1995

Temperature dependence of minority and majority carrier mobilities in degenerately doped GaAs

Michael L. Lovejoy
Sandia National Laboratories

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

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

Lovejoy, Michael L.; Melloch, Michael R.; and Lundstrom, Mark S., "Temperature dependence of minority and majority carrier mobilities in degenerately doped GaAs" (1995). *Department of Electrical and Computer Engineering Faculty Publications.* Paper 104.
https://docs.lib.purdue.edu/ecepubs/104

Temperature dependence of minority and majority carrier mobilities in degenerately doped GaAs

Michael L. LovejoyMichael R. Melloch and Mark S. Lundstrom

Citation: **67**, (1995); doi: 10.1063/1.114974
View online: http://dx.doi.org/10.1063/1.114974
View Table of Contents: http://aip.scitation.org/toc/apl/67/8
Published by the American Institute of Physics

Temperature dependence of minority and majority carrier mobilities in degenerately doped GaAs

Michael L. Lovejoy
Sandia National Laboratories, Albuquerque, New Mexico 87185

Michael R. Melloch and Mark S. Lundstrom
School of Electrical Engineering and the MRSEC for Technology-Enabling Heterostructure Materials, Purdue University, West Lafayette, Indiana 47907-1285

(Received 11 May 1995; accepted for publication 14 June 1995)

Measured minority and majority carrier mobility temperature dependencies in heavily doped *n*- and *p*-GaAs are compared. Majority carrier mobilities in heavily doped GaAs are essentially temperature (T) independent while minority carrier mobilities exhibit a roughly $1/T$ dependence. Majority carrier freezeout, which reduces both majority–minority carrier and ionized impurity scattering, is shown not to be responsible for the $1/T$ minority carrier mobility dependence. The difference in minority and majority carrier mobility T dependencies is explained in terms of the increased degree of degeneracy of majority carriers with decreased temperature, which decreases majority–minority carrier scattering. © *1995 American Institute of Physics.*

Minority carrier transport parameters are critical for accurate device modeling and device structure optimization. Of great importance for modeling all bipolar devices, including heterojunction bipolar transistors (HBTs), solar cells, and photodiodes, is the minority carrier mobility. Significant work has been performed to measure minority electron mobility in p^+-GaAs[1–7] while the reports of minority hole mobility are scarce.[8] The recent discovery that in heavily doped GaAs the 300 K minority carrier mobilities are higher than majority carrier mobilities significantly impacts device design. This is exemplified by a recent report of the performance of *Pnp* AlGaAs/GaAs HBTs[9] which was better than predictions because the predictions were based on majority hole mobility. The doping dependencies of minority mobilities in heavily doped GaAs, which differs greatly from that of majority mobility, have been established. However, a measurement of the temperature (T) dependence of minority hole mobility with a comparison of temperature dependencies of minority and majority carrier mobilities in heavily doped *p*- and *n*-GaAs has not been reported. T dependence of minority carrier mobility provides essential information for device design and serves as a sensitive probe of minority carrier scattering physics. In this letter, we report a rigorous comparison of T dependencies of both hole and electron, minority and majority, mobilities in degenerately doped GaAs.

We extended the zero-field time-of-flight (ZFTOF) technique to make continuously variable minority carrier mobility measurements[10] and have measured the minority hole mobility in heavily doped *n*-GaAs. The material for this study was grown in a GEN-II molecular epitaxy system with silicon and beryllium as the *n*- and *p*-type dopants, respectively. The ZFTOF technique uses specially designed photodiodes that are excited by a high-speed 600 nm laser system (5 ps FWHM).[11] The cryostat design, including device packaging, low-loss feedthroughs and temperature measurement scheme, has been described previously.[10] The ZFTOF device structure is as follows: p^+-substrate, 1.0 μm–5×10^{16} cm^{-3} *p*-GaAs, 1 μm–1.8×10^{18} cm^{-3} *n*-GaAs emitter, 0.04 μm to $\sim1\times10^{18}$ cm^{-3} *n*-$\mathrm{Al_{0.27}Ga_{0.73}As}$, and 0.15 μm to $\sim2\times10^{18}$ cm^{-3} *n*-GaAs. ZFTOF measurements were made at device temperatures of 295, 237, 181, 134, 103, and 83 K; measurement and analysis procedures were described previously.[10]

Hall effect measurements were performed on the *n*-GaAs in which the minority hole mobility was measured and on comparably doped *p*-GaAs. In addition, we measured both majority electron and majority hole mobility T dependencies in material comparably doped to that in which Beyzavi *et al.* measured the minority electron mobility.[3] Majority Hall mobilities were measured in the ZFTOF structure and in similar structures where the emitter doping concentration and type were 4.2×10^{18} cm^{-3} *n*-GaAs, 1.5×10^{18} cm^{-3} *p*-GaAs and 4.2×10^{18} cm^{-3} *p*-GaAs. Of course, other layer types and concentrations were changed to insure negligible depletion of the emitter layer and that good junction isolation were achieved. Contact layers were removed by wet etching to realize accurate Hall measurements. The samples are degenerately doped which implies a Hall factor of ~1. Hall measurements from 80 to 300 K were performed with a close-cycle cryostat, at 0.633 T and with a current density in the active layer of $\leqslant200$ A/cm^2.

In the T range investigated, the minority hole mobility in *n*-GaAs doped 1.8×10^{18} cm^{-3} has an approximately $1/T$ dependence that varied from 1015 cm^2/V s at 80 K to 235 cm^2/V s at 300 K. These data are shown in Fig. 1 along with the majority electron Hall mobilities measured in the *n*-GaAs sample in which the minority hole mobility was measured and in comparably doped *p*-GaAs (1.5×10^{18} cm^{-3}). Little T dependence is exhibited by either majority carrier Hall mobility. The majority hole mobility is approximately constant at ~185 cm^2/V s and the majority electron mobility is constant at ~2800 cm^2/V s. The very different T-dependent characteristics show that different dominant scattering mechanisms determine the mobilities of the majority carriers and the minority holes.

The same trend is found in a comparison of measured

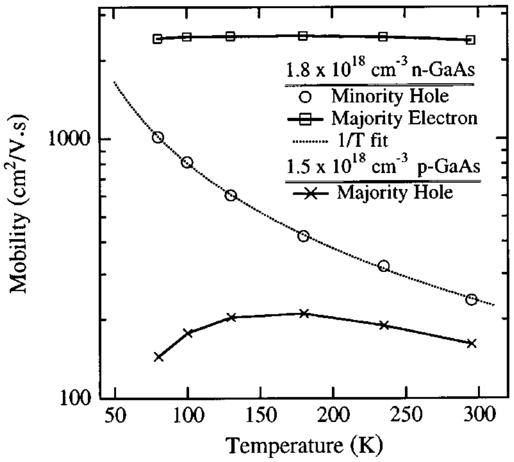

FIG. 1. Mobility vs temperature for minority holes in 1.8×10^{18} cm^{-3} n^+-GaAs measured with the ZFTOF technique, for majority electrons in the n^+-GaAs and for majority holes in p-GaAs doped to 1.4×10^{18} cm^{-3}. A $1/T$ temperature dependence is found for minority hole mobility while majority Hall mobilities are roughly constant.

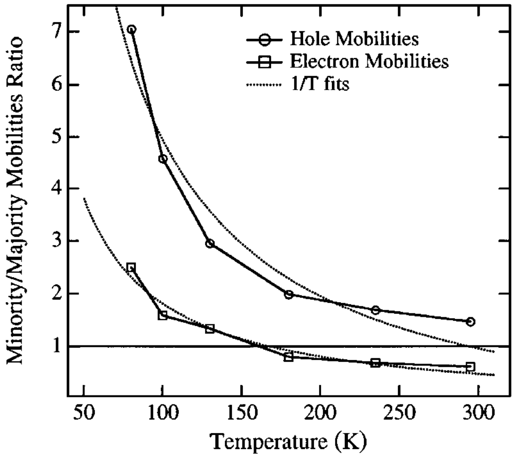

FIG. 3. Minority/majority mobility ratios for data shown in Figs. 1 and 2. For the entire temperature range investigated the ratio of hole mobilities is greater than 1, while the ratio of electron mobilities is greater than 1 only below 150 K. The ratios exhibit a roughly $1/T$ dependence.

majority carrier mobilities and the minority electron mobility of Beyzavi *et al.*[3] Shown in Fig. 2 is our majority electron mobility for n-GaAs doped to 4.2×10^{18} cm^{-3} and majority hole mobility in p-GaAs doped to 4.2×10^{18} cm^{-3} which is comparably doped to that in which Beyzavi *et al.* measured the minority electron mobility with HBT unity gain cutoff frequency (f_T) measurements. Beyzavi's data are also shown in Fig. 2. It is noted that their room-temperature measurement of minority electron mobility is slightly lower than our ZFTOF minority electron mobility measurement.[5] In the temperature range investigated, the majority carrier electron mobility and majority hole mobilities are relatively constant at ~2000 and ~120 cm^2/V s, respectively, while minority electron mobility exhibits a $1/T$ dependence as shown in Fig. 2.

Shown in Fig. 3 is the ratio of minority/majority mobilities versus temperature for the data shown in Figs. 1 and 2. For holes the ratio of minority–majority mobilities is greater than unity over the entire T range investigated while the ratio for electrons is less than unity at 300 K and does not become greater than unity until below 150 K. The ratios for holes and electrons show the same trends which suggests that the different scattering mechanisms that are responsible for determining the minority and the majority carrier mobilities for both carrier types are the same. As shown in Fig. 2, because the minority carrier mobilities exhibit a $1/T$ dependence while majority carrier mobilities in comparably doped material is relatively constant, both hole and electron mobility ratios exhibit a $1/T$ dependence with different multiplicative factors.

To the author's knowledge the only theoretical result for the T dependence of minority carrier mobility in GaAs is that by Walukiewicz *et al.*[12] In their treatment, minority–majority carrier scattering was treated by the Brooks–Herring impurity scattering rate formula which has a $T^{3/2}$ dependence and they included a screening length expression appropriate for degenerate majority carrier system; their result is that minority electron mobility was predicted to have a weaker than $1/T$ dependence. However, Szmyd *et al.* derived a scattering rate expression for degenerately doped material that is analogous to the Brooks–Herring expression which is for nondegenerate material.[13] The scattering rate expression for degenerate systems is essentially T independent. This result combined with the fact that the Walukiewicz *et al.* theory did not accurately predict mobility above 1×10^{19} cm^{-3} p-GaAs suggests that the scattering physics are more complicated than considered by the first theory.

The temperature independence of majority mobilities in heavily doped GaAs measured in this work is explained by the theory of Szmyd *et al.* for degenerately doped GaAs, but the $1/T$ dependence of minority carrier mobility is not at this time understood. It was speculated that carrier freezeout may be responsible for the higher mobility of minority carriers due to reduced ionized impurity scattering.[3] Shown in Fig. 4, is Hall concentration versus temperature for the samples reported in Fig. 1 and in material doped comparably to that in which minority electron mobility was measured. As shown in

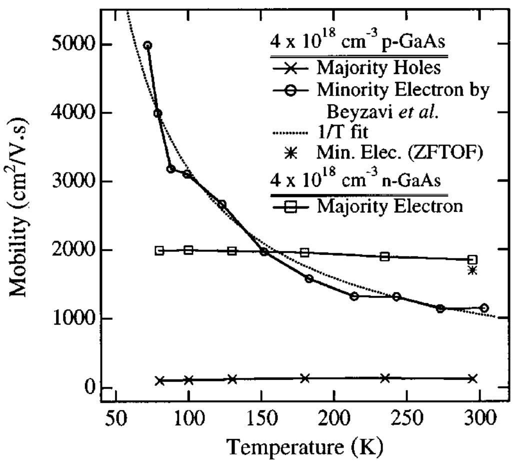

FIG. 2. Mobility vs temperature for both majority holes and majority electrons in comparably doped (4×10^{18} cm^{-3}) GaAs and for minority electrons in 4×10^{18} cm^{-3} p^+-GaAs [from Beyzavi *et al.* (Ref. 3)]. The majority Hall mobilities are found to be constant while a $1/T$ temperature dependence is exhibited by the minority electron mobility.

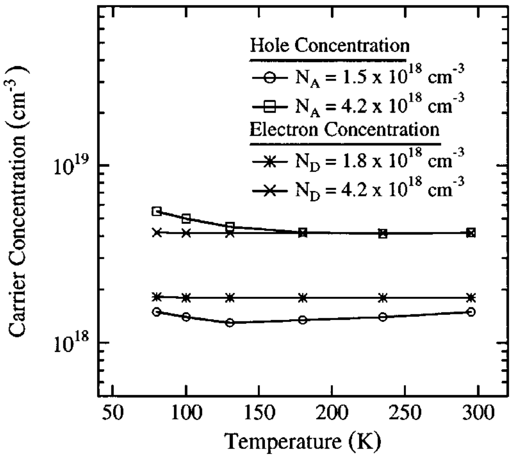

FIG. 4. Hall carrier concentrations for samples of which data are shown in Figs. 1–3. Significant carrier freezeout is not found for any of the samples.

the figure, no sample experienced significant carrier freezeout. Little freezeout is expected for degenerately Si- and Be-doped GaAs since the Si-dopant energy level is only 5.8 meV below the conduction band and Be is 28 meV above the valence band and impurity band overlap is expected at such high dopant levels.

A possible explanation for the *T*-dependence of minority mobilities is the increasing degree of degeneracy of majority carriers with decreasing temperature which reduces the number of majority carriers that can participate in scattering events with the minority carriers. In degenerately doped material, Lowney and Bennett showed that the 300 K minority electron mobility in heavily doped GaAs was dominated by ionized impurity and hole-electron scattering.[14] They went on to show that as the degree of degeneracy increased due to increased concentration, at sufficiently high concentrations, the hole-electron scattering actually decreased and minority carrier mobility increased; this was later confirmed experimentally.[6,7]

The reason for the mobility increase is that, as the doping increases, a larger number of holes are forbidden to participate in hole-electron scattering because the Fermi level moves deeper into the valance band with most states below the Fermi energy being occupied. Electron scattering off a hole, although nearly elastic due to the large mass difference, does result in a momentum exchange and an energy exchange between carriers; however, if all momentum states with energies near the hole energy are occupied, then the majority carrier is prohibited from participating in a scattering event.

The increased degree of majority carrier degeneracy may be the origin of increasing minority carrier mobilities with decreasing *T*. As *T* decreases the Fermi–Dirac distribution becomes more like a step function and there are fewer states within a few *kT* of the Fermi level. Hence, there are fewer majority carrier momentum states of comparable energy and fewer majority carriers that can participate in majority–minority carrier scattering. The result would be an increase in mobility with decreasing temperature which may be enhanced by changes in screening properties as the majority carrier systems increase in degree of degeneracy.

In conclusion, we report a comparison of measured minority and majority carrier mobility temperature dependencies. We show that majority carrier mobility in heavily doped *n*- and *p*-GaAs is essentially temperature independent while minority carrier mobility has a roughly $1/T$ temperature dependence. It is shown that reduced impurity scattering due to majority carrier freezeout is not the origin of the $1/T$ minority carrier mobility dependence. A possible reason for the strong minority carrier mobility *T* dependencies is the increased degree of degeneracy with lower temperature experienced by majority carriers which reduces the number of majority carriers that can participate in minority–majority carrier scattering events. More work is needed to understand this phenomenon. Furthermore, for accurate device design and optimization, the correct *T* dependencies of minority mobilities, as well as the correct doping dependence, which are discussed here, must be incorporated in device modeling tools.

Professor Robert F. Pierret is gratefully acknowledged for providing his laboratory for Hall characterization. This work was supported by the Department of Energy under Contract No. DE-AC04-94AL85000. The work at Purdue University was supported by the MRSEC Program of the National Science Foundation under Award No. DMR-9400415.

[1] M. I. Nathan, W. P. Dumke, K. Wrenner, S. Tiwari, and S. L. Wright, Appl. Phys. Lett. **52**, 654 (1988).

[2] 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* (Japanese Society of Applied Physics, Sendai, Japan, 1990), p. 613.

[3] K. Beyzavi, K. Lee, D. M. Kim, M. I. Nathan, K. Wrenner, and S. L. Wright, Appl. Phys. Lett. **58**, 1268 (1991).

[4] M. L. Lovejoy, M. R. Melloch, M. S. Lundstrom, B. M. Keyes, R. K. Ahrenkiel, T. J. de Lyon, and J. M. Woodall, Appl. Phys. Lett. **61**, 822 (1992).

[5] M. L. Lovejoy, Ph.D. thesis, Purdue University, 1992.

[6] D. M. Kim, S. Lee, M. I. Nathan, A. Gopinath, F. Williamson, K. Beyzavi, and A. Ghiasti, Appl. Phys. Lett. **62**, 861 (1993).

[7] E. S. Harmon, M. L. Lovejoy, M. R. Melloch, M. S. Lundstrom, T. J. de Lyon, and J. M. Woodall, Appl. Phys. Lett. **63**, 536 (1993).

[8] M. L. Lovejoy, M. R. Melloch, M. S. Lundstrom, and R. K. Ahrenkiel, Appl. Phys. Lett. **61**, 2683 (1992).

[9] D. B. Slater, Jr., P. M. Enquist, J. A. Hutchby, A. S. Morris, and R. J. Trew, IEEE Electron Device Lett. **15**, 91 (1994).

[10] M. L. Lovejoy, M. R. Melloch, M. S. Lundstrom, B. M. Keyes, and R. K. Ahrenkiel, J. Electron. Mater. **23**, 669 (1994).

[11] M. L. Lovejoy, M. R. Melloch, R. K. Ahrenkiel, and M. S. Lundstrom, Solid State Electron. **35**, 251 (1992).

[12] W. Walukiewicz, J. Lagowski, L. Jastrzebski, and H. C. Gatos, J. Appl. Phys. **50**, 5040 (1979).

[13] D. M. Szmyd, M. C. Hanna, and A. Majerfeld, J. Appl. Phys. **68**, 2376 (1990).

[14] J. R. Lowney and H. S. Bennett, J. Appl. Phys. **69**, 7102 (1991).