Hot-Electron Spectroscopy of GaAs

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We report a new technique that enabled us to measure nonequilibrium carrier transport in GaAs. Hot electrons were injected into n^+-GaAs with an excess energy of 0.25 eV above the conduction-band edge. The effect of scattering on the injected electrons was observed by use of a planar doped barrier as a "hot-electron spectrometer." The measured spectra indicated that significant scattering occurred and that mean free paths were on the order of a few hundred angstroms.

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In recent years much interest has centered on the problem of nonequilibrium electron transport.[1] This has been stimulated in part by a need to understand the physics of electron transport in small device structures. Until now, the study has been seriously impeded by the failure to determine experimentally the transport properties of hot electrons in semiconductors. In this paper we demonstrate a new technique, "hot-electron spectroscopy," which enabled us to obtain spectroscopic information about hot-electron transport in semiconductors.

The results described in this Letter were obtained by means of a planar GaAs structure, for which the conduction-band edge is shown schematically in Fig. 1. The structure was grown by molecular-beam epitaxy at 650 °C on a ⟨100⟩-oriented semi-insulating GaAs substrate with use of cracked As_4. After the growth of a thick n^+ (Si impurity) buffer layer, two separate triangular potential barriers were formed. Each potential barrier was made by placement of an approximately 100-Å-thick p^+ (Be impurity) layer in a region of low carrier concentration ($< 1 \times 10^{15}$ cm^{-3}) bounded on either side by n^+ (Si impurity) layers.[2] The molecular-beam-epitaxial layers were chemically etched into two-level mesa structures in order that the three n^+ regions could be contacted individually. Ohmic contacts were formed on the n^+ regions by the rapid annealing of an evaporated Au-Sn alloy.

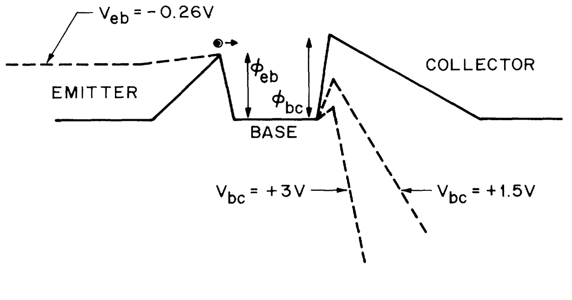

FIG. 1. Schematic diagram showing the conduction-band edge of the hot-electron injector (emitter-base junction), transit region (base), and hot-electron analyzer (base-collector junction). The broken lines indicate the conduction-band edge of the structure when biased.

Since the structure resembles a unipolar transistor, we use standard transistor notation to describe the currents and voltages involved. The emitter-base junction functioned as a hot-electron injector and the base-collector junction as a hot-electron analyzer. Between the hot-electron injector and analyzer was a short n^+ transit region, analogous to the base of a unipolar transistor, where electron scattering took place. The triangular potential barriers, which form the injector (emitter) and analyzer (collector), were fabricated such that the electron injection energy, ϕ_{eb}, was lower than the unbiased analyzer barrier energy, ϕ_{bc}. Both triangular barriers had an aspect ratio of approximately 10 with the shorter arm of each adjoining the n^+ transit region and being 150 Å thick. The short arm's impurity concentration and small thickness ensured that their contribution to electron scattering was insignificant. All electrical measurements were made with respect to a grounded base.

When the emitter was biased negative electrons were injected into the base region with an excess energy $\phi_{eb} - E_F$ above the Fermi energy (E_F). With a small positive bias on the collector no electrons were collected as none had sufficient energy to traverse the collector barrier, ϕ_{bc}. With increasing base-collector bias ϕ_{bc} is decreased, as indicated by the broken lines in Fig. 1. Hence, a means for continuous variation of the base-collector barrier energy was established, which enabled spectroscopic information about the current arriving at the analyzer barrier to be obtained. At a given base-collector bias, V_{bc}, the collector current flow, j_c, is proportional to the fraction of the injected electrons able to traverse the base-collector barrier. An outline of the factors determining j_c is given below.

Consider first electrons injected into the base from the emitter. Electrons can only be injected if, at the top of the barrier, they have a component of momentum in the direction of the base. For those electrons injected into the base, the component of momentum parallel to the emitter plane (P_p) is conserved, whereas the component of momentum normal to the emitter plane (P_n) is dramatically increased. Hence a maximum angle exists for electron injection ($\theta_{\max}$) that is given by

$$\theta_{\max} = \tan(P_p/P_n).$$

Given the assumption of a parabolic conduction band, an electron injected into the base at 0.25 eV would have a $\theta_{\max}$ of less than 10°.

Electrons injected into the base suffer elastic and inelastic collisions, which cause significant energy loss and angular scattering. Hence, hot electrons arriving at the analyzer barrier may be described in terms of a distribution of possible P_n values, $n(P_n)$, such that the total current flow, j_c for a given barrier energy, ϕ_{bc}, is

$$j_c = -(e/m_e)\int_{P_n^0}^{\infty} P_n n(P_n) dP_n, \qquad (1)$$

where m_e is the effective electron mass, e the electronic charge, and $P_n^0 = (2m_e\phi_{bc})^{1/2}$.

Taking the derivative of j_c [Eq. (1)] with respect to V_{bc} gives

$$\frac{dj_c}{dV_{bc}} = \frac{e}{m_e}\frac{d\phi_{bc}}{dV_{bc}}\frac{dP_n^0}{d\phi_{bc}} n(P_n^0)P_n^0. \qquad (2)$$

Equation (6) of Kazarinov and Luryi[3] shows that V_{bc} is related linearly to ϕ_{bc}, i.e., the analyzer energy varies linearly with bias. It then follows that

$$\frac{dj_c}{dV_{bc}} \propto n(P_n^0). \qquad (3)$$

Hence, by differentiating j_c with respect to V_{bc} we may obtain the electron momentum distribution at the base-collector junction.

Figure 2 shows the results of electrical measurements performed at 4.2 K on samples having an injection energy of 0.25 eV and an n^+ transit-region (base) carrier concentration of 1×10^{18} cm^{-3}. The base-grounded characteristics of two samples of base widths 1200 and 1700 Å are shown in Figs. 2(a) and 2(b), respectively, for four different emitter currents. There is a threshold for current collection at around 1.5 V since no electrons can be collected when $\phi_{bc} > \phi_{eb}$. Between 1.5 and 3.2 V the collected current is due to the hot electrons that have traversed the collector barrier. At around 3.2-V bias ϕ_{bc} is so small that thermally excited electrons in the n^+ transit region can be collected, which dominate the collector current (j_c). In order to obtain the correct hot-electron spectrum it is necessary to subtract this background contribution from the data. Figure 3 gives the measured hot-electron spectrum (dj_c/dV_{bc}) for the samples shown in Fig. 2.

As a preliminary to the discussion of these results it should be noted that if no scattering occurred in the transit region one would expect to see a narrow peak at around 1.5 V. In contrast, both samples show a rather

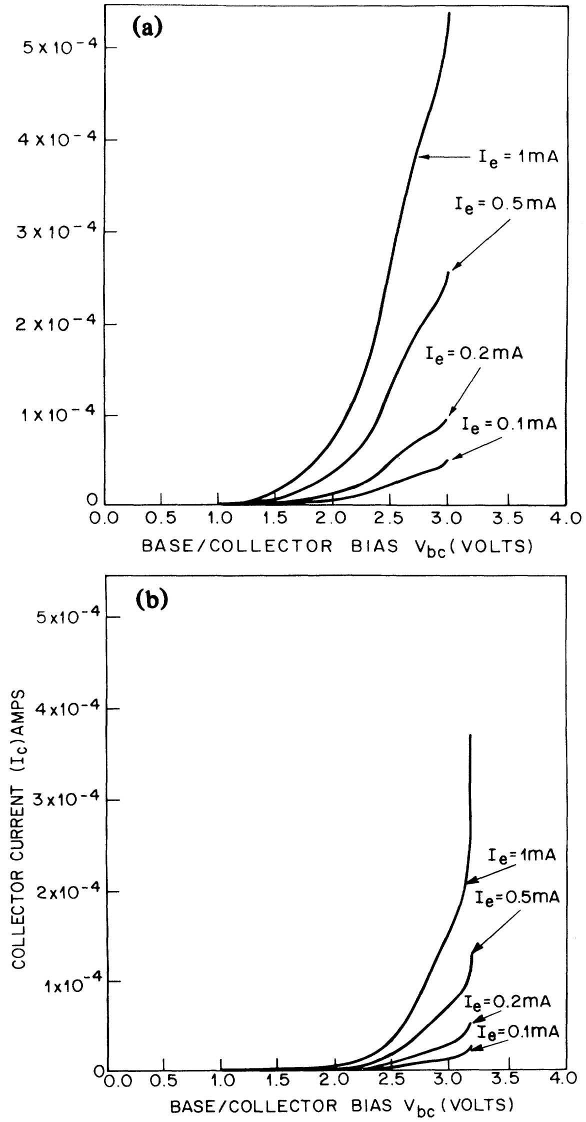

FIG. 2. (a) Typical grounded-base characteristics of a sample having a 1200-Å transit region shown for four indicated injection currents. (b) Typical grounded-base characteristics of a sample having a 1700-Å transit region shown for four indicated injection currents.

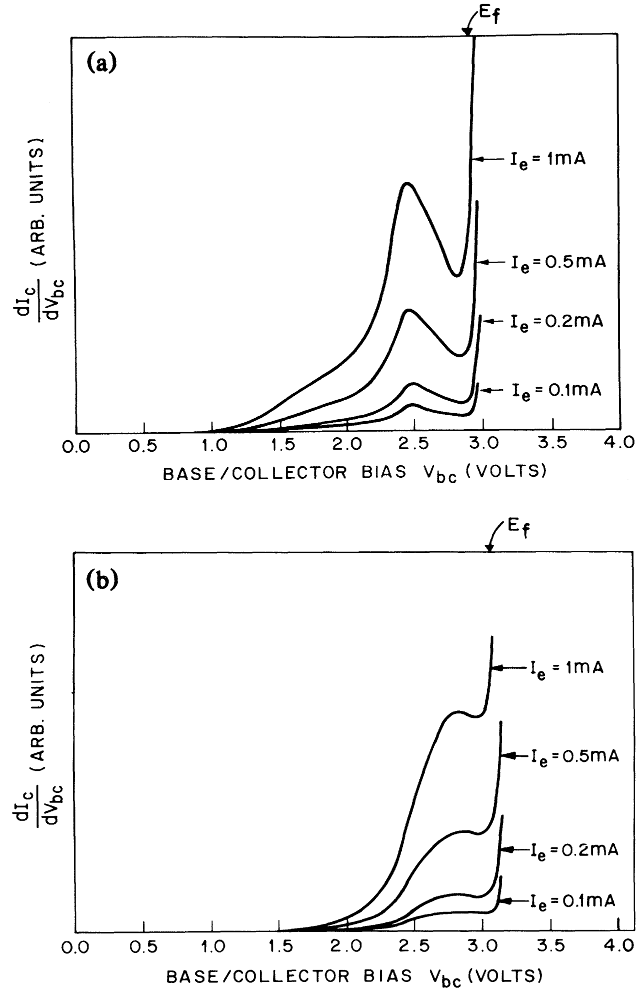

FIG. 3. (a) Hot-electron spectra obtained for a sample having a 1200-Å transit region. (b) Hot-electron spectra obtained for a sample having a 1700-Å transit region. In both diagrams the position of the Fermi energy is indicated.

broad distribution that peaks close to the Fermi energy which indicates that electrons have experienced significant scattering during transit. The sample with the 1200-Å transit region shows a pronounced peak further from E_F than the sample with the 1700-Å transit region, which indicates that electrons have experienced fewer collisions. In both samples it is obvious that the injected electrons have undergone significant momentum change. It is also clear that the electrons cannot be assigned a hot-electron temperature as they do not have a Maxwellian distribution.

In order to determine whether the observed spectra were due to hot-electron transport, a magnetic field was applied to the structure. When the magnetic field was applied in the P_n direction there was little change in the observed spectra with fields as high as 7 T. In this configuration electrons, classically, follow a helical path between collisions, and the effective base width remains constant. However, when the magnetic field was applied in the P_p direction there was a significant reduction in the total number of collected hot electrons. Indeed, a magnetic field of 3 T applied in the direction of P_p to the sample with the 1200-Å base width was sufficient to reproduce the spectra of the sample with the 1700-Å base width with no magnetic field. The results served to confirm that $n(P_n)$ was indeed being measured.

The technique of hot-electron spectroscopy yields important information on the physics of nonequilibrium transport in semiconductors. This technique lends itself easily to either planar doped or compositionally graded barriers. Our results on GaAs suggest that electron scattering varies significantly with base width, which indicates strong electron scattering. Preliminary Monte Carlo calculations give spectral line shapes which are in qualitative agreement with those measured and yield a mean free path around 400 Å. These calculations made use of the single-pole plasmon approximation to describe electron-electron scattering events and assumed that longitudinal-optical phonon scattering was of comparable strength. However, a detailed analysis of the spectra by means of a realistic dielectric function which takes into account coupled plasmon-phonon modes[4] and impurity scattering is awaited.

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[1] See, e.g., D. K. Ferry, in *Handbook of Semiconductors,* edited by W. Paul and T. S. Moss (North-Holland, New York, 1982), Chap. 11A.

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