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Ni-Silicide Ohmic Contacts on 4H-SiC Formed by Multi Pulse Excimer Laser Annealing

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Abstract. The formation of ohmic contacts by laser annealing approach is of great importance for SiC power devices, since it allows their fabrication on thin substrates, that is of crucial significance to reduce power dissipation. Ni silicide reaction under UV laser irradiation has been studied in detail with particular focus on single pulse approach, in order to describe the early stage of reaction process. The use of a multi pulse approach, for the formation of Ni silicide-based ohmic contacts by means of excimer laser annealing, has been investigated in this work. The reaction process has been characterized, as a function of number of pulses, by means of X-Ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) analysis. Laser process simulations, formulated in the framework of phase-field theory, have been performed in order to predict the evolution of material during reaction under annealing. Simulations show that reaction moves to Si-rich phases with increasing number of pulses, with a co-existence of Ni_2Si and Ni_3Si_2 phases for the three pulses process. Moreover, simulations show critical differences, in terms of the uniformity of the distribution of the silicide phases along the film, between the single pulse and the multi pulses cases and the increasing of thickness of silicide phases with the pulse sequence. These predictions are in good agreement with the findings of XRD and TEM analyses. The electrical properties of the reacted layer have been evaluated on Schottky Barrier Diodes (SBD) devices, confirming the ohmic behaviour of multi pulse annealed samples.

Introduction

Silicon carbide has been widely used in the last decade, due to its excellent physical properties, for high voltage power devices [1] and sensors [2]. For power electronics, the reduction of on-state resistance (R_{ON}) and power losses is significantly enhanced by wafer thinning. To prevent yield losses induced by the increased fragility of thin wafers, a new process integration approach is needed, including the replacement of Rapid Thermal Annealing (RTA) processes to form the ohmic contacts [3]. Ohmic contact formation, indeed, requires a high temperature RTA process, typically in the range between 900 °C and 1100 °C [4], that is not compatible with metals deposited on front side. For this reason, RTA process must be performed before front side metal definitions and it is usually followed by several process steps, resulting in a very complex workflow, with the risk of quality and yield losses. A solution to form backside ohmic contacts after front side device definition is therefore required. Among the alternative processes to RTA proposed for Si [5-8], laser annealing is the most promising one for ohmic contact formation on 4H-SiC [9-15]. Excimer UV laser annealing has been widely studied for Ni-based ohmic contacts [16], with particular focus on single pulse process, with the aim to understand the early stages of reaction process [17-18]. In this work, the reaction process induced by the multi-pulse approach has been investigated, by means of X-Ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) analyses. Laser process simulations have been performed, to predict the evolution of the reaction under annealing. Schottky Barrier Diodes (SBDs) have been characterized, in order to evaluate the electrical properties of the reacted layers.

Experimental Setup

SBD devices have been fabricated on 4H-SiC wafers grinded down to 110 µm [3]. A 100 nm thick Ni layer has been deposited on the grinded surface by DC sputtering in Ar ambient, at a base pressure of 1 x 10^{-3} mbar. The Ni layer has been annealed by using an excimer UV laser, with wavelength of 308 nm, pulse duration of 160 ns, fluence of 3.8 J/cm^2 and laser pulses in the range between one and three. Structural and morphological properties of the reacted layers have been characterized by XRD analyses using a Bruker AXS D8 DISCOVER diffractometer working with a Cu-Kα source and a thin film attachment and by TEM analyses using a JEOL-JEM microscope working at 200 keV. Laser process simulations have been formulated in the framework of the phase-field theory [18-20]. The results here discussed extend to the multi-pulse case the method and the calibration discussed in the details in ref. [18]. As a reference for electrical evaluation, SBDs have been fabricated by using a standard RTA process for Ni-based ohmic contacts (60 s at 1000 °C in N_2 ambient). The electrical characterization of SBDs has been performed by using a semiconductor device parameter analyzer (Agilent B1500A) and a high-power curve tracer (Sony Tektronix 371A).

Results and Discussion

XRD analyses have been performed in grazing incidence configuration on Ni samples annealed at 3.8 J/cm^2 with single, double and triple pulses to study the structural evolution of the reacted layers as a function of laser pulse repetitions. Fig. 1 show the XRD patterns of a single pulse annealed sample, with the deconvoluted contributions of the main peaks as a case study and protocol description that was applied to all cases.

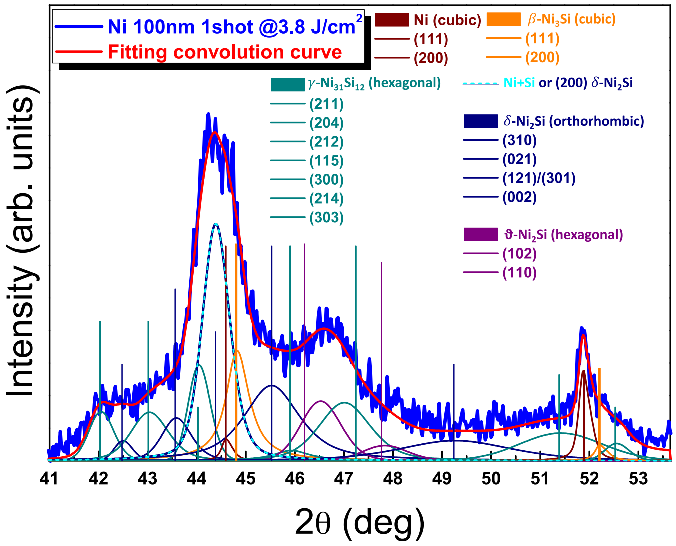

Fig. 1. Normalized XRD pattern acquired in grazing incidence configuration related to the Ni sample after laser annealing at 3.8 J/cm^2 single pulse. Deconvoluted component peaks are shown in the diagnostic range around the main peaks.

The same kind of study and analytical protocol were applied in samples at progressively increasing number of pulses from 1 to 3. The extracted quantitative fractions of the different phases reveal that Ni rich contributions vanish by moving from one to three pulses and that the composition evolves to Si richer towards the Ni_3Si_2 one, with the Ni_2Si being the predominant phase. Moreover, there is no evidence on the formation of the low-resistivity NiSi phase.

In details we can summarize the silicide layer composition after laser annealing as follows:

- 1 shot: β-Ni_3Si, γ-$Ni_{31}Si_{12}$ and θ/δ-Ni_2Si;
- 2 shot: γ-$Ni_{31}Si_{12}$, θ/δ-Ni_2Si and Ni_3Si_2;
- 3 shot: θ/δ-Ni_2Si and Ni_3Si_2.

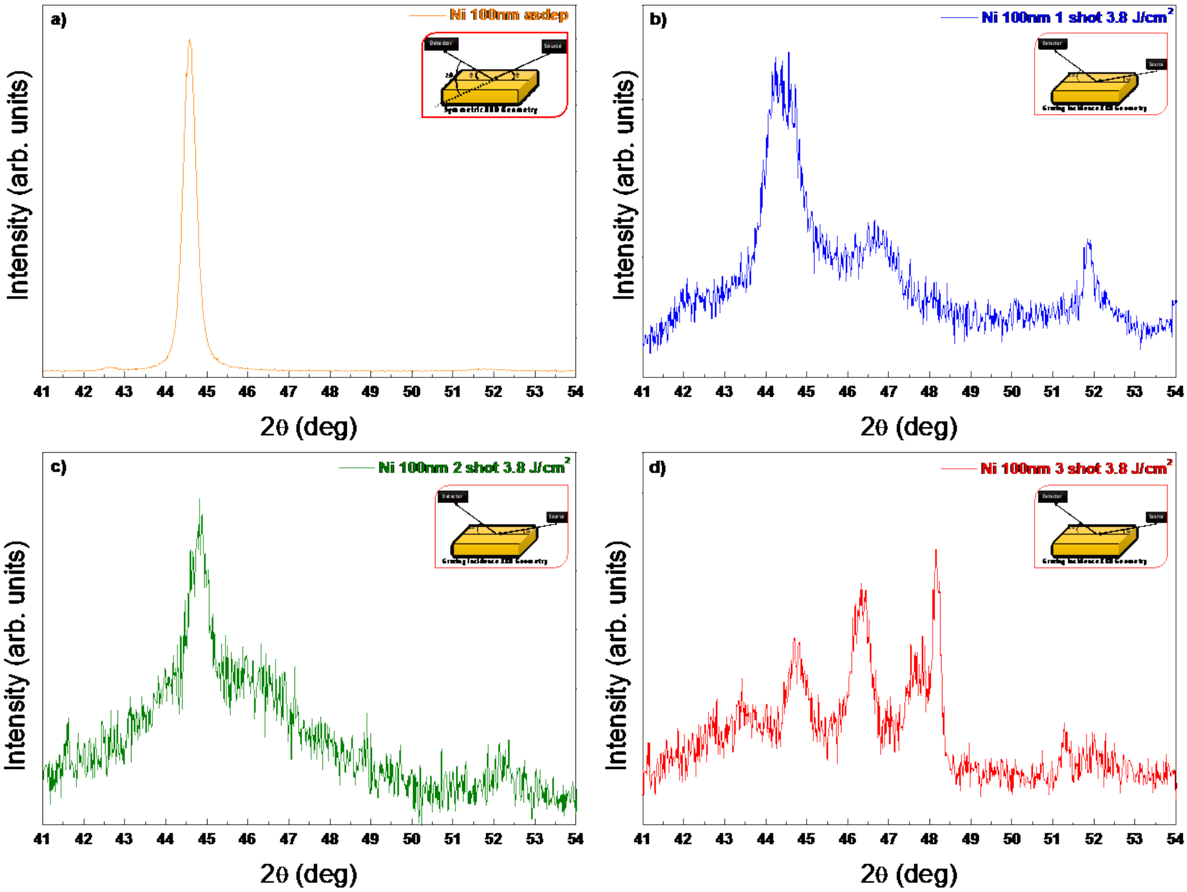

Fig. 2. Normalized XRD patterns related to the Ni/Si: **a)** before laser annealing in symmetric configuration; in grazing incidence after laser annealing at 3.8 J/cm² by **b)** 1shot; **c)** 2 shots **d)** 3 shots.

Transmission Electron Microscopy (TEM) and Scanning Transmission Electron Microscopy (STEM) analyses have been performed to investigate the morphology of reacted layer with the increasing of laser pulses. Fig. 3a and Fig. 3b show the comparison between cross sectional TEM analyses of single pulse and triple pulse treated samples, with energy density 3.8 J/cm². Cross sectional STEM analyses of the same samples are shown in Fig. 3c and in Fig. 3d. The Ni-Si-C alloy visible in the single pulse treated layer has an irregular interface with the silicided region; on the opposite, it was not detected in the triple pulse treated sample wherein the silicide film appears uniform along the whole thickness and with a regular shape and a flat surface.

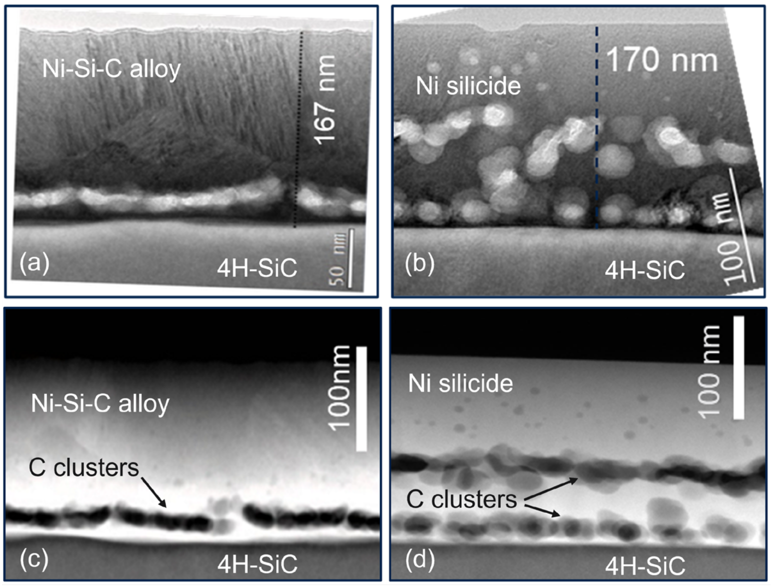

Fig. 3. Comparison of cross TEM analyses for one pulse (a) and three pulses (b) cases at a fluence of 3.8 J/cm^2. Comparison of cross STEM analyses for one pulse (c) and three pulses (d) case at a fluence of 3.8 J/cm^2.

A single band of C-clusters is visible after one pulse, whilst a double band is present after three pulses. This multiple structure can be attributed to the fact that the C-clusters, already present in the film after the first pulse, do not melt during the subsequent laser pulses, as instead the film does. The additional band of C-clusters indeed arises from the residual C nucleation close to the Silicide/SiC interface that undergoes a shift in the subsequent annealing.

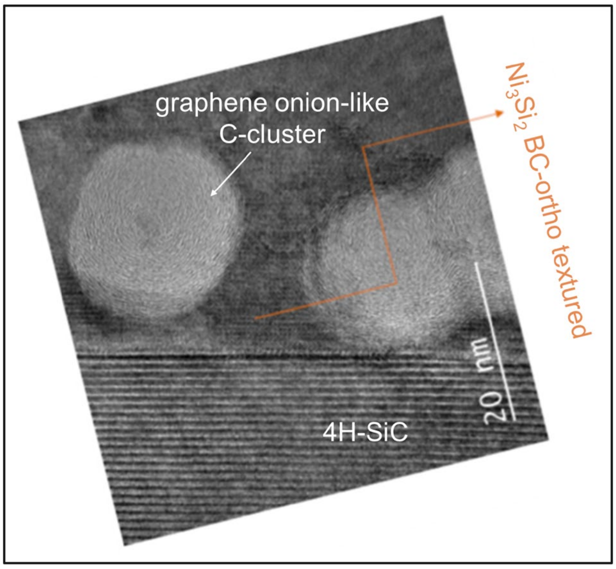

Fig. 4. High resolution cross TEM analysis of sample annealed at a fluence of 3.8 J/cm^2 with three pulses. A textured interface is observed between 4H-SiC substrate and Ni silicide. Graphene “onion-like” C-clusters are included in silicide layer.

High resolution TEM analysis at the silicide/SiC interface, reported in Fig. 4, shows a silicide compound, compatible with the Ni_3Si_2 crystal structure, textured with the 4H-SiC crystal structure. Moreover, high resolution TEM analyses show that the C-clusters tend to organize internally in the form of “graphene onions” and these structures can have a beneficial impact on the electrical properties of the reacted layer.

The findings of XRD and TEM analyses have been confirmed by laser process simulations, performed for the fluence of 3.8 J/cm^2, for one, two and three pulses cases. Simulations show that the

Ni_2Si is the dominant phase not only for the single pulse case but also for the multi-pulses case. However, as reported in Fig. 5, simulations show significant differences in the thickness and in the uniformity of the distribution of Ni_2Si phase along the depth of the reacted layer, with the increasing of laser pulses. The disordered Ni-Si-C alloy light blue region, present for the single pulse case, disappears after the second pulse, when the Ni_2Si phase starts to be present in the whole film. Moreover, when the process moves from two to three pulses, the Ni_2Si phase distribution becomes more uniform and tends to move towards the surface.

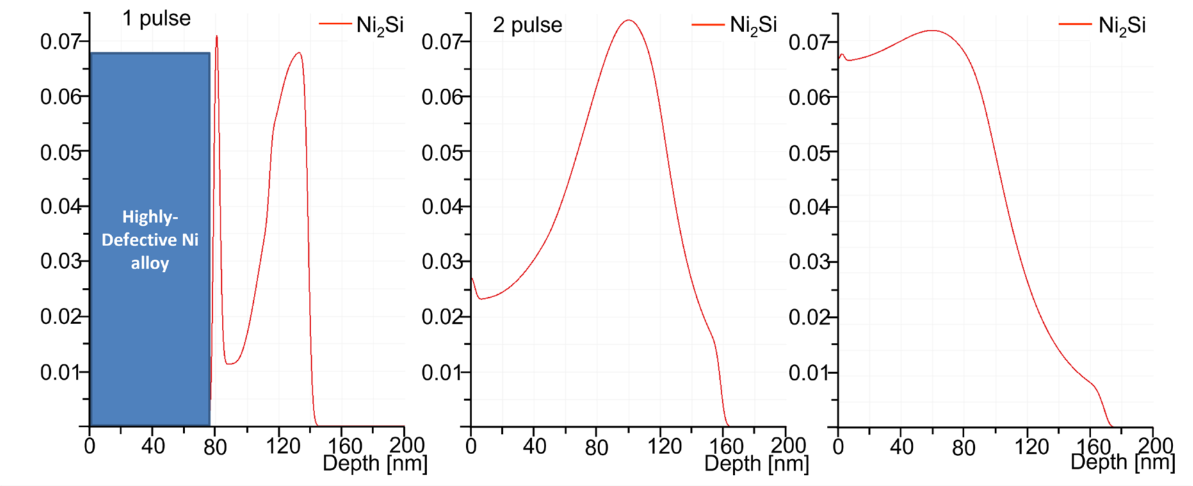

Fig. 5. Ni_2Si distribution predicted by the simulation at the end of irradiation for the 1, 2, 3 pulse cases at 3.8 J/cm^2 fluence. The light blue region shows the not fully reacted region where a highly defective Ni-Si-C alloy is predicted by the simulation. The compound fraction is normalized to the total Ni content in the film.

Although the reaction moves from Ni richer phases to Si richer phases, by increasing the laser pulses from one to three, simulations confirm that NiSi phase is not formed. The distribution of the Ni_3Si_2 phase is reported in Fig. 6, for one, two and three pulses cases.

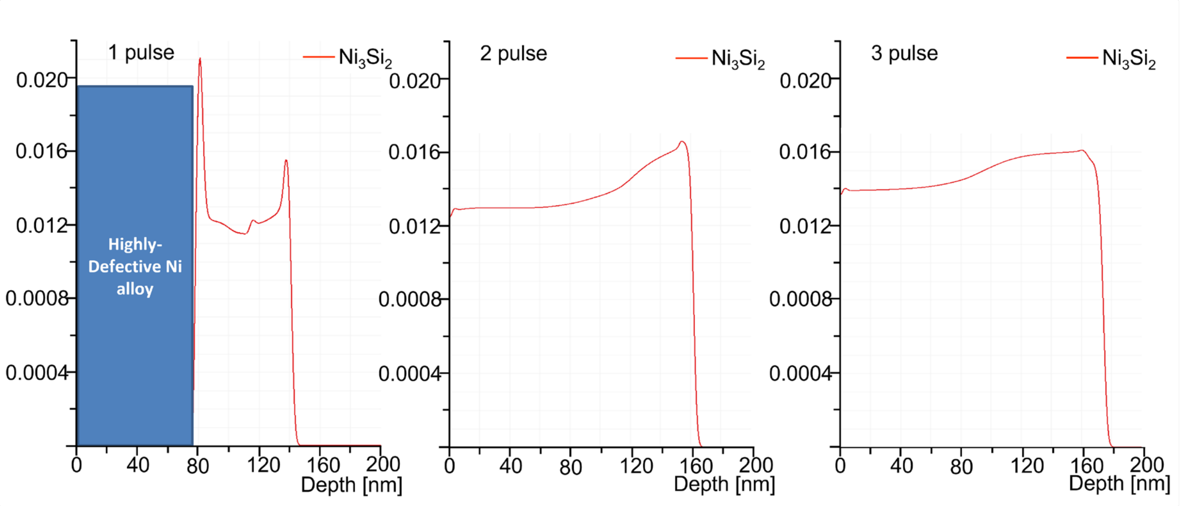

Fig. 6. Ni_3Si_2 distribution predicted by the simulation at the end of irradiation for the 1, 2, 3 pulse cases at 3.8 J/cm^2 fluence. The light blue region shows the not fully reacted region where a highly defective Ni-Si-C alloy is predicted by the simulation. The compound fraction is normalized to the total Ni content in the film.

The evolution of the Ni_3Si_2 phase with laser pulses is similar to the one of Ni_2Si phase, in terms of thickness and uniformity, with the main difference that the distribution has a maximum at interface between silicide and 4H-SiC substrate. We notice that the simulation scenario is in noteworthy agreement with the experimental microstructural characterization indicating the importance of a multi-pulse process to obtain a uniform silicide/SiC system.

The electrical properties of the reacted layers have been evaluated on power devices. The V_f at nominal current of SB diodes annealed at 3.8 J/cm^2 is reported in Fig. 7, as a function of laser pulses. As a reference, the V_f of a SB diode annealed by standard RTA is reported. The graph shows that three laser pulses are needed to get results comparable to the one obtained by RTA process.

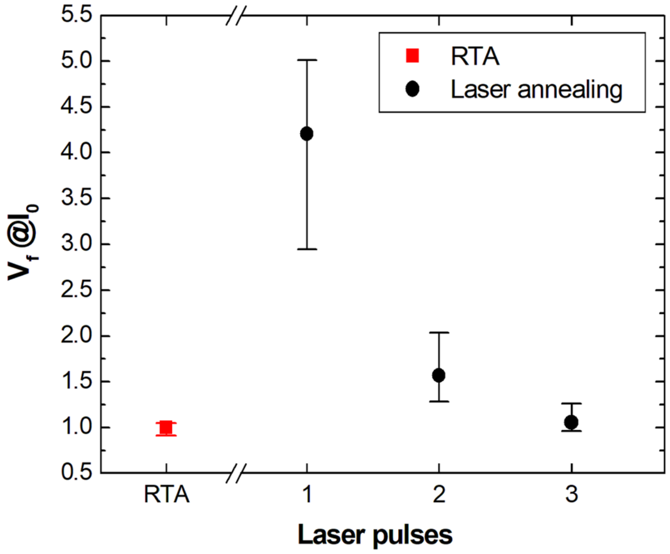

Fig. 7. Forward voltage (V_f) of diode at nominal current as a function of laser pulses at a fluence of 3.8 J/cm^2, compared with standard RTA (60 s at 1000 °C) results. V_f decreases with the increasing of laser pulses. Three laser pulses are needed at least to get V_f values comparable with ones obtained by RTA.

This evidence is in good agreement with simulations and with structural and electrical characterization. It is worth noticing that even if the NiSi phase has not been formed, the sample annealed with three laser pulses exhibits low resistivity characteristics, that can be attributable to the texturing of Ni silicide at the interface with SiC, to the presence of graphene “onion-like” C-clusters and to the dominant Ni_2Si phase.

Summary

The formation of Ni-based ohmic contacts on 4H-SiC by means of excimer UV laser annealing with multi-pulse approach has been investigated. The findings of simulations have been confirmed by structural and morphological analyses and are strictly related to the electrical properties of SB diodes. In conclusion, multi pulse UV laser annealing can be considered a suitable process for the formation of Ni-based ohmic contacts on 4H-SiC.

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