Analysis of breakdown phenomena in 4H-SiC p-n junction diodes with a wide range of doping concentration

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The relation between the critical electric field strength ($E_{\rm cr}$) and reduced doping concentration (N) is very important for designing device structures. The formula of $E_{\rm cr}$-N has been reported by Konstantinov and Niwa [1, 2]. However, the accuracy of these formulas in the high doping region is questionable since the doping concentration of the devices used in these previous studies is lower than 2×10^{17} cm^{-3}. At high doping concentration, the bandgap-narrowing effect appears. Besides, Zener breakdown due to tunneling may become dominant because very high electric field is applied to highly doped p-n junctions. In this work, 4H-SiC p-n junction diodes with a wide range of doping concentration were fabricated and the temperature dependence of reverse current-voltage (*I-V*) characteristics was investigated in order to elucidate the breakdown mechanism. Based on the breakdown voltage experimentally obtained, the reported $E_{\rm cr}$-N formula is modified.

Fig. 1 shows the schematic cross section of the fabricated p-n junction diodes. The reduced doping concentration ($N = N_{\rm a}N_{\rm d}/(N_{\rm a}+N_{\rm d})$) of p-n junction diodes varied from 2×10^{16} cm^{-3} to 1.9×10^{18} cm^{-3}. Mesa structure was fabricated to alleviate electric field crowding. The diode size was varied from 100 to 500 μm in diameter. *I-V* characteristics were measured in the temperature range of 300-465 K. In this work, the voltage at a current density of 1×10^{-3} A/cm^2 was defined as the breakdown voltage.

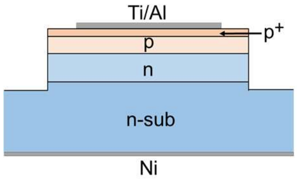

Fig. 1: Schematic cross section of a fabricated 4H-SiC diode.

The diodes with reduced doping concentration below 1×10^{18} cm^{-3} exhibited a positive temperature dependence of the breakdown voltage ($V_{\rm B}$), whereas the diodes with reduced doping concentration over 1.5×10^{18} cm^{-3} showed a negative temperature dependence, as shown in Fig. 2. The temperature dependence of $V_{\rm B}$ in several diodes is shown in Fig. 3. The negative temperature dependence of $V_{\rm B}$ observed in the diodes with reduced doping concentration over 1.5×10^{18} cm^{-3} is a typical feature of Zener breakdown. However, the *I-V* characteristics of the diodes near the breakdown experimentally observed (abrupt increase in the current) are totally different from the theoretical curves due to tunneling current. Since the abrupt increase in the current is rather similar to that of avalanche mechanism, the breakdown for the diodes even with the reduced doping concentration of $(1.0-1.9)\times10^{18}$ cm^{-3} may be caused by avalanche mechanism. The negative temperature dependence of $V_{\rm B}$ can be explained by the effect of bandgap narrowing caused by high doping concentration, the negative temperature dependence of bandgap, and the smaller effect of phonon scattering in the highly-doped material.

Using the measured breakdown voltage, the critical electric field strength ($E_{\rm cr}$) at 300 K as a function of the reduced doping concentration (N) was calculated. Fig. 4 shows experimental results and the $E_{\rm cr}$-N curves obtained in this study as well as Konstantinov and Niwa's formulas.

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[1] A. O. Konstantinov *et al.*, *Appl. Phys. Lett.* **71**, 90 (1997). [2] H. Niwa *et al.*, *IEEE Trans. Electron Devices* **62**, 3326 (2015).

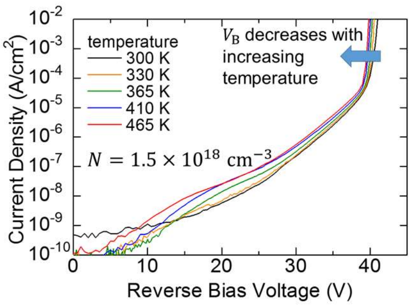

Fig. 2: *I-V* characteristics of the diode with a reduced doping concentration of 1.5×10^{18} cm^{-3}. The breakdown voltage decreases with temperature.

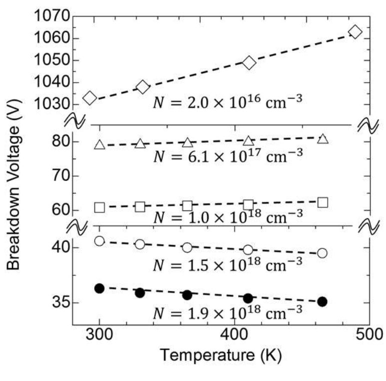

Fig. 3: Temperature dependence of the breakdown voltage in the diodes with different reduced doping concentrations.

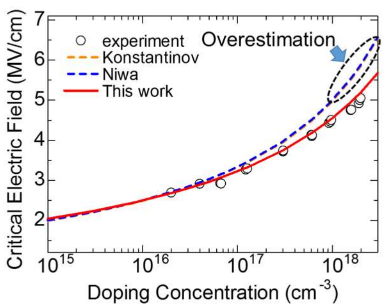

Fig. 4: $E_{\rm cr}$-N relationship obtained in this work, comparing with the results using Konstantinov and Niwa's formulas.