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Two-dimensional electron-gas heating and phonon emission by hot ballistic electrons

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We have used lateral injection of hot ballistic electrons to investigate heating of a two-dimensional electron gas. The electron temperature was found to oscillate with increasing injection energy, confirming optic phonon emission as the dominant inelastic process for electrons with excess energy above 36 meV. Our technique provides a method for determining the electron-electron scattering time of the hot electrons as a function of both energy and magnetic field. In the quantum Hall regime we found that hot-electron injection suppressed dissipationless transport, which we have interpreted as resulting from the excitation of cold edge-state electrons to higher Landau levels.

Electron heating in two-dimensional electron-gas (2DEG) systems is of considerable theoretical and technological interest. Much work in this area has used dc currents to produce Joule heating in the 2DEG.[1] If the electron-electron scattering rate is faster than the energy-loss rate to the lattice, the resulting nonequilibrium electron distribution will have a well defined electron temperature which is greater than the lattice temperature.[2] Here we present a method for studying electron heating and hot-electron energy-loss rates in a high-mobility 2DEG. Thermionic emission over a potential barrier is utilized to produce a laterally injected quasi-monoenergetic beam of hot electrons which heats a 2DEG, producing a measurable rise in the electron temperature. Matthews *et al.*[3] used a vertical structure with a limited range of injection energies to study 2DEG heating. In our system the injection energy is continuously variable. As this energy is increased, we observe significant oscillations in the electron temperature with a period of 36 meV. This results from sequential emission of longitudinal-optic (LO) phonons by the hot electrons, as recently observed[4] using the electron spectroscopy technique.[5,6] We use our data to extract an energy-loss time for the injected hot electrons which is longer than theoretical predictions. In the quantum Hall regime, we observe a breakdown of dissipationless transport which is dependent on the injection energy. We interpret this as being due to hot electrons exciting edge-state electrons into dissipative bulk states.

Our experimental structure is displayed in Fig. 1. Conducting channels of 2DEG [unshaded in Fig. 1(a)] were defined by wet etching an epilayer containing a GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunction. There were two regions where four-terminal resistance measurements could be made [$B1$ and $B2$ in Fig. 1(a)]. Two gold Schottky gates (G_i), separated by a narrow gap of 0.3 μm, produced an electrostatic barrier serving as a hot-electron injector. A third gate (G_c) was used to confine the injected electrons to region $B1$. Electron-beam lithography was used to define both the mesa and the gate levels. The carrier density and mobility of the 2DEG were measured at 4.2 K using a large Hall bar device of the same material. The values obtained were 1.5×10^{15} m^{-2} and 130 m^{2}V^{-1}s^{-1}, respectively, implying a Fermi energy $E_F \approx 5$ meV, and a mean free path $l \approx 8$ μm.

The four-terminal resistance of region $B1$ was determined using a small (100 nA) ac measurement current. One current probe served as an earth for both the ac measuring signal and the dc injection bias. The resistance of the narrow 2DEG region was found to vary with lattice temperature by $\approx 2\%$/K over the temperature range un-

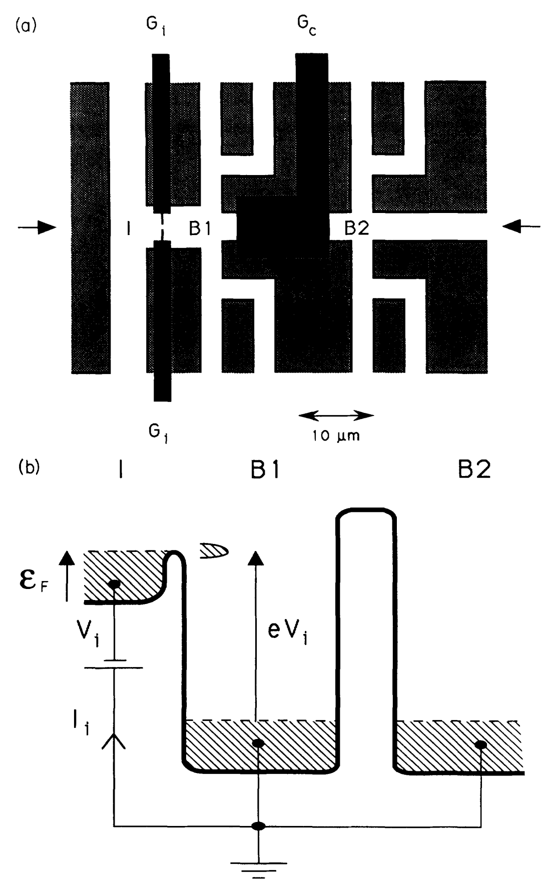

FIG. 1. (a) Schematic of the device, showing the 2DEG mesa (unshaded) and the metallic Schottky gates (dark). (b) Electron-energy diagram along the direction of the arrows in (a), showing electron injection over the barrier formed by the injection gates G_i. A large negative voltage on the confining gate, G_c, prevents the hot electrons from reaching the region $B2$.

der investigation. Assuming that the lattice and electrons were in equilibrium, we have used this variation as an electron thermometer, as has been done in other systems.[7] We determined the length over which a raised electron temperature fell to the lattice temperature by passing a dc heating current down the channel marked I in Fig. 1(a), and measuring the electron temperature remotely at points $B1$ and $B2$. This technique was first applied to the 2DEG of a Si metal-oxide-semiconductor field-effect transistor (MOSFET),[8] but ours are the first known measurements on a high mobility 2DEG where mesoscopic effects can also be investigated. We obtained a temperature decay length of the order of 20 μm, an order of magnitude greater than the corresponding value in a Si MOSFET, as expected from the far higher thermal conductivity in the heterojunction 2DEG.

A negative voltage on the injector gates (G_i) depletes the electrons beneath them, and eventually an electrostatic barrier forms between the injector region (I in Fig. 1) and the rest of the 2DEG. A negative bias V_i on the injector will raise the Fermi level in this region above the barrier, producing an injection current of hot electrons [Fig. 1(b)]. In these experiments the injector was biased with a constant current I_i. The injection voltage was then controlled by varying the injector gate voltage V_{Gi}, as detailed further below. By monitoring the four-terminal resistance of region $B1$, and comparing it with the lattice temperature variation, we obtained the local electron temperature during injection of hot electrons with energy $-eV_i$.

In Fig. 2(a) we show the resistance of region $B1$, as a function of the injector gate voltage V_{Gi}, with no injection, and with a constant injection current. At small negative gate voltages the injector barrier is not yet defined, and so the Fermi levels on both sides of the barrier are equal in energy. As the gate voltage V_{Gi} falls below ≈ -300 mV the injector barrier forms, and the Fermi energy of the injector rises by $-eV_i$ in order to maintain a constant injection current [see Fig. 1(b)]. This injection voltage was measured independently as a function of gate voltage. It was zero before barrier formation, and then increased linearly with V_{Gi}. The injection energy is indicated on the top axis of Fig. 2(a). As the power $P_i = V_i I_i$ injected by the hot electrons increases, the electron temperature T_e in $B1$ rises above the lattice temperature T_L. The resistance then falls, before showing a series of oscillations [see Fig. 2(a)]. The decrease in resistance with electron temperature agrees with the lattice temperature dependence that we observe, and we can attribute this to the effect of diffuse boundary scattering.[9] Diffuse boundary scattering is also indicated by low-field magnetoresistance data, and is expected for a wet-etched channel with dimensions less than the transport mean free path.

The derived electron temperature of region $B1$ is plotted against injection energy in Fig. 2(b). The electron temperature increases linearly with injection energy until the threshold for optic phonon emission ($\hbar\omega_{LO} = 36$ meV) is reached. The temperature then falls and displays oscillations of period ≈ 36 meV. This effect was originally considered by Sivan, Heiblum, and Umbach.[4] Optic phonon emission is the dominant energy-loss mechanism for hot electrons above the threshold energy of 36 meV. A

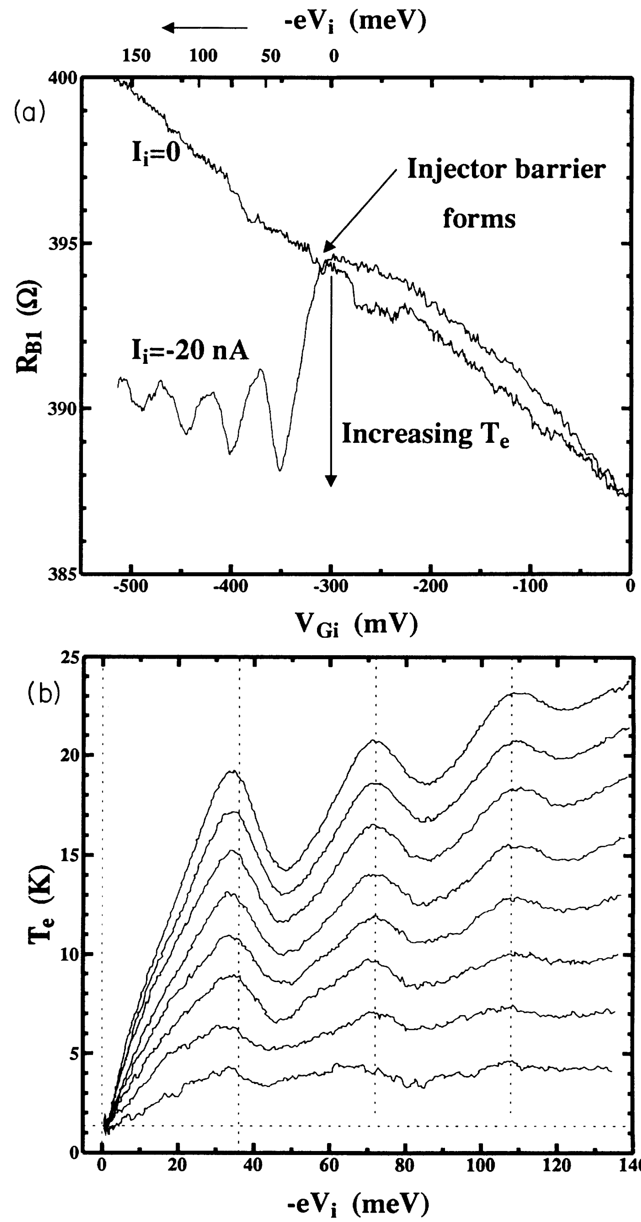

FIG. 2. (a) 2DEG resistance variation with V_{Gi}, for injection currents $I_i = 0$ and -20 nA, showing four phonon emission peaks. The background dependence on V_{Gi}, due to lateral depletion of the 2DEG, was subtracted for calculation of electron temperatures. The measured injection energy is marked on the top scale. (b) Calculated electron temperature variation with injection energy $-eV_i$, for a set of different injection currents: $I_i = -10, -20, \ldots, -80$ nA. The results were obtained at $T_L = 1.3$ K in zero magnetic field.

hot electron will very quickly emit n quanta of $\hbar\omega_{LO}$ to the lattice, leaving only ($-eV_i$ mod 36 meV) of energy to heat the 2DEG. We have used results from standard perturbation theory[10] to estimate the characteristic time τ_{LO} for optic phonon emission by hot electrons: this ranges from 380 fs for 41 meV electrons just able to scatter to the 2DEG Fermi energy, down to ≈ 220 fs at 60 meV, above which the time is roughly constant. Acoustic phonon emission by the injected electrons is negligible in comparison, as the scattering times are typically 100 times greater.

We will now consider the energy-loss mechanisms of the injected electrons in more detail. The excess energy $-eV_i$ of the hot electrons can be transferred either to the lattice, via phonon emission, or to the 2DEG, via collective excitations (plasmons) or single-electron scattering events. Reabsorption of LO phonons would produce electrons just below the emission threshold, trapping this energy in the 2DEG, and no oscillations in the electron temperature would occur. Our results preclude this possibility. Acoustic phonons are predominantly emitted out of the plane of the 2DEG,[11] again producing no electron heating. The characteristic times for energy loss by the injected electrons are then the LO phonon emission time τ_{LO}, and the time for energy loss via interactions with the 2D electrons τ_{ee}.

Below the LO emission threshold electron-electron scattering dominates the energy-loss rate and all of the injected energy $-eV_i$ is available for electron heating. In this regime the electron temperature increases linearly with energy, as shown in Fig. 2(b). *The electron temperature is then a measure of the power supplied to the 2DEG,* and we may use the temperature profiles to obtain information on the relative energy-loss rates. If $\tau_{\mathrm{LO}} \gg \tau_{ee}$ all the excess energy would be transferred to the 2DEG before LO phonons could be emitted, and T_e would rise monotonically with injection energy. Alternatively, if $\tau_{\mathrm{LO}} \ll \tau_{ee}$, then once $-eV_i$ exceeded 36 meV the injected electron would emit a LO phonon before interacting with the 2DEG, and the energy transferred to the 2DEG per electron would equal ($-eV_i$ mod 36 meV), resulting in a "sawtooth" temperature profile, with T_e falling periodically and abruptly to T_L. Our data shows a nonabrupt fall in T_e after the peaks, indicating some electron-electron scattering before LO emission. Phonon emission while the electron is the barrier was considered; however, the period of acceleration is only ≈ 200 fs and for most of this time its energy is below 36 meV, so most electrons reach the 2DEG with an energy of $-eV_i$.

A simple exponential-decay model was used to determine the characteristic energy-loss time of the injected electrons to the 2DEG. In the time τ_{LO} the (originally monotonic) energy distribution of the injected electrons will be spread downwards, with the peak falling in energy by ΔE, given by

$$\frac{-eV_i - \Delta E}{-eV_i} = \exp(-\tau_{\mathrm{LO}}/\tau_{ee}) \,. \qquad (1)$$

Hot electrons injected with energies just above $\hbar\omega_{\mathrm{LO}}$ will relax to below the LO emission threshold in a time shorter than τ_{LO}, and the remaining energy can only be lost to the 2DEG. When the injection energy reaches $\hbar\omega_{\mathrm{LO}} + \Delta E$, most injected electrons will still be above the threshold after τ_{LO} and the 2DEG will only gain an energy ($-eV_i$ mod 36 meV). We identify the minima in the temperature profile as corresponding to $n\hbar\omega_{\mathrm{LO}} + \Delta E$. This interpretation is strengthened by the insensitivity of the positions of the minima to injection current. Applying Eq. (1) to the first minimum we arrive at a value of $\tau_{ee} \approx 800$ fs, and an energy-relaxation length $l_{ee} \approx 0.4$ μm. These results indicate significantly less scattering than expected for plasmon or single-particle processes,[12] but considerably more than was recently deduced from spectroscopy studies.[4]

For injection energies below 36 meV we can assume that all of the injected power $P_i = V_i I_i$ is supplied to the 2DEG, and that by energy balance, this is equal to the energy-loss rate of the 2DEG to acoustic phonons. The power emitted by 2D electrons to 3D acoustic phonons is predicted to increase linearly with $(T_e - T_L)$ for a nondegenerate 2DEG.[13] Our results in Fig. 2(a) satisfy this dependence qualitatively, and indicate an energy-loss rate

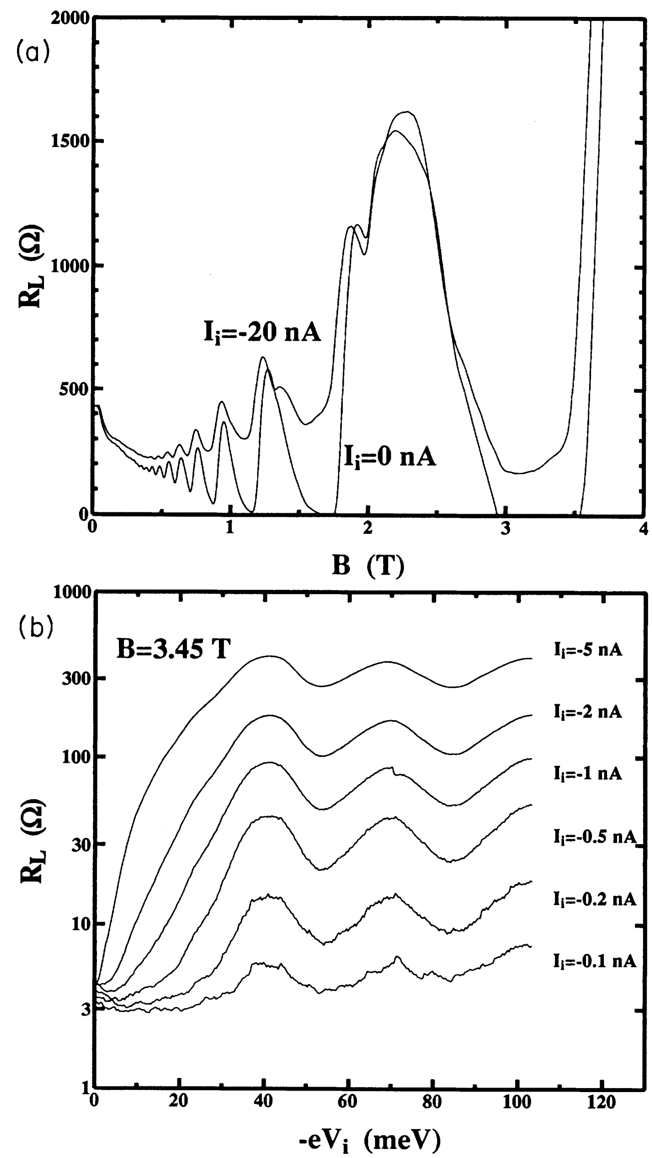

FIG. 3. Longitudinal resistance measurements in region $B1$ at $T_L = 4.2$ K. (a) Shubnikov-de Haas oscillations with an injector gate bias of $V_{Gi} = -400$ mV and $I_i = 0$ and -20 nA, showing the suppression of the zeros with nonzero injection. (b) Variation of R_L with injection energy $-eV_i$, for a magnetic field $B = 3.45$ T ($N_L = 1$) and $I_i = -0.1$, -0.2, -0.5, -1, -2, and -5 nA.

for the 2DEG of $\approx 10^{-14}$ W per electron, giving an energy relaxation time of 20 ns. These rates are similar to those obtained using dc heating,[14] and are in reasonable agreement with theory for deformation-potential scattering using the momentum confinement approximation.[13]

In a magnetic field the four-terminal longitudinal resistance R_L of region $B1$ exhibited the Shubnikov-de Haas effect, as shown in Fig. 3(a) for injection currents of $I_i=0$ and -20 nA. With no injection, we observe zero-resistance minima, however, a nonzero injection current suppresses the Shubnikov-de Haas oscillations at low fields, and destroys the resistance zeros in the quantum Hall regime. This effect was further investigated by setting a constant magnetic field of $B=3.45$ T (corresponding to the $N_L=1$ zero), and varying the injector gate voltage, as in zero field. The longitudinal resistance is plotted against injection energy $-eV_i$ in Fig. 3(b), for a set of different injection currents. For a given constant injection current, R_L remains at zero until the barrier forms at $V_{Gi} \approx -300$ meV, after which the injection energy rises above zero. Dissipationless transport then ceases in the 2DEG and R_L increases from zero to typically hundreds of Ohms, before oscillating with a period 36 meV.

When the Fermi level in the bulk of the 2DEG falls between adjacent Landau levels, all of the current is carried by dissipationless edge states.[15,16] If an electron passes over the injector barrier it can exist in any of the unfilled edge states in region $B1$, at an energy of $-eV_i$ above the Fermi energy. This hot electron can then excite cold edge electrons to higher unoccupied Landau levels, where they will be free to scatter to the opposite edge, decreasing the source-drain transmission probability below unity and breaking down dissipationless transport. Our results in Fig. 2(b) highlight the sensitivity of the resistance zeros to the hot electrons. An injection current of only 100 pA is sufficient to produce a noticeable departure from dissipationless transport, even though this current is 1000 times smaller than the measurement current in region $B1$.

In analogy with the zero magnetic-field data, we find that the longitudinal resistance depends on the excess energy of the injected electrons after LO phonon emission. The concept of electron temperature is no longer obvious here, since the edge-state electrons may not be in thermal equilibrium with the 2DEG in the bulk of the states. We can, however, apply Eq. (1) to the effective energy spread ΔE obtained from Fig. 2(b), to obtain an electron-electron scattering time of $\tau_{ee} \approx 1$ ps. The longitudinal resistance of the 2DEG was also measured in region $B2$, 28 μm away from the injector. No deviation from zero resistance was found, even for injection currents as large as $I_i=20$ nA, indicating that the hot electrons had relaxed into cold edge channels by the time they had reached $B2$.

In summary, we have studied the interaction of hot, laterally injected electrons with a cold 2DEG, by using the resistance of the 2DEG itself as a sensor. We found that the injected electrons caused significant heating of the 2DEG, and disrupted dissipationless transport by edge states in a magnetic field. The dominant energy-loss mechanism for electrons injected above 36 meV was found to be LO phonon emission, in agreement with previous studies. The electron-electron energy-loss time, in both zero and quantizing magnetic fields, was found to be ≈ 1 ps, considerably larger than theoretical predictions.

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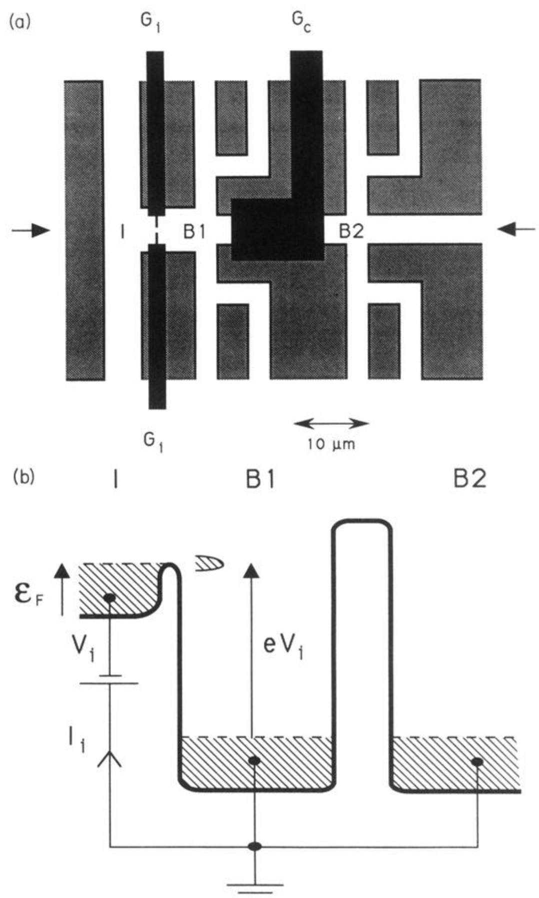

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