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Ti–Al based ohmic contacts to n-type 6H-SiC with P^+ ion implantation*

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The Ti–Al ohmic contact to n-type 6H-SiC has been fabricated. An array of TLM (transfer length method) test patterns with Au/Ti/Al/Ti/SiC structure is formed on N-wells created by P^+ ion implantation into Si-faced p-type 6H-SiC epilayer. The specific contact resistance ρ_c as low as $8.64\times10^{-6}\Omega\cdot cm^2$ is achieved after annealing in N_2 at 900°C for 5 min. The sheet resistance R_{sh} of the implanted layers is 975Ω/□. X-ray diffraction (XRD) analysis shows the formation of Ti_3SiC_2 at the metal/n-SiC interface after thermal annealing, which is responsible for the low resistance contact.

Keywords: ohmic contact, silicon carbide, specific contact resistance, P^+ ion implantation
PACC: 7340C, 6170T

1. Introduction

Silicon carbide (SiC) with a wide energy bandgap of about 3 eV is an attractive semiconductor material. Its high critical field strength and good thermal conductivity make SiC an excellent candidate for the development of superior high-power, high-temperature and high-frequency devices. 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. Ohmic contacts to SiC are typically formed by the deposition of transition metal layers (possibly in combination with other metals, silicon or carbon) onto heavily doped silicon carbide ($> 5\times10^{18}\,cm^{-3}$) followed by high-temperature annealing (>900°C).[1–4]

It is very difficult to form good ohmic contacts to both p- and n-type material using the same contact metal system since the difference in work function between heavily doped n- and p-type SiC is extremely large (approximately the bandgap of SiC). Ni is one of the metals that have been used for ohmic contact to both n- and p-type 4H-SiC,[5] but the specific contact resistance ρ_c is not low enough ($\sim 1.5\times10^{-4}\Omega\cdot cm^2$) for device applications. For p-SiC, Ti/Al or Au/Ti/Al ohmic contact systems have been well developed with low SCRs (specific contact resistances) in the 10^{-4}–$10^{-5}\Omega\cdot cm^2$ range.[6] However, few reports on ohmic contact to n-SiC using the Ti/Al contact system are available.[7,8]

In this study, an attempt is made to achieve the same Ti–Al based ohmic contact system to p-type SiC and also to n-type SiC. To increase the density of effective carriers, the ohmic contact is formed on N-wells created by P^+ ion implantation into Si-faced p-type 6H-SiC epilayer. A Philips X'PERT x-ray diffraction (XRD) system is used to identify the phase formation in the annealed contacts.

2. Experiment and results

6H-SiC wafer used in this experiment is purchased from the Cree Research Company. Orientation of the substrate is 8° off-axis ⟨1000⟩ direction. The patterns are made on a p-type epitaxial layer with a concentration of $N_a=1.2\times10^{16}\,cm^{-3}$ and depth of 2μm based on the N-type silicon faced substrate. N-wells are formed by P^+ ions implantation into epilayer at 550°C. The energy and dose for ion implantation are 100 keV and

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$8.3\times10^{14}\,\mathrm{cm}^{-2}$ respectively. The phosphorus ion concentration for implantation is $1\times10^{20}\,\mathrm{cm}^{-3}$. 100-nm-thick SiO_2 films are deposited on the surface of the SiC wafer. P^+ ion implantation is carried out through the oxide film in order to increase the density of effective carriers in the surface region of the SiC wafer. Post-implantation annealing is done at 1650°C in Ar ambient for 15 min, using the crucible coated by poly-SiC.

The structure of the transfer length method (TLM) pattern used in this study is shown in Fig.1,[9] and the image of the scanning electron microscope (SEM) is shown in Fig.2. The interspaces of seven rectangular N^+ regions are 24, 28, 32, 36, 40 and 44μm.

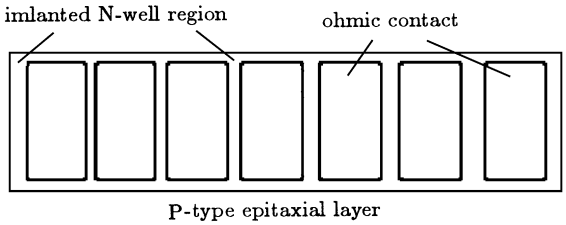


Fig.1. TLM structure used to determine the specific contact resistance.

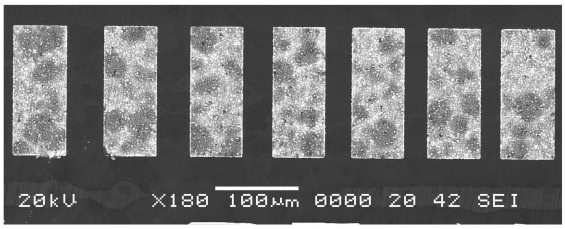


Fig.2. SEM image of TLM structure.

The samples are cleaned in acetone before metal deposition followed by a standard RCA cleaning process. Titanium (10 nm thick, especially to improve adhesion), aluminium (250 nm thick), and titanium (60 nm thick) films have been deposited in sequence on the surface of the SiC wafer. Considering the fact that Ti–Al based contact system usually suffers serious oxygen contamination, a thin layer of Au (100 nm thick) is intentionally deposited on the top of the Ti/Al contact in order to prevent possible oxidation during the thermal annealing. The ohmic contacts are patterned through conventional photolithography and lift-off techniques. Finally, high temperature annealing is performed in N_2 at 900°C for 5 min.

Figure 3 shows the variation in total resistance R_T between adjacent TLM pads with gap spacing L. 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 following form:

$$R_\mathrm{T} = 2R_\mathrm{c} + \frac{R_\mathrm{sh}L}{W}, \tag{1}$$

where W is the width of the contact, $2R_\mathrm{c}$ is the y-interception of the linear curve. The specific contact resistance ρ_c can be given by

$$\rho_\mathrm{c} = \frac{(R_\mathrm{c}W)^2}{R_\mathrm{sh}}. \tag{2}$$

The lowest value of the specific contact resistance of Au/Ti/Al/Ti/n-6H-SiC is $8.64\times10^{-6}\Omega\cdot\mathrm{cm}^2$. Furthermore, sheet resistance R_sh is W multiplied by the slope $\mathrm{d}R_\mathrm{T}/\mathrm{d}L$ of the linear curve shown in Fig.3. The value for sheet resistance R_sh of the implanted layer is about $975\Omega/\square$.

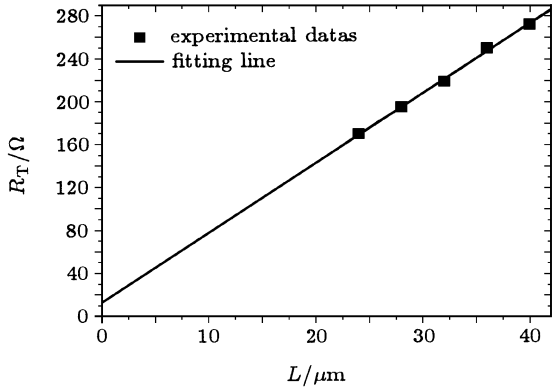


Fig.3. TLM total resistance versus gap spacing.

3. Discussion

Ti–Al ohmic contact to p-type SiC has be demonstrated by many groups.[10] It is thought to play such an important role in converting the contact from Schottky to ohmic that the Ti_3SiC_2 alloy is formed during the high temperature annealing. It must be noted that for Ti–Al ohmic contact to n-type SiC, the Ti_3SiC_2 alloy is also formed during the high temperature annealing because of the approximate metal system and annealing condition.[11]

A Philips X'PERT x-ray diffraction (XRD) system is used to identify the phase formation in the annealed contacts. Results obtained from XRD analysis for the prepared samples are shown in Fig.4. It is seen

that a ternary phase of Ti_3SiC_2 appears after the metallization annealing.

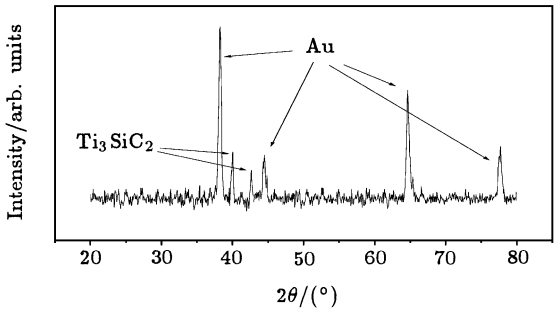


Fig.4. X-ray diffraction (XRD) result of the contact system after thermal annealing.

The Ti_3SiC_2 alloy behaves as a narrow-gap semiconductor with an electron affinity close to that of SiC ($\approx$4.2 eV). An interfacial layer of Ti_3SiC_2 would then lower the barrier height at the interface of metal/p-type SiC. An indirect band gap of 0.12 eV and an electron affinity of at least 4 eV for Ti_3SiC_2 have been theoretically determined.[12] According to what was mentioned above, the Schottky barrier height at the interface of Ti_3SiC_2/n-SiC would be very low because of the electron affinity close to SiC and the very narrow band gap, which may lead to the formation of the ohmic contact. Tsukimoto *et al*[13] pointed out that the Ti_3SiC_2 layer in the ohmic contact system would be a p-type semiconductor. In fact, the very narrow band gap of Ti_3SiC_2 results in the fact that it is not important for the converting the contact from Schottky to ohmic whether the alloy is p- or n-type. Sometimes Ti_3SiC_2 is even thought as a metal with high conductivity because of the electronic properties.[14]

Furthermore, as a reactively formed alloy, the heterointerface between Ti_3SiC_2 and SiC exhibits some degree of compositional grading, which will reduce or eliminate any band-edge discontinuities. Ti_3SiC_2 has a hexagonal crystal structure with a lattice mismatch to SiC being only 0.3%,[11,12] facilitating a gradual transition between the SiC and the stoichiometric Ti_3SiC_2 (Fig.5.).

Therefore, the thickness and structure of contact metal system are optimized to easily produce the Ti_3SiC_2 alloy, and annealing condition is designed. Chang *et al*[8] used the deposited film with a thickness ratio of Ti:Al being 1:1, so that a ternary phase of Ti_3SiC_2 appeared in 1050°C, higher than that in the present study. Moreover, from the x-ray diffraction (XRD) result, the Ti_3SiC_2 alloy is the dominant product of the annealing, while the other alloy phases almost do not exist. However, they were observed in Refs.[8, 11, 13].

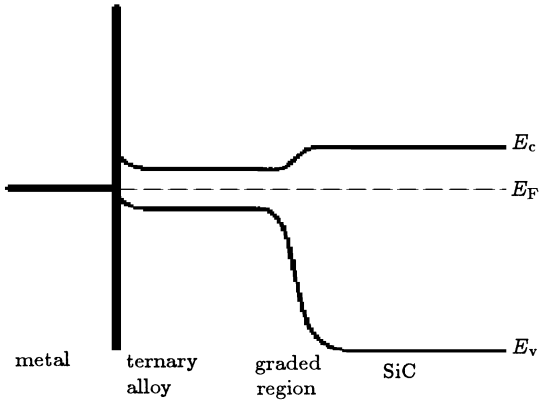


Fig.5. Energy band diagram for metal contact to n-type SiC with narrowgap interfacial alloy and graded junction between alloy and SiC.

The value for sheet resistance R_{sh} of the implanted layer is high compared with the result in Ref.[15], in which R_{sh} of the P^+ implanted layer is 106Ω/□. The high value is perhaps induced by the implantation of higher ion flux, which causes more damage, resulting in a reduction in carrier mobility of the implanted layer.

4. Conclusions

Au / Ti / Al / Ti / n-type 6H–SiC ohmic contact with the specific contact resistance ρ_c as low as $8.64\times10^{-6}\Omega\cdot cm^2$ is achieved on the N-wells formed by P^+ ions implantation into p-type epilayer at 550°C. P^+ ion implantation is carried out through the oxide film in order to increase the density of effective carriers in the surface region of the SiC wafer. Post-implantation annealing is done at 1650 °C in Ar ambient for 15 min. It has been demonstrated that the Au/Ti/Al/Ti /n-SiC contact is ohmic after annealing in N_2 at 900°C for 5 min. Furthermore, the sheet resistance R_{sh} of the implanted layer is about 975Ω/□. X-ray diffraction (XRD) analysis shows the formation of Ti_3SiC_2 at the metal/n-SiC interface after thermal annealing, which is responsible for the low resistance contact.

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