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P Implantation Effect on Specific Contact Resistance in 3C-SiC Grown on Si

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ABSTRACT

In this work, non-intentionally doped 3C-SiC epilayers were implanted using phosphorus at different energies and subsequently annealed at temperatures between 1100°C and 1350°C in order to form n^+ implanted layers. Different techniques such as Fourier Transformed InfraRed spectroscopy (FTIR) and Secondary Ion Mass Spectroscopy (SIMS) were used to characterize implanted 3C-SiC epilayers after the different annealing steps. Successively, metal layers were sputtered in order to form the contacts. The specific contact resistance (ρ_C) was determined by using circular Transfer Length Method (c-TLM) patterns. Specific contact resistance values were investigated as a function of doping and contact annealing conditions and compared to those obtained for highly doped 3C-SiC epilayers. As expected, ρ_C value is highly sensitive to post-implantation annealing and metal contact annealing. This work demonstrates that low resistance values can be achieved using phosphorus implantation and, hence, enabling device processing.

INTRODUCTION

Since last decades, silicon carbide (SiC) is the subject of intensive research and development activities. This growing attention is motivated by attractive mechanical and electrical properties which make silicon carbide a promising material for high power and high temperature electronic devices. According to the stacking sequence of the Si-C bilayers, silicon carbide exists in more than 200 different polytypes. Compared to the various existing structures, the 3C-SiC is the only one that can be hetero-epitaxially grown on cheap silicon substrates. The SiC growth capability on low cost and large diameter silicon substrates becomes then a very attractive solution for manufacturing [1]. Indeed, in such conditions, only the required silicon carbide thickness has to be grown according to the targeted application. For such a material, one of the main challenges is the achievement of high quality ohmic contacts in order to create efficient electronic devices. To reach that, ohmic contacts both in highly doped epitaxial or implanted layers may be required depending on process flow. Indeed, doping is a key process in semiconductor manufacturing. Ion implantation is a method of choice to obtain selective doping and the only available for silicon carbide. To obtain n^+ doping in 3C-SiC, both nitrogen and phosphorus implantation were already carried out [2, 3]. Even if nitrogen is often preferred for SiC devices, phosphorus exhibits the advantage of being widely used in all the semiconductor industry. Post-implantation annealing is also a great challenge in 3C-SiC on Si. In fact, this annealing must lead to dopant electrical activation that generally occurs at high temperature and must remain well below the Si melting point. In this work, we investigate the influence of phosphorus implantation and the associated annealing on specific contact resistance in 3C-SiC grown on Si.

EXPERIMENTAL DETAILS

The 3C-SiC films, used for this study, were hetero-epitaxially grown on 2 inches (100) silicon wafers by using a resistively heated hot wall CVD reactor [4]. The growth was performed using silane (SiH_4) and propane (C_3H_8) as precursor gases and purified hydrogen (H_2) as a carrier gas following the classical two stages process defined by Nishino [5] but without initial surface de-oxydation. The growth details are reported elsewhere [6]. Two types of 7 µm thick epilayers with different n doping levels were grown to carry out the ohmic contacts: a non-intentional doping of 6×10^{15} cm^{-3} and a highly doping of 3.5×10^{19} cm^{-3} [7]. The 3C-SiC epilayers were then polished using NOVASiC know-how. Non-intentionally doped samples were then implanted at room temperature with phosphorus using a commercial implanter. Implantations were carried out at multiple energies of 30, 50, 100 and 150 keV for a respective dose of 0.5, 1.2, 2.1 and 4.5×10^{15} cm^{-2} in order to form a phosphorus box-like profile. Parameters were calculated using SRIM simulation. Post-implantation annealing, with an Ar flow of 1.5 slm and at a pressure of 200 mbar, has then been accomplished to activate phosphorus implanted ions. Both temperature and duration of annealing have been investigated as summarized in table I.

Table I: Post-implantation annealing conditions and associated RMS roughness values for 3C-SiC phosphorus implanted samples.

Sample	A	B	C	D	E
Temperature (°C)	1100	1150	1250	1350	1350
Duration (min)	60	60	60	60	120
RMS roughness (nm)	1.36±0.26	1.33±0.37	1.23±0.39	1.23±0.21	1.31±0.21

Different techniques have then been applied to characterize the modifications of the 3C-SiC properties following the implantation. Fourier Transformed InfraRed (FTIR) measurements were performed on a Avatar 370 Thermo Nicolet spectrometer. Spectra were recorded with a 4 cm^{-1} resolution on a 700-1100 cm^{-1} spectral range in order to follow the evolution of the crystal disorder. Secondary Ion Mass Spectroscopy (SIMS) measurements were used to determine both phosphorus dopant concentration and layer homogeneity. The roughness was checked using a Fogale Nanotech "Photomap 3D" optical profiler.

Circular Transfer Length Method (c-TLM) patterns were prepared to determine specific contact resistance. This method presents a serious advantage over linear TLM structure as mesa isolation is not required for c-TLM pattern. Figure 1 shows a representation of the c-TLM of Marlow and Das [8] which consists of nine contact patterns. Each one has a constant contact inner diameter of 160 µm and a space (d) ranging from 12 µm to 48 µm between inner and outer contact.

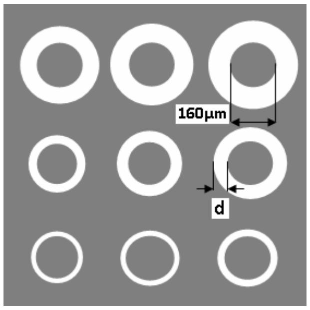


Figure 1: Contact patterns used to make c-TLM measurements.

A 150 nm thick nickel-titanium bilayer has been deposited by sputtering. Afterward, the samples were subjected to a Rapid Thermal Annealing (RTA) step of 1 minute in inert ambient (Ar) at 1000°C or 1050°C. The so-formed c-TLM structures were used to extract the specific contact resistance. A Keithley 2400 Sourcemeter was then used as a current source and voltage measurer. On each sample, more than 6 c-TLM patterns were measured and a regression method was employed to extract the specific contact resistance values as detailed in [9].

RESULTS AND DISCUSSION

Before metal contact step, all samples were first analyzed using different techniques in order to evaluate the implantation step impact of the 3C-SiC layers.

Physical characterization of 3C-SiC implanted layers

Figure 2 presents the obtained FTIR spectra for a non-intentionally doped epilayer, as-implanted sample, 1250°C and 1350°C annealed samples.

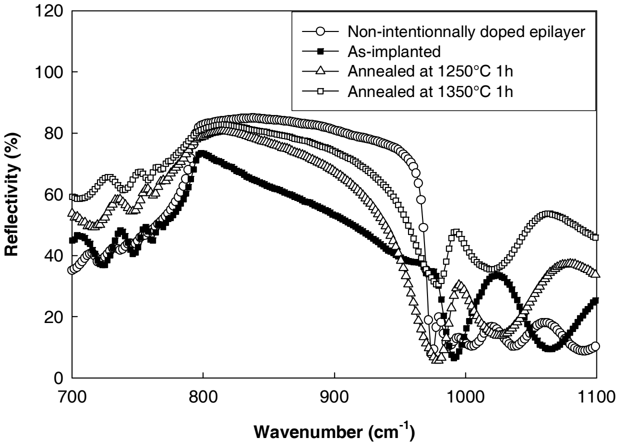
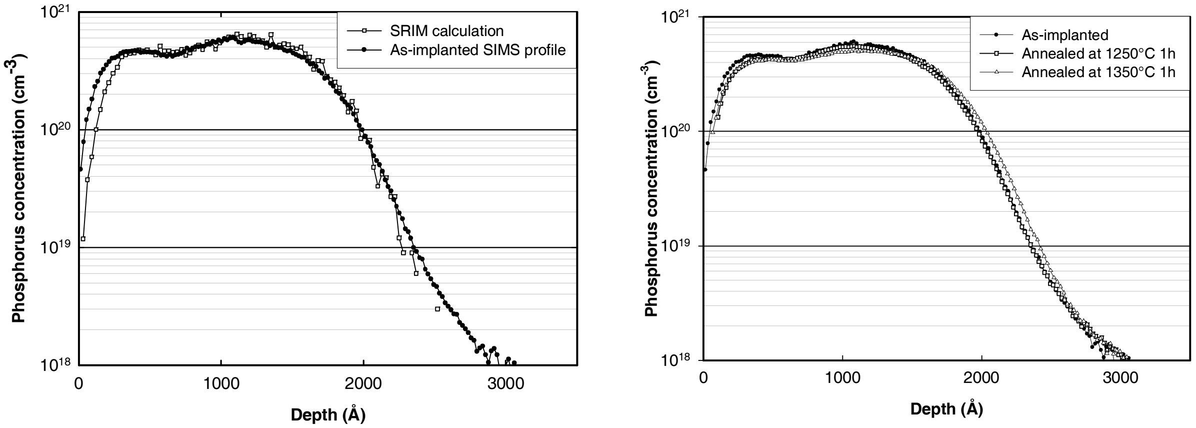


Figure 2: FTIR measurements for a non-intentionally doped epilayer, as-implanted sample, 1250°C annealed sample and 1350°C annealed sample.

We observe in this figure that the reflectivity in this spectral range is soundly modified with respect to the treatment (implantation and/or annealing). A qualitative evolution is noticeable between all the spectra considering the reststrahlen band (spectra between 790 and 970 cm^{-1}). It is straightforward to notice the strong evolution of the reststrahlen band in accordance to the surface treatment [10]. Indeed, if the implantation step drastically modifies the reststrahlen band, the further annealing tends to restore the spectral response towards a highly crystalline material. This evolution could be attributed to an initial lattice damage followed by a thermal healing of the atomic arrangement. Furthermore, the increase of the overall reflectivity on this spectral range after the 1350°C annealing is consistent with a better re-crystallization and, hence, with a higher activation efficiency in comparison to the activation achieved after the 1250°C thermal annealing.

In order to follow the evolution of the phosphorus profile upon annealing as well as the doping homogeneity, SIMS measurements were performed. First of all, it is important to mention that the as-implanted SIMS profile corroborates extremely well the SRIM calculated one, as presented in figure 3 (a). The phosphorus concentration profiles for as-implanted sample and annealed samples (1 hour at 1250°C and 1350°C) are presented in figure 3 (b). All the phosphorus profiles are very close to each other evidencing the extremely low diffusivity of phosphorus in 3C-SiC at considered temperatures. Moreover, the post-implantation annealing preserves the expected box-shape doping profile.



(a) (b)

Figure 3: Expected phosphorus concentration profile calculated by SRIM simulation and as-implanted SIMS profile (a) and SIMS measurements for as-implanted sample, 1250°C annealed sample and 1350°C annealed sample (b).

The surface quality is a major concern for device fabrication, even more crucial in the case of SiC where high surface quality is difficult to achieve. AFM measurements were performed in order to check the surface roughness before metallization. This method is fully used in many laboratories. However, a fast and non-contact method has also been exploited using a Fogale Nanotech "Photomap 3D" optical profiler, as previously shown [7]. This 3D tool has been employed to determine surface roughness for 200x200 µm^2 areas. These measures were made subsequently to the hetero-epitaxy, to the implantation step and to the high temperature post-implantation annealing, in order to check potential surface degradation. The results, average of 10 subsequent measures for each sample, are presented in table I. After epitaxy, the RMS roughness value has been evaluated to 1.36 nm. The implantation seems to have no effect on the roughness value which has been determined to 1.35 nm after this step. Subsequently to the post-implantation annealing, the roughness has also been measured, exhibiting no variation. This points out that the high temperature annealing does not damage the silicon carbide surface, whatever is the temperature.

Our results shed light on the implantation modification on the 3C-SiC layers. As expected, implantation enables to create a box-like profile with a limited degradation of surface roughness. The subsequent annealing step, performed as usually to anneal the implantation defects and activate the dopant, presents the best results for the higher temperature without surface degradation. Based on these results, the implementation of this technique for ohmic contacts can be studied.

Electrical characterization of the Ti-Ni contacts

By using the measurement procedure exposed previously, the specific contact resistance has been investigated. Figure 4 presents ρ_C as a function of temperature and post-implantation annealing duration. In the same figure, contact annealing temperature impact is also investigated.

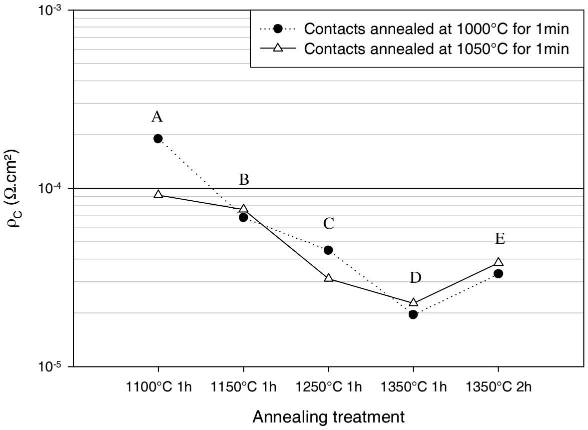


Figure 4: Influence of high temperature post-implantation annealing on the specific contact resistance after a contact RTA treatment of 1 minute in Ar ambient.

The temperature is a key parameter in order to activate phosphorus dopants. As expected, the lowest specific contact resistance value is obtained for the highest implantation annealing temperature for both contact annealing temperatures. Moreover, I-V characteristics (not presented here) underline a perfect ohmic behavior. Due to the silicon substrate melting temperature, 1350°C seems to be the maximal acceptable processing temperature for the annealing. Another parameter that has to be considered is the implantation annealing duration. According to the previous results, a 2 hours annealing at 1350°C has been completed. Subsequently to this treatment, the ρ_C value has drastically increased, around 70% in comparison with the 1 hour annealing at the same temperature. This result is surprising as a lower value was anticipated. A surface morphology modification cannot explain this degradation as roughness measurements do not suggest any surface damage towards the silicon carbide surface after a 2 hours treatment at 1350°C (sample E). Further experiments are necessary to well understand this behavior. Nevertheless, our work demonstrates that a low specific contact resistance value of $2x10^{-5}$ $\Omega.cm^2$ is obtained for samples annealed 1 hour at 1350°C. With the same measurement protocol, the ρ_C value for the highly doped 3C-SiC epilayer was evaluated to $1.7x10^{-5}$ $\Omega.cm^2$. Consequently, these two different doping methods lead to the same results. However, the A-sample points out a different ρ_C value according to the contacts annealing. This tendency is not confirmed for higher post-implantation temperature where the discrepancy in ρ_C values according to the RTA treatment is cut down. These results provide a wider process window to carry out the ohmic contacts in future devices.

CONCLUSION

In this paper, 3C-SiC non-intentionally doped samples were implanted with phosphorus at different energies and subsequently furnace annealed between 1100°C and 1350°C. First, FTIR, SIMS and optical profilometry measurements have been used to determine the influence of the post-implantation annealing on 3C-SiC properties. As expected, a box-like profile is obtained and seems to have the best electrical activation at the highest temperature. Moreover, this annealing step does not damage the silicon carbide surface, whatever is the temperature. Ohmic contacts were then formed using a Ti-Ni bilayer and studied with c-TLM structures. Our measurements demonstrate that good ohmic contacts were obtained successively to the high temperature annealing. The lowest specific contact resistance has been evaluated to $2\text{x}10^{-5}\ \Omega.\text{cm}^2$ consecutively to a 1 hour-1350°C annealing. A longer duration annealing at this temperature seems not to be suitable as the ρ_C value increased for a 2 hour treatment. Similar behaviors were found for both metal RTA treatments, offering a larger process window. As expected, ρ_C value is highly sensitive to post-implantation annealing and metal annealing conditions. Moreover, we demonstrate that low resistance value can be achieved for n^+-implanted layers, comparable with those obtained on in-situ highly doped 3C-SiC samples. These promising results are of high interest for future device fabrication using such processes and material.

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