EFFECT OF CRYSTAL DEFECTS ON MINORITY CARRIER DIFFUSION LENGTHS IN 6H SiC

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ABSTRACT

Minority-carrier diffusion lengths in n-type 6H-SiC were measured using the planar electron-beam induced current (EBIC) technique. Experimental values of electron beam current, EBIC, and beam voltage were obtained for n-type SiC with a carrier concentration of 1.7E17 cm^{-3}. This data was fit to theoretically calculated diode efficiency curves, and the diffusion length and metal layer thickness extracted. The extracted hole diffusion length ranged from 0.68 μm to 1.46 μm. The error for these values was ± 15%. Additionally, we introduce a novel variation of the planar technique. This "planar mapping" technique measures diffusion length along a linescan creating a map of diffusion length versus position. This map is overlaid onto the EBIC image of the linescan, allowing direct visualization of the effect of crystal defects on minority carrier diffusion length. Diffusion length maps of both n and p-type 6H SiC show that large micropipe defects severely limit the minority carrier diffusion length, reducing it well below 0.1 μm inside large defects.

INTRODUCTION

Recently, the viability of Silicon Carbide as a semiconductor material has been re-evaluated. The main thrust of research into SiC in the past two decades has been to exploit its high breakdown field and large thermal conductivity [1]. These two physical properties make SiC ideal for high power and high temperature applications, respectively. Additionally, SiC's wide bandgap (3.0 eV for 6H) makes it an attractive material for blue/UV sensors and emitters.

The minority carrier lifetimes and diffusion lengths are of critical importance in evaluation and computer simulation of devices. 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 densities on the electrical properties of the material [2].

In this work, we have used the Electron Beam Induced Current (EBIC) technique in order to measure the diffusion length. The planar method was first developed by Wu & Wittry in 1978 [3]. 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.

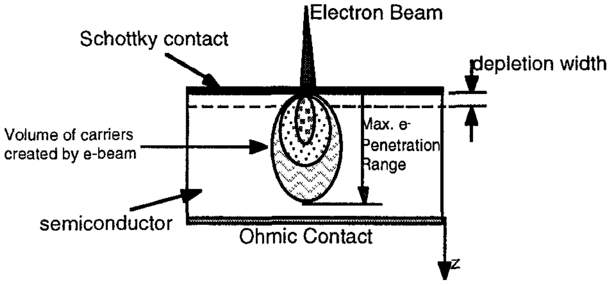

Fig. 1. Drawing of the experimental EBIC technique in the planer junction configuration.

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:

$$e = \frac{I_{cc}}{qG} \qquad (1)$$

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 [3]:

$$G(\sec^{-1}) = 1000 \frac{V_o i_{beam}}{q\varepsilon}(1 - \eta \frac{\overline{V}}{V_o}) \qquad (2)$$

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 values of η, $\overline{V}$, and ε were calculated from empirical formulas given in Goldstein [4], Tabet[5], and Holt [6], respectively.

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 [3].

The theoretical collection efficiency will depend on only four parameters:

$$e = f(R, L, Z, w) \qquad (3)$$

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, developed by Wittry and Kyser [7], was used in all our calculations:

$$R = 2.56 * 10^{-3} (\frac{V_o}{30})^{1.7} \text{g/cm}^2 \qquad (4)$$

The depletion width (w) was calculated using the doping concentration of the material. 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 Ti/SiC diode.

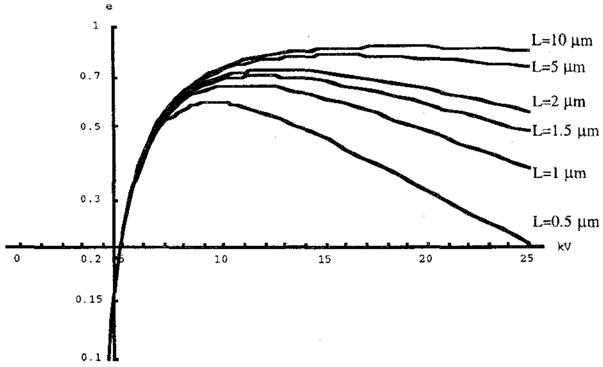

Fig. 2 Theoretical EBIC curves for Ti/SiC Schottky diodes. The metal layer thickness and the depletion layer width were both taken to be 1000Å.

B. Planar Mapping Technique

In the planar mapping technique, we combine both the linescan and planar EBIC methods. In the planar method only EBIC(V) was recorded. In the planar mapping technique we now record the two dimensional quantity EBIC(V,x). This 2-D measurement was accomplished using a computer controlled interface to the SEM and a Mathematica 3.0 program.

The Mathematica 3.0 program read in all of the EBIC data files and calculated a EBIC matrix, with the column position indicating scan voltage and row position indicating beam position. A collection efficiency matrix is calculated from the EBIC matrix and beam current data. Each row of the collection efficiency matrix is fit using the nonlinear fit routine in Mathematica. The resulting diffusion length versus beam position data was plotted to the screen, and then stored in a ASCII text file. A visualization of the effect of the defects on diffusion length was accomplished by overlaying the plot of diffusion length on top off the corresponding EBIC image.

EXPERIMENTAL

Sample A was an 5 µm n-type 6H SiC epilayer on an n^+ substrate [8]. Approximately 1500 Å of Ti were deposited using a diffusion pumped vacuum evaporator. After metallization, Schottky diodes of various sizes were created using reverse photolithography and etch. Ohmic contacts were made by evaporating 3000Å of Al on the back of the sample. Details of the sample preparation and contact procedure can be found in Hubbard [9].

Sample D was a Cree Research UV Photodiode. Its configuration was a thin (≈1000Å) n^+ layer on a 5µm p substrate. Information on this device can be found in Brown *et al.* [10]

All samples were analyzed using standard IV measurement techniques. Ideality Factor, Saturation Current Density and Barrier Height were extracted from the IV data [11]. Additionally, carrier concentration was extracted from CV profiles for each contact [9].

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 recorded using a GW Electronics Precision Specimen Current Meter [9]. The beam current was measured in a similar manner using a Faraday cup. A computer control was used in the planar mapping method [9]. The computer recorded EBIC as a function of position. Data was stored in ASCII text files.

RESULTS

A. Planar Results

The results of our experiments on Sample A are shown in Table 1. Diode ideality factors ranged from 1.12 to 1.21. Saturation current densities ranged from approx. 0.6 mA/cm^2 to 0.02 mA/cm^2. These current densities resulted in barrier heights ranging from 0.63 eV to 0.69 eV. Hole diffusion lengths ranged from 0.68 µm to 1.46 µm. The experimental error was ± 15% (±10% due to the fit error, and ±5% due to variations in EBIC and beam current).

A slight correlation between diffusion length and saturation current density was observed. This is expected, as a larger defect density will lead to increased leakage current and a corresponding increase in recombination centers which will drive down the effective bulk diffusion length.

B. Planar Mapping Results

The planar mapping technique was performed on Sample A, Dot A. Figure 3 shows the diffusion length map overlaid onto the EBIC image of the scan. The white line across the EBIC image indicates the position of the linescan. Diffusion lengths ranged from near 0.9 µm in defect free regions, to below 0.1 µm inside the largest defect. The extracted metal layer thickness remained near 1500Å for the entire linescan. Variations in metal layer thickness were usually less than 100Å [9].

In order to measure diffusion length of electrons in p-type SiC a linescan was performed on Sample D. The calculated doping concentration for the p side of the junction was 3.3E16 cm^{-3}. The result of our experiment is shown in Figure 4. The extracted metal layer thickness for our entire plot remained roughly constant, ranging from 1190Å to 1170Å. Electron diffusion length for this sample ranged from 1.42 µm to 0.8 µm.

CONCLUSION

In this paper we have reported two important results. First, we have measured a fundamental material characteristic in 6H SiC, the minority carrier diffusion length. Second, we have demonstrated a novel EBIC planar mapping method, which allows direct visualization of the effect of defects on minority carrier diffusion length.

In measuring diffusion length, we have reported minority carrier diffusion lengths in both n and p type 6H SiC. Using the planar EBIC method, hole diffusion lengths in defect free regions of n type 6H SiC, with a doping concentration of 1.5E17 cm^{-3}, ranged from 1.46 µm to 0.68 µm. In addition, using the planar mapping technique, we have shown that large defects in SiC severely limit the diffusion length, reducing it below well 0.1 µm at the center of large defects. Measurements of p-type SiC, with a doping concentration of 3.3E16 cm^{-3}, resulted in values of electron diffusion length ranging from 1.42 µm to 0.8 µm.

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Table 1 Results of Experiments on Sample A, Dots A-L

Dot	Carrier Density	Ideality Factor	Saturation Current Density (A/cm^2)	Barrier Height (eV)	Extracted Diffusion Length (μm)	Extracted Metal Thickness (Å)
A	1.5E+17	1.14	1.68E-04	0.63	0.87	1650
B	1.5E+17	1.13	1.51E-04	0.64	0.86	1646
C	1.5E+17	1.15	1.69E-04	0.63	0.88	1903
D	1.6E+17	1.21	9.13E-05	0.65	1.42	1588
E		1.18	4.18E-05	0.67	1.46	1503
F	1.5E+17	1.15	9.47E-05	0.65	0.98	1528
G	2.3E+17	1.12	1.68E-04	0.63	1.04	1522
H		1.15	5.93E-04	0.60	0.87	1629
I	1.4E+17	1.14	2.19E-04	0.63	0.68	1591
J	1.6E+17	1.16	2.03E-05	0.69	0.86	1518
K	1.5E+17	1.21	1.17E-04	0.64	1.02	1551
L	1.2E+17	1.13	8.40E-05	0.65	1.03	1659

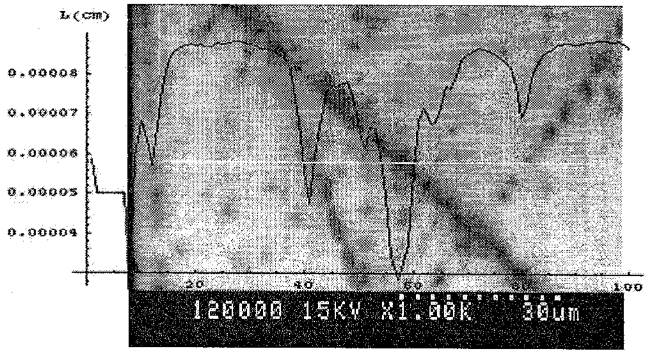

Figure 3. Diffusion length map for Sample A, Dot A overlaid onto the corresponding EBIC image.

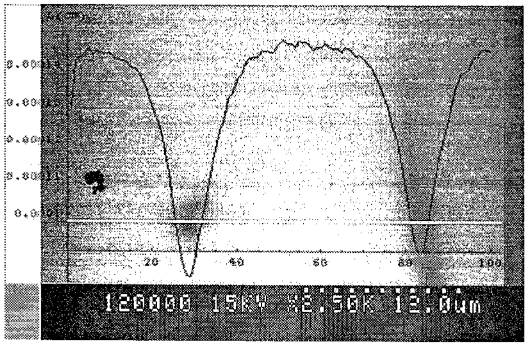

Figure 4. Diffusion length map for Sample D overlaid onto the corresponding EBIC image.