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Temperature dependence of 4H-SiC ionization rates using Optical Beam Induced Current

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Abstract. The behavior of 4H-SiC power devices in severe environment with varying temperature is a key characteristic indicating their reliability. This paper shows the dependence of the ionization rates of 4H-SiC with respect to temperature. Optical Beam Induced Current (OBIC) measurements have been performed on PN junctions to determine the multiplication coefficient for temperature varying between 100 and 450K. That allows extracting the ionization rates by fitting the curves of multiplication coefficient.

Introduction

Silicon carbide devices become more and more used in the power electronics. Advanced studies and characterizations are needed to improve the breakdown voltage of these devices. Many optical methods are often employed to study the physical characteristics of the silicon carbide. In this paper, Optical Beam Induced Current (OBIC) method is employed to determine ionization rates for a wide temperature range going from 100 up to 450K. Ionization rates are rarely studied and the results already found are, more or less, scattered [1-5]. Their determination helps to predict more accurately the critical electric field and hence the breakdown voltage of electronic devices. OBIC method can be also used to determine carrier lifetime [6] and finally it gives an image of the electric field in the device [7].

Ionization rates

Ionization rate is defined as the number of generated charge carriers by collision per length unit from one charge carrier. The energy acquired by a charge carrier depends on the electric field. This means that ionization rates of a material depends only on material characteristics and electric field. The models that describe ionization rates are functions of electric field, they are derived by taking into account some physical approximations or empirical equations. For example, Wolff considered that the acquired energy by a charge carrier between two collisions is too much higher than the lost energy due to a collision. The distance between the two collisions is the carrier mean free path. In these conditions, he solved transport equations of Boltzmann and he obtained the expression of the ionization rates as seen in equation 1 [8]. Wolff hypothesis is applicable only for high electric field.

$$\alpha_{n,p} = a. \exp\left(\frac{-b_{n,p}}{F^2}\right) \quad (1)$$

F: electric field

The model used in this paper is the Shockley model. Shockley supposed that carriers bringing about ionization are only ones that do not undergo shocks with phonons [9]. His definition is in good agreement with the empiric formula given by Chynoweth [10] for low electric field:

$$\alpha_{n,p} = a_{n,p} \exp\left(\frac{-b_{n,p}}{F}\right) \quad (2)$$

F: electric field

Experimental extraction of ionization rates using OBIC

Consider the reverse biased P^+N junction shown in figure 1. Once it is perpendicularly illuminated with an optical beam, photon absorption and electron-hole pairs (EHPs) generation occur. An induced current can be measured. J_p is the hole current in the N-region, J_n is the electron current in the P^+ -region, J_{SCR} is the generated SCR current in the space charge region (SCR), x_j is the metallurgical junction depth, $x_j - x_p$ is the SCR extension in the P^+ emitter, and $x_n - x_j$ is the SCR extension in the N region. Currents obey the following equations:

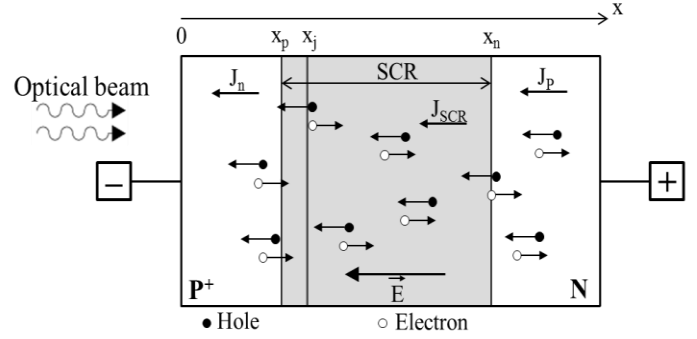


Figure 1: Schematic view of P^+N junction with different regions and currents.

$$\frac{dJ_n}{dx} = -\frac{dJ_p}{dx} = \alpha_n J_n + \alpha_p J_p - qu(x) \quad (3)$$

in which J_n and J_p are algebraic quantities, q is the elementary charge and $u(x)$ is the generation rate by light in the SCR. The total current $J = J_n + J_p$ is constant whatever x .

$$\frac{dJ_n}{dx} = (\alpha_n - \alpha_p)J_n + \alpha_p J - qu \quad (4)$$

$$\frac{dJ_p}{dx} = (\alpha_n - \alpha_p)J_p - \alpha_n J + qu \quad (5)$$

Solutions of equations (5) and (6), with $u = 0$, give respectively the multiplication coefficient of electrons (M_n) and holes (M_p). Assuming that $J_n(x_n) \gg J_p(x_n)$ and $J_p(x_p) \gg J_n(x_p)$, that means it is possible to write: $J_n(x_n) = J_p(x_p) = J$.

$$J_n \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx\right) = \int_{x_p}^x \alpha_p J \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx'\right) dx + J_n(x_p) \quad (6)$$

$$J_n(x_n) \exp\left(-\int_{x_p}^{x_n} (\alpha_n - \alpha_p) dx\right) = \int_{x_p}^{x_n} \alpha_p J \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx'\right) dx + J_n(x_p) \quad (7)$$

$$M_n = \frac{J_n(x_n)}{J_n(x_p)} = \exp\left(\int_{x_p}^{x_n} (\alpha_n - \alpha_p) dx\right) \times \left[\int_{x_p}^{x_n} \alpha_p M_n \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx'\right) dx + 1 \right] \quad (8)$$

$$M_n \left[1 - \exp\left(\int_{x_p}^{x_n} (\alpha_n - \alpha_p) dx\right) \times \int_{x_p}^{x_n} \alpha_p \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx'\right) dx \right] = \exp\left(\int_{x_p}^{x_n} (\alpha_n - \alpha_p) dx\right) \quad (9)$$

A few further steps give:

$$M_n = \frac{1}{1 - \int_{x_p}^{x_n} \alpha_n \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx'\right) dx} \quad (10)$$

In the same way, we obtain:

$$M_p = \frac{1}{1 - \int_{x_p}^{x_n} \alpha_p \exp\left(\int_x^{x_n} (\alpha_n - \alpha_p) dx'\right) dx} \quad (11)$$

Taking into account the generation rate $u \neq 0$, solution of equations gives the total multiplication coefficient which is the ratio between the current for a given voltage V and the current for the voltage V_0 for which there is no multiplication.

$$M = \frac{J_{ph}(V)}{J_{ph}(V_0)} = \frac{M_n J_n(x_p) + M_p J_p(x_n) + M_{SCR} J_{SCR}}{J_{ph}(V_0)} \quad (12)$$

With

$$M_{SCR} = \frac{M_n \int_{x_p}^{x_n} q u \exp\left(-\int_{x_p}^x (\alpha_n - \alpha_p) dx'\right) dx}{\int_{x_p}^{x_n} q u dx} \quad (13)$$

$$J_{SCR} = - \int_{x_p}^{x_n} q u dx \quad (14)$$

Φ and α are respectively the absorbed optical flux and the absorption coefficient of the semiconductor. In this work, the wavelength used is 349nm, its absorption rate in the 4H-SiC is 340cm^{-1} . So, the expression of $u(x)$ is given by:

$$u(x) = \alpha \Phi \exp(-\alpha x) \quad (15)$$

Then the photon generated current in the SCR is:

$$J_{SCR} = q \Phi [\exp(-\alpha x_n) - \exp(-\alpha x_p)] \quad (16)$$

The minority carriers currents $J_n(x_p)$ and $J_p(x_n)$ are determined by solving the continuity equations by taking into account the conditions on the limit [11]. From equations (2) and (12), it is possible to determine the ionization rates by fitting the experimental multiplication curve $M(V)$ using numerical solver. In this case, the electric field distribution must be calculated in terms of the reverse voltage V .

Experimental setup

A UV pulsed laser is used to generate electron hole pairs, the wavelength of incident light is 349nm, the repetition rate can be modified between 100Hz and 5kHz (figure 2a). The pulse energy can be adjusted up to 120 μ J. The pulse duration varies between 3 and 7ns according to frequency and pulse energy. An optical bench consisting of two semi-reflecting mirrors and a focusing lens is controlled with LabView to move the position (x, y and z) of the focal point. At the focal point the spot diameter is about 20 μ m and the beam power density is up to 100GW.cm⁻². In this work, the repetition frequency is set to 1 kHz and all measurements are realized under very low pulse energy (smaller than 1 μ J/pulse). This energy is high enough to generate EHPs so an OBIC current could be measured. The studied device is placed in a vacuum chamber and its temperature is controlled. The minimum temperature is 77K due to liquid nitrogen. The laser beam passes through the window of vacuum chamber to reach the device under test. The diameter of the diode is scanned with a step of 10 μ m for several voltages.

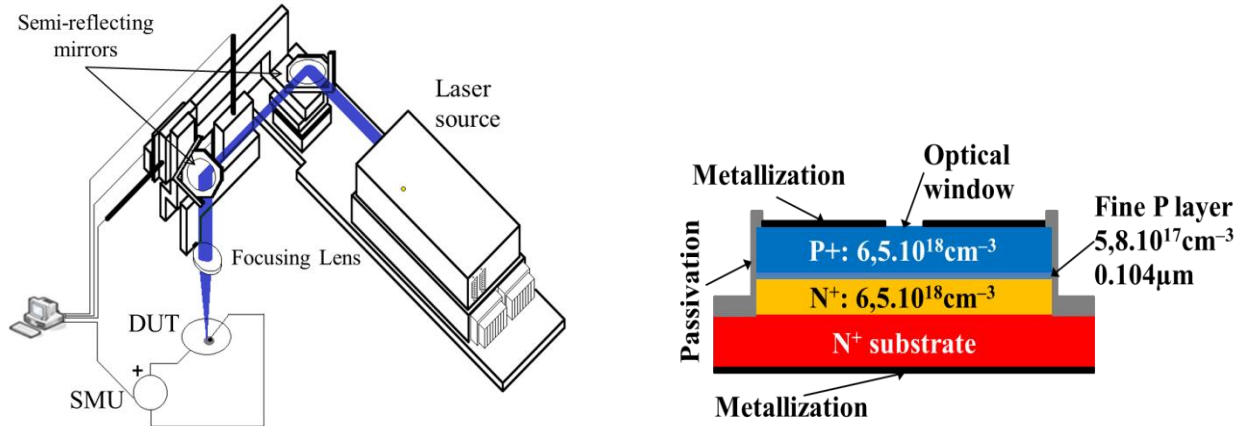


Figure 2: (a) Schematic of experimental bench, (b) Cross section view of the studied diode.

To realize OBIC measurements, a circular avalanche diode similar to those described in previous studies [3] (figure 2b). The diode is realized on an N⁺ 4H-SiC substrate. An epitaxial P⁺ layer of 2.2 μ m thickness was grown on a fine epitaxial transition P layer of 0.104 μ m overlying an N⁺ epitaxial layer. Since the diode presents a high doping level, its breakdown voltage is very low (59V), and the peripheral protection is realized with a MESA etching. In order to allow optical beam to penetrate towards the active part of the diode, an optical window of 100 \times 100 μ m² has been performed on the metallization using SIMS technique [12].

Results and discussion

Figure 3 shows the reverse I-V characteristics of the diode for a temperature ranging from 100K up to 450K. For low voltage level, the leakage current becomes higher when the temperature increases, however the breakdown voltage increases as well.

Figure 4a shows the OBIC current measured at 300K with reference to the cross section of the diode for multiple voltage levels. The current is high when laser beam illuminates the optical window. There is a weak signal when laser beam illuminates the extremity of the metallization, and it is zero everywhere else. OBIC does not change significantly for low voltages at the optical window but once approaching the breakdown voltage, it increases significantly.

For a given voltage V , the multiplication coefficient is the ratio between the current induced in the optical window and its value at 1V. Figure 4b shows experimental multiplication coefficient for this work at 300K fitted with numerical solver and compared to Konstantinov [1], Loh [4] and Hatakeyama [5] results in the same conditions. This figure reveals a significant dispersion of published multiplication coefficients between different authors.

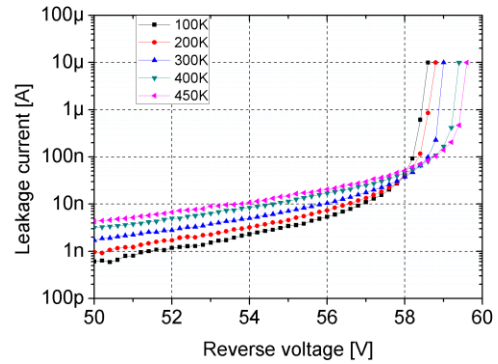


Figure 3: Reverse I-V characteristics for different temperatures.

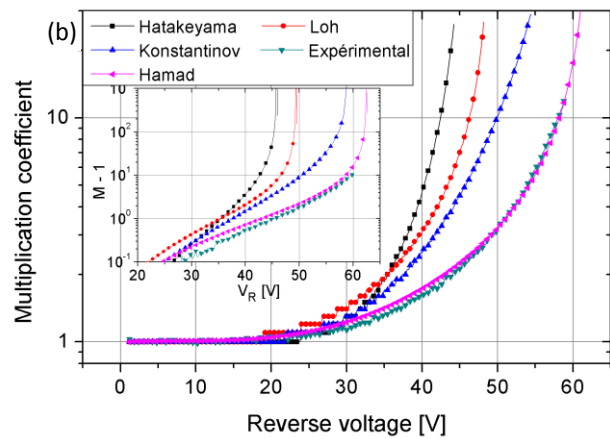
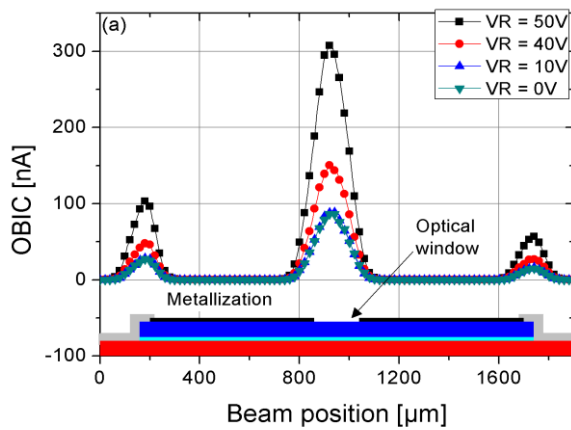


Figure 4: (a) OBIC vs. beam position for several reverse voltages, (b) multiplication coefficient for this work compared to others.

To fit the multiplication curve, four parameters are modified. a_n , b_n , a_p and b_p give the shapes of the ionization rates of electrons (α_n) and holes (α_p). Table 1 displays the values of the values of these parameters for temperature going from 100 to 450K. Figure 5 shows the variation of ionization rates vs. the inverse of the electric field for the same temperature range. For very low temperature ($\leq 150K$), α_n is higher than α_p . When temperature becomes higher than about 150K, the avalanche is dominated by α_p . It is shown that α_n decreases slightly when the temperature increases. Such results have been obtained for electrons in silicon at 100, 213 and 300K [13] for lower electric field. α_p increases with the temperature up to 300K, and seems constant above 300K. At high electric field, the temperature dependence is less pronounced than at lower electric field, as predicted by the theory [14]. Recent results by Niwa et al. [15] in SiC at $T > 300K$ show a decrease of α_p at $T > 300K$ but for lower electric field. Therefore there is no contradiction between our results and those of Niwa.

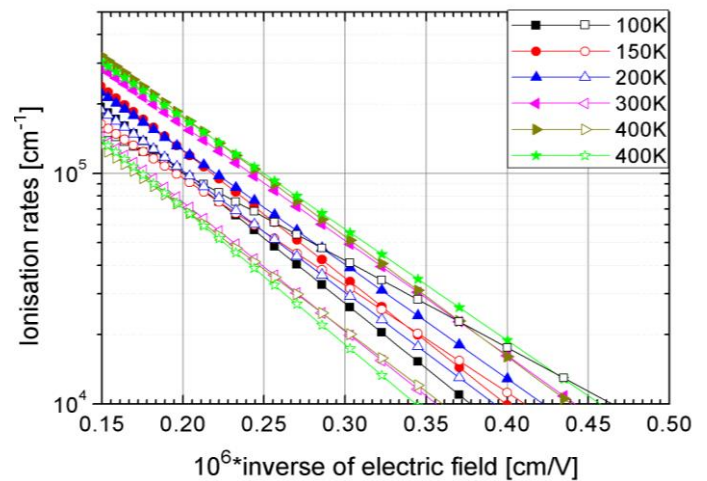


Figure 5: Ionization rates of electrons α_n (empty symbols) and of holes α_p (full symbols) vs. inverse of electric field.

Table 1: Temperature dependence of ionization rates

Temperature [K]	100	150	200	250	300	350	400	450
$a_n [10^6 \text{ cm}^{-1}]$	0.57	0.81	1.15	1.04	0.99	0.87	0.81	1.07
$b_n [10^7 \text{ V.cm}^{-1}]$	0.87	1.07	1.21	1.36	1.29	1.11	1.22	1.36
$a_p [10^6 \text{ cm}^{-1}]$	1.35	1.59	1.23	1.76	1.61	1.72	1.95	1.6
$b_p [10^7 \text{ V.cm}^{-1}]$	1.3	1.27	1.14	1.14	1.15	1.26	1.2	1.11

Summary

In this paper, a UV laser with appropriate power is used to generate electron hole pairs in 4H-SiC. Optical beam induced current (OBIC) is measured on an avalanche diode enabling the determination of the multiplication coefficient. The ionization rates are extracted by fitting the multiplication curves using the Shockley model. Results show that ionization rates do not vary significantly when temperature changes. A slight decrease of α_n was observed when the temperature goes from 100K to 450K and a light increase of α_p up to 300K. At higher temperature, α_p is rather constant. These results are obtained for high electric fields ($> 3 \times 10^6 \text{ V.cm}^{-1}$).

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