

"Ballistic" injection devices in semiconductors

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"Ballistic" electron transistors are of considerable interest for high-frequency operation. Regardless of the mechanism of electron injection or collection it is anticipated that device performance will be dominated by base transit dynamics. We address this issue by calculating the scattering rate for hot electrons in selected semiconductor materials holding some common band structure and transport properties. It is shown that the scattering rate is critically dependent on the carrier concentration and that GaAs is not suitable for fabrication of traditional "ballistic" electron transistors. We suggest that semiconductors with small effective electron mass or a two-dimensional system would be more suitable.

The "ballistic" transistor concepts of the early 1960's are finding their semiconductor analogues today with particular interest being shown in the development of a "ballistic electron transistor" (BET) in GaAs/AlGaAs.¹ In light of this fact we feel that an evaluation of the viability of fabricating truly useful "ballistic" electron devices is overdue. In this letter we outline the essential physics determining the performance of such devices with reference to experimental results supporting these ideas. A theory of hot-electron transport has been developed enabling us to explain the poor performance of BET's fabricated in GaAs and, in addition, study other semiconductor materials in which better results may be expected.

In a traditional BET, electrons are injected from the emitter into the base gaining kinetic energy from a potential difference, ϕ_{bc} , established between emitter and base. While transiting the base these electrons may suffer both elastic and inelastic collisions with ionized impurities and the thermal electron/phonon system, respectively. However, in a high performance transistor most of the injected electrons should transit the base "ballistically," i.e., interacting only with the static periodic part of the lattice potential. On arrival at the collector some electrons are quantum mechanically reflected. Assuming that by careful design, this reflection may be minimized and resonant processes may be neglected, then the fundamental limit to "ballistic" device performance is the scattering rate for the injected nonequilibrium electrons.

To gain further insight into the operation of such a device we fabricated a hot-electron transistor (HET) grown by organometallic chemical vapor deposition (OMCVD) in GaAs/AlGaAs. The epitaxial layers were grown at 650 °C in a rf heated, horizontal, atmospheric pressure reactor equipped with a fast switching manifold. In Fig. 1(a) we indicate the conduction-band edge of a HET consisting of two compositionally graded Al_xGa_{1-x}As bulk triangular barriers placed back to back. The samples were etched into two level mesa structures to reveal emitter, base, and collector. Ohmic contact was made to these regions by rapid thermal annealing of an evaporated Au-Sn alloy.

With the base at ground potential, biasing the emitter negative injects an almost monoenergetic, nonequilibrium

electron distribution into the base with energy $E_i = 0.19$ eV above the conduction-band minimum. The collector barrier energy ϕ_{bc} may be varied by changing the base collector bias V_{bc} . Hence, when $\phi_{bc} \lesssim \phi_{be}$, electrons transiting the base "ballistically" will be collected and contribute to the collector current j_c . However, any angular scattering causes electrons to be collected at lower values of ϕ_{bc} since the electron's component of momentum normal to the plane of the barrier determines whether it is able to surmount ϕ_{bc} . In a real device electrons suffer angular scattering and these scattered electrons may contribute to the base current, degrading device performance.

In Fig. 1(b) we show common base current gain α at 4.2 K of the HET sketched in Fig. 1(a) having a base width of 800 Å and carrier concentration $n = 1 \times 10^{18}$ cm⁻³. As may be seen, the ratio of injected current to collected current for

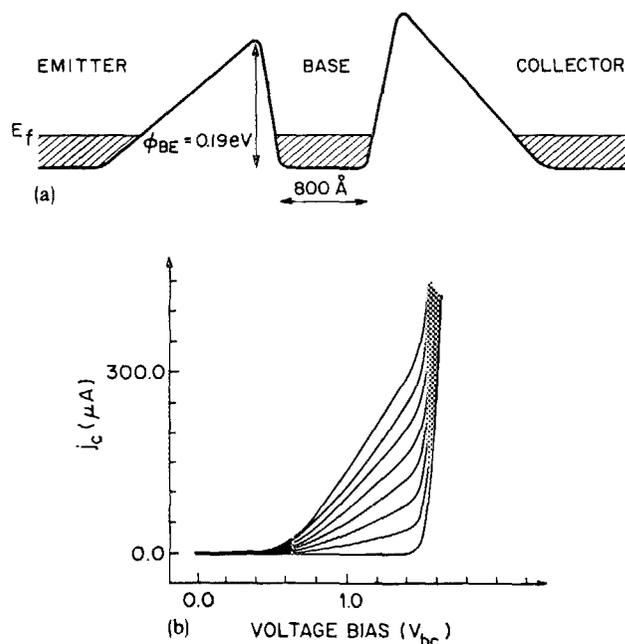


FIG. 1. (a) Schematic of the conduction-band minimum of a hot-electron transistor fabricated in GaAs/AlGaAs. The long and short arms of the triangular barriers have an aspect ratio of 5 with a short arm width of 200 Å. (b) Device I - V characteristics in the common base configuration of a HET having an emitter diameter of 100 μ m. Curves were taken in steps of 100 μ A beginning with an injected current of zero.

“ballistic” electrons is small, $\alpha_B \ll 0.1$. The reason for this is the presence of strong inelastic electron scattering in the base. By analyzing the α measurements in some detail² it is possible to estimate an electron scattering rate of $\sim 3 \times 10^{13} \text{ s}^{-1}$, corresponding to a mean free path of $\sim 300 \text{ \AA}$ for the injected electrons. This value is further supported by the measured magnetic field dependence of the spectra.³

The theory of hot-electron transport we developed to understand the scattering mechanisms giving rise to the poor characteristics shown in Fig. 1(b) included the coupled plasmon/phonon modes in the excitation spectrum of the electron/phonon system in the base.⁴ An electron of energy E_i and wave vector k_i may scatter losing energy $\hbar\omega$ and changing momentum by $\hbar q$. In the Born approximation the total inelastic scattering rate $1/\tau_{in}$ is

$$\frac{1}{\tau_{in}} = \frac{2m_e^*e^2}{\pi\hbar^2} \int -\text{Im} \frac{1}{\epsilon(q,\omega)} \frac{dq}{q} d\omega, \quad (1)$$

where m_e^* is the effective electron mass and $\epsilon(q,\omega)$, the wave vector and frequency dependent dielectric function, is that used in Ref. 4.

The calculated value of $1/\tau_{in}$ is plotted in Fig. 2(a) as a function of E_i for several carrier densities. As expected the scattering rates are zero below the Fermi energy E_F for finite n due to the Pauli exclusion principal and zero below the longitudinal optical phonon energy ($\hbar\omega_{LO}$) for undoped material. For $n = 1 \times 10^{18} \text{ cm}^{-3}$ the inelastic scattering rate increases reaching a maximum of $\sim 2 \times 10^{13} \text{ s}^{-1}$ for $E_i \sim 0.25 \text{ eV}$. At greater values of E_i the rate decreases because of the $1/q$ factor in Eq. (1).

For n as high as $1 \times 10^{18} \text{ cm}^{-3}$ elastic scattering from ionized impurities must also be considered. Elastic scattering is specified by momentum transfer $q = 2k_i \sin(\theta/2)$, where θ is the scattering angle. In the Born approximation the total elastic scattering rate $1/\tau_{el}$ is

$$\frac{1}{\tau_{el}} = \frac{2\pi n_i m_e^* e^4}{\hbar^3 k_i^3} \int \frac{\eta d\eta}{[\eta^2 \epsilon(2k_i, \eta, 0)]^2}, \quad (2)$$

where n_i is the density of ionized impurities ($n_i = n$) and $\eta \equiv \sin(\theta/2)$. In Fig. 2(b) $1/\tau_{el}$ is plotted as a function of E_i for two impurity concentrations. As expected for Coulombic scattering, $1/\tau_{el}$ decreases with increasing E_i ; therefore, to minimize elastic scattering in a device, electrons should be injected at high E_i . We cannot, however, take unlimited advantage of this decrease since intervalley scattering can occur when $E_i \geq 0.3 \text{ eV}$ due to the subsidiary L minimum in GaAs. For $n = 1 \times 10^{18} \text{ cm}^{-3}$ and $E_i = 0.19 \text{ eV}$ we obtain a total mean free path of around 300 \AA in agreement with the experimentally observed value. Additional support for the validity and accuracy of our theory comes from the excellent agreement between our experimental results and Monte Carlo calculations using our theory.⁵ The high scattering rate in GaAs makes it an unsuitable material in which to fabricate a BET. As an alternative one may either choose a semiconductor with a wide intervalley separation to take advantage of the decrease in scattering rate with increasing energy or consider a material with a low effective mass and thereby lower density of states, giving a reduced electron scattering rate.

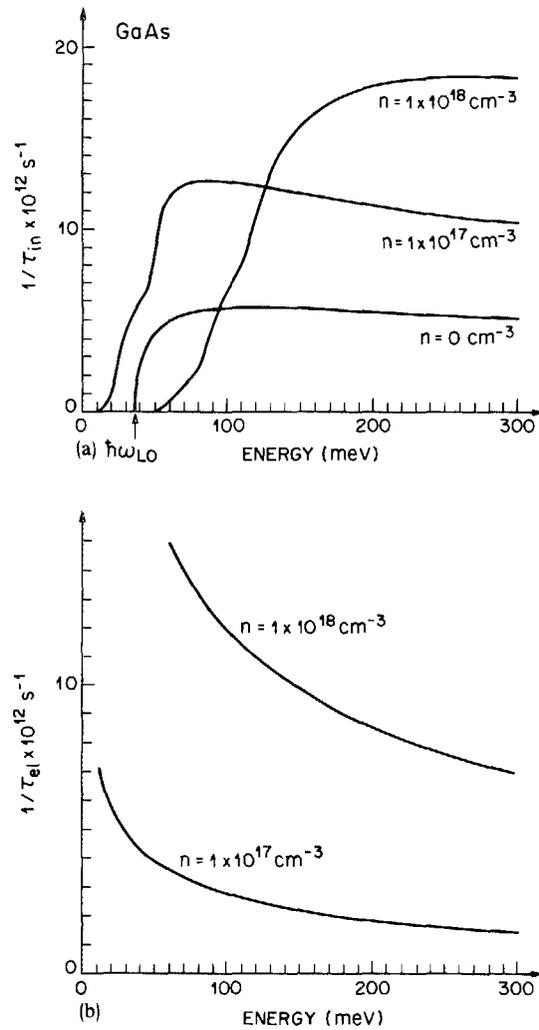


FIG. 2. (a) Total inelastic electron scattering rate as a function of injected electron energy measured from the conduction-band minimum for different carrier densities in GaAs. (b) Total elastic electron scattering. Parameters used in calculations were effective electron mass $m_e^* = 0.07m_0$, high-frequency dielectric constant $\epsilon_\infty = 11.1$, longitudinal optical phonon energy $\hbar\omega_{LO} = 36.3 \text{ meV}$, and transverse optical phonon energy $\hbar\omega_{TO} = 33.3 \text{ meV}$.

A semiconductor illustrating the first case could be CdTe which has a direct band gap of 1.3 eV and a subsidiary minimum 1.1 eV above the conduction-band minimum. Such a material, however, with its large effective electron mass $m_e^* = 0.1m_0$ is unsuitable for “ballistic” devices. On the other hand, semiconductors such as InAs or InSb satisfy the low mass condition and have significantly lower inelastic scattering rates compared to GaAs. Because InAs may be lattice matched to wider band-gap alloys such as GaInAsSb we consider it in preference to InSb. As with many low m_e^* semiconductors InAs has a small band-gap energy, $E_g \sim 0.41 \text{ eV}$, which is less than the energy difference between the subsidiary and conduction-band minimum. Consequently, whereas the maximum injection energy E_i^{max} in GaAs was determined by the subsidiary L minimum, for InAs E_i^{max} must satisfy $E_i^{\text{max}} \leq E_g + E_F$ to avoid the possibility of excitation of electrons from the valence band into the conduction band: as also occurs in InSb.⁶

In Figs. 3(a) and 3(b) we plot $1/\tau_{in}$ and $1/\tau_{el}$ respectively as a function of E_i for various base impurity concen-

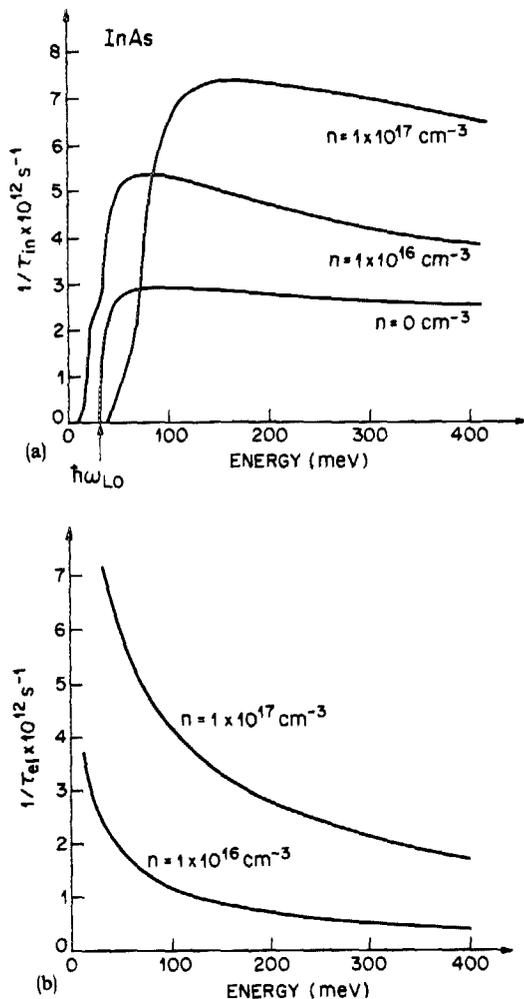


FIG. 3. (a) Total inelastic and (b) total elastic electron scattering rate as a function of injected electron energy measured from the conduction-band minimum for indicated carrier densities in InAs. Parameters used in calculations were $m_e^* = 0.021m_0$, $\epsilon_\infty = 11.8$, $\hbar\omega_{LO} = 30.2$ meV, and $\hbar\omega_{TO} = 27.1$ meV.

trations. For $n = 1 \times 10^{16} \text{ cm}^{-3}$ and $E_i = 0.4$ eV electrons in InAs have a total mean free path of around 3000 Å giving, for a 500-Å base width, $\alpha_B = 0.85$, a promising improvement when compared with GaAs. For better device performance we must consider a different means of confining ther-

mal electrons to the base region. One approach is to create a uniform (fluctuation free) potential well such as occurs in a two-dimensional electron gas at a GaAs/AlGaAs interface. In this case elastic scattering may be reduced to a minimum by use of "modulation doping" which spatially removes the donor ions from the confined electron gas.⁷ The base region will only be ~ 100 Å wide and inelastic electron scattering rates are reduced over those calculated for the three-dimensional case described above (because of the reduction in density of states) so that α_B could easily approach unity. In addition the high conductivity which may be achieved at low temperature leads to a significant reduction in base resistance, a desirable feature in a high performance transistor.

To summarize, elastic and inelastic scattering rates in semiconductors present *fundamental* limitations to the performance of traditional "ballistic" electron injection devices. However, epitaxial growth of semiconductors such as InAs, coupled with new ideas, such as modulation doping, may enable practical "ballistic" electron devices to be realized in the future.

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