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Schottky Barrier Height Modulation of the Metal/4H-SiC Contact by Ultra-Thin Dielectric Insertion Technique

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Abstract

Schottky barrier height modulation of the metal/ 4H-SiC contact by dielectric insertion is investigated. A thin TiO_2 layer can reduce the barrier height by 0.2 eV. The main mechanism is attributed to the interface dipole because the pinning factor does not change significantly. The dielectric-inserted contact is stable after high current stress. Therefore, this work provides a technique to control the barrier height of Schottky barrier diode and to form low resistance ohmic contact.

1. Introduction

Silicon carbide (SiC) is an important wide bandgap semiconductor material for high power devices. Several kinds of SiC power devices have been proposed. However, some fundamental properties have not been well understood, for example, Schottky barrier height (SBH) control and the contact resistance of the metal/SiC contacts. Due to the Fermi-level pinning effect, the SBH (ϕ_{bn}) can be expressed as $\phi_{bn} = S(\phi_m - \phi_{CNL}) + (\phi_{CNL} - \chi)$, where S is the pinning factor defined as $d\phi_{bn}/d\phi_m$, χ is the electron affinity of the semiconductor, and ϕ_{CNL} is the semiconductor charge neutrality level. Fig. 1 shows the published SBHs as a function of the metal work function (ϕ_m) [1-7]. The pinning factor is around 0.6~0.7. Basically, lower ϕ_m achieves lower SBH and thus lower contact resistance. However, low ϕ_m metals are active and maybe not compatible with semiconductor process. It has been reported that dielectric insertion can reduce the SBHs on Si, Ge, and GaAs [8~10]. In this work, the SBH modulation on 4H-SiC by the dielectric insertion technique is studied.

2. Experiments

Simple Schottky barrier diodes (SBDs) were fabricated on a nitrogen doped 4H-SiC substrate containing a 5-μm-thick epitaxial layer with a doping concentration of $3x10^{15}$ cm^{-3}. TiO_2 is selected as the insertion dielectric due to the negative electron barrier between SiC and TiO_2 as shown in Fig.2. The TiO_2 layers were deposited at 250 °C using TDMAT and H_2O as precursors. Contact metals were deposited by thermal evaporation and sputtering processes. Finally, a 300-nm-thick Al was deposited for probing followed by a 500 °C vacuum annealing. The key process conditions are listed in Table I.

3. Results and Discussion

Fig.3 shows the I-V characteristics of the Ti SBDs with various TiO_2 thicknesses. The SBD without TiO_2 layer exhibits the highest SBH and the lowest leakage current. Fig.4 shows the SBH extracted from the thermionic model. The SBH decreases from 0.9 eV to 0.63 eV as the TiO_2 thickness increases from 0 nm to 5 nm. As the dielectric thickness exceeds 5nm, a slightly increase of the SBH is observed. This phenomenon is similar to that observed on Ge substrate [10]. Fig.5 shows the on-resistance (R_{on}) extracted at $V=\phi_{bn}$. The R_{on} does not degraded by the TiO_2 layer as expected.

The possible mechanisms of the SBH reduction include metal-induced gap state (MIGS) model, dipole model, and fixed charge model [11]. Fig.6 shows the SBHs of the SBDs with various contact metals. The pinning factor of the SBDs without dielectric insertion is 0.8, which is similar to that reported in literatures. If the mechanism of the SBH reduction comes from the passivation of the MIGS by the inserted dielectric, the pinning factor should be close to 1. Since the pinning factor of the TiO_2-inserted SBDs increases slightly to 0.85 as shown in Fig.6, the MIGS model may be not the dominant mechanism. Because a 2-nm-thick TiO_2 insertion reduces the SBH by ~0.2 eV on the Al, Ti, and Ni contacted diodes, it is suggested that the interface dipole which resulting potential drop is the main mechanism for the SBH reduction. Fig.7 shows that the SBH and ideality factor of the Ti SBD with 2-nm-thick TiO_2 are stable after high current stress.

The I-V characteristics of the Ni SBDs with 2-nm-thick TiO_2 layer and without TiO_2 layer are compared in Fig.8. With dielectric insertion, a kink is observed at forward bias while the reverse biased leakage current increases. Most of the TiO_2-inserted SBDs show this phenomenon. It is unlikely that the thermal ALD process would increase defects in SiC. It is thus suggested that a very low SBH area exists in these diodes. The low SBH can be extracted from the reverse bias current considering the complete thermionic field emission model [11] and the SBH as low as 0.4 eV is shown in Fig.9. The mechanism is not clear at this moment.

4. Conclusions

A thin TiO_2 layer insertion can reduce the SBH of the metal/4H-SiC contact by 0.2 eV. The pinning factor increases slightly from 0.8 eV to 0.84 eV so that the SBH modulation is attributed to the interface dipole. The dielectric-inserted contact is stable after high current stress. It is suggested that this technique can be used to control the SBH of SBD and to form low resistance ohmic contact.

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Table I. Key process conditions.

Contact metal	Al (300nm)	Ti (100nm)	Mo (30nm)	Ni (100nm)
Deposition method	Thermal evaporation	Sputter	Sputter	Sputter
TiO_2 (nm)	0, 2	0, 1, 2, 5, 8	0, 2	0, 1, 2, 5, 8
Annealing	500 °C / 5min / vacuum furnace			

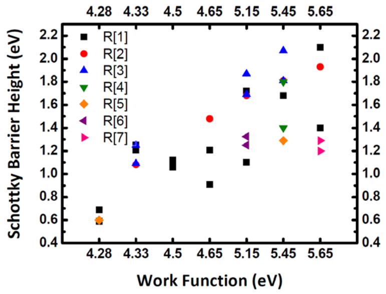

Fig.1 Schottky barrier height as a function of metal work function reported in literatures. The pinning factor is around 06~0.7.

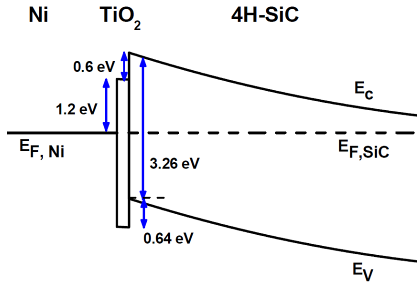

Fig.2 Band diagram of a TiO_2-inserted metal/4H-SiC Schottky barrier diode. The conduction band of TiO_2 is lower than that of the SiC, which is preferred to avoid electron tunneling resistance.

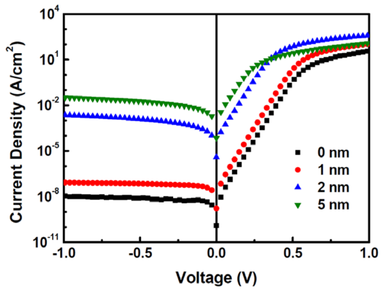

Fig.3 Current-voltage characteristics of the Ti SBDs with various TiO_2 thickness. Thicker TiO_2 results in lower SBH and higher reverse current.

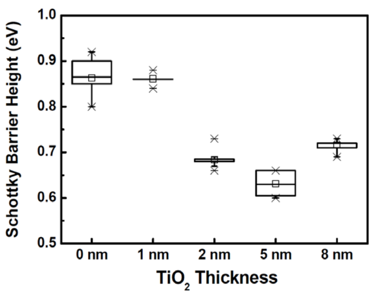

Fig.4 Schottky barrier height as a function of TiO_2 thickness. A 0.2 eV SBH reduction is achieved with a 2-nm-thick TiO_2 insertion.

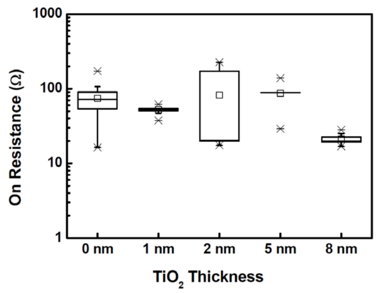

Fig.5 On-resistance as a function of TiO_2 thickness at $V=\phi_{bn}$. The inserted TiO_2 does not degrade the on-resistance.

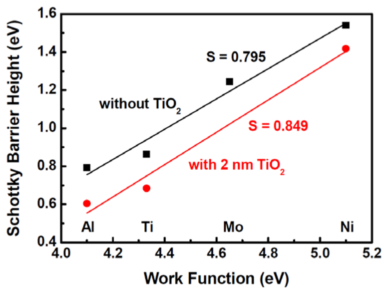

Fig.6 Schottky barrier height a a function of metal work function. The inserted TiO2 does not change the pinning factor significantly.

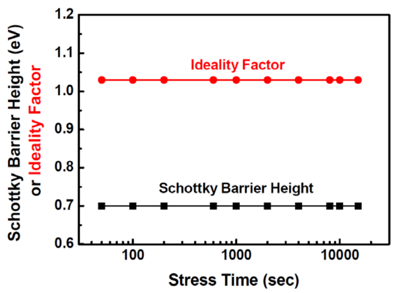

Fig.7 Schottky barrier height and ideality factor of the Ti/TiO_2(2nm)/SiC SBD after current stress at ~300 A/cm^2 for 15,000 seconds. Both parameters are very stable.

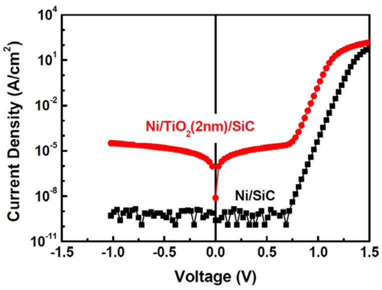

Fig.8 Current-voltage characteristics of Ni SBDs with and without TiO_2 insertion layer. Most of the TiO_2-inserted SBDs show similar kink effect, which indicate the existing of a low Schottky barrier area.

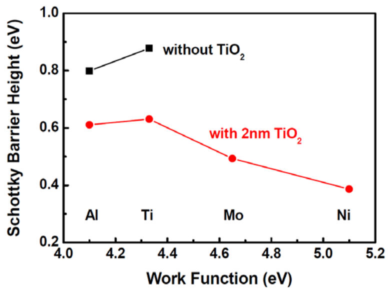

Fig.9 Schottky barrier heights extracted by the complete thermionic-field emission model at reverse bias. The Schottky barrier height of the low barrier region is about 0.4 eV.