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Thermal velocity limits to diffusive electron transport in thin-base np^+n GaAs bipolar transistors

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We present experimental evidence that minority electron transport across a thin, quasineutral p^+ GaAs region is limited by the thermal velocity of the electrons rather than by conventional diffusive transport. A set of GaAs homojunction np^+n transistors with base widths of 4000, 2000, 1000, and 500 Å was fabricated and characterized. The diffusive model predicts that the dc collector current of the 500-Å base width transistors should be eight times larger than the collector current of transistors with a 4000-Å-wide base. The experimental results, however, show only a factor of ~3.5 increase in collector current. The measured collector current versus base width characteristic agrees well with theoretical treatments of thin-base transport. These new results present evidence of quasiballistic electron transport in p^+ GaAs and have important implications for GaAs transistor design.

The conventional, diffusive model used to describe minority carrier transport across the base of a transistor assumes that the base width, W_B, greatly exceeds the mean-free path for scattering, l_{sc}. As the base width of a transistor shrinks, the number of such collisions is reduced, and in the extreme limit of no collisions, transport becomes ballistic. For the transport models discussed in this letter, we will assume that the base-collector junction acts as a perfectly absorbing contact (we discuss this assumption later). In the diffusive limit, $W_B \gg l_{sc}$, the collector current is given by

$$J_C = qn(0)D_n/W_B, \tag{1a}$$

while in the ballistic limit, $W_B \ll l_{sc}$, the collector current becomes

$$J_C = qn(0)2v_R, \tag{1b}$$

where v_R is the Richardson velocity defined below, and $n(0)$ is the electron density injected into the base. As the base width shrinks, one should observe a transition from Eq. (1a) to Eq. (1b).

Over the past 20 years, several theoretical treatments of near-equilibrium, thin-base transport have been presented,[1–7] but the effect has not yet been clearly demonstrated by experiment. Experimental work on off-equilibrium transport in abrupt junction heterojunction bipolar transistors (HBT's) is currently being studied, but uncertainties remain as both quasiballistic[8] and diffusive[9,10] results have been reported. In this letter, we experimentally examine the near-equilibrium, thin-base transport of minority carrier electrons in p^+ GaAs. Because electron-hole scattering is suppressed for high hole densities,[11,12] base widths on the order of a mean-free path are readily achieved. For base doping densities and widths typical of modern AlGaAs/GaAs HBT's, we find that room temperature base transport lies between the limits given by Eqs. (1a) and (1b). Studies of the dc collector current versus base width show that Eq. (1a) overestimates the collector current by as much as a factor of 2 when the base width becomes much shorter than the mean-free path. The experimental results indicate that the minority electron transport in the base region becomes limited by the electron thermal velocity. These results are in good agreement with theories of thin-base transport.[1,5]

The transistor structure used in this study was designed to have a long mean-free path and a minimum of extraneous effects. Thus we chose homojunction np^+n GaAs transistors over heterojunction bipolar transistors to avoid problems related to band offsets. The heavy base doping was chosen to make contacting the base easy, to reduce current crowding, and to reduce the Early effect. The heavy base doping also reduces minority electron scattering; recent measurements indicate a minority electron diffusivity of 75 cm^2/s at 4.0×10^{19} cm^{-3}, the base doping density used in this work.[11,12] The resulting mean-free-path, l_{sc}, is about 525 Å as evaluated from[13]

$$l_{sc} = 3D_n/4v_R, \tag{2a}$$

$$v_R = (k_BT/2\pi m^*)^{1/2}, \tag{2b}$$

where v_R is the thermal velocity of the electrons (the so-called Richardson velocity[5]), k_B is Boltzmann's constant, T is the electron temperature, m^* is the electron effective mass, and D_n is the minority electron diffusivity. Equation (2a) assumes that the mean-free path is independent of energy.

A cross section of the transistors used in this study is presented in Fig. 1. The films were grown in a Varian Gen II molecular beam epitaxy (MBE) system using an As_2/Ga pressure ratio of ~20. The As_2 was obtained from thermal cracking of As_4, and Ga from an elemental gallium source. Beryllium was used as the p-type dopant and silicon as the n-type dopant. The only difference between the four films was the width of the base region. The transistors were simultaneously fabricated using wet chemical etching. Alloyed AuGeNi/Ti/Au was used for the emitter contacts, and nonal-

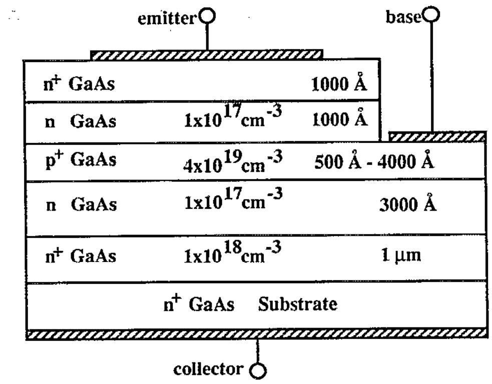

FIG. 1. Cross section of GaAs transistors used in this study.

loyed Au/Ti/Au was used for the base contacts. The common collector was contacted through the substrate using indium contacts.

Secondary ion mass spectroscopy (SIMS) analysis, performed on all the films, confirmed the nominal as grown base thicknesses and established negligible base dopant out-diffusion (see Fig. 2). Hall measurements, summarized in Table I, were performed to characterize the hole concentration in the base region of the transistors. The Hall measurements confirm that the base doping density is 4.0×10^{19} cm^{-3}, and the high mobilities reflect the high quality of the layers.

In the forward active region of operation, the collector current is described by

$$J_C=\frac{qn_{iB}^2D_n}{N_AW_B}\left[\exp\left(\frac{qV_{BE}}{k_BT}\right)-1\right], \tag{3}$$

where J_C is the collector current density, n_{iB}^2 is the equilibrium np product in the base, N_A is the base doping density, and W_B is the base width. For all the devices used in this study, the $J_C(V_{BE})$ characteristic displayed an ideality factor of unity over several orders of magnitude (see Fig. 3). Note that while these "transistors" display no gain, their ideal collector currents characteristics make them well suited to

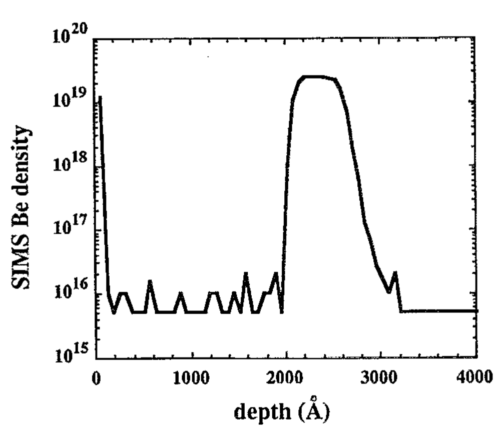

FIG. 2. SIMS Be dopant profile of the 500-Å base width transistor film.

TABLE I. Results of measurements on the base region of GaAs *npn* bipolar transistors at 297 K.

Base width (Å)	Hall carrier concentration ($\times10^{19}$ cm^{-3})	Hall mobility (cm^2/V s)	Collector current ratio
4000	4.02	78	1.00
2000	3.99	81	1.44
1000	4.03	78	2.68
500	4.03	75	3.47

base transport studies. Equation (3) assumes diffusive base transport with $W_B \gg l_{sc}$ and predicts that the collector current should vary inversely with the base width.

The experimental procedure consisted of extracting the saturation current densities from the ideal regions of the measured collector current versus base-emitter voltage characteristics at room temperature. The results are displayed in Table I. According to Eq. (3), the collector current should increase by a factor of 8 as the base thickness is reduced from 4000 to 500 Å. From the measured results, however, we find an increase of only about a factor of ~3.5, less than one-half of the predicted increase. These results are consistent with the expectation that the collector current becomes independent of base thickness in the ballistic limit. In fact, Fig. 4 shows that the measured results are well described by the thin-base theories of Persky[1] and Grinberg and Luryi.[5] Persky estimated the reduction in collector current utilizing a semi-empirical expression that smoothly transitions between the diffusive and ballistic models, while Grinberg and Luryi calculated the reduction in collector current by numerically integrating the Boltzmann transport equation.

Before we conclude that the measured results indicate quasiballistic transport, there are a number of factors to consider. One factor is the possibility of significant base recombination. Recombination in the neutral base region, however, would result in larger reductions in the collector current for the transistors with thicker bases and cannot explain the collector current saturation observed for thin bases. A second possibility is the influence of doping gradients, which would

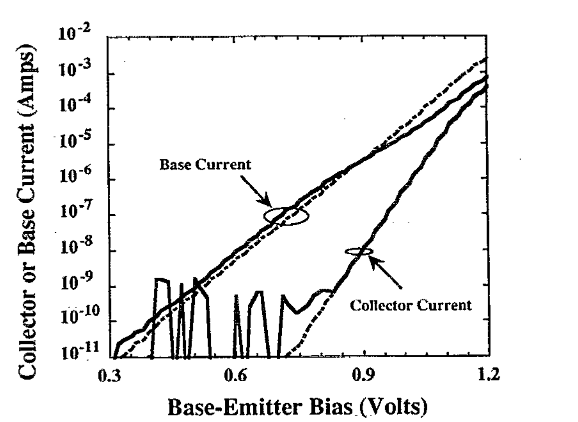

FIG. 3. Example Gummel plot of transistor with a 20×70 μm^2 emitter and a 500-Å base thickness. The dashed lines are for inverted mode operation (swap function of collector and emitter).

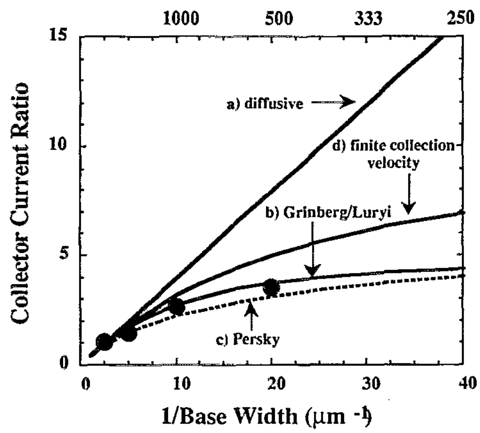

FIG. 4. Comparison of the measured results presented here (closed circles) with the predictions of (a) diffusive transport, (b) Persky (see Ref. 1), (c) Grinberg and Luryi (see Ref. 5), and (d) finite collection velocity for perfect absorber. All of the ratios are normalized to 1.00 at the base thickness of 4000 Å.

produce electric fields that would reduce the sensitivity of J_C to base thickness. The SIMS profiles, however, show quite flat base doping profiles (recall Fig. 2). We have performed calculations based on McKelvey's flux method[13,14] which reproduce Grinberg and Luryi's results for zero electric field. Such calculations show that fields as high as 1 kV/cm have little influence on the J_C vs $1/W$ characteristic.

Finally, we consider modifications to Eq. (1a) required by the fact that the velocity of electrons leaving the base at the base-collector junction must be finite. For a perfectly absorbing contact, the velocity of electrons leaving the base cannot be greater than the kinetic limit of $2v_R$ (the unidirectional thermal velocity). Roulston[6,7] demonstrated that a significant density of electrons will build up at the base-collector junction if the electrons exiting the base are limited to a finite collection velocity, v_{Col}. In the diffusion limit, Roulston demonstrates that Eq. (1a) is modified to become

$$J_C = \frac{qn(0)D_n/W_B}{1+(D_n/W_B)/v_{\mathrm{Col}}} \tag{4}$$

due to the build up of carriers at the base-collector junction. Roulston suggest that v_{Col} be set to the saturation velocity. For GaAs, however, one expects significant velocity overshoot which would allow the junction to act as a perfect absorber. Indeed, Monte Carlo simulations[15] confirm that the velocity of electrons at the base-collector junction is very close to $2v_R$. Limiting the velocity of electrons at the base-collector junction to the kinetic limit ($v_{\mathrm{Col}}=2v_R$) significantly reduces the collector current for thin bases (see curve d Fig. 4). This is not to say that Eq. (4) accounts for our measured results with purely diffusive transport theory, as the underlying assumption for diffusive transport requires $W_B \gg l_{\mathrm{sc}}$. By utilizing Eq. (2a) to relate D_n to l_{sc}, we find that $W_B \gg l_{\mathrm{sc}}$ is equivalent to $D_n/W_B \ll v_R$, showing that Eq. (4) applied with $v_{\mathrm{Col}}=2v_R$ reduces to Eq. (1a) when transport is diffusive. Figure 4 shows that the calculations of Grinberg and Luryi, which includes effects due to the thermal velocity of injected carriers and quasiballistic transport in the base region, as well as effects due to the build up of electrons at the base-collector junction, is in excellent agreement with the measured results.

In conclusion, we have experimentally demonstrated that the diffusive transport model of bipolar junction transistors breaks down for thin-base devices. Thin-base effects are strong for thermal electrons in p^+ GaAs because the heavy impurity doping suppress electron-hole scattering and leads to large mean-free paths.[9,10] The measured results show that the collector current begins to saturate as the base thickness becomes comparable to a scattering mean-free path. Part of this saturation may be explained by restricting the collection velocity at the base-collector junction to the kinetic limit for a perfectly absorbing boundary. However, when this collection velocity restriction is important, the diffusive assumption of $W_B \gg l_{\mathrm{sc}}$ is also violated. In order to fully explain the observed collector current saturation, quasiballistic transport as well as a finite collection velocity must be taken into account. These results demonstrate the need for careful modeling of base transport in compound semiconductor HBT's.

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