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Transistor-based studies of heavy doping effects in n-GaAs

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The $n_{ie}^2 D_p$ product (where n_{ie}^2 is the *np* product and D_p is the minority hole mobility) in heavily doped *n*-GaAs has been measured by electrical characterization of *p-n-p* GaAs homojunction transistors with base dopings ranging from approximately 1×10^{17} to 9×10^{18} cm^{-3}. The measured $n_{ie}^2 D_p$ product decreases as the doping density increases. These results suggest that n_{ie} is roughly constant with doping density, in sharp contrast to the large increase observed for *p*-type GaAs. This work shows that when designing GaAs bipolar devices, it is important to consider the large difference in effective band gap between n^+ and p^+ regions.

Bipolar devices often contain regions with heavy impurity doping. In a heavily doped semiconductor, band tails result from the fluctuating potential caused by impurity atoms, and a rigid band-gap shrinkage is caused by many body effects.[1] Along with majority carrier degeneracy, these heavy doping effects perturb the equilibrium *np* product, $n_0 p_0 = n_{ie}^2$. For p^+ GaAs, recent measurements of the product, $n_{ie}^2 D_p$, reported by Harmon *et al.*[2] indicates that n_{ie}^2 is strongly enhanced in p^+ GaAs, which has important implications for bipolar devices.[3] In this letter, we present corresponding measurements of $n_{ie}^2 D_p$ in n^+ GaAs and show that the results are strikingly different from those for p^+ GaAs.

We have measured the $n_{ie}^2 D_p$ product in the quasineutral base of GaAs homojunction transistors for dopings ranging from 1×10^{17} to 8.7×10^{18} cm^{-3}. The films were grown by molecular beam epitaxy (MBE) in a Varian Gen II system with a substrate temperature of 600 °C. Two Ga ovens were used with each producing a flux that would result in a GaAs growth of 0.5 μm/h. Except for the film with the most heavily doped base (030491B), all films were grown at a growth rate of 1.0 μm/h (using the two Ga ovens) with a group V to Ga beam equivalent pressure of approximately 20. For the base region of film 030491B, the group V to Ga beam equivalent pressure was increased to 40 by using just one of the Ga ovens. All other regions of this film were grown using the two Ga ovens. The films were all grown with As_2, except for film 100989A, which was grown using As_4. The *n*-type dopant was Si and the *p*-type, Be. Table I lists relevant details about the various films grown. Transistors with emitters ranging from 20×20 to 160×160 μm^2 were fabricated using conventional photolithography and wet etching techniques. Figure 1 shows a typical cross section of a transistor used for the measurements reported here.

The $n_{ie}^2 D_p$ product was deduced from the measured I_C vs V_{EB} characteristic. The collector current was measured as a function of the emitter-base forward bias voltage, keeping the base-collector voltage at zero volts. The collector current in this case is given by

$$I_C = qA_E \frac{n_{ie}^2 D_p}{N_D W_B} \left(e^{qV_{EB}/k_B T} - 1\right), \tag{1}$$

where N_B and W_B are the base doping and base width, respectively. Homojunction transistors were employed because Eq. (1) may not be valid for heterojunction bipolar transistors, because of a possible energy barrier at the heterojunction caused by improper compositional grading or by an offset between compositional and doping junctions.

An ideality factor was extracted from the slope of $\ln(I_C)$ vs V_{EB} graph at each of the measured voltages, and the data was fit to the above equation in the region where the ideality factor was very nearly 1. The slope obtained from the fit gave the value of the temperature of the device, which in most cases was within 0.5 K of the thermocouple temperature noted while measuring the *I-V* characteristics of the transistors. Only those devices which gave fit tem-

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

Film number	N_D From Hall measurements (cm^{-3})	Hall mobility (cm^2/V s)	Base width (Å)	$n_{ie}^2 D_p$ (cm^{-4} s^{-1})
030491C	1.41×10^{17}	4107	3000	7.12×10^{13}
091490C	1.89×10^{17}	4205	3500	6.07×10^{13}
091490B	7.20×10^{17}	3237	3000	4.98×10^{13}
091490A	1.39×10^{18}	2676	2500	3.77×10^{13}
100989A	2.03×10^{18}	2326	2500	2.75×10^{13}
030491B	8.70×10^{18}	1781	2500	2.27×10^{13}

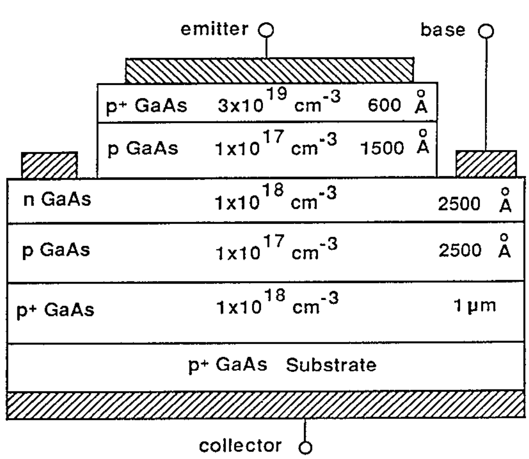

FIG. 1. Schematic illustration of a homojunction GaAs *p-n-p* transistor.

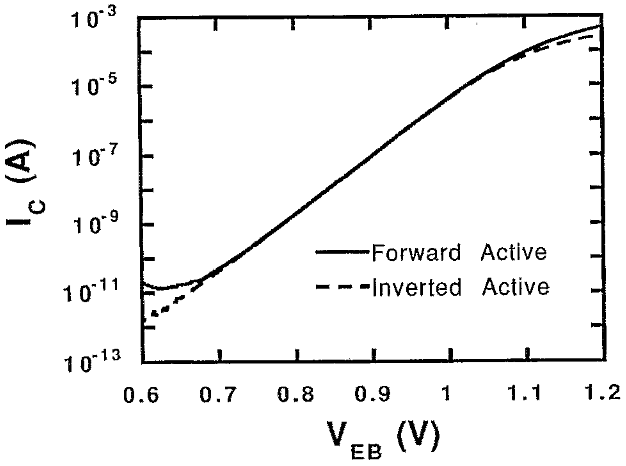

FIG. 2. $I_C - V_{EB}$ characteristics for a typical homojunction, *p-n-p*, GaAs transistor. For this device, the base doping is 1.87×10^{18} cm^{-3}.

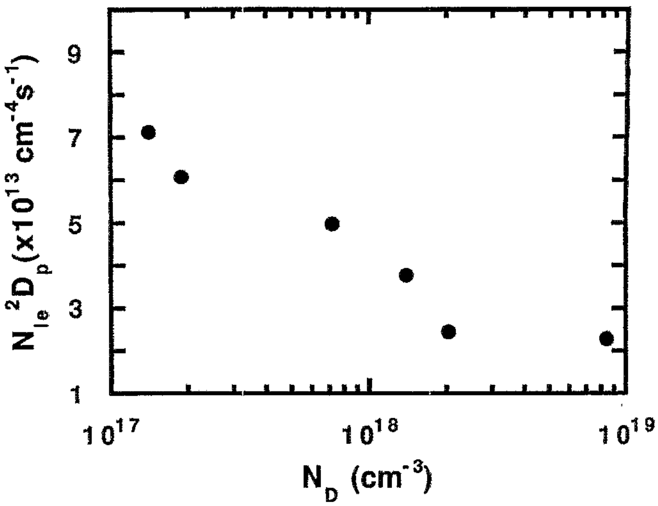

FIG. 3. $n_{ie}^2D_p$ for *n*-GaAs as a function the net, ionized doping density.

perature values that were within 0.5 K of the measured temperature were used to extract the $n_{ie}^2D_p$ values. At least ten such devices were available at each value of doping. The intercept calculated from the fit gave the value of the $n_{ie}^2D_p$ product. Both forward and reverse characteristics were used to extract the $n_{ie}^2D_p$ product. Figure 2 shows a typical *I-V* characteristic for a *p–n–p* GaAs transistor.

The net ionized dopant density needed to compute the $n_{ie}^2D_p$ product was obtained from Hall measurements performed on Hall bridges fabricated on the same wafer with the transistors. The base width W_B was calculated from reflection high-energy electron diffraction (RHEED) oscillations measured during film growth. The small change in the base thickness due to depletion widths extending into the base at emitter-base and collector-base junctions was taken into consideration while calculating the doping values. The values of $n_{ie}^2D_p$ thus obtained were scaled to 300 K using the known temperature dependence of n_{i0}.[4] Table I summarizes the measured results.

As shown in Fig. 3, the $n_{ie}^2D_p$ values obtained decrease monotonically with doping. The diffusion coefficient for majority carrier holes also decreases with increasing doping, and a similar decrease might be expected for minority carrier holes. Thus, the experimental results seem to suggest that n_{ie} is roughly independent of doping, in the range of doping densities explored. Theoretical calculations and experimental measurements do show substantial bad gap shrinkage in n^+ GaAs,[5,6] but the n_0p_0 product is roughly constant because the band-gap shrinkage effects are offset by strong majority carrier degeneracy.

To extract n_{ie}^2 from the measured results, accurate values for the minority hole mobility are required. The available data are very limited, but very recent measurements show that $D_p \simeq 5.8$ cm/s at $N_D \simeq 1.7\times10^{18}$ cm^{-3}.[7] From the data displayed in Fig. 3, we find that $n_{ie}\simeq2.5\times10^6$ cm^{-3} at $N_D\simeq1\times10^{18}$ cm^{-3}, which is quite close to $n_{i0}=2.3\times10^6$ cm^{-3}, the value in intrinsic GaAs at 300 K.[4]

In conclusion, $n_{ie}^2D_p$ was measured for *n*-GaAs for the doping values ranging from approximately 1×10^{17} to 8.7×10^{18} cm^{-3}. Within this range of dopings the $n_{ie}^2D_p$ product decreases with increasing value of doping. These results suggest that the effects of degenerate Fermi statistics largely offset the effects of bandgap shrinkage. This decrease in the $n_{ie}^2D_p$ product with doping is quite different from the trend observed in *p*-GaAs, where the $n_{ie}^2D_p$ product increases with doping until doping levels of about 5×10^{19} cm^{-3} (because of band gap shrinkage effects) and then decreases with doping (because of degeneracy effects). The distinct difference in n_{ie} in n^+ and p^+ GaAs is an important factor to consider when designing GaAs bipolar devices.

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