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The fabrication of nickel silicide ohmic contacts to n-type 6H-silicon carbide*

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This paper reports that the nickel silicide ohmic contacts to n-type 6H-SiC have been fabricated. Transfer length method test patterns with NiSi/SiC and $NiSi_2$/SiC structure are formed on N-wells created by N^+ ion implantation into Si-faced p-type 6H-SiC epilayer respectively. NiSi and $NiSi_2$ films are prepared by annealing the Ni and Si films separately deposited. A two-step annealing technology is performed for decreasing of oxidation problems occurred during high temperature processes. The specific contact resistance ρ_c of NiSi contact to n-type 6H-SiC as low as $1.78\times10^{-6}\Omega\text{cm}^2$ is achieved after a two-step annealing at 350 °C for 20 min and 950°C for 3 min in N_2. And $3.84\times10^{-6}\Omega\text{cm}^2$ for $NiSi_2$ contact is achieved. The result for sheet resistance R_{sh} of the N^+ implanted layers is about $1210\Omega/\square$. X-ray diffraction analysis shows the formation of nickel silicide phases at the metal/n-SiC interface after thermal annealing. The surfaces of the nickel silicide after thermal annealing are analysed by scanning electron microscope.

Keywords: ohmic contact, silicon carbide, nickel silicide, N^+ ion implantation
PACC: 7340C, 6170T

1. Introduction

Silicon carbide (SiC) is a promising semiconductor material for future high-power and high-frequency electronic devices because of its wide energy bandgap about 3 eV, high critical field strength and good thermal conductivity.[1−3] To utilize the excellent properties of SiC in an electronic device, thermodynamically stable ohmic contacts with low specific contact resistance are important, since parasitic resistances generally limit or even jeopardize device operation.[2] Nickel is the most widely used metal for fabrication of ohmic contacts to n-type SiC.[3] Although the contact shows the ohmic characteristics, Ni contact has the structural problems in contact layer. It has been reported that Ni_2Si alloy formed by a reaction between Ni and SiC usually contains graphite-state C atoms in the produced contact layer.[4] The large voids have also been observed in the vicinity of the interface in the contact layer. The generation of voids has been correlated to the dissociation of SiC during the reaction.[5] Although the formation of Ni_2Si layer due to the multilayer deposition of Ni and Si films is effective to reduce the amount of voids,[6] a few voids are observed even in the layer. It is suggested that excess Ni atoms tend to react with SiC substrate. Therefore, since Ni and Ni_2Si contacts include the structural fluctuation, the contacts would show a poor reliability for electrical properties.

However, other nickel silicide ($NiSi_2$ and NiSi) contacts could be attempted to be fabricated in this study. Since $NiSi_2$ is the Si-rich Ni phase in a Si–Ni system, it is expected that the abrupt $NiSi_2$/6H-SiC interface is formed without the dissociation of SiC by annealing the separately deposited Ni and Si films, whose thicknesses are designed to produce the stoichiometric $NiSi_2$ alloy. Therefore, $NiSi_2$ contact includes no voids without the direct reaction between the contact material and substrates. For NiSi, besides the advantages mentioned above, its work-function can be adjusted by dopant so that the Schottky barrier height of contact would be lower.

A Philips X'PERT x-ray diffraction (XRD) system is used to identify the phase formation in the annealed contacts. Analyses of the contact morphology are performed by using a JSM-6360LV scanning elec-

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tron microscope (SEM).

2. Experiment and results

The 6H-SiC wafer used in this experiment is purchased from Cree Research Company. Orientation of the substrate is 8°C off-axis ⟨1000⟩ direction. The patterns are made on a p-type epitaxial layer with concentration of $N_a = 1.2 \times 10^{16}$ cm^{-3} and depth of 2 μm based on the n-type silicon faced substrate. N-wells are formed by N^+ ions implantation into epilayer at 550°C. The energies and doses for ion implantation are 45 keV and 7.0×10^{14} cm^{-2} respectively. The targeted nitrogen concentration is 1×10^{20} cm^{-3}. 90-nm-thick SiO_2 films are deposited on the surface of the SiC wafer. N^+ion implantation is carried out through the oxide film in order to increase the density of effective carriers of the surface region of the SiC wafer. Post-implantation annealing is done at 1600°C during 30 min in Ar ambient, using the crucible coated by poly-SiC.

The samples are cleaned in acetone before deposition followed by a standard RCA cleaning process. And after HF treatment, to make a Ni/Si/SiC structure, Si film (185 nm for $NiSi_2$ and 92.5 nm for NiSi in thickness) and Ni (50 nm for all) films are deposited on the SiC wafer. The thicknesses of Si and Ni films are designed to produce the stoichiometric nickel silicide alloys. To reduce the oxidation problem, a two-step annealing is carried out: low temperature annealing is first performed for intermixing of Si and Ni while the formation of nickel silicide phase is achieved at elevated temperature annealing as the second step. For the samples to form $NiSi_2$, the annealing is performed at 500°C for 600 s and 950°C for 180 s in N_2 ambient, while the samples to form NiSi are annealed at 350°C for 1200 s, followed by 950°C for 180 s in N_2 too.

A Philips X'PERT XRD system is used to identify the phase formation in the annealed contacts. Result obtained from XRD analysis for the prepared samples is shown in Fig.1. It is seen that the binary phase of $NiSi_2$ (Fig.1(a)) and NiSi (Fig.1(b)) appears after the two-step annealing respectively.

The SEM image of the TLM (transfer length method) pattern used in this study is shown in Fig.2. Figure 3 shows the variation in total resistance R_T between adjacent TLM pads with gap spacing L. The interspaces of seven rectangular N^+ regions are 24, 28, 32, 36, 40 and 44 μm. The data shown in Fig.3 are the median values from multiple measurements using an Agilent 4156 semiconductor parameter analyser in order to reduce the errors. By assuming that the length of each contact is long enough, the total resistance R_T can be expressed in the form

$$R_T = 2R_C + \frac{R_{sh}L}{W}, \tag{1}$$

where W is the width of the contacts, $2R_C$ is the y-interception of the linear curve, R_{sh} is the sheet resistance. The specific contact resistances ρ_c can be given as

$$\rho_c = \frac{(R_C W)^2}{R_{sh}}. \tag{2}$$

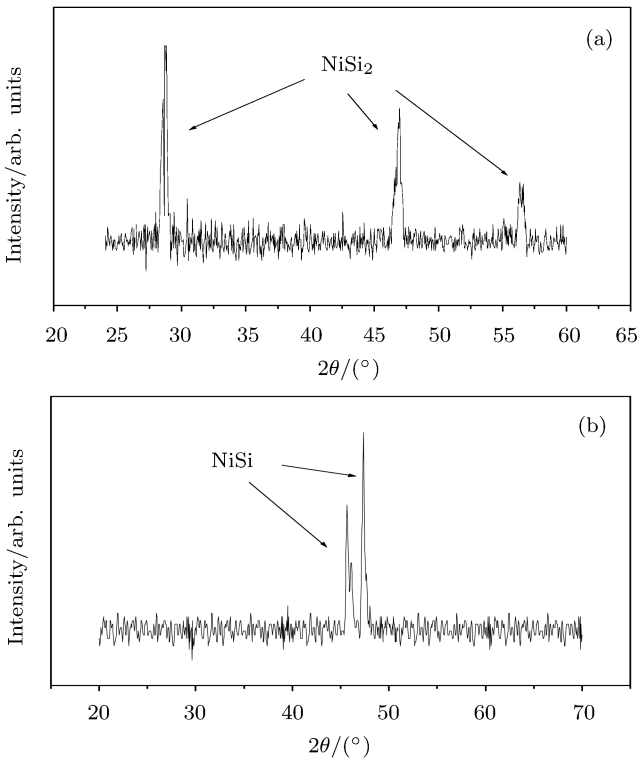


Fig.1. X-ray diffraction (XRD) result of the contact systems after the two-step thermal annealing. (a) $NiSi_2$ formed during the annealing. (b) NiSi formed during the annealing.

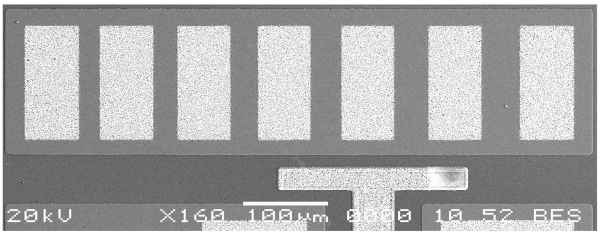


Fig.2. SEM image of TLM structure.

The lowest value of the specific contact resistances of NiSi/n-6H-SiC is $1.78\times10^{-6}\Omega$cm^2, and

$3.84\times10^{-6}\Omega\text{cm}^2$ for $NiSi_2$. Furthermore, R_{sh} is W multiplied by the slope dR_T/dL of the linear curve shown in Fig.3. The value for sheet resistance R_{sh} of the implanted layer is about $1210\Omega/\square$.

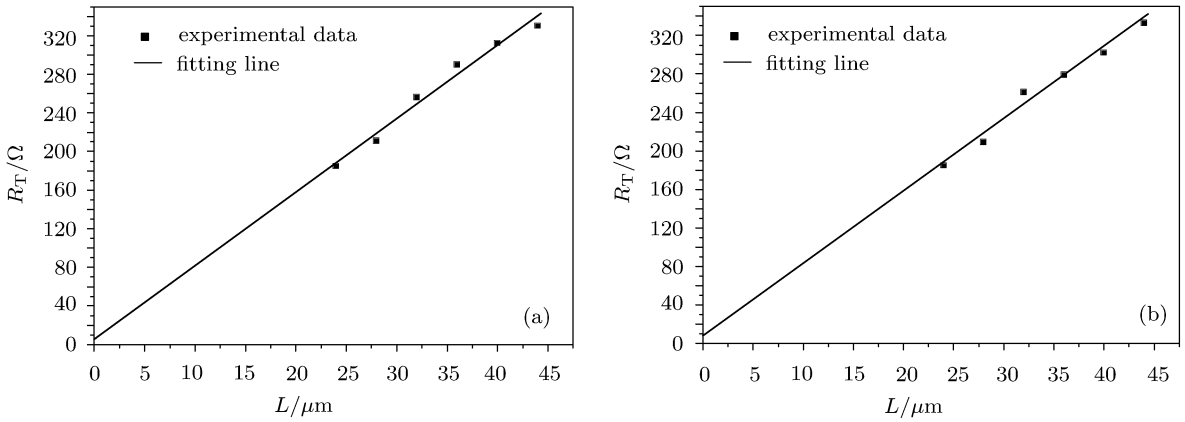


Fig.3. TLM total resistance versus gap spacing of the nickel silicide contacts. (a) NiSi contacts. (b) $NiSi_2$ contacts.

The nickel silicide is further analysed by SEM, and the SEM image shown in Fig.4(a) reveals that the grain size of the residual nickel (the black region) ranges from about 200 nm to 1μm. The short annealing time (180s) in 950°C should be the reason of the residual nickel. In Fig.4(b), only the NiSi grains exist.

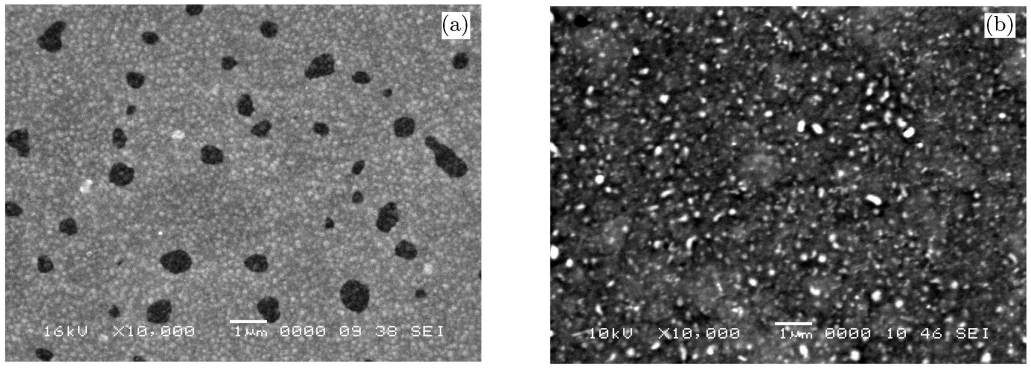


Fig.4. SEM image of the surfaces of the nickel silicide. (a) Surface of $NiSi_2$. (b) Surface of NiSi.

3. Discussion

The specific contact resistance ρ_c is proportional to the exponential of the barrier height (Φ_B) divided by the square root of the doping (N), shown in Eq.(3):[7]

$$\rho_c \propto \exp\left(\frac{\Phi_B}{\sqrt{N}}\right). \tag{3}$$

This relationship is very useful for predicting the trends of contact resistance as a function of barrier height and the semiconductor doping. There are two ways to obtain the low specific contact resistance: increasing the density of effective carriers in the thin layer just near the interface, or lowering the Schottky barrier of the metal/SiC interface.

The formation of ohmic contact in the Ni/n-type SiC system is deeply related to the out diffusion of C atoms rather than the Ni silicide. In SiC, C vacancies, V_C, act as donors for electrons and Si vacancies, V_{Si}, act as acceptor for electrons. The ionization energy level of V_C is located at 0.5 eV under the bottom of conduction band, and V_{Si} is at 0.45eV above the top of valence band. High temperature annealing provides the enough V_C, acting as donors, which contributes to the formation of ohmic contact.[8,9] It is the real reason of the formation of ohmic contacts in the Ni/n-type SiC structure, that the depletion layer width and effective tunnelling barrier height for the transport of electrons are simultaneously decreased, leading to the

reduction of specific contact resistance. It should be noted that Ni-Si composite structures are used in this study. The target is that the more C vacancies can be formed in the Si-rich condition to get ohmic contacts easier. And the amount of voids generated during the annealing also would be reduced in the vicinity of the interface in the contact layer. The dissociation of SiC would be restrained by Si film.

On the other hand, The Schottky barrier height of $NiSi_2$/SiC interface is about 0.6'eV, which is not low enough.[10] But for NiSi, the work-functions are adjusted to range from about 4.1 eV to 5.1 eV by dopant so that the Schottky barrier height of NiSi/SiC interface can be adjusted.[11] In this study, the work-function of NiSi is about 4.4 eV, and the Schottky barrier height is about 0.4 eV due to the band alignment. The specific contact resistance of NiSi/ SiC is lower than that of $NiSi_2$/SiC which is obtained from this paper for the difference of the Schottky barrier heights. If the Schottky barrier height of NiSi/n-6H-SiC could be lowered more, a lower value of the specific contact resistance is expected.

It must be noted that NiSi is a promising new candidate for Si CMOS gate metal material because its work-function can be adjusted by the implantation of dopants into the silicon before silicidation, and it received extended studies for many years. Furthermore, the first nucleation phase Ni_2Si is formed at 200–250°C if Ni films are deposited on a clean Si surface and heated by using a furnace or lamps. Ni_2Si changed to NiSi at about 300°C and to $NiSi_2$ at above 700°C.[12] So when the ambient temperature is high enough, the thermal stability of NiSi contacts to SiC should be taken into account because of the reaction between NiSi and SiC. Whereas the interface between $NiSi_2$ and SiC is abrupt and stable, since $NiSi_2$ is the Si-rich Ni phase in a Si–Ni system.

The value for sheet resistance R_{sh} of the implanted layer is much lower than the result in Ref.[13], in which R_{sh} of the N^+ implanted layer is 30 kΩ/square. The higher annealing temperature induces higher dopant activation rate and less residual defects, which result in a reduction of R_{sh} in the implanted layer.

4. Conclusion

In conclusion, an attempt is made to form the nickel silicide ohmic contacts to n-type 6H-SiC. TLM test patterns are formed on N-wells created by N^+ ion implantation into Si-faced p-type 6H-SiC epilayer. NiSi and $NiSi_2$ films are prepared by annealing the Ni and Si films separately deposited. To reduce the oxidation problem, a two-step annealing is carried out: low temperature annealing is first performed for intermixing of Si and Ni while the formation of nickel silicide phase is achieved at elevated temperatures as the second step. The specific contact resistance ρ_c of NiSi contact to n-type 6H-SiC as low as $1.78\times10^{-6}\Omega$ cm^2 is achieved after a two-step annealing at 350°C for 20 min and 950°C for 3 min in N_2, and $3.84\times10^{-6}\Omega$ cm^2 for $NiSi_2$ contact. The result for sheet resistance R_{sh} of the N^+ implanted layers is about 1210Ω/□. A lower value of the specific contact resistance is expected by adjusting the work-function of NiSi.

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