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Effect of Inserting an Intervening Layer on Φ_b Reduction in TiN Schottky

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Abstract. This report describes the application of titanium nitride (TiN) with a silicon nitride (SiN) intervening layer as a Schottky electrode in a Schottky barrier diode (SBD) made of 4H-silicon carbide (SiC). This reduced the Schottky barrier height (Φ_b) to 0.74eV at room temperature, and it was confirmed that the reduction in Φ_b was due not only to the application of TiN but also to the intervening layer containing SiN at the SiC/TiN interface. Furthermore, TiN with SiN was applied to a device as a Schottky electrode, and the electric field reduction effect was verified by changing the high energy implantation and JBS width. As a result, the forward voltage (V_f) was found to be reduced by a maximum of 0.23 V while suppressing leakage current. The reason for describing the interlayer as "intervening layer containing SiN" is that there may be other substances besides SiN.

Introduction

Silicon carbide (SiC) devices have the advantages of high breakdown voltage, low on-resistance, high-speed switching and high-temperature operation compared with silicon (Si) devices, and are expected to further expand the market to photovoltaic inverters (PVs), electric vehicle (EV) charging stations and on-board chargers (OBCs). For these applications, SiC Schottky barrier diodes are useful devices that take advantage of the excellent properties of SiC, such as low V_f, and various materials have been evaluated as a 4H-SiC Schottky electrode [1, 2]. However, it is necessary to select a material with a low work function and lower Schottky barrier height (Φ_b). Metal nitrides are known to have a lower work function than pure metals [3, 4], and it has also been reported that, for the case of Si, Φ_b can be reduced by inserting an extremely thin insulating film between the Schottky electrode and the substrate [5]. In order to reduce Φ_b in SiC devices, we adopted TiN as the Schottky electrode. In addition, we formed intervening layers containing SiN of different thicknesses as ultrathin films and investigated their impact on Φ_b. Furthermore, we applied TiN with SiN as a Schottky electrode in a device and verified the electric field reduction effect by changing the high energy injection and JBS width.

Sample Structure

Fig. 1 shows a sample structure used to confirm the effect of reducing Φ_b. We prepared 4H-SiC (0001) wafers and formed an oxide film, and then exposed part of the SiC surface by performing a contact opening. Intervening layers of different thicknesses were then formed at the SiC/TiN interface, after which a back electrode was formed. "Intervening layer of different thickness" mean that the thickness of the SiN layer has been varied.

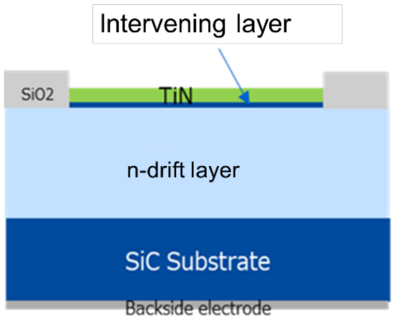


Fig. 1. Sample structure used to confirm the Φ_b.

Experimental Methods

Cross-sectional observation was performed using high-resolution scanning transmission electron microscopy (STEM) to confirm the details of the SiC/Schottky electrode interface. STEM is a technique in which a thin sliced sample is irradiated with an electron beam, and the electrons that pass through or are scattered by the sample are imaged and observed at high magnification, making it possible to observe and analyze the microstructure of and lattice defects in the sample at nano-level high resolution. The results are shown in Fig. 2. In both Fig. 2(a) and 2(b), it can be seen that an intervening layer was formed between the SiC and the Schottky electrode. Moreover, the thickness of the intervening layer differed between Fig. 2(a) and 2(b), with that in Fig. 2(b) being thicker. The thickness was at the atomic layer level under all conditions. In addition, as the intervening layer thickened, the TiN crystal orientation changed from a uniform azimuth to polycrystalline with strong anisotropy. Uniform azimuth means that TiN is in the same direction as SiC, polycrystalline with strong anisotropy means that TiN has different orientations than SiC.

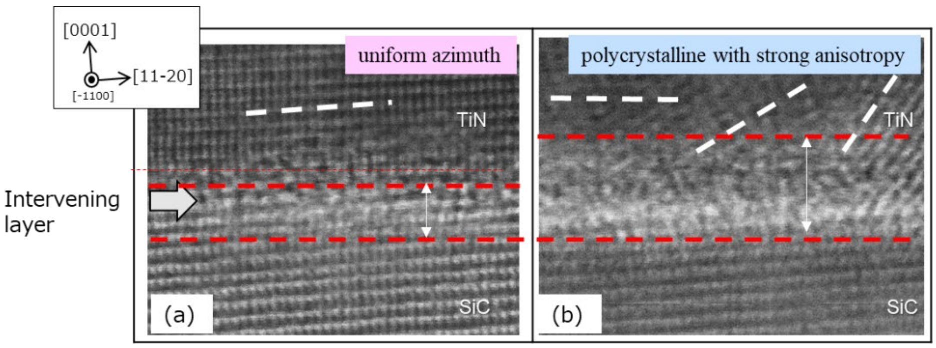


Fig. 2. High-resolution STEM images of the SiC/Schottky electrode interface.

Next, in order to observe the bonding state of atoms in the intervening layer, we performed electron energy-loss spectroscopy (EELS) analysis using the samples observed by STEM. EELS is a technique that measures the energy lost by electrons as they pass through a thin film, allowing the analysis of atoms and electronic structure. The results are shown in Fig. 3. Regardless of the thickness of the intervening layer, peaks were observed near 405 eV. It was found that these peaks originated from SiN. The intensity of the peak near 405 eV increased as the intervening layer became thicker.

The results of these high-resolution STEM and EELS analyses revealed that intervening layers of different thicknesses were formed at the SiC/TiN interface, and that the amount of SiN was greater when the intervening layer was thicker.

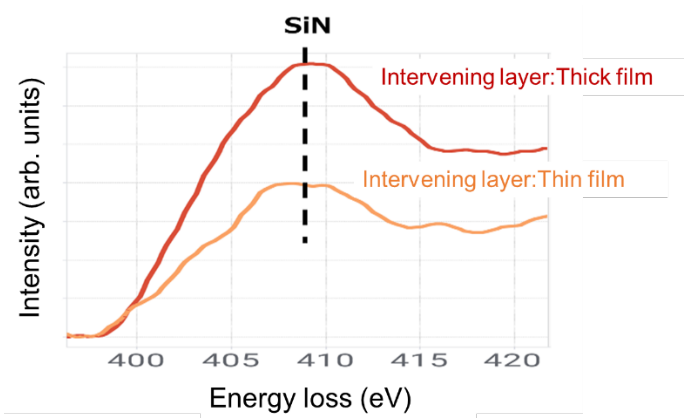


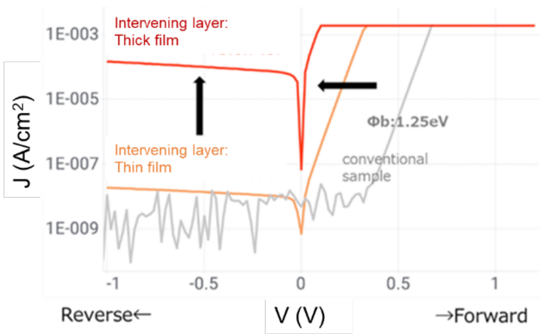
Fig. 3. EELS spectrum at the SiC/Schottky electrode interface.

In order to confirm the effect of using TiN with SiN, the current-voltage (IV) curve and Φ_b were investigated for the above sample and conventional sample. "Conventional sample" refers to SBDs that use TiN electrodes without an intervening layer. The IV curve was measured using a semiconductor parameter analyzer after assembling individual chips onto a direct bonded copper (DBC) substrate after forming the back electrode. Φ_b was calculated by calculating the saturation current density (J_s) from the IV curve measured at −1.0 to 1.0 V using the Shockley diode equation shown in equation (1), and then calculating Φ_b from J_s using equation (2), where J is the current density, V is the applied forward voltage, q is the elementary electric charge, k is the Boltzmann constant, T is the measurement temperature and n is an ideality factor. A Richardson constant of $A^*=146$ A/cm^2 /K^2 was assumed [6]. The results are shown in Fig. 4.

$$J = J_s(e^{\frac{qV}{nkT}} - 1) \quad (1)$$

$$\Phi_{SBH} = \frac{kT}{q}\ln\left(\frac{A*T^2}{J_s}\right) \quad (2)$$

Φ_b was 0.74 eV for a thick intervening layer and 0.89 eV for a thin intervening layer. Compared with the 1.25 eV of a conventional sample, Φ_b was therefore reduced by 0.51 eV by the thick intervening layer. In all conditions, the current of SBD is constant at 1E-003 A/cm^2, but this is due to the measurement conditions.



Condition		Φ_b (eV)
Intervening layer	Thick film	0.74
	Thin film	0.89
Conventional sample		1.25

Fig. 4. IV curve and Φ_b.

It was found that the anisotropy of TiN changed as the intervening layer became thicker and the amount of SiN increased. Even for metals with the same work function, the value of the work function changes depending on the crystal orientation. When the crystal orientation is aligned, electrons easily jump out of the crystal, and the crystal has a positive charge. Therefore, a lot of energy is required to produce residual electrons in the crystal, and the work function becomes larger. However, if the crystal orientation is not aligned, electrons are attracted between the crystals, and the crystals becomes close to neutral. Therefore, energy is not required for the emission of residual electrons, and it is thought that the work function decreases. This suggests that when the intervening layer was thick, Φ_b may have been significantly reduced.

Application to Devices

Although it was confirmed that it is possible to reduce Φ_b by using TiN with SiN, it is important to understand the degree of impact on V_f and I_r when applied to a device. While the device created in Fig.4 has a simplified SBD structure, the device in this chapter is a full device. Fig. 5 shows the V_f-I_f curve and the V_r-I_r curve when a TiN with SiN electrode is applied to a conventional device structure. V_f and I_r were checked at 12 A and 650 V. As shown in Fig. 5(a), it can be seen that V_f is 0.23 V lower for TiN with SiN. This is believed to be due to the reduction of Φ_b by TiN with SiN. However, as shown in Fig. 5(b), in the TiN with SiN sample, I_r is on the order of 10^{-3} A, which is two orders of magnitude larger than that in the conventional sample. This is due to low V_f, and it is clear that suppressing leakage is an issue.

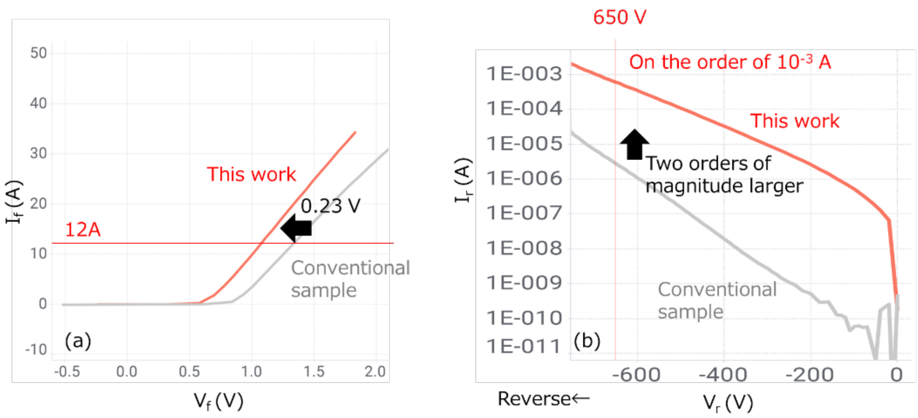


Fig. 5. (a) V_f-I_f curve and (b)V_r-I_r curve when using a conventional device structure.

The device structure was therefore changed to suppress leakage. Fig. 6 shows a schematic diagram of the device model. This device has a JBS structure in which a p-layer is embedded in a part of the n-layer on the semiconductor surface, with the length of the n-layer being W_n and the length of the p-layer being W_p. High energy implantation was performed to change the JBS width. During this process, the half-width of the n-region (W_n) was changed while keeping the cell pitch W_n+W_p constant.

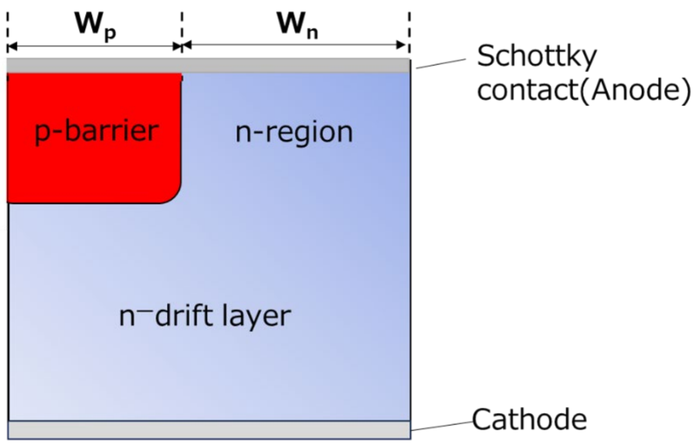


Fig. 6. Schematic diagram of a device model with modified element structure.

Fig. 7 shows the correlation between V_f and I_r when W_n and W_p are changed. I_r was less than 10^{-5} A regardless of the ratio of the n-region. This shows that it is possible to suppress leakage current by more than two orders of magnitude by changing the device structure. Moreover, as the proportion of the n-region increased, V_f decreased and I_r increased. This shows that by adjusting the W_n widths in a device with a modified element structure, it is possible to optimize V_f while suppressing leakage.

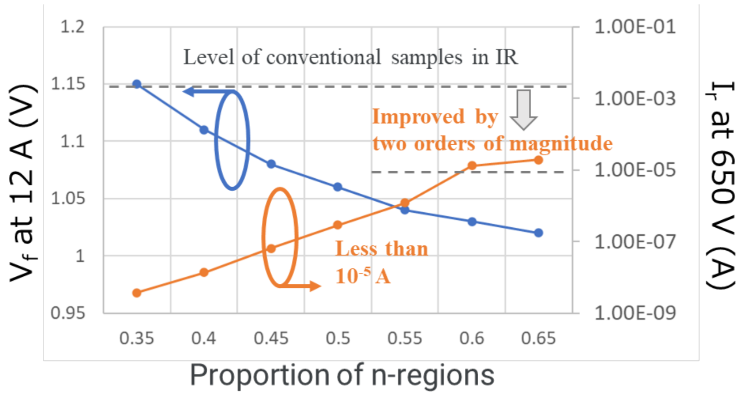


Fig. 7. Relationship between V_f and I_r.

Finally, Fig. 8 shows the relationship between V_f and I_r compared with a conventional sample when a modified device structure was applied using a TiN with SiN Schottky electrode. Compared with the conventional samples, V_f at 12 A was reduced by a maximum of 0.23 V. I_r at 650 V was on the order of 10^{-7} A, which was equal to or lower than that of conventional sample. From the above, it was possible to achieve both low V_f and I_r suppression even when applying TiN with SiN that can reduce Φ_b to a device.

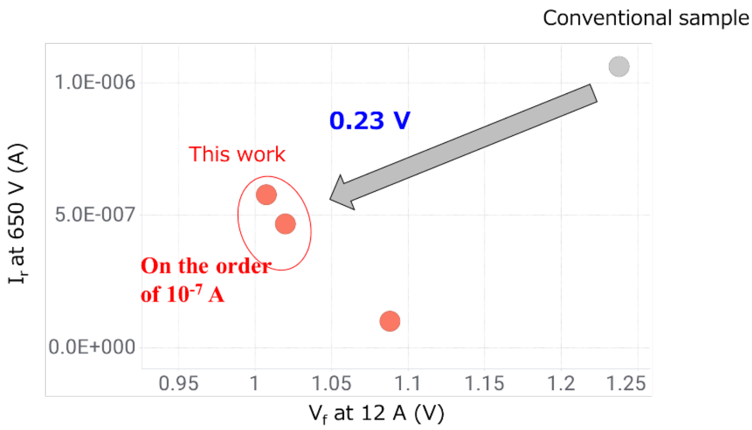


Fig. 8. Relationship between V_f at 12 A and I_r at 650 V.

Summary

It was found that a significant reduction in Φ_b in 4H-SiC can be achieved by selecting TiN with a low work function and by forming an intervening layer containing SiN. This is believed to be because the crystal orientation changes as the intervening layer becomes thicker, causing a change in the Schottky work function. Furthermore, TiN containing an intervening layer was applied to a device as a Schottky electrode, and the electric field reduction impact was verified by changing the energy implantation and JBS width. As a result, it was confirmed that the V_f was reduced by up to 0.23 V while suppressing leakage, demonstrating that it is possible to achieve both a low V_f and I_r suppression.

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