View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Purdue E-Pubs

Purdue University
Purdue e-Pubs

Department of Electrical and Computer Engineering Faculty Publications | Department of Electrical and Computer Engineering

1992

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

Michael L. Lovejoy
Purdue University

Michael R. Melloch
Purdue University, melloch@purdue.edu

Mark S. Lundstrom
Purdue University, lundstro@purdue.edu

R. K. Ahrenkiel
National Renewable Energy Laboratory, Golden, CO

B. M. Keyes
National Renewable Energy Laboratory, Golden, CO

See next page for additional authors

Follow this and additional works at: https://docs.lib.purdue.edu/ecepubs

Part of the Electrical and Computer Engineering Commons

Lovejoy, Michael L.; Melloch, Michael R.; Lundstrom, Mark S.; Ahrenkiel, R. K.; Keyes, B. M.; de Lyon, T. J.; and Woodall, J. M., "Comparative study of minority electron properties in p+-GaAs doped with beryllium and carbon" (1992). *Department of Electrical and Computer Engineering Faculty Publications.* Paper 93.
http://dx.doi.org/10.1063/1.107756

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

Authors
Michael L. Lovejoy, Michael R. Melloch, Mark S. Lundstrom, R. K. Ahrenkiel, B. M. Keyes, T. J. de Lyon, and J. M. Woodall

This article is available at Purdue e-Pubs: https://docs.lib.purdue.edu/ecepubs/93

·

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

M. L. Lovejoy, M. R. Melloch, and M. S. LundstromB. M. Keyes and R. K. AhrenkielT. J. de Lyon and J. M. Woodall

Citation: **61**, (1992); doi: 10.1063/1.107756
View online: http://dx.doi.org/10.1063/1.107756
View Table of Contents: http://aip.scitation.org/toc/apl/61/7
Published by the American Institute of Physics

RIGHTSLINK
Copyright Clearance Center

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

M. L. Lovejoy, M. R. Melloch, and M. S. Lundstrom
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907

B. M. Keyes and R. K. Ahrenkiel
National Renewable Energy Laboratory, Golden, Colorado 80401

T. J. de Lyon[a] and J. M. Woodall
IBM Thomas J. Watson Research Center, Yorktown Heights, New York, 10598

(Received 23 March 1992; accepted for publication 4 June 1992)

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 $\sim 10^{19}$ cm^{-3} with Be- and C-dopants. Zero-field time-of-flight analysis yields $D_n = 35$ cm^2/s and internal quantum efficiency analysis yields $L_n = 2.4$ μm, 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 $\sim 10^{19}$ 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 $\sim 10^{19}$ cm^{-3}, analyses showed that $D_n = 35$ cm^2/s and $L_n = 2.4$ μm 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 μm 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 (α^{-1}) of ~ 0.2 μm, is selected. Since α^{-1} is much less than the emitter thickness, there is low sensitivity to α. 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 ($S_f < 10^4$ cm/s) at the illuminated surface.

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

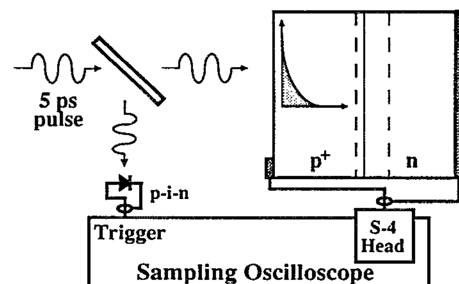

FIG. 1. Schematic diagram of the ZFTOF technique for measuring minority electron diffusivity in p^+-GaAs. The photodiode transient response characterizes minority carrier diffusion in the p^+-GaAs layer.

[a]Present address: Hughes Research Laboratory Malibu, CA, 90265.

 © 1992 American Institute of Physics

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 CCl_4.[1] The photodiode structure is described as follows. The first layer is a 1 μm buffer layer doped to 5×10^{17} cm^{-3} (1.1×10^{17} 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 μm thick in the Be-doped devices and 1.0 μm 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 μm thick, wide band-gap $Al_xGa_{1-x}As$ 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 μm p^+-GaAs layer is incorporated for formation of ohmic contracts. 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® dielectric mesas. The diode mesas, 500×500 μm^2 in size, are formed by wet etching with $NH_4OH:H_2O_2$: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® package, which has been characterized with S-parameter measurements to show that the contact lead inductance is <0.2 nH. Parasitic contact pad capacitance is <1 pF. For these devices, circuit effects are minimized with device design and microwave packaging.[2]

Fitting parameters for the ZFTOF data are D_n,τ_n, and S_f. For $S_f \lessdot 10^4$ 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 τ_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[2] by

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

As described previously,[2,3] the photocurrent is calculated by numerically solving the minority carrier diffusion equation using an absorption coefficient of 4.85×10^4 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 7.5×10^{18} and 8.9×10^{18} cm^{-3} were found for the

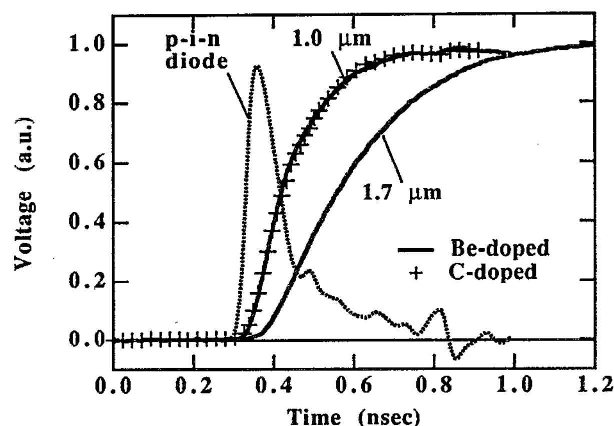

FIG. 2. Normalized measured responses for ZFTOF diodes with Be- (solid curves) and with C-doped (+) devices. The 1.0 μm Be- and C-doped device responses are essentially identical. Also shown is the p-i-n diode response that is used to correlate the experimental and simulation time axes.

Be- and C-doped films, respectively. SIMS analysis of the C-doped film shows 10% compensation. An identical Hall mobility of 105 cm^2/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 μm 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 μm emitters. Consistent results were obtained from analyses of the two data sets. Both sets are fit with the same diffusivity and lifetime, $D_n=35$ cm^2/s and $\tau_n \geqslant 1.5$ ns, as shown in Fig. 3. For $\tau_n \geqslant 1.5$ ns, collection efficiency is very high, therefore, there was little sensitivity to longer lifetimes. The measured $D_n=35$ cm^2/s is higher than we reported previously[3,4] for comparable doping. The main reason for the difference was traced to two-dimensional charge transport effects[2] which were minimized in this work.

Our value of $D_n=35$ cm^2/s is between other published D_n values. Furuta *et al.* reported a low-field mobility of $D_n=21$ cm^2/s for Be-doped p^+-GaAs.[5] Their results, however, were measured in the presence of an applied field, which could produce a lower mobility due to hole drag.[6] ZFTOF measurements of $\sim10^{19}$ cm^{-3} C-doped p^+-GaAs by Colomb *et al.* yielded comparable D_n, but much shorter lifetimes. At $\sim10^{19}$ cm^{-3}, $D_n=26$ cm^2/s, and $\tau_n=0.2$ ns were found, and at 6×10^{18} cm^{-3}, they found $D_n=37$ cm^2/s and $\tau_n=0.45$ ns.[7] With f_T analysis of HBTs, Lee *et al.* determined $D_n=56$ cm^2/s for p^+-GaAs with approximately three times greater doping.[8] Lowney and Bennett showed that above $\sim10^{19}$ cm^{-3} D_n should increase,[9] and a change from 35 to 56 cm^2/s agrees in magnitude with the greatest increase that they found. However, a lower diffusivity, ~25 cm^2/s, was predicted at $\sim10^{19}$ cm^{-3}. It is noted that the Hall mobility for the studies discussed above were comparable to our result of 105 cm^2/V s.

Using the Einstein relation, a minority electron mobil-

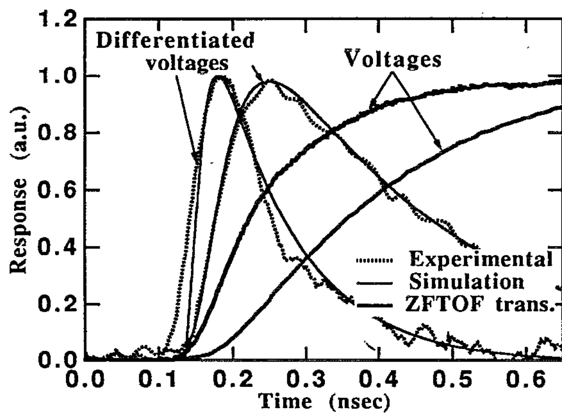

FIG. 3. Fits to the differentiated voltage data, which is approximately the photocurrent that is driven by the diffusion process. Excellent fits to both the 1.0 and 1.7 μm emitter responses are shown. Fit parameters are $D_n=35$ cm^2/s, $\tau_n=1.7$ ns and $S_f=0.0$. Also shown are the measured ZFTOF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

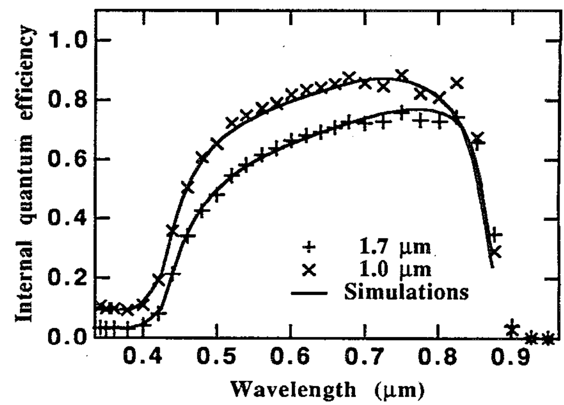

FIG. 4. Fits to the internal quantum efficiency vs wavelength for the 1.0 μm (C-doped) and the 1.7 μm (Be-doped) diode structures with $L_n=2.4$ μm and $S_f=0$. The thinner emitter devices have higher IQE response and were essentially the same for both Be- and C-dopants.

ity ($\mu_n^{(p)}$) of 1385 cm^2/V s is calculated from $D_n=35$ cm^2/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.[9]

Similar to the ZFTOF results, the 1.0 μm 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 μm emitters, but they were both fit with $L_n=2.4$ μm 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 $S_f < 10^5$ 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.[12] A fit to the latter data in the range $0.1\text{–}1\times10^{19}$ cm^{-3} yields a B coefficient of 0.75×10^{-10} cm^3/s ($\tau_{\rm rad}=1/BN_A$), 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 $\times10^{-10}$ cm^3.[13] 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 τ_n) and the majority hole mobility are the same for p^+-GaAs doped to $\sim10^{19}$ cm^{-3} with both Be- and C-dopants. Consistent results for devices with different active layers yielded $D_n=35$ cm^2/s and $L_n=2.4$ μm. 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.

The work was supported by the National Science Foundation and the Department of Energy. Author Lovejoy acknowledges support from the AT&T Ph.D. Scholarship Program. The authors thank D. J. Dunlavy for technical assistance with the ZFTOF measurements and K. Emery for external QE measurements.

[1] T. J. de Lyon, N. I. Buchan, P. D. Kirchner, J. M. Woodall, D. T. McInturff, G. J. Scilla, and F. Cardone, J. Cryst. Growth **111**, 564 (1991).
[2] M. L. Lovejoy, M. R. Melloch, R. K. Ahrenkiel, and M. S. Lundstrom, Solid-State Electron. **35**, 251 (1992).
[3] M. L. Lovejoy, B. M. Keyes, M. E. Klausmeier-Brown, M. R. Melloch, R. K. Ahrenkiel, and M. S. Lundstrom, *Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Part I, Sendai, Japan,* (Business Center for Academic Societies Japan, Bunkyo-ku, Tokyo, 1990), p. 613.
[4] M. L. Lovejoy, B. M. Keyes, M. E. Klausmeier-Brown, M. R. Melloch, R. K. Ahrenkiel, and M. S. Lundstrom, Jpn. J. Appl. Phys. **30**, L135 (1991).
[5] T. Furuta and M. Tomizawa, Appl. Phys. Lett. **56**, 824 (1990).
[6] W. P. Dumke, Solid-State Electron. **28**, 183 (1985).
[7] C. M. Colomb, S. A. Stockman, S. Varadarajan, and G. E. Stillman, Appl. Phys. Lett. **60**, 65 (1992).
[8] S. Lee, A. Gopinath, and S. J. Pachuta, Electron. Lett. **27**, 1551 (1991).
[9] J. R. Lowney and H. S. Bennett, J. Appl. Phys. **69**, 7102 (1991).
[10] D. A. Anderson, N. Apsley, P. Davies, and P. L. Giles, J. Appl. Phys. **58**, 3059 (1985).
[11] T. J. de Lyon, J. M. Woodall, J. A. Kash, D. T. McInturff, R. J. S. Bates, P. D. Kirchner, and F. Cardone, J. Vac. Sci. Technol. B **10**, 846 (1992).
[12] R. K. Ahrenkiel, in *Current Topics in Photovoltaics* (Academic, New York, 1988), p. 57.
[13] H. C. Casey, Jr. and M. B. Panish, *Heterostructure Lasers* (Academic, New York, 1978), p. 160.

RIGHTSLINK