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Ohmic contact behaviour of Co/C/4H-SiC structures*

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Abstract: The electrical contact properties of Co/4H-SiC structures are investigated. A carbon interfacial layer between a Co film and SiC is used to improve the Ohmic contact properties significantly. The C film is deposited prior to Co film deposition on SiC using DC sputtering. The high quality Ohmic contact and specific contact resistivity of 2.30×10^{-6} $\Omega\cdot$cm^2 are obtained for Co/C/SiC structures after two-step annealing at 500 ℃ for 10 min and 1050 ℃ for 3 min. The physical properties of the contacts are examined by using XRD. The results indicate that the Co-based metal contacts have better structural stability of silicide phases formed after the high temperature annealing and carbon-enriched layer is produced below the contact, playing a key role in forming an Ohmic contact through the reduction of effective Schottky barrier height for the transport of electrons. The thermal stability of Au/Co/C/SiC Ohmic contacts is investigated. The contacts remain Ohmic on doped n-type (2.8×10^{18} cm^{-3}) 4H-SiC after thermal aging treatment at 500 ℃ for 20 h.

Key words: ohmic contacts; SiC; contact properties; carbon-enriched layer; stability
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1. Introduction

4H-SiC is an attractive semiconductor for high-power electronic device applications owing to its superior electrical, thermal, chemical, and mechanical properties, such as wide band gap, high thermal conductivity, critical breakdown field, high-saturation electron drift velocity, high chemical stability, and strong mechanical strength[1,2]. High quality Ohmic contact with low specific contact resistance and good thermal stability on SiC is very important to device performance. Usually, Ohmic contact on n-type SiC can be formed by depositing a metal film on highly doped SiC and then annealing in an inert gas or vacuum. However, the high anneal temperature restricts high performance reliable SiC-based device fabrication and makes electrode morphology rough. Carbon vacancies (V_C) in the SiC surface just below the metals during the annealing were thought to be the reason for the formation of an Ohmic contact. The formation of nano-size graphitic flakes from amorphous carbon plays a determining role in the Schottky to Ohmic contact conversion in Ni/SiC structures[3]. The carbon diffusivity (or solubility) in the metal and the thermal stability of carbide determine the graphitization process. And the carbon effective solubility in Co (3.14%) is larger than that in Ni (2.03%). Co as a graphitization catalyst accelerates the formation of nano-size graphitic flakes and reduces the annealing temperatures to form an Ohmic contact[4,5].

In this article, Co, for which few studies have been done, was chosen as a suitable transition metal. Ideal Ohmic contacts were formed in Co/C/SiC after annealing above 700 ℃. I–V characteristics of the contacts with carbon film at different annealing temperatures were investigated. The specific contact resistance of the Co/C/4H-SiC was analyzed by the linear TLM method. Investigations of the microstructures at the Co/C/4H-SiC interface were conducted using X-ray diffraction (XRD). The high-temperature stability of Co/C/SiC Ohmic contacts was investigated. The catalytic graphitization effects of Co on a carbon-enriched layer and the formation of nano-graphitic structures were discussed. A Co–C-based contact system usually suffers from serious oxygen contamination. A thin layer of Au was intentionally deposited on the top of the Co/C contact to prevent possible oxidation during thermal annealing.

2. Experiments

In this experiment, two commercial Cree n-type 4H-SiC wafers with a low resistivity of 0.017 $\Omega\cdot$cm, which corresponds to a doping concentration in the range of 2.8×10^{18} cm^{-3}, and with 8° off-axis from (0001) were used. Before metal deposition, the samples were cleaned in acetone and sulfuric acid, followed by a standard RCA cleaning process. The samples were rinsed in deionized water after each surface treatment. The cleaned SiC substrates were put in the sputtering chamber, then a 2 nm carbon film and a Co (250 nm) thin film were deposited on the surface of the 4H-SiC wafer by means of a RF sputtering system in a base vacuum of the order of 10^{-7} Torr. A 150 nm-thick upper Au layer was deposited by DC sputtering of Au Targer in Ar plasma. Finally, the Co-coated SiC sample was annealed at 550 ℃ for 10 min and then subjected to rapid thermal annealing (RTA) at temperatures ranging from 700 to 1050 ℃ for 3 min in argon (Ar) ambient and then free-cooling without stopping the argon source, by using a ceramic sintering furnace in a pure argon atmosphere. For comparison,

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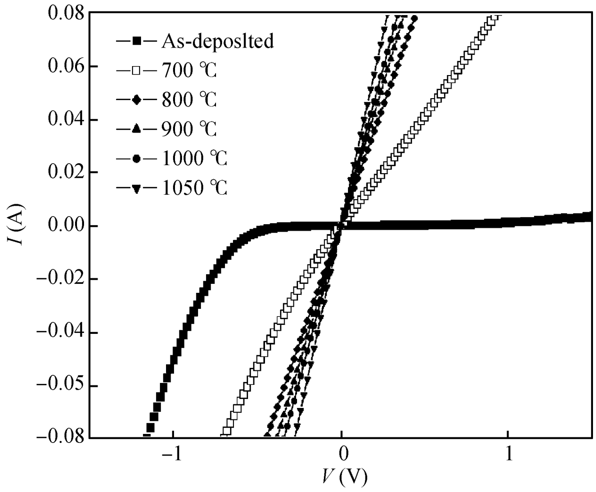

Fig. 1. I–V characteristics of Co/C/n-SiC contact systems before and after rapid thermal annealing in Ar for 10 min.

conventional Co electrodes without carbon film were also fabricated by annealing a Co-deposited sample at 700 ℃ for 2 h in pure Ar. The circular transmission line method (TLM) four-point probe method was employed for the specific contact resistance (SCR) measurements. The spaces in the contacts employed for the circular TLM measurements were 4, 8, 16, and 24 μm, respectively. The current–voltage (I–V) characteristics of the TLM contacts were measured by a Keithley 2400 Source-Meter. X-ray diffraction (XRD) analysis was used to identify compounds formed at the metal/SiC interface during annealing.

3. Results and discussion

3.1. I–V characteristics

A standard rapid thermal annealing process was applied to obtain lower values of specific contact resistances. The I–V characteristics before and after thermal annealing are compared in Fig. 1. The contacts with a 2 nm C-layer thickness showed nearly-Ohmic behavior at 700 ℃. After annealing at 800 ℃ or above, excellent Ohmic behavior was demonstrated by the I–V characteristics which possess linear characteristics with small resistance and are symmetric with the reversal of voltage polarity. A clear transition from Schottky behavior at lower annealing temperature to nearly-Ohmic behavior for higher temperature is observed. The 1050 ℃ annealed sample has the lowest Ohmic contact resistance 2.30×10^{-6} $\Omega\cdot cm^2$. Table 1 lists the average values of SCR for samples from the TLM measurements after annealing at various temperatures. Smooth SCR reduction, from 2.71×10^{-5} to 2.30×10^{-6} $\Omega\cdot cm^2$, is obtained when the annealing temperature is increased from 700 to 1050 ℃. It is noted that, as compared to experimental results of the similar contact system (Ni–C/n-SiC) reported in Ref. [6], the resistivity of the Co-based metal contact was one order lower than that of the Ni-based contact.

Figure 2 shows the I–V curves of Co/SiC and Co/C/SiC after annealing at 700 ℃ in Ar for 2 h. As shown, the Co/SiC sample exhibits rectifying behavior, while the Co/C/SiC sample shows a nearly-Ohmic contact. It has been known that

Table 1. Specific contact resistivity of Co contact on n-type 4H–SiC as a function of annealing temperature.

Annealing temperature (℃)	Specific contact resistivity ($\Omega\cdot cm^2$)
As-deposited	Schottky
700	Nearly-Ohmic contact
800	2.71×10^{-5}
900	1.84×10^{-5}
1000	7.25×10^{-6}
1050	2.30×10^{-6}

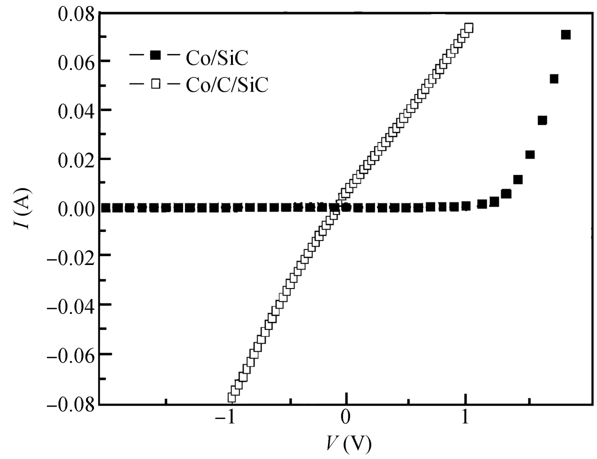

Fig. 2. I–V characteristics of Co/C/SiC and Co/SiC after annealing at 700 ℃ in Ar.

Ohmic contact on Co/SiC is formed at about 950 ℃ or above on highly doped SiC, and a high quality Ohmic contact is difficult to form on moderately doped SiC (10^{17} cm^{-3})[7]. An interfacial carbon layer between Co and SiC can improve significantly the Ohmic contact formed on SiC at 700 ℃, as shown in Fig. 2. In other words, the addition of an interfacial carbon layer may decrease the annealing temperatures required to form Ohmic contacts for metal Co.

3.2. Carbon Raman spectra of Co/C/SiC structures after annealing

Carbon atoms on the surface of electrodes are ungraphitized carbon layer structures. In Co/SiC, a carbon phase is detected in the film on SiC after thermal annealing by XRD. Figure 3 displays the depth profiles of Co, Si, and C atoms after annealing at 700 ℃. This indicates a 20 nm carbon phase layer followed by a deposition of 140 nm-thick Co–Si layer detected on the surface of SiC after thermal annealing. The count ratio of Co to Si is 2 : 1, which indicates a crystalline Co_2Si phase. The results show that the Co-based metal contacts have better structural stability of silicide phases formed after the high temperature annealing. Figure 4 exhibits XRD profiles of Co/C/SiC sample annealing at 700 ℃, which means the peaks corresponding to Co_2Si and graphite C atoms. The formation temperature of the first crystalline Co_2Si in the Co/Si interface reaction was reported to be 380–400 ℃[8]. This demonstrates that the formation of an Ohmic contact on n-type SiC is not due to the formation of Co_2Si. The graphite C phase from the interface to the surface is important to the formation of the Ohmic contact. The formation of the Ohmic contacts and the graphitic

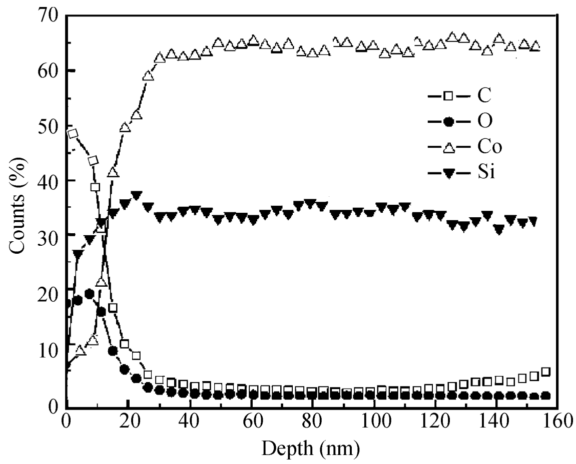

Fig. 3. Depth profiles of Co, Si, O and C atoms for Co/C/SiC after annealing at 700 ℃.

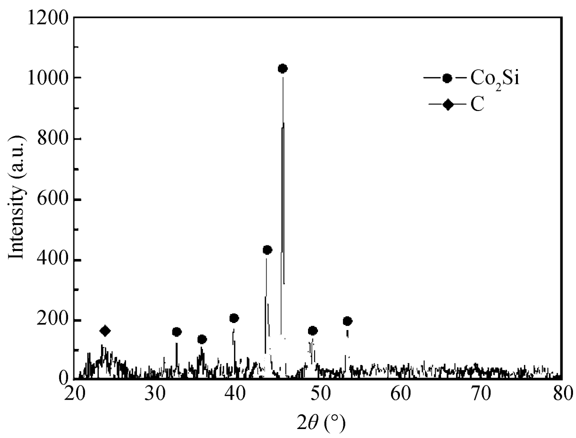

Fig. 4. X-ray diffraction patterns after annealing at 700 ℃.

structures in the annealed film of Co/C/SiC are similar to that of Ni/SiC annealing at 1050 ℃[9].

The annealing temperature at 700 ℃, out-diffusion of Si and C atoms is preferred to the in-diffusion of Co. This means that the silicidation through out-diffusion of Si is faster than the out-diffusion of C, leaving elemental C atoms (carbon-enriched layer) at the interface. The C atoms followed after Si atoms through the Co diffuse toward the surface, an abundance of C atoms out-diffused and accumulated at the surface, as shown in Fig. 3. Good quality Ohmic contact with a low contact resistivity is formed, as shown in Fig. 1. This is consistent with the observation of graphite about Ni/C/SiC annealing at 800 ℃, but the required annealing temperature for Co/C/SiC structure with a doping concentration of 10^{18} cm^{-3} decreases because the carbon effective solubility in Co as a graphitization catalyst is larger than that in Ni at higher temperature. For the annealing temperature of 1000 ℃, the carbon solubilities in Co and Ni are 3.14% and 2.03%, respectively.

The depth profiles in Fig. 3 suggest that Ohmic contacts are formed after C is decomposed and converted to graphitic states[10, 11]. Then a carbon-enriched layer is built with C atoms continuously out-diffused to the surface of the silicide. In the metal catalytic graphitization process, amorphous carbon atoms diffuse into metal and recrystallize as graphite-like structures. This reaction could produce more C atoms under the Co silicides. This causes net concentration of electrons to increase under the contact. Therefore, the depletion layer width and effective tunneling barrier height for the transport of electrons are simultaneously decreased at the interface between SiC and metal Co because of the creation of a carbon-enriched layer during annealing in the near SiC interface region of the SiC, which allow increased electron transport through the Schottky barrier, leading to Ohmic behavior of the contact[12].

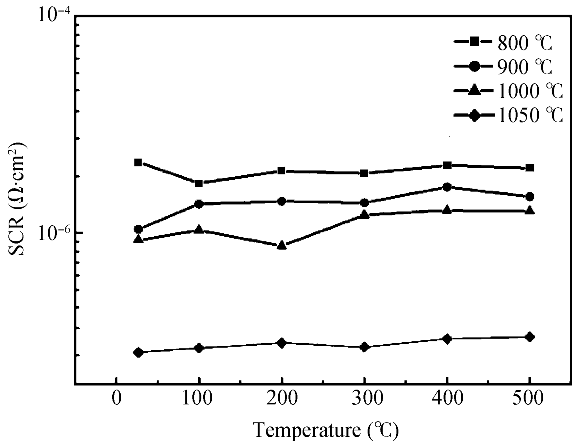

Fig. 5. Thermal stability analysis for the Au/Co/C/n-SiC contact system.

3.3. Thermal stability test

The contact reliability at high temperature ambient is usually considered as the crucial factor determining the feasibility of a contact system for power device applications[13]. The effect of thermal aging treatment on the electrical properties of the Au/Co/C contact was also investigated. The prepared Au/Co/C/4H-SiC Ohmic contact samples were subjected to thermal treatment at 100–500 ℃ in Ar for 20 h and the results are shown in Fig. 5. It is observed that, before and after the thermal aging treatment at 500 ℃ for 20 h, although a gradual change in the resistances on SCR from 2.13×10^{-5} to 1.97×10^{-5} $\Omega \cdot cm^2$ was observed for the 800 ℃ annealing sample, the values appeared to stabilize after 900 ℃ or above the annealed samples. The small variations in SCR of all samples indicate that the Au/Co/C/4H-SiC Ohmic contact is thermally stable, which might be attributed to not only the formation of a chemically stable contact compound of $CoSi_2$ and carbon-enriched layer at the metal/SiC interface but also a top Au layer prevented oxide formation[14].

4. Conclusions

The electrical properties and graphitic structures of Co/C/4H-SiC structures were investigated after annealing. A 2.0 nm thick carbon interfacial layer between Co film and SiC improves Ohmic contact properties significantly. This provides the evidence that a carbon-enriched layer contributes to the formation of Ohmic contact in terms of the reduction in effective Schottky barrier height for the transport of electrons. Ohmic contacts are formed on Co with an interfacial carbon film on 4H-SiC n-type, Si-face, and the doping concentration of 2.8×10^{18} cm^{-3} after annealing at 800 ℃ in argon. The contacts exhibited relatively stable electrical characteristics after thermal aging treatment at 500 ℃ for 20 h. The results of XRD showed that a carbon-enriched layer is built with carbon atoms continuously out-diffused, which lead to Ohmic behavior of the contacts. Co acts as a graphitization catalyst which accelerates the formation of the nano-size graphitic structures, and better catalysts form better Ohmic contacts on SiC.

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