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Ni-Al Ohmic contact to p-type 4H-SiC

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Abstract:

Investigations on Ni/-Al alloys to form ohmic contacts to p-type 4H-SiC are presented in this paper. Several ratios of the Ni/Al contact were examined. Rapid thermal annealing was performed under Argon atmosphere at 400°C during 1 minute, followed by an annealing at 1000°C during 2 minutes. In order to extract the specific contact resistance, transmission line method (TLM) test-structures were fabricated. A specific contact resistance of $3 \times 10^{-5} \Omega \cdot \text{cm}^2$ was obtained reproducibly on p-type layers, with a doping of $N_A = 1 \times 10^{19} \text{ cm}^{-3}$ performed by Al^{2+} ion implantation. The lowest specific contact resistance value measured was $8 \times 10^{-6} \Omega \cdot \text{cm}^2$.

Introduction

Silicon carbide is a semiconductor which has several superior properties to silicon such as a wide bandgap three times greater, high electric field strength (six times), a high thermal conductivity as good as copper and a high electron saturation drift velocity. Since SiC single-crystal growth wafers were commercialised, intensive investigations have been performed to fabricate SiC devices for high temperature, high frequency and high power applications [1].

The switching speed and power dissipation of semiconductor devices depend strongly on the contact resistance [2]. To manufacture high performance SiC devices, development of low contact resistance is one of the key issues. It is currently limiting SiC devices performances particularly due to the contacts to p-type [3-10] because of the high work function. These contacts employ generally an aluminium-based alloy [3, 9], thus using Al which is also a dopant to p-SiC, local diffusion at the surface is expected to increase the doping. Many different solutions have been investigated and a great deal of attention has been focused on Ti/Al contact [3-5], which has produced specific contact resistances in the range of $10^{-4} - 10^{-5} \Omega \cdot \text{cm}^2$ to p-SiC. Recent attempts to produce improved contacts by using alternative materials [6, 7] such as TiC

have resulted in specific contact resistances lower than $1 \times 10^{-5} \Omega \cdot \text{cm}^2$, but these realizations required non-conventional materials and non standard fabrication techniques. In another hand, some investigations were focused on the Ni/Al contact [9, 10], the advantage is the easiness to obtain an ohmic behaviour.

In this paper, the formation of the Ni/Al ohmic contact to p-SiC is presented and discussed through the different process parameters. A set of samples was processed in different configurations. Kind attention was first focused on the surface preparation and especially on the necessity of an oxidation step. Then, the composition of the ohmic contact is investigated and discussed. Finally, the effect of the annealing sequence is analysed. A standard trapezoidal thermal treatment profile is used for the annealing at 1000°C then it was modified by the addition of an intermediate step at 400°C .

Experimental

The samples are 4H-SiC n-type substrates with an n-type epilayer doped at $1 \times 10^{15} \text{ cm}^{-3}$ purchased from CREE Research. The p-type regions were obtained by Al^{2+} ion implantation, the doping concentration is $N_A = 1 \times 10^{19} \text{ cm}^{-3}$. The post-implantation annealing was performed at 1650°C during 45 minutes under argon atmosphere [11]. Samples were first cleaned in solvents followed by a “piranha” solution. After rinsing, an RCA cleaning is applied to the samples, then they were dipped into buffer oxide etch (BOE). Immediately after the cleaning, a SiO_2 layer was grown in dry oxygen at 1150°C during 2 hours. The transmission line method patterns were obtained by a lift-off process. The oxide was being etched prior to introducing the samples into the evaporation chamber. The formation of the ohmic contact is established after annealing the samples in an RTA furnace under argon atmosphere at 1000°C .

Results and discussion

The samples were processed with different parameters as a function of the surface preparation, the annealing sequence and the contact composition. In any case, an ohmic behaviour is observed. The specific resistance was extracted from TLM analyses. The samples were contacted with a probe station and the $I(V)$ measurements were performed with a Source-Meter Unit Keithley 2410.

The results of the specific resistances extracted from the samples are summarised in the table 1.

Table 1.
Summary of specific resistances from the samples.

Sample	Ref.	N_A (cm^{-3})	Composition		Al content (at%)	Oxyd.	Annealing		ρ_c ($\Omega \cdot \text{cm}^2$)
			Ni (nm)	Al (nm)			Temp. ($^\circ\text{C}$)	Duration (s)	
1	R0321-7 n°29	10^{19}	50	200	73	yes	1000	120	$7,3 \times 10^{-3}$
2	DC20C2-23-SY-7	10^{19}	50	400	84	yes	1000	120	$1,85 \times 10^{-4}$
3	CN – B	10^{19}	50	500	87	yes	1000	120	$3,2 \times 10^{-5}$
4	CN – C	10^{19}	50	500	87	yes	1000	120	$2,8 \times 10^{-5}$
5	CN – D	10^{19}	50	500	87	no	1000	120	$5,6 \times 10^{-4}$
6	DC20C2-23-SY-8	10^{19}	50	400	84	yes	1000	120	$7,9 \times 10^{-6}$
7	R0321-7 n°28	10^{19}	50	450	86	yes	1000	120	$5,6 \times 10^{-3}$
8	CN – A	10^{19}	50	450	86	yes	1000	120	$4,5 \times 10^{-5}$
9	FL0288-10 n°2	10^{19}	50	0	0	yes	1000	120	not ohmic

The values are in the range of $7.3 \times 10^{-3} - 7.9 \times 10^{-6} \Omega \cdot \text{cm}^2$. Thus, the lowest specific resistance (sample #6) was obtained only once and with the optimal configuration a reproducible contact resistance of about $3 \times 10^{-5} \Omega \cdot \text{cm}^2$ (sample #3 and #4) is observed. The optimal process is established for an oxidation surface preparation and a contact composition of 87 at% Al content.

Surface preparation

Attentions were first focused on the surface preparation. All the samples were cleaned with the same chemical solutions and only the sample #5 were not oxidised. The well effect of the oxidation is observed by comparing two samples. Samples #4 and #5 have got the same metallization composition with 87 at% of Al content. The sample #4 which has the oxidation preparation exhibits a specific resistance of $2.8 \times 10^{-5} \Omega \cdot \text{cm}^2$ while the sample #5 without oxidation is one order of magnitude worse with a value of $5.6 \times 10^{-4} \Omega \cdot \text{cm}^2$. Since the oxide was etched just before the metal evaporation, it protects and prevents the surface from contamination. The other influence of the oxidation preparation is the breaking of the Si-C bound. Indeed during the oxidation, oxygen atoms react with silicon atoms to form the oxide and with the carbon atoms into CO or CO₂ volatile species [12]. However these reactions create also some carbon clusters at the interface [13] that facilitate the beginning of the reactions between the SiC and the metals atoms.

Metallization composition

The metallization is based on nickel and aluminium alloys. Several compositions were tested as a function of Al content in the contact. The figure 1 shows the specific resistance evolution versus the Al content in the metallization. With an Al content of 73 at% (sample #1), the specific resistance extracted is $7.3 \times 10^{-3} \Omega \cdot \text{cm}^2$ while in the case of higher Al content, the ohmic contact resistance is one order of magnitude better with 84 at% (sample #2). Moreover a contact with a higher Al concentration (87 at%, sample #4) is two orders of magnitude lower. The specific resistance values are 1.84×10^{-4} and $2.8 \times 10^{-5} \Omega \cdot \text{cm}^2$ respectively. The higher Al content in the metallization, the lower is the ohmic contact resistance.

The metallization of the sample #9 does not exhibit any ohmic behaviour; this proves that the presence of Al atoms is necessary to obtain an ohmic contact. The increasing of Al atoms causes more reactions with C atoms from the substrate to form Al₄C₃ alloy [10]. This chemical reaction creates many carbon clusters and it enhances the formation of the Ni₂Si alloy. As mentioned in several works [9, 10], the higher concentration of the Ni₂Si in the contacts, the lower is the specific resistance.

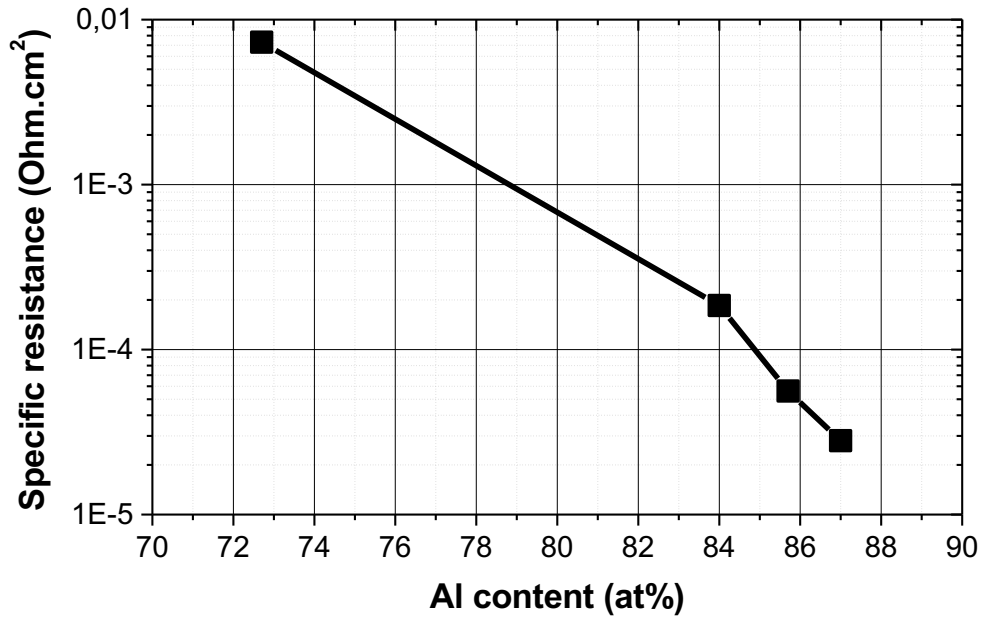


Fig. 1. Specific resistance versus the Al content in the contact.

Table 2.

Summary of specific resistances in the literature.

Composition	P-Layer doping (cm ⁻³)	Annealing temperature (°C)	ρ_c (Ω .cm ²)	reference
Ti/Al (10/90)	$1,3 \times 10^{19}$	1000	5×10^{-6}	[4]
Ti/Al (30/70)	1×10^{19}	1000	$4,9 \times 10^{-5}$	[3]
TiC	$>1 \times 10^{20}$	350	$1,9 \times 10^{-5}$	[7]
Co/Si/Co	$1,1 \times 10^{19}$	550 / 800	$1,5 \times 10^{-6}$	[8]
Ni/Al (20/80)	$6,4 \times 10^{18}$	1000	$9,5 \times 10^{-5}$	[9]
Ni/Al (13/87)	1×10^{19}	1000	$2,8 \times 10^{-5}$	This study
Ni/Al (16/84)	1×10^{19}	1000	$7,9 \times 10^{-6}$	This study

The advantage of the Ni/Al contact compared to the Ti/Al contact is the possibility to form an ohmic behaviour whatever the concentration of Al in the contact. In the case of Ti/Al composition, the ohmic behaviour is very sensitive to the Al concentration [3]. The results presented in this paper are as well as the Ti/Al contacts obtained in other investigations on p-SiC ohmic contacts [3-5] (table II).

Annealing

According to the investigations on SiC ohmic contacts, a high temperature annealing at 1000°C is necessary to form a good ohmic contact even for contacts to n-type layers [14]. This high temperature is required to cause reactions between the SiC and the metals at the interface to form silicide and carbide alloys. However the configuration of the metallization with an aluminium layer on the top then a rapid ramp to 1000°C is required to avoid evaporation. A ramp superior to 50°C/s is preferred; the fast arrival of thermal energy might involve rapidly reactions of Al atoms with Ni and C atoms to form AlNi alloy and Al₄C₃. Theses compounds are stable at high temperature. Two annealing profiles were performed. The first one is a standard process, with a rapid ramp to 1000°C and a plateau during 2 minutes before cooling. The second begins with a first stage at 400°C during 1 minute followed by a step at 1000°C during 2 minutes (fig. 2).

Sample #7 was annealed with the first configuration and the sample #8 with the second temperature profile. Samples #7 and #8 specific resistances are 5.6×10^{-3} and $4.5 \times 10^{-5} \Omega \cdot \text{cm}^2$ respectively.

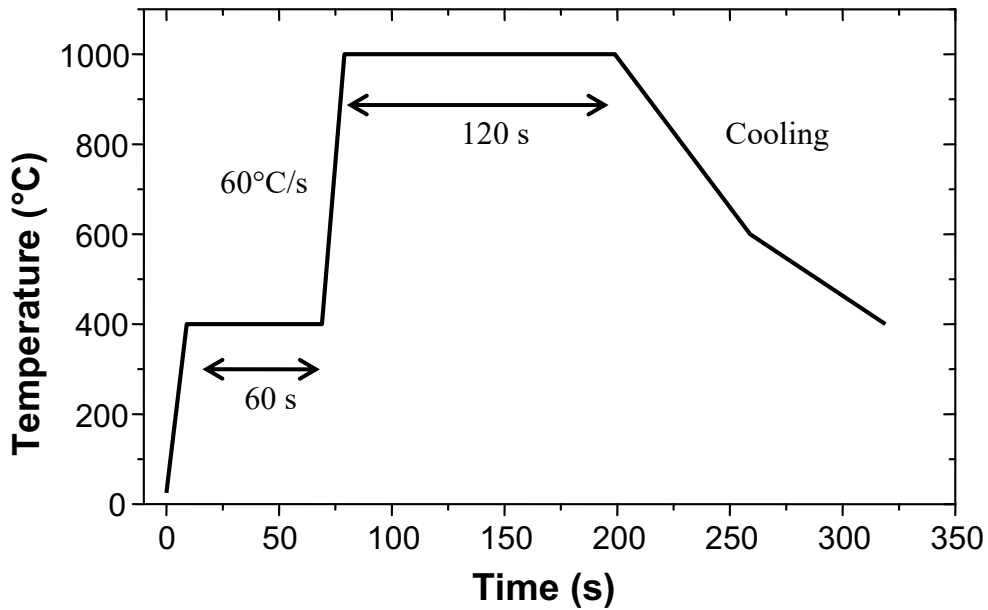


Fig. 2. Temperature profile of the annealing.

For the second sample, the ohmic contact is two orders of magnitude lower than the first one. It could be assumed that during the step at 400°C, AlNi alloys are formed and are stable at high temperature and this phenomenon limits the evaporation of aluminium. Profilometry measurements after the annealing demonstrate a contact thickness reduction of 25 % and less than 10 % for the two annealing profiles respectively. Thus with the increasing of AlNi concentration, more Al atoms could react with C atoms from the SiC to enhance the formation of Ni₂Si alloy which is predominant in the formation of the ohmic contact.

Conclusion

In this paper, a Ni/Al ohmic contact to p-type 4H-SiC was developed. After optimization of the process through the surface preparation, the contact composition and the annealing, a reproducible ohmic contact with a specific resistance of $3 \times 10^{-5} \Omega \cdot \text{cm}^2$ was demonstrated to a p-type SiC layer doped at $1 \times 10^{19} \text{ cm}^{-3}$. This result is obtained with an oxidation surface preparation to protect the surface until metals deposition. The contact composition is a nickel layer of 50 nm thick and an aluminium layer of 500 nm thick which represents an Al content of 87 at%. After annealing at 400°C for 1 minute followed by another step at 1000°C during 2 minutes, the ohmic contact becomes effective.

Further characterizations will be performed to observe the ohmic contact behaviour at high temperature for the possibility of implementation in high temperature SiC devices fabrication.

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