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# Comparative study of minority electron properties in $p^+$ -GaAs doped with beryllium and carbon

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Minority electron properties in  $p^+$ -GaAs doped with beryllium (Be) and with carbon (C) are reported. Measurements of essentially identical responses for structures differing only in dopant element demonstrate that the diffusivity ( $D_n$ ) and the diffusion lengths ( $L_n$ ) are the same in  $p^+$ -GaAs doped to  $\sim 10^{19} \text{ cm}^{-3}$  with Be- and C-dopants. Zero-field time-of-flight analysis yields  $D_n = 35 \text{ cm}^2/\text{s}$  and internal quantum efficiency analysis yields  $L_n = 2.4 \mu\text{m}$ , which implies a lifetime that is approximately at the estimated radiative limit. In addition, the majority Hall mobility was also found to be identical for the Be- and C-doped material.

Minority electron transport in  $p^+$ -GaAs can limit the performance of bipolar devices. One example is  $Npn$ -heterojunction bipolar transistors (HBT) in which the base is typically doped to  $\sim 10^{19} \text{ cm}^{-3}$ . As an alternate dopant for HBT bases, carbon (C), rather than beryllium (Be), has been suggested. Since Be and C are incorporated in the lattice differently (Be on a gallium site and C on an arsenic site, with a resulting different core electronic structure), minority electron properties may also be different for the two dopants. To aid in the design and optimization of HBTs, and other bipolar devices, accurate minority carrier transport parameters for Be- and C-doped  $p^+$ -GaAs are needed.

In this letter we report the results of a study of minority electron diffusivity ( $D_n$ ), or equivalently mobility, and diffusion length ( $L_n$ ) in  $p^+$ -GaAs doped with Be and C. We found that  $D_n$  and  $L_n$  are the same for both Be- and C-dopants. The zero-field time-of-flight technique (ZFTOF) was used to measure  $D_n$ , and  $L_n$  was deduced from internal quantum efficiency (IQE) analysis. For  $p^+$ -GaAs doped to  $\sim 10^{19} \text{ cm}^{-3}$ , analyses showed that  $D_n = 35 \text{ cm}^2/\text{s}$  and  $L_n = 2.4 \mu\text{m}$  for both Be- and C-dopants. In addition to the finding of identical minority mobility with Be- and C-dopants, the Hall mobility was also found to be independent of dopant ion.

The ZFTOF technique is diagrammed in Fig. 1. In this technique, specially designed photodiodes with junctions 1–2  $\mu\text{m}$  deep in the structure are photoexcited by a picosecond laser pulse. The resulting transient voltage response characterizes diffusion of minority carriers in the zero-field region between the diode surface and junction; this region will be referred to as the emitter. For photogeneration, we use a mode-locked argon laser, synchronously pumping a dye laser containing Rhodamine 6G dye. The laser system is tuned for transform-limited pulse widths of 4–5 ps and is cavity dumped at a rate of 4 MHz. So that most of the carriers are generated near the diode surface in the emitter,

600 nm excitation, with an absorption length ( $\alpha^{-1}$ ) of  $\sim 0.2 \mu\text{m}$ , is selected. Since  $\alpha^{-1}$  is much less than the emitter thickness, there is low sensitivity to  $\alpha$ . Carriers that diffuse across the emitter to the junction are swept through the depletion region by the built-in field. These carriers charge the  $pn$ -junction capacitor giving rise to a transient response that is measured with a Tektronix 7854 digitizing sampling oscilloscope equipped with an S-4 sampling head. The diffusivity is deduced from appropriate fits to the measured data.

The diffusion lengths, of the same films studied with the ZFTOF technique, are deduced from the analysis of steady-state internal quantum efficiency (IQE). In IQE analysis, the steady state short-circuit collection efficiency of minority carriers and the reflectivity is measured as a function of monochromatic generation to yield the internal IQE versus wavelength. Simulations of the IQE response are fit to the measured data to extract  $L_n$ . Contributions to the current from all layers in the structure are considered in the analysis. In the energy range of interest, the IQE is sensitive to only  $L_n$ , since the diodes are designed with a low surface recombination velocity ( $S_f < 10^4 \text{ cm/s}$ ) at the illuminated surface.

For this study, two Be-doped (one C-doped) film

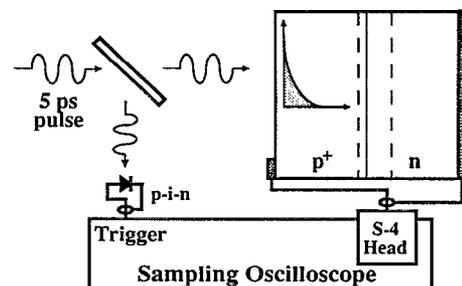


FIG. 1. Schematic diagram of the ZFTOF technique for measuring minority electron diffusivity in  $p^+$ -GaAs. The photodiode transient response characterizes minority carrier diffusion in the  $p^+$ -GaAs layer.

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structures were grown by MBE on [100]  $n^+$ -GaAs substrates in a Varian GEN-II Solid (Modular Gas) Source System. The C-gas source was  $\text{CCl}_4$ .<sup>1</sup> The photodiode structure is described as follows. The first layer is a  $1\ \mu\text{m}$  buffer layer doped to  $5 \times 10^{17}\ \text{cm}^{-3}$  ( $1.1 \times 10^{17}\ \text{cm}^{-3}$ ) with silicon (germanium) for junction formation in the Be-doped (C-doped) device; essentially all of the depletion region lies in the  $n$ -type layers. The  $p^+$ -GaAs emitter layers are  $1.7$  and  $1.0\ \mu\text{m}$  thick in the Be-doped devices and  $1.0\ \mu\text{m}$  thick in the C-doped devices. Emitter thicknesses are accurately controlled by calibrated growth rates determined from RHEED oscillations. SIMS analysis verified the C-doped emitter thickness and a uniform emitter doping profile. An approximately  $0.04\ \mu\text{m}$  thick, wide band-gap  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer ( $x=0.27$  and  $x=0.2$  for Be- and C-doped devices, respectively) passivates the emitter surface to provide a low surface recombination velocity at the illuminated surface. Finally, an approximately  $0.04\ \mu\text{m}$   $p^+$ -GaAs layer is incorporated for formation of ohmic contacts. To avoid damaging the low  $S_f$  AlGaAs-emitter interface, the cap layer is not removed.

Contact pads for the mesa isolated photodiodes are moved off the diode mesa onto adjacent Du Pont Pyralin<sup>®</sup> dielectric mesas. The diode mesas,  $500 \times 500\ \mu\text{m}^2$  in size, are formed by wet etching with  $\text{NH}_4\text{OH}:\text{H}_2\text{O}_2:\text{DI}$  (10:3.5:500). Nonalloyed ohmic contacts that shadow  $<1\%$  of the junction are formed with Au:Ti:Au metallization, and alloyed AuGe:Ti:Au ohmic contacts are used to contact the backside of the  $n^+$ -substrates. The devices are packaged in a modified Wiltron K Connector<sup>®</sup> package, which has been characterized with  $S$ -parameter measurements to show that the contact lead inductance is  $<0.2\ \text{nH}$ . Parasitic contact pad capacitance is  $<1\ \text{pF}$ . For these devices, circuit effects are minimized with device design and microwave packaging.<sup>2</sup>

Fitting parameters for the ZFTOF data are  $D_n$ ,  $\tau_n$ , and  $S_f$ . For  $S_f < 10^4\ \text{cm/s}$ , which is reasonable for the low mole fraction AlGaAs interfaces that are present in these devices, the ZFTOF transient is insensitive to  $S_f$ . In addition, the diodes were designed to have photocurrent responses that are relatively insensitive to  $\tau_n$ . The photocurrent peaks when the diffusion process, which we are characterizing, is the strongest. Therefore, we fit to the differentiated measured response ( $v_m$ ), which is related to the photocurrent<sup>2</sup> by

$$\frac{dv_m(t)}{dt} = \frac{1}{C_j} i_{\text{ph}}(t). \quad (1)$$

As described previously,<sup>2,3</sup> the photocurrent is calculated by numerically solving the minority carrier diffusion equation using an absorption coefficient of  $4.85 \times 10^4\ \text{cm}^{-1}$ . To correlate the time axes of the measured data and the simulations, we use the response of a  $p$ - $i$ - $n$  diode, which is shown in Fig. 2; the  $p$ - $i$ - $n$  diode is mounted in an identical ZFTOF package.

Several devices of each structure were characterized with ZFTOF transient analysis, IQE analysis, Hall effect measurements, and  $C$ - $V$  measurements. Hall concentrations of  $7.5 \times 10^{18}$  and  $8.9 \times 10^{18}\ \text{cm}^{-3}$  were found for the

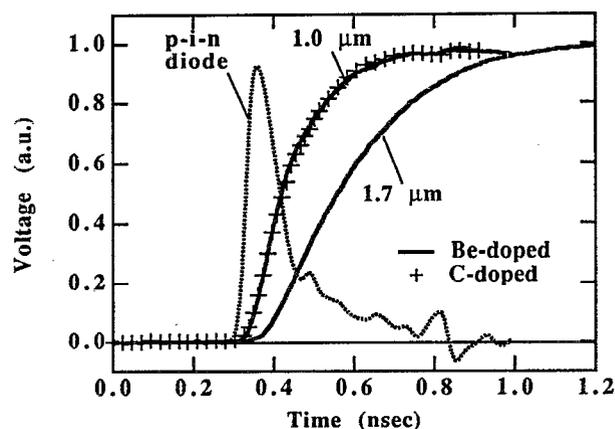


FIG. 2. Normalized measured responses for ZFTOF diodes with Be- (solid curves) and with C-doped (+) devices. The  $1.0\ \mu\text{m}$  Be- and C-doped device responses are essentially identical. Also shown is the  $p$ - $i$ - $n$  diode response that is used to correlate the experimental and simulation time axes.

Be- and C-doped films, respectively. SIMS analysis of the C-doped film shows 10% compensation. An identical Hall mobility of  $105\ \text{cm}^2/\text{V s}$  was found for both dopants and is consistent with the upper range of values that have been reported for Be- and C-doped  $p^+$ -GaAs.

As shown in Fig. 2, the transient ZFTOF measurements showed essentially identical responses for the  $1.0\ \mu\text{m}$  Be- and C-doped devices, which implies, independent of data analysis, that  $D_n$  is the same for the Be- and C-doped films. Also shown in Fig. 2 is the difference in signal rise times for the devices with  $1.0$  and  $1.7\ \mu\text{m}$  emitters. Consistent results were obtained from analyses of the two data sets. Both sets are fit with the same diffusivity and lifetime,  $D_n = 35\ \text{cm}^2/\text{s}$  and  $\tau_n \geq 1.5\ \text{ns}$ , as shown in Fig. 3. For  $\tau_n \geq 1.5\ \text{ns}$ , collection efficiency is very high, therefore, there was little sensitivity to longer lifetimes. The measured  $D_n = 35\ \text{cm}^2/\text{s}$  is higher than we reported previously<sup>3,4</sup> for comparable doping. The main reason for the difference was traced to two-dimensional charge transport effects<sup>2</sup> which were minimized in this work.

Our value of  $D_n = 35\ \text{cm}^2/\text{s}$  is between other published  $D_n$  values. Furuta *et al.* reported a low-field mobility of  $D_n = 21\ \text{cm}^2/\text{s}$  for Be-doped  $p^+$ -GaAs.<sup>5</sup> Their results, however, were measured in the presence of an applied field, which could produce a lower mobility due to hole drag.<sup>6</sup> ZFTOF measurements of  $\sim 10^{19}\ \text{cm}^{-3}$  C-doped  $p^+$ -GaAs by Colomb *et al.* yielded comparable  $D_n$ , but much shorter lifetimes. At  $\sim 10^{19}\ \text{cm}^{-3}$ ,  $D_n = 26\ \text{cm}^2/\text{s}$ , and  $\tau_n = 0.2\ \text{ns}$  were found, and at  $6 \times 10^{18}\ \text{cm}^{-3}$ , they found  $D_n = 37\ \text{cm}^2/\text{s}$  and  $\tau_n = 0.45\ \text{ns}$ .<sup>7</sup> With  $f_T$  analysis of HBTs, Lee *et al.* determined  $D_n = 56\ \text{cm}^2/\text{s}$  for  $p^+$ -GaAs with approximately three times greater doping.<sup>8</sup> Lowney and Bennett showed that above  $\sim 10^{19}\ \text{cm}^{-3}$   $D_n$  should increase,<sup>9</sup> and a change from 35 to  $56\ \text{cm}^2/\text{s}$  agrees in magnitude with the greatest increase that they found. However, a lower diffusivity,  $\sim 25\ \text{cm}^2/\text{s}$ , was predicted at  $\sim 10^{19}\ \text{cm}^{-3}$ . It is noted that the Hall mobility for the studies discussed above were comparable to our result of  $105\ \text{cm}^2/\text{V s}$ .

Using the Einstein relation, a minority electron mobil-

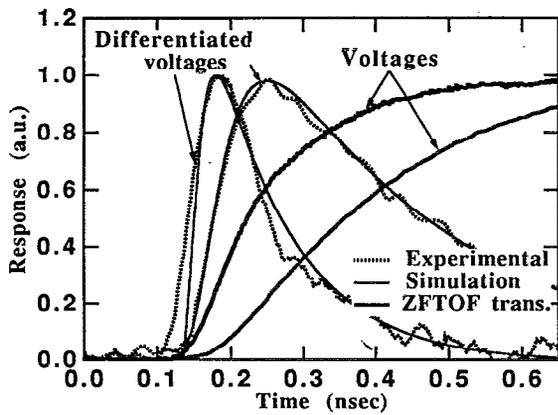


FIG. 3. Fits to the differentiated voltage data, which is approximately the photocurrent that is driven by the diffusion process. Excellent fits to both the 1.0 and 1.7  $\mu\text{m}$  emitter responses are shown. Fit parameters are  $D_n=35 \text{ cm}^2/\text{s}$ ,  $\tau_n=1.7 \text{ ns}$  and  $S_f=0.0$ . Also shown are the measured ZFTOF transient voltages.

ity ( $\mu_n^{(p)}$ ) of  $1385 \text{ cm}^2/\text{V s}$  is calculated from  $D_n=35 \text{ cm}^2/\text{s}$ . A comparison of  $\mu_n^{(p)}$  with the majority electron mobility in comparably doped  $n^+$ -GaAs (Ref. 10) shows that the majority electron mobility is  $\sim 35\%$  higher. This result may be explained by the additional scattering of minority electrons by the degenerate hole gas.<sup>9</sup>

Similar to the ZFTOF results, the 1.0  $\mu\text{m}$  C- and Be-doped devices exhibited essentially the same IQE response. Again independent of analysis, this indicates that  $L_n$  is comparable for the two dopants. As shown in Fig. 4, quite different spectral responses were measured for the structures with 1.0 and 1.7  $\mu\text{m}$  emitters, but they were both fit with  $L_n=2.4 \mu\text{m}$  and  $S_f=0$ . The short wavelength response indicated that the C-doped caps were slightly thinner than those of the Be-doped devices. This is inconsequential for the ZFTOF analysis, but was considered in the IQE analysis. The fit was insensitive to  $S_f < 10^5 \text{ cm/s}$ . It is noted that a higher  $S_f$  requires an even longer  $L_n$  to yield a reasonable fit to the data.

Combining this diffusion length with  $D_n$  from the ZFTOF analysis yields a lifetime of 1.7 ns. This is in good agreement with recent results for time-resolved photoluminescence studies of C-doped  $p^+$ -GaAs (Ref. 11) and with results published in a recent review of measured lifetimes.<sup>12</sup> A fit to the latter data in the range  $0.1-1 \times 10^{19} \text{ cm}^{-3}$  yields a B coefficient of  $0.75 \times 10^{-10} \text{ cm}^3/\text{s}$  ( $\tau_{\text{rad}}=1/BN_A$ ), which also agrees with our lifetime. In degenerate material where the band structure is perturbed from the intrinsic structure, estimates for the B-coefficient vary from  $0.9-1.7 \times 10^{-10} \text{ cm}^3$ .<sup>13</sup> Within the uncertainties of the data, there is good agreement between the radiative lifetime and our measured lifetime.

In conclusion, we found that  $D_n$ ,  $L_n$ , (or equivalently  $D_n$  and  $\tau_n$ ) and the majority hole mobility are the same for

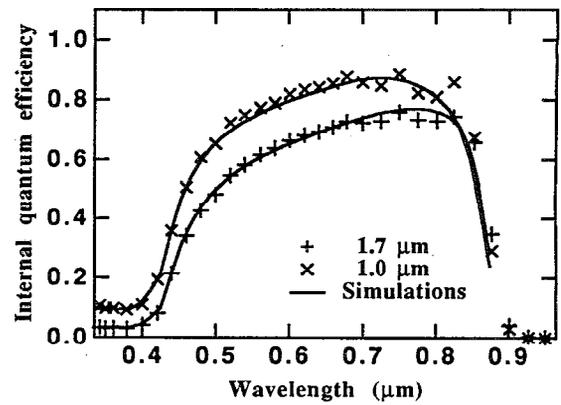


FIG. 4. Fits to the internal quantum efficiency vs wavelength for the 1.0  $\mu\text{m}$  (C-doped) and the 1.7  $\mu\text{m}$  (Be-doped) diode structures with  $L_n=2.4 \mu\text{m}$  and  $S_f=0$ . The thinner emitter devices have higher IQE response and were essentially the same for both Be- and C-dopants.

$p^+$ -GaAs doped to  $\sim 10^{19} \text{ cm}^{-3}$  with both Be- and C-dopants. Consistent results for devices with different active layers yielded  $D_n=35 \text{ cm}^2/\text{s}$  and  $L_n=2.4 \mu\text{m}$ . These parameters imply a lifetime of 1.7 ns, which is at the radiative limit and indicates that the material used in this study is of high quality.

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