

# Numerical study of nonequilibrium electron transport in AlGaAs/GaAs heterojunction bipolar transistors

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(Received 2 March 1989; accepted for publication 11 May 1989)

We have simulated numerically the dynamics of nonequilibrium electron transport in *n-p-n* AlGaAs/GaAs heterojunction bipolar transistors. We show that collector transit time is intimately related to base transport dynamics and high *p*-type carrier concentration in a thin base improves device performance. However, even for a very thin collector depletion region, the small  $\Gamma$ - $X$  intervalley energy separation in GaAs places severe constraints on efficient collector transport.

In a typical high-speed AlGaAs/GaAs *n-p-n* heterojunction bipolar transistor (HBT) conduction-band electrons are injected from an AlGaAs emitter with excess energy  $E_i$  into a *p*-type GaAs base region of thickness  $Z_b$ . For  $Z_b$  similar to the electron mean free path in the base, extreme nonequilibrium base transport plays a role in determining device performance. In a useful HBT a reduction in  $Z_b$  requires an increase in *p*, the majority charge carrier concentration in the base, to keep the base sheet resistance  $R_{b\Box}$  acceptably small (e.g.,  $R_{b\Box} \lesssim 500\Omega_{\Box}$  and  $Z_b \lesssim 700 \text{ \AA}$  requires  $p \gtrsim 3 \times 10^{19} \text{ cm}^{-3}$ ). However, increasing *p* changes both the electron mean free path in the base and the distribution of nonequilibrium electrons impinging on the base/collector junction which, in turn, influences the efficiency of nonequilibrium collector transport. Thus, in contrast to devices utilizing diffusive transport, nonequilibrium base transport can change collector transit time. In itself this fact highlights the inadequacy of all previous device models which assume a diffusive transport mechanism and illustrates the need for an alternative approach to assess the consequences of nonequilibrium electron transport in HBTs. For this type of physical problem it is natural to adopt numerical techniques. In this letter we report results of calculating base and collector transit times and the associated intrinsic limits to high-speed operation of AlGaAs/GaAs HBTs.

We first consider base transport. A conduction-band electron of initial wave vector  $k_i$  and energy  $E_i$  above the conduction-band minimum is injected into the *p*-type base. This electron may scatter inelastically losing energy  $\hbar\omega$  and changing momentum by  $q$ . The electron may also scatter elastically from statically screened ionized impurities in the base. The relevant scattering rates may be calculated using the dielectric response function  $\epsilon(q, \omega)$  within the random phase approximation. We calculate  $\epsilon(q, \omega)$  using a previously developed formalism,<sup>1-3</sup> we then use established techniques to relate this to the scattering rates.<sup>2,3</sup> The trajectories of electrons traversing the base are calculated and pseudo-stochastic scattering events generated by comparing an energy-dependent survival probability with random numbers on the unit interval according to a standard Monte Carlo procedure.

This semiclassical approach assumes that the electrons may be described as wave packets whose position and momentum may be simultaneously specified, i.e.,  $2\pi/k_i \lesssim Z_b$  or  $Z_c$ .

Hot-electron spectroscopy has been used to measure the projection of the nonequilibrium electron momentum distribution perpendicular to a base/collector potential barrier whose energy  $\phi_{bc}$  depends on base/collector bias  $V_{cb}$ . In Fig. 1(a) we show previously published experimental results<sup>5</sup> of measuring two spectra for electrons tunnel injected at the emitter/base junction with initial excess energy  $E_i = 170$  and  $220 \text{ meV}$ .<sup>6,7</sup> The *p*-type GaAs base has an impurity concentration  $p = 3 \times 10^{18} \text{ cm}^{-3}$  and a thickness  $Z_b = 260 \text{ \AA}$ . We simulate the electron motion which gives rise to this spectrum using parameters for GaAs taken from Ref. 8 and an algorithm similar to that previously applied to hot-electron spectroscopy in unipolar structures.<sup>9</sup> In Fig. 1(b) we plot results of our numerical simulation which include a collision broadening factor of around  $50 \text{ meV}$  due to the total scattering rate. For  $E_i = 220 \text{ meV}$  the "ballistic" peak at the injection energy is the dominant feature in the spectra at a base/collector bias  $V_{cb} \approx -1.2 \text{ V}$ . With increasing  $V_{cb}$  (decreasing  $\phi_{bc}$ ) there is a feature at  $V_{cb} \approx -0.7 \text{ V}$  corresponding to the single scattering average energy loss  $\langle \hbar\omega \rangle \approx 60 \text{ meV}$  (average scattering angle  $\langle \theta \rangle \approx 35^\circ$ ). At a bias  $V_{cb} \sim +1 \text{ V}$ ,  $\phi_{bc} \sim 0 \text{ eV}$ , and both spectra show a peak associated with those electrons which have suffered multiple collisions while traversing the base. The excellent overall agreement between the experimental [Fig. 1(a)] and calculated [Fig. 1(b)] spectra gives us confidence in our model. Differences, such as small experimentally unresolved spectral features, may be accounted for by finite spectrometer resolution.

We now discuss the transit time  $\tau_b$  associated with nonequilibrium electron base transport. We calculate the current flowing across the GaAs base/collector boundary as a function of time in response to an input pulse of continuous current at the emitter/base junction. In Fig. 2 we plot impulse response time for 50% (corresponding to unity current gain) of uniformly injected current to traverse the base as a function of base thickness,  $Z_b$ . As may be seen, for an injection energy  $E_i = 220 \text{ meV}$ , a very heavily doped thin base with  $p = 3 \times 10^{20} \text{ cm}^{-3}$  has a delay  $\tau_b^{50\%}$ , which is similar (in fact marginally less) than a less heavily doped base

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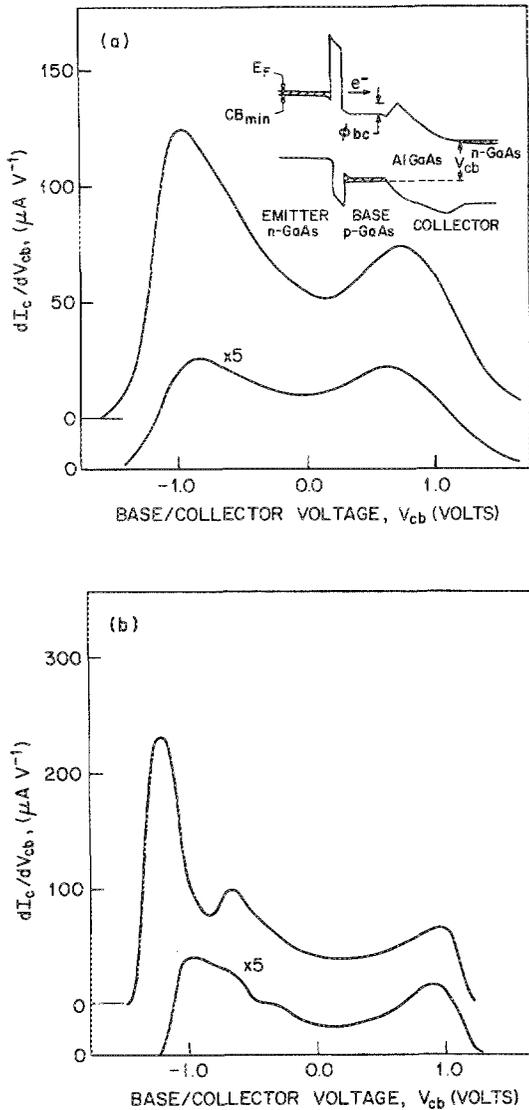


FIG. 1. (a) Derivative of the collector current,  $dI_c/dV_{cb}$ , with collector voltage  $V_{cb}$  for the bipolar transistor sketched in the inset. The lower curve (5 $\times$  scale) is for an injection energy  $E_i = 170$  meV. The upper curve is for an injection energy  $E_i = 220$  meV. The measurements were performed at a temperature of  $T = 4.2$  K. Data taken from Ref. 5. (b) Numerical simulation of the spectra shown in (a). Materials parameters for GaAs taken from Ref. 8.

with  $p = 3 \times 10^{19} \text{ cm}^{-3}$ . This is the result of a reduced inelastic electron scattering rate at high doping levels<sup>2</sup> and demonstrates an otherwise unexpected improvement in device performance with decreasing  $Z_b$  and increasing impurity concentration,  $p$ . Thus, a GaAs HBT with  $E_i \approx 220$  meV,  $Z_b \lesssim 300 \text{ \AA}$ , and  $p \gtrsim 3 \times 10^{20} \text{ cm}^{-3}$  has an insignificant base transit delay  $\tau_b^{50\%} \lesssim 0.05$  ps.

We now consider the transit time associated with transport in a GaAs collector of thickness  $Z_c$ . The device simulated in this case has  $E_i = 220$  meV,  $p = 3 \times 10^{20} \text{ cm}^{-3}$ , and  $Z_b = 250 \text{ \AA}$ . In Fig. 3 we plot impulse response for 50% of electrons to traverse a collector of thickness  $Z_c$  as a function of base/collector bias,  $V_{cb}$ . As may be seen, for  $Z_c = 1000 \text{ \AA}$ , transit time  $\tau_c^{50\%}$  increases from  $\tau_c^{50\%} \approx 0.4$  ps at  $V_{cb} \approx -1$  V

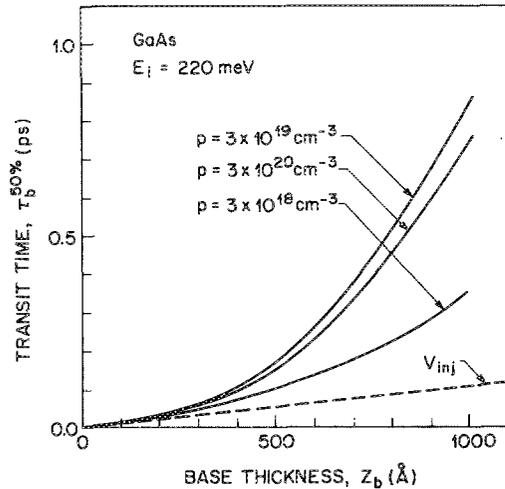


FIG. 2. Base transit time  $\tau_b^{50\%}$  as a function of base thickness  $Z_b$  for  $E_i = 220$  meV and the indicated  $p$ -type carrier concentrations. Injection velocity  $V_{inj}$  is indicated.

to  $\tau_c^{50\%} \approx 1$  ps at  $V_{cb} \approx 0$  V due to the increasing importance of  $\Gamma$ - $X$  intervalley scattering in determining  $\tau_c^{50\%}$ . In realistic applications we expect the base/collector junction to be reverse biased, i.e.,  $V_{cb} > 0$  V. However, for  $V_{cb} > 0$  V velocity overshoot is unimportant and  $\tau_c^{50\%}$  is essentially established by the saturation velocity ( $\approx 1 \times 10^7 \text{ cm s}^{-1}$ ) in the collector.<sup>10</sup> Thus, for  $Z_c = 1000 \text{ \AA}$ , collector transit time  $\tau_c^{50\%} \approx 1.0$  ps ( $\gg \tau_b \approx 0.05$  ps) is the most significant factor limiting device speed. Under these operating conditions for devices in which collector transit time is important there is no advantage using GaAs in preference to Si which has the same saturation velocity. Attempts have been made to improve GaAs HBT device performance by using a modified design to optimize nonequilibrium collector transport.<sup>11</sup> Unfortunately, these devices have a very restricted operating

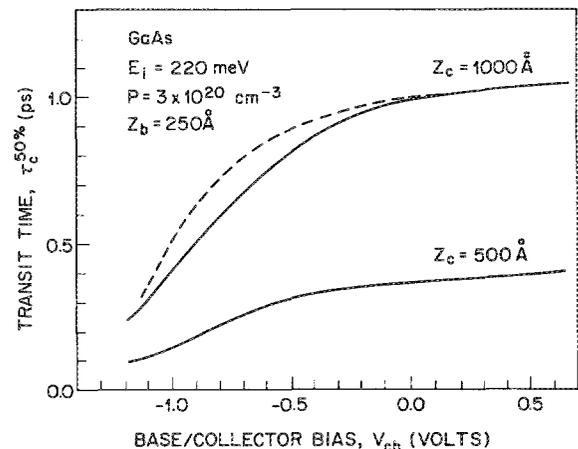


FIG. 3. Collector transit time  $\tau_c^{50\%}$  as a function of base/collector voltage  $V_{cb}$  for  $E_i = 220$  meV,  $Z_b = 250 \text{ \AA}$ ,  $p = 3 \times 10^{20} \text{ cm}^{-3}$ ,  $T = 300$  K, and the indicated values of  $Z_c$ . The broken curve for  $Z_c = 1000 \text{ \AA}$  is for the extreme case of no electron scattering in the base and  $E_i = 220$  meV.

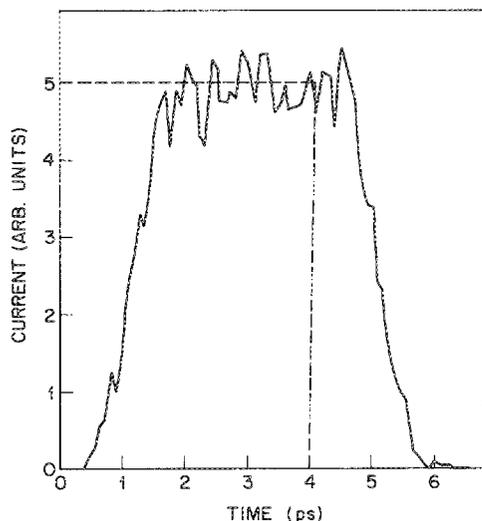


FIG. 4. Impulse response averaged over 0.16 ps (solid curve) to 5000 electrons continuously injected over a period of 4 ps (broken curve) into a HBT. Electron injection energy into the GaAs base is  $E_i = 220$  meV, base thickness is  $Z_b = 250$  Å, GaAs collector thickness is  $Z_c = 1000$  Å, and  $V_{cb} = 0$  V.

range. However, it is worth noting that, in contrast to GaAs, smaller band-gap semiconductors such as InGaAs with large intervalley energy separation have a much more useful operating range ( $V_{cb} > 0$  V) in which collector velocity overshoot may be used to reduce  $\tau_c^{50\%}$ .<sup>12</sup>

To illustrate the dependence of collector transit time on base transport dynamics we consider the extreme case of electrons injected at energy  $E_i$  and no electron scattering in the base region. Thus, the momentum distribution of electrons arriving at the base/collector junction is sharply peaked in the forward direction. Electrons accelerated in the collector's electric field rapidly reach the energy threshold for  $\Gamma$ - $X$  intervalley scattering. As shown in Fig. 3, for the case  $E_i = 220$  meV and  $Z_c = 1000$  Å saturation velocity occurs at a lower value of  $V_{cb}$  (broken curve) than previously (solid curve). A consequence of this fact is that collector transit time  $\tau_c^{50\%}$  cannot be specified independently of the non-equilibrium base transport parameters  $E_i$ ,  $p$ , and  $Z_b$ .

In Fig. 4 we show impulse response (averaged over 0.16 ps) to transport through a GaAs device with  $E_i = 220$  meV,

$p = 3 \times 10^{20}$  cm<sup>-3</sup>,  $Z_b = 250$  Å,  $Z_c = 1000$  Å, and  $V_{cb} = 0$  V. The pulse of duration  $t' = 4$  ps contains  $n = 5000$  electrons of charge  $e$  corresponding to a signal current density  $j_e = ne/t'A_e = 2 \times 10^4$  A cm<sup>-2</sup> for a HBT with emitter area  $A_e = 1$  μm<sup>2</sup>. Because in our calculation electrons are introduced in uniform time intervals of  $t'' = t'/n$  for the duration of the pulse, the noise in Fig. 4 is intrinsic to the device and is a direct consequence of the random nature of semiclassical scattering events in the base and collector. Relative noise in the impulse response may be reduced by increasing the signal current density  $j_e$ .

In conclusion, we have simulated dynamics of nonequilibrium electron transport in  $n$ - $p$ - $n$  AlGaAs/GaAs heterojunction bipolar transistors. Our results illustrate the advantage of using a thin, highly doped base and the dependence of collector transit time on base transport dynamics. However, even for a thin collector depletion region, collector transit time is the important intrinsic delay limiting the performance of AlGaAs/GaAs HBTs. Finally, we demonstrate that an intrinsic source of noise in HBTs is due to the stochastic nature of scattering events in the base and collector.

We wish to thank K. Berthold, Y. K. Chen, and R. N. Nottenburg for useful discussions.

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