Hot Ballistic Transport and Phonon Emission in a Two-Dimensional Electron Gas

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Hot-electron transport in a 2D electron gas is investigated as a function of the electron's excess energy. The inelastic mean free path at energies below the longitudinal-optical-phonon energy is found to be an order of magnitude longer than theoretical predictions. For higher injection energies, LO-phonon emission is found to be the main scattering mechanism. This, together with the ballistic motion for energies below the phonon energy, leads to previously unobserved periodic oscillations in the maximum energy of hot electrons as a function of their injection energy.

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Electronic transport in a high-mobility 2D electron gas (2DEG) over distances shorter than the total mean free path has recently attracted considerable interest. The discovery of quantized contact conductance,[1] magnetic focusing,[2] etc., revealed several features characteristic to ballistic electronic motion. Most of the research, however, was concerned with cold-electron transport at the surface of the Fermi disk. Most recently, Palevski *et al.*[3] have demonstrated ballistic transport, for hot electrons as well, across short distances (up to 170 nm) in a high-mobility 2DEG. Here we explore hot, ballistic electron transport as a function of excess energy relative to the Fermi energy of the 2D cold-electron background along distances as large as 2 μm. The long distance, combined with the energy spectroscopy technique to be described later, enables a direct probing of the scattering processes experienced by the hot electrons. We find that the main scattering mechanism at 4.2 K, for hot electrons with excess energy larger than the longitudinal-optical- (LO-) phonon energy ($\hbar\omega_{\mathrm{LO}} = 36$ meV), is LO-phonon emission. For electrons with energy below 36 meV we find a surprisingly long inelastic mean free path (mfp), at least of the order of the device's size, namely 2 μm. The measured mean free path is about an order of magnitude longer than theoretical predictions for electron-hole excitation and more than that for electron-plasmon scattering. Weaker than expected coupling of hot, ballistic electrons to plasmons in bulk GaAs was also reported by Heiblum, Galbi, and Weckwerth.[4] The combination of short mfp for phonon emission and ballistic motion below the phonon energy results in a previously unobserved, periodic oscillation in the maximum energy of the collected electrons as a function of injection energy. Unlike previously reported phonon-induced oscillations in the photoconductivity of bulk GaAs[5] and in the tunneling current through n^+-GaAs-AlGaAs-n^--GaAs[6] structures, the present oscillations are characteristic of quasiballistic motion of the electrons once they have been scattered to energies below the phonon energy.

The structure used in the experiment is schematically shown in Fig. 1. Two pairs of metallic gates [dark areas in Fig. 1(a)] were defined employing electron-beam lithography on the surface of a GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructure containing a 2DEG (in the heterojunction between GaAs and AlGaAs). One pair of gates was utilized to produce a barrier for use as a hot-electron injector [the injector is designated I in Fig. 1(a)] and the second one was used to produce a spectrometer barrier for analyzing the energy distribution of the collected beam [C in Fig. 1(a)]. The nominal size of the injector and collector openings were approximately 180 nm and the distance between the injector and the collector was 2 μm. The various 2DEG regions, namely the injector (I), the base (having two contacts B_1,B_2), and the collector (C), were contacted by standard NiGeAu alloyed Ohmic contacts. The carrier density and mobility of the 2DEG were measured at 4.2 K using the standard van der Pauw procedure and were found to be 2×10^{11} cm^{-2} and 8×10^5 cm^2/V sec, respectively, leading to a Fermi energy of $E_F \simeq 7$ meV and a transport mean free path (for cold electrons) of $l \simeq 4.5$ μm.

An application of a negative gate voltage with respect to the 2DEG in the base forms an electrostatic barrier under the gates, thus confining the electrons to the un-

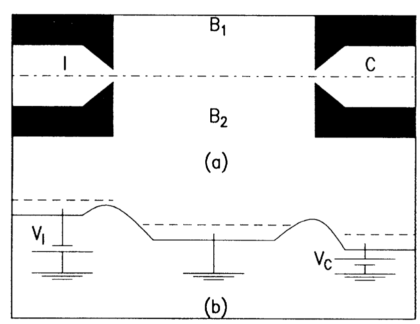

FIG. 1. (a) A schematic drawing of the structure used. Two pairs of metallic gates (dark regions) define injector (I) and collector (C) regions in the 2DEG. (b) Schematic presentation of the bottom of the conduction band under operation conditions [a cut along the dash-dotted line in (a)].

gated regions. An even higher gate voltage depletes the 2DEG in the openings of the injector and collector, creating a potential barrier separating them from the base [Fig. 1(b)]. Hot electrons were injected by applying large enough voltage across the injector barrier [V_I in Fig. 1(b)]. The collector barrier height was controlled both by changing the collector gate voltage and by changing the collector biasing relative to the base [V_C in Fig. 1(b)]. Monitoring the resistance between the two base contacts, B_1 and B_2, we ensured that the base was not depleted of carriers for the gate voltages used in the experiment. Energy spectroscopy of the current-carrying states was performed via monitoring, for a given injection energy, the collected current as a function of the collector barrier height.[3] The variations in that current, assuming a given distribution for the injected electrons, contain information on the scattering processes experienced by an electron traversing the base. Since tunneling through the collector barrier is negligible, only hot electrons with longitudinal (i.e., perpendicular to the collector) energy larger than the collector barrier height are collected. Electrons which relax to energies below the collector barrier height are not collected and are drained through the base to ground.

Typical results, at 4.2 K, for the collector current I_C (dashed lines) and the transfer ratio $\alpha = I_C/I_I$ (solid lines), as a function of the injection voltage V_I (all voltages are measured relative to the base), are depicted in Fig. 2. The two sets of curves correspond to different injector gate voltages $V_{GI} = -1.2$ and 1.24 V, and a fixed collector barrier height of approximately 23 meV above the Fermi level in the base. For small injector biasing, its opening is pinched off. An increased voltage lowers the injector barrier below the Fermi energy in the injector, leading to a finite injection current. The collector current starts as soon as the injection energy exceeds the collector barrier height, proving ballistic transport. The transfer ratio, α, reaches a sharp maximum at $V_I \simeq 36$ mV, then drops down to a minimum at $V_I \simeq 55$ mV, and reaches a second peak at $V_I \simeq 70$–75 mV and a third one at approximately 110 mV. The peak magnitude of α agrees with ballistic transport in the solid angle covered by the collector (approximately 30 deg), implying no or very weak large-angle scattering. The three distinct peaks in α lie in the vicinity of one, two, and three phonon energy quanta above the Fermi energy in the base (i.e., $V_I = 36$, 72, and 108 mV) and result from the emission of one, two, and three sequential LO phonons by the injected hot electrons.

The transfer ratio, α, as a function of the collector

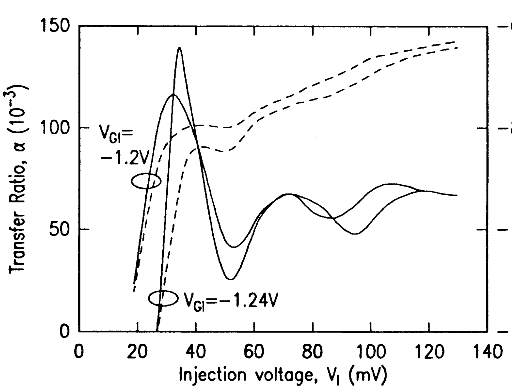

FIG. 2. The oscillations in the transfer ratio (solid lines) and the collector current (dashed lines) vs the injection voltage for two values of injector gate voltages measured at $T = 4.2$ K. Notice the negative differential transconductance (dI_C/dV_I). The collector barrier is fixed at approximately 23 meV above the Fermi energy in the base.

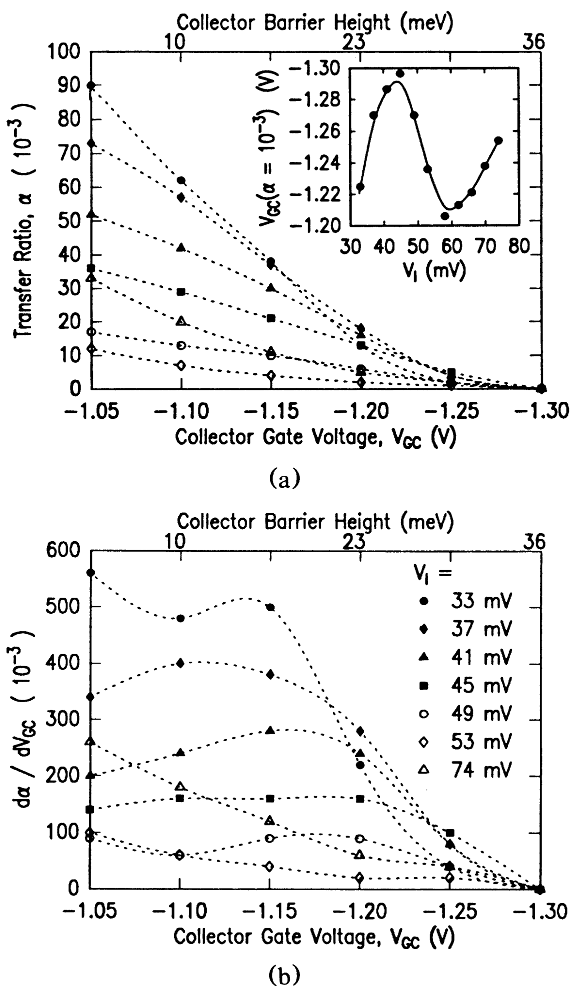

FIG. 3. Spectroscopy of the current-carrying states. (a) The transfer ratio and (b) its derivative vs the collector gate voltage and the corresponding collector barrier height for different injection voltages measured at $T = 4.2$ K with a fixed injector barrier height. The different curves correspond to various injection voltages (V_I). Inset: The periodic oscillations in the collector gate voltage needed to cut off α as a function of the injection energy.

gate voltage and the corresponding collector barrier height, for a constant injector barrier height, is depicted in Fig. 3(a) for various injection energies. The legend for the different curves is given in Fig. 3(b) and the dotted lines merely serve as a guide to the eye. At low and intermediate collector barrier heights (up to $|V_{GC}| \leq 1.15$ V), α decreases monotonically as the injection energy is increased, reaches a minimum at $V_I = 53$ mV, and thereafter rises again at higher injection energies. For $|V_{GC}| > 1.3$ V, α vanishes for all injection energies, indicating that the maximum energy of the electrons arriving at the collector is bounded above. This bound is the LO-phonon energy, namely 36 meV. More detailed information on the transfer ratio for a collector barrier height close to 36 meV appears in the inset of Fig. 3(a). There we plot the collector gate voltage needed to cut off α versus the injection energy (we have arbitrarily chosen $\alpha = 0.001$ as a criterion for a cutoff). An oscillation of the cutoff voltage (and hence the cutoff collector barrier height) with a period corresponding to the LO-phonon energy is clearly observed.

At 4.2 K, the occupation number of LO phonons is negligible and the emission rate for an electron with energy E, in the parabolic-band approximation and for an intrinsic material, is given by[7]

$$\tau^{-1}(E) = 5.61 \times 10^{15} (m^*/m_e)^{1/2} \hbar\omega_{\mathrm{LO}} (K_\infty^{-1} - K_0^{-1}) \times E^{1/2} F_0(E, E'), \quad (1)$$

with

$$F_0(E,E') = \ln \frac{E^{1/2} + E'^{1/2}}{E^{1/2} - E'^{1/2}},$$

and $E' = E - \hbar\omega_{\mathrm{LO}}$.

For GaAs, the Γ-band effective mass is $m^* = 0.067 m_e$ with m_e being the free-electron mass, and the high- and zero-frequency dielectric constants are $K_\infty = 10.92$ and $K_0 = 12.9$, respectively. Substituting these quantities into the expression for $\tau(E)$, one obtains for $E = 43$ meV ($E_F + 36$ meV) a mfp of the order of 500 Å, much shorter than the separation between the injector and the collector. We thus expect folding of all collected electron energies to the range between 0 and 36 meV above the Fermi energy in the base. Electrons having an energy $E + n \times 36$ meV above E_F in the base, where $n = 0, 1, 2, \ldots$, and $E < 36$ meV, emit n phonons sequentially and relax to an energy E. Indeed, as demonstrated in Fig. 3(a) and its inset, the maximum attainable energy of the electrons impinging on the collector barrier is bounded above by 36 meV (the collector barrier height corresponding to $V_{GC} = -1.3$ V) and oscillates with a 36-meV period as a function of the injection energy. The minimum transfer ratio is attained for eV_I equal to the collector barrier height plus 36 meV. This criterion was used to calibrate the collector barrier height. The second peak in α, for $V_I \simeq 72$ mV, is achieved when a maximal portion of the injected electrons can emit one phonon and still surmount the collector barrier. Similarly, the third peak is expected at $V_I \simeq 108$ mV, and so on. The peaks might occur at a somewhat higher energy due to the finite energy width of the injected beam. The transmission through the collector barrier depends on the momentum perpendicular to the barrier and not on the total energy. Therefore, the occurrence of the maxima in α at an integral multiple of phonon energies, and the total value of α which is comparable with the expected transfer ratio due to geometrical factors, reconfirms that scattering due to LO-phonon emission is mainly in the forward direction.[7]

The effective opening width of the collector seen by the impinging electron depends both on energy and on the applied gate voltage (V_{GC}); hence, this collector is not optimal for carrying out quantitative spectroscopy. Yet, the derivative of α with respect to V_{GC} is a monotonic function of the number of electrons at a given longitudinal energy in the collected beam and a qualitative spectroscopy can be done. These data are presented in Fig. 3(b). For $V_I = 33$ mV, $d\alpha/dV_{GC}$ changes slowly up to $|V_{GC}| \simeq 1.15$ V where it drops down very sharply. This "drop" is due to the collector barrier becoming higher than the injection energy at $V_{GC} \simeq 1.25$ V. At somewhat higher injection energies, namely 37–45 meV, the $d\alpha/dV_{GC}$ curves are nonmonotonic functions of V_{GC} and display a maximum for some intermediate value of V_{GC}. This feature indicates that the energy distribution of the collected electrons is very different from a local thermal equilibrium one. As the injection energy is increased further, the curves flatten and for $V_I \gtrsim 53$ mV become monotonically descending functions of V_{GC}, implying that electrons injected at high energies are severely scattered.

The results described above do not show evidence of significant scattering below 36 meV. This is a surprising result since electron-hole excitation (in the conduction band) and electron-plasmon scattering are expected to yield a relatively short mfp.[8,9] The first mechanism dominates the scattering at energies close to the Fermi energy while the latter one is operative above some critical energy relative to E_F. For our carrier concentration, the threshold wave vector, k_C, for plasmon scattering is expected at $k_C \simeq 1.85 k_F$ (k_F is the Fermi wave vector) or $E_C \simeq 17$ meV above the Fermi energy.[8] A comparable threshold is also given in Ref. 9 for slightly higher carrier concentration (3×10^{11} cm^{-2}). For energies above this threshold, the inelastic mfp is predicted to be 200–250 Å while below E_C it is roughly of the order of $\simeq 2000$ Å,[8,9] an order of magnitude shorter than the device's size.

In contrast to the theoretical predictions, our results clearly indicate ballistic motion for electron energies below the phonon energy. Yet, oscillation in the maximum energy of the collected electrons can also occur, in principle, in the presence of inelastic scattering of the electrons injected at energies below 36 meV or of those that have already been relaxed to that range by optical-phonon emission. In the presence of such scattering, a quasi thermal equilibrium of the 2DEG would be established with an effective temperature depending on the injected power (injector current times the injection energy modulo 36 meV) and the cooling rate of the 2DEG to the lattice by acoustic phonons, boundary imperfections, etc. Since for injection energies above 36 meV, an LO phonon would be emitted and its energy would be transferred directly to the lattice without heating the 2DEG, the effective electron temperature would also oscillate as a function of the injection energy with a periodicity of 36 meV. If the temperature rise is high enough, hot, nonballistic electrons would have high enough energy to surmount the collector barrier, leading to oscillations in the apparent α which might be qualitatively similar to the results presented above. Fortunately, we can exclude that possibility on the basis of our experimental data. The power transferred to the 2DEG is proportional to the injected current which varies by more than 2 orders of magnitude between $V_I = 33$ and 74 mV. The above mechanism would thus predict a substantial heating of the 2DEG for the higher injection energies and hence an increased α. No such effect is observed in the experiment. An independence of α on the current is also evident from the similarity between the two curves in Fig. 2. Moreover, a quasi equilibrium condition, characterized by higher electron occupation of lower energies (a Maxwellian tail), must be reflected in our spectroscopy measurements in a monotonic decrease of $d\alpha/dV_{GC}$ as V_{GC} is increased. It is evident from the data presented in Fig. 3(b) that this is not the case, except maybe for $V_I = 74$ meV. This leads us to restate that electrons injected below 36 meV traverse the base and approximately preserve their initial distribution.[10] The energy relaxation mean free path for electrons with $E < 36$ meV must therefore be at least of the order of the device's size—2 μm, about an order of magnitude larger than the theoretical predictions[8,9] for electron-hole excitation mfp.

In summary, we have studied transport of hot electrons over distances as large as 2 μm in a high-mobility 2DEG. The main scattering mechanism above 36 meV was found to be due to LO-phonon emission which also led, due to the absence of any other scattering, to large, periodic oscillations in the maximum energy of the collected electrons and their transmission through a barrier as a function of the injection energy. Energy spectroscopy of the current-carrying states below 36 meV, in conjunction with these oscillations, reveals a very long inelastic mfp below the phonon energy, at least an order of magnitude longer than theoretical predictions.

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[10] The nonvanishing value of α for say $V_I \simeq 50$ mV (see Fig. 2) suggests that the initial energy width of the injected beam is wider than the Fermi energy. Had that not been the case, the electrons would emit a phonon, relax to energies below the collector barrier, and never be collected by the collector. We do not currently understand the reasons for this apparent broadening of the injected beam.