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High-Voltage Ti/6H-SiC Schottky Barrier Diodes

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Abstract: The Schottky Barrier Diodes (SBD) are fabricated on 6H-SiC by using the thermal evaporation of Ti, and electrically characterized as well. The 6H-SiC epitaxial layers are grown on commercially available single-crystal 6H-SiC wafers by chemical vapor deposition. The reverse I-V characteristics of these diodes exhibit a sharp breakdown, with a breakdown voltage (V_B) of 400V at room temperature. A low reverse leakage current below 1×10^{-4}A/cm^2 at the bias voltage of -200V has been obtained. By using neon implantation, an amorphous layer as the edge termination, is formed. The V_B of Schottky barrier diodes is measured to be about 800V.

Key words: silicon carbide; Schottky barrier diode; 6H-SiC

EEACC: 2520M; 2530D; 2560H; 2530B

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1 Introduction

Silicon Carbide (SiC) recently receives increasing attention, due to its unique inherent electrical and thermal properties, including wide band gap (3.0eV for 6H-SiC and 3.2eV for 4H-SiC), large critical electric field (2×10^6V/cm), large saturated electron drift velocity (2×10^7cm/s) and high thermal conductivity (4.9W/(cm·K)). Because SiC is hard, chemically stable, and resistant to the radiation damage, it is regarded as the most appropriate semiconductor material for high-power, high-frequency, high-temperature and radiation hard microelectronic devices[1—3].

Used in the power electronic and high-frequency applications, SiC Schottky diodes have significant advantages over Si or GaAs based devices. Since Si Schottky barrier diodes with blocking voltages over 100V are very problematic, SiC Schottky barrier diodes are especially attractive in high-voltage, high-speed and low power loss applications because of its high breakdown field and relatively high barrier heights of most metals on SiC. In addition, considering the wide band-gap and high thermal conductivity, SiC SBD is more capable of high temperature operation than silicon devices. With the development of high-quality crystal growth of 6H-SiC by using step-controlled epitaxy, SiC SBD has been successfully applied in many power devices. The high-voltage 6H-SiC Schottky diodes have also been demonstrated in several groups[4—8]: Bhatnagar *et al*. has fabricated 400V Schottky rectifiers with a Pt/6H-SiC structure using a N-doped homoepitaxial layer; by using the high-quality epilayers at a low donor concentration of 5.8×10^{15}cm^{-3} and a relatively small thickness of 9.6μm, a high-blocking voltage over 1.1kV has been obtained successfully by Kimoto *et al*.; Ni/4H-SiC Schottky rectifiers have been reported by Schoen *et al*. with a born implant edge termination, whose reverse blocking voltage is

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1720V, and specific on-resistance ($R_{on,sp}$) is 5.6mΩ · cm^2.

In this paper, we report a high-voltage (> 800V) 6H-SiC Schottky barrier diode. The current-voltage characteristics and on-resistance at the elevated temperatures are experimentally investigated as well.

2 Experiment

The substrates we used were n-type 3.5° off-axis 6H-SiC (0001) provided by Cree Research, Inc. The net doping concentration was 1.6×10^{18} cm^{-3} and the thickness was 420μm. The homoepitaxial growth of SiC on the substrate was performed in a modified gas source molecular beam epitaxy (MBE) system. Si_2H_6, C_2H_4 and H_2 were used as source and carrier gases[9]. The concentration and thickness of the grown layers were 5.5×10^{15}cm^{-3} and 10μm, respectively.

Prior to the fabrication of SBD, the silicon carbide wafer was given the modified RCA clean[10], followed by a dip in diluted HF(1∶10); Ti(150nm) was then evaporated in the vacuum of 7.5×10^{-4}Pa; covered by Al metallization of 1μm, which was employed to reduce the spreading resistance of the Schottky contact; the circular dots with the diameter of 80, 100, 150, 200 and 300μm, were drawn with a standard photolithography, respectively. Blanket evaporation of an Al layer was also done on the heavily doped substrate to form a large area backside ohmic contact. The high resistivity edge termination was achieved by implanting an inert gas, such as argon and neon[11,12]. In this experiment, one part of the wafer was subjected to the doses of the neon implantation at 20keV, 1×10^{14}cm^{-2}. It was self-aligned to the Schottky contact because the Schottky metal was acting as a mask preventing damage under the contact. The energy was carefully chosen so that the ions could be completely stopped by Al/Ti metal layer and any degradation of the on-state characteristics of the Schottky barrier diodes could be avoid.

3 Results and Discussion

3.1 Forward Characteristics of SiC SBD

The current-voltage measurements were conducted with Keithley 2400. Figure 1 shows the semilogarithmic plots of the typical forward current density-voltage characteristics at different temperatures. From Fig. 1, we can see that at any temperature, the J_F-V_F curves consists of two regions: low current density region, where with the increase of temperature, V_F having a low current density will decrease because the current is controlled by the thermionic emission. The linear $\ln J_F$-V_F plot indicates that the diode characteristics follow the ideal diode equation:

$$J = J_{st}\exp(qv/\eta kT)[1 - \exp(-qv/kT)] \quad (1)$$

where J_{st} is the reverse saturation current density. The ideality factor η is obtained from the slope of the forward J-V plot. At the temperature of 297, 343 and 373K, η is 1.08, 1.2 and 1.24, respectively, as shown that the current conduction mechanism follows the thermionic emission theory.

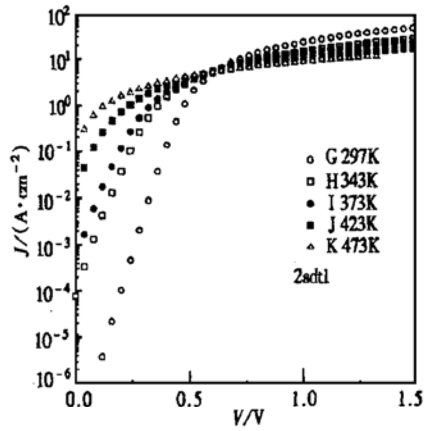

FIG. 1 Forward I-V Characteristics as a Function of Temperature for Ti/6H-SiC Schottky Diodes (Semilogarithmic Plots)

The Shottky barrier height is obtained from the equation below:

$$J_{st} = A^* T^2 \exp(-q\Phi_{bn}/kT)$$
$$= A^* T^2 \exp[-q(\Phi_{bn}^{I\text{-}V} - \Delta\Phi)/kT] \qquad (2)$$

where $J_{st} = 3\times10^{-8}\mathrm{A/cm^2}$, $A^* = 110\mathrm{Acm^{-2}K^{-2}}$, the effective barrier height $\Phi_{bn} = 0.86\mathrm{eV}$. The equation (2) include the image-force that is lowered with the barrier $\Delta\Phi_{bi}$ and the barrier lowered with the tunneling effect $\Delta\Phi_{b0}$. At room temperature and zero bias, $\Delta\Phi_{b0} = 0.0068\mathrm{eV}$, $\Delta\Phi_{bi} = 0.0275\mathrm{eV}$, which indicate that the image-force is dominant in the barrier height's lowering and the tunneling effect can be neglected. The barrier height $\Phi_{bn}^{I\text{-}V}$ is calculated to be 0.89eV. In addition, from I-V characteristics, the SBH can be calculated at different temperature. It can be seen that SBH changes little with the temperature: it is 0.89eV at 297K and 0.81eV at 473K.

At a high current densty, $\ln J_F$ versus V_F plot deviates from the linearity, and the series resistance comes into effect to limit the conduction. At room temperature, a current density of $75\mathrm{A/cm^2}$ is achieved at a forward voltage of 2V; the V_F drop is almost across the series resistance. Figure 2 shows the forward voltage drop of the diodes as a function of temperature at the current densities of $1\mathrm{A/cm^2}$

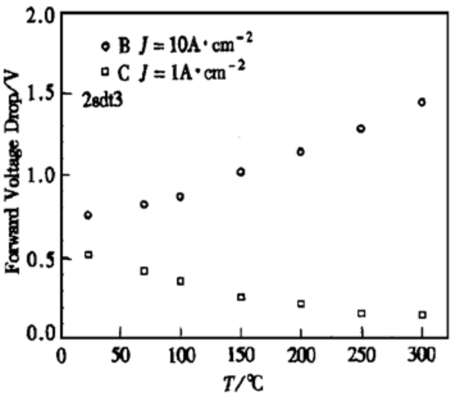

FIG. 2 Forward Voltage Drop as a Function of Temperature for Different Current Density Levels in a Ti/6H-SiC Schottky Diode

and $10\mathrm{A/cm^2}$. At $1\mathrm{A/cm^2}$, V_F is almost across the diodes. With the increase of temperature, V_F decrease because the current is mostly controlled by the electron injection across the Schottky barrier; while at $10\mathrm{A/cm^2}$, V_F increases with the temperature increasing due to the decrease in the mobility. The $R_{on,sp}$ values are calculated from the slopes of I-V characteristics at forward voltages (1—2V), where the forward current density saturates and the series resistance limits the conduction. Figure 3 shows the dependence of the specific on-resistance for the Ti/6H-SiC diodes on temperatures. It is found that $R_{on,sp}$ increases from $19\mathrm{m\Omega\cdot cm^2}$ at 297K to $39\mathrm{m\Omega\cdot cm^2}$ at 343K and $47.8\mathrm{m\Omega\cdot cm^2}$ at 373K, respectively.

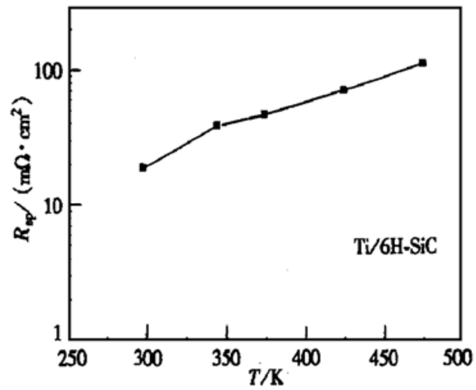

FIG. 3 Series Resistance of Ti/6H-SiC Diode as a Function of Temperature

The effect of diode area on the current density has been investigated, with the forward current density dependence on diode area shown in Fig. 4. The diameter of the circular diodes varies from 80μm to 300μm. As seen in Fig. 4, the current density can be reduced by increasing the area/perimeter ratio at a forward bias[14].

3.2 Reverse Characteristics of SiC SBD

The reverse current-voltage measurement is conducted by using Keithley 2400. Figure 5 shows the semilogarithmic plots of the typical reverse current density (J_R)-voltage (V_R) characteristics at different temperatures. At room temperature, reverse leakage current J_R is found below $1\times10^{-4}\mathrm{A/cm^2}$ when $V_R = -200\mathrm{V}$; at 373K, J_R is found to be $0.228\mathrm{A/cm^2}$ when $V_R = 200\mathrm{V}$, which

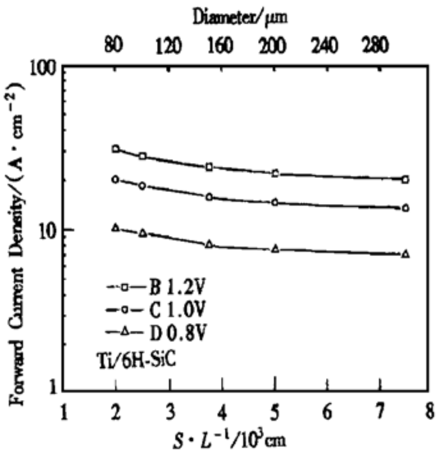

FIG. 4 Dependence of Forward Current Density on Diode Area/Perimeter Ratio

can be attributed to the defects in 6H-SiC.

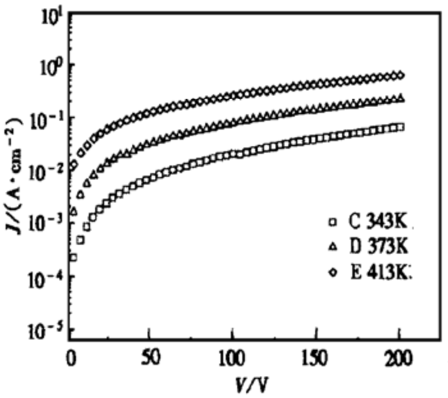

FIG. 5 Reverse I-V Characteristics as a Function of Temperature for Ti/6H-SiC Schottky Diodes

The reverse breakdown voltage of SiC SBD has been measured with a QT2A transistor characteristics graphic meter. The reverse breakdown voltage (V_B), defined as the breakdown point of the unterminated diodes, is 400V. V_B of the terminated SBD is found to be about 800V, which is much higher than that of the unterminated one. The typical reverse breakdown voltage characteristics are shown in Fig. 6. The measurement conditions is as follows: in X-axis—200V/div, in Y-axis—10μA/div. The neon implantation is believed to create a thin high resistivity layer at the surface beyond the edges of the diode, which promotes the spread of the potential along the surface. As a result, the edge electric field is reduced and the breakdown voltage increased.

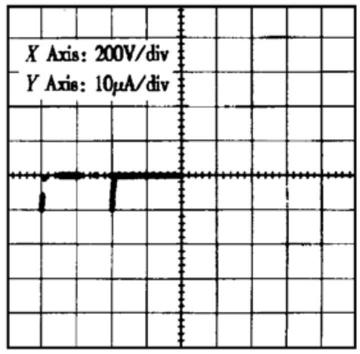

FIG. 6 Typical Reverse Breakdown Voltage Characteristic of SiC SBD

Figure 7 shows the forward characteristics of SiC SBD (implanted and unimplanted). There is a little difference between the devices with and without implantation. At the same current density, the forward voltage drop of implant terminated SBD is larger than that of unterminated SBD, this is ascribed to some voltage drops across the high resistivity region at the edge of the device.

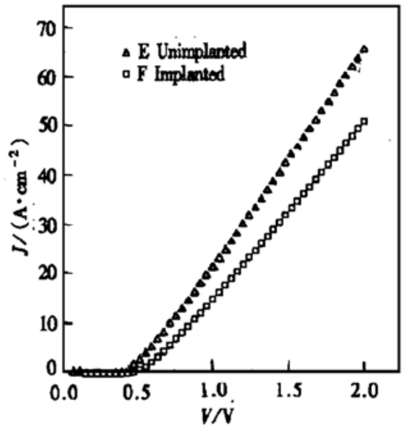

FIG. 7 Forward Characteristics of SiC SBD (Implanted and Unimplanted)

4 Conclusions

By using the layer's homoepitaxially grown on 6H-SiC substrate with LPCVD in a modified gas

source MBE system, Ti/6H-SiC Schottky barrier diodes are fabricated with thermal evaporation. The breakdown voltage measured is 400V. It is demonstrated that a low reverse leakage current below $1\times10^{-4}A/cm^2$ is obtained at the bias voltage of − 200V. At room temperature, the ideality factor and barrier height are 1.08 and 0.9eV, respectively. The breakdown characteristics of the Schottky barrier diodes are improved by using neon implantation to form the edge termination. The V_B of Schottky barrier diodes is measured to be about 800V.

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高压 Ti/6H-SiC 肖特基势垒二极管

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摘要: 在 N 型 6H-SiC 外延片上, 通过热蒸发, 制作 Ti/6H-SiC 肖特基势垒二极管 (SBD). 通过化学气相淀积, 进行同质外延生长, 详细测量并分析了肖特基二极管的电学特性, 该肖特基二极管具有较好的整流特性. 反向击穿电压约为 400V, 室温下, 反向电压 V_R= 200V 时, 反向漏电流 J_R 低于 $1\times10^{-4}A/cm^2$. 采用 Ne 离子注入形成非晶层, 作为边缘终端, 二极管的击穿电压增加到约为 800V.

关键词: 碳化硅; 肖特基势垒二极管; 6H-SiC

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