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Invited

Hot Electron Transistors

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Hot Electron Transistors are being extensively investigated for future high speed digital and microwave applications. If these devices are to be given serious consideration it is necessary to understand the transport properties of non-equilibrium electrons. In this article I will review our current understanding of non-equilibrium electron dynamics, obtained using "Hot Electron Spectroscopy", and propose future directions for improved Hot Electron Transistor performance.

In the early 1960's considerable effort was directed toward the development of metal base hot and "ballistic" electron transistors, for high-speed applications. Unfortunately, fundamental material properties severally limited the performance of these devices, to current gains of less than unity [1], and interest in their development quickly declined. With the continuing advancement of semiconductor fabrication and processing technology, interest is again being shown. This advancement enabled Shannon to realize a Hot Electron Transistor (HET) in silicon [2], having a Schottky barrier emitter and Camel diode collector (fabricated by ion-implantation). The high emitter capacitance of the Schottky barrier led Shannon to fabricate an alternative HET having both a Camel diode emitter and collector, creating an all semiconductor HET [3]. Shortly following, Malik et al. [4] fabricated a HET in GaAs similar to Shannon's but replacing the Camel diodes with precisly controlled charge sheets referred to as "planar-doped barriers".

Thus, the advent of thin film epitaxial crystal growth techniques has led to a resurgent interest in the "ballistic" transistor concepts of the early 1960's. Epitaxial crystal growth of the GaAs/AlGaAs semiconductor alloy system is sufficiently well characterized that one can translate metal-oxide-metal tunnel junctions into GaAs/AlGaAs/GaAs tunnel junctions and metal-semiconductor Schottky barriers into either GaAs/AlGaAs heterojunctions, camel diodes or planar doped barriers. Electronic devices fabricated with such structures are very attractive since the injected charge carriers will have velocities far in excess of equilibrium values. If such devices are to be given serious consideration it is essential that the transport properties of these non-equilibrium electrons be understood. In order to do this we invented "Hot Electron Spectroscopy" a spectroscopic technique which enabled us to obtain direct information on the non-equilibrium distribution function in such structures [5,6].

The hot electron spectra, presented here, were obtained using single crystal GaAs samples grown by MBE on <100> oriented semi-insulating GaAs substrates. The structure, for which the energy band diagram is shown schematically in Fig. 1, was fabricated into a two level mesa structure so that the three n^+ degenerate regions, separated by the two bulk triangular potential barriers, could be contacted individually. Ohmic contacts were formed to the three degenerate regions by rapidly thermal annealing an evaporated Au-Sn alloy.

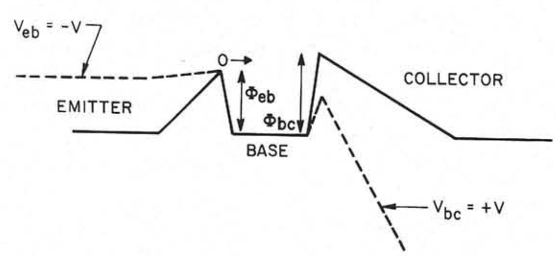


Fig. 1 Schematic diagram showing the conduction-band edge of the hot-electron injector (emitter-base junction), transit region (base) and hot electron analyzer (base-collector junction). The broken lines indicate the conduction band edge of the structure when biased.

In this structure the potential barrier between the emitter and base functions as the hot electron injector and the potential barrier between the base and collector as the hot electron analyzer. Between the hot electron injector and analyzer was a thin n^+ transit region, analogous to the base of a unipolar transistor in which electron scattering, of the injected non-equilibrium distribution, took place. A typical structure was fabricated with the electron injection energy (E_i) lower than the unbiased analyzer barrier energy (ϕ_{bc}). Both barriers had aspect ratios of approximately 10 with the shorter arm of each being 150Å. The short arm's low impurity concentration and width ensured that their contribution to electron scattering was insignificant.

In order to perform "Hot Electron Spectroscopy" the transit region (base) was grounded and a negative bias ($-V_{be}$) was applied to the emitter enabling a near mono-energetic beam of electrons to be injected into the transit region. With the collector potential (ϕ_{bc}) greater than the injected electron energy no electrons will be collected as none have sufficient energy to surmount the barrier. However, with increasing base/collector bias (V_{bc}), the barrier, ϕ_{bc}, is lowered and electrons satisfying the necessary criteria to surmount the barrier will be collected. Hence by continuously varying the base/collector voltage we establish a means of spectroscopically resolving the resulting distribution after interaction with the electron/phonon system in the transit region.

Electrons injected into the transit region will interact with the electron/phonon system. The resulting electron distribution may be described in terms of a distribution $n(P_\perp)$ of electrons having particular values of momentum normal to the analyzer barrier: $P_\perp$. The collector current, I_c, for a particular barrier energy ϕ_{bc} is then given by

$$I_c = -(e/m_e^*) \int_{P_\perp^0}^{\infty} P_\perp \, n(P_\perp) \, dP_\perp$$

where m_e^* is the effective electron mass, e the electron charge, and $P_\perp^0 = (2m_e^* \phi_{bc})^{1/2}$. Taking the derivative of I_c with respect to V_{bc} one can show that

$$\frac{dI_c}{dV_{bc}} \; \alpha \; n(P_\perp)$$

Hence by differentiating I_c with respect to V_{bc} the electron momentum distribution, at the base/collector junction, can be obtained. The results of four spectra, measured at 4.2K to eliminate thermal smearing effects, are shown in Fig. 2. Each sample had an injection energy $E_i \simeq 0.25$ eV and a transit region doping $n = 1 \times 10^{18}$ cm^{-3}. However they differed in their transit region width; sample (a) 650Å, (b) 850Å (c) 1200Å and (d) 1700Å. Clearly there is a significant change in the spectra with transit region width indicating that the injected electrons are being strongly scattered. The high energy peak (low voltage bias) in the thin sample was the first experimental evidence of ballistic electrons [7].

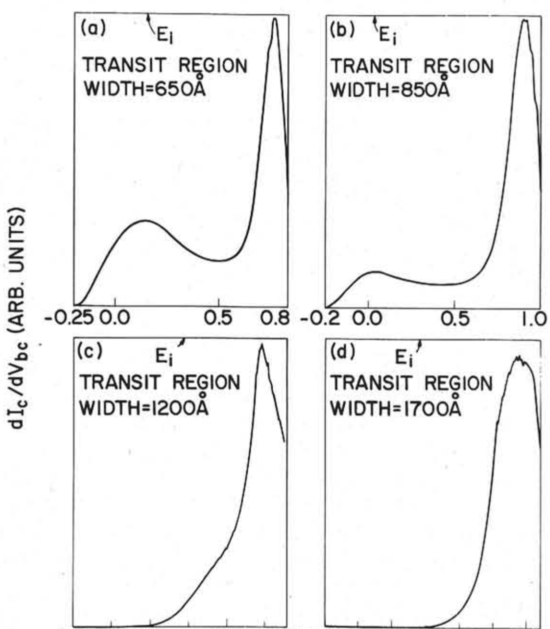


Fig. 2. Measured hot-electron spectra of four samples having the same transit region doping of 1×10^{18} cm^{-3} but different indicated transit region widths. The injection energy E_i(~0.25eV) is indicated on the upper axis.

To understand the electron scattering mechanisms giving rise to the hot electron spectra shown in Fig. 2 we have developed a theory of non-equilibrium electron transport that takes into account scattering from the whole electron/phonon system. In GaAs at the carrier concentrations used in these experiments ($n = 1 \times 10^{18}$ cm^{-3}) the long wavelength collective oscillatory mode (plasmon) of the electron gas couples strongly with the LO phonons. These two oscillation do not exist independent of each other but couple together strongly to form a coupled electron/phonon system. In addition to scattering by the long wavelength coupled plasmon/phonon modes, they also scatter via the creation of single electron-hole pairs. With decreasing wavelength the collective modes are damped by the continuum leaving only the continuum and optical phonons to contribute to the scattering. The calculated dispersion relationship for GaAs at a doping $n = 1 \times 10^{18}$ cm^{-3} is shown in Fig. 3. Details of this calculation have been presented elsewhere [7,8] and in addition to obtaining the dispersion relationship it also enabled us to calculate the energy dependent scattering rate at a particular carrier density. The calculated inelastic scattering rate from the electron-phonon system ($1/\tau_{in}$) together with the elastic scattering rate from ionized impurities ($1/\tau_{el}$) is shown in Fig. 4. By considering both inelastic and elastic scattering we obtain a mean free path for hot electrons in GaAs doped to 1×10^{18} cm^{-3}, injected at $E_i = 0.25$ eV, of ~350Å.

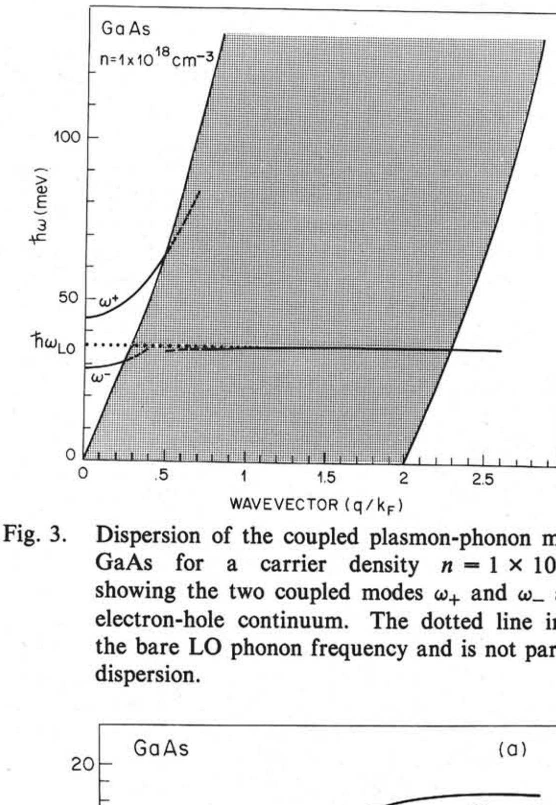
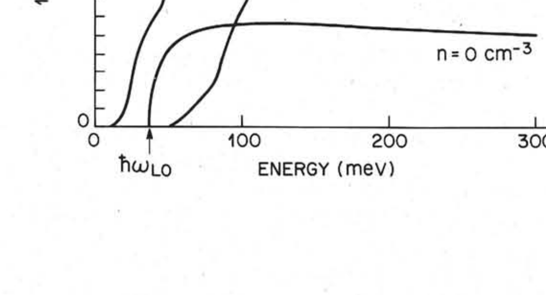


Fig. 3. Dispersion of the coupled plasmon-phonon modes in GaAs for a carrier density $n = 1 \times 10^{18}$ cm^{-3} showing the two coupled modes ω_+ and ω_- and the electron-hole continuum. The dotted line indicates the bare LO phonon frequency and is not part of the dispersion.



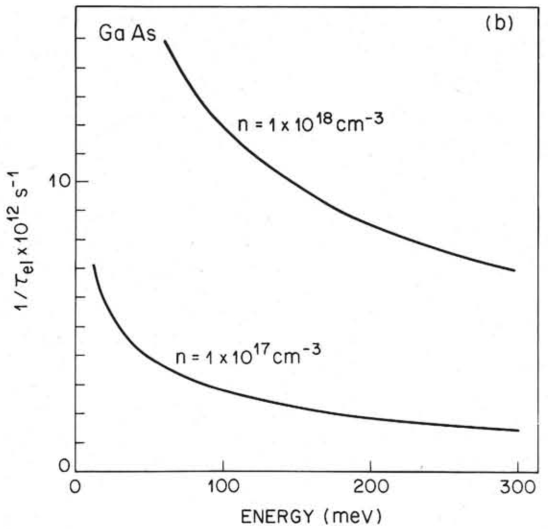


Fig. 4. Calculated total inelastic (a) and elastic (b) scattering rates for GaAs as a function of injection energy for indicated carrier concentrations.

Experimental verification of this theoretical calculation can be obtained by applying a magnetic field perpendicular ($B_\perp$) to the electron injection direction in the sample having the narrowest transit region width: 650Å [9,10]. To understand the effect of the magnetic field consider what would happen to an electron transiting from the injector to the analyzer "ballistically." A nonequilibrium electron injected into the transit region with energy E_i and momentum $p = \sqrt{2m_e^* E_i}$ in the forward direction is analyzed after traversing d, the transit region width. When $B_\perp$ is applied to the sample two effects occur that influence the collection of the injected electron. Firstly, the electron trajectory is increased from d to d', and hence the probability for an electron to be scattered is increased. Secondly, although the magnitude of the momentum of a "ballistic" electron remains unchanged its normal component is reduced when it reaches the analyzer because of the imposed circular orbit. The analyzer barrier, discriminating only against the normal component of momentum, collects the electron at a lower barrier energy. Using these assumptions we have obtained a scattering rate for the injected electrons of $2–3 \times 10^{13}\ s^{-1}$; in excellent agreement with the calculated value. In addition the theory enables us to identify the low energy peak of the spectra, shown in Fig. 2, which for thin samples is predominantly due to electron activated from the Fermi sea via the electron-electron interaction. For thicker samples the low energy peak also has a contribution from electrons scattered down from the initial distribution.

Both our experimental and theoretical results indicate that GaAs is unsuitable for the fabrication of a useful, high-performance, "Ballistic" Electron Transistor (BET), because of the short mean free path of injected hot electrons. Regardless of the mechanism of electron injection or collection it is anticipated that device performance will be dominated by base transit dynamics. There are two approaches to consider whilst designing a BET in a material system other than GaAs/AlGaAs [11]. One possibility is to chose a semiconductor with a wide intervalley separation, in order to take advantage of the decrease in scattering rate with increasing energy. The other is to consider a material with a low effective mass and thereby lower density of states, giving a reduced electron scattering rate.

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 $m_e^* = 0.1 m_0$ is unsuitable for "ballistic" devices. Alternatively, a semiconductor which satisfies the low mass condition would be InAs or InSb. InAs and InSb both have significantly lower inelastic scattering rates than GaAs. Because it may be possible to lattice match wider band gap alloys such as GaInAsSb to InAs we consider it in preference to InSb. As is the case with many low m_e^* semiconductors InAs has a small band gap energy, $E_g \sim 0.41$ 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 energy of the subsidiary L minimum [12], for InAs E_i^{max} must satisfy $E_i^{max} \lesssim E_g + E_F$ to avoid the possibility to direct excitation of electrons from the valence band into the conduction band: as also occurs in InSb [13].

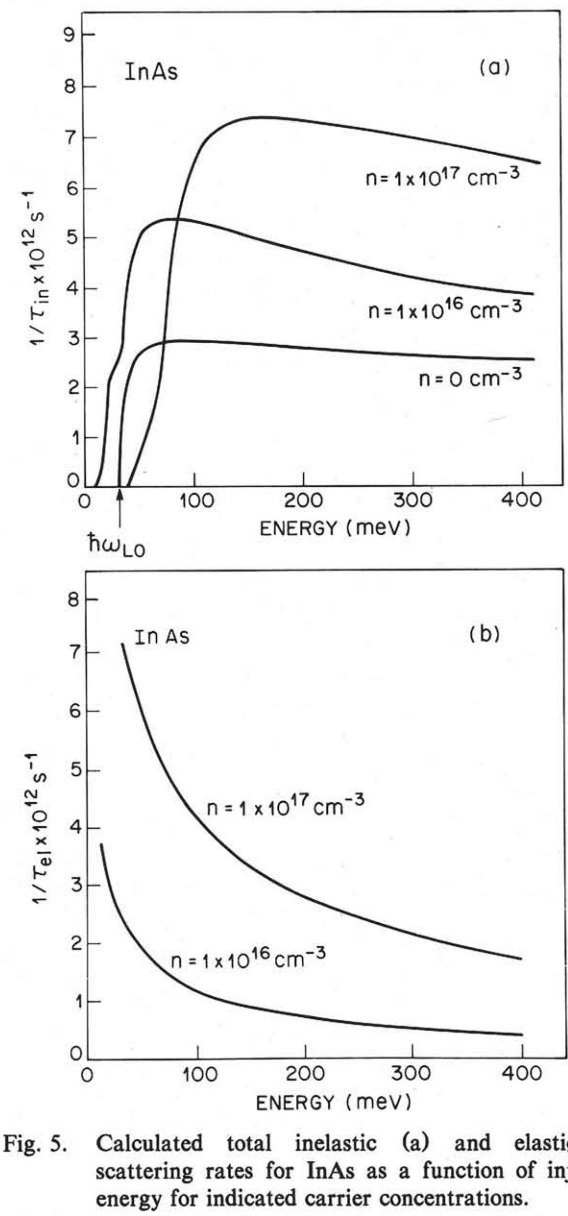


Fig. 5. Calculated total inelastic (a) and elastic (b) scattering rates for InAs as a function of injection energy for indicated carrier concentrations.

In Fig. 5(a) and (b) we plot $1/\tau_{in}$ and $1/\tau_{el}$, respectively, for InAs as a function of E_i for various base impurity concentrations. The calculated scattering rates have features similar to those shown in Fig. 4 only now the rates for a given E_i are significantly reduced. Differences in electron mobility between InAs and GaAs mean that a BET device with an $n = 1 \times 10^{18}\ \mathrm{cm}^{-3}$ doped GaAs base should be compared to an $n \sim 1 \times 10^{16}\ \mathrm{cm}^{-3}$ doped InAs base. For $n = 1 \times 10^{16}\ \mathrm{cm}^{-3}$ 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, a "ballistic" common base current gain $\alpha_B = 0.85$. This is a promising improvement when compared to GaAs.

Irrespective of whether the semiconductor used is GaAs or InAs to improve device performance still further we are forced to consider a different means of confining thermal electrons to the base region. An obvious 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 [14]. The base region will only be ~100Å 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 very desirable feature of a high-performance transistor.

In conclusion we have designed and implemented a unique spectroscopic probe with which to study nonequilibrium electron transport in semiconductors. Our technique of hot electron spectroscopy has enabled us to establish the existence of "ballistic" electron transport together with a complete picture of the dynamics of injected electron cooling in GaAs. A full description of the measured spectra has been obtained by considering scattering from the coupled electron/phonon system, with the low-energy portion of the spectrum attributed to electrons excited from the Fermi sea. We find excellent agreement between experimental and theoretical determinations of hot electron mean free paths. It has also been shown that the short mean free paths in doped GaAs make it an unsuitable material from which to fabricate a useful hot electron transistor. We suggest InAs as a more favourable material and a two-dimensional electron gas as a more suitable means of confining electrons to the transistor base.

* Work done in collaboration with A. F. J. Levi, A. C. Gossard, P. M. Platzman, R. Bhat, J. English and W. Weigmann.

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