Effects of Si Interlayer Conditions on Platinum Ohmic Contacts for p-Type Silicon Carbide

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A study of Pt ohmic contacts with Si interlayers on p-type SiC (7.0×10^{18} cm^{-3}) was performed as a function of the Si interlayer thickness, deposition temperature, and dopant incorporation. All contacts were ohmic after annealing at 1100°C for 5 min in vacuum. The use of a Si layer was found to decrease the specific contact resistance (SCR) relative to Pt contacts that did not contain Si, regardless of the deposition conditions used in this study. The SCR values were reduced further by three independent effects: the deposition of the Si layer at 500°C, the incorporation of B in the layer, and the design of the Pt:Si layer thicknesses in a 1:1 atomic ratio. By combining all of these effects, the lowest average SCR values ($2.89 \times 10^{-4}\ \Omega\ cm^2$) were obtained. After annealing for 5 min at 1100°C, x-ray diffraction of the contacts with the 1:1 Pt:Si ratio showed a single phase of PtSi. Analyses by cross-sectional transmission electron microscopy revealed no reaction of the films with the SiC substrate. The electrical characteristics of these contacts were stable after annealing at 400°C and 600°C for 96 h and 60 h, respectively. These results are in contrast to those observed for pure Pt contacts and for contacts containing a higher Pt:Si ratio.

Key words: Ohmic contact, p-type SiC, Pt, Si, interlayer, thermal stability, TEM, specific contact resistance, single phase

INTRODUCTION

The wide band gap of silicon carbide (2.3–3.2 eV depending on the polytype) makes it an ideal material for many semiconductor devices. However, the fabrication of reproducible ohmic contacts with low contact resistances to p-type SiC is a critical problem for reliable performance. The traditional approach is to anneal an Al-based contact (e.g., TiAl) on highly doped SiC at temperatures between 900°C and 1150°C.[1] However, Al-based contacts are often considered to have morphological problems resulting from high processing or operating temperatures. These problems may be associated with the high tendency for oxidation, phase separation with low melting point phases, a low eutectic temperature between Al and Si, or a nonuniform interface[2] with the SiC substrate.

Refractory materials such as Co,[3] Pt,[4,5] Pd,[6] and CrB_2[7,8] have also been investigated for ohmic contacts to p-type SiC. In some cases (e.g., Co,[3] Pt,[9] and Al[10]), a Si layer was deposited in addition to the elemental metal to improve the ohmic behavior. Lundberg et al.[3] formed $CoSi_2$ ohmic contacts after annealing a Si/Co bilayer structure. The Si layer prevented the formation of residual carbon as a result of a reaction between Co, which is a noncarbide former, and SiC. Papanicolaou et al.[9] formed ohmic contacts on p-type SiC with a Si/Pt bilayer structure. After annealing, uniform intermixing of Si and Pt and out-diffusion of C were found. Olowolafe et al.[10] also reported that Si and Al combined to improve the ohmic behavior. In the present study, we compare Pt contacts with and without Si interlayers on p-type SiC to determine whether the use of Si interlayers is beneficial for this type of contact. In addition, we demonstrate the control of the specific contact resistance by varying the Si deposition temperature and the Pt:Si thickness ratio and by incorporating B into the contacts.

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EXPERIMENTAL PROCEDURE

An aluminum-doped, p-type (7.0 × 10^{18} cm^{-3}) homoepitaxial layer on a 0.08 Ω cm, n-type 6H-SiC (0001) Si-face wafer was grown by Cree Research, Inc. (Durham, NC). The epilayer thickness was 0.5 μm. All of the samples used in this study were cut from this wafer. The substrates were cleaned using acetone and methanol for 5 min in an ultrasonic bath, etched by 10% HF for 10 min, and rinsed in deionized water and dried with N_2 gas.

Platinum and Si were deposited by direct current (DC) magnetron sputtering in a system with a base pressure of $<3.0 \times 10^{-7}$ torr. The Pt target was 99.99% pure. One of the Si targets was 99.999% pure; the other Si target contained $5 \times 10^{19}-1 \times 10^{20}$ cm^{-3} B. Prior to each deposition, the targets were presputtered for 30 sec to remove contaminants. Subsequently, the samples were annealed in the sputtering system at 550°C for 10 min to desorb hydrocarbon contamination from the substrate surfaces.

Each sample was patterned by photolithography using two masks consisting of 300 × 50 μm rectangular transmission line model (TLM) pads and rectangular mesa structures. The spacings between rectangular pads were 5, 10, 20, 30, and 50 μm, respectively. Following the deposition of the contact layers (Pt or Pt/Si), an Al mask layer (0.3 μm) was deposited. The Al mask layer (0.3 μm) was etched with H_3PO_4:HNO_3:H_2O (10:1:2.5) to yield the mask pattern for mesa etching. The mesas in the SiC epilayers were fabricated by reactive ion etching (RIE) in SF_6 and Ar in a 1:1 ratio at 200 W. The contact layers above the mesa trench were also reactive ion etched. Following definition of the mesas and removal of the remaining Al film, the rectangular TLM patterns in the contact layers were defined by Ar ion etching with photoresist as a mask layer. Therefore, in this process, the regions of the SiC surface where the contacts were deposited were not exposed to RIE.

The ohmic contacts were formed by annealing in vacuum ($<3 \times 10^{-7}$ torr) at 1100°C for 5 min. Some of the samples were subsequently annealed at 400°C and 600°C in vacuum to test the contact stability.

Current-voltage measurements were performed at room temperature using an HP 4155B Semiconductor Parameter Analyzer (Agilent Technologies, Englewood, CO) and a Signatone (Lucas Signatone Corp. Gilroy, CA) S-1060H-4QR high-temperature prober. The specific contact resistances were calculated from measurements of the rectangular TLM patterns. Measurements of the contact end resistance (R_E) were included in the calculations.

Both a Philips 420 conventional transmission electron microscope (TEM, Philips Electronic Instruments Corp., Mahwah, NJ) and a Philips CM200 high-resolution TEM were used to investigate the microstructure of the interfaces between the contacts and the SiC. A Philips X'PERT x-ray diffraction (XRD) system was used to identify the phases in annealed contacts. Secondary ion mass spectrometry (SIMS) data were obtained with a Cameca (Cameca Instruments, Trumbull, CT) IMS-3f magnetic sector instrument.

RESULTS AND DISCUSSION

The use of Pt as a high work function ohmic contact to SiC has been reported previously.[4,9] Due to equilibration of the electron chemical potentials of materials in contact and the position of the Fermi level near the valence band maximum in a p-type semiconductor, contacts with a high work function tend to reduce the Schottky barrier height for a p-type semiconductor (e.g., Ref. 11). Platinum has one of the highest work functions (~5.6 eV) of any metal. Moreover, at least one of the platinum-silicides (PtSi, work function 5.15–5.75 eV[12]) has a barrier height on n-type Si that is only 0.06 eV lower than the barrier height for Pt on Si.[13]

In one study,[14] annealing Pt/SiC Schottky contacts above 700°C resulted in a two-phase reaction zone comprising Pt-silicide and amorphous C. The incorporation of Si in the contacts therefore could prevent the formation of the amorphous C phase, as in the case of annealed Si/Co contacts.[3] In this study, we have examined the role of Si in Pt-based ohmic contacts by characterization of the specific contact resistance, morphology, microstructure, and phase formation.

The deposition of Pt on a moderately doped (7.0 × 10^{18} cm^{-3}) p-type SiC substrate resulted in rectifying contacts. As shown in Fig. 1, the contact characteristics progressed toward ohmic behavior after annealing for 5 min increments at temperatures between 700°C and 1000°C and became ohmic after annealing at 1100°C. Based on these results, all other contacts described in this study were annealed at 1100°C for 5 min.

To investigate the effects of (1) the presence of Si, (2) the deposition temperature of the Si, (3) the incorporation of B in the Si layer, and (4) the thickness ratio of Si:Pt, we fabricated eight types of samples. As described in Table I, each sample is identical to

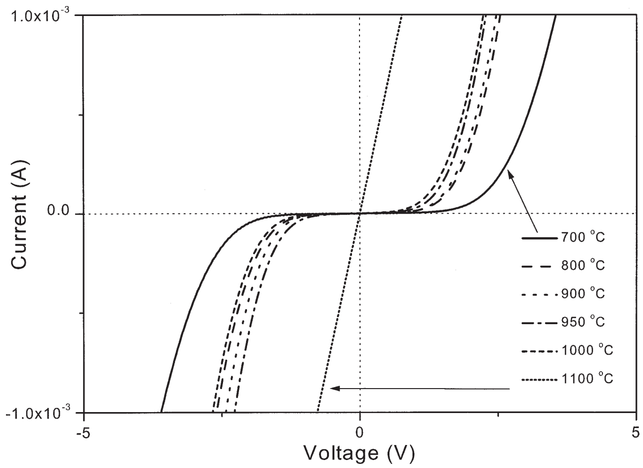


Fig. 1. Current-voltage measurements of Pt on p-type (7.0 × 10^{18} cm^{-3}) 6H-SiC as a function of annealing temperature. All contacts were annealed for 5 min.

Table I. Specifications of the Sample Types in Terms of the Variables for the Contact Layers*

Sample Type	t_{Pt} (Å)	t_{Si} (Å)	T_{Si} (°C)	B-Doped or Undoped Si	ρ_c (Ω cm^2)
1	1000	0	—	—	9.10×10^{-3}
2	1000	100	Room temperature	Undoped	2.31×10^{-3}
3	660	500	Room temperature	Undoped	1.20×10^{-3}
4	1000	100	500	Undoped	1.10×10^{-3}
5	1000	100	Room temperature	B doped	4.67×10^{-4}
6	1000	100	500	B doped	3.29×10^{-4}
7	660	500	Room temperature	B doped	3.01×10^{-4}
8	660	500	500	B doped	2.89×10^{-4}

*The Si layers were deposited immediately prior (i.e., without breaking vacuum) to the deposition of the Pt layers. The Pt layers were deposited at room temperature. The deposition temperature of the Si layers, T_{Si}, is given in the table. The other columns in the table list the thickness of the Pt layer (t_{Pt}), the thickness of the Si layer (t_{Si}), and the presence or absence of B doping in the Si sputtering target. The last column lists the average specific contact resistances, ρ_c, for the contacts, which were annealed at 1100 °C for 5 min in vacuum ($\sim 10^{-7}$ torr). The doping concentration in the p-type SiC epilayers was 7.0×10^{18} cm^{-3}.

one of the other samples, except for a single modification to permit the desired comparisons.

The Effect of the Si Interlayer

Table I shows that the average specific contact resistances (SCRs) of the contacts that contained a Si interlayer were less than the average SCR of the Pt contacts that did not contain any Si. For example, the SCR of sample type two is four times lower than the SCR of sample type 1. The SCRs of the other undoped contacts are reduced again by a factor of 2. Therefore, we conclude that the use of Si in a noncarbide-forming contact such as Pt is beneficial for ohmic contacts to SiC.

The Effect of the Deposition Temperature of the Si Layer

The Si interlayers were deposited at either room temperature or 500°C, while the Pt films were deposited at room temperature. Table I shows that depositing the Si at 500°C reduced the SCR values relative to comparable samples deposited at room temperature. For example, one may compare sample types 2 and 3, 5 and 6, or 7 and 8.

The microstructures of Si layers deposited at room temperature and 500°C are shown in the cross-sectional TEM images in Fig. 2a and b, respectively. Both deposition temperatures resulted in amorphous Si films. However, deposition at 500°C resulted in Si films of higher density. Thus, it is believed that deposition at 500°C resulted in higher quality, lower resistance films that contributed lower resistance contacts. (Sheet resistance values of the Si films could not be obtained from the samples in this study.) Deposition at a temperature above 500°C to produce crystalline Si films may result in even lower contact resistances; however, further research is required to determine this effect.

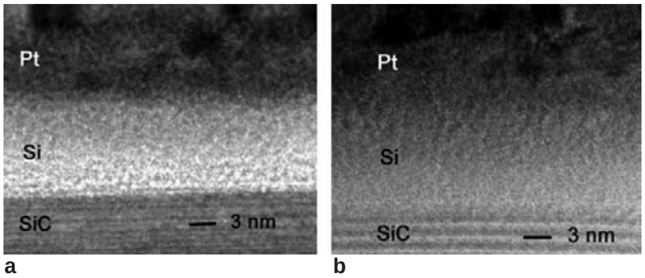


Fig. 2. Cross-sectional TEM images of as-deposited (a) Pt/Si (deposited at room temperature)/SiC and (b) Pt/Si (deposited at 500°C)/SiC.

The Effect of B Incorporation

Another obvious effect was the reduction in SCR for the contacts with Si layers deposited from the B-doped target relative to contacts deposited from the undoped target. Boron is a p-type dopant in both Si and SiC and therefore may improve ohmic contacts by forming a low-resistance, highly doped interface. Secondary ion mass spectrometry analysis of an as-deposited sample of type 5: Pt/(100 Å, room temperature, B-doped) Si/SiC confirmed that the boron in the Si sputtering target was incorporated in the Si film at a peak level of approximately 4×10^{19} cm^{-3}.[15] (It should be noted that O was detected in the as-deposited contacts. The source of the O is unknown but was probably introduced from the sputtering atmosphere. Reduction of the O concentration may result in reduced SCR values). Table I shows that the SCR values for the B-doped contacts (sample types 5–8) are notably lower than the SCRs for the undoped contacts (sample types 1–4). For example, reductions in the SCR values as a result of the B incorporation can be made by comparing sample types 2 and 5, 3 and 7, and 4 and 6. The SCR values were reduced by factors of 5, 4, and 3.3, respectively. Thus, the incorporation of B in the Si interlayer consistently improved the ohmic contacts.

Quantification of the concentration profiles for annealed contacts was limited because of their surface roughness. The SIMS profiles of the annealed B-doped contacts showed similar decay profiles for the B and Pt at the interface with the SiC substrate. There was no measurable diffusion of B into the SiC substrate beyond the reaction zone, as expected due to the extremely low diffusion rate in SiC at 1100°C. However, B doping in the reaction zone to create a highly doped graded junction may be responsible for the improved ohmic behavior.

The Effect of Si Thickness

In this study, the Pt:Si ratio was varied by varying the thicknesses of the layers as follows: 1000 Å Pt/0 Å Si, 1000 Å Pt/100 Å Si, and 660 Å Pt/500 Å Si. The sample that contained no Si was used as a reference. The 1000:100 thickness values were arbitrarily chosen for a contact with a “thin” layer of Si. The 660:500 thickness ratio (also referred to as contacts with a “thick Si layer”) was selected based on the amounts necessary to form stoichiometric PtSi if the layers were to react completely with each other and not with the SiC substrate. Based on the atomic volumes of Pt (15.06 $Å^{-3}$) and Si (20.01 $Å^{-3}$), 1.32 Å of Si is required per 1 Å of Pt to form PtSi.[16]

Comparison of the undoped sample types 1, 2, and 3 (Table I) shows that the SCR value was highest for the Pt contacts without a Si layer and lowest for contacts with the thick (500 Å) Si layer. The B-doped contacts also showed lower SCR values for the contacts with a thick Si layer relative to those with a thin Si layer.

The interface morphology of sample types 1, 2, and 3 was analyzed with cross-sectional TEM. Images of the three samples after annealing at 1100°C for 5 min are shown in Fig. 3. It can be seen that some of the SiC substrate was consumed in the reaction for both the contacts without a Si layer and those with a thin Si layer (Fig. 3a and b). However, contacts with the thick Si layer, i.e., a 1:1 Si-to-Pt ratio (sample type 3), showed little or no reaction with the SiC substrate (Fig. 3c).

X-ray analyses were performed on these three sample types to identify the phases formed after annealing. A list of the 2θ values for the diffracted beams that were observed in one or more of the samples is provided in Table II. The corresponding phases and crystallographic planes are also listed. The sample without a Si layer (Pt/SiC) showed peaks associated with unreacted Pt, Pt_2Si, and PtSi (Fig. 4). In agreement with the TEM results (Fig. 3a), these results indicate that part of the Pt film reacted with the SiC substrate to form Pt-silicides. When Si is available, the reaction proceeds more quickly. The sample with a thin layer of Si formed more of the Pt silicide phases and less Pt. Increasing the thickness of the Si layer such that Si/Pt = 1:1 yielded only the PtSi phase. These results indicate that the reaction kinetics between Pt and Si are sufficiently fast to prevent reaction of Pt/Si with SiC under these conditions.

The electrical measurements showed that the PtSi single-phase contacts yielded lower SCRs than the multiphase contacts. The same contacts also showed dramatic differences in thermal stability at 400°C and 600°C (Fig. 5a and b). The SCR values of the multiphase contacts showed small increases after 96 h at 400°C; however, the SCR of the single-phase contacts remained constant within the experimental error.

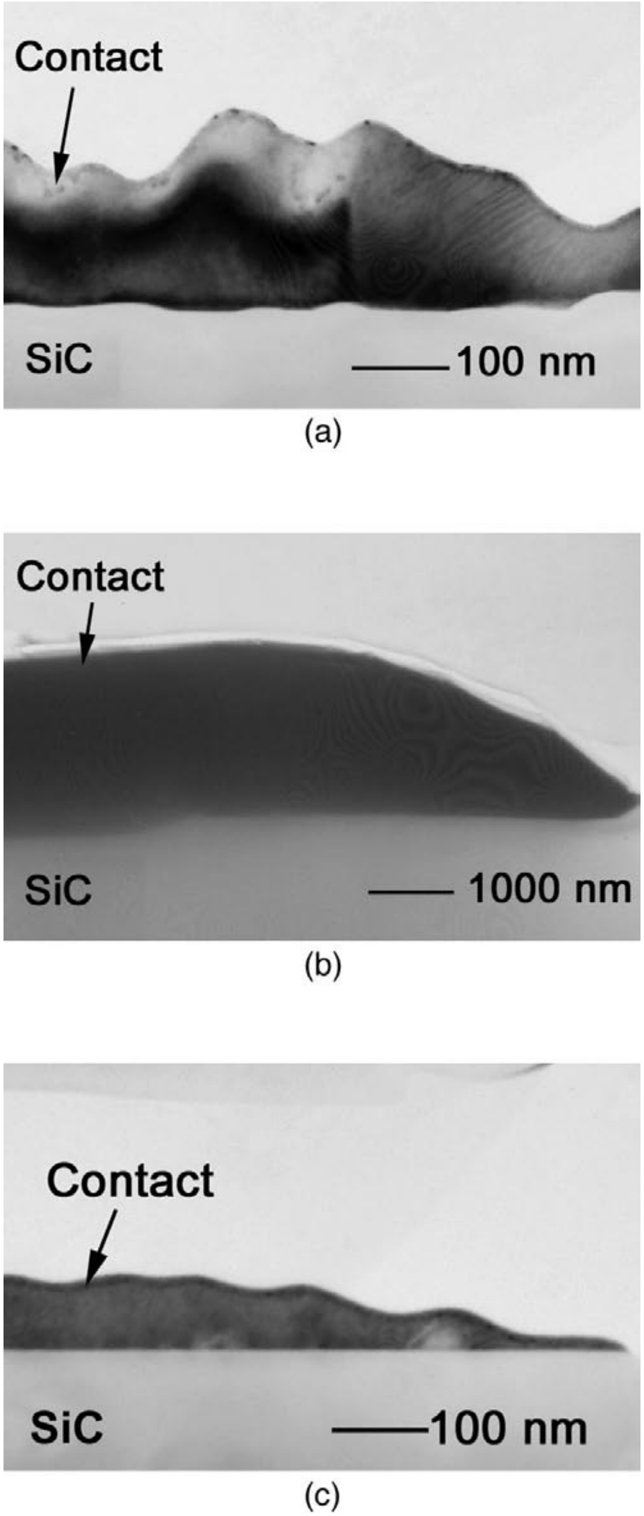


Fig. 3. Cross-sectional TEM images of (a) Pt (1000 Å)/SiC, (b) Pt (1000 Å)/Si (100 Å)/SiC, and (c) Pt (660 Å)/Si (500 Å)/SiC. The samples were annealed at 1100°C for 5 minutes.

Differences among these samples are even more pronounced after annealing at 600°C. Figure 5b shows that the annealed Pt/SiC samples increased in resistance and lost their ohmic behavior after 36 h. The samples with a thin Si layer also showed a

Table II. List of All of the 2θ Diffraction Angles and the Corresponding Phases and Crystallographic Diffracting Planes Obtained from X-ray Diffraction Analyses of Annealed Pt/SiC or Pt/Si/SiC Samples*

2 Theta	Phase	Plane	2 Theta	Phase	Plane
41.792	6H-SiC	007	67.454	Pt	220
44.438	PtSi	220	68.179	6H-SiC	0011
44.730	Pt_2Si	112	69.113	PtSi	330
46.243	Pt	200	75.387	6H-SiC	0012
48.112	6H-SiC	008	82.965	6H-SiC	0013
54.591	6H-SiC	009	85.712	Pt	222
56.226	Pt_2Si	202	91.016	6H-SiC	0014
59.938	PtSi	202	97.186	PtSi	303
61.265	6H-SiC	0010	99.689	6H-SiC	0015
66.761	PtSi	040			

*The 2θ diffraction conditions for Pt, Pt_2Si, and PtSi were obtained from Ref. 18. The diffraction conditions for 6H-SiC were calculated.

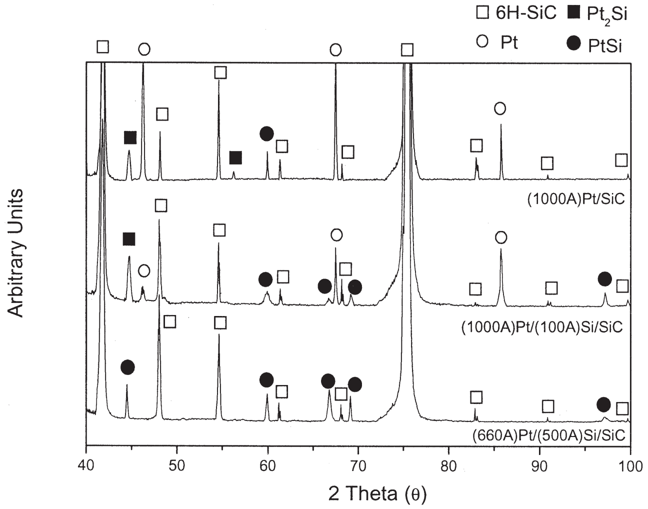


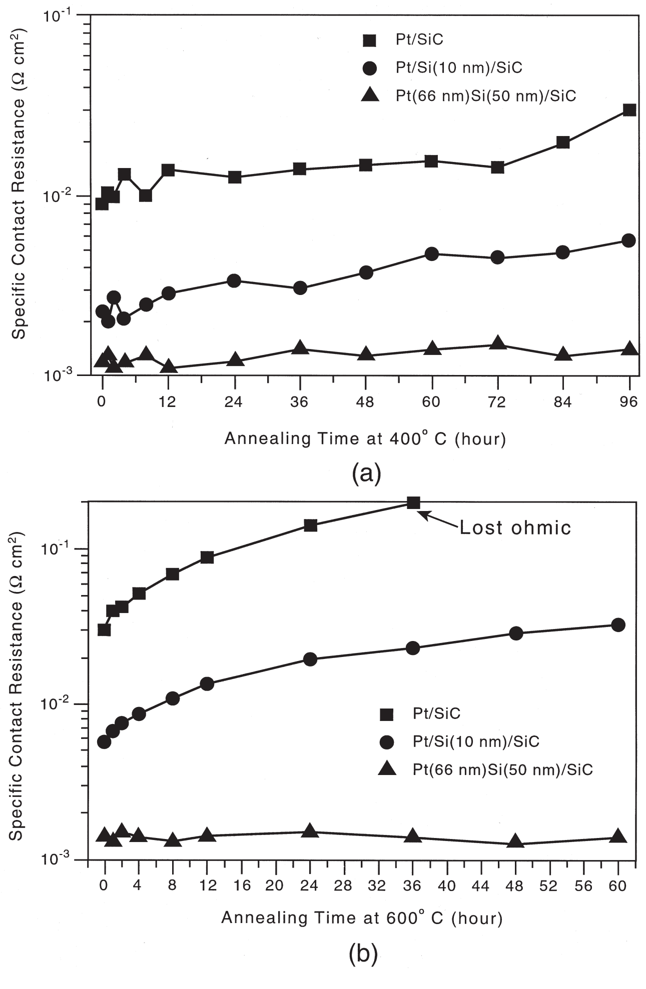
Fig. 4. X-ray diffraction spectra for (a) Pt (1000 Å)/SiC, (b) Pt (1000 Å)/Si (100 Å)/SiC, and (c) Pt (660 Å)/Si (500 Å) / SiC. The samples were annealed at 1100°C for minutes.

significant increase in contact resistance with annealing time. In contrast, the sample with the thick Si layer (i.e., the single-phase contact) was stable throughout the annealing process at 600°C.

The absence of an observed reaction with the SiC in the single-phase contacts precludes the formation of "free" C at the interface; thus, the superior electrical characteristics of the contacts with the thick Si layer may be associated with the absence of free C[17] or to a higher degree of homogeneity at the interface. It is also likely that the smooth interface observed in the single-phase contacts contributed to the improved ohmic properties.

Combination of Effects

We achieved the lowest SCR values by combining the effects discussed in the previous sections. As shown in Table I, sample type 8 {660 Å Pt/(500 Å, 500°C, B-doped)Si/SiC} yielded the lowest average SCR value of $2.89 \times 10^{-4}\ \Omega\ \text{cm}^2$. While the largest decrease in the SCR values resulted from the incorporation of B in the contacts, the Si deposition temperature and the Si:Pt ratio were also shown to have independent effects.



(a)

(b)

Fig. 5. Specific contact resistances for the samples described in Figs. 3 and 4. The data are shown as a function of annealing time at (a) 400°C and (b) 600°C.

Thus, by combining all these effects, we produced contacts with SCR values that were 30 times lower than the SCR value obtained from the Pt/SiC contacts.

CONCLUSIONS

In this study, we have demonstrated consistent effects of four conditions on the SCR of Pt-Si contacts on p-type 6H-SiC. These conditions include the use of a Si interlayer, the deposition temperature of the Si, incorporation of B in the contacts, and the Pt:Si thickness ratio.

We conclude that the use of Si in a noncarbide forming contact such as Pt is beneficial for ohmic contacts to SiC. In addition, design of the contact structures to comprise a 1:1 atomic ratio of Pt:Si avoided reaction with the SiC substrate, and, as a result, smooth interfaces and single-phase contacts were observed. Moreover, these contacts yielded lower specific contact resistances than comparable multiphase contacts, which originally contained different layer thicknesses of Si and Pt. The single-phase contacts also showed much better thermal stability. It is believed that a flat interface between the contact and the substrate plays a role in the contact reliability at elevated temperature. We believe that the superior electrical characteristics of the single-phase contacts may be associated with the absence of free C, with a higher degree of homogeneity and with the smoother interface.

Deposition of the Si at higher temperature (500°C) and incorporation of B in the contacts also improved the ohmic contacts. The lowest specific contact resistance was achieved when all four of the above effects were combined.

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