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Potential barrier height of Metal/SiC(4H) Schottky diode

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Metal/SiC(4H) 쇼트키 다이오드의 포텐셜 장벽 높이

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Abstract We have fabricated Sb/SiC(4H) Schottky barrier diode (SBD) of which characteristics compared with that of Ti/SiC(4H) SBD. The donor concentration of the n-type SiC(4H) obtained by capacitance-voltage (C-V) measurement was about 2.5×10^{17} cm^{-3}. The ideality factors of 1.31 was obtained from the slope of forward current-voltage (I-V) characteristics of Sb/SiC(4H) SBD at low current density. The breakdown field of Sb/SiC (4H) SBD under the reverse bias voltage was about 4.4×10^{2} V/cm. The built-in potential and the Schottky barrier height (SBH) of Sb/SiC(4H) SBD were 1.70 V and 1.82 V, respectively, which were determined by the analysis of C-V characteristics. The Sb/SiC(4H) SBH of 1.82 V was higher than Ti/SiC(4H) SBH of 0.91 V. However, the current density and reverse breakdown field of Sb/SiC(4H) were low as compared with those of Ti/SiC(4H). The Sb/SiC(4H), as well as the Ti/SiC(4H), can be utilized as the Shottky barrier contact for the high-power electronic device.

요 약 Sb/SiC(4H) 및 Ti/SiC(4H) 쇼트키 다이오드(SBD)를 제작하여 그 특성을 조사하였다. 용량-전압(C-V) 측정으로부터 얻은 n-형 SiC(4H)의 주개(donor) 농도는 약 2.5×10^{17} cm^{-3}이었다. 순방향 전류-전압(I-V) 특성의 기울기로부터 얻은 Sb/SiC(4H) 쇼트키 다이오드의 이상계수는 1.31이었고, 역방향 항복전장(breakdown field)은 약 4.4×10^{2} V/cm이었다. 용량-전압(C-V) 측정으로부터 얻은 Sb/SiC(4H) SBD의 내부전위(built-in potential) 및 쇼트키 장벽 높이는 각각 1.70 V 및 1.82 V이었다. Sb/SiC(4H)의 장벽높이 1.82 V는 Ti/SiC(4H)의 0.91 V 보다 높았다. 그러나 Sb/SiC(4H)의 전류밀도와 역방향 항복전장은 Ti/SiC(4H)의 것보다 낮았다. Ti/SiC(4H)는 물론 Sb/SiC(4H) 쇼트키 다이오드는 고전력 전자소자로서 유용하다.

1. Introduction

SiC(4H) is a wide bandgap (3.3 eV) semiconductor with excellent electronic properties and thermal stability to be able to operate at higher temperatures and power levels [1-4]. The SiC(4H) photodiode can be applied in optoelectronic devices as a ultraviolet (UV) photodetector [5-8]. The electron mobility of SiC(4H) was two times larger than that of SiC(6H) in {0001} plain owing to the small effective mass of SiC(4H). Anisotropy of effective mass in SiC(4H) is small. The breakdown field is large. Hence, SiC(4H) has been regarded as the most hopeful material for high-power/frequency electronic applications [9, 10]. The Schottky barrier height (SBH) for Ti/, Au/, Ni/ SiC(4H) structures has been studied [11-13]. However, there are few report on determination of Sb/SiC (4H).

In this study, we have fabricated SiC(4H) SBDs using Sb of which characteristics compared with that of Ti/SiC(4H) SBD. SBHs of Metal/SiC(M/SiC) structures were analyzed by capacitance-voltage (C-V) characteristics.

2. Experiment

Undoped SiC(4H) crystals grown by the modified Lely method with the donor concentration of 2.5× 10^{17} cm^{-3} were used for the fabrication of Schottky diode [14]. Raman spectrum of SiC(4H) was measured in back scattering geometry using a wavelength of 325 nm from a He-Cd laser at room temperature. The incident light for the excitation was normal to 4H(0001) surfaces. The scattering light was detected by using the model of the Ramanor U-1000 (Jobin-Yvon Co.). The Raman spectrum of the crystal of 4H-SiC is shown in Fig. 1. The Raman peaks of SiC (4H) were observed at 970 cm^{-1} for the longitudinal optic (LO) region, and at 799 cm^{-1}, 778 cm^{-1} for the transverse optic (TO) region. The polytype of this sample was identified by Raman spectrum in Fig. 1 and was a 4H-SiC single crystal [15].

For the fabrication of Schottky rectifiers, Ti/Al was evaporated on the back of SiC(4H) substrate, and annealed for 10 minutes at 1200℃ to form ohmic contact. Before Sb and Ti deposition for Schottky contacts, the surfaces of SiC(4H) crystal were cleaned in organic solvents, and HCl, aqua regia, and HF, and then rinced in deionized water. Schottky contacts were formed by thermal evaporation of Sb and Ti metals through a shadow-mask. The pressure before the evaporation of Schottky metal was about 5×10^{-6} torr. The areas of Schottky contacts were circles with the diameters 500 μmϕ, 800 μmϕ, and 1000 μmϕ for I-V and C-V measurements.

3. Barrier heights of Metal/SiC(4H)

Figure 2 shows the energy-band diagram of

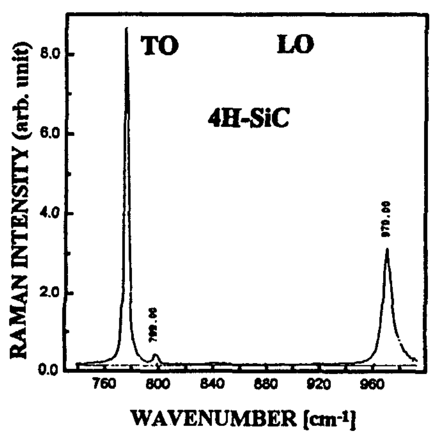

Fig. 1. Raman spectrum of SiC(4H) from [0001] direction.

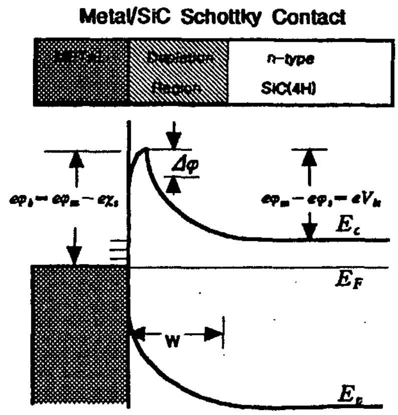

Fig. 2. The energy-band diagram of Metal/SiC(4H) SBD at equilibrium.

M/SiC(n-type) junction at equilibrium. SBH is defined as the potential difference between the conduction band of the semiconductor at the junction and Fermi level of the metal [16]. SBH ($e\phi_b$) is given by

$$e\phi_b = e\phi_m - e\chi_s \tag{1}$$

where $e\phi_m$ is the work function of the metal and $e\chi_s$ the electron affinity in real M/SiC junction. In Fig. 2, V_{bi} is the built-in potential, e the magnitude of electron charge, W the depletion width, and Δφ the SBH lowering at the interface due to the Schottky effect.

Foward bias allows electrons to flow from SiC to metal, increasing the current. The foward current-density (J_F) given by the thermionic emission theory is [17]

$$J_F = J_{st}\exp[(eV/nkT)-1] \tag{2}$$

where J_{st} is the saturation current-density, V the bias voltage, n the ideality factor of diode, k the Boltzman constant, and T the absolute temperature. J_{st} is given by

$$J_{st} = A^* T^2 \exp[-e(\varphi_b - \Delta\varphi)/kT \tag{3}$$

where A* is the effective Richardson constant, and φ_b the SBH. A* is given by

$$A^* = m^* e k^2 / 2\pi^2 \hbar^3 \tag{4}$$

where m* is the effective mass of electrons of 0.206 m_o (m_o is electron mass) for the SiC(4H) and ħ the Planck constant devided by 2π. The theoretical A* of 25 A/K^2cm^2 is calculated by Eq. (4).

Figures 3 and 4 show I-V curves of Sb/ and Ti/SiC (4H) SBDs under forward bias voltage, respectively. The n-type SiC(4H)s form Schottky contact with Sb and Ti metals. The break-down fields for Sb/ and Ti/SiC(4H) were measured to be about 4.4×10^2 V/cm and 1.7×10^3 V/cm, respectively.

In Fig. 5, the ideality factors of 1.31 and 1.02 were obtained from the slopes at a low current density level ($<10^{-2}$ A/cm^2) for Sb/ and Ti/SiC(4H), respectively, indicating ideal thermionic emission theory. From the intercept of the current density axis, saturation current densities (J_{st}) were measured to be 1.0×10^{-11} A/cm^2 and 5.0×10^{-8} A/cm^2 for Sb/ and Ti/SiC(4H), respectively.

As for the C-V measurement, the results for the M/SiC potential barrier are similar to those of the one-sided abrupt p^+/n junction under the abrupt approximation that $\rho \simeq eN_d$ for $x < W$, and $dV/dx \simeq 0$ for $x > W$. We can obtain [17]

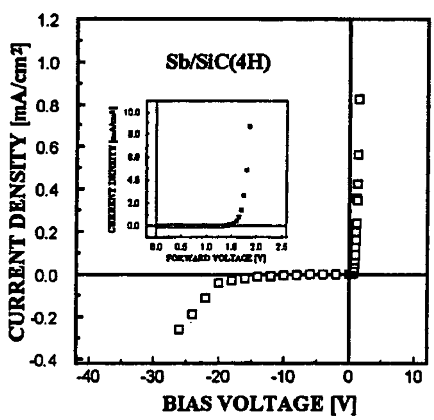

Fig. 3. I-V characteristics of Sb/SiC(4H) SBD.

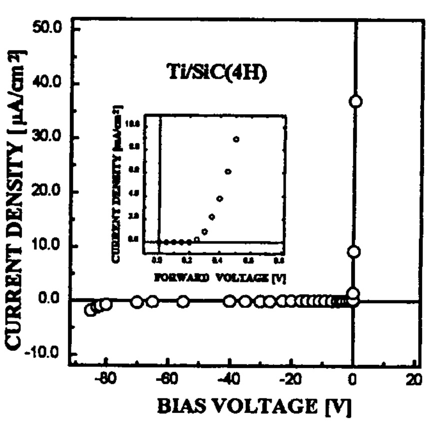

Fig. 4. I-V characteristics of Ti/SiC(4H) SBD.

$$W=\sqrt{\frac{2\varepsilon_s}{eN_d}\left(V_{bi}-V-\frac{kT}{e}\right)} \tag{5}$$

where ε_s is the permitivity and Nc the effective density of states for electrons in the conduction band. The space charge (Q_{sc}) per unit area of the semiconductor, and the depletion region capacitance C per unit area are given by

$$Q_{sc}=eN_dW=\sqrt{2eN_d\varepsilon_s\left(V_{bi}-V-\frac{kT}{e}\right)} \tag{6}$$

$$C\equiv\frac{|\partial Q_{sc}|}{\partial V}=\sqrt{\frac{e\varepsilon_s N_d}{2(V_{bi}-V-kT/e)}}=\frac{\varepsilon_s}{W} \tag{7}$$

Equation (7) can be written in the form

$$\frac{1}{C^2}=\frac{2(V_{bi}-V-kT/e)}{e\varepsilon_s N_d} \tag{8}$$

or

$$N_d=\frac{2}{e\varepsilon_s}\left[-\frac{1}{d(1/C^2)/dV}\right]. \tag{9}$$

If the donor concentration (N_d) is constant throughout the depletion region, one should obtain a straight line by plotting $1/C^2$ versus V. From the intercept on the voltage axis, SBH (φ_b) can be determined:

$$\varphi_b=V_{bi}+V_n-\Delta\varphi+\frac{kT}{e} \tag{10}$$

where the voltage (V_n) between the bottom of conduction band and Fermi level can be estimated from

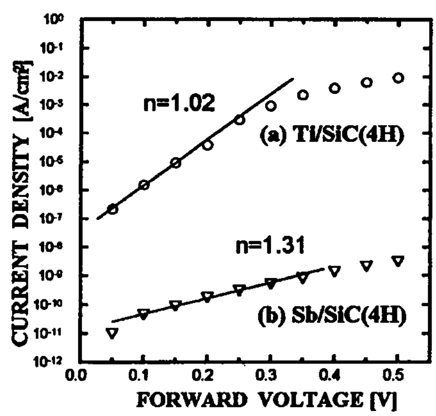

Fig. 5. Ideality factors from the I-V characteristics of (a) Ti/ and (b) Sb/SiC(4H) SBDs under forward bias voltage.

$$V_n = \frac{kT}{e}\ln(\frac{N_c}{N_d}). \quad (11)$$

N_c is calculated to be $2.5\times10^{19}\,cm^{-3}$. V_n is estimated as 0.10 V in SiC(4H) with donor concentration of $2.5\times10^{17}\,cm^{-3}$. $\Delta\varphi$ is given by

$$\Delta\varphi = \sqrt{eE_m/4\pi\varepsilon_s} \quad (12)$$

where E_m is the electric field at the M/SiC interface. ε_s is $9.7\varepsilon_o$ for SiC(4H) (ε_o is the dielectric constant in vacuum). $\Delta\varphi$ is calculated to be below 0.01 V under forward bias condition of about 1 V. Thus, SBH (φ_b) is determined by Eq. (10).

Figures 6 and 7 show plots of the inverse square capacitance ($1/C^2$) versus bias voltage (V) of the of Sb/ and Ti/SiC(4H), respectively. The inverse square capacitance increased with increasing reverse bias voltage as seen in Eq. (8). The straight line obtained by plotting $1/C^2$ versus V, indicated that N_d is constant throughout the depletion region.

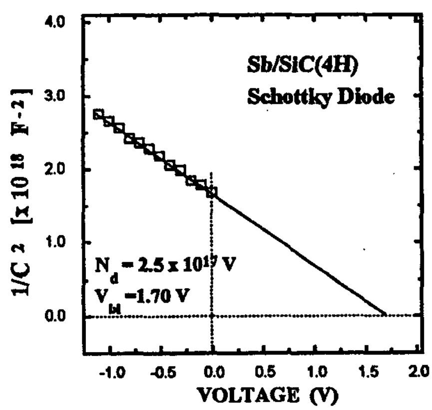

Fig. 6. Plot of $1/C^2$-V in the Sb/SiC(4H) SBD.

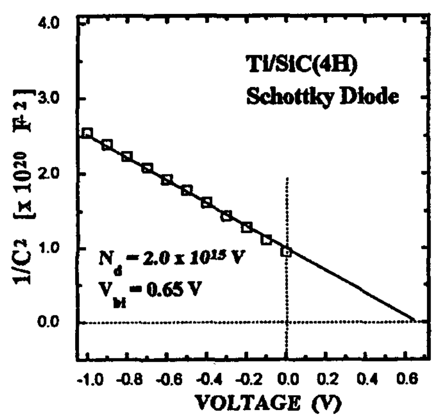

Fig. 7. Plot of $1/C^2$-V in the Ti/SiC(4H) SBD.

From the Eq. (9), N_d was determined to be $2.5\times10^{17}\,cm^{-3}$, and the built-in potentials (V_{bi}) for Sb/SiC(4H) was 1.70 V as written in Fig. 6. In the case of Ti/SiC(4H), N_d of SiC(4H) substrate was determined to be $2.0\times10^{15}\,cm^{-3}$, and the built-in potentials (V_{bi}) was 0.65 V as written in Fig. 7 [18]. The perfomance of power devices based on Schottky contacts depends strongly on the interface property of M/SiC.

4. Conclusions

Sb/ and Ti/SiC(4H) SBDs were fabricated. Schottky contacts on SiC(4H) were formed by thermal evaporation of Sb and Ti metals. The polytype of SiC(4H) was identified by Raman spectrum. Donor concentration of SiC(4H) contacted with Sb was determined to be $2.5\times10^{17}\,cm^{-3}$. The built-in potentials (V_{bi}) for Sb/SiC(4H) were 1.70 V. The ideality factors of 1.07 and 1.31 were obtained from the slopes of forward I-V curves at a low current density level ($<10^{-2}\,A/cm^2$) for Ti/ and Sb/SiC(4H) SBDs, respectively. The breakdown fields were measured to be about 4.4×10^2 V/cm and 1.7×10^3 V/cm for Sb/ and Ti/SiC(4H) SBDs, respectively. The SBHs were calculated to be 1.82 V and 0.91 V from the C-V measurement for Sb/ and Ti/SiC(4H) SBDs, respectively. The SBH and breakdown field of the Sb/ and Ti/SiC(4H) SBDs were very high. The reverse saturation currents were very low. The Sb/ and Ti/SiC(4H) can be utilized as the Shottky barrier contacts for the power electronic device.

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