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Abstract—Wide band gap semiconductors are more and more used, especially to design high voltage devices. However, some devices show lower breakdown voltages than those predicted in theory. These early breakdown are in general due to imperfections in the peripheral protections of the active junction. The aim of these protections is to reduce electric field peaks at the periphery of the junction. Thus, it is important to study the electric field distribution on the device periphery to detect any protection weakness. This paper presents a 2D electric field imagery using OBIC (Optical Beam Induced Current) technique. 2D cartographies are realized on JTE (Junction Termination Extension) protected diodes in order to display electric field on diode peripheries. Other measurements are also performed on circular avalanche diodes protected with a MESA etching and provided with optical window. In both cases, OBIC techniques is demonstrated to be an efficient method to obtain electric field distribution within the device and to locate defects.

Keywords—4H-SiC, Device characterization, Electric field, OBIC, Bi-photonic absorption.

1. Introduction

Wide bandgap semiconductors (WBG) such as 4H-SiC are studied to design power electronic devices. Due to their high critical electric field, power devices realized with WBG semiconductors present higher breakdown voltages than those designed using traditional silicon [1]. Their high thermal conductivity allows them to be used in the high temperature domain [2]-[3]. WBG power devices are also efficient when turning under high frequencies [4]. However, local breakdown was observed for voltages much lower than theoretical breakdown voltage. This means that more studies are also essential to increase the voltage rating of electronic devices. To realize these studies, some methods like OBIC (Optical Beam Induced Current) use an optical beam to generate charge carriers in the device [5]. OBIC is used to determine minority carriers lifetime [6]. Impact ionization coefficients are also extracted using OBIC method [7]. An image of the distribution of electric field in the power devices is also delivered using OBIC method. It consists to generate free charge carriers by illuminating the semiconductor by a laser beam with an appropriate wavelength. Nowadays, the majority of published papers bring out the mono-photonic absorption where photon energy E_{φ} is higher than the bandgap E_G of the studied semiconductor. M. Goepert-Mayer was the first to theoretically demonstrate the principle of bi-photonic absorption in 1931 [8]. Later, bi-photonic OBIC was operating to analyze integrated circuit failures [9]. Recently, OBIC measurements were used to show bi-photonic absorption in 4H-SiC [10].

In this paper, 2D OBIC measurements are realized to obtain an image of electric field distribution in the diode. This method helps the detection of structural defects. In fact, a defect is manifested by a change of material characteristic and then, a local variation of electric field. A local breakdown may take place around the defect center. OBIC technique allows studying the efficiency of the junction peripheral protections. Two protection architectures are studied: Junction Termination Extension (JTE) protection and MESA protection.

2. OBIC principle

The $P^+/N/N^+$ junction shown in Figure 1 is used to explain photonic generation of carriers. Once, the junction is reverse biased, space charge region SCR will extend mainly in the low doped region which is N-region. When a laser beam illuminates perpendicularly the junction, electron-hole pairs (EHPs) are generated by photon absorption. The EHPs generated inside the SCR are submitted to a high electric field, therefore they acquire kinetic energy, and they will accelerate to reach the edges of the SCR. An optical beam induced current OBIC is measured. The EHPs generated outside the SCR, where electric field is negligible, will recombine and any effect cannot be observed. If the distance between generated EHP and the edge of the SCR is lower than the diffusion length, a free charge carrier may reach the SCR and may lead to an OBIC signal.

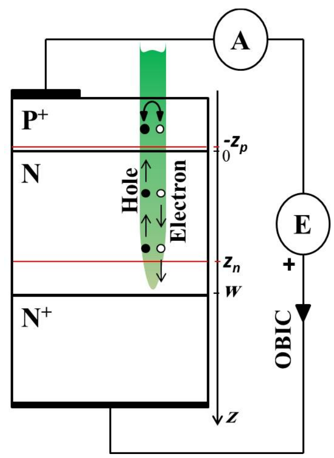

Figure 1: Schematic of OBIC principle for a plane-parallel infinite PN-junction.

Under high reverse voltages, the electric field in the SCR increases significantly, and it approaches the critical electric field of the semiconductor. Kinetic energy of charge carriers becomes very high and it may result another charge carriers by collision. The avalanche is defined as the sequence of free charge generation by collision. OBIC current is correlated to the electric field: OBIC technique gives an image of the electric field in the device.

Since the method consists of using an optical beam, the photon energy E_Φ (or wavelength) is a critical parameter. Photon generation is based on mono-photonic absorption: E_Φ is higher than the semiconductor bandgap E_G, one photon is able to generate an EHP. Single absorption coefficient α is related to the incident light intensity I transmitted through a layer of material as shown in equation 1. For low photon energies ($E_\Phi << E_G$), one photon absorption becomes impossible and two-photon absorption takes place. In this case, two photon absorption coefficient β is defined in equation 2 (z is the semiconductor depth).

$$\frac{dI}{dz} = -\alpha I \quad \text{Equation 1}$$

$$\frac{dI}{dz} = -\beta I^2 \quad \text{Equation 2}$$

In this paper, the distribution of the electric field in the volume of the diode is studied using OBIC method based on two photon absorption. Since the absorption depends on the square of the beam intensity, the latest must be enough high. This happens near the focus only: photon absorption is negligible elsewhere. So, two-photon absorption offers a better spatial resolution compared to single photon absorption and it occurs only at one particular depth. Note that we do not take into account the possibility of absorption via a deep level in the bandgap. In fact, as deep levels are typically in concentration of several decades lower than the doping level, we neglect the carrier generation via deep levels.

3. Experimental setup

A pulsed green laser (532 nm) is applied on 4H-SiC bipolar diodes. The repetition frequency is 20 kHz and the pulse duration is about 1 ns. The incident mean power is adjustable, and it can reach 100 mW (energy of 5 µJ per pulse). Two semi-reflecting mirrors are used to "guide" the laser beam toward a focusing lens. The outgoing beam is vertical and it reaches the device under test (DUT) that is located in the focus of the lens. The positions of mirrors and the lens are adjustable allowing the control of the coordinates of the focus. Optical bench is governed automatically via LABVIEW by controlling 3 translation motors. The minimum motor step is 1 µm. Laser beam scans the DUT which is reverse biased using the Source Measurement Unit (SMU) Keithley 237. The maximum voltage supplied by the SMU is 1100 V and the minimum measured current is about 10 fA. Electrical contact on the front side (anode) is made with a thin tip. On the backside, the sample is glued on a conductive support. Figure 2 shows a schematic of the OBIC bench. It is important to note that focusing the beam systematically lead to the diode destruction if the beam illuminates the metal. This destruction means that the diode does not block any current in reverse state. So measurements have been performed with a defocused beam to avoid destruction of the test diodes. We used a divergent beam with a diameter of about 15 µm on the substrate.

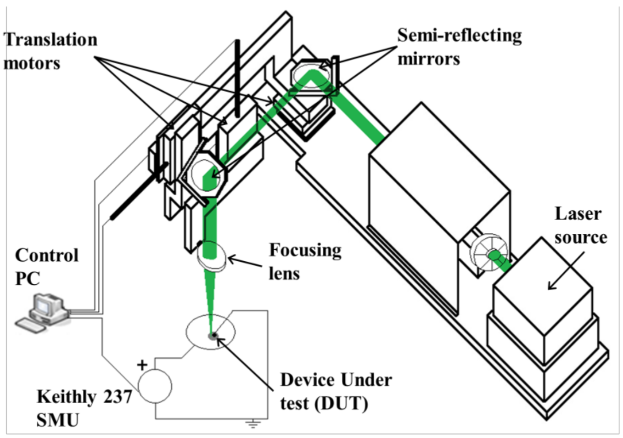

Figure 2: Schematic of experimental OBIC bench.

Studied samples are bipolar diodes protected with two protection types. First samples are circular avalanche diodes protected with a MESA etching. They have been produced by the Research Institute of Saint-Louis (ISL) and their breakdown voltage is 59 V. These diodes have been fabricated in the aim to be Zener diodes, with a constant breakdown voltage in a wide range of temperature. In fact, analyses of their breakdown voltage have shown that the breakdown mechanism is a mix of Zener and avalanche mechanism [11]. So they are called avalanche diodes. An optical window has been performed on the diodes using SIMS technique [12] in order to allow the laser beam to penetrate through the semiconductor (Figure 3a). Second samples are $P^+/N/N^+$ square diodes. Low doped N region is realized with a 7 µm thick epitaxial layer. P^+ (10^{19} cm^{-3}) region is realized by ionic implantation with a depth of 0.5 µm. Peripheral protection is realized with a 200 µm length JTE P layer (10^{17} cm^{-3}). Active area of the diode is of 500×500 $µm^2$ and its breakdown voltage is about 800V (Figure 3b).

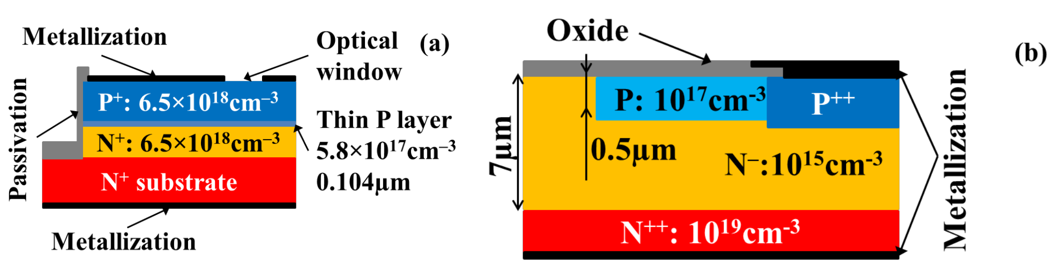

Figure 3: Partial cross sectional view of DUTs, (a) Avalanche diode, (b) P+/N/N+ diode.

4. OBIC simulations

Finite element simulations are performed using SENTAURUS TCAD: an optical beam scans the surface of a reverse biased JTE protected diode (shown in Figure 4) and OBIC current is simulated as a function of the beam position for several voltage values. In this simulation, JTE layer is not optimized allowing electric field peaks especially on the recovery region between emitter and JTE. This anomaly is brought out by a non-homogenous OBIC when illuminating different points on the JTE. The beam parameters like wavelength, power density, beam orientation and dimensions are adjusted to be in conditions close to the experimental ones [13].

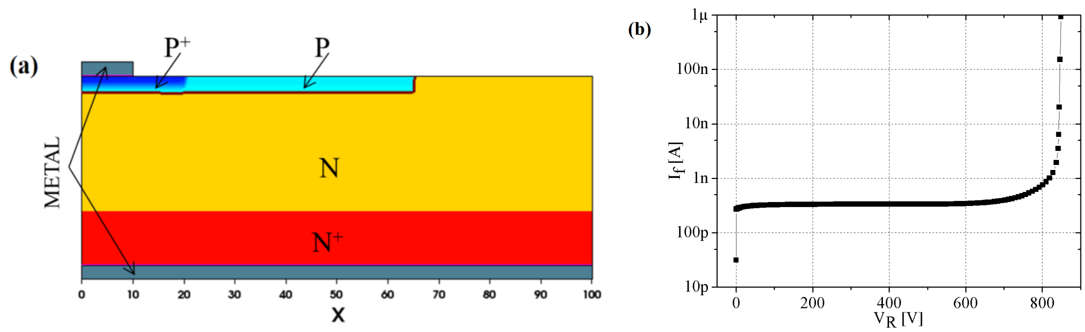

Figure 4: Structure (a) and leakage current (b) of simulated diode.

Figure 5 shows the variations of simulated OBIC as a function of the beam position for a reverse bias varying between 0 and 800 V. Simulations show a high OBIC when the beam illuminates the JTE and the recovery region, it is null when the beam is on the metallization (reflecting area) and outside the JTE where the electric field is negligible. For low voltages ($V_R < 600$ V), OBIC signal does not change significantly and it increases highly for reverse voltages near the breakdown voltage.

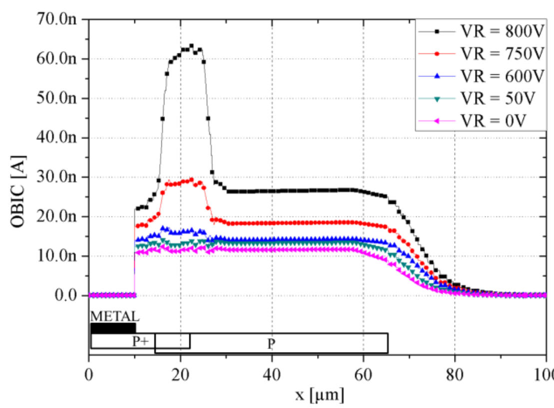

Figure 5: OBIC simulation as a function of beam position for several reverse voltages (0, 50, 600, 750 and 800 V).

5. Experimental Results

Figure 6 displays top view of the avalanche diode and $P^+/N/N^+$ diode. The time needed to realize a full 2D OBIC cartography for a fixed voltage is about 15 hours meaning that the time needed to perform all measurements for different voltages can reach 150 hours (with a reverse biased diode). The exposure of a device under high voltage for a long time may age it and results cannot be reproducible. The adopted solution is to study a part of each device. For avalanche diode, the optical window, and a part of the MESA etching are studied. OBIC measurements are performed on a corner of the $P^+/N/N^+$ diode to show the efficiency of the JTE layer and the performance of the curve radius (Figure 6).

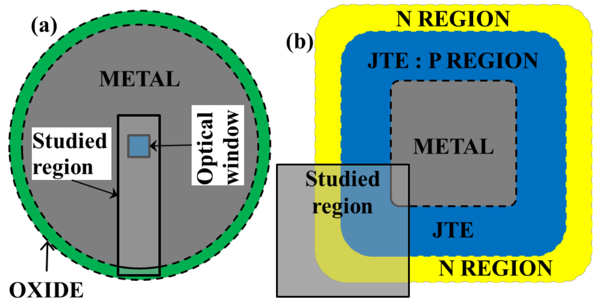

Figure 6: Top view of DUTs with studied regions. (a) Avalanche diode, (b) $P^+/N/N^+$ diode.

Results of 2D OBIC cartographies on avalanche diode are shown in Figure 7. A high OBIC is measured when illuminating the optical window. An OBIC signal is also measured on a thin ring around the metallization. OBIC current is null elsewhere. A small OBIC current is measured along a straight line on the metallization; it is due to a scratch obtained with a non-enough defocused laser. For all measurements, OBIC is higher on the optical window than the ring of the diode. This means that electric field is higher at the center than the extremity of the diode meaning that the MESA protection is effective and the breakdown (when it takes place) will be a bulk breakdown voltage. From the figure, OBIC in the optical window is almost constant for low voltages (V_R < 40 V). However, it increases significantly at 50 and 55 V; this result is consistent with the simulation shown in figure 5. For high electric field, the generation of an EHP causes other generated EHPs in a chain reaction of collisions and then an increase of OBIC current.

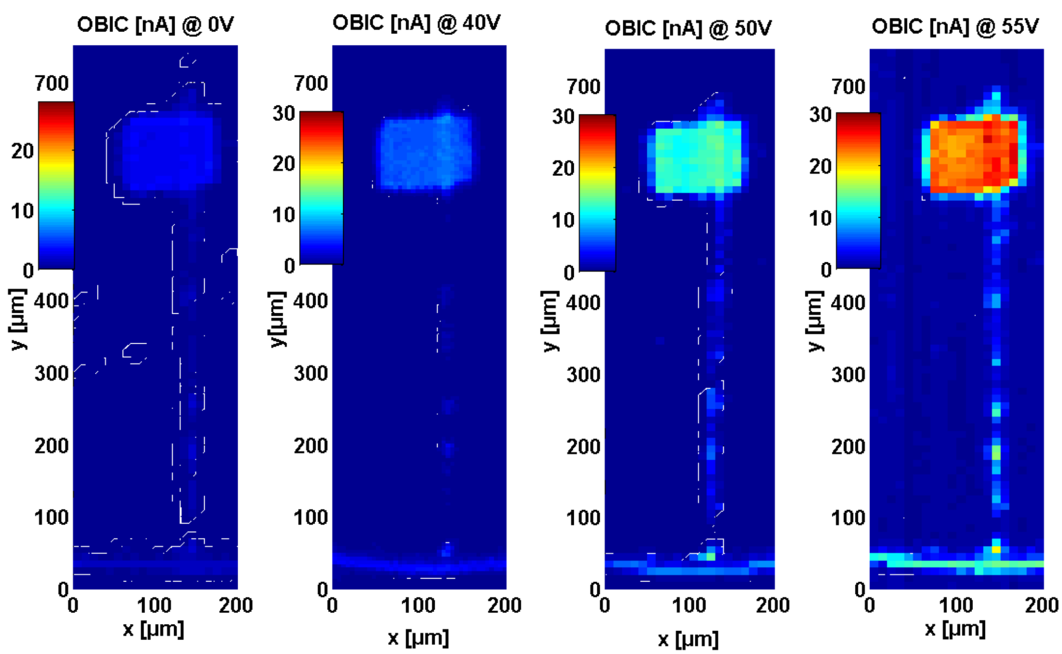

Figure 7: 2D OBIC cartographies of avalanche diodes for several reverse voltages (0, 40, 50, 55 V; step displacement in both directions x and y is fixed 10 µm).

Figure 8 shows OBIC cartographies on a $P^+/N/N^+$ diode. At 0 V, the decreasing OBIC signal when the laser crosses outside the diode indicates that the SCR does not extend over the entire JTE. For voltage between 50 and 700 V, OBIC current is homogenous when illuminating the JTE and it is null elsewhere. This result means that electric field is almost uniform in the JTE below JTE layer, and then the JTE characteristics (length, dose and radius at the curvature) are well adapted to insure peripheral protection of the diode. For this voltage range, OBIC stays almost constant when reverse voltage change. For higher reverse voltage, OBIC current is almost constant on the JTE but it increases strongly on the limit JTE/METAL, this behavior change means that electric field is higher at this point and multiplication takes place. This action appears clearly at 800 V, where OBIC signal becomes very high (~ 10 µA) around the metallization. The limit of the operating voltage of the diode is reached.

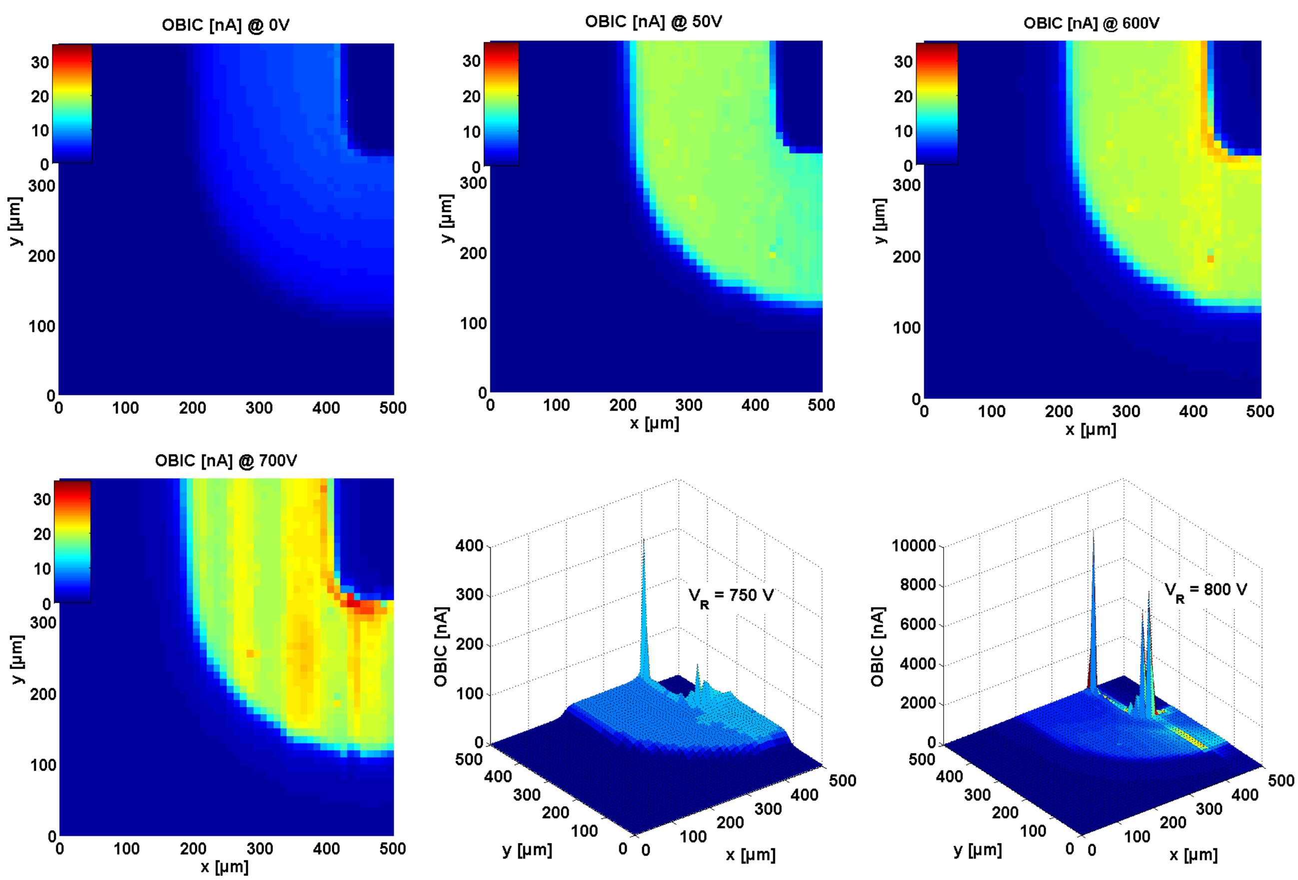

Figure 8: OBIC cartographies on $P^+/N/N^+$ diodes for several reverse voltages. At 750 and 800 V, 2D representation is replaced by a 3D representation in order to better visualize the peak of currents (step displacement in both directions x and y is fixed 10 µm).

OBIC measurements are also performed on another $P^+/N/N^+$ diode that presents a high leakage current (greater than 10 nA at 300 V). OBIC cartographies at 50 and 100 V show a point on the curvature of the diode for which OBIC is higher than other measurement points (Figure 9). This means that electric field is higher at this point. Since the curvature of the JTE is an important parameter determining the efficiency of the protection, such a defect can strongly reduce the breakdown voltage of the diode. OBIC technique shows that it is able to detect structural defects in the device without destructing it.

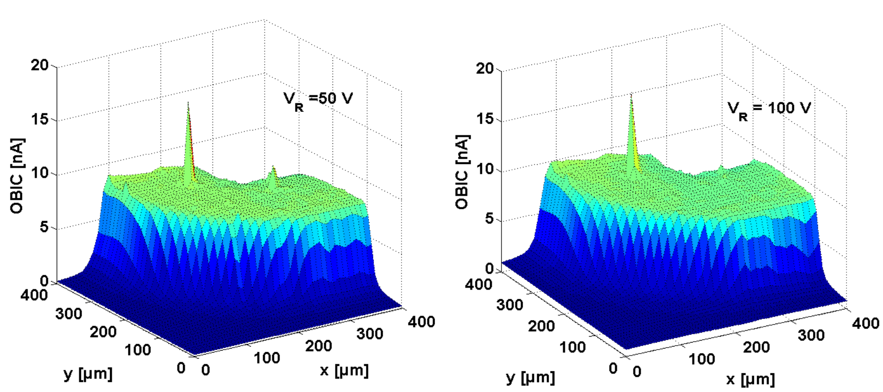

Figure 9: 2D OBIC cartographies on a diode presenting a high leakage current.

6. Conclusion

OBIC method gives an image of electric field, and it is able to show if a peripheral protection is efficient or not. In this paper, two-photon generation principle is used to realize OBIC measurements. Two-photon absorption depends on the beam power which is a Gaussian wave around the focus. So, two-photon OBIC offers a better spatial resolution than single photon OBIC since the charge carrier generation can take place only at a thin diameter near the focus. 2D OBIC cartographies are shown in this paper using two different diode structures with two different peripheral protections. For avalanche diodes with a low breakdown voltage (59 V), a simple MESA etching is enough to provide a near theory breakdown voltage. In case of diodes with higher breakdown voltage (800 V), the JTE protection is studied using OBIC method. We have shown that OBIC method based on two photon absorption allows studying the defects on the structure surface under high voltage, in a non-destructive way. However, care must be taken for the wavelength 532 nm: it is mandatory to defocus to avoid scratches on the device that can lead to the device destruction.

7. Acknowledgment

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