D-4-01
Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp209-210

Accurate Determination of Barrier Heights in Heavily-Doped SiC Schottky Barrier Diodes Fabricated with Various Metals

Masahiro Hara, Mitsuaki Kaneko, and Tsunenobu Kimoto

Dept. of Electronic Sci. & Eng., Kyoto University, Nishikyo, Kyoto, 615-8510, Japan
Phone : +81-75-383-2302, E-mail: hara@semicon.kuee.kyoto-u.ac.jp

Abstract

We investigated the barrier heights in Ti/ and Ni/n-SiC Schottky barrier diodes (SBDs) with a wide range of the donor concentration (2×10^{17} – 1×10^{19} cm^{-3}). Forward current-voltage characteristics in heavily-doped SiC SBDs (> 2×10^{17} cm^{-3}) can be well described by the thermionic field emission (TFE) model and the barrier height can be precisely determined by the analysis based on the TFE model. Carefully considering the contribution of the image force lowering, the slope (S) of the barrier height versus the metal work function plot was 0.72 independent of the donor concentration.

1. Introduction

A barrier height is one of the most important properties at metal/semiconductor interfaces since it determines the forward voltage drop and the magnitude of the reverse leakage current in Schottky barrier diodes (SBDs) as well as the contact resistivity of ohmic contacts. Until now, the barrier heights in lightly-doped SiC SBDs fabricated with various metals have been extensively investigated aiming at power electronics applications [1, 2], while the barrier heights in heavily-doped SiC SBDs have not been studied. This fundamental property is crucial to clarify the mechanism of formation of ohmic contacts on SiC, which is not fully understood even now despite the continuous research [3, 4]. In particular, characterization of the barrier height at metal/heavily-doped SiC interfaces using various metals is essential to explore a proper metal which can achieve good ohmic contacts on SiC. However, determination of barrier heights in heavily-doped SBDs is not straightforward because of several reasons. In this study, the barrier heights in Ti/ and Ni/n-SiC SBDs with various donor concentrations were carefully investigated. Significant tunneling current was observed in heavily-doped SiC SBDs and, by calculation of the tunneling current, the barrier height was accurately determined. Considering the contribution of the image force lowering caused by the high electric field at the Schottky interface, we revealed that metal/SiC junctions are nearly free from Fermi-level pinning independent of the donor concentration.

2. Experiments

We prepared n-type 4H-SiC epitaxial wafers with widely varying the donor concentration (2×10^{17} – 1×10^{19} cm^{-3}) and conducted chemical mechanical polishing (CMP) on the surface of each epitaxial layer. After the RCA cleaning, Ti or Ni was deposited as the Schottky electrodes and then the contacts were annealed at 300°C in vacuum to obtain a uniform barrier height. The barrier height in these SBDs was investigated by capacitance–voltage (C–V) and forward current–voltage (I–V) measurements, taking account of electron tunneling.

3. Results and Discussions

Figure 1 shows the forward I–V characteristics of (a) Ti/ and (b) Ni/SiC SBDs with various donor concentrations. In heavily-doped SiC SBDs (1×10^{19} cm^{-3}), the depletion layer width is very thin (~ 10 nm) and such a thin barrier results in very high electric field strength (> MV/cm) even at zero bias, as shown in Fig. 2. This is a typical condition that electron tunneling occurs, and thus we determined the barrier height by calculation with an analytical formula of the thermionic field emission (TFE) model [5], which includes a tunneling process of thermally excited electrons. Figure 3 depicts the calculated and experimental forward I–V characteristics of heavily-doped SiC SBDs (1×10^{19} cm^{-3}) fabricated with (a) Ti and (b) Ni. The calculated I–V characteristics based on the TFE model agreed well with the experimental results for both SBDs, while the calculation based on the thermionic emission (TE) model could not reproduce the experimental curves. The extracted barrier heights were 0.88 eV for Ti SBD and 1.47 eV for Ni SBD, which were consistent with those obtained from C–V measurements as shown in Fig. 4. Besides, the barrier height lowering in these heavily-doped SBDs corresponded well to the calculated image force lowering as shown by the red dashed lines in Fig. 4.

Then, we compared the slope (S) of the barrier height (ϕ_{B}) versus the metal work function (ϕ_{M}) plot between SBDs with the donor concentration of 2×10^{17} cm^{-3} and 1×10^{19} cm^{-3}. It is noted that the barrier height under the same electric field condition, not the same donor concentration condition, should be used for comparison of the S value when the image force lowering strongly affects the barrier height. This is because the image force lowering depends on not the donor concentration but the electric field at the Schottky interface ($F_{\mathrm{max}} = \sqrt{2eN_{\mathrm{d}}(V_{\mathrm{d}} - V)/\varepsilon_{\mathrm{s}}}$). When SBDs are fabricated with different metals, the built-in potential V_{d} should also vary and this difference results in the different electric field strength even for the same donor concentration as shown in Fig. 5. Therefore, stronger image force lowering exsists in the case of larger V_{d} (larger ϕ_{B}) as shown in Fig. 6. Figure 7 depicts the ϕ_{B} versus ϕ_{M} plot under the low and high electric field (F_{max} = 0.24 MV/cm and 2.4 MV/cm, respectively). The S values extracted from these plots were 0.72 for both of the electric field conditions. This result indicates that the metal/SiC interfaces are nearly free from Fermi-level pinning independent of the donor concentration of SiC, and supports that the change in the barrier height with increasing the donor concentration can be explained by the image force lowering.

4. Conclusions

We investigated the barrier heights in Ti/ and Ni/n-SiC SBDs with various donor concentrations (2×10^{17} – 1×10^{19} cm^{-3}). The barrier heights in the heavily-doped SiC SBDs (> 2×10^{17} cm^{-3}) were accurately determined by calculation based on the TFE model. By the detailed analysis taking the image force lowering into account, the donor-concentration-independent S value of 0.72 could be obtained.

References

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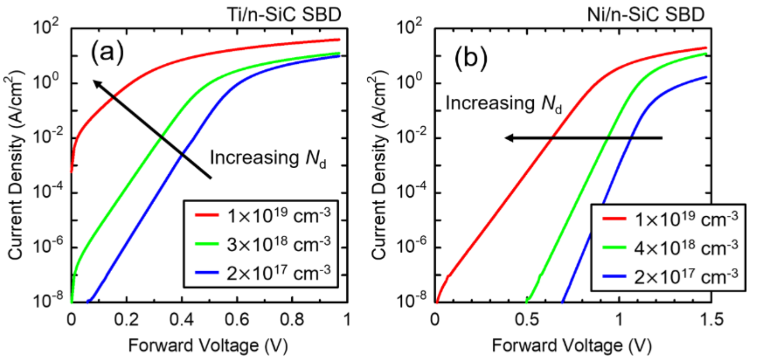

Fig. 1: Experimental current–voltage characteristics of (a) Ti/ and (b) Ni/SiC SBDs with various donor concentrations.

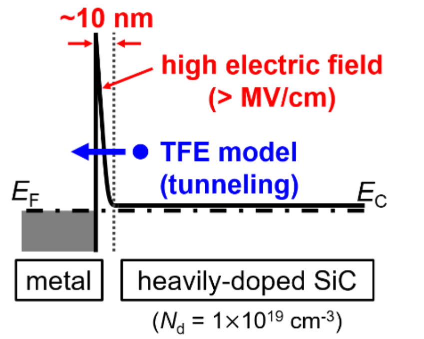

Fig. 2: Band diagram near a metal/heavily-doped SiC interface.

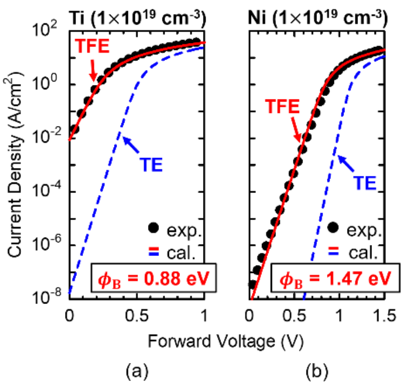

Fig. 3: Calculated and experimental current–voltage characteristics of heavily-doped SiC SBDs (1×10^{19} cm^{-3}) fabricated with (a) Ti and (b) Ni. The calculated curves agree well with the experimental curves for both SBDs when calculating based on the TFE model, not the TE model.

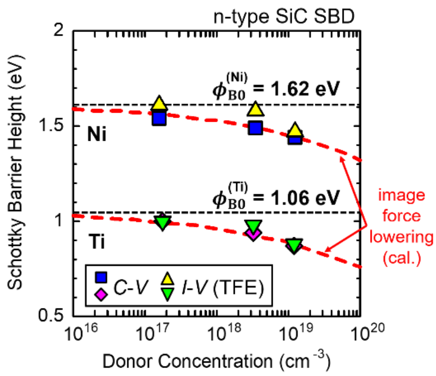

Fig. 4: Barrier heights in Ti/ and Ni/SiC SBDs as a function of donor concentration. The decrease in the barrier height with increasing the donor concentration shows good agreement with the calculated image force lowering.

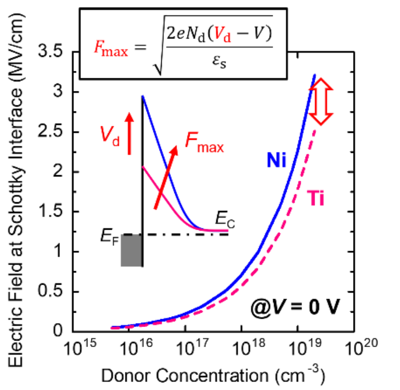

Fig. 5: Electric field at the Schottky interface versus donor concentration in Ti/ and Ni/SiC SBDs. The different built-in potential causes the different electric field.

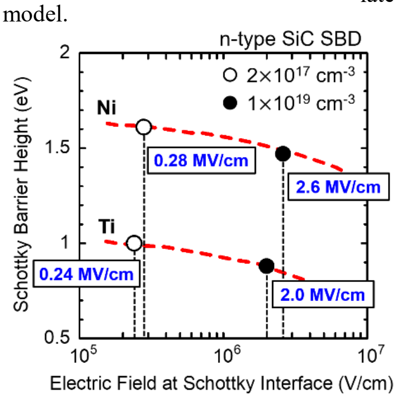

Fig. 6: Barrier heights in Ti/ and Ni/SiC SBDs as a function of electric field at the Schottky interface. The amount of the image force lowering is different even for the same donor concentration due to the difference in the built-in potential.

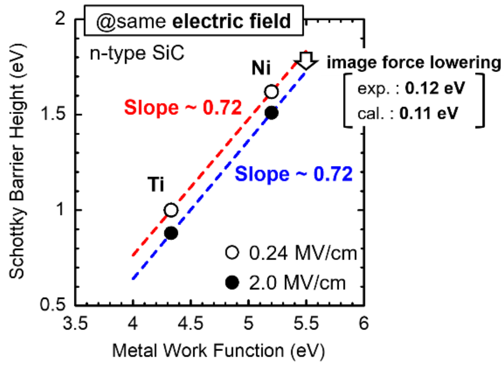

Fig. 7: Barrier height versus metal work function plot of SiC SBDs under the electric field of 0.24 MV/cm and 2.0 MV/cm. The S values are the same for both cases when comparing them at the same electric field and changes in the barrier height can be explained only by the image force lowering.