Measurement of Electron and Hole Impact Ionization Coefficients for SiC

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Introduction

Silicon carbide has received increasing attention for power switching, microwave and high temperature applications due to its high breakdown electric field, thermal conductivity and electron saturation drift velocity. One of the most important parameters of a SiC power device is its breakdown voltage. In order to obtain a clear understanding of its breakdown characteristics, it is important to have an exact knowledge of the impact ionization coefficients for SiC. However, there is very little information available in literature for 6H-SiC (1-3) and none for 4H-SiC. In this work, measured impact ionization coefficient data for 4H and 6H-SiC are provided as a function of temperature. It is demonstrated that that the data obtained from these measurements allows a more accurate simulation of reverse breakdown voltage characteristics than that obtained using previously published data. These results have widespread utility for SiC device analysis and design.

I. Measurement Methodology

The method used in this work for measurement of impact ionization coefficients (α) is based upon the multiplication of carriers generated by a pulsed electron beam in the depletion region of a reverse biased diode. There are many important issues that need to be considered to obtain accurate measurement of α:

(1) There is electric field crowding at the edges of diodes which leads to enhanced multiplication of the carriers in this region. Since the magnitude of the electric field at the edge is not known, any carrier generation near the edges leads to errors in measurements. This problem was solved during our measurements by localizing the carrier excitation away from the diode edges using an electron beam with spot size of less than 20 μm in diameter in the center of the diode. In spite of this, any electric field crowding at the diode edges is still a major problem because this results in reducing the breakdown voltage to below the parallel plane case. This can severely limit the maximum electric field at the measurement site and reduce the range of the fields over which α can be measured. Hence, it is crucial to create a good edge termination in the diodes. In our work, a Schottky diode structure with argon ion implant edge termination (4) was used to obtain nearly ideal breakdown voltage.

(2) Defects are known to severely affect the breakdown characteristics of devices. Therefore, it is important that the measurement be made in a defect free location. In our measurements, the Electron Beam Induced Current (EBIC) technique was used to identify the location of electrically active defects. Thus, it was possible to choose a defect free region for the α measurements. Further, since the defect density of commercially available SiC wafers is known to be in the order of 10^4 cm^{-2}(5), devices were fabricated with area of less than 5×10^{-5} cm^2 so that at least half of the diodes were free of dislocations and micropipes.

It is necessary to extract the α from the measured multiplication rates. To achieve this, a thin drift region with a low doping density is required to obtain a nearly constant electric field profile with depth. Equations were therefore derived for the extraction of the impact ionization coefficients from the multiplication data assuming a constant electric field profile in the drift region (for a P-type Schottky diode):

$$1-\frac{1}{M_p} = \left(\frac{\alpha_p}{\alpha_n-\alpha_p}\right)[\exp(\alpha_n-\alpha_p)W-1] \qquad (1)$$

where M_p is the multiplication due to holes and α_p and α_n are impact ionization coefficients due to electron and holes, respectively and W is the thickness of the epilayer. In a P-type Schottky diode, where ionization due to holes is dominant, it can be shown that

$$\alpha_p = \frac{\ln(M_p)}{W} \qquad (2)$$

Thus, α_p can be calculated from the measured multiplication factor M. Similar expressions were developed for electron impact ionization using N-type Schottky diode structures. In order to verify the methodology for extracting α, simulations were performed using MEDICI with and without including the impact models using the actual doping profile measured on the fabricated devices. The resulting reverse I-V characteristics and the corresponding electric field profile obtained from simulations are shown in Fig. 1 and Fig. 2, respectively.

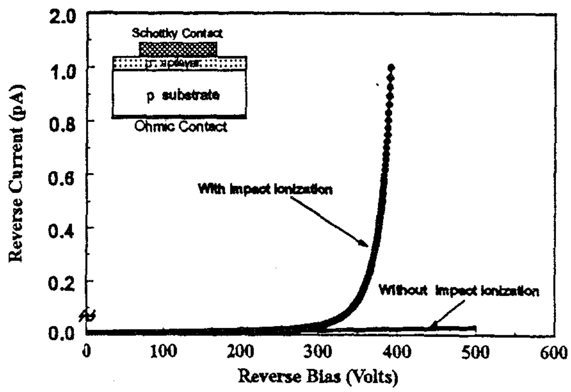

Fig. 1 Reverse IV for a 6H-SiC SBD obtained from simulations with and without impact ionization to determine multiplication rate from which α is extracted.

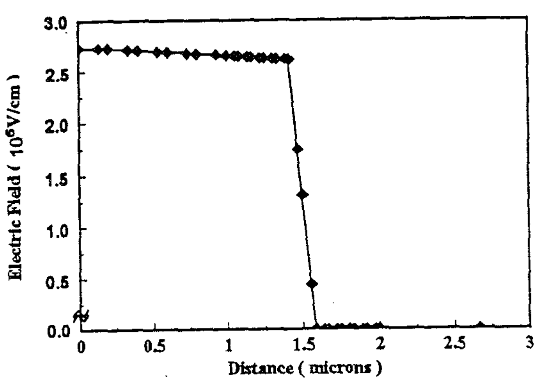

Fig. 2 The electric field profile obtained for a structure simulated is Fig. 1 showing that constant field profile is a reasonable assumption.

The multiplication factor M was then calculated by taking the ratio of the reverse current at each reverse bias value. The corresponding electric field was calculated using E = V/W. For an epitaxial layer doping of 5 x 10^{15} cm^{-3}, the constant electric field profile approximation was found to be a reasonable assumption as demonstrated in Fig. 3 which compares the α values extracted using this procedure with the values input into the simulator. It can be seen that the extraction procedure works well over wide electric field range for P-type SiC due to high impact ionization rates for holes in SiC.

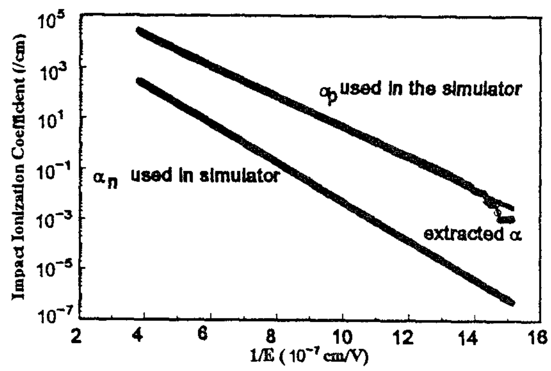

Fig. 3 α extracted for holes using analytical solution developed for a P-type SBD fits well with the values input into the simulator

However, for N-type SiC, it was found that α_n can only be extracted at smaller electric fields as shown in Fig. 4 before the onset of a strong contribution from the generated holes. For this reason, only data on α_p is reported in this paper.

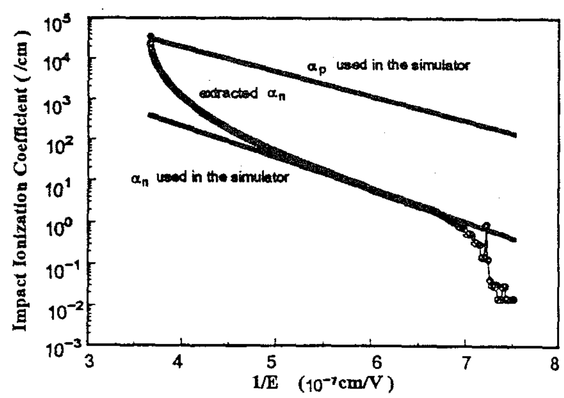

Fig. 4 α extracted for electrons using the analytical solution for a N-type SBD fits well with the value input into the simulator for low field values. However, at high fields there is onset of large contribution from holes.

II. Measurement Setup

A schematic of the impact ionization measurement setup is shown in Fig. 5. A scanning electron microscope (Hitachi S-2700) was used for the generation of carriers using the electron beam. The electron beam was pulsed using a beam blanking setup in conjunction with the scanning electron microscope. The beam blanking device essentially consists of two electrodes, placed in the electron gun region, which are used to deflect the beam with an externally applied bias. The external bias is a pulse produced by a pulse generator which is also input into the lock-in- amplifier as a reference. The photocurrent generated by the pulsed electron beam excitation of the reverse biased Schottky diode is tracked using the lock-in-amplifier. This current is then ploted as a function of the applied reverse bias voltage measured using a digital multimeter across the Schottky diode.

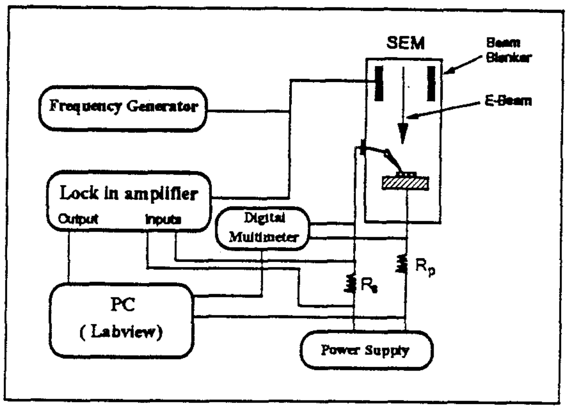

Fig. 5 Schematic of the experimental setup

A curve of the multiplication versus electric field is then obtained from this data, from which impact ionization coefficients are extracted using equation (2). The setup was interfaced with a personal computer and controlled using LABVIEW, a graphical programming tool, to allow extensive and accurate data acquisition. A heated sample stage was used to obtain α data as a function of temperature.

III. Device Fabrication and Characterization

Schottky barrier diodes were fabricated on P-type 6H and 4H-SiC (5×10^{15} cm^{-3}, 2 μm thick) homoepitaxial layers grown on off-axis SiC substrates (3×10^{18} cm^{-3}). Prior to metal deposition, the SiC wafer was given a Huang clean. Schottky diodes (60-100 μm diameter) were fabricated using a shadow mask with sequential evaporation of Ti (2000 A) and Al (2000 A) layers. Blanket evaporation of a Ti/Al layer was also done on the heavily doped substrate to form a large area backside contact. An argon implant was performed around the edges to obtain nearly ideal breakdown (4). The exact doping concentration and thickness of the epitaxial layers was obtained using the C-V measurement. The forward and reverse characteristics of the diode was studied using I-V measurement. The P-type 6H and 4H-SiC were found to exhibit breakdown voltages of 530 V and 570 V, respectively.

IV. Impact Ionization Data

Typical plots of multiplication factor M at room temperature vs. bias obtained from measurements on 6H and 4H-SiC are shown in Fig. 6.

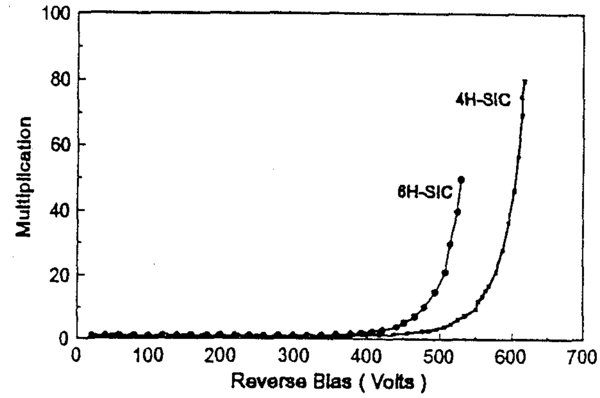

Fig. 6 Multiplication with increasing reverse bias in 4H- and 6H-SiC SBD structure

Using this data, the impact ionization coefficients for holes in 4H and 6H-SiC were obtained as a function of the electric field E as shown in Fig. 7 and Fig. 8, respectively.

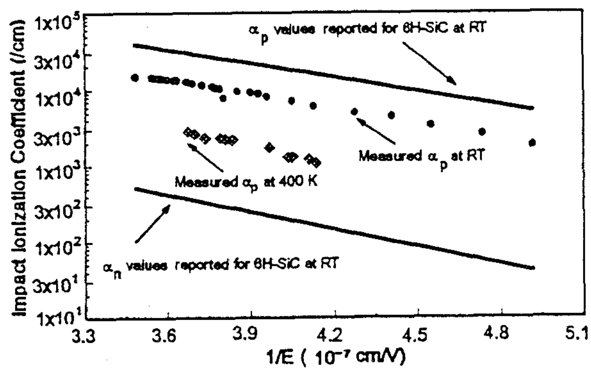

Fig. 7 Measured impact ionization coefficients for holes in 6H-SiC SBD at RT and at 400K compared to data available in literature.

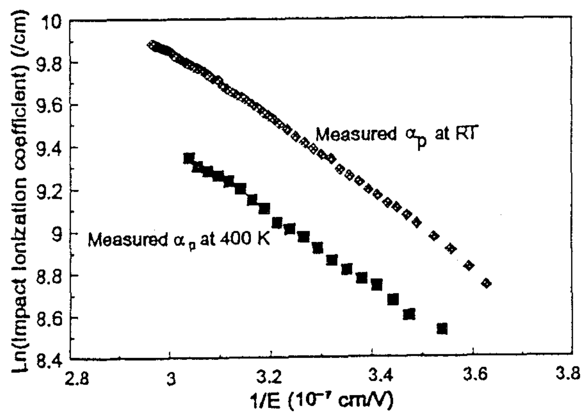

Fig . 8 Measured impact ionization coefficients for holes in 4H-SiC SBD at RT.

Using the Van Overstraeten equation:

$$\alpha = a\, e^{-b/E} \qquad (3)$$

our measurements gave an a_p value of $(2.5 \pm 0.1) \times 10^6$ /cm and a b_p value of $(1.48 \pm 0.1) \times 10^7$ V/cm for 6H-SiC at room temperature. Values of a_p and b_p for 4H-SiC were found to be $(3.5 \pm 0.5) \times 10^6$ /cm and $(1.7 \pm 0.4) \times 10^7$ V/cm, respectively. Using the heating stage inside the SEM, impact ionization coefficient measurements were also performed at 400 K for both 4H and 6H-SiC. These measurements gave an a_p value of 1.68×10^6 /cm and a b_p value of 1.47×10^7 V/cm in 6H-SiC and an a_p value of 1.8×10^6 /cm and a b_p value of 1.65×10^7 V/cm in 4H-SiC. The α_p was found to decrease with increasing temperature (as has been observed in silicon). This indicates that the breakdown voltage of the 4H and 6H-SiC devices should increase with temperature, which is an important desirable characteristic for power devices. We therefore conclude that the previously reported (6) reduction in breakdown voltage with temperature is due to the presence of defects or edge effects. As a final corroboration of our extracted α values with the measured reverse breakdown voltages on our diodes, simulations were performed using the measured α coefficients (a and b). This gave a breakdown voltage of 520 V in 6H-SiC as shown in Fig. 9 which is the same as the experimentally observed data for 6H-SiC. In comparison, the breakdown voltage obtained using data available in literature was only 450 V.

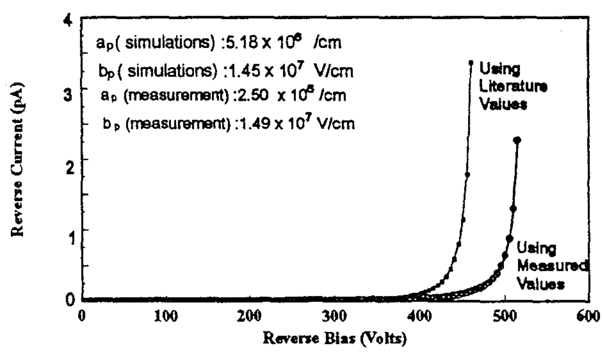

Fig. 9 Comparison of simulated reverse IV for a 6H-SBD using hole ionization coefficients available in literature and using new measured data

The critical electric field calculated from simulations using the extracted α_p parameters was found to be 3.2×10^6 V/cm as shown by the electric field profile near breakdown in Fig. 10. Simulations using the data available in literature gave lower values of 2.8×10^6 V/cm. This implies a 15% increase in the breakdown field strength (E_c) for 6H-SiC and a 20% increase in E_c for 4H-SiC. Using this data, it is shown in Table 1 that Baligas Figure of Merit (BFOM) increases by about 1.5 x 6H-SiC and by about 1.8 x in 4H-SiC indicating even superior specific on resistance for SiC FETs than projected earlier (7).

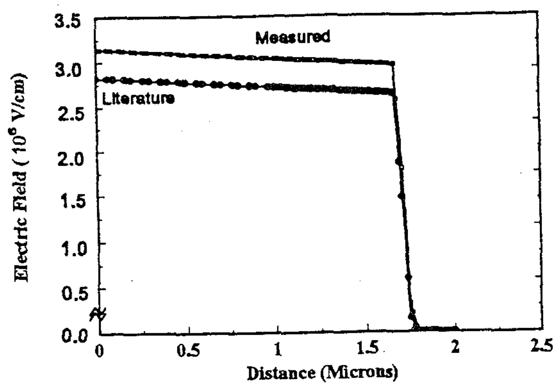

Fig. 10 Comparison of simulated electric field for a 6H-SBD using hole ionization coefficients available in literature and using new measured data

Parameters	6H-SIC	4H-SIC
Previous Ec Values	2.8×10^6 V/cm	2.8×10^6 V/cm
Previous BFOM	25	309
New Ec Values	3.2×10^6 V/cm	3.4×10^6 V/cm
New BFOM	37	553

Table. 1 Comparison of critical electric field (E_c) and Baliga's Figure of Merit (BFOM) values obtained for N-type SiC using the data available in literature and using new measured data

V. Acknowledgments

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