Nonequilibrium electron transport in bipolar devices

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The dynamics of nonequilibrium electron transport in bipolar devices have been investigated by calculating minority-carrier elastic and inelastic scattering rates as a function of energy for different majority-carrier concentrations in typical p-type III-V semiconductors. Scattering rates depend on the majority-carrier concentration and a constraint involving the ratio of electron and heavy-hole effective mass.

The maximum possible switching speed of a bipolar transistor is determined by the time it takes an electron to transit from the emitter to collector. Hence, base transport dynamics, in particular hot-electron effects, can influence this speed. Recent results for ultrafast n-p-n GaAs/AlGaAs heterojunction bipolar transistors indicate that hot-electron effects are important in the operation of the device.[1]

In addition to these considerations, there is interest in developing ballistic electron transistors (BET's) concepts for bipolar devices.[2,3] This work was initiated despite a lack of any information on scattering of nonequilibrium conduction-band electrons from majority carriers in the valence band. Recently, hot-electron transport in high-performance n-p-n heterojunction bipolar transistors fabricated in GaAs/AlGaAs has been investigated experimentally using hot-electron spectroscopy[4] and electroluminescence.[5] Results indicate that nonequilibrium electrons in the GaAs conduction band scatter strongly from excitations involving majority carriers in the valence band of the p-type base. However, until now, there was no satisfactory theoretical interpretation of these results. The purpose of this letter is to present an accurate description of nonequilibrium conduction-band electron scattering rates in the presence of mobile charge carriers in the $p^{3/2}$-symmetry valence band of typical III-V semiconductors. Our results may then be used to design useful bipolar BET devices and aid modeling of high-performance heterojunction bipolar transistors.

We consider the zero-temperature limit and adopt the effective mass approximation so that the valence band consists of a heavy hole of mass m_1 [band 1 in Fig. 1(a)] and a light hole of mass m_2 [band 2 in Fig. 1(a)]. We ignore the $j = 1/2$ split-off band. Mobile charge carriers of density p in the valence band have Fermi energy E_F and Fermi wave vector k_{F_1} (k_{F_2}) for band 1 (2). The conduction-band electrons [band 3 in Fig. 1(a)] have an effective electron mass, m_3. A nonequilibrium conduction-band electron of initial wave vector $\mathbf{k}_i$ and energy E_i above the conduction-band minimum may interact with excitations of the system and scatter, changing momentum by $\mathbf{q}$ and losing energy $\hbar\omega$, creating, for example, an electron-hole pair in the valence band. This situation is illustrated schematically in Fig. 1(a) in which an electron in band 2 is excited into an unoccupied state in band 1.

The dielectric function $\epsilon(q,\omega)$, which describes the response of the coupled majority-carrier/phonon system, may be written as

$$\epsilon(q,\omega) = \epsilon_\infty \left(\frac{\omega^2 - \omega_{LO}^2}{\omega^2 - \omega_{TO}^2} \right) + \chi(q,\omega) , \qquad (1)$$

where ω_{LO} and ω_{TO} are the longitudinal and transverse optical phonon frequencies and ϵ_∞ is the high-frequency dielectric constant. The first term in Eq. (1) is the long wavelength phonon contribution and the second term $\chi(q,\omega)$ derives from mobile charge carriers in the valence band (holes), and has been calculated using the random phase approximation.[6]

Information on dissipative processes described by the

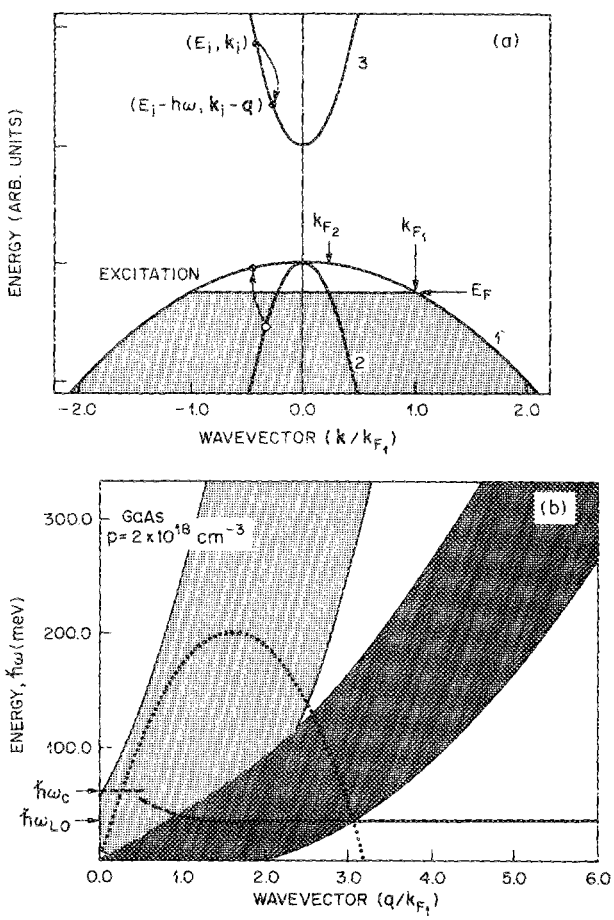

FIG. 1. (a) Schematic diagram of a typical III-V semiconductor band structure showing valence heavy-hole band 1, light-hole band 2, and conduction band 3. (b) Dispersion relation for the coupled majority-carrier/phonon system in p-type GaAs at a carrier concentration $p = 2\times10^{18}$ cm^{-3} for which $E_F = 11$ meV. The dotted curve represents a "parabola of integration" for calculating the inelastic scattering rate of a conduction-band electron with initial energy $E_i = 200$ meV.

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loss function, $-\mathrm{Im}[1/\epsilon(q,\omega)]$ is given by the dispersion relation shown in Fig. 1(b) for the particular case of GaAs doped $p = 2\times10^{18}\,\mathrm{cm}^{-3}$. At $q\sim0$ there is an interband plasmon of energy $\hbar\omega_c$ and a range from $\hbar\omega_{\min} = (1 - m_2/m_1)E_F$ to $\hbar\omega_{\max} = (m_1/m_2 - 1)E_F$ of single-particle interband excitations. The limits to possible single-particle excitations are conveniently expressed in terms of a normalized energy loss $y \equiv \hbar\omega/E_F$ and scattered wave vector $x_1 \equiv q/k_{F_1}$. For interband excitations the bounds for light- to heavy-hole transitions from k_{F_2} are $y = [x_1 \pm (m_2/m_1)^{1/2}]^2 - 1$, heavy- to light-hole transitions from k_{F_1} are $y = m_1/m_2(x_1 \pm 1)^2 - 1$, and heavy- to light-hole transitions from k_{F_2} are $y = 1 - [(m_2/m_1)^{1/2} \pm x_1]^2$. The intraband expressions are $y = x_1(x_1 \pm 2)$ for heavy holes and $y = (m_1/m_2)x_1^2 \pm 2(m_1/m_2)^{1/2}\,x_1$ for light holes. With increasing wave vector the $\hbar\omega_c$ mode enters the single-particle continuum and is Landau damped [indicated by the broken line in Fig. 1(b)]. At large q there exist only the continuum and the dispersionless longitudinal optic phonon mode. In any given inelastic scattering event there will be a contribution from the collective modes and from the single-particle continuum. However, because of the high density of states of the heavy-hole band [band 1 in Fig. 1(a)] a large portion of the single-particle scattering strength lies within the heavy-hole intraband transitions bounded by $y = x_1(x_1 \pm 2)$ and shaded darker in the dispersion curve in Fig. 1(b).

To calculate the total inelastic scattering rate $1/\tau_{\mathrm{in}}$ for a conduction-band electron of initial energy E_i above the conduction-band minimum, we integrate over all scattered wave vectors q and and energy loss $\hbar\omega$ consistent with energy and momentum conservation. In the Born approximation this gives

$$\frac{1}{\tau_{\mathrm{in}}} = \frac{2m_3e^2}{\pi\hbar^2k_i}\int -\mathrm{Im}\frac{1}{\epsilon(q,\omega)}\frac{dq}{q}\,d\omega\,. \tag{2}$$

To illustrate the role energy and momentum conservation play in calculating $1/\tau_{\mathrm{in}}$ a "parabola of integration" for an electron of initial energy $E_i = 200$ meV has been included as the dotted curve in Fig. 1(b). All inelastic processes within the parabola $y = y_i - (m_1/m_3)\,[x_1 - (y_i m_3/m_1)^{1/2}]^2$ are included in the integral (note that $y_i \equiv E_i/E_F$). Although a significant portion of the scattering strength from mobile charge carriers comes from heavy-hole intraband single-particle transitions, the ratio of heavy-hole to electron mass, m_1/m_3, imposes a kinematic constraint (the parabola of integration) which excludes many heavy-hole excitations. This fact may be used to reduce the inelastic scattering rate. For example, increasing the ratio m_1/m_3 decreases the width of the parabola, thereby limiting the area of integration and hence reducing the inelastic scattering rate, $1/\tau_{\mathrm{in}}$.

In Fig. 2(a) the calculated value of $1/\tau_{\mathrm{in}}$ for p-type GaAs is plotted as a function of initial conduction-band energy E_i for several carrier densities. For $p = 2\times10^{18}\,\mathrm{cm}^{-3}$ the inelastic scattering rate increases from $1/\tau_{\mathrm{in}} = 0$ at $E_i = 0$ (due to phase space constraints) to $1/\tau_{\mathrm{in}} \sim 2.3\times10^{13}\,\mathrm{s}^{-1}$ for $E_i = 200$ meV. In Fig. 2(b) the elastic scattering rate from ionized impurities $1/\tau_{\mathrm{el}}$ is plotted as a function of E_i for two carrier densities. When $p = 2\times10^{18}\,\mathrm{cm}^{-3}$ and $E_i = 200$ meV, $1/\tau_{\mathrm{el}} \sim 2\times10^{12}\,\mathrm{s}^{-1}$ and the average scattering angle is around 50° (the average elastic scattering angle in similarly doped n-type GaAs is 20°). Overall, the elastic scattering rate is low compared to the inelastic rate because heavy holes in the valence band are very effective at statically screening ionized impurities but poor at dynamic screening which determines inelastic scattering [very approximately, static screening determined from ϵ scales with m_1 in the limit $\omega\sim0$ whereas dynamic screening scales as $(1/m_1)^{1/2}$ in the limit $q\sim0$]. This result should be contrasted with the case of n-type GaAs for which both inelastic and elastic scattering rates are high.[7]

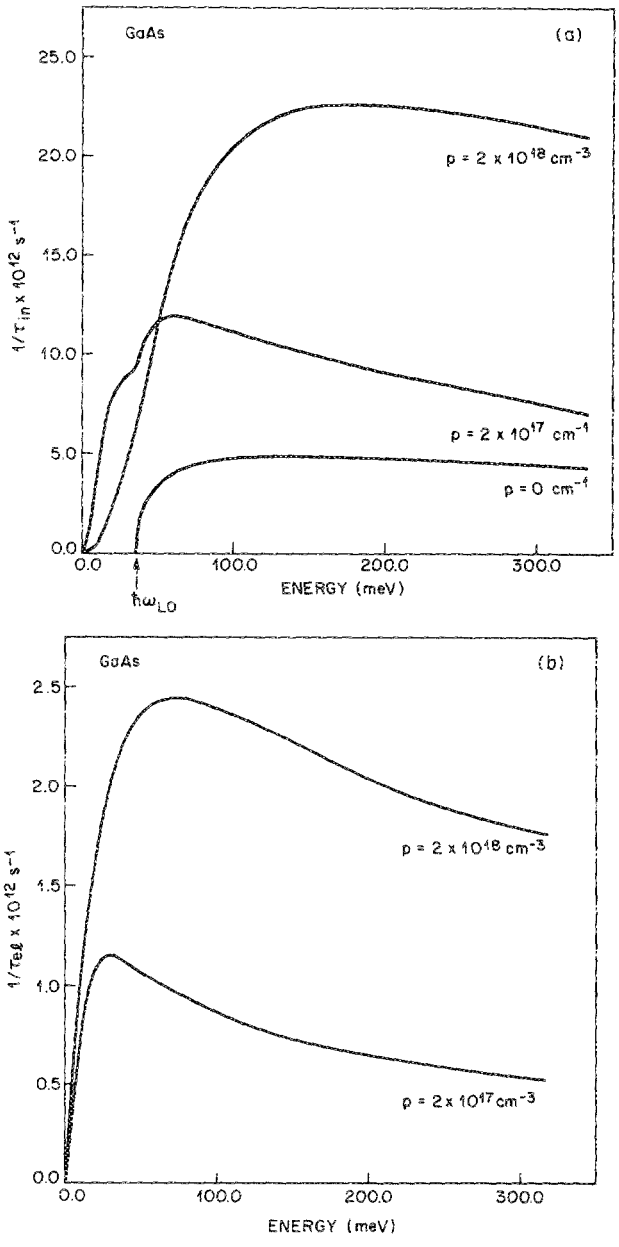

FIG. 2. (a) Total inelastic electron scattering rate $1/\tau_{\mathrm{in}}$ as a function of electron energy measured from the conduction-band minimum for different carrier densities in p-type GaAs. (b) Total elastic electron scattering. Parameters used in calculations were $m_1 = 0.5m_0$, $m_2 = 0.082m_0$, $m_3 = 0.07m_0$, $\epsilon_\infty = 10.91$, $\hbar\omega_{\mathrm{LO}} = 36.5$ meV, and $\hbar\omega_{\mathrm{TO}} = 33.8$ meV.

Using a velocity calculated taking into account nonparabolicity, the total mean free path of a 200-meV conduction-band electron in GaAs doped $p = 2\times10^{18}\,\mathrm{cm}^{-3}$ is less than

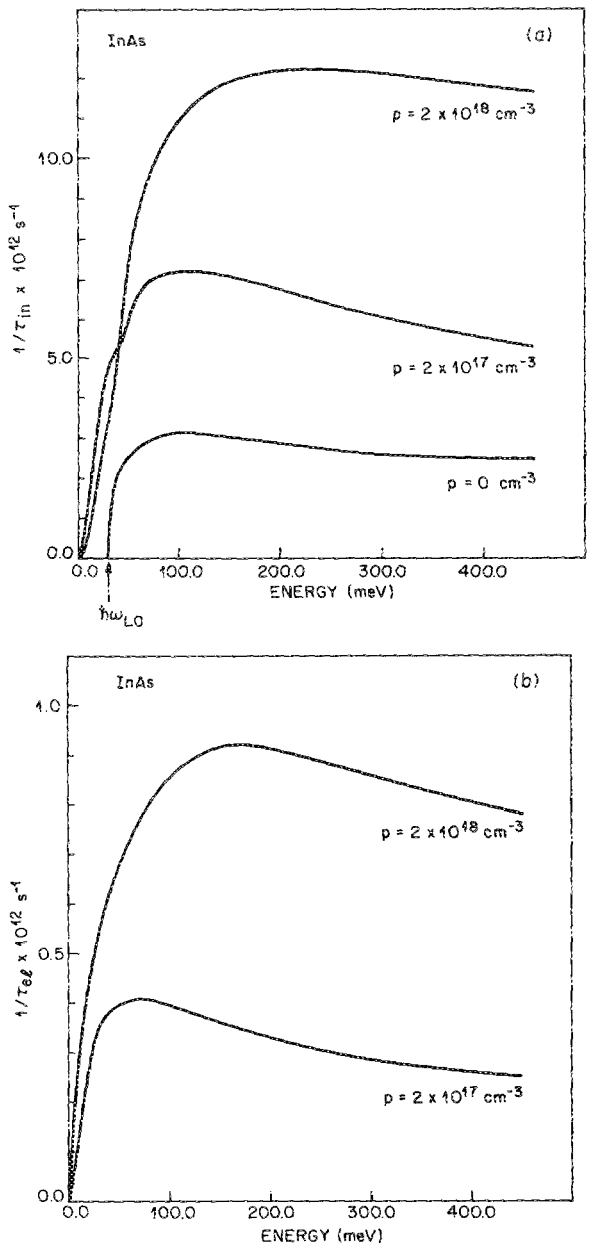

FIG. 3. (a) Total inelastic electron scattering rate as a function of electron energy measured from the conduction-band minimum for different carrier densities in p-type InAs. (b) Total elastic electron scattering. Parameters used in calculations were $m_1 = 0.41m_0$, $m_2 = 0.025m_0$, $m_3 = 0.021m_0$, $\epsilon_\infty = 11.8$, $\hbar\omega_{LO} = 30.2$ meV, and $\hbar\omega_{TO} = 27.1$ meV.

350 Å and is in qualitative agreement with experimental results obtained at low temperatures.[4,5] We note that at finite temperatures the mean free path will be even shorter. Given this short mean free path and the large average scattering angles it seems unlikely that useful bipolar BET devices can be fabricated in GaAs. However, because of the kinematic constraint discussed earlier, semiconductors such as InAs and InSb, for which m_1/m_3 is large, are more suitable candidates for a bipolar BET as they have reduced scattering rates compared to GaAs.

Figures 3(a) and 3(b) show the calculated inelastic and elastic scattering rates as a function of E_i for different carrier densities in p-type InAs. The total mean free path of an electron with energy $E_i = 400$ meV in the conduction band of InAs doped 2×10^{18} cm^{-3} is around 1000 Å (average elastic scattering angle 50°). This is a promising improvement when compared to the GaAs result and suggests InAs is a more appropriate material from which to fabricate a bipolar BET.

In summary, we have presented a theoretical treatment of elastic and inelastic scattering rates for nonequilibrium conduction-band electrons interacting with mobile charge carriers in the valence band of typical III-V semiconductors. For a given p-type carrier concentration in materials such as InAs and InSb, scattering is significantly reduced over that in GaAs due to a kinematic constraint imposed by a large effective mass ratio m_1/m_3. This, when combined with additional kinematic constraints on scattering imposed, for example, by a two-dimensional system,[8] suggests that useful bipolar BET's may be fabricated in III-V semiconductors with large m_1/m_3.

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[1]M. F. Chang, P. M. Asbeck, K. C. Wang, G. J. Sullivan, N. H. Sheng, J. A. Higgins, and D. L. Miller (unpublished). These authors report a base transit time 0.56 ps, electron velocity 1.8×10^7 cm s^{-1} and collector transit time 0.68 ps, electron velocity 2.2×10^7 cm s^{-1}.

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[8]We note that the calculations presented in this letter are only valid for a p-type region of semiconductor in which the electronic wave functions are three dimensional in character. For example, our calculations cannot be applied to a GaAs/AlGaAs n-p-n ($p \lesssim 5\times10^{18}$ cm^{-3}) heterojunction bipolar transistor with a base width less than around 200 Å.