Long-mean-free-path ballistic hot electrons in high-purity GaAs

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The mean free path (mfp) of hot ballistic electrons, injected into high-purity GaAs, was measured and found to be several micrometers long. The hot electrons were injected at energies just below the LO-phonon emission threshold and their mfp was measured by two techniques: first, by comparing different devices with different layer thickness; and second, in a single device, utilizing the cyclotron motion of ballistic electrons in tilted magnetic fields. We find the mfp scales roughly inversely with impurity concentration. We suggest that the dominant scattering is due to impact ionization of neutral impurities. [S0163-1829(96)52348-9]

Two-dimensional electron systems, with their long mean free path (mfp), have been intensively exploited for the study of ballistic and coherent effects. However, the mfp in these systems drops sharply, due to electron-electron (e-e) interactions, as either the electron's excess energy or the temperature increases (even only to 1–2 meV).[1] Alternatively, high-purity bulk GaAs may present a medium which supports long mfp ballistic transport of *hot electrons*. In lightly doped GaAs, at low enough temperatures, the bulk electrons are trapped by their parent donors (*frozen*), neutralizing them and thus minimizing both e-e and ionized impurity scattering. Since acoustical phonon scattering in GaAs is very weak, injecting electrons below the threshold for LO-phonon emission (36 meV in GaAs) may lead to a *free* motion of hot electrons with extremely long mfp ($\gg 1\ \mu$m). In this paper we study the mfp of hot electrons injected into high-purity GaAs at low temperatures. Two methods are being employed in order to measure the mfp: the first relies on comparing the transmission in several devices, each with a different layer thickness; and the second utilizes the cyclotron motion performed by the ballistic electrons around a tilted magnetic field. Since the path length depends on the tilt angle the mfp can be measured with a *single* device.

The measurements are being performed utilizing a tunneling injection hot-electron transistor (THETA, see Fig. 1).[2,3] Quasimonoenergetic hot electrons (with an ≈ 10 meV wide distribution)[4] are injected via a tunneling barrier, pass briefly through a very thin conductive base layer and then traverse a thick layer ($d = 1$ to 3 μm) of high-purity GaAs (*drift region*). At the other end of the drift region a layer of $Al_{0.03}Ga_{0.97}As$ forms a low collector barrier, with height $\phi \approx 26$ meV. Electrons can traverse this barrier if their energy component in the direction *normal* to the layers, ${}_{\perp} = \hbar^2 k_\perp^2/2m$, is larger than ϕ. Electrons that changed their direction markedly, or lost enough energy, will be reflected by the collector barrier thus contributing to the base current. In order to avoid large band bending in the drift region the unintentional p-type doping was slightly compensated by n-type doping, achieving $N_D - N_A \cong 2 \times 10^{14}$ or 1×10^{15} cm^{-3}, where N_D and N_A are the donor and acceptor concentrations, respectively. Material purity was measured separately on layers grown under the same conditions, exploiting persistent photoconductivity:[5] measuring the electron concentration and the mobility as a function of temperature allows one to extract both N_D and N_A. We obtained a peak mobility of some 23 m^2/V sec (around 40 K for $N_D \cong 3 \times 10^{14}$, $N_A \cong 1 \times 10^{14}$), which is comparable to the best published data for molecular-beam-epitaxy (MBE) -grown GaAs layers. The layers were fabricated into three terminal devices using previously developed lithographic techniques.[3]

The differential transfer ratio, $\alpha = dI_c/dI_{inj}$, where I_c and I_{inj} are the collected and injected currents, respectively, measures the probability of electrons to pass the drift region without significant scattering. In order to measure the mfp of the hot electrons we fabricated several devices with the same parameters but with different drift region thickness[6] and measured the differential transfer ratio below the threshold for longitudinal optical (LO) phonon emission (36 meV) at 4.2 K. The transfer ratio was found to scale exponentially with length as seen in Fig. 2, $\alpha = \alpha_0 e^{-L/\mathrm{mfp}}$, with mfp=0.7 μm for total impurity concentration $N_D + N_A \approx 3 \times 10^{15}$ cm^{-3}. Extrapolating the drift region length to zero leads to $\alpha_0 \approx 0.7$, indicating that some 30% of the electrons are being scattered by the doped base. Applying a longitudinal magnetic field (in the direction of the growth) we found a monotonous increase in the collected current and in the mfp. At a field $B = 6$ T the measured mfp increases by some 30% relative to that at $B = 0$.

Although the results given in Fig. 2 seem consistent this method of determining the mfp has an inherent difficulty due to the multiple growths and heavy processing leading to unavoidable differences among the different devices. We therefore developed a technique that allows the measurement of

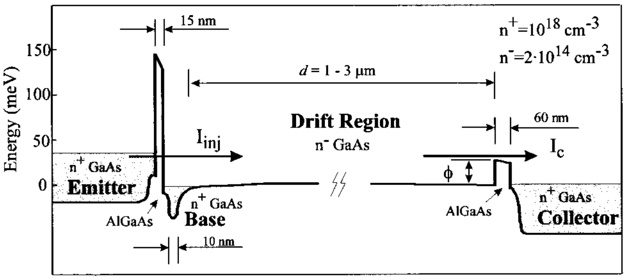

FIG. 1. Conduction-band profile of the modified THETA device.

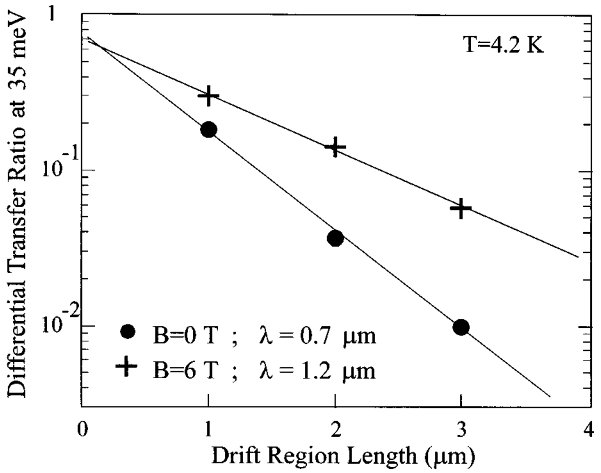

FIG. 2. The transfer ratio at an injection energy of 36 meV in devices having different drift region lengths.

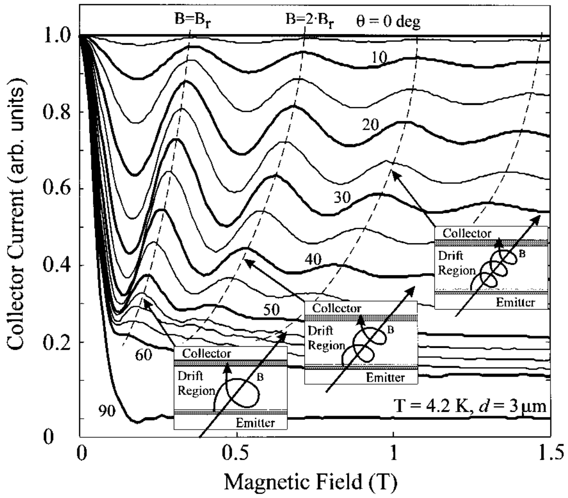

FIG. 3. The cyclotron motion performed by ballistic hot electrons around a tilted magnetic field is clearly evident from the collected current plots. This current is maximized whenever the electrons arrive at the collector with their momentum *normal* to the barrier.

the mfp with a *single* device. The method employs a magnetic field B, applied at an angle θ with respect to the direction of the electron injection (which is approximately normal to the layers) at an energy just below the threshold for LO-phonon emission. Sweeping the magnetic field amplitude leads to large oscillations in the collected current, which are periodic in B (Fig. 3). These oscillations result from the cyclotron motion performed by the normally injected electrons around the titled magnetic field axis: whenever the magnitude of the applied magnetic field is such that the electrons complete an integer number of rotations around the magnetic field axis as they cross the drift region, their *normal* energy when hitting the collector barrier is maximized, and so will be the collected current.

A simple model, assuming all the electrons are injected at the same energy and normal to the layers and neglecting scattering, yields the condition for maximal normal energy at collection:

$$B = n 2\pi \frac{m\nu}{ed}\cos^2\theta \equiv nB_r, \tag{1}$$

where d is the length of the draft region, ν is the electron velocity, e and m are the electron's charge and mass, and n is an integer. In a real situation, where the electrons are injected within a range of energies and angles, resonance conditions for different electrons in the beam are achieved at different magnetic fields, leading to smearing of the oscillations and to minor changes in the expected periodicity. Still, if the injected distribution is sharp enough, both in energy and in angle, the effect should be clearly observable.

The current oscillations, shown in Fig. 3 for different angles θ of the magnetic field, are drawn after normalizing out a monotonous increase of some 15% of the collected signal with B (by dividing each trace by the one measured with a normal, $\theta=0°$, magnetic field). Up to eight periods (not all shown) are observed. The scaling of the periodicity was verified for different drift region lengths, different injection energies and different angles. The dependence of the oscillation frequency on tilt angle is somewhat weaker than that predicted by Eq. (1), most likely due to the angular distribution of the injected electrons (as was also verified via simple Monte-Carlo simulations). The fact that the contrast of the oscillations is quite large clearly shows that the injected distribution is rather peaked in energy and angle. It also indicates that the collector barrier indeed conserves the lateral momentum (the component parallel to the layers) of the traversing electrons and that no significant scattering takes place within the barrier. This conservation of lateral momentum in transmission across a potential barrier is often assumed in the literature but never experimentally proved in such a clear manner. The fact that the oscillations do not smear indicates that no significant broadening of the ballistic distribution takes place during the lengthy motion through the drift region. This strengthens our conclusion about the dominance of an inelastic scattering process of the hot electrons in high-purity GaAs; a point to which we return later. The oscillations are also preserved at temperatures as high as 25 K; above that temperature leak currents and thermal noise become prominent.

The effect of scattering is clearly observed when we compare the collected current at $B=B_r$ (first maximum) and at $B=0$ at a given tilt angle of the magnetic field. The total path length of the helical trajectory at $B=B_r$ is longer than that of the straight path (at $B=0$) and hence the number of collected electrons is smaller. Since the path length increases with increasing tilt angle we observe a monotonous decrease in the collected current with tilt angle. Using the same simplified model leading to Eq. (1) we find the total path length covered by the electrons, for any integer number of rotations n to be $L=d/\cos^2\theta$. If the dominant scattering mechanism is inelastic it is reasonable to assume that an electron will not be collected after a single collision and thus the collected current at $B=B_r$ decays exponentially with path length, i.e.,

$$I_c(B_r) = I_c(B=0)\exp(-L/\lambda) = I_c(B=0)\exp(-d/\lambda\cos^2\theta), \tag{2}$$

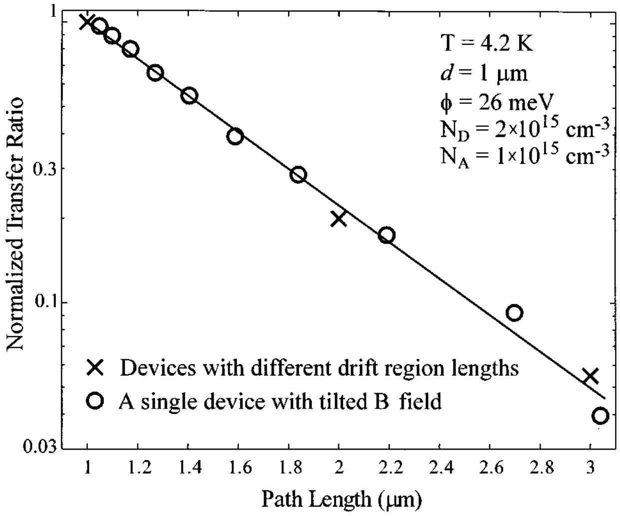

FIG. 4. The transfer ratio through the drift region, normalized to a path length of 1 μm, is shown as a function of path length for both measurement techniques: using different devices (X) and using the tilted magnetic field in a 1-μm-long device (○). The mfp's measured by the slopes of the transfer ratios using both methods are almost identical.

where the decay coefficient λ is the inelastic mfp for a certain ϕ. In Fig. 4 we plot the normalized transfer ratio as a function of the total path length L (circles): an exponential decay is indeed observed. Furthermore, we find that the extracted mfp in the single device is in close agreement with that deduced from measurements of samples with different drift region length. At tilt angles larger than ≈60° some of the electrons hit back the *emitter* barrier in their cyclotron motion, possibly changing the simple exponential behavior of the transfer ratio; this allows the analysis to be valid only up to $L \approx 4d$.

The mean free path was measured at 4.2 K in samples grown in two different MBE systems, with total impurity concentrations of $N_D + N_A = 6 \times 10^{14}$ and 3×10^{15} cm^{-3}, and was found to be $\lambda = 4.0$ μm and 0.7 μm, respectively. The fact that the mfp scales roughly inversely with the impurity concentration clearly proves that the dominant scattering mechanism is due to impurities and that acoustical phonon scattering is not important. As the temperature is being raised we observe a slow and monotonous decrease in the mfp, and at 18 K it is found to be 30% lower than its 4.2 K value.

Note that the measured mfp, λ, is different than the mfp for momentum relaxation, λ_p, frequently used in linear response theory: λ_p is calculated weighing each scattering event according to its contribution to the momentum relaxation using a weighing factor of $(1-\cos\Psi)$, where Ψ is the scattering angle. In our device, however, every electron that has a normal energy higher than the collector barrier height ϕ is collected and counted with the same weight. The mfp measured in our device is thus a function of the collector barrier height ϕ as we indeed found (a ±30% change in λ was found as the barrier height was changed by ∓ 5 meV). By measuring $\lambda(\phi)$ for a large number of barrier heights, one could, in principle, extract the angular dependence of the scattering mechanism, which also allows the inference of the momentum relaxation mfp.

A remaining question is the identification of the dominant scattering mechanism. Since the mfp was found to scale roughly inversely with the impurity concentration the scattering is clearly related to the impurities. Ionized impurity scattering is an *elastic* process, giving rise predominantly to small angle scattering (especially in the absence of screening as in our case) leading to angular diffusion in momentum space. Such diffusion is expected to smear out the observed oscillations and to result in a power law dependence of the collected current on length ($\approx 1/L$) instead of the observed exponential dependence. Note however that, contrary to an angular diffusion, when an electron is scattered by an *inelastic* process with a large energy exchange, the scattered electron is immediately taken out from the ballistic distribution, leaving this distribution unchanged, allowing thus the clear features of the ballistic motion to be still observed. Hence, both the exponential dependence and the clear ballistic features lead us to conclude that the dominant scattering process is *inelastic*. A relevant scattering process is *impact ionization or excitation of neutral donors* (whose density is $N_D - N_A$). This process is in qualitative agreement with the behavior of the measured mfp at different temperatures and with longitudinal magnetic fields. With the application of magnetic field the electron's binding energy increases by approximately $\hbar\omega_c/2$, reducing thus the cross section for scattering and leading to a longer mfp. As temperature increases some of the neutral impurities are ionized and the free electrons contribute to e-e scattering. Since the binding energy of the scattering electrons to their parent donors is much smaller than the kinetic energy of the injected hot electrons it could be expected that the two scattering mechanisms, e-e and *e-impurity*, lead to similar scattering cross sections, explaining the weak temperature dependence.

Translating the measured mfp to a scattering cross section per neutral donor, $\sigma = [(N_D - N_A)\lambda]^{-1}$, we find $\sigma \approx 8\pi a_B^2$, where a_B is the effective Bohr radius in GaAs. This figure is about twice larger than the expected value, calculated by assuming the donor behaves similarly to a Hydrogen atom[7] and taking into account both the cross section for ionization from the ground state and those for excitations from the ground state to higher bound states. This discrepancy can be related to inaccuracies in the determination of the impurity concentration or deficiencies in the theory.

Finally, it is interesting to note that we have shown that the semiclassical model provides a good explanation to the experimental results; however, in the presence of the magnetic field it should be asked *why* does it work? Since the number of rotations the electrons perform is larger than one, implying $\omega\tau > 1$, quantum effects could be expected. Two different answers can be given. One answer is that according to the correspondence principle the semiclassical behavior should not change abruptly once the limit $\omega\tau > 1$ is exceeded, but should rather change smoothly. Since we are in a regime where the number of rotations is very small, and we analyze only the data of the first peak, $\omega\tau = 1$, it could be expected that the main results of the semiclassical model still hold.

Another answer is that the condition $\omega\tau < 1$, which is frequently used to characterize the semiclassical regime, actually means that the trajectory should not close on itself, since in that case one ''part'' of the wave function will interfere with another and a quantum description will be required. However, in our configuration the electron has a significant velocity component in the direction of the magnetic field and it does not close on itself. Since the distance between successive windings of the helical trajectory (being the drift region length divided by the number of rotations) is much larger than the lateral extent of the wave function (usually believed to be of the order of the wavelength, being about 200 Å for an electron with an energy of 36 meV), interference between different windings is not likely and hence a quantum treatment is not required. In any case, it seems that further study is called for, which will clarify the way in which the semiclassical behavior turns into a quantum one. It is also important to notice that as far as the dynamics of the scattering is concerned the presence of the magnetic field should not make a significant difference since $\hbar\omega_C$ is below 1 meV over the whole experimental regime, and is thus much smaller than both the ionization energy of the impurities (5.5 meV), the energy width of the ballistic distribution (10 meV) and the hot electron energy (36 meV).

In conclusion, we utilized a novel technique, relying on the cyclotron motion of ballistic electrons in tilted magnetic fields, in order to measure the mfp of ballistic hot electrons injected into high-purity GaAs at low temperatures. This measurement technique has been verified by comparing it with measurements done on an ensemble of devices, each with a different path length. The resulting mfp is several microns long for electrons with energy just below the LO-phonon emission threshold in GaAs doped to $N_D + N_A = 6 \times 10^{14}$ cm^{-3}, and scales roughly inversely with the total impurity concentration. We propose that the dominant scattering mechanism is due to impact ionization and excitation of neutral donors by the ballistic hot electrons with a cross section for scattering $\sigma \approx 8\pi a_B^2$.

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