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# Transistor-based measurements of electron injection currents in $p$-type GaAs doped $10^{18}$–$10^{20}$ cm$^{-3}$

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Measurements of electron currents injected into $p^+$-GaAs are presented for molecular beam epitaxially grown material doped from $2\times10^{18}$ to $8\times10^{19}$ cm$^{-3}$ with Be. The collector current versus base-emitter voltage characteristics of $n$-$p^+$-$n$ GaAs homojunction bipolar transistors are analyzed, and the results are interpreted in terms of the quantity $(n_0D_n)$, where $n_0$ is the equilibrium minority-carrier concentration and $D_n$ is the minority-carrier diffusion coefficient. The results are consistent with earlier measurements of $(n_0D_n)$ made using metalorganic chemical vapor deposited $p^+$-$n$ GaAs solar cells, Zn doped as heavily as $1\times10^{19}$ cm$^{-3}$. The large electron injection currents observed are interpreted as evidence for significant effective band-gap shrinkage. These effects must be accounted for in the modeling and design of GaAs-based heterojunction bipolar transistors and solar cells.

Measurements of the collector current versus base-emitter voltage characteristics of $n$-$p$-$n$ Si bipolar transistors showed a strong enhancement of the electron current injected into $p^+$-Si.[1] Those enhanced electron injection currents have been attributed to doping-induced perturbations of the band structure which increase the $n_0p_0$ product.[2] Such heavy doping effects must be treated for accurate design and modeling of Si bipolar transistors and solar cells.[1,3] While heavy $p$-type doping has been known to affect optical transitions in GaAs,[4] its effect on the electrical performance of GaAs devices has only recently been explored. In a previous paper we characterized electron injection currents in $p^+$-$n$ GaAs diodes with $p$ layers doped from mid $10^{17}$ to $10^{19}$ cm$^{-3}$.[5] Those results showed heavy doping effects in $p^+$-GaAs analogous to those observed in $p^+$-Si, but the technique used was limited to dopings $\leqslant10^{19}$ cm$^{-3}$. In this letter we present new results obtained using a technique based on characterization of the collector saturation current of $n$-$p^+$-$n$ GaAs homojunction bipolar transistors. The results show significant heavy doping effects up to $8\times10^{19}$ cm$^{-3}$ and are consistent with the diode measurements below $10^{19}$ cm$^{-3}$. These heavy doping effects must be treated to accurate model GaAs bipolar devices.

Consider an $n$-$p$-$n$ homojunction bipolar transistor (BJT) having a spatially uniform base doping profile. When the emitter-base junction is forward biased and the base-collector junction short circuited or reverse biased, the collector current density versus base-emitter voltage characteristic is described by

$$J_C=\frac{q(n_0D_n)}{W_B}\exp\left(\frac{qV_{BE}}{k_BT}-1\right), \qquad (1)$$

where $n_0$ is the equilibrium electron concentration in the $p$-type base, $D_n$ is the diffusion coefficient of the minority-carrier electrons, and $W_B$ is the width of the quasi-neutral portion of the base. A quantity called the effective intrinsic carrier concentration $n_{ie}$ may be introduced to relate $n_0$ to the ionized dopant density $N_A$, such that $n_0\equiv n_{ie}^2/N_A$. Measurements in heavily doped Si have shown that $n_{ie}$ considerably exceeds $n_{i0}$, the intrinsic carrier concentration in lightly doped Si. For the purpose of device modeling the measured relationship between $n_{ie}$ and $n_{i0}$ may be described by defining a nonphysical effective band-gap shrinkage parameter.[3,6]

Homojunction bipolar transistors were chosen for this work instead of the more common heterojunction bipolar transistors (HBTs); misalignment of the doping and compositional junctions due to dopant diffusion, or improper grading of the emitter aluminum composition in a HBT could result in a conduction-band energy barrier at the emitter-base junction which would invalidate Eq. (1). The technique used in this work to quantify electron injection currents as a function of $p$-layer hole concentration was pioneered by Slotboom and de Graaff,[1] and was recently described in detail for GaAs BJTs.[7] Such transistor measurements facilitate the separation of hole and electron current components. In this letter the results are reported in terms of the quantity most directly obtained from the measurement of collector current versus base-emitter voltage, the product $(n_0D_n)$.

The targeted layer thicknesses and dopings of the films used in these experiments are described in Table I. The films were all grown in a Varian GEN-II molecular beam epitaxy (MBE) system on $n^+$-GaAs substrates at a substrate temperature of 600 °C (the oxide desorption temperature was 580 °C). The growth rate was 1 μm/h; film thickness was monitored by counting oscillations in the reflection high-energy diffraction (RHEED) pattern during noncritical portions of the growth. The $p$- and $n$-type dopants were Be and Si, respectively. Standard optical lithography and wet etching procedures were employed in device fabrication. Seven films were studied, with targeted base layer Be concentrations of $2\times10^{18}$–$8\times10^{19}$ cm$^{-3}$. The slope of a plot of

TABLE I. Targeted layer thicknesses and dopings of the MBE-grown homojunction bipolar transistor films used in this study.

| Layer composition | Function | Thickness (Å) | Dopant concentration (cm$^{-3}$) |
|---|---|---|---|
| $n^+$-GaAs | Contact layer | 1000–2000 | $\geqslant2\times10^{18}$ |
| $n$-GaAs | Emitter | 1000 | $5\times10^{17}$ |
| $p^+$-GaAs | Base | 1000–3000 | $2\times10^{18}$–$8\times10^{19}$ |
| $n$-GaAs | Collector | 2000–3000 | $2\times10^{17}$ |
| $n^+$-GaAs | Sub-collector | 10 000 | $\geqslant10^{18}$ |
| $n^+$-GaAs | Substrate | ⋯ | $\geqslant10^{18}$ |

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TABLE II. Summary of the measurements made using homojunction bipolar transistors.

| Be concentration from SIMS ($cm^{-3}$) | Targeted base width (Å) | Hole concentration from Hall effect ($cm^{-3}$) | Hole mobility from Hall effect ($cm^2 V^{-1} s^{-1}$) | Measurement temperature (K) | $(n_0D_n)$ at 300 K ($10^{-5} cm^{-1} s^{-1}$) |
|---|---|---|---|---|---|
| $2.0\times10^{18}$ | 3000 | $1.4\times10^{18}$ | 178 | 297.4 | 51.5 |
| $6.5\times10^{18}$ | 2000 | $4.6\times10^{18}$ | 134 | 299.2 | 23.1 |
| $1.5\times10^{19}$ | 1000 | $1.0\times10^{19}$ | 104 | 298.1 | 10.5 |
| $2.4\times10^{19}$ | 1000 | $2.4\times10^{19}$ | 88 | 297.9 | 6.30 |
| $3.2\times10^{19}$ | 1000 | $2.6\times10^{19}$ | 86 | 298.7 | 4.94 |
| $5.3\times10^{19}$ | 1000 | $4.1\times10^{19}$ | 82 | 298.3 | 3.60 |
| $7.9\times10^{19}$ | 1000 | $6.0\times10^{19}$ | 76 | 299.4 | 2.63 |

carrier concentration in the *p*-type material as a function of Be oven temperature was consistent with the vapor pressure curve of Be in this doping range, implying the absence of significant precipitation of Be even at the highest doing level. Further details of film growth and device fabrication have been described elsewhere.[7]

Dopant and carrier concentrations in the *p*-type base layer of each film were characterized in several ways. Secondary-ion mass spectroscopy (SIMS) was used to probe the Be profile. Use of a Be-implanted calibration standard resulted in an absolute accuracy of $\pm 20\%$. Si concentration was also monitored during the SIMS analysis, and the Si profile was used to calibrate the spatial coordinate; beam mixing limited spatial resolution to 150 Å. The base layer hole concentrations were also probed by Hall effect. The average Be concentration found in the base layer of each film by SIMS is listed in the first column of Table II; also displayed in Table II are the base layer hole concentration and mobility found by Hall effect measurements (assuming a Hall *r* factor of unity). Although the hole concentration values derived from Hall effect measurements are as much as 30% lower than the Be concentration values given by SIMS, we believe that the *p*-type material is essentially uncompensated. Several authors have pointed out that the Hall *r* factor may be quite different than unity in *p*-type GaAs, leading to uncertainty concerning the reliability of hole concentration values derived from Hall effect measurements.[8,9] Since the incorporation of Be in the films was ideal,[7] we equate the base layer hole concentration $p_0$ with the average base layer Be concentration in each film.

The SIMS profiles of Be in all but two of the films were ideal, within the resolution of the analysis, exhibiting very steep sides and flat peaks. The Be profile was slightly nonuniform in each of the two most heavily doped films, displaying broad flat peaks over most of the base width, but showing evidence of some diffusion of Be on the substrate side of the base.[7] The base width and average base doping for those two films was estimated by a careful spatial integration of the Be profile, and the reported value of $(n_0D_n)$ necessarily represents an average quantity as described in Ref. 7. (The results reported in Ref. 6 at $N_A = 10^{19}$ $cm^{-3}$ was omitted in this letter because the SIMS profile indicated a nonuniform Be profile.)

The collector current density was measured as a function of emitter-base voltage, with the base and collector shorted, for a number of transistors on each film. The $J_C$-$V_{BE}$ data were well described by Eq. (1) in all cases, except at low biases where leakage currents were important, and at high biases where series resistance was important. The quantity $(n_0D_n)$ was determined from the intercept of the linear portion of a plot of ln $J_C$ vs $V_{BE}$; the device temperature could also be found from the slope of the plot. The temperature measured by a thermocouple agreed with the temperature found from fitting the ln $J_C$ vs $V_{BE}$ plot to within the 0.2 K for all devices.

Equation (1) is valid only so long as recombination in the base is not significant. This constraint is most severe for the film with the most heavily doped base layer ($7.9\times10^{19}$ $cm^{-3}$). For this film we estimate that an electron diffusion length less than 1250 Å would be required to reduce the measured collector current by 10%, whereas Lievin *et al.* reported a diffusion length of $\approx$2500 Å at a hole concentration of about $10^{20}$ $cm^{-3}$,[10] so it seems likely that Eq. (1) is valid even in this case.

Results of the extraction of $(n_0D_n)$ from the measured $J_C$-$V_{BE}$ data are listed in the last column of Table II. The actual measurement temperature is also listed in Table II. Following del Alamo,[3] we have scaled all $(n_0D_n)$ products to $T = 300$ K using the known temperature dependence of $n_{i0}$.[11] The maximum error introduced by this temperature scaling should not exceed 2%.

Figure 1 is a plot of $(n_0D_n)$ as a function of hole concentration in *p*-type GaAs at $T = 300$ K. Both the transistor data listed in Table II and the previously reported diode data[5,12] are shown in Fig. 1. [Recall that $(n_0D_n)$ is proportional to the electron current injected into the base of a bipolar transistor, so its value has a direct relationship to the gain of a HBT.[6]] Two other curves are shown in Fig. 1 for comparison with the measured data. The lower curve, labeled "No Bandgap Shrinkage", was computed without considering any heavy doping effects except degeneracy of the hole gas,[5] with $n_{i0} = 2.25\times10^6$ $cm^{-3}$ (Ref. 11); $D_n$ was estimated from a fit to the measured minority-carrier mobility values.[6] The curve is dashed above $4\times10^{18}$ $cm^{-3}$ because that is the highest hole concentration at which the minority electron mobility has been measured.[13] The difference between this curve and the measured data is more than an order of magnitude above $10^{19}$ $cm^{-3}$, and underlines the importance of considering these effects. The second curve in Fig. 1, labeled "Theory", makes use of the theoretical work of Bennett and Lowney, who used a detailed many-body approach to calculate the ratio $n_{ie}/n_{i0}$ as a function of hole concentration in $p^+$-GaAs.[14] Again, $n_{i0} = 2.25\times10^6$ $cm^{-3}$, and $D_n$ was estimated from measured values as just described. The

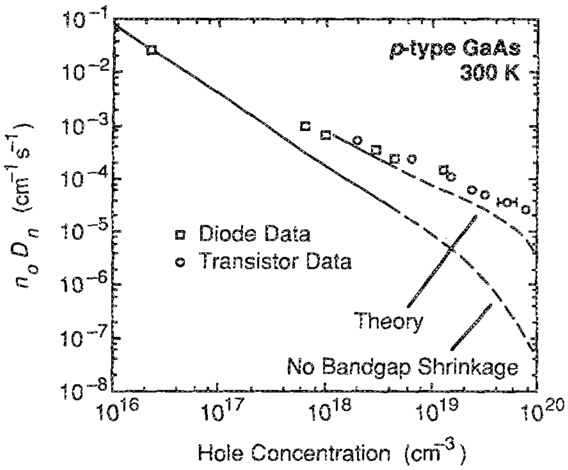


FIG. 1. Quantity $(n_0 D_n)$ in $p$-type GaAs at $T = 300$ K. The squares represent diode data and the circles represent the transistor data from Table II. The error bar represents an uncertainty of $\pm 20\%$ in the magnitude of the Be concentration from SIMS analysis of the transistor films. The curve labeled "Theory" was constructed from calculations of $n_{ie}/n_{i0}$ [14] combined with a fit to measured minority-carrier mobility data.[6] The curve labeled "No Bandgap Shrinkage" was constructed assuming no heavy doping effects except hole gas degeneracy.[5]

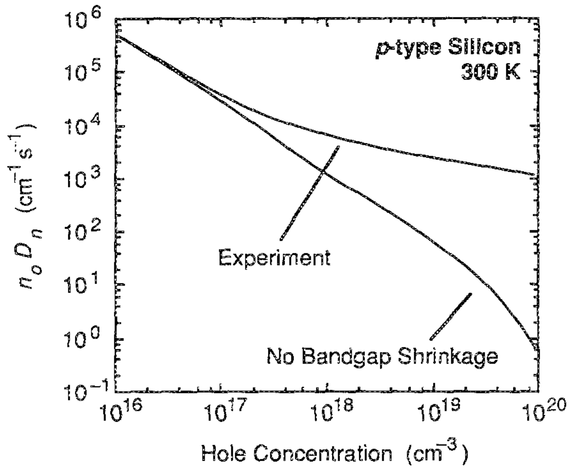


FIG. 2. Quantity $(n_0 D_n)$ in $p$-type Si at $T = 300$ K. The curve labeled "Experiment" was constructed using fits for minority electron mobility (i.e., $D_n$) and effective band-gap shrinkage as functions of hole concentration, as given by Swirhun *et al.* The curve labeled "No Bandgap Shrinkage" was constructed assuming no heavy doping effects except hole gas degeneracy.

theoretical curve agrees within a factor of 2 with the measured results over most of the measured range of hole concentrations.

One might expect that effective band-gap shrinkage in $p^+$-GaAs would be qualitatively similar to the well-characterized effects in $p^+$-Si. Figure 2 is a plot of $(n_0 D_n)$ as a function of hole concentration in $p$-type Si at $T = 300$ K. The experimental curve was constructed using fits for minority electron mobility (i.e., $D_n$) and effective band-gap shrinkage as functions of hole concentration, as given by Swirhun *et al.*[15] The curve labeled "No Bandgap Shrinkage" was constructed in the same way as the analogous curve in Fig. 1, using the minority-carrier mobility fit of Swirhun *et al.* Both curves in Fig. 2 were constructed using $n_{i0} = 1.18 \times 10^{10}$ cm$^{-3}$. A comparison of Figs. 1 and 2 reveals that the behavior of $(n_0 D_n)$ as a function of hole concentration in $p^+$-GaAs and $p^+$-Si displays a similar trend. (The large difference in the vertical scale factor is accounted for by the large difference in $n_{i0}$ for GaAs and Si.) While caution is necessary in extrapolating the $p^+$-GaAs minority-carrier mobility data, it appears that the effective band-gap shrinkage is somewhat stronger in $p^+$-Si for dopant concentrations above $10^{19}$ cm$^{-3}$.

For the purpose of device modeling, a nonphysical effective band-gap shrinkage parameter $\Delta_G^0$ is often introduced to describe the measured relationship between $n_{ie}$ and $n_{i0}$, where $n_{ie}^2 \equiv n_0 N_A$. A commonly used definition is[3,6]

$$\Delta_G^0 \equiv k_B T \ln(n_{ie}^2/n_{i0}^2) .$$

We do not quote apparent band-gap shrinkage values in this letter because extraction of $\Delta_G^0$ from the measured $(n_0 D_n)$ values depends on knowledge of the minority-carrier mobility (or $D_n$). In Ref. 6 we estimated $\Delta_G^0$ by using available data for $D_n$ and diode measurements of $n_0 D_n$ for $N_A \leqslant 10^{19}$ cm$^{-3}$. The transistor measurements presented in this letter confirm the data presented in Ref. 6 for $N_A \leqslant 10^{19}$ cm$^{-3}$ but suggest that the expression for $\Delta_G^0$ presented in Ref. 6 overestimates $\Delta_G^0$ for $N_A > 10^{19}$ cm$^{-3}$.

In summary, measurements of electron current injected into the base of $n$-$p^+$-$n$ GaAs homojunction transistors were presented. The large magnitude of the measured currents was attributed to heavy doping effects in $p^+$-GaAs. These effects are analogous to the so-called band-gap shrinkage effects observed in $p^+$-Si. As was found to be the case for Si, heavy doping effects must be treated to correctly model GaAs-based bipolar transitors and solar cells.[6,16] However, further work is necessary to measure the minority electron mobility for hole concentration greater than $10^{19}$ cm$^{-3}$, and to examine the effects of heavy doping in $n$-type GaAs.

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