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Electron heating in GaAs due to electron-electron interactions

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The interaction between hot electrons, injected into a confined doped GaAs layer, and cold electrons residing in this layer is studied. Utilizing a hot-electron transistor, we found that the output current is larger than the input current, indicating that electron heating is taking place in the layer. Two possible pictures were considered, one assuming single-particle energy and momentum transfer from hot to cold electrons, and the other assuming that thermal equilibrium is reached among the heated cold electrons. By comparing different devices we conclude that the *equilibrium* picture describes better the heating process, with measured electron temperatures of 10–20 K. Using a power-balance criterion we estimate the energy relaxation time of the hot injected electrons.

The interactions of hot electrons in doped GaAs layers were extensively studied in the last few years both experimentally[1–4] and theoretically.[5–8] It was found that the dominant inelastic scattering mechanisms are due to the emission of longitudinal-optical (LO) phonons, possibly coupled to plasmons, and electron-electron (e-e) interactions. These scattering mechanisms were usually thought to affect only the injected hot-electron distribution, leaving the cold electrons and the lattice in thermal equilibrium. However, if the energy transfer from hot to cold electrons is sufficiently large the cold-electron distribution is expected to be significantly modified, as was previously observed in a two-dimensional electron gas (e.g., Refs. 9 and 10). In most previous works, however, the hot electrons were assumed to be fully thermalized, due to the long time available for interaction, although it was never directly proven.

In this paper we study the interactions of injected hot electrons, passing *briefly* through a thin doped GaAs layer, with cold electrons confined in the layer. This situation allows us to discuss separately the cold- and hot-electron distributions, and our device allows us to probe both. We find that the output current is larger than the injected current, indicating that a current amplification process is taking place in the layer. We show that this process is mainly due to heating of the confined cold electrons which reach a thermal equilibrium among themselves, leading to thermionic emission. An alternative picture that assumes single particle e-e interactions, leading to a highly nonequilibrium state of the cold-electron system, is excluded by comparing different devices.

The study was carried out using a tunneling hot-electron transfer amplifier (THETA),[1] with a heavily doped base, confined between two barriers, serving as the transport layer. In this device, hot electrons are injected by tunneling through a thin $Al_xGa_{1-x}As$ barrier (*emitter barrier*) into the base and are collected over a second $Al_xGa_{1-x}As$ barrier (*collector barrier*) as seen in Fig. 1. The differential transfer ratio, $\alpha = dI_c/dI_{\rm inj}$, where $I_{\rm inj}$ is the injected current and I_c is the collected current, measures the probability for electrons, injected within a narrow energy range into the base, to be collected over the collector barrier. To surmount the collector barrier the collected electrons must have a *normal* energy (associated with the component of motion perpendicular to the layers) higher than the barrier height, $e\phi$. In order to probe the heated cold-electron distribution the collector barrier must be very low and thick enough to prevent tunneling of cold electrons.

In the structures under investigation, grown by molecular-beam epitaxy (MBE), the collector barrier is 60 nm wide and is typically $e\phi \cong 20$ meV high. The base is 30 nm thick and is n-type doped to 2×10^{18} cm^{-3} (details are given in Ref. 11). Typical differential transfer ratios α are shown in Fig. 2(a), for different barrier heights. The onset of α at $eV_{\rm inj} = e\phi$ measures the collector barrier height, which decreases as V_c increases (as shown in Fig. 1). At an injection energy of $\simeq$36 meV a sharp drop in α is observed, indicating the emission of an LO phonon.[12] The two broader oscillations in α, seen at higher injection energies, shift in energy with ϕ, and

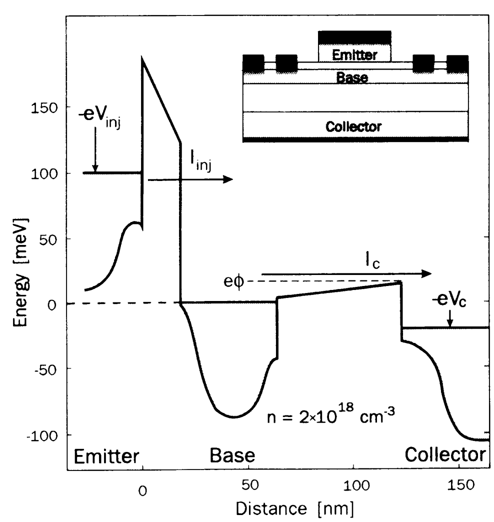

FIG. 1. Conduction-band profile of the THETA device with typical biasing, including band bending calculated from the Poisson equation. Inset: device geometry.

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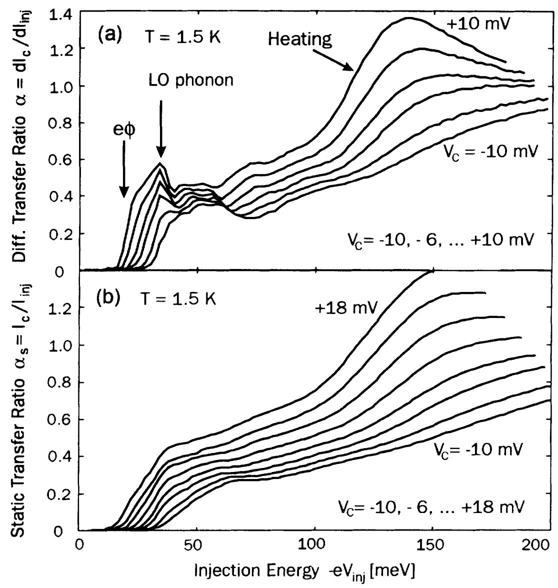

FIG. 2. (a) The differential and (b) the static transfer ratios, measured vs injection energy for different collector biases V_c. Transfer ratios larger than unity are observed for low barrier heights and high injection energies.

thus are probably related to the emission of LO phonons in the collector barrier.

A surprising result is found at still higher energies: the differential transfer ratio α *exceeds unity*, i.e., the differential output current is larger than the differential input current. The static transfer ratio, $\alpha_s = I_c/I_{\text{inj}}$, plotted in Fig. 2(b) after subtracting a small and constant tunneling current between base and collector, has a smoother behavior but it also exceeds unity. The maximal value of α, which increases with decreasing collector barrier height, can reach in some devices a value as high as 2. Spurious effects due to voltage drop along the base were found to be negligible, except at very high injection currents.[13]

We interpret the excess output current, manifested in $\alpha > 1$, as resulting from heating of the cold electrons by the injected hot electrons. Two possible heating pictures may be relevant.

(a) A hot electron can transfer energy and momentum to a cold one, either directly via *e-e* interactions or by emitting a collective excitation (plasmon-phonon coupled mode) which is then absorbed by a cold electron. Such a process can directly produce an additional hot electron which can surmount the collector barrier, thus increasing the collector current. In this model the energy and momentum of the injected electrons play an important role and the cold-electron distribution is out of equilibrium. We checked this hypothesis using a Monte Carlo simulation, including *e-e* and ionized-impurity scattering, and followed the injected and the heated electrons until they leave the base. As also predicted by Long, Berton, and Kelly,[14] we indeed find that $\alpha > 1$ is attainable under suitable conditions.

(b) The cold-electron system is assumed to be thermalized, with an electron temperature higher than that of the lattice. Thermionic emission over the low collector barrier leads then to an increased collector current and

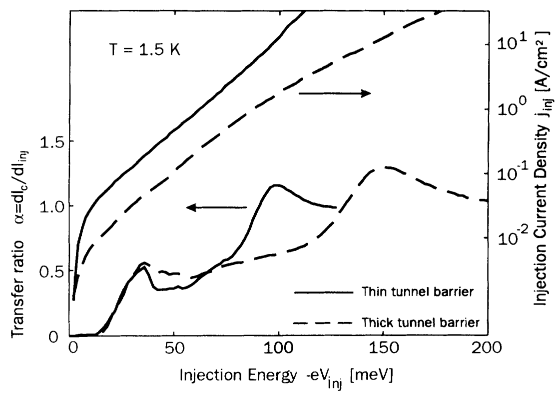

FIG. 3. Differential transfer ratios and injection current densities measured vs injection energy in two similar devices different only in the tunnel barrier thickness.

$\alpha > 1$. In this picture there is no memory left of the momentum imparted by the forward-moving hot electrons to the cold ones. We treat this process via power balance, namely, the accumulated effect of all the energy transferred from hot to cold electrons, resulting in a total power imparted to the base, should be equal to the total power leaving it.

We distinguish between the two possible pictures by noting that if the first, nonequilibrium picture, is dominant, then α should be a function of the injection energy only and independent of the injected current. If, however, the second, *equilibrium* picture is correct, then the input power, which is a function of both the injection energy and current, should be the relevant parameter in determining α. In Fig. 3 we plot the injected current densities and the measured α's for two devices having identical structures except for the tunnel emitter thickness, thus injecting different current densities at the same injection voltage. We find that α exceeds unity at a lower injection energy in the device having higher current densities, clearly indicating that the *equilibrium* picture is the more relevant one.

The fact that the final state of the cold-electron system is probably an *equilibrium* one can teach us about the underlying single-particle interactions leading to this final state. Since electrons with energies *higher* than $e\phi$ can escape the base prior to thermalization, an equilibrium final state can be reached only if a significant number of the heated electrons have energies *below* the collector barrier height. This can happen if the interactions between hot and cold electrons in our device are mostly characterized by small energy exchange, as also supported by the energy distribution of heated electrons found in Monte Carlo simulations.[14] The confinement of the heated electrons allows them to thermalize over a large time scale, contrary to the case of injection into bulk GaAs where the cold-electron system after 30 nm would be far from equilibrium. Small energy transfer may also be possible if energy is transferred from the hot to cold electrons mainly through the emission of phonon-plasmon coupled modes which subsequently decay, by some unknown mechanism, into low-energy electron excitations.

If indeed the *equilibrium* picture is correct, one should be able to measure the electron temperature T_e in the base. We performed two different types of temperature measurements utilizing the magnetoconductance and the resistance of the base, both measured with a standard four-terminal ac technique. The magnetoconductance of the base, being a diffusive layer, is expected to increase with increasing magnetic field, due to the weak localization (WL) effect. This effect, a consequence of the suppression of coherent backscattering, decreases in magnitude with increasing temperature due to the reduction of the coherence length.[15] WL was first measured without hot-electron injection, at different lattice temperatures T_L, and then compared with measurements taken at $T_L = 1.5$ K with hot-electron injection [Fig. 4(a)]. Temperature was also deduced from the base resistance at zero magnetic field which was found to be very sensitive to temperature since thermionic emission can be viewed as partially shunting the base via the low resistance collector. For example, the base resistance reduced by ≈30% when the lattice temperature increased from 1.5 to 25 K.

The temperatures measured by the two techniques are shown in Fig. 4(b). While the agreement between the two measurement techniques is very good at low injection energies, a temperature difference of up to 6 K is found at larger injection energies. The thermionic current at the measured temperatures of 10–20 K is found indeed to be large enough to explain the observed enhancement in the collector current. Moreover, the temperatures measured in several devices having different base densities (in the range 5×10^{17}–3×10^{18} cm^{-3}), at the injection energies where $\alpha = 1$, were all found to be 10–12 K, confirming again the equilibrium picture. Note that the two measurement methods are complementary when temperature variations exist along the base, as indeed is expected since only the central part of the base, located directly underneath the emitter, is heated by the injected current (see inset of Fig. 1). The WL measurement places a heavier weight on the colder parts for which the conductance is more sensitive to magnetic fields, whereas the base resistance measurement is more sensitive to the hotter parts from which thermionic emission is exponentially larger. The two measurement techniques can thus help in estimating the temperature variations along the base.

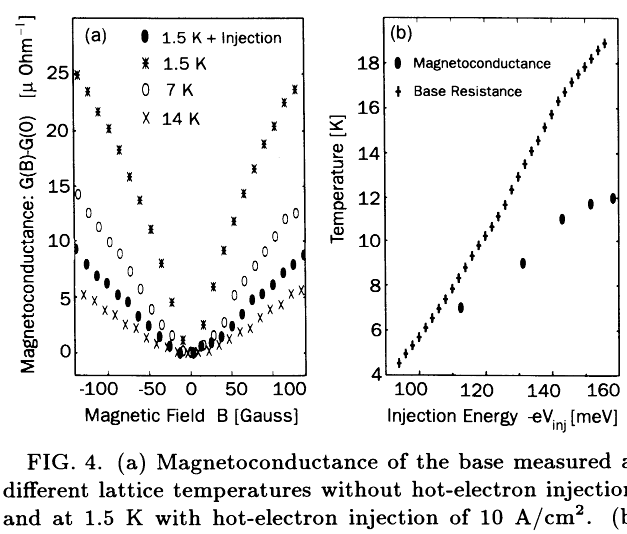

FIG. 4. (a) Magnetoconductance of the base measured at different lattice temperatures without hot-electron injection, and at 1.5 K with hot-electron injection of 10 A/cm^2. (b) Average electron temperatures in the base during hot-electron injection deduced from the base resistance (crosses) and from the magnetoconductance (ellipses) measurements.

Adopting the equilibrium heating model, which assumes a steady-state power balance, we can use the measured temperature and device parameters to estimate the rate of energy transfer from the injected hot electrons to the cold electrons. We express the power balance in the cold-electron system as

$$I_{\mathrm{inj}}V_{\mathrm{inj}}(1 - e^{-t_B/\tau_\epsilon}) = N\kappa_{e\text{-ph}}(T_e^3 - T_L^3) + I_{\mathrm{th}}\phi + P_{\mathrm{diff}} \,, \qquad (1)$$

where the left-hand side expresses the power input from hot to cold electrons, with τ_ϵ being the corresponding energy relaxation time and t_B the transit time of the hot electrons across the base. The power output on the right-hand side includes the acoustical-phonon energy loss rate, with $\kappa_{e\text{-ph}} = 6.4 \times 10^{-18}$ W/K^3 per electron[16,17] and N the total number of electrons in the base; the cooling rate due to the thermionic emission current, I_{th}, where each electron is assumed to carry an energy equal to $e\phi$; and the last term, describing (via the Wiedemann-Frantz law) the electron diffusion from the central, hotter part of the base to the external, colder parts. A detailed analysis, solving for the temperature profile along the base, leads to an almost constant temperature under the emitter, higher by 2–4 K than the values shown in Fig. 4(b) (which assumes a constant temperature profile), and a steep drop to T_L in the external parts.

For the measured temperatures, in the range 10–20 K, we find that the dominant energy loss mechanism is due to acoustical-phonon emission. For example, at a typical temperature of 13 K the cooling power due to phonon emission is ≈260 nW, whereas I_{th} is typically a few μA and for $\phi \approx 20$ mV the cooling power due to thermionic emission is only several tens of nW. Using Eq. (1) we find for $V_{\mathrm{inj}} = 130$ mV, $I_{\mathrm{inj}} = 20$ μA, and $T_e = 13$ K an energy relaxation time of $\tau_\epsilon \cong 250 \pm 100$ fs, where the error is due to a possible ±2 K uncertainty in determining T_e. It is difficult to compare this figure with theory since detailed calculations for our electron densities and injection energies have not been published to our knowledge. However, an inelastic lifetime of $\tau_{\mathrm{in}} \approx 50$ fs was calculated[7] for the emission of plasmon-phonon modes at similar electron densities and $eV_{\mathrm{inj}} \approx 400$ meV. In order to estimate τ_ϵ, as defined above, we multiply τ_{in} by the ratio of eV_{inj} and the energy of a typical excitation. For a typical coupled mode with an energy of ≈50 meV, we find $\tau_\epsilon \cong 400$ fs, which is not far from the value we estimate.

It is interesting to note that the plasmon-phonon coupled modes predicted by theory were observed in numerous optical experiments but had never been seen in transport measurements. Moreover, in this and in a previous experiment,[12] a sharp drop in α was observed at 36 meV, suggesting the emission of a *bare phonon*, a discrepancy not yet understood.

In summary, we have observed heating of *cold* electrons, confined in a thin doped layer of GaAs, by the injection of *hot* electrons into the layer. The heating effect was shown to depend on both the injection energy and current, indicating that the heated electrons are probably equilibrated among themselves (although it is difficult to prove that full equilibrium is reached). We measured the electron temperature to be in the range of 10–20 K and estimated from our results an energy relaxation time for 130 meV hot electrons of ≈250 fs.

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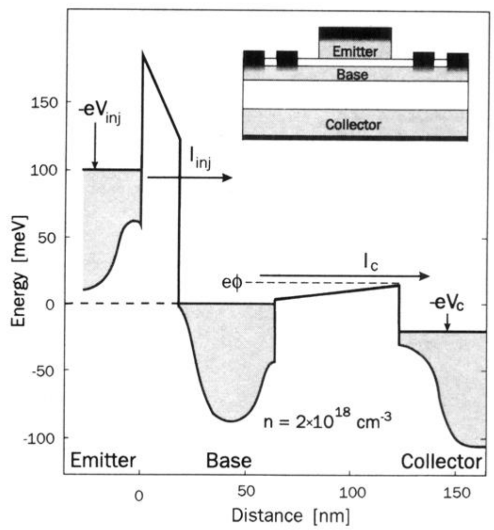

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