Material properties of *p*-type GaAs at large dopings

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We summarize the room-temperature minority-carrier mobility, minority-carrier lifetime, and effective band-gap shrinkage for *p*-type GaAs at large dopings, as determined from measurements on heterostructure bipolar transistors and published literature. The minority-carrier mobilities are significantly smaller than the majority-carrier mobilities, the lifetime data show a change in dependence on doping at 1×10^{19} cm^{-3}, and the effective band-gap shrinkage is $\approx 5\%$ at 1×10^{19} cm^{-3}. The fits to electrical parameters described here should be of interest in modeling of minority-carrier devices.

The performance and operation of the GaAs heterostructure bipolar transistor (HBT) is partly dependent on the electronic properties of the *p*-type GaAs base which is doped in excess of 5×10^{18} cm^{-3}. However, these properties: the minority-carrier mobility (μ_n^p), the minority-carrier diffusion length (L_n), the minority-carrier lifetime (τ_n), and the effective band-gap shrinkage (ΔE_g) are neither adequately known nor is their behavior adequately understood at large doping levels. The published results on these properties are generally at low dopings appropriate to optical devices. These data show significant scatter in minority-carrier parameters depending on the material growth technique, the measurement technique, and assumptions made in interpretation. Better consistency should be expected at larger dopings such as those employed in HBTs. In this work, we report these properties as inferred from our measurements on HBTs, and from other reports in the literature. We also report parametric fits to these data that are suitable for modeling, and we speculate on the nature of the dependence of these properties.

The network response of a HBT can be reduced to simple pole and zero functions at frequencies well below that of unity current gain. Under these conditions, the input admittance of the intrinsic device can be modeled as a bias-dependent resistance and diffusion capacitance, and a transition capacitance. The product of the former, a time constant τ_B, is a constant at moderate injection conditions, and is related to the base width (W_B) and the electron diffusion coefficient (D_n) through the relation $\tau_B = W_B^2/2D_n$ for a base that is uniformly doped and that employs no alloy grading. Knowing the base width, microwave characterization, and parametric fitting can thus provide a reasonable estimate of the diffusion coefficient, and hence the drift mobility through the Einstein relationship. Sensitivity analysis suggests that the diffusion coefficient and hence the mobility for a 1000 Å base can be determined with $\approx 20\%$ accuracy since the device network parameters can be measured as a function of bias and frequency, and several elements of the physical model determined independently.[1] The accuracy can be improved significantly by designing the bipolar to have its current response largely dependent on τ_B,[2] but this requires specialized structures.

Figure 1 contains the mobility information in the doping range of interest showing the data determined from our self-aligned HBTs[3] using the above technique, and the results from Refs. 2, 4, and 5. This figure also includes the fit to these data of

$$\mu_n^p = \frac{8300}{\sqrt[3]{1 + N_A/(3.98\times10^{15} + N_A/641)}}, \qquad (1)$$

where the mobility is in units of cm^2 V^{-1} s^{-1} and the acceptor doping N_A in units of cm^{-3}. We also plot, in this figure, the majority-carrier electron mobility[6] for compensation ratios of 1 and 2. Surprisingly, the inferred minority-carrier mobilities are lower than the majority-carrier mobilities even for the higher compensation ratio. The magnitude of this minority-carrier mobility vis-à-vis the majority-carrier mobility has been a matter of some debate.[7-9] One probable cause for the lower minority mobility is that electron-hole scattering is similar in magnitude as the ionized impurity scattering, and that the electron-hole drag effect in bipolar[10] is not adequately compensated for by field changes in GaAs. However, these can only partially explain the behavior since the minority mobility is even smaller than the majority mo-

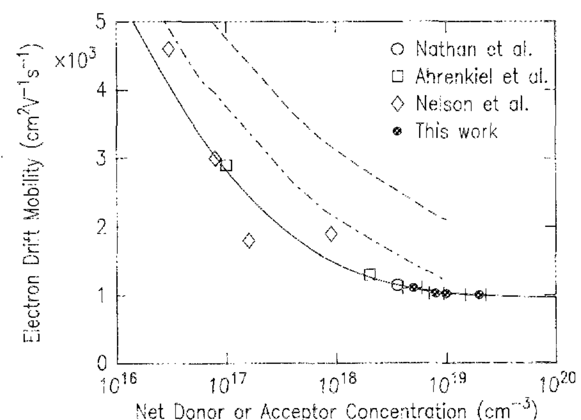

FIG. 1. Electron drift mobility in *p*-GaAs as a function of net dopant concentration at 300 K. The filled circles are drift mobilities from this work. The solid line is the parametric fit to the data, and the dashed and dot-dashed lines are the mobility of electrons as majority carriers for compensation ratios of 1 and 2, respectively.

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bility that corresponds to a compensation ratio of 2. The trend, at large dopings, points to saturation in the mobility, similar to that in silicon. However, unlike silicon,[11] these results indicate a substantially smaller minority-carrier mobility than majority-carrier mobility at zero field.

When the conventional GaAs HBT is biased to operate below high-level injection conditions, its gain is determined primarily by recombination at the surface and in the quasi-neutral base region. The importance of both of these is amply demonstrated by the decrease in current gain with increasing perimeter to area ratio as device size shrinks, and by the larger gains obtained in material grown by liquid phase epitaxy. With increase in current density, surface recombination becomes an increasingly smaller fraction. Single heterostructure devices designed to avoid Kirk effect, and double heterostructure devices designed to avoid the alloy barrier which results at high current density, show highest current gains that are within ~50% of the base transport factor limited current gain. This gain is given by $\beta = \text{sech}(W_B/L_n)/[1-\text{sech}(W_B/L_n)]$. Single heterostructure devices with surface barriers that suppress the surface recombination show current gains close to the theoretical maximum. In Fig. 2, we summarize interpreted L_n based on bipolar measurements using our surface passivated devices, and those from the literature (unpassivated devices). In view of the above, the bipolar-based inferences from the literature[12–22] are generally an underestimation, while the results from our measurements are fair indicators of the actual L_n in these structures. At the largest doping listed [2×10^{20} cm^{-3} (Ref. 12)] though, L_n is sufficiently short, with the base surface possibly unpinned, that L_n ought to be close to its real value. This figure also includes data at the lower dopings from the work of Nelson,[5] and Jastrzebski.[23] The maximum diffusion lengths appear to show a change in the slope of the monotonic decrease at a doping of 1×10^{19} cm^{-3}.

Based on our inferred μ_n^p dependence and the L_n data, τ_n can now be derived (see Fig. 3). These data also indicate a change in the nature of variation of τ_n with doping at 1×10^{19} cm^{-3}. This figure also includes our parametric estimate to the more reliable of these data:

$$\frac{1}{\tau_n} = \frac{1}{\tau_{\text{SRH,rad}}} + \frac{1}{\tau_A} = \frac{N_A}{1\times10^{10}} + \frac{N_A^2}{1.6\times10^{29}}. \quad (2)$$

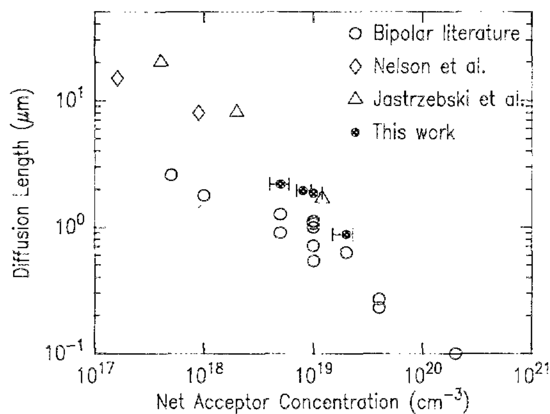

FIG. 2. Inferred diffusion lengths in p-GaAs as a function of net acceptor concentration. The filled circles are from this work, and the open circles are from published unpassivated bipolar results cited in this letter.

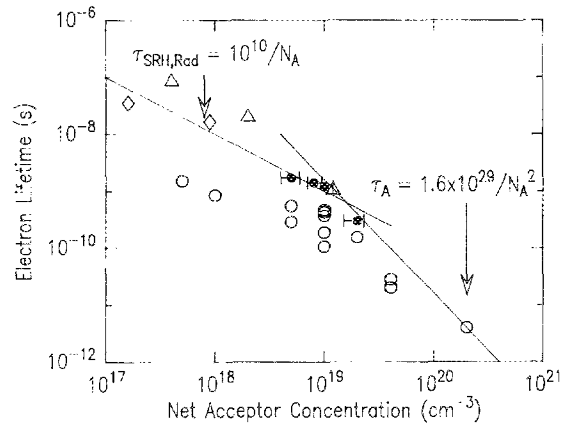

FIG. 3. Inferred electron lifetime in p-GaAs as a function of net acceptor concentration. The symbols have the same definition as in Fig. 2. The open circles are an underestimate of the actual lifetime because these are inferred from unpassivated bipolar structures. The lines are our best estimate of a parametric fit to lifetime.

Here, $\tau_{\text{SRH,rad}}$ is the lifetime dominated by Shockley–Read–Hall recombination and radiative recombination, and τ_A is the lifetime that we believe is dominated by Auger recombination. The unit of lifetimes in the above expression is s and the unit of acceptor doping N_A is cm^{-3}. The variation at lower doping is in conformity with earlier optical data,[24] but the higher doping results are lower.

Auger processes are strongly believed to be the leading cause of laser threshold variation with temperature for small band-gap materials such as InGaAs, GaAlAsSb, and InGaAsP.[25,26] In GaAs, the effect has been usually ignored because of the larger doping at which it occurs. Gel'mont *et al.*[27] report an Auger coefficient of 6.5×10^{-30} cm^6/s for nondegenerate GaAs, and the calculations for pure and phonon-assisted Auger processes involving conduction band, heavy hole band, and split-off band (CHSH)[28] at a doping of 2×10^{18} cm^{-3} indicate a coefficient of 2.1×10^{-30} cm^6/s. The empirical result here corresponds to an Auger coefficient of 6.25×10^{-30} cm^6/s in accord with these results.

The bipolar is also very suitable for measurement of effective band-gap shrinkage. This shrinkage is most significant in the base because of the large dopings employed and it leads to a reduction in the injection barrier. Following Slotboom *et al.*,[29] the effective electrical np product in the base ($n_{i,\text{eff}}^2$) can be determined since the collected electron current density (J_C) is related to the base Gummel number Q_B by

$$J_C = \frac{qD_n n_{i,\text{eff}}^2}{Q_B} \exp\left(\frac{qV_{\text{be}}}{kT}\right) \quad (3)$$

for an applied bias of V_{be} at the base-emitter junction. Here, $n_{i,\text{eff}}^2 = n_{i0}^2 \exp(\Delta E_g/kT)$, where ΔE_g is the effective reduction in band gap. At low dopings, $n_{i0}^2 = 5.0625\times10^{12}$ cm^{-6} for GaAs at 300 K. Two structural sources of inaccuracy for ΔE_g are: the accuracy of doping in the base which is quite well characterized by Hall measurements for uniformly doped structures, and the accuracy of base width which is known within $\approx 10\%$ by growth calibration and microscopy. Additional major sources of inaccuracy may arise from inadequate grading of the injection junction, diffusion

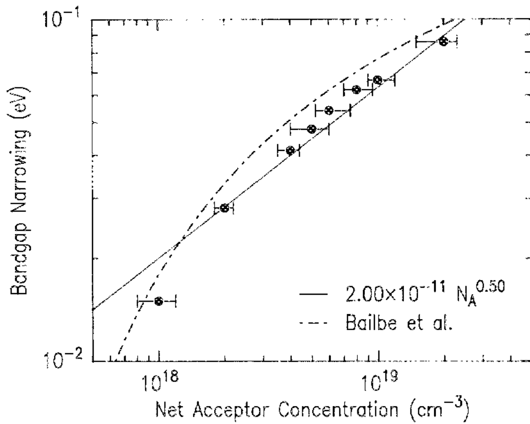

FIG. 4. Inferred effective band-gap shrinkage as a function of acceptor concentration in p-GaAs. The solid line is the parametric fit reported in this work.

of base dopant, or device nonlinearities at high current densities. However, since the doping in the emitter is limited, a single heterostructure device can be used to verify that these are not a problem by measuring J_C with the transistor operated in the reverse mode also. Identical collector current behavior at medium and low current density assures that neither of these are a problem.

Figure 4 summarizes ΔE_g at 300 K for GaAs derived using the above technique. A parametric fit to this data, optimized for higher dopings, is given by the relation

$$\Delta E_g = 2.00\times 10^{-11}\times N_A^{0.50}, \tag{4}$$

where the unit of ΔE_g is eV and that of N_A is cm^{-3}. Activation energy analysis agrees with this result. The magnitude of this shrinkage is quite substantial. At an acceptor doping of 1×10^{19} cm^{-3}, this shrinkage is $\approx$0.07 eV, nearly 5% of the turn-on voltage of the junction. It is obviously of substantial significance in bipolar simulations. Klausmeir-Brown *et al.*[30] have reported the electron concentration and diffusion coefficient product from measurements on homostructure bipolar transistors. The effective band-gap shrinkage derived from these, using our mobility model, indicates close agreement near dopings of 1×10^{19} cm^{-3}. Our inferred band-gap shrinkage, however, is lower at lower dopings and larger at larger dopings. In Fig. 4, we have also included the effective band-gap shrinkage from a theoretical calculation of Bailbe *et al.*[31] We emphasize that neither of these are actual band parameters; they are quantitative fits that allow our simple theoretical treatment to be extended for modeling purposes into a region where the treatment is otherwise questionable. Casey and Stern,[24] e.g., provide an expression for band-gap shrinkage based on optical data and with substantially weaker variation than these results. The calculated results of Bailbe *et al.* agree better with our measurements. We can only speculate that this agreement is a consequence of the assumptions related to inclusion of the many-body effects. The results of Ref. 31 are based on a theoretical electrical idealization assuming a skewed impurity band and a screening length which is more accurate at higher dopings while the results of Ref. 24 are based on optical data assuming alternate idealization. Kane[7] has pointed out the complexity and assumptions inherent in such calculations.

In conclusion, we have summarized experimental data and parametric fits of μ_n^p, τ_n, and ΔE_g at room temperature for p-type GaAs at large dopings. μ_n^p shows a trend of being lower than majority-carrier mobility and having a value closer to the majority-carrier mobility at a compensation ratio exceeding 2. We conjecture that the Auger processes become increasingly important in limiting the carrier lifetime at dopings exceeding 1×10^{19} cm^{-3}, and that the effective band-gap shrinkage is also quite substantial. Reference 2 had found a substantial increase in μ_n^p at 77 K. This is of significance to HBTs operating at lower temperatures, and may be of significance to understanding the dominant mechanisms in minority-carrier transport in compound semiconductors. Thus, similar work at 77 K should also be of interest.

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