MEASUREMENT OF N-TYPE 6H SIC MINORITY-CARRIER DIFFUSION LENGTHS BY ELECTRON BOMBARDMENT OF SCHOTTKY BARRIERS

S. M. Hubbard, M. Tabib-Azar
Case Western Reserve University; Dept. of Elect. Eng. & Applied Physics
Cleveland, OH

S. Bailey, G. Rybicki, P. Neudeck
NASA Lewis Research Center
Cleveland, OH

R. Raffaelle
Florida Institute of Technology; Dept. of Physics & Space Science
Melbourne, FL

Minority-Carrier diffusion lengths of n-type 6H-SiC were measured using the electron-beam induced current (EBIC) technique. Experimental values of primary beam current, EBIC, and beam voltage were obtained for a variety of SiC samples. This data was used to calculate experimental diode efficiency vs. beam voltage curves. These curves were fit to theoretically calculated efficiency curves, and the diffusion length and metal layer thickness were extracted. The hole diffusion length in n-6H SiC ranged from 0.93±0.15 μm to1.37±0.20 μm.

I. Introduction

Silicon Carbide(SiC) has been recognized for its excellent mechanical properties for over 150 years. It has only been in the past 2 decades that its electronic properties have been explored [1]. With increasing need for high temperature sensors and high power electronics, SiC promises to be one of the premiere semiconductors of the next century.

The main thrust of research into SiC in the past two decades has been to exploit its high breakdown field and high thermal conductivity. These two physical properties make SiC ideal for high power and high temperature application, respectively. Additionally, SiC's wide bandgap (3.0 eV for 6H) makes it an attractive material for blue/UV sensors and emitters. In fact, all of the above devices are commercially available.

In spite of all the progress made in SiC crystal growth and device fabrication [2], much research remains in order to lower the current levels of defect and micropipe density in SiC. It has only been since 1989, through the use of the modified Lely seeded sublimation technique, that large area, low defect density substrates became available [3]. Crystal growth of SiC is still a budding technology, much work remains if acceptable high quality electronic grade SiC is to be produced.

Minority-Carrier diffusion length is an important parameter in the electrical characterization of semiconductor materials. It describes the mean length that a carrier will travel before recombining with the opposite type of carrier. The minority-carrier diffusion length can be related to minority-carrier lifetime using the familiar relation:

$$L = \sqrt{D * \tau} \quad (1)$$

where D is the diffusion coefficient given by the Einstein relation [4] and τ is the carrier lifetime.

The carrier lifetime is of critical importance in evaluation and computer simulation of devices. It is used in the calculations of leakage current and non-ideal diode characteristics. It is also necessary for calculating amplification factors, turn on, and turn off times in Bipolar Junction Transistors (BJT). Additionally, open-circuit voltages and short circuit

currents in solar cells are calculated based on the values of diffusion lengths and lifetimes. In order to evaluate potential uses of SiC in solar cells, semiconductor lasers, BJTs, etc., the researcher must have some knowledge of the minority-carrier lifetime.

Additionally, lifetimes/diffusion lengths can give us some handle on the material quality. Large amounts of defects create recombination centers, thereby reducing the effective diffusion length. Measurement of diffusion length in SiC could be useful in gauging the effect of large micropipe [2] densities on the electrical properties of the material.

In this work, we have used the Electron Beam Induced Current (EBIC) technique in order to measure the diffusion length. Our particular method was first developed by Wu & Wittry in 1978 [5]. This method calls for the bombardment of Schottky barriers, or shallow p-n junctions, by electrons of varying energy (Figure 1). By assuming a Gaussian excitation distribution of electron-hole pairs within the material, Wu&Wittry were able to arrive at a theoretical model of collection efficiency vs. applied beam voltage. By comparing our experimental collection efficiency with this model, we were able to extract the diffusion length. Because the material surface lies underneath the metal layer, surface recombination velocity does not effect our experiments. The Wu & Wittry method is an excellent way to measure the smaller diffusion lengths typical of SiC.

II. Theory

A. Wu &Wittry method (planer configuration)

In the configuration shown in Figure1, the electron beam is exposed to a metal-semiconductor junction. As the beam voltage is raised, the center of the excitation distribution will move deeper into the sample. The excess carriers will diffuse toward the junction, where they are collected. The collected current I_{cc} will depend primarily on the range of the generated carriers and the diffusion length of the minority carriers.

The experimental collection efficiency e is given by:

$$e = \frac{I_{cc}}{qG} \quad (2)$$

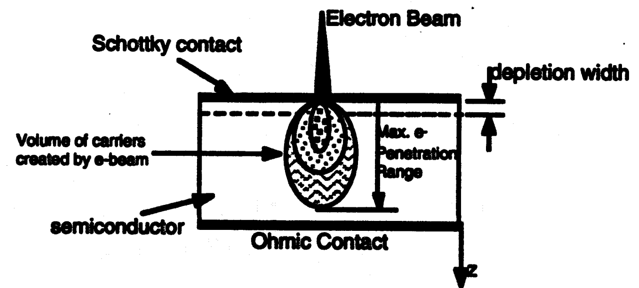

Fig. 1. Drawing of the experimental EBIC technique in the planer junction configuration. The collection efficiency of the Schottky diode is measured as a function of beam voltage.

where I_{cc} is the collected EBIC current, G is the total generation rate, and q the electronic charge. The generation rate is given by [5]:

$$G(sec^{-1}) = 1000\frac{V_o i_{beam}}{q\varepsilon}(1-\eta\frac{\overline{V}}{V_o}) \quad (3)$$

where, V_o is the incident beam voltage in kV, i_{beam} the beam current in Amperes, ε the mean energy to create one electron-hole pair in eV, η is the fraction of backscattered electrons, and $\overline{V}$ the mean energy of backscattered electrons. The value of η at 20keV was calculated for SiC using an empirical formula cited in Goldstein [6]:

$$\eta_{SiC} = 0.134 \quad (4)$$

Goldstein shows that the η value changes slightly from a 10keV to a 50 keV beam voltage. This change is extremely small for lower atomic numbers, therefore, the above η value for SiC is assumed constant for our calculations.

The mean energy of backscattered electrons was determined using a simplified expression proposed by Sternglass [7]:

$$\overline{V} = (0.45 + 2*10^{-3}Z)V_o \quad (5)$$

where Z is the average atomic number of the sample (Z=10 for SiC). Our calculated backscattered correction factor $(1-\eta\frac{\overline{V}}{V_o})$ for SiC was 0.93. Because SiC is 70% Si by weight, we expect our backscatter correction to be near the value of 0.9 given for Si [5].

The hole-electron pair generation energy ε has been measured for a variety of materials over the past 50 years. The data has shown that this energy is linearly related to the bandgap [8]. Ehrenberg and Gibbons [9] have given this relation as:

$$\varepsilon = 2.1E_g + 1.3 \qquad (6)$$

where E_g is the bandgap. We have used this relation in all our calculations.

The theoretical collected current actually depends on the sum of two currents, I_d and I_b. I_d is the current due to carriers generated in the depletion region, while I_b is the current due to carriers generated in the bulk of the semiconductor. By assuming a collection probability near unity inside the depletion layer, Wu and Wittry have derived expressions for I_d and I_b [5].

The theoretical collection efficiency can be written as:

$$e = \frac{|I_{cc}|}{qG} = \frac{|I_d + I_b|}{qG} \qquad (7)$$

The above equation in functional form is:

$$e = f(R, L, Z, w) \qquad (8)$$

Where R is the maximum range of electrons, L the diffusion length, Z the metal layer thickness, and w the depletion layer width. The following range-energy function was developed by Wittry and Kyser [10]:

$$R = 2.56 * 10^{-3} \left(\frac{V_o}{30}\right)^{1.7} \text{ g/cm}^2 \qquad (9)$$

This range-enegry equation is one of a number of range-energy relations given in the literature(Grun, Everhart-Hoff, etc.) [8]. Wu & Wittry have successfully applied this equation to both Si and GaAs [5]. Therefore, we have decided to use it in all of our calculations. The depletion width w was calculated using the doping concentration of the material [4]. We then used a nonlinear fit routine in Mathematica 3.0 to fit our experimental data to the theoretical equation using Z and L as free parameters. Figure 2 shows a set of theoretical collection efficiency curves for a Pd/SiC diode.

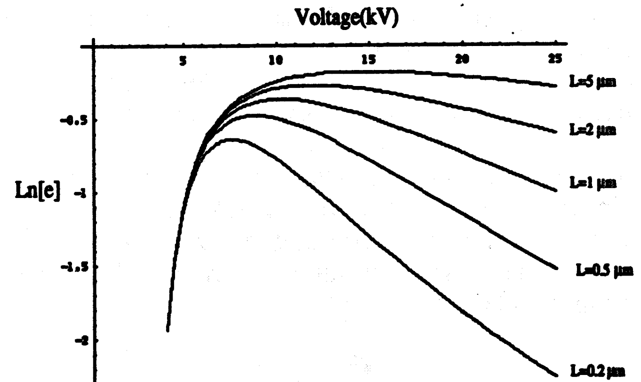

Fig. 2 Theoretical EBIC curves for Pd/SiC Schottky diodes. The metal layer thickness was taken to be 300Å, and the depletion layer width, 1000Å.

III. Experimental

A. Sample Preparation

Samples of n-type 6H SiC were obtained from NASA Lewis Research Center. We would like to extend our thanks to Gary Hunter for providing us with these samples. All samples were Nitrogen doped n/n^+ 6H SiC grown by CVD[8]. The top n side of each sample was a highly polished Si face. The bottom n^+ side was a rough polycrystalline face.

Samples 1636 and 2419 were first cleaned in concentrated HCl for 1 minute. Following this they were dipped in buffered HF, then deionized water. After drying with nitrogen, they were placed in a diffusion pumped vacuum evaporator. After reaching a base pressure of $1.2*10^{-6}$ Torr, Ti wire was thermally evaporated using a tungsten boat source. The thickness of the Ti film was monitored using a digital quartz-crystal thickness monitor.

The monitor was previously calibrated by evaporating approx. 1000Å of Ti, then measuring the thickness using a DekTak profilometer. After calibration, the thickness monitor was within ±100Å of the actual thickness.

After metallization, a pattern of varying diode sizes was laid down using reverse photolithography. The excess Ti was etched away using very dilute HF. A final cleaning was performed by cleaning in a beaker of acetone, then propanol. Samples 18202F & G were fabricated by Gary Hunter at NASA Lewis Research Center[NASA Technical Memorandum 107255]. These samples were also cleaned with acetone and propanol before use.

Ohmic contacts to the Ti samples were made by evaporating 3000Å of Al on the back of the samples using the vacuum evaporator. The Pd samples had back side ohmic contacts made by Al sputtering.

All samples were analyzed using standard IV measurement techniques. A Keithily 236 High Current Source Unit was used to take the IV data. The IV data was analyzed using the following equation [11]:

$$I = I_o[\exp(\frac{qV}{\eta kT}) - 1] \qquad (10)$$

where η is the ideality factor and I_o is the saturation current. The barrier height was calculated from the following relation [11]:

$$I_o = SA^*T^2\exp[-\frac{\phi_B}{kT}] \qquad (11)$$

Where S is the diode area, T the temperature, A^* the modified Richardson constant, and ϕ_B is the barrier height.

Values for our samples are reported in Table I. Values for samples with Pd contacts (18202F-G) show extremely small saturation currents and large barrier height. These barrier heights were much larger than for the Ti/SiC samples. This was expected due to the difference in the relative work functions for Ti (≈4.3 eV) and Pd (≈5.2eV).

In the Ti samples (1636/2419), the saturation current was much larger. These diodes were observed to conduct immediately upon forward bias. This may be due in part to barrier height lowering and/or large tunneling currents. Fortunately, very near the origin, these diodes exhibit almost ideal behavior.

Table I. IV Analysis of our samples.

Sample	η	I_o(Amps)	ϕ_B(eV)
1636A	1.04	$7.32*10^{-8}$	0.66
1636B	1.06	$4.33*10^{-8}$	0.68
18202F	1.23	$8.21*10^{-21}$	1.42
18202G	1.08	$8.21*10^{-21}$	1.42
2419	0.97	$3.14*10^{-8}$	0.69

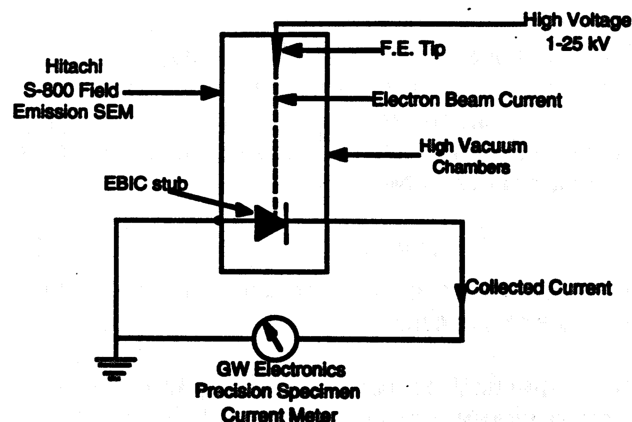

Fig. 3. Schematic of the experimental setup.

B. Instrumentation

A Hitachi S-800 Scanning Electron Microscope was used for electron bombardment. All measurements were made at room temperature and in a reasonably high vacuum (10^{-5}-10^{-6} Pa). The EBIC was collected using a special EBIC sample stub. A sharp copper clip was attached to the top of the diode. The clip itself was attached to a insulated ring around the sample stub. This ring was contacted by a lever arm on the sample stage. Through the use of a coaxial feedthrough, the top side of the diode was connected to a GW Electronics Precision Specimen Current Meter. The beam current was measured in a similar manner using a standard Faraday cage. Figure 3 shows the experimental schematic.

C. Results

Most of the results of our experiments show good agreement with theory. These results are shown in Figures 4-7 and summarized in Table II. Figures 4-5 show a good agreement between theory and experimental data. Our measured values of diffusion length ranged between 0.93 to 1.37 μm for a variety of doping densities. The extracted metal thickness' were within experimental error, ±10%, of our expected values.

Samples 1636A and B were two different dots on the same wafer. The dots were approximately 2.5 mm apart. The results show no change in the diffusion length. This illustrates one of the advantages of the technique, the ability to measure diffusion lengths on different diodes over the 2-dimensional plane of the wafer. We will be extending this study in the near future to obtain a

more detailed map of diffusion length over the surface of the sample.

Samples 18202F and G do not show any significant differences in L, althought the have different doping densities. Part of our future study will be to measure L for a wide variety of doping densities.

Samples 2419 (Figure 7) illustrates one of the limitation of this technique. This sample had a much larger leakage current (100 nA at -0.1 V) than either 1636 (<5 nA at -0.1V) or 18202 (<100 pA at -0.1 V). This large reverse leakage will subtract from actual EBIC causing our measured EBIC to deviate significantly from predicted values. It was not surprising that the 2419 data did not fit theory as well as expected.

III. Conclusion

By curve fitting our experimental data to our theoretical curves, we were able to extract the minority-carrier diffusion lengths of n-type 6H SiC. Good agreement between theory and experiment was observed. The diffusion lengths of our samples ranged from 0.93 to 1.37 µm. These values have an estimated accuracy of better than ±20%. The extracted values of our metal layer thickness were well within range of our expected values, providing further evidence of the accuracy of the technique. Some of the limitations of the technique were seen with very leaky diodes, but overall, this technique appears to be an excellent way to measure the smaller diffusion lengths typical of SiC.

Table II. Results of experiment.

Specimen	Type	Carrier Conc.	Ohmic Contact	Schottky Contact	Extracted Metal Thickness	Expected Metal Thickness	Depletion Width	Diffusion Length L_p	Error +/-
1636 A	n/n+	1.35×10^{17}	Al	Ti	1563 Å	1500 Å	500 Å	1.28 µm	0.15 µm
1636 B	"	"	"	"	1519 Å	"	"	1.25 µm	0.15 µm
18202F	n/n+	1.65×10^{17}	Al	Pd	304 Å	300 Å	800 Å	0.98 µm	0.15 µm
18202G	n/n+	6.75×10^{16}	Al	Pd	407 Å	300 Å	1280 Å	0.93 µm	0.25 µm
2419	n/n+	6.14×10^{16}	Al	Ti	1292 Å	1500 Å	735 Å	1.37 µm	0.25 µm

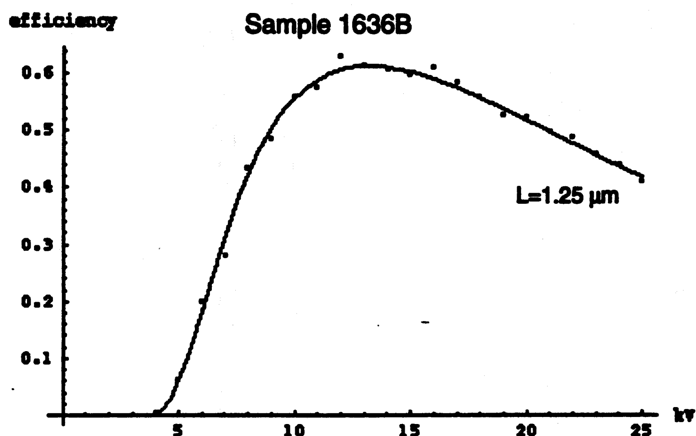

Fig 4. EBIC collection efficiency vs. beam voltage for Sample 1636 A and B. The dots are experimental data for 1636B. Data for 1636A was almost identical, and is not shown here.

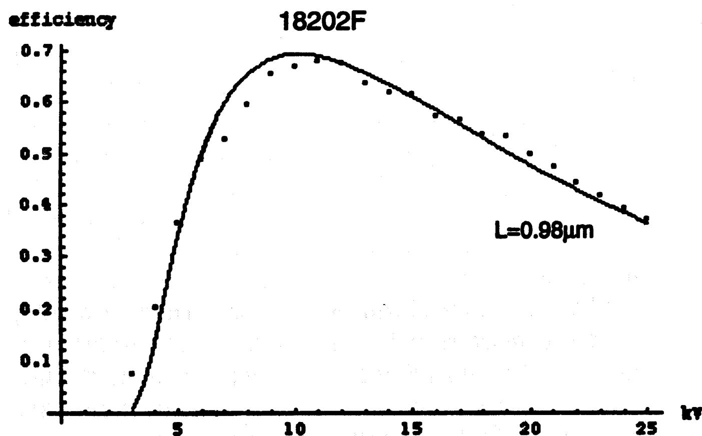

Fig 5. EBIC collection efficiency vs. beam voltage for Sample 18202F.

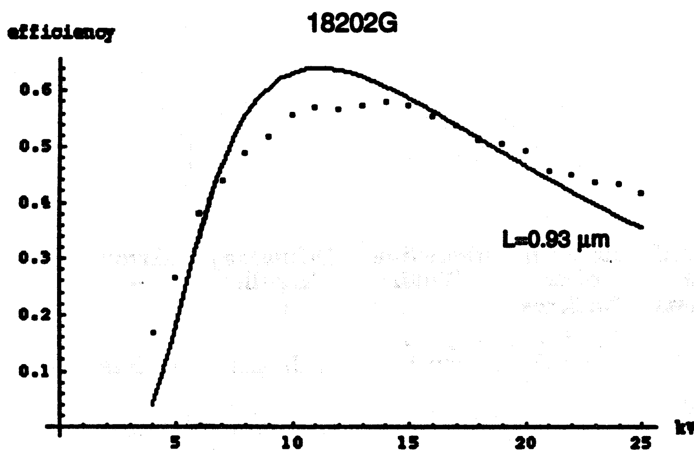

Fig 6. EBIC collection efficiency vs. beam voltage for Sample 18202G.

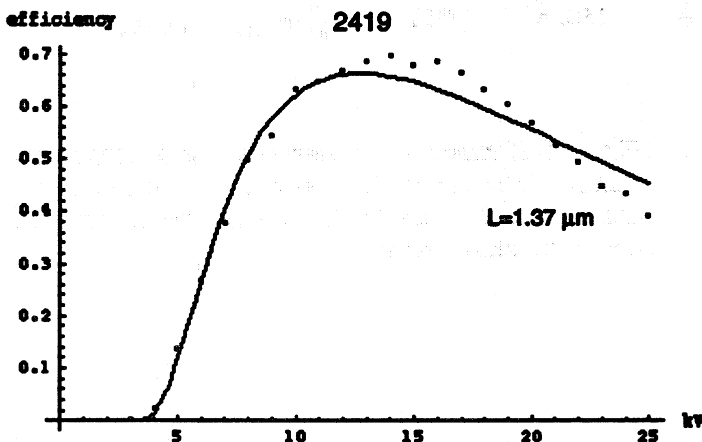

Fig 7. EBIC collection efficiency vs. beam voltage for Sample 2419.

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