

Advances in Silicon Carbide Electronics

J.C. Zolper and M. Skowronski, Guest Editors

Abstract

After substantial investment in research and development over the last decade, silicon carbide materials and devices are coming of age. The concerted efforts that made this possible have resulted in breakthroughs in our understanding of materials issues such as compensation mechanisms in high-purity crystals, dislocation properties, and the formation of SiC/SiO₂ interfaces, as well as device design and processing. The progress accomplished over the last eight years in SiC-based electronic materials is summarized in this issue of *MRS Bulletin*.

Keywords: silicon carbide, electronic materials, high-frequency power electronics, reliability.

Since the 1950s, we have been living in the “silicon world,” with silicon as the foundation of the electronics era. At the beginning of the 21st century, the electronics industry is still dominated by silicon and is likely to remain so for at least another decade. No other semiconducting material can compete with silicon in terms of low defect densities, long minority carrier lifetimes, perfection of the semiconductor/dielectric interface, or doping control. Other materials—for example, GaAs and its alloys—only fill niche applications such as light-emission, where silicon is at a disadvantage due to its indirect bandgap. An indirect bandgap allows for the recombination of electrons and holes only with the participation of a phonon, a four-particle process that is inherently less likely than the three-particle process possible in a direct-bandgap semiconductor.

This situation could soon change in high-voltage switching and high-frequency power devices. The new material that can replace well-established silicon is hexagonal silicon carbide, a related semiconductor, which is the focus of this issue of *MRS Bulletin*. SiC technology is clearly not nearly as mature as that of silicon, and it is still more expensive than silicon, but its inherently superior properties, such as high breakdown field and thermal conductivity, provide a strong driving force for its development and implementation. Materials advances have reduced defect densities and improved the interface properties of SiC, and improvements in design and processing

are bringing it to the fore as a serious competitor in electronics applications. For more background on SiC technology, see the article by Dhar in this issue.

Silicon carbide was also the theme of the March 1997 issue of *MRS Bulletin*, eight years ago. At that time, the only commercially available SiC products were conducting wafers (with diameters of up to 1 3/8 in.) and blue light-emitting diodes (LEDs). These were, however, the last days of SiC-based LEDs. They were replaced by more efficient devices based on direct-bandgap GaN and other Group III nitrides. Surprisingly, however, the explosive growth of the nitride LED market and full-color displays had a positive impact on the development of silicon carbide technology. Single-crystal SiC wafers formed an ideal template for nitride epitaxy due to good lattice match and higher thermal conductivity than any other available wafer material, and a stable, sizeable market for silicon carbide wafers was created. This provided support and incentive for the continued development of silicon carbide growth technology. Today, there are six companies—Cree Inc., II-VI Inc., Intrinsic Semiconductor, Dow Corning Compound Semiconductor Solutions, SiCrystal AG, Sixon, and Norstel AB—based in the United States, Europe, and Japan that offer single-crystal SiC substrates. The recent production standard—namely, 2-in.-diameter wafers—is being replaced by 3-in.-diameter wafers, with 100-mm-diameter wafers (4-in.-diameter) in development. Volume production has lowered

the cost of a wafer unit area by a factor of 3, compared with 1997 (\$1,400 for a 1 3/8 in. wafer in 1997 versus \$2,400 for a 3-in.-diameter wafer today).

Although much improved, the quality of silicon carbide materials remains an active area of research and development. In 1997, the predominant material concern was the so-called micropipe defect (Figure 1), which seemed unique to silicon carbide grown by physical vapor transport. Micropipes are tubular voids with diameters between 0.1 μm and 1.0 μm that can extend through the entire SiC crystal. Since then, several different nucleation mechanisms for micropipes have been identified, such as nucleation on second-phase inclusions in SiC crystals¹ and coalescence of elementary screw dislocations.² As the result, the micropipe densities have been reduced significantly. They still represent a yield issue for large-area devices, but do not constitute a fundamental, insurmountable problem.

Besides micropipes, considerable effort has been focused in the last three years on basal-plane dislocations. These defects are responsible for the degradation of SiC bipolar devices, most notably high-voltage pin diodes³ (see the articles by Chow and by Ha and Bergman in this issue). A typical dislocation density in commercial crystals is in the 10³–10⁴ cm⁻² range, but an exciting breakthrough in material quality was announced just several months ago. A research group at Toyota Central R&D Laboratories and DENSO Corp. reported the growth of SiC boules (2-in.-diameter by 1-in.-thick

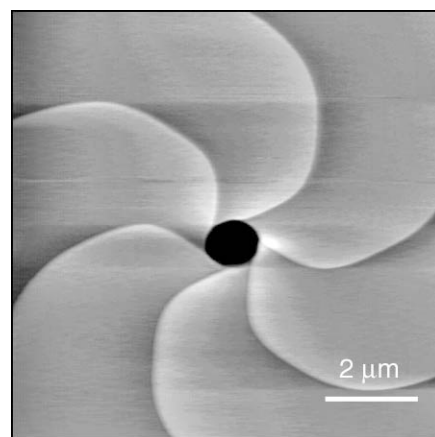


Figure 1. Atomic force microscopy image of a micropipe defect intersecting the SiC growth surface. The step height in this image is 1.5 nm and corresponds to one unit cell of 6H-SiC. The black area in the middle of the image is an open core of a superscrew dislocation with a Burgers vector of $7c$ (where c is the lattice constant along the $[0001]$ axis). Courtesy of G.S. Rohrer.

bulk crystal) with exceptionally low defect densities using a novel "repeated *a*-face" approach.⁴ This method takes advantage of the tendency of extended defects in hexagonal silicon carbide to propagate only along specific crystallographic directions. A sequence of growth experiments using seeds cut along the [1120] direction, followed by growth along the perpendicular [0001] axis, tends to lower defect densities. Two-inch-diameter wafers had total defect densities in the low hundreds per square centimeter, 1–2 orders of magnitude lower than previously reported. This development could lead to the growth of dislocation-free SiC crystals and epilayers, a distinction reserved only to silicon so far. "Dislocation-free" has been used to refer to crystals with dislocation densities below 1/cm²; the lowest dislocation density reported for SiC is 75/cm².

Another important accomplishment in bulk growth is the availability of high-resistivity substrates for low-loss, high-frequency devices (see the article by Sumakeris et al. in this issue). The original approach to fabricating such material was intentional compensation of shallow residual impurities (with electron binding energies on the order of *kT* at room temperature) by deep electron levels induced by vanadium doping.⁵ This approach reliably produced crystals with the Fermi level pinned by deep vanadium levels far from the conduction- and valence-band edges. However, a high density of vanadium centers resulted in the trapping of electrons in the substrate and a gradual reduction of the transconductance during operation of SiC metal semiconductor field-effect transistors (MESFETs). Such drift of the rf performance is known as current collapse.⁶

An alternative approach was the development of high-purity material, which relies on compensation due to deep levels associated with native point defects.⁷ One of the most attractive characteristics of silicon carbide is the high breakdown field (3.5 MV/cm, six times higher than that of silicon; see Table I) due to its strong bonds and large bandgap. This, together with the availability of low-defect-density material,

makes silicon carbide ideally suited for next-generation high-voltage switching devices (discussed by Zhao and by Chow in this issue). The first such device, namely, the Schottky diode, became commercially available in 2001. These devices, rated for 300–1200 V, are competing with silicon pin diodes for applications in power supplies of such ubiquitous products as personal computers and industrial electric motor controls.

SiC-based diodes are still significantly more expensive than their silicon counterparts, but they offer one considerable advantage: better energy efficiency. Every time the voltage reverses sign, the injected minority carriers in a silicon bipolar diode cause the current to flow until they are eliminated by recombination. This "current overshoot" is a major part of efficiency loss. Enter silicon carbide: the much higher energy barrier in SiC Schottky structures makes it possible to replace the Si bipolar device with a SiC unipolar metal–semiconductor junction. Since there is no minority carrier injection, the current overshoot is eliminated, and the switching losses are reduced by about an order of magnitude. At times of abundant cheap energy, this would not be a major consideration, but in the era of the Kyoto Protocol and the impact of greenhouse gas on the planet's climate, it represents a definite advantage.

For blocking voltages in excess of about 3 kV, the Schottky diode ON-state resistance becomes prohibitively high, and for such applications, the SiC pin diode appears to be the rectifier of choice. The already mentioned high breakdown field of SiC allows one to make these devices with blocking layers having one-sixth of the thickness of their silicon counterpart with the same nominal blocking voltage. This results in much lower ON-state losses and increased energy efficiency. The more advanced high-voltage switching devices currently under development include metal oxide semiconductor field-effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs).

MOSFET structures could enter the commercial market as soon as 2006. They em-

ploy a native thermally grown oxide layer as the gate insulator, using the same approach that has been successfully used in silicon technology. In the SiC case, however, the making of a perfect SiO₂/semiconductor interface is more difficult than in the case of SiO₂/Si. For one, silicon carbide has two types of atoms and, therefore, two types of potential dangling bonds: carbon and silicon. Second, since the bandgap in the 4H polytype* of SiC is 3.2 eV and about three times that of silicon, the states associated with dangling bonds are more likely to induce levels located within the bandgap. The interface charge associated with dangling bonds contributes to the scattering of electrons and low electron mobilities in MOSFETs. A recent breakthrough in post-oxidation nitrous oxide annealing reduced the interface charge density to an acceptable level.⁸ A detailed discussion of SiC/SiO₂ interfaces is presented in the article by Dhar et al. in this issue.

Another intriguing intrinsic property of silicon carbide is its high saturated electron velocity (*v*_{sat}). This parameter corresponds to the velocity of electrons traveling through the material in the high electric fields that are encountered in field-effect transistors. It is used to determine the material figure of merit for high-frequency power devices (Table I), as it controls the gain in FETs. It is quite apparent that silicon carbide has significant potential in this field as well. The possible applications range from commercial base stations for cell phones to military S-band radar. It is worth noting that as early as 1996, Westinghouse Electric/CBS demonstrated high-definition TV broadcasting using a solid-state SiC-based transmitter. Cree Inc. has developed and is marketing a range of MESFETs. These devices offer lower loss, higher input and output impedances that are easier to match to antenna impedances, and higher power densities than standard Si- or GaAs-based components. In terms of frequencies, SiC will likely be used for intermediate-frequency applications, while GaN will work better in high-frequency situations.

In summary, silicon carbide electronics appears to be on the verge of wide commercial production. The material issues are being resolved, multiple device structures

Table I: Comparison of Material Properties and Figures of Merit for High-Voltage Switching and High-Frequency Devices.

Property	Silicon	GaAs	4H-SiC	GaN
Bandgap (eV)	1.1	1.43	3.2	3.4
Breakdown field (MV/cm)	0.6	0.65	3.5	3.5
Saturated electron velocity ($\times 10^7$ cm/s)	1	1	2	1.5
Bulk electron mobility (cm ² /V s)	1400	8000	800	900
Combined figure of merit (normalized to Si)	1	10	136	153

* Silicon carbide can crystallize in many different forms, called polytypes, corresponding to different stacking sequences of closely packed planes of atoms. The most commonly used forms of SiC are 4H-SiC and 6H-SiC, having four or six Si-C bilayers in the unit cell, respectively. These are intermediate structures between purely a hexagonal form called 2H and a cubic form called 3C. The 4H polytype of SiC is strongly preferred for silicon carbide electronic devices due to its higher electron mobility compared with 6H-SiC.

are gaining increasing acceptance in the marketplace, and additional new applications such as high-temperature electronics are waiting to be developed.

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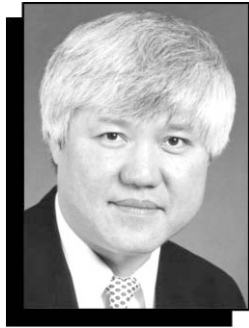
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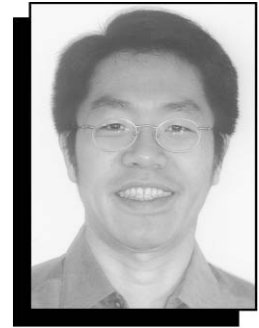
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