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## **Design, fabrication and characterisation of 5 kV 4H-SiC p<sup>+</sup>n planar bipolar diodes protected by junction termination extension.**

C. Raynaud, M. Lazar, D. Planson, J.-P. Chante, Z. Sassi.

Centre de Génie Electrique de Lyon (CEGELY) INSA-Lyon, UMR 5005 CNRS, Bat. Léonard de Vinci, 20 av. Albert Einstein, F-69621 Villeurbanne, France

Tel.: (+33) 4 72 43 83 77, Fax: (+33) 4 72 43 85 30, raynaud@cegely.insa-lyon.fr

High voltage 4H-SiC bipolar diodes have been realised using a 40  $\mu\text{m}$  thick n-type epilayer, with a doping level at  $1.1 \times 10^{15} \text{ cm}^{-3}$ . These diodes have been designed with only one Junction Termination Extension as edge termination, whereas previous high voltage diodes described in literature are protected either by mesa either by a combination of JTE and mesa. JTE are optimised using numerical computations, and are realised by a multiple aluminium implantation followed by an thermal annealing. Ohmic contacts are Ti/Al on p-type and Ni on n-type. Theoretical breakdown voltage is then calculated using realistic doping profile of aluminium in the JTE and in the emitter and is equal to 5.8 kV. The surface of the diodes is not passivated.

Current voltage measurements show best  $V_{\text{br}}$  at 4.8 kV when testing in Galden®. After cutting the wafer into pieces ( $\sim 5 \times 5 \text{ mm}^2$ ),  $V_{\text{br}}$  seems to be reduced : best values are 3.7 kV, and are in the same range both in Galden® and in SF<sub>6</sub>. In air,  $V_{\text{br}}$  is always  $< 1.3 \text{ kV}$ . This shows the efficiency of the JTE. In forward bias, the current density is found in the range of  $100 \text{ Acm}^{-2}$  at 5 V, but decreases rapidly when duration of bias increases.

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Up to now, high voltage bipolar diodes have been realised with breakdown voltage as high as 19 kV [1]. In most of the cases, the edge termination is realised by a mesa structure or a combination of mesa and JTE (Junction Termination Extension). We have designed and realised 4H-SiC bipolar diodes in order to block up to 5 kV, with only one JTE as edge termination.

We have used for this purpose an n-type epitaxial layer of 40  $\mu\text{m}$  and doped at  $1.1 \times 10^{15} \text{ cm}^{-3}$ .

By numerical computations, geometrical and physical characteristics of the p<sup>+</sup> emitter and the p-type JTE (e.g. length, depth and doping level of the JTE...) have been optimised for the highest breakdown voltage  $V_{\text{br}}$ . This is obtained when the electric field reaches two maximum both at the emitter edge and at the JTE edge (Fig.1). Figure 2 shows that the maximum  $V_{\text{br}}$  is obtained for a short range of doses. Variations of  $V_{\text{br}}$  are faster above the optimum dose value than below. Experimentally we have chosen a dose of  $10^{13} \text{ cm}^{-2}$ , because of the smaller variations. Indeed an error made on the dose should less reduce  $V_{\text{br}}$  than for a higher dose.

Emitter and JTE were realised by a multiple Aluminium implantations followed by a thermal annealing in order to achieve box profiles. Profiles were then verified by SIMS (Secondary Ion Mass Spectrometry) measurements. Then theoretical  $V_{\text{br}}$  (5.8 kV) were calculated with the realistic profiles, and using ionisation coefficient of Konstantinov [2]. Metallisation were realised with Al/Ti on p<sup>+</sup> for the front side and Ni on n<sup>+</sup> for the back side [5]. The surface of the devices was not passivated. Several kinds of diodes are available, with and without JTE, and different emitter areas.

Current-voltage (I-V) measurements have been carried out using a Keithley K2410 sourcemeter for forward bias. For reverse measurements, a 12.5 kV FUG power supply and a K485 picoammeter have been used. Diodes have been tested in different ambients (air, Galden® and SF<sub>6</sub>).

In reverse direction, the highest  $V_{\text{br}}$  is 4.8 kV. This value has been obtained, in Galden®, and before cutting the wafers in dies. We consider the breakdown when arcing occurs at the surface of the diodes. Figure 3 shows reverse characteristics of the diodes for different testing ambients. For diodes protected by JTE, the breakdown voltages in SF<sub>6</sub> or in Galden® are in the same range: most of the diodes shows  $V_{\text{br}}$  ranging from 3.1 to 3.7 kV, but in air,  $V_{\text{br}}$  is always < 1.3 kV. This problem can probably be solved with a passivation layer. After cutting the wafers into small pieces ( $\sim 5 \times 5 \text{ mm}^2$ ),  $V_{\text{br}}$  seems to be seriously reduced, down to 3.7 kV. For diodes without JTE, the best  $V_{\text{br}}$  is 1.3 kV. This shows the efficiency of the JTE realised by Al implantation.

Under forward bias, current densities of  $\sim 100 \text{ A cm}^{-2}$  at 5 V were measured. But the current decreases rapidly in time (e.g. from 67 to 30 mA in 30 s). Current decreasing vs. time curves will be shown and discussed in the full article.

### ***Acknowledgements***

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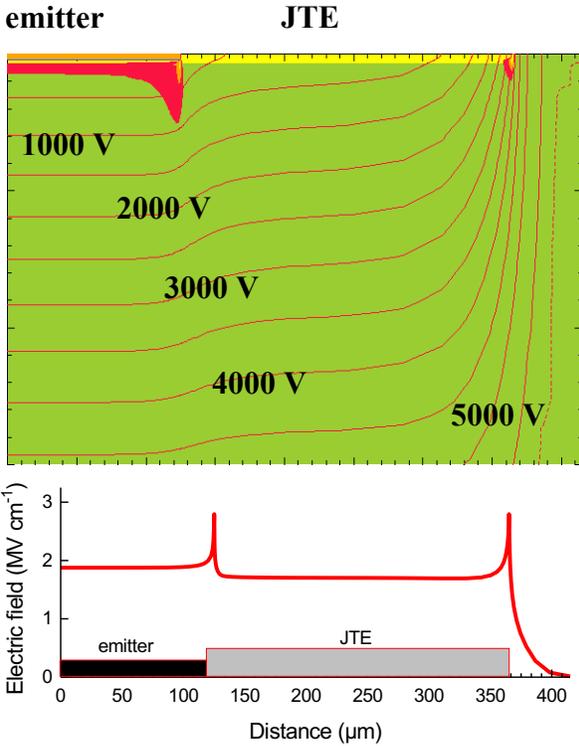


Fig. 1 : Cross sectional view of the equipotential lines in the half cell of the high voltage bipolar diodes protected by JTE. Maximum electric field in the structure vs. the distance from the center of the emitter to the edge of the diode.

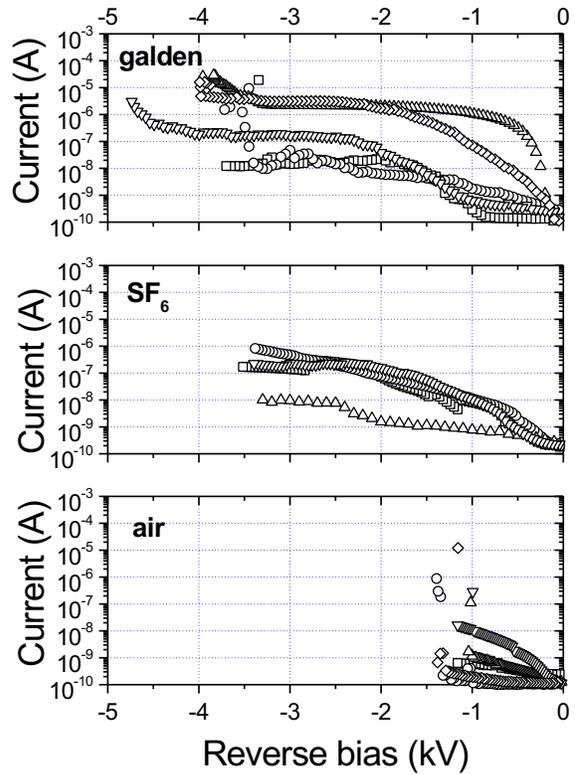
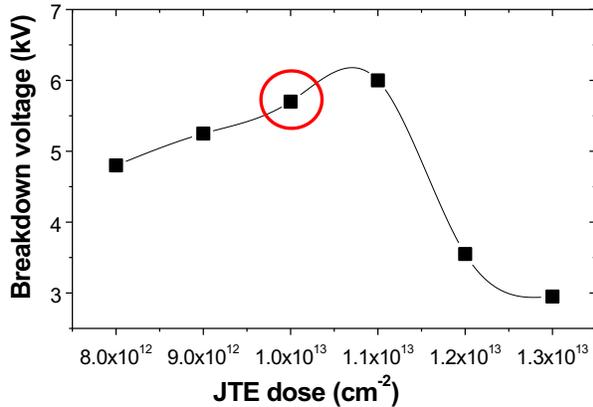


Fig. 3 : Experimental current-voltage reverse characteristics of bipolar diodes in three different ambients (air, SF<sub>6</sub>, and galden).

Fig. 2 : Simulated breakdown voltage of bipolar diodes as a function of the dose of Al implanted in the JTE, using a realistic implanted profile. Encircle square indicates the value we have used.

**References should be listed as below**

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