

semiconductor**TODAY**

C O M P O U N D S & A D V A N C E D S I L I C O N

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CS MANTECH report

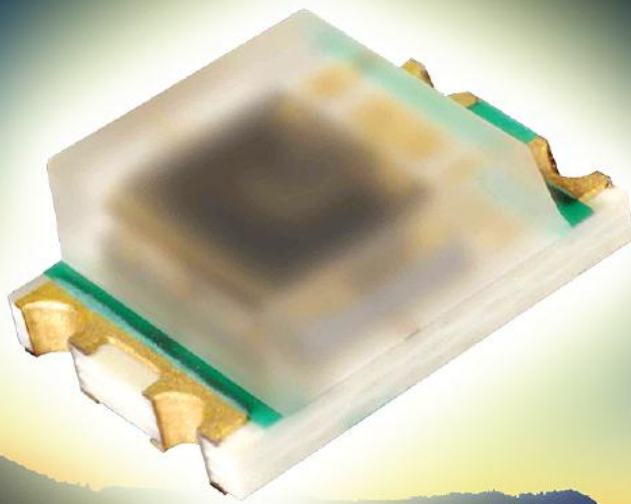
GaAs RFIC sector upbeat

GaAs technology

Enhanced BiFETs

Nitride substrates

Bridging the gap

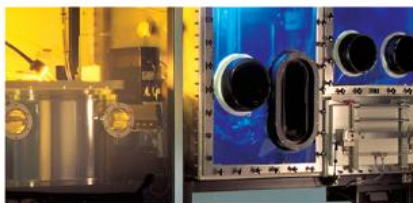


Optical telecoms: the next wave • GaAs pHEMT expansions
GaN HEMT launches • Asia tools up for GaN HB-LEDs

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Beaten-up industry turns upbeat

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Contribute to Semiconductor Today

Semiconductor Today wants to hear from researchers, engineers and managers interested in contributing articles. If you have an idea for a Feature article or a one-page Opinion article, then please contact the Editor, Mark Telford, at mark@semiconductor-today.com

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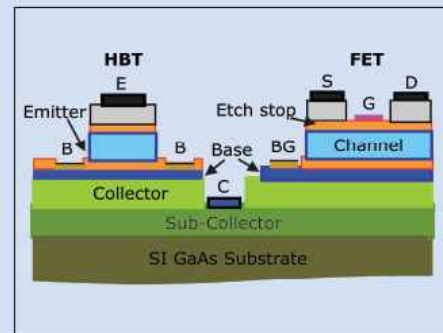
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Welcome to a digital dawn

Welcome to the launch issue of *Semiconductor Today*, the first digital-only magazine for the compound semiconductor and advanced silicon industries, published independently by a dedicated team with many years of experience in the semiconductor industry.

Each of the 10 issues a year is accessible free via a web-link delivered by e-mail to a global circulation involved in the manufacturing and R&D of compound semiconductor and advanced silicon materials and devices.

Editorial content covers devices such as RF ICs, light-emitting diodes, lasers, photodiodes and photovoltaic cells, as well as applications including wireless and fiber-optic communications, displays, solid-state lighting, and solar power generation, based on the following types of materials:

- III-V materials (gallium arsenide, indium phosphide, nitrides etc);
- II-VI materials (cadmium mercury telluride, zinc selenide etc);
- IV-IV materials (silicon carbide, silicon germanium etc); and
- Advanced silicon (e.g. strained silicon and silicon-on-insulator).

For example, this issue features articles on GaAs (both BiFET technology and manufacturing developments reported at the CS MANTECH conference), InP, and nitride substrates. News sections cover market forecasts as well as business and technical developments in microelectronic, optoelectronics, and equipment and materials. Highlights include expansions in GaAs pHEMT manufacturing capacity for mobile phones, the launch of GaN HEMT power transistors by both Cree and RF Micro Devices, and substrate developments (both larger-diameter GaN and AlN substrates, and III-Vs on silicon).

Compared to a print-based magazine, which can take several weeks to print and then distribute and have circulations restricted in reach and number, *Semiconductor Today* can go from creating content to reader receipt in days (without being tied to print schedules) and has unrestricted distribution worldwide. Forwarding to colleagues anywhere is fast and easy, and is encouraged. Also, content is interactive: clicking on any web address cited in the editorial or advertising content will link to the corresponding website.

See www.semiconductor-today.com, where you can view our issue publishing schedule and editorial calendar of upcoming feature topics, and register for free to join the circulation of both *Semiconductor Today* magazine and its weekly E-Brief newsletter.

Also included are full details about how to submit proposed content for *Semiconductor Today*, for both the news pages and contributed articles. We encourage suggestions for editorial coverage, so we look forward to hearing from you!

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***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 RF ICs, lasers and LEDs in wireless and optical communications etc).

Regular issues contain:

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

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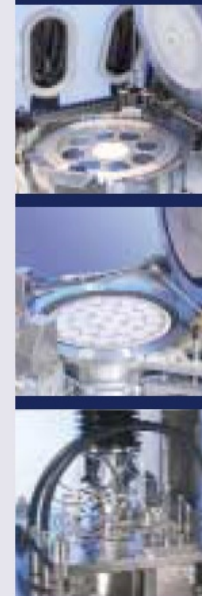
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 **Thomas Swan**

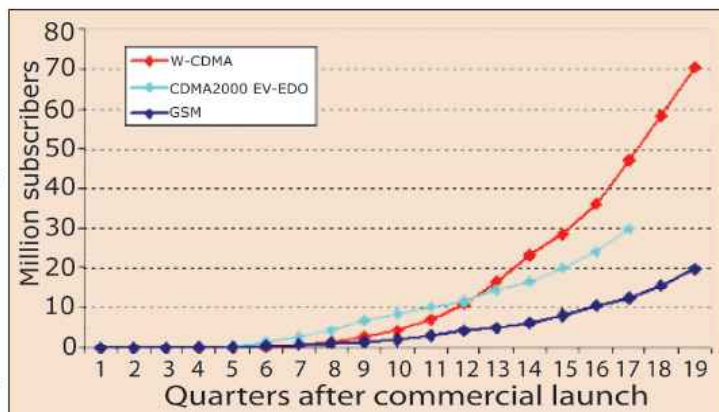
 **EPIGRESS**

3G users pass 100m, driven by West European operators

The number of people using WCDMA and CDMA2000 1x EV-DO 3G mobile technology is growing faster than GSM in the early 1990s, reaching 106m by mid-2006, says Strategy Analytics' report 'Global 3G Subscribers Hit 100 Million Mark in June'.

Complementing a rich portfolio of handsets, "much is due to the strong pushes by influential carriers like NTT DoCoMo, Hutchison 3G and SK Telecom, and more recently Vodafone and Verizon Wireless, who have worked hard to drive 3G uptake among their subscribers," says Sara Harris, senior industry analyst.

Western Europe has overtaken Japan as the 3G leader. "However, the US market is set to grow rapidly in 2007, when Cingular rolls-out its HSDPA coverage in an attempt to catch up to the first-mover advantages enjoyed by Verizon Wireless and Sprint Nextel, companies which have benefited from Qualcomm leadership in EV-DO," added David Kerr, vice



Subscribers by technology (source: Strategy Analytics).

president of Strategy Analytics' Global Wireless Practice.

www.strategyanalytics.com

Wi-Fi/cellular convergence

Shipments of cellular handsets containing Wi-Fi will exceed 132m devices by 2010, forecasts In-Stat in 'The Road to Convergence: Wi-Fi/Cellular Handsets Get a Voice'.

"In the end, most US cellular carriers will embrace Wi-Fi in their handsets, as carriers know that, if they don't, other carriers will," says Allen Nogee. "Combo handsets also offer carriers opportunities to provide services such as VoIP over Wi-Fi, lessening impact on their cellular data system," he adds.

Over 20 handset models have been, or soon will be, released with embedded Wi-Fi access. Some carriers are already planning to offer services that support voice calls over both cellular and Wi-Fi, and some Wi-Fi/cellular handsets are incorporating VoIP clients for services like Skype.

www.instat.com

Wireless handset market to grow 23% in 2006, then to \$250bn by 2011

The wireless handset market will grow 23% from \$110bn in 2005 to \$136bn in 2006, then more slowly to \$250bn in 2011 (more than doubling, from 935m units), reports In-Stat in its report 'The Big Trends for Cell Phones, 2006-2011'.

But this depends on phone manufacturers continuing to add features that consumers value and that the industry can support. The greatest challenge is to add the features that different customers want without adding cost or complexity from unneeded or unwanted features.

The goal for wireless phone makers is to make users forget they ever tolerated a phone without the new innovations. Fewer than 5% of US users do not use at least one of the technological innovations introduced over the past several years, reports In-Stat.

Consumers now seem ready to embrace other new features, including location-based services and Bluetooth connectivity, but only a narrow segment have interest in multimedia features, and camera-phone use will see a decline, says In-Stat.

"Big trends over the next five years include adoption of wireless phones as a mobile wallet, that and more users will carry multiple devices," says In-Stat analyst Bill Hughes.

"The primary changes in phones over the next five years are that they will become more capable, incorporate beefier security, and be more targeted as organizations have greater involvement in the wireless service decisions of their employees," Hughes adds in conclusion.

www.in-stat.com

HB-LED growth slowing to 15–20%

Strategies Unlimited's report 'High-Brightness LED Market Update and Forecast — 2006' says that HB-LED market growth slowed from an average annual rate of 46% over 2001–2004 to just 6.2% in 2005 (to \$3.9bn).

Reasons for this slowing in growth include saturation of the cell-phone market for full-colour displays and overcapacity in Asia leading to price erosion. Other HB-LED market sectors collectively grew at 18% in 2005. However, the mobile appliance segment still accounted for 52% of the HB-LED market in 2005.

As the mobile appliance application begins to saturate, the HB-LED market is entering a period of slower growth. For the next five years, growth may be 15–20% per year, rather than the historic 40–50%.

But even with these lower growth rates, the HB-LED market is still expected to reach \$8.3bn in 2010, well over twice the 2005 level. Growth will be driven by emerging applications such as illumination, automotive headlamps, and backlights for LCD monitors and TV screens.

<http://su.pennnet.com>

Optical components \$6.6bn by 2011

The market for optical components in telecom and datacom networks will grow from \$1.5bn in 2006 to over \$6.6bn in 2011, says Communications Industry Researchers (CIR) in its report 'Optical Components: The Next Wave'.

With continued build-out of more advanced and higher-capacity networks, the active components market will grow from just under \$1bn to almost \$4.8bn, due to the rapid penetration of fiber into enterprise and access networks needed to support passive optical networks (PONs), Fibre Channel, coarse wavelength division multiplexing (CWDM) and 10 Gigabit Ethernet (10 GigE) and the larger bandwidth applications riding over them.

Although there are just a few suppliers left (e.g. Intel, JDSU, Santur and Syntune), tunable laser shipments now number tens of thousands annually, and many equipment company and service provider RFPs also require them. CIR expects that sales of tunable lasers and transmitters should exceed \$460m by 2011.

CIR believes that firms that have developed reconfigurable optical add-drop multiplexers (ROADMs) over the past few years, such as JDSU, Metconnex, Optium, Optoplex and Xtellus, will finally see a payoff, as the ROADM market reaches almost \$300m by 2011.

40Gb/s networks are becoming a reality and may well be necessary for new video services on which many service providers are focusing. At the component level, 40Gb/s will increasingly represent an opportunity for those firms that can provide innovative ways of meeting the chromatic dispersion, polarization mode dispersion (PMD) and spectral efficiency challenges inherent in 40Gb/s networking.

CIR research indicates that the quality of products coming out of China and other low-labor-cost countries is often not good enough for high-end telecom/datacom products. It is possible that the movement towards Chinese manufacturing may be over, the firm concludes.

www.cir-inc.com

IN BRIEF

Ethernet driving 10G module ramp

The market for 10 and 40Gb/s optical communication modules based on semiconductor lasers and modulators will quickly expand from \$0.9m in 2005 to nearly \$4.3bn in 2011, says CIR in its report 'Market for 10G and 40G Modules'. The main reason will be deployment of products short-range 10Gb/s applications.

"The biggest story for 10G is the growth in Ethernet port sales, fuelled by the need for aggregating the surging number of ports on both business and even consumer computers," says CIR, citing increased optimism among both optical networking equipment vendors and component makers.

In 2006, sales of 10 and 40Gb/s modules for wavelength division multiplexing (WDM) and Ethernet applications should be \$266m and \$398m, respectively. However, in five years, the disparity will be clear. CIR predicts that the WDM market will grow by 179% to \$743m in 2011, but the Ethernet segment will grow six-fold to \$2.3bn. The Ethernet market for 10Gb/s modules should more than double in 2008 to over \$1.5bn.

Although the market for modules does not equate directly to that for lasers, many module suppliers also make III–V-based optical components. Avago and JDSU are the two biggest. But, since it supports all the standard module platforms, and is working on the new 'SFP+' form factor that should challenge today's standards before long, Sunnyvale-based Finisar may be in the best position to exploit the rapid growth of the market.

In 2011, 26m ports for 10Gb/s Ethernet will ship, equating to an average price just under \$90 per port, reckons CIR.

www.cir-inc.com

IN BRIEF

Ansoft & UMC team on MMIC design

Ansoft has implemented a GaAs IC design methodology for millimeter-wave frequencies using on-chip electromagnetic extraction and a new Ansoft Designer/Nexxim RF design kit for the PH15 pHEMT process of foundry United Monolithic Semiconductor.

"MMIC design at millimetre-wave frequency requires a combination of powerful circuit and accurate electromagnetic simulation of the whole circuit. Ansoft with Nexxim, Ansoft Designer and HFSS provides the level of performance and accuracy expected by UMS Foundry customers, especially those that perform Q, V or W band designs," said UMS' foundry manager Eric Leclerc.

The millimeter-wave qualified kit implements rigorous device modeling and validation by the foundry and is combined with advanced frequency-domain simulation for highly nonlinear and highly integrated circuits as well as integrated electro-magnetic simulation for on-chip extraction.

The Designer/Nexxim design kit supports electrical design and physical circuit layout, enabling reliable MMIC design at millimetre-wave frequencies. It provides all parameterized electrical models and layout cells for hot and cold FETs, diodes, MIM capacitors, spiral inductors, thin-film resistors and distributed interconnects.

The library is easily configured for use within the Ansoft Designer design management front-end, planar EM simulator and Nexxim circuit simulator. The kit is available on Microsoft Windows 2000 and XP, Red Hat Enterprise Linux v3 as well as Solaris 8 and 9 systems.

www.ansoft.com

Navy contract for S-band amplifiers

Via the Naval Research Laboratory, the US Office of Naval Research has awarded TriQuint Semiconductor a 20 month, \$3.1m contract to improve manufacturing methods at its Richardson, TX facility for producing high-power, high-voltage S-band GaAs amplifiers.

The contract program manager, TriQuint's director of R&D Anthony Balistreri, says its high-voltage pHEMT technology (developed since 2000) provides the higher power density and efficiency required for near-term production applications, including phased array radar, electronic warfare and communications systems. An advanced X-band process was developed under a previous ONR contract.

The two main objectives, split into phases, are: (i) an MMIC design optimization task; (ii) a manufacturing cost-reduction task. In the first phase, TriQuint will design an S-band high-power amplifier, to be updated throughout the program

and used to validate manufacturing process improvements. Goals include high power and efficiency with a minimum 24V operating voltage. The main focus is manufacturing, with two principal goals: reducing cost and improving throughput. 'Sub-tasks' will improve manufacturing variability, reduce cycle time, and improve wafer and device yields.

"This program will help TriQuint accelerate cost reductions, making the technology more affordable for near-term production programs," said TriQuint's principal investigator Dr Steve Evans. "TriQuint currently supplies high-volume, cost-effective foundry services and standard products based on high-voltage GaAs," said military business unit director, Dr Gailon Brehm. "This enhanced S-band technology provides the higher voltage needed for both military and commercial applications at frequencies below 6GHz."

www.onr.navy.mil

Design center reaches High Point

As part of its ongoing program to "work more closely with partners and customers to develop next-generation wireless modules and components", TriQuint Semiconductor is in August moving into a new North Carolina Design Center (NCDC) in High Point, NC, USA.

NCDC is TriQuint's second product development location to open in less than a year and its sixth overall. "It will further enhance TriQuint's creative resources and foster collaboration among engineers and scientific experts from both within the company and our customers throughout the Eastern Seaboard and our European staff," said VP Brian Balut.



TriQuint's North Carolina Design Center.

Staffed initially by six engineers (growing eventually to 20-25), its focus is to "leverage TriQuint's wireless expertise, translating that into new solutions for our customers," he added. Work will cover a wide array of GaAs and surface acoustic wave (SAW) technologies.

www.triquint.com

Filtronic expanding pHEMT foundry

Filtronic plc has agreed to sell its Wireless Infrastructure division's filter-based transmit receive module and power amplifier businesses (excluding power amplifier modules) by Q3/2006 to California-based wireless network solution supplier Powerwave Technologies, for \$150m in cash plus 20.7m shares (13% of Powerwave's stock).

While retaining its Defence Electronics division (which uses GaAs technology), much of the proceeds will go towards a £45m (\$83m) expansion of the 6" GaAs foundry in Newton Aycliffe, UK of its Compound Semiconductors division (whose sales grew 45% in the quarter to May). The fab had already ramped

up capacity for pHEMT switches (for cellular handset transmit modules), mainly for RF Micro Devices. Despite RFMD's aim to move pHEMT fabrication in-house, Filtronic aims to grow the compound business threefold in the next two years, driven by "strong long-term market growth as mobile handsets adopt switches based on GaAs pHEMTs, with the expectation that they will be used in around 80% of handsets produced by 2008".

To help finance the expansion, Filtronic already has an additional bank facility of £15m, available until end-November, bringing total bank facilities to £35m.

www.filtronic.co.uk



Filtronic's GaAs foundry in Newton Aycliffe, UK.

RFMD assembles 100 millionth module in its Beijing facility

RF Micro Devices has assembled its 100 millionth module in its Beijing assembly facility, which it attributes to continued strong sales of its portfolio of cellular power amplifiers.

"Our power amplifiers are found in approximately one half of the world's phones, and our customers include all of the world's major handset manufacturers," said president and CEO Bob Bruggeworth, while touring the facility. "We are particularly focused on supporting the growing presence of handset manufacturers in Asia, and we are committed to increasing our manufacturing capabilities in Asia as the region continues to evolve as the

handset industry's manufacturing centre," he added.

RF Micro Devices says that it is on track to double its assembly capacity in Beijing in response to the robust handset market and continued strong demand for its module products.

In addition, RF Micro Devices is also expanding its GaAs chip fabrication capacity at its headquarters in Greensboro, NC, USA. The company expects to increase total GaAs wafer capacity by about 40%.

RFMD said that both the assembly and fabrication expansions should be completed by Q4/2006.

www.rfmd.com

IN BRIEF

WJ and GCS team

US-based Global Communication Semiconductors has agreed to act as a second wafer source for InGaP HBT and GaAs technology for WJ Communications.

"This advantage provides our customers with two qualified sources, thereby ensuring a steady supply of wafers," said WJ's VP of operations Mark Knoch.

www.gcsincorp.com

www.wj.com

AWSC to triple GaAs capacity

To meet growing demand for handsets (expecting continued market growth over the next five years), Advanced Wireless Semiconductor Company (AWSC) aims to triple its GaAs foundry capacity from 1100 4-inch wafers per week to 3000 by the end of 2007, reported DigiTimes.

"The GaAs sector had been in the doldrums for more than a year due to over-supply until the second half of 2005, when demand began picking up. Currently, there is a supply shortage."

www.awsc.com.tw

Sumika grows pHEMT capacity

Sumitomo Chemical's epiwafer manufacturing subsidiary Sumika Electronic Materials of Phoenix, AZ, USA has ordered a E450 MOCVD system from Veeco Instruments to expand GaAs-based pHEMT production. Sumika originally added pHEMTs to its existing HBT and diode product lines in 2004.

"Sumika believes that the market for epiwafers will increase at an 8% compound annual growth rate through 2009, reflecting demand from the cellular market," said business development manager John Milliron of Sumika.

www.sumikamaterials.com

IN BRIEF

High-linearity HFET foundry for wireless infrastructure

III-V wafer foundry Global Communication Semiconductors Inc of Torrance, CA, USA has announced that it is offering its 0.5 μ m high-performance Heterostructure FET (HFET) process to address the high dynamic range requirement of base-station driver amplifiers.

With a breakdown voltage of 16V and a pinch-off voltage of -2.0V, the technology was developed for high linearity and is ideal for linear amplifiers that require high dynamic range, claims CEO Jerry Curtis.

"As a performance example at 2.0GHz, when biased at 8V and 50% I_{dss} , our 1.2mm HFET device can achieve an output power of 28.1 dBm with a Third Order Intercept (TOI) point of 48.5 dBm. With a 20.4 dB linear figure of merit, a difference between TOI and P1dB, our HFET is by far one of the most linear foundry processes ever available," claims Curtis. "Similar linear performance can also be achieved at 5.0V bias."

"The superior linearity makes it well suited for use in both analog and digital wireless communication infrastructure and subscriber equipment including 3G, cellular, personal communications systems (PCS) and fixed wireless system," continued Curtis.

GCS offers foundry service for InGaP and InP HBT, power and switch PHEMT processes (0.5 μ m and 0.25 μ m) and provides optoelectronic foundry services for various components such as PIN photodiodes, PIN POD arrays, avalanche photodiodes (APDs), VCSELs and lasers used in the fiber-optic communication market.

www.gcsincorp.com

WJ launches devices for base-stations

At June's 2006 IEEE MTT-S International Microwave Symposium in San Francisco, WJ Communications showcased a range of new III-V-based products for base-stations.

● High-performance 28V InGaP HBT PAs for mobile infrastructure

Developed from its 5V InGaP HBT process, WJ Communications has developed new +28V InGaP HBT process technology for mobile infrastructure power amplifiers.

"It offers significantly improved ACPR/ACLR performance at equivalent or higher efficiencies than LDMOS products," claims Morteza Saidi, VP of engineering. "Units can be operated as Class B amplifiers and still achieve very low ACPR/ACLR performance."

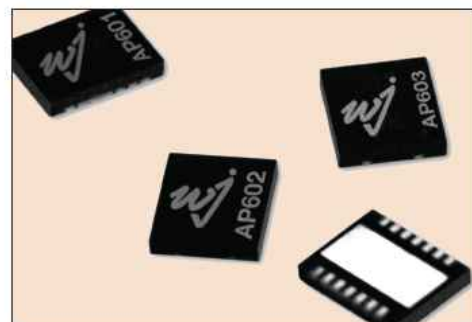
Several products up to 10W P1dB will be released in Q3/2006, but the technology is suitable for products with higher power as well.

The process has exceptional breakdown voltage and power handling capabilities, claims WJ. Lifetime tests have been run for over 4000 hours at 315C junction temperature with minimal beta degradation. The process can handle up to 6dB overdrive on the input without failure.

A new surface-mountable power QFN package incorporates a eutectic die attach to minimize thermal resistance and ensure highly reliable operation.

● Expanded 12V PA product line for mobile infrastructure

WJ has expanded its 12V power amplifier product line (which includes the 4W AP501, AP502, AP503, and AP504) with 8W InGaP-based modules in a small 13mmx9mmx4.1mm flange mount package. WJ says they are ideal as drivers for mobile infrastructure power amplifiers or as output stages in repeaters, for which low adjacent channel power is critical.



WJ's AP60X series 28V InGaP HBTs.

For UMTS, the 2110–2170MHz AP512 can provide +28dBm W-CDMA power output at -56.5dBc ACLR at +/-5MHz offset as a driver amplifier, and +31dBm at -45dBc ACLR as an output amplifier.

For DCS, the 1805–1880MHz AP513 can provide +28dBm CDMA2000 (7 carrier) power output at -64dBc ACPR at +/-885kHz offset as a driver amplifier, and +32dBm at -45dBc ACPR as an output amplifier. A power-down mode uses a simple +5V control line.

In a 50 Ω matched, three-stage amplifier, they allow trade-off of features and costs to fully meet the needs of wireless infrastructure applications," said Haresh Patel, senior VP of sales and marketing. "These devices exhibit exceptionally low ACPR/ACLR with good efficiency for demanding power amplifier applications. The bias is adjustable from Class AB to Class B operation." All bias, thermal control and matching circuits are included.

The AP512 has output IP3 of 53dBm, 28dB power gain, and a P1dB of 39dBm. and 1.72A operating current configured for Class AB operation.

The AP513 has output IP3 of 50dBm, 30dB power gain, and a P1dB of 39dBm. and operates at 1.67A configured for Class AB operation.

www.wj.com

LNAs for cellular infrastructure and WiMAX base-stations

RFMD has started pre-production sampling of five GaAs pHEMT low noise amplifiers (LNAs) for GSM, CDMA, UMTS, EDGE and WiMAX air interface standards to key cellular infrastructure and WiMAX base-station OEM customers, for production release in September.

"Through our collaboration with leading infrastructure OEMs, we have developed a family of LNAs that combine the bandwidth and performance necessary for highly linear WCDMA UMTS and OFDM WiMAX modulation standards," said Jeff Shealy, VP, Infrastructure Product Group.

Offering a broadband frequency range of 380-3800MHz with low noise figure (0.7dB) and a variety of LNA configurations (single-stage, dual-stage and dual-channel), the



RF Micro Device's new RF386x family GaAs pHEMT low-noise amplifiers.

RF3861, RF3863, RF3865, RF3866 and RF3867 (part of the RF386x product family) provide flexible supply voltages (2.5-6.0V), high gain (up to 30dB), very high output IP3 (up to +38dBm), and excellent input and output return loss, RFMD claims. RFMD's LNAs are packaged in a low-cost, extremely small (5x5 mm) plastic QFN package.

"With minimal external matching, our customers can optimize these

parts for a variety of wireless infrastructure applications, including CDMA, PCS, DCS, UMTS, WLAN and WiMAX," adds Shealy. "RF Micro Devices' wireless infrastructure strategy is driven by our design expertise across multiple semiconductor process technologies and our ability to match the optimum technology to our customers' evolving needs."

www.rfmd.com

Direct demodulator with integrated low-noise amplifier for 5GHz broadband wireless frequencies

Skyworks Solutions has introduced a direct quadrature demodulator with integrated low-noise amplifier (LNA) for the 5GHz band that delivers new levels of integration and performance for standard products in this spectrum, it claims. Given its simplified design, the solution facilitates access to various broadband applications in a low-cost approach.

The demodulator provides the flexibility to design receivers for various licensed and unlicensed broadband wireless data systems using low-cost and low-power direct conversion architecture. In addition, it is an ideal RF solution for the unlicensed WiMAX market, dedicated short-range communications, 802.11, 5.8GHz industrial and medical RFID readers, and proprietary wireless data links, Skyworks claims.

"Our solution enables broadband wireless data innovators to easily adapt to the industry's requirements for 5GHz," said Sean Martin, senior director of marketing for Linear Products.

Skyworks launched its Linear Products business to aggressively leverage its core RF and analog product portfolio and modeling capabilities, along with its strong catalog sales channels and specialized rep and distributor networks, in non-handset applications. Skyworks says that it has secured several strategic design wins in the medical, broadband, automotive and industrial markets.

The SKY73013 offers superior quadrature accuracy performance, noise figure and linearity specifications, making the device ideal for even the most difficult modulation

formats, including 64-quadrature amplitude modulation (QAM) orthogonal frequency division multiplexing (OFDM). The internal "no-pull" architecture offsets the voltage-controlled oscillator from the carrier frequency by a factor of 3 to 2. The innovative architecture eliminates LO pulling and dynamic direct current offset issues — solving the classic direct conversion radio design challenges, while allowing the use of readily available synthesizer products, including the SKY72302.

The direct demodulator operates from 4.9-5.925GHz (at an LO range of 3.2-3.9GHz), has a 6dB noise figure, and an input 1dB compression point of -15dBm. The device operates at 3.3V at just 35mA, in a 4x4 QFN package.

www.skyworksinc.com

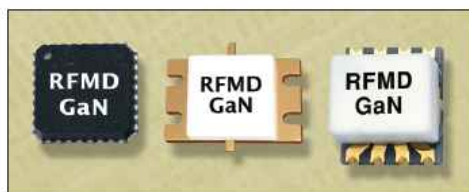
Cree, RFMD launch GaN HEMTs on SiC

At June's IEEE MTT-S International Microwave Symposium, GaAs RFIC maker RF Micro Devices launched a family of nine GaN HEMT high-power transistors, grown on 4" SiC wafers, for wireless base-stations. Outputs are 8, 60, 90 and 120W for UMTS, and 50, 75 and 100W (2.5GHz) and 8 and 50W (3.5GHz) for WiMAX. Peak drain efficiency is up to 67% (UMTS) and 60% (WiMAX) and gain is 16dB, with 4W/mm power density at 28V. High-temperature reliability of 1000 hours has been shown.

RFMD is now sampling early-stage GaN HEMTs to top-tier cellular base-station equipment makers. RFMD is aiming to prove reliability by end-2006, before agreeing its first design-ins with customers.

Also, Cree launched three GaN HEMTs made on semi-insulating SiC substrates at its new fab, targeted at 2.4–3.9GHz WiMAX applications:

- the 30W CGH35030 and 120W CGH35120 join the 15W CGH35015 (sampled in May), together covering WiMAX applications requiring 2–12W average orthogonal frequency division multiplexing (OFDM) output power at 3.3–3.9 GHz; and



RFMD's new high-power GaN HEMTs

- the 15W CGH27015, the first in a line for the 2.4–2.9GHz North American WiMAX market.

For full release later in 2006, they should "provide great versatility to WiMAX base transceiver station and consumer premise equipment designers," said Jim Milligan, wide-bandgap RF product manager.

Cree also demonstrated an S-band GaN HEMT for mobile WiMAX with a record 400W peak pulsed power at 3.3GHz with 10.6dB of power gain and 62% drain efficiency at 40V. "Upcoming mobile WiMAX applications are expected to require average OFDM output power of 10–25W with peak-to-average ratios as high as 12dB," said Milligan. "This will require transistors capable of delivering up to 400W." Initial sampling is targeted for later this year.

www.rfmd.com www.cree.com

PDK for SiC MMIC design

After acquiring APLAC Solutions (whose RF design simulation and analysis software has been used for over 30% of all cell-phone RFICs, it is claimed), in September 2005, at the 2006 IEEE MTT-S International Microwave Symposium, Applied Wave Research Inc (AWR) of El Segundo, CA, USA, which supplies high-frequency electronic design automation (EDA) products, launched a process design kit (PDK) that supports Cree's high-power SiC process.

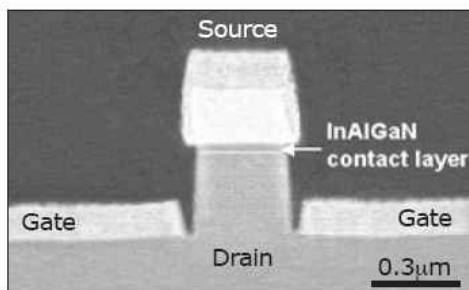
This enables use of Cree's monolithic microwave design process within AWR's Microwave Office software environment. Designers can improve productivity by applying AWR's open and integrated design platform to Cree's wide-bandgap SiC MMIC foundry services and discrete products. "Cree is committed to making its industry-leading power wide-bandgap MMIC technologies accessible through the EDA tools and flows our customers prefer," said Jim Milligan, Cree's manager of wide bandgap RF Products. "We are pleased to be working with AWR to provide this and future GaN solutions as well."

www.appwave.com

First GaN vertical transistor for high-power switching

At the Device Research Conference 2006 at Pennsylvania State University on 26–28 June, Japan's Matsushita Electric Industrial Co Ltd (parent company of the Panasonic brand) presented results for what it claims is the first GaN transistor with a vertical structure that can be used in high-power switching devices.

Through a new, proprietary epitaxial growth strategy, the use of InAlGaN in the contact layer reduces the barrier height from the top electrode, enabling a contact resistance 33% lower than normal, giving low on-state resistance.



Matsushita's GaN vertical transistor.

Also, the design reduces the chip's surface area to about one-eighth the area of conventional planar devices, the company says, allowing more transistors to be produced on

each wafer. Also, this reduces the effect of surface trapping of charge, which contributes to the collapse of drain current often seen in GaN-based transistors under high-voltage operation. However, current collapse can also result from other effects in the bulk structure.

Due to a novel self-aligned fabrication process, the transistor has a 0.3 μm -wide channel, giving the good pinch-off characteristics that are key for power switching devices.

Panasonic has filed 17 patent applications relating to the device.

<http://panasonic.net>

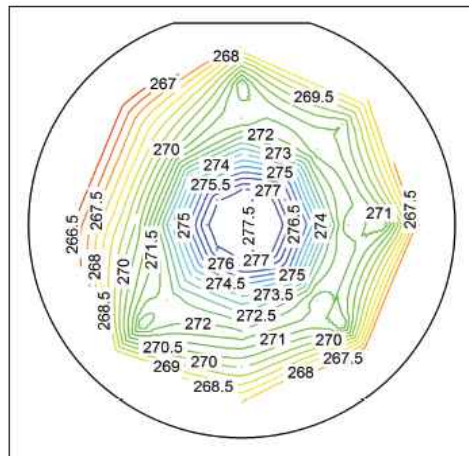
High-uniformity AlGaIn/GaN HEMTs on 150mm silicon

At May's International Conference on MOVPE in Japan, Belgian research institute IMEC reported that it has used its new 150mm Thomas Swan Close-Coupled Showerhead reactor, in the framework of the European Space Agency's Epi-GaN project, to demonstrate high-uniformity AlGaIn/GaN HEMT epi-structures on 150mm silicon wafers. Sheet resistivity is as low as $272 \pm 5 \Omega/\text{square}$ and standard deviation is just 1.9% (edge excluded).

Mismatches in lattice constants and thermal expansion coefficients between Si and GaN are bridged by an AlGaIn buffer layer that provides compressive stress in the top GaN layer, plus a proprietary in-situ Si_3N_4 passivation layer.

IMEC is now offering access to its AlGaIn/GaN epiwafers in a service mode to labs and partner firms involved in developing GaN devices, it says. IMEC is also able to grow AlGaIn/GaN HEMT epilayers on either sapphire or SiC.

www.imec.be



GaN HEMT on Si sheet resistance map

Riber joins III-V/Si program

France's Riber has joined IMEC's Industrial Affiliation Program (IIAP) on 'Germanium and III-V devices for CMOS beyond the 22nm node' (part of the sub-45nm CMOS research platform with partners Infineon, Intel, Matsushita, Philips, Samsung, ST, Texas Instruments, and TSMC).

Riber has supplied an MBE cluster tool, compatible with 200mm wafers, with deposition chambers for both:

(i) III-V layers on germanium-on-insulator (GeOI) or other Ge-based substrates; (ii) high-k dielectric insulator and metal gate contact layers on Ge and on III-V materials.

Ge's higher mobility than silicon could yield lower intrinsic gate delay in CMOS devices, and replace silicon in manufacturing lines on shrinking devices to sub-22nm geometries (for volume production in 2016).

In 2005, IMEC demonstrated the feasibility of sub-micron pMOS devices on GeOI. To solve the problems in processing Ge nMOS transistors, III-V nMOS devices on the same Ge substrates are targeted. The process will be based on silicon wafers, enabling manufacturing in standard silicon process lines using CMOS-compatible equipment. One challenge is to improve the gate stack for MOS devices on Ge as well as on III-V compounds.

The collaboration will also form the basis for a possible extension of the IIAP beyond CMOS to photonics.

www.riber.com

Nitronex raises \$21.8m to expand GaN-on-Si range

After agreeing a deal to supply GaN-based power amplifier (PA) products for WiMAX applications to a Korean customer late last year, GaN-on-silicon device maker Nitronex Corp of Raleigh, NC, USA has closed a \$21.8m venture capital funding round led by Silicon Valley-based Alloy Ventures. Other new investors Intersouth Partners (of Durham, NC) ARCH Venture Partners, and Diamondhead Ventures were joined by returning investors VantagePoint Venture Partners and Contender Capital.

Nitronex, which was founded in 1999, last October launched the first GaN-based power transistor products grown on silicon for the

commercial and broadband wireless markets — a family of RF power transistors for the WiMAX market, initially consisting of 10W and 50W devices for both 2.5GHz and 3.5GHz segments. Nitronex says that its patented SIGANTIC GaN-on-Si platform technology — which was originated at North Carolina State University — simultaneously combines the high power, high frequency, high operating voltage and broad bandwidth performance of GaN (currently unavailable using existing technologies) with the low-cost, large-area availability of silicon. Devices for the 5.8GHz WiMAX sector are planned for introduction this year.

Nitronex will use the funds to complete development and expand manufacturing of several new products; accelerate hiring in operations, engineering, sales and marketing and finance; expand into new global markets; and take advantage of emerging opportunities in cellular and WiMax, broadband markets.

"Our GaN-on-silicon based products offer significant advantages over existing LDMOS and GaAs solutions for the WiMax, cellular, and broadband wireless markets," claims CEO Charles Shalvoy. "We plan to accelerate our efforts to introduce a broad family of innovative RF power transistor products."

www.nitronex.com

IN BRIEF

GaN electronics markets: wireless infrastructure lags military/high-power

According to Strategy Analytics' study, 'Gallium Nitride Markets: Commercial Markets Drive Power Electronics', the GaN microelectronic device market will grow at a compound annual growth rate (CAGR) of 151% through 2010, catalysed by military applications (50% of demand) and high-power electronic (HPE) applications (26% of demand), which "both have future needs that will make use of the advantages offered by wide-bandgap materials such as GaN," says Asif Anwar, Director of the Strategy Analytics GaAs service.

GaN's unique material properties make it possible to create new devices with high breakdown voltage, extremely high power density, and high gain at microwave frequencies. GaN's high temperature tolerance, alongside excellent thermal conductivity properties, make it a good material for high-power applications as well as for high-temperature, extreme-environment applications.

Commercial wireless infrastructure applications will lag, but will driving demand in the future. "The needs of the commercial telecommunications wireless market have yet to really place the incumbent technologies, Si LDMOS and GaAs pHEMT, under major competitive strain, although GaN will start to penetrate these markets over the next few years regardless", reckons Anwar.

Although silicon-based substrates will gain market traction, SiC will remain the dominant substrate of choice through to 2010, the report concludes.

www.strategyanalytics.com

Grant for 100mm GaN-on-diamond

sp3 Diamond Technologies Inc of Santa Clara, CA, USA, a supplier of wafer-scale diamond and diamond products for thermal management challenges, has received a \$750,000 Phase II Small Business Innovation Research contract from the US Missile Defense Agency to develop GaN on silicon-on-diamond (SOD). The project will result in the delivery of GaN-on-SOD devices suitable for radar transmit/receive modules, as well as a documented process for producing GaN-on-SOD substrates and initial reliability data.

In Phase I, sp3 delivered 100mm SOD wafers with a GaN top surface, as well as extensive modeling that demonstrated performance gains obtainable in a HEMT device built on a thermal layer of diamond (showing junction temperature reduction of 80K, combined with a 37% boost in output power).

"The development of GaN devices on our SOD substrate is a significant next step in our overall development of Diamond-On-Silicon (DOS)," said Dwain Aidala, president and chief operating officer. "We have now demonstrated that our DOS platform is appropriate for other active circuit devices, as well as MEMS applications."

Two key applications are being pursued by collaborating companies:

- GaN-on-silicon device maker Nitronex Corp of Raleigh, NC, USA is working with sp3 on the fabrication of GaN material on the SOD substrate. Nitronex will now build active high-power devices as part of Phase II. "The ability to integrate a diamond thermal layer into our GaN-on-silicon strategy is of great interest to Nitronex," stated Kevin Linthicum, co-founder and CTO. "The fact that sp3 is offering us a known silicon interface on 100mm wafers provides an easy migration to future productization and a path-



100mm diamond-on-silicon wafers.

way to scale to 150mm GaN wafers when the markets require."

- TriQuint Semiconductor of Hillsboro, OR, USA will also be modeling the technology for their high-frequency MMIC development. "With

A known silicon interface on 100mm wafers provides a pathway to 150mm GaN the push by the military for tripling device power and adding 50% greater efficiencies, materials such as sp3's

GaN-on-SOD have a high probability of being the substrate solution of the future," stated Tom Cordner, VP, TriQuint Texas. "We will work closely with the material to move it toward products as soon as possible."

www.sp3inc.com



Deposition reactors at sp3.

Asia tools up for GaN HB-LEDs

Several epiwafer and chip makers in Asia have placed orders for MOCVD reactors over the past few months, as they continue to ramp GaN blue high-brightness LED production.

Driven by emerging small-panel LCD backlighting applications, June saw Veeco Instruments Inc receive multi-unit orders for GaNzilla II MOCVD reactors from Huga Optotech of Taiwan, Dalian Meiming Epitaxy Technology of China and LG Innotek of South Korea.

Also in June, Veeco entered into a collaboration with Korea Photonics Technology Institute (KOPTI) that sees Veeco place its latest-generation GaNzilla MOCVD tool, technical experts and other process support into KOPTI's facility.

The Veeco-KOPTI site will be used for R&D, training and demonstrations by both KOPTI other Korean HB-LED makers. Also, Veeco and its clients gain access to KOPTI's LED characterization and chip fabrication facilities. Veeco and KOPTI may also share solid-state lighting technology and the intellectual property resulting from the collaboration.

Piero Sferlazzo, VP and general manager of Veeco's MOCVD operations, said: "KOPTI's world-class development center and close relationships with Korea's important LED manufacturers, including Samsung and LG Innotek, make it the ideal place for Veeco to establish our base of operations in the rapidly growing Asian marketplace."

Veeco's Q2/2006 sales of \$111.6m were up 19% on Q1 (guidance was \$105-110m). Orders were \$143.2m (guidance was \$125-130m), driven by HB-LEDs/ wireless (\$27.4m, up 106%, guidance was \$24.3m), due to the advent of LED backlighting of flat-panel TVs. Veeco has raised its 2006 sales forecast from \$440-450m to \$455-465m.

www.veeco.com

Taiwan-based HB-LED makers have also been ordering Aixtron reactors.

Uni Light Technology of Taoyuan Hsien has bought another Aixtron Thomas Swan MOCVD CCS 19x2" multiwafer reactor for making GaN-based epiwafers, forming "the basis of our continued expansion plans". ULT already has an AIX 2600G3 HT Planetary Reactor and AlGaInP system in 24x2" wafer configuration for mass producing InGaN LEDs.

After "encouraging results" from its existing CCS reactor, Advanced Epitaxy Technology has also installed a further CCS 19x2" reactor to expand its GaN HB-LED production.

Epitech Technology of Tainan ordered Aixtron's latest 30x2"-wafer Thomas Swan CRIUS reactor for mass-producing GaN HB-LEDs. The design is based on Aixtron's new 'Integrated Concept', which optimizes uptime and reduces cost.

In March, Epistar (which merged with UEC in late 2005) ordered five GaN Planetary Reactors for LEDs: four 24x2"-wafer AIX 2600G3s and the first 42x2"-wafer AIX 2800G4, the world's largest-capacity epitaxy reactor (developed specifically for HB-LEDs).

In June, Highlink Technology ordered two AIX 2800G4 HT 42x2" reactors, for producing GaN HB-LED epiwafers for advanced lighting.

In South Korea, Samsung Electro-Mechanics Co (SEMCO) ordered two more AIX 2600G3 HT 24x2" reactors for blue and white HB-LEDs at its plant in Kyungki-Do.

In Q1/2006, Aixtron's compound semiconductor equipment orders were Euro 26.6m (up 17% year-on-year), out of total equipment orders of Euro 31.7m (up 40%). Total sales grew 44% (although a third of sales were due to silicon-related business after the acquisition of ALD tool maker Genus Inc).

www.aixtron.com

IN BRIEF

EpiCurve on the up

Korea's Samsung Electro Mechanics Corp has confirmed the final acceptance of an Aixtron AIX 2600G3 HT reactor (installed in Q1/2006), configured for 8x4" wafers, for the growth of GaN opto devices.

This is the first reactor equipped with LayTec's EpiCurve in-situ sensor technology, which combines curvature, true temperature and growth rate measurements in a monolithic system. It can monitor distortion such as wafer bowing during MOCVD growth induced by mismatch with sapphire substrates (which is critical on moving from 2" to 4" wafers).

"The EpiCurve option, provided by Aixtron, will aid advanced process diagnostics during critical stages of the growth of epitaxial layers for devices such as LEDs," said E.S. Choi, general manager of Aixtron Korea.

Also, curvature monitoring can assist the implementation of next-generation technologies such as GaN-on-silicon.

www.laytec.de

UCSD orders another reactor

Aixtron has a repeat order for a Thomas Swan MOCVD Close Coupled Showerhead (CCS) reactor from the University of California, San Diego.

Configured for 3x2" wafers, the reactor will be used to research new materials and micro- to nano-scale structures for telecoms, computing and energy research applications.

The CCS reactor will also provide materials for several US Department of Defense funded research programs into areas such as optoelectronic ICs and nano-electronics, including materials for devices such as quantum wells, dots and wires.

www.aixtron.com

IN BRIEF

Nitride advance

Business development company EntreMetrix Inc of Irvine, CA, USA has formed a new company, Advanced Nitride Devices to make and commercialize GaN and AlN materials for power transistors, solid state lighting, and blue lasers for high-density optical storage and Blu-ray disc technology (driven by shipments of HD-DVD players and the introduction of Blu-Ray movies by Sony and players by Samsung).

The plan includes a wafer fab based on an extensive patent portfolio for GaN and AlN manufacturing processes. Scott W. Absher, EntreMetrix's CEO, said, "Our investment and support efforts will include immediate market entry through a direct industrial sales agenda but will also include acquisitions to allow Advanced Nitride to integrate its materials science into device manufacturing and beyond."

www.entremetrix.com

GaN matching grant

North Carolina's SBIR/STTR Matching Grants Program in May awarded Kyma Technologies funds to match a Phase I Small Business Innovative Research award in February from the Missile Defense Agency to continue improving the size, quality, and availability of native semi-insulating GaN substrates for the project "High Electrical Efficiency GaN Field Effect Transistors for Innovative Radar/RF Sensors".

This follows completion of an MDA-funded Phase I Small Business Technology Transfer program demonstrating 3" substrates, and last October's award of \$1m Phase II funding for "Production of Large-Area Semi-Insulating GaN Substrates". 2" wafers should ship in volume within a year, and the first device-grade 3" material mid-to-late 2007.

www.kymatech.com

AlN semi-insulating substrates reach 4"

After introducing the first 2" AlN-on-SiC substrates three years ago followed by 3" product a year ago, Technologies and Devices International Inc of Silver Spring, MD, USA has fabricated the first prototype 4" AlN-based semi-insulating substrate. As well as reducing device production cost per unit area, this enables the use of 4" processing lines standard for GaAs RF ICs.

Proprietary stress control technology and crystal growth equipment developed by TDI allows the deposition of crack-free single-crystal AlN film about 10µm thick (enough for reliable insulation and low current leakage to the conductive SiC substrate). So, as well as having good lattice and thermal match to GaN-based devices, says president and CEO Vladimir Dmitriev, AlN-on-SiC substrates combine the high



thermal conductivity of SiC and the high intrinsic electrical resistivity of AlN for high-power AlGaIn/GaN devices (including HEMTs and high-frequency power amplifiers for next-generation wireless communications). Other target applications include high-power blue and UV LEDs and lasers.

TDI is starting pilot production and plans to make the first product shipments in last-quarter 2006.

www.tdii.com

Low-defect-density 2" bulk AlN

Crystal IS of Green Island, NY, USA has launched the first commercial low-defect-density (1000 cm⁻²) 2" bulk single-crystal AlN substrates (compared to 1" 'quasi-bulk' AlN grown on non-native substrates by HVPE with million times larger defect densities, the firm says). Currently, about 50% of the substrate area is usable; Crystal IS aims to raise this towards 100% over 2006.

A low thermal mismatch and no lattice mismatch to AlN/AlGaIn epilayers (minimizing stress), as well as higher thermal conductivity than sapphire and SiC, could open up markets for high-power RF electronics and high-reliability UV optoelectronics (e.g. LEDs for purifying water or air, phototherapy, curing industrial materials, and bio-agent sensors).

After raising \$5.1m in first-round funding in September 2004, in June 2005 the firm moved from 6000 ft²

of space in a Rensselaer Polytechnic Institute incubator in Watervliet, NY to its present 10,500 ft² facility to accommodate the recent addition of more furnaces and an expansion in the substrate preparation facility. The firm now aims to close a second round of funding in Q3/2006.

As it ramps up AlN substrate production, in April the firm recruited Timothy Bettles (ex-sales manager, optoelectronic products for IQE Inc in Bethlehem, PA) as VP of business development, sales and marketing.

In February, Crystal IS hired Dr Ding Day as CEO. Day was founder of InGaP HBT epi foundry Network Device Inc and, most recently, VP of global business development for Skyworks. Co-founder Dr Leo Schowalter (former president and CEO) became chief technical officer to focus on technical development.

www.Crystal-IS.com

Cree buys Intrinsic for low-defect SiC

In late June, Cree Inc of Durham, NC, USA, which supplies materials and devices made from SiC, agreed to acquire privately held Intrinsic Semiconductor Corp of Dulles, VI, USA, for \$46m.

Intrinsic was founded in 2002 to develop materials and device technologies based on SiC and GaN materials. In 2004, it acquired Bandgap Technologies and AMDS, both of which were dedicated to either SiC crystal growth or SiC device development.

Intrinsic makes both insulating and conducting SiC wafers, as well as SiC and GaN epitaxial products in 2", 3" and 4" diameters. This March, Intrinsic started commercial shipments of its zero-micropipe ZMP SiC wafers, as well as 4" diameter SiC wafers. It is also developing ZMP production for 4" product.

Cree says that integration of Intrinsic's technology into its materials product line should accelerate development of larger-diameter, high-quality SiC wafers, enabling

new high-power devices and lower-cost LEDs. "We believe the combination of Cree's technology and manufacturing expertise with Intrinsic's ZMP technology will accelerate the commercialization of low-defect 4" and 6" substrates. These substrates should not only support our cost roadmap for LEDs, but more importantly, they should also enable us to more rapidly commercialize higher-power devices for motor-control applications and hybrid vehicles," stated Chuck Swoboda, Cree's chairman and CEO.

"The contribution of Intrinsic's ZMP process to Cree's existing world-class SiC technology and high-volume manufacturing capability represents a unique opportunity to make a new generation of cost-effective SiC devices available sooner than had previously been envisioned," reckons Dr Cengiz Balkas, Intrinsic's president and CEO.

www.cree.com

Substrate maker AXT Inc of Fremont, CA, USA has promoted Robert Ochrym to the new post of VP of business development. He was senior director of international sales and joint venture operations since June 2005.

Ochrym will focus on enhancing AXT's joint venture operations and worldwide sales efforts. He will also continue to maintain selected high-level substrate customers in North America and Europe. In addition, he will explore possible investment opportunities into complementary businesses where there are product synergies with AXT's compound substrate and raw material products.

Ochrym will report directly to CEO



Ochrym has held posts in sales and marketing, business development and product management at Northrop Grumman and Uniroyal Optoelectronics, and then was national sales manager at Aixtron Inc, responsible for North American sales and marketing. He is currently on SEMI's standards committee for Electronic Materials (GaAs).

www.axt.com

Phil Yin, with 'dotted line' reporting to Davis Zhang (president of JV operations) and John Cerilli (VP of global sales and marketing).

IN BRIEF

IQE buys Emcore's epi division for RF

Epiwafer foundry IQE is buying Electronic Materials Division (EMD), the New Jersey-based epi foundry business of Emcore Corporation Inc, for \$16m.

EMD provides foundry production of electronic epi materials (e.g. for power amplifier products), focusing on wireless markets for both handsets and infrastructure. "As we continue to focus our strategy on broadband infrastructure, solar power and value-added products, it became clear we needed to find a more strategic fit for EMD's products and employees", says Emcore's chief operating officer Scott Massie. "The sale will lower our cost base, improve gross margins company-wide and permit us to further consolidate operations in New Mexico and California."

EMD has 10 epi tools and is one of the top five third-party suppliers of epiwafers, says IQE. For its fiscal year to end-September 2005, sales were \$12.2m. Assets are \$9.0m. IQE's board intends EMD to continue to be run as a stand-alone entity in New Jersey. All 50 staff will be offered jobs.

EMD has concentrated on HBT-based technologies for power amplifiers, as well as integrated BiFET and GaN structures. Consequently, it supplies a range of highly complementary products to a range of customers different to that of IQE's own customer base, says Dr Drew Nelson, IQE plc's president and CEO.

To fund the acquisition, IQE aims to raise £12m in a placement of new shares on the London Stock Exchange's AIM market (about 21.6% of IQE's enlarged ordinary share capital), conditional on passing a shareholder resolution at an extraordinary general meeting in Cardiff, UK on 15 August.

www.iqep.com

IN BRIEF

LED lighting funded

Under its program to develop solid-state lighting (SSL) with a product system efficiency of 50% by 2025, the US Department of Energy (DoE), via its National Energy Technology Laboratory (NETL), has allocated a total of \$7m in funding to five projects: two focused on organic LED materials (Eastman Kodak and SRI International) and three on III-V LED technology.

* Color Kinetics will develop a hybrid LED that combines direct emission with phosphor down-conversion for an efficacy of 80lm/W to replace 60W incandescent bulbs.

* General Electric Global Research will use novel nanophosphors to convert violet LED emission into white light, with 96lm/W efficacy.

* Osram Sylvania aims to raise external quantum efficiency using remote phosphors and a multi-layer thin-film coating technique to extract more light from LEDs.

Third-round SSL funding call

In the third round of SSL Program funding, the NETL, on behalf of the Office of Energy Efficiency and Renewable Energy's Building Technologies Program, is seeking applications (by 5 September) from industrial organizations to:

- use R&D knowledge to develop and improve commercially viable materials, devices and systems for SSL LED & OLED products (Program Areas of Interest 1 & 2);
- develop a technical information network to disseminate SSL information to target markets (Program Area of Interest 3).

The funding available is \$3.75m for 2–5 awards in Areas 1 and 2 and \$300,000 for 5–7 awards within Area. Awards will not exceed \$900,000 and \$50,000 (Federal share) per year for 12–36 months for Areas 1 and 2, and Area 3, respectively. The cost share (from non-Federal sources) must be at least 20% of the total.

www.grants.gov

SET and Seoul Opto team on UV LEDs

Sensor Electronic Technology Inc (SET) of Columbia, SC, USA, which makes AlGaIn-based deep UV LEDs (DUV LEDs) with peak wavelengths of 247–365 nm, has entered into a strategic partnership and stock purchase agreement with Seoul Optodevice Company (SOC) of Ansan-city, Kyunggi-do, vertically integrated volume manufacturer of blue, green and near-UV LED chips and a subsidiary of Seoul Semiconductor Company (SSC), the largest packager of visible LEDs in Korea (with a capacity of 3bn per year).

The alliance will combine SET's DUV LED technology with high-volume manufacturing capabilities and global marketing and sales network of SSC/SOC, says Dr Remis Gaska, SET's president and CEO. "This will accelerate the bringing of low-cost, high-quality products to market."

Applications include: optical sensors (e.g. bio-agent sensors), water and

air purification, surface and tissue disinfection, biomedical, medical and analytical instrumentation, protein analysis, and UV curing.

"By partnering with SET we set in motion our strategic plan of becoming the largest manufacturer of DUV LEDs", says Dr Jae Jo Kim, SOC's executive VP. "Our global presence in visible LED markets and distributed sales network will facilitate broad market penetration."

As well as ramping production of DUV LED epiwafers, SET is realigning its operations to develop application-oriented products that use DUV LEDs. SSC/SOC will make standard products for high-volume markets, and will be responsible for products sales worldwide, except for the Americas. SET will distribute DUV LEDs in the Americas and high-end products worldwide.

www.s-et.com

www.seoulsemicon.com

Fox launches 350nm UV LEDs

Fox Group Inc of Deer Park, NY, USA, has launched products based on its new FoxUV 350nm UV LEDs:

2" diameter epiwafers; 320x320µm die; packaged lamps; and a TO-66 power-pack containing 60 die.

Like its existing FoxBlue LEDs (launched in October 2004) and its 360nm UV LEDs (launched in August 2005, which have an output power of 0.8mW at 20mA and 4mW at 100mA), Fox's proprietary FoxHVPE hydride vapor phase epitaxy process gives an emission wavelength that is consistent to typically +/-1nm and is highly stable with changes in forward current. The typical peak wavelength is 351nm (for 20mA) with a FWHM spectral width of about 10nm.

The average output power is 200µW for a drive current of 20mA



FoxUV 350nm UV LED products.

and a forward voltage of 4.5V, and 500µW for a drive current of 50mA.

Applications include: medical and biomedical applications; sensors for materials with a fluorescence response at 350–355nm; fluorescence "disclosing" and specialized inspection lamps; and scientific applications requiring absorption or response at 350–355nm.

www.thefoxgroupinc.com

Production transfer limits Cree's capacity

Based on preliminary financial results, LED chip and SiC wafer supplier Cree Inc of Durham, NC, USA says it expects revenue for its fiscal fourth quarter (ended 25 June) of about \$106.7m (slightly down from the previous quarter's record \$107.7m). This is at the low end of its targeted range of \$106–110m due to lower LED sales stemming mainly from production challenges, which limited Cree's ability to meet orders.

Gross margin is expected to be about 42%, below Cree's targeted range of 46–47%, due mainly to lower LED revenue as a proportion of total sales, a less favorable mix within the LED product line, and incrementally higher production costs associated with new products.

CEO and chairman Chuck Swoboda had said in April that unexpectedly high demand from mobile applications meant that chip output

was capacity-limited while Cree was transitioning from 2" to 3" wafers and from its Durham fab to its new fab in Research Triangle Park, NC and starting up production of high-power products.

"Although we knew this was going to be a transition quarter, it proved to be more challenging than we expected," says Swoboda now. "Despite these near-term challenges, we are making progress in growing our new lighting and power product lines, which are key to driving our future growth."

For fiscal Q1/2007, Cree expects that LED chip sales may decline slightly due to a recent slowdown in demand for mobile products, but this should be mostly offset by increased sales of its XLamp LED and Schottky diode products.

Cree will release final results on 10 August.

www.cree.com

IN BRIEF

Cree wins purchase agreements

In May, following on from a distributorship agreement in fiscal 2006, Cree's leading customer Sumitomo Corp of Japan agreed to purchase \$180m of LED chips and wafers during Cree's fiscal year to end-June 2007 (10% up on fiscal 2006, although 2006's total was below the original \$200m agreed). The new agreement covers products across Cree's full range, including MegaBright, XBright, XThin and the new EZBright LEDs.

"Breakthroughs in performance are opening doors to multiple new applications, especially in the consumer electronics and general lighting areas," said Koichiro Kusano, who is the assistant general manager of Sumitomo's Electronics Division. Chuck Swoboda, Cree's chairman and CEO, added that the agreement "reflects the increasing optimism our sales team sees in Japan for increased market share in white mobile applications and new design wins in emerging markets for LED lighting".

Also in May, after several years of cooperating on white LEDs design wins in the Korean market, Cree signed a worldwide five-year supply agreement (extendible by up to five additional years) with leading Korean LED maker Seoul Semiconductor Co Ltd, which has committed to buy at least \$40m of LED products in the first five quarters.

The companies have also agreed to cross-license some white LED patents (including US Patent No. 6,600,175, which has already been licensed to Taiwan's Kingbright Electronic late last year, as well as Stanley, Cotco and Rohm). The companies have also agreed to cooperate in defending these rights.

www.cree.com

White LED efficacy reaches 131lm/W

Cree has achieved record white LED efficacy of 131lm/W using a prototype cool-white device operated at 20mA, as confirmed by NIST. The correlated color temperature was 6027K. This points the way to commercial LEDs soon with efficacies exceeding 100 lm/W, compared to 10–20lm/W for conventional incandescent bulbs and 50–60lm/W for compact fluorescent lamps.

The LEDs were fabricated using Cree's EZBright chips, which are 0.29mmx0.29mm and designed for use in backlighting in LCD screens on mobile phones, PDAs, TVs and monitors, as well as for indoor and outdoor LED display, camera flash, gaming and indicator applications.

Cree released its EZBright LED chip platform in March. It features a new, easy-to-die-attach chip,

enabling assembly into LED packages using industry-standard processes. "Compatibility with epoxy die attach processes greatly increases the number of potential customers who could take advantage of our highest performance chips, and increases the number of applications that can leverage our brightest products," said Scott Schwab, VP and general manager of LED chips.

The first product is the EZBright290, available in both green and blue colors. It is targeted at white backlighting applications in LCD screens on mobile phones, PDAs, televisions and monitors, as well as for indoor and outdoor LED display, camera flash, gaming and indicator applications.

www.cree.com

IN BRIEF

Unaxis invests in Novalux for displays

In June, Novalux Inc of Sunnyvale, CA, USA closed a Series B financing round of up to \$21.7m, led by Liechtenstein's Unaxis Optics, a division of Switzerland's Unaxis Holding AG that coats optical components for projection displays, and joined by previous investors including Crescendo Ventures, Morgan Stanley Venture Partners, Dynafund Ventures and Tredegar Corp. Novalux will use the funds to complete NECSEL product development and enhance its production infrastructure.

Novalux also entered into a joint development and license agreement with Unaxis Optics (Switzerland) for red, green and blue (RGB) illumination devices for projection display products based on its Novalux Extended Cavity Surface Emitting Laser (NECSEL) technology.

Novalux licenses its RGB laser reference design and will supply Unaxis with NECSEL chips. Unaxis will mass produce and distribute RGB laser modules for rear-projection TV, front projectors, pocket- and pico-projection.

"NECSEL sources are well suited for these next-generation projection devices—they're longer life and lower cost than competitive light sources," said Novalux chairman and CEO Jean-Michel Pelaprat.

"Novalux's technology can be applied across the entire range of micro display and scanning devices," said Unaxis CEO Thomas P. Limberger.

In March, Novalux also struck a joint development and license agreement with Seiko Epson Corp for NECSEL-based RGB illumination devices for microdisplay-based products such as projection TVs.

www.novalux.com

Light sensor that matches the eye

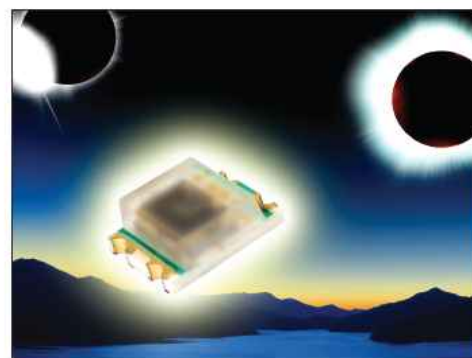
Osram Opto Semiconductors of Regensburg, Germany claims that its SFH 5711 ambient light sensor is the first sensor that precisely matches the sensitivity curve of the human eye (see graph below). The company has achieved this by replacing traditional silicon with a 'new material system'. It acknowledges that this is a compound semiconductor, but does not divulge the precise material.

Like the human eye, the SFH 5711 has its maximum sensitivity at the wavelength 560nm. This makes it suitable, for example, for switching headlights on and off automatically, depending on the ambient light levels.

Also, it can be used for adjusting the brightness of displays more precisely than before for optimum readability in the available light.

In LCD displays, the sensor prevents the rapid onset of eye strain — a common problem if the display is too bright in a dark room.

Also, a supply voltage of 2.3–5 V and dimensions of just 2.2x2.8x1.1mm make the sensor suitable (as an SMT chip) for applications in small mobile terminals

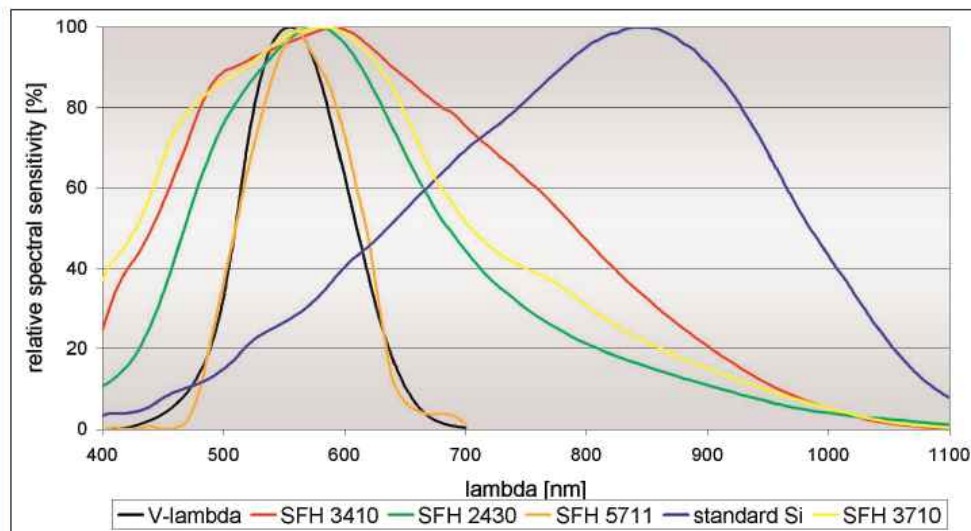


Artist's impression of Osram Opto's SFH 5711 ambient light sensor.

such as mobile phones and PDAs, which will be easier to read in all lighting conditions and consume less power, because the display will only be lit as required, saving both battery power and the eyes.

A logarithmic amplifier IC acts on the sensor, enabling a large brightness range (3lx to more than 30000lx) to be detected with great accuracy without the series resistors needed with linear detectors to adjust the sensitivity externally for different brightness ranges. The SFH 5711's accuracy enables virtually infinite dimming of backlighting systems.

www.osram-os.com



Spectral sensitivity of SFH 5711 (brown) matches the human eye (black), compared to previous generations and the traditional silicon sensor (blue).

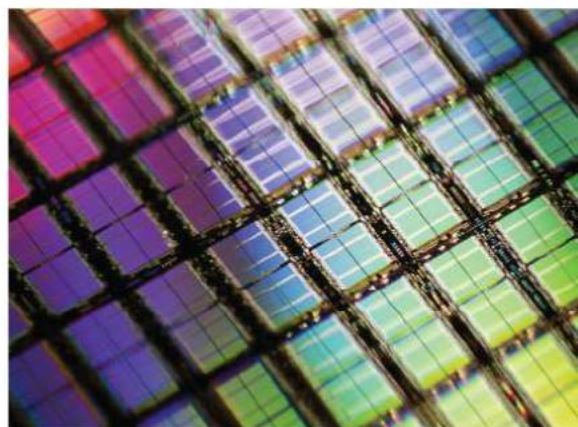


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Beaten-up industry turns upbeat



Mark Telford reports from the CS MANTECH conference in Vancouver. This year's event gave a snapshot of the ongoing recovery in the GaAs sector of the compound semiconductor industry, which is being driven by burgeoning uses for RFICs in new multi-mode, multi-band mobile phone handsets.



This April's 21st annual International Conference on Compound Semiconductor Manufacturing Technology (CS MANTECH 2006) in Vancouver, Canada attracted both more delegates (368) and more exhibitors (60) than in recent years. This reflected financial reports pointing to 2006 sustaining continued industry recovery over 2005 and 2004 (albeit still some way off the peak year of 2000). This is evident particularly in the GaAs RF IC market, which is driven by increasing cell-phone handset sales and increasing GaAs content per handset.

Indeed, in contrast to the normally low cell-phone market at the start of a year, MANTECH coincided with RF Micro Devices, Skyworks, TriQuint and Anadigics all reporting March-quarter GaAs RFIC sales up sharply both quarter-to-quarter and year-on-year, with projections for further growth in the June quarter and second-half 2006.

TriQuint Semiconductor's sales were \$87.9m (at the high end of its guidance), up 4% on Q4/2005 and 31% on a year ago. It forecast sales up 8–10% in Q2/2006 and up 34–37% for 2006 (versus 2005's \$294.8m).

Excluding baseband products and legacy assembly and test services, Skyworks Solutions' sales were up 11% year-on-year to \$172.3m (above its guidance) due to demand for front-end modules, RF solutions and linear products. It forecast total June-quarter sales up more than 5% sequentially, driven by increasing demand across its EDGE, CDMA and WCDMA portfolio, followed by an "even stronger back half of 2006".

Anadigics' sales were up 7.2% sequentially and 63.8% year-on-year, driven by demand for GSM/EDGE/WCDMA PAs, WLAN and tuner ICs. For

Q2/2006, Anadigics expected sales up 10% sequentially and 64% year-on-year, but has since just reported growth of 12.6% and 68%, respectively.

RF Micro Devices' sales were up 8.6% sequentially and 50% year-on-year (driven partly by increasing use of multiple power amplifiers and switches in handsets and wireless LAN applications). To support the forecasted revenues, RFMD had just announced a 40% expansion in GaAs wafer fabrication capacity "as the handset market grows and as GaAs content requirements increase with the adoption of transmit modules and multimode handsets", it said.

The health of the GaAs RFIC manufacturing sector was evidenced at MANTECH by the job vacancies advertised on the conference noticeboard by the likes of Skyworks, as well as Freescale and Infineon.

The resurgence in GaAs demand for RFICs was also evident in demand rippling through the supply chain to epiwafer foundries and equipment and materials suppliers present at the exhibition (see news pages). Yung-Chung Kao, for example, president and CEO of epiwafer supplier Intelligent Epitaxy Technology Inc, explained how the company was bringing a further MBE reactor online for GaAs pHEMT switches, doubling throughput and taking on staff.

In addition, of the 60 companies exhibiting, several were returnees to the event after some years away, drawn by the upturn in the GaAs industry. These included companies that sell mostly to the silicon industry, such as etch system supplier Tegal, and Gold Canyon, which is returning afresh to its Cordero Gallium Project mine in Nevada, driven by rising gallium prizes over the last year.

GaAs microelectronic device market to grow to over \$3bn in 2006, driven by the launch of multi-mode, multi-band wireless handsets

At the CS Vision meeting at CS MANTECH, Asif Anwar, director of Strategy Analytics' GaAs and Compound Semiconductor Technologies service, in his presentation "2006 Compound Semi Industry Supply and Demand Market Update" summarized Strategy Analytics' annual five-year outlook for the GaAs microelectronics industry, "GaAs Industry Forecast: 2005-2010".

GaAs microelectronic device revenues grew from \$2.6bn in 2004 to \$2.8bn in 2005 (dominated by handset components) and will grow by 36% at a compound average annual growth rate (CAAGR) of 7% over 2005 to 2010, breaking the \$3bn barrier in 2006, the company forecasts. Overall market growth will continue to be derived from wireless markets, with cellular handsets as the primary driver. Demand for cell-phone handsets remains strong, with shipments expected to grow by 15% year-on-year in 2006, exceeding 1bn units by end-2007.

"But it's not just a case of increasing handset shipments, which helps to increase GaAs device demand from the handset market," observed Anwar. The introduction of increasingly complex multi-mode, multi-band handset architectures over 2006 and 2007 will increase GaAs device penetration, offsetting erosion in average selling prices. "2006 and beyond will see the market shift towards EDGE/GPRS-based and WCDMA/EDGE multi-mode, multi-band architectures. This will actually increase the number and size

of HBT and pHEMT die going into increasingly complex RF front-end module solutions."

GaAs substrate sales over \$600m by 2010

"The added complexity of multi-mode and multi-band handsets will increase GaAs device penetration in handsets and lead to a significant increase in the overall GaAs real estate in cellular handset front-end

Increasingly complex multi-mode, multi-band handset architectures over 2006 and 2007 will increase GaAs device penetration

modules," Anwar adds.

Demand for GaAs bulk and epitaxial substrates will grow by 30-40% over 2006 and 2007, effectively doubling

by 2008. Over the period from 2005 to 2010, volume demand for substrates will grow by over 150%. Substrate market revenues will exceed \$600m by 2010, concludes Strategy Analytics.

"We will see fab utilization for the industry approaching 100% over the next two to three years," adds Stephen Entwistle, VP of the Strategic Technologies Practice. "Substrate suppliers will need to increase material output and make any necessary investments to ensure that they can continue to meet demand. Otherwise, these suppliers risk losing market share to competitors."

www.strategyanalytics.com

Compound semiconductor manufacturing

As well as a paper by Brian Daly of Skyworks Solutions on the innovation and integration of devices for the emerging 3G, WiFi and WiMAX market (see the feature article on page 24 of this issue), the conference session on "Manufacturing" (chaired by P. C. Chao of BAE Systems) included a presentation by the foundry OMMIC of Limeil-Brevannes, France.

With the aim of extending the 100GHz f_T performance of its existing 135nm-gate 26%-In GaAs pHEMT D01PH process to minimize the number of new processing steps to be introduced while maintaining a high degree of manufacturability and robustness, OMMIC's J Bellaiche *et al* detailed the foundry manufacturer's successful transfer from development and release to production of a 150GHz 125nm-gate 40%-In MHEMT MMIC process that uses a composite channel of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$. The shorter gate length was achieved by slightly modifying the electron-beam resist system (changing the thickness of one layer of resist) and increasing the gate foot height to minimize

parasitic gate capacitance due to the gate mushroom shape, and replacing the wet-dry-wet gate recess etching sequence by a single wet etch using a succinic acid- H_2O_2 mixture to take advantage of the high selectivity between the InGaAs cap and the 120Å-thick AlInAs Schottky barrier layer.

Using the process, OMMIC has demonstrated a three-stage low-noise amplifier (LNA) designed by Centre National d'Etudes Spatiales that exhibited 28dB of gain with an associated noise figure of 1.2dB over a 10GHz bandwidth.

TriQuint's C. Youtsey *et al* presented the results of a three-year program at TriQuint Semiconductor Texas (in Richardson) to use a production GaAs fab (with established GaAs manufacturing equipment and processes) for the volume fabrication of MBE-grown lasers and detectors on 4" InP wafers with high yield and low cost. The devices were specifically multi-wavelength 1310nm InAlGaAs ridge-waveguide $\lambda/4$ -phase-shifted distributed feedback (DFB) lasers and mesa-based 10 and 40Gbit/s PIN and 10Gbit/s InAlAs avalanche

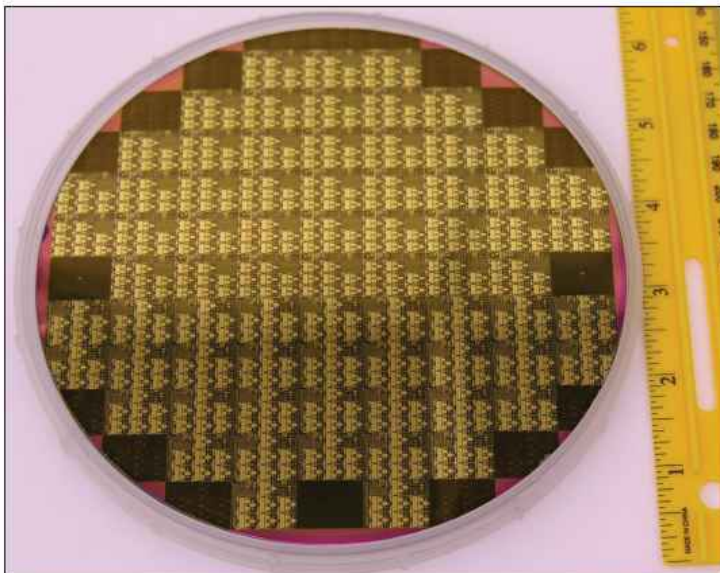


Figure 1. A 6" GaAs wafer bearing 0.1mm T-gate pHEMT MMICs (courtesy BAE Systems).

photodiode (APD) photodetectors, targeted for their potential to enhance device yield and uniformity and for their ability to explore TriQuint's manufacturing strengths.

In the current climate of consolidation and cost reduction in the optical component industry, TriQuint cites the 2005 Communications Technology Roadmap (which was coordinated by the Massachusetts Institute of Technology) to develop a roadmap for the optical communications semiconductor industry similar to that of the silicon industry, for industry-wide effort to develop new optical component manufacturing processes and standardized design rules.

TriQuint claims that the experience demonstrates the yield, process capability and cost advantages that are possible by leveraging existing III-V electronic manufacturing infrastructure.

Device cost is estimated to be competitive due to the larger substrate sizes, high yields, and through leveraging available capacity on existing high-volume production toolsets and systems.

Although there have been previous reports (by Taiwan's WIN Semiconductors) of 0.15 μ m GaAs pHEMTs on 6" 4-mil thick wafers, Liberty Gunter of BAE Systems in Nashua, NH, USA reported the first 0.1 μ m GaAs pHEMT MMIC process on 6" wafers (2mil thick, critical for high-frequency power operation, says Liberty) — see Figure 1. BAE Systems had previously fabricated 0.1 μ m pHEMTs and MHEMTs on 3" GaAs wafers, as well as 0.15 μ m pHEMTs and 0.25 μ m MESFETs on 6" GaAs wafers.

BAE Systems says that there is increasing demand for high-performance millimeter-wave IC (MMIC) GaAs technology for both military and commercial electronic applications such as phased array radar applications, VSAT and millimeter-wave digital radios — moving

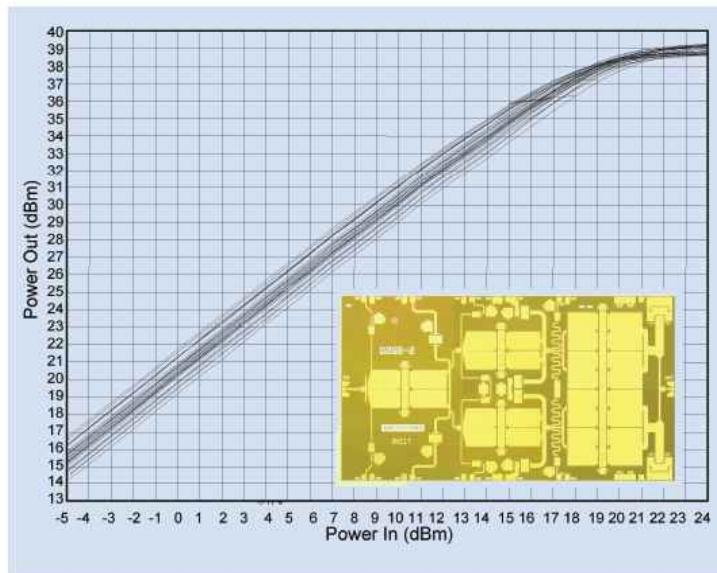


Figure 2. Record 8.3W Ka-band amplifier using a 6" GaAs process (courtesy BAE Systems).

from Ku-band to Ka and E-band frequencies — creating a demand for high-performance, low-cost MMICs (a 2x cost advantage compared to industrial-standard 4" wafers).

There is also an increasing need for high-gain, broad-bandwidth solid-state power amplifiers for W-band operation, which is more easily met using 0.1 μ m rather than current 0.15 μ m pHEMT technology, says Gunter.

BAE Systems has therefore demonstrated Ka-band through W-band MMICs. This includes a three-stage Ka-band pHEMT MMIC amplifier with a high 7–8dB of gain per stage (allowing for a drive ratio of 2:1 for all stages and a smaller driver chip) and a record output power of 8.3W (690mW/mm) at 35 GHz. This is 1.5–2 times the industry's previous best reported power output of 3–5W, partly due to the device design allowing the bias voltage to be as high as 6.5V. This is a "significant milestone" according to session chair and co-author P. C. Chao of BAE Systems, as it enables the availability of very high-performance pHEMT MMICs at low cost.

The paper also focused on the fabrication of a two-stage balanced V-band MMIC amplifier (with a 1.6mm output stage) to demonstrate statistical DC and RF power performance and reliability that is closely comparable with its mature 3" counterpart (i.e. giving an output power of 28dBm with a power added efficiency of 21%).

High-temperature reliability testing indicated negligible power change, proving the robustness of the process. The performance is attributed to the epilayer design, MMIC design, and the processing techniques used on BAE Systems' 6" pHEMT foundry line. BAE Systems is currently offering the 0.1 μ m pHEMT 6" GaAs process to select customers.

Best Paper award to Fujitsu's Toshihide Kikkawa for GaN HEMTs

For CS MANTECH 2006, the He Bong Kim prize for Best Paper has been awarded to Toshihide Kikkawa (pictured right), senior researcher at Fujitsu's Compound Semiconductor Devices Laboratory. His paper "Recent progress of highly reliable GaN HEMTs for mass production", co-authored by Kenji Imanishi, Masahito Kanamura and Kazukiyo Joshin, details the failure mechanisms that can occur in GaN HEMTs and outlines methods to prevent them, as well as describing Fujitsu Laboratories' progress in scaling its production process for making gallium nitride HEMTs on semiconducting silicon carbide wafers. Kikkawa was also a recipient, in 2004, of the Young Scientist Award at the *International Symposium on Compound Semiconductors*.



Toshihide Kikkawa
(source: Fujitsu).

The winner of the Best Student Paper Award is the University of Alberta's Nasim Morawej, Douglas G. Ivey, and Siamak Akhlaghi for "Improvements in the Process for Electrodeposition of Au-Sn Alloys".

The 2006 prizes will be presented at

next year's CS MANTECH in Austin, TX, 14-17 May 2007. For further information, see www.gaasmantech.org

Silicon versus compounds: GaAs and GaN

A panel session on "The Future of Compound Semiconductors in the Wireless Communication Infrastructure, chaired by Mike Barsky of Northrop Grumman Space Technology, discussed future technology insertions for compound semiconductors, where they are losing their lead in current technology (if they will survive in mobile handsets), and the effects of changes in infrastructure.

Strategy Analytics' Asif Anwar highlighted the trend to 3G mobile communications, multi-mode/multi-band handsets and high-data-rate standards (e.g. high-speed downlink packet access, HSDPA) as being "good for GaAs", since silicon "can't do multi-mode". Of RF components, SiGe dominates in transceivers, but GaAs still has a 31% share. For power amplifiers, GaAs is "still critical", and will grow from a 80% share to over 90% by 2010, compared to silicon, Anwar reckons.

For WLAN applications, Si/SiGe dominates at 2.4GHz for the transceiver. But, as applications migrate from 80211b through higher-frequency 80211a, then 80211g to 80211n (dual-band) standards, GaAs will "remain critical" for the PA, with SiGe's market share falling from 80% in 2001 to 20% in 2010, Anwar reckons.

However, he concludes that silicon will dominate lower-power applications and integration.

Brian Daly, Skyworks Solutions' VP of marketing for Mobile Platforms, emphasized how EDGE and multi-mode technology is driving upgrading of mobile handsets, with the radio content per phone increasing, for example in the front-end module from \$4 for GPRS to \$5-7 for EDGE and \$8-10 for multi-mode (giving a possible 43% compound annual growth rate).

Monte Miller, engineering manager of compound semiconductor products for silicon RF LDMOS power transistor maker Freescale Semiconductor, concedes that GaAs has the most design wins for 3.5GHz appli-

cations, and that GaN is the leader in power density and frequency performance. However, he highlights how silicon LDMOS is low cost and dominates for applications below 3GHz (WiBro and WiMax) and is the "RF performance leader" in terms of gain and linearity. "The game is over for GaAs below 3GHz", he reckons. LDMOS' high efficiency is good enough for applications over 3.5GHz, with Freescale launching five products for WiMax, and a generation under development with an f_T of 15GHz and an f_{max} of 25GHz ("comparable with GaAs and even GaN").

When Barsky questioned LDMOS' suitability for use at 5.8GHz, Miller said that "developers have some things up their sleeves".

A few years ago, people thought the limit of LDMOS was 2.5GHz and that it couldn't do 3.5GHz, added Anwar, "but its here now...so don't rule it out".

Allen Hanson, the product development manager of GaN-on-Si specialist Nitronex, which launched its first products in 2005 for 3.5GHz WiMax and makes about 1500 wafer starts per year, said that 3G represents an opportunity for GaN in Classes D, E, F and S amplifiers, due to its 40-50% efficiency.

However, replying to a comment that LDMOS was not always cheap, Miller claimed that most of the cost was due to the packaging, not the die, and that he still "does not see GaN competing with silicon on cost". Anwar, too, "does not see GaN as a drop-in replacement for LDMOS". To take advantage of GaN's power density requires a change in design methodology, e.g. moving the base-station nearer to the antenna (eliminating cooling etc). Nevertheless, GaN is due to be deployed in base-stations in Japan in 2008-9, he added. In addition, says Hanson, Nitronex is developing MMICs, for release in 2007, and is looking at military applications "perhaps including commercial partners". ■

Enhanced BiFET boosts

Skyworks' **Ravi Ramanathan** and colleagues detail how the BiFET process is integrated into a high-volume GaAs HBT manufacturing facility, allowing integration of external bias control circuitry into wireless power amplifier die.

Handset designers continue to strive for higher levels of integration in order to reduce the size and cost of next-generation products while improving battery life. One key integration target for the industry has been the incorporation of external bias control circuits into the power amplifier (PA) die. This is now possible using enhanced bipolar field effect transistor (BiFET) process technology for gallium arsenide-based products. BiFET technology uniquely integrates indium gallium phosphide-based heterojunction bipolar transistors (HBTs) with field effect transistors (FETs) on the same GaAs substrate using a high-yielding InGaP/GaAs HBT process. This article will explore the manufacturability requirements of this innovative BiFET process technology that opens up new opportunities to embed analog signal processing and control functionality in mobile handsets as well as infrastructure wireless applications.

The addition of FETs to Skyworks' fourth-generation, high-yielding InGaP/GaAs HBT process allows advanced bias control features to be embedded in the same PA die, thereby eliminating the need for external bias control circuits for many applications. When coupled with other proprietary design techniques that extend battery life and reduce the radio-frequency loss between integrated components, semiconductor manufacturers are able to increase functionality and simplify designs while leveraging production costs across a suite of GaAs-based solutions, and address additional markets that require embedded analog signal processing and control functionality.

Several BiFET integration schemes have been proposed and demonstrated by a variety of research groups [1-4]. To establish a BiFET process in Skyworks' high-volume GaAs HBT production line, we have evaluated some of these possible BiFET integration approaches and found most of these methods have drawbacks with respect to high-volume manufacturing. Due to Skyworks' stringent yield requirement in a cost-conscious environment, a

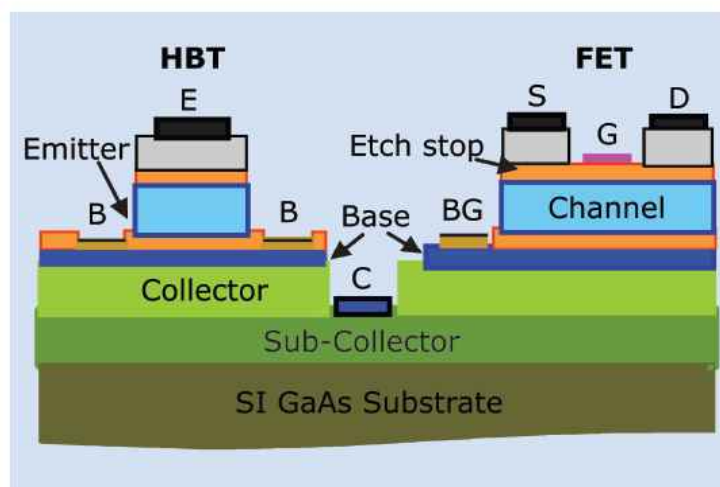


Figure 1: Schematic cross section of an integrated HBT and FET. S, D, G and BG are the source, drain, gate and back-gate contacts of the FET, and E, B and C are the emitter, base and collector contacts of the HBT.

hybrid BiFET approach, achieved through a single epitaxial growth run, was selected and developed.

Material growth and device fabrication

Epitaxial layers, consisting of the InGaP emitter, base and collector of the HBT, are grown on semi-insulating (SI) GaAs (100) by using metal organic chemical vapor deposition (MOCVD). The FET-specific layers such as the channel and an optimized etch stop layer are grown within the emitter of the HBT. A schematic cross-sectional profile of the BiFET layer scheme is shown in Figure 1.

In a high-volume GaAs HBT manufacturing environment, the starting epitaxial materials should be 'pre-screened' and sufficient quantities need to be kept in material inventory or in consignment for uninterrupted lot starts. A quick-lot (QL) process is often used by material suppliers to ensure that the incoming HBT wafers meet the desired specifications. Typically, large-area (75µm x 75µm) HBT devices are fabricated and electrical parameters such as direct-current gain, offset voltage, base-emitter/base-collector turn-on voltages, sheet resistances, and junction breakdown voltages are measured from multiple sites on a witness wafer. However, since FET devices are sensitive to process conditions, electrical measurements such as pinch-off voltage, saturation current and transconductance vary significantly due to the process and mask the growth variations. Hence, the FET QL process and electrical characterization of FETs, at the material

wireless integration

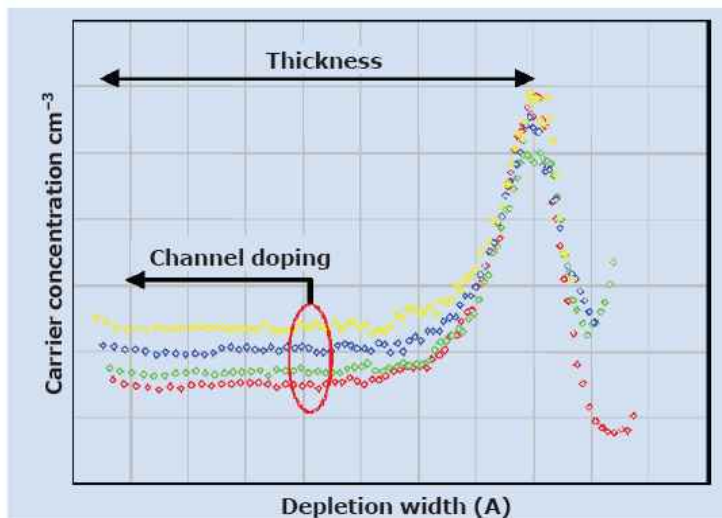


Figure 2: C-V profile of emitter layer stack in a BiFET wafer. Various curves are collected from design of experiment wafers with various doping concentrations.

supplier sites, are often inadequate to screen the quality of the epitaxial layers.

In addition, an alternate FET QL procedure should also be simple to interpret, faster, and depend only on run-to-run and machine-to-machine growth variations. To this end, in collaboration with the epi supplier, a capacitance-voltage (C-V)-based QL procedure has been established. Figure 2 illustrates a typical emitter-base junction C-V profile collected from a set of design of experiment (DOE) wafers with different doping concentrations. From the C-V profile, one can extract the FET channel thickness and doping concentration, as depicted in Figure 2. Using this simple characterization technique, consistent thickness and doping information have been obtained to establish a correlation with the FET electrical parameters that are acquired after full wafer fabrication. Failure to implement such QL strategy can result in very costly yield issues and potential scraps at the end of the line.

In defining the FET, the challenge is to add a minimum number of masking steps to define the channel and gate regions, and these FET-specific process steps have to be introduced into the HBT flow at the appropriate steps and still preserve the electrical integrity of the FET and HBT devices. The source and drain contacts of the FET share the same fabrication steps that are used to form the emitter contacts of the HBTs. In placing the gate metallization step, care should be taken to limit the exposure of gate metal Schottky contact to high

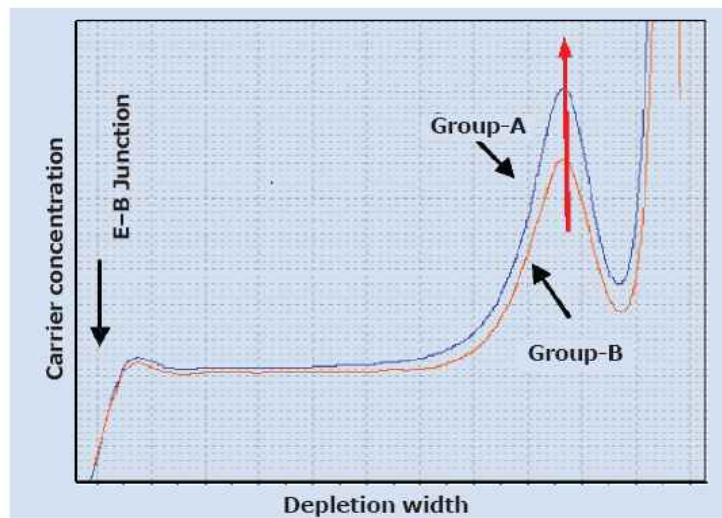


Figure 3: C-V profiles of the emitter-base (E-B) junction of BiFET wafers. Group A wafers and Group B wafers come from different MOCVD growth runs.

temperatures (>300°C) and longer isothermal anneal cycles. FET device-to-device isolation is achieved by the combination of dry etch and ion implantation process, both of which are used in the definition of the HBTs.

Influence of fabrication steps on FETs

To achieve the goal of high yield for FETs, similar to that of HBTs, the following process variations must be studied and controlled:

Epitaxial variation

The implication of run-to-run growth variation on the C-V profile and the correlation to FET pinch-off voltage is shown in Figures 3 and 4. From the C-V profile, one can infer that the bulk channel doping and channel thickness of the two groups of wafers are the same.

However, the charge difference between the groups, as shown in Figure 3, could be the result of either charge build-up at the interface of the etch-stop layer and the channel layer and/or the doping in the etch-stop layer, which results in a shift of 100 mV in the pinch-off voltage, as shown in Figure 4.

Gate definition process

The metal-semiconductor FET in BiFET technology consists of a thin etch-stop layer between the electron-beam-evaporated Ti/Pt/Au/Ti Schottky gate electrode and the GaAs channel layer. In this structure, the gate metal/etch-stop layer Schottky contact is the key component, although these Schottky contacts are not intimate metal-semiconductor contacts, and are

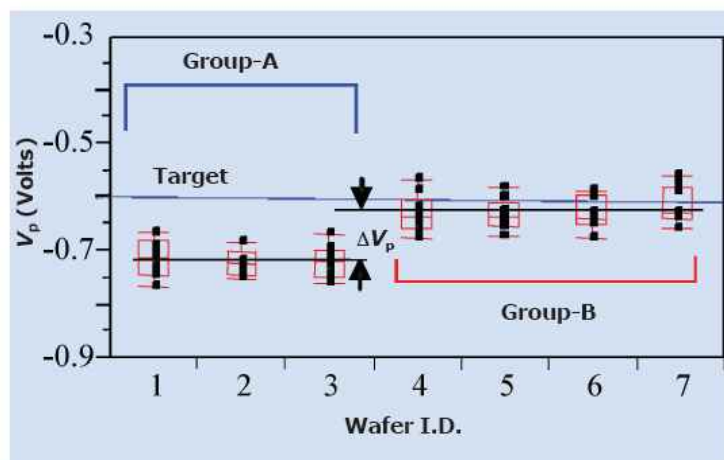


Figure 4: Pinch-off voltage versus wafer I.D. of a depletion-mode FET from a single fabrication run. Note that the ΔV_p of 100 mV between the two groups arises due to the difference in epitaxial layers.

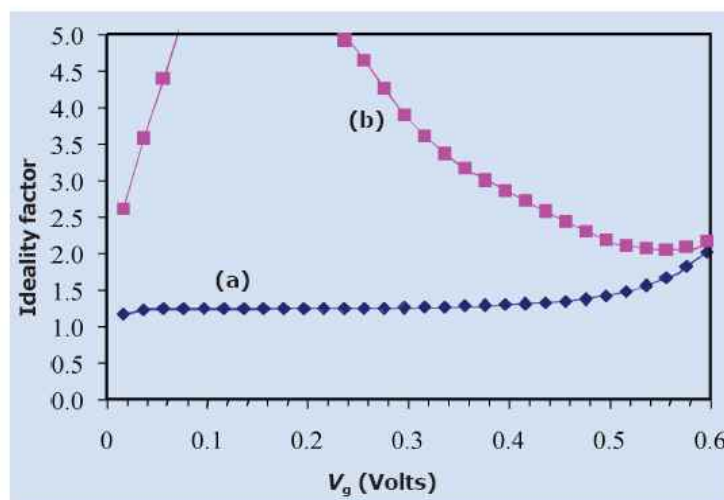


Figure 5: Ideality factor as a function of gate voltage of the Schottky contact. Curve (a) is generated from an FET with good electrical characteristics, and (b) from an FET with poor electrical characteristics.

separated by a thin inadvertent interfacial layer formed due to cross-diffusion, out-diffusion and chemical reactions between the metal and the semiconductor. It is therefore critical to optimize the gate definition process steps which prepare the surface consistently prior to gate metallization. Several wet and plasma surface passivation processes are investigated. The ideality factor, $n = (q/k_B T) (dV_{gs}/d \ln I_g)$, is determined from the forward I-V characteristics of the gate at 300K.

The change in ideality factor as a function of the applied voltage, as illustrated in Figure 5, is used to determine the quality of the metal-semiconductor contact. Curve (a) in Figure 5 is collected from an FET and fabricated with an optimized gate process. On the other hand, curve (b) in Figure 5 is collected from an FET with a pinch-off voltage of $-0.2V$ and the saturation current was dropped by more than 10 times the target value. For an imperfect Schottky contact (Figure 5b),

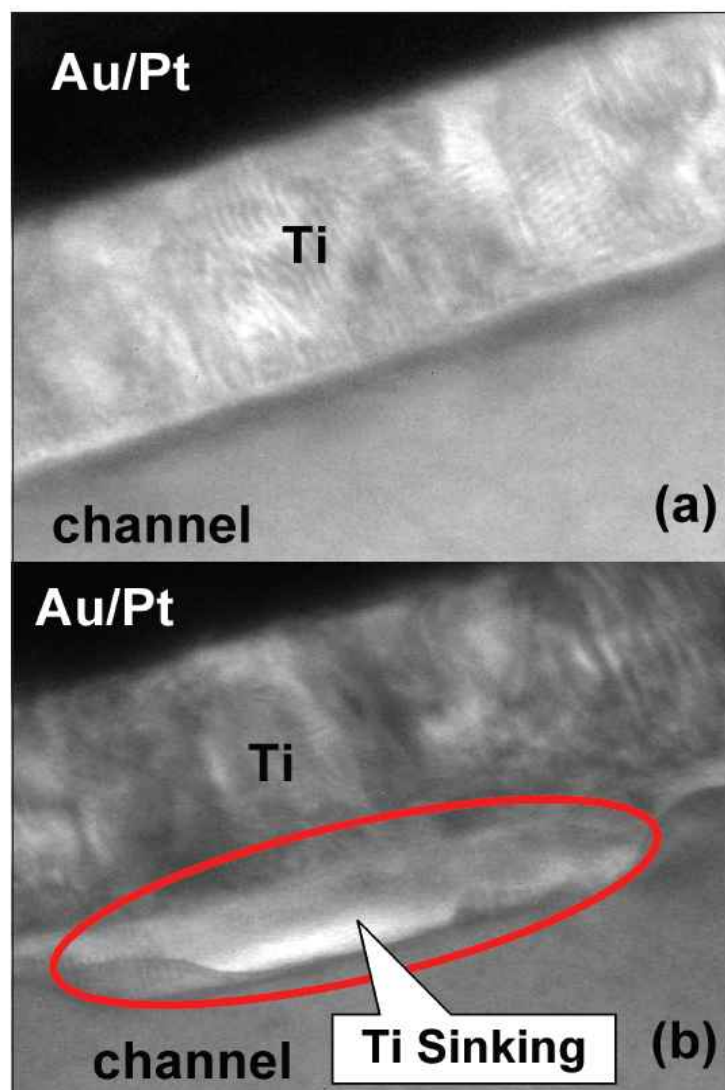


Figure 6: Transmission electron micrographs of the gate region. Image (a) is from the gate Schottky with $n = 1.23$ and image (b) is from the non-ideal Schottky contact with $n > 2$. Note the sinking gate, which is highlighted in (b).

the ideality factor increases with bias to almost 5, and then decreases. Such a voltage dependence of n is very unique in III-V semiconductors with a high density of surface states. Surface imperfections and a sinking gate, leading to the distribution of interface states in the forbidden gap, are the major causes of non-ideal behavior in Schottky contacts, and are revealed by transmission electron microscopy (TEM) of the gate region, as shown in Figure 6.

Manufacturability

In addition to establishing the control procedures for the incoming epitaxial material, each process module in the fabrication steps was carefully optimized. The process capabilities (Cp, Cpk) were assessed from the electrical parameters of both HBT and FET devices, and the statistical data was used for circuit designs. Besides process control procedures, it is also critical

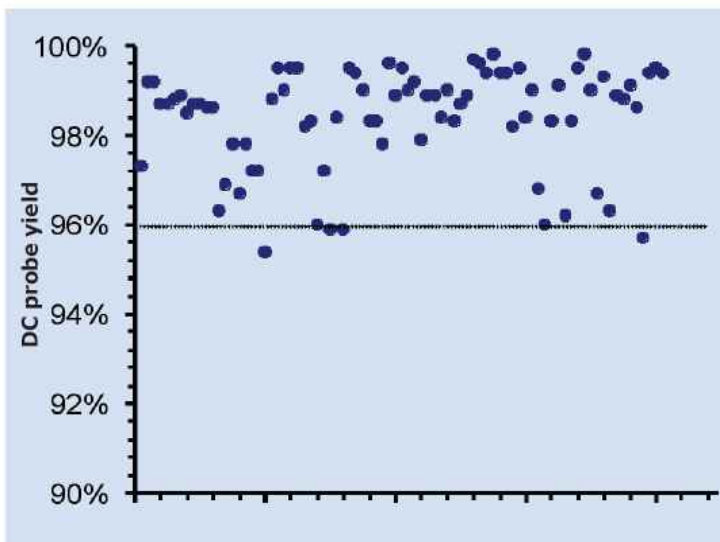


Figure 7: DC probe yield of BiFET designs as a function of wafer/lot numbers collected over a period of four months. Gross yielding dies per wafer is computed after performing a series of DC tests for both HBT and FET active devices as well as passive devices such as resistors and capacitors in the design.

that the FETs in the BiFET circuits can be probed, either directly or indirectly, in order to calculate the gross yielding dies per wafer accurately. For example, indirect measurement in the bias enable path could be simply toggling the gate voltage to the FET and measuring the bias voltage to the amplifier in the FET on-state and the bias leakage in the FET off-state. Extensive test coverage during the early stage in high-volume manufacturing will identify possible epitaxial material, process and/or tool issues. As a result, high DC probe yield in CDMA/WCDMA and WLAN products based on BiFET technology, comparable to HBT-only based products, have been achieved, and are depicted in Figure 7.

Summary

The importance of screening incoming epitaxial material has been shown to be crucial for achieving/maintaining high yield in manufacturing. To this end, the capacitance-voltage characterization method was used to qualify the FET-specific layers, along with the electrical characterization of HBTs using large-area processing in the BiFET wafers. The sensitivity of the C-V method was found to be adequate for quantifying growth run-to-run variations, and good correlation has been made to the FET electrical parameters at the end of the line. The bias-dependent ideality factor n and the decrease in transconductance g_m as a function of different process steps were studied, and optimized process conditions, which preserve the integrity of the FET and HBT, were chosen. With the implementation of stringent control procedures as well as circuit-validated control limits, high-probe yield in the BiFET-based circuits has been demonstrated. ■

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Authors: Ravi Ramanathan (director of engineering), Peter Zampardi (technical director), Mike Sun (engineering manager), Hongxiao Shao (engineering manager), Skyworks Solutions Inc

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Nitride substrates bridging the gap

Dr Mike Cooke summarizes the relative merits of the various substrate types for nitride-based devices, as well as the latest commercial developments.

Since Shuji Nakamura invented and developed the first commercial processes for blue-green light emitting devices based on gallium nitride (Figure 1a), nitride semiconductor technology has become an important focus for research, development and commercial products. Renewed interest has been sparked by the prospect of GaN high-electron-mobility field effect transistors (HEMTs) being used in wireless base-stations to provide RF power amplification up to 40GHz (Figure 1b) [1]. This application is dependent on increasing the reliability of the devices, partly through reducing the defect density in the GaN substrate layer. Defects are even more effective at killing high-stress devices such as continuous-wave operation laser diodes. Other possible applications of nitride technology include power switching, ultraviolet detection and bio-chemical sensing.

GaN's commercial success has been enabled by GaN being grown hetero-epitaxially on other materials such as silicon carbide (SiC) and sapphire (Al₂O₃). In recent years, there have been attempts to grow single-crystal GaN (Table 1) to provide a substrate for homo-epitaxial GaN. Other firms have aimed to produce epitaxial GaN layers more cost effectively using substrates such as aluminium nitride (Crystal IS, Fox Group and HexaTech), zinc oxide (Cermet), and silicon (Nitronex, PicoGiga).

Figure 1 shows schematic diagrams of GaN-based light-emitting diodes (LEDs) and field-effect transistors

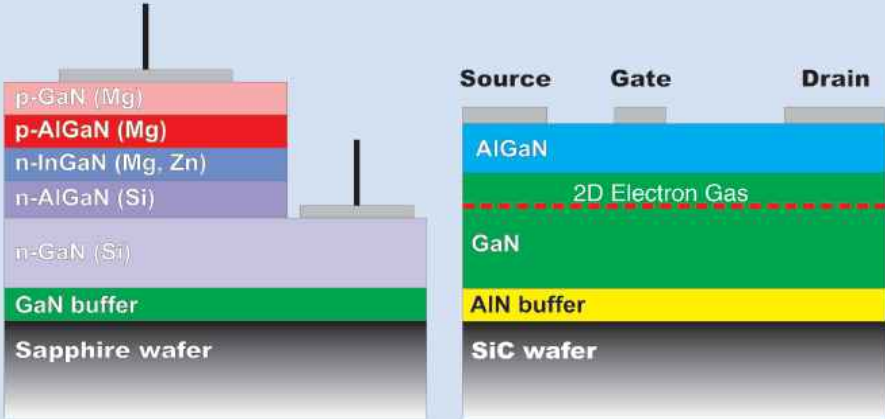
Table 1: Firms working on pure GaN substrates.	
Company	Website
Hitachi Cable	www.hitachi-cable.co.jp
Sumitomo Electric Industries	www.sei.co.jp
Cree Inc	www.cree.com
Kyma Technologies	www.kymatech.com
TDI	www.tdi.com
TopGaN	www.topgan.fr.pl

(FETs), where the GaN epilayer on these wafers is followed by a series of layers consisting of alloys of Group III elements (Al, Ga, In) with nitrogen. Ternary (e.g. AlGaIn) and quaternary (e.g. InAlGaIn) combinations can be used to engineer the band structures and lattice properties required. Although a linear interpolation between the properties of the binary compounds (Table 2) can give a first approximation, it is often necessary to include higher-order effects.

Sapphire

At first sight, sapphire does not provide the most promising surface on which to grow GaN. The lattice mismatch is about 15% (Table 3) and the coefficients of thermal expansion differ, which is a problem as the GaN layers are fabricated, and often designed to run, at high temperature. GaN layers on sapphire that are

Figure 1: Typical structure of a GaN-based light-emitting diode (a) and a GaN-based high-electron-mobility transistor (b).



stable during growth at 1000°C can crack on cooling to room temperature. Further, thermal stresses can cause propagation of defects up from the GaN layer either before or during operation.

Despite these problems, in the late 1980s, Japanese researchers pioneered viable techniques to grow GaN on sapphire by MOCVD, triggering the explosion in commercial blue-green light-emitting devices of the 1990s. First,

researchers from Nagoya University and Matsushita Electric Industries produced substrates with an AlN buffer layer between the sapphire and GaN materials [4]. Then Shuji Nakamura at Nichia used a GaAlN buffer [5].

Typical MOCVD steps for producing GaN on sapphire include a pre-treatment at around 1000°C (to nitride the sapphire surface, typically using ammonia, NH_3), production of a nucleation layer at about 600°C, then reheating to a growth temperature of 1000°C. The resulting wafer consists of a highly dislocated buffer layer near the sapphire substrate that gradually becomes more crystalline (Figure 2a).

To improve the final GaN layer, various techniques have since been developed, such as lateral epitaxial overgrowth (LEO), where GaN is grown around a SiO_2 mask that blocks the threading dislocation defects propagating upwards from the buffer region (Figure 2b). The method can lead to crystallographic 'tilt' between regions that have overgrown the mask and coalesced.

Alternatively, in 'pendeo-epitaxy' (Figure 3), GaN crystal growth proceeds from the sidewalls of columns of GaN seed layers etched onto the substrate, and then overgrows the SiN mask on top of the column. Further growth options are available, such as continuous GaN or AlGaIn films. These techniques can be used independently of the initial substrate material (e.g. on SiC substrates). North Carolina State University developed two separate 'pendeo' patent portfolios: one, for SiC substrates, was sold to Cree of Durham, NC under an exclusive agreement; the other, for GaN/sapphire and GaN/Si, helped to found Nitronex Corp of Raleigh, NC.

Table 2: Properties of binary Group III-N semiconductors [2]. Other properties, such as thermal conductivity, can improve with material development.

Material	Crystal structure	Mismatch with GaN	Thermal conductivity (W/cm.K)	Bandgap ^a (eV)	Breakdown field (MV/cm)
GaN	Wurtzite	0%	1.3	3.39 (d)	~5
AlN	Wurtzite	2%	2.85	6.2 (d)	1.2–1.8
InN	Wurtzite	10%	0.45	0.7 (d) ^b	1.2
BN	Wurtzite	20%	7.4	4.5–5.5 (i)	6

^a d=direct bandgap; i=indirect bandgap.

^b The bandgap for InN has recently been drastically reduced from 1.9eV [3].

Table 3: Properties of common and potential GaN substrate materials.

Material	Crystal structure	Mismatch with GaN	Thermal conductivity (W/cm.K)	Bandgap ^a (eV)	Breakdown field (MV/cm)
Sapphire	R ^b	16%	0.31–0.47	—	—
SiC	6H	4%	4.9	3 (i)	3–5
Si	Diamond	18%	1.5	1.12 (i)	0.3
ZnO	Wurtzite	2%	0.6	~3.3 (d)	>1

^a d=direct bandgap; i=indirect bandgap. ^b R=rhombohedral.

Silicon carbide

Compared to sapphire, 4H and 6H polytypes of SiC have much smaller lattice mismatches with GaN of 3–4%. Also, at room temperature, SiC's thermal conductivity is ten times that of sapphire (a thermal insulator, unusable for high-power-density GaN devices). Good thermal conductivity is particularly important for devices operating at over 200°C, such as RF power transistors and high-power lighting devices, which need an effective dissipation path to heat sinks.

The main drawback is that good-quality, large-diameter SiC is very difficult to produce and is hence expensive. Czochralski's method for producing high-quality silicon crystal does not work, since there is no SiC liquid phase at atmospheric pressure (and likewise for AlN). In fact, solid SiC only melts at about 2800°C and at a pressure greater than 35 atmospheres. Bulk SiC crystals are sublimated directly from the gas phase. Careful process control is needed to avoid defects such as dislocations, the inclusion of different polytypes, and micropipes.

Much effort has been made to improve SiC crystal quality, especially since it is important for high-voltage devices in its own right: SiC power transistors will be used for RF amplification of wireless base-station transmission signals in the next few years while GaN-based device reliability is being improved.

In the past, the density of micropipes has been the dominant defect in limiting wafer cost-reduction and device size. However, micropipe density has since been reduced so it no longer dominates. In March (before its acquisition by Cree) Intrinsic Semiconductor started commercial shipments of zero-micropipe SiC wafers.

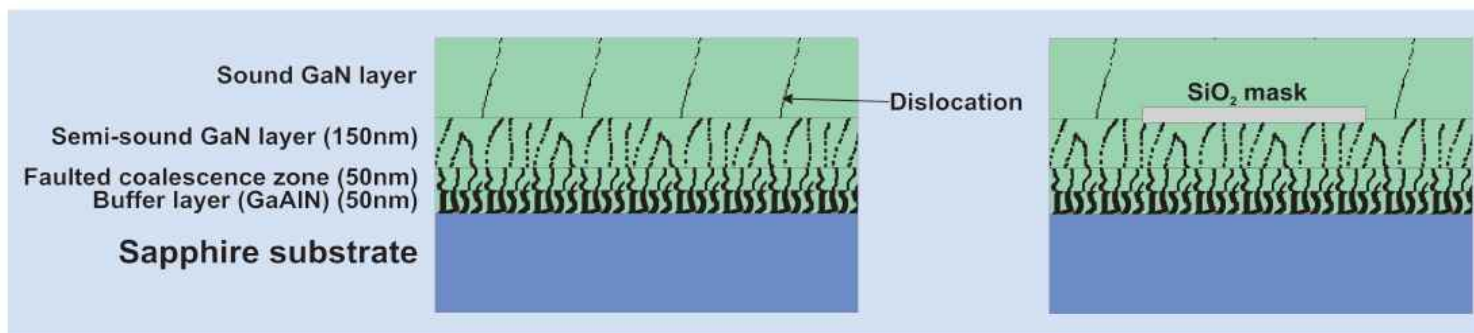


Figure 2: (a) Structure of GaN crystal layer deposited on a non-lattice-matched substrate. (b) SiO₂ mask is used in lateral epitaxial overgrowth (LEO) to block the propagation of crystal defects in the GaN layer.

GaN

In addition to the established substrates, there is a wide range of other possibilities. Pure GaN substrates would avoid all the problems of lattice matching and thermal expansion, although its thermal conductivity (half that of SiC) is a slight drawback.

But, again, liquid-phase growth is not possible, as the N atom has a tendency to dissociate at about 1600°C, while the GaN melt temperature is about 2500°C. Despite this, many groups and companies have worked to produce pure GaN wafers via other processes.

In hydride vapour phase epitaxy (HPVE), gallium and hydrochloric acid are made to react, creating volatile gallium chloride. The vapour is then transported to the crystal growth zone to react with an ammonia layer on the growing GaN crystal. Growth rates of hundreds of microns an hour can be achieved. Alternatively, GaN can be grown as a thick layer on a sapphire or SiC template, which is then removed, leaving a pure GaN wafer. Hitachi Cable has used a perforated titanium nitride film between the GaN and the template to ease separation.

Sumitomo Electric Industries has a process where dislocations are reduced by forming inverse-pyramidal pits on the crystal surface (Dislocation Elimination by Epitaxial growth with inverse-pyramidal Pits/DEEP). It has also developed a technique that controls where dislocations are concentrated to form larger low-dislocation areas, e.g. 500µm-diameter areas with dislocation densities of 10⁴–10⁵cm⁻² on a 50mm-diameter GaN wafer. Its original target was the production of lasers for Blu-ray optical disks, shipping samples in 2002.

Silicon

Since the GaN-on-sapphire lattice mismatch has not prevented production of devices, the same is possible on silicon. Research on GaN/Si was diverted by Nakamura's success with sapphire, but more recently firms have been producing GaN/Si wafers for commercialization.

The GaN/Si lattice mismatch is about 18%, but its thermal conductivity is about four times that of sapphire (40% that of SiC). A further attraction is the availability of larger and much lower-cost substrates from the mainstream silicon industry. Among the buffer layers used to

bridge the lattice mismatch are GaAs, AlAs, ZnO, LiGaO₂ (lithium gallate, or LGO for short), SiO₂, Si₃N₄, sputtered AlN, low-temperature GaN (LT-GaN), LT-AlN, and deposited and converted SiC. Nitronex uses a proprietary recipe of transition layers in its SIGANTIC GaN/Si product. It can also use its trademarked PENDEO process to improve the GaN crystal quality, but has found this unnecessary for its most recent products.

Professor Alois Krost's team at the Otto-von-Guericke University, Magdeburg, Germany in 2000 was first to grow thick, crack-free GaN-on-Si. Its epiwafer-foundry spin-off AZZURRO Semiconductors AG offers 50 and 100mm wafers, and in August 2005 (at the ICNS conference) presented 150mm GaN-on-Si wafers. AZZURRO now offers GaN-on-Si HEMT epi for RF and high-power electronics as well as LEDs.

SOITEC's Picogiga International compound semiconductor material division in Europe has also produced thin layers of single-crystal GaN on 150mm (111) Si wafers, using a proprietary buffer layer. Picogiga claims a capacity of 70,000 100mm-equivalent epiwafers per year using 10 MBE reactors from Riber and Veeco. In 2005, PicoGiga announced a joint development program with Veeco on the industrial-scale use of MBE in producing GaN/Si, based on the GEN200 system, which can handle wafers of up to 150mm in diameter.

SOITEC also hopes to apply its wafer bonding and SmartCut hydrogen implant technology (used in its commercial silicon-on-insulator wafer production) to provide GaN substrates based on polycrystalline SiC (pSiC) with improved thermal performance. Initially, a thin layer of (111) Si will be applied to the pSiC before epi growth of GaN, but the eventual aim is to put a pure GaN layer on the pSiC, for epi growth of GaN.

Diamond

High-power and high-speed transistors suffer problems of heat build-up, and are becoming performance limited. With a thermal conductivity that is 10 times better than silicon and 2–3 times better than SiC, diamond films can provide a path for integrated thermal management.

This February, a GaN-on-diamond wafer was launched by Group4 Labs, founded in Menlo Park, CA, USA in 2003.

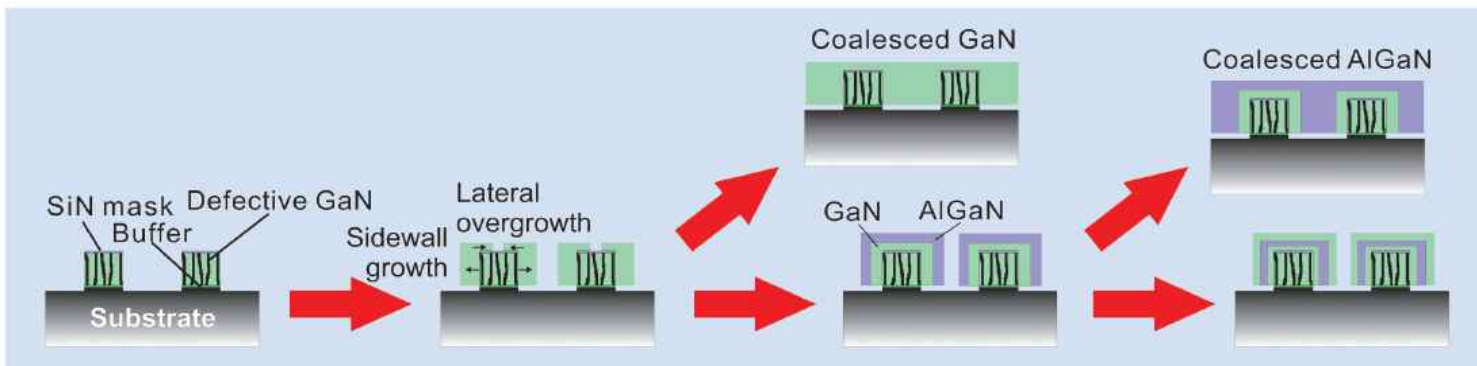


Figure 3: Steps and options for producing better GaN layers through pendeo-epitaxy, derived from [6].

In its 10mm x 10mm square Xero Wafer (available at \$450 per unit, the atomically smooth, epi-ready GaN layer lies less than 0.5nm away from a 25µm-thick substrate of CVD-deposited polycrystalline diamond, which has a thermal conductivity 3–30x that of conventional semiconductors. Heat can be extracted very efficiently from the active layers, boosting the power density of a transistor array by at least 10x over GaN-on-SiC.

sp3 Diamond Technologies Inc of Santa Clara, CA, USA, in a Phase I Small Business Innovation Research contract from the US Missile Defense Agency, delivered 100mm silicon-on-diamond (SOD) wafers with a GaN top surface, and modelled performance gains obtainable in a HEMT device on a thermal layer of diamond (showing a junction temperature reduction of 80K, combined with a 37% boost in output power).

In June, sp3 received a \$750,000 Phase II contract to develop GaN-on-SOD for devices suitable for radar transmit/receive modules. Two key applications are being pursued by collaborating companies. Nitronex will fabricate active high-power devices. "The fact that sp3 is offering us a known silicon interface on 100mm wafers provides an easy migration to future productization and a pathway to scale to 150mm GaN wafers," said its chief technology officer Kevin Linthicum. TriQuint Semiconductor will model the technology for their high-frequency MMIC development. "With the push by the military for tripling device power and adding 50% greater efficiencies...we will work closely with the material to move it toward products as soon as possible," stated Tom Cordner, VP, TriQuint Texas.

Aluminium nitride

Aluminium nitride has also attracted interest as a substrate for nitride devices. A lattice mismatch with GaN of about 2% and a thermal conductivity of about 80% that of SiC could open up markets for high-power RF electronics and high-reliability UV optoelectronics (e.g. LEDs for purifying water or air, phototherapy, curing industrial materials, and bio-agent sensors).

HexaTech claims a commercially viable process combining the benefits of physical vapor transport (PVT) growth and seeded growth for the reproducible pro-

duction of AlN single crystals. Although no figures are given, it says that its seeded growth technique enables the fabrication of AlN boules of pre-defined crystallographic orientation, and of reproducible quality.

One technique for producing bulk AlN crystal is sublimation-recondensation. Schowalter *et al* [7] of Crystal IS (formed in 2004 in a Rensselaer Polytechnic Institute incubator in Watervliet, NY, USA) together with the State University of New York (SUNY) comment that the basics of this growth process are "straightforward". But a less sanguine view is taken by Liu *et al* [8], a group from Kansas State University, SUNY (again!), the UK's University of Bristol and the USA's Oak Ridge National Laboratory, who discuss the difficulty of the inherently reactive growth environment at 2100°C, and compare the suitability of materials such as tantalum carbide, niobium carbide, tungsten, graphite, and hot-pressed boron nitride for furnace fixtures.

In June 2005 Crystal IS moved into a larger facility in Green Island, NY, USA to expand substrate production, and this May launched commercial 50mm substrates with a dislocation level of less than 1000/cm², although this is for the AlN substrate alone (without a GaN layer). Also, the firm recruited a VP of business development, sales and marketing (from IQE Inc in Bethlehem, PA) and a CEO (Dr Ding Day, former Skyworks' VP of global business development), with co-founder Leo Schowalter becoming CTO to focus on technical development.

Fox Group Inc of Deer Park, NY, USA has developed and patented both tantalum carbide crucible technology and a bulk crystal growth method (a modified vapor transport process). Since March, Fox has been selling epi-ready monocrystalline AlN substrates, initially available as 15mm discs.

Fox also makes AlGaN-based devices, including blue and UV LEDs, at a subsidiary in Montreal, Canada. These are grown on sapphire using its proprietary Fox-HVPE hydride vapor phase epitaxy technique (initially developed by researchers at TDI of Silver Spring, MD, USA), but Fox is aiming to migrate to AlN substrates.

After introducing the first 50mm AlN-on-SiC substrates three years ago followed by 75mm product a year ago, in June TDI fabricated prototype 100mm

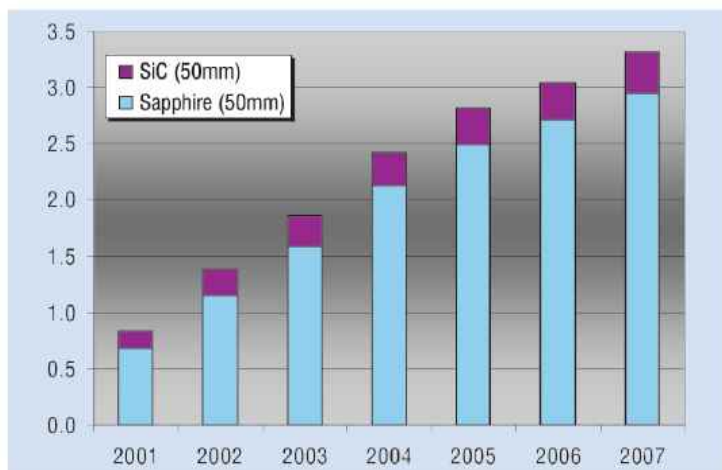


Figure 4: SiC and sapphire substrate use (millions of 50mm wafer-equivalents) and forecast for GaN-based LED production. Graph courtesy of Yole Développement.

semi-insulating substrates. Proprietary stress control technology and crystal growth equipment allows the deposition of crack-free single-crystal AlN film about 10µm thick (enough for reliable insulation and low current leakage to the conductive SiC substrate). So, as well as having good lattice and thermal match to GaN devices, says president and CEO Vladimir Dmitriev, AlN-on-SiC substrates combine the high thermal conductivity of SiC and the high intrinsic electrical resistivity of AlN for high-power AlGaIn/GaN devices (including HEMTs and high-frequency power amplifiers). TDI is starting pilot production and plans to make the first product shipments in last-quarter 2006.

Other substrates

Other possible substrates for nitride devices considered in research include MgO, MgAl₂O₄, LiAlO₂, LiGaO₂, ZnO, and NiAl. The best lattice matches are given by LiAlO₂ (0.2%), LiGaO₂ (1.4%) and ZnO (2.2%).

ZnO was proposed by Cermet of Atlanta, GA, USA, which aimed to produce substrates at a cost comparable to sapphire. Cermet claims a patented technology for bulk crystal growth of high-melting-point materials such as ZnO. It says these systems have also been used to melt and solidify AlN, and that a process for GaN is "under development".

The firm sees opportunities for light-emitting device applications, since ZnO is conductive, allowing a bottom contact, unlike sapphire-based LEDs. But ZnO has some hurdles that must be overcome. Foremost is that atomic hydrogen and dissociated ammonia attack ZnO, and both are present in large concentrations during standard MOCVD growth of GaN or InGaIn.

Cermet and its neighbor Georgia Institute of Technology are developing alternative growth methods to produce phosphor-free solid-state visible light sources with funding from the US Department of Energy. The

aim is to integrate large-area ZnO substrate and lattice-matched nitride epitaxy technologies to address substrate, epitaxy, and solid-state lighting device limitations in terms of defect densities in both the nitride emitters and the bulk substrates.

Applications

According to the recent report "2003–2009 Silicon Carbide Market Analysis" by France's Yole Développement, 90% of SiC wafer production is dedicated to GaN-based blue/white LED production (Figure 4). However, SiC substrates are very costly, so this could dwindle if companies can find less expensive alternatives.

John Palmour, Cree's executive vice president Advanced Devices, believes that GaN-on-SiC is the best option for RF, at least at frequencies above 3GHz, because of the thermal conductivity advantage. GaN on Si could be useful at lower frequencies, where there is a trade-off between performance and cost. Above 3GHz or so, says Palmour, GaN/Si experiences microwave losses in the substrate (since there is no semi-insulating silicon), and the thermal conductivity just one third that of SiC.

Last year, Nitronex announced pre-production samples of GaN transistors on its silicon substrate technology aimed at WiMAX broadband wireless networking. Its family of WiMAX power transistors initially consists of 10W and 50W devices supporting both the 2.5GHz and 3.5GHz segments. Chris Rauh, Vice President of Sales and Marketing, says that, with initial design-ins and early revenue already rolling in, Nitronex expected to complete full production qualification by early July. Nitronex also aims to introduce transistors supporting 5.8GHz operation in 2006.

Dr Edwin Piner, director of materials engineering, challenges the view that GaN/Si cannot handle more than 3GHz. Nitronex uses float-zone silicon, where a polysilicon rod is passed through an RF furnace, allowing a thin layer of the silicon to be re-melted. The impurities prefer to remain in the melt region and are swept along to the end. Commercially available float-zone silicon is close to "intrinsic", with impurity levels of the order of 10¹¹cm⁻³, just short of the process' supposed physical limit of 10⁹–10¹⁰cm⁻³. Resistivities exceeding 10⁵Ωcm can be achieved, two orders of magnitude better than silicon's usual 100–1,000Ωcm and comparable to Cree's semi-insulating 4H SiC wafer. For high-power GaN HEMT production, care is still needed to ensure that subsequent GaN/Si processing does not allow Al and Ga impurities (p dopants!) to reach the silicon, particularly in the buffer region.

Others producing GaN-based HEMTs for this market include Cree, Fujitsu, NEC and RF Micro Devices. To compete with existing silicon lightly doped drain MOS (LDMOS) chips, the target price for reliable wireless

devices is no more than \$1 per Watt. Other possible options include SiC MESFETs and GaAs devices.

One application where free-standing GaN substrates would be most beneficial is for lasers, since homo-epitaxy always gives the lowest defect densities. Extending the unfeasibly short lifetimes of GaN-based laser diodes depends critically on defect reduction (Table 4).

Bulk AlN substrates could prove useful for LEDs emitting in the deep-ultraviolet (DUV) region of the spectrum (less than 300nm) due to its much reduced light absorption compared with other options. This is because absorption in AlN is much suppressed below its bandgap energy of 6.2eV, which corresponds to a photon wavelength of 200nm. Applications for DUV LEDs include biological agent detection, non-line-of-sight (NLOS) covert communications, water purification, the curing of polymers and other chemicals, and in decontamination equipment. The first two of these applications explain the interest of the US Defense Advanced Research Projects Agency (DARPA), which, among others, funds research in the area.

Indeed, in May a 210nm UV PIN LED grown homo-epitaxially on an AlN substrate was reported in *Nature* by Japan's NTT Basic Research Laboratories after achieving controllable n-type doping in low-defect-density AlN. Such AlN-based devices will be explored more in the next issue of *Semiconductor Today* in the context of AlGaIn blue lasers. ■

Table 4: Properties of GaN on various substrates.

Substrate	Diameter (mm)	FWHM* (arcsec)	GaN dislocations (cm ⁻²)
Sapphire	50-100	250-450	~10 ⁸
SiC	50-100	<250	~10 ⁸
GaN	25-75	100	~10 ⁷
Si	50-150	<380	<10 ¹⁰

*Full width at half maximum = breadth of an x-ray diffraction peak when the sample is rocked through a small angle (rocking curve). Smaller FWHM = greater crystallinity.

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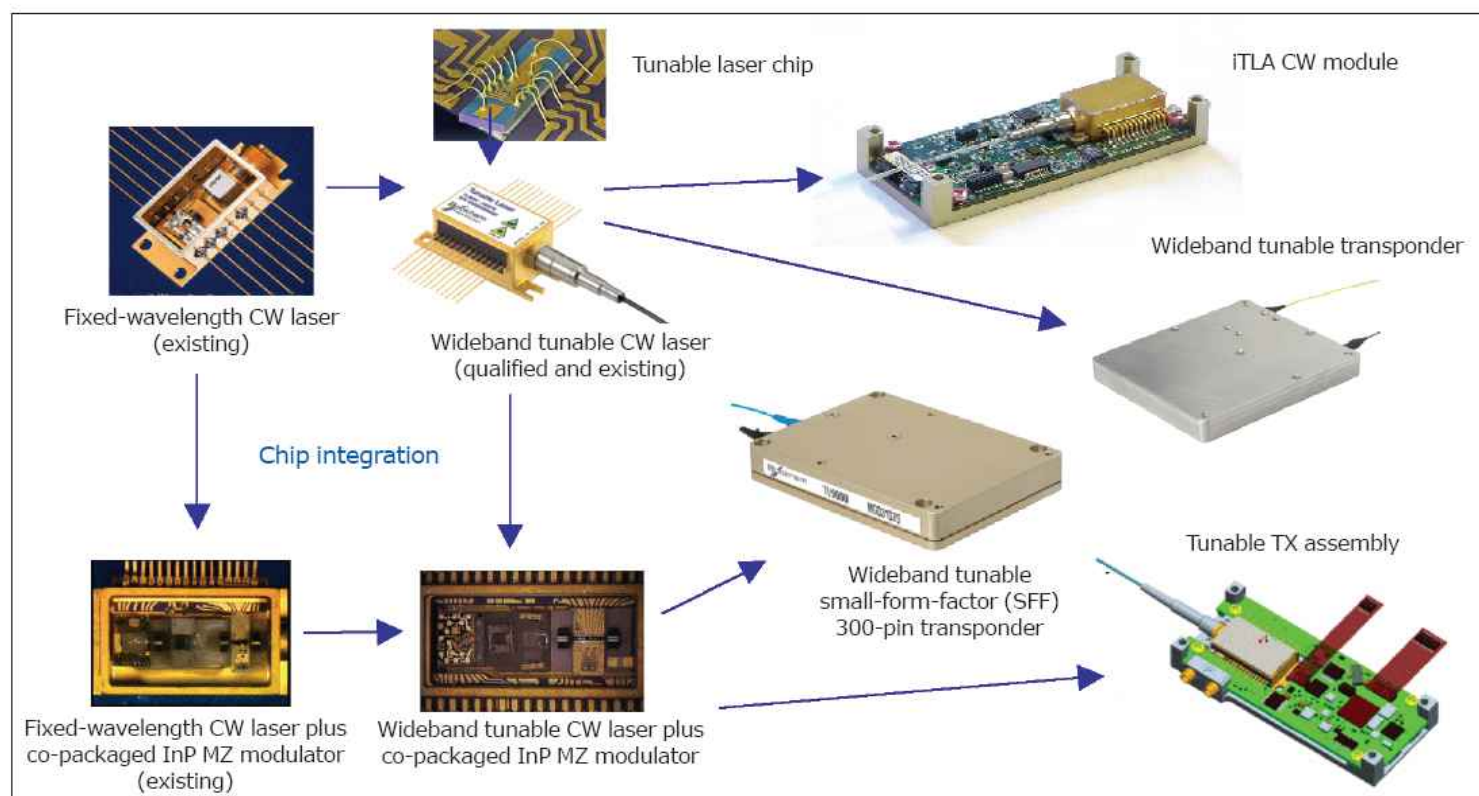


Figure 1: The evolution of wideband tunable components.

Bookham explains how state-of-the-art equipment in its Caswell 3" InP wafer fabrication line is enabling increasing integration of optoelectronic devices.

The Bookham wafer fabrication plant at Caswell in the UK contains one of the world's largest and best equipped 3" InP wafer fabrication lines dedicated to optical devices. The fab's state-of-the-art equipment toolset includes wafer steppers, photolithography tracks, ICP (inductively coupled plasma) etch tools, cassette-to-cassette wafer handling, a Leica VB6HR electron-beam lithography machine, and Aixtron multi-wafer MOCVD reactors, as well as extensive in-line inspection and analytical tools for capabilities such as secondary-ion mass spectroscopy (SIMS), focussed ion beam (FIB) analysis, and critical-dimension scanning electron microscopy (CD-SEM).

Such a facility provides numerous benefits. Known good die from the fab makes assembly highly efficient and allows for high-volume, low-cost assembly in the company's factory in Shenzhen, China. In-house capa-

bilities of this kind facilitates the rapid introduction of new products, permits class-leading chip yields on complex integrated devices, provides critical infeed cost management, and allows for rapid ramp-up to volume production. Working on modern tools for 3" diameter wafers allows superior production tolerance control with high uniformity across the wafer; the resulting yield improvements facilitate further improvements in specifications.

There is, however, an additional motivation for developing and maintaining such an advanced facility, which goes well beyond provision for high-volume production or even the demands of achieving high yields and tight production tolerances. A key differentiator lies in the use of unique III-V semiconductor device designs, manufactured in-house. Although many of today's optical components are presented in formats determined by multi-source agreements (e.g. in transceivers, transponders and integrated laser assemblies), differentiating content in terms of optical semiconductor devices is crucial in achieving a market advantage. Many of Bookham's products are leading-edge designs, and are totally dependent on highly developed, proprietary wafer processing technology.

Here, we highlight three families of devices for

device integration

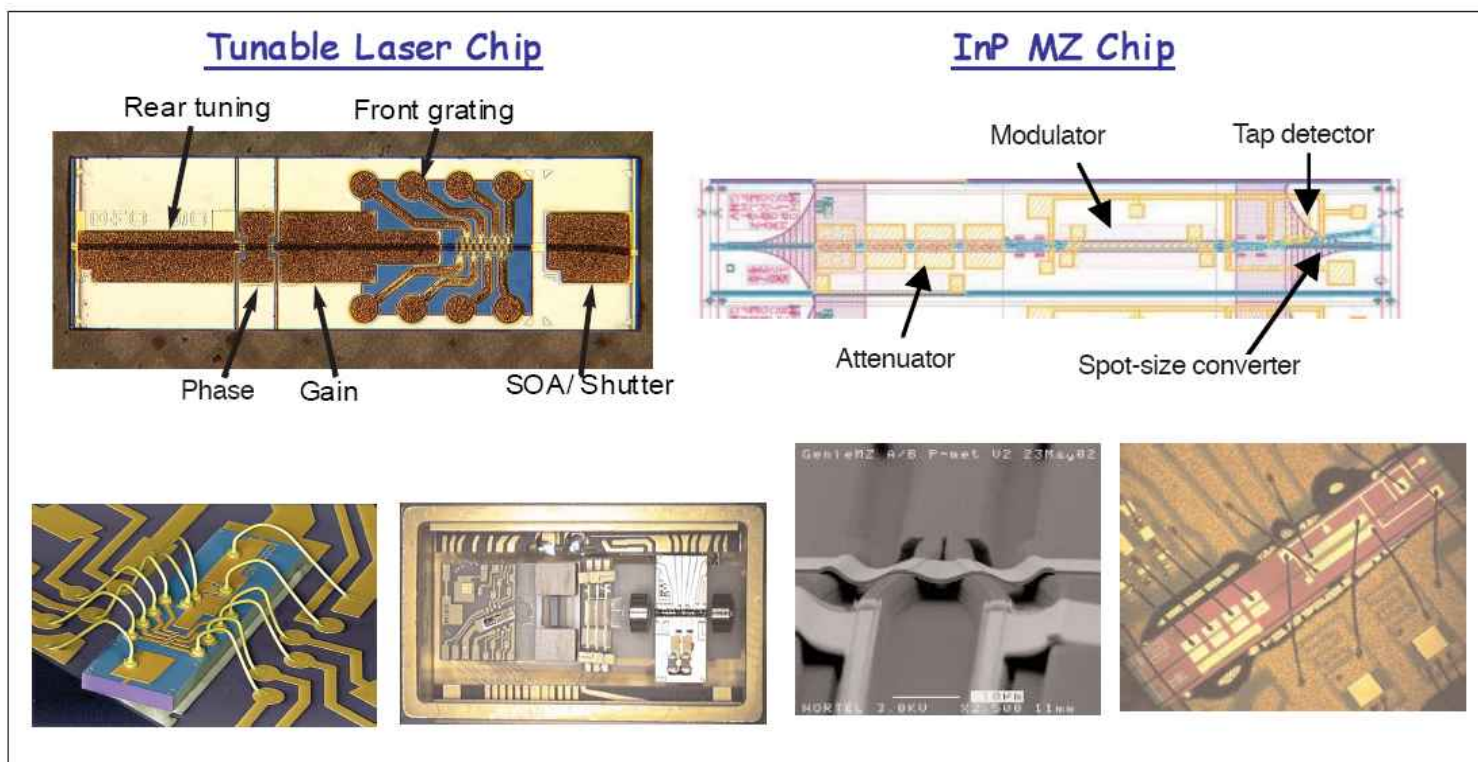


Figure 2: Key chips for tunable transmitters: a DSDBR laser (left) and a Mach-Zehnder modulator (right), with an example of transmitter component assembly (centre).

10Gbit/s transmission systems which are dependent on the Bookham wafer fab and show how their viability is dependent on the process capabilities outlined. These are, respectively, a wideband tunable laser; a complex, highly compact, multifunctional integrated optical Mach-Zehnder modulator; and a monolithically integrated DFB laser-electroabsorption (EA) modulator, all of which have been designed to address major market opportunities in optical communications networks.

Wideband tunable lasers

Key trends in the optical communications industry today include a rapid migration to tunability in the network core and the adoption of carrier-grade pluggable transceivers at the network edge.

Tunability in the network core allows automated service provision and reconfigurability, as well as offering a solution to the logistical challenges posed by dense wavelength division multiplexing (DWDM) systems. (In the absence of tunability, large numbers of parts operating at specific wavelengths are needed, resulting in very expensive 'bin fill' provisioning at product introduction as well as continuing costs in maintaining inventory throughout the product life). Bookham's product strategy in this area is based on monolithic

full-band tunable lasers and InP Mach-Zehnder modulators, which together make possible a range of physically compact transmitter and transponder products, including integrated tunable laser assemblies (iTLA) and integrated tunable transmitter assemblies (iTTA), along with small-form-factor (SFF) transponders. This evolution is shown in Figure 1; the key chips are shown in detail in Figure 2.

The full-band tunable laser that Bookham has developed, the digital supermode distributed Bragg reflector (DSDBR) laser, is a relatively complex monolithic device, but complexity in design provides for simplicity in use [1,2]. It has five sections, using two different epitaxial layer structures (one to provide gain and one, which is transparent at the optical wavelength, to provide tuning). The laser cavity is formed by a rear grating section, which provides a comb of reflection peaks corresponding to seven 'supermodes' and a chirped, electrically addressable front grating, which selects the supermode needed to access a specific wavelength range within the C- or L-bands. Within a given supermode, primary tuning is provided by injecting current into the rear section, while fine tuning is achieved through a phase-control section within the cavity. There are two gain sections: one internal to the cavity, to provide the pri-

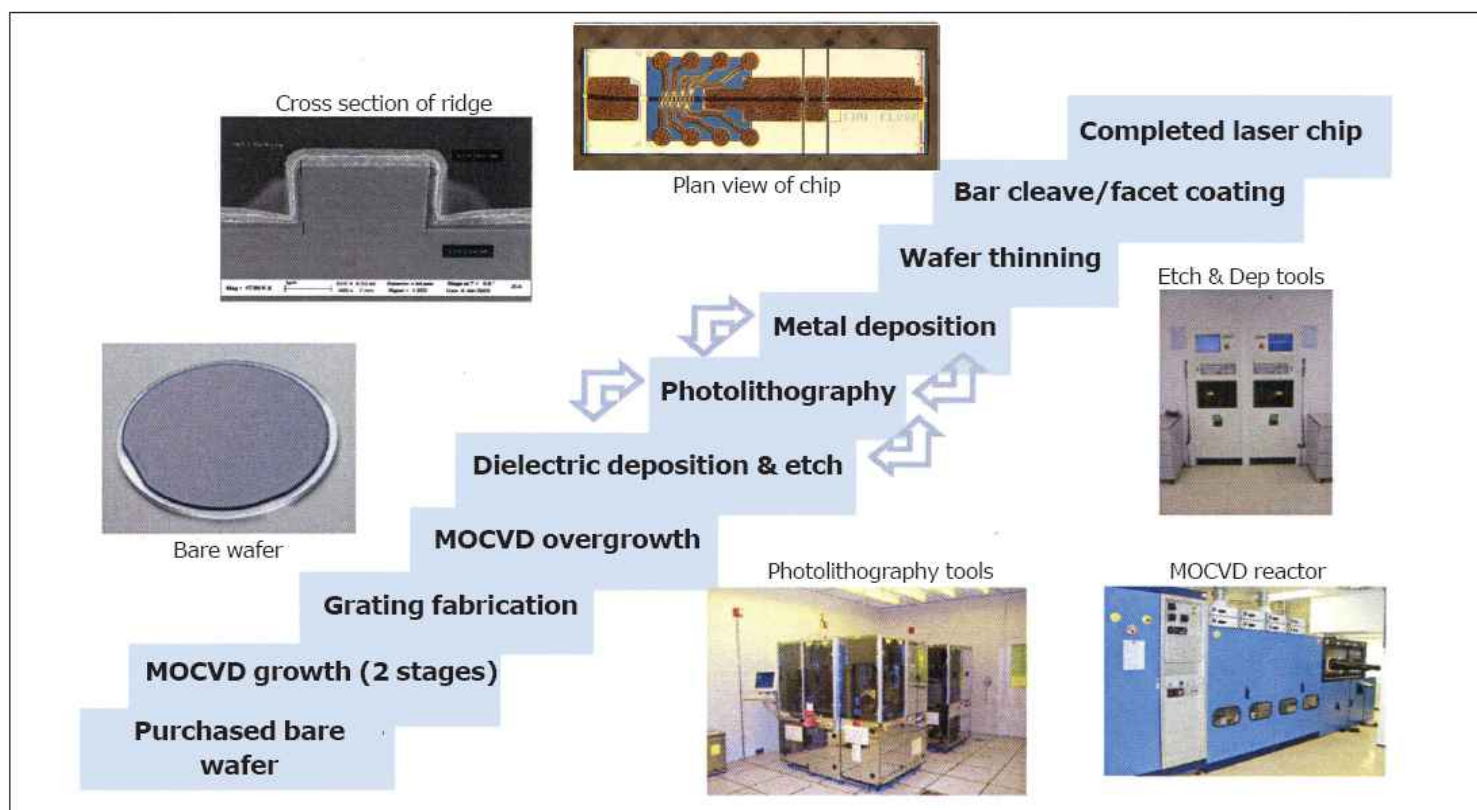


Figure 3: Process sequence for the DSDBR laser, with some of the key tools used in its manufacture.

mary light generation within the device; the other as an optical amplifier at the output, providing additional gain (typically 3dB), power control and shuttering functions. This unique design provides very high performance: >20mW output power in fibre and >40dB side mode suppression ratio (SMSR) over the full C-band or L-band, with narrow linewidth and low noise.

Figure 3 shows the fabrication sequence for this device, along with some of the key equipment used. The tools employed to fabricate the gratings are of vital importance here, as the grating uniformity and coherence are extremely critical. Bookham uses direct electron-beam writing to achieve the very high precision required in these complex grating structures. Figure 4 gives an indication of the excellent grating uniformity achieved in this process.

Mach-Zehnder modulator

The Mach-Zehnder (MZ) device achieves a performance that competes directly with existing lithium niobate modulators, while being more than an order of magnitude smaller. These devices, which exploit the quantum-confined Stark effect in a multi-quantum well waveguide in InP rather than the usual electro-optic effect, have proved extremely successful in fixed-wavelength products — over 100,000 have been sold — and the same technology is now being introduced into full-band tunable devices. As shown in Figure 2, the MZ chip is co-packaged with the DSDBR laser in a hermetic, fiber-coupled module. The MZ chip provides a number

of functions: as well as data modulation, the device also provides power monitoring and control and is equipped with spot-size converters to improve fiber coupling and thus allow increased output power [3]. The latter function is integrated on-chip using selective area epitaxial growth. The chip's overall length is about 3mm, with 0.6mm devoted to the data modulator.

This device requires stepper lithography for the high precision that is needed in the MZ waveguides, as well as to cope with the difficult chip topography, while multi-stage epitaxy is required to realise the spot-size converters. Furthermore, the ICP etch process used to fabricate the waveguide is critical in achieving the smooth side-walls that are essential for low optical loss. Close control of epitaxial growth as well as of the lithography and etch processes results in a high degree of uniformity in device characteristics across a 3" wafer, as shown in Figure 5.

Network edge

A 3" fab is equally valuable in addressing components for the network edge. Here, new services are predominantly based on Ethernet and internet protocol (IP) standards. The prevailing operating scenarios are based on 'plug and play' with hot-swappable optical transceivers, which have to operate to telecom standards with high functionality and reliability. This need is being addressed with 'carrier-grade' pluggable transceivers following industry standards such as XFP (see Figure 6). A key device here is an integrated DFB-electroabsorption modulator that can offer 10Gbit/s transmission at

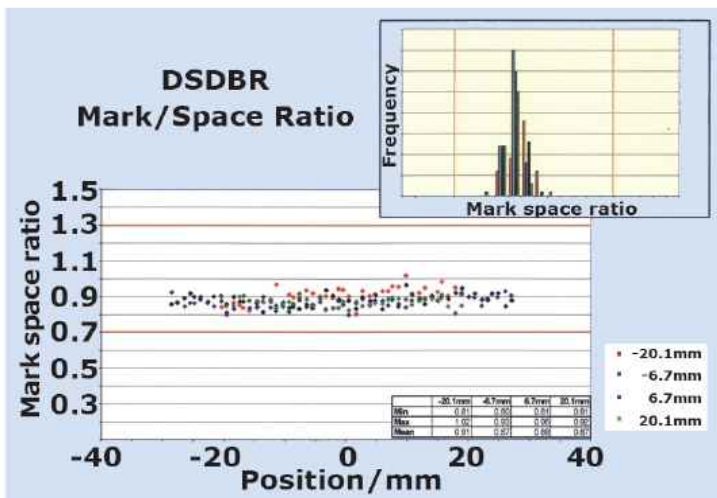


Figure 4: Profile of grating mark-space ratio for DSDBR lasers across a wafer.

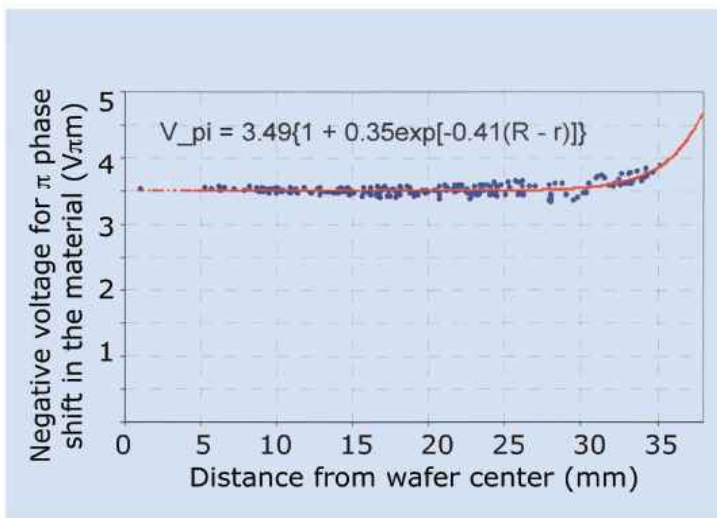


Figure 5: Profile of a key InP MZ characteristic – the switching voltage V_{π} – across typical production wafer.

1550nm over 40–80km spans at minimum cost. Bookham's device (see Figure 7) uses a monolithic active-passive waveguide integration scheme similar to that used in the tunable laser [4]. Once again, 3" wafer tools provide high throughput and yield, as well as accommodating the device topography.

Future integration

For the future, Bookham has devices with even higher degrees of integration in the pipeline, for example, monolithically integrated tunable laser–Mach Zehnder transmitters and complex encoders for new modulation schemes such as optical differential phase-shift keying, which is a very attractive option for 40Gbit/s transmissions systems. These components can only be contemplated with the sort of fabrication technologies and proven device processes that Bookham now has.

Such a state-of-the-art fab is an essential prerequisite for the development and manufacture of leading-edge devices. The Bookham facilities amply meet that

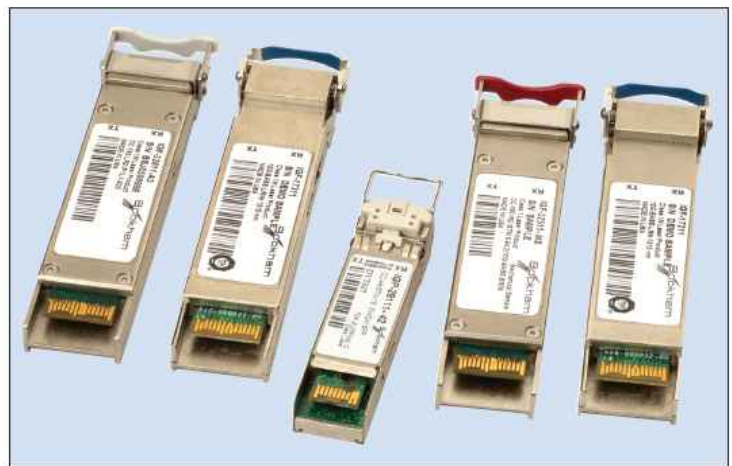


Figure 6: Carrier-grade 2.5Gbit/s small-form-factor pluggable (SFP) and 10Gbit/s small-form-factor (XFP) transceivers.

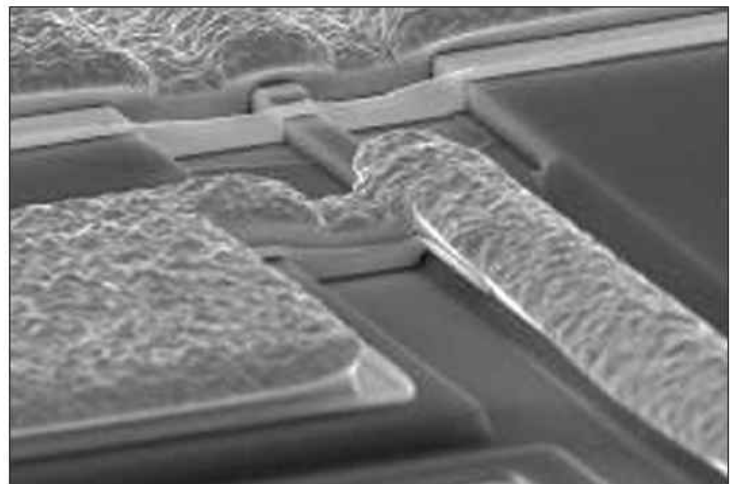


Figure 7: An integrated DFB laser–electroabsorption modulator, showing the join between the laser (top left) and modulator (bottom right) sections.

criterion and the devices now in production and under development demonstrate the power of combining world-class design and production capabilities. ■

Author: Dr Mike Wale, Director Active Products Research

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<http://spie.org/conferences/calls/06/op/>

13–17 August 2006

ICSC 2006 (33rd International Symposium on Compound Semiconductors)

University of British Columbia, Vancouver, Canada

www.ICSC2006.ca

13–17 August 2006

Optics and Photonics 2006

San Diego, Ca, USA

<http://spie.org/conferences/calls/06/op/>

27 August – 1 September

Summerschool on Wide-bandgap Semiconductor Quantum Structures

Monte Verità (Ascona), Switzerland

<http://monteverita.epfl.ch/page59137.html>

3–7 September 2006

Asia-Pacific Optical Conference 2006

Gwangju, South Korea

E-mail: apoc2006@apoc2006.org

www.apoc2006.org

3–7 September 2006

ECSCRM 2006 (6th European Conference on Silicon Carbide and Related Materials)

Newcastle upon Tyne, UK

E-mail: ECSCRM@eece.ncl.ac.uk

www.ecscrm2006.org

3–8 September 2006

MBE2006: 14th International Conference on Molecular Beam Epitaxy

Waseda University, Tokyo, Japan

E-mail: mbe@mbe2006.all-nano.waseda.ac.jp

www.mbe2006.all-nano.waseda.ac.jp

4–8 September 2006

21st European Photovoltaic Solar Energy Conference & Exhibition

Dresden, Germany

E-mail: peter.helm@wip-munich.de

www.photovoltaic-conference.com

6–9 September 2006

China International Optoelectronic Expo

Shenzhen, Guangdong, China

E-mail: info@wgs-china.com

www.cioe-online.com

10–15 September 2006

European Microwave Week

Manchester, UK

E-mail: eumw@horizonhouse.co.uk

www.eumw2006.com

11–13 September 2006

Semicon Taiwan 2006

Taipei, Taiwan

E-mail: iyu@semi.org

www.semi.org

24–28 September 2006

ECOC 2006 (European Conference on Optical Communications)

Cannes, France

E-mail: ecoc2006@see.asso.fr

www.ecoc2006.org

26–27 September 2006

Deutscher MBE-Workshop 2006

Hamburg, Germany

E-mail: MBE_2006@physnet.uni-hamburg.de

www.physnet.uni-hamburg.de/mbetag/

2–4 October 2006

15th European Workshop on Heterostructure Technology: HETECH 06

Manchester, UK

www.eee.manchester.ac.uk

2–4 October 2006**SEMI Expo CIS 2006**

Moscow, Russia

E-mail: tyaroshenko@semi.org**www.semi.org****3–6 October 2006****4th International Workshop on ZnO and Related Materials**

Giessen, Germany

E-mail: info@zno-giessen.de**www.zno-giessen.de****4–6 October 2006****Quantum Dots 2006**

San Francisco, CA, USA

E-mail: pkinzer@intertechusa.com**www.intertechusa.com/conferences****8–11 October 2006****NAMBE 2006 (25th North American Conference on Molecular Beam Epitaxy)**

Durham, NC, USA

E-mail: chair2006@nambe.info**www.nambe.info/2000s/nambe2006.html****16–18 October 2006****Light Emitting Diodes 2006**

San Diego, CA, USA

www.intertechusa.com/conferences**16–19 October 2006****OPTO 2006 exhibition (and European Optical Society Annual Meeting 2006)**

Porte de Versailles, Paris, France

E-mail: gdodeman@exposium.fr**www.optoexpo.com/fr/2006****22–27 October 2006****IWN 2006 (International Workshop on Nitride Semiconductors)**

Kyoto, Japan

E-mail: iwn2006@iwn2006.org**http://iwn2006.org****24–27 October 2006****Asia Optical Fiber Communication & Optoelectronic Exposition & Conference (AOE)**

Shanghai Expo Convention Center, China

E-mail: info@aoe-expo.com**www.aoe-expo.com****12–15 November 2006****Compound Semiconductor Week 2006 (including CSIC Symposium and CS-MAX)**

Marriot Riverwalk Hotel, San Antonio, TX, USA

E-mail: customer.service@ieee.org**http://compoundsemiconductor.net/csmax****27 November–1 December 2006****2006 MRS Fall Meeting**

Boston, MA, USA

E-mail: info@mrs.org**www.mrs.org****5–7 December 2006****ILOPE-2006 (11th China International Lasers, Optoelectronics, Photonics and Display Exhibition) and China International Optoelectronics Industry Exposition**

Beijing, China

E-mail: heyu@ciec.com.cn**www.coema.org.cn/E_ilopec2006.html****6–8 December 2006****Semicon Japan 2006**

Chiba, Japan

E-mail: jeventinfo@semi.org**www.semi.org****11–13 December 2006****International Electron Devices Meeting**

San Francisco, CA, USA

20–25 January 2007**Photonics West**

San Jose, CA, USA

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