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4H-SiC P$^+$N UV Photodiodes : a Comparison between Beam and Plasma Doping Processes

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Abstract. This paper presents a study of 4H-SiC UV photodetectors based on p$^+$n thin junctions. Two kinds of p$^+$ layers have been implemented, aiming at studying the influence of the junction elaborated by the ion implantation process (and the subsequent annealing) on the device characteristics. Aluminum and Boron dopants have been introduced by beam line and by plasma ion implantation, respectively. Dark currents are lower with Al-implanted diodes (2 pA/cm^2 @ - 5 V). Accordingly to simulation results concerning the influence of the junction thickness and doping, plasma B-implanted diodes give rise to the best sensitivity values (1.5x10^{-1} A/W @ 330 nm).

Introduction

During the past years there has been considerable interest in systems able to record very low light levels in the ultraviolet range in severe conditions of use. The advantage of Silicon Carbide (SiC) with respect to nitride alloys – the major wide band-gap semiconductor used today in industry – relies on three major points : a low residual doping for epitaxial layers (in the 10^{14} cm^{-3} range and concentrations of residual defects/impurities at least one order of magnitude lower), a high thermal conductivity allowing high temperature operations, and a very good radiation hardness. It is then possible to use SiC for fabrication of devices capable to operate under extreme conditions. Photodetectors based on SiC allow to obtain good wavelength selectivity in the UV range, without any optical filters.

Experimental

The role of the p$^+$ emitter layer properties has been particularly studied in this paper. Among these properties, the doping and the thickness are thoroughly key parameters for controlling the device reliability. Photodetector simulations based on finite element method were performed, optimizing the design of the thin junctions for improvement of the light absorption and the carrier harvest. We also investigated the technological process giving rise to the dopant introduction into the SiC matrix. The comparison between standard ion implantation and pulsed-Plasma Immersion Ion Implantation (PIII) processes is expected to be fruitful, since PIII technology produced impressive results for Si solar cells in the UV range [1]. To our knowledge, PIII doping has never been carried out in SiC material. 4H-SiC n-type epilayers were either implanted with Aluminum by standard ion implantation at 27 keV, or with Boron by PULSION^{TM} system (pulsed-plasma ion immersion) –

B_2H_6 at 8 kV, in order to produce p^+-type layer thicknesses of 30 and 10 nm, respectively. The doses were adjusted for obtaining peak concentrations of few 10^{19} cm^{-3} for Al (samples A) and few 10^{20} cm^{-3} for B (samples B). This concentration discrepancy takes into account the difference of ionisation energies between Al and B dopants, and should give rise to similar values of the final hole concentrations in p^+ layers. Each sample was then annealed at 1700°C (samples A1, B1) or at 1650°C (samples A2, B2), aiming at analysing the influence of the annealing temperature on the device characteristics.

A prototype of furnace was used during this work (purchased from VEGATEC^{TM}), consisting in a vertical resistive reactor allied with a lift system. This allows to perfectly control the heating-up and the cooling-down rates, up to ~ 20°C/s. After Al implantations, we observed that a high heating-rate improved the sheet resistance whatever the annealing temperature, and preserved the surface roughness for annealing temperatures lower than 1700°C, which is crucial for thin implanted layers. The heating rate has indeed proven to be an important parameter for controlling the reverse current of the related diodes [2].

After thermal annealing, ohmic contacts were realized by sputtering with Ti/Al/Ni on p-type implanted layer (top contact) and Ni on n^+-type substrate layer (bottom contact). The back contact on the substrate was annealed at 900°C and the contact on implanted layer was annealed at 800°C. Both contacts have been annealed during 2 min under Argon atmosphere. Finally, the UV-photodetector surface shape has a circle geometry with 250 µm-diameter. A window area allows to detect the UV photons. Fig.1 shows the photodetector structure.

The optical simulations of photodetectors under the UV light have been realised by FDTD method (Finite Difference Time Domain), using the commercial software Sentaurus edited by Synopsys society [3]. Electromagnetic solver based on the FDTD method is used to calculate the electromagnetic field propagation inside UV-photodetector device.

Plasma Implantation in SiC

We propose to study the combination of PIII with a proper annealing, which should results in thin p^+ implanted layers (lower than 30 nm) particularly suitable for UV photon detection. PIII were performed on PULSION^{TM} (Plasma ion implantation tool from the french company I.B.S.) using B_2H_6 gas (see Fig.2). Specificity of PULSION^{TM} consists in using a pulsed DC polarization and a remote ICP plasma source allowing to work at low pressure ($< 1x10^{-3}$ mbar) with the use of low gas flow rate (< 10 sccm). This helps to minimize parasitic etching or deposition usually encountered on Plasma doping tools.

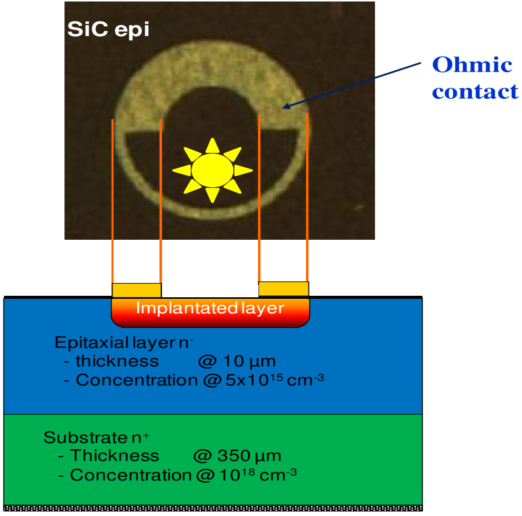


Fig.1 Photodetector pn structure

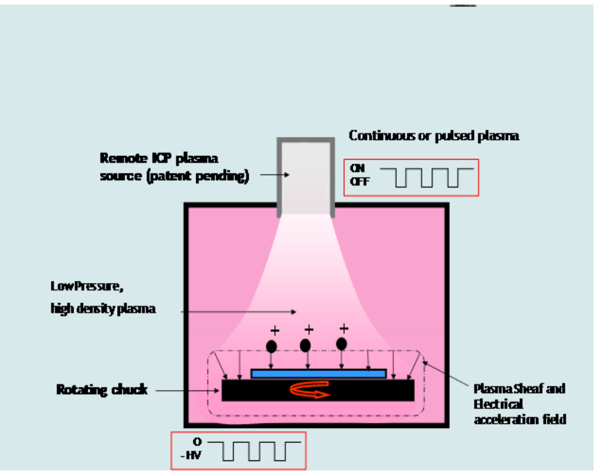


Fig.2 PULSION^{TM} set-up

A former study proved that, at a given energy, the plasma-process leads to a better surface morphology, a lower defect concentration and a thinner junction than a standard beam implantation process. This is accompanied with some dopant outdiffusion during the annealing, and a higher sheet resistance of the implanted layer [4].

Results and Discussion

Simulation

Figures 3 display the variation of the current density with the reverse bias (for an incident light wavelength at 200 nm), varying the p^+-layer thickness (Fig. 3a) and the p^+-layer concentration (Fig. 3b). In a general way, the current density increases with a thinner junction and a lower hole concentration. When the space charge region is closer to the surface, much more carriers undergoing the electric field are then harvested, leading to a better UV photodetector response.

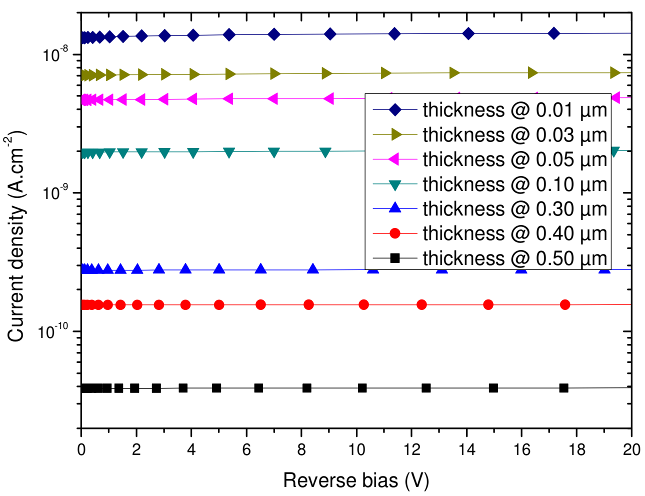


Fig.3a Simulated current density vs reverse bias @ 200 nm, with a p^+ doping fixed at $5x10^{19}$ cm^{-3}

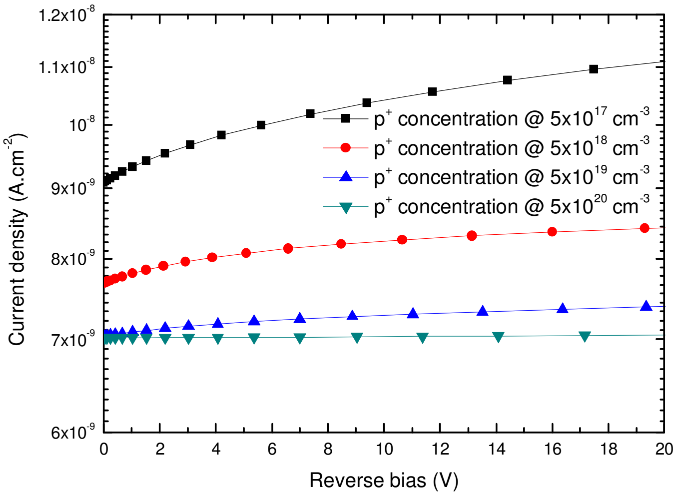
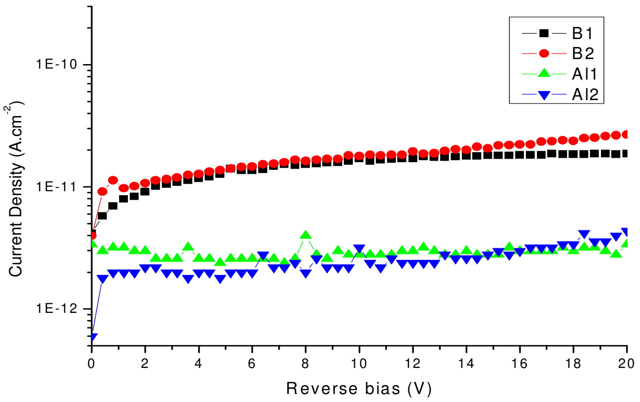


Fig.3b Simulated current density vs reverse bias @ 200 nm, with a p^+ thickness fixed at 30 nm

Device Characteristics

The evolution of dark currents with reverse bias of the realised devices is shown in Fig.4. Dark currents reveal to be lower with Al-implanted diodes (2 pA/cm^2 @ - 5 V), whatever the annealing temperature. On the contrary, B-implanted diodes show higher forward currents than Al-implanted diodes (not shown here), revealing a “JBS-behaviour” due to in-diffusion of B atoms in the ternary compound formed within the top metal during the annealing at 800°C (see Ref. 5 for details). The SIMS profile of B atoms shows no diffusion during the annealing [5].



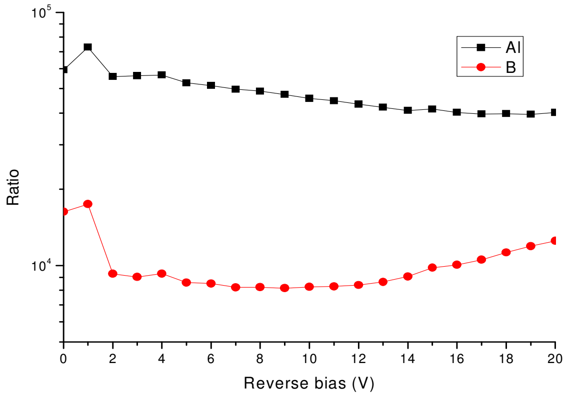


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Fig. 4 Dark currents of Al- and B- implanted photodiodes

Fig.5 Ratio between UV(365 nm) and dark current for Al- and B- implanted photodiodes (annealed at 1700°C)

Characteristics of the diodes have been then measured under light, with an incident wavelength of 365 nm. Fig.5 displays the evolution of the “signal-to-noise” ratio with reverse bias. Al-implanted photodiodes reveal a ratio six times higher than B-implanted diodes. Fig.6 gives the spectral response of these A1 photodiodes. As seen in Fig.5, there is no influence of the reverse bias, which is a clear advantage if a fully autonomous system is required (for space applications).

The spectral responsivities of the four kinds of diodes are compared in Fig.7. For a given dopant, the sensivity increases with the annealing temperature, which is surely related to a better recombination of the defects produced by the implantation process [6]. For a given annealing temperature, B-implanted diodes give rise to a higher signal than Al-implanted diodes. This can be due to a thinner junction and/or a lower hole concentration in the p^+-layer, which lead to increase the current density of the device under light.

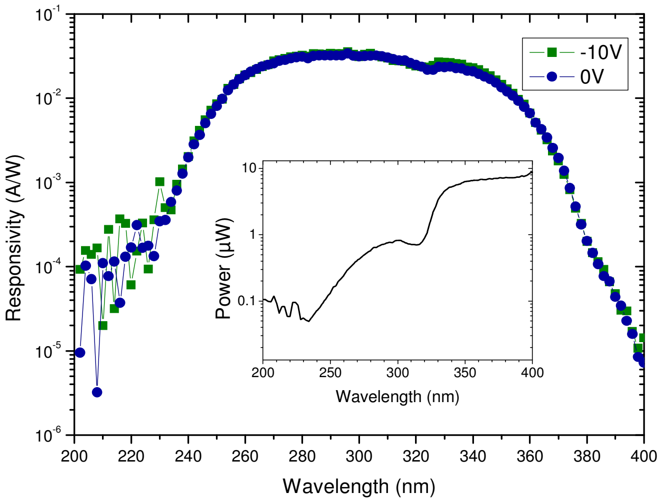

Fig.6 Spectral responsivities of Al-implanted photodetector (the power source light is shown in the inset)

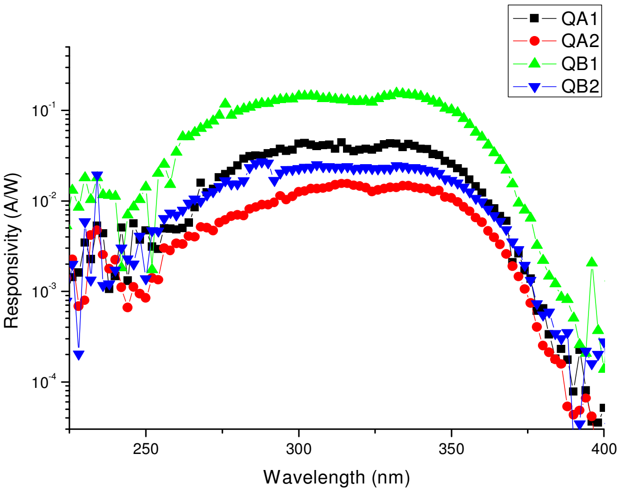

Fig.7 Spectral responsivities of Al- and B-implanted photodetectors

Summary

4H-SiC UV photodetectors were realised, based on implanted p^+n junctions either by Al standard beam or by B plasma. Thanks to the optimised furnace for post-implantation annealings, the leakage current of the diodes remain as low as 2 pA/cm^2. Boron plasma-implanted devices give rise to the best spectral responsivities. The behaviour of the diodes after irradiations is currently under study.

Acknowledgement

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