SiC driving interest for power semiconductors

Silicon carbide has formerly been the preserve of niche industrial applications such as power generation and control, but is now attracting interest from major silicon power semiconductor manufacturers. As material quality and size rises, attention is focusing on devices and applications.

The 6th European Conference on Silicon Carbide and Related Materials (ECSCRM 2006) took place on 3–7 September at the striking, two-year-old, £70m Sage Centre in Gateshead, a former industrial powerhouse in north-east England from the industrial revolution through to the 1970s (home to companies such as Reyrolle Ltd of Hebburn, a maker of electrical protection and control equipment since 1886) but long since overshadowed by the more dominant city of Newcastle on the opposing north bank of the river Tyne.

Now Gateshead is resurgent after attracting government funding and investment back across the prize-winning, electric-powered, *Gateshead* Millenium Bridge (the world's only tilting bridge) as part of a £250m re-generation of the south bank of the Tyne.

An appropriate venue, then, for a conference on a technology, SiC, that has formerly been the preserve of niche industrial applications such as power generation and control and overshadowed by the success of silicon, but is now attracting long-overdue interest from many mainstream silicon manufacturers (including Infineon, which abandoned the former Siemens North Tyneside DRAM memory chip fab in Newcastle).

In his invited plenary presentation, Peter Friedrichs, managing director of the Siemens/Infineon joint venture SiCED Electronics Development GmbH, gave an overview of SiC power device development, from the first wafer-like base material in the early 1990s, through demonstrations of high-voltage Schottky diodes in 1993 and switching devices in the mid-1990s, the first MOS interfaces in the late 1990s, to the availability of the first commercial SiC Schottky barrier diodes in 2001 (from just two suppliers: Infineon and Cree). This was boosted in 2003 by the development of 3" SiC wafers with a macro defect density of under $<10\text{cm}^{-2}$.

No, not Sydney but Gateshead! The Sage Centre's shell-like roof, venue for ECSCRM 2006, reflecting both past and future technologies (Tyne Bridge, top; the Gateshead Millennium Bridge, background-left).

Initial SiC Schottky diodes were fast but had limits in surge mode, and many failures due to over-temperature, whereas users were familiar with silicon PIN diodes. However, Infineon's second-generation ThinQ!2G devices had additional p-doped islands (a combination of a Schottky diode and a pn diode) for improved surge current stability and an avalanche safety feature, and further p-doped regions only at the periphery to give a higher blocking voltage in 1200V Schottkys, as well as to reduce electric fields from <2kV/cm to <1.8kV/cm. Turn-off behaviour is now as good as for a pure Schottky diode, says Friedrichs. SiCED is prototyping 1700V Schottkys, but expects to extend this to 3300V. For Schottky diodes, the killer application for is power factor correction (PFC), he adds.

An additional consideration, says Friedrichs, is that the price of silicon has doubled in the last two years, reducing the price difference between silicon and SiC devices.

Apart from the established SiC device makers SiCED, Cree, Northrop Grumman, Rohm and SemiSouth, ECSCRM 2006 was distinguished by interest in SiC from many of the major silicon-based power semiconductor manufacturers, including STMicroelectronics and Philips (represented via its collaborator Chalmers University of Technology in Sweden), Microsemi (which started up its new SiC fab this year, after acquiring Advanced Power Technology, which has SiC technology licensed from Northrop Grumman), International Rectifier, Rockwell Scientific and Fairchild in the USA, and, in

ECSCRM draws main players in power semiconductors

ECSCRM 2006 drew a healthy contingent of over 420 delegates — over 50% from Europe, but as many as 25% from the Far East and 20% from the USA.

Most European delegates came from traditional SiC powerhouse Sweden (dominated by KTH Royal Institute of Technology and Linköping University, plus contrast research organization Acreo, Chalmers University of Technology, substrate and epiwafer maker Norstel, and SiC/SiGe CVD reactor maker Epigress) as well as Germany (dominated by the University of Erlangen and Erlangen-based Siemens/Infineon SiC power device making joint venture SiCED, plus substrate maker SiCrystal and reactor maker Aixtron).

In addition to delegates from the UK (mainly the universities of Newcastle and Sheffield, plus etch system maker STS) and Poland's Institute of Electronic Materials Technology (IEMT), other large contingents came from France (research institutes UMR CNRS, INSA Lyon, Centre de Génie Électrique de Lyon and Institut National Polytechnique de Grenoble-CNRS, substrate polishing service provider NovaSiC, and materials supplier Saint-Gobain Crystals) and Italy (hot-wall CVD reactor maker LPE and epiwafer-making subsidiary ETC of Catania, Sicily, as well as the University of Catania and Catania-based CNR-IMM, which collaborates with French/Italian silicon device maker STMicroelectronics, whose Central R&D facility is also in Catania).

Delegates from Japan came from substrate makers SiXON and Hoya, SiC MESFET maker New Japan Radio, and silicon device makers Rohm, Sumitomo Electric Industries, Mitsubishi Electric, Toshiba Corp R&D Center, Matsushita Electric Industrial, Fuji Electric and Oki Electric Industry, car makers Honda R&D, Nissan, Toyota Motor and automotive component supplier Denso, and AIST (the National Institute of Advanced Industrial Science and Technology), CRIEPI (the Central Research Institute of Electric Power Industry) and the Japan Atomic Energy Centre.

The US contingent was dominated by device and substrate maker Cree, along with substrate makers II-VI Inc and Dow Corning Compound Semiconductor, SiC device makers SemiSouth and Northrop Grumman, power silicon device maker International Rectifier, system maker GE Global Research Center, the Naval Research Laboratory and NASA Glenn/OAI.

Japan, Toshiba, Hitachi, Sumitomo Electric Industries, Mitsubishi Electric, Matsushita, and Oki Electric.

Such interest is indicative of the rapid trend among manufacturers — including the world's largest manufacturers of power electronic devices in Europe, Japan and the USA — that are now embracing SiC as an essential material for power electronics.

The applications attracting much interest include energy generation and distribution, especially in Japan (CRIEPI and the Japan Atomic Energy Centre) and the USA (General Electric), which have strong reasons — ecological, economic and political — for reducing energy wastage and consumption.

Roger Bassett of French power transmission and distribution company Areva T&D highlighted SiC's three-fold reduction in switching losses compared to silicon. Also, whereas silicon-based devices can shrink the real estate needed for voltage source converters six-fold, SiC can give a further three-fold reduction. Boosted by US defense funding of $20m per year on SiC R&D (with Cree as a leading contractor) for applications like lighter, all-electric ships, in 2007 Cree is due to sample 10kV, 20A p-channel SiC insulated-gate bipolar transistors (IGBTs), for prototype equipment in 2010. Bassett expects this to lead to a 'significant market' for 10kV/1kA IGBTs in 2012 (e.g for solid-state sub-stations).

Another major application is automotive electronics, especially in switching power in hybrid electric vehicles, attracting the involvement of Japanese car makers Toyota (which already has its own in-house silicon chip manufacturing facilities), Honda and Nissan. Hence Fuji Electric Advanced Technology Co Ltd is starting SiC MOSFET production in 2007–2009 for inverters, initially for industrial motors, and then later for hybrid electric vehicles (HEVs), said Yoshiyuki Yonezawa, manager of its Semiconductor Laboratory's SiC Project. The devices can reduce inverter losses by 30%, increase drive frequency, and reduce the space needed for passive devices. Toyota, for example, is aiming to shrink the system size 10–50-fold.

A characteristic of silicon power device makers is that, according to Philippe Roussel of Yole Developpement, of 82 power device fabs surveyed, 10% use 3″ wafers, 33% 4″, 18% 5″, 35% 6″, and just 4% 8″, with no move to 12″ wafers forecast. So, as many as 43% could use existing available SiC wafers (up to 4″).

SiCED's Peter Friedrichs reckons on 6″ SiC substrates being available by 2010 ("before 6″ equipment vanishes from [silicon] fabs"). Adrian Powell of Cree, in the conference's 'Industrial News' session, reckoned Cree would make 6″ SiC available "by 2009".

However, Thomas Kippes of wafer maker SiCrystal points out that some manufacturers (e.g. International Rectifier Corporation Italiana S.p.A. in Milan as well as many Japanese power semiconductors manufacturers) fabricate power semiconductors on 5″ silicon wafers, suggesting the possibility that the next step from 4″ SiC could be 5″ SiC substrates.

Wafer scale-up: from hero to zero-micropipe

It was said that this year's ECSCRM had more of a device focus than previous events and less focus on material quality. This is a sign, perhaps of concerns now shifting to device design and processing, as some of the previous application-limiting material defects such as micropipe density have now been reduced to zero for 2″ substrates and almost negligible densities on 3″ substrates.

At ECSCRM 2006, Cree Inc of Raleigh, NC, USA, which makes the vast majority of all commercial SiC wafers (including those for its own SiC-based blue and white LED manufacturing, which make up 80% of its $400m annual revenues), launched its zero-micropipe substrate technology (which was acquired in July when it bought Intrinsic Semiconductor of Dulles, VI, USA, now Cree Dulles Inc, in order to speed quality improvement).

In the 'Industrial News' session, Cree's Adrian Powell detailed how its standard n-type semiconducting 100mm 4H-SiC was achieving a lowest micropipe density of 0.31MP/cm^2, with a monthly median of 5MP/cm^2 in production. The latter should be reduced to zero next year, Powell said. Cree's 100mm high-purity semi-insulating (HPSI) SiC substrates have 'hero' micropipe densities of 2.5MP/cm^2. However, the micropipes are 'mostly at the edges', says Powell. The next step will be zero-micropipe 100mm wafers, says Powell, followed by 150mm substrates.

Although Cree dominates the SiC substrate market, other suppliers are scaling up, in terms of both size and quality.

II-VI Inc manufactures SiC substrates, but only for electronic applications, says Dr Andrew Souzis, manager, Programs & Business Development of the Wide Bandgap Materials Group (WBG), since "only Cree and Infineon [which uses Cree substrates] use SiC for opto applications". II-VI first demonstrated its 100mm SiC substrates in late 2005, and plans to make initial sales of engineering samples in early 2007, with volume quantities available later in the year, says Souzis.

Souzis also explained that II-VI has achieved micropipe density of zero on its 2″ wafers, less than 1 on 3″ wafers and from 600 per square in June 2005 to 9 per square now on 100mm wafers. But Souzis stated that, at current levels, even for 4″ SiC, "micropipe density is not such a big issue any more, other than for the largest devices — dislocation density is more important". In addition, as SiC moves into full-scale manufacturing, issues such as particulates become more important. Following the purchase of an atomic force microscope last February, a new standard cleaning process with extremely low particulate levels was introduced.

II-VI performs all SiC crystal growth and fabrication at its Technology Center in Pine Brook, NJ, but is in the process of moving the manufacturing portion of its polishing capacity to its new facility in Starkville, MS, USA (leasing space in SemiSouth's new SiC epiwafer and device fabrication plant in the Ralph E. Powe Center for Innovative Technology, adjacent to Mississippi State University's campus in the Thad Cochran Research, Technology and Economic Development Park). Initially, the polished wafers will undergo final quality control inspection back in New Jersey, shipping from Starkville once the process transfer is fully qualified.

Benefits of the Mississippi plant include cheaper energy and labor costs, as well as tax breaks for training etc, says Souzis. Proximity to MSU, which has an active SiC R&D program, is also a benefit. Plans currently call for a separate, full-scale manufacturing plant to be built elsewhere in the research park within the next 3–4 years to meet anticipated demands, adds Souzis. All manufacturing will then move from New Jersey, with R&D and new process and product development remaining there.

Thomas Straubinger of SiCrystal AG, based in Erlangen, Germany, outlined their priorities as being: 2″ and 3″ n-type 6H-SiC wafers for optoelectronic (i.e. LED) applications (focusing on cost); 3″ n-type 4H-SiC, now in production for high-power applications (focusing on dislocations); and 3″ semi-insulating wafers for high-frequency applications (focusing on improving the surface quality). He gave their typical micropipe density for 3″ wafers in production as 4MP/cm^2 for 4H-SiC and 0.9MP/cm^2 for 6H-SiC. Straubinger says that substrate quality is determined mainly by the initial seed crystal, since micropipes are transferred from the seed crystal to the growing crystal. So, SiCrystal has improved the quality by developing a new generation of seed crystal for 3″ 4H-SiC substrates, said Straubinger. However, the challenge is to transfer that quality improvement to larger diameters, for high-quality 4″ 4H-SiC.

The most critical type of dislocations for failure in high-power devices are basal plane dislocations (BPDs). Their occurrence shows a correlation with thermo-elastic stress generated during growth. Stress can be reduced by minimizing temperature gradients and improving the crystal-wall contact in the growth chamber. For the 3″ 4H-SiC wafers now in production, crystals grown with lower thermal stress contain fewer slip bands, improving from 70% to 95% free of BPDs.

Thomas Zoes, Dow Corning's global commercial manager for Compound Semiconductor Solutions in Midland, MI, USA, said that the firm "does not have zero micropipe yet", but is working on it.

Also present at ECSCRM were: Japan's SiXon Ltd, which was spun off from Kyoto University in 1998 (with initial funding from Sumitomo Electric Industries) and manufactures SiC electronic devices as well as 6H-SiC n-type, 6H-SiC semi-insulating and 4H-SiC n-type wafers; and Okmetic spin-off Norstel, which opened its SiC substrate and epitaxy manufacturing plant in Norrköping, Sweden in late August (see Issue 4, page 12).

Equipment for silicon carbide processing

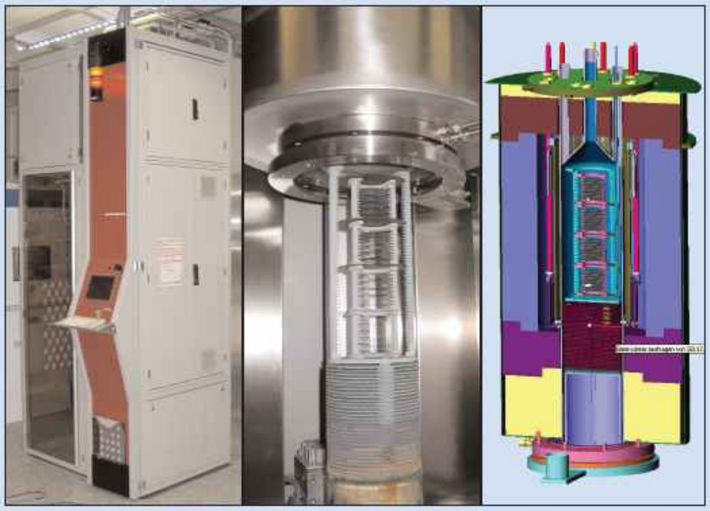
At ECSCRM, Centrotherm Thermal Solutions of Blaubeuren, Germany introduced the CHV100 (Centrotherm High-temperature Vertical vacuum furnace, with a maximum wafer size of 100mm). Developed in cooperation with Fraunhofer IISB (Institute of Integrated Systems and Device Technology) in Erlangen, it is the world's first mass-production high-temperature annealing furnace developed specifically for SiC electronic materials, it is claimed.

The system originated as the CVS HT (Centrotherm Vertical Special-application High Temperature) in 2003. The first system was built for the University of Erlangen and installed at the Fraunhoefer IISB in Erlangen as a part of a joint program in 2003.

Compared to the CVS HT, the CHV100 has a faster cool-down rate, improved vacuum seals, an updated temperature controller, increased temperature of operation (from 1750°C up to 1850°C annealing temperature, ramping at up to 100°C/min).

The CHV100 is designed for Al post-implant activation annealing of SiC devices at high temperatures. Traditionally, comparatively low-volume annealing furnaces are used for SiC device manufacturing. But the system can process up to 50 2″, 3″ or 4″ wafers per batch (intermixed in the same process run) and has a small footprint of 1.3m^2, reducing cost of ownership. The flexibility in wafer diameter and process capability also enables the development of individual processes as well as use for mass production, with options for robot handling and a load-lock/minienvironment, says Uwe Keim, product manager for SiC Processing Systems.

A second system was bought in June by Microsemi for its former APT fab in Bend, OR, USA, for annealing Al implants in SiC power semiconductor devices. Dr Douglas Meyer, executive scientist for Centrotherm Technologies in Danvers, MA, USA, says that the increased acceptance of SiC devices and rapidly growing market, driven by the need for exceptional performance from Schottky diodes and FETs at high temperatures, has motivated a recent maturation of SiC manufacturing techniques, necessitating high-productivity process tools with greatly reduced cost of ownership, small footprint and minimal particulate contamination.



The CHV100 Centrotherm high-temperature vertical vacuum furnace for 100mm wafers.

Other systems have recently been sold in Europe. "We are negotiating two more sales in the US right now and there is growing interest in Japan," says Meyer. centrotherm is beginning a product offering for annealing (sintering) of metal contacts for SiC devices, and is doing some demonstrations.

Also, Italy's LPE S.p.A. is supplementing its ACiS M8 horizontal hot-wall CVD reactor for 4H-SiC epitaxy up to 2000°C (which has a capacity of 6x2″, 3x3″ or 1x4″ wafers) with the new high-throughput ACiS M10 reactor (with a capacity of 9x2″, 5x3″ or 3x4″ wafers and 12x2″ on request), to be available in Q2/2007. A new-generation process chamber and inductor design give improved temperature uniformity. M8 reactors can be retrofitted, says LPE.

SiC epitaxy

Powell says that Cree's 100mm 4H-SiC epi achieves thickness uniformity of <2% and doping uniformity of <7% — "epi quality is as good as 3-inch", he adds. The next development, he says, will be epi that is free of basal plane defects, and 150mm epi.

Italy's LPE S.p.A. developed SiC epi over three to four years, together with the Epitaxial Technology Center. For over a year, using a new 2500m^2 plant in Catania, it has been making epiwafers for commercial sale.

In addition, ESICAT Japan LLP, a partnership formed in September 2005 between Showa Denko KK and several researchers belonging to AIST (Japan's National Institute of Advanced Industrial Science and Technology) and CRIEPI (the Central Research Institute of Electric Power Industry), aimed to start selling SiC epi services in fourth-quarter 2006, according to marketing manager Takayuki Sato.

Also, Dow Corning presented a poster on in-situ gas phase etching for defect reduction in epilayers and chlorosilane-based SiC CVD epi, and is planning to supply epi commercially, says the firm's Thomas Zoes.

No doubt, by the time of the International Conference on Silicon Carbide and Related Materials 2007, 14–19 October in Otsu, Japan, such developments will have advanced the SiC industry to even greater maturity. ■