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Analysis of Ohmic Contacts Simultaneously Formed on both n-Type and p-Type 4H-SiC

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Abstract. In this paper, various annealing conditions using Al-based (Ti/Al/Ti/Au=70nm/100nm /5nm/120nm) and Ni-based (Ti/Ni/Ti/Au=20nm/90nm/5nm/120nm) metal contacts to n-type and p-type ion-implanted 4H-SiC epi layers have been studied in the effort to optimize simultaneous ohmic contact formation with the lowest specific contact resistance (SCR) values. Values of 1.091×10^{-4} $\Omega\cdot cm^2$ and 1.158×10^{-5} $\Omega\cdot cm^2$ were achieved using Al-based Ohmic metal contacts for p-type and n-type 4H-SiC, respectively, at an annealing temperature of 950°C and under vacuum for 90 sec. Ohmic formation mechanisms were analyzed using the X-Ray Diffraction (XRD) surface analysis method, indicating Ti_3SiC_2 alloys to be the key intermediate layer formed at SiC/Ti interface, responsible for Ohmic properties to p-type SiC. The paper summarizes the metal process combinations possible for the formation of Ohmic contacts to both n-type and p-type 4H-SiC, offering various options in either using the same metal materials and/or common annealing conditions.

Introduction

Simultaneous formation of Ohmic contacts to both n-type and p-type 4H SiC is essential to simplifying the fabrication process and optimizing the device size of SiC MOSFETs and PiN diodes. Especially for vertical power SiC MOSFETs, in order to effectively reduce the cell pitch to further increase channel density and improve device performance, simultaneous formation of ohmic contacts both on n^+ source region and p-well region with low specific contact resistance using the same contact metal and/or common annealing condition is essential. Not only device performance is dependent on n^+ drain/source contact resistance and its current conduction capability, quality p-well contact is also required to short out the base and emitter through source metallization to disable the parasitic NPN transistor and provide the substrate contact for the inversion channel in the MOSFET structure.

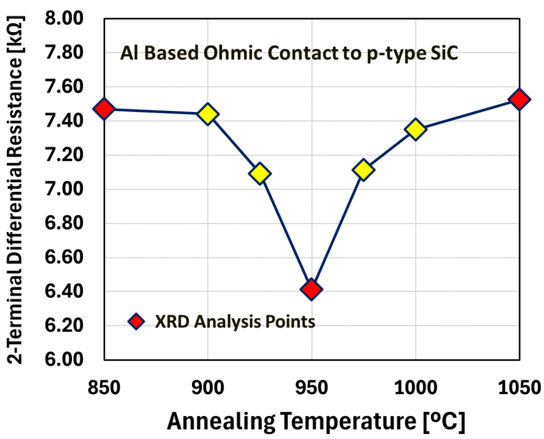

Fig. 1. Two-terminal differential resistance value at various annealing temperature.

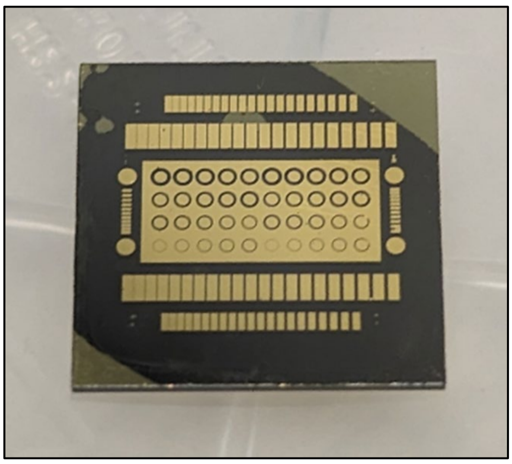

Fig. 2. Fabricated Transfer Length Method (TLM) pattern with mesa-isolation etch.

Fabrication

In this experiment, a 4H-SiC substrate with an epi layer in a thickness of 10 µm and a nitrogen doping concentration of 9×10^{15} cm^{-3} was used. The implantations of phosphorus ions were performed at room temperature, using different ion energies (50 ~ 200 keV) and doses of 9.0×10^{14} ~ 2.7×10^{15} cm^{-2} to create a box profile with a depth of roughly 280 nm and a concentration of 8×10^{19} cm^{-3} for the formation of n^+ layer (Summarized in Table I and Fig. 3(a)). The implantations of aluminum ions were performed at 400 °C, using different ion energies (20~160 keV) and doses of 2.5×10^{14} ~ 8.5×10^{14} cm^{-2} to create a box profile with a depth of approximately 250 nm and a concentration of 8×10^{19} cm^{-3} for the formation of p^+ layer (Summarized in Table II and Fig. 3(b)). Both layers were formed on opposite polarity well of a 4H-SiC epi wafer.

The activation process involves the deposition of a Diamond-Like Carbon (DLC) layer through the method of plasma-based ion implantation and deposition (PBIID) in a thickness of 70nm as the cap layer, followed by annealing at 1700°C for 30 min to electrically activate both implanted dopants. It is known that high-temperature annealing at 1600~1700 °C is necessary to obtain an activation ratio higher than 90% [1].

In this paper, we will be exploring two different types of Ohmic metal stacks: Al-based Ohmic metal contact stacks (Ti/Al/Ti/Au=70nm/100nm/5nm/120nm) and Ni-based Ohmic metal contact stacks (Ti/Ni/Ti/Au=20nm/90nm/5nm/120nm). The role of the 2^{nd} thin Ti layer (thickness of 5nm) is to prevent oxidation from occurring further inward by forming titanium oxides [2]. Titanium oxide can take oxygen away from Ni, Al, and SiC to prevent further oxidation. Transfer Length Method (TLM) patterns were formed through photolithography and then mesa-isolated with a shallow fluorine-based ICP etch as shown in Fig. 2. The annealing temperature was optimized using the two-terminal differential resistance method shown in Fig. 1. All contacts were annealed under a vacuum of 4×10^{-5} Torr using Annealsys Rapid Thermal Processor (RTP).

Table I. Phosphorus implantation series for n-type ohmic contact.

Dopant	Dose [cm^{-2}]	Energy [keV]	Angle/Twist [degree]
Phosphorus	2.7×10^{15}	200	Tilt 7, Twist 23
Phosphorus	1.4×10^{15}	100	Tilt 7, Twist 23
Phosphorus	9.0×10^{14}	50	Tilt 7, Twist 23

Table II. Aluminum implantation series for p-type ohmic contact.

Dopant	Dose [cm^{-2}]	Energy [keV]	Angle/Twist [degree]
Aluminum	8.5×10^{14}	160	Tilt 7, Twist 23
Aluminum	5.0×10^{14}	80	Tilt 7, Twist 23
Aluminum	2.5×10^{14}	20	Tilt 7, Twist 23

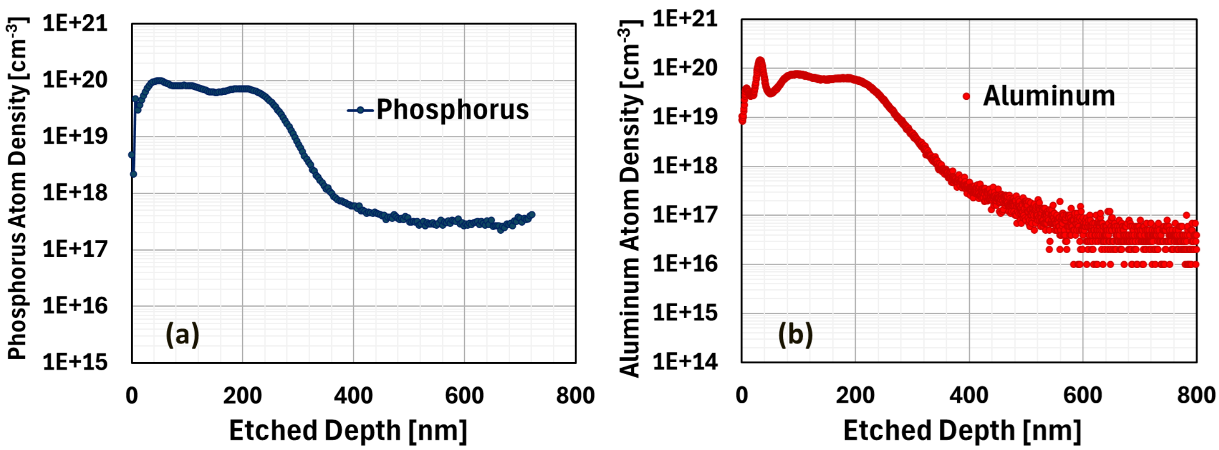

Fig. 3. Secondary Ion Mass Spectrometry (SIMS) profiles of Phosphorus and Aluminum implantation to the 4H-SiC epi wafers.

Results and Discussion

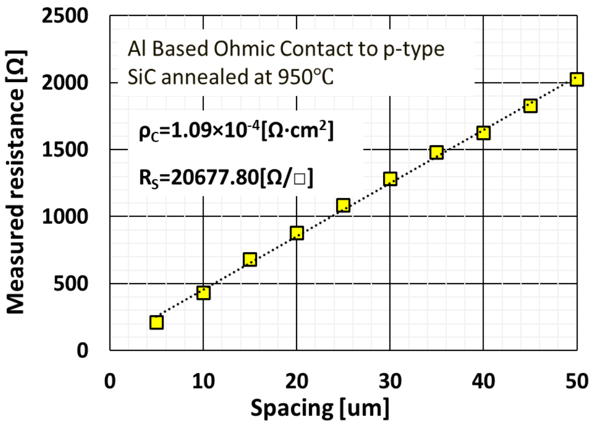

Fig. 4. TLM evaluation of Al-based ohmic contact to p-type SiC annealed at 950°C.

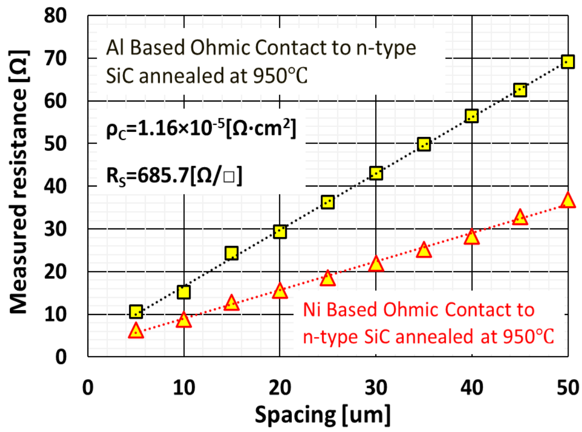

Fig. 5. TLM evaluation of Al-based ohmic contact to n-type SiC annealed at 950°C.

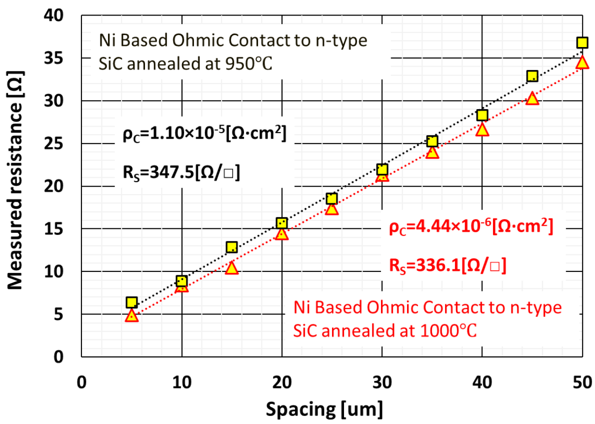

Fig. 6. Comparison of Ni-based ohmic contact to n-type SiC at various annealing temperature.

The fabricated TLM structures were electrically characterized and the sheet resistance R_S, the contact resistance R_C, as well as the specific contact resistance ρ_C were extracted. The nickel silicide (Ni_2Si) layers formed from Ni-based metal contacts, at an annealing temperature above 900 °C, exhibited good ohmic behavior to heavily doped n-type layer and continued to show lower specific contact resistance ρ_C with respect to the increasing annealing temperature (Fig. 6). This is because the out-diffusion of C atoms during high temperature annealing (>1000°C) creates carbon vacancies in SiC, which acts as donors, thus contributing to even lower specific contact resistance [3]. On the other hand, this is not the same against p-type layer, as Ni-based ohmic metal shows slightly non-linear *I-V* characteristics. A different system is necessary for forming quality ohmic contacts to p-type 4H-SiC and Ohmic formation mechanism will be explained in the following XRD spectra results. The obtained specific contact resistance ρ_C against p-type SiC layer using the alternative Al-based metal contacts was 1.091×10^{-4} $\Omega\cdot cm^2$ at an annealing temperature of 950°C (Fig. 4). Additionally, the Al-based metal contact was also effective against n-type SiC layer, showing specific contact resistance ρ_C value of 1.158×10^{-5} $\Omega\cdot cm^2$ achieving simultaneous formation (i.e., using the same contact materials and a one-step annealing process) of Ohmic contacts to both n-type and p-type 4H-SiC (Fig. 5). Table III below summarizes past reports of specific contact resistance for ohmic contacts simultaneously formed on 4H-SiC, indicating the competitiveness of the values obtained from our current work.

Table III. Reported specific contact resistance for ohmic contacts simultaneously formed on 4H-SiC.

Metallization	Extracted Parameters		Annealing Temperature [°C]	Annealing Duration [min]	Doping Concentration		Refs
	$\rho_{C n\text{-type}}$	$\rho_{C p\text{-type}}$			N_D [cm^{-3}]	N_A [cm^{-3}]	
Ni/Ti/Al	2.5×10^{-3}	2.1×10^{-3}	800	30	1×10^{19}	8×10^{18}	[4]
Ni	1×10^{-4}	1×10^{-3}	1000	1	3×10^{20}	1×10^{20}	[5]
Ni/Al	1.8×10^{-4}	1.2×10^{-2}	1000	5	1.3×10^{19}	7.2×10^{18}	[6]
W:Ni	6.8×10^{-6}	7.3×10^{-6}	1150	30	2×10^{19}	3×10^{20}	[7]
Pt80:Ti20 at. %	7.3×10^{-4}	7×10^{-5}	1000	0.16	7×10^{18}	2.5×10^{20}	[8]
Ti/Al/Ti/Au	**1.158×10^{-5}**	**1.091×10^{-4}**	950	1.5	8×10^{19}	8×10^{19}	This work

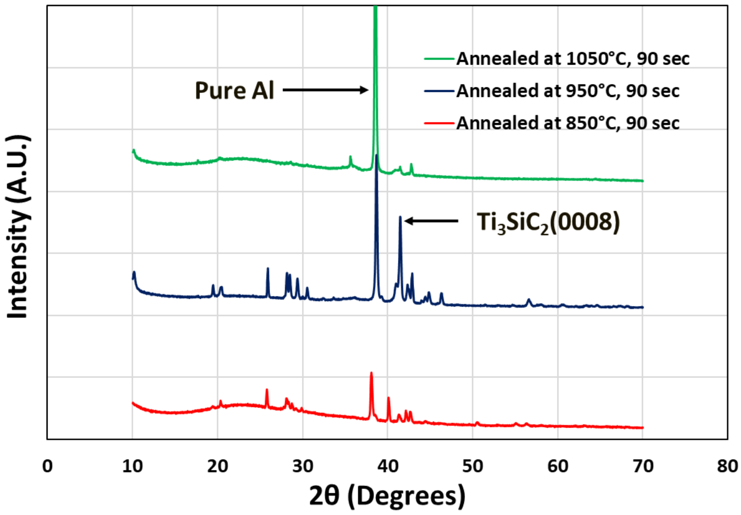

Fig. 7. XRD spectra of Al-based (Ti/Al/Ti/Au) Ohmic contact to p-type SiC annealed at 850°C, 950°C, and 1050°C.

Fig. 7 illustrates the XRD spectra of Al-based Ohmic contacts formed on p-type 4H-SiC at various annealing temperatures. Rapid thermal annealing (RTA) at 950°C, under vacuum, forms Ti_3SiC_2 alloys, which grow at the SiC/Ti interface responsible for Ohmic properties to p-type SiC. These alloys have a work function of 5.07eV, which corresponds to an intermediate value between Ti and p-type SiC, dividing the large barrier height into two smaller ones as shown in Fig. 8 [9]. As a result, the height of the original Schottky barrier is lowered and the carrier transport is enhanced through thermionic emission for Ohmic conduction.

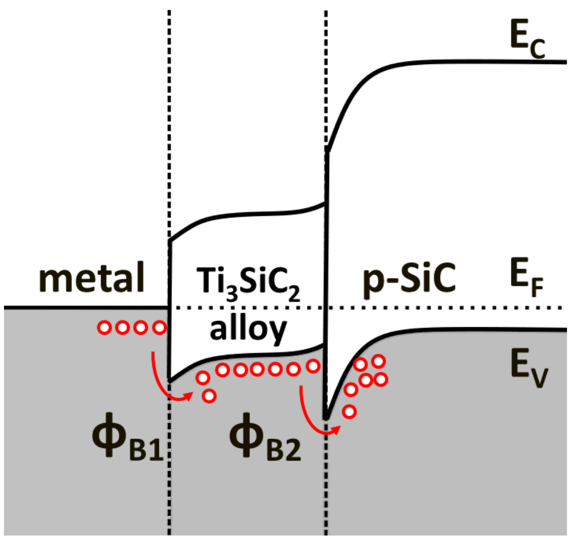

Fig. 8. Schematic of band offsets for metal/Ti_3SiC_2 alloy/p-type SiC sequence.

Consequently, it becomes easier for holes, whose movement is represented by the red arrows in Fig. 8, to transport from the metal electrode to the valence band of p-type 4H-SiC. The peak of Ti_3SiC_2 is only clearly visible in the 950°C sample (blue spectrum in Fig. 7), and this alloy contributes to the decrease of differential resistance value observed in Fig. 1. In addition, the main role of the Al mid layer in the Al-based Ohmic metal stacks (Ti/Al/Ti/Au) is to assist the formation of a liquid alloy that both facilitates and accelerates the reaction between the SiC and the Ti to form Ti_3SiC_2 alloys [10]. The intense reflection peaks, observed around $2\theta = 38°$ degrees, correspond to the pure Al, which increases with annealing temperature. Al starts to melt to the surface at 660°C in vacuum and this phenomenon accelerates as the annealing temperature increases, which results in intensifying peaks observed through XRD surface analysis. Large droplets of Al can also be confirmed with the microscope image in Fig. 9. These surface morphology transitions only take place under annealing at a high temperature, high vacuum condition due to the evaporation of the liquid phase, such as the Al-based liquid alloy with a low melting point and high vapor pressure.

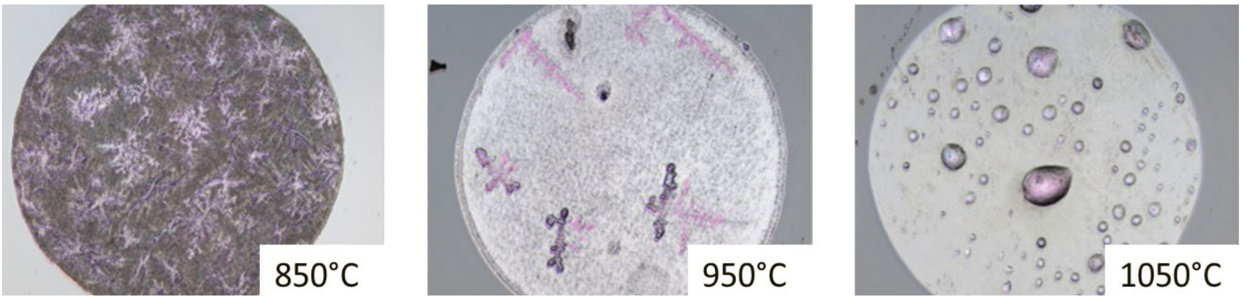

Fig. 9. Microscope image of Al based electrodes (850°C ~ 1050°C).

Table IV. Summary of various Ohmic metal process to *n*-type and *p*-type 4H-SiC and extracted parameters.

Metal Process	Ohmic Metal Contacts	SiC Epi Layer Type	Annealing Temperature [°C]	Extracted Parameters from TLM	
				Specific Contact Resistance ρ_C [Ω·cm²]	Sheet Resistance R_S[Ω/□]
1.	Al-based	*p*-type	950	1.091×10^{-4}	20677.80
2.	Ni-based	*p*-type	1000	*I-V*: slightly nonlinear	
3.	Al-based	*n*-type	950	1.158×10^{-5}	685.67
4.	Ni-based	*n*-type	950	1.099×10^{-5}	347.57
5.	Ni-based	*n*-type	1000	4.444×10^{-6}	336.13

Table IV summarizes the metal process combinations possible in the formation of ohmic contacts to both *n* and *p*-type 4H-SiC, offering various options in either using the same metal materials and/or common annealing conditions. Although Al-based metal contact forms quality Ohmic contact with a relatively low specific contact resistance (SCR) value, Ti/Al system alone may not be ideal for the n-type Ohmic contact formation (Metal Process 3 and Fig. 5 comparison). The adaptation of an additional Ni layer within the Ti/Al system to form nickel silicide (Ni_2Si) is expected to further reduce the SCR values close to that of Metal Process 4 or 5. On the other hand, for p-type SiC, the Ni atoms added to the Ti/Al system will react with SiC to form Ni_2Si, leaving more unreacted C atoms to react with Ti and Si atoms to form Ti_3SiC_2. Thus, the combined blend of Al-based and Ni-based metal contact through thickness optimization may offer further benefits (lower SCR values, lower annealing temperature, etc.) in achieving simultaneous formation (i.e., using the same contact materials and a one-step annealing process) of Ohmic contacts to both n-type and p-type 4H-SiC.

To summarize the obtained results, the formation of nickel silicide (Ni_2Si) layers is necessary in forming quality ohmic contacts to n-type SiC. Ni-based metal contacts continue to show lower specific contact resistance ρ_C with respect to increasing the annealing temperature up to 1000°C and possibly even at a higher temperature until surface deterioration cannot be ignored any further. Ohmic contacts to p-type SiC requires an Ti/Al system (Al-based), and the optimal annealing temperature for the formation of necessary Ti_3SiC_2 alloys is at 950°C. Additionally, the Al-based metal contact is also effective against the n-type SiC layer, achieving simultaneous formation of Ohmic contact to both n-type and p-type 4H-SiC.

Summary

In conclusion, various annealing conditions using Al-based (Ti/Al/Ti/Au=70nm/100nm/5nm /120nm) and Ni-based (Ti/Ni/Ti/Au=20nm/90nm/5nm/120nm) metal contacts to n-type and p-type ion-implanted 4H-SiC epi layers have been investigated in the effort to optimize simultaneous ohmic contact formation with the lowest specific contact resistance (SCR) values. Values of 1.091×10^{-4} $\Omega\cdot cm^2$ and 1.158×10^{-5} $\Omega\cdot cm^2$ were obtained using Al-based Ohmic metal contacts for p-type and n-type 4H-SiC, respectively, at an annealing temperature of 950°C and under vacuum for 90 sec, achieving simultaneous formation. Ohmic formation mechanisms were analyzed using the X-Ray Diffraction (XRD) surface analysis method, indicating Ti_3SiC_2 alloys to be the key intermediate layer formed at SiC/Ti interface, responsible for Ohmic properties to p-type SiC. We have successfully investigated the metal process combinations possible in forming Ohmic contacts to both n-type and p-type 4H-SiC, offering various options in either using the same metal materials and/or common annealing conditions.

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