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Minority electron transport in InP/InGaAs heterojunction bipolar transistors

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Electron transport across the base of InP/InGaAs heterojunction bipolar transistors is examined by Monte Carlo simulation. The base transit times and electron distribution functions are examined as a function of basewidth. Clear ballistic behavior is observed only for extremely thin bases (much less than 100 Å). Over the range of basewidths of interest for devices, base transport appears diffusive, but the electrons are very far from thermal equilibrium. The diffusive behavior is shown to arise from the sensitivity of the steady-state carrier population to small amounts of large-angle scattering.

For thin-base InP/InGaAs heterojunction bipolar transistors (HBTs), electron transport across the p^+ base can be very far from thermal equilibrium because electrons are launched into the base with an energy of $\sim 10\ k_BT$ and the electron scattering rate in InGaAs is low. Although there is clear evidence that base transport in InP/InGaAs and AlInAs/InGaAs HBTs is quasiballistic,[1–4] a recent study suggested that it is diffusive for basewidths as small as 200 Å.[5] In this letter, a simple, semiclassical transport model is used to examine base transport in InP/InGaAs HBTs. The results show that a surprisingly small amount of scattering can produce device characteristics that appear to be diffusive, although transport is very far from thermal equilibrium.

The base transit time can be deduced from either dc or ac measurements. For InGaAs transistors, the common emitter current gain is often dominated by recombination within the quasineutral base, so $\beta_{dc}=\tau_n/\tau_B$, where τ_n is the minority electron lifetime, and τ_B is the base transit time. The transit time limited unity current gain cutoff frequency is related to the base transit time by $1/2\pi f_T=\tau_B+\tau_C$, where τ_C is the collector delay. The transit times deduced from dc and ac measurements can differ, but when f_T is determined by extrapolating the initial falloff in $|\beta|$ vs f at 20 dB/decade, then the base transit time extracted from the extrapolated f_T is identical to the transit time deduced from dc measurements.

The base transit time can be computed theoretically from the impulse response, which is evaluated by injecting a δ function of electrons into the base and monitoring the current that exits as a function of time. The steady-state electron concentration is related to the time an electron spends in the base,[6] and the steady-state current is the integral of the impulse response. The base transit time is the base charge divided by the collector current which gives

$$\tau_B=\frac{\int_0^\infty h(t)t\,dt}{\int_0^\infty h(t)dt}, \tag{1}$$

where $h(t)$ is the impulse response of the base. Equation (1) can also be obtained by Fourier transforming $h(t)$ to find the base transport factor $\alpha(\omega)$, from which $\beta(\omega)=\alpha/(1-\alpha)$ can be determined. By expanding $\beta(\omega)$ for small ω and setting $|\beta|=1$, the extrapolated, base transit time limited f_T is found. The transit time deduced from the extrapolated f_T is precisely Eq. (1), the value deduced from steady-state analysis.

Electron transport across an InGaAs base was examined with a semiclassical treatment using a Monte Carlo simulation program based on the work of Williams.[7] A three-valley model was assumed, and screened polar optical phonon, nonpolar acoustic phonon, intervalley, ionized impurity, and hole plasmon scattering were treated. Because the base is heavily doped, the plasma frequency is well separated from the optical phonon energy, so a simple treatment of hole plasmon scattering which ignores the coupling to LO phonons was employed.[8] To simulate the thermionic emission of electrons across the InP/InGaAs heterojunction, electrons are injected from a thermal Maxwellian distribution across a 0.24 eV launching ramp. Since our focus was on base transport, the collector was modeled as an absorbing contact. The base is $In_{0.53}Ga_{0.47}As$-doped p-type to 7×10^{19} cm^{-3}, and the temperature is 300 K. Material parameters for InAs and GaAs were taken from Ref. 9.

A series of Monte Carlo simulations for basewidths ranging from 10 to 20 000 Å was performed. It should be clarified that 10 Å is far below the range of validity for the semiclassical model. Such thin bases were investigated only so that the ballistic limit of the semiclassical model could be probed. The base impulse responses were evaluated by injecting a δ function of electrons at $t=0$ and computing the current response by counting the number of electrons that exited the device during a sampling time, ΔT. Similar techniques were recently used to evaluate the collector delay of bipolar transistors.[10] Base transit times were evaluated from the moment of the impulse response according to Eq. (1). In addition, the steady-state solution was also evaluated to obtain τ_B from the steady-state base charge divided by the collector current. The transit times were also evaluated by Fourier transforming the impulse response and determining the extrapolated f_T. Each of these three different techniques produced the same transit times.

The base transit times obtained are plotted in Fig. 1. Except for ultrathin bases, the transit times are observed to scale roughly as W_B^2, which suggests diffusive transport.

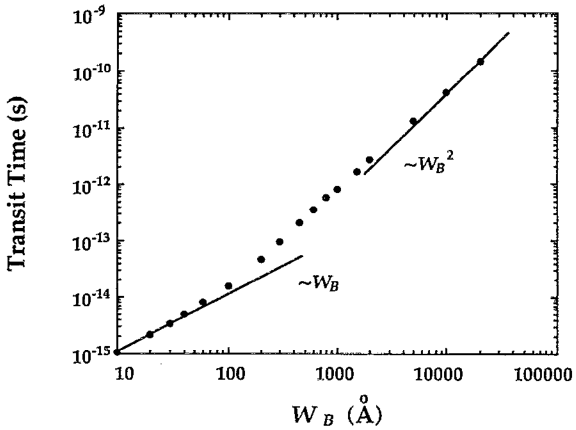

FIG. 1. Base transit time vs basewidth as evaluated by Monte Carlo simulation for an $In_{0.53}Ga_{0.47}As$ p-type base doped to 7×10^{19} cm^{-3}. The lattice temperature is 300 K.

We observe that ballistic behavior (defined as τ_B scaling as W_B) occurs only for basewidths much smaller than about 100 Å, when the ballistic fraction exceeds ~80%. Stated differently, the mean free path must be greater than $\sim 5W_B$ to observe a clear ballistic dependence of the transit time on basewidth. These results suggest that the semiclassical model itself will break down before ballistic transport is observed.

To understand these results, it is instructive to examine a computed impulse response, as shown in Fig. 2 for a 300-Å-thick base. For ballistic transport, carriers would traverse the base at the injected velocity ($v_{\rm inj}\simeq 9.0\times10^7$ cm/s), so the current response would be an impulse in time located at $t_{\rm ball}=W_B/v_{\rm inj}$. The ballistic transit time, $t_{\rm ball}$, is noted in Fig. 2, as is the actual transit time τ_B. For the 300-Å-wide base, over one-half of the carriers exit within 10 fs of $t=t_{\rm ball}$, which suggests that transport is quasiballistic. The transit time, however, is determined by the moment of the impulse response, so the few carriers that scatter and exit the base at long times significantly lengthen the base transit time. For wide bases, the effects of scattering are much more pronounced, and the impulse responses begin to appear more diffusive.

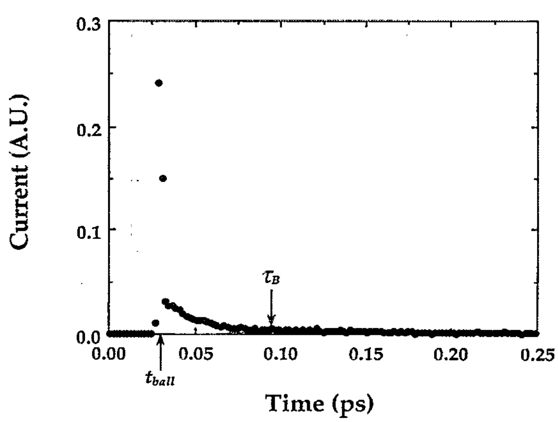

FIG. 2. Current response due to a δ function of electrons injected into the p^+ InGaAs base at $t=0$. The base width is 300 Å, and the sampling time is $\Delta T=2$ fs.

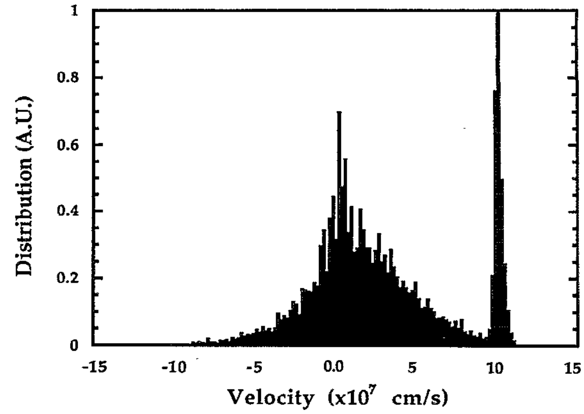

FIG. 3. Steady-state distribution function for electrons in a 300-Å-wide p^+, InGaAs base. The distribution function at the center of the base is shown plotted vs the longitudinal velocity.

Diffusive transport implies that the steady-state distribution function within the base is Maxwellian in shape (when plotted vs the longitudinal velocity) rather than peaked about $v_{\rm inj}$. The steady-state distribution function at the center of the 300-Å-wide base is displayed in Fig. 3. Although the distribution function shows a pronounced ballistic peak, more than 80% of the electrons are located in a Maxwellian distribution. The dominance of the Maxwellian component is surprising because about one-third of the electrons cross the base without scattering at all, and more than 80% of the electrons suffer three or fewer scattering events.

The large Maxwellian component in steady-state arises because the steady-state distribution is especially sensitive to large-angle scattering events. Ballistic electrons cross the base at $v_z\simeq v_{\rm inj}$, which is near the band-structure limited velocity, but the few carriers that do undergo a large-angle scattering event must diffuse out of the base. While these carriers are slowly diffusing out of the base, many more are continually being injected, so the steady-state population of scattered carriers builds up.

The steady-state populations of quasiballistic and diffusive electrons can be estimated with a simple argument. Assume that a flux of $n_0v_{\rm inj}$ electrons is injected into the base and that a fraction Γ undergo large-angle scattering. The current leaving the base is $(1-\Gamma)n_0v_{\rm inj}+n_{mw}(D/W_B)$, where n_{mw} is the density of scattered electrons, and (D/W_B) is roughly the velocity at which they diffuse out of the base. Under steady-state conditions, the incident and emerging fluxes are equal

$$n_0v_{\rm inj}=(1-\Gamma)n_0v_{\rm inj}+n_{mw}(D/W_B), \tag{2}$$

which can be solved for

$$\frac{n_{mw}}{n_0}=\Gamma\times\frac{v_{\rm inj}}{(D/W_B)}. \tag{3}$$

The fraction of the electrons located in the Maxwellian population is not simply the fraction of carriers that undergo scattering; it is multiplied by the ratio of the ballistic to diffusive velocities. Since this ratio is very large, a small amount of scattering can produce large steady-state populations of scattered electrons which control the steady-state performance of the device. Because the extrapolated f_T is determined by the moment of the impulse response, it is similarly sensitive to the strongly scattered electrons.

Returning to Fig. 1, we note that over most of the range of base thicknesses of interest for HBTs, τ_B scales as $\sim W_B^{1.7}$. The linear dependence expected for ballistic transport occurs only for ultrathin bases, and the quadratic dependence expected for thermalized diffusive transport is just beginning to occur for extremely thick bases. These characteristics indicate that electron transport is far from thermal equilibrium, even for these surprisingly wide bases. Because of the InP/InGaAs launching ramp, minority electrons are hot upon entering the base. In the center of the 300 Å base structure, the average energy of electrons computed by Monte Carlo simulation is $u=0.114$ eV, which should be compared to $u_0=0.039$ eV for electrons in thermal equilibrium at 300 K. If one simply equates the transit time for the 2000-Å-wide base to $W_B^2/2D_n$, one finds a diffusion coefficient of $D_n \simeq 75$ cm^2/s. Finally, note that if the scattering rate is artificially enhanced by unscreening POP scattering, then τ_B scales as W_B^2 because the enhanced scattering maintains conditions that are more nearly equilibrium.

To summarize, Monte Carlo simulations reveal that the base transit time is strongly influenced by small amounts of carrier scattering. The steady-state distribution function within the base shows a Maxwellian shape even when a significant fraction of electrons cross the base ballistically. The reason is that the base electron population largely consists of the carriers that strongly scatter. The strongly scattered carriers also play a dominant role in determining the extrapolated f_T. Specific, numerical results depend on the details of injection energy, base thickness and doping, quantum effects in ultrathin bases,[11] and the subtleties of electron-hole scattering,[12] but the simple calculations presented here are consistent with the results of Ritter *et al.*[5] and demonstrate how sensitive base transit times are to small amounts of scattering.

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