μLED display module for AR/MR

Compound Photonics US Corp (CP) of Vancouver, WA, USA, a provider of compact high-resolution microdisplay technologies for augmented reality (AR) and mixed reality (MR) applications, and UK-based Plessey Semiconductors Ltd, which develops embedded micro-LED technology for AR/MR display applications, have produced the first fully addressable micro-LED display modules resulting from their strategic partnership (announced last October) to develop and introduce GaN-on-silicon micro-LED-based micro-display solutions for AR/MR applications.

Functional micro-LED display modules have been fabricated that combine CP's high-speed digital low-latency display backplane with Plessey's GaN-on-Si monolithic micro-LED array technology. Plessey produced the micro-LED array wafer bonded to CP's backplane wafer at its facility in Plymouth, UK. CP assembled and packaged display modules from the bonded wafer pair at its facility in Phoenix, AZ, USA. Both teams are currently performing initial characterization work at CP's headquarters in Vancouver, WA.



First functioning micro-LED prototype

"This successful proof-of-concept demonstration validates both companies' goals to produce the industry's highest-performance micro-LED display modules that deliver improved brightness at the smallest pixel sizes, higher frame rates, with extended bit depth at the lowest power consumption to best serve next-generation emissive-display-based AR/MR smart glasses and heads-up/head-mounted displays (HUD/HMDs) applications," says Mike Lee, Plessey's president of corporate & business development.

"These prototype micro-LED displays provide important confirmation that Plessey's monolithic GaN-on-silicon IP, fabrication technology and bonding processes match perfectly with CP's industry-leading 3.015μm pixel-pitch 1080p (1920x1080 pixel) backplane design to deliver compact high-resolution micro-displays," says Compound Photonics' CEO Yiwan Wong. "Combined with CP's NOVA high-performance display driver architecture, these micro-LED displays support an industry-standard MIPI interface to take advantage of CP's unique display pipeline solution designed for the real-time needs of AR/MR applications," he adds. "CP's display drive technology is extensible across multiple display technologies enabled by full software configurability, allowing customers to build their systems for specific power and performance needs."

Initial samples of a 0.26-inch diagonal, Full-HD 1080p-resolution micro-LED display module integrated with display driver IC and MIPI input are expected to be available by this summer.

www.compoundphotonics.com
www.plesseysemiconductors.com/

Plessey and WaveOptics partner on micro-LED display technology for smart glasses

Plessey's micro-LED display and WaveOptics' waveguide technology and projector design to form AR display module

At Photonics West 2020 in San Francisco, CA, USA, Plessey of Plymouth, UK, which develops embedded micro-LED technology for augmented-reality and mixed-reality (AR/MR) display applications, has announced a partnership with WaveOptics Ltd of Milton, Abingdon, UK, a designer and manufacturer of diffractive waveguides founded in 2014.

The partnership will focus on creating a new optical module, designed specifically for the next generation of smart glasses. The module will incorporate Plessey's high-brightness micro-LED native-green full-HD display along with WaveOptics' latest waveguide technology Katana (unveiled at Photonics West) and projector design. Critically, the module aims to be the smallest and lowest-mass AR display module on the market. The full-HD micro-LED display from Plessey is the result of its partnership with Compound Photonics (announced in October) to combine Plessey's gallium nitride/silicon (GaN/Si) micro-LED display technology with Compound Photonics' digital low-latency backplane and high-performance NOVA display driver architecture.

The next generation of AR and MR systems depends on a technological leap in the performance of the optical module, says Plessey. Advances in image quality, brightness, resolution and efficient power consumption are sought to make these new AR and MR systems a compelling practical and visual experience. The collaboration between Plessey and ➤

Plessey partners with Axus to process GaN-on-Si monolithic micro-LED displays

CMP and scrubber systems enable wafer planarization and preparation for wafer-scale bonding

At Photonics West in San Francisco, (4–6 February), Plessey announced a partnership with Axus Technology of Chandler, AZ, USA (a provider of CMP, wafer thinning and wafer polishing surface-processing solutions for semiconductor, MEMS/nanofabrication and substrate applications) to bring high-performance GaN-on-silicon monolithic micro-LED technology to the mass market.

Plessey says that it continues to invest heavily in its manufacturing facility to boost its proprietary micro-LED display capabilities with the purchase of metal and oxide chemical-mechanical polishing (CMP) and associated tools from Axus to enable the wafer-scale bonding of micro-LED wafers to high-performance CMOS backplanes.

Axus' CMP and scrubber systems have been deployed to enable critical wafer planarization and preparation for wafer-scale bonding. Wafer-level bonding poses significant technical challenges and, even with the right equipment, requires extensive know-how and refined processes, notes Plessey. Shortly after installation of the systems in 2019, Plessey achieved what is claims was the first functional wafer-level-bonded GaN-on-Si monolithic 1080p 0.7" diagonal 8μm-pixel-pitch micro-LED active-matrix display.

Plessey has further optimized these systems and processes to achieve wafer-to-wafer bonding of a much smaller monochrome native-green 1080p micro-LED display 0.26" diagonal to a 3μm-pixel-pitch backplane display system engineered by Compound Photonics US Corp of Vancouver, WA, USA (a provider of compact high-resolution microdisplay technologies for AR/MR), creating over 2 million individual electrical bonds.

The formation of the Plessey/Axus partnership has led to the development of critical CMP processes for various materials key to enabling Plessey's proprietary monolithic GaN-on-Si technology.

Engineers from both firms have collaborated to accomplish these objectives at both Axus' CMP foundry in Chandler, Arizona and Plessey's semiconductor fabrication facility in the UK.

Going forward, the partnership will support scaling the technology for high-volume manufacture on the existing Axus equipment set and, in the near future, Axus' new high-flexibility/throughput Capstone CMP system (launched in late 2019).

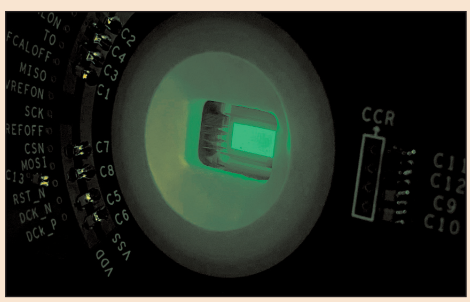
"We'll be working closely with Plessey's engineers for upgrades to their current tooling and subsequently scaling the technology on Capstone," says Axus' president Dan Trojan. "Our ever-expanding investment in our manufacturing facility in the UK is allowing Plessey to innovate rapidly and deliver leading-edge technology for AR and other display applications," adds Plessey's chief operating officer Mike Snaith.

www.axustech.com

WaveOptics aims to deliver the necessary innovation by bringing together Plessey's GaN/Si micro-LED display technology and WaveOptics new-generation waveguide technology and projector design.

The substantial reduction in size and power requirements in this module enables enhanced features such as wireless transceivers for true, untethered AR applications, which are key for technology and mobile companies looking to launch smart glasses as a mobile accessory.

"This partnership will create a new product opportunity for companies building AR wearables," says WaveOptics' CEO David Hayes. "For the first time,



customers will be able to buy the lightest, ultra-low-power module which combines the unique combination of WaveOptics and Plessey technologies. This is a crucial development to enable this technology to reach the consumer market in 2020," he adds.

"Our partnership with WaveOptics is a significant endorsement of Plessey's GaN-on-silicon micro-LED approach," states Mike Lee, Plessey's president of corporate and business development. "Our micro-LED displays are recognized as being at the forefront in delivering the high-performance display panels demanded by AR and MR devices."

AR headsets that allow the user to seamlessly transition between the bright outdoors to darker indoor environments require a display technology that can deliver both very high brightness and low power consumption for long battery life. Plessey says that its displays with WaveOptics technology can meet the challenge of this demanding requirement.

www.enhancedworld.com
www.plesseysemiconductors.com/products/microleds

Cree's quarterly revenue falls less than expected as LEDs counteract China-related trade, 5G and EV issues

CapEx for new Mohawk Valley SiC fab brought forward as power device customers accelerate plans

For fiscal second-quarter 2020 (ended 29 December 2019), Cree Inc of Durham, NC, USA has reported revenue of $239.9m, down 14% on $280.5m a year ago but only 1% on $242.8m last quarter, and at the top of the $234–240m guidance range.

LED Product revenue was $119.2m (50% of total revenue), down 18% on $145.2m (52% of total revenue) a year ago but up 4% on $115.1m (47.4% of total revenue) last quarter (amid ongoing soft market conditions and Chinese trade and tariff issues) and above the targeted range.

Revenue for Cree's Wolfspeed silicon carbide (SiC) materials, power and gallium nitride (GaN) RF device business was $120.7m (50% of total revenue), down 11% on $135.3m (48% of total revenue) a year ago and 5.5% on $127.7m (52.6% of total revenue) last quarter (and towards the far end of the guidance range of down 3–6%). The drop is due to ongoing weakness in power & RF device sales. "While we continue to see growth in our materials business, our power business continues to be impacted by softness in electric vehicle (EV) sales in China, with a sharp decline seen in the second half of calendar 2019, following the withdrawal of government EV subsidies," notes chief financial officer Neill Reynolds. "In our RF business, we are experiencing continued delays in purchasing activity, as it relates to the rollout of 5G networks," he adds.

Also, last May the US Department of Commerce added China's Huawei Technologies to its 'Entity List' prohibiting the sale to Huawei of products covered by the Export Administration Regulations (EAR) without obtaining a license. "Recently, we received notice from the US Department of Commerce that our license application to resume shipment of product to Huawei would not be granted… We will continue to comply with the ban as it relates to Huawei and do not currently expect to record any RF revenue for this customer during fiscal 2020," says Reynolds. "Considering this development and the fact that it has been eight months since the ban has gone into effect, we don't see any opportunity at this time where we will resume shipping any product we currently have on hand to the customer," he adds. "As such, we have taken an inventory reserve on Huawei-related products," notes CEO Gregg Lowe.

On a non-GAAP basis, gross margin has fallen further, from 38% a year ago and 31% last quarter to 26.8% (below the targeted 30%), although the sequential decline was almost entirely due to an impact of 350 basis points from the Huawei inventory reserve of $8.3m.

By sector, Wolfspeed gross margin fell further, from 48% a year ago and 46.3% last quarter to 34.6% (or, without the Huawei inventory reserve, 41% — at the bottom of the targeted range of 41–44%). This was also impacted by lower materials factory utilization and lower yields related to ramp-up of the new 150mm SiC MOSFET product.

LED gross margin was 22.2%, down from 30% a year ago but up from 19.2% last quarter (and above the targeted 19.5–20.5%), due mainly to improved factory utilization, lower impact from tariffs, improved product mix and ongoing cost measures.

Operating expenses were $85m (35.4% of revenue), up only slightly on $84m (34.6% of revenue) last quarter.

Compared with net income of $21.9m ($0.21 per diluted share) a year ago, net loss from continuing operations has risen from $3.6m ($0.03 per diluted share) last quarter to $10.4m. However, $8.3m of this came from a reserve on inventory related to Huawei, doubling the loss per diluted share from $0.05 to $0.10 (i.e. from above the midpoint of the targeted range to below it).

"If you adjust for the impact of the reserve, we exceeded the midpoint of the guidance for revenue, gross margin percentage and EPS," notes Lowe.

Cash generated from operations was $8.2m (down on $68.7m a year ago, but a recovery from cash outflow of –$20m last quarter). Capital expenditure (CapEx) was $61m (rising again, from $43m last quarter). Free cash outflow was hence –$53m, as Cree continues to invest for growth to expand capacity in its Wolfspeed business.

During the quarter, cash and short-term investments hence fell from $994m to $952m. The firm has zero balance on its line of credit and convertible debt with a face value of $575m.

"While we continue to navigate a challenging operating environment in the short-term, we continue to invest for the future to support several growth opportunities across multiple sectors," says Lowe. Last May, Cree started a multi-year factory optimization plan, to be anchored by an automated 200mm silicon carbide wafer fabrication facility, which in September it announced would be built in Marcy, NY (Mohawk Valley), complementing the 'mega materials' factory expansion underway at its US campus headquarters in Durham (forming a 'silicon carbide corridor' on the East Coast of the USA). "We continue to see growing momentum for silicon carbide, as demonstrated by our robust opportunity pipeline and recent customer wins," says Lowe. "We were awarded new design-ins for Wolfspeed products totaling hundreds of millions of dollars... Customers tell us that they expect to make decisions on about half of our $9bn device pipeline over the next 6–18 months. We are working hard to convert these opportunities into wins."

For fiscal third-quarter 2020 (to end March), Cree expects revenue to fall further, to $221–229m. Wolfspeed revenue should be $116–120m, flat to slightly down sequentially as the firm continues to face external headwinds, softness in 5G network spending, and lower electric vehicle sales in China. LED Products revenue is expected to be at the lower end of typical fiscal Q3 seasonality, at $105–109m (down about 10% sequentially, compared with the normal seasonal drop of 5–10% due to the Chinese New Year holiday).

These targets reflect the Chinese government's decision on 27 January to extend the Lunar New Year holiday due to the coronavirus outbreak. So, Cree's LED factory in China was due to reopen only on 10 February. The outlook does not account for any future measures taken by the Chinese government that could further delay business from returning to a normal operating schedule. Reynolds reckons that China contributes about 40% of Cree's LED Product revenue (albeit slightly less in fiscal Q3) but only 10% of Wolfspeed's revenue (which is therefore less impacted). "We do have some suppliers in China related to Wolfspeed," he notes. "As things stand today that seems to be working."

Gross margin should be about 30%. LED gross margin is targeted to be 20–21%, down slightly due to lower licensing revenue and lower volumes partially offset by improved cost execution. Wolfspeed gross margin is targeted to be 39–42% (roughly flat on fiscal Q2, excluding the effect of the Huawei inventory reserve). "We are working through temporarily lower-than-expected yields on our 150mm MOSFET product line [due to a significant scrap event in the Durham fab last quarter, since resolved]. While we saw improvements during the previous quarter, yields have not yet fully returned to expected levels," notes Reynolds. "In addition, given lower 5G demand, we have lowered our utilization in our RF business, further impacting gross margin," he adds. "We expect to return to higher levels of gross margin once the yield improvements are implemented and the volumes increase. It may however take a full manufacturing cycle to see these results in our financial statements once the improvements take hold."

For fiscal Q3, operating expenses should grow to $88m as Cree continues to invest in its Wolfspeed business, including increased investment to prepare products for production in the fab in Mohawk Valley (which it plans to ramp in 2022). Cree expects net loss to rise to $16–10m ($0.15–0.09 per diluted share, impacted by about $0.02 due to the ongoing effects of tariffs).

For full-year fiscal 2020, Cree has now increased its targeted CapEx from $200m (announced at the firm's Investor Day last November) to $230m (followed by more than $200m annually for the next couple of years after this). "Power device customers have recently indicated that their production schedules may be earlier than originally anticipated, which will require more manufacturing capacity than we have in our current plan," reports Reynolds. "Given the time required to install and qualify these tools, we have decided to invest now to ensure we have maximum flexibility in the event our customers need us to ramp our production sooner. These were tools we were planning to purchase in fiscal 2021, but have decided to invest now so we have some additional buffer for our planned ramp," he adds.

"There's no change to our overall capacity expansion plans. Our capital allocation priorities remain focused on expanding capacity in our Wolfspeed business. We're pulling CapEx in just to ensure we have enough buffer and flexibility to meet our customers' needs based on the feedback that they've given us," Reynolds explains. "As we build out the Mohawk Valley fab and we get the benefits of the incentives from that program, we're actually going to see that CapEx go down as that factory starts to ramp based on the partnership we have with the State of New York. During that period the [fiscal] 2020 and 2021 timeframe are very much investment years. That will drive some negative free cash flow in advance of those ramps."

Cree appoints Glenda Dorchak to board

Cree says that Glenda Dorchak, an experienced corporate operating executive and director, has been appointed to its board of directors.

"With deep experience as an executive in the semiconductor sector, Glenda will bring valuable insight and understanding of the market challenges and opportunities we face," says chairman Darren Jackson. "I look forward to welcoming her to the board and working closely with her as Cree continues to lead the global transition from silicon to silicon carbide."

Dorchak has served as a director of Mellanox Technologies Ltd since July 2009. Additionally, she serves as a director of Viavi Solutions Inc, ANSYS Inc, and GlobalFoundries. She also advises OMERS Private Equity and is a trustee for the San Jose Museum of Art.

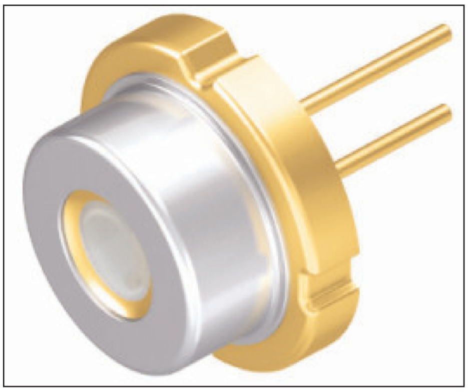
www.cree.com

Osram launches 3W blue laser for stage lighting

Osram Opto Semiconductors GmbH of Regensburg, Germany has launched a new blue high-power laser to expand the range of options available to manufacturers of show lasers and stage spotlights.

The PLPT9_450LA_E is a multi-mode laser diode mounted in a hermetically sealed TO metal can package. Lasers combine an outstanding form factor with excellent beam quality, making them particularly suitable light sources for show lasers and stage lighting, says Osram.

Offering advantages over LEDs in terms of brightness, the PLPT9_450LA_E laser diode achieves an optical power of 3W (at a typical operating current of 2A) and emits blue light with a wavelength of 447nm. In a typical optical system, the laser light is focused to a point only a few microns in diameter. The laser can be directly used as a blue light source or in combination with a special phosphor for white conversion. The achieved luminance of the white light source is around three times higher than that of a comparable LED.



Osram's new PLPT9_450LA_E high-power blue laser for stage lighting.

The PLPT9_450LA_E comes in the proven, robust TO90 package. Compared with the first TO56 generation that included three pins, the new TO90 package contains only two pins for contact. Due to the simpler cooling, the generated heat can be easily dissipated from the component. In addition, integration of the laser into the final lighting solution is much less complicated.

"The PLPT9_450LA_E completes our broad portfolio of indium gallium nitride (InGaN) lasers with a 3W version," says Christoph Walter, product manager for Visualization & Lasers. "Thanks to the easier cooling, an application range up to 85°C and an operating voltage of less than 5V, we are able to offer our customers particularly small and lightweight designs of high-quality lighting solutions for show lasers, endoscopy, professional laser torches and other numerous applications."

www.osram.com

Osram adds 65W single-channel pulsed infrared laser for short-range LiDAR in autonomous driving

Osram Opto Semiconductors has added the 65-Watt SPL DP90_3 laser to its light detection & ranging (LiDAR) photonics portfolio.

For autonomous driving to become widespread, several legal and technological hurdles must be overcome in the upcoming years, notes the firm. Nevertheless, car manufacturers and mobility service providers are already working on their visions for driverless vehicles. The need for autonomous vehicles to more comprehensively and reliably detect their surroundings makes the number and arrangement of sensors, such as LiDAR, more critical. With the SPL DP90_3, Osram Opto is expanding its portfolio with a component that has been specially developed for high-resolution, near-field detection in LiDAR systems.

Osram notes that there is now a broad consensus that only a sensor fusion of LiDAR, radar and camera systems can provide the necessary security for fully autonomous driving. Each of these technologies has advantages and disadvantages depending on the respective scenario, but overall the better they are coordinated the safer the vehicle moves through traffic. For example, LiDAR systems are strong in generating high-resolution 3D information in real time.

Long-range LiDAR is used to detect objects up to about 250m away. The immediate surroundings of the car must also be reliably captured by short- or mid-range LiDAR, which covers a distance up to about 90m from the vehicle (i.e. classic traffic situations such as passing cars on highways or driving in urban traffic).

With the SPL DP90_3, Osram is presenting a new single-channel pulsed laser that features improved beam quality and particularly compact dimensions. Due to its space-saving footprint of just 0.3mm x 0.6mm, system manufacturers can create extremely compact designs, says the firm. An efficiency of about 30% helps to reduce the overall cost of the system during operation. With an optical output of 65W at 20A, the new device is suitable for capturing the immediate vehicle surroundings, ensuring high-resolution images for subsequent systems.

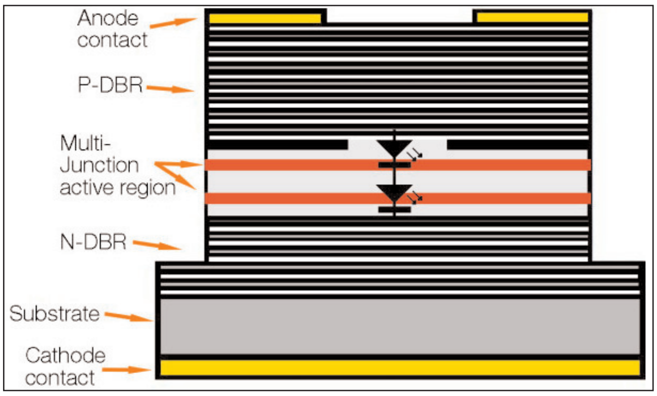
"Groundbreaking decisions are currently being made about which components will be used in which systems for autonomous driving," says Jörg Strauss, general manager & VP for Visualization & Laser at Osram Opto. "Thanks to our many years of experience in the development and production of special infrared lasers for LiDAR systems, we enjoy a high level of trust among our customers," he claims.

www.osram.com

Vixar launches multi-junction VCSELs for 3D sensing

At Photonics West 2020 in San Francisco (4–6 February), Vixar Inc of Plymouth, MN, USA (a subsidiary of Osram GmbH of Munich, Germany) launched its multi-junction vertical-cavity surface-emitting laser (VCSEL) technology with a power conversion efficiency of 60% at 940nm. Following its acquisition of Vixar in 2018, Osram has demonstrated dual- and triple-junction VCSELs that provide lower current, increased efficiency and higher speed.

The VCSEL market continues to grow rapidly due to benefits including outstanding beam quality, simple design and compact size, says Osram. VCSELs power consumer applications such as 3D cameras and facial recognition in mobile devices, as well as industrial applications like short-range light detection & ranging (LiDAR), machine vision and robotics. There is also



Structure of Vixar's new multi-junction VCSEL.

potential for use in automotive applications such as in-cabin sensing.

As the next development in VCSELs, the new multi-junction technology can be applied to products in the company's portfolio, with slope efficiencies of 2W/A in dual junction and 3W/A in triple junction. The power conversion efficiency is a record 60% — significantly higher than the comparable single-junction's 53% peak wall-plug efficiency.

Osram says that the multi-junction VCSEL offers many significant benefits. For example, greater efficiency reduces the overall thermal load. Higher power density leads to a dramatically reduced chip and package size, enabling simpler optic designs and system architecture.

The higher slope efficiency means that a much lower pulsing forward current is required to reach the same optical power as a single-junction VCSEL. The advantage is greatly reducing the current required, which improves the switching speed of the driver. This reduction of current allows the VCSEL to deliver a 1ns pulse for tens or even hundreds of watts.

www.vixarinc.com

Vixar unveils 10W VCSEL chip for 3D sensing

At Photonics West Vixar expanded its VCSEL chip portfolio by introducing a higher-power 10W 940nm-wavelength chip with greater efficiency, aimed at 3D sensing applications.

The product can allow customers to use just a single chip, instead of a subassembly incorporating multiple VCSEL chips, yielding reduced overall size and lower costs. The 10W VCSEL chip is a suitable fit for industrial applications such as mapping, automatic guided vehicles and mobile robots.

VCSELs combine the properties of two lighting technologies: high power density and simple packaging of an infrared LED (IRED) with the spectral width and speed of a laser. Also, unlike Fabry-Perot laser diodes, the VCSEL's spectral shift with temperature is four times less, making it more compatible with the filters used in 3D cameras.

Because of their advantages — including superior beam quality, excellent focusing and a very small footprint — VCSELs are quickly finding their way into consumer applications such as 3D cameras and facial recognition for mobile devices, as well as proximity sensors to detect the presence of nearby objects. The technology can also enable gesture recognition in gaming systems and greater situational awareness for augmented reality and virtual reality systems.

"Customers want a chip that is perfectly matched to their power requirements, without having to use multiple chips in a single application," says Vixar's co-founder & CEO Mary Hibbs-Brenner. "Our new 10W VCSEL maintains power efficiency in a compact package, so customers don't have to worry about compromised performance or too high thermal loads. They can now build powerful, streamlined and cost-effective applications with a single VCSEL chip."

The 10W chip comes in a compact size of 1.94mm x 1.94mm and offers low thermal impedance. It also features a pad layout for a low-inductance driving design and has a wall-plug efficiency of up to 40% at 60°C, despite the chip's compact size and high operating temperature. In addition, the chip operates at up to 10 times the optimum power, which increases the distance measured.

The 940nm chip is available immediately, and an 850nm version will be available later this year.

FBH exhibits diode lasers & modules at Photonics West

At Photonics West 2020 in San Francisco, CA, USA (4–6 February), Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) of Berlin, Germany and its spin-off companies presented their developments and advances in diode lasers and UV light-emitting diodes (LEDs), for applications including materials processing, light detection & ranging (LiDAR), medicine and Raman spectroscopy.

Specifically, at the German Pavilion, the institute showcased its full range of capabilities, from design through chips to modules and prototype systems. The spin-off BeamXpert demonstrated its software, enabling real-time simulation of laser radiation in optical systems.

In addition to its established diode-laser-based light sources, FBH exhibited a terahertz camera sensor that operates over a broad frequency range of 500–2500GHz. Offering high sensitivity of NEP <50pW/Hz0.5 along with a fast response time, it is suitable for imaging systems used for quality control in industrial applications. It can also be integrated into medical equipment, e.g. for diabetes diagnostics and spectroscopy.

Further exhibits included:

High-power diode laser stacks for high-duty-cycle operation

In industrial laser technology continuous-wave (CW) high-power diode lasers are used as pump sources for fiber and disk lasers, where they have conquered the multi-billion-dollar market of cutting and welding. There are also many existing and emerging applications in industry and basic research for high-energy-class pulsed lasers, which need customized pump sources. To address such high-pulse-energy applications, FBH combines efficient large-aperture (1200μm) single-emitter diode lasers into novel passively side-cooled multi-kW-class stacks, to support high-duty-cycle quasi-CW pump applications. Available sources include >3kW stacks emitting at a frequency of 940nm for pumping Yb:YAG (1ms, 200Hz) lasers and, in a first demonstration at Photonics West 2020 (LASE - Conference 11262, Session 1), >1kW stacks at 780nm for pumping Th:YAG (10ms 10Hz) lasers.

Next-generation LiDAR laser source for line scanners

FBH's high-pulse-power laser source with a 48-emitter diode laser bar is suitable for 3D object detection, e.g. for line scanners in automotive LiDAR. Scanning LiDARs emit rapid laser pulses which are reflected by objects. The return time of each pulse is then measured by a detector, creating a point cloud of the measured surface. Unlike point scanners, which capture objects point by point via 2D steering mirrors, line scanners use a laser array. Scanning points are thus measured over a wide line covering a large area via 1D laser beam steering and the detection of returning laser pulses in a detector row. FBH's laser source delivers 4–10ns-long optical pulses with >600W pulse peak power at 905nm. The wavelength shifts with temperature by only 0.06nm/K. The DBR-stabilized laser emission has a width of 0.15nm and >30dB side-mode suppression. The bar is electrically driven by a new in-house-developed high-speed gallium nitride driver providing current pulses of up to 800A with a repetition frequency of 100kHz and higher.

Compact dual-wavelength laser turnkey system for SERDS

Shifted excitation Raman difference spectroscopy (SERDS) is a powerful and easy-to-use tool to extract Raman signals efficiently and rapidly from disturbing backgrounds such as fluorescence and daylight. Based on its dual-wavelength Y-branch DBR-RW lasers, FBH has developed a compact turnkey system that is a fully operational light source with integrated temperature control and five individual current sources to tailor and adjust the emission. It is programmable using a USB interface. The system offers fast alternating operation between both laser lines for SERDS to extract Raman signals efficiently from disturbing backgrounds. The spectral distance between the two SERDS wavelengths can be electrically adjusted using implemented on-chip micro-heaters. The system has been demonstrated for wavelengths around 785nm and 671nm and successfully utilized for measurements on food, soil and plants.

At Photonics West, FBH also contributed 20 scientific presentations at the accompanying conferences. In particular, progress in UV LEDs was presented jointly with spin-off UVphotonics.

www.fbh-berlin.com

Emcore completes sale & leaseback of Concord facility, generating $12.8m

Emcore Corp of Alhambra, CA, USA — which provides mixed-signal products for the aerospace & defense and broadband communications markets — says it has completed the sale and leaseback transaction of its property in Concord, CA (announced on 6 January), generating $12.8m in net proceeds.

The Concord facility (which is AS9100 aerospace quality certified) manufactures quartz MEMS navigation products (gyroscopes and accelerometers), and was acquired when Emcore bought Systron Donner Inertial (SDI) last June.

www.emcore.com

BluGlass presents paper at Photonics West on manufacturing high-performance lasers using RPCVD

Dr Josh Brown, head of epitaxy at BluGlass Ltd of Silverwater, Sydney, Australia — which was spun off from the III-nitride department of Macquarie University in 2005 and develops remote-plasma chemical vapor deposition (RPCVD) technology for the manufacture of high-performance semiconductor devices — presented 'High brightness MOCVD-grown laser diodes using RPCVD tunnel junctions' (paper 11262-26) at the Photonics West 2020 conference on 3 February in San Francisco

In October, BluGlass launched a new direct-to-market business unit (managed by VP of business development Brad Siskavich in the firm's US office) to leverage the advantages of RPCVD tunnel junctions for GaN laser diode applications.

"The potential to apply what we've learned with LED tunnel junctions has been validated by a university partner, modelling our design for RPCVD epitaxial growth techniques," says Siskavich. "This collaboration has also stress-tested some of the assumptions and some of the results of our own lab work in Sydney," he adds.

"We continue that work... At the same time, we will start manufacturing laser diodes using existing MOCVD techniques later this calendar year, using the expertise we have developed over the past decade, and we will continue to research how tunnel junctions grown using RPCVD can be deployed in the future in laser diode manufacture," continues Siskavich.

"BluGlass is also building the downstream supply chain that will allow us to launch our new test facility in the US later this year. Together, these operations form the core of a customizable, end-to-end market approach that will enable BluGlass to generate growing revenues in the high-value laser diode market," he believes.

BluGlass says its RPCVD process has already delivered breakthroughs in the growth of tunnel junctions for high-performance LEDs, and that these also apply to lasers. RPCVD tunnel junctions can hence enable a novel way of growing laser diodes, addressing optical losses and resistive losses in particular.

www.bluglass.com.au/laser-diodes
http://spie.org/photonics-west.xml

II–VI showcases portfolio of product and technology

At Photonics West 2020 and at BiOS Expo (part of Photonics West) in San Francisco (1–6 February), engineered materials and optoelectronic component maker II–VI Inc of Saxonburg, PA, USA exhibited products and capabilities for diverse markets, including communications, materials processing, life sciences, automotive and consumer electronics:

- *High-speed datacom VCSELs on 150mm GaAs technology platform*: II–VI's high-speed vertical-cavity surface-emitting lasers (VCSELs) developed for data-center transceivers are now available on its scalable 150mm gallium arsenide platform to meet expected high-volume demand for optical HDMI cables.
- *Water-cooled aluminium variable radius mirror (VRM) for 20kW lasers*: II–VI's new VRM is water-cooled to enable laser processing heads to achieve a power rating of 20kW and above. The VRM is made of aluminium, which is 80% lighter than comparable copper and stainless-steel solutions. VRMs enable laser processing heads to precisely maintain the focal point of the laser beam on the workpiece by adjusting the mirror's radius of curvature.

Also, participating in the Lasers & Photonics Marketplace Seminar were the following II–VI representatives.

- Dr Giovanni Barbarossa, chief strategy officer, II–VI Inc, and president, Compound Semiconductors, in the Executive Panel 'The Global Photonics Marketplace–Key Trends, Markets, and Technologies';
- Dr Karlheinz Gulden, VP, Laser Devices & Systems business unit in the Sensors and Sensing Panel 'VCSELs vs Edge-Emitters and the Race for New Applications'.

II–VI also participated in a special presentation hosted by the University of Arizona's Wyant College of Optical Sciences:

- Dr Julie Sheridan Eng, senior VP & general manager, Optoelectronic and RF Devices business unit, in Influencing the Future '3D Sensing Market and Technology'.

Conference papers presented by II-VI included:

- Polarization-Stable 940nm VCSELs for Sparing (Invited Paper) — by Petter Westbergh, Sonia Quadery, Haiquan Yang, Hao Chen, Frank Flens, Richard Chan and Tsurugi Sudo of II–VI and Dan Kuchta of IBM Thomas J. Watson Research Center;
- OPTO 2020 – Vertical-Cavity Surface-Emitting Lasers XXIV — Session 3: 'High-Speed VCSELs', Commercial Paper 11300-11;
- Directly Modulated Lasers for 100 Gbaud Nyquist PAM4 Transmission (Invited Paper) — by Yasuhiro Matsui, Roberto Rhode, Ferdous Khan, Martin Kwakernaaka and Tsurugi Sudo of II–VI, Di Che, Sethumadhavan Chandrasekhar, Junho Cho, Xi Chen and Peter Winzer of Nokia Bell Labs in the USA, and Ricard Schatz of KTH Royal Institute of Technology in Sweden.
- OPTO 2020 – Novel In-Plane Semiconductor Lasers XIX — Session 6 'Datacom and Telecom', Paper 11301-25.

http://spie.org/photonics-west.xml
www.ii-vi.com

POET completes Optical Interposer development project

POET Technologies Inc of Toronto, Ontario, Canada and San Jose, CA, USA — a designer and manufacturer of optoelectronic devices, including light sources, passive waveguides and photonic integrated circuits (PIC) for the sensing and datacom markets — has announced updates related to recent developments across the company.

In January, POET completed its proof-of-concept project with its existing North American-based networking customer. As previously announced, POET received orders from them in 2018 to provide initial device prototypes of its Optical Interposer platform to systematically address specific integration requirements under a paid development program. At its Annual General Meeting in September, POET disclosed that it had completed all but one of an eight-step project and that it expected to complete the final milestone by the end of 2019. It recently completed this final deliverable and is now engaged in follow-on discussions aimed at products to be designed, qualified and incorporated into the customer's product portfolio.

"The low-loss coupling of light from a laser into our waveguides (which are additionally configurable as coarse wavelength division multiplexing (CWDM) multiplexers or de-multiplexers) through passive wafer-scale placement techniques and then into fiber demonstrates the complete functionality of the Optical Interposer platform technology," says chairman & CEO Dr Suresh Venkatesan. "Moreover, we believe our wafer-scale integrated athermal CWDM filters represent an industry first," he adds. "With optical losses at a fraction of that of other materials, our waveguides and filters enable the fabrication, assembly and testing of integrated optical engines at wafer-scale, providing maximum flexibility across a broad range of applications, from datacom to co-packaged optics."

Additionally, the firm provided an update regarding the remaining payments related to the sale of its Singapore-based subsidiary DenseLight Semiconductors Pte Ltd to DenseLight Semiconductor Technology (Shanghai) Ltd (DL Shanghai, a special-purpose company organized by China Prosper Group on behalf of a consortium of investors). POET negotiated a delay in the payment schedule from the buyer, due in part to an unrelated third party expressing interest in acquiring DenseLight in late December. Payment of Tranche 1 (which occurred in November) transferred a 30% interest in DenseLight to the buyer, with the remaining 70% going into escrow. Over the past several weeks, POET negotiated with the buyer to split Tranche 2 into two parts, with 2a due at the end of January and 2b due at the end of February. The Tranche 2a payment of US$4.75m will initiate the transfer of an additional 19% of DenseLight shares from escrow to the buyer (bringing the total to 49%), while the 2b payment of US$8.25m will transfer an additional 32% (for a total of 81%). The final Tranche 3 payment of US$5m for the remaining 19% is due at the end of May. The unrelated third party continues to be in confidential discussions with all parties to participate in the current transaction.

Responding to the coronavirus outbreak, the government of the People's Republic of China extended the Lunar New Year holiday to 2 February (9 February in Shanghai) resulting in the closure of all government offices. Once reopened and final approval is received for the overseas direct investment (ODI) applications previously underway, POET expected immediate disbursement of the 2a payment. Receipt of the 2b payment is expected to be delayed beyond February due to the extended holiday's disruption of the ODI application process.

Furthermore, the firm announced the appointments of James Lee as VP & general manager of POET Technologies Pte Ltd (the firm's recently opened Singapore-based subsidiary) and Edward Cornejo as VP of technical marketing. Lee came to POET from IMEC of Leuven, Belgium, where he was VP of logic technology. Previously, he held increasingly responsible positions over 19 years with GLOBALFOUNDRIES. Cornejo has over 30 years of experience in the optical components industry in senior marketing and engineering roles at Lucent, OpNext (now Lumentum), and MACOM.

POET is hosting analysts and strategic partners in conjunction with the Optical Fiber Communications (OFC 2020) Conference & Exhibition in San Diego, CA, USA (8–12 March).

www.poet-technologies.com

POET receives Tranche 2a payment of $4.75m from DenseLight buyer

POET says that, despite the recent business interruptions in China resulting from the COVID-19 virus, it has received the scheduled Tranche 2a payment of US$4.75m from the buyer of its Singapore-based subsidiary DenseLight Semiconductors Pte Ltd. POET has hence initiated the transfer of an additional 19% of DenseLight shares from escrow to the buyer (bringing the total to 49%).

It also confirmed that the Tranche 2b payment of US$8.25m, which will transfer an additional 32% of shares (making a total of 81%) is on track to be paid by the end of March.

Additionally, POET has announced the planned opening on 1 April of an office and lab in Allentown, PA, USA. Concurrently, it has taken the required actions to close its office in San Jose, CA.

CEA-Leti unveils silicon nitride 200mm platform for developing ultralow-loss, high-power photonics in UV through mid-IR wavelengths

Multi-project-wafer program targets designers in integrated quantum optics, LiDAR, biosensing and imaging

At Photonics West 2020 in San Francisco (4–6 February), micro/nanotechnology R&D center CEA-Leti of Grenoble, France unveiled a silicon nitride (Si_3N_4) 200mm platform for developing ultralow-loss, high-power photonics in ultraviolet (UV) through mid-infrared wavelengths (‘Ultralow-loss tightly confining Si_3N_4 waveguides and high-Q micro-resonators’, Optics Express, vol 27 (2019), issue 21, p30726). Available in CEA-Leti’s SiN platform in a multi-project-wafer program, the breakthrough targets designers in integrated quantum optics, LiDAR (light detection and ranging), biosensing and imaging whose projects require ultralow propagation losses and high power handling capability.

The ultralow-loss SiN layer is available for multi-level photonic circuits. It can be combined with a heater layer and a silicon layer in a unique platform to integrate passive and active components, such as Mach–Zehnder interferometers (MZI), multi-mode interferometers (MMI), ring resonators, filters, arbitrary waveform generators (AWG), modulators and photodiodes. This ultralow-loss layer can also present a local opening for biosensing applications.

“Companies requiring III–V/SiN laser co-integration or working on integrated quantum photonics for communication and computing applications can use this unique capability to combine those ultralow-loss properties with high-thickness SiN in a CMOS-compatible photonics platform,” states business developer Eléonore Hardy.

The ultra-low-loss silicon nitride layer is available for multi-level photonic circuits

“This breakthrough process will contribute to the Quantum 2.0 revolution and will lead to photonic devices that actively create, manipulate and read out quantum states for the emergence of quantum computing, imaging, sensing, communication and clocks,” she believes.

The best-in-class performance obtained with an 800nm-thick SiN layer includes a 2x reduction in propagation loss, with average attenuation coefficients as low as 3dB/m for high-confinement 1.6μm-wide, 800nm-high strip waveguides across the S-, C- and L-optical-wavelength bands. CEA-Leti also improved aging in the photonics devices and produced high-Q photonic micro-resonators with intrinsic quality factors approaching 10^7 across the C-band and reduced feature size.

Deposition of SiN uses CEA-Leti’s high-quality twist-and-grow, low-pressure chemical vapor deposition (LPCVD) technique that deposits relatively thick, pure and stoichiometric SiN with good thickness uniformity, unlike standard chemical vapor deposition techniques, it is claimed. Furthermore, a multi-step chemical-physical annealing smoothed the sidewall roughness of SiN waveguides, which further decreased propagation losses.

www.osapublishing.org/oe/abstract.cfm?uri=oe-27-21-30726
http://spie.org/photonics-west.xml
www.leti.fr

Keysight, NOEIC and CompoundTek establish open standards for layout, design & automation of PIC testing

Keysight Technologies Inc of Santa Rosa, CA, USA, the National Information Optoelectronics Innovation Center (NOIEC) in Wuhan China Optics Valley and Singapore-based silicon photonic (SiPh) foundry services provider CompoundTek Pte Ltd are to work together to establish layout design standards for the automated testing of photonic integrated circuits (PICs).

PICs offer advantages over their discrete components and bulk optics counterparts including significant footprint reduction, improved stability and lower energy consumption. Ubiquitous in telecom networks solutions, PICs are attracting increasing attention in new applications like sensing, bio-medical, cryptography and quantum computing. As the range of applications widens, a high level of standardization and automation becomes essential to ensure the scalability, process monitoring and yield required for volume production.

Keysight, NOEIC and CompoundTek are collaborating to establish a globally recognized standardized approach to PIC layout, enabling access to automated testing, generic assembly and packaging services for scaling to volume production. The goal is to interface with PIC designers who define the test protocols during the design stage and with the test facilities that will enable automation and define measurement procedures and their parameters.

The consortium will work together to standardize PIC layout conventions and design rules for edge-coupled circuits, which include, but are not limited to, die orientation, location of I/O ports, placement of DC pads, fiducials and indication of restricted areas important for automated testing, assembly and packaging. Adopting and deploying a proven integrated solution, featuring Keysight's Photonic Suite on a fully automated probe station with speed optimized test executive algorithm, facilitates high-throughput testing. It also enables design-for-test (DFT) and first-design-right (FDR) techniques to reduce overall costs associated with the test. Keysight's Photonic Suite consists of the firm's PathWave and Photonic Application solutions.

https://compoundtek.com
www.noeic.com
www.keysight.com/gb/en/products/software.html

NeoPhotonics samples high-power SOAs and narrow-linewidth lasers for coherent LiDAR transceivers

NeoPhotonics Corp of San Jose, CA, USA (a vertically integrated designer and manufacturer of hybrid photonic integrated optoelectronic modules and subsystems for high-speed communications) is sampling high-power semiconductor optical amplifiers (SOAs) and narrow-linewidth (NLW) distributed feedback (DFB) lasers for long-range automotive LiDAR (light detection and ranging) applications.

Operating in eye-safe wavelength regions, the new devices include 1550nm-wavelength SOAs with >24dBm (>250mW) output power along with 1550nm NLW-DFB lasers that enable automotive LiDAR systems to 'see' considerably further than 200m, significantly enhancing safety.

Existing LiDAR systems for autonomous vehicles (AVs) use expensive discrete optical components and employ direct detection measurement of the reflected light intensity, which limits range and sensitivity. Next-generation LiDAR systems will use coherent technology, which was pioneered by NeoPhotonics for communications networks, to greatly increase the range and sensitivity by measuring the phase of the reflected light. Coherent LiDAR systems are fabricated using chip-scale manufacturing to reduce costs and enable high volume.

Chip-scale manufacturing requires coherent photonic integrated circuits (PICs) powered by low phase- and intensity-noise semiconductor lasers and high-output-power SOAs. Narrow-linewidth and low-phase-noise lasers enable the precise phase measurements required by coherent detection and optical amplifiers to boost the optical signal power for long-reach detection. When combined with coherent PIC receivers, a high-power SOA and NLW-DFB laser enable coherent LiDAR transceivers for high-volume manufacturing.

"Our laser components are key elements for chip-scale LiDAR systems that can be manufactured in high volumes," says chairman & CEO Tim Jenks. "LiDAR architectures based on coherent technologies have the advantage of leveraging high-volume, chip-scale technologies developed by NeoPhotonics for telecommunications and data-center interconnect applications," he adds. "Laser components are manufactured in our internal fabs and utilize our advanced hybrid photonic integration technology for high performance and high reliability, allowing system integrators to quickly leverage coherent technology and its established manufacturing supply-chain for LiDAR applications."

www.neophotonics.com

VPIphotonics and Infinera cooperate to streamline design process for indium phosphide PICs

Designers using InP open foundry services to increase productivity with new design workflow

Infinera Corp of Sunnyvale, CA, USA, a vertically integrated manufacturer of digital optical network systems incorporating its own indium phosphide (InP)-based photonic integrated circuits (PICs), says that designers that want to use its InP open foundry services, part of the Infinera Optical Innovation Center, will now benefit from a new design workflow that starts from a graphical PIC design and system simulation environment. This workflow is enabled by the new VPItoolkit PDK Infinera — a pluggable toolkit extension to VPIcomponentMaker Photonic Circuits by adding the support of the process design kit (PDK) building blocks for the InP-based PIC foundry process offered by Infinera.

Simulation software provider VPIphotonics GmbH of Berlin, Germany and Infinera collaborated to develop compact models for the PDK building blocks based on the characterization data of the individual devices and the test measurements of fabricated chips. The foundry capability was developed in collaboration with the consortium AIM Photonics (American Institute for Manufacturing Integrated Photonics, an industry-driven public-private partnership advancing the USA's photonics manufacturing capabilities) and the US Department of Defense. This ensures that each building block is represented by an adequate simulation model with only a few parameters to control. A designer can rapidly prototype application-specific PICs with prerequisite functionality without going deep into the details of device layout and fabrication process. Once the design is completed and optimized, the schematic can be exported to a netlist and passed to Infinera's InP foundry for physical layout implementation, verification and fabrication.

All the building blocks available in VPItoolkit PDK Infinera can be used alongside a broad set of standard modules and instrumentation available in VPIphotonics Design Suite, especially VPIcomponentMaker Photonic Circuits (circuit-level design and analysis) and VPItransmissionMaker Optical Systems (system-level evaluation). Hierarchical circuit designs and advanced parameter scripting, sweep and optimization of parameters, sensitivity and yield analysis as well as systems benchmarking and characterization are supported transparently for designers, helping to increase their productivity.

Infinera says that, given its experience with manufacturing high-performance PICs, the foundry PDK offers fully optimized devices to ensure optimal performance and yield within the foundry's integration platform (G. E. Hoefler et al., 'Foundry Development of System-On-Chip InP-Based Photonic Integrated Circuits', IEEE Journal of Selected Topics in Quantum Electronics, vol.25, no.5, p1–17, Sept–Oct. 2019, Art no. 6100317). The capability of embedding these building blocks into the VPIphotonics software framework enables the simulation and modeling of complex photonic integrated circuits with a high degree of reliability, adds the firm.

www.infinera.com
www.vpiphotonics.com

Patterned sapphire silica substrate for ultraviolet LEDs

Researchers improve aluminium gallium nitride crystal quality and light extraction efficiency to boost output power.

Researchers based in China and the USA have used a patterned combination of sapphire substrate and silica (SiO_2) layer to improve the performance of ultraviolet light-emitting diodes (UVLEDs) [Hongpo Hu et al, Nano Energy, vol69, p104427, 2020]. The enhanced light output was due to a combination of improved crystal quality of the III–nitride light-emitting material and a boost in light extraction efficiency (LEE) from reducing internal reflection and absorption of the generated photons.

The team from Wuhan University, HC SemiTek Corp, University of Science and Technology of China, Huazhong University of Science and Technology in China and University of Michigan in the USA see the technology as having potential for increasing the performance of LED-based solid-state UV light sources for curing, water purification, sterilization and phototherapy.

The researchers used three types of sapphire substrate: flat (FSS), patterned (PSS) and patterned with silica array (PSSA). The pointed cones of the PSS were created using thermal reflow of patterned photoresist and inductively coupled etching. With the PSSA the pointed cones were etched into a 2μm plasma-enhanced chemical vapor deposition (PECVD) silica layer. The etch was continued down into the sapphire substrate.

Contact	p^+-GaN	5nm
Contact	p-GaN	35nm
Electron blocking superlattice	4x(p-$Al_{0.2}Ga_{0.8}N$/GaN)	
	p-$Al_{0.2}Ga_{0.8}N$	20nm
Quantum barrier	$Al_{0.1}Ga_{0.9}N$	13nm
Multiple quantum well	8x($In_{0.05}Ga_{0.95}N$/ $Al_{0.07}Ga_{0.93}N$)	8x(1.6nm/ 6.5nm)
Superlattice	12x($In_{0.02}Al_{0.03}Ga_{0.95}N$/ $Al_{0.05}Ga_{0.95}N$)	12x(3nm/ 3nm)
	$Al_{0.05}Ga_{0.95}N$	15nm
Superlattice	6x($In_{0.01}Al_{0.03}Ga_{0.96}N$/ $Al_{0.05}Ga_{0.95}N$)	6x(3nm/ 3nm)
	n-$Al_{0.05}Ga_{0.95}N$	78nm
	n^--$Al_{0.065}Ga_{0.935}N$	170nm
	n-$Al_{0.16}Ga_{0.84}N$	30nm
	n^+-$Al_{0.065}Ga_{0.935}N$	2.5μm
	n-$Al_{0.12}Ga_{0.88}N$	100nm
Buffer	undoped-$Al_{0.05}Ga_{0.95}N$	4.5μm
Nucleation	AlN	20nm
Substrate	FSS/PSS/PSSA	

Figure 1. UVLED epitaxial structure.

The effect of the patterned sapphire was to redirect dislocations in aluminium gallium nitride (AlGaN) growth, bending their path so that they annihilate rather than threading through the indium gallium nitride (InGaN) light-emitting active layers. Such dislocations become centers for electron-hole recombination without the emission of UV photons, sapping efficiency.

The patterned sapphire technique is not as effective in AlGaN, compared with GaN-based devices. This is related to the stronger sticking of Al, compared with Ga, in the growth process. This generates misoriented crystal growth. One effect of the silica array layer is to reduce misoriented crystal regions.

The nucleation for III–N deposition consisted of 20nm sputtered AlN. Further growth was by metal-organic chemical vapor deposition (MOCVD) with trimethyl-metal and ammonia precursors. The n- and p-type doping were via silane (SiH_4) and bis(cyclopentadienyl)magnesium (Cp2Mg), respectively. Hydrogen and nitrogen were used as carrier gases.

The final epitaxial structure (Figure 1) was completed with a 720°, 20 minute thermal anneal to activate the Mg doping.

The material was fabricated into LEDs with a 1.25μm mesa etch to expose the n-AlGaN contact layer. The p-GaN contact layer was covered with an annealed indium tin oxide (ITO) transparent conductor current-spreading layer. Chromium/platinum/gold were evaporated to create both the n- and p-electrodes of the diode structure. The wafer was thinned to 120μm by grinding and polishing. The 254μmx685μm chips were then singulated.

The threading dislocation density (TDD) was assessed using x-ray diffraction (XRD) and scanning transmis-

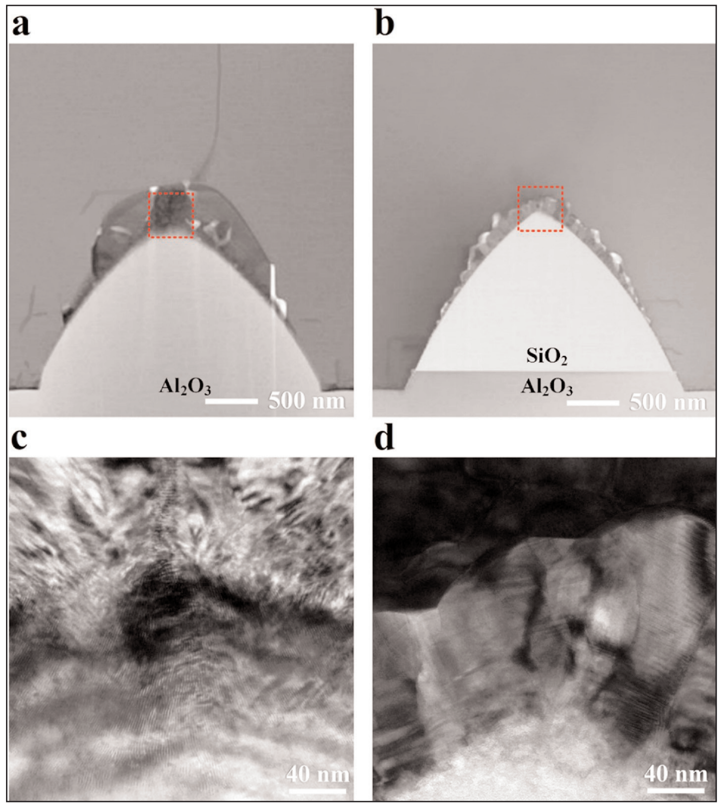


Figure 2. Cross-sectional STEM images of AlGaN grown (a) on PSS and (b) PSSA. (c) Enlarged STEM images of the marked areas in (a) and (d) that in (b).

sion electron microscopy (STEM). The TDD in III–N material grown on flat sapphire is typically of the order of $10^{10}/cm^2$. The estimate from the STEM analysis gave values for the PSS and PSSA samples of $5.63x10^8/cm^2$ and $2.80x10^8/cm^2$, respectively. These results were consistent with the less reliable XRD data.

The STEM studies also suggested that the dislocations formed at the sapphire interface became bent and terminated at the cones (Figure 2). The PSSA further reduced the upward propagation of dislocations. The PSSA sample also suffered less from parasitic crystal formation on the cones. The researchers comment: "The AlGaN epilayer grown on PSSA had a lower TDD than that grown on PSS by taking advantages of the more preferred vertical growth in the 3D growth stage and reduced misfit at the coalescence boundary."

Under photoluminescence the peak wavelength was 368nm. Electroluminescence from the FSS, PSS and PSSA UVLEDs resulted in light output powers of 68.3, 153.8 and 193.9mW, respectively, at 150mA injection (Figure 2). The researchers attribute the enhanced performance of the PSSA device to "improved crystal quality and higher LEE". The corresponding peak external quantum efficiencies were 23.1%, 44.9% and 50.4%. The researchers claim the 50.4% is "better than those reported in previous publications". The current–voltage performance of the devices was similar.

The LEE factor in the improved performance was explored using numerical simulations of the light reflection at interfaces. With the FSS substrate the flat interface tends to reflect most of the light back into the diode due to the refractive index contrasts, drastically reducing light extraction. Reflectivity measurements suggested improved reflectivity and transmittance at 368nm over FSS diodes of 10.2% for PSS devices and 15.8% for PSSA. ■

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Author: Mike Cooke

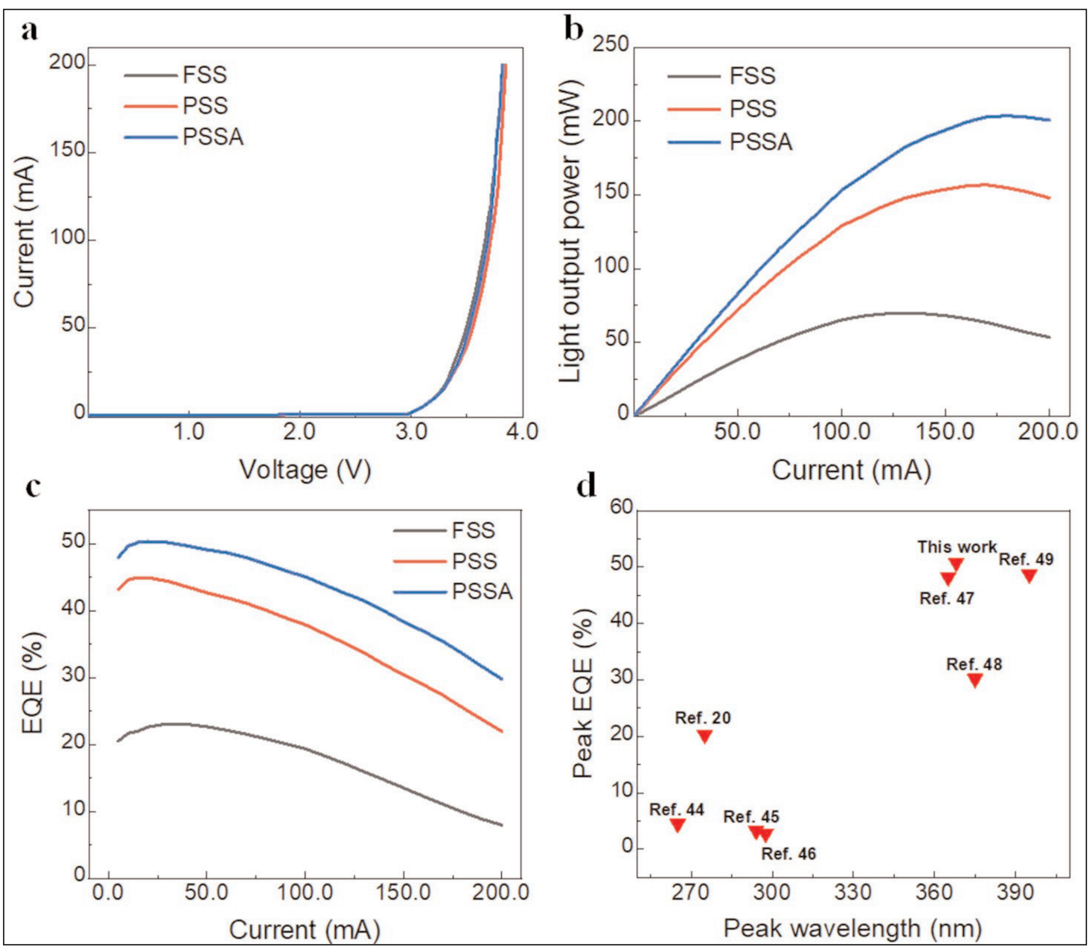

Figure 3. (a) I–V and (b) L–I characteristics of UVLEDs grown on FSS, PSS and PSSA. (c) EQEs of UVLEDs grown on FSS, PSS and PSSA versus current curves. (d) State-of-the-art in EQE for UVLEDs.

Enhancing AlGaN hole injection with germanium-doped tunnel junctions

Light output power increased between 3 and 6 times over reference aluminium gallium nitride diode.

Université Côte d'Azur and MINATEC Campus in France have used germanium (Ge) doping to improve current injection into aluminium gallium nitride (AlGaN) ultraviolet (UV) light-emitting diodes [V. Fan Arcara, J. Appl. Phys., vol126, p224503, 2019].

The Ge-doped layers were used to create the n-type side of tunnel junctions (TJs) to supply the holes for injection and recombination with electrons in quantum well (QW) light-emitting active regions. Ge doping has attracted increasing interest, compared with the more established silicon (Si).

The team comments: "Claims in favor of Ge-doping are their similar size to Ga atoms (introducing less stress in the structure than Si at high doping levels, also being compressive instead of tensile, which is the case for the latter) and the shallow behavior of its donors in GaN."

A further advantage is that, in molecular-beam epitaxy (MBE), silicon tends to react with the ammonia (NH_3) used as the nitrogen source, limiting its doping effectiveness. Ge is less prone to such reactions.

III-nitride semiconductors like AlGaN suffer from poor p-type performance since the magnesium (Mg) dopant used has a high activation energy, which increases with higher aluminium content. Even Mg-doped GaN has a poor p-type conductivity relative to many other semiconductor systems.

The AlGaN range of semiconductors have potential for UV wavelength light emission from 365nm (GaN) to 200nm (AlN). Mixed with indium (In), InGaN semiconductors are used in the visible light range (380–740nm).

The researchers used metal-organic chemical vapor deposition (MOCVD) on 2-inch sapphire up to and including the last heavily-doped p^{++}-AlGaN/GaN layer of the LED structure — i.e. the 'reference' sections of the devices (Figure 1).

In the MOCVD process, Si and Mg were used as n-type and p-type dopants, respectively. The light-emitting region consisted of AlGaN or InGaN QWs. After the MOCVD, the samples were annealed at 700°C for 20 minutes in nitrogen to drive out hydrogen, activating the p-type layers.

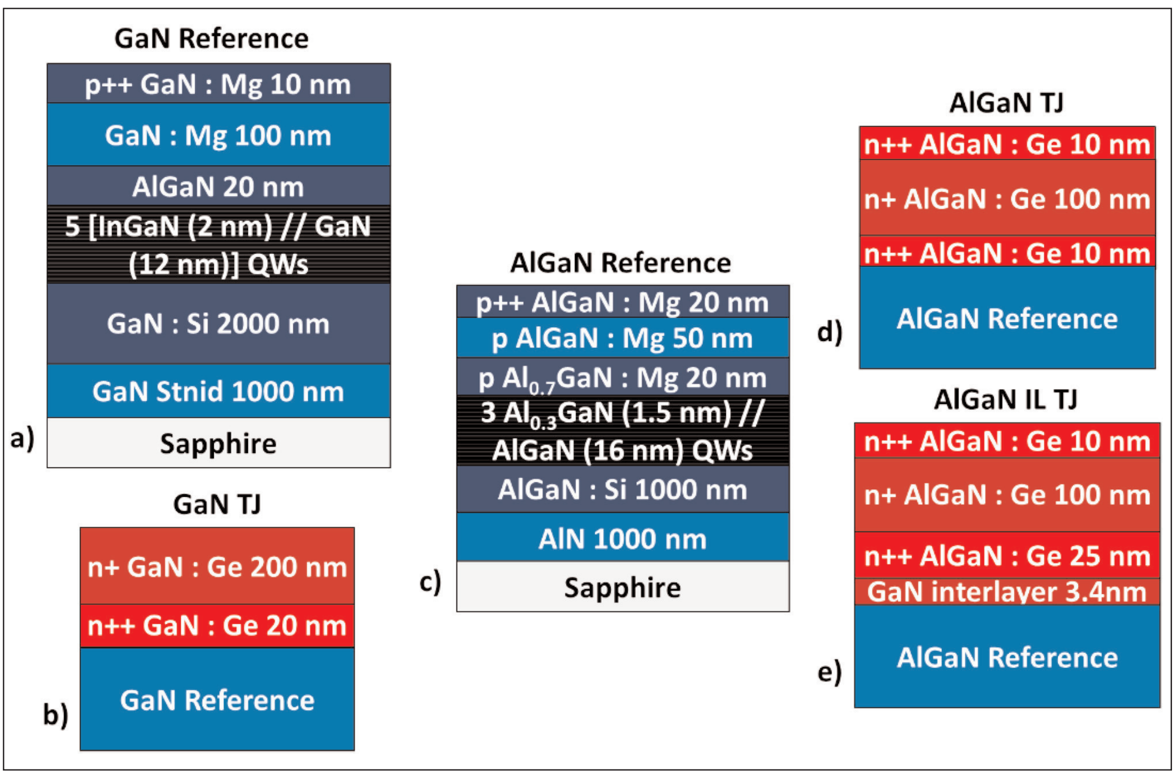

Figure 1. LED structures: (a) GaN reference (without TJ); (b) GaN TJ; (c) AlGaN reference (without TJ); (d) AlGaN TJ; (e) AlGaN IL TJ.

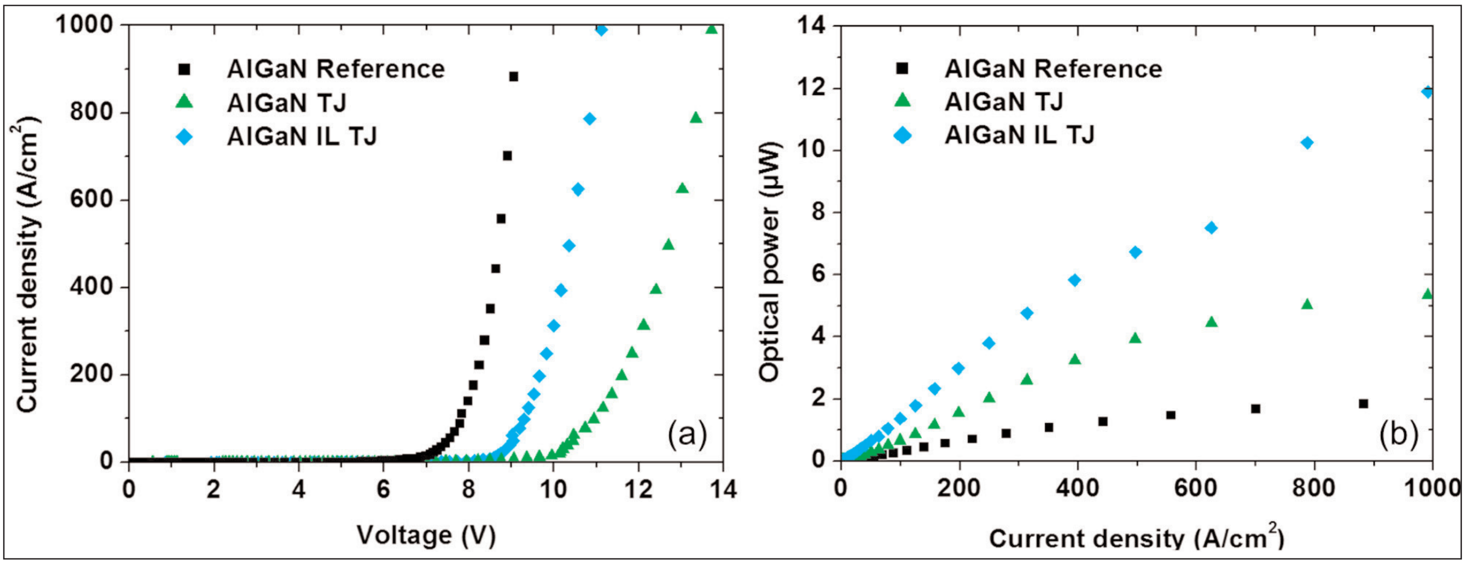

Figure 2. Current density versus bias (a) and optical power (b) for AlGaN TJs and AlGaN reference without TJ. LED areas 0.0016mm^2.

The n-type tunnel junction portions of the relevant structures were grown by molecular-beam epitaxy. The Ga and Ge came from solid sources. (Al is not mentioned, but one suspects a solid source for that metal too.) The nitrogen came from NH_3.

The mesa LEDs were fabricated using reactive-ion etching and electron-beam evaporation of titanium/aluminium/nickel/gold and nickel/gold n- and p-contacts, respectively. The p-contacts of the reference devices included a 5nm/5nm semi-transparent nickel/gold layer covering the whole top of the mesa to enable better current spreading from the main 20nm/200nm p-electrode. The n-contact was rapidly annealed at 700°C in nitrogen. The semi-transparent p-contact was rapidly annealed at 450°C.

To develop the Ge-doping technology, the researchers performed calibration experiments, producing n-GaN samples with 5.5x10^{20}/cm^3 carrier concentration and 67cm^2/V-s mobility. These values are described as 'state-of-the-art'. The resistivity of the material was 1.7x10$^{-4}\Omega$-cm.

Continuous-wave electroluminescence spectra gave peaks around 304nm and 436nm for the AlGaN and InGaN QW devices, respectively. The emissions were attributed to band-edge electron–hole recombination rather than deep-level transitions. The 304nm wavelength falls in the UV-B 280-315nm range, which has medical applications such as in the treatment of psoriasis, and is also used in the curing of photoresist layers.

In the visible 436nm-wavelength blue LEDs, the use of tunnel junctions reduced the voltage needed for a given current injection: for 100 and 500A/cm^2 current densities, the GaN LEDs with and without TJs showed voltages reduced from 5.6V to 5.3V, and from 7.0V to 6.6V, respectively. The corresponding light output powers increased from 0.7mW to 0.9mW, and from 2.3mW to 2.9mW.

The researchers comment: "The slight improvement in optical power between the GaN TJ and its reference is attributed to a better transparency of the TJ-based LED since the semi-transparent Ni/Au electrode has been suppressed."

For the AlGaN QW devices, the TJs increased the voltage for given current injection: However, inserting a GaN interlayer (IL) reduced the voltage penalty over the reference LED at 1000A/cm2 from 4.6V to 2V. The team believes that using an InGaN IL could reduce the penalty further by increasing the tunnel current, "due to a larger band-bending across the space charge region, thus decreasing the barrier width and increasing the tunneling probability".

In terms of AlGaN QW LED optical performance, the TJ structures increased output power at 1000A/cm^2 injection: 12μW for the TJ with IL, and 5.3μW without IL, compared with 1.9μW for the reference device. The team admits: "These values are low compared to the current state of the art due to the high dislocation density in the AlN buffer layer (>10^{10}/cm^2), which decreases the internal quantum efficiency (IQE) of the AlGaN/AlGaN QWs."

The researchers believe the improved output power derives from enhanced electrical injection efficiency promoted by the use of the TJs. They comment: "As the TJ injects out of equilibrium holes into the LED, the balance between electrons and holes in the quantum wells is improved, which enhances the injection efficiency. In other words, while electrons tend to overflow above the QW in the standard UV LED due to the lack of holes and recombine in the p region, electrons recombine in the quantum wells with holes injected from the TJ in TJ-based UV LEDs." ■

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Author: Mike Cooke

Monolithic InGaN white LED

Researchers used pulsed current injection to achieve color rendering index of more than 80 with 2700–6500K correlated color temperature.

US-based Ostendo Technologies Inc has demonstrated the color rendering index (CRI) capabilities of its monolithic color-tunable light-emitting diodes (LEDs) across a range of correlated color temperatures (CCTs) [Hussein S. El-Ghoroury et al, Optics Express, vol.28, p1206, 2020].

The devices consist of three sets of indium gallium nitride (InGaN) quantum wells (QWs) that emit at different wavelengths (460–650nm) according to the injected current. The different QW layers are separated by carrier-blocking regions of aluminium gallium nitride (AlGaN). The barriers are tailored by AlGaN composition, thickness and dopant concentration to guide carriers into targeted QWs, producing specific wavelengths at a given bias.

White light is generated using pulses of current injection at different levels to give various spectral balances. The ability to change the CCT is seen as advantageous for its effect on human circadian rhythms, mood and health. 'Cool' bright light in the 4000–6000K range is better at keeping people awake, while dimmer 'warm' light, at 3000K, is better for relaxation and preparing for sleep.

The epitaxial structure (Figure 1) was grown using metal-organic chemical vapor deposition (MOCVD) — the top-most p-type magnesium-doped layers were activated by in-situ annealing in the reaction chamber.

The devices were tested on-wafer with contacts created through pressing an indium ball on the p-GaN surface and on a scribed region exposing the buried n-type material. The researchers comment: "For production purposes, transparent p-contacts like annealed [nickel/gold] Ni/Au or [indium tin oxide] ITO must be used for p-GaN and [titanium/aluminium] Ti/Al or Ti/Au should be used for n-GaN contacts to improve the contact resistivity."

The drive set-up consisted of two-step pulse generators, an operational amplifier-based summing network, and a voltage-to-current converter, based again on op-amps and a bipolar transistor. The circuit targeted fast response and large current handling.

The researchers used manual fine-tuning of the pulse circuit, making it difficult to obtain spectra at the exact color coordinates. The team believes that this would be easy for a computer-controlled feedback system.

The LEDs produced CRI values above 80 across the range of CCTs from 2700K to 6500K (Figure 2). At the highest CCT the CRI was 87. The team suggests that improved CCT would result from "additional spectral emission peaks to increase the range and overlap in the spectral mixture".

Simulations of a structure with four emission peaks and driven by a three-step pulse set-up indicate that CRIs above 90 (and up to 95.4 at 4100K CCT) would be possible. The extra peak would come from an extra red emission from low (~625nm wavelength) and medium (~585nm) current injections, enhancing spectral coverage in the long-wavelength range. The two red peaks arise from significant blue-shift effects at the higher injection current.

The team comments: "The spectral content of the blue and green QW emissions is similar to those shown in the two-step pulse design due to the minimal blue-shift of the blue and green QW emission. By optimizing the blue and green QW growth parameters, the spectral

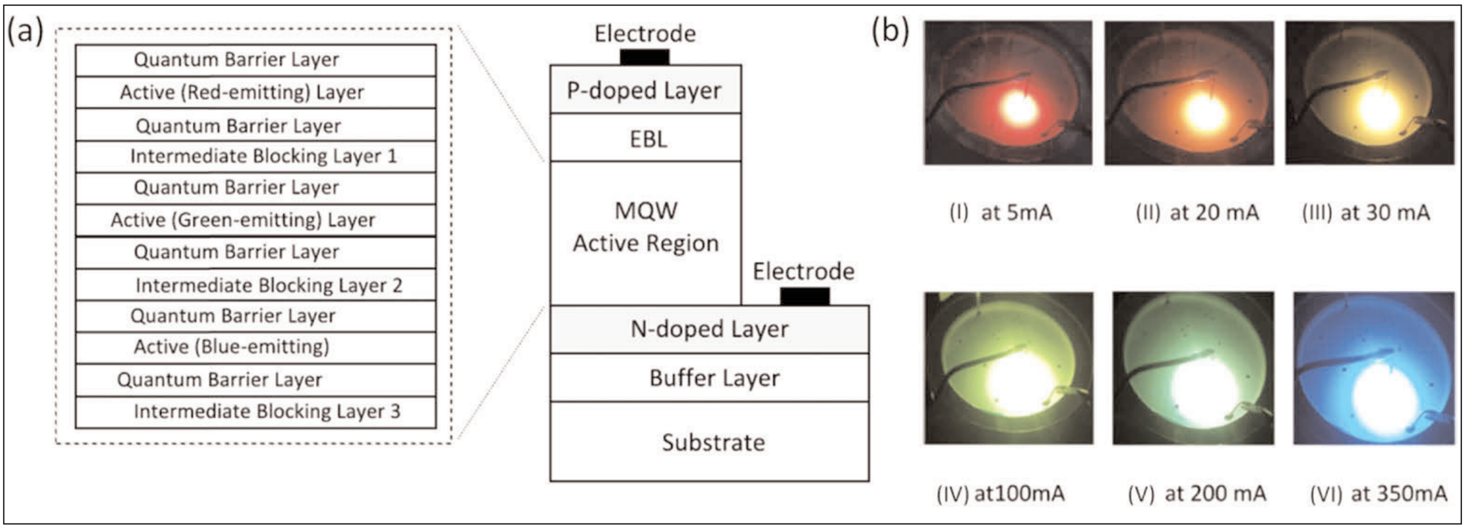

Figure 1. (a) Simplified cross-sectional view of monolithic color-tunable InGaN-based LED structure and (b) emission from 5mA to 350mA injection current.

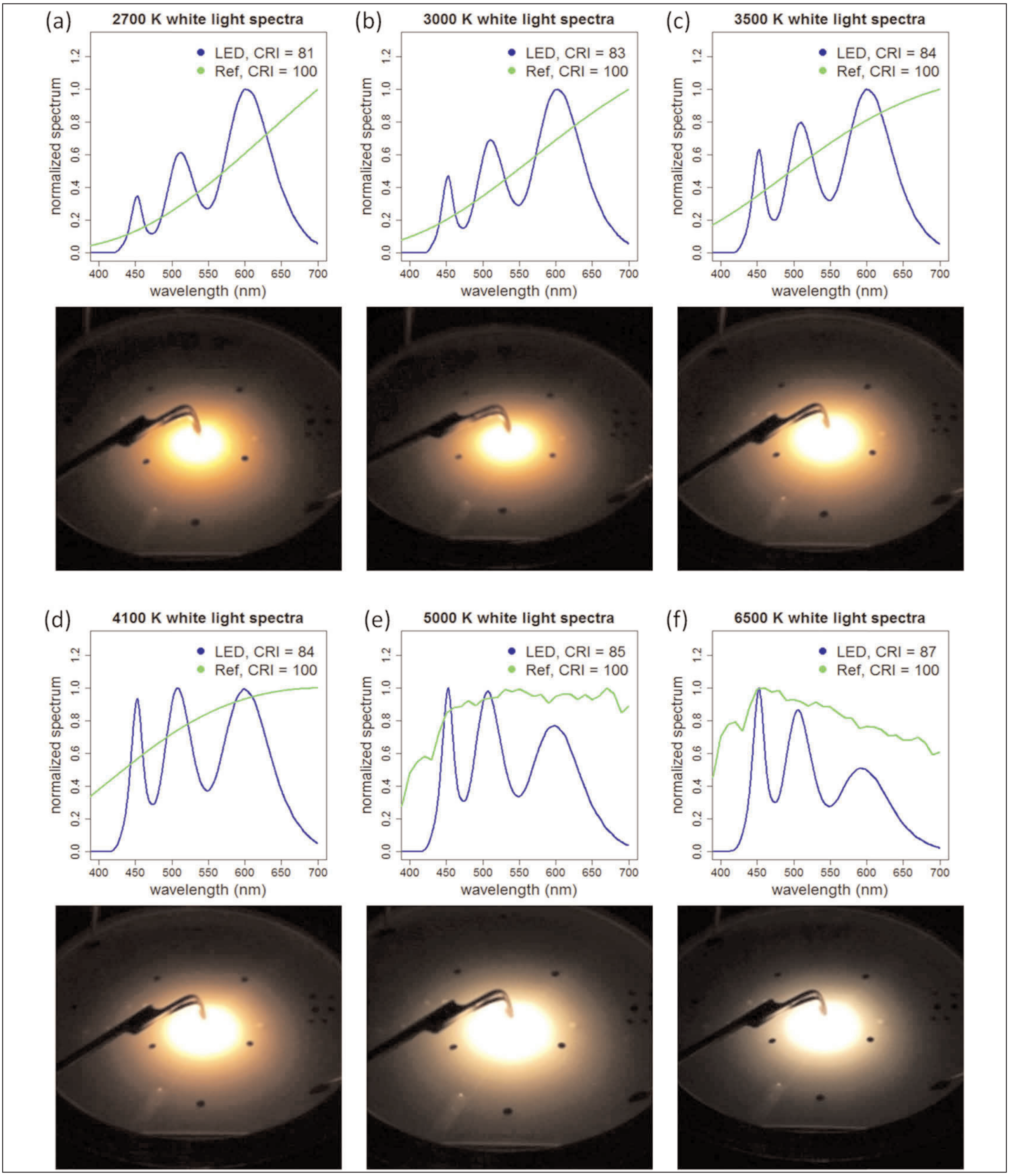

Figure 2. Light spectra (top) and photographic capture (bottom) of pulsed color-tunable emission at color temperatures of (a) 2700K, (b) 3000K, (c) 3500K, (d) 4100K, (e) 5000K and (f) 6500K.

coverage in the short-wavelength range can be enhanced and thus further improvement of CRI is possible."

The use of such a monolithic chip would reduce material, complexity and packaging costs, compared with RGB designs based on separate chips emitting single colors or devices with filters. ■

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Author: Mike Cooke

Thermal droop in InGaN LEDs

Researchers see power losses at high temperature as being caused mainly by transport effects.

A study of indium gallium nitride (InGaN) light-emitting diodes (LEDs) suggests that the thermal droop in external quantum efficiency (EQE) is mainly caused by transport effects such as carrier overshoot, according to researchers at Soraa Inc in the USA [Aurelien David et al, Appl. Phys. Lett., vol115, p223502, 2019].

Thermal droop refers to the loss in efficiency when the junction is heated either by high-temperature operation or due to poor heat dissipation in continuously operating devices ('Joule heating'). This is in contrast to current droop, which refers to an efficiency loss at high current injection. Often current droop is isolated by pulsed operation designed to avoid heat build up in LED junctions.

The researchers used material grown by metal-organic chemical vapor deposition (MOCVD) on c-plane bulk GaN. The light emissions came from 13% indium-content InGaN single or multiple quantum wells (SQW/MQW). The use of expensive bulk GaN substrates gives best-case devices with low defect levels that should reduce leakage currents through dislocations.

Photoluminescence (PL) experiments on a SQW in the 25–160°C temperature range suggested a peak internal quantum efficiency (IQE) of 84%. The structure that was tested consisted of the SQW lodged in 200nm of intrinsic GaN material. The IQE response to the laser pumping was fairly consistent across the temperature range. The researchers even suggest that, allowing for differences in absorption, the peak IQE increased slightly at higher temperatures.

The researchers used an optical differential lifetime technique to derive the various parameters of the standard ABC model. The separate terms of the model — Shockley–Read–Hall (A), radiative (B) and Auger (C) — can be extracted by studying the luminescence at different carrier levels generated by different pump laser powers.

The team explains: "A diode laser having a time-dependent output excites the QW resonantly; the PL signal is collected by an avalanche photodiode connected to a network analyzer, which determines the phase and amplitude response of the PL signal, from which the differential carrier lifetime is derived. This technique directly probes the carrier lifetime in the active region and therefore circumvents transport effects."

Analysis of the carrier lifetime behavior allows extraction of the current-dependent ABC coefficients, along with IQE.

The total recombination lifetime was found to be only weakly dependent on temperature with the 'A' portion attributed to non-radiative Shockley–Read–Hall (SRH) transitions through mid-gap levels slightly decreasing at high temperature against expectations, according to the researchers' analysis based on the ABC model.

The team suggests that temperature-dependent effects reported previously can be attributed to two factors: "(1) in heteroepitaxy samples, additional dislocation-

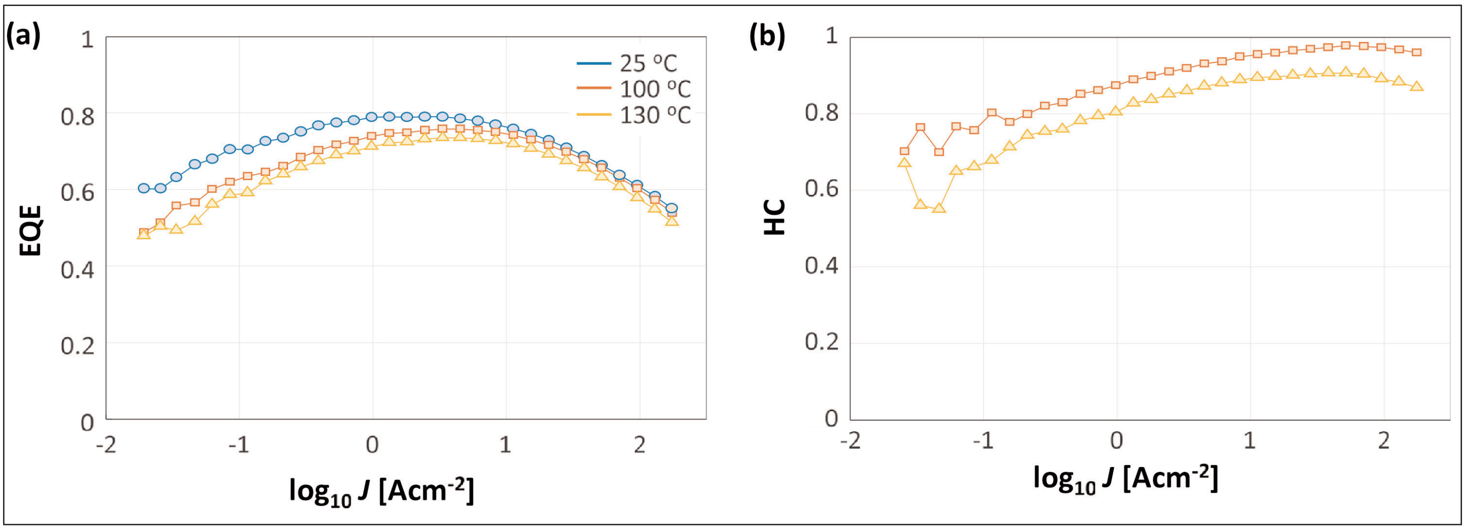

Figure 1. PL measurements of thermal droop on SQW sample: (a) IQE, (b) differential lifetime versus carrier concentration. (c) Extracted SRH coefficient A. Inset: non-radiative current divided by carrier density: A value extracted from low-current plateau. (d) Radiative coefficient B. (e) Auger coefficient C. (f) Calculated value of B (considering many-body effects and alloy disorder) shows trend qualitatively similar to experimental data of (d).

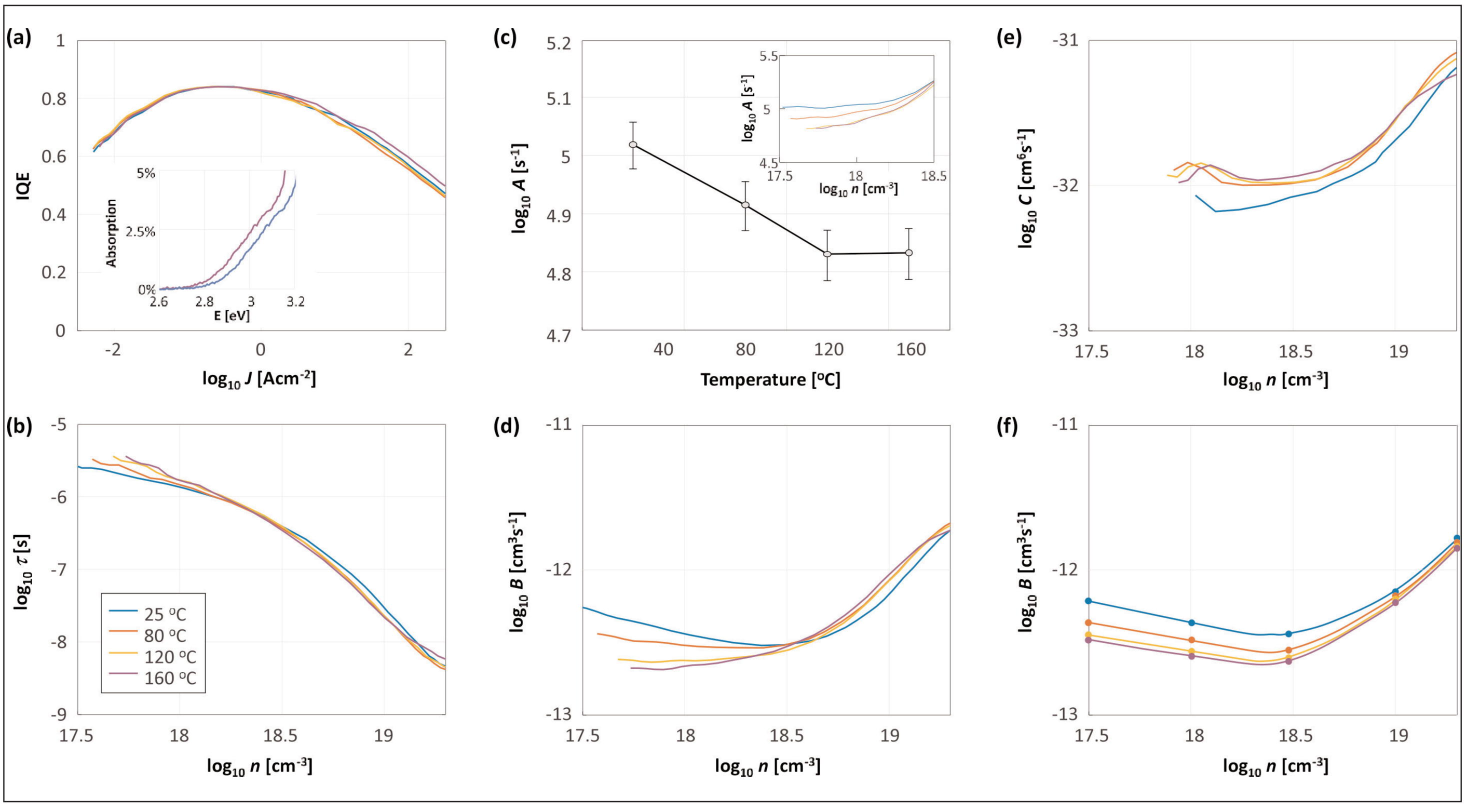

Figure 2. Electroluminescence thermal droop in MQW LED: (a) EQE and (b) HC ratio.

related effects may lead to a different thermal activation (especially for A); (2) previous studies have derived lifetimes from EL [electroluminescence] measurements, where recombination effects and transport effects were not disentangled. Our measurements directly probe active-region recombinations in low-defect material and therefore provide a more direct insight into the intrinsic nature of thermal droop."

The researchers believe therefore that thermal droop in their LEDs' EL performance is not due to recombination problems in the active QW region of the devices. The SQW LEDs consisted of 30nm p-i-n structures with a magnesium-doped aluminium gallium nitride (AlGaN) electron-blocking layer. The LED was assembled with the chip flipped onto a silver p-contact. One aim of the silver contact was high light extraction efficiency, presumably through reflection back to the top of the device.

Thermal droop is attributed to transport effects, such as electrons escaping from the active region by crossing the electron-blocking layer into the p-contact layer and recombining non-radiatively. The researchers performed a time-resolved study that allowed measurement of carrier escape time from the QW. The exponential temperature dependence was consistent with thermionic emission.

The researchers found that an optimized MQW structure enabled higher EQE and hot/cold (HC) ratio values (Figure 2). 'Cold' refers to room-temperature performance. The team observes that the HC ratio "reaches near-unity at a temperature of 100°C and at operating current density—a higher value than typically observed in commercial LED samples. Crucially, this improvement in the HC ratio is not obtained at the expense of peak EQE (instead, the room-temperature peak EQE of the MQW structure reaches a state-of-the-art value of 80%, surpassing that of the SQW structure). This reveals that thermal droop is not a fundamental limit to LED performance."

The team suggests that the MQW structure reduces escape from the active region into the p-contact region. If the electron is not captured by one QW it may be by the next. However, there may also be a compensation effect going on, where higher temperatures enable broader use of the QWs in the MQW structure. Some studies have found that the MQW structures under EL testing have very non-uniform emissions, with most light coming from wells near the p-end of the device, since holes tend to have more sluggish transport properties.

This compensation may partially explain the HC performance, but not that of the EQE. The SQW LEDs showed a relative drop in peak EQE of 15% at 100°C, compared with 5% for the MQW structure. The researchers claim that the drop is not influenced by carrier spreading since it is the peak EQE being considered, regardless of current). The team adds that this "indicates that a majority of the HC improvement has a separate cause." ■

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www.soraa.com

Author: Mike Cooke

Epitaxy equipment market to grow from $940m to over $6bn by 2025, driven by VCSEL and disruptive LED devices

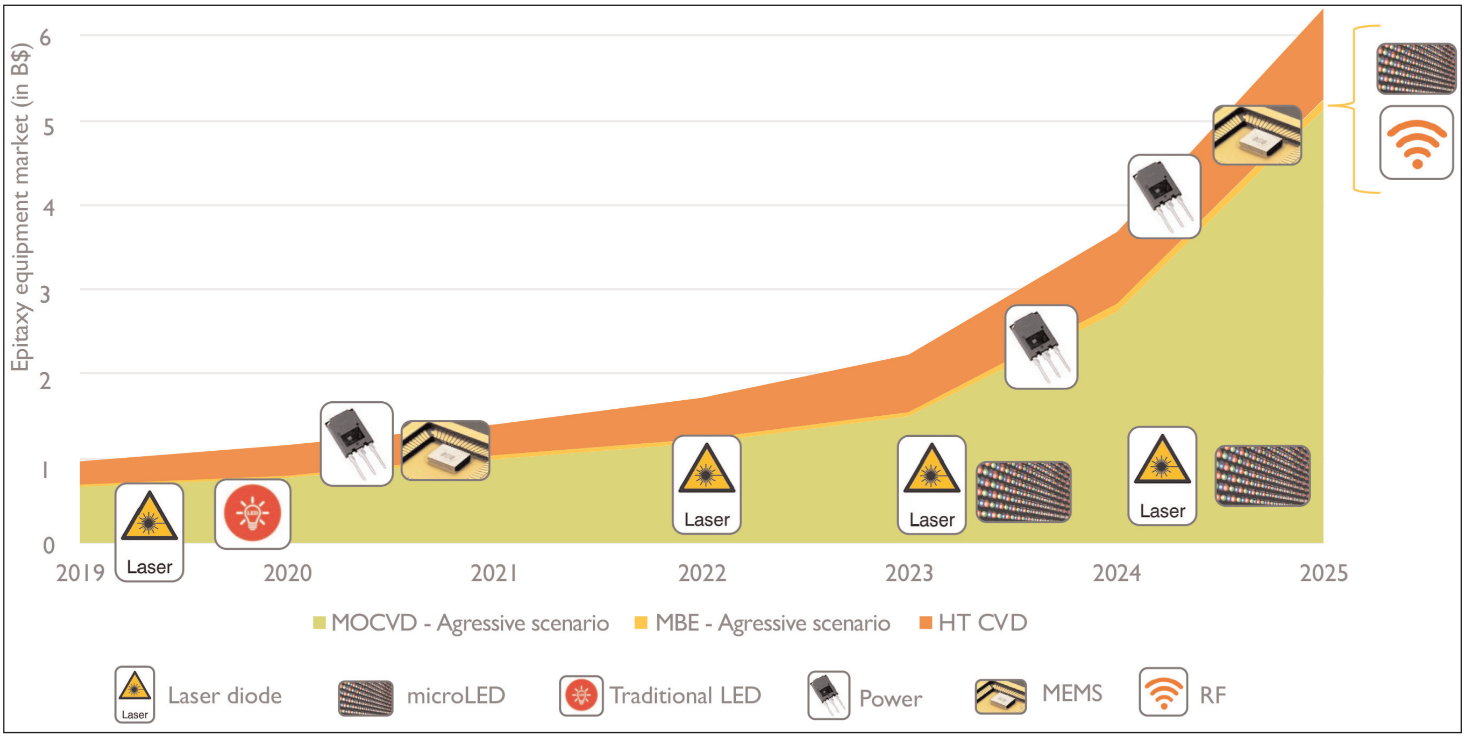
Disruptive non-silicon-based 'More than Moore' devices are leading to a more competitive epitaxy growth landscape, says Yole Développement.

The epitaxy growth equipment market for 'More than Moore' devices was worth nearly $940m in 2019, and it is expected to exceed $6bn by 2025 in an aggressive scenario, according to Yole Développement's technology & market report 'Epitaxy Growth Equipment for More Than Moore Devices'.

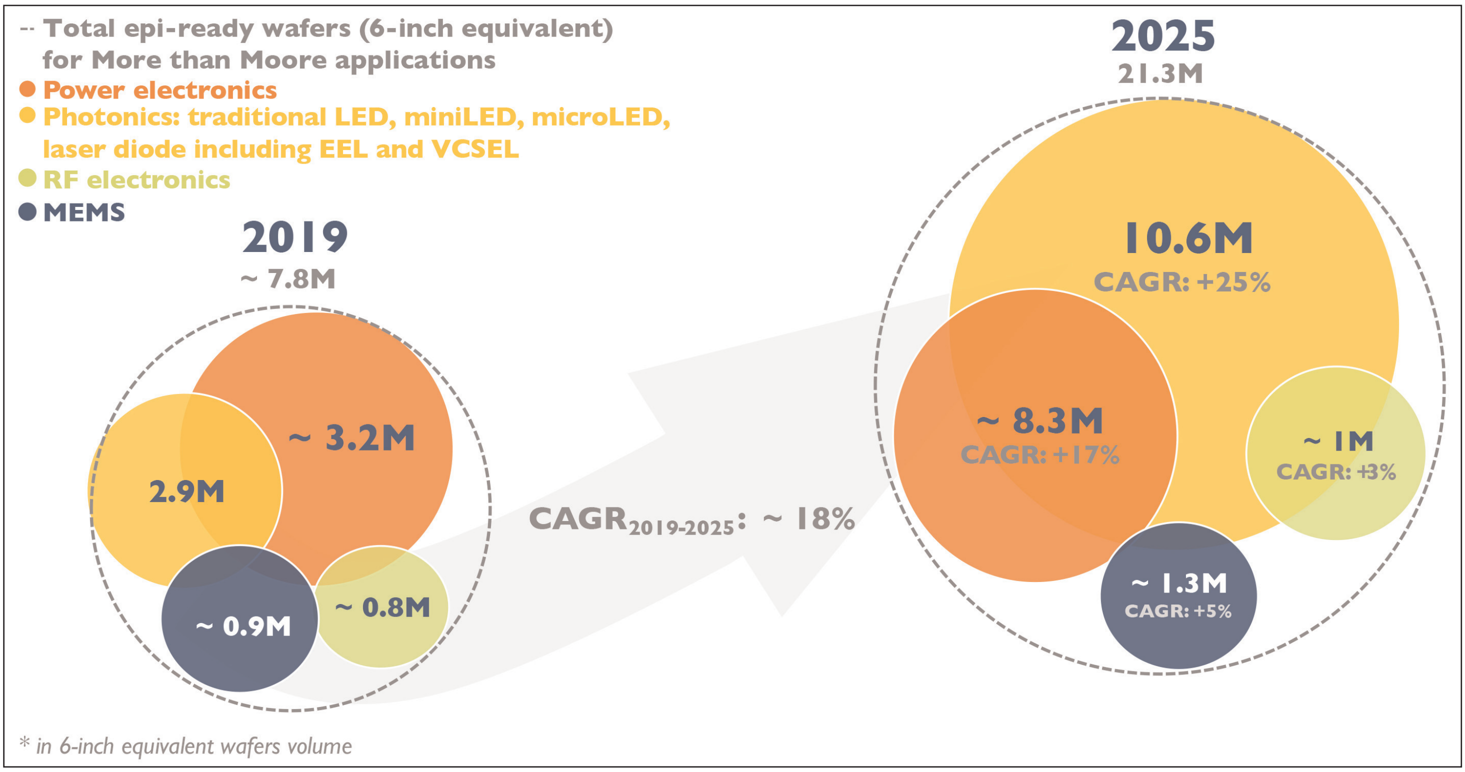
From a technical point of view, metal-organic chemical vapor deposition (MOCVD) serves most of the III–V compound semiconductor epitaxy industry, such as gallium arsenide (GaAs)- and gallium nitride (GaN)-based devices. High-temperature (HT) chemical vapor deposition (CVD) serves the majority of mainstream silicon-based components and silicon carbide (SiC) devices.

The semiconductor industry has been traditionally dominated by silicon substrates. Although silicon is still by far the most dominant material (with more than 80% market share), alternative non-silicon-based substrates like GaAs, GaN, SiC and InP (indium phosphide) are gaining momentum within the 'More than Moore' industry. Indeed, new applications are emerging along with stringent requirements where silicon solutions are not able to provide the performance expected. Innovative substrate materials are hence being considered by semiconductor manufacturers.

GaN material represents the main epitaxy market after silicon substrates, driven mostly by traditional GaN-based light-emitting diode (LED) devices. However, the overall visible LED industry is currently diversifying towards more specialized ultraviolet (UV) and infrared (IR) LEDs based on GaAs substrates. Additionally, manufacturers are developing new types of LEDs to



Epitaxy equipment market for 'Moore than Moore' devices: 2019–2025 breakdown by technology.



Forecast of epi-ready wafer demand, by application, 2019–2025.

continue creating value in consumer displays, such as mini-LEDs and micro-LEDs. Apple is initiating this with adoption in its higher-end 2021 smartwatch model. In the best-case scenario, micro-LEDs could also spread into smartphone products, which will definitely reshape the epi-ready wafer market, says Yole.

On the other hand, wide-bandgap (WBG) materials like SiC substrates have found opportunities in the power electronics market. Here, power consumption reduction is required for electrification of transportation, renewable energy, motor drives and some power supply applications. Despite the high price of SiC, such substrates represent a strong asset for high-voltage applications, and are thus considered to be a technology choice for some metal-oxide-semiconductor field-effect transistor (MOSFET) and diode products.

Looking ahead, photonics products like vertical-cavity surface-emitting lasers (VCSELs) operating in the IR spectrum (typically processed on GaAs) are making serious inroads into the epitaxy market. In addition, GaAs is especially advantageous for radio-frequency (RF) products such as small-cell implementation, for both sub-6GHz frequencies and the first millimetre-wave (mmWave) small cells in the 28–39GHz range. With the cellphone transition from 4G to 5G, Yole hence expects GaAs to remain the mainstream technology for sub-6GHz frequencies instead of complementary metal-oxide-semiconductor (CMOS) silicon, since it is the only technology able to meet increasing power level and linearity requirements imposed by antenna board-space reductions as well as carrier aggregation and multiple-input multiple-output (MIMO) technology.

Choosing the appropriate substrate technology will depend strongly on the technical performance associated with device requirements, as well as the cost, notes Yole.

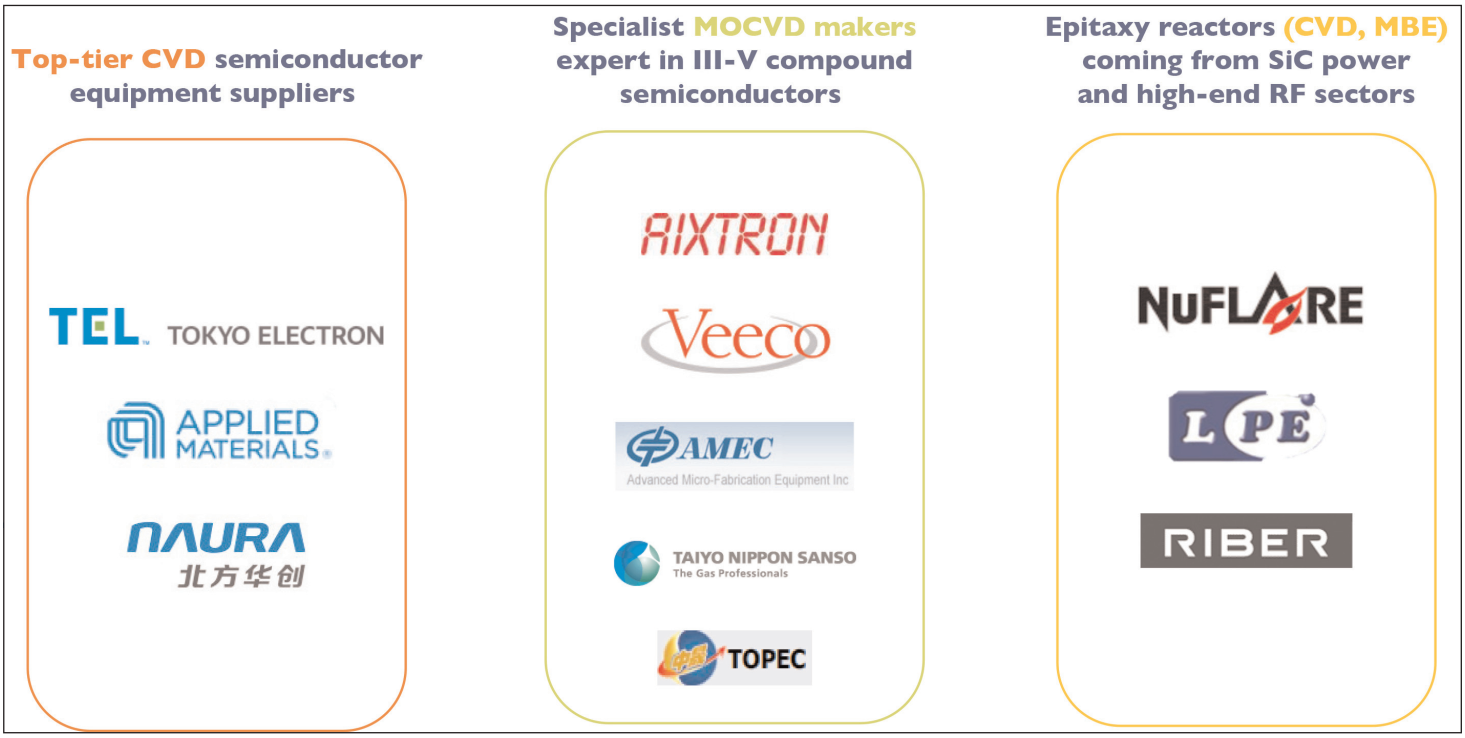
"As of today, the epitaxy growth equipment market is mainly driven by LED and power applications," says Amandine Pizzagalli, technology & market analyst, Semiconductor Manufacturing, at Yole. "In fact, massive subsidies in China have led to an excessive LED capacity build-up. The MOCVD market is now in a situation of significant overcapacity for GaN LED production compared to what is actually produced," he adds. "MOCVD investment is particularly tough to forecast in the next few years and could change year to year. The situation could be reversed if the government decides to strictly prevent the major LED manufacturers from producing more GaN wafers."

The report has therefore considered different scenarios for the traditional LED and micro-LED markets.

For traditional GaN-based LEDs, MOCVD investment trends will not follow LED wafer demand. Specific upsides and downsides with respect to GaN LEDs might arise, as used to happen in the past.

Nevertheless, given recent competitive trends in China, the general lighting and backlighting markets have become commoditized. Hence, epitaxy vendors do not expect significant revenue from these markets going forward.

However, requirements for micro-LED epitaxy in terms of defects and homogeneity are more stringent than for traditional LEDs. There are credible roadmaps for improvement in tools and equipment to reach



Epitaxy equipment suppliers: competitivelandscape.

approximately 0.1 defects/cm^2 or less, based on defects larger than 1µm. Tighter operating conditions are needed in cleanrooms, including for automation and wafer cleaning, compared with traditional LED manufacturing. This is especially true for the smallest dies (below <10µm), which will have smaller killer defects.

Meanwhile, laser diodes represent an additional fast-growing opportunity as the consumer goods industry massively adopts edge-emitting lasers and VCSELs.

Yole notes that, for compound semiconductor-based devices such as laser diodes, micro-LEDs and VCSELs, the MOCVD reactor market could be affected by possible technology transitions to molecular beam epitaxy (MBE). In fact, MBE could bring greater advantages in terms of yield and uniformity for VCSELs as well as for high-frequency 5G RF applications. In the case of SiC power devices, MOCVD manufacturers are trying to identify and develop new MOCVD technologies to address the SiC market, where HT CVD is currently predominant. ■

www.i-micronews.com/products/epitaxy-growth-equipment-for-more-than-moore-devices-technology-and-market-trends-2020

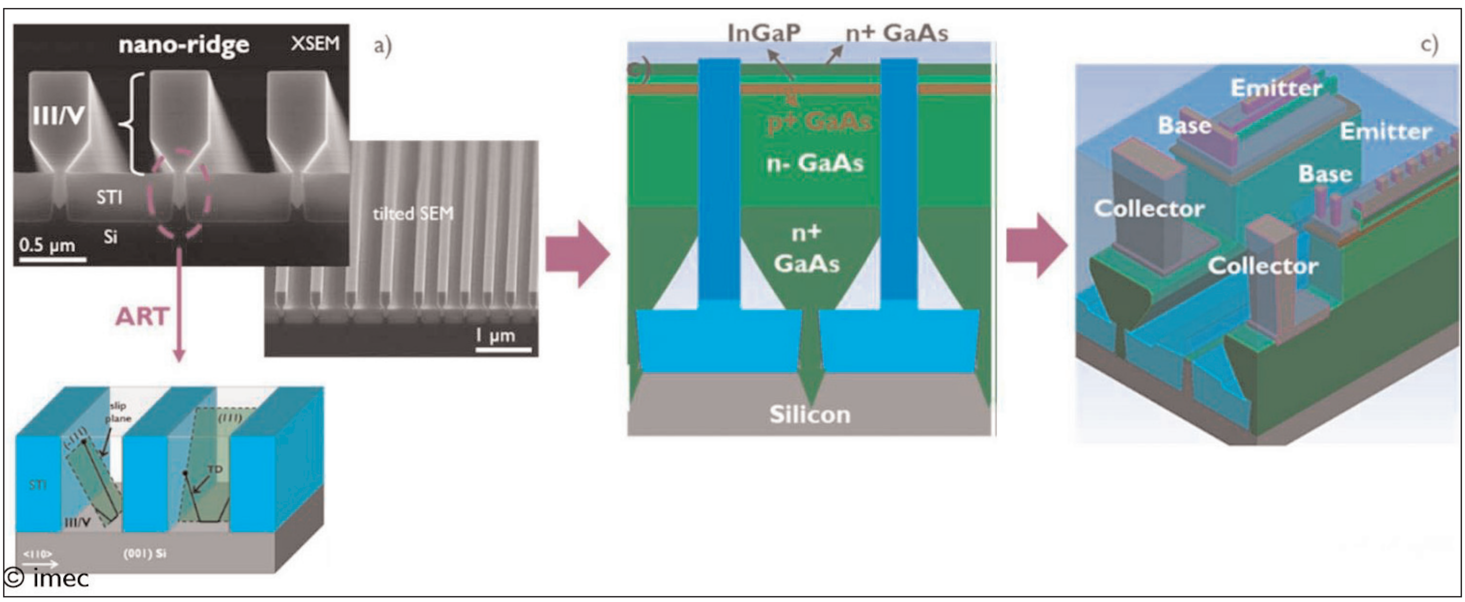
Imec demos scalable III–V and III–N devices on silicon, targeting beyond-5G RF front-end modules

First functional GaAs HBTs on 300mm silicon and CMOS-compatible GaN devices on 200mm silicon for mm-wave applications presented at CCNC 2020

Demonstrating the potential of both III–V-on-Si and GaN-on-Si as CMOS-compatible technologies for enabling RF front-end modules for beyond-5G applications, nanoelectronics research centre imec of Leuven, Belgium presented the first functional gallium arsenide (GaAs)-based heterojunction bipolar transistor (HBT) devices on 300mm silicon as well as CMOS-compatible gallium nitride (GaN)-based devices on 200mm silicon for millimeter(mm)-wave applications at December's IEEE International Electron Devices Meeting (IEDM 2019) in San Francisco, and featured them in a keynote presentation by Michael Peeters (imec's program director connectivity + humanized technology) on consumer communications beyond broadband at the IEEE Consumer Communications and Networking Conference (CCNC 2020) in Las Vegas (10–13 January).

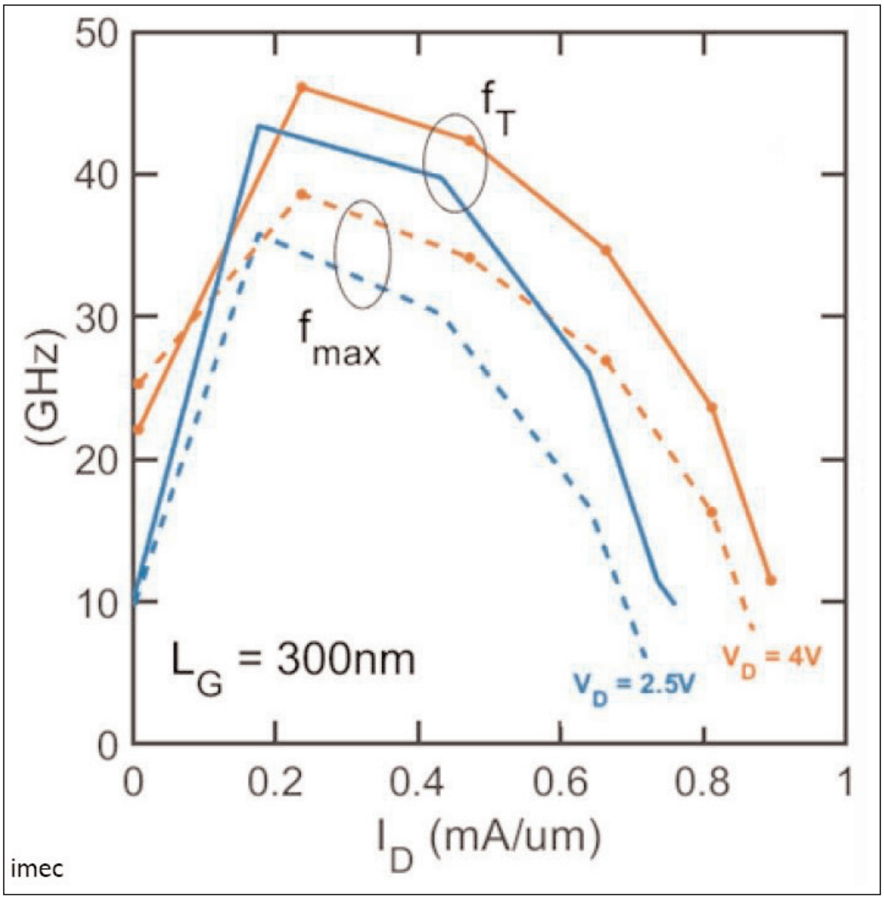
In wireless communication, with 5G as the next generation, there is a push towards higher operating frequencies, moving from the congested sub-6GHz bands towards mm-wave bands (and beyond). The introduction of these mm-wave bands has a significant impact on the overall 5G network infrastructure and the mobile devices. For mobile services and fixed-wireless access (FWA), this translates into increasingly complex front-end modules that send the signal to and from the antenna. To be able to operate at mm-wave frequencies, the RF front-end modules will have to combine high speed (enabling data rates of 10Gbps and beyond) with high output power.

In addition, their implementation in mobile handsets puts high demands on their form factor and power efficiency. Beyond 5G, these requirements can no longer be achieved with today's most advanced RF front-end modules that typically rely on a variety of different technologies, including GaAs-based HBTs for the power amplifiers — grown on small and expensive GaAs substrates.



Description of the NRE approach for hybrid III-V/CMOS integration on 300mm silicon: (a) nano-trench formation (defects are trapped in the narrow trench region); (b) HBT stack growth using NRE; and (c) different layout options for HBT device integration.

"To enable the next-generation RF front-end modules beyond 5G, imec explores CMOS-compatible III–V-on-Si technology," says Nadine Collaert, program director at imec. "Imec is looking into co-integration of front-end components (such as power amplifiers and switches) with other CMOS-based circuits (such as control circuitry or transceiver technology) to reduce cost and form factor, and enabling new hybrid circuit topologies to address performance and efficiency," he adds. "Imec is exploring two different routes: (1) indium phosphide (InP) on silicon, targeting mm-wave and frequencies above 100GHz (future 6G applications) and (2) GaN-based devices on silicon, targeting (in a first phase) the lower mm-wave bands and addressing applications in need of high power densities. For both routes, we have now obtained first functional devices with promising performance characteristics, and we identified ways to further enhance their operating frequencies."



Measured cut-off frequencies of the current gain (f_T) and unilateral power gain (f_{max}) for GaN/AlGaN devices on 200mm silicon.

Functional GaAs/InGaP HBT devices grown on 300mm silicon have been demonstrated as a first step towards the enablement of InP-based devices. A defect-free device stack with a threading dislocation density below $3x10^6cm^{-2}$ was obtained by using imec's unique III–V nano-ridge engineering (NRE) process. The devices are said to perform considerably better than reference devices, with GaAs fabricated on silicon substrates with strain relaxed buffer (SRB) layers. In a next step, higher-mobility InP-based devices (HBT and HEMT) will be explored.

Moreover, CMOS-compatible GaN/AlGaN-based devices on 200mm silicon have been fabricated comparing three different device architectures — HEMTs, MOSFETs and MISHEMTs. It was shown that MISHEMT devices outperform the other device types in terms of device scalability and noise performance for high-frequency operation. Peak cut-off frequencies of f_T/f_{max} around 50/40 were obtained for 300nm gate lengths, which is in line with reported GaN-on-SiC devices. Besides further gate-length scaling, the first results with AlInN as a barrier material show the potential to further improve the performance and hence increase the operating frequency of the device to the required mm-wave bands. ■

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Developing complementary p-channel transistors for GaN-on-silicon power

Researchers use commercial epitaxial material designed for 650V normally-off p-type gallium nitride gate power devices.

Hong Kong University of Science and Technology (HKUST) report on p-channel metal-oxide-semiconductor field-effect transistors (MOSFETs) produced on gallium nitride (GaN) on silicon (Si) substrates [Zheyang Zheng et al, IEEE Electron Device Letters, vol.41, p26, 2020]. The researchers used commercial 8-inch-diameter GaN-on-Si wafers with epitaxial structures designed for 650V normally-off p-GaN gate power high-electron-mobility transistors (HEMTs) (Figure 1).

GaN is being developed for high voltage and power handling based on the material's high critical electric field before breakdown. Devices with n-type channels with negatively charged carriers (electrons) have been intensively developed in recent years. Much progress has been made in developing devices with normally-off 'enhancement-mode' (E-mode) characteristics, rather than the more easily achieved normally-on 'depletion-mode' (D-mode). The E-mode is desired for lower power consumption and for fail-safe features.

The n-channel devices largely depend on the creation of 'two-dimensional electron gas' (2DEG) channels, which arise near the interface between GaN and a barrier layer, often aluminium gallium nitride (AlGaN). The 2DEG occurs due to band-bending effects arising from contrasts in the charge distribution in the chemical bonds holding the Ga, Al and N atoms together.

Devices with p-channels would enable complementary integrated circuit (IC) designs, which would further reduce power loss in logic control systems. Although some progress has recently been made in developing an analogous 2D hole gas for p-channels, effective devices remain to be achieved. The HKUST work focuses instead on using p-GaN material achieved using magnesium doping.

The team comments: "The p-GaN/AlGaN/GaN-on-Si platform paves the way to monolithically integrating E-mode pFET and nFET for possible GaN complementary and more robust GaN power ICs."

The GaN-on-Si material included a ~12nm AlGaN

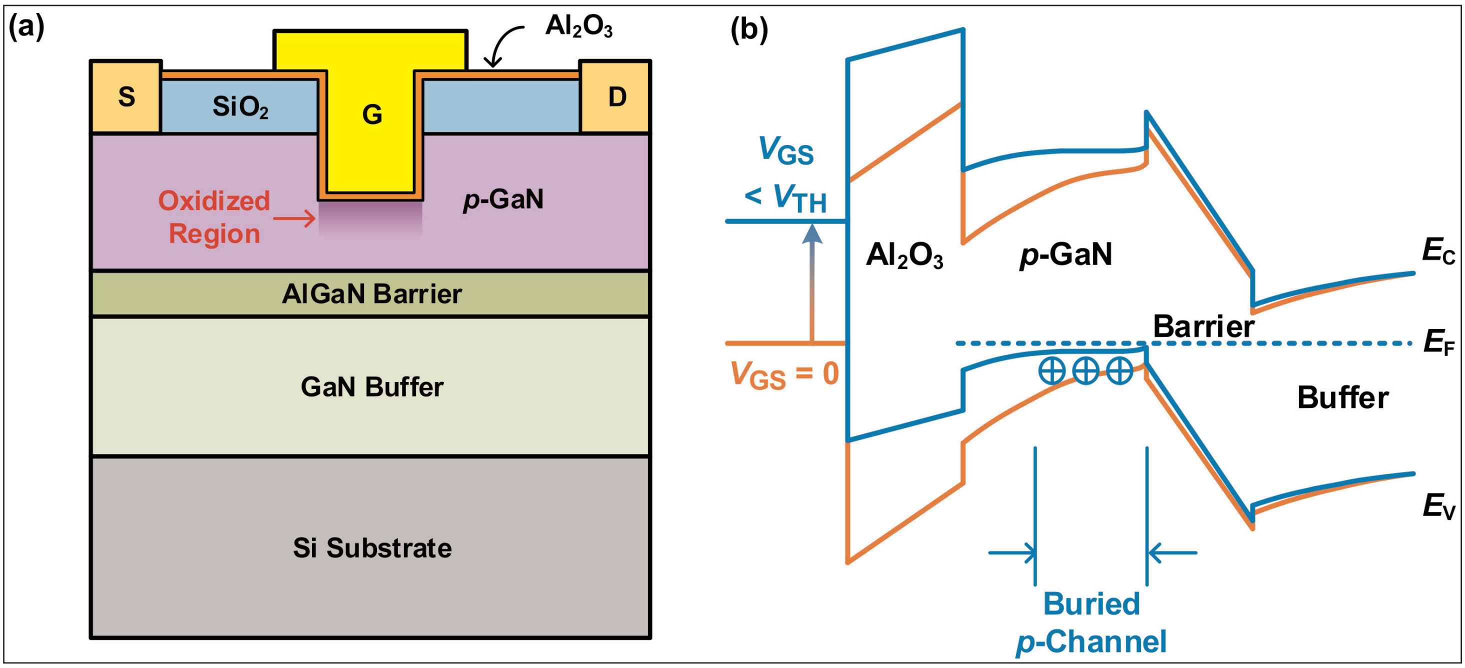

Figure 1. Schematic of (a) E-mode GaN pFET ($L_{GS}/L_G/L_{GD}$ = 4/2/4μm) and (b) energy band diagram at gated region of buried p-channel with 0V (OFF) and beyond threshold (ON) gate potentials (V_{GS}).

barrier and a ~85nm p-GaN top layer. The undoped GaN buffer was ~4.5μm thick. The structure was found to have a hole sheet density of 1.23x10^{13}/cm^2 and mobility 10.2cm^2/V-s, according to Hall measurements.

Standard p-GaN gate E-mode n-channel HEMTs realized on the substrate typically have threshold voltages of +1.7V and an on-current of 350mA/mm with 5V drain bias. The on/off current ratio is usually of order 10^9.

The HKUST p-channel devices were fabricated with 500°C-annealed nickel/gold ohmic source-drain (S–D) contacts evaporated onto the p-GaN, which had previously been subjected to a 5-minute buffered oxide etch, presumably to improve the surface and remove contaminants.

The gate (G) recess was defined by a 200nm plasma-enhanced chemical vapor deposition (PECVD) silicon dioxide (SiO_2) hard mask, which also served as surface passivation. The p-GaN recess was formed using inductively coupled plasma reactive-ion etch.

An oxygen plasma treatment increased the surface roughness at the bottom of the recess from 0.36nm root-mean-square to 0.41nm, according to atomic force microscopy. The recess depth was found to be about 54nm, leaving ~31nm of p-GaN material above the AlGaN barrier for the channel.

The gate structure was completed with 20nm atomic layer deposition (ALD) aluminium oxide (Al_2O_3) insulation and 400°C-annealed nickel/gold metal electrode. The electrical isolation of the devices was from fluorine ion implantation rather than mesa etching. The researchers used fluorine implant to avoid current leakage along rough mesa sidewalls. The implant occurred between the Al_2O_3 and gate metal deposition steps.

The device demonstrated a threshold voltage of −1.7V, giving normally-off enhancement-mode behavior at 0V gate. The oxygen plasma treatment enabled the negative threshold – without the treatment, the device became depletion-mode (normally-on at 0V gate) with the threshold at +2.2V. The on-current of the enhancement-mode device was 67% that of the depletion-mode transistor without oxygen plasma treatment.

The on-resistance for the E-mode device was a "relatively large" 2.4kΩ-mm at low drain bias. This reduced somewhat at −5V drain to 1.6kΩ-mm. The maximum drain current was 6.1mA/mm at −10V drain.

Affinity	Platform	V_{TH} [a] (V)	lg(I_{ON}/I_{OFF}) [b]	I_{ON} [c] (mA/mm)	SS (mV/dec)
Notre Dame [10]	*p*-/*i*-GaN /AlN Al_2O_3 MOS gate	0.89 (−80 V)	3 (−80 V)	3.87 (−80 V)	1415
RWTH [9]	*p*-/*i*-GaN/AlInGaN/ GaN/AlN, Schottky gate	−1.12 (−8V)	7 (−8V)	6.79 (−8V)	91.3
AIST [5]	*p*-/*i*-GaN/AlGaN/GaN Al_2O_3 MOS gate	> 4	N.A.	4.00	N.A.
RWTH [11]	*p*-/*i*-GaN/AlInGaN/ GaN/AlN, Schottky gate	−0.5	8	1.81	77
HRL [6]	*p*-/*i*-GaN/AlGaN/GaN AlN/SiN_x MIS gate	−0.36 (−0.1V)	6 (−0.1V)	1.65	304
AIST [7]	*p*-/*i*-GaN/AlGaN/GaN SiO_2 MOS gate	−0.75	3	0.09	817
Cornell [12]	*p*-/*i*-GaN/AlN SiO_2 MOS gate	1.32	4	9.10	1027
MIT [13]	*p*-GaN/AlGaN/GaN Al_2O_3 MOS gate	2.60 (−0.5V)	5 (−0.5V)	1.40	399
This work	*p*-GaN/AlGaN/GaN Al_2O_3 MOS gate	**−1.7**	**7**	**3.38**	**230**

[a] extracted at $|I_D| = 10$ μA/mm and $V_{DS} = -5$ V unless otherwise specified.
[b] (orders of magnitude) with $V_{DS} = -5$ V unless otherwise specified.
[c] at $V_{DS} = -5$ V and with overdriven V_{GS}, unless otherwise specified.

Table 1. Benchmark of p-channel GaN FETs.

The off-current with 0V gate was 1.2x10^{-7}mA/mm. The team sees this low off-current as "delivering an ultra-low static power consumption required in CMOS logic gates."

The researchers explain the action of the oxygen plasma treatment: "It is known that oxygen induced into p-GaN could either behave as shallow donors to compensate the Mg acceptors or form inert Mg-O complexes to de-activate the Mg acceptors, both of which would result in depletion of holes. Hence, it is plausible to assume that the top oxidized GaN has its Mg doping compensated and the energy band bent downward to form a hole barrier that buries the p-GaN channel away from the top GaN surface."

The downward band bending pushes the depletion region under the recessed gate to extend through the p-GaN layer, reaching the AlGaN barrier. This enables enhancement-mode operation by turning off the buried p-channel at 0V gate potential.

The researchers compared their device with others previously presented in the scientific literature (Table 1). The team comments: "Among all the p-channel GaN MOSFETs, the one from this work exhibits the combination of high I_{ON}, high I_{ON}/I_{OFF}, the lowest sub-threshold swing (SS) and E-mode operation. Devices implemented on the platform with quaternary back-barrier and Schottky gate exhibit outstanding SS and I_{ON}, but suffers large gate leakage at the ON state." ■

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Author: Mike Cooke

Wide-bandgap next-generation semiconductor performance moving beyond standard technology

Giuseppe Vacca gives an overview summarizing the advantages of compound semiconductors compared with traditional silicon, including benefits from their use in many applications and where these new technologies are leading.

Silicon carbide (SiC) and gallium nitride (GaN) devices will increasingly replace established silicon technology because silicon has already reached the intrinsic limitations of its physical-electrical properties. Due to this, since 2007 silicon-based devices have no longer been able to keep pace with Moore's Law, and a plateau has appeared in the curve: Moore's prediction was that, every year, integrated circuit manufacturers should have been able to double the number of transistors that can fit on a single silicon chip. Instead, transistor size is decreasing at a slower rate; since 2007 the process of size reduction has slowed down notably.

The smallest silicon MOSFETs fabricated recently by Lawrence Berkeley National Labs (LBNL) have a width (channel length) of just 7nm, i.e. just one order of magnitude larger than the dimension of an individual silicon atom. With this geometrical size, quantum tunneling can occur and the device can lose the ability to control the flow of current. So, recent advances in development mean that silicon technology is approaching the theoretical physical limits of the material. Since the characteristics of silicon preclude further improvement in device performance, microelectronics R&D has become more challenging and requires great effort in terms of investment, and it sometime appears to be uneconomical because it is too expensive.

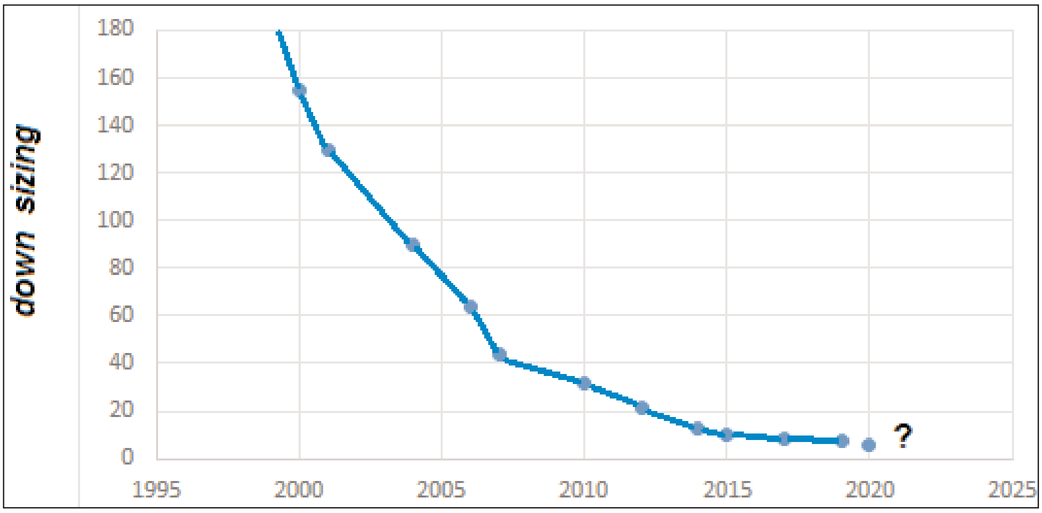

Figure 1. Moore's Law behavior.

Post-silicon materials

To overcome and improve the above performance limitations from silicon, in recent years the world's most important semiconductor players have been starting to adopt compound semiconductor materials.

In doing so, many companies have moved towards devices manufactured using silicon germanium (SiGe), silicon carbide (SiC), gallium arsenide (GaAs) and gallium nitride (GaN). Amongst these, the most

MATERIAL PROPERTIES	4H-SiC	GaN	Si
Band Gap Energy [ev]	3.26	3.39	1.12
Critical Electrical Field [kV/cm]	3400	3550	300
Electron Mobility [$cm^2/V*s$]	950	1300	1400
Saturation Velocity [$cm*10^6/s$]	22	25	10
Thermal Conductivity [W/cm*K]	4	1.55	1.5

common are currently silicon carbide (4H-type) and gallium nitride, which are driving significant innovation in the semiconductor industry and are likely candidates to replace traditional silicon devices in the near future.

While SiC and GaN are both binary compounds containing equal proportions of their constituent atoms, the III–V compound GaN has a wurtzite-type crystal structure, whereas the IV–IV compound SiC has an hexagonal structure with two kind of polytypes: 6H-SiC and 4H-SiC. The latter has become prevalent because it exhibits identical electron mobility along the horizontal and vertical crystal planes, whereas 6H-SiC is anisotropic.

The table compares material properties for silicon carbide (4H-SiC), gallium nitride (GaN) and silicon (Si), showing how those properties have a major influence on the fundamental device performance.

Silicon carbide and gallium nitride are quite similar to each other in terms of physical characteristics of the material, yielding many important benefits compared with traditional silicon counterparts by offering fundamental advantages with features 3–4 times better than silicon.

In some parameters GaN appears slightly superior than SiC. However, SiC works well in high-temperature environments because its thermal conductivity is significantly better than that of GaN.

For both GaN and SiC, their high breakdown voltage, high electron mobility and saturation velocity make them suitable candidates for high-power applications. In particular, the higher critical electrical field makes these compounds very attractive for power systems due to having outstanding values of specific on-state resistance ($R_{ds\text{-}on}$). Based on these key factors, a significant reduction in on-state power conduction loss can be achieved. At the same time, such devices can reduce switching power losses due to the lower input capacitances compared with silicon transistors.

With these features, such new devices are becoming the best candidates for the management of very high-power systems. Indeed, GaN HEMTs and SiC MOS seem perfect for very high-speed switching equipment. Such wide-bandgap semiconductors show the best results in many key applications compared with traditional silicon switching power devices like insulated-gate bipolar transistors (IGBTs) and power-MOS.

Regarding the requirement for high power, researcher have no doubts that in the future switching frequencies will rise to exploit the full benefits obtainable from GaN and SiC device characteristics being much better than those of conventional devices. This will allow the achievement of improved performance combined with a significant downsizing of devices and related equipment.

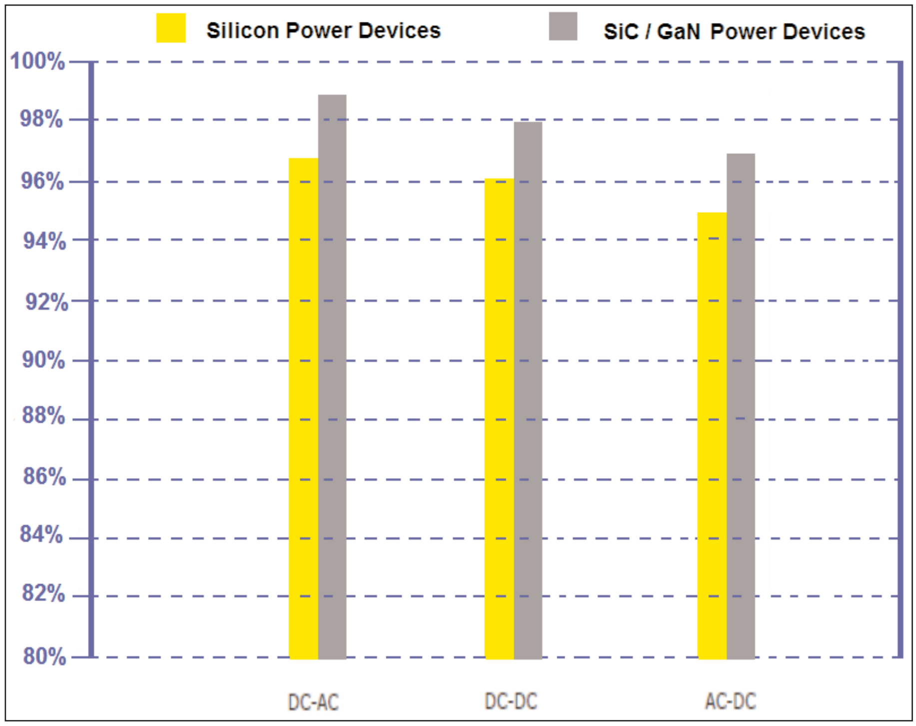

Figure 2. Expected efficiency improvement in switching power conversion using SiC/GaN devices.

GaN and SiC power semiconductors have emerged as such devices find application in inverters, hybrid & electric vehicles (HEVs), converters, uninterruptible power supplies (UPS) and other high-power applications, moving the field beyond silicon's limits; they are driving innovation in power semiconductors: scaling, costs, performance and design opportunities are all important factors for evaluating these two materials, which represent the new paradigm in power electronics.

Even for RF and microwave applications, the demand for higher frequencies is at the point where it is not easy to use only the available silicon RF power devices. Before the advent of wide-bandgap semiconductors, due to silicon's low breakdown voltage it was not possible to design and fabricate transistors that could yield radio-frequency output power of hundreds to thousands of watts, and this issue has seriously limited the use of solid-state technology in RF high-power and microwave applications. Recent improvements in the growth of compound semiconductor materials in SiC- and GaN-based devices have demonstrated impressive performance by offering the opportunity to now design and manufacture microwave transistors that exhibit performance previously achievable only by using vacuum tube technology.

The most promising electronic devices for these RF power applications are metal-semiconductor field-effect transistors (MESFETs) fabricated with 4H-SiC and heterojunction field-effect transistors (HFETs) fabricated using AlGaN/GaN heterojunctions; these devices can provide RF output power of 5–6W and 10–12W per mm of gate periphery, respectively.

4H-SiC MESFETs produce useful performance at least through X-band frequencies (7–12.5GHz) while AlGaN/GaN HFETs should produce useful performance well into the millimeter-wave region, and potentially as high as 100GHz.

GaN devices are expected to radically change the power electronics sector, starting with 100W power supplies and also impacting the field of RF power amplifiers thanks to the same characteristics that make them suitable for conversion and power systems.

SiC technology is finding application in higher-power products such as motors, electric drives and inverters or frequency converters, Powertrain inverters and on-board charger (OBCs) are playing in general an important role in the future of electronics because they have great potential in high-power applications and at radio-frequency and microwave frequencies over 10GHz. SiC can withstand higher temperatures before failure, and also its thermal conductivity is more than three times better than silicon. In practice these attributes promise high-frequency, high-temperature operation (managing working temperatures above 150°C) at high voltage and high power levels.

Why wide-bandgap materials?

Work on wide-bandgap materials and devices has been going on for a few years because the properties of these materials promise substantial performance improvements over their corresponding silicon-based devices.

In semiconductors, the bound electrons are located in distinct bands of energy levels (the valence band and the conduction band) around the atomic nucleus. Given an amount of energy corresponding to the difference in energy between the bands, electrons can jump from the top of the valence band to the bottom of the conduction band, making them available for current flow. The characterization of a material is related to the energy required for an electron to jump this gap between the energy bands. In wide-bandgap semiconductors this value is much greater than that for silicon. In general, materials that require energies typically larger than 2 electron volts (eV) are called wide-bandgap semiconductors.

Specifically, the bandgap energies of 3.26eV for SiC and 3.39eV for GaN are about three times higher than silicon's 1.12eV, which translates to a breakdown voltage and critical electric field at least one order of magnitude higher. The excellent performance resulting from these properties can conveniently be exploited in RF power amplifiers and efficient power electronics equipment and related systems, so wide-bandgap semiconductors allow new devices to operate at much higher voltages, frequencies and temperatures than conventional semiconductors.

As a direct consequence of this, using silicon carbide and gallium nitride technologies with their potential future developments allows them to provide higher energy in an extremely effective and efficient manner, reducing power loss and therefore improving average efficiency by up to 4% and simultaneously diminishing die size and enabling downsizing of 3–4 times.

On the other hand, new wide-bandgap (WBG) semiconductors can handle a much higher level of power than traditional devices with the same active area. So, fabricating devices with an equal level of performance, it is possible to achieve significant downsizing in dimensions, simplifying thermal management, saving on heatsinking and related costs.

The pursuit of higher power density paired with higher working voltages, frequencies and efficiency are the most important factors currently driving electronics innovation in numerous global industries, including data centers, renewable energy, consumer electronics, electric vehicles (EV) and autonomous vehicles (AV), in general making them very interesting for all future electronic applications.

Tech differences between SiC and GaN

Currently there is a great deal of on-going discussion, questions and different approaches regarding gallium nitride versus silicon carbide in order to make the right choice, what kind of devices can be fabricated, and what kind of device or material is best suited for various switching and RF power applications. Material properties, device architectures, size reduction and cost saving are all important and inter-related factors that drive this decision. In any case, SiC and GaN will surely play important roles in the future, although each will settle into its own niche.

An analysis of the differences between the two main WBG material platforms GaN and SiC allows us to understand which solution is more advantageous regarding possible requirements such as output power, voltage level, performance capabilities and cost saving. The key criterion for choosing a system design is primarily how GaN or SiC can increase the competitive advantage and at the same time reduce operating expenditure (OpEx) and capital expenditure (CapEx), as well as grow profit and market share, compared with silicon-based devices (being the baseline standard in the semiconductor industry for many years).

GaN systems offer users more options due to being a robust and easy-to-manage solution, reducing the time to market compared with SiC devices. Recently GaN devices have achieved significant gains in this sector, with increases in efficiency and power density having benefits for consumers and enterprises alike, whether it's a smaller form factor and a faster charging

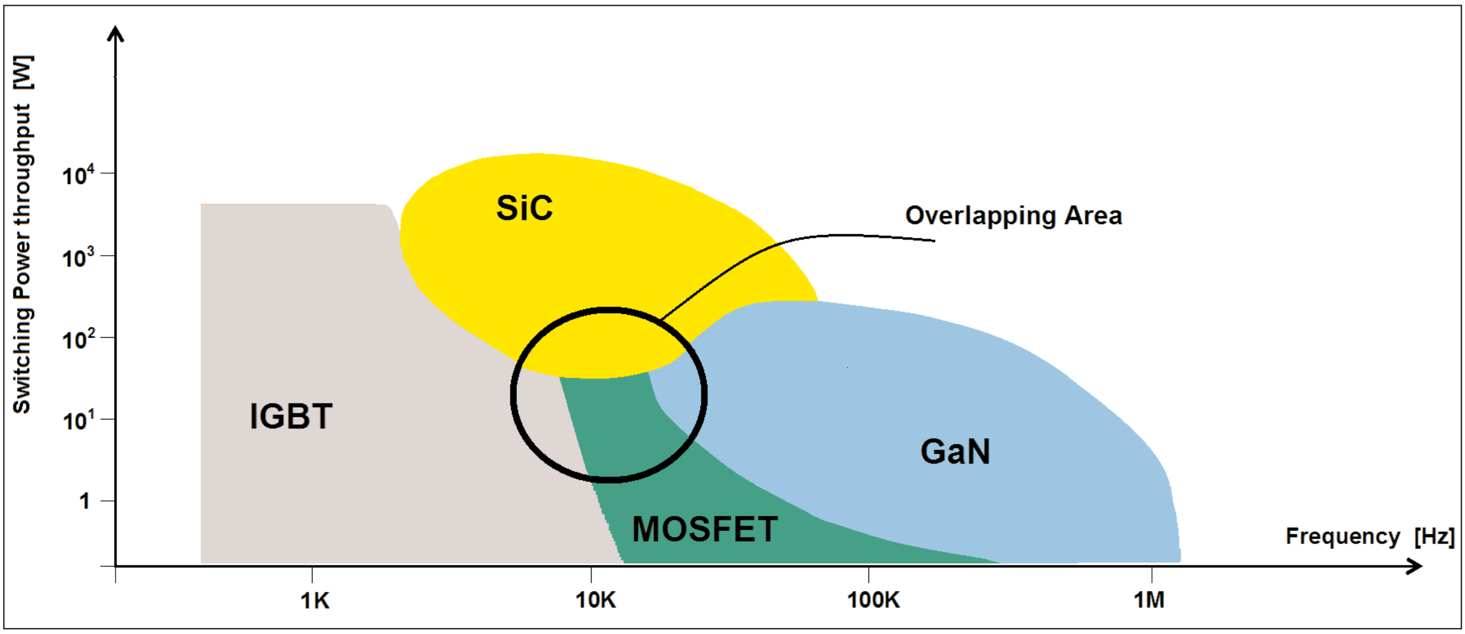

Figure 3. Overlapping area in Power versus Frequency diagram.

rate in consumer adapters or reductions in cooling costs and wasted energy for data centers and other applications in which SiC is involved to some extent.

It is possible to compare first-generation GaN devices with the recent fifth generation of SiC devices. The performance gap is expected to widen, with GaN performance growing 5–10 times in the mid to long term because systems built with GaN will have greater power density improvement than those built with SiC. With GaN, new power systems with smaller size are emerging because SiC cannot be used to create systems as small as GaN.

SiC semiconductors are more expensive and, above all, SiC displays supply-chain limitations compared with GaN; as the industry has proven repeatedly, when volumes go up, prices come down, and GaN prices can easily be projected to be competitive with silicon over time, especially since GaN can be produced on silicon wafers (using CMOS processing).

SiC has limited supply due to a small number of suppliers and supply-chain constraints, resulting in lead times of up to a year. Due to this it is thought that SiC is not expected to meet the demand of electric vehicle manufacturing in 2025 and beyond.

While SiC is in short supply, the demand for GaN is rising steadily, with manufacturing and material costs declining. Automotive, industrial and other applications that require smaller size, lighter weight and more efficient operation are increasingly being designed using GaN.

Regarding production, GaN is infinitely scalable as it can be made on the same silicon wafers with similar machines and equipment that is used to fabricate CMOS devices. This is not true for SiC. GaN will soon be capable of being fabricated on 8”-, 12”- and even 15”-diameter wafers, while SiC MOSFETs are typically only fabricated on 4” wafers currently and are migrating to 6” wafers.

From an electrical point of view, in the case of the requirements of the low-to-medium voltage range, GaN shows more favorable results, whereas SiC results prevail if used in high-voltage applications, i.e. greater than 1200V, because in the low-to-medium voltage range (below 1200V) GaN’s switching losses are about three times less than SiC at 650V. Regarding operating frequency, most silicon-based designs today work at 60–300kHz. Doubling the switching frequency to 120kHz achieves some improvement (more so with GaN than with SiC), yet the power density issue is not well solved. The need is to go to 500kHz or higher, and this can only be accomplished with GaN; it has superior ability to meet a power system’s voltage levels from 30V to 1200V, so it supports key power-dependent sectors such as consumer electronics, renewable energy, automotive, and industrial applications.

SiC is generally designed for working voltages of 1200V and higher, with some product availability at 650V. With a restricted solution set below 1200V, SiC is limited in the design of a wide variety of power systems. In fact, there is no role for SiC in important markets such as 30–40V devices in consumer electronics, and 48V in hybrid electric vehicles and data centers. Silicon carbide’s most important feature is the maximum junction temperature, which reaches at least 200°C, i.e. 50°C higher than the absolute maximum temperature rating of other semiconductors (150°C typical). This advantage allows SiC power devices to work well in hot and hostile environments, avoiding performance de-rating and related problems regarding mean time to failure (MTTF) and life-time, while achieving an appreciable increase in quality and reliability.

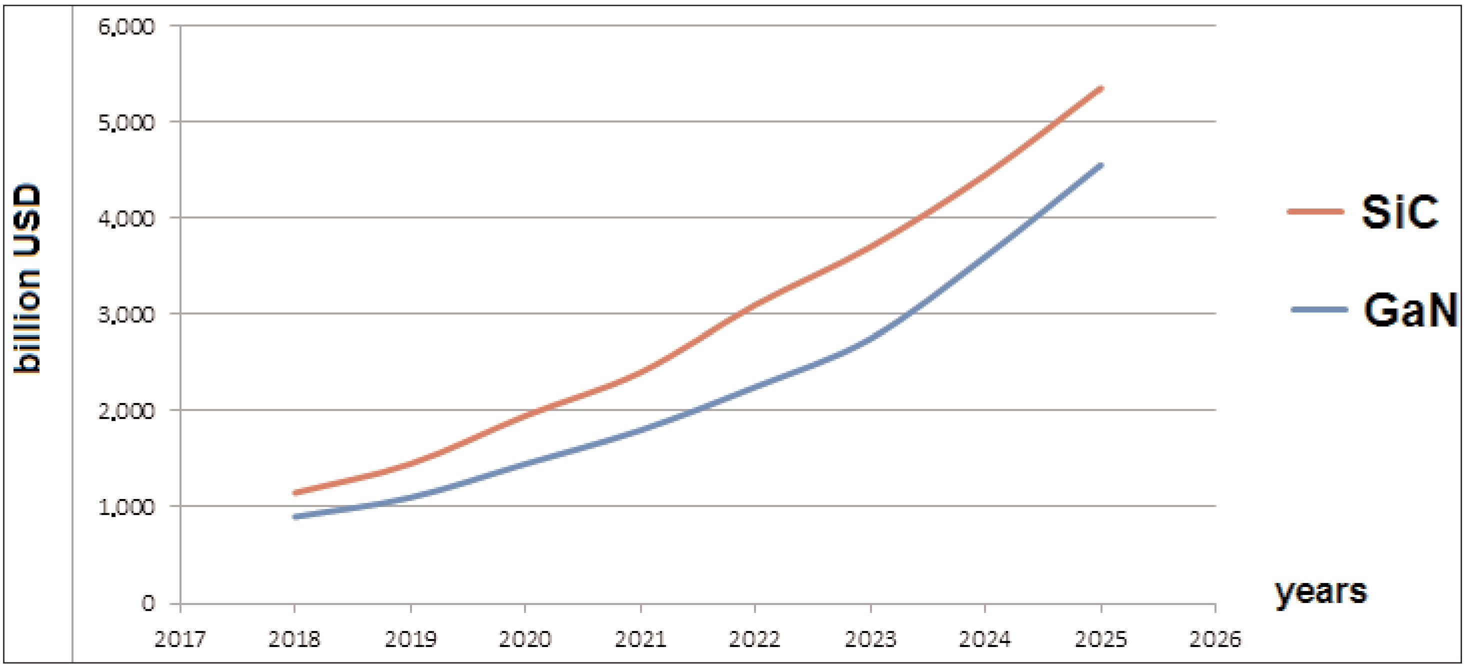

Figure 4. GaN and SiC device market forecast for next five years.

A common area where all solutions can be applied is in the Power versus Frequency relationship (see Figure 3): only in the future will one particular technology prevail over other technologies.

Users currently relying on SiC will need to move to GaN soon for two reasons: limited material supply and the rising cost of keeping up with the increasing power demands in industries ranging from data centers to automotive applications. Shifting directly from silicon to GaN now can save the need to transition from SiC to GaN later in order to catch up with the competition. GaN-powered devices are superior due to benefits such as a low gate charge, zero reverse recovery current and flat output capacitance, all of which yield high-quality switching performance.

GaN foundry is a way to not only improve existing product offerings but also to create innovative solutions to remain competitive. Regarding the semiconductor industry transition, GaN is now going from 'early adoption' to 'mass production'.

SiC and GaN forecast

Even if GaN seems to be projected as a great protagonist in the future, at the moment SiC represents the main semiconductor material used to manufacture innovative power devices, because SiC currently comprises the largest share of investment in R&D, both by microelectronic design centers and foundry.

In the next five years, silicon carbide is forecasted to comprise the largest wide-bandgap power market, followed by gallium nitride (considering power and RF devices together).

Figure 4 shows that, in the next few years, the SiC and GaN sectors will develop rapidly. Sales of SiC and GaN power devices have brought a lot of opportunities, and more companies will enter the industry, especially in developing countries. Specifically, the graph focuses on SiC and GaN devices in the global market, including North America, Europe and Asia-Pacific, South America, Middle East and Africa.

Regarding the wide-bandgap device market for power semiconductors specifically, the compounded average growth rate (CAGR) is expected to be greater than 32% over the next five years; reaching about US$2000m in 2024.

Looking further afield, according to another study, the GaN and SiC power semiconductor market will grow at a CAGR of 35% from $1bn in 2020 to about $10bn in 2027. ■

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Author:
Giuseppe Vacca PhD,
senior hardware design engineer,
SITAEL SpA,
Mola di Bari, Bari, Italy.
E-mail: giuseppe.vacca@sitael.com
www.sitael.com

Adding indium selenide to prospects for 2D electronics

Mike Cooke looks at work exploring properties and possibilities of the material.

Indium selenide (InSe) is a recent addition to the stable of two-dimensional (2D) materials where the crystal structure can consist of relatively easily separated layers. This results from an atomic lattice with strong in-plane bonds and weak 'van der Waals' bonds between the layers. The 2D nature of van der Waals materials is achieved by moving from bulk material to progressively thinner layers down to a monolayer (ML).

Two relatively recent open-access reviews/studies of the InSe's electronic and other properties, and its prospects, are: Danil W. Boukhvalov et al, Nanomaterials vol7, p372, 2017 [doi:10.3390/nano7110372] and A. Politano et al, Scientific Reports vol7, p3445, 2017 [doi:10.1038/s41598-017-03186-x]. According to these, lateral field-effect transistors can reach effective electron mobility values beyond ~1000cm^2/V-s.

A number of polytypes have been studied, some with direct bandgaps around 1.25–1.30eV in the near infrared (950–1000nm wavelengths). Such a bandgap could be useful in extracting energy from solar radiation and more generally for photodetection at shorter visible wavelengths (790–450nm). The bandgap gets wider, and the corresponding photon wavelength shorter, as the material becomes thinner due to quantum confinement effects. In addition, the character of the bandgap shifts to an indirect one, which inhibits light emission. Some indirect polytypes have bulk gaps of ~1.4eV (885nm).

Here we look at some recent reports on work developing InSe for use in electronics.

Vertical field-effect transistors

Northwestern University in the USA reports on its recent work probing the conduction properties of InSe vertical field-effect transistors(VFET) in contrast to the more usual lateral devices [Vinod K. Sangwan et al, Appl. Phys. Lett., vol115, p243104, 2019]. The researchers comment: "By elucidating fundamental vertical charge transport mechanisms in InSe, this work provides guidance to ongoing efforts to employ InSe in vertical heterostructures, photovoltaics, photo-detectors, and related vertical device technologies."

The devices used a silicon back-gate configuration with the 2D layers manipulated on an oxidized layer of silicon dioxide (SiO_2, Figure 1). The InSe was positioned

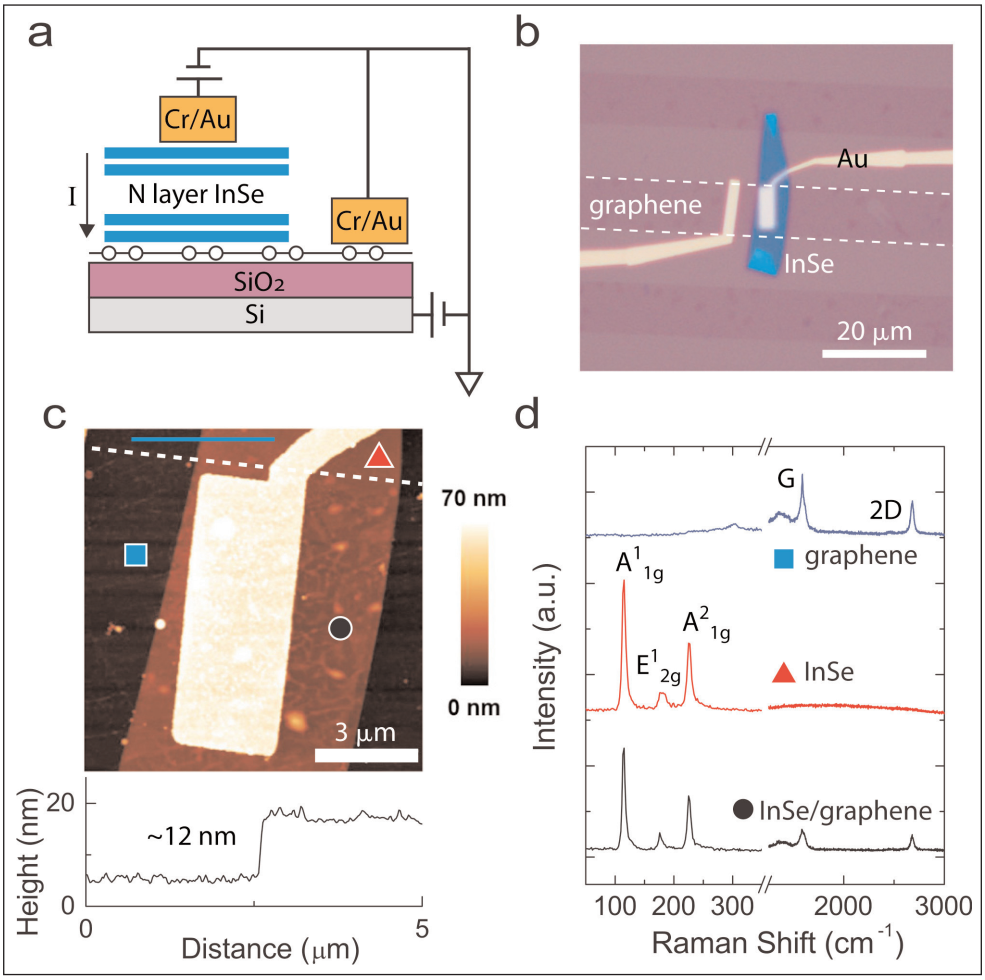

Figure 1. (a) Schematic of graphene-InSe VFET on oxidized Si substrate. (b) Optical image. White dashed lines show etched graphene stripes. (c) Atomic force microscopy topography image (top). Height profile (solid blue line) shows 12nm InSe flake thickness (bottom). White dashed line marks graphene edge. (d) Raman spectral peaks for graphene (blue square in (c)), InSe (red triangle), and combined InSe/graphene (black circle) regions.

on patterned graphene. The top drain electrode consisted of chromium/gold (Cr/Au), which gives an ohmic contact with InSe. The graphene layer provided the grounded source.

The InSe flakes were mechanically exfoliated from material supplied by American Elements Corp. Mechanical exfoliation describes the creation of flakes of material by application of sticky Scotch tape to bulk material.

The components for the transistor were handled in an inert nitrogen environment to avoid performance degradation from surface contamination and so on. Measurements were made in vacuum conditions with the pressure less than $5x10^{-5}$Torr. Some 14 samples were studied with the InSe thickness ranging from 9.5nm up to 43nm.

With the drain positively biased, the graphene/InSe interface was found to have a reverse-biased Schottky barrier (Figure 2). The silicon back-gate modulated current flow through the barrier. The InSe was found to be unintentionally n-type in conduction behavior.

The maximum/minimum on/off current (I_{ON}/I_{OFF}) 'switching' ratio increased by a factor of 50 as the InSe thickness increased from 9.5nm to 43nm. This increase is attributed to a higher Schottky barrier in the contact between graphene and the thicker material, reducing the off-current leakage.

The on current density was of the order 5–10 down on what is found in black phosphorus (BP) VFETs. The researchers explain: "Black phosphorus has a smaller bandgap (~0.3eV in bulk), higher intrinsic doping, and an out-of-plane electron lone pair in phosphorus, which enhance out-of-plane conductivity."

The InSe switching ratio was $\sim10^4$ for thicker layers, while that of comparable BP devices is ~50. The transition-metal dichalcogenide, tungsten diselenide (WSe_2), gives switching of more than 10^6.

Reducing the device temperature from 295K to 190K resulted in an increase in the switching ratio by a factor of around six. While there was a decrease in conductivity at the lower temperature, there was also a more rapid decrease in off-current leakage.

There was a larger conductivity variability in thicker InSe flakes — this suggests a more thermionic emission behavior with hot electrons crossing above the barrier rather than Fowler–Nordheim quantum tunnel-

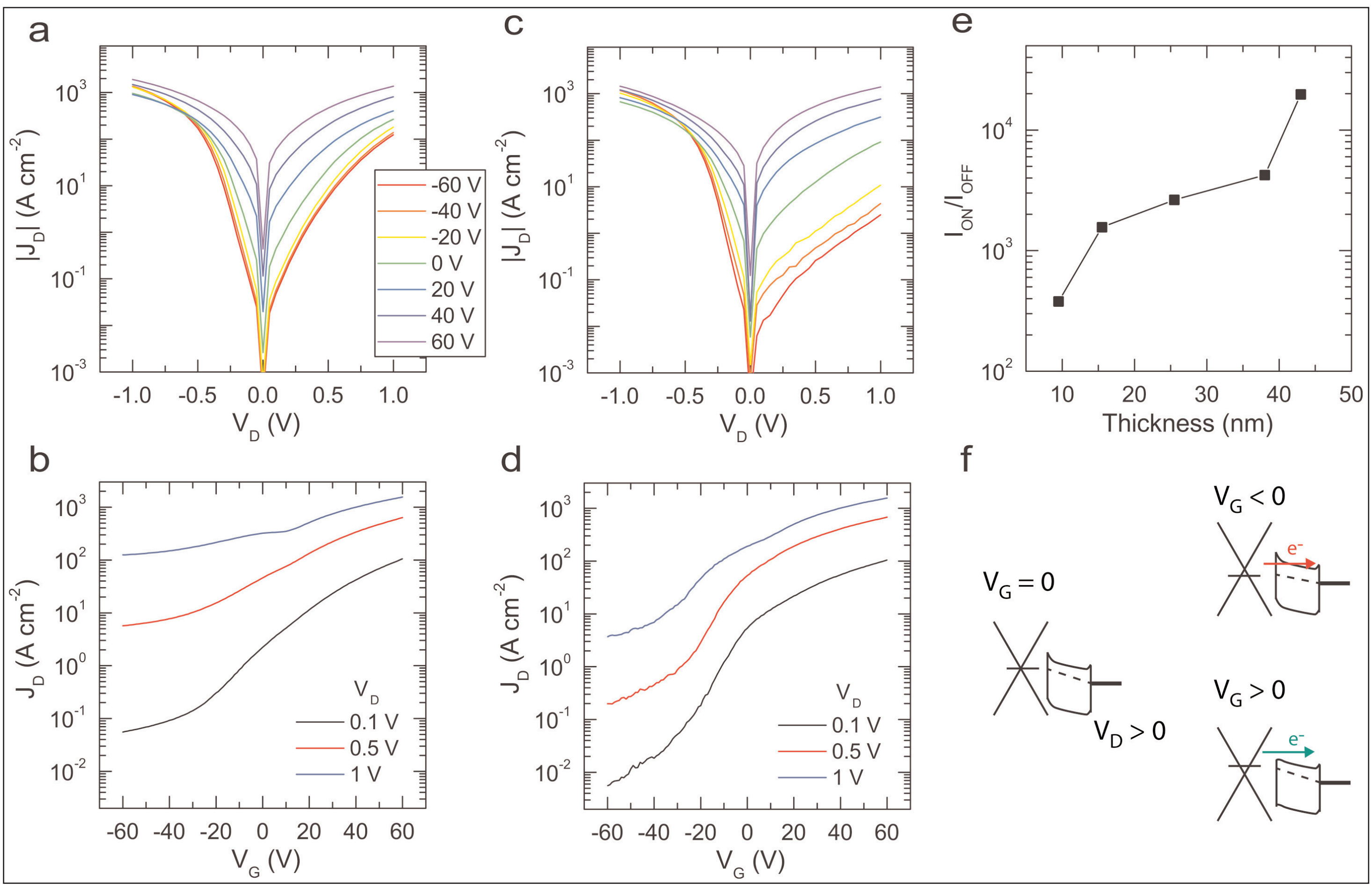

Figure 2. Room-temperature charge transport characteristics of InSe VFETs. (a) Current density (J_D) versus drain voltage (V_D) output characteristics of thin InSe VFET. (b) J_D versus gate voltage (V_G) transfer characteristics of thin InSe VFET. (c) Output characteristics of thick InSe VFET. (d) Transfer characteristics of thick InSe VFET. (e) I_{ON}/I_{OFF} switching ratio versus InSe thickness. (f) Schematic band diagrams of InSe VFET with zero, negative, and positive back-gate bias.

ing through the barrier. By contrast, devices with thinner InSe layers showed a relatively constant Schottky barrier height of ~100meV. The thick InSe VFETs had about a two-fold increase in extracted Schottky barrier height at room temperature, relative to 190K.

The analysis led the researchers to attribute an out-of-plane effective mass of 2.57x that of a free electron at 190K. Previous cyclotron resonance and optical absorption measurements gave values in bulk InSe ranging from 0.25x (20K) to 34.3x (200K).

The team comments: "Layered materials often show large anisotropy of the effective mass and carrier mobility (μ), which results in InSe VFETs possessing intrinsically weaker out-of-plane transport ($\mu_{\perp}/\mu_{||}$ = 0.002 for InSe)." The researchers also point out that the 2.57x value "is substantially higher than the in-plane effective mass." They do not provide a comparison figure for the latter.

Optoelectronic structures

Researchers in the UK, Spain and Portugal have found that 2D InSe has infrared emissions that are preferentially in-plane, which could expand the capabilities of 2D optoelectronics [Mauro Brotons-Gisbert et al, Nature Communications, vol10, p3913, 2019].

The team from Heriot–Watt University in the UK, Universidad de Valencia in Spain and International Iberian Nanotechnology Laboratory (INL) in Portugal attribute the emission to excitons — bound electron–hole pairs — with a dipole moment directed out-of-plane (OP).

Other 2D semiconductors such as the transition-metal dichalcogenides (TMDs) tend to have excitons with the dipole pointing in-plane (IP) with emission directed out of the plane of the semiconductor. The transition metals used include molybdenum (Mo) and tungsten (W), combined with two chalcogenide atoms such as Se or sulfur (S). Other 2D materials with IP dipoles include black phosphorus and cadmium selenide.

The IP dipole orientation is desirable for out-coupling radiation through vertical structures. However, for in-plane photonic waveguide circuits, the OP orientation is more useful. The researchers also say that "OP dipoles present higher Purcell enhancements and couple more efficiently than IP ones to multimode

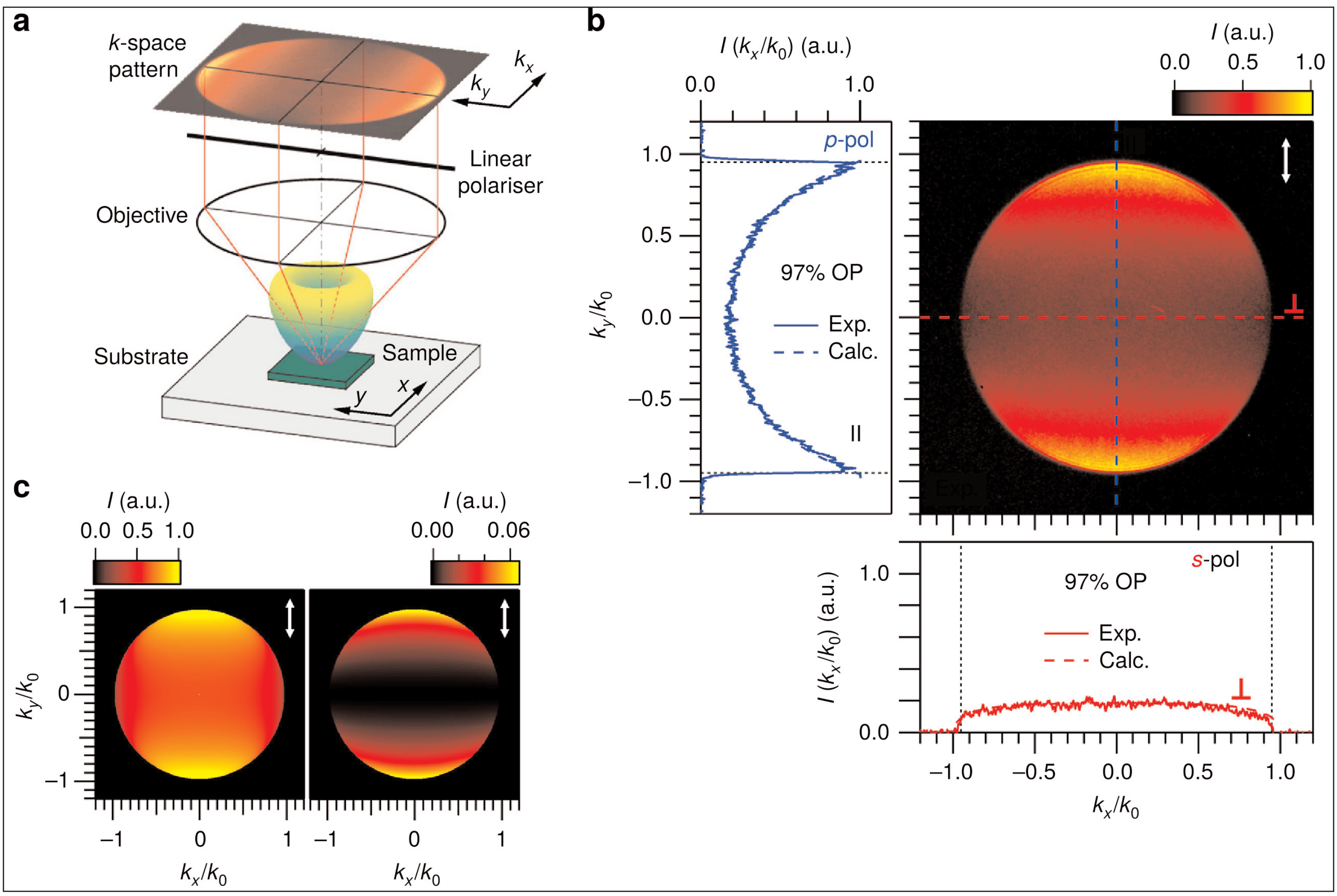

Figure 3. (a) Basic concept of k-space spectroscopy. (b) Intensity-normalized k-space emission pattern of InSe flake as function of IP photon wavevector normalized to that in air. White arrow in top right indicates linear polarizer axis orientation. Blue and red solid lines (left and bottom) show experimental k-space cross-sections || and ⊥ to polarizer (blue and red dashed lines, respectively). (c) Normalized emission patterns calculated for pure IP (left) and pure OP (right) dipoles.

cylindrical waveguides and optical fibers when placed in the vicinity of the waveguides." Purcell enhancement refers to increased spontaneous emission rates due to environmental effects, such as being placed in a resonant cavity.

The researchers comment: "The orbital nature of the electronic states at the bandgap edges makes 2D InSe a valuable building block in the design of van der Waals heterostructures with tailored optoelectronic properties. On the one hand, the strong p_z orbital nature of the top valence band endows InSe with one of the largest bandgap tunability ranges found in a 2D semiconductor when its thickness varies between the bulk and the ML. On the other hand, electronic states of p_z orbital nature are even under mirror symmetry operation; combining these states with the odd symmetry of the bottom of the conduction band determines the OP orientation of the luminescent excitons in this 2D semiconductor."

Study of the polarization and directionality of the light from photoluminescence (PL) on a thick 90nm InSe layer showed exciton emissions with an out-of-plane dipole distribution of 97% (Figure 3). The substrate for the experiment was a 105nm SiO_2 layer on silicon. Reducing the flake thickness to 8nm, around 10 monolayers, 2D InSe demonstrated an OP distribution of 95% (Figure 4). Compared with the 90nm flake, there was a blue-shift in the emission of 5meV from 1.244eV. The blue-shift is attributed to the 2D quantum confinement increasing the effective bandgap.

The researchers also studied $MoSe_2$ and WSe_2, since there was the possibility of 'grey' IP excitons with state splitting leading to allowed and forbidden transitions. The researchers comment: "Low-temperature PL measurements of ML WSe_2 and WS_2 with high-NA objectives have shown that grey excitons contribute significantly to the emitted PL signal, making the low-temperature PL of these semiconductors originating not exclusively from IP dipoles but from a combination of IP and OP dipoles. However, a quantitative and unambiguous determination of the contribution of the grey excitons to the room-temperature PL of W-based TMDs is still missing."

The team's experimental work suggests that the IP contribution at room temperature is in fact 100% for WSe_2.

The researchers are part of the European project 'Quantum Flagship'. The Valencia participants are also part of the Instituto de Ciencia de Materiales (ICMUV), which is advancing a 'Scalable Two-Dimensional Quantum Integrated Photonics' (S2QUIP) venture with the aim of developing "circuits of quantic photonics by integrating two-dimensional semiconductor materials that are compatible with CMOS technology, often used when manufacturing traditional integrated circuits". Such work could also lead to progress towards quantum information processing.

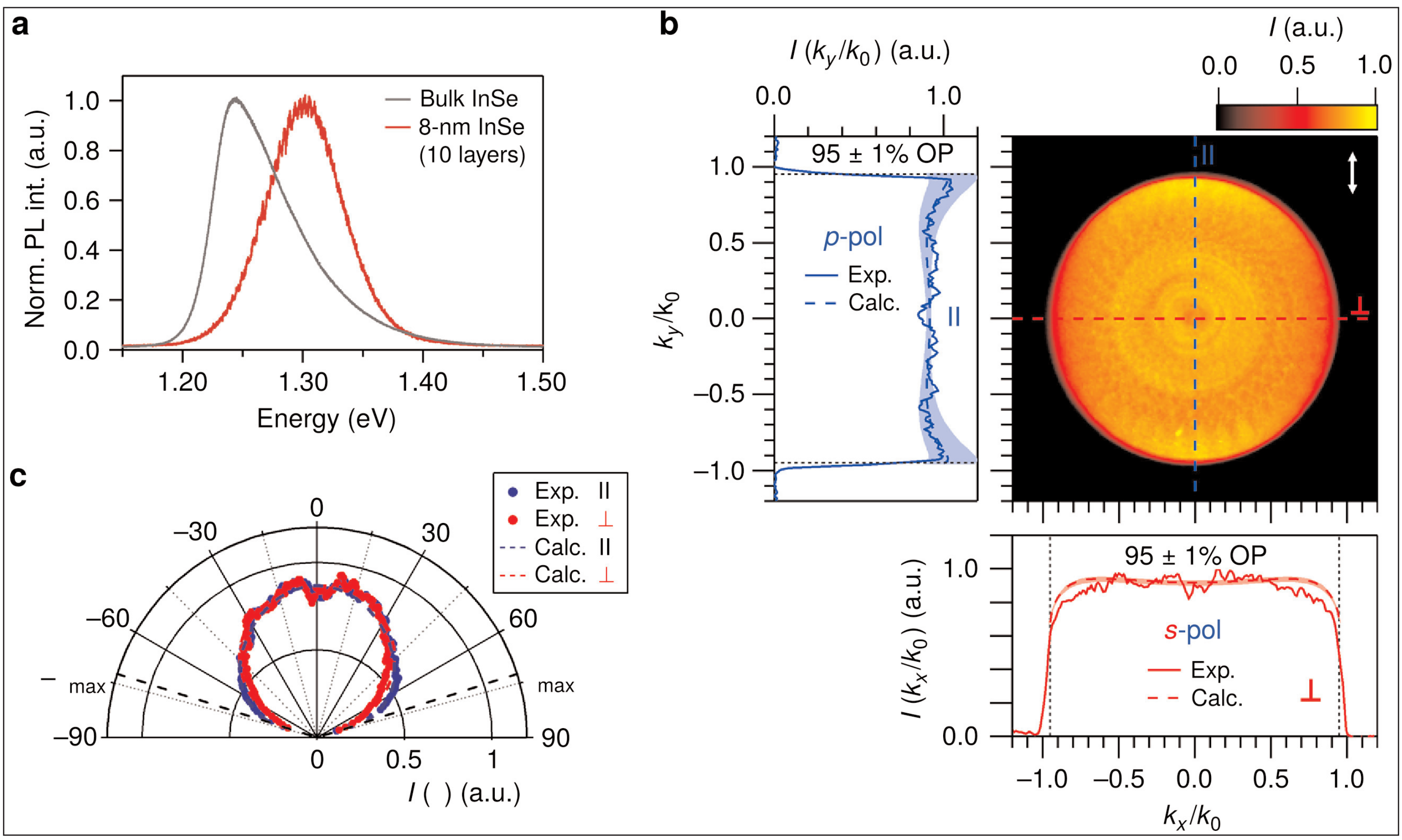

Figure 4. (a) Comparison of intensity-normalized room-temperature PL of bulk and 8nm-thick InSe. (b) Emission pattern of 8nm-thick InSe flake. (c) Measured and calculated far-field patterns as function of angle θ.

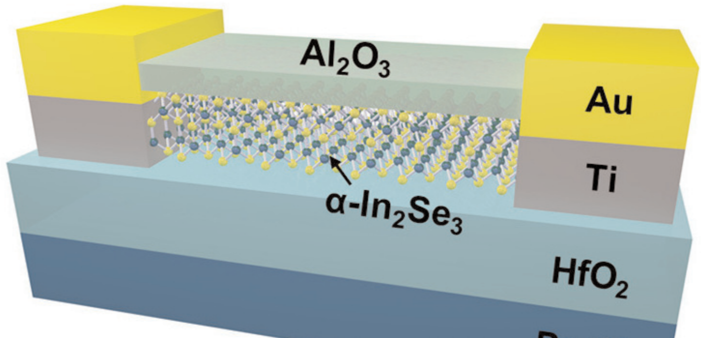

Figure 5. Schematic diagram of an α-In_2Se_3 FeS-FET.

Ferroelectric performance

A couple of presentations at the most recent IEEE International Electron Devices Meeting (IEDM 2019) in December reported work developing InSe devices using the material's ferroelectric and piezoelectric properties.

Purdue University and Georgia Institute of Technology in the USA described using both the ferroelectric and semiconducting nature of α-In_2Se_3 as the channel material for a 'synaptic' device [Session 6.6]. The ferroelectric semiconductor field-effect transistor (FeS-FETs) consisted of 30nm hafnium dioxide (HfO_2) and InSe channel on p^+-Si substrate with titanium/gold source–drain electrodes (Figure 5). The transistor used the p^+-Si as a back-gate. The InSe was grown by chemical vapor transport. The bulk InSe was found to have a bandgap of around 1.39eV, according to photoluminescence analysis.

The team has also used chemical vapor deposition (CVD) to grow atomic-scale InSe layers on SiO_2. The researchers hoped that such techniques will provide "a clear route for future large-area fabrication and integration".

Piezo-force microscopy showed two stable states of the Se atom in the crystal structure, giving different ferroelectric dipole moments in the lateral and vertical directions. The team suggests that these properties could be used to create planar and cross-bar ferroelectric–semiconductor junction (p- and c-FSJ) performance (Figure 6).

The p-FSJ is given simply by biasing the source–drain electrodes to control the in-plane polarization. A c-FSJ would consist of crossed metal wires above and below the InSe, controlling out-of-plane polarization. The vertical polarization can also be controlled by using the gate of the FeS-FET configuration. The devices used varying thicknesses of InSe: 15.9nm for the FeS-FET, 57.5nm for a p-FSJ, and 120nm and 70nm for two c-FSJ structures.

A c-FSJ was used as a synaptic device in a training simulation based on the MLP+NeuroSimv3.0 device-to-system evaluation framework for neuro-inspired accelerators in the compute-in-memory (CIM) paradigm. The device achieved ~92% accuracy in an adaptive momentum estimation training algorithm. There were 31 conductance states defined.

Extrapolating to a notional 32nm node, the team expects the device to demonstrate the lowest latency and energy consumption compared with alternative structures. The device benefits from a short write pulse width (low latency) and large on-resistance (reduced energy drain).

Piezoelectric strain sensing

National University of Singapore and Singapore's Institute for High Performance Computing have used InSe as a flexible strain sensor for human-activity monitoring (IEDM 2019, session 26.6]. The three-terminal device, claimed as a first using InSe, depended on the changes of bandgap as the 2D material was strained, which in turn affected the conductivity. The gauge factor (GF) was 32 and 36 even at low respective tensile and compressive strains of 0.25%.

The researchers see 2D materials able to sustain large deformations without breaking as an important component of wearable, flexible devices. An advantage of InSe over other 2D options, such as graphene or transition-metal dichalcogenides, is a factor of ten lower Young's modulus (23GPa, compared with 100–300GPa), which means InSe is more easily deformed. In fact, the InSe modulus is comparable with that of organic semiconductors.

Photoluminescence experiments showed the emission peak of a 15nm-thick flake varying from more than 1.45eV (–0.96% compression) to less than 1.25eV (+0.96% tension), giving a slope of ~100meV/% over a 200meV reversible tunability range.

The three-terminal device was fabricated on polyimide (PI) flexible

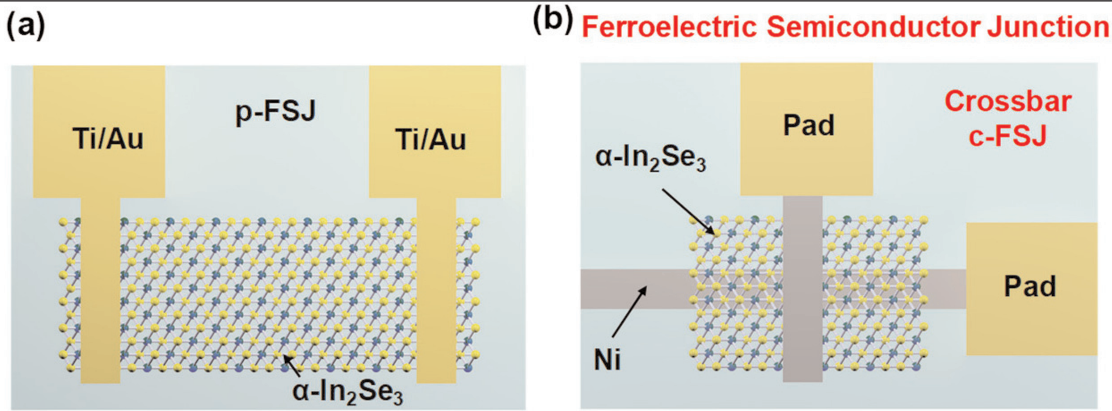

Figure 6. Top-view schematics of (a) p-FSJ and (b) c-FSJ.

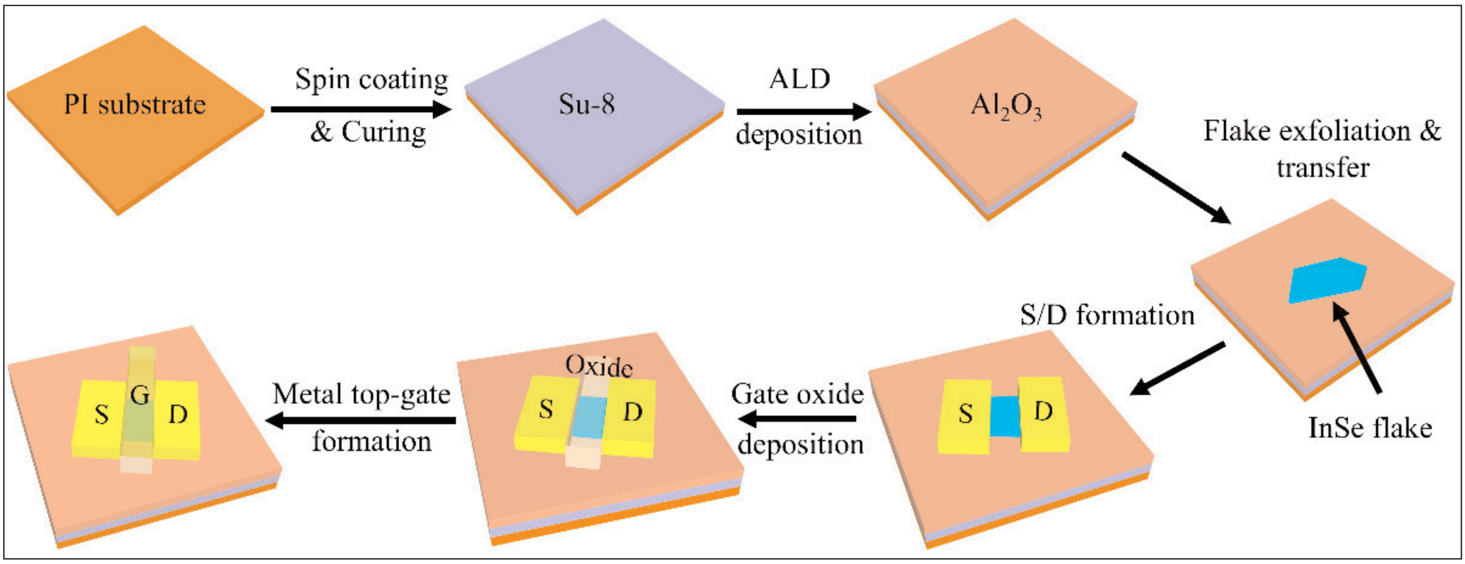

Figure 7. Process flow for realizing flexible three-terminal InSe based strain sensor on polymeric substrate.

polymer (Figure 7). First, SU-8 photoresist was spin-coated onto the PI and cured to reduce surface roughness. Then, 30nm aluminium oxide (Al_2O_3) was atomic layer deposited (ALD) at 150ºC. A mechanically exfoliated InSe flake was transferred to the substrate on a poly(methyl methacrylate) (PMMA) carrier. The source and drain electrodes consisted of 20nm chromium (Cr) and 100nm gold (Au). The gate stack was 23nm ALD Al_2O_3 insulation and 20nm/100nm Cr/Au. Patterning was via laser lithography.

The effect of strain on piezoresistance was to decrease with tension and increase with compression. Piezoconductance naturally showed the opposite tendency. The piezoresistance versus strain curve was well described by a linear fit. This is seen as "indicating the promise of InSe for strain sensor applications to monitor human motion activities, which outperforms other organic/inorganic strain sensors with highly nonlinearity properties."

The gauge factor was defined as the relative change in resistance from the zero-strain value per strain ($(\Delta R/R_0)/\varepsilon$). For tensile strain, the best gate voltage was around 1V (~8x), while compressive strains experience a ~7x improvement in gauge factor with the gate at 0.5V (Figure 8).

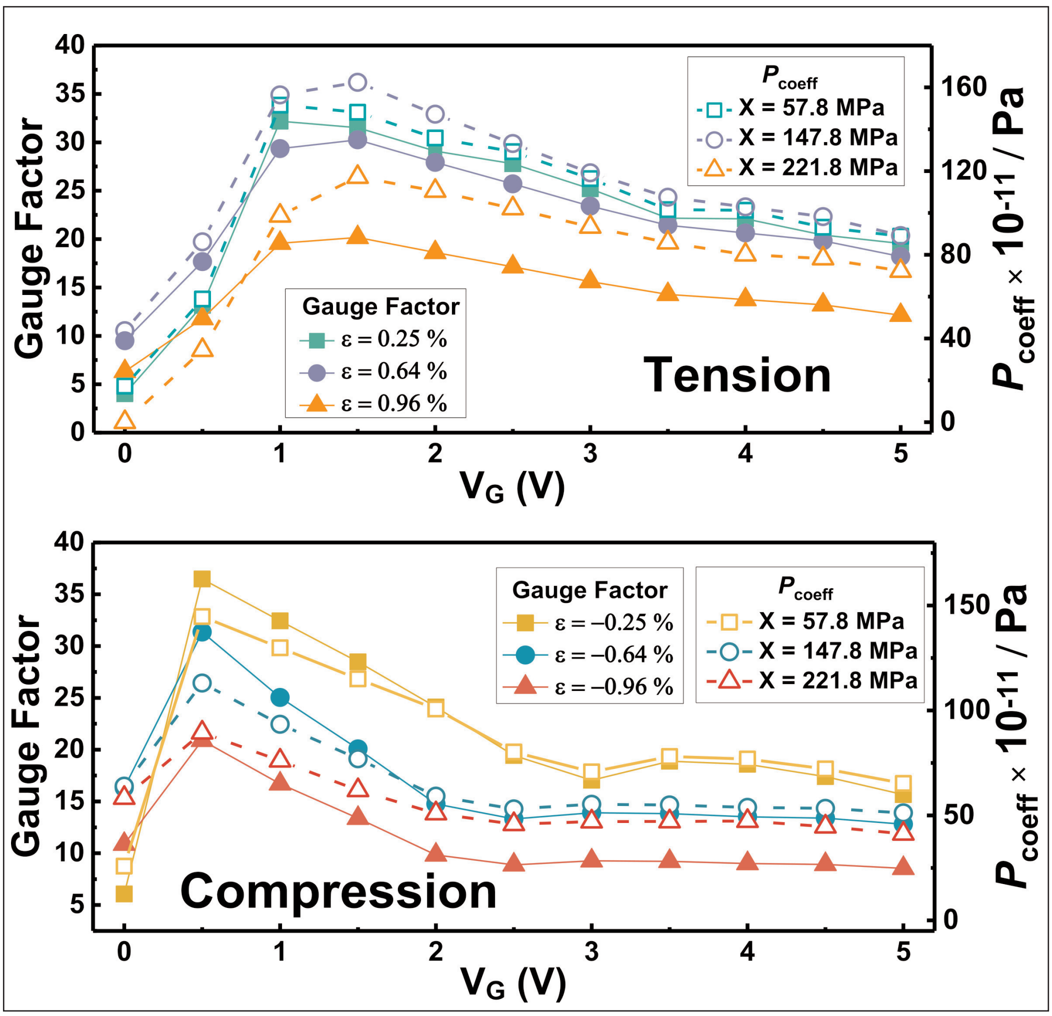

Figure 8. GF and P_{coeff} as function of applied gate voltage (V_G) under (top) tension and (bottom) compression.

Piezoresistance coefficient is the relative change in conductance per stress X ($P_{coeff} = (\Delta G/G_0)/X$). ■

The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.

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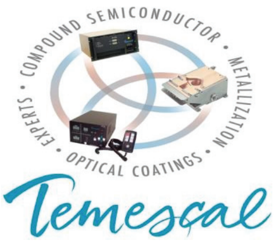

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www.epak.com

Gel-Pak
31398 Huntwood Avenue,
Hayward, CA 94544, USA
Tel: +1 510 576 2220
Fax: +1 510 576 2282
www.gelpak.com

Wafer World Inc
(see section 3 for full contact details)

Materion Advanced Materials Group
2978 Main Street,
Buffalo, NY 14214,
USA
Tel: +1 716 837 1000
Fax: +1 716 833 2926
www.williams-adv.com

16 Assembly/packaging equipment

Ismeca Europe Semiconductor SA
Helvetie 283, La Chaux-de-Fonds,
2301, Switzerland
Tel: +41 329257111
Fax: +41 329257115
www.ismeca.com

Kulicke & Soffa Industries
1005 Virginia Drive,
Fort Washington, PA 19034,
USA
Tel: +1 215 784 6000
Fax: +1 215 784 6001
www.kns.com

Palomar Technologies Inc
2728 Loker Avenue West,
Carlsbad, CA 92010,
USA
Tel: +1 760 931 3600
Fax: +1 760 931 5191
www.PalomarTechnologies.com

TECDIA Inc
2700 Augustine Drive, Suite 110,
Santa Clara, CA 95054,
USA
Tel: +1 408 748 0100
Fax: +1 408 748 0111
www.tecdia.com

17 Assembly/packaging foundry

Quik-Pak
10987 Via Frontera,
San Diego, CA 92127,
USA
Tel: +1 858 674 4676
Fax: +1 8586 74 4681
www.quikicpak.com

18 Chip foundry

Compound Semiconductor Technologies Ltd
Block 7, Kelvin Campus,
West of Scotland, Glasgow,
Scotland G20 0TH,
UK
Tel: +44 141 579 3000
Fax: +44 141 579 3040
www.compoundsemi.co.uk

United Monolithic Semiconductors
Route departementale 128,
BP46, Orsay, 91401,
France
Tel: +33 1 69 33 04 72
Fax: +33 169 33 02 92
www.ums-gaas.com

19 Facility equipment

MEI, LLC
3474 18th Avenue SE,
Albany, OR 97322-7014,
USA
Tel: +1 541 917 3626
Fax: +1 541 917 3623
www.marlerenterprises.net

20 Facility consumables

W.L. Gore & Associates
401 Airport Rd, Elkton,
MD 21921-4236,
USA
Tel: +1 410 392 4440
Fax: +1 410 506 8749
www.gore.com

21 Computer hardware & software

Ansoft Corp
4 Station Square,
Suite 200,
Pittsburgh, PA 15219,
USA
Tel: +1 412 261 3200
Fax: +1 412 471 9427
www.ansoft.com

Crosslight Software Inc
121-3989 Henning Dr.,
Burnaby, BC, V5C 6P8,
Canada
Tel: +1 604 320 1704
Fax: +1 604 320 1734
www.crosslight.com

Semiconductor Technology Research Inc
10404 Patterson Ave.,
Suite 108, Richmond, VA 23238,
USA
Tel: +1 804 740 8314
Fax: +1 804 740 3814
www.semitech.us

22 Used equipment

Class One Equipment Inc
5302 Snapfinger Woods Drive,
Decatur, GA 30035,
USA
Tel: +1 770 808 8708
Fax: +1 770 808 8308
www.ClassOneEquipment.com

23 Services

Henry Butcher International
Brownlow House, 50–51
High Holborn, London WC1V 6EG,
UK

Tel: +44 (0)20 7405 8411
Fax: +44 (0)20 7405 9772
www.henrybutcher.com

M+W Zander Holding AG
Lotterbergstrasse 30,
Stuttgart, Germany
Tel: +49 711 8804 1141
Fax: +49 711 8804 1950
www.mw-zander.com

24 Consulting

Fishbone Consulting SARL
8 Rue de la Grange aux Moines,
78460 Choisel,
France
Tel: + 33 (0)1 30 47 29 03
E-mail: jean-luc.ledys@neuf.fr

25 Resources

Al Shultz Advertising Marketing for Advanced Technology Companies
1346 The Alameda,
7140 San Jose, CA 95126,
USA
Tel: +1 408 289 9555
www.alshuktz.com

SEMI Global Headquarters
3081 Zanker Road,
San Jose,
CA 95134,
USA
Tel: +1 408 943 6900
Fax: +1 408 428 9600
www.semi.org

Yole Développement
45 rue Sainte Geneviève,
69006 Lyon,
France
Tel: +33 472 83 01 86
www.yole.fr

event calendar

If you would like your event listed in *Semiconductor Today*'s Event Calendar, then please e-mail all details to the Editor at mark@semiconductor-today.com

8–12 March 2020
OFC: The Optical Networking and Communication Conference & Exhibition
San Diego Convention Center, San Diego, CA, USA
E-mail: OFC@compusystems.com
www.ofcconference.org

12–14 March 2020
International Conference on Nano Research and Development (ICNRD-2020) — Breakthrough and Innovation in Nano Science and Technology
Grand Copthorne Waterfront Hotel, Singapore
E-mail: laura@icnrd.com
www.istci.org/ICNRD2020/Program.asp

15–19 March 2020
IEEE Applied Power Electronics Conference and Exposition (APEC 2020)
Ernest N. Morial Convention Center, New Orleans, LA, USA
E-mail: apec@apec-conf.org
www.apec-conf.org

29 March – 2 April 2020
2020 IEEE International Reliability Physics Symposium (IRPS)
Hilton DFW Lakes Executive Conference Center, Dallas, TX, USA
E-mail: IRPSreg@ieee.org
www.irps.org

15–17 April 2020
EPIC Annual General Meeting 2020
Radisson Blu Hotel Lietuva, Vilnius, Lithuania
E-mail: neringa.norbutaite@epic-assoc.com
www.epic-assoc.com/epic-annual-general-meeting-2020

21–23 April 2020
24th Annual Components for Military & Space Electronics Conference & Exhibition (CMSE 2020)
Four Points by Sheraton (LAX), Los Angeles, CA, USA
E-mail: info@tjgreenllc.com
www.tjgreenllc.com/cmse

26–29 April 2020
2nd International Conference on UV LED Technologies & Applications (ICULTA 2020)
MELIÃ Hotel, Berlin, Germany
E-mail: contact@iculta.com
www.ICULTA.com

4–6 May 2020
16th International Conference on Concentrator Photovoltaic Systems (CPV-16)
Golden, near Denver, CO, USA
E-mail: info@cpv-16.org
www.cpv-16.org

7–8 May 2020
EPIC Meeting on Nanophotonics for Communication, Sensing and Data Processing at Nanoscribe
Karlsruhe, Germany
E-mail: neringa.norbutaite@epic-assoc.com
www.epic-assoc.com/epic-events

advertisers' index

10–15 May 2020
2020 Conference on Lasers & Electro-Optics (CLEO)
San Jose Convention Center,
San Jose, CA, USA
E-mail: CLEO@compusystems.com
www.cleoconference.org

11–14 May 2020
CS MANTECH:
2020 International Conference on Compound Semiconductor Manufacturing Technology
JW Marriott Starr Pass, Tucson, AZ, USA
E-mail: registration@csmantech.org
www.csmantech.org

17–21 May 2020
32nd International Symposium on Power Semiconductor Devices and ICs (ISPSD 2020)
Hofburg Palace, Vienna, Austria
E-mail: ispsd2020@guarant.cz
www.ispsd2020.com

21–26 June 2020
Microwave Week,
including:
IEEE MTT-S International Microwave Symposium (IMS 2020)
Radio Frequency Integrated Circuits Symposium (RFIC 2020)
Automatic Radio-Frequency Techniques Group Conference (ARFTG)
Los Angeles, CA, USA
E-mail: e.niehenke@ieee.org
www.ims-ieee.org

21–23 July 2020
SEMICON West 2020
Moscone Center, San Francisco, CA, USA
E-mail: semiconwest@semi.org
www.semiconwest.org

22–25 July 2020
International Congress on Advanced Materials Sciences & Engineering (AMSE-2020)
Vienna, Austria
E-mail: eve@istci.org
www.istci.org/amse2020

23–27 August 2020
SPIE Optics + Photonics 2020
San Diego Convention Center, San Diego, CA, USA
E-mail: customerservice@spie.org
https://spie.org/Optics_Photonics

23–28 August 2020
International Workshop on Nitride Semiconductors (IWN 2020)
Maritim Hotel Berlin, Germany
E-mail: iwn2020@conventus.de
www.iwn2020.org

23–28 August 2020
9th International Conference on Optical, Optoelectronic and Photonic Materials and Applications (ICOOPMA)
University of Pardubice, Czech Republic
E-mail: info@icoopma.com
www.icoopma.com

7–11 September 2020
22nd European Conference on Power Electronics and Applications (EPE 2020 ECCE Europe)
Lyon, France
E-mail: info@epe2020.com
www.epe2020.com

9–11 September 2020
22nd China International Optoelectronic Exposition (CIOE 2020)
Shenzhen World Exhibition & Convention Center,
Shenzhen, China
E-mail: cioe@cioe.cn
www.cioe.cn/en

13–18 September 2020
23rd European Microwave Week (EuMW 2020)
Utrecht, The Netherlands
E-mail: eumwreg@itnint.com
www.eumweek.com

20–24 September 2020
46th European Conference on Optical Communication (ECOC 2020)
Brussels Expo, Brussels, Belgium
E-mail: info@ecoc2020.org
www.ecoco2020.org

10–13 November 2020
SEMICON Europa 2020
Munich, Germany
E-mail: SEMICONEuropa@semi.org
www.semiconeuropa.org

6–8 December 2020
2020 IEEE 51st Semiconductor Interface Specialists Conference (SISC)
San Diego, CA, USA
E-mail: mpasslack@ieeesisc.org
www.ieeesisc.org