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Lawrence G. Matus and J. Anthony Powell
Lewis Research Center
Cleveland, Ohio

and

Jeremy B. Petit
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

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DEVELOPMENT OF SILICON CARBIDE SEMICONDUCTOR DEVICES FOR HIGH TEMPERATURE APPLICATIONS

Lawrence G. Matus and J. Anthony Powell
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Jeremy B. Petit
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Abstract

The semiconducting properties of electronic grade silicon carbide (SiC) crystals, such as its wide energy bandgap, make it particularly attractive for high temperature applications. Applications for high temperature electronic devices include instrumentation for engines under development, engine control and condition monitoring systems, and power conditioning and control systems for space platforms and satellites. Discrete prototype SiC devices have been fabricated and tested at elevated temperatures. Grown p-n junction diodes have demonstrated very good rectification characteristics at 870 K. A depletion-mode metal-oxide-semiconductor field-effect transistor was also successfully fabricated and tested at 770 K. While optimization of SiC fabrication processes remain, we believe that SiC is an enabling high temperature electronic technology.

INTRODUCTION

In recent years, the aerospace propulsion and space power communities have expressed a growing need for electronic devices that are capable of sustained high temperature operation. Applications for high temperature electronic devices include development instrumentation within engines such as multiplexers, analog-to-digital converters, and telemetry systems capable of withstanding hot section engine temperatures in excess of 850 K. Similarly, engine mounted integrated sensors and electronics could reach temperatures which exceed 750 K while uncooled operation of control and condition monitoring equipment in advanced sustained supersonic aircraft is expected to subject electronic devices to temperatures in excess of 573 K (Nieberding and Powell 1982). Hypersonic vehicles will ultimately pose even more severe temperature demands on electronic devices and integrated sensors.

In addition to aeronautics, there are many other areas that would benefit from the existence of high temperature electronic devices. Space applications include power electronic devices for Space Station Freedom, space platforms, and satellites. Since power electronics require radiators to dissipate waste energy (heat), electronic devices that are capable of operating at higher temperatures would allow a reduction in radiator size. This results in a weight savings and thereby reduces the cost of placing the hardware into orbit.

The need for electronic devices capable of sustained operation at high temperature is not restricted to the aerospace community. Earth-based applications include deep-well drilling instrumentation, power electronics for motor control, nuclear reactor instrumentation and control, and automotive electronics and integrated sensors.

To meet the needs of the applications mentioned above, the High Temperature Electronics Program at the Lewis Research Center is developing silicon carbide (SiC) as a high temperature semiconductor material. Research is focused on developing the crystal growth, crystal characterization, and device fabrication technologies necessary to produce a family of SiC devices. This paper will first present an overview of the properties of SiC and then present our current progress in fabricating and characterizing discrete prototype SiC devices.

SILICON CARBIDE: THE SEMICONDUCTOR

Silicon carbide (SiC) is familiar to most as the abrasive grit material on sandpaper. It is however, a material that possesses many other unique and useful properties. SiC can also be found in refractory, structural, and electrical applications. An unusual aspect of SiC is that its crystal structure exhibits a form of one-dimensional polytypism. That is, the crystal structures of the many possible polytypes of SiC differ from one another only in the stacking sequence of double layers of silicon and carbon atoms. The SiC polytypes do, however, display differences in electronic and optical properties.

The electronic properties of single-crystal SiC, such as its wide energy bandgap, make it particularly attractive for high temperature applications. Depending on the particular polytype of SiC, the bandgap energy varies from 2.2 eV to 3.3 eV. Presently, the two most commonly studied polytypes of SiC are 3C-SiC, a cubic structure with a 2.2 eV bandgap energy, and 6H-SiC, one of the many possible hexagonal structures. The bandgap energy of 6H-SiC is 2.9 eV. The maximum operating temperature for a semiconductor material is determined by the bandgap energy, provided of course, that the semiconductor material does not become chemically unstable at lower temperatures. The useful operating temperature limit is reached when the number of intrinsic carriers, thermally excited across the energy bandgap, approaches the number of purposely added (extrinsic) carriers. For SiC with impurity doping levels typical of semiconducting devices, this temperature is well above 1000 K.

A more complete appreciation of the potential of SiC for electronic applications can be gained by examining Table 1, which is a comparison of its properties with the two most common commercially available semiconductors, silicon (Si) and gallium arsenide (GaAs) and two other contenders for high temperature applications, gallium phosphide (GaP) and diamond. In the SiC column of the table, the quantities in parenthesises pertain to 6H-SiC. The maximum operating temperature for the semiconductors was calculated relative to that of Si by assuming a maximum for Si of 600 K and multiplying this temperature by the ratio of the bandgap energies. In comparing the potential candidate materials for high temperature semiconductor devices, SiC also stands out because it is a very stable ceramic material up to temperatures of 2050 K. The combination of the material's high breakdown field (tolerant of high electric fields) and high thermal conductivity (heat transfer) provides the potential for improved power electronic systems and for increasing the number of devices per unit die area. Those properties which determine the high frequency characteristics of semiconductor devices also appear to be excellent for SiC. From a theoretical point of view, the characteristics of SiC result in a higher figure-of-merit for SiC when ranked against other available semiconductor materials for possible high-power or high-frequency electronic devices that are capable of high temperature operation (Shenai et al. 1989 and Baliga 1989).

Component reliability is a key issue in all aerospace applications because failure can lead to expensive or tragic consequences. Electronic devices or sensors that are capable of operating at high temperatures have the immediate payoff of improved reliability when operated at lower temperatures. For example, if electronic devices capable of 573 K operation possess the same failure rate at 573 K as devices specified for 400 K operation, the failure rate will be reduced by 1000 when the "573 K" electronic devices are operated in a 400 K environment. This three orders of magnitude improvement in reliability is due to the exponential dependence of failure rates on temperature. Based on its properties, the reliability of electronic devices and sensors fabricated from SiC should be much higher than that obtained from any current semiconductor material.

SiC DEVICE TECHNOLOGY

SiC device technology has been developing for more than thirty years. The major impediment to this development had been the lack of single-polytype SiC substrates of sufficient quality and size. A significant breakthrough in SiC growth was made by Tairov and Tsvetkov (1978), who pioneered the modified sublimation process for growing SiC boules. More recently, a SiC research team (Carter et al. 1987) at North Carolina State University announced the successful implementation of a seeded-growth sublimation method to produce the 6H-SiC polytype in boule form. A private company, Cree Research Inc., has developed this process to the point where one inch diameter wafers of 6H-SiC are now being produced. The significance of this accomplishment is that these 6H-SiC crystals can now be used as substrates for SiC epitaxial growth via the chemical vapor deposition (CVD) processes already developed at the Lewis Research Center (Powell et al. 1990).

The availability of SiC substrates makes it possible to accelerate SiC device fabrication studies. At the Lewis Research Center, we are developing processes to grow SiC epitaxial films, introduce controlled amounts of dopants (both donors and acceptors) into the SiC epitaxial films, and are developing processes to oxidize, etch, and metallize SiC device structures. The remaining portion of this section briefly summarizes our work in these areas.

Controlled Doping

Either aluminum (Al) or boron (B) can be used as p-type dopants in SiC. Al is preferred because its ionization energy is less (257 meV compared to 735 meV in 3C-SiC). Nitrogen (N) is electrically active in SiC and is the preferred n-type dopant because of its high solubility in SiC and its low ionization energy (54 meV in 3C-SiC). These dopants can be introduced in-situ during the CVD growth process. Al is introduced via the bubbler method using trimethylaluminum (TMA) while diborane and nitrogen gases are used for introducing B and N, respectively.

In commercial silicon (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 advantages of SiC; dopants do not move at elevated temperatures. Ion implantation has been successfully applied to SiC by Edmond et al. (1987). Implanting at high temperatures (approx. 825 K) instead of room temperature, followed by annealing at 1473 K, resulted in improved structural and electrical properties.

Electrical evaluation of the doped epitaxial SiC films has been accomplished by Hall measurements using the van der Pauw (1958) method. Segall et al. (1986) showed that 3C-SiC epitaxial films were highly compensated. Presently, Hall measurements are underway for the 6H-SiC films. It is expected that these films will be less compensated because the 6H-SiC films contain fewer structural defects than the 3C-SiC films grown on Si.

Oxidation

Silicon dioxide (SiO_2) is the native oxide for SiC. Therefore, the thermal oxidation of SiC can be achieved using the same methods as used for Si. Studies with metal-oxide-semiconductor (MOS) structures (Kopanski and Novotny 1989, and Tang et al. 1990) have shown that wet oxidation environments result in the best oxide for device purposes for 3C-SiC. The oxide can be used for insulation, passivation, masks for ion implantation, and as the gate dielectric in the fabrication of SiC field-effect transistors (FETs). Our typical oxidation conditions use a furnace temperature of 1425 K and oxygen gas saturated with water vapor by bubbling it through a water reservoir held at 368 K.

Etching

There is not any known wet chemical solution for etching SiC. In the past, molten salts (sodium peroxide) and gases (chlorine-oxygen) at high temperatures have served as etchants for SiC. Neither of these etching methods can be considered commercially-viable as device fabrication processes. Recently, reactive ion etching (RIE) of SiC has been successfully employed. Clean RIE-etched SiC surfaces with a high degree of anisotropic etching can be achieved. An etch rate of 0.11 micrometers per minute has been measured when etching SiC in a sulfur hexafluoride/oxygen (4:1) gas mixture. Sputter deposited Al has been used as a mask for the RIE process.

Metallization

The development of suitable metallization for electrical contacts to SiC is crucial, especially for high temperature applications. Below 700 K, the problem may not be very difficult. An alloy of gold (Au) with a few percent of tantalum (Ta) has been used for n-type SiC, while Al has been used for p-type SiC at these temperatures. At higher temperatures, a multi-layer metallization structure will probably be required. The various layers must provide an ohmic contact, while also creating a diffusion barrier to prevent intermixing of materials. Metal carbides and silicides are being investigated for this purpose.

SiC PROTOTYPE DEVICES

Our in-house research is currently pursuing the fabrication of in-situ grown junction diodes and metal-oxide-semiconductor field-effect transistors (MOSFETs) from SiC. These two discrete devices are described in this section.

P-N Junction Diode

Junction diodes were produced by first growing an 8-micrometer-thick n-type 6H-SiC epitaxial film onto a 6H-SiC substrate. This was followed by growing an Al-doped p-type 6H-SiC film. Photolithography and RIE were used to fabricate an array of mesa diodes. After passivating the junction boundary with SiO_2, metal contacts were applied to the p and n regions.

Excellent diode characteristics were observed up to 870 K, the highest temperature measured. Typical current-voltage (I-V) curves for one of the 6H-SiC grown-junction diodes at room temperature and at 870 K are shown in Fig. 1. Note the voltage and current scale changes in Fig. 1. The leakage current at -300 volts increased from its room temperature value of 0.4 microamperes to 5 microamperes at 870 K.

The fabrication of quality p-n junctions is a significant result because it is a basic building block for electronic devices. In addition to rectification, junctions are also used extensively as isolation layers. For example, an n-channel field-effect transistor (FET) can be fabricated by first growing a p-type layer followed by an n-type layer. Current flow will then be confined to the upper n-layer if the voltage polarities are chosen so as to reverse bias the junction.

MOSFET

The second prototype SiC device fabricated was a MOSFET. A depletion-mode MOSFET was fabricated using the principles of channel isolation as describe above. For this device, the sequence of 6H-SiC epitaxial 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-micrometer-thick n-type channel layer. An array of MOSFETs were then fabricated from this structure using the additional steps of photolithography, oxidation, and metallization.

In an FET structure, the current flow is controlled by applying a voltage to the gate electrode. For an n-channel FET, a negative voltage applied to the gate will deplete the channel of electrons and thus "pinch-off" the current flow. In this manner, an FET resembles a switch. The switch is turned on and off by the application of the gate voltage. The early stage of development of this device is illustrated by the characteristics of the source-drain I-V curves shown in Fig. 2 of a MOSFET tested at 770 K. This particular MOSFET can not be completely shut-off. It is believed that this is caused by a non-optimized oxide and n-channel thickness. Although the electrical characteristics of the FET are not yet ideal, the achievement of transistor I-V characteristics at 770 K is an extremely important starting point.

CONCLUSION

Ultimately, the goal of the Lewis High Temperature Electronics Program is to develop SiC integrated circuits and monolithic sensors with compensating and signal conditioning electronics integrated into the sensor structure. Electronic devices and sensors that are capable of operating at elevated temperatures eliminate or reduce the amount of cooling that is required. In many space applications, this can be a significant weight savings. Other payoffs of high temperature integrated sensors include reduced cabling and shielding requirements and development of distributed control architectures, for example, smart actuators.

SiC semiconductor technology was just a promise for many years but has accelerated rapidly over the last several years. Recent advances in the crystal growth of SiC and the increased knowledge of the bulk material properties of the grown SiC are cause for enthusiasm. The electronic devices fabricated at the Lewis Research Center and elsewhere demonstrate that excellent device performance can be achieved. While we want to emphasize that much development and optimization remain for SiC processes, we believe that SiC is an enabling high temperature electronic technology.

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References

Baliga, B.J. (1989) "Power Semiconductor Device Figure of Merit for High-Frequency Applications," IEEE Electron Device Lett., **EDL-10**(10): 455-457.

Carter, Jr., C.H., L. Tang, and R.F. Davis (1987) "Sublimation Growth of Large 6H-SiC Single Crystals," Presented at the Fourth National Review Meeting on the Growth and Characterization of SiC, Raleigh, NC.

Edmond, J.A., K. Das, and R.F. Davis (1988) "Electrical Properties of Ion-Implanted p-n Junction Diodes in Beta Silicon Carbide," J. Appl. Phys., **63**(3): 922-929.

Kopanski, J.J. and D.B. Novotny (1989) "Development and Characterization of Insulating Layers on Silicon Carbide," Contract Report, NISTIR 89-4157, National Institute of Standards and Technology, Gaithersburg, MD.

Nieberding, W.C. and J.A. Powell (1982) "High-Temperature Electronic Requirements in Aeropropulsion Systems," IEEE Trans. on Industrial Electronics, **IE-29**(2): 103-106.

Powell, J.A. et al. (1990) "Growth of High Quality 6H-SiC Epitaxial Films on Vicinal (0001) 6H-SiC Wafers," Appl. Phys. Lett., **56**(15): 1442-1444.

Segall, B., S.A. Alterovitz, E.J. Haugland, and L.G. Matus (1986) "Compensation in Epitaxial Cubic SiC Films," Appl. Phys. Lett., **49**(10): 584-586.

Shenai, K., R.S. Scott, and B.J. Baliga (1989) "Optimum Semiconductors for High-Power Electronics," IEEE Trans. Electron Devices, **ED-36**(9): 1811-1823.

Tairov, Y.M. and V.F. Tsvetkov (1978) "Investigation of Growth Processes of Ingots of Silicon Carbide Single Crystals," J. Cryst. Growth, **43**:209-212.

Tang, S.M., W.B. Berry, R. Kwor, M.V. Zeller, and L.G. Matus (1990) "High-Frequency Capacitance-Voltage Characteristics of Thermally Grown SiO_2 Films on Beta-SiC," J. Electrochem. Soc., **137**(1): 221-225.

van der Pauw, L.J. (1958) "A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape," Philips Res. Repts., **13**: 1-9.

TABLE 1. Comparison of Semiconductors.

Property	Si	GaAs	GaP	3C 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

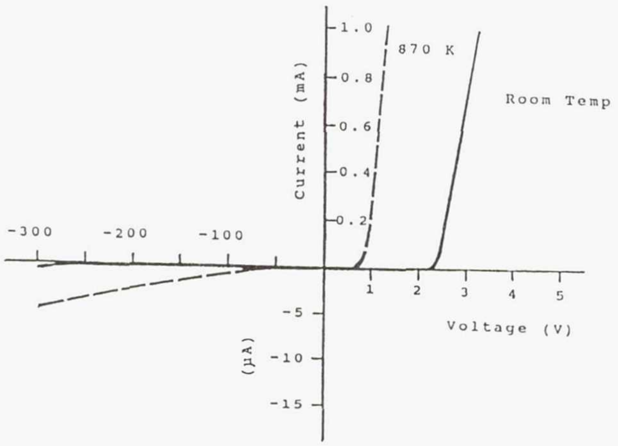

FIGURE 1. Comparison of 6H-SiC p-n Junction Diode Characteristics at Room Temperature and 870 K. Note Scale Changes.

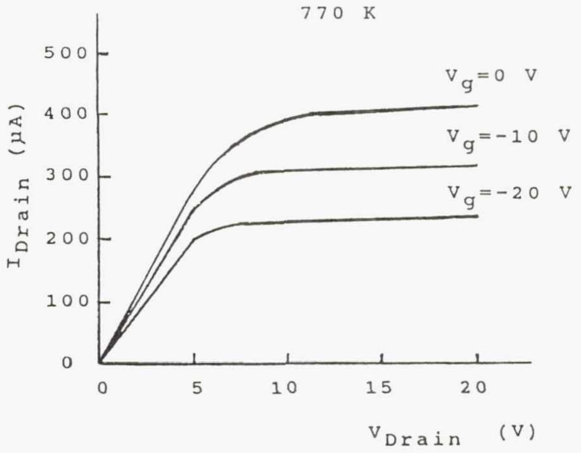

FIGURE 2. MOSFET I-V Characteristics at 770K.

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The semiconducting properties of electronic grade silicon carbide (SiC) crystals, such as wide energy bandgap, make it particularly attractive for high temperature applications. Applications for high temperature electronic devices include instrumentation for engines under development, engine control and condition monitoring systems, and power conditioning and control systems for space platforms and satellites. Discrete prototype SiC devices have been fabricated and tested at elevated temperatures. Grown p-n junction diodes have demonstrated very good rectification characteristics at 870 K. A depletion-mode metal-oxide-semiconductor field-effect transistor was also successfully fabricated and tested at 770 K. While optimization of SiC fabrication processes remain, we believe that SiC is an enabling high temperature electronic technology.

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