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Low-Ohmic Nickel Contacts on N-Type 4H-SiC by Surface Roughness Dependent Laser Annealing Energy Density Optimization

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Abstract. In this work, the influence of different surface roughness and surface treatments on the minimum energy density required to form low-ohmic nickel contacts on n-type 4H-SiC by laser annealing was investigated. The annealing was performed by a frequency-tripled Nd:YVO_4 laser with a pulse duration of 50 ns. To evaluate the effects, the grinded or polished C-side of 4H-SiC wafers with surface roughness between 0.3 and 70 nm was sputter-deposited with nickel and subsequent laser annealed. Sheet resistance measurements showed that the minimum energy density required to achieve a low-resistance contact depends significantly on the surface roughness. The rougher the surface, the lower the minimum energy density to form a low-ohmic contact.

Introduction

SiC power semiconductor devices experienced a lot of development and optimization in the last years, especially with the focus to minimize power losses [1]. There are several ways to improve the performance of vertical SiC power devices regarding the on-resistance. One option is to thin the substrate. The thickness of the epitaxial layer, the electrically relevant layer of SiC power devices, is in the range of a few micrometers and depends on the voltage class where it is later used. However, the substrate onto which the epitaxial layer is usually grown has an initial thickness of 350 µm. This leads to relatively high part to the total on-resistance, although the substrate itself is not required to ensure electrical functionality of the devices [2].

Therefore, it is common nowadays to reduce the 350 µm thick SiC substrate to a final thickness in the range between 50 and 100 µm for vertical power devices. The thinning process takes place in various grinding steps. The process starts with a rough grinding step to quickly remove as much material as possible. Afterwards a fine grinding or polishing step is performed for stress relief [3, 4]. To prepare a backside (C-side) contact on n-type SiC, usually nickel or nickel compounds are deposited on the grinded or polished surface side [5]. In order to create a low-ohmic backside contact, a thermal treatment is necessary. Due to the fragility of thinned wafers, the back thinning of the wafer takes place very late in the process, where the front side is already finished processed. Therefore, the thermal treatment of the backside contacts has to be done by laser annealing, where only the wafer backside is heated up to silicidation temperature of the nickel layer, while the thermosensitive layers on the frontside are not influenced or even damaged. This showed that the minimum energy density required for low-resistance contacts depends significantly on the previous surface treatment, i.e. explicitly on the surface roughness.

The purpose of this work is to use an UV laser for backside ohmic contact formation and to optimize the laser parameters required to form low-ohmic contacts for the first time depending on different surface roughness.

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Experimental

In this work, experiments were performed on the C-side of 4H-SiC wafers. To investigate different surface roughnesses, the C-side was thinned back by 10 µm using a Disco DAG810 grinder. A rough grinding wheel was used for sample A, a fine grinding wheel for sample B and an additional dry polishing pad after the fine grinding for sample C (see table 1). Sample D was not further treated, except the substrate manufacturer's pretreatment.

Table 1. Surface treatment

Sample	Treatment	Surface roughness R_q [nm]
A	Rough grinded	60 – 70 nm
B	Fine grinded	3 – 4 nm
C	Fine grinded & polished	0.3 – 0.5 nm
D	Only factory pretreatment	2 – 3 nm

AFM measurements were performed after the grinding steps and the AFM images from which the surface roughness was determined can be seen in fig. 1. The surface treatments result in a roughness R_q of 60 to 70 nm for sample A, 3 to 4 nm for sample B, 0.3 to 0.5 nm for sample C and 2 to 3 nm for sample D, respectively.

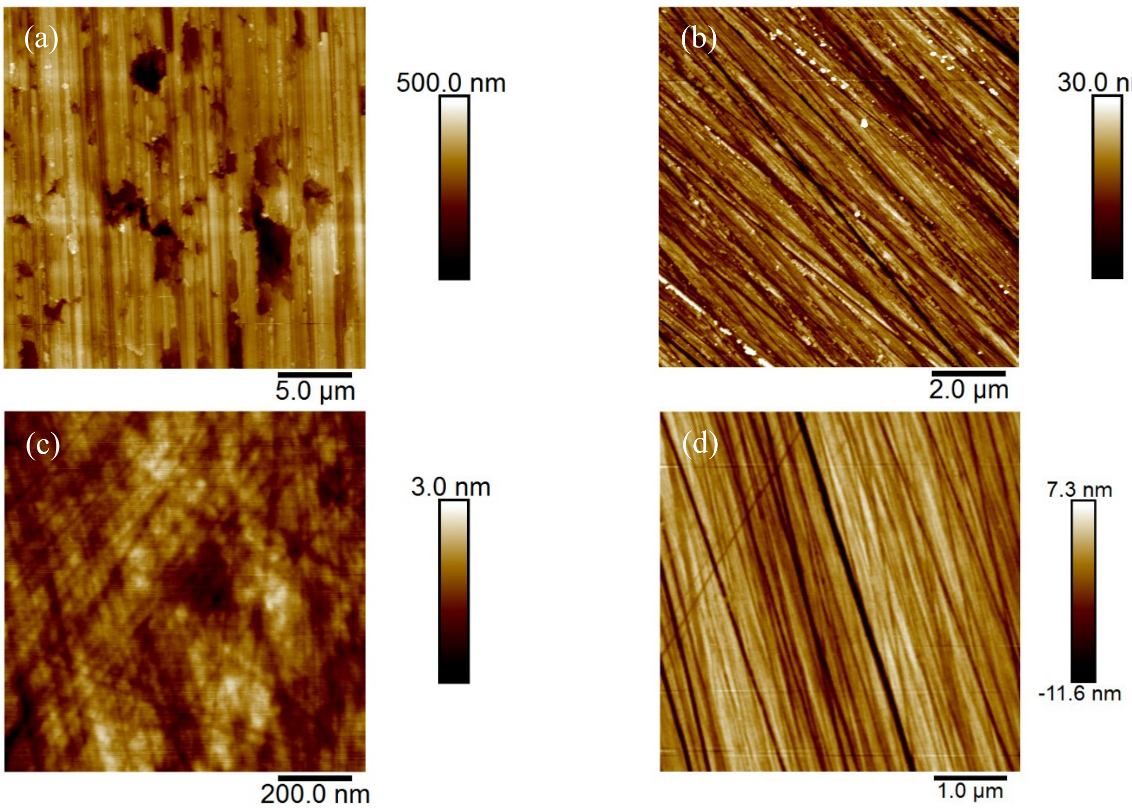

Fig. 1. AFM measurement of (a) sample A, (b) sample B, (c) sample C and (d) sample D (note the different measurement sizes adjusted to the different sample roughness)

A 60 nm thick NiAl 2.6 wt% layer was sputtered as contact metal after an argon sputter clean. The nickel layer was silicided by a Sumitomo SWA20US-M laser annealing tool with a frequency-tripled $Nd:YVO_4$ laser with 355 nm wavelength, a beam size of 80 µm and a pulse duration of 50 ns. The energy density was varied from 1.2 to 3.3 J/cm^2. The single pulses have an overlap of 67 % in scan direction and 50 % in step direction. After laser annealing four-point sheet resistance measurements were performed on all laser treated surfaces.

Results and Discussion

Figure 2 shows the sheet resistance measurement results of four-point measurement of the wafer's backside after the contact formation anneal. As can be seen, for relatively high energy densities above 2.7 J/cm² all samples exhibited low-ohmic resistances. However, the minimum energy density required to achieve a low-resistance contact depends significantly on the surface roughness. Looking at the sheet resistance values, low-resistance contacts could already be produced for energy densities starting from 1.4 J/cm² for sample A, whereas sample B required at least 2.0 J/cm² and sample C even 2.2 J/cm². For sample D the minimum energy density for low-ohmic contacts is, with at least 2.7 J/cm², still higher. This means that the minimum energy density for producing a low-ohmic contact can be reduced by a previous grinding or polishing step. When the surface has been treated, this results in the correlation that the minimum energy density is lower, the rougher the surface is.

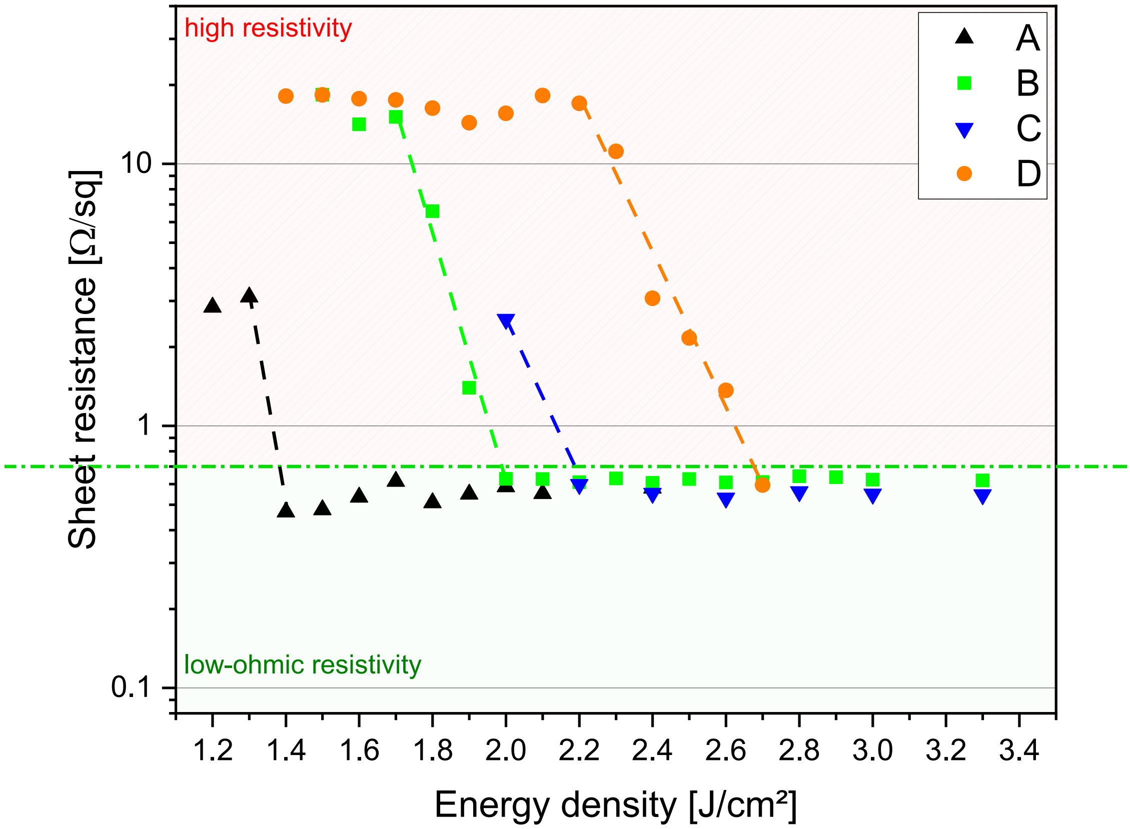

Fig. 2. Sheet resistance of samples A – D depending on the energy density per laser pulse

Figure 3 shows microscope images and FIB cross sections of the nickel contacts of samples A – D. Sample A shows a distinct higher surface roughness compared to the other samples. The nickel layer on the surface seems to be completely melted. Caused by the large surface roughness, the nickel silicide layer thickness is very inhomogeneous after irradiation (see fig. 3b). Looking at the cross section of sample A, fine carbon clusters (black dots in nickel silicide layer) can already be seen which permeate the entire silicide layer and reach to the surface, in comparison to sample B. XRD analysis of the samples show that $NiSi_2$ is the main phase [6]. The FIB cross-sections of sample B show a more homogeneous layer distribution compared to sample A. At the interface of nickel silicide to SiC, an almost continuous layer of carbon clusters can be seen. Through the nickel silicide layer, smaller carbon clusters are distributed throughout the layer. The cross section of sample C shows a very smooth surface even after laser processing. The concentration of carbon clusters decreases with increasing distance from the Ni_xSi_y-SiC interface. In the FIB image fig. 3g, inhomogeneous melting of the nickel silicide layer can be observed. An inhomogeneous layer thickness and distribution of carbon clusters can be observed in this process, too.

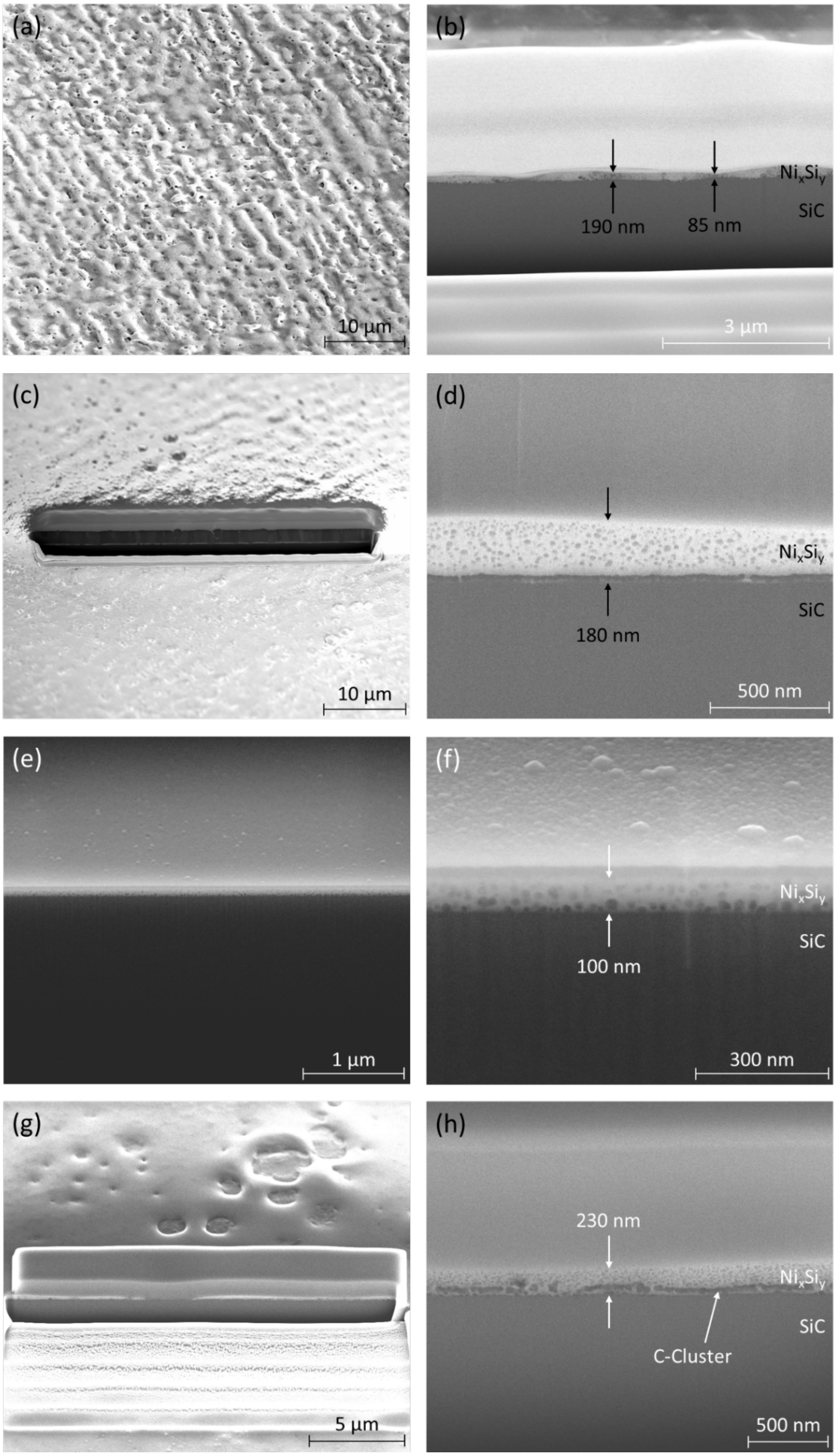

Fig. 3. Representative (a) top view SEM and (b) FIB cross sections of sample A, (c) – (d) sample B, (e) – (f) sample C and (g) – (h) sample D after laser annealing with 2.4 J/cm² in different magnifications

Carbon clusters can also be seen in sample D especially near the Ni_xSi_y-SiC interface (see fig. 3h). Overall, even after laser processing, the varying surface roughness are imaged in the silicide layers.

There are different possible explanations, why the minimum energy density required to produce low-ohmic contacts is strongly dependent on the previous surface treatment or the surface roughness.

One possible reason why the samples with higher surface roughness require lower energy density to form low-ohmic contacts is the highly increased surface area. Sample A, which has a roughness of 60 to 70 nm, has a larger surface area where silicidation can occur during laser processing compared to the other samples covered by nickel. However, since the surface increase according to AFM measurements in fig. 2 is just 3% between sample A and B and 1 % between sample B and C, this alone is most probably not be the reason for the reduced minimum energy density.

On the other hand, due to the distinctive topography of sample A, an inhomogeneous metal layer thickness distribution may occur during the sputtering process. Thus, it can be assumed that the nickel layer thickness at the flanks is much smaller than at the maxima and minima of the grinding marks. On these flanks, less energy is required for complete alloying due to the lower layer thickness [7].

Another possible explanation lies in the altered optical properties of the nickel layer due to the increased surface roughness. On very rough surfaces, like sample A, the vertically incoming laser beam is no longer reflected to such a high degree as with a smooth surface [8]. Instead, the beam refracts at the surface structures, which nominally reduces the reflectivity R. Since the reflectivity of the surface metallization enters directly into the heat flux with $1 - R$ [8], a reduction in the reflectivity also results directly in an increase in the heat flux and thus an increase in the surface temperature. As a result, ohmic contacts can already be produced at much lower energy densities on rough grinded surfaces even.

Rough grinding also causes much deeper and more severe crystal damage than fine grinding or polishing of the wafers [9, 10]. This is particularly evident in the increased bow and warp of rough grinded wafers compared to fine grinded ones [11]. These near-surface crystal damages in the SiC substrate can act as condensation nuclei, at which chemical reactions occur more easily [12]. If these are absent due to prior polishing steps as in sample C, the reactivity is reduced.

To clarify which effect is responsible for the dependence of the minimum energy density on the surface roughness further work is necessary like In-situ TEM analysis to see the extent of subsurface damages and to confirm the mentioned explanation attempts above.

Summary

In conclusion, we have investigated the influence of different surface roughness on the minimum energy density required to form low-ohmic nickel contacts on n-type 4H-SiC by laser annealing. It could be shown that the minimum energy density depends significantly on the surface roughness. This means that the minimum energy density for producing a low-ohmic contact can be reduced by the previous grinding or polishing step. This results in the correlation that the minimum energy density to form a low-ohmic contact is lower, the rougher the surface is.

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