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Long-term stability of Ni–silicide ohmic contact to n-type 4H–SiC

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ABSTRACT

The thermal stability of Ni_2Si/n-SiC ohmic contacts with Au overlayer without or with Ta–Si–N diffusion barrier was investigated after long anneals at 400 °C in air. Current–voltage characteristics, sheet resistance measurements, Rutherford backscattering spectrometry, X-ray diffraction and scanning electron microscopy were used to characterize the contacts before and after aging. It is shown that aging of Au/Ni_2Si/n-SiC contact at 400 °C for 50 h resulted in electrical failure, as well as complete contact degradation for 150 h due to interdiffusion/reaction processes in the contact. The Au/$Ta_{35}Si_{15}N_{50}$/Ni_2Si/n-SiC contact is thermally stable after 150 h of aging at 400 °C and has great potential for use in SiC-based devices for high-temperature operation.

1. Introduction

The future of SiC as a semiconductor material is very promising because of its superior properties such as wide band gap, high breakdown field strength, high saturation electron drift velocity, high thermal conductivity and mechanical resistance. They open new possibilities of advanced semiconductor devices application for high-temperature/power electronics. One of the complex issues in developing of SiC-based devices is creation of reliable metal contacts for high-temperature operation [1,2].

Up to now several metal-SiC contacts have been studied and Ni-based ohmic contacts are considered the superior candidates for n-SiC [2]. In general, high-temperature annealing (~1000 °C) is necessary for ohmic contact formation to both n- and p-type SiC [1,2]. In spite of excellent electrical properties of Ni-based contacts, the metallurgical processes in metal-SiC interface at elevated temperature limits their reliability and causes subsequent devices degradation. Furthermore, a lot of attempts were devoted to study the mechanism of ohmic contact formation, but their thermal stability still remains unknown. Thus, development of long-term stable ohmic contacts to n-SiC above 350 °C is of great interest [1,2].

In the past work [3], the long thermal stability at 400 °C was demonstrated for TaC/n-SiC ohmic contacts (with Au, Pt, or W/WC overlayers) annealed in Ar or vacuum. However, the degradation of these contacts was observed after annealing in air. More recently, reliable Ni and Al/Ni/p^+-4H–SiC ohmic contacts aged at 350 °C in air have been developed by using Ta–Ru–N diffusion barriers [4]. Thus, a diffusion barrier that prevents interdiffusion between neighbor layers and in-diffusion of oxygen in contact at elevated temperature is necessary for semiconductor metallization technology.

One prospective approach was developed with contacts on Si [5], and GaN [6], utilizes the high-melting point Ta–Si–N diffusion barriers. Their nanocomposite structure, which is composed of nc-TaN nanocrystals embedded in amorphous a-Si_3N_4 matrix, suppresses the oxidation and crystallization processes at high-temperature [7]. Moreover, their microstructure is free of fast diffusion paths usually observed in polycrystalline materials. In the present study, we investigate the possibility of improving the thermal stability of ohmic contacts to n-SiC by Ta–Si–N diffusion barrier.

In our previous work [8], stoichiometric phase δ-Ni_2Si has been proved as optimal from Ni-silicide, which form relatively low resistance ohmic contact to n-4H–SiC, with low contact metallization expansion and very smooth surface. Gold as high conductivity metal and compatible with standard semiconductor technology has been chosen as overlayer for interconnection or bonding metallizations. We report on the long-term thermal stability at 400 °C in air of Ni_2Si/n-SiC ohmic contacts with Au overlayer without or with Ta–Si–N diffusion barrier.

2. Experimental

Commercial Cree n-type 4H–SiC (0001) wafers with resistivity of 0.074 Ω cm, 0.14° off-axis and Si-face were used in this study.

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Before deposition of contacts the substrates surface was cleaned according to the procedure previously described in details [8].

Firstly, Ni/Si(66/60 nm) multilayer structures were deposited by DC magnetron sputtering of Ni and Si targets in Ar plasma. The structures were annealed at 600 °C in N_2 for 15 min to form stoichiometric phase of δ-Ni_2Si on 4H–SiC substrate [8], and following at 1000 °C in N_2 for 3 min to obtain Ni_2Si/n-SiC ohmic contacts with specific contact resistance $r_c \sim 4 \times 10^{-4}\,\Omega\,cm^2$. Next, contact multilayer structures of the Au/Ni_2Si/n-SiC and Au/TaSiN/Ni_2Si/n-SiC were fabricated.

Ternary Ta–Si–N thin films were prepared by reactive RF magnetron sputtering of high pure Ta_5Si_3 target in Ar–N_2 plasma. The deposition parameters were as follows: the gas flow rate ratio during sputtering was Ar/N_2 = 15; the total gas pressure 0.6 Pa; the RF power 250 W. The resistivity measured by the four-point probe of 100 nm-thick Ta–Si–N film is 1 mΩ cm, and is applicable in diffusion barriers. A 150 nm-thick upper Au layer was deposited by DC sputtering of Au target in Ar plasma. The contact structures were aged in air at 400 °C.

Current–voltage (*I–V*) characteristics of the contacts were measured by Keithley 2400 Source-Meter. The sheet resistance (R) of metallization was measured by a four-point probe. A stoichiometry of the contacts was examined by Rutherford backscattering spectrometry (RBS) using 2 MeV He^+ beam. The SIMNRA code was used

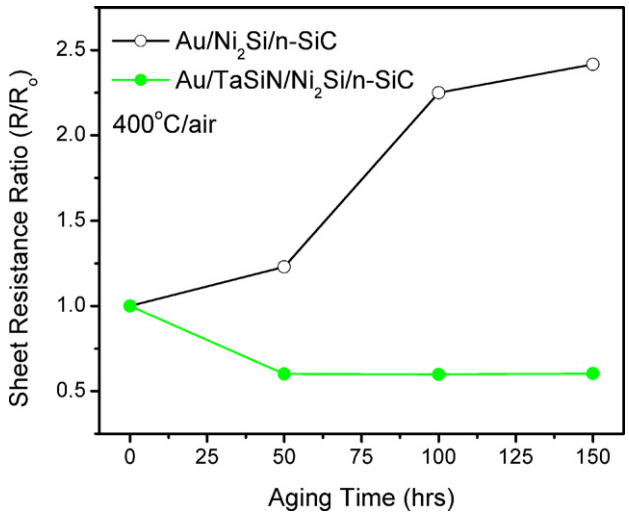

Fig. 2. Thermal stability test for Au/Ni_2Si/n-SiC and Au/$Ta_{35}Si_{15}N_{50}$/Ni_2Si/n-SiC contacts aged in air at 400 °C: variation of contacts sheet resistance (R/R_o) as a function of aging time.

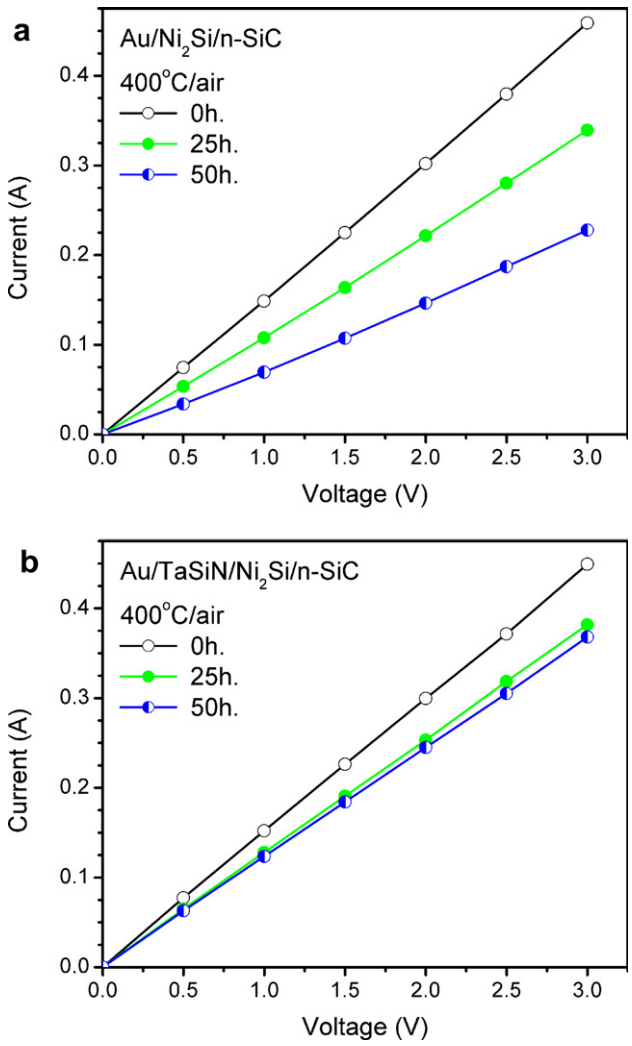

Fig. 1. *I–V* characteristics of the Au/Ni_2Si/n-SiC (a) and Au/$Ta_{35}Si_{15}N_{50}$/Ni_2Si/n-SiC (b) contacts before and after aging in air at 400 °C up to 50 h.

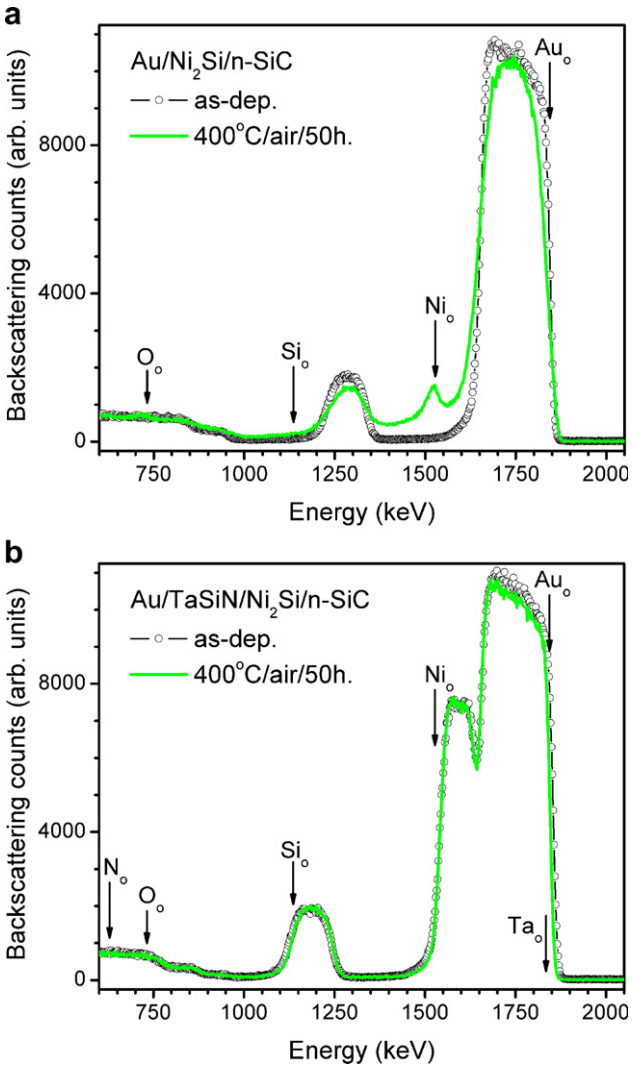

Fig. 3. The 2 MeV He^+ backscattering spectra of the Au/Ni_2Si/n-SiC (a) and Au/$Ta_{35}Si_{15}N_{50}$/Ni_2Si/n-SiC (b) contacts before and after aging in air at 400 °C for 50 h.

for simulation of experimental RBS spectra. The contacts structure was investigated by X-ray diffraction (XRD) using Philips X'Pert diffractometer with Cu K_α X-ray source. The contacts surface morphology was analyzed by Philips XL-30 scanning electron microscopy (SEM).

3. Results

The *I–V* characteristics of the Au/Ni_2Si/n-SiC and Au/TaSiN/Ni_2Si/n-SiC ohmic contacts before and after aging in air at 400 °C are shown in Fig. 1a and b, respectively. For the Au/Ni_2Si/n-SiC contacts it is evident increase of contact resistance with aging time. Calculated by circular TLM specific contact resistance (r_c) shows strong increase in r_c from $4 \times 10^{-4}\,\Omega\,cm^2$ for as-deposited contact to $6 \times 10^{-4}\,\Omega\,cm^2$ after aging for 25 h, and to $8 \times 10^{-4}\,\Omega\,cm^2$ after aging for 50 h. In the case of Au/TaSiN/Ni_2Si/n-SiC contact, the resistance increases of about 12% after aging for 25 h and following remained unchanged upon aging for 50 h.

Fig. 2 shows the sheet resistance changes for Au/Ni_2Si/n-SiC and Au/TaSiN/Ni_2Si/n-SiC contacts aged in air at 400 °C as a function of aging time. The initial sheet resistance ($R_o \sim 0.27\ \Omega$/ sq.) for both as-deposited contacts corresponds to the resistivity of highly conductive 150 nm-thick Au overlayer ($\rho \sim 4\ \mu\Omega\,cm$). This value exceeds the resistivity of bulk Au ($\rho \sim 2\ \mu\Omega\,cm$) due to the electrons scattering by the film grains boundaries. Aging of Au/Ni_2Si/n-SiC contact results in increase of sheet resistance with aging time. The sheet resistance increases by about 25% after aging for 50 h, as well as by a factor of 2.2 and 2.4 after subsequent aging for 100 and 150 h, respectively. The increase of Au/Ni_2Si/n-SiC contact sheet resistance is most likely related to interdiffusion between contact layers. For the Au/TaSiN/Ni_2Si/n-SiC contact the sheet resistance decreased of about 40% after aging for 50 h and following remained unchanged after aging up to 150 h. The initial sheet resistance reduction is not related with interdiffusion processes, and may be explicated by a decrease of the grain boundary density after recrystallization of Au layer.

In order to explain changes of the electrical properties of contacts, we have performed and compared the RBS elemental depth profiles, XRD phase composition and SEM surface morphology of contacts before and after aging.

Fig. 3 shows the RBS spectra of the Au/Ni_2Si/n-SiC and Au/TaSiN/Ni_2Si/n-SiC ohmic contacts before and after aging in air at 400 °C. The surface energies of the respective elements are marked by an arrow in all the RBS spectra. Shifts of high-energy edges of Ni, Si and Ta signals to lower energies are due to loses of energy of backscattered particles in the overlying films. The SIMNRA simulation of the RBS spectra for the as-deposited structures gives the atomic compositions of the Au/$Ni_{64}Si_{36}$/n-SiC and Au/$Ta_{35}Si_{15}N_{50}$/$Ni_{66}Si_{34}$/n-SiC contacts.

Aging at 400 °C for 50 h of Au/Ni_2Si/n-SiC contacts results in a considerable change of the RBS spectrum, comparing to the spectrum for as-deposited contact (Fig. 3a). The changes of slope, width and shift of low-energy edge for Au signal to lower energy, and appearance of Ni surface signal with energy at ~1.5 MeV are observed for aged Au/Ni_2Si/n-SiC contacts. This indicates the beginning of possible interdiffusion at the contact interfaces. Simulation of this spectrum shows the in-diffusion of Au atoms into the contact, out-diffusion of Ni and Si atoms to the surface, as well as oxygen penetration into the contact. As it is shown in Fig. 3b, the RBS spectra for as-deposited and aged at 400 °C for 50 h of Au/TaSiN/Ni_2Si/n-SiC contacts are overlapped. Unchanged

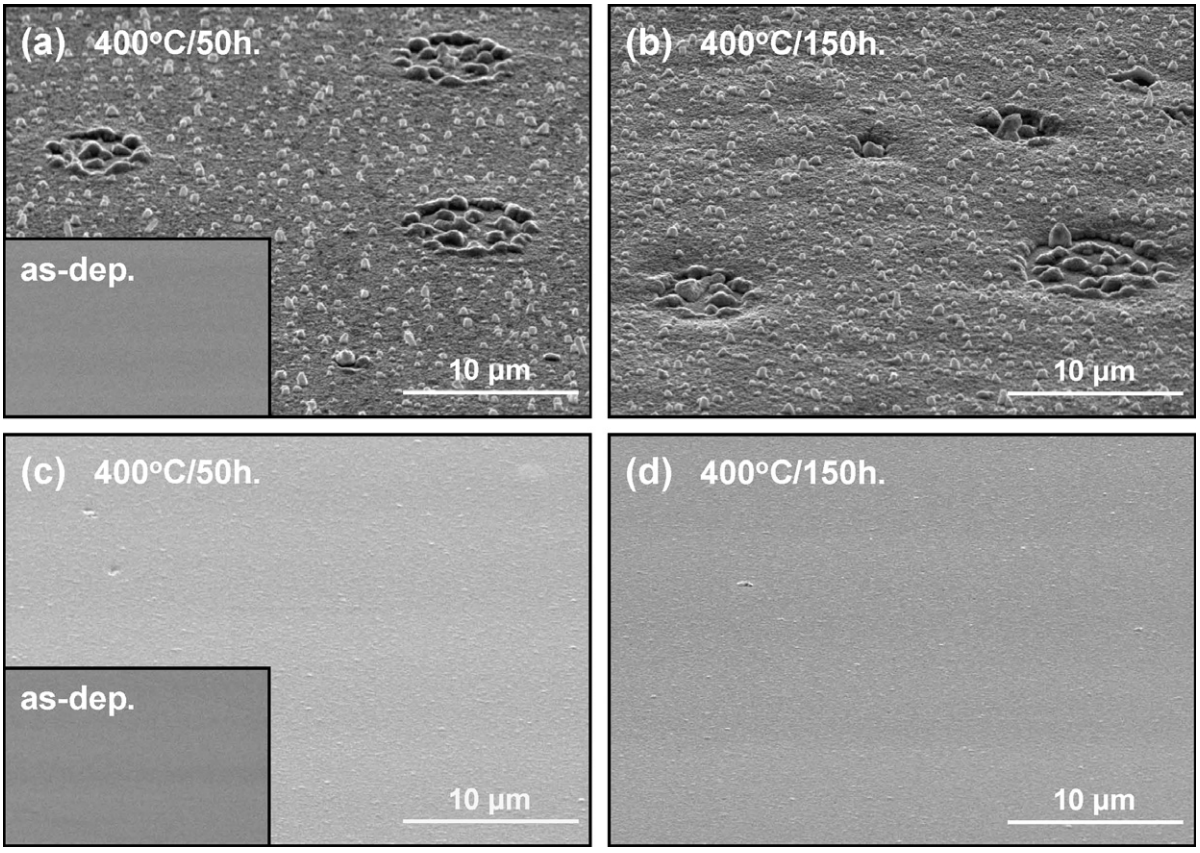

Fig. 4. SEM micrographs of the Au/Ni_2Si/n-SiC (a and b) and Au/$Ta_{35}Si_{15}N_{50}$/Ni_2Si/n-SiC (c and d) contacts: (a,c) as-deposited and after aging in air at 400 °C for 50 h; (b,d) aged in air at 400 °C for 150 h.

spectra proves, that Ta–Si–N diffusion barrier placed between Au overlayer and Ni_2Si/n-SiC ohmic contact retain their abrupt interfaces and composition during aging in air at 400 °C for a long time.

Fig. 4 shows the surface morphology of contacts before and after aging in air at 400 °C. The surface of initial contacts is smooth with shiny gold colour, as it is shown in Fig. 4a and c. It can be seen on the same SEM images that after aging at 400 °C for 50 h the surface morphology become rough for Au/Ni_2Si/n-SiC and remain still smooth for Au/TaSiN/Ni_2Si/n-SiC. Furthermore, for the contact without Ta–Si–N diffusion barrier, the change of colour to dark gold, a granular areas and craters appearing in Au layer are observed. The average surface density of craters with depth in the range of the Au thickness is about 2000 per 1 mm^2. After further aging of Au/Ni_2Si/n-SiC for 150 h (Fig. 4b), the colour changes to dark brown, and the depth of craters doubles, indicating severe morphology degradation. Aging the Au/TaSiN/Ni_2Si/n-SiC contact at 400 °C for 50 h changes the gold surface colour to yellow shade and increases Au grain size due to film recrystallization. After further aging up to 150 h (Fig. 4d), the contact surface still resembles that of the 50 h aged smooth surface.

The XRD spectra (not shown here) of as-deposited contacts without and with Ta–Si–N barrier are similar. Apart from the (0004) peak of the single crystal 4H SiC only (111) peak of polycrystalline Au and (121) peak of the δ-Ni_2Si orthorhombic phase are observed. After aging of Au/Ni_2Si/n-SiC in air at 400 °C for 50 h, only a small shift of Au and δ-Ni_2Si peaks, respectively, to higher and lower Bragg angles are observed due to lattice changes by interdiffusion of atoms. After further aging for 150 h, the intensity of (121) δ-Ni_2Si peak is strongly decreased and formation of $Au_x(Ni,Si)_{1-x}$ solid solution is observed. Unchanged XRD spectra of Au/TaSiN/Ni_2Si/n-SiC contacts aged in air at 400 °C up to 150 h suggest, that amorphous Ta–Si–N diffusion barrier preserves the initial phase composition of these contacts.

4. Discussion

Aging in air at 400 °C of Ni_2Si/n-SiC ohmic contact with Au overlayer shows different influence on the contact properties depending on the presence of the Ta–Si–N diffusion barrier.

For the contact without diffusion barrier, the aging for 50 h results in an increase of specific contact resistance and sheet resistance by a factor of about 2 and 1.2, respectively. Changes in the electrical characteristics may by correlate with oxygen penetration and depth redistribution of elements in the aged contacts. Oxygen incorporation may have been responsible for the increase mostly in the specific contact resistance, as previously observed [9]. We suppose that oxygen diffuses into the contact preferentially via craters created in the Au films. The craters will be also responsible for the appearance of a Ni surface signal (~1.5 MeV) in the RBS spectrum for aged Au/Ni_2Si/n-SiC contacts. After further aging up to 150 h, contact sheet resistance increases more than twice due to decomposition of Ni_2Si and pronounced strong interdiffusion with Au in the contact-SiC structure.

Investigations of the Au/TaSiN/Ni_2Si/n-SiC contacts aged at 400 °C in air for 150 h points out their superior thermal stability. This can be concluded from (i) the abrupt contact interfaces, (ii) none post-aged redistribution of the elements over the depth, and from (iii) preserved both a smooth surface and the phase composition. Thus, nanocomposite 100 nm-thick $Ta_{35}Si_{15}N_{50}$ diffusion barrier placed between Ni_2Si/n-SiC ohmic contact and Au overlayer prevents interdiffusion and oxygen penetration during aging in air at 400 °C even for long anneals.

5. Conclusions

We conclude that the Au/Ni_2Si/n-SiC ohmic contact degradation comes from the interdiffusion between Au and contact metallization neighbor layers as well as from the diffusion of oxygen into the contact.

Thermally stable Au/TaSiN/Ni_2Si/n-SiC ohmic contacts with $Ta_{35}Si_{15}N_{50}$ diffusion barrier have promising perspective to apply in reliable devices operated at high power and/or high-temperature.

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