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► **To cite this version:**

Karine Isoird, Mihai Lazar, Laurent Ottaviani, Marie-Laure Locatelli, Christophe Raynaud, et al.. Study of 6H-SiC high voltage bipolar diodes under reverse biases. Applied Surface Science, 2001, 184 (1-4), pp.477-482. 10.1016/S0169-4332(01)00537-2 . hal-00140118

HAL Id: hal-00140118

<https://hal.science/hal-00140118>

Submitted on 1 Sep 2019

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STUDY OF 6H-SiC HIGH VOLTAGE BIPOLAR DIODES UNDER REVERSE BIASES

K. Isoird, M. Lazar, L. Ottaviani, M.L. Locatelli, C. Raynaud,
D. Planson, J.P. Chante

CEGELY (UMR n°5005), INSA de Lyon, 20 Av. A. Einstein,
F-69621 Villeurbanne cedex, France

Abstract

Silicon carbide presents electrical properties suitable for many applications especially for high voltage devices. 6H-SiC P⁺NN⁺ structures have been fabricated following ISE software simulation in order to block voltages as high as 1.5 kV. In particular, these diodes are realized by surrounding

the emitter by a p-type region called JTE (Junction Termination Extension). Electrical characterizations under reverse bias at room temperature and in various environments (air, silicone oil) show a premature breakdown of the diodes. This breakdown is localized at the emitter periphery. OBIC (Optical Beam Induced Current) measurements show a peak of photocurrent at the junction end, indicating the presence of a high electric field. These results show an effectiveness of 60 % of the JTE. This is probably related to a bad electrical activation of the implanted aluminum during the post-implantation annealing.

Keywords: 6H-SiC, Bipolar diodes, Breakdown voltage, OBIC, JTE.

1. Introduction

Silicon carbide presents interesting electrical properties for many applications and especially for the high voltage devices. To benefit the advantages of SiC and avoid any premature breakdown of the high voltage diodes, it is necessary to realize efficient junction termination. The object of this work is to estimate the JTE influence on the electrical behavior of the 6H-SiC P⁺NN⁺ diodes under reverse biases. In this paper we present current-voltage characteristics (I-V) measured in different ambient (air, silicone oil). These results are completed by OBIC (Optical Beam Induced Current) measurements. This technique allows to investigate the electric field distribution in the structure and especially at the junction periphery.

2. Experiments

2.1. Devices structure.

The P⁺NN⁺ diode is formed by multiple aluminum implantation at 300 °C on 6H-SiC n-type epilayer (thickness = 10 μm, doping level = 6×10¹⁵ cm⁻³). The JTE (Junction Termination Extension) is created by five successive aluminum implantation at 300 °C. Some parameters of the junction termination (depth = 0.5 μm, doping level = 1×10¹⁷ cm⁻³, length ≥ 50 μm) are determined by ISE software simulation (the ionization coefficients used are those given by Konstantinov et al. [1]) in order to obtain blocking voltage up to 1,7 kV. The samples were annealed at 1700 °C during 30 minutes [2], and metallized for anode and cathode ohmic contacting at the end. During contact annealing the metallization overflowed and covered the entire emitter region and a few microns of the JTE length. Two types of diodes are tested: D1 diodes with JTE non covered by metallization and D2 diodes with 30 μm of JTE length cover by anode contact (Fig. 1). A part of tested diodes underwent a RIE etching of 30 nm, thus decreasing the implanted dose of the JTE (Implanted dose = 6.4×10¹² cm⁻²). We will name those diodes D1E and D2E.

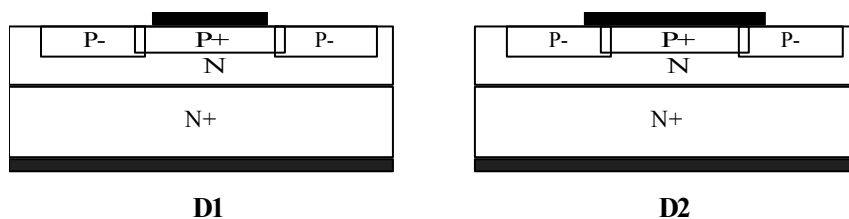


Fig. 1: P⁺NN⁺ diodes.

2.2. OBIC method and setup.

The OBIC technique is often used to study electric field distribution in diodes structures [3]-[6]. It consists in measuring the variations of the current induced by a light beam focused in the surface of a device under reverse biases. If the energy of photons is larger than the band gap material electron-hole pair are generated in the sample. When those carriers are generated in a space charge region (SCR) they are separated and speeded up by the electric field and then collected at contact where a current is detected. Fig. 2 shows experimental setup used to measure the variations of OBIC signal according to the spotlight position.

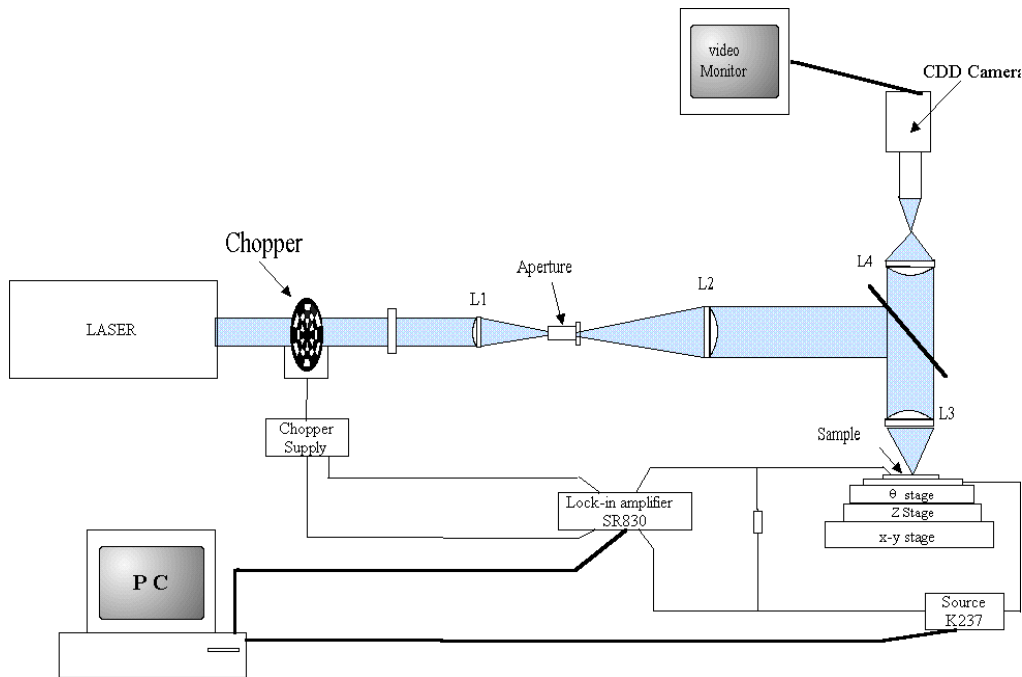


Fig. 2: OBIC experimental setup.

Because of SiC large band gap the sample is illuminated by UV beam produced by an Ar^{++} laser ($300 \text{ nm} < \lambda < 363,8 \text{ nm}$). This beam is focused at the device surface by several lenses and

modulated at $f = 70$ Hz by a mechanical chopper. The $3.3 \mu\text{m}$ incident spotlight induces a local variation of current onto a diode, which is detected by a lock in amplifier (SR 830). A computer ensures the horizontal moving of the sample by controlling two stepper motors and records the signal measured as a function of the spotlight position.

3. Results.

3.1. Electric characterizations.

The I-V characteristics and test of breakdown voltages were realized under DC conditions at room temperature in different ambient (air and silicon oil). The demonstrations of the breakdown were observed by means of a CCD camera and a video monitor.

The forward I-V characteristics present a good rectifying properties. Fig. 3a shows reverse I-V curves measured in air at 300 K. These curves present two distinct zones. In the first part ($V_R < 500$ V), the current increases as $V_R^{1/2}$, which corresponds to the generation/recombination of minority carriers in the space charge region. For $V_R \geq 500$ V, the current rises quickly until breakdown ($800 \text{ V} < V_{BR} < 1000 \text{ V}$). When the breakdown appears, electric arcs between the emitter edge and the anode contacting probe are observed. That illustrates a localized breakdown of the diode, induced by a high electric field at the P+N junction periphery. The electrical behavior observed during the tests in oil is almost identical. We find both zones of growth of the current and the breakdown occurs for the same range of voltage (Fig. 3b). We can note that the diodes, which are etched (D1E & D2E), present the same electrical characteristics in air and in oil. The breakdown voltage measured for D1E and D2E diodes is about 900 V. This value is not very different than this obtain

for not etched diodes. These results indicate that ambient and implanted dose of JTE have a poor influence on the premature breakdown of diodes. The experimental breakdown value is lower than that obtained by ISE simulation, which can be explained by too low doped JTE regions.

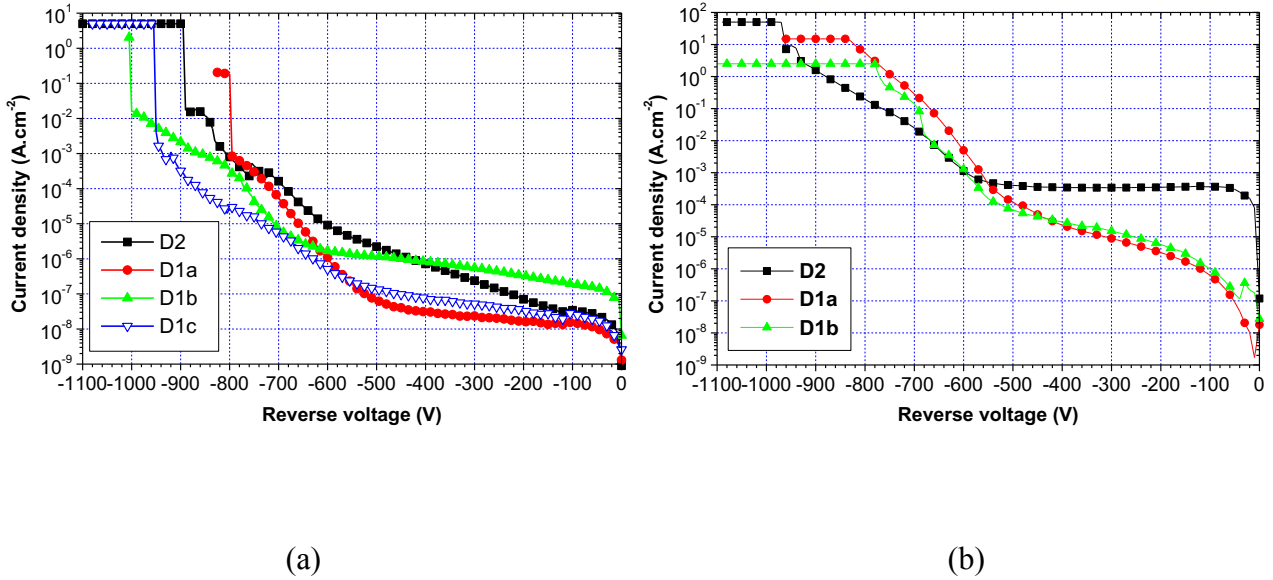


Fig. 3: Reverse characteristics of bipolar diodes D1 and D2 at room temperature on different ambient: (a) air, (b) silicon oil.

3.2. OBIC measurements.

Fig. 4 shows OBIC signal measured on D1 diodes along a diameter line at 351.1 nm corresponding to a light penetration length of 10 μm in 6H-SiC [7], with a spot diameter of 3.3 μm and optic power density of 1 W/cm^2 .

On Fig. 4a for $V_r < 400$ V, we observe rather a constant signal when a spot scans the JTE region (130-220 μm and 400-490 μm), which increases with the voltage due to the space charge region spreading. In the anode region (220-400 μm) we detect a photocurrent, which means that the metallization is partially transparent. When $V_r = 500$ V, a peak of photocurrent occurs at the JTE edge (490 μm) that indicates an equipotential line tightening. Note that the curves are not

symmetrical, which can be due on one hand to a slight misalignment of the JTE mask, and on the other hand to the overflow of anode metal which induces a different electric field distribution.

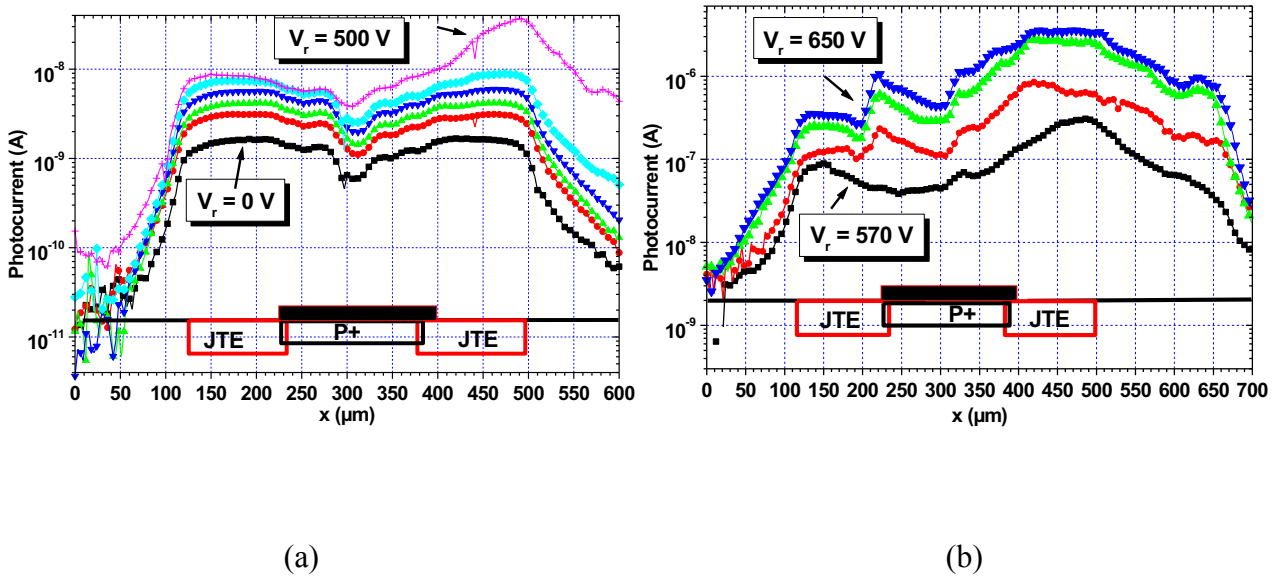


Fig. 4: OBIC measurement performed on D1 diode at $\lambda = 351.1 \text{ nm}$ with $P_{\text{opt}} = 1 \text{ W/cm}^2$ (semi-logarithmic scale), for different range of reverse voltage: (a) from 0 V to 500 V, (b) from 570 V to 650 V.

The curves obtained for higher voltages are presented on the Fig. 4b. At $V_r = 570 \text{ V}$ we notice a strong signal at the periphery of the two JTE, but the junction terminations are not yet totally depleted. However, one should detect a peak of photocurrent at the emitter edge revealing the increase of the electric field at its end. A part of the UV beam is absorbed by the metal extension. So detected current is thus weaker and these variations in the anode region (220-400 μm) do not indicate the real electric field distribution at this place of the structure. When the bias reaches 600 V, a peak of photocurrent emerges at the metal periphery (230 μm) and the peak at the JTE end disappears. This means that the electric field becomes more important at the edge of the contact than at the JTE periphery. These results are coherent with a full depletion of the protections.

We describe now the OBIC measurements obtained from D2 diode on Fig. 5. First we recognize the same OBIC signal due to JTE region (110–190 μm and 390–490 μm) as for D1. A peak of OBIC signal emerges at one side of the metal (390 μm) when the bias reaches 400 V. Above 500 V, the photocurrent increases on both side of the metal contact. The JTE of the diodes D2 are covered by metal over a length of 30 μm . It is thus logical to detect a strong electric field at the anode periphery for weaker reverse bias than in the D1 diode.

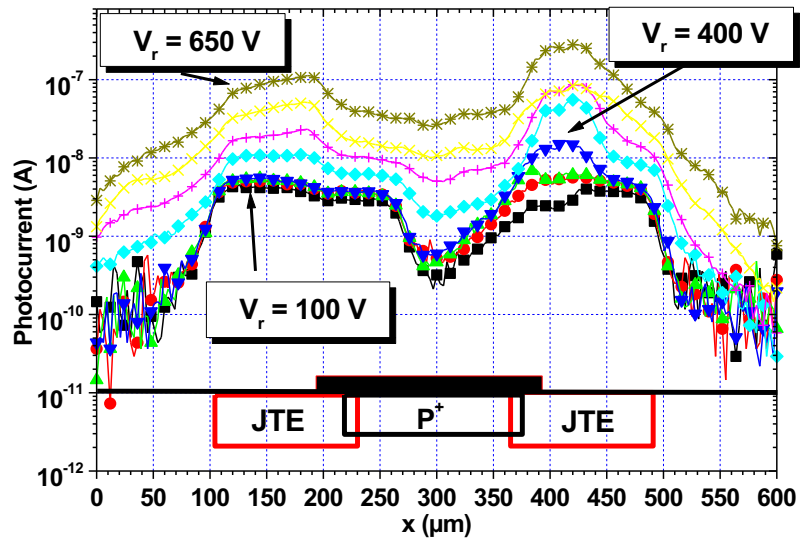


Fig. 5: OBIC measurement performed on D2 diode at $\lambda = 351.1$ nm with $P_{\text{opt}} = 1$ W/cm² (semi-logarithmic scale), from 100 V to 650 V.

4. Discussion.

The electrical tests have shown that the breakdown voltage of devices is lower than the theoretical value (1720 V) and that the ambient conditions do not have any influence. Results obtained with OBIC method tend to confirm a certain inefficiency of protections, in particular by showing an

early depletion of the JTE. Although the total chemical dose implanted of not etched diode ($1 \times 10^{13} \text{ cm}^{-2}$, as verified by SIMS analysis) to form the JTE is in good agreement with the acceptor dose determined by simulation, it clearly appears that this dose is not high enough to ensure a maximum protection. As we said previously certain diodes were etched. Therefore the acceptor dose of the JTE is $6.4 \times 10^{12} \text{ cm}^{-2}$. The breakdown value measured for etched diode (D1E & D2E) is weaker different than this obtain for non etched diode. These results mean that the acceptor dose has weak influence on breakdown voltage. The Fig. 6 shows the variation of V_{BR} versus the acceptor dose of JTE. So we see in this curve that to obtain a breakdown voltage of about 1000 V, the necessary dose for the JTE is $2\text{-}3 \times 10^{12} \text{ cm}^{-2}$, which corresponds approximately to a rate of electrical activation of the aluminum of 30 %. However uncertainties on the parameters values used in the simulator such as the ionization coefficients or the doping and the thickness of the epilayer can involve errors on the obtained results. We have evaluated this errors to be in the 10 % range. So we can say that the electric activation is located in the range [20 % - 40 %] and that it is much lower than that desired.

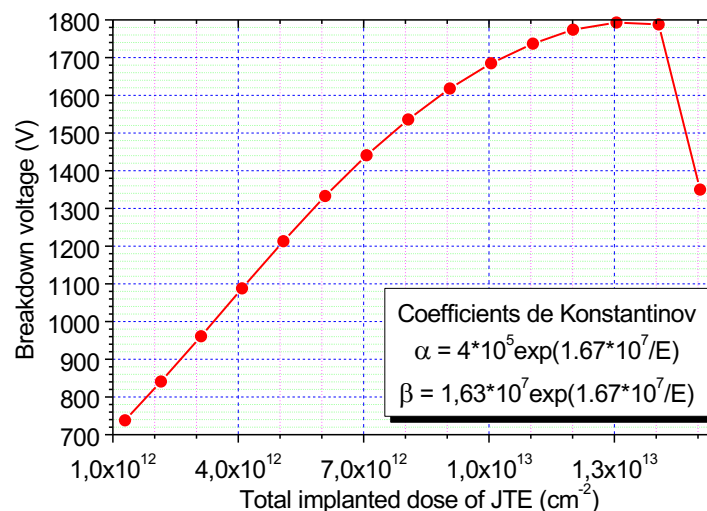


Fig. 6: Variations of the breakdown voltage versus acceptor dose of JTE obtain by ISE simulation

5. Conclusion.

The OBIC measurements performed on our planar SiC-6H bipolar diodes have indicated the JTE influence on electric field distribution and the place of breakdown. These results correlated with the electrical characterizations in different ambient tend to prove that the premature breakdown of our structures is due to a low rate of aluminum electrical activation.

Acknowledgements.

This work was supported by GIRCEP group and Schneider Electric Research Center. We are also grateful to R. Nipoti from LAMEL Bologne for the realization of the ohmic contacts.

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