Solid State Phenomena
ISSN: 1662-9779, Vol. 359, pp 79-84
doi:10.4028/p-t2sWXi

Submitted: 2023-09-08
Revised: 2024-05-08
Accepted: 2024-05-09
Online: 2024-08-22

Plasma Treatment after NiSi-Based Ohmic Contact Formation on 4H-SiC to Enhance Adhesion of Subsequent Backside Metallization

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Keywords: 4H-SiC, Ohmic Contact, Laser Annealing, Nickel Silicide Metallization, Adhesion

Abstract. To achieve low on-resistance in any vertical 4H-SiC semiconductor power device, it is essential to create a suitable ohmic contact on the corresponding n-doped SiC substrate. In particular after wafer thinning, a common technology to reduce substrate resistivity, laser annealing for ohmic contact formation on the wafer backside is the only option due to temperature sensitive materials (such as Titanium or Aluminum) on the partially or fully processed wafer frontside. In this work, to solve adhesion issues of the backside metallization, plasma treatments, as easy to integrate process steps, were examined. By stripping obstructive carbon layers, formed after ohmic contact laser annealing, and without damaging the wafer frontside, an enhanced adhesion of following metallization layers was achieved. Both O_2- and H_2-plasma processes were investigated and demonstrated significant improvements to the adhesion of metallization stacks on the wafer backside compared to untreated surfaces and without drawbacks in the ohmic contact quality.

Introduction

Since adhesive strength of the metallization on the ohmic contact is key for proper device performance, great effort has been invested in these investigations. Aside from ohmic contacts of sufficient electrical quality [1], long-term stability and reliability are of utmost importance [2], which translates into a certain stability of the backside metallization, deposited on top of the ohmic contact necessary for packaging of power electronic devices, such as soldering or silver sintering. As shown by Hellinger et al., a graphite layer is formed at the surface of the ohmic contact due to excess unbound carbon which results during the silicidation of nickel with the 4H-SiC substrate during the annealing process [3–5]. This 5 to 6 nm graphite layer is suspected to be the cause of poor adhesion of any subsequent metallization [3–5]. Graphite clustering and its layer thickness at the surface as well as the delamination of thereon deposited metal layers are presumably dependent on the energy density used during the laser annealing process. However, reducing laser annealing energy densities to decrease the extent of graphite formation bares the risk of not achieving a homogeneous low-resistance ohmic contacts [6]. To resolve this issue, we investigated different plasma treatments approaches (O_2-plasma and a combination of O_2- and H_2-plasma) in an easy to integrate batch process to remove this obstructive graphite layer to avoid delamination of the backside metallization. To shift the focus on NiSi-based ohmic contact annealing in general, wafers with RTA (Rapid Thermal Annealing) processing steps were processed and examined as well.

Experimental Methods

In this work, eighteen 150 mm 4H-SiC substrates were prepared by fine grinding 10 µm of the 4H-SiC backsides, resulting in a surface roughness of 3 to 4 nm [3], extracted from atomic force microscope (AFM) images shown in Fig. 1, and depositing 60 nm NiAl2.6$\%_{wt}$ onto it after an argon sputter cleaning. To determine the process window of ohmic contact formation by laser annealing, 10 different laser energy density zones, from 1.6 J/cm² to 3.5 J/cm² were used on the first six wafer, as shown in Fig. 2. Thereby, a Sumitomo SWA20US-M laser annealing tool with a frequency-tripled

$Nd:YVO_4$ laser with 355 nm wavelength, a beam diameter of 80 µm and a pulse duration of 50 ns was used. The single pulses had an overlap of 67 % in scan direction and 50 % in step direction.

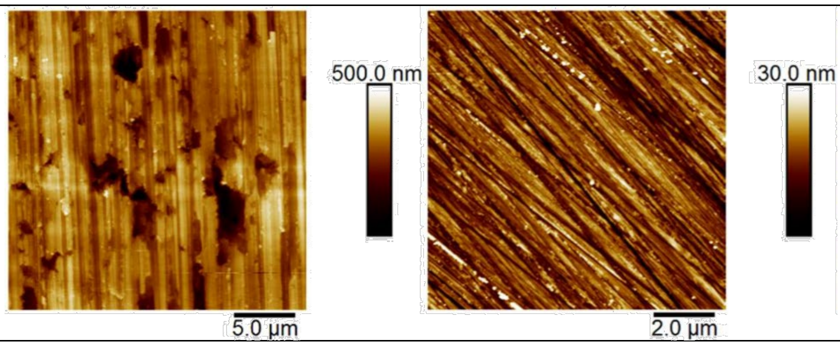

Fig. 1. Atomic Force Microscope (AFM) images after rough (left) and fine (middle) grind to determine the backside surface roughness before $NiAl2.6\%_{wt}$ metallization. [3]

On the remaining 12 wafers two different RTA recipes were used to determine the influence on the backside ohmic contact. The first recipe was a standard RTA step with a peak temperature of 980 °C retained for 2.0 minutes used on the first six wafers. The second recipe with a maximum temperature of 1050°C for 2.5 minutes, motivated by May et al. to improve ohmic contacts on p+ regions on the wafer front side in a combined annealing step of all ohmic contacts on SiC-CMOS devices, was used on the second set of RTA processed wafers [7]. The design of experiment for the wafers subjected to laser annealing is shown in table 1.

Table 1. Design of experiment for *laser annealed* wafers and parameters of the plasma treatment on NiSi-based ohmic contacts.

Process step	Wafer					
	1	2	3	4	5	6
Preheating (O_2 plasma)	-		500 W, 4 min			
O_2 plasma	-		800 W, 30 min		800 W, 25 min	
H_2 plasma	-		-		500 W, 5 min	
Tape test	x	-	x	-	x	-

Fig. 3 shows the sheet resistance, measured via four-point-measurement on the deposited $NiAl2.6\%_{wt}$, to exclude any impact of the deposition itself such as out of spec layer thicknesses or inhomogeneities of the same. The median sheet resistance over all wafers was about 6.13 Ω/sq, which fits the typical values of 6.0 to 6.5 Ω/sq of the sputtering tool used and the intended layer thickness.

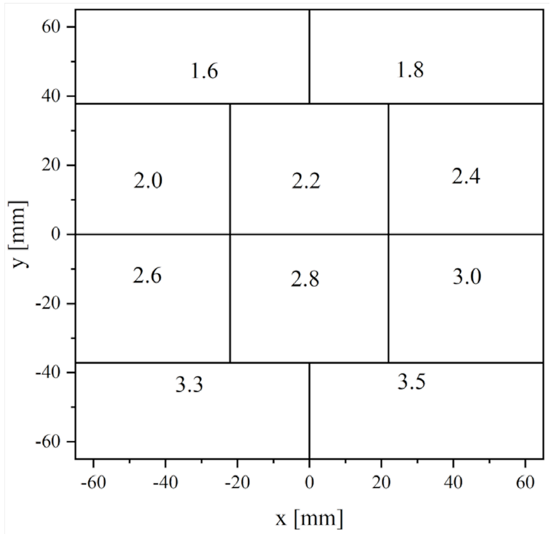

Fig. 2. Distribution of the 10 laser annealing energy densities used over the 150 mm 4H-SiC substrates, from 1.6 to 3.5 J/cm².

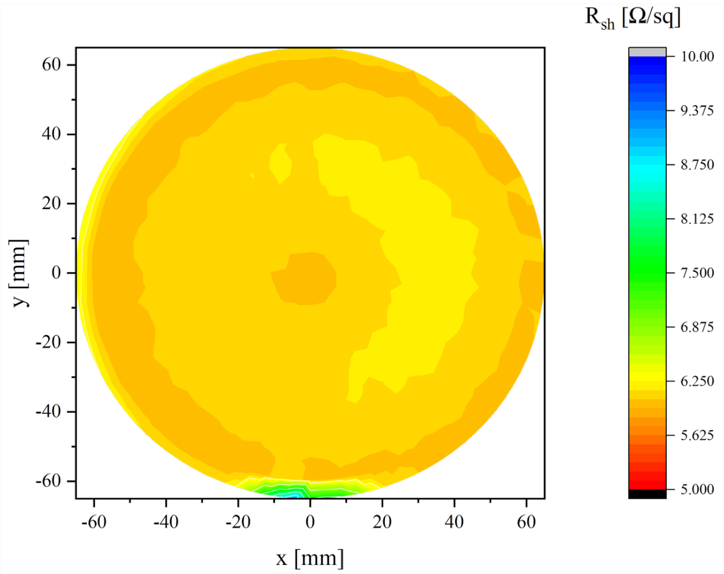

Fig. 3. Sheet resistance measurement on 60 nm NiAl2.6%$_{wt}$ as-deposited on a 150 mm 4H-SiC wafer, with 625 data points. The median measured sheet resistance measured is about 6.13 Ω/sq, which lies within the specification of the sputtering tool used.

After annealing, sheet resistance measurements were carried out to assess the ohmic contact formation. Fig. 4 shows the sheet resistance after laser annealing, superimposed with the grid of the respective laser energy densities used. In Fig. 4a) the scaling was extended to show the complete data range, including very high values where 1.6 J/cm² as laser energy density was used. Values of 10-20 Ω/sq, which are higher than the values of the deposited metallization, can be explained by high-resistance nickel-silicide compounds that are usually an intermediate form when annealing the ohmic contact and are an indication to a lack of energy [3]. For sufficient laser energy densities to create an ohmic contact, the contact resistance can be neglected and instead the 4H-SiC substrate sheet resistance of about 0.5 Ω/sq is measured. The wafer thickness after fine grind in this work is about 340 µm.

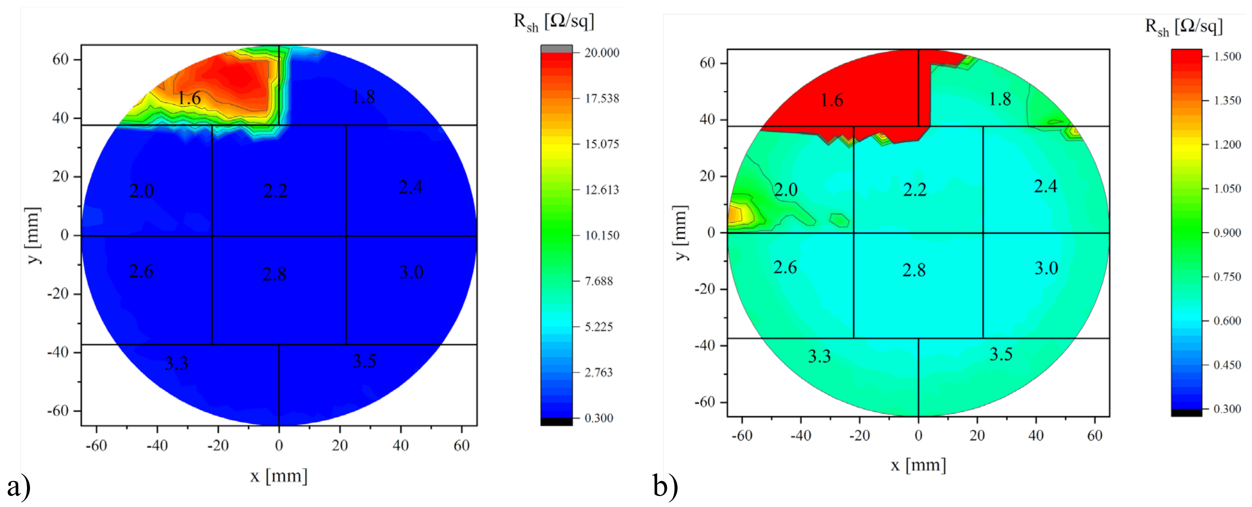

Fig. 4. Sheet resistance after laser annealing with different energy densities on wafer 6. Scaling from 0.3 Ω/sq to 20.0 Ω/sq (a), to acommodate for the high resistance of schottky-like Ni_xSi_y compounds and from 0.3 Ω/sq to 1.5 Ω/sq (b), to show a more subtle resolution on the low-resistance ohmic areas, annealed with energies above 1.8 J/cm², which are homogeneous from about 2.2 J/cm².

To get a higher resolution of the successfully created ohmic areas, Fig. 4b) has an adjusted scale, so that details and inhomogeneities in sheet resistance can be observed. Above 1.8 J/cm² the energy density of the laser annealing appears to be sufficient to form homogeneous ohmic contacts. Table 2 shows the design of experiment regarding the RTA processed wafers and corresponding plasma treatments and tape testing.

Table 2. Design of experiment for *RTA processed* wafers and parameters of the plasma treatment on NiSi-based ohmic contacts.

Process Step	Wafer											
	7	8	9	10	11	12	13	14	15	16	17	18
RTA	980 °C for 2 min								1050 °C for 2.5 min			
Preheating (O_2 plasma)	-		500 W, 4 min				-		500 W, 4 min			
O_2 plasma	-		800 W, 30 min		800 W, 25 min		-		800 W, 30 min		800 W, 25 min	
H_2 plasma	-		-		500 W, 5 min		-		-		500 W, 5 min	
Tape test	x	-	x	-	x	-	x	-	x	-	x	-

In Fig. 5, the sheet resistance measurements after RTA processing are shown. Fig. 5a) depicts a wafer with the 980 °C RTA recipe and Fig. 5b) a wafer with the 1050 °C RTA recipe. The median sheet resistance for wafers annealed at 980 °C for 2 minutes was 0.49 Ω/sq, the sheet resistance of wafer annealed at 1050 °C for 2.5 minutes about 0.47 Ω/sq. As expected, 980 °C for 2 minutes is sufficient to generate an NiSi-based ohmic contact with neglible contact resistance on the wafer back side.

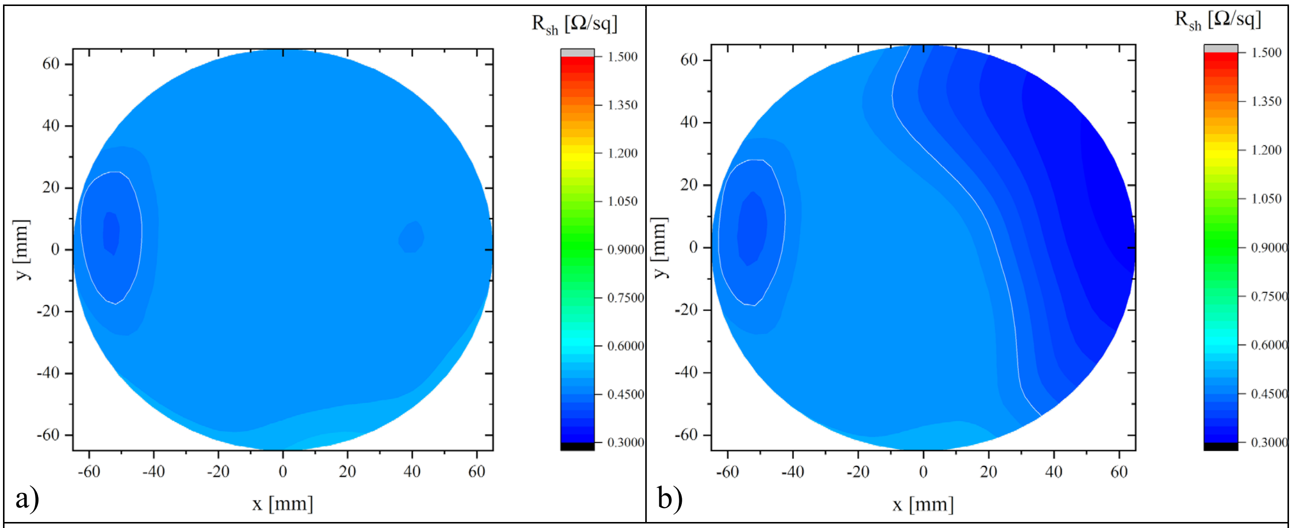

Fig. 5. Sheet resistance after RTA for a) 2 minutes at 980 °C and b) 2.5 minutes at 1050 °C. Both peak temperatures and timings yield approximately the same quality of ohmic contact, as in all cases the 4H-SiC substrate resistance was measured at about 0.5 Ω/sq.

The following plasma treatments were implemented to remove the graphite layer via both chemical reactions and physical erosion with an O_2-plasma power of 800 W for 30 minutes. To evaluate the degree of graphite formation for each laser energy density, a tape test using a standard UV sensitive dicing tape was conducted. Residues on these dicing tape after laser annealing can be seen in Fig. 6. Fig. 6a) shows residues of wafer 1, which has not been subjected to any plasma treatment and shows the highest amount of what we expect to be part of the graphite cluster layer. The tape of wafer 3 is shown in Fig. 6b), where the contrast is the lowest and from which a correlation of laser energy density and graphite creation can be deducted. Dicing tape of wafer 5 is not shown but displays contrasts of residues slightly stronger than wafer 3. This leads to the conclusion that 5 minutes of O_2-plasma at 800 W is more efficient than the 500 W of H_2-plasma used for wafer 5. The wafers 2, 4 and 6 were not tape tested on the ohmic contact but kept for tape testing the subsequent aluminum layer.

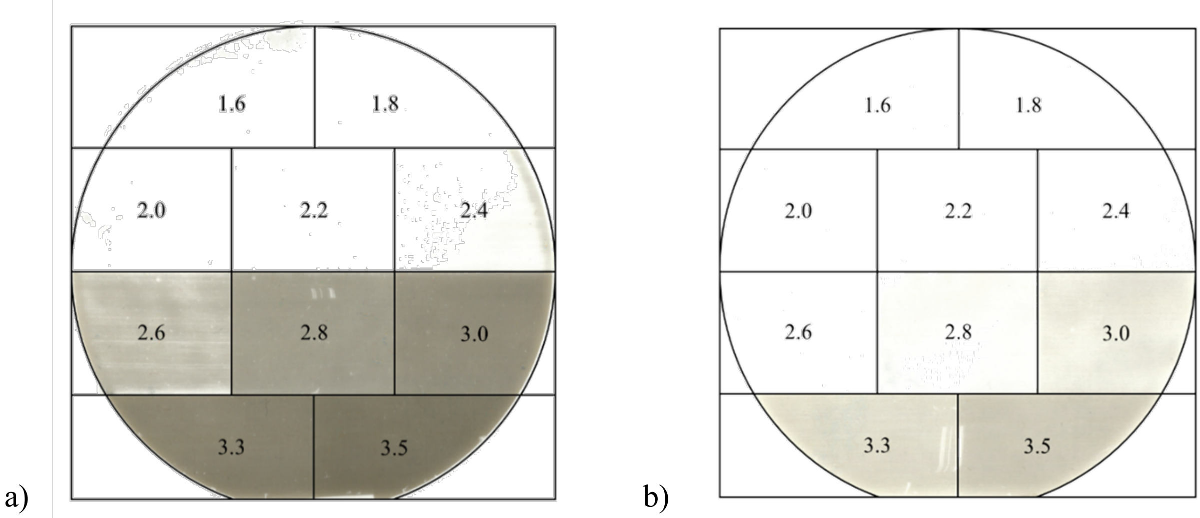

Fig. 6. Scans of the dicing tape after UV curing pulled from the NiSi on the wafer backside, to see the extend of graphite/NiSi-cluster layers on reference wafer 1 (a), which has not seen any post annealing plasma processing and wafer 3 (b), which has been processed in purely O_2-plasma. Wafer 3 shows the lightest pigmentation on the dicing tape which indicates that the O_2-plasma treatment seems to be more effective than a mixture of O_2- and H_2-plasma.

After aluminum sputtering a final tape test, again using dicing tape and UV treatment, was conducted to see the impact of the graphite layer on the adhesion of subsequent metallization. Considering in a real device fabrication the process wafers would be temporarily bonded on a carrier-wafer for mechanical stability, forming gas tempering would not be possible so this tempering step was skipped. Fig. 7a), displays wafer 2, which has not been subjected to any plasma processing or tape testing and shows severe delamination in areas consistent with laser energy densities of 2.8 J/cm² and above. In contrast to this, wafer 4, which has been treated with O_2-plasma and is shown in Fig 7b), depicts no or only minor delamination of the aluminum layer on fields where the laser energy densities of 2.8 J/cm² and 3.0 J/cm² were used. Again, the wafer treated with both O_2- and H_2-plasma showed slightly higher delamination that the wafer treated purely with O_2-plasma and is not shown here.

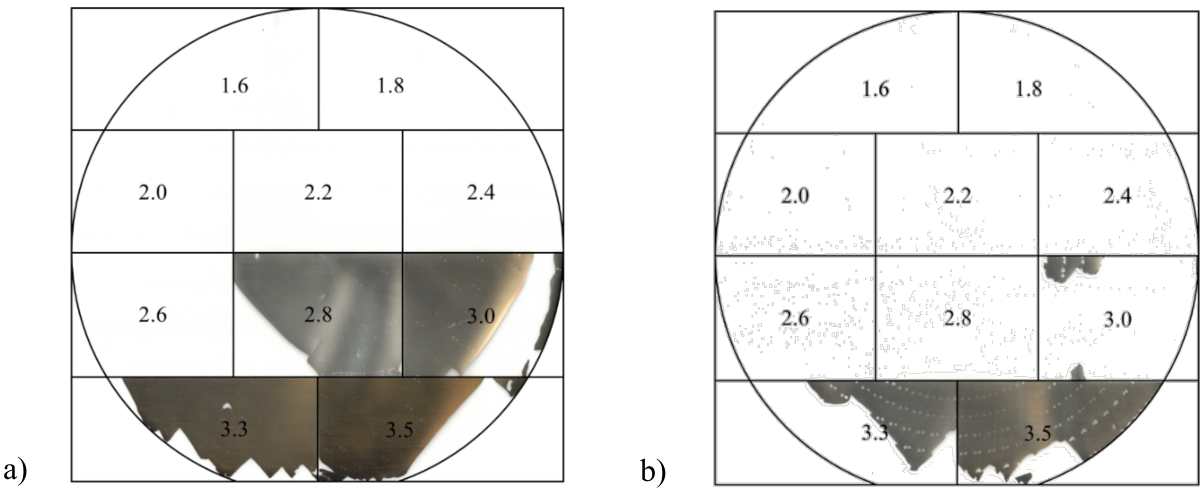

Fig. 7. Scans of the dicing tape after UV curing pulled from 2 µm aluminium backside metallization to show delaminated aluminum residues from the laser annealed ohmic contact. The tape of wafer 2 (a), which has not seen any plasma processing or tape testing afer laser anealing, depicts severe delamination on areas of 2.8 J/cm² and upwards. In contrast, the tape from wafer 4 (b), which has been subjected to O_2-plasma processing only, exhibits the least amount of delamination. The areas with 2.8 J/cm² and even partially 3.3 J/cm² show no or less separation of the aluminum layer, respectively.

The wafers with ohmic contacts annealed via RTA did not show any carbon residues at all. Even wafer 13 which was not treated with any plasma and was annealed for 2.5 minutes at 1050 °C displayed any signs of carbon built-up that could be delaminated with the implemented tape-testing. Therefor the dicing tapes are not shown, and the aluminum deposition and subsequent tape-tests where not carried out. It seems, that the RTA processing is less likely to generate carbon layers traceable with this tape testing method and it can be assumed that adhesion of subsequent metallization layers will be impaired. These results coincide with the work of Hellinger et al. where during RTA up to 1100 °C mainly Ni_2Si is created whereas during the laser annealing process (from 2.4 J/cm²) $NiSi_2$ is generated, which leads to four times higher carbon release [3,4].

Summary

In this investigation we could show that plasma treatments on laser annealed backside ohmic contacts can improve adhesion of subsequent metallization, in this case 2 µm of aluminum, and extend the process window of laser energy densities used, allowing greater tolerances in terms of process variations, like the thickness of the ohmic contact metallization or laser energy densities. For RTA processed NiSi-based ohmic contacts, even for higher temperatures like 1050°C, the carbon built-up at the ohmic contact surface, suspected to be the origin of poor adhesion of subsequent metallization layer, was not detectable with the tape-test used in this work. Therefore, it is concluded that, as shown for lower laser energy densities and plasma treated wafers, no delamination is expected after RTA processed with these parameters.

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