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Silicon Carbide, a Semiconductor for Space Power Electronics

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SILICON CARBIDE, A SEMICONDUCTOR FOR SPACE POWER ELECTRONICS

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Abstract

After many years of promise as a high temperature semiconductor, silicon carbide (SiC) is finally emerging as a useful electronic material. Recent significant progress that has led to this emergence has been in the areas of crystal growth and device fabrication technology. High quality single-crystal SiC wafers, up to 25 mm in diameter, can now be produced routinely from boules grown by a high temperature (2700 K) sublimation process. Device fabrication processes, including chemical vapor deposition (CVD), in situ doping during CVD, reactive ion etching, oxidation, metallization, etc. have been used to fabricate p-n junction diodes and MOSFETs. The diode was operated to 870 K and the MOSFET to 770 K.

INTRODUCTION

In recent years, there has been a growing need for electronic components capable of operating at high temperatures for extended periods of time. The desired operating temperature in some applications approaches 900 K, which is well beyond the capability of currently available semiconductor devices. Silicon carbide possesses unique properties which make it suitable for such applications (Harris and Yang 1989). Because of these properties, NASA Lewis is developing a new family of semiconductor devices based on SiC for aerospace propulsion and power applications. This paper reviews pertinent SiC properties and describes recent advances in SiC semiconductor technology at NASA Lewis and elsewhere.

PROPERTIES

An unusual aspect of SiC is that its crystal structure exhibits a form of one-dimensional polymorphism called polytypism. The many polytypes of SiC differ from one another only in the stacking sequence of double layers of Si and C atoms. This paper considers only the two most common polytypes, a cubic structure known as 3C-SiC or ß-SiC, and a hexagonal structure known as 6H-SiC.

An appreciation of the potential of SiC can be gained by examining Table 1, which is a comparison of its properties with diamond and GaP (two other contenders for high temperature semiconductor applications) and the two most common commercially available semiconductors, Si and GaAs. In the SiC column of the table, the quantities in parenthesis pertain to 6H SiC. The maximum operating temperature was calculated relative to that of Si by assuming a maximum for Si of 600 K and multiplying this temperature by the ratio of bandgaps. The maximum for diamond is imposed by a phase change.

Silicon carbide does not melt at any reasonable pressure, but does sublime at temperatures greater than 2100 K. Below 1800 K, its physical stability is

TABLE 1. Comparison of Semiconductors

Property	Si	GaAs	GaP	β-SiC (6H SiC)	Diamond
Bandgap (eV) at 300 K	1.1	1.4	2.3	2.2 (2.9)	5.5
Maximum operating temperature (K)	600	760	1250	1200 (1580)	1400(?)
Melting point (K)	1690	1510	1740	Sublimes > 2100	Phase change
Physical stability	Good	Fair	Fair	Excellent	Very good
Electron mobility R.T., $cm^2/V\text{-}s$	1400	8500	350	1000 (600)	2200
Hole mobility R.T., $cm^2/V\text{-}s$	600	400	100	40	1600
Breakdown voltage E_b, 10^6 V/cm	.3	.4	—	4	10
Thermal conductivity σ_T, W/cm-°C	1.5	.5	.8	5	20
Sat. elec. drift vel. v(sat), 10^7 cm/s	1	2	—	2.5	2.7
Dielectric const., K	11.8	12.8	11.1	9.7	5.5
Relative Z_J	1	7	—	1100	8100
Relative Z_K	1	.5	—	6	32

$Z_J \propto E_b^2 v^2(sat)$ $\qquad$ $Z_K \propto \sigma_T [v(sat)/K]^{1/2}$

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excellent and its stability in an oxidizing atmosphere gives it an edge over diamond. We believe that long term stability at high temperatures will be a problem with the more common III-V compounds, such as GaAs and GaP. Thus, SiC has a significant advantage where long-term reliable operation is a requirement. For high temperature power applications, the advantages of SiC and diamond are illustrated by their much higher values of breakdown electric field and thermal conductivity. Another potential area of application for SiC (and diamond) is high frequency. Two Figures of Merit of semiconductors for high frequency applications are the Johnson (Z_J) and Keyes (Z_K). Relative values (to that of Si) for these quantities illustrate the high potential of SiC and diamond. While SiC is advancing rapidly, the difficulty of diamond crystal growth casts doubt over its near-term commercial semiconductor development.

CRYSTAL GROWTH

An essential element of a viable SiC semiconductor device technology is the availability of large-area substrates on which to grow single-crystal SiC films for device fabrication. For many years, the only substrates available were small irregular-shaped SiC crystals that were grown by a sublimation process, known as the Lely process. During the 1980s, much progress was made in growing single-crystal 3C-SiC films on single-crystal Si substrates (Nishino et al. 1983). But the 20% lattice mismatch between SiC and Si resulted in a large defect density in the SiC films, making the films unsuitable for device fabrication. A process, known as the modified sublimation process, has been developed to grow large single-crystal SiC boules from which wafers can be sliced. In Fig. 1, a 6H-SiC wafer (grown by Cree Research, Inc.) illustrates the extent of improvement over the small Lely-grown crystals. The following sections describe SiC boule and epitaxial film growth processes.

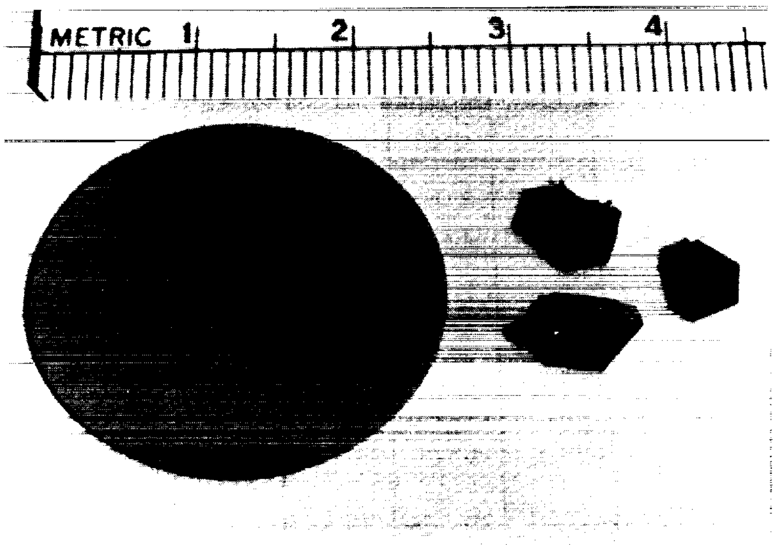

FIGURE 1.

Left: 6H-SiC Wafer Obtained from Cree Research, Inc.

Right: Typical Lely-Grown 6H-SiC Crystals

Boule Growth

The modified sublimation process for growing SiC boules was pioneered by Tairov and Tsvetkov (1978) in Russia. In this process, nucleation takes place on a SiC seed crystal located at one end of a cylindrical growth cavity. A temperature gradient is established within the cavity such that the polycrystalline SiC is at 2700 K and the seed crystal is at 2500 K. At these temperatures SiC sublimes from the polycrystalline material and condenses on the cooler seed crystal. Growth takes place on the seed crystal in an atmosphere of argon at 200 Pa. Boules of single polytype 6H-SiC can be grown with growth rates up to 4 mm/h and sizes greater than 25 mm in diameter and 20 mm long. This process is now also being used by groups in the U. S., Germany, and Japan.

Epitaxial Film Growth

Although a variety of epitaxial growth processes has been used to produce SiC films on SiC substrates, we believe that the most promising is the CVD process; hence, we discuss only this process in this paper.

At a CVD growth temperature of 1750 K, the orientation of the 6H-SiC substrate determines the polytype of the grown film. If the growth surface is within about 1° of the (0001) plane, then a 3C-SiC film will form, if the angle is greater than 1.5°, then 6H-SiC will form (Matsunami 1989). Generally, 6H-SiC substrates with tilt angles of 3° to 4° are used to grow 6H-SiC films.

In the NASA CVD growth (Powell 1990), substrates were cut from 3.5° 6H-SiC wafers obtained from Cree Research, Inc. The CVD system utilized a water-cooled horizontal growth chamber operating at atmospheric pressure. The carrier gas was hydrogen, and the sources of Si and C were silane and propane, respectively. After an initial etch of the SiC substrate with hydrogen chloride at 1450 K, the substrate temperature was increased to 1730 K for film growth. Typically, a 4-μm/hr growth rate was achieved for the 6H-SiC films.

DEVICE TECHNOLOGY

Much SiC device technology has been developed over the last several decades and much can be borrowed from Si technology. To fabricate devices, a variety of processes are used to introduce controlled amounts of dopants (i.e. donors and acceptors), and to oxidize, etch, and metallize the material. This section reviews some of these processes and describes two SiC devices, a p-n junction diode and a MOSFET, that were fabricated at NASA Lewis.

Controlled Doping

Either Al or B can be used as p-type dopants in SiC, but Al is preferred because its ionization energy is less (257 meV vs 735 meV in 3C-SiC). Nitrogen is electrically active in SiC and is preferred as the n-type dopant because of its high solubility and relatively low ionization energy (54 meV in 3C-SiC). These dopants can be introduced during CVD growth.

In commercial Si technology, diffusion and ion implantation are the key processes used to introduce dopants during device fabrication. Diffusion is not practical with SiC because diffusion coefficients are negligible below 2100 K. In fact this is one of the strengths of SiC; dopants don't move at elevated temperatures. Ion implantation has been successfully applied to SiC. Recent work by Edmond et al. (1987) demonstrated that implanting at high temperatures (approx. 800 K), followed by annealing at 1500 K, resulted in improved structural and electrical properties.

Oxidation, Etching, and Metallization

Silicon carbide can be oxidized similar to Si. The oxide can be used for insulation, passivation, and as masks for ion implantation. Also, thermal oxidation has been used successfully to produce the gate dielectric in the fabrication of SiC field-effect transistors (FETs).

During device fabrication, etching processes for removing portions of the semiconductor are required. In the past, molten salts and gases (e.g. Cl_2/O_2 mixture) at high temperatures served as etchants for SiC. Recently reactive ion etching (RIE) has been used very successfully for SiC. Clean RIE-etched SiC surfaces with a high degree of anisotropic etching can be achieved.

Since a major use of SiC devices will probably be in high temperature environments, the development of suitable metallization for electrical contacts is crucial. Below 700 K, the problem may not be very difficult. An alloy of Au with a few percent of Ta has been used for n-type, and Al has been used for p-type at these temperatures. At higher temperatures, a multi-layer structure will probably be required. The goal of the various layers will be to provide an ohmic contact, while also providing a diffusion barrier to prevent intermixing of materials. Various metal carbides and silicides are being investigated.

P-N Junction Diode

The first high-temperature prototype SiC device fabricated at NASA Lewis was a p-n junction diode. The junction structure was produced by first growing a nitrogen-doped n-type 6H-SiC film followed by an aluminum-doped p-type film. Photolithography and RIE were used to fabricate an array of mesa diodes. After passivating the junction boundary with SiO_2, metal contacts were then applied to the p and n regions. Excellent diode characteristics were observed up to 870 K, the highest temperature measured, as shown in Fig 2. The forward voltage drop at room temperature for 20 ma was 12 volts, but decreased to 3.4 volts at 870 K. The leakage current at -300 volts was 48 μa at 870 K.

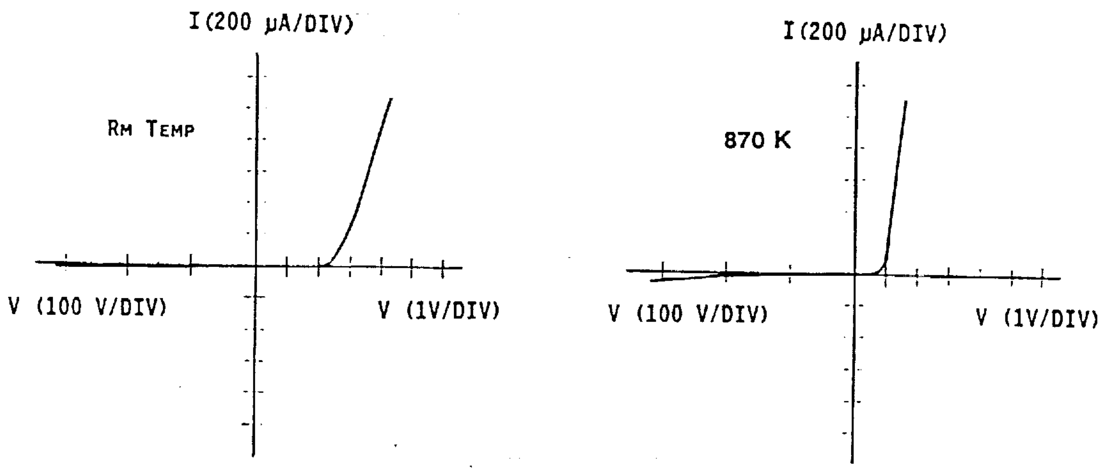

FIGURE 2. Current-Voltage (I-V) Curves for a 6H-SiC Junction Diode.

MOSFET

Another prototype SiC device fabricated at NASA Lewis was a MOSFET. For this device, the sequence of 6H-SiC films grown on the 6H-SiC substrate consisted of (1) an n-type buffer layer, (2) a p-type isolation layer, and (3) a 0.7-μm-thick n-type channel layer. An array of MOSFETs were then fabricated from this structure using many additional steps that included photolithography, oxidation, and metallization. The source-drain I-V curves of one of the MOSFETs are given in Fig. 3. An excellent characteristic of the curves is that the saturated room-temperature drain currents are horizontal out to 100 volts. The early stage of development of this device is illustrated by some characteristics of the curves. For example, the non-linear I-V behavior near the origin is most likely due to non-ohmic contacts. Also, the MOSFET does not shut off with 20 volts applied to the gate. The effect is greater at 770 K as expected. This is probably due to non-optimized oxide and channel thicknesses.

CONCLUSIONS

Silicon carbide semiconductor technology was just a promise for many years, but has accelerated rapidly over the last several years. The devices fabricated at NASA Lewis and elsewhere demonstrate that excellent performance can be achieved. We want to emphasize that much development and optimization remain. However, we believe that SiC can be an enabling electronic technology for many of the ambitious plans that man has for both earth and space.

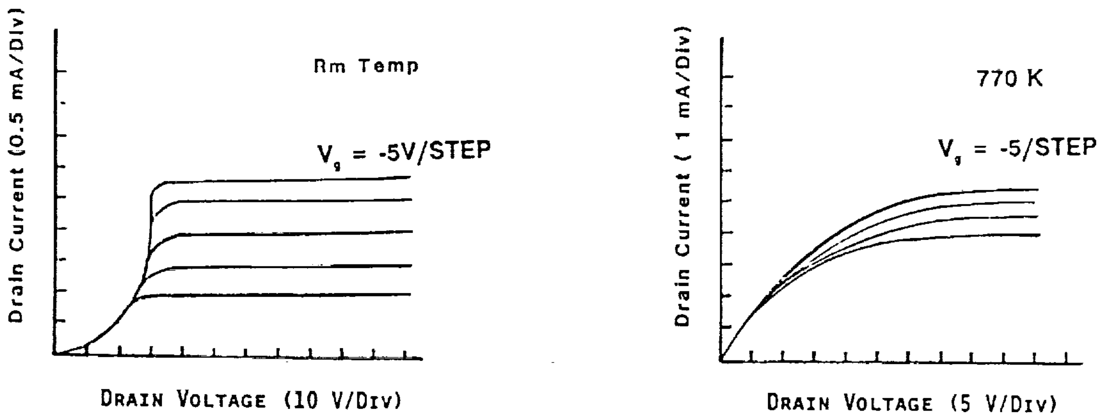

FIGURE 3. Source-Drain Current Voltage (I-V) Curves for a 6H-SiC Depletion-Mode MOSFET. Note Change in Horizontal Scale.

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