1994

Effective Bandgap Shrinkage in GaAs

E. S. Harmon
Purdue University

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

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

Effective band-gap shrinkage in GaAs

E. S. Harmon, M. R. Melloch, and M. S. Lundstrom

Citation: **64**, (1994); doi: 10.1063/1.111110
View online: http://dx.doi.org/10.1063/1.111110
View Table of Contents: http://aip.scitation.org/toc/apl/64/4
Published by the American Institute of Physics

Effective band-gap shrinkage in GaAs

E. S. Harmon, M. R. Melloch, and M. S. Lundstrom
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907-1285

(Received 7 September 1993; accepted for publication 23 November 1993)

Electrical measurements of the equilibrium np product (n_{ie}^2) in heavily doped n- and p-GaAs were performed. The $n_{ie}^2 D$ product (where D is the diffusivity) was measured by fitting the collector current-voltage characteristic of a homojunction bipolar transistor to an ideal diode equation modified to account for transport in thin base transistors. The n_{ie}^2 product was then extracted from $n_{ie}^2 D$ by utilizing diffusivity results obtained with the zero-field time-of-flight technique. Our results show significant effective band-gap shrinkage in heavily doped p-GaAs, and very little effective band-gap shrinkage in heavily doped n-GaAs. At extremely heavy dopings, an effective band-gap widening is observed for both n- and p-GaAs and is attributed to the effects of degeneracy.

So-called band-gap narrowing effects play an important role in bipolar devices with heavily doped regions.[1] With the recent interest in GaAs-based solar cells and heterojunction bipolar transistors (HBTs), it is important to characterize the effective band-gap shrinkage for use in device modeling and analysis. During the past few years, our group has reported on a number of studies directed at electrical characterization of heavily doped GaAs.[2–5] In this letter, we combine and reanalyze these experiments in order to deduce the effective band-gap shrinkage in both n- and p-type GaAs. Our previous data must be reanalyzed in light of recent theoretical and experimental results indicating that the standard solution for the collector current must be modified for short base transistors.[6,7] The corrected band-gap shrinkage results show good agreement with recent theoretical predictions and demonstrate that, for p^+ GaAs, band-gap narrowing effects can increase minority electron injection currents by an order of magnitude. For n^+ GaAs, however, band-gap narrowing provides only a modest increase in minority electron injection currents. For the heaviest dopings in both p- and n-GaAs, a reduction in minority electron injection currents is observed, which is directly attributed to degeneracy.

In the forward, active region of operation, the collector current density of a homojunction bipolar transistor may be described by a modified ideal diode equation,[6]

$$J_c = \frac{q(n_{ie}^2 D_B)\alpha}{N_B W_B}\left[\exp\left(\frac{q|V_{BE}|}{kT}\right) - 1\right], \qquad (1)$$

where the subscripts B and E refer to the base and emitter of the transistor, respectively, k is Boltzmann's constant, and $N_B W_B$ is the charge per unit area in the quasineutral base. The factor α corrects the ideal diode equation for thin base transport, which occurs when carriers injected into the base do not experience enough collisions to suitably randomize their momentum before they are collected. The correction factor $\alpha(\alpha \leq 1)$ was determined from the results of Grinberg[6] based upon a numerical integration of the Boltzmann transport equation. In another letter,[7] we experimentally demonstrated that Grinberg's results appear to accurately describe transport in thin base homojunction transistors. Further details of the transistor-based $n_{ie}^2 D$ measurement technique are described in Ref. 2.

In Fig. 1 and Tables I and II we summarize the results of measurements on a large number of heavily doped GaAs bipolar transistor films.[2–5] Since the results are corrected to account for thin base transport effects, Fig. 1 supersedes our previously published results.[2–5,8] For n-GaAs we observe a monotonic decrease in $n_{ie}^2 D$ with increasing doping. For p-GaAs we observe a significant rise in $n_{ie}^2 D$ as the doping is increased from 1×10^{18} to 9×10^{19} cm^{-3}, followed by a reduction in $n_{ie}^2 D$ for dopings greater than 9×10^{19} cm^{-3}.

To extract n_{ie}^2 from $n_{ie}^2 D$ we must determine the minority carrier diffusion coefficient (D). To do so, we developed the zero-field time-of-flight (ZFTOF) technique to allow measurement of D in heavily doped semiconductors.[9] The results of ZFTOF measurements on a number of p-GaAs[10] and n-GaAs[11] diode structures at ~297 K are summarized in Fig. 2. The n-GaAs results show that the minority hole mobility decreases by 20% as the doping is increased from 1 to 7×10^{17} cm^{-3}, and then appears to remain constant for heavier dopings. The p-GaAs measurements show a decrease in the minority electron mobility with increasing doping until the doping is increased beyond 2×10^{19} cm^{-3}, where a strikingly sharp rise in mobility for increasing doping is observed. The factor of 2.7 rise as the doping is increased from 1 to 8×10^{19} cm^{-3} has been attributed to reductions in plas-

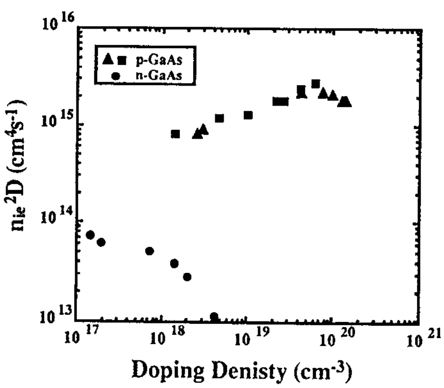

FIG. 1. Measured $n_{ie}^2 D$ vs doping for heavily doped n- and p-GaAs at 300 K (Refs. 3–5). These results have been corrected for thin base transport effects. The (▲) denote results from BJTs with the base grown at a reduced substrate temperature.

 0003-6951/94/64(4)/502/3/$6.00

TABLE I. Summary of BJT measurements for heavily doped p-GaAs at 300 K. Note that the Hall mobility (μ_p) values are for majority holes.

Hall N_A ($\times 10^{19}$ cm^{-3})	$(n_{ie}^2 D_n)\alpha$ ($\times 10^{14}$ cm^{-4} s^{-1})	Base width (Å)	Hall μ_p (cm^2 V^{-1} s^{-1})	Diffusivity[a] (cm^2 s^{-1})	Correction factor (α)	Corrected $n_{ie}^2 n_{io}^2$	Δ_G (meV)
0.14[b]	7.40	30 00	178	50.0	0.908	3.22	30.3
0.26[c]	6.04	1000	136	45.6	0.749	3.49	32.4
0.31[c]	6.83	1000	131	44.4	0.755	4.02	36.0
0.46[b]	10.70	2000	134	41.5	0.885	5.76	45.3
1.00[b]	10.50	1000	104	36.9	0.795	7.07	50.7
2.20[b]	13.60	1000	···	48.0	0.737	7.60	52.5
2.60[b]	13.00	1000	86	52.4	0.715	6.85	49.8
4.10[b]	15.00	1000	82	77.0	0.610	6.30	47.7
4.30[c]	13.30	1000	74	78.0	0.607	5.55	44.4
6.00[b]	15.90	1000	76	87.1	0.574	6.28	47.6
7.59[c]	12.00	1000	65	93.8	0.553	4.57	39.4
9.73[c]	6.99	500	63	101.0	0.337	4.05	36.2
12.8[c]	8.99	1000	62	108.9	0.508	3.21	30.2
13.5[c]	9.00	1000	58	110.5	0.504	3.19	30.0
13.9[c]	5.60	500	57	111.3	0.313	3.17	29.9

[a]Obtained with ZFTOF technique and interpolated to match BJT doping densities (see Ref. 10).
[b]Results from BJTs with the base grown at normal substrate temperatures (see Ref. 3).
[c]Results from BJTs with the base grown at reduced substrate temperatures (see Ref. 4).

mon and carrier–carrier scattering between minority electrons and majority holes.[12,13]

Having determined both D and the corrected $n_{ie}^2 D$, the n_{ie}^2 product can be extracted and the variation of n_{ie}^2 with doping can be examined. Since the dopings for which D were measured are not identical to the dopings of the samples for which $n_{ie}^2 D$ were measured, interpolation and extrapolation were used to estimate the diffusion coefficient as shown in Fig. 2 and Tables I and II. To scale the diffusivity measurements to 300 K, we assumed that D does not vary with temperature between 297 and 300 K, which was the same assumption used when scaling $n_{ie}^2 D$ to 300 K (Refs. 3–5).

In Fig. 3, the values of n_{ie}^2/n_{io}^2, where n_{io}^2 is the equilibrium np product in lightly doped GaAs,[14] are plotted versus doping density. Tiwari and Wright[15] have measured effective band-gap shrinkage in GaAs with a similar technique utilizing Npn HBTs. Tiwari obtained a n_{ie}^2/n_{io}^2 product that is four times larger than the results presented here at the doping density of 2×10^{19} cm^{-3}. Even accounting for differences in diffusion coefficient and thin base transport, Tiwari's results at 2×10^{19} cm^{-3} are more than two times larger than the results presented here. Casey and Stern have also measured the absorption and spontaneous emission of heavily doped GaAs, fit their measurements to the Halperin–Lax theory of band tails, and from this inferred the equilibrium np product.[16] Our results are similar to the n_{ie}^2 product calculated by Casey and Stern for the lower dopings, however for the doping level 2×10^{19} cm^{-3}, our results are twice as large as those reported by Casey and Stern. Note that the transistor experiments directly measure the np product while the optical experiments infer the np product from an assumed band structure.

It is often useful to relate an effective band-gap shrinkage (Δ_G) to the n_{ie}^2/n_{io}^2 ratio by[1]

$$n_{ie}^2 = n_{io}^2 \exp(\Delta_G/kT). \quad (2)$$

For doping levels above 3×10^{19} cm^{-3} in p-GaAs and above 1×10^{18} cm^{-3} in n-GaAs we observe a decreasing trend in n_{ie}^2/n_{io}^2, indicating that band-gap shrinkage is being offset by another effect. This decreasing trend is attributed to the effects of degeneracy, which strongly reduces the equilibrium np product.[4] A semiempirical fit to the effective band gap including both the effects of band-gap shrinkage and degeneracy may be obtained with[17]

TABLE II. Summary of BJT measurements[a] for heavily doped n-GaAs at 300 K. The correction factor α is ≈0.96 for all the transistors measured.

Hall N_D ($\times 10^{17}$ cm^{-3})	$(n_{ie}^2 D_p)\alpha$ ($\times 10^{13}$ cm^{-4} s^{-1})	Corrected n_{ie}^2/n_{io}^2	Δ_G (meV)
1.41	7.12	1.97	17.6
1.89	6.07	1.75	14.5
7.20	4.98	1.70	13.7
13.90	3.77	1.29	6.6
20.30	2.75	0.94	−1.6
42.00	1.10	0.38	−25.1

[a]See Ref. 5.

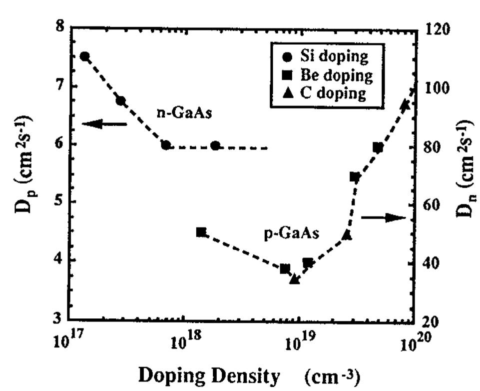

FIG. 2. Diffusivity vs doping at 297 K (Refs. 10,11).

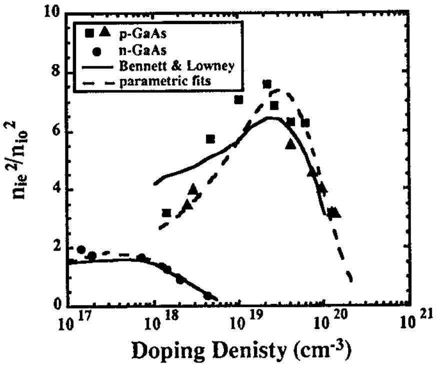

FIG. 3. Plot of n_{ie}/n_{io} at 300 K extracted from the measured values of $n_{ie}^2 D$ and D. The (▲) denote results from BJTs with the base grown at a reduced substrate temperature. The theoretical predictions of Bennett and Lowney (See Ref. 18) are also shown (solid line), along with a semiempirical fit to the data (dashed line).

$$\Delta_G = A \times N^{1/3} + kT \ln[\mathscr{F}_{1/2}(E_f/kT)] - E_f, \tag{3}$$

where E_f is the Fermi level position relative to the majority carrier band, $\mathscr{F}_{1/2}$ is the Fermi–Dirac integral of order one-half, N is the doping density, and A is the fitting parameter. The first term in Eq. (3) treats band-gap shrinkage while the last two terms treat the effects of degeneracy. A least-squares fit to the data gives $A = 2.55 \times 10^{-8}$ eV for p-GaAs and $A = 3.23 \times 10^{-8}$ eV for n-GaAs (see the dashed lines in Fig. 3). Note that, in general, Δ_G is not equivalent to optical band-gap shrinkage.[1]

The solid lines in Fig. 3 represent the theoretical calculations of n_{ie}^2/n_{io}^2 from Bennett and Lowney,[18] who modeled the effects of carrier-dopant ion interactions and carrier–carrier interactions on the density of states to determine n_{ie}/n_{io} versus doping. Their theoretical calculations are in excellent agreement with our measured values of n_{ie}^2/n_{io}^2 for both n- and p-GaAs. Not shown are the theoretical results of Jain *et al.*,[17] who determined $A = 2.6 \times 10^{-8}$ eV in Eq. (3) for p-GaAs, which is in excellent agreement with our experimental results.

In conclusion, we have determined the effective band-gap shrinkage from measurements on heavily doped GaAs. The equilibrium np values versus doping presented here are in good agreement with the values calculated by Bennett and Lowney. At the heaviest dopings, these results are significantly smaller than the results obtained by Tiwari from electrical measurements on GaAs npn HBTs and significantly larger than the values obtained by Casey and Stern from optical measurements. Accurate values of the equilibrium np product are extremely important for the simulation and optimization of minority carrier currents in bipolar devices such as HBTs and solar cells.

This work is the result of a long term study funded by SERI (XL-5-05018-1), NSF (ECS8901638), and the Indiana Business Modernization and Technology Corporation.

[1] C. M. Van Vliet, IEEE Trans. Electron Devices **ED-40**, 1140 (1993).
[2] M. E. Klausmeier-Brown, M. S. Lundstrom, and M. R. Melloch, IEEE Trans. Electron Devices **ED-36**, 2146 (1989).
[3] M. E. Klausmeier-Brown, M. R. Melloch, and M. S. Lundstrom, Appl. Phys. Lett. **58**, 160 (1990).
[4] E. S. Harmon, M. R. Melloch, M. S. Lundstrom, and M. L. Lovejoy, Appl. Phys. Lett. **58**, 1647 (1991).
[5] M. P. Patkar, M. S. Lundstrom, and M. R. Melloch, Appl. Phys. Lett. **59**, 1853 (1991).
[6] A. A. Grinberg and S. Luryi, Solid-State Electron. **35**, 1299 (1992).
[7] E. S. Harmon, M. R. Melloch, M. S. Lundstrom, and F. Cardone, Appl. Phys. Lett. Scheduled for 10 Jan. (1994).
[8] M. S. Lundstrom, *Semiconductors and Semimetals*, edited by R. K. Willardson, A. C. Beer, and E. R. Weber (Academic, New York, 1993), Vol. 39, p. 193.
[9] M. L. Lovejoy, M. R. Melloch, R. K. Ahrenkiel, and M. S. Lundstrom, Solid-State Electron. **35**, 251 (1992).
[10] 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).
[11] M. L. Lovejoy, M. R. Melloch, M. S. Lundstrom, and R. K. Ahrenkiel, Appl. Phys. Lett. **61**, 2683 (1992).
[12] J. R. Lowney and H. S. Bennett, J. Appl. Phys. **69**, 7102 (1991).
[13] D. M. Kim, S. Lee, M. I. Nathan, A. Gopinath, F. Williamson, K. Beyzavi, and A. Ghiasi, Appl. Phys. Lett. **62**, 861 (1993).
[14] J. S. Blakemore, J. Appl. Phys. **53**, R123 (1982).
[15] S. Tiwari and S. L. Wright, Appl. Phys. Lett. **56**, 563 (1990).
[16] H. C. Casey, Jr. and F. Stern, J. Appl. Phys. **47**, 631 (1976).
[17] S. C. Jain, J. M. McGregor, and D. J. Roulston, J. Appl. Phys. **68**, 3747 (1990).
[18] H. S. Bennett and J. R. Lowney, J. Appl. Phys. **62**, 521 (1987).