Applied Surface Science 355 (2015) 59–63

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Enhanced TiC/SiC Ohmic contacts by ECR hydrogen plasma pretreatment and low-temperature post-annealing

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ARTICLE INFO

Article history:
Received 9 March 2015
Received in revised form 8 June 2015
Accepted 15 July 2015
Available online 17 July 2015

Keywords:
SiC semiconductor
Ohmic contacts
Schottky barrier
Surface states
Annealing
Hydrogen plasma pretreatment

ABSTRACT

We proposed an electronic cyclotron resonance (ECR) microwave hydrogen plasma pretreatment (HPT) for moderately doped (1×10^{18} cm^{-3}) SiC surfaces and formed ideal TiC/SiC Ohmic contacts with significantly low contact resistivity (1.5×10^{-5} Ω cm^2) after low-temperature annealing (600 °C). This is achieved by reducing barrier height at TiC/SiC interface because of the release of pinned Fermi level by surface flattening and SiC surface states reduction after HPT, as well as the generation of donor-type carbon vacancies, which reduced the depletion-layer width for electron tunneling after annealing. Interface band structures were analyzed to elucidate the mechanism of Ohmic contact formations.

1. Introduction

Silicon carbide (SiC) has promising applications in high-temperature and high-power electronic devices because of its excellent physical properties [1]. However, the realization of SiC Ohmic contacts with low contact resistivity is a critical challenge in SiC-based devices [2–4]. To achieve low ρ_c, the effective Schottky barrier height ($q\phi_{Bn}$) must be reduced. In general, Ohmic behavior can be achieved by using heavily doped (10^{19}–10^{20} cm^{-3}) SiC layer or high-temperature metallization (i.e., >1000 °C) [5]. However, heavily doped substrates bring high cost and difficult technology; high-temperature metallization causes rough morphologies of electrodes [2,5]. In theory, selecting a metal with a low work function ($q\phi_m$) for n-type semiconductors is an alternative way to reduce $q\phi_{Bn}$. In practice, however, different $q\phi_m$ values are limited to the control of $q\phi_{Bn}$ between the metal and the semiconductor because of the physicochemical nature of the surface before contact and the interfacial chemistry [4,6]. Numerous experiments demonstrated that $q\phi_{Bn}$ reduction improves Ohmic properties through the release of Fermi level pinning (FLP) at the metal/SiC interface, which is controlled by various SiC surface treatments [5,7].

Low-temperature electronic cyclotron resonance (ECR) microwave hydrogen plasma treatment (HPT) is an advanced surface-cleaning technique that provides effective chemical and electrical passivation of SiC surfaces [8,9]. In addition, the transition metal carbide TiC is an excellent material for SiC Ohmic contact applications because of its low $q\phi_m$ (3.94 eV) [10], low mismatch, and high interface stability at the TiC/4H–SiC interface [2]. Therefore, the present study hypothesized that controlling the surface properties of 4H–SiC via HPT, in combination with TiC, can yield satisfactory TiC/SiC Ohmic contacts without the need for heavy impurity doping and high-temperature annealing.

2. Experimental

Two Si-face (0 0 0 1) groups n-type 4H–SiC with a doping concentration of 1×10^{18} cm^{-3} (Cree Research Inc.), cleaned by a standard Radio Corporation of America (RCA). Then samples treated with HPT (650 W, H_2 flow 60 mL/min, 270 °C for 3 min) by an independently-developed ECR plasma generator (National Invention Patent provided by State Key Laboratory of Material Modification by Laser, Ion and Electron Beam, Dalian University of Technology) [11]. The circular transmission line method (CTLM)

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http://dx.doi.org/10.1016/j.apsusc.2015.07.100
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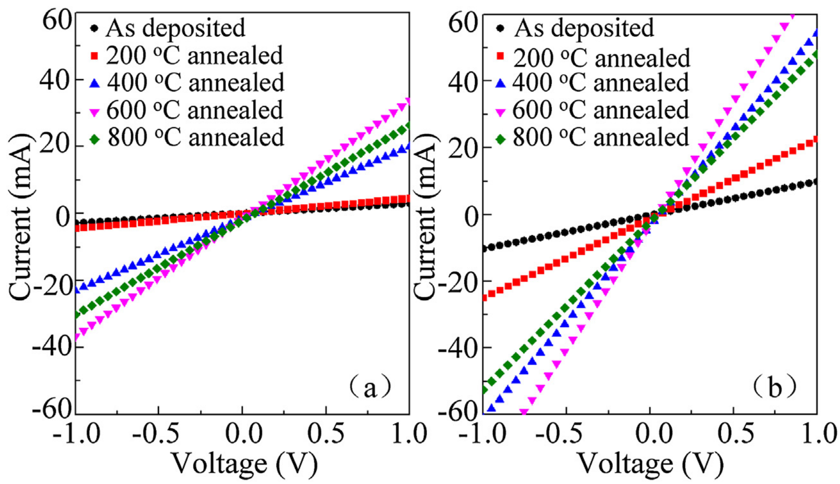

Fig. 1. *I*–*V* characteristics of TiC contacts to 4H–SiC samples (a) without and (b) with HPT as a function of annealing temperature (AT).

patterns with 10–50 μm gaps were formed by optical lithography with AZ703 positive photoresist (3500 rpm/min for 40 s). The radius *r* of each CTLM structure is 150 μm. Then, TiC (200 nm) was deposited using a JGP-450 RF magnetron sputtering system from ShenYang Academy of Instrumentation Science (180 W, 250 °C for 50 min, 4.2 Pa). After the lift-off process, samples were annealed in N_2 at 200, 400, 600, and 800 °C for 5 min, respectively. The Ohmic properties were evaluated by current–voltage (*I*–*V*) measurements at room temperature using a Keithley 4200 semiconductor parameter analyzer (scanning voltage −1 to 1 V, step 0.05 V, hold time 100 ms). The surface morphological properties of unmetallized 4H–SiC samples were monitored by VEECO D-3100 atomic force microscopy (AFM) in tapping mode. To investigate the surface chemical and electrical properties by HPT and post-annealing, clean unmetallized 4H–SiC surfaces were characterized using an VG ESCALAB MK2 X-ray photoelectron spectroscopy (XPS) in an Axis Ultra delay-line detector system equipped with a monochromated Al Kα X-ray source. The phases that formed in the contact interfaces at post-annealing were examined using a D/max-2400 X-ray diffractometer (XRD).

3. Results and discussion

Fig. 1 shows *I*–*V* characteristics of the contacts without and with HPT samples before and after annealing at 200, 400, 600, and 800 °C. The as-deposited TiC contacts on both samples exhibited linear *I*–*V* curves, which indicated that Ohmic contacts were formed without post-annealing. The slopes of the *I*–*V* curves gradually increased as the annealing temperature (AT) was increased from 200 to 600 °C. This result suggested that the Ohmic quality of both samples gradually improved. However, the slopes of the curves slightly decreased after 800 °C AT, which indicated that the TiC contacts did not require high-temperature annealing (>600 °C) to improve their Ohmic properties.

Using the CTLM model [12], the total resistance (R_T) between two adjacent pads placed at a disitance (*d*) denpends on the contact resistance (R_C) and the sheet resistance (R_{SH}), which can be expresses as $R_T = R_{SH}d/2\pi r + 2R_C$. Fig. 2 shows R_T values as a function of *d* for HPT-treated sample at 600 °C AT. Slope is $R_{SH}/2\pi r$, the intercept with the *y*-axis is $2R_C$, and with the *x*-axis is $2L_T$ (transfer length). Thus, ρ_c can be calculated by $\rho_c = R_{SH}\, L_T{}^2$ as shown in Fig. 3. The ρ_c value of the sample with HPT was approximately two orders of magnitude lower than that of the sample without HPT at the same AT. This result indicated that HPT remarkably improved the contact quality of the TiC/SiC interfaces. ρ_c decreased to $1.5 \times 10^{-5}\ \Omega\,\mathrm{cm}^2$

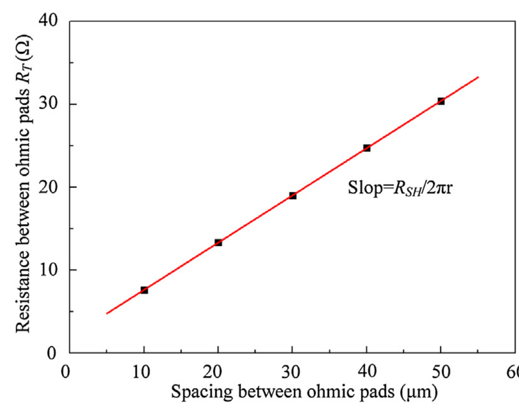

Fig. 2. Total resistance (R_T) as a function of contact spacing (*d*) for HPT-treated sample annealing at 600 °C.

after 600 °C AT. However, the contact quality only slightly deteriorated after 800 °C AT. Moreover, ρ_c with HPT apparently became worse than that without HPT, indicating that HPT did not further decrease ρ_c exceeding 600 °C AT. Nonetheless, HPT enhanced the property of Ohmic contact after 800 °C AT, as evidenced by the relatively lower ρ_c.

At moderate doping concentrations, thermionic field emission (TFE) [13] is the predominant carrier transport process. Therefore,

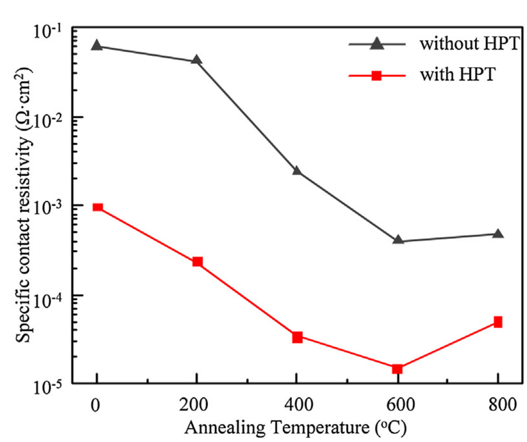

Fig. 3. Contact resistivity (ρ_c) as a function of AT for TiC Ohmic contacts to 4H–SiC samples without and with HPT.