Fabrication and characterization of nickel silicide ohmic contacts to n-type 4H Silicon Carbide

A Kuchuk[1*], V Kladko[1], M Guziewicz[2], A Piotrowska[2], R Minikayev[3], A Stonert[4], R Ratajczak[4]

[1]V. Lashkaryov Institute of Semiconductor Physics of NASU, Kyiv 03028, Ukraine
[2]Institute of Electron Technology, Warsaw 02668, Poland
[3]Institute of Physics, Polish Academy of Sciences, Warsaw 02668, Poland
[4]The Andrzej Soltan Institute for Nuclear Studies, Warsaw 00681, Poland

E-mail: kuchuk@isp.kiev.ua

Abstract. In this paper, we report on fabrication and characterization of nickel silicide ohmic contacts to n-type 4H-SiC. The contacts on Si-faced 4H-SiC were fabricated by DC magnetron sputtering of Ni and Si thin films. One set of structures has the Ni/Si/SiC scheme; the second one has the Si/Ni/SiC scheme. The Ni/Si thickness ratios of 66/60 and of 27/101 (nm) were designed to produce the stoichiometric Ni_2Si and $NiSi_2$ compound, respectively. The contact structures were annealed at 600°C for 15 min, and subsequently from 800 to 1100°C for 3-5 min in N_2 flow. The structure, composition, morphology and electrical properties of the contacts were examined using XRD, RBS, optical microscope and *I-V* measurements, respectively. The results indicate that the stoichiometric nickel silicides are formed after first step annealing (600°C). Only the Ni_2Si/n-SiC contact annealed at 1050°C show Ohmic behaviour with low contact resistivity of $\rho_c \sim 5\times10^{-4}$ Ω cm^2 and excellent surface morphology.

1. Introduction

Silicon Carbide (SiC) combines unique material properties (wide band gap, high breakdown electric field, high electron drift velocity, high thermal conductivity, chemical inertness), which makes it a very promising material for development of high -power, -temperature and -frequency semiconductor devices. However, for realization of such application potential, developing of reliable and low resistive Ohmic contacts is still required [1].

The transition metals, especially Ni, are most frequently investigated materials for fabrication of Ohmic contacts to n-SiC due to low specific contact resistance. Thermal formation of Ni/SiC ohmic contacts require annealing at high temperature (> 900^{o}C) annealing, where nickel silicides is formed, and some graphite inclusion and voids are observed [2, 3]. These non-controlled reaction processes limit the reliability of Ni contacts because of rough surface, protrusion into subcontact region and non-uniform metallization in submicron scale. A possible way to improve ohmic contact it would be adding of Si in the Ni metallization, to reduce reaction between Ni and SiC. Hypothesis consists in form of stoichiometric nickel silicides (Ni_2Si, NiSi, and $NiSi_2$).

* To whom any correspondence should be addressed.

In this paper, we report on fabrication and characterization of Ni_2Si and $NiSi_2$ contacts to 4H n-SiC, where Ni-rich Ni_2Si and Si-rich $NiSi_2$ phases are formed by solid-state reaction between Ni and Si prepared in multilayer form. We compare the features of the contacts and investigate the effect of Ni- and Si- film as a first deposited layer on the ohmic contact properties.

2. Experimental details

The Si-faced (0001) n-type 4H-SiC wafers from Cree Research Inc. were used in this study. The epitaxial layer is characterized by a resistivity of 0.074 Ω cm and a thickness of 2 μm. The surface was chemically cleaned by following steps: (i) degreasing in hot organic solvents (trichloroethylene, methanol, acetone); (ii) etching sequentially for 10 min in hot solutions of $NH_4OH:H_2O_2:H_2O$=1:1:5 at 65°C, and $H_2O_2:HCl:H_2O$=1:1:5 at 70°C; (iii) etching for 2 min. in buffered HF ($HF:NH_4F:H_2O$ = 2:7:1). Before each step the samples were rinsed in deionized water and dried using blowing nitrogen.

The circular transmission line method (c- TLM) was applied to measure contact resistivity. Patterned structures were prepared by *lift off* photolithography technique. Immediately prior to loading in sputtering chamber the samples were dipping in buffered HF (30 s), and complete etch by *in-situ* Ar^+ ion mailing at 300V for 30 s, in order to remove native oxide possible existing on SiC.

The Ni and Si films were deposited by magnetron sputtering of Ni (purity of 99.99%) and Si (99.99%) targets in Ar plasma, respectively. The deposition rates were calculated as 9.5 Å/s for nickel and 5 Å/s for silicon. Four series of multilayer structures were fabricated to form stoichiometric Ni-silicides: A) Ni/Si/Ni/Si(33.1/30.3/33.1/30.3nm)/n-SiC; B) Ni/Si/Ni/Si/Ni (19/30.3/28.2/30.3/19nm)/n-SiC; C) Ni/Si/Ni/Si(13.75/50.5/13.75/50.5nm)/n-SiC; D) Ni/Si/Ni (13.75/101/13.75nm) /n-SiC. The contact structures were annealed at 600°C for 15 min, and next subsequently at temperature from 800 to 1100°C for 3-5 min in N_2 flow. Current-voltage (*I-V*) characteristics of the contacts were measured by Keithley 2400 Source-Meter between circle contact pads with a diameter of 100 μm and a metallized area separated by rings with a space of 10, 15, 20, 40 and 60 μm. The phase composition of the contact was investigated by X-ray diffraction (XRD) using Philips X'Pert–MPD diffractometer equipped with Cu K_α radiation source. The profile of composition of the metal/semiconductor contacts was examined by Rutherford backscattering spectrometry (RBS), using 1.7 MeV He^+ beam. Simulations of the RBS spectra were analyzed the computer code RUMP [4]. An optical microscope with Nomarski contrast was used to study the surface morphology of the contact structures.

3. Experimental results

XRD spectra of contacts before and after annealing are presented in the Figures 1(a,b). There are visible 0004 peak of single crystal SiC 4H and 111 peak of polycrystalline Ni and "halo" signal corresponding to amorphous Si for every as-deposited multilayer. The XRD spectra of the annealed at 600°C for 15 min. structures A and B show a few Bragg reflections of the Ni_2Si phase, but for the similarly annealed structures C and D there are visible in spectra the peaks of the $NiSi_2$ phase. Taking into account that no trace of the 111 Ni or a Si peak in the spectra we conclude that as results of thermally activated interaction between Ni and Si are nickel silicides: Ni_2Si phase for samples A and B, and $NiSi_2$ phase for samples C and D.

The Figure 2 shows the *I-V* characteristics measured between the two c-TLM contact pads of A, B, C and D structures after annealing at different temperatures. It can be observed the non-Ohmic characteristics after annealing even at 1000°C, and a decrease in contact resistance when the annealing temperature was higher than about 900°C. The linear *I-V* characteristics were measured only on the samples A and B, both annealed at 1050°C [see Figure 2(a,b)]. The specific contact resistivities of 5.1×10^{-4} Ω cm^2 and of 5.5×10^{-4} Ω cm^2 were calculated by c-TLM method for samples A and B, respectively. Further annealing of these structures at 1100°C caused the increase in its contact resistance, and transition to quasi-linear *I-V* characteristic for sample A ($\rho_c \sim 5.4\times10^{-4}$ Ω cm^2) and to rectifying *I-V* characteristics for sample B. Annealing at 1050 and 1100°C of both C and D samples does not enhance significantly the conduction current through the contacts, and *I-V* characteristics are still nonlinear [see Figure 2(c,d)].

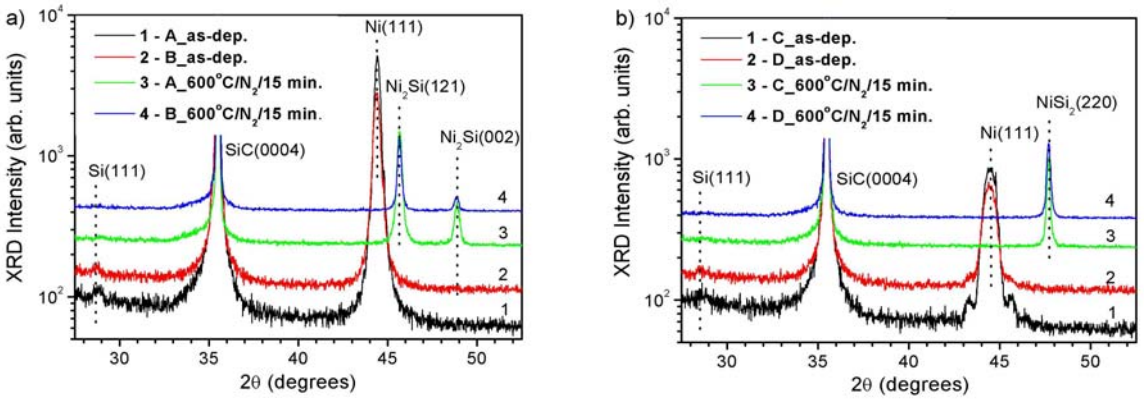

Figure 1. XRD spectra from the as-deposited and annealed at 600°C structures: a) A, B; b) C, D

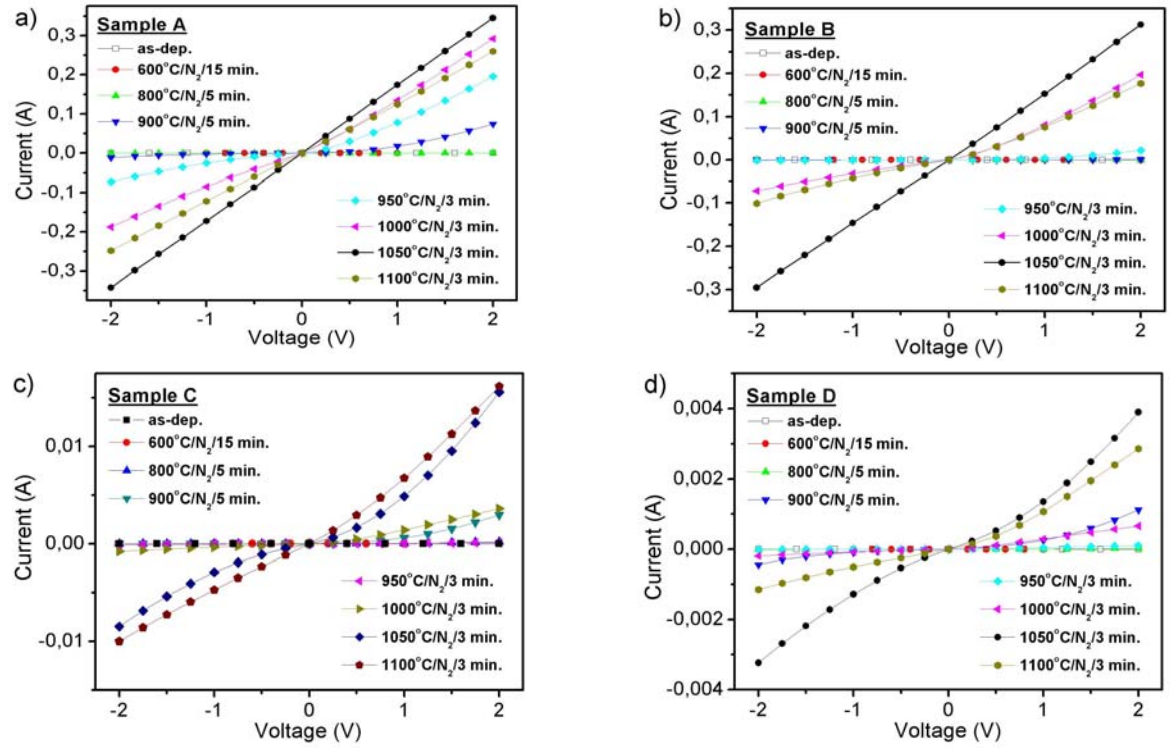

Figure 2. *I-V* spectra of A (a), B (b), C (c) and D (d) structures as function of annealing temperature.

Inspected by optical microscope surface morphology of structures are shown in Figure 3. The homogeneous and smooth surface is visible after annealing at 1050°C. Some drops are observed after annealing at 1100°C on the sample A [Figure 3(b)]. The begin of the spots formation on the sample B was observed at 1050°C with increase of their sizes after annealing at 1100°C [Figures 3(c), 3(d)]. For the samples C and D, the thermally induced heterogeneity and roughening was detected after annealing at 950°C as can be seen in the Figures 3(e) and 3(f).

The Figures 4(a) and 4(b) shows the backscattering depth profiles of the as-deposited and the annealed at 600, 1050 and 1100°C samples A and B, respectively. The changes in the RBS spectra for both A and B samples after annealing at 600°C, indicate the interdiffusion between Ni and Si. From the RUMP code simulation of these spectra the atomic ratio of Ni:Si ~ 2 has been obtained what confirms formation the stoichiometric nickel silicide Ni_2Si as it was observed in the XRD spectra.

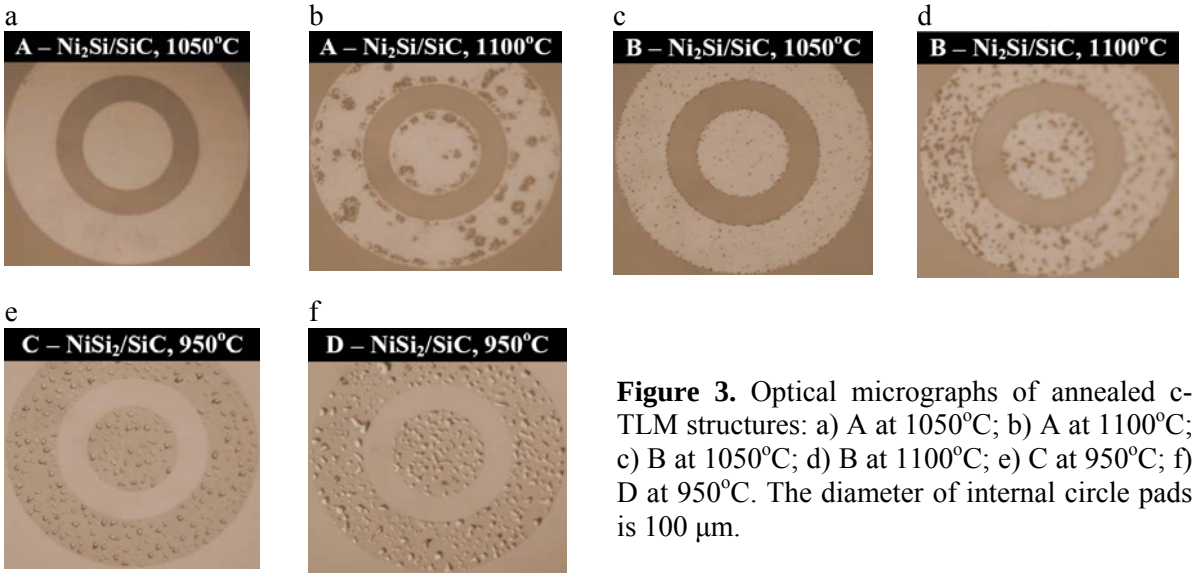

Figure 3. Optical micrographs of annealed c-TLM structures: a) A at 1050°C; b) A at 1100°C; c) B at 1050°C; d) B at 1100°C; e) C at 950°C; f) D at 950°C. The diameter of internal circle pads is 100 μm.

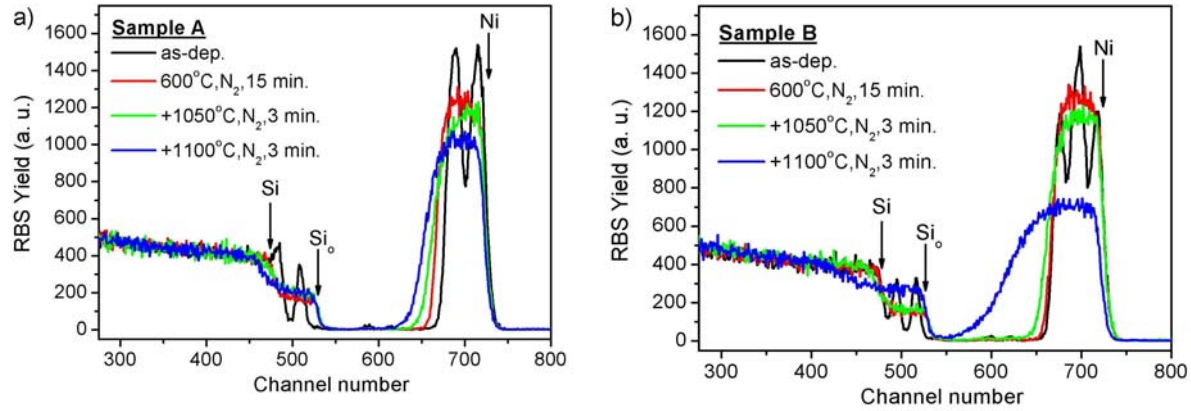

Figure 4. RBS spectra from the as-deposited and annealed structures: a) Sample A; b) Sample B.

After annealing at 1050°C a small decrease of height and increase of width of the Ni signals are visible for both A and B samples. These changes may be related with complete interdiffusion between Ni and Si layers or with a tiny interaction between Ni_2Si and SiC at this temperature. According to the RUMP simulation both Si and C redistribution at the Ni_2Si/SiC interface can modify the changes of the Ni signals. Comparing the slopes of high energy edges of the Si signal from the SiC, we would conclude that during annealing sample B at 1050°C some amounts of Si atoms out-diffuse from the SiC.

The RBS spectra for the A and B samples annealed at 1100°C revealed noteworthy difference in the profiles of the Ni and Si signals. The low energy edge of Ni signal is moved a little to lower energy and a lower slope of the Ni signal is observed for the annealed contact structure B. Simulation show that Ni penetrate into the substrate about 20 nm. These suggest enhanced interdiffusion at Ni_2Si/SiC interface. Comparing the RBS spectra of the contacts after annealing we conclude that more pronounced reaction between Ni_2Si and SiC was observed for sample B where Ni penetration into the SiC is above 100 nm after annealing at 1100°C.

4. Discussion

The analysis of XRD and RBS results demonstrate the fabrication of Ni_2Si and $NiSi_2$ contacts to 4H n-SiC, with Ni- and Si- first layer, as a results of annealing at 600°C for 15 min. of Ni/Si multilayers, with thickness ratios of Ni:Si ~ 1.1 and Ni:Si ~ 0.27, respectively. The rectifying *I-V* characteristics

are observed after the annealing at 600°C for the all of Ni- and Si- first layered Ni_2Si and $NiSi_2$ contacts on 4H n-SiC, unless the reaction of Ni with SiC at temperatures as low as 600°C was observed and presented in the paper [3]. Our electrical measurements show that the formation at 600°C of the stoichiometric nickel silicides of Ni_2Si or $NiSi_2$ is not sufficient to obtain Ohmic characteristics even after annealing at 1000°C and 1100°C, respectively. These results are in agreement with similar study described in the papers [2, 3], but there are contradicting with results published in [5].

The thermally induced degradation of the surface on $NiSi_2$/SiC contacts (the structures C, D) at 950°C indicates droplets of metallization and re-crystallizations of Si-rich Ni phases on the SiC. These degradation processes can be explained by low melting temperature of about 980°C for the $NiSi_2$ bulk material [6]. Therefore, the nonlinear character of $NiSi_2$/SiC contacts even after annealing at 1100°C may by explained by nonuniform morphology and interaction between $NiSi_2$ and SiC.

The Schottky-Ohmic transition was observed only for Ni_2Si/SiC contacts after annealing at 1050°C. For this nickel silicide Ni_2Si the melting temperature is about 1200°C [6]. Therefore, the Ni_2Si/SiC Ohmic contacts keep homogenous surface even after annealing at 1100°C. The resistivity of 5.1×10^{-4} Ω cm^2 was measured in the case of the Si-first deposited layer. A small amount of drops on surface and resistivity of 5.5×10^{-4} Ω cm^2 was registered for the contact with the Ni-first deposited layer. This fact and more evident interdiffusion at 1100°C can be correlated with the non-linear *I-V* characteristics for the contact after annealing at this temperature. Therefore, it is very important that the Si layer is initially positioned between the Ni and SiC to allow the Si and Ni to react completely and thereby prevent a low temperature reaction between the Ni and SiC. That fact explains the homogenous surface of the Si-first layered metallization in Ni_2Si/SiC contact and more stable electrical properties.

Analysis of experimental results indicates that for fabrication of Ohmic contacts to SiC a minimum elemental diffusion and/or interfacial reactions between metallization and SiC it is necessary. Probably, change of the atoms distribution at the Ni_2Si/SiC interface after annealing at 1050°C, are responsible for the ohmic contact formation. As it was well described by Nikitina et al. [2], the out-diffused C atoms during high temperature annealing (>1000°C) create C vacancies in SiC, which acts as donors and thus contribute to the formation of Ohmic contacts. It is likely possible that the Si in Ni/Si contacts restrains dissociation of SiC, therefore, more carbon vacancies V_C can be formed on the SiC surface and in the subsurface region.

5. Conclusions

By annealing Ni/Si multilayers at 600°C for 15 min., we fabricate the Ni-rich Ni_2Si/SiC or Si-rich $NiSi_2$/SiC contact structures depending on the film thickness ratio. Ohmic contact is obtained for Ni_2Si/SiC structure after annealing at 1050°C. In view of homogenous surface, relatively low specific contact resistivity ($\rho_c \sim 5.1\times10^{-4}$ Ω cm^2) was measured only on the Ni_2Si/SiC contact where Si was first deposited on n-SiC substrate. This contact could give new possibility for application in high temperature semiconductor device technology.

Acknowledgements

The work was supported by grants from INTAS (No. 06-1000014-5957) and from the Ministry of Science and Higher Education of Poland (No. 3T11B 042 30).

References

[1] H. Matsunami 2006 Microelectronic Engineering **83** 2.
[2] I.P. Nikitina, K.V. Vassilevski, N.G. Wright, A.B. Horsfall, A.G. O'Neill, C.M. Johnson 2005 *J. Appl. Phys.* **97** 083709.
[3] J. Crofton, L.M. Porter, J.R. Williams 1997 *Phys. Stat. Sol. (b)* **202** 581.
[4] L.R. Doolittle 1985 *Nucl. Instrum. Methods Phys. Res. B* **9** 344.
[5] E. Kurimoto, H. Harima, T. Toda, M. Sawada, M. Iwami, S. Nakashima 2002 *J. Appl. Phys.* **91** 10215.
[6] G.V. Samsonov, I.M. Vinitskii 1980 *Handbook of Refractory Compounds* (Plenum, New York).