Dr Mike Cooke

Silicon carbide (SiC) has been proposed for some time as a substrate for high-speed, high-temperature devices, and products are now entering the market. Dr Mike Cooke reviews some of SiC's device opportunities and tough process challenges.

Semiconductor hardnut

There's something strange about a material in which one proposal for etch processing is to use molten salt fluxes in platinum beakers. But again, everything about using silicon carbide is hard. Indeed, after diamond it is one of the hardest materials known to humanity. A quick perusal of the process technology challenges for SiC device production impresses one with the 'simplicity' of pure silicon or III-V IC production.

While for some researchers the very difficulty of making SiC work as a semiconductor material is possibly what attracts, for others it is the potential thermal and electrical benefits of the compound.

High-temperature capabilities are attractive in such areas as automotive, aerospace, manufacturing and deep-well drilling

Wide potential

Silicon carbide's main benefits centre on its wider energy band gap in comparison with pure silicon or gallium arsenide (Table 1, [1]). While GaAs has a 1.43 eV gap and silicon 1.12 eV, one crystal structure of SiC has a 3.2 eV gap. There are wider gaps – pure diamond has one of 5.6 eV and GaN has a 3.4 eV value. In an ideal world, a wide band gap would reduce intrinsic carrier concentrations for higher-temperature operation and reduced leakage currents.

Potentially, a wide band gap opens up applications for high-temperature devices, high-frequency/ultraviolet light detection, high junction electrical field strengths and high-frequency switching. SiC – with some 20 years of research behind it – is beginning to yield commercial products in some applications. GaN also has future interest for RF electronics and work has been progressing for some 10 years. Some laboratories have recently produced demonstrations of diamond devices, but marketable products are a long way off.

High-temperature capabilities are attractive in such areas as automotive, aerospace, manufacturing and deep-well drilling [2]. Currently, electronics used to monitor and control high-temperature processes such as fuel combustion have to be sited in cooler areas some distance away from the sensors and control devices. This often results in long wiring, more connectors and the addition of localised cooling, making for more complex systems and increasing the potential for failure. Indeed, some commercial air disasters have been linked to degraded wiring (e.g. TWA flight 800, near Long Island, New York, 1996; SwissAir flight 111, near Nova Scotia, 1998).

GaN is one possible alternative for some of these high-temperature applications. However, Dr Phil Neudeck, a leading SiC electronics researcher at NASA's Glenn Research Center in Cleveland, Ohio, has a personal opinion that SiC is closer to 'beneficial functionality'. He adds: "What is more questionable for GaN than SiC in my personal opinion is the electrochemical durability/reliability of the material to

	(Unit)	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	2H-GaN	Diamond
E_g	(eV)	1.12	1.43	2.4	3.0	3.2	3.4	5.6
E_c	(MV/cm)	0.25	0.3	2.0	2.5	2.2	3.0	5.0
Th. cond. λ	(W/cmK)	1.5	0.5	5.0	5.0	5.0	1.3	20.0
v_{sat}	(10^7cm/s)	1.0	1.0	2.5	2.0	2.0	2.5	2.7
$\mu_{n,\perp c}$	(cm^2/Vs)	1350	8500	1000	500	950	400	2200
$\mu_{n,\parallel c}$	(cm^2/Vs)	n.a.	n.a.	n.a.	100	1150	n.a.	n.a.
μ_p	(cm^2/Vs)	480	400	40	80	120	30	1600
ε_r		11.9	13.0	9.7	10.0	10.0	9.5	5.0

Table 1. Physical comparison between SiC and other materials.

function for prolonged periods under high-temperature (>300°C) electrical stress. GaN has considerably higher defect densities than SiC, both in terms of point 'traps' and extended 'dislocations'. To date, GaN has proven less stable/durable under high-temperature electrical operation than SiC."

The issue of durability/stability also arises in connection with contacts and semiconductor–insulator interfaces, which are key components of any electronic device. Neudeck comments: "While future GaN breakthroughs might conceivably change this situation, Group IV semiconductors have historically proven easier to make electrically stable/durable/reliable than Group III-V materials. The latter tend to have more reactive/complex chemistries (which will be exacerbated at high temperature) leading to device degradation. At high temperature, i.e. more than the 300°C limit of silicon-on-insulator (SOI) devices, durability/reliability is *the* key challenge."

Market analysis

According to recent research by Yole Développement [3], the total market for SiC substrates in 2004 was equivalent to 320,000 50 mm wafers. Some 90% of this SiC material production is dedicated to the production of blue/white LEDs (Figure 1). Here, SiC is merely used as a substrate for the active material, gallium nitride (GaN), and its variants. This is because the SiC crystal structure is closely matched to that of GaN. However, this market could dwindle if companies transfer GaN to sapphire rather than SiC.

Yole's Dr Philippe Roussel, Project Manager for Compound Semiconductor Materials & Equipment Research, explains the relative merits of SiC and sapphire in GaN-based devices: "SiC's high thermal conductivity makes it attractive as a substrate for devices with high junction temperatures, such as some high-power lighting devices. By contrast, sapphire is a thermal insulator, so GaN/sapphire devices cannot be used at high power density. AlN could be a good alternative to SiC – low lattice mismatch with GaN, high thermal conductivity – but its availability remains poor and its diameter is at most 1.5". GaN/bulk GaN could also provide a pertinent solution when the average selling price of bulk GaN becomes compatible with market requirements. For high-power-density devices, homo-epitaxy (SiC on SiC) remains the best option."

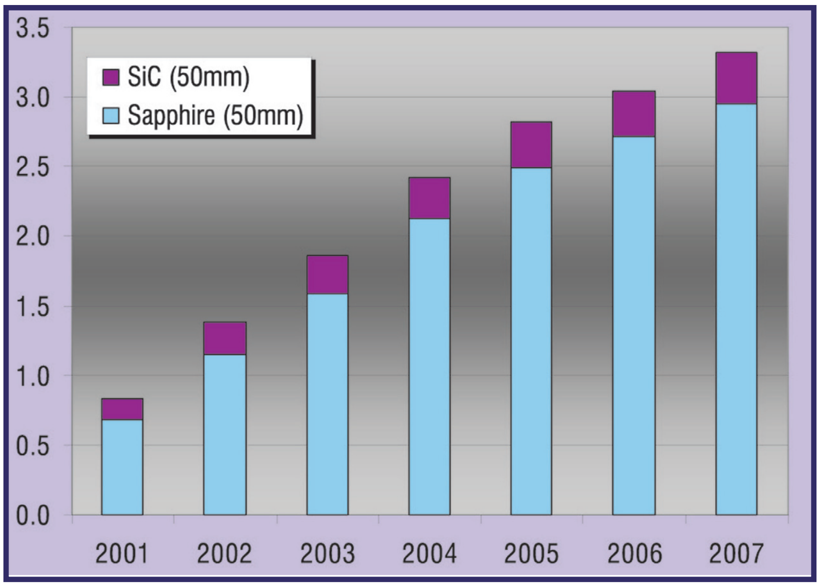

Figure 1. Stacked bar chart showing SiC and sapphire substrate use (millions of 50 mm wafer equivalents) and a forecast for GaN-based LED production. (Courtesy of Yole Développement.)

In terms of active electronics in SiC, Yole sees applications in Schottky diodes for use in power supply power factor correctors (PFCs) and metal-semiconductor field-effect transistors (MESFETs) for RF systems.

For the PFC market, uptake of SiC devices is impeded by the need for a redesign of the power supply unit to accommodate the new technology. As usual, the market is beginning with the high-end and migrating to the mid-range (Figure 2). Hopes for wider application depend on the SiC device price of around $0.5/amp being reduced to $0.2/amp, according to Yole. SiC Schottky diodes are expected on the market soon from such suppliers as Rohm, International Rectifier and STMicroelectronics. Beyond power supplies, SiC is slowly gaining markets for motor control such as in hybrid electric vehicles. Power electronics is a slow moving, conservative market, and commercial progress is often one design-win at a time.

In RF applications, SiC MESFETs are competing with existing GaAs and silicon devices along with new GaN high-electron-mobility transistors (HEMTs). The challenge for any RF device is to achieve long life-time, high power efficiency (PAE), good reliability, and flat frequency response on the whole bandwidth, all at a low price. Companies offering SiC MESFETs include Cree and Rockwell. GaN devices can also be obtained from Cree, along with Nitronex, Fujitsu, NEC and RFMD. For use in wireless communication base stations, Yole's opinion is that reliable devices would need to cost no more than $1 per Watt to compete with silicon lightly doped drain MOS (LDMOS) chips.

GaN has proven less stable/durable under high-temperature electrical operation than silicon carbide

Device potential

John Palmour, one of Cree's founders and executive vice-president for the company's Power, Wireless and Materials business groups, sees opportunities for both SiC and GaN high-frequency products. One advantage of SiC is that it is here now in a series of robust products, he says. Palmour reports "a lot of business", particularly in monolithic microwave ICs (MMICs) for markets such as military communications. He is also excited about the potential applications in base-station devices for the WiMAX broadband wireless networking standard (IEEE 802.16). Both markets require devices that can maintain power gains and efficiencies at high frequency. SiC is suitable for frequencies up to 6 GHz, while GaN has the capability to operate effectively at frequencies up to 40 GHz.

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Accelerated lifetime testing of Cree's latest 'Gen 2' SiC MESFETs is shown in Figure 3, where the devices are DC biased at high junction temperature and periodically brought down to room temperature and RF measurements made. The criterion for failure is a 20% change in either DC or RF parameters. In a full-up active RF test at elevated temperature, the device went more than 6300 hours at a junction temperature of 255°C. This temperature was as high as RF testing would go without large-scale connector failure, etc.

In December 2005, Cree plans to shut down its existing LDMOS operation and focus on its SiC/GaN expertise. The dominant producer of LDMOS products is Motorola's Freescale spin-off.

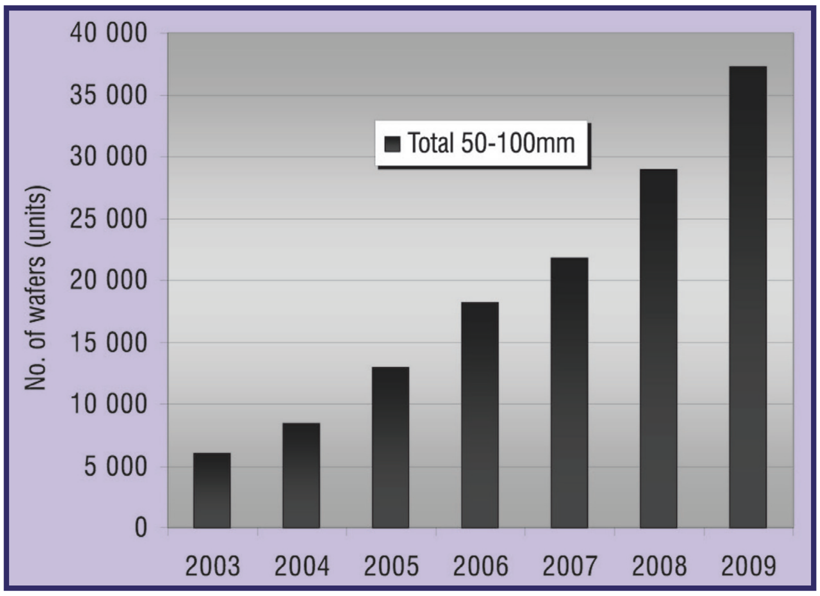

Figure 2. Wafer unit consumption and forecast for SiC Schottky diode production. (Graph courtesy of Yole Développement.)

Process nightmares

To realise SiC semiconductor devices, the hard work starts right from the crystal. The most successful technique so far has been a seeded sublimation – that is, the crystal is formed out of gas and not out of liquid, as for silicon. One reason that molten liquid is not used is that the material only becomes molten at 3200°C at pressures greater than 100,000 bar. Seeded sublimation is also called the modified Lely process.

Although much progress has been made in improving the quality of bulk SiC, it remains necessary to use epitaxial growth – the deposition of a highly uniform layer on top of a lesser-quality substrate – to produce effective electronic devices. Some epitaxial techniques used a liquid silicon solution (liquid phase epitaxy), but even here gas phase epitaxy or chemical vapour deposition are more common.

The source material in the seeded crystal sublimation growth process is solid SiC that is heated to 1800-2400°C, evaporating into Si_2C and SiC_2 (Figure 4, left). These volatile molecules then condense on cooler surfaces such as the seed crystal. The relative proportion of Si_2C and SiC_2 depends on the process temperature. Si_2C dominates at cooler operating temperatures, with the situation reversing at higher temperatures.

SiC easily forms defects and inclusions of different, unwanted crystal structures (polytypes). Hollow core 'micropipe' defects are particularly easy to form. The inclusion of foreign polytypes is less of a problem in recent years due to improvements in growth techniques.

The most desirable polytypes are the hexagonal crystal structures labelled 4H (band gap 3.2 eV) and 6H (3.0 eV). The numbers 4 and 6 refer to the periods for stacking different layer types. Other polytypes that can frequently occur are the cubic structure 3C, another hexagonal arrangement 2H, and the rhombohedral 15R.

Until recently, commercial substrates were less than 75 mm in diameter. However, in September 2005, Cree announced the availability of 100 mm diameter wafers. The 100 mm SiC material contains n-type doping. The Cree development work was the result of 'significant support' from the US Army Research Laboratory and Defense Advanced Research Projects Agency (DARPA). The n-type material is used mainly for LED production and has applications in power electronics.

Cree also produces high-purity semi-insulating (HPSI) SiC wafer substrates aimed at SiC and GaN high-frequency MESFET production and other applications. Point defects are used to create these wafers. Cree's Palmour reports that his company could also be producing these wafers at 100 mm in one to two years, depending on demand. Palmour also sees no problem if the industry demands larger-diameter wafers in due course.

A number of approaches have been made to improving substrate quality, such as mathematical modelling to determine the key factors in process control. The seed crystal is also vitally important, since this is often the root of many defects.

In 2004, researchers from a collaborative effort between Toyota's central R&D facility and DENSO Corporation reported a technique for reducing the number of dislocations in SiC crystals by two to three orders of magnitude through careful control of the seed growth process [4]. The Japanese solution gradually improves the seed quality in what the scientists call 'repeated a-face' (RAF) growth.

In the SiC crystal structures there are two structurally equivalent 'a-faces'. Repeated growth on just one of these faces produces defects. However, if this is followed by growth on the other a-face, fewer defects result. Repeating the process produces seeds with fewer and fewer defects. In the final-stage seeded sublimation process, 'c-face' growth is used to produce a SiC ingot.

"These substrates will promote the development of high-power SiC devices and reduce energy losses of the resulting electrical systems", the Japanese team believes.

The most common doping in SiC is n-type since nitrogen acts as a donor and it is a relatively simple matter to feed the gas into the process through the walls of the graphite crucible by making them porous. This enables the doping to occur in a continuous manner. The ionisation energy for the lowest nitrogen donor level in 4H SiC is 50 meV, comparable with those of phosphorous (45 meV) and arsenic (54 meV) in silicon. Acceptors in SiC are not so obliging – aluminium's ionisation energy in 4H SiC is 200 meV. This compares very badly with boron's 45 meV ionisation in Si and the 26 meV (kT) energy equivalent of room temperature (300 K). Alternative acceptors (boron, gallium) have even higher ionisation energies.

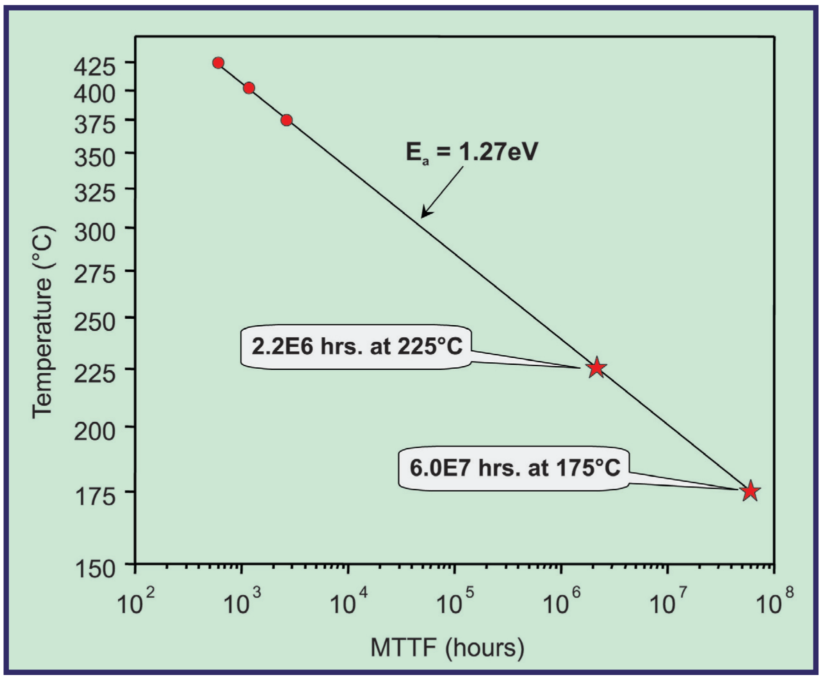

Figure 3. SiC MESFET mean time to failure (MTTF) reliability data. Failure is defined as a 20% change in any parameter. The data point at 225°C = 250 years; point at 175°C = 6850 years. Straight line = MTTF proportional to exp(-E_a/kT) with E_a=1.27eV; circles = measured devices; stars = projections for 225°C and 175°C. (Graph courtesy of Cree.)

If one wants to go ahead and dope with aluminium, then there are further difficulties. Researchers at the University of Erlangen in Germany have found a 50-fold variation in an Al-doped boule grown in a normal seeded sublimation process with Al added to the source SiC [5]. Accepting the challenge, the Erlangen group has therefore modified its growth chamber by adding a pipe to feed in dopant materials in a controlled manner (Figure 4, right), calling their new process modified physical vapour transport (MPVT). By using the technique, the 50-fold variation in Al concentrations has been reduced to two, and the Erlangen team expects to eliminate even this by varying the gas supply.

The MPVT technique has produced substrates with an aluminium concentration of 1.3x10^{20}cm^{-3}, a room-temperature hole concentration of 2x10^{19}cm^{-3}, and a specific resistivity of 0.1–0.2 Ωcm. Phosphorous doped SiC (n-type) has also been produced with the pipe bringing in the standard phosphine material used with other semiconductors, achieving phosphorous concentrations up to 1.3x10^{18}cm^{-3}. Another potential use of the MPVT process is to control the carbon:silicon ratio through gases such as silane and propane. This could control the stacking process and hence the SiC polytype. The Erlangen researchers believe that insulated gate bipolar transistor (IGBT) production is among the possible uses of its p-type SiC material.

When one proceeds to device processing, further problems emerge. Diffusion doping of

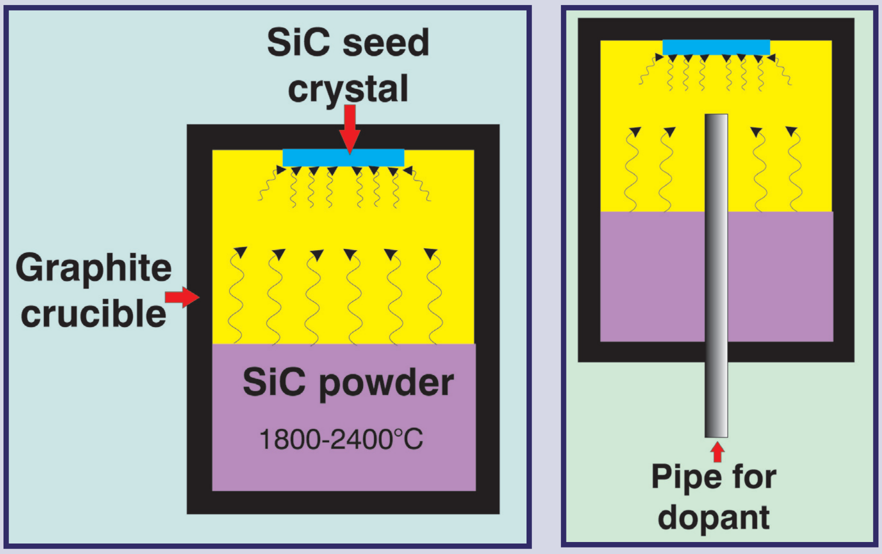

Figure 4. (Left) Schematic of seeded sublimation silicon carbide growth process. (Right) Researchers at the University of Erlangen in Germany have added a pipe to the seeded sublimation growth process for supplying a wider variety of dopant materials or other gases to control the growth process.

Diffusion doping of patterned SiC substrates suffers from very low diffusion coefficients... very high process temperatures are needed for any useful effect

patterned SiC substrates suffers from a very low diffusion coefficients, due to the hardness of the material. This makes diffusion doping particularly useless, because very high process temperatures are needed (2000°C) for any useful effect. Ion implantation, on the other hand, benefits from low diffusion levels in terms of maintaining dopant profiles. However, the thermal anneal processes often needs temperatures of 1700°C to repair crystal damage from the implant process.

Again SiC's hardness makes wet etch difficult. The previously mentioned molten salt flux would be difficult to implement successfully, since most masks would etch first. In addition to the beakers, one could use costly Pt for the mask. In reality, it is plasma processing that dominates etching of SiC. Fluorine-based plasmas have the most effective etch rate. Chlorine-based etches can be enhanced by ultraviolet illumination.

Most recently, UK etch specialist Surface Technology Systems (STS) has announced the capability to etch SiC at rates up to 2.7 µm/minute, which is almost a three-fold improvement on the 1µm/minute rates of just a few years ago [6]. STS has two inductively coupled plasma sources using SF_6 as the etch gas. One source has better selectivity (100:1) to SiC over patterned nickel as the mask, but a lower etch rate (up to 1.6 µm/minute) on n-type 6H SiC. The selectivity for the faster source is 45:1, but this can be almost doubled by introducing up to 5% oxygen without reducing the etch rate, STS reports.

One reason that MESFETs are the most common form of SiC transistor is that dielectrics also present a problem for the material. SiC MOSFETs suffer from anomalously low electron channel mobility. This has been traced to channel electrons in n-channel devices being trapped in interface states close to the SiC conduction band. This means that, rather than being free to move in the conduction band, the electrons are fixed. These states appear in thermally grown as well as deposited oxide dielectrics. Annealing the oxide in nitrous oxide (NO) lowers the density of these states, but not enough for practical use. Replacing silicon dioxide has also not been successful, although ONO dielectric stacks have improved reliability characteristics.

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