



HAL
open science

Lifetime of holes determination in 4H-SiC using two-photon optical beam induced current method

Hassan Hamad, Christophe Raynaud, Pascal Bevilacqua, Dominique Planson

► **To cite this version:**

Hassan Hamad, Christophe Raynaud, Pascal Bevilacqua, Dominique Planson. Lifetime of holes determination in 4H-SiC using two-photon optical beam induced current method. CAS, Oct 2015, Sinaia, Romania. 10.1109/SMICND.2015.7355226 . hal-01388024

HAL Id: hal-01388024

<https://hal.science/hal-01388024>

Submitted on 27 Jan 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Lifetime of holes determination in 4H-SiC using Two-Photon Optical Beam Induced Current method

H. Hamad^{1*}, C. Raynaud^{*}, P. Bevilacqua^{*}, D. Planson^{*}

^{*}Université de Lyon, INSA de Lyon, CNRS UMR 5005, Ampère Laboratory, F-69621 Villeurbanne, France

¹hassan.hamad@insa-lyon.fr

Abstract—Wide bandgap semiconductors such as silicon carbide, gallium nitride and diamond have been recently investigated in order to replace silicon in the power electronic domain. In this paper, silicon carbide devices are studied using an optical method. It consists on illuminating a reverse biased junction with a laser beam with an appropriate wavelength, and then measuring the induced current due to the photon absorption. According to the wavelength, one- or two-photon absorption is triggered when photon energy is respectively higher or lower than the semiconductor bandgap. In the latter case, the probability of electron hole pair (EHP) generation is very small, which leads to use a powerful incident beam. In this paper, two-photon generation is used in order to determine the lifetime of minority charge carriers in N doped 4H-SiC. The incident beam is a pulsed green source with a wavelength of 532 nm and a high power density that can reach up to 6 GW.cm⁻². Test devices are PN diodes protected by a junction termination extension (JTE). Results show a hole's lifetime of 730 ns.

Keywords—OBIC; two-photon absorption; charge carrier lifetime; PN junction;

I. INTRODUCTION

In the last decades, wide bandgap (WBG) semiconductors (especially silicon carbide SiC) have become popular in the domain of power electronics. Silicon (Si), used for a long time in the power electronics, has reached its physical limits in many applications. High voltage direct current (HVDC), railway and aeronautic domains are examples of high electric power exchange domains where the WBGs have advantage over Si. Due to their high critical electric field (E_c), high thermal conductivity and high saturation velocity of charge carriers, WBGs devices surpass the Si devices [1-2]. Hence, PN junctions made from WBG, designed with a thinner drift layer, have higher breakdown voltage. Switching losses are reduced and hence the cooling system too. However, local breakdown was observed at electrical fields that are significantly lower than E_c . Thus, additional research is needed in order to overcome all the shortcomings and to improve the overall performance of these WBG semiconductors.

The lifetime of charge carriers is a key parameter to predict the static and dynamic losses of a junction. They are defined as the mean duration before the excess minority charge carriers recombine. To achieve low conduction losses, drift layers must have a high carrier lifetime. However, a very long carrier lifetime leads to slow switching and then to high switching losses. Many methods are used to determine the carrier lifetime

such as time resolved photoluminescence (TRPL), microwave induced photoconductivity decay (μ -PCD), open circuit voltage decay (OCVD) and optical beam induced current (OBIC). For the TRPL technique, carriers are excited above the bandgap using a pulsed laser, and the photoluminescence decay is monitored by photomultiplier tubes [3]. μ -PCD technique consists in measuring the decay of conductivity caused by the generation of an excess of minority carriers using a pulsed laser [4]. The OCVD is a pure electric method; it consists in measuring the transient voltage decrease on a junction in open circuit after a direct conduction period [5]. In this paper, 4H-SiC bipolar diodes are studied in order to determine the minority carrier lifetime using OBIC method. It consists in measuring the diffusion length on the periphery of the junction [6].

II. OBIC PRINCIPLE

When a semiconductor is illuminated with an optical beam of appropriate wavelength, EHPs are generated due to photon absorption. If the photon energy (E_ϕ) is larger than the semiconductor bandgap (E_G), single photon absorption is able to generate an EHP; this is the one-photon absorption process. If the photon energy is low ($E_\phi < E_G$), single photon absorption becomes negligible and two photons or more must interact with the atom at the same time to generate an EHP; this is the multi-photon absorption process. In this case, generation probability decreases strongly and high beam power is then required. Two-photon absorption process was predicted in 1931 for the first time [7]. Later, two-photon absorption process has been demonstrated using an IR laser beam on a Si substrate [8]. Recently, two-photon absorption process has been evidenced using OBIC method with a pulsed green laser on 4H-SiC devices [9]. In this work, a powerful green (532 nm) pulsed laser illuminates 4H-SiC devices. Since E_ϕ is of 2.33 eV, much smaller than semi-conductor bandgap (3.3 eV), two-photon absorption process takes place. This absorption mode is advantageous compared to single-photon absorption process since the generation takes place only within a thin diameter where the beam density is higher; the beam has a Gaussian spatial distribution and two-photon generation depends on the beam power.

In order to bring out the carrier generation, the reverse biased $P^+/N/N^+$ junction, shown in Fig. 1, allows the presence of an electric field and then the separation of the generated pairs. EHPs generated outside the SCR will recombine and no effect can be measured. The EHPs generated in the space charge

region (SCR), where an important electric field dominates, are splitted, the electron towards the cathode, the hole towards the anode. These carriers will acquire kinetic energy and will be accelerated to reach the edge of the SCR. An optical beam induced current (OBIC) is then measured. For high voltage level, the kinetic energy acquired by the carriers becomes high and EHP generation may take place by collision between the free carriers and the atoms of the crystal. This can lead to another generation and then to the avalanche at the breakdown voltage. Generated EHPs near the SCR (at a distance smaller than their diffusion length) may attain the SCR and then give rise to an OBIC signal.

Many device characterizations use OBIC method. OBIC gives an image of the electric field in the device [10]. It is also used to determine the ionization rates of semiconductors [11].

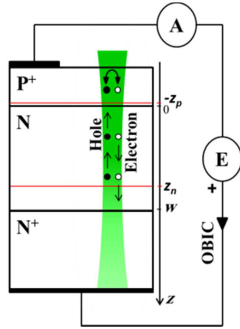


Fig. 1: Schematic view of OBIC principle on a reverse biased P⁺/N/N⁺ junction.

III. MINORITY CARRIER LIFETIME DETERMINATION

The peripheral protection of the P⁺/N/N⁺ diode presented in Fig. 2 is realized with a JTE layer. At the edge of the JTE layer, the junction is supposed to be vertical (fig. 2) and the minority charge carriers are holes. When the laser beam scan the diode, the OBIC signal measured at the periphery of the junction decreases as a function of the minority carrier diffusion length L_{dp} as shown in (1). The logarithm of OBIC current at this region is inversely proportional to the minority carrier diffusion length.

$$OBIC(x) = u \exp\left(-\frac{x}{L_{dp}}\right) \quad (1)$$

where u is the optical generation rate.

Minority carrier lifetime is related to the diffusion length and the diffusion coefficient of holes D_p as shown in (2).

$$\tau_{n,p} = \sqrt{D_p L_{dp}} \quad (2)$$

Diffusion coefficient is given by the (3).

$$D_p = \frac{kT}{q} \mu_p \quad (3)$$

where k is Boltzmann constant, T the temperature, q the electron charge and μ_p is hole mobility. Carrier lifetime can be then written as follows:

$$\tau_p = \frac{qL_{dp}^2}{KT\mu_p} \quad (4)$$

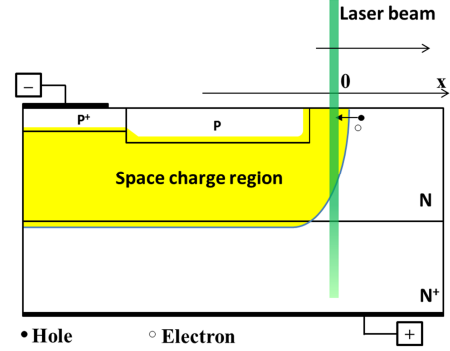


Fig. 2: Horizontal motion of charge carriers at the edge of the SCR.

IV. EXPERIMENTAL SETUP

Device under test (DUT) are squared P⁺/N/N⁺ diodes. Low doped N region (10^{15} cm^{-3}) is realized with a 7 μm thick epitaxial layer on an N⁺ substrate. P⁺ region is realized by ionic implantation with a depth of 0.5 μm and a doping level of 10^{19} cm^{-3} . Peripheral protection is realized with a JTE P layer with a length of 200 μm and a doping level of 10^{17} cm^{-3} . The active area of the DUT is $500 \times 500 \mu\text{m}^2$ (Fig. 3). The breakdown voltage of this diode is about 800 V. A 75 mm diameter wafer, containing about 150 test diodes, is used in this study.

A powerful pulsed green laser source (532 nm) is used in this work. The repetition frequency is of 20 kHz and the pulse duration is about 1 ns. Beam average power is adjustable up to 100 mW, the pulse energy can then reach up to 5 μJ with an instant power up to 5 kW. The beam is canalized through two semi-reflecting mirrors and it is focused on the sample by a lens with a focal length of 100 mm. In order to scan the sample with the laser beam, mirrors and lens are moved using three linear stepper motors of a minimum path of 1 μm (Fig. 4). Motors are driven via a LABVIEW interface allowing the control of the position of laser beam and its depth. At the focus point, spot diameter is about 10 μm which represents an equivalent instant power density of about 6.6 GW.cm^{-2} . DUT is put in a vacuum chamber to avoid any electrical arcing between the electrodes due to the air, which can damage the device. Electric contact on the front side (anode) is made using a thin tip. Cathode contact is insured by the backside of the DUT. Mean current is measured using a Source Measurement Unit Keithley 237 delivering voltage up to 1100 V and measuring current less than 1 pA.

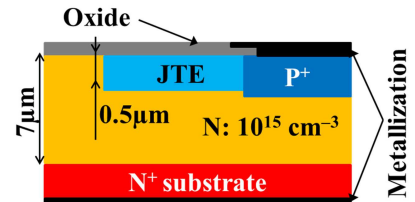


Fig. 3: Partial cross section view of the test diode.

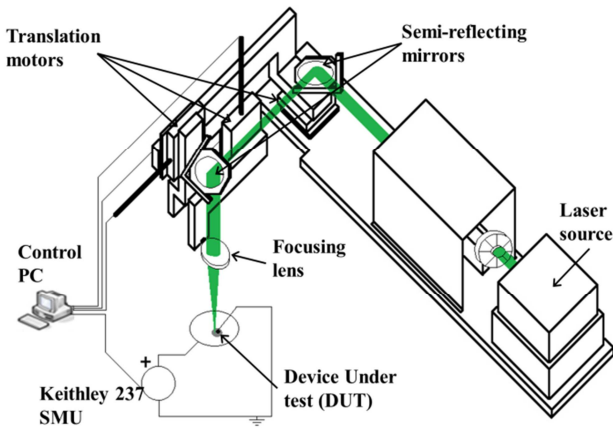


Fig. 4: Schematic view of the OBIC bench.

V. RESULTS AND DISCUSSION

First OBIC measurements led systematically to scratches on the diodes where the beam hits on the surface of the DUT (Fig. 5). If the laser beam hits the metallization, the device is electrically destroyed and it does not block any voltage. To solve this problem, the beam was defocused and a divergent beam (diameter = $15\mu\text{m}$) hits the surface of the diode. This solution allows realizing OBIC measurements without any scratches on the DUT.

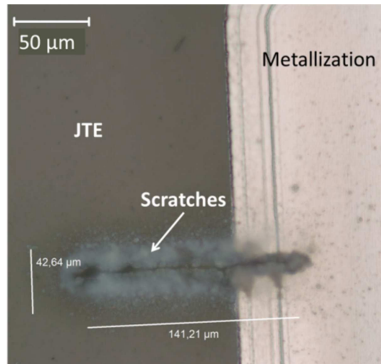


Fig. 5: Scratches created when focused laser beam illuminates DUT.

Since OBIC current is measured in reverse biased mode, leakage current must then be small to not mask OBIC signal. After many tests, a leakage current of 10 nA is set as a criterion to realize or not OBIC measurements. A preliminary work is then performed to select the diodes that can be used in OBIC studies. Only 10 diodes have a leakage current smaller than 10 nA for voltage near 800 V. OBIC measurements are realized on the length of the selected diodes for voltages varying from 0 V up to 700 V. Fig. 6 shows the logarithm of the OBIC signal. A non-null OBIC signal is measured only when the JTE is illuminated with the laser beam. Electric field is high at this region. When the beam illuminates the metallization (reflecting surface) or outside the JTE, there is no measured induced current.

At the edge of the JTE, the slope of the OBIC signal vs. the distance is measured for different values of V_R . It varies between $0.0784\ \mu\text{m}^{-1}$ at 0V, and $0.067\ \mu\text{m}^{-1}$ at 700 V (it is

almost constant for voltages between 100 and 700 V). The measured point at 0 V is then rejected and the slope average for other voltage is of $0.06787\ \mu\text{m}^{-1}$. Referring to (1), this value is the reverse of the minority charge carrier diffusion length. The diffusion length of the minority free holes is then $14.7\ \mu\text{m}$. Using (4) with hole's mobility of $115\ \text{cm}\cdot\text{V}^{-1}\cdot\text{s}^{-1}$, the lifetime of holes found is of 730 ns.

This value of hole lifetime is in good agreement with the results of Ivanov published in 1999 using OCVD method (680 ns at 300K) [12]. The found lifetime of holes is not contradictory with the results published in [13] where two dimensional cartographies were realized on 125 mm diameter 4H-SiC wafer using μ -PCD and TRPL techniques. Results show a charge carrier lifetime between 0.5 and 6 μs [13].

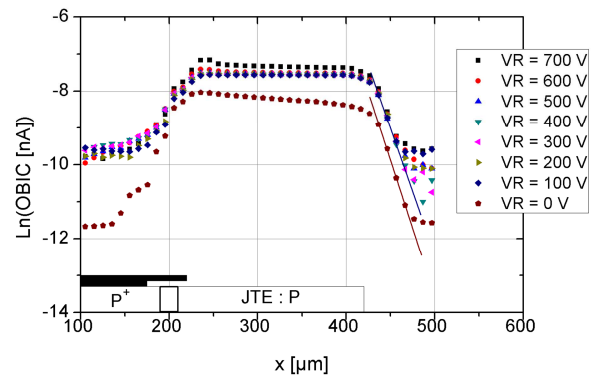


Fig. 6: Ln(OBIC) vs. the beam position for $0 \leq V_R \leq 700\ \text{V}$.

VI. SUMMARY

In this paper, 4H-SiC JTE protected bipolar diodes were studied in order to determine minority carrier lifetime. The breakdown voltage is about 800 V. OBIC method is then used and it is based on two-photon absorption process. This absorption mode is advantageous on single photon absorption process since the absorption takes place on a very thin diameter. After analysis failure using a focused green laser beam, a defocused green laser beam shows good performance in OBIC measurements on SiC-devices. Minority carrier diffusion is extracted by analyzing the OBIC decay at the periphery of the JTE. The hole's diffusion length found is of $14.7\ \mu\text{m}$ and then the lifetime found is of 730 ns.

VII. REFERENCES

- [1] S-H. Ryu, L. Cheng, et al. "Development of 15 kV 4H-SiC IGBTs", Materials Science Forum, vols. 717-720, p. 1135 (2012).
- [2] H. S. Lee, M. Domeij, et al. "Electrical Characteristics of 4H-SiC BJTs at Elevated Temperatures", Materials Science Forum, vols. 483-485, p. 897 (2005).
- [3] D. Kiliani, G. Micard, et al. "Minority charge carrier lifetime mapping of crystalline silicon wafers by time-resolved photoluminescence imaging", Journal of Applied Physics, vol. 110, 0545508 (2011).
- [4] Z. Liu, A. Masuda and M. Kondo, "Investigating minority-carrier lifetime in small spherical Si using microwave photoconductance decay", Journal of Applied Physics, vol. 103, 104909 (2008).
- [5] N. Dheilly, D. Planson, et al. "Measurement of Carrier Lifetime Temperature Dependence in 3.3kV 4H-SiC PiN Diodes Using OCVD Technique", Materials Science Forum, vol. 615-617, p. 703 (2008).
- [6] T. Flohr and R. Helbig, "Determination of minority-carrier lifetime and surface recombination velocity by optical-beam-induced-current

- measurements at different light wavelengths*", Journal of Applied physics, vol. 66, no. 7, p. 3060 (1989).
- [7] M. Goepfert-Mayer. "*Über Elementarakte mit zwei quantensprüngen*", Ann. Phys, vol. 9 p.273 (1931).
 - [8] C. Xu and W. Denk, "*Two-Photon Optical Beam Induced Current Imaging through the Backside of Integrated Circuits*", Applied Physics Letters, vol. 71, no. 18, p. 2578 (1997).
 - [9] H. Hamad, C. Raynaud, et al. "*Optical Beam Induced Current measurements based on two photon absorption process in 4H-SiC bipolar diodes*", Applied Physics Letter, vol. 104, 082102 (2014).
 - [10] H. Hamad, P. Bevilacqua, et al. "*Two-Dimensional Optical Beam Induced Current measurements i 4H-SiC bipolar diodes*". 10th Conference on Ph. D. Research in Microelectronics and Electronics PRIME, Grenoble (2014).
 - [11] H. Hamad, C. Raynaud, et al. "*Temperature dependence of 4H-SiC ionization rates using Optical Beam Induced Current*", Materials Science Forum, vols. 821-823, p. 223 (2015).
 - [12] P-A. Ivanov, M-E. Levinshtein, et al. "*High hole lifetime (3.8 μ s) in 4H-SiC diodes with 5.5 kV blocking voltage*". ELECTRONIC LETTERS, vol. 35 No. 16, p. 1382 (1999).
 - [13] B. Kallinger, M. Rommel, et al. "*Comparison of Carrier Lifetime Measurements and Mapping in 4H SiC Using Time Resolved Photoluminescence and μ -PCD*", Materials Science Forum, vol. 778-780, p. 301 (2014).