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October 2010 Volume 16 Number 7

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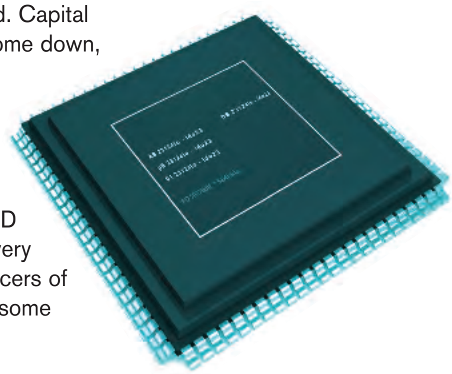
Shifting landscapes

The phrase "real men have fabs" summed up the feeling within the silicon industry a decade or so ago. But times have changed. Capital expenditure costs have soared as node sizes have come down, and today, aside from a very small number of heavyweights, silicon chipmakers now outsource production.



Within the III-V industry, it seems that some sectors are taking a slow stroll down a similar path. While LED manufacture, certainly by the biggest players, is still very much an in-house affair, the trend amongst the producers of GaAs chips for wireless applications is to outsource some production.

This transition started several years ago, with contracts such as the epiwafer supply agreement between Skyworks and Kopin. But it has been gathering pace, thanks to moves such as Anadigics' pursuit of a hybrid manufacturing model. IQE is used as a source for epiwafers, and some of the company's chip production is handled by WIN Semiconductors.

Activities such as this are helping to swell IQE's revenue, which is increasingly dominated by sales of wireless products. But the continued success of this global epiwafer supplier may depend on whether it loses market share to a new player in the wireless epiwafer business: RFMD. Yes, that's right, the world's biggest in-house manufacturer of GaAs RF chips is opening the doors of its MBE facility.

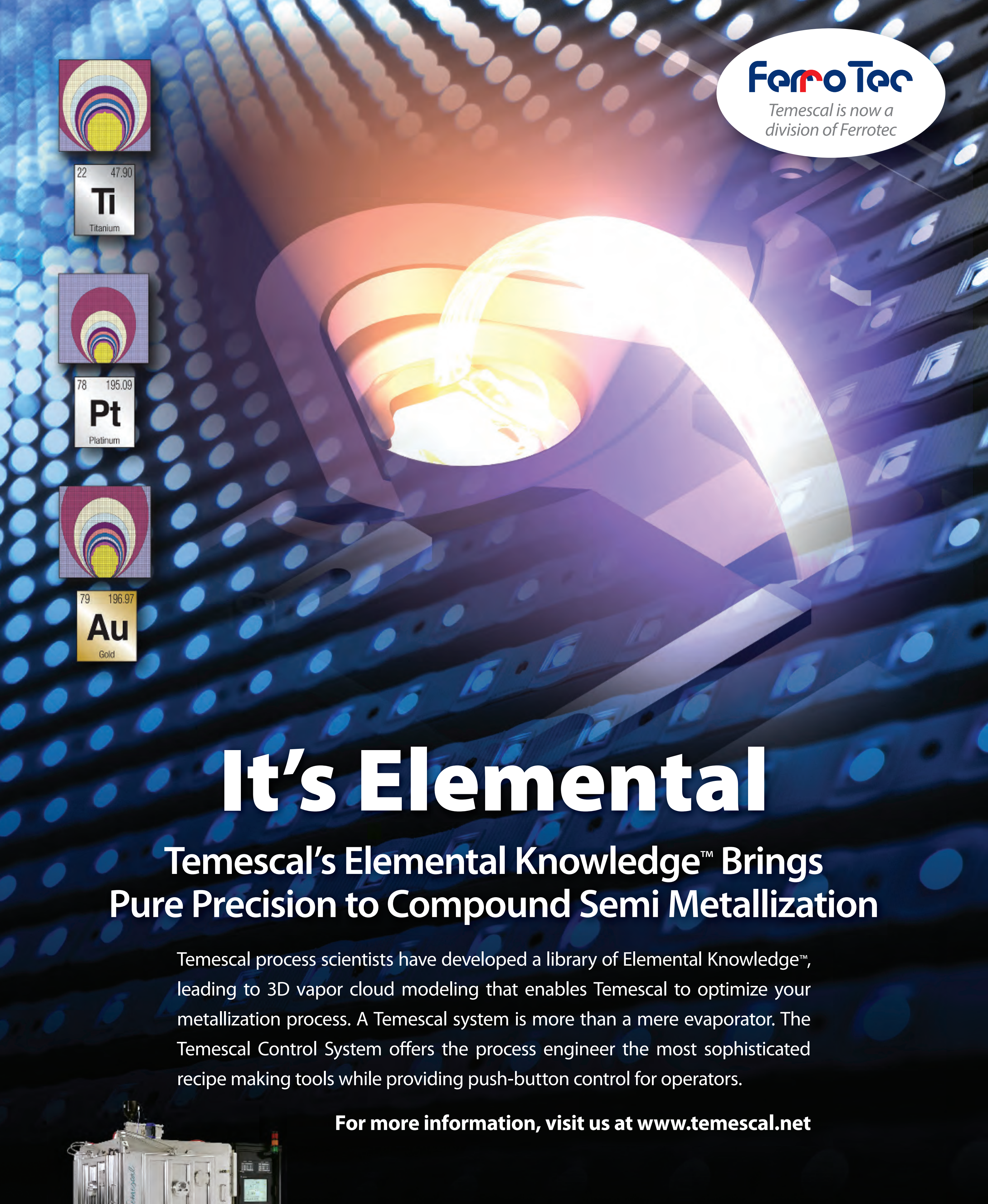
RFMD's motivations for entering the epiwafer supplier market are entirely predictable. It's keen to open up a new revenue stream and net a good return on its substantial investment in capital equipment.

The company is certainly well equipped for its new venture. It can offer customers a selection of multi-wafer 6-inch MBE kits equipped with the latest *in-situ* monitoring tools, plus a strong portfolio of metrology tools for characterizing these epiwafers. This includes a multi-field Hall probe for non-destructive measurements of mobility and carrier concentration in multiple layers.

Armed with these attributes, RFMD should enjoy some success as an epiwafer supplier.

What will be interesting to see is if this offering leads to further outsourcing of epiwafer growth, and whether it spurs the trend amongst GaAs chip makers to move away from vertical integration.

Richard Stevenson PhD
Consultant Editor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industry & technology

news

IEDM to showcase record-breaking III-Vs

THIS YEAR'S IEEE Electron Devices Meeting (IEDM) will include coverage of a 400 GHz GaN HEMT, an InGaAs terahertz transistor, an InGaAs FinFET for low-power logic and the world's first InGaAs MOSFET on an insulating substrate.

At IEDM 2010, which will be held in San Francisco from 6-8 December, a team from HRL will be claiming the speed record for a GaN HEMT. The GaN-on-SiC transistor produced by this US defence giant has a 40 nm gate and produces a cut-off frequency of 220 GHz and a maximum oscillation frequency of 440 GHz.

According to HRL, one of the challenges associated with making a transistor out of GaN is the realization of a good electrical contact with the material, given its high resistance. The team overcame this by re-growing the ohmic contacts using molecular-beam epitaxy. Ultra-high speed transistors will be reported by a team led by Teledyne Scientific. This effort has led to a 1-THz InGaAs Transistor with "good" gain.

This team's transistor is a 50nm gate-length enhancement-mode PHEMT that was built on InP and has good transconductance (1.7S/mm) at moderate voltage levels. Key to its performance are the short gate length and a small channel (10nm thick), which maximize carrier transport and minimize

contact resistance and capacitance parasitics. The 1.7S/mm transconductance at 1THz (fmax) was achieved at 0.75V input voltage.

The meeting will also detail the efforts of a team led by University of Tokyo that has fabricated the world's first InGaAs MOSFET built on an insulating substrate, and also the thinnest InGaAs MOSFET ever made, with a tiny 3.5nm channel. Nonconducting substrates are key to the eventual integration of such devices with silicon CMOS architectures because they reduce short-channel effects. This device has dual gates and demonstrated good on/off characteristics (~107) and transconductance. The team direct wafer-bonded their transistor to silicon. They avoided creating unwanted source-drain junctions, which, because of the extremely thin films that make up the device, would have been difficult to anneal and would have made ion implantation difficult. Instead, they substituted an n-doped accumulation-mode channel.

Meanwhile, a partnership between Intel and IQE will report the development of a InGaAs FinFET for low-power logic. FinFETs are nanoscale transistors with long, thin channels surrounded by multiple gates that provide superior on/off control versus planar devices. InGaAs, meanwhile, is a compound semiconductor that yields faster, more energy-efficient transistors than silicon.

FinFETs made from InGaAs may make possible ultra-dense yet low-power logic circuits. The first surface-channel InGaAs FinFET was described at the 2009 IEDM, but this year a team led by Intel will discuss InGaAs quantum-well FinFETs with enhanced overall electrical performance, including good control of troublesome short-channel effects. The performance was made possible by 35nm-wide and smaller fins; ultra-small 5nm gate-to-drain and gate-to-source separations; a high-k gate dielectric, and a simplified source/drain architecture.

TSMC Begins Building first Thin Film Solar R&D Centre and Fab

TAIWAN SEMICONDUCTOR MANUFACTURING COMPANY, LTD broke ground in Taichung's Central Taiwan Science Park on the company's first Thin Film Solar R&D Centre and Fab, laying the foundation for the company's entry into the thin-film solar photovoltaic (PV) market.

"TSMC's New Businesses team has reached many important milestones since it was formed last year, first with our LED facility in Hsinchu, and now with construction in Taichung on our first solar facility. Our solar and LED businesses will not only bolster TSMC's revenue and profit growth in the coming decades, they also play a key role in TSMC's corporate social responsibility by making products that support a greener earth." said TSMC Chairman and CEO Dr. Morris Chang. "In addition, construction of this solar R&D centre and fab, along with our Fab 15 Gigafab next to it, means Taichung's Central Taiwan Science Park will become home to much of TSMC's most advanced and innovative production."

"TSMC has always been committed to technology leadership, and our solar business will be no different," said Dr. Rick Tsai, TSMC President of New Businesses. "The research performed at this R&D centre will help us achieve our goal of offering a leading thin-film solution and the production at this fab, drawing on TSMC's wealth of manufacturing know-how, will pave the way for us to become a top provider of solar PV modules."

TSMC plans to invest US$258 million for the first phase of the Thin Film Solar R&D Centre and Fab, which is scheduled for equipment move-in in the second quarter of 2011 and achieve initial volume production of 200MW (megawatts) per year in thin-film photovoltaic modules in 2012.

TSMC also plans to add a second phase to the facility and expand production to more than 700MW, employing about 2,000 total staff in the facility.

In addition, the R&D centre in the facility will continue to develop the CIGS technology licensed from Stion in June of this year. TSMC will offer its solar products around the world under its own brand.

Epistar and Toyoda enter An LED cross license agreement

EPISTAR CORPORATION and Toyoda Gosei have entered a cross license agreement to allow the companies (including subsidiaries)to use each other's patents for specific technologies in Group III-V compound semiconductor light emitting diodes ("LEDs"), which include InGaN LEDs and AlGaInP LEDs.

Epistar is the only company in Taiwan, getting the cross license from Toyoda Gosei and no any other company in Taiwan gets any cross license from Toyoda Gosei .

Epistar holds valuable patents for high-brightness AlGaInP LEDs and high-power GaN LEDs. Toyoda Gosei likewise holds a number of valuable patents for InGaN LEDs. Epistar and Toyoda Gosei agreed to construct an environment wherein they will respect and mutually utilize each other's technologies in order to further advance the market for LED products.

This agreement will allow both Epistar and Toyoda Gosei significantly more freedom in their development efforts by eliminating the need for concern about each other's patents. By facilitating research at both companies, new developments in LED technology are anticipated, including an acceleration of research to improve the luminosity of LEDs. Epistar and Toyoda Gosei each intend to maintain a friendly business relationship and pursue the development of superior high-luminosity LEDs and further expansion of the LED market through fair competition.

IQE's Singapore operation recognized as a top supplier to TriQuint

IQE, a supplier of advanced semiconductor epitaxial wafer products and wafer services to the semiconductor industry, announces that IQE's Singapore operation, MBE Technology Pte Ltd, has been recognized as a top supplier to leading wireless chip manufacturer, TriQuint Semiconductor, Inc. TriQuint, a leading RF front-end product manufacturer and foundry services provider, announced its Top Supplier Awards for 2009 during TriQuint's Supplier Day Conference, an annual educational and networking event for TriQuint's top suppliers held in Portland, Oregon.

Winners were selected by members of TriQuint's Supply Chain and Business Unit organizations in recognition of TriQuint's top suppliers for their overall performance to TriQuint including innovation, operational excellence, service levels, and industry leadership.

Steve Grant, Vice President of Worldwide Operations said: "The capability of our strategic suppliers to provide us with zero-defect material, position capacity to support TriQuint's continued growth, and collaborate on reducing costs while developing innovative solutions greatly contributes to our ability to deliver RF solutions that improve the performance and lower the cost of our customers' applications."

Receiving the award, together with Dr J Jiang Sales Director of MBET, Dr. Drew Nelson, IQE Group CEO and President said: "We are delighted that MBE Technology has been honoured with this award from one of the leading chip manufacturers in the wireless industry. IQE enjoys a close working relationship with many of its customers globally and the particular recognition of our Singapore operation by TriQuint demonstrates the Group's commitment to providing the highest level of quality in terms of products, services and innovation.

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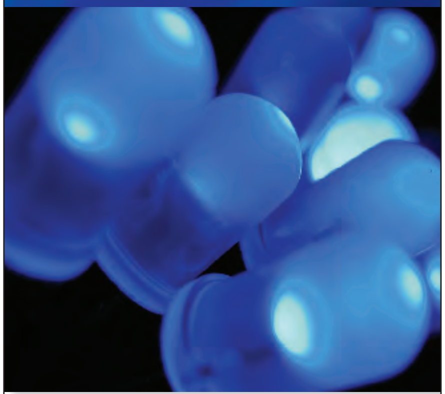

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Aldo Kamper succeeds Dr. Rüdiger Müller as President and CEO of OSRAM

AS of October 1, 2010, Aldo Kamper (40), a proven LED expert and time-tested executive, is succeeding Dr. Rüdiger Müller (65) who, after heading optoelectronic semiconductor business for 22 years at OSRAM and formerly at Siemens, is bidding farewell on reaching retirement age.

Martin Goetzeler, CEO of the parent company OSRAM said: "Down to this very day, Dr. Rüdiger Müller has been one of the driving forces worldwide in the development of LED technology, which now reaches far into our everyday lives. With Aldo Kamper we have been able to win a successor from our own ranks – someone who will advance OSRAM Opto Semiconductors and make his own mark."

Dr. Müller hands over the reins of OSRAM Opto Semiconductors to Aldo Kamper on October 1, 2010. Kamper started his professional career at OSRAM in 1994 after completing his business administration studies. Since 2006, he has held the post of Executive Vice President & General Manager Specialty Lighting at OSRAM Sylvania in the US.

Dr. Rüdiger Müller's retirement brings an era to an end at OSRAM Opto Semiconductors and in LED technology. Müller headed the optoelectronic semiconductor business at Siemens from 1988 and, in 1999, was also founding CEO of OSRAM Opto Semiconductors, in which Siemens' LED and infrared business was pooled with OSRAM's lighting competence. Besides strong growth and the continuous expansion of production capacities his name is most closely linked with technological advances in optoelectronic semiconductor technology.

Crucial innovations, such as thin-film technology, direct blue or green semiconductor laser diodes, the first OLED product or the first surface-mountable LED (SMT-LED), innovations that set standards to this very day, emerged under his leadership.

Kopin Awarded $750,000 to Develop Advanced Nitride Electronic Materials

KOPIN CORPORATION has received a two-year, Phase II Small Business Innovative Research (SBIR) contract. The contract will cover the development of Aluminum Indium Nitride-based high electron mobility transistors (AlInN HEMTs). The $750,000 award through the Missile Defense Agency (MDA) will leverage Kopin's established capability in Group III-Nitrides to enhance the performance and manufacturability of AlInN materials.

"This SBIR program by MDA validates the potential of the AlInN material system for high-performance electronic devices," stated John C.C. Fan, Kopin's President and CEO. "Our long-term objective is to commercialize AlInN-based electronic materials, which parallels our highly successful GaAs HBT wafer business."

Wayne Johnson, Kopin's Vice President of Technology said, "The AlInN material system has shown promise to extend the power and frequency capability of GaN-based HEMTs."

"During the Phase I effort, we demonstrated results in AlInN/GaN heterostructures including record-low sheet resistance. The goals of Phase II will involve optimization of the AlInN HEMT structures and fabrication of HEMT devices for X-band electronics applications in collaboration with leading-edge GaN foundries," concluded Johnson.

GaAs device demand will continue to see continued growth through 2014

The GaAs market staged a strong recovery toward the end of a tumultuous 2009 as a result of positive trends in wireless markets. The Strategy Analytics GaAs and Compound Semiconductor Technologies (GaAs) service report, "GaAs Industry Forecast 2009-2014," calculates that despite a recession, GaAs industry revenues managed to escape a drop in 2009, with a strong performance in the second half of the year translating to year-on-year revenues remaining flat at $3.7 billion.

GaAs technology will maintain its position as the enabling technology for next generation cellular handsets. The smartphone category of the handset market, in particular, provided a vital lifeline in 2009, boasting stronger than average annual growth in terminal volumes.

With an increasing average number of GaAs power amplifiers per terminal as well as increasing switch complexity in this sector, GaAs device demand from next generation handsets will grow faster than overall industry revenue growth.

"Our analysis incorporates individual wireless, consumer, infrastructure and defence market forecasts—taking into account technology trends," noted Asif Anwar at Strategy Analytics. "There is no question that the improving capabilities of silicon and silicon germanium technologies, as well as emerging technologies such as gallium nitride, will provide increasing competition for GaAs technologies."

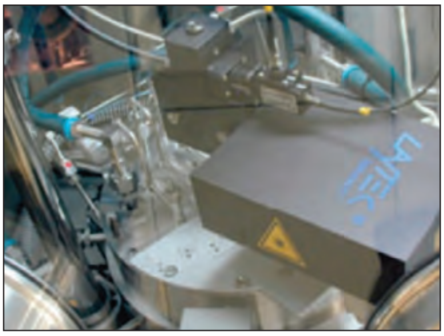
"Despite this competition, GaAs device demand will continue to see continued growth through 2014. The market will grow at a compound annual growth rate of 5% to be worth over $4.7 billion," concluded Anwar.

Laytec installs Single-port EpiCurveTT for Aixtron showerhead

LayTec has successfully installed an EpiCurveTT on an Aixtron Close Coupled Showerhead (CCS) MOCVD system at Fraunhofer Institute for Applied Solid State Physics (IAF) in Freiburg, Germany. This is the first time an EpiCurveTT has been installed on a showerhead system on only one viewport.

In the past, since the viewports of such systems are so small, 2 separate windows were used: one for curvature and one for temperature and reflectance measurements. Now, due to the improved design, all three parameters are measured through one standard AIX CCS viewport.

Chunyu Wang and his team at IAF will use the tool for growth control of GaN on silicon substrates. The simultaneous in-situ monitoring of wafer temperature, reflectance and curvature will be used to engineer the stress in the epilayers. Wang commented, “The new sensor will help us to get flat and crack-free GaN layers on Si substrates for future sophisticated electronic devices.”



Recently, LayTec launched EpiCurveTT AR (advanced resolution) for measurements of the aspherical curvature component during epitaxial growth. The tool is claimed to be the perfect solution for Planetary and other gas-foil rotation MOCVD systems where the azimuth of the rotating wafers is unknown.

The standard EpiCurveTT without AR measures randomly either along the major axis (larger bow - blue arrow in Fig. 2) or along the minor axis (smaller bow - red arrow in Fig. 2). In a Planetary reactor the phase of rotation is unknown. As a result, the signal looks “noisy” (red line in Fig. 3): it oscillates between the maximum and the minimum of the azimuthal aspherical bow.

The new tool measures curvature along two perpendicular axes and eliminates 2nd order azimuthal bowing effects. The signal-to-noise ratio of the tool with advanced resolution improves the curvature signal from ±8 km-1 (red line) to ± 0.2 km-1 (black line) and measures only the main curvature component by eliminating the aspherical contribution.

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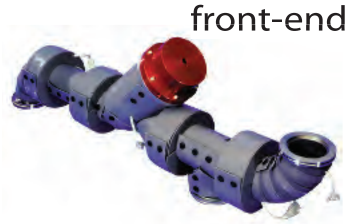

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Albemarle builds in South Korea To meet growth

ALBEMARLE CORPORATION have announced that it has begun its largest capital investment in the fast growing Asia Pacific region of Yeosu, South Korea.

The Yeosu site contains existing R&D as well as pilot plant equipment that will be modified to enable customer qualification efforts in 2010. The site will effectively mirror Albemarle's world scale metallocene polyolefin catalyst and Trimethyl Gallium (TMG) capabilities located in Baton Rouge, Louisiana.

Albemarle will build on its leading supply and technology position in metallocene catalysts by leveraging its breakthrough ActivCat(TM) technology for polyolefin production. The company will also leverage its 50+ years of production experience in metal organics to supply High Purity Metal Organics (HPMOs) such as TMG to the High Brightness LED (HBLED) market. Mark Rohr, Albemarle's Chairman and Chief Executive Officer, commented, "This strategic investment signifies our commitment to expand our footprint in regions that provide substantial growth opportunities for Albemarle and its customers. By providing local manufacturing and Albemarle's renowned excellence in technical service and support, we are giving our customers a competitive advantage in a growing market. We thank the governor of Jeollanam-do province and the mayor of Yeosu city for their support and advice as we undertake this important project."

The Yeosu site will be capable of producing mPO catalyst lab samples followed by pilot samples for qualification trials with local customers this year. Intermediate commercial operations will begin in mid-2011, with the commercial facility being fully operational in 2012. The site will produce finished catalysts, activators like methylaluminoxane (MAO) and organoborons, as well as metallocene components. The site will also purify metal organics, creating a portfolio of HPMOs for electronic applications. TMG production will begin in early 2011, with other HPMOs phased into the project throughout 2011.

"We are excited to announce the quick startup of this new facility and look forward to meeting our Asian customers' current needs through local supply in both the mPO industry as well as the HBLED industry. The premier location of this new manufacturing site will give Albemarle a strong competitive advantage in Asia Pacific and secures our position as the global leader for metallocene Polyolefins catalysts," said Amy Motto, Division Vice President, Polyolefin and Chemical Catalysts."

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INNOVATIVE SOLUTIONS FOR SEMICONDUCTOR INDUSTRY RIBER

Growth expected in mid-infrared lasers, says Strategies Unlimited

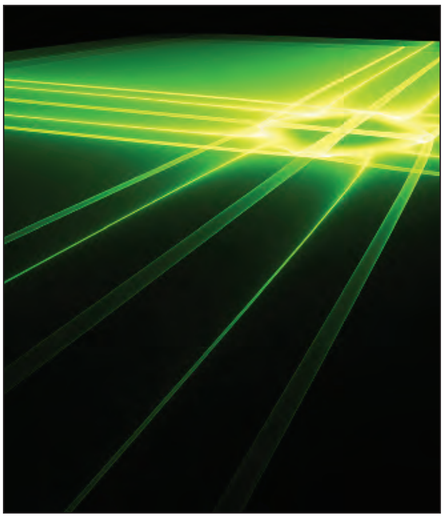
ADVANCEMENTS in several new laser technologies are opening new opportunities in the part of the spectrum between telecom lasers and the nascent terahertz range, called the mid-infrared.

This range is currently dominated by applications in materials processing and medical procedures, but new military and sensing applications will add sizeable and exciting opportunities in the next few years. The new segments will grow 30% per year, compounded annually through 2014. But, the mid-IR range remains a complex and confusing segment, with competition from other laser and non-laser solutions, and with many companies ripe for acquisition. These are among the findings in a new report, Mid-Infrared Lasers 2010, from Strategies Unlimited, the leader in market research of the photonics industry.

The mid-infrared is best known for being a covert and eye-safe range, for the thermal vibrations of molecules (used in sensing and thermal imaging), and for the cheap photons of high-power CO2 lasers. CO2 lasers today dominate the sales, from 10 Watt lasers using sealed gas tubes to multi-kilowatt lasers using flowing gas blowers, for use in materials processing. Solid-state lasers are also established in medical applications.

Next to come are high-brightness sources for military applications: infrared countermeasures against heat-seeking missiles, illuminators for thermal imaging, mid-IR beacons, and so forth. These military applications are key to funding the new mid-infrared technologies while other applications get off the ground.

Another long-awaited segment is sensing for molecular detection, with many exciting new opportunities in environmental monitoring, industrial process controls, security standoff detection of hazardous chemicals, and new breathalyzer instruments for medical diagnostics. Other sensor applications include mid-infrared rangefinding and Doppler scatterometry.



But, mid-infrared laser suppliers face many unique challenges. Mid-infrared components are expensive because of requirements for exotic materials and coatings, cryogenic cooling, and low manufacturing volumes.

Lasers have been bulky and the output power of compact laser solutions has been low. And, the new technologies face challenges from other laser and nonlaser technologies, such as Raman spectroscopy, near-infrared laser and LED sources, lamps, and non-optical approaches.

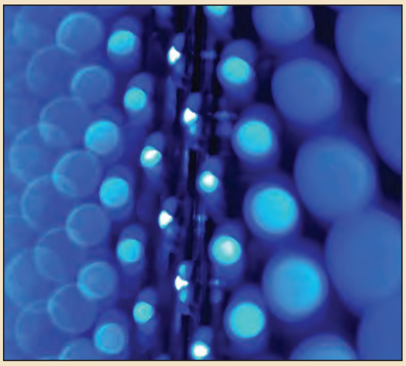
Now, new solutions in quantum cascade and interband cascade lasers, GaSb diode lasers and OPSLs, fiber lasers, solid-state lasers, and compact OPOs promise to expand sales into new applications. Other innovations will also help the market, such as inexpensive QEPAs, uncooled focal plane arrays, and hollow-core optical fibers. The report lists over 50 companies offering lasers in the mid-IR range, spanning the technologies listed above, as well as legacy technologies. Well more than half of the companies are headquartered in North America.

With such a wide range of suppliers and applications, the market is highly fragmented and there is no overall leader. Some industries prefer to bring differentiating technology in-house, making several laser suppliers targets for acquisiton.

Austin Scientific has highest ever order book

OXFORD INSTRUMENTS subsidiary Austin Scientific, has secured a major order for 56 helium compressor systems with a total value of $1,111k. The product is a unique application that has significant implications in the High Brightness Light Emitting Diode (HBLED) market, using helium gas as a heat-exchange medium in high temperature processes.

Austin Scientific also secured a further significant order with a major manufacturer of HBLEDs for 17 Cryopump systems with a total value $205k, another very significant order for the business. These two orders have contributed to the business hitting its highest order month in its 10 year history as part of the Oxford Instruments Group.



General Manager of Austin Scientific, Donald Gordon, said "This is a great achievement for our business. HBLEDs will undoubtedly play a huge role in protecting our environment in the future, and I am delighted that our products have been chosen to support this growing market. Everyone here has contributed to this success and I congratulate them."

Austin Scientific supplies, refurbishes and services cryopumps and compressors for the semi-conductor industry, and is based in Austin, Texas USA. It was recently won the best of local business award in the Gas Compressors category by the U.S. Commerce Association (USCA) for the second year running.

SETI and Kyma join Forces to Develop High-Efficiency Deep UV LEDs

SENSOR ELECTRONIC TECHNOLOGY (SETI) has entered a Joint Development Agreement with Kyma Technologies, of Raleigh, NC, USA.

The collaboration is aimed at developing low defect AlGaN substrates and high performance optoelectronic and electronic devices based on these substrates.

Under the agreement, SETI will centre its device development efforts on next generation high efficiency Deep UV LEDs on these novel substrates as it grows its markets in high power applications such as water disinfection.

SETI claims to be the world's only commercial manufacturer of Deep UV LEDs and LED lamps. With a product portfolio from 240nm through 400nm SETI serves a wide range of markets including sensing and instrumentation.

The firm has recently announced the development of high power single chip LEDs exceeding 30 mW and with high power lamps commercially available; SETI has recently been experiencing rapid growth in the disinfection/sterilization market.

"The LED performance improvements that will be enabled by developments under this Agreement will help us grow the foundation we have already built in the disinfection market" said President and CEO of SETI, Remis Gaska, "and will maintain our position as leaders in Deep UV LED products".

Recently, SETI has successfully completed a Small Business Innovation Research (SBIR) Phase I program by the National Science Foundation to develop a prototype of a commercially viable all-LED based portable water disinfection system.

Kyma Technologies is a leading supplier of crystalline III-nitride semiconductor materials including GaN and AlN. Each semiconductor device layer stack has a preferred substrate composition. AlN and GaN substrates are preferred for device layer stacks which are AlN-rich and GaN-rich, respectively.

For device layer stacks which have an intermediate preferred lattice constant, such as UV LEDs and certain next generation high frequency and high power electronics, AlGaN substrates are preferred.

"We appreciate the opportunity to work with SETI to develop a low defect AlGaN substrate product line, which should benefit a range of advanced nitride semiconductor device technologies," stated Keith Evans, President and CEO of Kyma Technologies.

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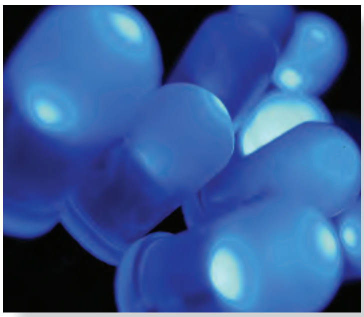

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Cree Brings Lighting-Class LEDs to the Market

Cree is raising the standard for half-Watt LED devices with the commercial availability of its XLamp ML-E LED. The lighting-class XLamp ML-E provides lighting designers with a compact and cost-effective solution for distributed LED arrays that can enable them to meet the stringent U.S. Environmental Protection Agency ENERGY STAR performance criteria.

“When we set out to build our new linear light engine, we required the efficacy and reliability of XLamp LEDs, but wanted a smaller package size,” said Markus Vockenroth, managing director, MAL Effekt-Technik GmbH. “The XLamp ML-E LED was the perfect combination of price and performance for our application.”

The XLamp ML-E delivers lighting-class performance in applications where a smooth, uniform appearance is required, such as LED fluorescent tube replacement, ceiling-mounted panel lights and under-cabinet lighting. Unlike other low-power LEDs originally developed for consumer electronics and backlighting applications, the XLamp ML-E delivers the segment-leading color binning, efficacy, thermal resistance and reliability required for luminaires and bulbs.

“The ML-E offers the lighting design community a simple and affordable solution for a major portion of the solid state lighting market,” said Paul Thieken, Cree, director of marketing, LED Components.

SDK ups Blue LED chip production capacity

SHOWA DENKO K.K. has increased its production capacity of blue LED chips at its Chiba site to 340 million units per month, from 200 million units per month. After completion of expansion work in July, SDK made a trial run to secure product quality and stable operations. Commercial operation has already started.

Demand for blue LEDs is expected to grow around 10% a year on the average in coming years due to increased use in such applications as backlight for LCD TVs and general lighting. SDK will promote technical development to further increase output of LED chips and improve production efficiency, thereby providing high-quality, high-performance products that fulfill customers’ requirements.

SDK is aiming to reduce impact on the environment and address such issues as the depletion of resources. In its ultrabright LED business, SDK will continue providing energy-saving products in order to contribute to sustainable development of society.

JPSA exceeds laser system shipments in 2010 by 250%

JP SERCEL ASSOCIATES, a manufacturer of laser scribing and laser lift-off (LLO) systems for LED production, announced that their 2010 shipments of laser processing systems for LEDs is up 250% in the first 3 quarters of 2010 from 2009 shipments.

The increasing demand for high throughput 266nm front side scribing tools for sapphire, and HB LED wafers is being driven primarily by major Taiwanese and Korean manufacturers.

Founder and Chief Technical Officer of JPSA, Jeffrey Sercel said, "Our 266nm front side scribing continues to dominate the market because we are able to provide LED manufacturers higher throughput systems that enable more die to be packed onto each wafer. The increased die density and reduced damage from the laser scribing produces significantly higher yields than mechanical or saw dicing methods. To maintain our strong market presence, we continue to develop advanced processes in both scribing and laser lift-off applications, and expect these applications to lead the way for the LED market."

JPSA's recently released automation platform for the IX 6100 laser scribing and

laser lift-off systems is also shipping to LED manufacturers. The new wafer load and unload automation module, the IAP (Integrated Automation Platform), provides customers with dual-cassette wafer ports, further streamlining the manufacturing process, and increasing yields.

For continued development of advanced micromachining processes and production space, JPSA is in the final stages of expanding their Manchester, NH headquarters.

The completion is scheduled for October 2010 and will also provide state-of-the-art clean rooms, R&D laboratories, and ergonomic office space to accommodate growing customer service and engineering teams.

Long De Xin orders systems for GaN HB blue LED production

AIXTRON AG have announced an order for two further CRIUS 31x2-inch configuration deposition systems from Long De Xin. A company based in the PR China, Long De Xin placed the order during the second quarter of 2010 with both systems scheduled for shipment in the third quarter of 2010. They will be used for the manufacture of GaN ultra-high brightness (UHB) blue LEDs.

The local AIXTRON support team will commission the new reactors at the new Long De Xin facility at their mainland China production plant.

Mr. Jay Lin of Long De Xin comments, "Since the demand for our blue LEDs has been continuously growing we now have to significantly increase our production capacity. As we have found, the AIXTRON CRIUS ives up to its worldwide reputation for excellent process characteristics such as uniformity and efficiency becoming crucial for high-end HB LED production. My team is awaiting the arrival of the systems and looking forward to sharing the experience of their technical support team."


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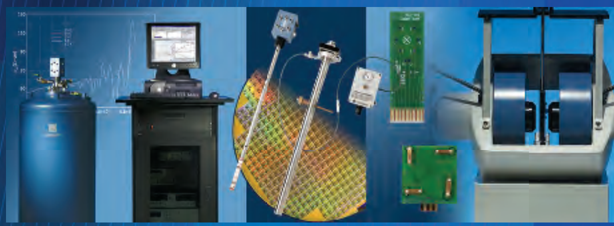

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Anadigics attacks the femtocell market with BiFET power amplifiers

The emergence of 4G smartphones is placing a tremendous strain on mobile carriers. But this can be relieved by adding femtocells to the network that are built around customized high performance power amplifiers, such as the portfolio of products being unveiled by **Anadigics, argues the company's Joe Cozzarelli.**

Smartphones such as the Samsung Epic 4G and the Apple iPhone are spawning a new generation of gadget lovers. Armed with such a device, it is possible to dip in and out of a vast array of applications while socially networking any time, anywhere.

Thanks to these alluring attributes, smartphone sales are rocketing, and now account for one-fifth of all handset purchases. The owners of these cutting-edge devices are exchanging more and more data as time goes by, so it is not surprising that mobile operator networks are creaking under increasing strain.

Today's networks are built around a traditional infrastructure model, which involves blanket deployment of macrocells to a geographic area. Any gaps that the macrocells cannot cover are filled with microcells. Regardless of the local cell technology, calls tend to be routed to their destinations through either terrestrial T1 lines or microwave backhaul, which are typically leased by the network operator.

However, even with this extensive and costly infrastructure in place, many people have either poor or no coverage in their homes and offices. Small cell solutions offer significant relief to this problem.

Complementing today's networks with small cells, and femtocells in particular, is the best way forward from both an economic and quality-of-service perspective. By placing coverage exactly where it's needed, the mobile operators will be able to keep pace with the growing customer demand and redirect backhaul traffic to the user's internet. Imagine a network where the user's sessions are almost always open. These cells are an attractive option for both upgrading the existing 3G network infrastructure and for deploying 4G. By adding hundreds of thousands of small local cell sites, users will enjoy great coverage in their homes, shops or businesses.

Left: This May Anadigics introduced its first two power amplifier modules for the femtocell market. These single-ended amplifiers feature InGaP-based HBTs and produce an average power of 24.5 dBm

Figure 1. Anadigics has recently developed the AWB7227 power amplifier module with a rated power of 27dBm. This balanced design that is slated for release later this year can be used to amplify the waveforms of the most demanding air interfaces such as CDMA, WCDMA, and LTE. When driven with a WCDMA waveform – test mode 1, 64 channel waveform, and a 10.5 dB peak-to-average ratio – this high-performance amplifier has margin to the ACOP requirement

Figure 2. The AWB7227 amplifier is capable of supporting multiple carriers, a feature that can be useful in certain deployment scenarios. Each carrier represents a group of users operating at a particular frequency. Here, the device has been subjected to 2 WCDMA Test Mode 1, 64 DPCH carriers at maximum separation

The femtocell market is expected to expand to approximately 49 million access points by 2014, according to the industry organization Femto Forum. By then 114 million users across the globe will be accessing mobile networks via femtocells. Considering that these small cells contain all the functional elements of a traditional base station, the importance of the RF power amplifier (PA) module becomes apparent.

To enjoy significant commercial success in this growing market, the femtocell design must balance features, functionality and pricing. For the PA, these requirements translate to characteristics that include exceptional RF and DC performance, multi-mode support, multi-standard support and reliability. The biggest factor that influences all of these characteristics is the semiconductor process used to manufacture the PA itself.

Going with GaAs

GaAs-based chips are employed in the vast majority of mobile handsets, as well as many components for low- to mid-power infrastructure. By building devices around this material it is possible to create amplifiers delivering great performance at competitive prices, and there is every reason to believe that this material will be widely used to build the amplifiers deployed during the build-out of 3G and 4G networks.

For the last ten years or so most PAs have been built from GaAs-based HBTs. Initially these transistors combined GaAs with AlGaAs, but more recently alternatives employing the pairing of GaAs and InGaP have been introduced that offer superior performance.

At Anadigics, which is based in Warren, NJ, we have built upon the huge success of the InGaP/GaAs HBT. Our InGaP-Plus process combines bipolar and FET devices on the same GaAs die, a move that allows features usually residing off of the chip to be integrated into conveniently sized, surface mount parts. The upshot is that switches, step attenuators, power detectors, and voltage regulators are commonly found in our PAs.

Pioneering RF Performance

We are currently designing a family of balanced and single-ended power amplifier modules for use in femtocells, picocells and in-home customer premises equipment. Each of our modules is specifically designed to deliver optimal performance in one or more of the several popular frequency bands used by wireless carriers. While specific features vary from module to module and are based on the target application, the design approach for each is similar.

The availability of a family of devices offers significant advantages to design teams, which may be tasked with providing femtocell products that implement different standards and operate over different frequency bands.

PA module designers want amplifiers that combine linearity with adequate RF power for good coverage and the capability of handling high capacity waveforms with high peak-to-average ratios (PAR). The PAs that we produce excel on all these fronts, uniting high power with outstanding linearity, plus good thermal performance for high reliability. As expected, these products draw on the many years of experience that we have in developing PAs for mobile handsets and broadband infrastructure products.

One of our primary goals is to create modules that combine extremely linear performance with a full complement of functional integration. To realize this ambition, we exploit the native efficiency and broadband capabilities of GaAs devices, and turn to state-of-the-art RF circuit simulation and thermal analysis tools to design the circuitry.

Since small cell products are available in several transmit powers, we developed single-ended and balanced PA modules with common features for each of the popular wireless bands. Earlier this year we released our first PAs for the small cell market, the AWB7123 and AWB7127, a pair of singled-ended parts with average powers of +24.5 dBm.

Before the year is out we will launch balanced equivalents of these modules. These two additions - the AWB7223 and the AWB7227 - operate at frequencies centered on 1.9 GHz and 2.1 GHz, respectively. They deliver a linear output of +27 dBm, which is more than adequate to cover a home or small office space. The modules operate at 4.5 V, and can handle a high peak-to-average ratio (PAR) waveform, making them ideal for networks employing CDMA, WCDMA or LTE technology. All of these products take advantage of the capabilities of our patented InGaP-Plus technology.

The remainder of this article will focus on the higher-frequency, balanced PA module: the AWB7227. Measurements show that this device can deliver a high level of performance when driven with a WCDMA signal (see Figure 1). Even when this module is driven with the

Figure 3. When designing the AWB series, the engineers at Anadigics had one eye on the future. As mobile carrier technology evolves, it is likely that the frequency division duplex LTE protocol will be used widely. The AWB7227 is capable of making this transition, as shown by this measurement with a 10 MHz, fully filled 64 QAM (50RB) test model

most demanding conditions, such as a 'Test Mode 1', 64-channel waveform with a PAR of 10.5 dB, there is headroom to the standards requirements. Figure 1 shows there is performance margin to the adjacent channel power (ACP) requirement, so there is no need to back-off the PA from its rated power to meet the ACP requirement at the antenna. Additionally, the module has integrated matching networks so it's extremely easy to use.

The AWB7227 is also capable of supporting multi-carrier operation (see Figure 2). This provides deployment flexibility to mobile operators by providing handoff options. This feature will become even more important as the number of femtocells increases.

Future proof technology

As air interfaces evolve, the associated technology must keep pace. The PA module is certainly affected by these

To prevent the AWB modules from becoming ineffective as the latest standards are deployed, we have designed them with the future in mind. Thanks to this approach, we have enabled the creation of femtocells that can adapt to standards and support migration and growth strategies.

Our PA modules are designed for long operating life. They employ HBTs featuring InGaP, which have a very strong track record in creating PAs that combine high reliability with extremely high efficiency

changes. To prevent the AWB modules from becoming ineffective as the latest standards are deployed, we have designed them with the future in mind. Thanks to this approach, we have enabled the creation of femtocells that can adapt to standards and support migration and growth strategies.

One of the technologies that is on the horizon is frequency division duplex LTE, which is compatible with our AWB7227. Figure 3 shows the AWB7227 performance with an LTE waveform. Again, there is a healthy margin to the performance required by the standard. When building an infrastructure, particularly one based on femtocells, it is critical to deploy robust components that are capable of reliable operation for many years. This means that power amplifiers must have a long mean-time-to-failure (MTTF). The MTTF is primarily dictated by the semiconductor material itself and the junction temperature.

Our PA modules are designed for long operating life. They employ HBTs featuring the ternary material InGaP, which

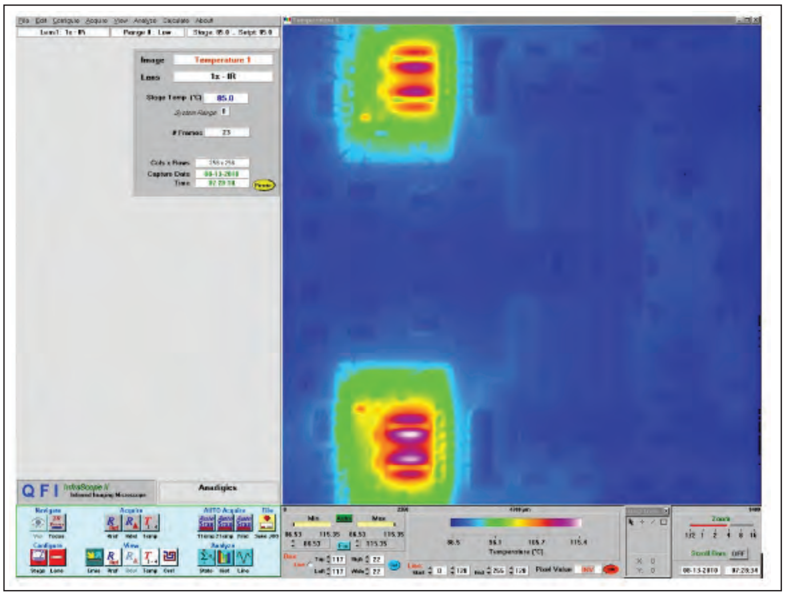

Figure 5. A thermal scan of the AWB7227 power amplifier module reveals a junction temperature of just 115 °C when the device was operated at its rated voltage and driven to its rated power with a CW signal

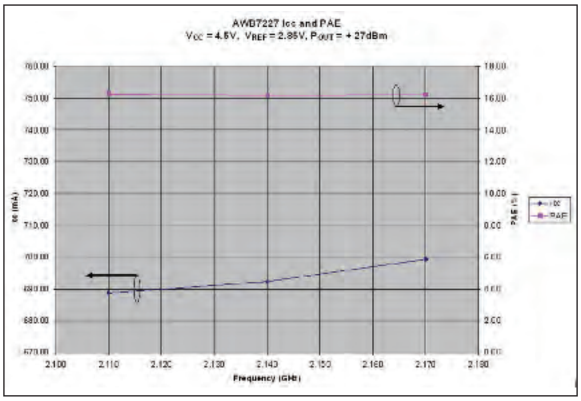

Figure 4. The power-added efficiency of the AWB7227 is best in class, thanks in part to the inclusion InGaP

have a very strong track record in creating PAs that combine high reliability with extremely high efficiency (see Figure 4). This pairing of attributes has made this type of module a very popular choice for many years in applications demanding similar power levels to those used in femtocell networks.

Figure 5 shows the thermal scans of the AWB7227 when operated at its rated voltage and driven to its rated power with a CW signal. The measured die junction temperature is just 115 °C, which translates to an extremely high MTTF. The AWB series has been designed to do an excellent job of converting DC input power to usable RF transmit power. Considering that the PA remains one of the key consumers of power in any base station, efficiency is an extremely important parameter. Thanks to the high efficiency of the AWB7227, the overall power consumption of the femtocell will be more manageable, supporting 'green' initiatives and enabling other key femtocell features such as battery back-up.

By carefully selecting materials and applying sound design principles, we are continuing to build a growing portfolio of high-performance PA modules that should lead to the construction of higher-performance femtocells. As the small cell market for both service providers and consumers grow, our AWB series of PA modules will provide a catalyst for ubiquitous coverage from 3G and 4G wireless networks while delivering a high quality of service.

Fraunhofer IAF targets terahertz circuits

Gate scaling is the key to penetrating the depths of the sub-millimeter-wave frequency range. It improves RF performance, empowering active electronics at these ultra-high frequencies, say **Axel Tessmann, Ingmar Kallfass and Arnulf Leuther from Fraunhofer IAF.**

A band of researchers around the world are united in their quest to build faster and faster circuits. If they can fulfill their dream, they will not only be able to investigate widely unchartered regions in the high millimeter, sub-millimeter and terahertz frequency range, but also start to develop novel systems operating in these spectral domains. Opportunities exist for spectroscopy in these spectral ranges along with trials of communication at staggering bit rates. What's more, at terahertz frequencies in particular, there is the chance to fabricate incredibly compact imaging systems with tiny antennae operating at breathtaking bandwidths.

The most promising device for reaching these incredibly high frequencies is the MMIC. Unlike rival diode electronics and optical technologies, this miniature integrated circuit offers an incredibly attractive combination of value-for-money, mass manufacturability, small size and on-chip multi-functionality.

Many approaches can be taken to building a high speed transistor, and at Fraunhofer IAF we are pursuing an InAlAs/InGaAs metamorphic HEMT (mHEMT) architecture. This design has much to recommend it: a great deal of freedom, in terms of epitaxial design; outstanding electrical performance; and an easy-to-handle, underlying GaAs substrate.

We have been able to successfully scale this device down to gate-lengths of 20 nm, and can now offer circuit designers a tremendously fast transistor. Cutoff-frequencies, f_T, exceed 600 GHz and the f_{max} value is well beyond 900 GHz. If these transistor speeds are to be really useful, they need to be exploited at the circuit level. To this end, we are continuously refining our passive components, the transmission line approach of the entire

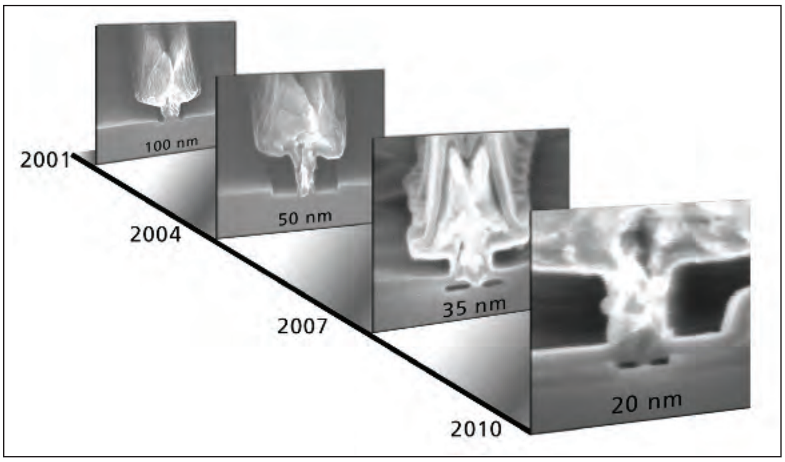

Figure 1. Smaller gates can speed transistors. Between 2001 and 2010 Fraunhofer IAF made great strides in this direction, reducing the length of its gates employed in its InAlAs/InGaAs metamorphic HEMT technology

MMIC process, and the waveguide packaging technique for ultra high frequency operation. Our success has been built on long-standing expertise in the design, fabrication and packaging of MMICs based on metamorphic HEMT technology. The virtues of this class of transistor stem from its metamorphic buffer, which allows the use of substrates made from GaAs, rather than InP. These are larger, cheaper, and less brittle. In addition, mHEMTs grown on GaAs have a higher degree of flexibility for heterostructure growth, thanks to a lift in restrictions related to the lattice parameter.

The upshot of all of this is that we can perform successful epitaxial growth of InAlAs/InGaAs layers with very high indium concentration on 4-inch GaAs. The 1 μm-thick quaternary buffer that we employ begins with an $Al_{0.52}Ga_{0.48}As$ layer, and the group III element gallium is linearly exchanged for indium.

Towards terahertz

Armed with an InGaAs channel, these HEMTs are the most advanced device technology for building the upcoming terahertz monolithic integrated circuits (TMICs). That's because they deliver high transistor gain at very high frequencies and produce the lowest noise figure of any active device technology. The key to these high speeds has been a cut in gate length (see Figure 1). Advancing beyond 200 GHz while maintaining reasonable gain was not trivial - it demanded proper scaling of the entire process parameters.

So at every technology node adjustments were made to the scaling rules of the gate-to-channel separation, source resistance, and electron density in the channel.

Increasing the indium content in the InGaAs channel has also helped to speed our mHEMTs (see Figure 2). Ramping the indium content to its upper limit to create a pure InAs film has increased electron mobilities and

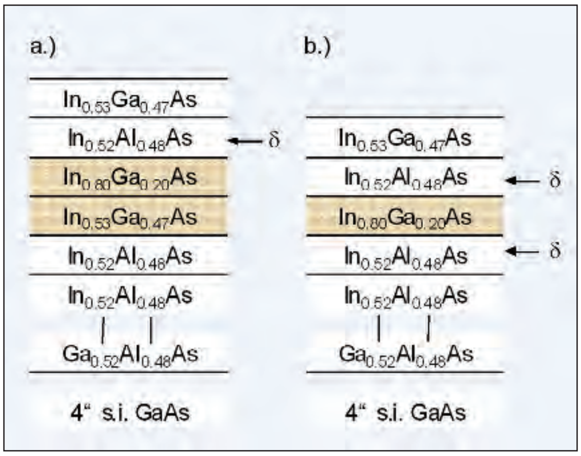

Figure 2. Reduction in the gate size of Fraunhofer IAF's transistors has been accompanied by adjustments to device design. This is evident in the layer composition of the 50 nm (a) and the 35 nm (b) mHEMT heterostructure. The 35 nm mHEMT layer sequence includes a double-side doped, single $In_{0.80}Ga_{0.20}As$ channel to avoid short channel effects

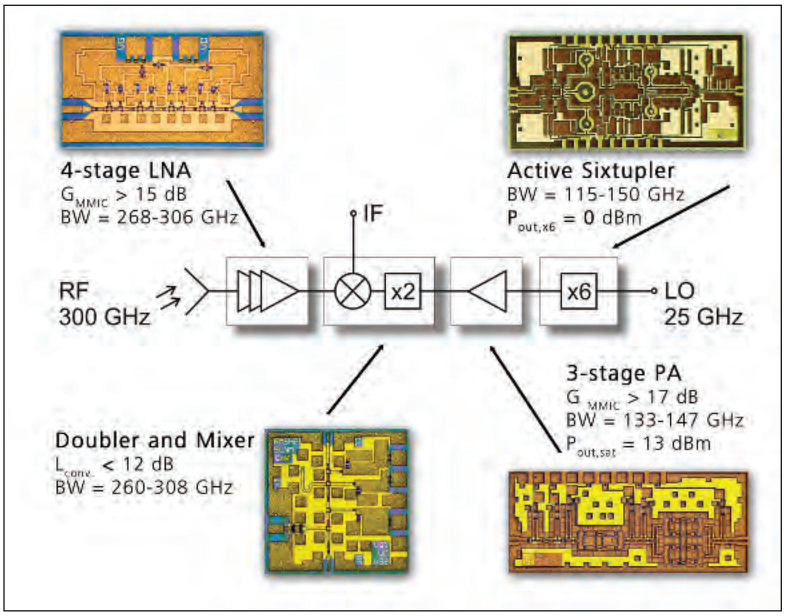

Figure 3. Fraunhofer IAF has fabricated a MMIC chipset for broadband performance at 300 GHz. This is based on active circuit concepts and employs 100 and 50 nm gate-length mHEMT technology. The chipset incorporates a low-noise amplifier, resistive mixer with integrated frequency-doubler, LO power amplifier and frequency-multiplier-by-six. The role of the balanced active frequency-multiplier-by-six is to provide 0 dBm of output power in the 110 to 152 GHz range. When directly driven by the multiplier output power, the combination of frequency doubler and resistive mixer produces a conversion loss of 20 dB. With the intermediate LO power amplifier, conversion loss is reduced to only 12 dB across the 260-308 GHz frequency range. The LNA provides pre-amplification by 20 dB at 290 GHz with an estimated noise figure of 7.5 dB. This takes the overall receiver performance to a maximum conversion gain of 8 dB.

delivered superior charge confinement. In turn, the transit frequency, f_T, of these mHEMTs has rocketed from 220 GHz for the 100 nm mHEMTs to 515 GHz for the 35 nm gate length devices. The faster variant can hit a drain current, I_d, as high as 1600 mA/mm at a drain voltage of 1 V, thanks to a very low source resistance of only 0.1 Ω.mm. Both of the mHEMTs feature a 250 nm-thick MOCVD-deposited SiN layer, which is employed in all our devices.

There is more to realizing an IC with terahertz capability than producing super-fast transistors. Adapted passive circuit elements are essential for confining electromagnetic fields and suppressing unwanted substrate modes. To meet these needs we employ a grounded coplanar waveguide topology with coplanar transmission lines on the MMIC front side, connected to grounded backside metallization with miniaturized through-substrate vias.

This topology also provides a low source inductance of the active devices, along with compact transmission line dimensions. The crosstalk within the circuits is minimized by cutting the coplanar line ground-to-ground spacing to 14 µm. This, in turn, slashes chip size. To suppress substrate modes, a small spacing between the through substrate vias is necessary. By reducing the size of the vias from 35 to 20 µm, enough of them can be accommodated in the miniaturized MMIC topology. The final substrate thickness is 50 µm.

These processes have been used to build a mHEMT portfolio featuring 100, 50 and 35 nm gate length technologies, which can be used to fabricate circuits operating at up to 220, 340 and 500 GHz, respectively. A 20 nm gate length process is currently under development, which will replace the 35 nm technology and enable the design of novel terahertz ICs operating at 750 GHz and beyond.

How fast?

In response to the fabrication of faster transistors by our team and others around the world, commercial suppliers are starting to develop and fabricate frequency extension modules for accurate S-parameter measurements of ICs and modules up to approximately 1.1 THz. In addition, RF probes are now available for frequency bands between 0 and 500 GHz.

Although these efforts are welcomed, there are still major challenges associated with ultra-high-frequency measurements. For example, increases in operational frequency come at the penalty of a reduction in the dynamic range of these measurement systems. This increases the noise floor, complicating system calibration, which in turn affects the measurement of both active devices and passive circuit components. The consequence is that as we push further into unchartered frequency domains, we have to devote far more time to accurate calibration, testing and device model extraction in order to ensure successful circuit design and fabrication.

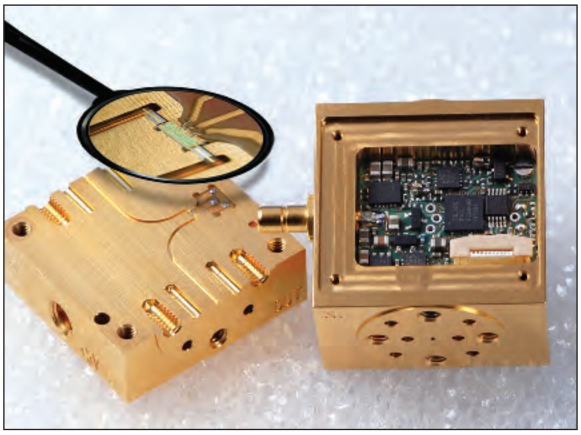

Figure 4. Fraunhofer IAF's sub-millimeter-wave amplifier module in split-block technology. The dissection plane divides the input and output rectangular waveguides along the centerline of the longer side. The monolithic 50 nm gate length amplifier circuit is mounted between two microstrip lines realized on 50 µm-thick quartz substrates.
These two lines are serving as waveguide-to-microstrip transitions

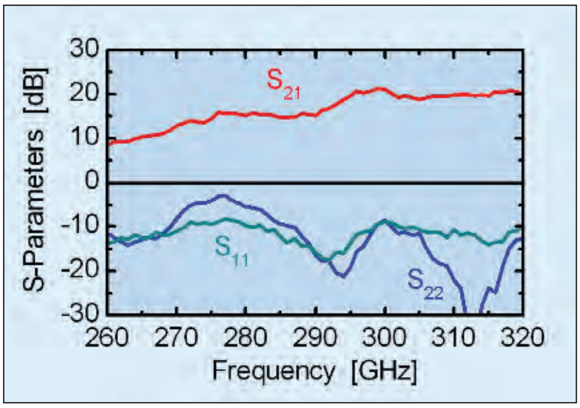

Figure 5. Fraunhofer IAFs mHEMT amplifier modules produce a maximum gain of 21 dB at 300 GHz. Small-signal gain exceeds 19 dB between 295 and 320 GHz

In addition to small-signal amplifiers, we are developing all of the required functional blocks for transmitters and receivers. This ever-expanding portfolio encompasses frequency generation and multiplication, power amplification and frequency conversion.

One example of our efforts is an all-MMIC-based broadband heterodyne receiver front-end spanning 268 - 306 GHz (see Figure 3). The wideband receiver is formed by a monolithic chip set that combines a cascading low-noise amplifier; resistive mixer with integrated frequency-doubler; LO power amplifier; and frequency-multiplier-by-six. The result is a chip that delivers up to 8 dB of conversion gain and has a noise figure of 7.6 dB. These performance figures rival those of state-of-the-art Schottky receivers.

Recently, we have focused our development on sub-millimeter-wave ICs and modules for operation above 300 GHz. This hinges on the realization of TMICs, which is the short-term target. Progress in this direction includes the fabrication of a 320 GHz mHEMT amplifier package with a waveguide module in split-block configuration (see figure 4). The MMIC is thinned down to a substrate thickness of 50 µm, allowing the use of very short bond wires. This ensures low parasitics and low loss. To increase operational reliability, the power supply was integrated into the module.

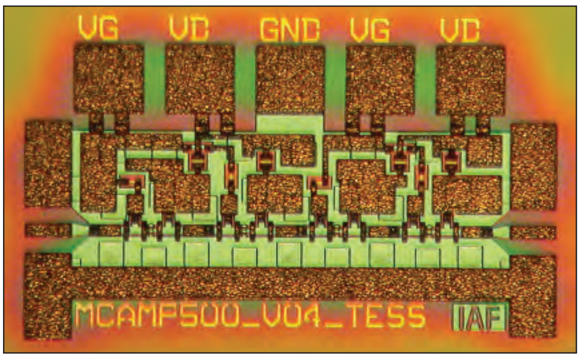

Figure 6. The four-stage, 460 GHz mHEMT amplifier S-MMIC employs transistors with a gate width of only 2 x 5 µm. Die size is only 0.37 x 0.63 mm²

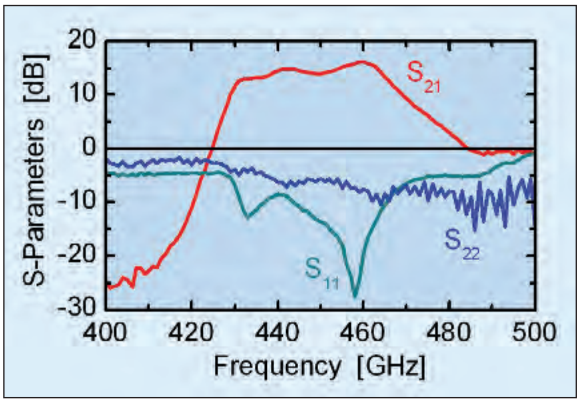

Figure 7. On-wafer measured S-parameters of a four-stage mHEMT amplifier SMMIC. Small signal gain of more than 16 dB is realized at 460 GHz.

Measurements of this amplifier reveal that it delivers a very flat gain characteristic. Linear gain exceeds 19 dB from 295 to 320 GHz, and it hits a maximum gain of 21 dB at 300 GHz (see Figure 5).

We have also produced a handful of amplifier MMICs with remarkable bandwidth and low noise figures for operation in frequency bands between 220 and 500 GHz. These amplifiers should help to spur development of high resolution imaging systems, wireless ultra-high-capacity communication links and sub-millimeter-wave spectroscopy.

One example of this type of amplifier is a four-stage, 460 GHz S-MMIC (see Figure 6). In this case, the amplifier was designed to deliver high small-signal gain and low noise. It fulfills these goals, delivering a peak gain of 16.1 dB at 460 GHz when driven at a drain voltage of $V_d = 1$ V, a gate voltage of $V_g = 0.2$ V, and a drain current of 23 mA (see Figure 7). Small-signal gain exceeded 13 dB across the range 433-465 GHz.

Amplifiers such as this, along with others that we have showcased in this article, are proof of our expertise in high-speed transistors and accompanying MMIC and packaging technology.

These recent scaling advances, which re-enforce our position as the leading pioneer of high-speed devices and circuits within Europe, have equipped our mHEMTs for terahertz operation and are paving the way for terahertz ICs.

Further reading

I Kallfass et al. 2009 Proc. of SPIE **7485**
A Leuther et al. 2010 IPRM Technical Digest **425**
A Tessmann et al. 2010 IMS Technical Digest **53**

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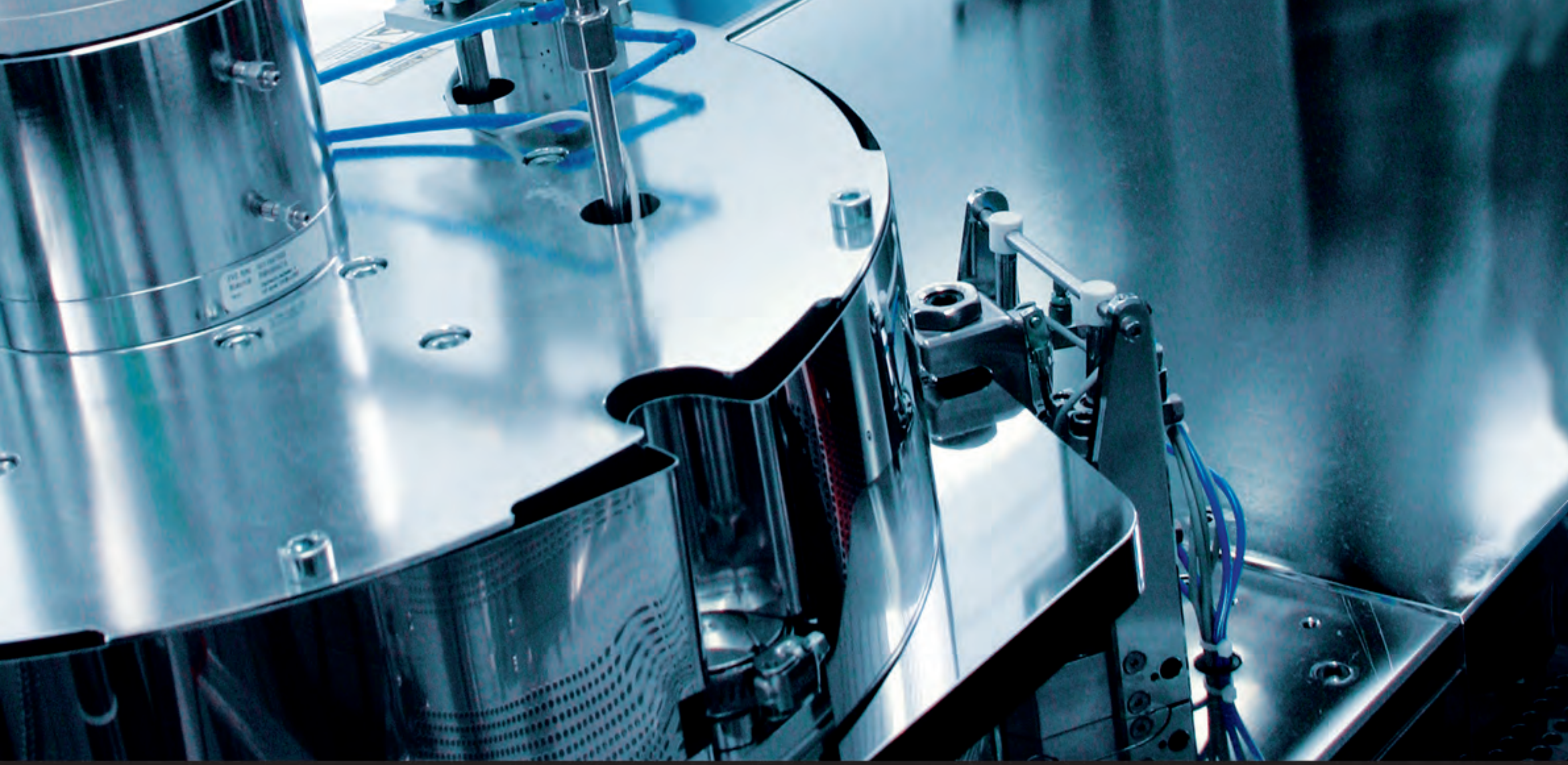

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RFMD opens the doors of its MBE facility

Diversification: that's the central pillar of RF Micro Devices' growth strategy. To continue to execute on that front it is opening up its MBE facility and starting to offer various services that include shipments of arsenic- and phosphorous-based epiwafers. **Richard Stevenson investigates.**

RF Micro Devices is renowned for its manufacture of power amplifiers. In the late 1990s it convinced handset makers to turn away from MESFET-based amplifiers and switch to its HBT-based variant. Since then it has gone from strength to strength to become one of the world's largest manufacturers of power amplifiers, which it churns out in-house on a 6-inch line equipped with multi-wafer MBE tools.

While there is no denying that RFMD's fame derives from its manufacture of billions of HBTs at its Greensboro, NC, headquarters, it is wrong to think of this company as just a captive GaAs chipmaker. Since 2003 it has been outsourcing growth of InGaP HBTs – it now has several established suppliers of MOCVD-grown epiwafers – and during the last few years it has added another string to its bow, GaN. The company continues to expand its portfolio of wide bandgap RF products, and last year it started to offer foundry services for this technology, including fabrication of GaN-on-SiC wafers to customer-specific circuit designs.

The company's diversification strategy has taken another significant stride this year: The introduction of MBE-related epitaxial products and services, including ultra-high vacuum cleaning services. Profitable new revenue streams could result from this move, leading to a good return on the company's substantial investment in capital equipment.

"Our offerings include working with customers to develop epitaxial structures and MBE growth conditions; the delivery of epiwafers grown to exact customer specifications; and designing epitaxial DOEs [design of experiments]," explains Robert Van Buskirk, president of RFMD's multi-market products group.

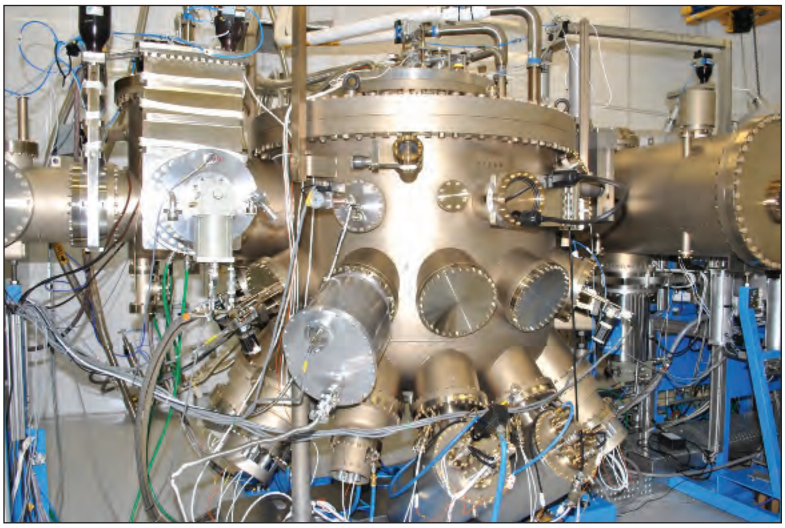
RFMD's MBE services are available to all. There is no minimum order, so start-ups and small companies will not be put off working with this RF giant. And RFMD's proven pedigree in high volume manufacturing makes it an appealing option for far bigger players looking to off-load epiwafer growth, or qualify an external material supplier that can supplement internal manufacture during peak periods.

An RFMD technician loads substrates in preparation for epitaxial growth

The battle ahead

If RFMD is to have significant success in this new venture, it will have to tender and win MBE-based epiwafer supply contracts. The strongest competition will surely come from IQE, an epiwafer supplier with large MBE facilities in Singapore and Bethlehem, PA, that has experience in producing material for RF applications in high volume, thanks in part to its contract with Anadigics.

The Greensboro outfit is certainly up for the challenge of competing in the epiwafer supply market. It is no stranger to high-volume manufacture, and Van Buskirk points out that the company can draw on its experiences associated with developing several generations of epitaxial structures that have been instrumental in the creation of one of the most successful RF companies in the world.



RFMD's portfolio of multi-wafer MBE tools includes reactors built by Veeco, Riber and VG

What is certain is that RFMD's new venture will get off the ground. Over the years the company has had several inquiries and engagements for MBE products and services, including the ones that they are offering, and this interest will not diminish now.

A significant proportion of RFMD's revenue from its new venture is likely to come from the sale of arsenic and phosphorous-based epiwafers. These structures can be grown on 4-inch or 6-inch GaAs substrates, which can either be supplied by the customer, or purchased from RFMD. "We do not have the capability for nitride growth, but beyond that limitation, we are open to any epi structure," says Chris Santana, director of the company's MBE operations. According to him, RFMD has experience in growing and developing many different types of structure, including metamorphic designs, BiHEMTs, MOSFETs and even optoelectronic material such as VCSELs.

RFMD's introduction of a GaN-based foundry service in 2009 has provided a great stepping-stone for this year's foray into MBE services. "We now have all the aspects of a full-service, commercial turn-key foundry in place – including purchasing and IP agreements, work-flow procedures, and web-based customer support processes – and we can quickly tailor those commercial business processes and systems to our MBE-based service," explains Van Buskirk.

Customer services

Although GaN and MBE foundry customers can just instruct RFMD to supply wafers to their specifications, there is more help on hand if they want it. For example, in RFMD's GaN foundry, customers can tap into the company's design kits that are supported by industry standard design software and device models. What's more, it is normal for RFMD's engineers to interact with customers in the final stages of their circuit design efforts to make sure that customer designs do not violate any in-house design rules or layout services, as documented in RFMD's design kits. "However, while we offer a wide range of GaN-based proprietary products, we do not offer circuit design services for our foundry customers," explains Van Buskirk.

Santana claims that his team will be even more flexible when it comes to MBE structures and profiles. In this case, so long as they can support the customization required, the engineers will be willing to help to develop epiwafer designs needed to develop a product. "We will be happy to engage customers in this technical dialogue."

Any company weighing up the pros and cons of working with an epiwafer supplier will demand the protection of their intellectual property. RFMD can assure customers of this, and show them the plans put in place that draw on its previous foray into foundry services. "We have established robust firewalls within RFMD for our GaN-based foundry service," explains Van Buskirk. "Our foundry service teams are separated from our internal development teams, and RFMD employees at large cannot access the IP or data for foundry services."

There are times when customer-sensitive information has to be transferred to RFMD employees, but this is minimized, with technical data and information disclosed on a 'need-to-know' basis. When a customer wants to access design kits and models, they can do this through an external, web-based portal that allows them to see the status of their wafer fabrication orders.

Aside from IP issues, the big question for many customers is how long it will take them to get their epiwafers. Van Buskirk has some reassuring news for them: "We have the industry's fastest cycle times, and expect to use that as a key performance discriminator in our foundry service." Cycle time commitments are already in place for customers using RFMD's GaN services, and they have a clause in these contracts entitling the customer to a discount if shipments are late.

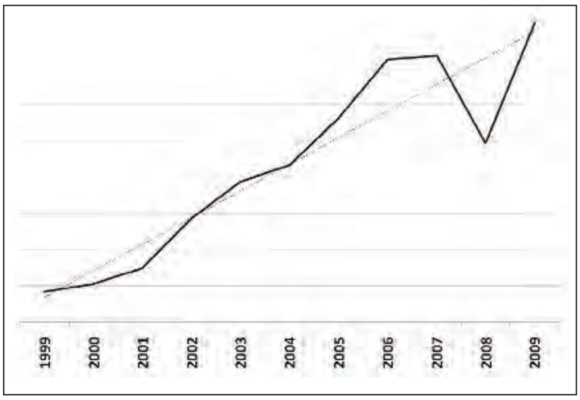
Van Buskirk can also assure customers that they will not lose out if RFMD has a substantial hike in orders for its own GaAs chips. "We are committed to growing our foundry services, and we have the installed capacity to meet our internal needs and the needs of our potential external foundry customers." In fact, this installed capacity is so large that it makes RFMD one of the world's largest MBE, GaAs and GaN wafer production facilities, claims Van Buskirk.

The MBE facility at RFMD runs '24-7', but it is only staffed from 7 a.m. to 7 p.m. Automation allows the MBE tools run through the night, with growth aborted if *in-situ* monitoring tools determine that the processes have deviated beyond acceptable windows for production. Customers can select the tool for epiwafer production from a portfolio of MBE reactors: a Veeco Gen2K, which has a 7 x 6-inch capacity; a Riber R7000 with identical capacity; a Riber R6000, which can accommodate four 6-inch wafers; and a single wafer, 6-inch tool, the VG V100. RFMD equips these tools with state-of-the-art monitoring apparatus. “Our MBE systems are outfitted with what we believe to be the most effective tools at delivering quality, consistent products,” claims Santana.

To ensure that the facility is run as efficiently as possible, the company’s process engineers interlace growths for the customers with those for internal production. “However, if the customer chooses, we can enter into an agreement that provides exclusive use of an MBE tool for a period of time,” reveals Santana. In fact, RFMD has already taken this type of arrangement with one of its MBE foundry customers.

The Greensboro outfit has an impressive toolkit for characterizing epiwafers. Alongside the more common methods for determining material characteristics, such as a Lehighton instrument for resistivity measurements and an X-ray diffraction tool, the company can analyze wafers with a multi-field Hall probe and a photoreflectance technique.

“Multi-field Hall is primarily used to give the mobility and carrier concentrations of the conductive layers in the epi,” explains Santana. It can, for example, be used to determine the mobility and carrier concentrations in both the channel and the highly conductive cap layer of pHEMT epiwafers. This is beneficial, because it eliminates the need to grow a ‘capless’ calibration structure. “In addition, it is also an excellent method for process control,” argues Santana.



The throughput of MBE-grown material at RFMD has climbed over the last decade. The dip in 2008 resulted from a sharp decline in handset orders, plus a move from within that industry to slash inventory levels. The continuous line shows actual wafer output, and the dashed line is a linear fit of this data.

Photoreflectance, another non-destructive technique, provides a qualitative measurement of HBT gain. Samples are probed with a broadband light source, and insights into the structure are gleaned by collecting and spectrally analyzing light that has been reflected off of the many interfaces of the transistor. The data from all of these measurements can accompany material shipments to customers. And if the customer wants the data collected by the *in-situ* monitoring tools, including values for growth rates and temperatures, this can be sent as well.

In short, it seems that RFMD is willing to stay as flexible and accommodating as possible to meet the customer’s needs. At present the only tasks that the company is not prepared to do are to process GaAs wafers into chips and package them. But even this may become an option one day – after all, it certainly ties in with the company’s goal of diversification. Will it do it? We’ll just have to wait and see.

RFMD’s long-standing affair with MBE

When RFMD launched in the early 1990s, it had just one technology – the AlGaAs HBT. Initially this was produced on 4-inch wafers at TRW, but in 1997 RFMD transferred the MBE process to its own fabrication facility, known as fab 1. A larger facility, fab 2, was added two years later, in response to a rapidly growing order book.

During the last decade the company expanded its technology. In 2002 it added a second generation of AlGaAs HBT to its technology portfolio, and soon after that it started working towards the addition of switches to its product mix. Initially these were outsourced from the UK firm Filtronic, but soon after RFMD started to develop an in-house production process and become less dependent on imports.

The RF Micro Devices MBE Facility is located in Greensboro, North Carolina

Further down the line RFMD acquired Filtronic’s 6-inch fab line, which it now uses to produce switches based on epiwafers grown at Greensboro. Filtronic’s line was equipped with two Veeco Gen2K systems, but one has been shipped across the Atlantic to support the foundry business.

Today RFMD manufacturers exclusively on 6-inch GaAs, and uses MBE to produce four generations of AlGaAs-based HBTs and two generations of pHEMT. The latest pHEMT combines switching characteristics with amplification to create products for WLAN.

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Europe backs a central foundry for photonic integrated circuits

High costs and long development times are impairing the chances of success for small companies pioneering novel devices based on photonic integrated circuits. To cater for these needs, Europe is funding the creation of an InP foundry that will use generic processes to create devices for multiple applications. **Richard Stevenson discusses this venture with the project's two coordinators, David Robbins from Willow Photonics and Meint Smit from the Technical University of Eindhoven.**

Q Explain the motivation for creating a European foundry for InP photonic integrated circuits?

A MS: What we're trying to do is introduce into InP-based photonics a similar foundry model to that which is so successful in CMOS microelectronics.

I think it's good to distinguish between what we call custom foundries and generic foundries. A lot of fabs that call themselves foundries offer to develop a process for you, but with generic foundries, the process is standardized. That's new and it makes access to this PIC technology much easier and cheaper.

There are two institutes that already offer that kind of foundry service on a research basis: ePIXfab for silicon photonics; and JePPIX (Joint European Platform for InP-based Photonic Integrated Components and Circuits) for InP. What we are talking about here is transferring the JePPIX approach into industry. Hopefully a European PIC foundry will exist in 2013.

Q The millions and millions of dollars poured into PIC technology have not provided a great return on investment. How will the European manufacturing platform for photonic integrated circuits (EuroPIC) change that?

A DR: Actually, the technology in these types of photonic integrated circuits is having quite a lot of commercial success. But this is only in the telecoms arena, where there is enough money and drive to deliver the integration needed to make those systems work.

One issue is that by and large the equipment suppliers in the telecoms, which are very dedicated in their own narrow commercial structures, don't give access to their fabs. However, even if they did, the cost of development of the chips for someone else would be pretty horrendous. Even custom fabs, which operate at a lower cost level, are pretty expensive.

If we can develop along generic lines, PICs can become much cheaper - maybe one or two orders of magnitude cheaper. From there we can start to grow the market volumes in other sectors.

MS: Another important point is that once you have the platform technology and a lot of companies are using it, it will be worth the effort of creating a dedicated design kit and component library. Once you have that, you will design to accurate models, speeding up the whole design process and making it more accurate. That's what has happened in microelectronics. Photonics technology is much too fragmented, with design software at a very basic level compared to the electronics industry.

Q Once the foundry is up and running, who will be its main users?

A MS: They will be University spin-offs and SMEs that want to investigate the application of PICs in novel or improved products, and also larger companies that can develop their PICs at significantly lower costs. We have a list of fifty companies, our user group, with potential interest in this generic approach. The target is to increase that to at least one hundred within two years.

DR: The strength of the EuroPIC approach is that companies can get a handful of chips relatively cheaply and quickly. If they end up wanting many wafers a year, the same plants can produce that volume as well, because all processes are carried out using industrial facilities capable of high-volume production.

Q Why will SMEs have a better chance of success by working with EuroPIC?

A DR: Any fabs would find it extremely difficult to work with large numbers of SMEs. You really need some kind of independent expertise in between the fabs and the applications: people to organize the whole process; people to do the design. The companies with the fabs do not have the manpower available. However, it is true that if a company was ramping its production to high volumes, it would be worth its while to talk directly with a fab, but we are talking about the companies starting in low volume. The photonics industry has thinned down a lot since the dot.com boom-and-bust at the turn of the century, and very few of the big players who are left have the spare capacity to take on this work.

Q Will the EuroPIC foundries help companies to speed products to market?

A DR: Yes. You can imagine a small SME with half a dozen people trying to sort everything out for themselves and struggling to get anywhere. When you have this infrastructure available, rapid prototyping becomes a reality. You will be able to go from an idea to having a chip in your hands in a few months. It will be incredibly different to the position we have now.

Q Do you think that Europe lags the US and Asia, in terms of PIC development and commercialization?

A MS: Europe had the lead in photonic integration in the 1990s. However, after the turn of the century US companies, such as Infinera, came up very rapidly. However, in this novel approach - the generic technology - Europe has a lead. Something like this is not happening in the US or Japan. To succeed you need two things: a

"We can see that the chip price may go down by a factor of more than ten. If the cost of packaging is not to become the bottleneck, it will have to go down too, which basically means cutting the cost of alignment using leading edge packaging technologies; 'clip-it-together' and 'plug-and-play' techniques."
Meint Smit, Technical University of Eindhoven

consortium that is very closely co-operating, which we have in Europe; and substantial supporting funding.

Q Where does the European foundry stand today?

A DR: It's at an R&D level. The University of Eindhoven is supporting the JePPIX operation, which runs an R&D generic line on its open facility.

What we are trying to do is to move that understanding and capability out into industry, where you can get all the good things like volume, reliability, throughput. To do this, EuroPIC is working with Oclaro in the UK and HHI (Heinrich Hertz Institute) in Berlin. Philips is also playing a role, although it is a little bit behind those to two foundries.

Although Oclaro's technology is not advertised as large-scale photonic integrated circuits in quite the way Infinera's technology is, it is every bit the equal of it. It can do very similar things, but Oclaro has chosen until now to apply it specifically to tunable lasers, modulators, and so on.

Q What are the benefits for Oclaro and HHI, the key foundries in the EuroPIC project?

A DR: They are both fabs with a telecom base with a huge amount of highly sophisticated technology firmly directed in one narrow application area. They would both like to see their technological abilities more broadly deployed.

Q Tell me about the progress of EuroPIC?

A DR: It started on 1st August last year, and it's a relatively long cycle time to get the first generic line set up. We have spent a year putting existing and new pieces together in the process phase, and we are just about to start our first runs at the InP processing facilities. EuroPIC will aim to go through this cycle twice, in order to iron out difficulties.

MS: What has been achieved now is mainly coming from the JePPIX platform. This is research, but within two to three years we hope to bring this to an industrial level. We have selected ten different applications [see box "PIC applications" for details], and they will all be put on the two foundry lines. By the middle of next year we should have one set of wafers from each of the foundries, each wafer having a lot of quite different chips integrated on it.

Q Are the foundries continuing to refine their technology?

A DR: Very much so. Although to be honest, EuroPIC is a very broad, SME-based program, and there's not that much space for developing a radically new semiconductor technology. The novelty in the program is largely to do with putting end-to-end process together, but there will be new technologies in packaging and software.

However, the platform is capable of considerable development in terms of the semiconductor technology that goes into it, because there are a lot of different InP alloys that you can use. There is the whole area of quantum dots and nanotechnology, which we could go into in the future.

Q What wavelengths will these PICs operate at?

A MS: Initially the telecom C-band (around 1550 nm), but the platform is capable of extension.

Q Are there facilities to package these chips?

A DR: Our packaging effort is rather small. There is a resource limitation – EuroPIC is a € 6 million program. We have one partner who is beginning to look at the prospects of a generic packaging technology, CIP Technologies in the UK. We are also starting new programs, where packaging is a very large part of the activity.

MS: Our process is standardized on the interface electrically and optically, so that you can use the same package for a lot of different chips.

We can see that the chip price may go down by a factor of more than ten. If the cost of packaging is not to become the bottleneck, it will have to go down too, which basically means cutting the cost of alignment using leading edge packaging technologies; 'clip-it-together' and 'plug-and-play' techniques.

Q Do companies need to be worried about compromising IP if they work with EuroPIC?

A DR: We have drawn up non-disclosure agreement so we can work with our user group.

In the future we may have a brokering organization sitting between the application and the InP fab. Contracts between the broker and the fab, and the broker and the application holders can sew up IP in a completely watertight fashion.

Q How will SMEs work with the European PIC foundry to develop products and bring them to market?

A MS: If they have sufficient expertise in-house they can design their mask set. But we expect that most companies will not have that expertise, so we are also working on the creation of design houses to generate designs, just as you have design houses in microelectronics.

Q How is the foundry funded at the moment?

A MS: Essentially European and national funding, with some matching funding from industry, depending on the scheme. The COBRA research school at TU/e is underwriting JePPIX next year. COBRA runs training courses based in the university's electrical engineering department on the design of the overall technology, and it occasionally offers multi-project wafer runs.

In the Netherlands we have the so-called Memphis (Merging Electronics and Micro & Nano-Photonics for Integrated Circuits) Smart Mix project. It's a big and rather broad program, but there is substantial funding for this generic approach.

There is another program in the Netherlands: the STW Perpectief program GTIP, worth € 5.5 million, which is fully devoted to generic integration technologies. It will start at the end of this year.

DR: There is also PARADIGM (Photonic Adavanced Manufacturing Platform for Photonic Integrated Circuits), another EU project under negotiation, which will hopefully start in the early autumn. It can be viewed as a successor to EuroPIC. Paradigm will focus on technology developments, such as packaging and InP processing technologies.

Assuming that Paradigm is funded, we will then have € 20-30 million going into this area, spread over about twenty five different companies. This gives you a critical mass to make you feel that you can make a central European InP foundry a reality.

Q Given all the talk about austerity measures by the governments of many European countries, are you concerned over future funding of EuroPIC?

A MS: This technology will make product development much cheaper, which must be a good message in the current climate. For the coming two-to-three years foundry based R&D will be in a good position with secured funding. The critical point is this: will the commercial market for low-cost PICs grow fast enough?

DR: I would add that these austerity measures by the European governments are not over everything. Governments are trying to cut their government expenditure and stimulate their industries, and we are one of the industries that can stimulate growth.

PIC applications

EuroPIC is aiming to assist the development of devices based on PICs that can be deployed in a wide range of applications including:

- Telecom access networks, where they can be used in offices to integrate many circuits, eliminating repetition for each subscriber or group of subscribers.

- 10 Gbit/s access networks, where they could become competitive in the subscriber transceiver module.

- Fiber-based sensors that monitor the integrity of large constructions, such as bridges, dikes, roofs of large buildings and windmill propeller blades. The cost of the sensor is dominated by that of the readout unit - a light source, a detector and some signal processing circuitry – and a PIC could replace a significant part of the existing module. According to the Optoelectronics Industry Development Association, this market will be worth more than $1 billion in 2011.

- Medical instruments, such as those based around the techniques of Optical Coherence Tomography or Raman Scatterometry. PICs fabricated from InP and its related alloys can operate at 1500 nm, a region of the infrared spectrum where the penetration depth in skin is relatively high.

- High-speed pulse generators and clock recovery circuits; forms of ultrafast analog-to-digital-converters; and multi-photon microscopy. All three applications require lasers with very short pulse lengths, which can be produced with PICs featuring mode-locked lasers, optionally combined with pulse shapers.

- Computer backplanes that use photonic interconnects to allow switching in the optical domain. A EuroPIC fast photonic switch could serve terabit-server backplanes, high-performance computing and multi-core architecture connections.

- Radio-over-fiber systems providing wireless access.

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Simplifying GaN VCSEL fabrication

THE process for making a room-temperature GaN-based VCSEL capable of continuous wave (CW) emission has been simplified, thanks to efforts at National Chiao-Tung University, Taiwan.

Corresponding author Tien-Chang Lu claims that the group is this first to use an AlN/GaN-based bottom DBR in this class of device. "This is the first step toward the all-epi type structure used in mature, GaAs-based, 850 nm VCSELs."

The breakthrough by Lu and his co-workers could help to spur GaN VCSEL commercialization. These devices have a far lower threshold current than their edge-emitting cousins, and could provide a more efficient blue light source for Blu-ray pick-up heads, portable micro-projectors, and high-resolution laser mice.

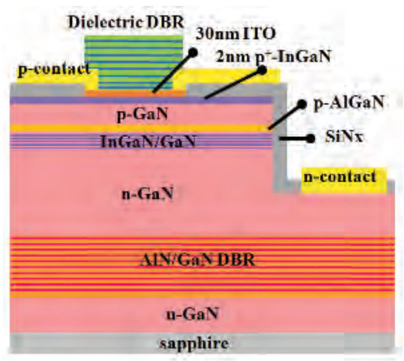
Success at National Chiao-Tung University follows Nichia's report of the fabrication of the first room-temperature, CW VCSEL in 2008. The Taiwanese researchers attribute Nichia's breakthrough to the introduction of a thinner transparent conducting layer, which cuts internal loss; and the growth of a high-quality active region, thanks to deposition on a GaN substrate.

Nichia's approach to VCSEL fabrication is complex, and involves laser lift-off and elaborate polishing and bonding processes. A far simpler approach is to grow a nitride-based DBR and an active region on sapphire by MOCVD, before adding a dielectric DBR with an electron gun.

The Taiwanese researchers have pioneered such a process, which begins with the growth of a GaN buffer layer; a 29-pair AlN/GaN DBR; a GaN/InGaN active region featuring ten, 2.5 nm-thick quantum wells; an electron-blocking layer; a 110 nm-thick p-GaN layer; and a 2 nm-thick GaN-cap. AlN/GaN superlattices were inserted into the DBR to prevent cracking.

A 10 nm diameter aperture was defined by deposition and selective removal of SiN. The team deposited a current spreading layer and n- and p-contacts on this, and then added a ten-period Ta_2O_5/SiO_2 DBR to complete device fabrication.

Lu claims that this is the first GaN VCSEL to feature an AlGaN electron-blocking layer. This resulted in a relatively low threshold current density of 9.7 mA, corresponding to a threshold current density of 12.4 kA/cm^2. Turn-on voltage for the 412 nm laser was 4.3 V, output power peaked at just over 35 μW, and beam divergence was 8°.



VCSEL growth involves MOCVD deposition of a GaN-based epitaxial stack, followed by ion-assisted electron gun deposition of a Ta2O5/SiO2 DBR

The team's next goal is to improve laser beam quality. Lu says that this will be accomplished through further reduction of the threshold current, plus the addition of an optical confining structure.

T.-C. Lu et al Appl. Phys. Lett. **97** 071114 (2010)

Nichia's LEDs hit new highs

Nichia has increased the efficacy of its LEDs that are being developed for solid-state lighting.

Results from this Japanese optoelectronic device manufacturer include a LED chip that delivers 1913 lumens at 135 lm/W when driven at 1A. This chip combines four, 450 μm by 450 μm die in series. According to the researchers, this LED has a higher flux than a 20W-class fluorescent lamp and an efficacy 50 percent higher than a tri-phosphor fluorescent lamp.

Nichia's engineers have also fabricated a 1 mm by 1 mm chip that produces 183 lm/W at 350 mA and 130 lm/W at 1A.

This set of results is broadly comparable to Cree's recent announcements. Nichia's record for efficacy at 350 mA is not as high as its US rival, which announced a 208 lm/W LED at 350 mA. However, the dimensions of the more efficient device are unknown. Cree has also unveiled a single chip device, the Xlamp XM LED, which produces 110 lm/W at 2A and is slated for release this Fall.

Nichia's recent success has stemmed from reducing the operating voltage of its LEDs from 3.1 V to 2.8 V. Improvements in epitaxial wafer quality and the introduction of 'current-expanding' electrodes have help to cut operating voltage.

Y. Narukawa *et al*. J. Phys. D. Appl. Phys. **43** 354002 (2010)

Trapezoidal wells combat LED droop

WIDER WELLS, slimmer barriers and polarization-matched active regions have all been used over the past few years to minimize droop, the decline in LED efficiency at higher drive currents. Inserting trapezoidal wells into the active region can now be added to this growing list, thanks to the efforts of a team of researchers from Korea.

These scientists from Gwangju Institute of Science and Technology and Samsung LED company claim that the addition of trapezoidal wells increases electron-hole overlap, which in turn cuts droop.

Two of the hallmarks of the Korean LED are a slight reduction in forward voltage and series resistance. Seong-Ju Park from Gwangju Institute of Science and Technology claims that these attributes stem from superior carrier transport, which is the result of a graded indium-composition in the trapezoid well layer. The Korean team compared the performance of their blue-emitting trapezoidal LED with a conventional equivalent. They made both of the devices by depositing a GaN-based epitaxial stack on sapphire by MOCVD, and then etching 550 µm by 550 µm mesas with an inductively coupled plasma. Deposition of ITO added transparent contacts.

Trapezoidal wells had a 0.5 nm-thick InGaN core sandwiched between two 1.5 nm-thick layers that were linearly graded in alloy composition to 7.5 nm-thick GaN barriers. Identical barriers featured in the conventional LED, which had a 2.5 nm-thick InGaN well. External quantum efficiency (EQE) measurements revealed that the trapezoidal LED produces a 19 percent higher output at 35 A cm^{-2}, rising to a 20 percent improvement at 70 A cm^{-2}.

The EQE of the novel LED overtook the control LED at 5 A cm^{-2}. This is a very low value compared with the crossover current densities reported in previous studies by other groups, according to the team. Both of the devices were devoid of any light extraction technology. This accounts for the low values of EQE, which peaked at about 30 percent.

Modeling both device architectures with LED simulator SiLENSe uncovered a relationship between electron-hole overlap and droop. Switching from the conventional well to the trapezoidal one smoothed conduction and valence bands profiles, increased electron overlap from 37.2 percent to 41.6 percent, and cut the distance between the maxima of the electron and hole wavefunctions from 1.5 mm to 1.1 mm.

“Since the volume of the trapezoidal well is 20 percent smaller than the standard well, our study shows that overlap of the electron-hole wavefunction in the trapezoidal well is more important than the non-radiative Auger process,” claims Park.

Interestingly, Park can account for the improved EQE of the double heterostructure LEDs, which have been pioneered by Lumileds as an approach for cutting droop. He says that in this wide-well LED there is very little band-bending of the InGaN layer. “This result indicates that the electron-hole wavefunction overlap in the double heterostructure can be much higher than in the quantum well.”

S.-H. Han *et al.* J. Phys. D. Appl. Phys. **43** 354004 (2010)

HRL speeds E-mode transistor

HRL Laboratories claims to have simultaneously broken three records for an enhancement-mode, GaN HFET: maximum transconductance; highest cut-off frequency; and the highest value for maximum oscillation frequency.

The AlN/GaN/AlGaN double heterojunction FET developed by HRL had a peak transconductance of 700 mS/mm, a cut-off frequency of 112 GHz and maximum oscillation frequency of 215 GHz.

Although these values are inferior to best figures produced by their far more common depletion-mode cousins, the E-mode version has one major advantage: it is normally off. This simplifies circuit design; aids power switching, by reducing power consumption and increasing safety; and enables creation of E/D-mode logic for digital circuits and mixed-signal applications.

HRL’s motivation for its efforts is focused on the development of GaN transistors and integrated circuit technology for high-performance analog-to-digital converters that can be deployed in future advanced electronic systems. This work is funded by DARPA’s NEXT program.

The engineers at HRL attribute their success to aggressive reduction of parasitic resistances and vertical scaling.

Fabrication of the double-heterostructure FETs involved the growth of a GaN-based epitaxial stack on 3-inch SiC. This comprised an $Al_{0.08}Ga_{0.92}N$ buffer, a 20-40 nm GaN channel, a 2 nm AlN barrier and a 2.5 nm cap.

Mesas were formed in the material, before plasma-enhanced CVD deposited a SiO_2 mask. This was patterned and etched to within 20 nm of the sample surface in the source and drain regions. MBE growth of a 50 nm, heavily silicon-doped GaN layer was added to facilitate the formation of low-resistance ohmic contacts, before the silicon mask was removed.

After Ti/Al/Pt contacts were deposited, T-shaped Pt/Au gates were added by: depositing a sacrificial mask layer; patterning the gate foot with e-beam lithography; and performing gate top lithography, metallization, liftoff and mask removal.

These record-breaking E-mode double heterostructure FETs had a 2 x 37.5 µm gate periphery and produced a maximum drain current of 0.92 mA/mm at 2 V gate bias. On-resistance was 1.06 Ω mm.

Cut-off frequency and maximum oscillation frequency records were realized at a drain bias of 2.0 V. According to HRL’s engineers, previous claims for these records have tended to employ higher drain biases, typically 5-10 V, which were needed to overcome the excess voltage drop across parasitic resistances.

The team claims that optimized lateral-device scaling could spur further improvements in its E-mode FET performance.

A. Corrion *et al.* to appear in Electron. Dev. Lett. (2010)



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