CHARACTERISATION OF GALLIUM NITRIDE AND TYPE IIa NATURAL DIAMOND CARRIER TRANSPORT PROPERTIES

By A.D. Cropper*

ABSTRACT

This research project examined the carrier transport properties; diffusion length, effective excess minority carrier lifetime and resistivity in two wide bandgap materials, GaN and type IIa natural diamond. Also, the role of the GaN/Sapphire interface was analysed with respect to these transport properties. A combination of two methods was used to obtain these transport properties. The two were optical beam induced current (OBIC) and electron beam induced current (EBIC) time of flight transient measurements. These techniques consist of measuring the current response to the drift and diffusion of generated electron-hole pair carriers created by a short-duration pulse of radiation.

Under OBIC, a short duration pulsed optical source, with an electron beam excitation pulse time much less than the transit time of the material, was used to generate excess carriers within the absorption depth of the material. The second method of excitation, EBIC involved the use of a modified SEM with a photo emission source (L-EBIC) and a high speed pulsed thermionic electron source (T-EBIC) to generate an electron beam. This electron beam was used to create a large number of electron-hole pairs at various penetration depths within the materials.

Measurements on GaN found the diffusion length was 7.84 μm with the L-EBIC and 7.78 μm with the T-EBIC. After annealing at 900°C for 30 mins., the GaN diffusion length increased to 9.89 μm (L-EBIC). These results showed that the interface did not play a significant role in the carrier diffusion process. The dark resistivity was 1.79×10^{10} *Ω-cm, and the carrier lifetimes were 1.7 μs with L-EBIC and 3.36 and 3.9 ns with OBIC. The author believed that the L-EBIC result was a good representation of the carrier lifetime within the material, while the shorter OBIC results were due to interface intervention in the recombination processes. The diamond dark resistivity was found to be* 6.14×10^{11} *Ω-cm and the diffusion lengths were 94.1 μm and 97 μm from the L-EBIC and T-EBIC respectively. All measurements were within 10% spread.*

1.0 INTRODUCTION

The continual need for microelectronic devices that operate under severe electronic and environmental conditions (high temperature, high frequency, high power, and high radiation fields) has sustained research in wide bandgap semiconductor materials. The transport properties of GaN and diamond wide bandgap semiconductor materials meet these requirements and have tremendous potential for industrial and military applications. High frequency field effect transistors, and short wavelength optical devices have been proposed for these materials [1-3]. Although research efforts involving the study of transport properties in these wide bandgap materials have made significant advances, much work is still needed to understand the material electronic properties so that the electrophysical behaviour of device structures can be further understood and exploited. Carrier transport measurements serve to verify theoretical calculations and device predictions to develop the next generation of devices. These factors in turn, tend to indicate that some wide bandgap semiconductor materials hold

---

* *Lecturer, Dept. of Electrical & Computer Engineering, The University of the West Indies (UWI)*

Pertinent discussion will be published in January 1997 West Indian Journal of Engineering if received by November, 1996.

promise for substantial improvements over today's devices. The thermal, mechanical, chemical and electronic properties of diamond and gallium nitride (GaN), to name a few, make these applications possible.

The electrical transport properties for GaN and diamond wide bandgap materials have presented experimental problems in their determination. The conventional Hall effect technique is difficult to perform due to the minuscule currents that flow within these materials in their intrinsic form at room temperature. The time of flight transient measurement technique was effective and provided a very direct approach in the investigation of transport properties [4-6]. Using the time of flight technique, the observation of the drift/diffusion of carriers across a sample led to the extraction of the electrical transport properties. This device-oriented measurement technique is very useful, particularly for materials of high resistivity and low carrier mobility. This research project examined the carrier transport properties (diffusion length, effective carrier lifetime and resistivity) in two of the wide bandgap materials, GaN and diamond.

Two methods were used to generate electron-hole pairs in GaN and diamond for this project. Optical beam induced current (OBIC) and electron beam induced current (EBIC) time of flight transient measurements techniques were utilised to obtain the transport properties. These techniques basically consist of measuring the current transient response to the drift and diffusion of carriers created by a short-duration pulse of radiation. When voltages are applied across the high resistivity materials with non-injecting contacts, a high field region is created with little dark current flow. The measurement of the transit time across the high field region led to the determination of the carrier lifetime. These methods differ from other experimental techniques (Hall effect technique, Haynes-Shockley technique and Many-Rakavy transient space charge limited currents technique) because they are based on a femto-second laser (OBIC) which produced a fast transient electron beam probe created from a high speed, laser-pulsed photo cathode (L-EBIC) or from an electron beam thermal pulsing source (T-EBIC).

The pulsed electron beam probe used in this project generated free carriers at a specific depth within the sample as shown in **Figure 1**. In the absence of an electric field, the diffusion current can be expressed as [7]:

$$I_{ph} = [I_o]\exp\left(-\frac{d}{L_n}\right) \qquad \text{.........(1)}$$

where L_n is the diffusion length, d is the distance from the collecting contact to the injected point and the amplitude (I_0) is a function mainly due to the depth of penetration, number of electron-hole pairs (ehp) generated and the primary energy. From the slope of the Ln (I_{ph}) versus distance, the diffusion length is extracted.

The effective excess carrier decay time (τ_m) is extracted from the transient analysis. Under transient conditions, the one dimensional continuity current equation for excess electron concentration Δn is given by [8]:

$$\frac{\partial \Delta n}{\partial t} = D\frac{\partial^2 \Delta n}{\partial t^2} - \frac{\Delta n}{\tau} + G \qquad \text{..........(2)}$$

where D is the diffusion coefficient and G is the generation rate. If the carrier decay is monitored after the electron pulse, G=0, the general solution can be expressed as:

$$\Delta n = \sum_m A_m \exp\left(-\frac{t}{\tau_m}\right) \qquad \text{...........(3)}$$

where A_m is the number of carriers generated in a unit volume at time zero for a given incident electron beam energy. The effective excess carrier decay time for each time constant τ_m is obtained by fitting the decaying portion of the transient response to the above equation.

2.0 EXPERIMENT

2.1 Measurement Setup

The set up for this experiment is shown in **Figure 2**. The experimental layout is broken into three parts: the electron beam generation section, and the modified scanning electron microscope (SEM) and the signal detection system. The electron beam was pulsed to avoid heating in the structures. This pulsed electron beam was created by either a laser-driven photo cathode gun (L-EBIC method) or a conventional tungsten filament thermal source electronically blanked with a parallel plate field deflector (T-EBIC method). The lasing system provided a pulse width of 200 femtoseconds at a 76 MHz repetition rate. The use of harmonic generators tripled the output of the Titanium: Sapphire model-locked laser to produce ultraviolet light between 250 - 300 nm at up to 30 mW of power. At this output wavelength and power, the electron beam induced current was in excess of 10 mA which was adequate in detecting the transport properties. The modified SEM was constructed with an interchangeable electron gun and a modified stage for electrical connections to various measurement apparatus. The beam spot size was measured to be 0.3 µm at 20 keV acceleration voltage. The detection system used utilised a variable input impedance high speed sampling oscilloscope and a data acquisition unit.

2.2 Technical Results

The GaN samples used in this project were 1.3 µm thick epitaxial layers on sapphire substrates. The structures were fabricated with 25 µm gap transmission lines made with electrode metalisation of A1/Ti. The details on the material growth and fabrication can be found in reference [1]. The dark currents were measured on an HP4145 parameter analyser. At a bias of positive 50 volts, the dark current was measured to be 7.0 pA and the dark resistivity was found to be 1.8 x 10^{10} ohm-cm. The diffusion length was found to be 7.84 µm and 7.78 µm for the L-EBIC and T-EBIC respectively. After annealing for 30 minutes at 900°C, the diffusion length was measured to be 9.898 µm. The results of the diffusion length are shown in **Figure 3** [9, 10]. The effective excess carrier decay time was found to be 1.7 µs from the electron beam probe across the structure. **Figure 4** shows the fitted effective excess carrier decay time for the GaN/Sapphire structure [9, 10]. Using the optical experimental measurement method (OBIC) at a wavelength of 320 nm, the effective excess carrier decay time was found to have the characteristics of a double exponential fit of values 3.36 ns and 3.9 ns. The fitted results from the OBIC method is shown in **Figure 5** [9, 10].

The type IIa natural diamond samples contacts were separated by a gap of 350 µm. At a bias of positive 100 volts, the dark current was measured to be 5.7 pA and the dark resistivity was found to be 6 x 10^{11} ohm-cm. The normalised EBIC current versus distance plots for diamond is shown in **Figure 6** [9, 11, 12]. The diffusion lengths of 94.1 µm and 97.0 µm were measured for the L-EBIC and T-EBIC measurements, respectively.

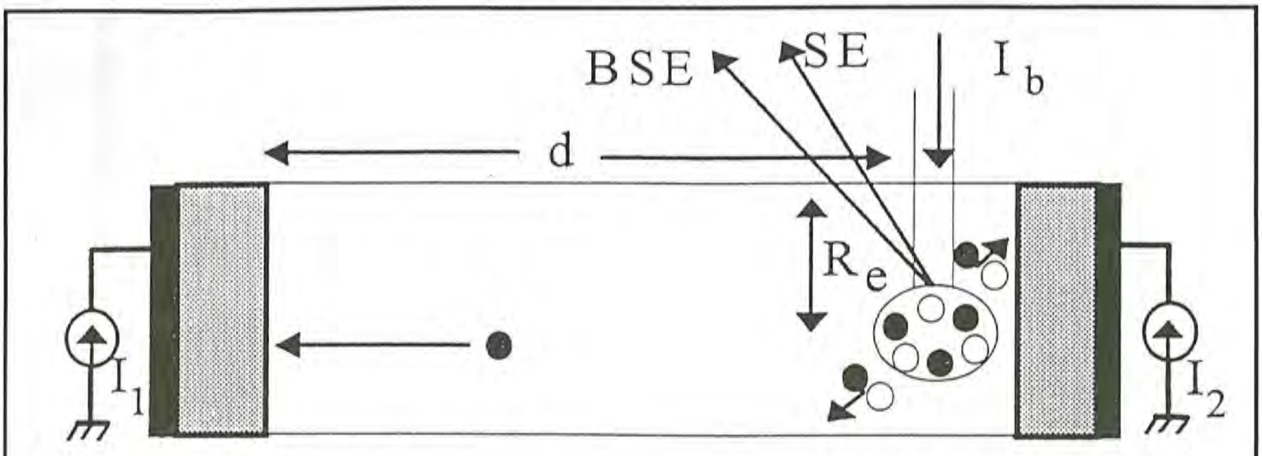
3.0 DISCUSSION AND CONCLUSION

The purpose of the research was to obtain diffusion lengths, effective excess carrier decay time and verify the high resistivity of two wide bandgap materials. The diffusion lengths of GaN and type IIa natural diamond measured for both the L-EBIC and T-EBIC methods were approximately the same. The same sample exhibited a slight reduction in diffusion length after continuous exposure to the electron beam bombardment. After annealing the GaN sample at 900°C for 30 minutes, the diffusion length showed improvement, possibly due to annealing out of structural defects. A possible explanation for the decrease in diffusion length after continuous electron beam exposure is that there is some damage from the beam itself. In this case, the results will be affected by the intensity and size of the electron probe.

The interface of the GaN/Sapphire structure did not play a significant role in the diffusion length from the EBIC methods. This was so because the depth of penetration was controlled by the primary energy and the volume of excess carriers was kept away from the interface region. However, the findings indicated that the closer the volume of the excess carriers were to the interface, the lower the diffusion length. For example, with larger primary energy, the diffusion length was observed to decrease to as low as 1.5 µm for the same sample.

The effective excess minority carrier decay time for GaN was found to be larger for the EBIC method than from the OBIC method. One possible explanation for this condition is multiple recombination within the structure from the OBIC method due to the presence of the interface region. Using the OBIC method, at a wavelength of 320 nm, the absorption depth [13] was found to be larger than the thickness of the GaN layer,

(Continued on page 22)



BSE	Back scattered electrons
SE	Secondary electrons
d	Distance between electron-hole pairs and collecting contact for minority carriers
I_b	Primary electron beam from electron gun
R_e	Depth at which the electron-hole pairs are created within the material
I_1 & I_2	Photoinduced electron or hole current

Figure 1: **Geometry of Electron Beam Interaction with Sample**

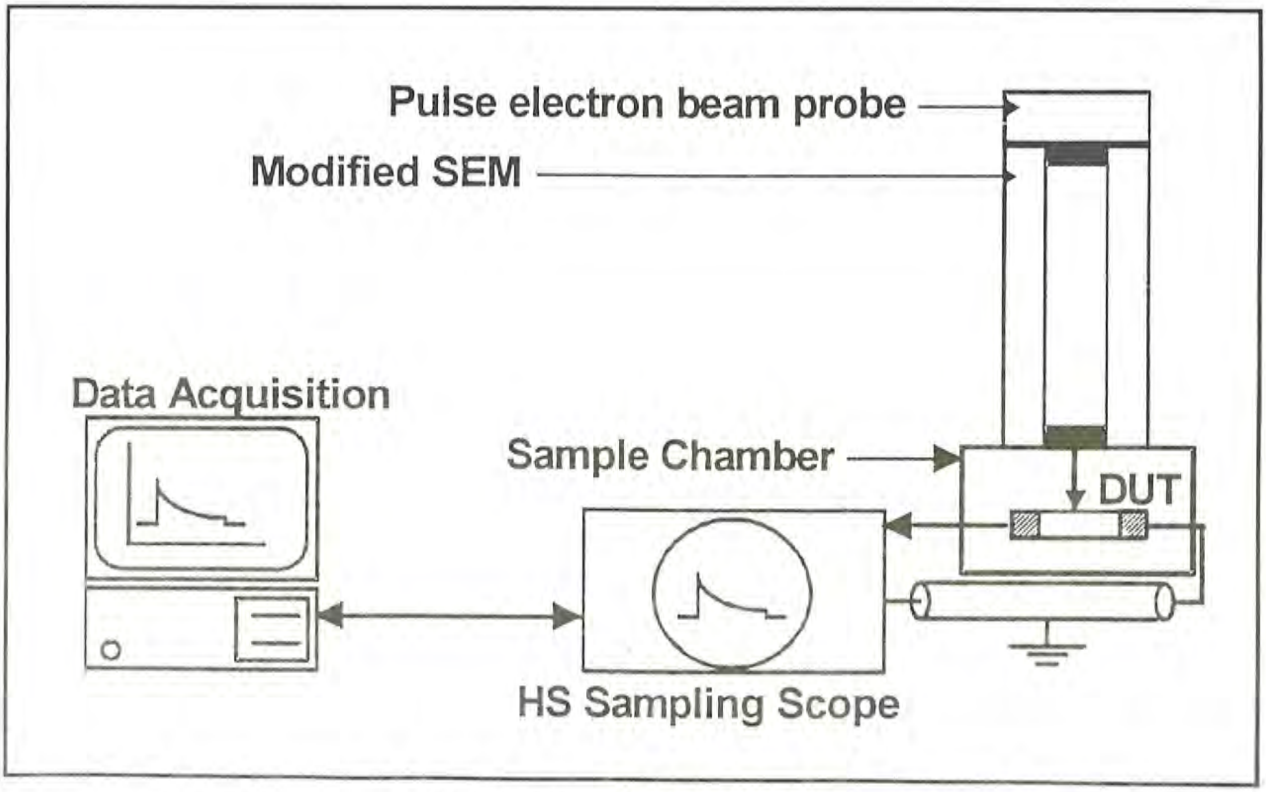


Figure 2: **EBIC Experimental Setup**

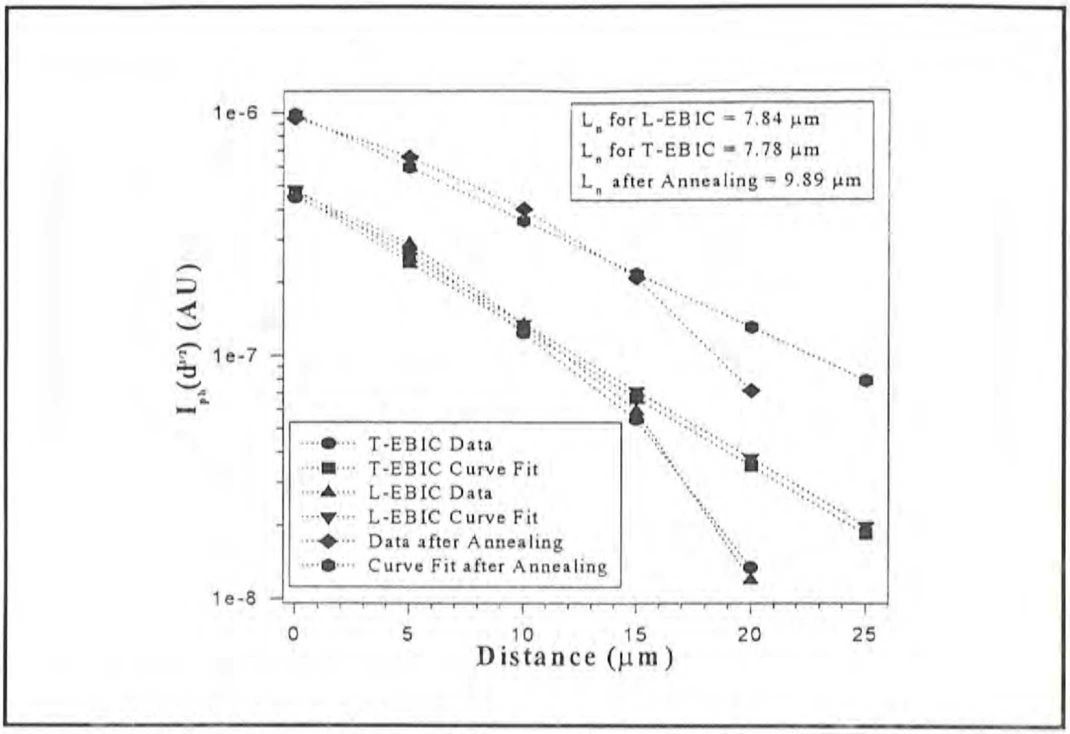


Figure 3: Diffusion Lengths in GaN/Sapphire Structure

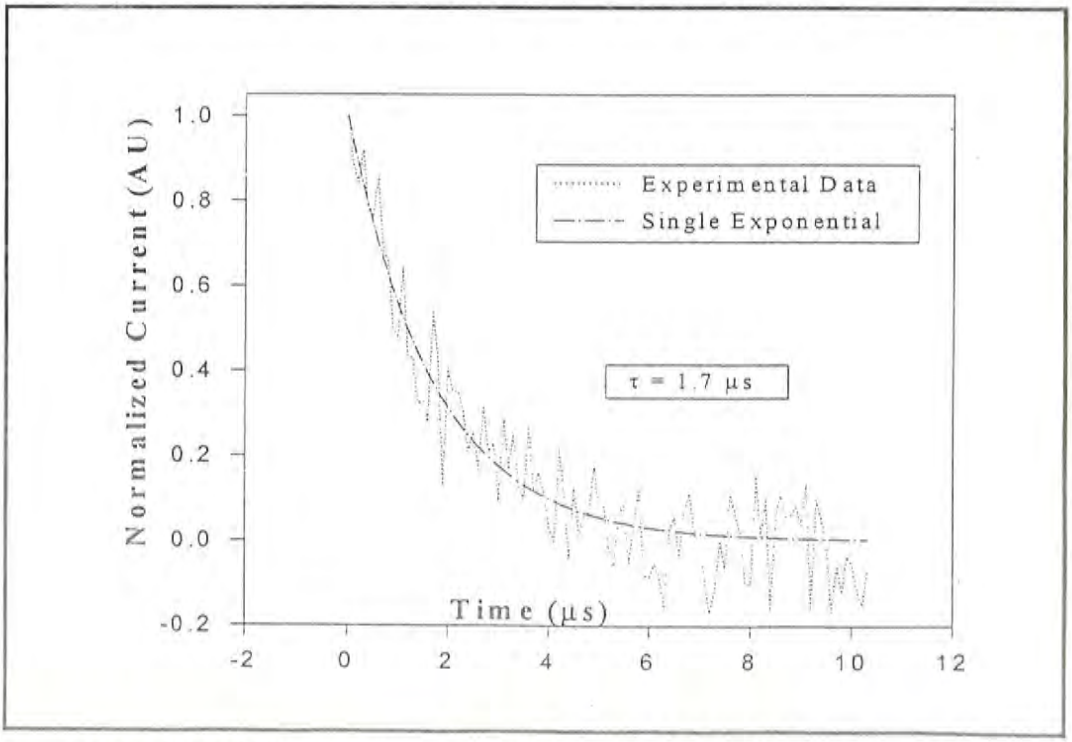


Figure 4: EBIC Effective Excess Carrier Decay Time for GaN/Sapphire Structure

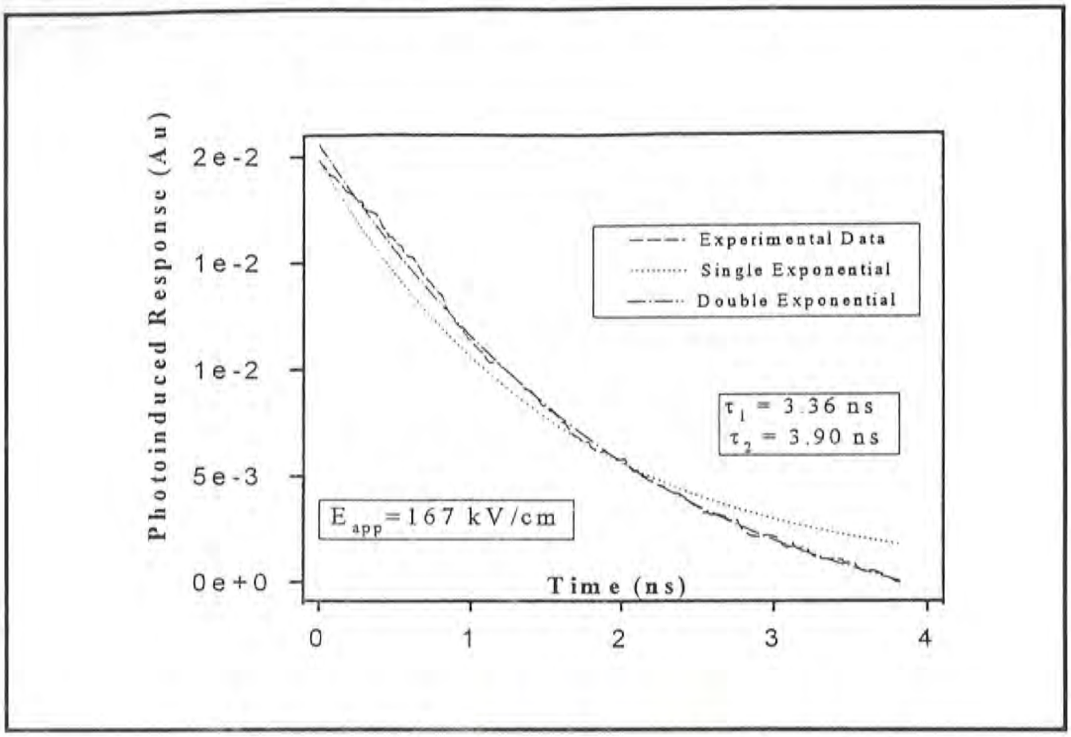


Figure 5: **Extracted OBIC Effective Excess Carrier Decay Time for GaN/Sapphire Structure**

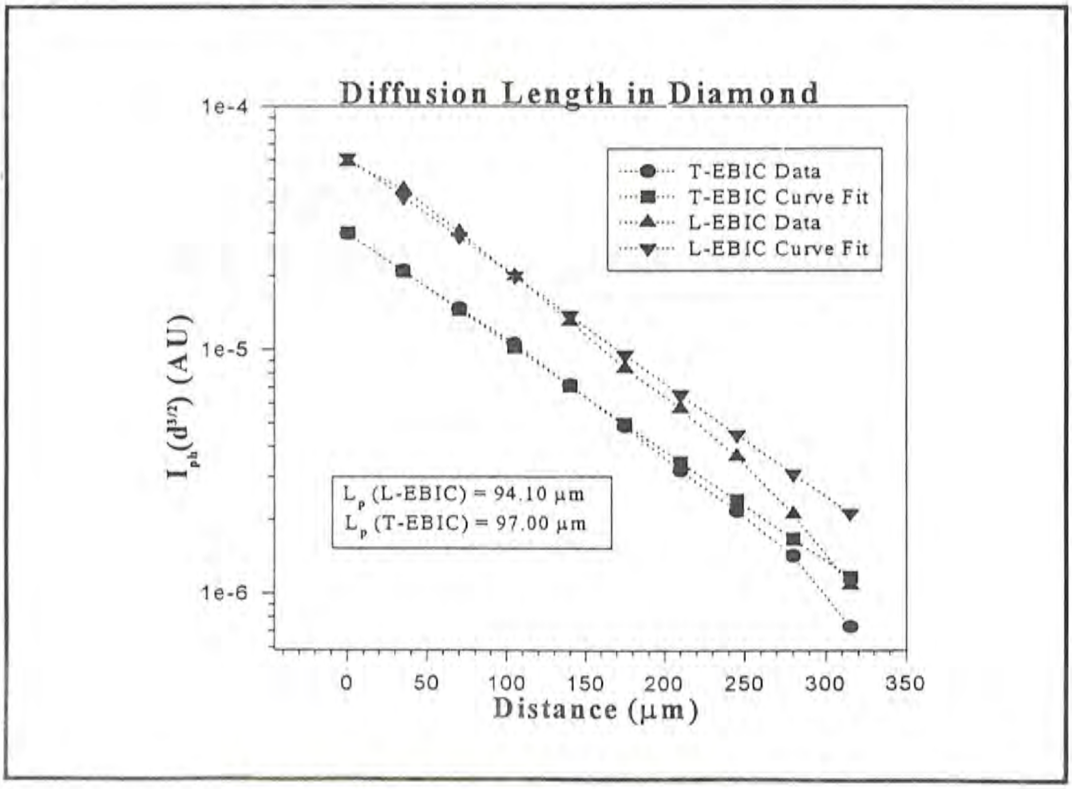


Figure 6: **Diffusion Length for Type IIa Natural Diamond**

(Continued from page 18)

indicating that the light interacted with the GaN/Sapphire interface. This resulted in reflection of some of the light within the GaN layer, therefore leading to a multiple recombination process as indicated by the double exponential fitted curve. However, from the EBIC method, the penetration depth was approximately one-third of the thickness of the GaN layer. Thus, the excess carriers were generated well away from the high recombination regions near the surface and interface. The results obtained from the EBIC method were believed to be a good representation of the effective thin film excess carrier decay time of the GaN layer and the OBIC results were representative of the multiple recombination process of the more dominant GaN/Sapphire interface region.

The resistivity for both GaN and type IIa natural diamond was found to be on the order of 10^{11} Ω-cm. These resistivities correlated with results found by Hofsas et al [15], Konorava et al [15] and Pan et al [16] for diamond and showed that in fact both materials were highly resistive.

REFERENCES

1. Binari, S.C. et al., Electronics Letters 30, 11, p. 909, 1994.

2. Davison, J.L. Proc. Third International Symposium on Diamond Materials, CECS Proc., p. 93, 1993.

3. Binari, S. C., Marchywka, M., Koolbeck, D.A., Dietrich, H.B. and Moses, D. Diamond and Related Materials, 2, p. 1020, 1993.

4. Hillmer, H., Mayer, G. and Forchel, A. Applied Physics Letters, 49, p. 948, 1986.

5. Westland, D.J. et al. Applied Physics Letters 51, p. 590, 1987.

6. Norris, Jr., C.B. and Gibbons, J.F. IEEE Transactions on Electron Devices, ED-14, p. 38, 1967.

7. Inoannov, D. and Dimitriadis, C. IEEE Trans. Electron Dev., ED-29, p. 445, 1982.

8. Schroder, D. *"Semiconductor Materials and Device Characterisation"*, John Wiley, NY 1990.

9. Cropper, A., Moore, D., Scott, C. and Green, R. SPIE Proc. XXVI Annual Symposium on Optical Materials for High Power Lasers, Boulder, Colorado 1994.

10. Cropper, A.D., Scott, C. and Moore, D. Proc. Fifth International Conference on the Formation of Semiconductor Interface, Princeton, New Jersey1995.

11. Cropper, A.D., Scott, C., Moore, D., Binari, S. and Wickenden, D. Electrochemical Society Proc. Fourth International Symposium on Diamond Materials, Las Vegas, Nevada 1995.

12. Scott, C.J., Cropper, A., Millings, A., Moore, D. and Binari, S. Proc. Third International Conference on the Applications of Diamond Films and Related Materials, Gathersburg, Maryland 1995.

13. Comphausen, D. and Connell, G. Journal of Applied Physics 42, no. 11, p. 4438, 1971.

14. Hofsass, H., Binder, H., Klumpp, T. and Recknagel, E. Diamond and Related Materials, 3, no. 1-2, p. 137, 1994.

15. Konarava, E.A. and Sherchenko, S.A. Soviet Physics-Semiconductor, 1, no. 3, p. 299, 1967.

16. Pan, L.S. et al. Applied Physics Letters, 57, no. 6, p. 623, 1990.■