

Electrical properties of Al/Al₄C₃/4H-SiC diodes

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ABSTRACT

The impact of aluminum carbide (Al₄C₃) at the metal/silicon-carbide (SiC) interface is presented here with respect to 4H-SiC Schottky barrier diodes (SBDs). A post-annealing process at a high temperature (1000 °C) has been employed for the reaction between the aluminum and the carbon. The current density of the fabricated device was measured as $\sim 13.4 \text{ A/cm}^2$ at 5 V with a leakage current density of less than $\sim 6.84 \times 10^{-9} \text{ A/cm}^2$ at -5 V . The thermal-activation energy ($E_A = 0.35 \text{ eV}$) extracted from the Arrhenius plot decreased by $\sim 37\%$ via the formation of the Al₄C₃. According to the experiment results, the sample with the Al₄C₃ layer yields a rectification ratio of 1.95×10^9 that is 33 times higher than that of the reference SBDs. The structural defects of the SiC interface may be available for the formation of the Al₄C₃ layer.

1. Introduction

Silicon carbide (SiC) is an established alternative to silicon (Si) for high-performance power devices. The superior material properties of SiC enable the excellent electrical characteristics of SiC devices such as high-temperature operability, high critical electrical fields, high mobility, low on-resistance, and ultrafast switching speed [1]. Schottky barrier diodes (SBDs) made from 4H-SiC are attractive devices because of their high switching speed and a simple fabrication process; however, the higher reverse-leakage current of SBDs compared with the other devices is a considerable concern [2–4]. To realize SiC devices, it is therefore important to investigate the interfacial properties of metal and SiC structures.

In this paper, the Al₄C₃ that is formed in the Al-SiC interlayers is one of the key factors for the improvement of the 4H-SiC SBDs. Al₄C₃ comprises a hexagonal structure with unit-cell parameters that are similar to those of 4H-SiC, and it is an important compound in the technology of aluminum (Al) metal and its composite materials [5]. Further, Al₄C₃ is an attractive material in terms of lightweight components such as power devices and internal-engine parts due to a low thermal expansion and a high thermal conductivity [6].

In many studies, an important method for the formation of Al₄C₃ from the Al-carbon (C) melt has been reported. It is known that Al activates the growth of diamond crystals at high temperatures [7,8]. Moreover, its formation in the interfacial reactions between the Al and SiC increases the properties of the device performance due to the removal of the Si-face and a decrease of the contact resistance [9]. In this study, the properties of Al/Al₄C₃/4H-SiC diodes and the impact of post-

annealing on the device performance are investigated. From the experiments, improved electrical characteristics were observed after the formation of the Al₄C₃ layer that occurred after the Al interlayer was subject to annealing process.

2. Experimental

The SBDs form the basic structure of the fabricated devices. The 4H-SiC substrates that were used in this work comprise an n-type epitaxial layer ($N_D = 1 \times 10^{15} \text{ cm}^{-3}$) that was grown on an n-type substrate ($N_D = 1 \times 10^{18} \text{ cm}^{-3}$). The standard sample size is $1 \times 1 \text{ cm}^2$. After the chemical cleaning of the substrate in a 4:1 solution of sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) (SPM), the native oxide layers were treated using a buffered oxide etch (BOE) solution. Then, a $\sim 15 \text{ nm}$ -thick Al film was deposited on the Al₄C₃ structure samples under a $5 \times 10^{-3} \text{ Torr}$ vacuum condition with an Ar working pressure using dc-magnetron sputtering. Thermally grown α -Al₄C₃ layers formed in the Al₄C₃ structure samples, and the device was subject to successive 10-min-long treatments of the rapid thermal annealing (RTA) process at 1000 °C. Prior to the annealing and after the samples were cleaned in an SPM and BOE dip, a large-area ohmic contact was formed on the back through the deposition of a 100 nm-thick Al film using DC-magnetron sputtering, and this was followed by the RTA process in N₂ at 950 °C for 90 s. The 100-nm-thick Al film was deposited on the front side of the samples using a shadow mask with an area of $3.14 \times 10^{-2} \text{ cm}^2$, and this enabled the formation of macroscopic circular patterns. We confirmed the formation of the Al₄C₃ by using field emission scanning electron microscopy (FE-SEM) and X-ray photoelectron spectroscopy

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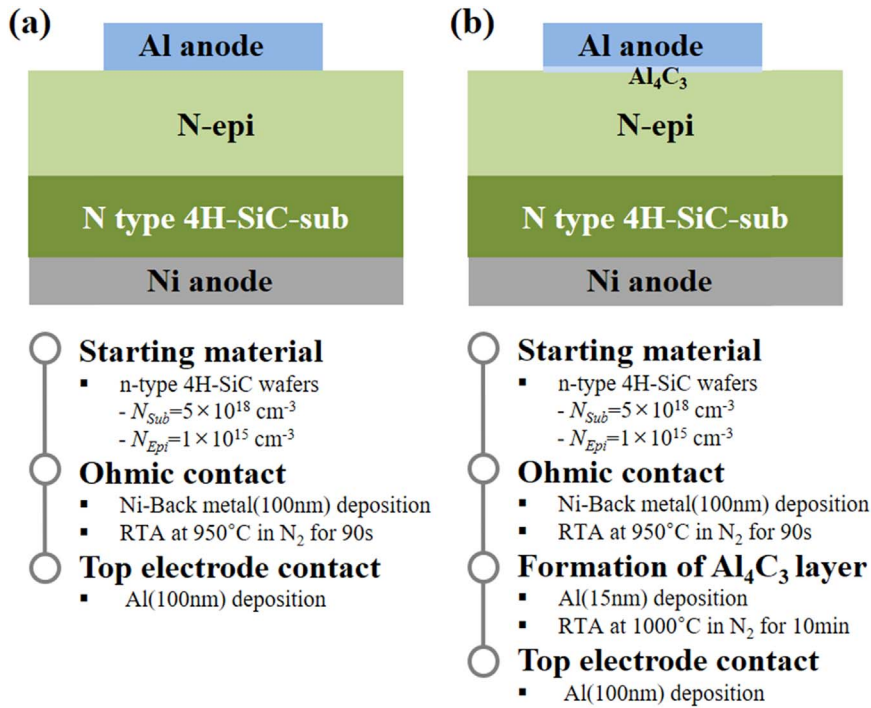


Fig. 1. Structure of the fabricated 4H-SiC diodes and process flows: (a) Reference and (b) Al_4C_3 structure.

(XPS) in Al_4C_3 structure. The Keithley 4200 semiconductor parameter analyzer (Keithley Instruments Inc., Cleveland, OH, U.S.A.) was employed for the measurement of the current density-voltage (I - V) characteristics.

3. Results and discussion

The SBD devices that were fabricated (Al_4C_3 structure) with and (Reference structure) without the Al_4C_3 are shown in Fig. 1. Reference structure was fabricated basically as a 4H-SBD; by contrast, Al_4C_3 structure was additionally annealed. Note that the post-annealing was carried out to form the Al_4C_3 layer (see Fig. 1(b)). The scanning electron microscopy (SEM) images of the fabricated samples are shown in Fig. 2(a) and (b), wherein it is evident that the Al reacts with the C and oxygen for the Al-C bonding during the high-temperature annealing process. Since the reaction of Al-C in Al_4C_3 structure is not uniform due to melting of Al during the annealing process, inhomogeneous barrier height in the interface was considered by using measured I - V characteristics for extracting barrier height using the Eq. (5).

To explain the formation of Al_4C_3 on surface of 4H-SiC in Al_4C_3 structure, the device was further characterized using XPS as shown Fig. 2(c) and (d). The original peak position of C 1s of Reference structure was located at 283.1 eV (C-Si) [10]. However, the C 1s spectrum of Al_4C_3 structure has additional peak which is ascribed to C-Al. As for C species on surface, C-Si and C-Al species are dominant. Based on the present XPS results, the C-Al peak (282.7 eV) intensity observed on surface can be explained by the presence of Al_4C_3 [11]. It is favorable that the Al_4C_3 is formed at the interface of the Al-SiC through the use of the dewetting method with the simple fabrication process. The reaction between SiC and pure Al creates a phase equilibrium in terms of the binary chemical system. A post-annealing process at a temperature above 750 °C is needed for the completion of the Al-C bonding because the free energy for the formation of the Al_4C_3 is 168 kJ/mol at ~ 750 °C [12]. The formation of Al_4C_3 is according to the chemical reaction of $4Al + 3SiC \rightarrow Al_4C_3 + 3Si$.

Lattice defects created by deposition and surface preparation would be responsible for decrease of performance by leading to trap carriers. In this region, the defects can be removed by bonding with Al and the C atoms on surface become available to form Al_4C_3 as the Si is depleted

[13].

The formed α - Al_4C_3 layer on the SiC is not uniform due to the annealing temperature is above the melting point of Al and the different thermal-expansion coefficients between the Al and the SiC [14]. Fig. 3 shows the measured J - V characteristics of the devices. The current density of Reference and Al_4C_3 structure is 2.8 and 13.4 A/cm², respectively. The value of current density of both Devices is not similar to each other while the leakage current density of Reference and Al_4C_3 structure is 4.84×10^{-8} and 6.83×10^{-9} A/cm², respectively, when negative bias ($-5V$) is applied as shown in the inset of Fig. 3. The I - V and J - V characteristics in the forward bias were driven by the following equation of the thermionic-emission model (1, 2) [15–17]

$$J = J_S [\exp(qV/kT) - 1], \quad (1)$$

$$J_S = A^* T^2 \exp[-q(\Phi_b - \Delta\Phi_{bi})/kT], \quad (2)$$

where J_S is the saturation current density, A^* is the Richardson constant (146 A/cm²K² in 4H-SiC), T is the temperature, q is the electron charge, $\Phi_b - \Delta\Phi_{bi}$ is known as the effective barrier height, and k is the Boltzmann constant. The I - V characteristics in forward bias can be rewritten as follow:

$$J = J_S [\exp(qV/\eta kT)], \quad (3)$$

where η is the ideality factor, which can be extracted by using following equation:

$$\eta = q/kT [dV/d(\ln J)], \quad (4)$$

At room temperature, Al_4C_3 structure has low leakage current density comparing with Reference structure.

For Reference structure, the average Schottky barrier height is 0.93 eV whereas it is 1.12 eV for Al_4C_3 structure for the range of 50–200 °C. Through post annealing process, the barrier height of Al_4C_3 structure is higher than that of Reference structure and it can be explained by the depletion region increased due to bonding of Al-C like p-type dopant [18]. The Schottky barrier height increases for Reference and Al_4C_3 structure with increasing temperature, as shown in Fig. 4. The ideality factor of Reference structure was 1.24, which increases with temperature, indicating that thermionic emission is dominant. In Al_4C_3 structure, the ideality factor slightly increases from 1.09 to 1.16

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