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Nickel Ohmic Contacts Formed on 4H-SiC by UV Laser Annealing

Jean-François Michaud[1,a*], Clément Berger[1,b], Daniel Alquier[1,c]

[1]GREMAN UMR-CNRS 7347, Université de Tours, INSA Centre Val de Loire, 16 rue Pierre et Marie Curie, 37071 TOURS Cedex 2, France

[a]jean-francois.michaud@univ-tours.fr, [b]clement.berger@univ-tours.fr, [c]daniel.alquier@univ-tours.fr

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Abstract. Laser Thermal Annealing (LTA) is a key process step to improve the 4H-SiC devices by reducing their on-state resistance. In this study, we investigate the electrical, structural and morphological properties of nickel contact fabricated by LTA. A contact formed by a classical Rapid Thermal Annealing (RTA) was also fabricated as reference. Based on structural analysis, the phases formed by LTA do not match with RTA sample ones that has better ohmic properties. Nevertheless, the LTA contacts reach a specific contact resistance of 2.4×10^{-5} $\Omega.cm^2$ for an annealing at 4.75 $J.cm^{-2}$, which represents a significant improvement in comparison with our previous contacts fabricated with the same experimental protocol using titanium.

Introduction

Since couple of decades, silicon carbide (SiC) is depicted as a promising material for working at high frequency, high temperature or high power, due to its electrical and thermal properties [1]. Thanks to the huge efforts engaged, 4H-SiC-based commercial devices are increasingly present on the semiconductor market, particularly driven by the electrical vehicle field. However, to improve the electrical characteristics of future devices, further advances are required, among which, for instance, using thin SiC substrates is one. Such a thinning leads to improved electrical properties for the devices, lowering the on-state resistance, that is crucial. Nevertheless, as manipulating thin wafer remains complicated, the thinning step can be achieved only at the end of the process flow. Consequently, some technological steps must be modified. For example, in the case of Junction Barrier Schottky diodes, the ohmic contact, in the rear face of the 4H-SiC substrates, is generally achieved at the early stage of the process due to the high temperature required. With thinned substrates, the use of a classical annealing, at a temperature around 1000°C to form ohmic contacts, is not possible on the rear face without modifying the front face materials, especially the Schottky contact. Based on that, Rupp *et al*. proposed to introduce a laser thermal annealing (LTA) step to achieve these ohmic contacts, instead of a classical furnace annealing [2]. The objective is to reach high temperature on the rear face and to limit, as much as possible, the temperature elevation on the front one. Indeed, using an appropriate LTA allows to heat the irradiated SiC surface up to 2000°C, while keeping the opposite face at low temperature ($T < 600$°C) [3].

In the last 10 years, several investigations were focused on ohmic contact formation by LTA, on 4H-SiC. Considering the optical properties of the materials involved, 4H-SiC and metals, ultra-violet (UV) lasers are commonly used. Based on the metals classically involved to complete ohmic contacts on 4H-SiC, titanium (Ti) and nickel (Ni) are the most studied ones [4–8]. In our group, thanks to an optimized process, we succeeded to obtain Ti ohmic contacts presenting a specific contact resistance (SCR) of 1.0×10^{-4} $\Omega.cm^2$ for a 5.0 $J.cm^{-2}$ fluence, thanks to a triple frequency YAG pulsed laser (355 nm), equipped with a 40×40 µm² top-hat beam profile, under nitrogen flow. This value was 4 times lower than the lowest value ever mentioned in the literature dealing with laser contact on 4H-SiC using Ti [8].

In this study, based on the same experimental protocol developed previously, we present new results using nickel, sputtered on highly nitrogen-doped (~2×10^{18} $at.cm^{-3}$) 4H-SiC wafers.

Experimental

For the contact electrical characterizations, we used a substrate configuration including an isolation layer. To do so, a highly nitrogen-doped epilayer (2.6 µm - 1.9×10^{18} at.cm^{-3}) was grown onto a non-intentionally doped (nid) epilayer (5.6 µm thick - 5×10^{13} at.cm^{-3}) on the Si-face of a 4H-SiC wafer. The effects of a such isolation on electrical conduction into our structure were studied with TCAD Sentaurus Device software. The isolated configuration is represented by the Fig. 1(a) and the non-isolated structure is represented on Fig. 1(b). The Fig 1(c) presents a cross-section of the simulated current density circulating into our isolated configuration when a potential of 1 V is applied between two electrodes A and B. Similarly, Fig 1(d) presents the simulated current density without isolation of the substrate, that means when electrodes are directly deposited onto the bulk 4H-SiC substrate. By comparing these two configurations, we can see that the isolation layer allows to confine most of the current density into the highly doped top layer, near to the electrodes, whenever the current flows across hundreds of µm into the substrate without isolation. Current-voltage (I-V) simulations were performed for a separation distance of 12, 24 and 48 µm between the electrodes, to simulate Transfer Length Method (TLM) structures. The results are presented on Fig 1(e) for the isolated configuration and on Fig. 1(f) for the bulk structure. When the isolation is used, the I-V curves are easily discriminated by varying the electrode spacing, their associated resistance varies from 1 to 2 Ω. On the other hand, for the bulk structure, I-V curves are almost superposed, and their associated resistance varies from 0.098 to 0.099 Ω. In this case, resistances are very similar and their variation is such low that it can be smaller than the measuring device resolution, possibly leading to mistaken electrical properties [9]. These TCAD simulations indicate that our isolated configuration allows to accurately perform electrical characterization of the contacts.

After the fabrication of the isolated structure, the substrate was cut into 22×22 mm² samples. These samples were cleaned by dipping into Caro's, SC-1, SC-2 and hydrofluoric acid. Before the deposition of a 100 nm thick Ni layer by DC magnetron sputtering at 5 mTorr in an argon (Ar) ambient, a back-sputtering treatment was performed. The samples, covered by the unpatterned Ni layer, were laser irradiated at 30 kHz, with a scanning speed of 800 mm.s^{-1}, under nitrogen flow. The irradiation of this layer can generate Ni nanoparticles onto the surface that can be detrimental for subsequent device fabrication. As a consequence, we choose to eliminate this excess of Ni by dipping the samples into a Ni etching solution, leaving only nickel silicide phases. The Fig. 2 presents Scanning Electron Microscope (SEM) images of a contact annealed at 5.0 J.cm^{-2}, before and after the particle treatment. After dipping the sample into the acid mixture, pure Ni materials were removed, including the nanoparticles. X-Ray Diffraction (XRD) measurements (not shown here) did not reveal noticeable contact composition modification resulting from this chemical treatment.

For electrical characterizations, circular Transfer Length Method (cTLM) structures were fabricated by the mean of Ion Beam Etching (IBE) as described in [8]. The measured real spacings vary from 13 to 49 µm with a constant inner electrode presenting a diameter of 205 µm. Finally, an aluminum layer was deposited on the cTLM patterns to thicken the contacts, for the electrical characterization.

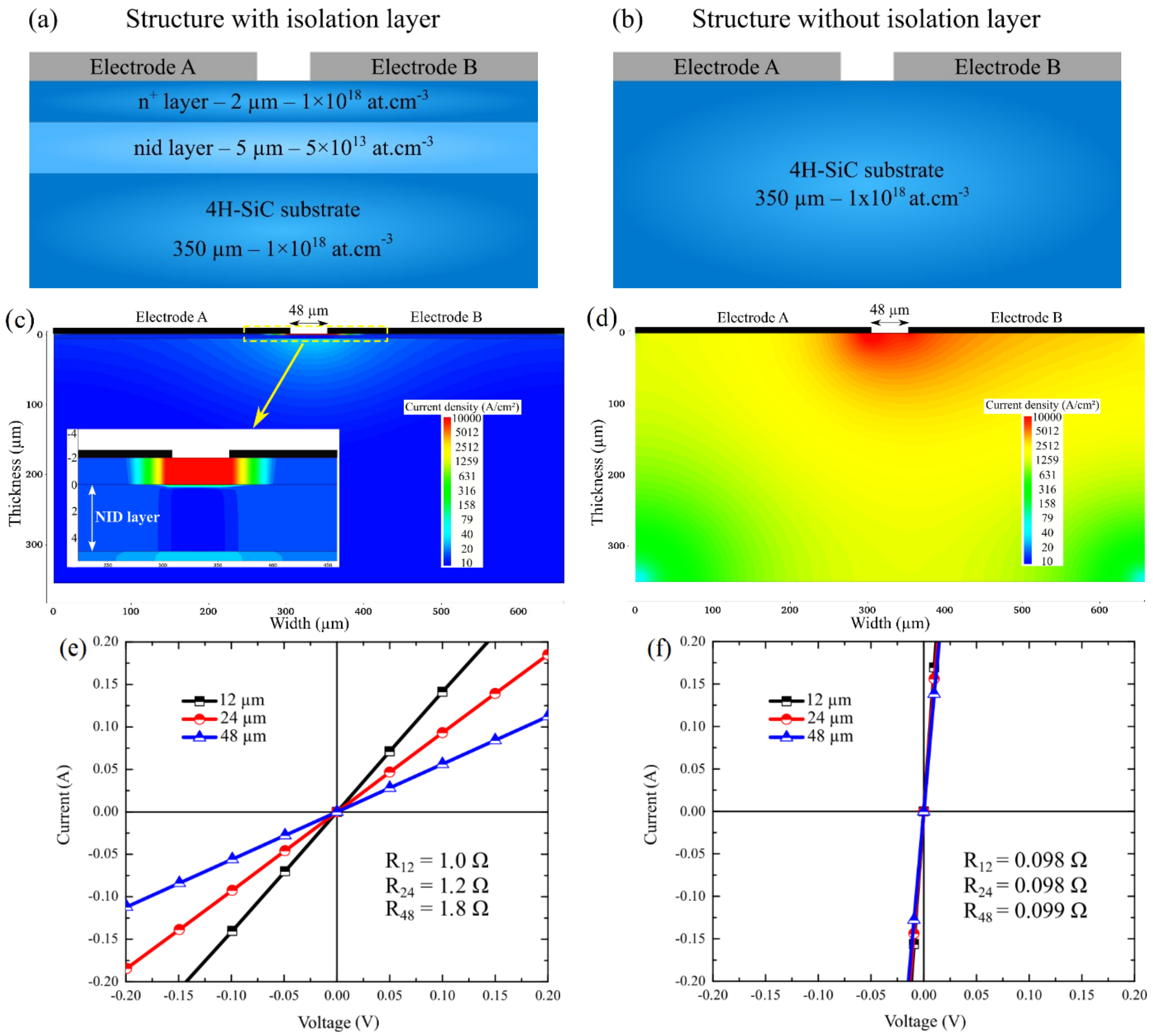

Fig. 1. Schematic representation of simulated structure (a) with the use of an isolation layer and (b) without isolation layer (electrodes directly on the 4H-SiC wafer). Simulated current density into the substrate by applying a voltage of 1 V between the electrodes A and B for two different configurations: (c) with and (d) without isolation layer. Simulated current-voltage characteristics for several spacings between electrodes (e) with and (f) without isolation layer.

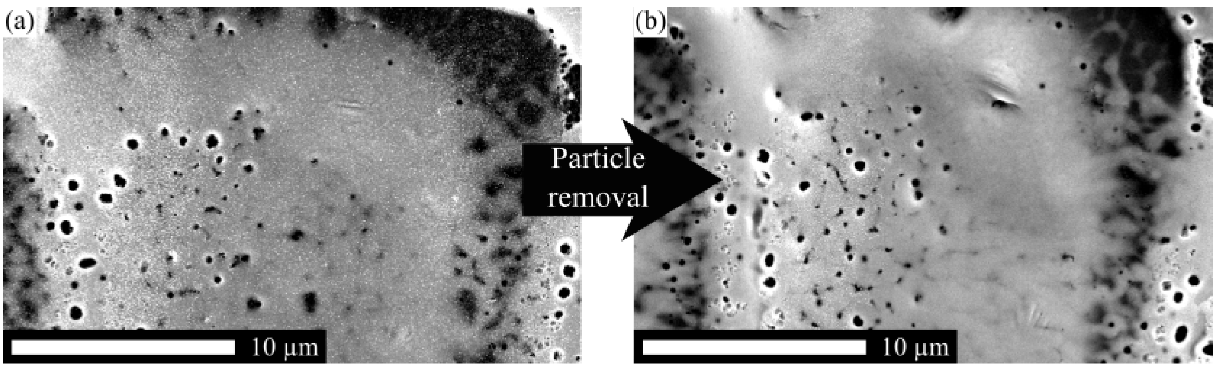

Fig. 2. SEM images of a contact annealed at 5.0 J.cm^{-2} (a) before and (b) after particle removal.

Results and Discussion

The cTLM structures fabricated from Ni contacts annealed between 3.5 and 6.0 J.cm^{-2} were characterized by current-voltage (I-V) measurements. The representative I-V curves of each contact are displayed on Fig. 3(a). A Rapid Thermal Annealing (RTA) sample (2 min - 1000°C) is taken as reference. As highlighted by the linear curves, from 4.0 J.cm^{-2} the Ni contact presents an ohmic behavior. With similar laser irradiation conditions, the ohmicity threshold occurred at the same fluence with a 100 nm thick titanium layer, although the Ni melting temperature is ~200°C lower than Ti [8]. If the highest slope of the I-V curves, suggesting the lowest resistance, is observed for the RTA sample, the best LTA value is observed for the contact annealed at 4.75 J.cm^{-2}. Corresponding SCR values are presented in Fig. 3(b). The SCR improves with the increase of the fluence, then it stabilizes in the range of 2-4×10^{-5} Ω.cm^2 for irradiation fluences higher than 4.5 J.cm^{-2}, which represents a large process window. As predicted from I-V curves, for the laser annealed contacts, the lowest SCR value is obtained consecutively to the 4.75 J.cm^{-2} irradiation. For this condition, a SCR value as low as (2.4±1.1)×10^{-5} Ω.cm^2 has been reached. It should be noted that due to the patterning consecutive to the irradiation step, the TLM structure dimensions can vary of ± 1 µm from the photolithographic mask dimensions, leading to a small additional SCR error, less than 1×10^{-5} Ω.cm^2. Nevertheless, our SCR value is one order of magnitude lower than the one obtained in nearly the same laser conditions by De Silva *et al.* [5]. More, to the best of our knowledge, this value is twice lower than the lowest value ever published in the literature, from Zhou *et al.*, especially since the doping level of their 4H-SiC substrate under the contacts (8×10^{18} at.cm^{-3}) were 4 times higher than the one of the epilayer used in this study (2×10^{18} at.cm^{-3}) [10]. Nevertheless, our lowest SCR value obtained consecutively to the laser treatment is still one decade higher than the one observed for the RTA sample. To investigate this difference of ohmic properties between LTA and RTA, the contact structures need to be analyzed.

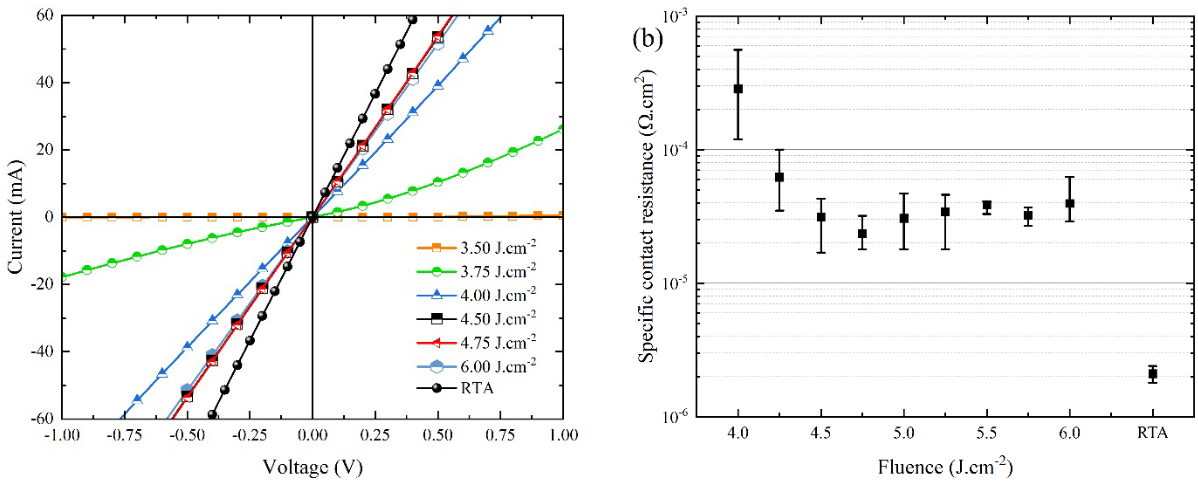

Fig. 3. (a) Current-Voltage characteristics of Ni/4H-SiC contacts annealed at several laser fluences, and comparison with a RTA treatment. (b) Evolution of the specific contact resistance as a function of the annealing fluence of contacts, and comparison with a RTA treatment. Error bars represent the min/max SCR value for each condition.

We investigated nickel silicide phase formation, depending on the nature of the annealing by X-Ray Diffraction analysis, as presented on Fig. 4. The main peaks at 35.5° and 75.2° correspond respectively to (0004) and (0008) plans of 4H-SiC. For RTA sample, most of the peaks refer to the orthorhombic Ni_2Si phase and the peak at 26.6° corresponds to graphite. This contact composition is usual for nickel contact fabricated by RTA and it is often attributed to be the origin of its remarkable electrical properties [11]. For LTA treatment, the sample irradiated at 4.5 J.cm^{-2} is presented. We observed the graphite peak at 26.6° like for the RTA sample, the other peaks could correspond to orthorhombic Ni_3Si_2, hexagonal $Ni_{31}Si_{12}$ or orthorhombic Ni_2Si. Contrary to the RTA treatment, the LTA sample does not present a unique form of nickel silicide, which makes the phase determination complicated. The presence of multiple phases consecutively to LTA might be the origin of the lower electrical performances compared to the RTA treatment.

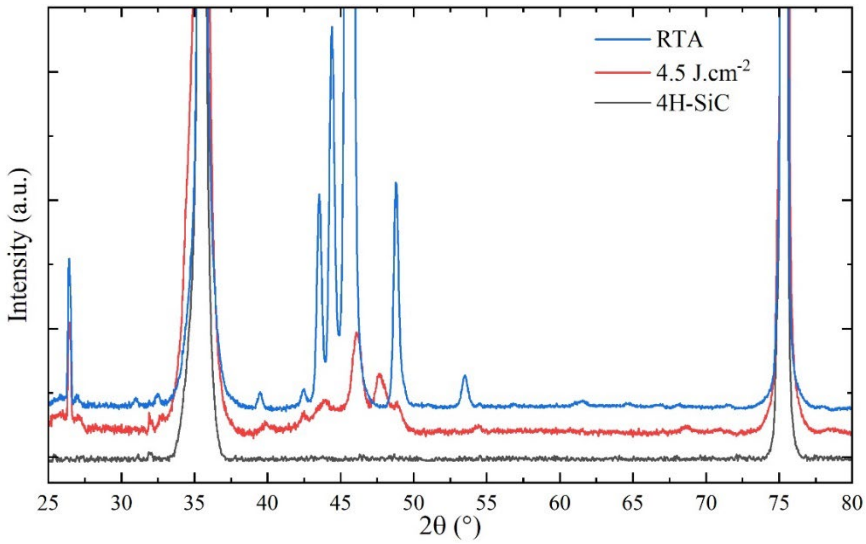

Fig. 4. XRD measurements of Ni/4H-SiC contacts annealed at several fluences, a contact fabricated by RTA and the 4H-SiC substrate.

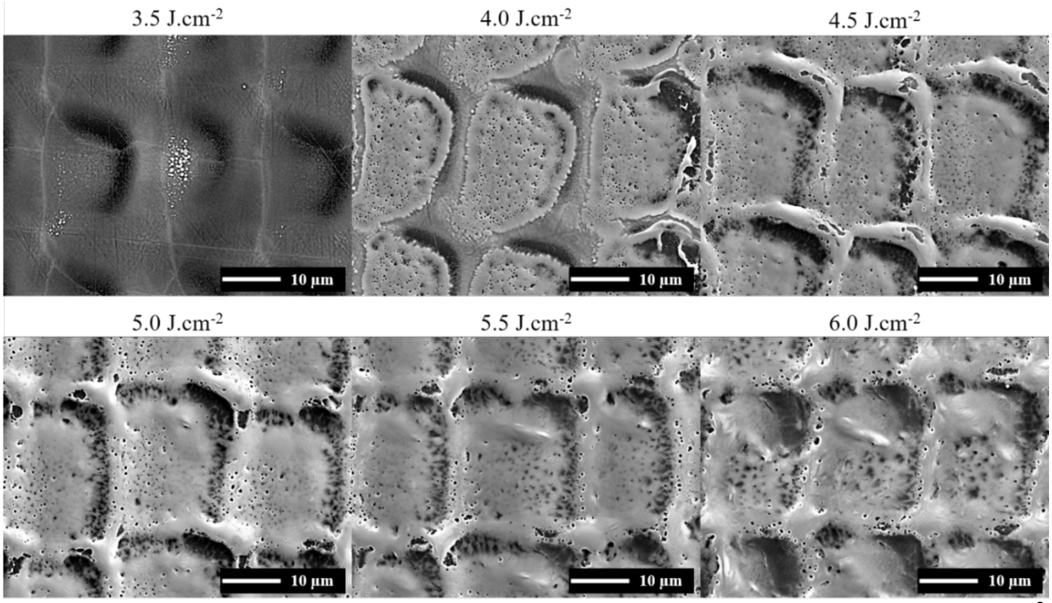

Fig. 5. SEM measurements of Ni/4H-SiC contacts annealed from 3.5 to 6.0 J.cm^{-2}.

Finally, the morphology of Ni contacts after the irradiation and the acid treatment was studied by SEM microscopy, as presented on Fig. 5. At 3.5 J.cm^{-2}, the nickel poorly reacts with SiC, leaving only few silicides after the Ni removal. The most part of the surface is directly SiC, that is why we can distinguish traces made by wafer polishing. From 4.0 J.cm^{-2}, the nickel silicide formation is highlighted in the laser footprint area. At this fluence, the contact morphology looks like islands, which means that the temperature generated at the pulse edges was not high enough to form silicides. The non-continuous contacts generated reduce its effective area which could be responsible of the poor SCR at 4.0 J.cm^{-2}. From 4.5 J.cm^{-2}, the Ni-based contacts entirely cover the SiC, the overlap areas forming higher thickness regions than at the laser pulse centre. Surprisingly, the fluence increasing seems not strongly affect the morphology, but it needs to be confirmed by Atomic Force Microscopy measurements.

Summary

Following a similar process than in our previous study on titanium, we fabricated nickel ohmic contact by UV laser annealing. The electrical characteristics of the ohmic contacts are almost one decade better than for our Ti contacts and are few times better than Ni contacts in the literature.

Contact formation was analyzed by XRD but, due to the multiple peak presence in the spectra, it is difficult to identify the phases that could explain the origin of ohmicity. The Ni_2Si phase is often depicted as the main compound in Ni contact formed by LTA and RTA. However, based on our structural characterizations, its presence is not so clear, and additional analysis are needed. Beyond this point, it would be interesting to evaluate the influence of this state-of-the-art Ni contact towards the electrical characterization of JBS diodes elaborated on thinned 4H-SiC substrates.

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