Simultaneous Formation of p- and n-Type Ohmic Contacts to 4H-SiC Using the Ternary Ni/Ti/Al System

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Fabrication procedures for silicon carbide power metal oxide semiconductor field effect transistors (MOSFETs) can be improved through simultaneous formation (i.e., same contact materials and one step annealing) of ohmic contacts on both the p-well and n-source regions. We have succeeded with the simultaneous formation of the ohmic contacts for p- and n-type SiC semiconductors by examining ternary Ni/Ti/Al materials with various compositions, where a slash symbol "/" indicates the deposition sequence starting with Ni. The Ni(20 nm)/Ti(50 nm)/Al(50 nm) combination provided specific contact resistances of 2×10^{-3} Ω-cm^2 and 2×10^{-4} Ω-cm^2 for p- and n-type SiC, respectively, after annealing at 800°C for 30 min, where the doping level of Al in the SiC substrate was 4.5×10^{18} cm^{-3} and the level of N was 1.0×10^{19} cm^{-3}.

Key words: 4H-SiC, Ni/Ti/Al, ohmic contact, simultaneous formation

Silicon carbide (SiC) is a wide-band-gap compound semiconductor with excellent intrinsic properties such as high thermal conductivity, high electric field breakdown strength, and high saturation electron velocity; thus, it is suitable for application to next-generation high-power devices operated in high-temperature environment.[1] However, several technical issues such as growth of defect-free substrates and doping at high levels by ion implantation must be overcome to realize the high-power devices. Development of reliable ohmic contacts is also a key issue.[2]

For power metal oxide semiconductor field effect transistor (MOSFET) devices with a double-implanted vertical structure, the ohmic contacts on both the n^+-source region and p-well region are needed.[3] No simultaneous formation technique for both the contacts is available, and the ohmic contacts for p- and n-type SiC are currently fabricated using different contact materials and different annealing processes. Simultaneous formation of ohmic contacts for both p- and n-type semiconductors using the same contact materials and a one-step annealing process will therefore simplify the device fabrication processes and miniaturize the cell sizes, possibly leading to wide applications for SiC devices as replacements for conventional Si and GaAs devices.

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Although a variety of ohmic contact materials to SiC have been developed, only a few materials are suitable ohmic contacts for both p- and n-type SiC.[4,5] Fursin et al.[4] reported that a nickel contact, which was known as a typical ohmic contact for n-type SiC,[6] showed ohmic behavior after annealing at 1,050°C for both p- and n-type SiC in which aluminum and nitrogen were implanted at 10^{21} cm^{-3} and 10^{19} cm^{-3}, respectively. Tanimoto et al.[5] also reported simultaneous formation for Ni-based contacts to heavily doped SiC ($N > 10^{20}$ cm^{-3}) following anneals at 1,000°C. However, these high annealing temperatures are not desirable in a MOSFET fabrication process due to the deterioration of the gate oxide layers. Therefore, reduction of the annealing temperature is one of the requirements for a simultaneous contact formation technique.

Ternary Ni/Ti/Al materials are good candidates for the ohmic contacts that will be fabricated by the simultaneous formation technique at relatively low temperature. Titanium/aluminum[7,8] and Ni/Ti/Al[9] were developed as ohmic contacts for p-type SiC, and pure Ni contacts[6] demonstrated excellent ohmic behavior with low contact resistances for n-type

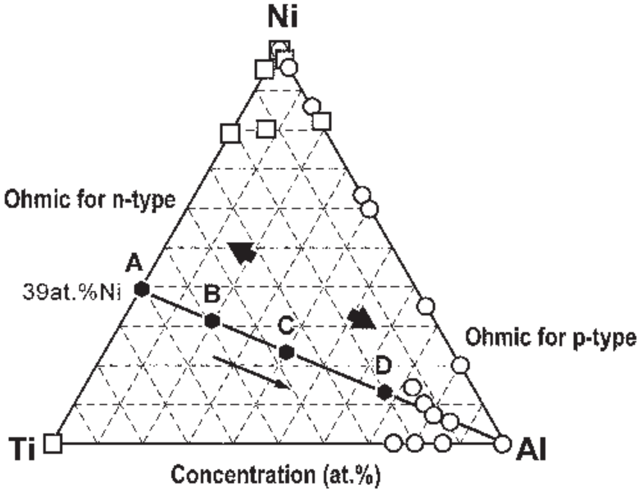

Fig. 1. Contact properties of ternary NiTiAl ohmic contacts with various compositions for p- and n-type SiC. The compositions of ohmic contacts for p- and n-type SiC are marked by symbols ○ and □, respectively.

SiC. Thus, ohmic behavior for both p- and n-type SiC may be possible if the Ni, Ti, and Al layer thicknesses in a ternary system are adjusted properly. The properties of the Ni/Ti/Al contacts of various compositions studied previously for p- and n-type SiC[4–13] are shown in the ternary NiTiAl compositional diagram of Fig. 1, where the Ni-Ti-Al compositions that showed ohmic behavior for p- and n-type SiC are shown by open circles and squares, respectively. The contact properties are strongly influenced by the Al concentrations, and the ohmic contacts for n- and p-type SiC tend to form for Ti- or Ni-rich, and Al-rich compositions, respectively. Therefore, by controlling mainly the Al composition in the Ni/Ti/Al ohmic contacts, we expect the simultaneous formation of ohmic contacts for both p- and n-type SiC. In the present study, the electrical properties of the Ni/Ti/Al contacts with various Al concentrations are investigated for a constant of 0.39 for Ni/(Ni + Ti). The samples A–D used in this study are shown in Fig. 1 as closed hexagonal symbols.

The p- and n-type 4H-SiC epitaxial layers, doped with Al at 4.5×10^{18} cm^{-3} and N at 1.0×10^{19} cm^{-3}, were grown on the 4H-SiC wafers manufactured by Cree, Inc. (Durham, NC). The SiC substrates had 8°-off Si-terminated (0001) surfaces inclined toward the <$\bar{2}$110> direction. After chemical cleaning, a 10-nm-thick sacrificial oxide (SiO_x) layer was grown on the SiC epitaxial layer by dry oxidation at 1,150°C for 60 min. The circular electrode patterns on the substrates were prepared using a photolithographic technique to remove portions of the SiO_x layers. The substrates were cleaned by dipping in diluted hydrofluoric acid solution and rinsing in deionized water prior to metal depositions. The Ni, Ti, and Al layers were deposited sequentially by evaporation in a high vacuum. The thicknesses of the Ni, Ti, and Al layers for samples A–D are given in Table I. After lifting off the photoresist, the samples were annealed at temperatures up to 800°C in an ultra-high vacuum chamber where the vacuum pressure was below 1.3×10^{-7} Pa. (The electrical properties given in Table I will be explained later.) The electrical properties of the contacts were measured by a two-point probe method using circular patterns with an interspacing of 8 μm. The specific contact resistances were measured using a circular TLM four-point probe method.

The electrical properties samples A–D fabricated on both the p- and n-type SiC were determined by current-voltage (I-V) measurements before and after annealing. All contacts (p and n) showed rectifying (nonohmic) behavior before annealing. The contact properties of the samples after annealing at 800°C for 30 min are given in Table I. With increasing Al concentration in the samples, the contact properties are found to improve for both p- and n-type SiC. However, the contact properties for only n-type SiC were deteriorated in the Al-rich contact (sample D). Among the Ni/Ti/Al contacts, only sample C exhibited ohmic behavior for both p- and n-type SiC after annealing, with specific contact resistances of 2×10^{-3} Ω-cm^2 and 2×10^{-4} Ω-cm^2 for p- and n-type SiC, respectively. The (simultaneous) formation temperature of this Ni/Ti/Al ohmic contact was about 200°C lower than that of the Ni-based contacts previously reported by Fursion et al.[4] and Tanimoto et al.[5]

The effect of annealing temperature on the electrical properties of sample C was studied. Figure 2 shows the I-V characteristics of the sample C for (a) n-type and (b) p-type SiC, respectively. As described above, rectifying behavior was observed for both n- and p-type SiC before annealing (as

Table I. Layer Structures, Al Concentrations, and Contact Properties of Ni/Ti/Al Contacts for p- and n-Type 4H-SiC after Annealing at 800°C for 30 Min

Sample	Deposition Sequence (nm)	Al Concentration (At.%)	Contact Property to 4H-SiC (after Annealing at 800°C)	
			n-Type	p-Type
A	Ni(20)/Ti(50)/Al(0)	0	Rectifying	Rectifying
B	Ni(20)/Ti(50)/Al(20)	21	Ohmic	Rectifying
C	Ni(20)/Ti(50)/Al(50)	39	Ohmic	Ohmic
D	Ni(20)/Ti(50)/Al(140)	64	Rectifying	Ohmic

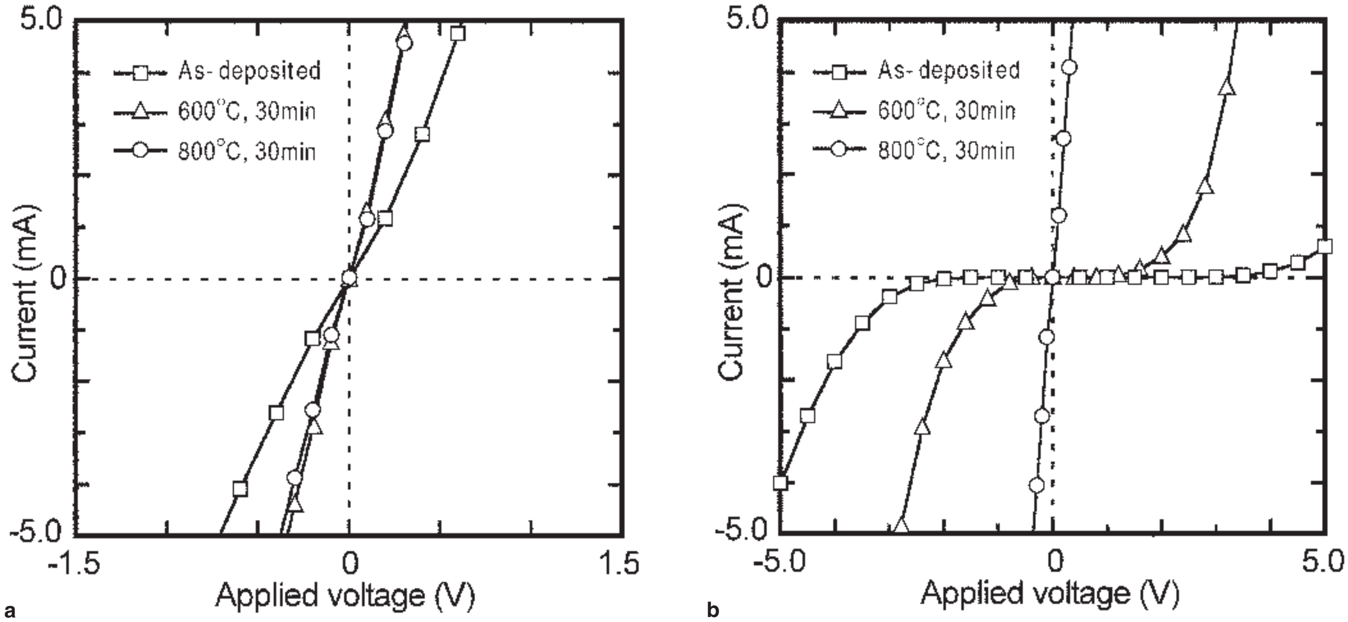

Fig. 2. Current-voltage (I-V) characteristics of Ni(20 nm)/Ti(50 nm)/Al(50 nm) contact for (a) n- and (b) p-type SiC before and after annealing.

indicated by symbol □). The contact properties improved after annealing at 600°C for 30 min, and ohmic behavior was observed only for n-type SiC (as indicated by symbol Δ). After annealing at 800°C, the ohmic behavior was observed for both p- and n-type SiC, and simultaneous contact formation was achieved (as indicated by symbol ○). The contact properties of sample C were observed to improve with increasing anneal temperature to 800°C. However, further annealing of sample C at 1,000°C for 5 min was found to slightly deteriorate the electrical properties for both p- and n-type SiC. This result indicated that the annealing temperature around 800°C was close to optimum for the simultaneous formation of the Ni/Ti/Al contacts. An effort to further reduce the contact resistance of the n-type contacts to 10^{-6} Ω-cm^2 is in progress using heavily-doped substrates.

In conclusion, we succeeded in simultaneously forming both p- and n-type SiC by annealing Ni(20 nm)/Ti(50 nm)/Al(50 nm) layers at 800°C for 30 min in vacuum. This simultaneous formation temperature is about 200°C lower than that of Ni-based contacts reported previously. The specific contact resistances of the Ni/Ti/Al contact were 2×10^{-3} Ω-cm^2 and 2×10^{-4} Ω-cm^2 for p- and n-type SiC, respectively. The Al compositions of the contacts are believed to play a key role in the electrical properties and the formation temperature. Investigations of microstructures at the contact/SiC interface using x-ray diffraction and cross-sectional transmission electron microscopy techniques are in progress as part of an effort to understand formation mechanisms and further reduce contact resistances.

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