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I - V characteristics in Surface-Activated Bonding (SAB) based Si/SiC junctions at raised ambient temperatures

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Abstract. The physical and electrical properties of p^+-Si/n-4H-SiC and n^+-Si/n-4H-SiC heterojunctions fabricated by using surface-activated bonding (SAB) were investigated by scanning electron microscopy (SEM), current-voltage (I-V) and breakdown characteristics measurements at raised ambient temperatures. The I-V characteristics for the reverse bias voltages of the two junctions were compared with the expectations based on Frenkel-Poole, and trap-assisted tunneling models. The results of calculations using the trap-assisted tunneling model were close to the measurements.

Introduction

Due to its large bandgap and the excellent electrical properties of its native oxide layers, silicon carbide (SiC) is a promising material for high-power and high-efficiency devices [1]. SiC-based electron devices such as Schottky barrier diodes and MOSFETs have been intensively investigated. SiC-based power modules were recently commercialized [2].

In the next step of the progress in power modules, it is assumed that the SiC- and Si-based electron devices are integrated into single modules with high power capabilities and large functionalities. Possibilities of Si/SiC heterojunctions, which are likely to be one of the essential elements for realizing such modules, have been explored [3]. Si/SiC heterojunctions were fabricated by using chemical vapor deposition, molecular beam epiatxy, electron beam evaporation, and layer transfer of thin Si films to SiC substrates [4].

In this work, we fabricated the p^+-Si/n-4H-SiC and n^+-Si/n-4H-SiC heterojunctions by using the surface-activated bonding (SAB) [5-6] of Si and SiC substrates. Note that using SAB dissimilar materials with different lattice constants and thermal expansion coefficients are firmly bonded without being heated. We examined the electrical properties of the bonding interfaces in the SAB-based Si/SiC heterojunctions with emphasis on their current-voltage (I-V) characteristics at raised ambient temperatures and discussed the properties across the bonding interfaces.

Experimental procedure

We employed n^+-, p^+-Si substrates and n-4H-SiC layers epitaxially-grown on n^+-SiC substrates. The Hall measurements at room temperature revealed that the carrier concentrations of Si substrates were 2.6×10^{19} cm^{-3} (n^+-Si) and 2.6×10^{19} cm^{-3} (p^+-Si), respectively. The capacitance-voltage (C-V) measurement of n-4H-SiC schottky junction at room temperature and a frequency of 100 kHz revealed that the carrier concentration in n-4H-SiC layers was 1.4×10^{17} cm^{-3}. The nominal carrier concentrations in buffer layers and n^+-SiC substrates were $> 2 \times 10^{18}$ cm^{-3} (buffer) and $\sim 1 \times 10^{19}$ cm^{-3} (n^+-SiC substrates), respectively.

These substrates were bonded to each other after the surface activation process by means of Ar atom beams in the chamber of SAB facilities. The temperature of substrates was not intentionally raised while they were bonded. After bonding, ohmic contacts were formed on their tops and bottoms by evaporating Al/Ni/Au for p$^+$-Si and n-4H-SiC, and Ti/Au for n$^+$-Si, respectively.

We observed a cross-sectional FE-SEM image of the interface in Si/SiC junction and measured the I-V characteristics at raised ambient temperatures of n$^+$-Si/n-4H-SiC and p$^+$-Si/n-4H-SiC junctions by using an Agilent B2902A Precision Measurement Unit.

Results and discussion

A cross-sectional FE-SEM image of the Si/SiC junction is shown in Fig. 1. The bonding interface between Si and SiC layers manifests itself as a straight line in this figure, which indicates that there occur no mechanical deficits such as cracks at the interface.

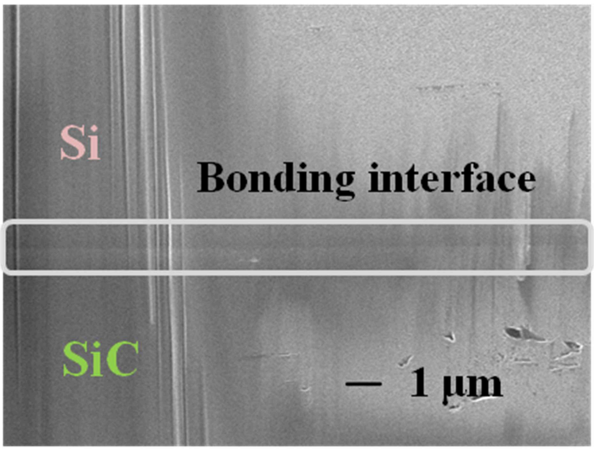

Fig. 1. A cross-sectional FE-SEM image of the bonding interface of Si/SiC junction.

The I-V characteristics of the n$^+$-Si/n-4H-SiC junction measured at temperatures between 288 and 473 K are shown in Fig. 2(a). The I-V characteristics show rectifying properties at the respective temperatures. The magnitude of the current for the reverse-bias voltages at 288 K is equal to or lower than those in Si/SiC junctions formed using different methods [4]. We also find that a hump appears in the characteristics for low forward bias voltages (~0.1 V) at 288K. Furthermore the current for the reverse bias voltages increases by ~10^3 times as the temperature increases up to 473K. It is notable that the slope in the current for the reverse bias voltages in the logarithmic scale is almost invariant to the temperatures. The results for the p$^+$-Si/n-4H-SiC junction are shown in Fig. 2(b). The features of the I-V characteristics of the n$^+$-Si/n-4H-SiC junctions are also observed for the p$^+$-Si/n-4H-SiC junctions. The rectifying properties observed for the two kinds of junctions are likely to be due to the conduction band offset of the Si/SiC junction. We actually found that the energy-band diagram of the Si/SiC junction reveals type-I features in other works.

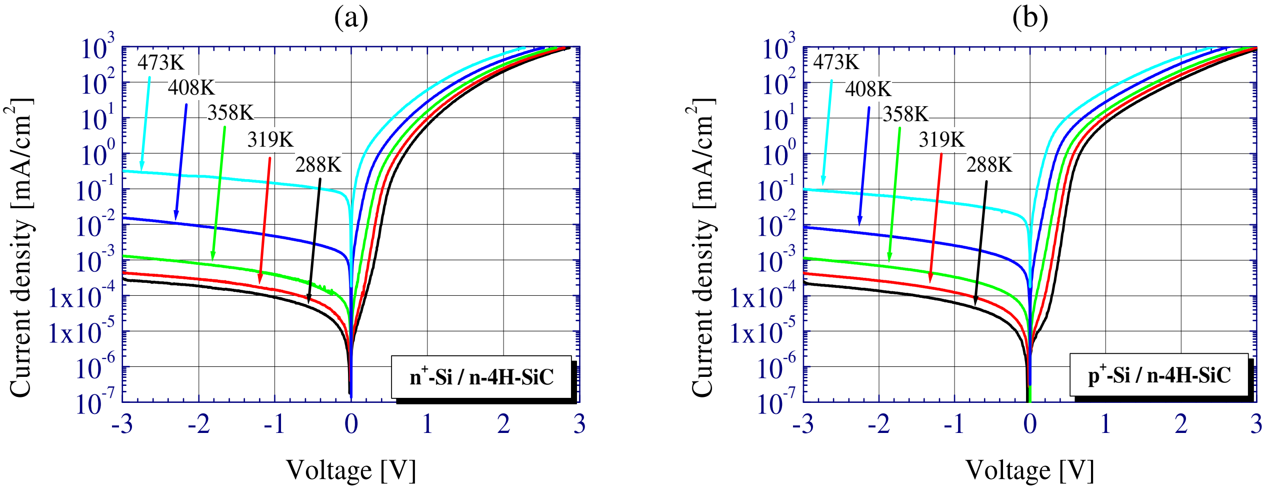

Fig. 2. (a) I-V characteristics of n$^+$-Si/n-4H-SiC at temperatures between 288 and 473K. (b) I-V characteristics of p$^+$-Si/n-4H-SiC at temperatures between 288 and 473K.

The I-V characteristics for the reverse bias voltages of the two junctions are compared with the expectations based on Frenkel-Poole [7], and trap-assisted tunneling models [8]. In the framework of Frenkel-Poole and trap-assisted tunneling models, the behaviors of the currents for the reverse-bias voltages, which are denoted as J_{FP} and J_{TAT}, respectively, are expressed as

$$\frac{d\log(J_{FP}/E_b)}{d\sqrt{E_b}} = \frac{q}{kT}\sqrt{\frac{q}{\pi\varepsilon_0\varepsilon_{sh}}}\,, \qquad (1)$$

and

$$\frac{d\log(J_{TAT})}{d\,(1/E_{ave})} = -\frac{8\pi\sqrt{2qm^*}}{3h}\varphi_r^{1.5}\,, \qquad (2)$$

respectively. In the above expressions, E_b is the electric field at n-4H-SiC surface, E_{ave} is the averaged electric field in the depletion region, φ_r is the energy level of traps dominating the tunneling process, respectively. m* is the effective mass of tunneling carriers ($m^* = 0.33m_o$ [9]), and T is the ambient temperature. ε_{sh} is the relative dielectric constants of 4H-SiC at the high-frequency limits ($\varepsilon_{sh} = 6.52$ [10]). q, h, k, and ε_o are the elementary charge, the Planck constant, the Boltzmann's constant, and the permittivity in vacuum, respectively.

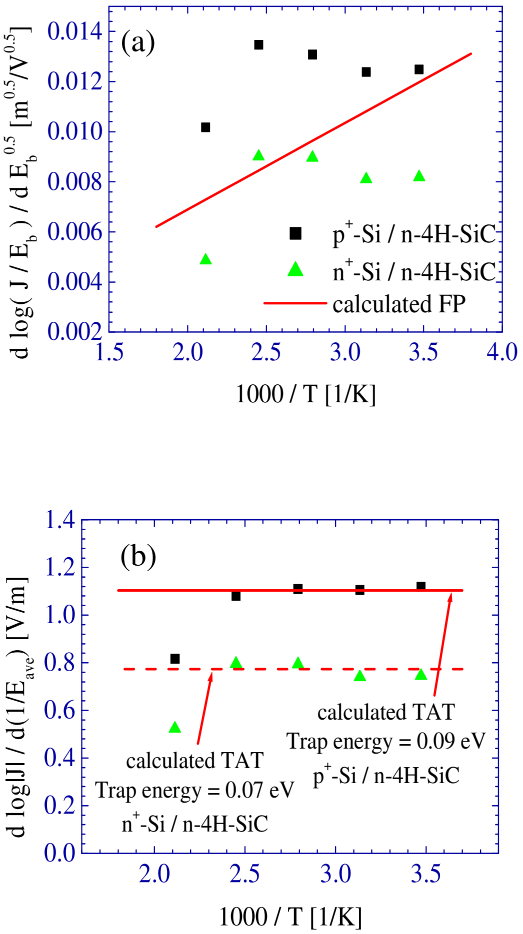

Fig. 3. Dependence of (a) d $\log(J/E_b)$/d $E_b^{0.5}$, and (b) d log|J|/d ($1/E_{ave}$) for reverse bias voltages on the temperature in p^+-Si/n-4H-SiC and n^+-Si/n-4H-SiC junctions. Results of calculations based on (a) Frenkel-Poole, and (b) trap-assisted tunneling models are also shown.

The data for reverse-bias voltages between -1 and -3 V at each temperature are compared with the expectations from each model, which we obtained using eq. (1), and (2). Results are shown in Figs. 3(a) and 3(b). The calculations using trap-assisted tunneling model with a trap depth of 0.07 (n^+-Si/n-4H-SiC) and 0.09 eV (p^+-Si/n-4H-SiC) are close to the measurements as is shown in Fig. 3(b), which suggests that the transport properties in reverse-bias voltages are characterized by the tunneling through a kind of shallow (~0.1 eV) traps although the origin of the traps is unclear. The occurrence of the hump in the I-V characteristics for forward bias voltages might be understood in this scheme. The decrease in trap energy at 473K describes other carrier transport processes may contribute to the I-V characteristics at 473K. In contrast, marked discrepancies between measurements and calculations are observed in Fig. 3(a) .

The dependence of the reverse-bias breakdown voltage (V_{BD}) for the respective junctions on the temperature is shown in Fig. 4. The inset of this figure shows the breakdown characteristics of the respective junctions at 288 K. The obtained V_{BD} values correspond to the electric field of as low as ~1200 (n^+-Si/n-4H-SiC) and ~880 kV/cm (p^+-Si/n-4H-SiC), which means that the breakdown characteristics are related to the tunnelling of carriers. We also find that V_{BD} decreases as the temperature increases for each junction, which might be attributed to the decrease in bandgap of SiC due to the increase of temperature.

Conclusions

We fabricated p^+-Si/n-4H-SiC and n^+-Si/n-4H-SiC junctions by surface activated bonding (SAB) and investigated their physical and electrical properties. Their I-V characteristics at raised ambient temperatures showed rectifying properties. Among Frenkel-Poole, and trap-assisted tunneling models, the trap-assisted tunneling model provided us with results of calculation that were the closest to measured properties for reverse-bias voltages. The breakdown voltages, which corresponded to electric field ~1200 (n^+-Si/n-4H-SiC) and ~880 kV/cm (p^+-Si/n-4H-SiC), decreased as the temperature increased for each junction. These results suggested that the tunneling process through traps dominated the electrical transport properties in the Si/SiC junctions. Further studies are required for understanding the origin of traps.

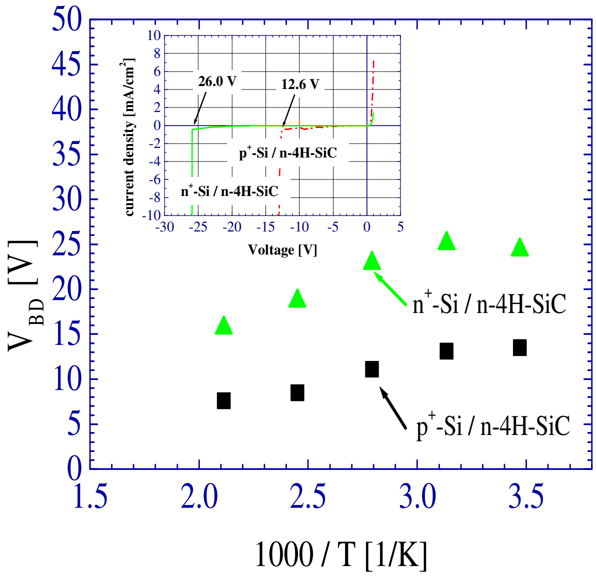

Fig. 4. The dependence of reverse breakdown voltages on the temperature between 288 and 493 K in n^+-Si/n-4H-SiC and p^+-Si/n-4H-SiC junctions.The inset shows the breakdown characteristics of the respective junctions at 288 K.

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