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Strong Fermi-level pinning induced by argon inductively coupled plasma treatment and post-metal deposition annealing on 4H-SiC

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ABSTRACT

The effect of pre–metal deposition cleaning on 4H-SiC Schottky barrier diodes (SBDs) by using Ar ion bombardment in an inductively coupled plasma (ICP) chamber was investigated. The ICP treatment produced a thin and Si-depleted amorphous layer on the SiC surface. Partial graphitization was observed in the amorphous layer after post-metal deposition (PMD) annealing. This interfacial layer strongly pinned the Schottky barrier height (SBH). PMD annealing at 500 °C resulted in a constant SBH (approximately 1.1 eV) and narrow SBH distribution (standard deviation < 3 meV). However, the amorphous layer was consumed after 600 °C PMD annealing due to interfacial reactions. These results suggest that the Ar ion bombardment technique with a suitable thermal budget can be used to form relatively uniform SBDs.

1. Introduction

Schottky barrier diodes (SBDs) are extensively used in all types of power electronics modules. Because SiC-based SBDs have numerous advantages over Si-based SBDs—such as a higher breakdown voltage, wider safe operating area, and lower switching loss—Si-based SBDs are gradually being replaced [1,2]. For a favorable SBD process, controlling the mean value and variation are both crucial. For 4H-SiC SBDs, many types of metal contact have been investigated [3–5]. The Fermi-level pinning (FLP) effect plays a critical role in the Schottky barrier height (SBH). The SBH for an electron in an n-type semiconductor (Φ_{bn}) can be expressed as $\Phi_{bn} = S(\Phi_m - \Phi_{CNL}) + (\Phi_{CNL} - \chi)$, where S is the pinning factor, χ is the electron affinity of the semiconductor, Φ_m is the metal work function, and Φ_{CNL} is the semiconductor charge neutrality level [6]. The FLP effect in various semiconductor materials has been widely reported. As illustrated in Fig. 1 [3–5], the S-factor of SiC, extracted from the slope, is approximately 0.6–0.7; thus, the FLP effect in SiC is much weaker than that in Si and Ge [7]. The benefit of a weak FLP effect is that the SBH is easily adjusted by changing the metal used. However, the characteristics of SBDs are sensitive to the fabrication process, especially those steps that affect the metal–SiC interface such as the surface cleaning and post-metal deposition (PMD) thermal processes. Nonetheless, all semiconductor devices require an ohmic metal–semiconductor contact. The contact resistance is related to the SBH of the metal–semiconductor interface. A weak FLP effect indicates that a low-work-function metal must be employed to obtain a low-resistance contact in n-type SiC. Nevertheless, low-work-function metals are generally active to oxygen and easily form metal oxides, which increase the resistance in the current conduction path. These issues limit metal selection and process flexibility.

Some pre–metal deposition cleaning methods have been proposed, such as dipping in dilute HF or acid-base/organic solution, CF_4 plasma cleaning, and the growth of a sacrificial oxide [8]. CF_4 plasma etching was used to clean the surface of 6H-SiC in a previous study [8]; the SBH was reduced, but the contact resistance was increased. Another study applied 8-MeV Si^{4+} ion irradiation to a Ti/4H-SiC SBD; this was reported to modify the interface by hundreds of nanometers and induce an increase in the SBH and specific on-resistance without any subsequent thermal treatment required [9]. These previous studies have revealed that plasma etching and high-energy ion irradiation are not feasible methods for SiC surface preparation.

Little research has been focused on the effect of Ar ion bombardment, which is a commonly used method in Si processing for the removal of native oxide and polymer residue and can be easily

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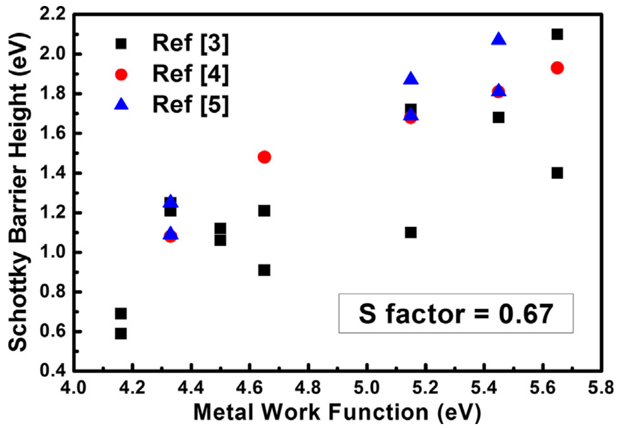

Fig. 1. SBH as a function of metal work function, as reported in the literature. The pinning factor extracted from the slope was approximately 0.67, indicating that the FLP effect was weak on the original SiC surface.

integrated into sputtering systems [10]. However, the damage caused by Ar ion bombardment during plasma processing, including deposition and etching, should be considered if this method is to be used [11]. Lower-power Ar ion bombardment can disorder the SiC surface to a depth of a few nanometers and induce numerous defects in order to change Φ_{CNL} [6]. Concurrently, the stoichiometry of the SiC near-surface region can be altered by mobile defects and the higher sputtering yield of Si compared with C [12,13]. Previous studies have suggested that carbon atoms play a crucial role in the modification of the metal–SiC contact due to the interdiffusion, reaction, or even graphitization of excess carbon atoms and metal [14–16]. Using Ar ion bombardment and a subsequent thermal process in the process flow is suspected to modify the characteristic of SiC SBDs.

In this study, 4H-SiC SBDs were fabricated and characterized using Ar ion bombardment. Strong SBH pinning and a narrow SBH distribution were observed. Transmission electron microscopy (TEM), energy dispersive spectroscopy (EDS), and X-ray photoelectron spectroscopy (XPS) were performed to determine the effect of Ar ion bombardment and PMD annealing on the metal–SiC contacts.

2. Experimental procedure

The SBDs were fabricated using an n-type (0001) 4° off-axis 4H-SiC wafer that contained a 5.5-μm-thick epitaxial layer with a nitrogen doping concentration of $1 \times 10^{16}\ cm^{-3}$ on a 350-μm-thick substrate with a nitrogen doping concentration of $1 \times 10^{18}\ cm^{-3}$. First, samples were cleaned using the standard RCA cleaning process, after which a 300-nm-thick SiO_2 layer was deposited using plasma-enhanced chemical vapor deposition to serve as a field oxide. A nickel film was sputtered onto the back of the wafer and then annealed at 1000 °C for 30 s to form backside ohmic contacts. The front-side Schottky contact area was patterned using photolithography and wet etching.

Before contact metal deposition, samples were cleaned through immersion in diluted HF solution. Ar ion bombardment was performed using an inductively coupled plasma (ICP) chamber with a bias power of 400 W and radiofrequency power of 100 W in a clustered sputtering system. This step is termed ICP treatment in the remainder of this paper. Three metals, namely Ni (100 nm), Ti (100 nm), and Al (300 nm), were deposited using a sputtering system immediately after ICP treatment. A 10-nm-thick TiN layer as a capping layer to isolate oxygen in the atmosphere was deposited using the same sputtering system without breaking the vacuum. The contact metals were patterned using chemical etching (Ni) or high-density plasma etching (Ti and Al). PMD annealing was performed at 400–600 °C using a vacuum furnace for 5 or 30 min, after which a 300-nm-thick Al layer was deposited using thermal evaporation. The Al pads were patterned using a lift-off process.

3. Results and discussion

The typical current density–voltage (J–V) characteristics of the SBDs are illustrated in Fig. 2, with the Ti-SBD used as an example. The diameter of the circular SBD was 100 μm, and ICP treatment was performed for 30 s. The reverse current density displayed in Fig. 2(b) was limited by the probing system when the applied voltage was less than −40 V. In this range, the ICP-treated SBD without PMD annealing exhibited the highest leakage current density, which is attributed to the defects generated by ICP treatment. When the applied voltage exceeded −40 V, the reverse current density was approximately proportional to the SBH of each SBD, and no obvious ICP-treatment-induced leakage current degradation was observed. The forward-bias characteristic was degraded severely in the ICP-treated SBDs when the PMD annealing temperature was less than 400 °C. This indicates that numerous defects were generated by the ICP treatment, resulting in high and multiple SBHs, and that these defects were not repaired by the 400 °C PMD annealing. A low conduction current was observed at +3 V, indicating that the damaged layer also contributed a high parasitic resistance. When the PMD annealing temperature was increased from 400 to 600 °C, the J–V characteristic curve recovered

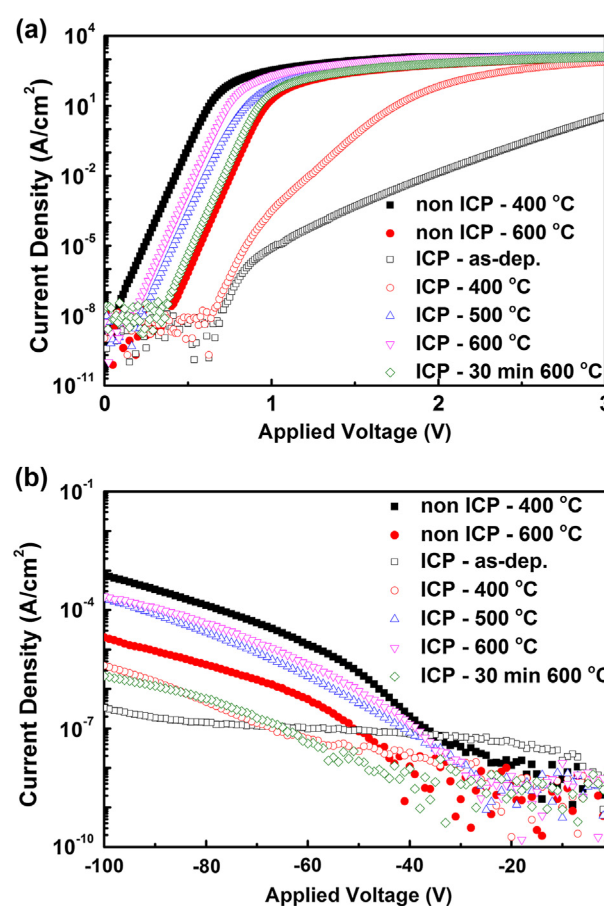

Fig. 2. (a) Forward and (b) reverse J–V characteristics of non- and ICP-treated Ti-SBDs. The ICP treatment duration was 30 s.