SiC Lecture Series

4. Physical properties of SiC

Physical properties of SiC

SiC possesses many excellent properties as a semiconductor material for power devices. Table 1 compares the physical properties of 4H-SiC related to power device characteristics with those of Si and GaN. Compared to Si, 4H-SiC has ten times the dielectric breakdown field strength, making it advantageous for high voltage applications. When compared to another wide bandgap semiconductor, GaN, although the physical property values are similar, there are significant differences in the control of p-type conductivity and the feasibility of forming gate oxide films through thermal oxidation processes. These differences make 4H-SiC advantageous in the fabrication of power MOSFETs used in many applications. Additionally, since GaN is a direct transition type semiconductor, it has a short minority carrier lifetime and insufficient device resistance reduction through conductivity modulation.

Table 1 Comparison of Physical Properties of SiC, Si, and GaN

	4H SiC	Si	GaN
Energy Bandgap	3.26 eV	1.12 eV	3.42 eV
Band Structure	Indirect bandgap	Indirect bandgap	Direct bandgap
Breakdown Electric Field	3 MV/cm (c-axis direction)	0.3 MV/cm	3 MV/cm
Electron Mobility	1200 cm2/Vs (c-axis direction)	1500 cm2/Vs	1500 cm2/Vs
Hole Mobility	120 cm2/Vs	450 cm2/Vs	20 cm2/Vs
Relative Permittivity	10	12	10
Control of p-n Conductivity	Possible	Possible	Difficult. p-Type
Thermal Conductivity	4.9 W/cmK	1.5 W/cmK	1.3 W/cmK
Thermal Oxide Gate Formation	Possible	Possible	Impossible
BFOM (Relative to Si)	667	1	833

When comparing the performance of power devices across different materials, the performance index known as BFOM (Baliga's Figure of Merit) is often used. BFOM is a value that is proportional to the inverse of the resistance of an ideal unipolar device, and it can be calculated using the following formula.

$$BFOM = \varepsilon \mu {E_{BD}}^3 \qquad (eq.1)$$

$$R \propto {V_{BD}}^2 / BFOM \qquad (eq.2)$$

where ε is the dielectric constant, μ is the mobility, E_{BD} is the breakdown electric field strength, R is the resistance of the device, and V_{BD} is the breakdown voltage of the device.

Since BFOM is proportional to the cube of the breakdown electric field strength, the fact that SiC has a value 10 times that of Si is decisively advantageous for reducing the resistance of unipolar devices. From the values listed in Table 1, the resistance of SiC unipolar devices can potentially be reduced to 1/667 compared to Si. Additionally, since resistance is proportional to the square of the device's breakdown voltage, increasing the breakdown voltage (rated voltage) rapidly increases the resistance of unipolar devices. When using Si, unipolar devices with kilovolt-class breakdown voltages become impractically high in resistance, but using SiC makes them feasible. The primary target for SiC devices lies in this breakdown voltage range, and Mitsubishi Electric has pioneered the realization of kilovolt-class unipolar devices using SiC, bringing innovation to many power electronics systems such as railway drive systems.

Regarding the anisotropy of SiC's physical properties, there are several considerations to be considered when fabricating devices. The breakdown electric field strength of 4H-SiC is greater in the <0001> direction (thickness direction of the substrate) compared to other directions. Similarly, the bulk electron mobility is also greater in the <0001> direction than in other directions. On the other hand, when comparing the channel mobility of MOSFET structures fabricated using various crystal planes of SiC, the value for the (0001) plane is smaller, while the value for planes perpendicular to the (0001) plane is larger. This is understood to be due to the higher density of electron trap states formed at the MOS interface on the (0001) plane, meaning that trench MOSFET has lower channel resistance compared to planar MOS fabricated on the (0001) plane.

The trap states at the SiC MOSFET interface are a cause of instability and long-term changes in the characteristics of SiC MOSFETs, and efforts to improve this are ongoing. Mitsubishi Electric has developed methods for forming MOS interfaces that enhance characteristic stability, achieving top-class stability in MOSFET characteristics.

The growth rate of thermal oxide films also varies significantly depending on the crystal plane; for example, the oxidation rate of the (000-1) plane is about 10 times greater than that of the (0001) plane. This anisotropy in oxidation rate needs to be considered in the device fabrication process, requiring process adjustments according to the structure.

Wide bandgap semiconductors generally have difficulty controlling p-type or n-type conductivity. Despite being a wide bandgap semiconductor, SiC is one of the few materials that can be fabricated with high carrier concentrations for both p-type and n-type conductivity. Typically, group V elements such as nitrogen or phosphorus are used as dopants for n-type conductivity control, while group III elements such as aluminum or boron are used for p-type conductivity control. Boron, due to its deep acceptor level, does not yield low-resistance p-type conductivity and is used for forming device termination regions for voltage retention. Compared to Si, SiC has a more complex crystal structure, causing differences in the energy levels formed depending on the substitution site of the dopant atoms. While this needs to be strictly considered when deriving carrier mobility or estimating the temperature dependence of resistance, using averaged values for device characteristic estimation poses no significant issues.

Another advantage of SiC as a material for power devices is its high thermal conductivity, about three times that of Si. This advantage is due to the short bond length and strong bonding force between atoms in SiC, which greatly helps in suppressing the maximum temperature during device operation. Additionally, SiC can maintain its semiconductor properties even at high temperatures up to 800°C. Currently, the upper limit of the operating temperature is restricted by materials other than SiC, and development is ongoing.

Furthermore, a property of SiC that needs consideration when applying chips to power modules is its high Young's modulus, about three times that of Si. SiC is an extremely hard material, so the stress induced by temperature cycles and other factors can be very large, potentially becoming a factor that determines the lifespan of the module.

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