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E. S. Harmon
Purdue University

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

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

Michael L. Lovejoy
Purdue University

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Experimental determination of the effects of degenerate Fermi statistics on heavily *p*-doped GaAs

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

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The effects of degenerate Fermi statistics on electron injection currents for p^+-GaAs grown by molecular beam epitaxy are presented. To achieve Be dopant concentrations of greater than 8×10^{19} cm^{-3}, the substrate temperature during growth was reduced to approximately 450 °C from the usual 600 °C. In this heavily doped material, we measure unexpectedly large electron injection currents which are interpreted in terms of an effective narrowing of the band gap. At extremely heavy doping densities, the Fermi level pushes into the valence band and degenerate Fermi statistics must be taken into account. For doping concentrations greater than 1×10^{20} cm^{-3}, effects due to degenerate Fermi statistics oppose the band-gap shrinkage effects; consequently, a reduction in the electron injection currents is observed. The result is a substantial reduction in gain for AlGaAs/GaAs heterostructure bipolar transistors when the base is doped above 10^{20} cm^{-3}.

The electron current injected into the base of an AlGaAs/GaAs heterojunction bipolar transistor (HBT) is strongly enhanced by heavy doping effects.[1,2] This enhancement has been attributed to doping-induced perturbations of the band structure which have the effect of increasing the n_0p_0 product.[3] The increase in the n_0p_0 product may be interpreted as an effective shrinkage of the band gap in the base of the transistor.[4,5] The results presented by Klausmeier-Brown *et al.*[1,2] have included Be-doped GaAs in the range 6×10^{17}– 8×10^{19} cm^{-3}. With modern HBT design requiring progressively higher doping levels, the effects of these extremely high dopant levels on minority-carrier transport must be understood. The results presented here show significant band-gap shrinkage for all doping concentrations above 10^{18} cm^{-3}. However, for doping concentrations above 8×10^{19} cm^{-3}, increases in injection currents due to perturbations of the band structure are offset by reductions in injection currents due to degenerate Fermi statistics.[5,6] To adequately model and design heavily doped GaAs bipolar devices, these heavy doping effects must be examined.

The collector current density of an *n-p-n* homojunction bipolar transistor when the emitter-base junction is forward biased and the base-collector junction is reverse biased may be described by

$$J_C=\frac{qn_{ie}^2D_n}{N_AW_B}\left[\exp\left(\frac{qV_{\rm BE}}{k_BT}\right)-1\right], \qquad (1)$$

where $n_{ie}^2 = n_0p_0$, the equilibrium carrier concentration product, D_n is the diffusion coefficient of the minority-carrier electrons, k_B is the Boltzmann constant, and N_AW_B is the charge per unit area in the quasi-neutral base. The $n_{ie}^2D_n$ product may be obtained directly from the J_C (collector current density) vs $V_{\rm BE}$ (base-emitter bias) characteristics by utilizing Eq. (1) provided that the base doping is spatially uniform.[7]

The targeted transistor cross sections and doping profiles are summarized in Fig. 1 and Table I. Homojunction bipolar transistors were chosen for this study instead of heterojunction bipolar transistors because misalignment of doping and compositional junctions, or improper grading of the junction may invalidate (1). These transistor films were grown in a Varian GEN-II molecular beam epitaxy (MBE) system on n^+-GaAs substrates. To reduce out diffusion of Be in heterostructure bipolar transistors (HBTs), the heavily doped base has been grown at a reduced substrate temperature.[8–10] Substrate temperatures during growth were approximately 600, 450, and 600 °C for collector, base, and emitter layers, respectively. The growth rate was 1 μm/h as determined from the reflection high-energy electron diffraction (RHEED) pattern at the beginning of each film growth. The *p*-type dopant was Be and the *n*-type dopant was Si. Eight transistor films with base doping concentration ranging from 3×10^{18} to 1.4×10^{20} cm^{-3} were studied. The slope of the measured carrier concentration versus the inverse Be oven temperature was consistent with the vapor pressure curve of Be, implying the absence of significant precipitation of Be even at the highest doping levels.[10,11] All transistors were fabricated with standard optical lithography and wet etching procedures.

Base doping profiles were characterized by both Hall effect measurements and by secondary-ion mass spectros-

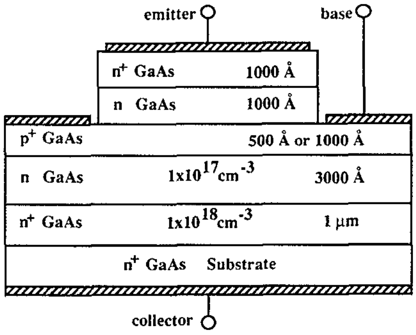

FIG. 1. Schematic representation of the GaAs bipolar transistors used to measure electron injection currents.

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TABLE I. Summary of measurements on the heavily doped base of GaAs *n-p-n* bipolar transitors.

Hall N_A (cm^{-3})	SIMS N_A (cm^{-3})	Hall μ ($\mathrm{cm}^2\,\mathrm{s}^{-1}$)	Base width (Å)	$n_{ie}^2D_n$ ($\mathrm{cm}^{-4}\,\mathrm{s}^{-1}$)
2.59×10^{18}	4.55×10^{18}	136	1000	6.04×10^{14}
3.07×10^{18}	3.31×10^{18}	131	1000	6.83×10^{14}
4.30×10^{19}	6.13×10^{19}	74	1000	1.33×10^{15}
7.59×10^{19}	8.56×10^{19}	65	1000	1.20×10^{15}
9.73×10^{19}	7.47×10^{19}	63	500	6.99×10^{14}
1.28×10^{20}	1.37×10^{20}	62	1000	8.99×10^{14}
1.35×10^{20}	1.33×10^{20}	58	1000	9.00×10^{14}
1.39×10^{20}	1.06×10^{20}	57	500	5.60×10^{14}

copy (SIMS). MBE growth allows precise base thickness resolution if negligible outdiffusion of the Be dopant occurs. SIMS analysis performed by Charles Evans and Associates confirms that Be diffusion in these films grown at low substrate temperature is negligible (see Fig. 2). Hall effect measurements were performed on Hall structures adjacent to the BJTs. Values of mobility and hole concentration were calculated assuming a Hall factor of unity. Note that the N_AW_B product is measured directly by the Hall measurement technique so that there is no error in N_AW_B due to base thickness (W_B) estimation. The values for Hall and SIMS carrier concentration (N_A) are reported in Table I assuming an as-grown base thickness. The reported values of $n_{ie}^2D_n$ were calculated using the Hall measurements; if SIMS measurements were used instead, comparable values for $n_{ie}^2D_n$ are obtained with more scatter in the data.

The collector current density was measured as a function of the applied base-emitter voltage with the base-collector junction held at a zero volt bias. The linear portion of the $\ln(I_C)$ vs V_{BE} plot was then fit to Eq. (1). Device temperatures measured with a thermocouple in the probe station chuck agreed well with the temperature of the device as determined by the slope of the fit to Eq. (1). The quantity $n_{ie}^2D_n$ was determined from the intercept of the linear fit to this data. These results were scaled to 300 K using the known temperature dependence of n_i (Ref. 12) and are presented in Table I and Fig. 3. Inverting the transistor operation by forward biasing the base collector and reverse baising the base emitter was used to confirm the $n_{ie}^2D_n$ product obtained from the normal operation configuration. No dependence on emitter perimeter to area ratio was observed. We estimate less than 5% error in the $n_{ie}^2D_n$ product due to collector current measurement accuracy and an additional 5% error in the $n_{ie}^2D_n$ due to the N_AW_B estimation. Several authors have pointed out that the Hall factor may be much different from unity,[13,14] which may lead to an additional systematic error in the N_AW_B determination. Results from these low growth temperature structures are consistent with the results obtained for the normal temperature growth.[1,2] The significant features of Fig. 3 are the increase in the $n_{ie}^2D_n$ product as base dopant concentration increases from 1×10^{16} to 8×10^{19} cm^{-3}, and the rapid decrease in $n_{ie}^2D_n$ for higher dopant concentrations.

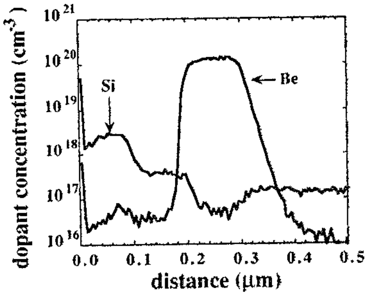

FIG. 2. SIMS profile for the GaAs bipolar transistor with the base doped 1.35×10^{20} cm^{-3}.

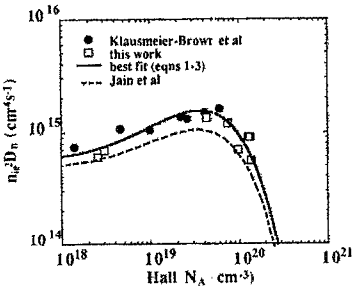

FIG. 3. Plot of $n_{ie}^2D_n$ at 300 K vs Hall concentration as deduced from bipolar transistor injection current measurements. The solid line represents the best fit to the data using Eqs. (2)–(3) and the dashed line represents the theoretical prediction of Jain *et al.* (see Ref. 6).

Equation (1) is only valid as long as recombination in the base is not significant. We estimate that a diffusion length of less than 700 Å would be required to reduce the measured collector current by 9% in the 500 Å base width BJTs. However, a diffusion length of 700 Å would reduce the measured collector current by 38% for the 1000 Å base transistors. Thus, if the diffusion length in the transistor base is 700 Å, measurements of transistors with 500 Å base widths would yield an $n_{ie}^2D_n$ that is approximately 30% higher than that of transistors with 1000 Å base widths. This is not the case with the measurements presented here, implying that the diffusion length in the transistor base is significantly longer than 700 Å. An extrapolation of published lifetime data[15] gives a lifetime of 76 ps for *p*-GaAs doped 1.4×10^{20} cm^{-3}. For $D_n = 20$ $\mathrm{cm}^2\,\mathrm{s}^{-1}$, a lifetime of 76 ps gives a diffusion length of 3900 Å. Thus, for high-quality GaAs material, one would not necessarily expect much recombination in transistors with these thin bases. Also, the Hall measurements reported in Table I show very good majority-carrier mobilities, implying that this low growth temperature material is high-quality GaAs.

These results can be interpreted using a simple rigid band shrinkage model for GaAs. This approach necessarily includes some error from the assumption for D_n. Here we use the fit given by Tiwari and Wright[16] for electron drift mobility (μ_n) and the Einstein relationship to obtain D_n. The dependence of intrinsic carrier concentration upon degenerate Fermi statistics and band-gap shrinkage in *p*-type material may be represented by[5,6,12]

$$n_{ie}^2 = N_C^* N_V(\eta_F) \exp(-E_g/k_B T) \mathscr{F}_{1/2}(\eta_F) \times \exp(-\eta_{\mathscr{F}})(\Delta E_g/k_B T), \tag{2}$$

where $\mathscr{F}_{1/2}(\eta_F)$ is the Fermi integral of order 1/2, η_F is the normalized energy difference between the Fermi level and the valence-band edge, N_C^* is the effective density of states of the conduction band, $N_v(\eta_F)$ is the effective density of states of the valence band including a nonparabolicity factor for the light hole band,[6,12] E_g is the intrinsic energy gap, and ΔE_g is the amount of rigid band-gap shrinkage of the form[5]

$$\Delta E_g = A N_A^{1/3} \quad (\text{eV}). \tag{3}$$

By fitting our measured $n_{ie}^2 D_n$ results to Eqs. (2)–(3) we obtain $A = 2.85 \times 10^{-8}$, which is reasonably close to the theoretical projections of Jain *et al.*[5] who obtain $A = 2.6 \times 10^{-8}$ for *p*-GaAs (see Fig. 3). Recent measurements for electron drift mobility and diffusivity[17,18] give slightly lower values than predicted by Tiwari and Wright,[16] so our fit to n_{ie}^2 should be viewed as a lower limit. The results presented in Fig. 3 show a strong enhancement in electron injection implying that significant band-gap shrinkage occurs. Note that the turnover in the experimental data points should be expected when degenerate Fermi statistics effects become strong enough to dominate over the band-gap shrinkage effects.[3,5] We find an effective band-gap shrinkage which is significantly larger than that predicted by most theoretical calculations[3,19] but is reasonably close to the calculations of Jain *et al.*[6]

These band-gap shrinkage and degenerate Fermi statistics results have some interesting applications for device design. For solar cell structures it is common practice to use a doped isotype homojunction to confine minority carriers. Chuang *et al.*[20] demonstrated that for a p^+ doping of 10^{19} cm^{-3}, the p^+/p-GaAs isotype homojunction is not an effective barrier due to band-gap shrinkage. However, if the p^+ layer is doped greater than 10^{20} cm^{-3}, degenerate Fermi statistics counteract the effects of band-gap shrinkage and a p^+/p isotype homojunction could effectively confine minority carriers as was recently demonstrated by de Lyon *et al.*[21] For HBT structures, the gain of the transistor is enhanced by band-gap shrinkage and degraded by degenerate Fermi statistics effects.[3,10] These effects can be treated by considering their infuence on the common emitter gain[2] of a HBT which should be proportional to $n_{ie}^2 D_n / N_A$. For example, consider two similar HBT structures, the first with a base doped 2×10^{20} cm^{-3} and the other with a base doped 5×10^{19} cm^{-3}. Normally, one would expect the gain of the lighter doped HBT to be four times greater than the gain of the HBT with the heavier base doping. However, if band-gap shrinkage and Fermi degeneracy effects are included, the HBT with lighter base doping would have a gain that is almost 23 times greater than the gain of the heavier doped HBT.

In summary, results that extend previous measurements of $n_{ie}^2 D_n$ to Be doping densities of 1.4×10^{20} cm^{-3} have been presented. These experimental results show significant band-gap narrowing for all the doping densities studied. However, the effects of degenerate Fermi statistics strongly oppose the band-gap shrinkage effects for doping concentrations greater than 8×10^{19} cm^{-3}, resulting in a decreasing $n_{ie}^2 D_n$ for increasing doping. These results indicate that the gain of an AlGaAs/GaAs HBT is significantly degraded when the base is doped above $\sim 10^{20}$ cm^{-3}.

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