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Reliability Tests of Au-metallized Ni-based Ohmic Contacts to 4H-n-SiC with and without Nanocomposite Diffusion Barriers

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Abstract. The reliability of Ni_2Si/n-SiC ohmic contacts with Au overlayer either without or with Ta-Si-N diffusion barrier was investigated after long-time aging in air at 400°C and rapid thermal annealing in Ar up to 800°C. It is shown that aging of the Au/Ni_2Si/n-SiC contacts in air at 400°C resulted in complete degradation due to both oxygen penetration and interdiffusion/reaction processes. In contrast, only a small change in properties was detected on the contacts annealed in Ar at 800°C. The stability of both electrical and structural properties of Au/TaSiN/Ni_2Si/n-SiC thermally stressed contacts at different conditions points out their superior thermal stability.

Introduction

Fabrication of low-resistive ohmic contacts to Silicon Carbide (SiC) is not sufficient for application to SiC-based devices. For their application investigation of their reliability, e.g. thermal stability is needed. This condition is necessary for usage of SiC-based devices in harsh environments.

One perspective approach to developing of reliable ohmic contacts is to using nanocomposite nc-TM/a-Si_3N_4 (TM - transition metal) diffusion barriers [1]. For experiment Ta-Si-N diffusion barrier was selected, which is composed of nc-TaN nanocrystals embedded in amorphous a-Si_3N_4 matrix. These layers suppress the oxidation and crystallization processes at high temperature [1] and serve as a good barrier in contacts to GaN [2] and Si [3].

In our past work [4], Ni-based contacts to 4H-n-SiC, e.g. Ni, Ni_2Si and $NiSi_2$ were investigated. Stoichiometric phase δ-Ni_2Si has been proved as optimal to form relatively low resistance ohmic contacts to n-SiC. In this report two types of structures of Au/Ni_2Si/n-SiC and Au/TaSiN/Ni_2Si/n-SiC were investigated. We study the influence of heat treatment conditions, as long-term aging in air at 400°C and rapid thermal annealing (RTA) up to 800°C in neutral atmosphere (Ar), on reliability of Au-metallized Ni-based ohmic contacts to 4H-n-SiC with and without nanocomposite Ta-Si-N diffusion barriers. This work follows up our previous results published in [5], where the same structures after aging in air at 400°C (only up to 50 h) were studied.

Experimental

The Nitrogen-doped n-type ($\sim 2 \times 10^{17}$ cm^{-3}) 4H-SiC (0001) wafers from Cree Research Inc were used in this study. Before deposition of contacts the substrates surface was cleaned according to the procedure described in [4] and following placed in magnetron sputtering system.

First, by DC magnetron sputtering of Ni and Si targets in Ar plasma the multilayer Ni/Si(66/60 nm) structures were fabricated, and a pattern for c-TLM electrodes was formed using lift-off technique. These structures were annealed at 600°C (N_2, 15 min.) to form the stoichiometric phase δ-Ni_2Si and following at 1000°C (N_2, 3 min.) to obtain Ni_2Si/n-SiC ohmic contacts with specific contact resistivity $r_c \sim 4 \times 10^{-4}$ $\Omega\,cm^2$ [4]. Next, the contact multilayer structures

Au(150nm)/Ni_2Si/n-SiC and Au(150nm)/$Ta_{35}Si_{15}N_{50}$(100nm)/Ni_2Si/n-SiC were fabricated [5]. The contact structures were long-time aged in air at 400°C up to 150 h or rapid thermal annealed (RTA) in neutral atmosphere (Ar) for 3 min. up to 800°C.

Current-voltage (*I-V*) characteristics of the contacts were measured by Keithley 2400 Source-Meter. Circular transmission line method (c-TLM) was applied to measure contact resistivity (r_c). The sheet resistance (R_{sh}) of metallization was measured by a four-point probe. The elements depth profiles in the contacts were examined by Rutherford backscattering spectrometry (RBS). The contacts surface morphology was analyzed by Philips XL-30 scanning electron microscopy (SEM).

Results and discussion

Au/Ni_2Si/n-SiC. The electrical characteristics of Au/Ni_2Si/n-SiC ohmic contacts before and after heat treatments are summarized in Table 1. Aging in air at 400°C apparently induces (i) two times increase in contact resistivity (r_c) for 50 h, and (ii) non-ohmic behaviour of *I–V* characteristics for 150 h. The r_c of annealed contacts in Ar for 3 min. remains unchanged up to 700°C and increases by about 10% after RTA at 800°C.

The initial sheet resistance (R_{sh} ~ 290 mΩ/sq.) for as-deposited contacts corresponds to the resistance of highly conductive 150 nm thick Au overlayer. Subsequent aging in air at 400°C results in increase of R_{sh} by about 20 and 135% for 50 and 150 h, respectively. After RTA in Ar for 3 min., the sheet resistance decreased by about 10% at both 700 and 800°C. The changes of r_c and R_{sh} indicate mostly on diffusion processes in metallization systems under thermal stress at different conditions. Further studies were performed by RBS and SEM techniques.

Fig. 1 shows the RBS spectra of the Au/Ni_2Si/n-SiC contacts before and after heat treatments. An arrow in all the RBS spectra marks the surface energies of the respective elements. Aging in air at 400°C results in a considerable change of the RBS spectrum, comparing to the spectrum for as-deposited Au/Ni_2Si/n-SiC contact (Fig. 1a). The changes of slope, width and shift of low-energy edge for Au signal to lower energy, as well as appearance of Ni (E ~ 1.5 MeV) and O (E ~ 0.7 MeV) signals are observed for 50 h aged contact. This indicates on the beginning of interaction at the Au/Ni_2Si interface: (i) in-diffusion of Au atoms into the contact, (ii) out-diffusion of Ni and Si atoms to the surface, as well as (iii) oxygen penetration into the contact. These interdiffusion processes lead to disappearance of RBS signal from Ni_2Si and stronger interaction at both Au/Ni_2Si and Ni_2Si/n-SiC interfaces after aging for 150 h. As shown in Fig. 1(b), overlapping RBS spectra for as-deposited and annealed in Ar at 600°C Au/Ni_2Si/n-SiC contacts indicates on non-depth redistribution of the elements after annealing. From the overlap of RBS spectra only small Ni surface signal (E ~ 1.5 MeV) after annealing at 700°C appears steady to conclude that Au/Ni_2Si/SiC interfaces are abrupt.

Fig. 2 shows the SEM micrographs of the Au/Ni_2Si/n-SiC contacts before and after heat treatments. The surface morphology of initial un-annealed contacts is quite smooth (Fig. 2a). As shown in Fig. 2(b), visible depth craters in metallization and granular surface both indicate on strong morphology degradation after aging in air at 400°C (150 h). After RTA in Ar at 700°C (Fig. 2c), morphology degradation following from pores formation indicates on the beginning of contact degradation.

Table 1. Electrical characteristics of Au/Ni_2Si/n-SiC and Au/$Ta_{35}Si_{15}N_{50}$/Ni_2Si/n-SiC ohmic contacts before and after heat treatments.

Treatment		As-dep.	Aging (400°C, air)		RTA (Ar, 3 min.)	
			50 h	150 h	700°C	800°C
Au/Ni_2Si/n-SiC	r_c [mΩ cm^2]	0.40	0.85	non-ohmic	0.40	0.45
	R_{sh} [mΩ/sq.]	290	350	680	270	260
Au/TaSiN/Ni_2Si/n-SiC	r_c [mΩ cm^2]	0.40	0.45	0.45	0.40	0.40
	R_{sh} [mΩ/sq.]	290	170	170	170	220

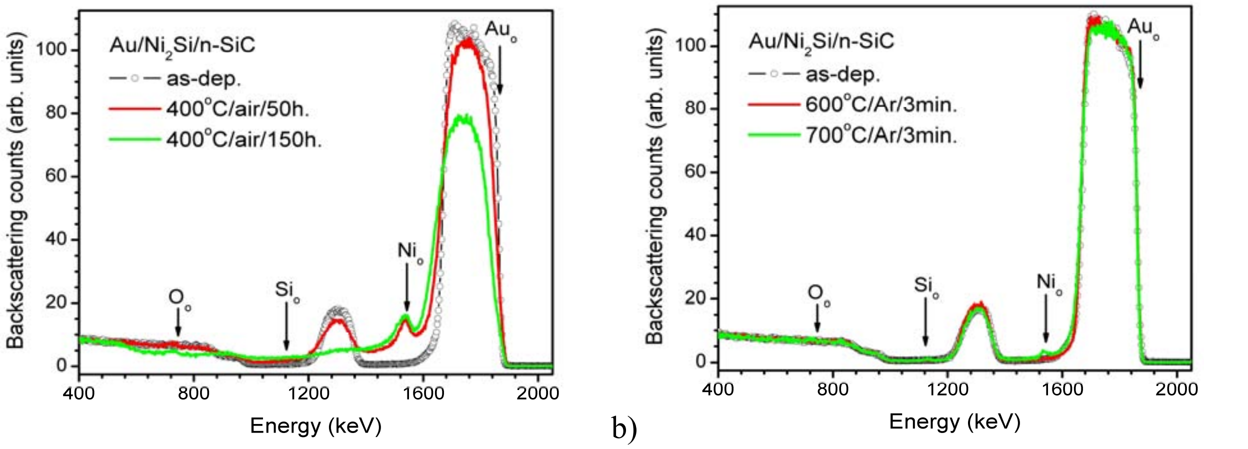


Fig. 1. The 2-MeV He^{+} backscattering spectra of the $Au/Ni_2Si/n\text{-}SiC$ ohmic contacts before and after aging in air at 400°C (a) and after RTA (3 min.) in Ar (b).

a) b) c)

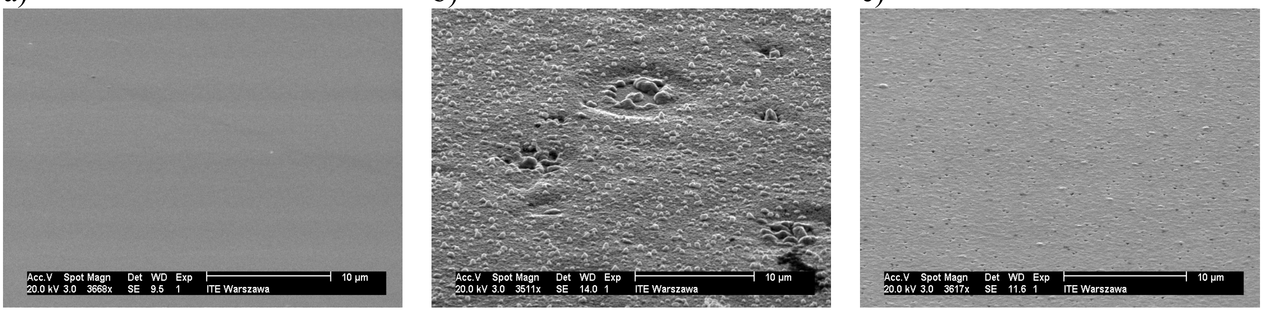


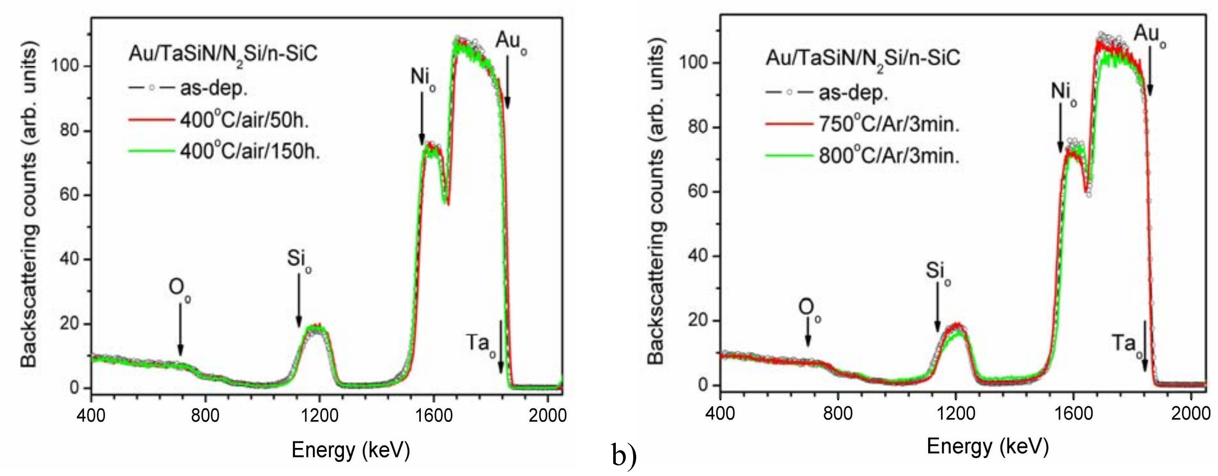
Fig. 2. SEM micrographs of the $Au/Ni_2Si/n\text{-}SiC$ ohmic contacts: (a) as-deposited; (b) aged in air at 400°C for 150 h; (c) annealed in Ar for 3 min. at 700°C.

$Au/TaSiN/Ni_2Si/n\text{-}SiC$. As it is shown in Table 1 for $Au/TaSiN/Ni_2Si/n\text{-}SiC$ contacts, the resistivity (r_c) increases of about 10% after aging in air at 400°C for 50 h and following remainder unchanged upon aging for 150 h. The RTA in Ar induces no-detectable changes in r_c up to 800°C. The sheet resistance (R_{sh}) for these contacts decreases of about 40% after aging in air at 400°C for 50 h and following remained unchanged after aging up to 150 h. After RTA in Ar for 3 min., the R_{sh} decreases of about 40% at 700°C and increases by about 30% at 800°C.

Fig. 3 shows the RBS spectra of the $Au/TaSiN/Ni_2Si/n\text{-}SiC$ contacts before and after heat treatments. As it is shown in Fig. 3(a), the RBS spectra for as-deposited and aged samples in air at 400°C for 50 and 150 h are overlapped. Unchanged spectra prove that Ta-Si-N diffusion barrier placed between Au overlayer and $Ni_2Si/n\text{-}SiC$ ohmic contact preserves their interfaces abrupt and composition unaltered during aging in air at 400°C for a long time. The overlapping of RBS spectra of $Au/TaSiN/Ni_2Si/n\text{-}SiC$ contacts before and after annealing in Ar at 750°C indicates that distribution profiles of the elements remain the same (Fig. 3b). Thus, the initial reduction of R_{sh} is not related with interdiffusion processes, and may be explained by a decrease of the grain boundary density after recrystallization of Au layer. However, by comparing the RBS spectra of the contacts before and after RTA at 800°C a small change is observed.

Fig. 4 shows the SEM micrographs of the $Au/TaSiN/Ni_2Si/n\text{-}SiC$ contacts before and after the heat treatments. By comparing the Figs. 4(a) with 4(b), we may conclude that aging of $Au/TaSiN/Ni_2Si/n\text{-}SiC$ contact in air at 400°C for 150 h does not changes the surface morphology and contact surface still preserves smooth surface. However, after RTA at 800°C the formation of small number of pores is observed (Fig. 4c). The changes in RBS spectra and increase of R_{sh} after RTA at 800°C may be explained by thermally induced modification of only Au overlayer.

Thus, the effective diffusion barriers must prevent penetration of oxygen from environment into the ohmic contacts and the interdiffusion between neighbour layers.



a) b)

Fig. 3. The 2-MeV He$^+$ backscattering spectra of the Au/TaSiN/Ni_2Si/n-SiC ohmic contacts before and after aging in air at 400°C (a) and after RTA (3 min.) in Ar (b).

a) b) c)

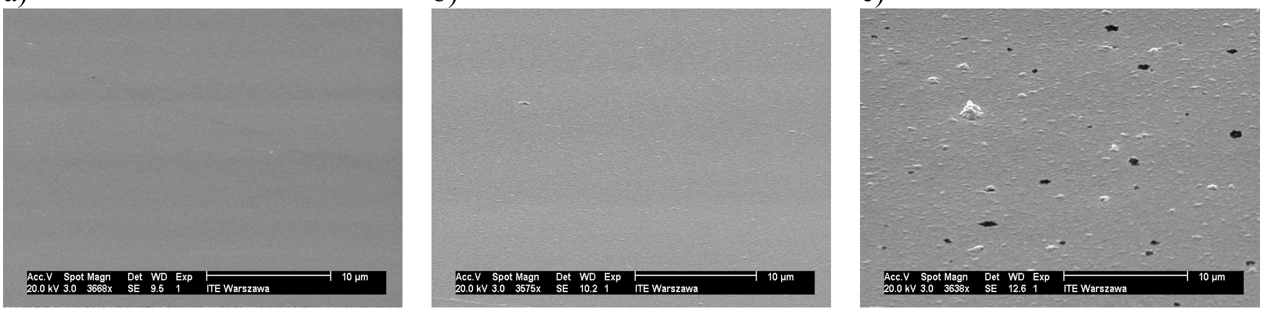


Fig. 4. SEM micrographs of the Au/TaSiN/Ni_2Si/n-SiC ohmic contacts: (a) as-deposited; (b) aged in air at 400°C for 150 h; (c) annealed in Ar for 3 min. at 800^{o}C.

Summary

We conclude that degradation of Au/Ni_2Si/n-SiC ohmic contacts becomes stronger after long-time aging in air at relatively low temperature (400°C) compared to rapid thermal annealing up to 800°C in neutral gas (Ar). The degradation process in air comes mainly from the diffusion of oxygen into the contacts, as previously observed [6]. The optimised $Ta_{35}Si_{15}N_{50}$ diffusion barrier placed between Ni_2Si/n-SiC ohmic contact and Au overlayer prevents interdiffusion between metals into the contact region, as well as penetration of oxygen during aging in air for long time. Thus, the diffusion barriers free of diffusion path microstructures are key elements to improve the thermal stability of metal-SiC ohmic contacts for high-temperature electronics.

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