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4H-SiC Diodes to Probe Stark Effect Detection in 7Be Decay Lifetime

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Abstract. This study presents the design, fabrication, and electrical characterization of 4H-SiC p+/n diodes employed to provide a high electric field able to induce Stark effect in ^{7}Be atoms implanted in the space charge region. Indeed, a variation in the half-life of the ^{7}Be radioactive decay is expected to be achieved by applying an electric field of the order of 10^6 V/cm, which can be produced by reverse-biasing 4H-SiC diodes close to the breakdown voltage.

A set of diodes of area ranging between 2.12×10^{-3} cm^2 and 9.88×10^{-3} cm^2 was designed and fabricated to reach breakdown voltages up to 1000 V. When tested under reverse current limitation set equal to 300 nA, over 50% out of 24 devices could withstand reverse bias exceeding 800 V. This work reports on the characteristics of one diode of 9.88×10^{-3} cm^2 area, implanted with ^{7}Be and subject to continuous reverse-bias at 750 V for 107 days. Electrical characterization conducted before, during, and after long-term polarization highlighted an increase in the reverse current generation due to implantation-related defects, which however does not affect the breakdown voltage. These considerations lead to the conclusion that the electric field acting on the implanted ^{7}Be remains stable over time, confirming the suitability of 4H-SiC diodes for both induction and measurement of ^{7}Be lifetime variations.

Introduction

This work focuses on a novel application of 4H-SiC diodes, i.e. their use to provide the electric field required to demonstrate the Stark effect in the radioactive decay of ^{7}Be atoms implanted in the depletion region of a p/n junction. Indeed, a precise measurement of the ^{7}Be half-life in 4H-SiC resulted in (53.284 ± 0.016) days at zero bias [1]; this value can vary by applying a high reverse bias resulting in an electric field of the order of 10^6 V/cm [2]. 4H-SiC represents the material of choice to conduct such experiment thanks to its high critical electric field and to its tolerance to ion implantation processes. Electrical characterizations, performed by current-voltage (I-V) and capacitance-voltage (C-V) at different fabrication stages, as well as after a high number of radioactive decay events, allow to demonstrate the suitability of 4H-SiC diodes as environment to host ion implanted ^{7}Be atoms while maintaining their blocking capabilities under prolonged high reverse bias operation. Furthermore, identifying the mechanisms of reverse current conduction enables the assessment of electric field stability and sets the basis for result interpretation.

Experimental

p^+/n diodes were realized starting from a 4H-SiC wafer purchased from II-VI, with a 6 µm thick, 1×10^{16} cm^{-3} n-type doped epitaxial layer and 2 µm buffer layer. The epitaxial layer thickness and doping were determined by Synopsys TCAD Sentaurus simulations to obtain the required electric field in the ^{7}Be implanted region of around 1MV/cm at -750V. Al ion implantation followed by 1950°C 30 min annealing led to the formation of the anode and JTE regions extending 350 nm below the sample surface with 5×10^{19} cm-3 and 1.25×10^{17} cm^{-3} Al concentration respectively. The front side ohmic contact was made by thin Ti, Al, and Ni layers alloyed in vacuum at 1100 °C for 5 min. A first round of characterization by I-V and C-V was performed in the as-made diodes to select the diode exhibiting the lowest current at 900 V reverse bias, but it is not reported in this work. The chosen device had an anode area equal to 9.88×10^{-3} cm^2.
High energy ^{7}Be ion implantation was performed at the Tandem Accelerator Laboratory, DMF, University of Campania. The beam energy during the implantation was modulated to obtain a box-shaped depth profile with 1×10^{16} cm^{-3} ^{7}Be concentration extending between 2.8 µm and 4 µm below the sample surface. A double AZ10XT photoresist layer was used as mask to selectively implant ^{7}Be in the inner region of the diode in a circular area of 960 µm diameter. At 750 V reverse bias the electric field value in the region comprising ^{7}Be is expected to be (1.3±0.2) MV/cm. The diode layout is shown in Fig. 1.

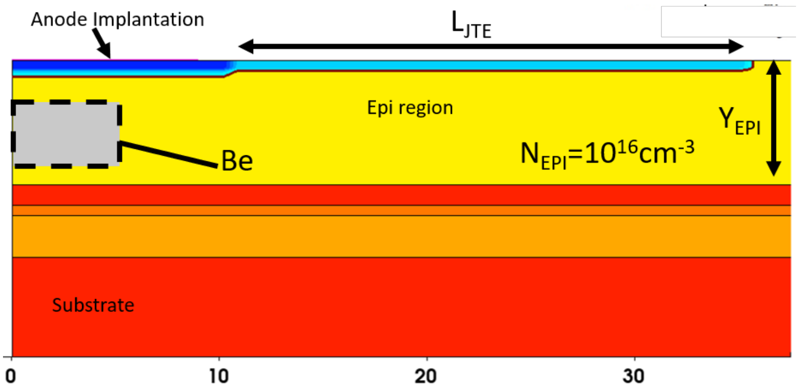
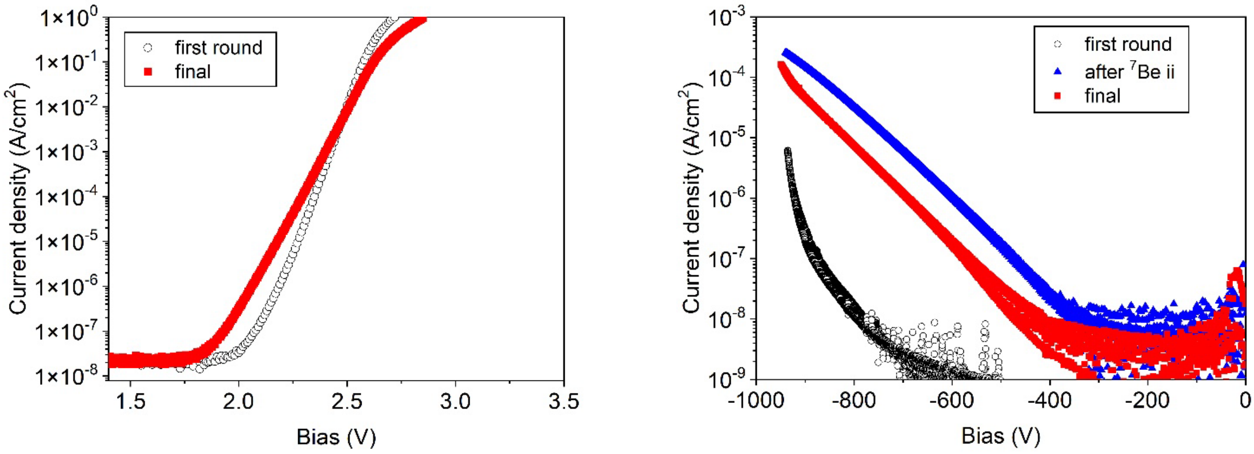


Fig. 1. Layout of the epitaxial layer. The horizontal axis scale is in micron, while the vertical axis is not in scale. The grey area represents the ^{7}Be implanted region.

750 V reverse bias was applied for 107 days at Gran Sasso National Laboratories (LNGS, Italy) on the wire-bonded device to measure the ^{7}Be decay time in a high electric field. The current flowing through the diode was continuously monitored throughout the progress of the experiment. Finally, I-V and C-V curves were acquired after the experiment.

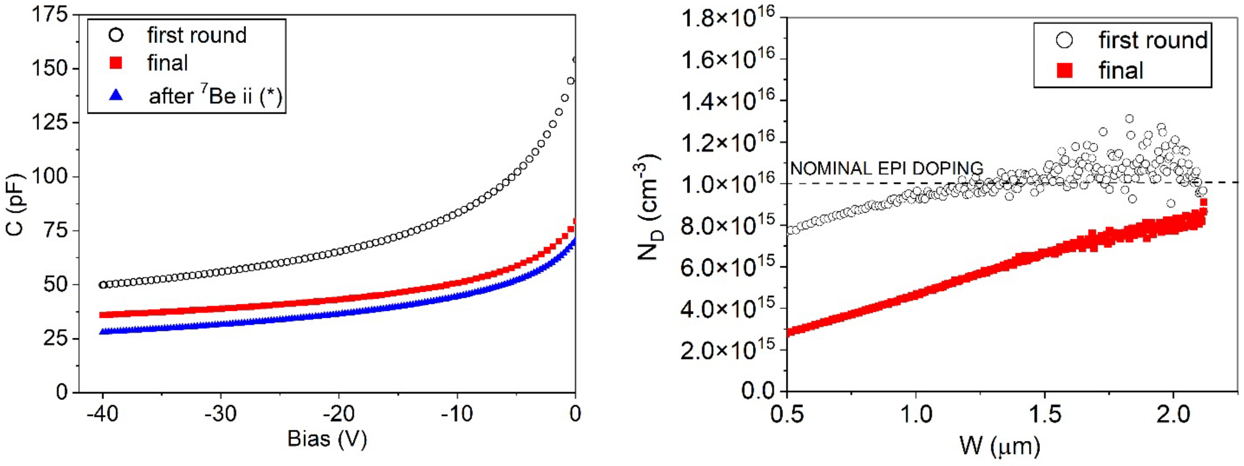
Results and Discussion

The high-voltage I-V curves measured in the as-made diodes (called *first round measurements*) and at the end of the experiment (*final measurements*), i.e. after ^{7}Be ion implantation and 107 days of reverse bias operation, are shown in Figure 2. Figure 3 shows the corresponding C-V curves at 100 kHz (a) together with the N_D vs W plot (b). The final forward I-V characteristics (Fig. 2a) shows a single exponential slope over more than 6 decades even if with an increase of recombination current, while the reverse bias, though experiencing an increase following the ^{7}Be implantation and the long-term reverse bias, maintains its blocking behaviour. After 107 days a current reduction is observed. For 4H-SiC PiN diodes it has been demonstrated that displacement damage caused by irradiation (thus likely also by ion implantation), can induce an increase in carrier recombination due to lifetime-killer defects (affecting forward I-V characteristic), an increase in generation current (causing reverse leakage), the compensation of n-type region due to acceptor centers and a decrease in carrier mobility caused by scattering [3,4]. After Be implantation the observed increase in reverse current can be ascribed to charge generation at centers within the bandgap induced by defects, but a fairly preserved blocking capability.



(a) (b)

Fig. 2. Forward (a) and reverse (b) current flowing in the as-made diodes (first round, black circles) and after ^{7}Be ion implantation and 107-days continuous polarization at -750 V (final, red squares); high voltage reverse current density in as-made diodes, after ^{7}Be ion implantation (blue triangles) and after long-term bias.



(a) (b)

Fig. 3. C-V curves measured (a) in the as-made diodes (first round, black open circles), after ^{7}Be ion implantation (*different device and different implantation sequence, blue triangles), and 107 days continuous polarization at -750 V (final, red squares); calculated doping concentration in the depletion layer width (b).

Fig. 3a shows the C-V curves of the diode under study in the final round (black open circles) and at the final stage of the experiment (red circles), together with the C-V curve of a p+/n diode with the same geometry in the as-implanted stage (blue triangles); the latter underwent a different ^{7}Be ion implantation sequence, achieving a higher ^{7}Be concentration (i.e. 4×10^{16} cm^{-3}), so that the C-V curves of the implanted diodes are not directly comparable. Nevertheless, it is apparent that the capacitance undergoes a decrease after the ^{7}Be ion implantation process. Fig 3b shows the doping profile in the depletion region calculated from the C-V curves. The region probed by the measurement is expected to correspond to a depth comprised between 1.5 µm and 3.5 µm below the sample surface, under the hypothesis of an Al implant tail as long as 1 µm. The first round of measurements yields doping values in the as-grown diodes close to the nominal concentration. The apparent donor profile at the final stage shows a decrease close to the junction, that tends to approach the nominal value while probing deeper inside the space-charge region. It is worth to remark that the quantitative analysis of the C-V curve of the as-implanted diodes was carried out by considering the whole diode area, whereas the ^{7}Be ion implantation is restricted to a selected portion of the diode area. Consequently, the reported concentration has only a qualitative validity. Since the location featuring dopant deactivation is shallower than the ^{7}Be projected range, the observed capacitance decrease is not related either with ion implantation damage induced by nuclear scattering at the ^{7}Be projected range, nor to compensation by ^{7}Be. More likely, it can be attributed to the deactivation occurring close to the junction, where the Al implant tail results in lighter net doping. In this region, even a small amount of irradiation defects can induce a non-negligible capacitance decrease. Indeed, this phenomenon was observed in particle- [5, 6] and light-ion [7] irradiated 4H-SiC detectors.

These considerations show that the actual electric field acting on ^{7}Be remains stable and close to its expected value, as i) the capacitance variation occurs after ^{7}Be ion implantation; ii) the calculated epitaxial layer doping levels in the ^{7}Be region do not show any dramatic change between the first round of measurements and the final stage.

Conclusion

We reported the design, fabrication, and electrical characterization of 4H-SiC p+/n diodes suitable to provide a high electric field that can induce Stark effect in ^{7}Be atoms implanted in the space charge region. One diode with the best rectifying behaviour at 900 V reverse bias was chosen for the final experiment. I-V measurements showed a single slope forward current with low recombination and a low reverse leakage with a principle of breakdown at 900 V with a current of 3 nA. Such behaviour ensured the possibility of polarizing the device at 750 V thus achieving an electric field of about (1.3±0.2) MV/cm in the region were ^{7}Be will be implanted. After ^{7}Be ion-implantation and a continuous reverse bias at 750 V for 107 days, the repeated I-V and C-V measurements showed that the electrical properties of the device weren't changed substantially. A slight increase in carrier recombination was seen under forward bias, while under reverse bias we observed a higher generation current due to defects left by ^{7}Be ion-implantation. The breakdown voltage didn't visibly lower and since C-V measurements demonstrated a drop in the doping concentration close to the junction but reducing while entering deeper in the space-charge region, it can be affirmed that the actual electric field acting on ^{7}Be remains close to its expected value. This proofs the suitability of 4H-SiC diodes as host material to probe the Stark effect possibly affecting ^{7}Be.

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