Observation of giant oscillations in the phonon-induced conductivity of a GaAs quantum wire

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We have made phonon measurements of the electron-phonon interaction in a long quantum wire using the phonoconductivity technique. The wire was formed in a $GaAs/Al_xGa_{1-x}As$ heterojunction using the split-gate method. It was subjected to a pulsed beam of nonequilibrium phonons generated by a heater on the opposite side of the substrate. The incident phonon pulses caused a transient *increase* in the device conductance. The strength of the detected signal displayed giant oscillations as the wire was narrowed by increasing the negative bias on the gate. We give a qualitative account of these observations in terms of phonon-induced delocalization of weakly localized electron states in the wire. [S0163-1829(97)01715-3]

Electron-phonon interactions play a central role in the behavior of semiconductor devices. Energy relaxation by hot electrons is predominantly through phonon emission with electromagnetic radiation contributing only a very small part. Furthermore, phonon scattering processes dominate the electron mobility in high-quality devices at all but the lowest temperatures. Reducing the dimensionality of the electronic system can greatly affect the carrier-phonon interaction because it imposes restrictions on the available phase space for electron scattering. This means that, at low temperatures, electrons in low-dimensional devices are less efficient at relaxing energy. The interaction of one-dimensional (1D) and quasi-1D electrons with acoustic phonons has been considered in several theoretical papers; see, for example, Refs. 1–5. However, to our knowledge, until now there have been no direct phonon experiments on these systems despite the fact that such experiments provide one of the best ways to obtain detailed information about the electron-phonon interaction in low-dimensional systems; for a review see Ref. 6.

Besides providing information regarding the electron-phonon interaction, phonons can be used to spectroscopically probe the electronic states in low-dimensional devices. The phonoconductivity technique has recently been used to study edge excitations in the integer quantum Hall regime[7] and excitations in the fractional quantum Hall state.[8] In this paper we describe such measurements on electrons in a long quantum wire (by ‘‘long’’ in this case we mean that the channel length exceeds the electron mean free path in the two-dimensional electron gas from which the device is fabricated).

The experimental sample, see Fig. 1, was based on a $GaAs/Al_xGa_{1-x}As$ heterojunction having a two-dimensional electron gas (2DEG) density of 4.4×10^{15} m^{-2} and 4.2-K mobility of 100 $m^2\,V^{-1}\,s^{-1}$ (both after illumination). A 2×1-mm area of 2DEG was defined by etching and 1×0.5-mm Ohmic contacts were fabricated at its ends. Above the center of the device a TiAu split gate was fabricated using electron-beam lithography. The gap in the gate structure was 10 μm long and 400 nm wide. A 100×10-μm, 50-Ω CuNi thin-film heater was vacuum deposited on the polished back face of the wafer, opposite the center of the device. Infrared front-to-back alignment was used to accurately position the heater directly opposite the gate split with their long axes perpendicular. The sample was mounted in a cryostat under liquid helium at 1.3 K. Nonequilibrium phonons were generated by applying short, ≈50 ns, voltage pulses to the heater. In order to prevent spurious responses due to electromagnetic pickup of the heater pulse by the gate, a 1-nF low-impedance chip capacitor was used to decouple the gate at low temperature. The device source and drain were connected via a 1-m length of miniature coaxial cable to a wide-band, high-input impedance preamplifier at room temperature. A constant bias current was passed through the device and phonon-induced changes in the conductivity showed up as a transient voltage signal at the preamplifier. This ‘‘phonoconductivity’’ signal was detected by means of a high-speed digitizer and signal averager.

In Fig. 2 is shown the gate characteristics of the device measured at a drain-source current I_{DS} of 100 nA: at a gate bias voltage V_G of about −0.2 V the areas of 2DEG under the gate metallization are depleted of electrons leaving a narrow channel. As the bias is increased the channel narrows

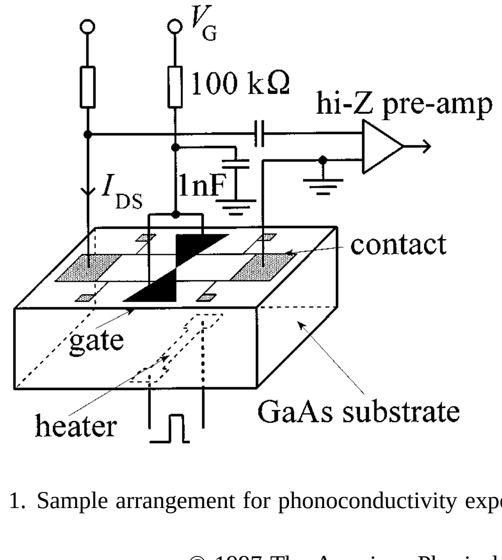

FIG. 1. Sample arrangement for phonoconductivity experiment.

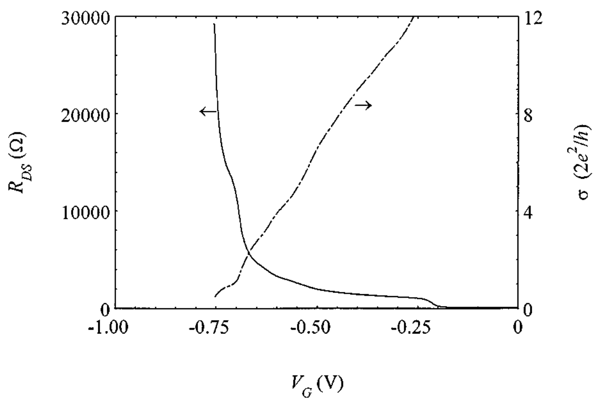

FIG. 2. Two-terminal resistance R_{DS} and conductance σ of the device as a function of gate bias voltage. Temperature=1.3 K; bias current=100 nA.

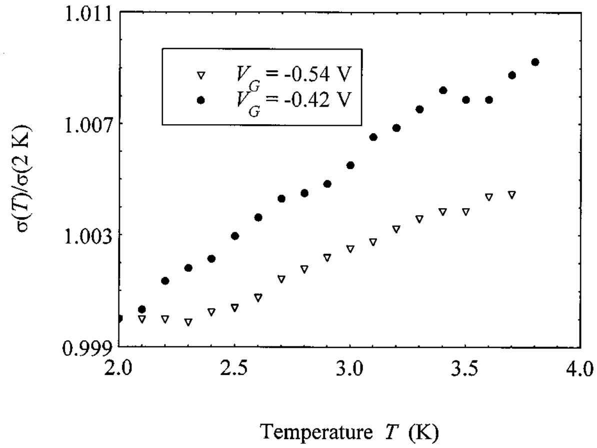

FIG. 4. Dependence of device conductance on equilibrium temperature at two values of gate bias.

further and its resistance increases. An inflection at $R_{\mathrm{DS}}\approx 13$ kΩ is clearly seen; this value corresponds to quasiballistic transport through a region where there is only a single occupied 1D band.

The response of the device to a phonon pulse of 50 ns duration is shown in Fig. 3. In this case, $V_G=-0.5$ V, $I_{\mathrm{DS}}=100$ nA, and the heater excitation power, $P_h=20$ mW corresponding to a heater temperature T_h of 14 K. The initial negative going spike is the residual breakthrough of the excitation pulse. The rising edge of the phonoconductivity signal starts about 80 ns after the start of the excitation pulse and continues for a further 200 ns. This encompasses the time of arrival of both the longitudinal acoustic and transverse acoustic mode ballistic phonons and also some of the phonons scattered in the substrate. The signal peak is followed by a long decay corresponding to the *RC* time constant of the device and the cable connecting it to the preamplifier, $\tau\approx R_{\mathrm{DS}}C_{\mathrm{cable}}=1$ μs.

To minimize the effects of cross-talk from the heater excitation pulse, the signal shown is the difference between the signals obtained with positive and negative device bias. Reversing the bias has the effect of reversing the sign of the phonon signal but not the polarity of the electromagnetic breakthrough. A further check that we were observing the effect of phonons and not pickup was made by reversing the

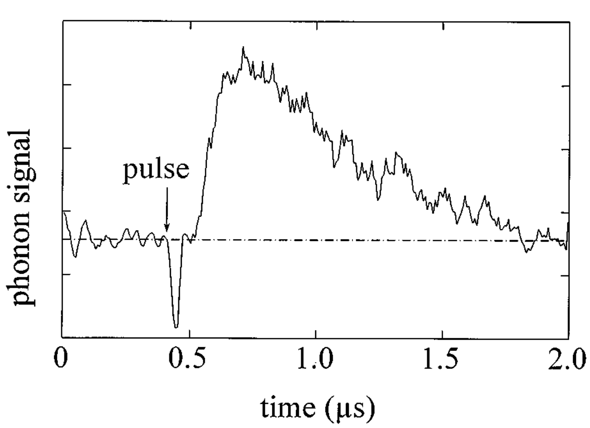

FIG. 3. Time-resolved phonoconductivity signal. The arrow indicates the start of the 50-ns heater pulse.

heater excitation voltage. This reversed the pickup but not the phonon signal, which depends on the power dissipated in the heater. There was no response in the absence of a bias current, and so we discount the possibility that we were observing a thermopower signal as seen in point contact devices by Molenkamp *et al.*[9] The careful positioning of the heater directly opposite the quantum wire ensured that inhomogeneous heating or phonon drag could not occur. Another possible source of the signals that must be discounted is that the nonequilibrium phonons are being thermalized in the GaAs wafer and the quantum wire is simply working as a thermometer measuring substrate temperature changes. We have made steady-state measurements of the wire conductance as a function of equilibrium temperature between 2 and 4 K; see Fig. 4. In this temperature range the conductance increased with increasing temperature, which is consistent with the polarity of the phonon signal. However, the size of the conductance changes we measured were tiny, of order 1 μS K^{-1} at $V_G=-0.54$ V. The amplitude of the phonon signal at $P_h=20$ mW and the same gate bias is 4 μS, i.e., equivalent to an equilibrium temperature change of 4 K. Considering that the energy delivered in a single pulse is a mere 1 nJ, the pulse repetition rate is 100 Hz and the sample is immersed in superfluid liquid helium, it is inconceivable that the substrate temperature could increase by as much as 4 K. In fact, measurements made using a conventional superconducting bolometer instead of the quantum wire as the detector showed temperature changes of the order only 10 mK. So, having eliminated the possibilities of the signal being due to electromagnetic breakthrough or bulk heating, we must conclude that the electron system is absorbing energy directly from the nonequilibrium phonons and, owing to its small heat capacity, it is heated well above the substrate temperature.

It is interesting to note that the polarity of the signal implies an *increase* in conductance (decrease in resistance) of the device when the phonons are incident. This effect is contrary to what would be expected in the case of an ideal ballistic quantum wire with the equilibrium conductance $\sigma=e^2N/\pi\hbar$, where N is the number of occupied subbands. In that case phonons cause additional backscattering of electrons decreasing σ, as was considered quantitatively for ther-

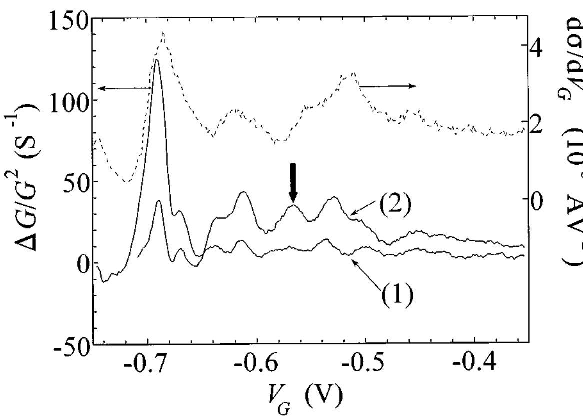

FIG. 5. Phonoconductivity as a function of the gate bias for P_h=3.2 mW (curve 1) and P_h=20 mW (curve 2). Also shown is the derivative of the device conductance as a function of V_G (dashed line). The bold arrow indicates the position of a peak believed to be due to intersubband transitions.

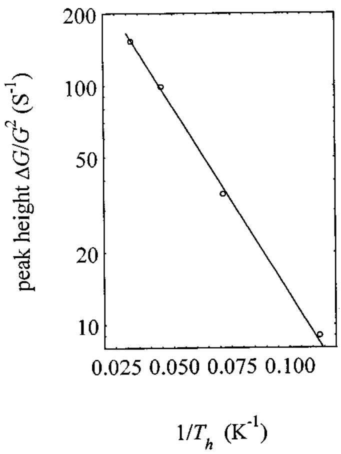

FIG. 6. Intersubband peak height on logarithmic scale as a function of inverse heater temperature.

mal phonons in Ref. 10. The theory in Ref. 10 can be generalized to our case of nonequilibrium phonons but the result is *a priori* evident: that is, the phonons will cause a decrease in the conductivity (increase in resistance) in stark contradiction to our observation.

To account for the observed increase in conductance we must take into account the effects of elastic scattering by impurities and imperfections in the wire. There are two alternative approaches to this problem: we may either think in terms of individual scattering events described by the elastic mean free path l_i,[11] or consider the effects of weak localization characterized by the phase relaxation length L_ϕ.[12,13] The most appropriate approach depends on the relation between l_i, L_ϕ, and the wire length L. For both models it has been shown[14] that additional scattering due to the nonequilibrium phonons will *increase* the wire conductivity. For individual scattering it is caused by the decrease of Coulomb scattering with the increase in electron energy (or effective electron temperature T_e) due to phonon absorption, while in the condition of weak localization, inelastic phonon scattering will cause a partial delocalization of carriers, formally described as a decrease in L_ϕ. In the case of thermal phonons these effects lead to the increase of σ with temperature, which is also observed in our experiments.

Of course, the effects described above can take place only in structures where the influences of elastic scattering and localization are considerable under the particular experimental conditions. This manifests itself in a strong deviation of the low-temperature equilibrium conductivity of the wire as a function of electron concentration from an ideal stepwise one. For our sample this is just the case; see Fig. 2. We also observed negative magnetoresistance and suppression of the phonoconductivity upon application of a weak magnetic field ($B \leqslant 0.1$ T) to the sample. Both of these effects point to weak localization as being the most important effect in this particular sample.

Figure 5 shows the amplitude of the phonoconductivity signal as a function of the gate bias voltage V_G. Also shown for comparison is the derivative of the two-terminal conductance of the device; the peaks indicate the positions of the conductance steps, which are harder to see in a normal conductance plot. The phonoconductivity signal exhibits giant oscillations with increasing negative gate bias (reducing wire width) with peaks occurring when the Fermi energy E_F is close the edge of any 1D band E_N, i.e., at gate voltages corresponding to the weak steps in σ. Its amplitude is expected to be proportional to the number of absorbed phonons. Since the density of states in 1D systems has a strong maximum near the subband edges, the phonon absorption is maximal when E_F approaches E_N. The peak heights increase with the power applied to the heater as should be expected, however, the increase is slower than if the response were purely bolometric (directly proportional to P_h). One possible reason for this is that phonon scattering in the GaAs substrate is attenuating the high-frequency phonons generated at high heater temperatures. However, in the 0.4-mm semi-insulating GaAs wafers used here, the effects of phonon scattering only start to become significant at heater temperatures over 10 K. This is above the heater temperature at which the wire response first deviates from bolometric behavior ($\approx$3 K). The form of the heater power dependence of the signal is consistent with there being a cutoff in the electron-phonon interaction at phonon frequencies above about 200 GHz. Owing to their confinement in the structure, the electrons interact mainly with the low-wavevector (low energy) phonons in the approximately Planckian heater spectrum. The integrated phonon flux in a restricted part of the spectrum well below its peak at $\approx 3k_BT_h/h$ does not increase in direct proportion to P_h.

One peak, indicated by the arrow in Fig. 5, behaved rather differently from the rest. It was seen to increase in amplitude more rapidly in proportion to the others as the heater power was increased. The position of this peak does not appear to correspond to a step in σ, instead it seems to fall between two. We propose that this peak may be due to phonon-induced intersubband electronic transitions. For absorption of near normally incident phonons that we consider here, there is only a small change in the electron momentum along the length of the wire. Hence the interband transitions are close to vertical. The dependence of the peak height on heater temperature should therefore show thermally activated behavior, i.e., $\propto \exp(-\Delta/kT_h)$ for $\Delta > k_BT_h$, where Δ is the subband separation. This is indeed the case as shown in Fig.

6, from which we can determine $\Delta = 3$ meV at $V_G = -0.55$ V (the heater temperature can be determined from P_h using acoustic mismatch theory[15]). Assuming that the confining potential is parabolic in shape, the effective channel width can be determined from $w = (\hbar^2/m^*\Delta)^{1/2}$. We obtain a value of 19 nm, which seems quite reasonable and is close to the value obtained from magnetotransport measurements on the same sample, 25 nm. We can only clearly resolve this interband signal at the one value of V_G because at lower gate biases the system is not sufficiently well quantized, while at higher V_G the signal is strongly suppressed due to its exponential dependence on the square of the channel width.

In summary, we have observed direct phonon absorption by electrons in a quantum wire structure using the phonoconductivity technique. The nonequilibrium phonons caused an increase in the wire conductance and we attribute this to inelastic phonon scattering causing delocalization of weakly localized electron states. Giant oscillations in the phonon absorption with V_G followed the density of states at the Fermi energy. We have also seen phonon-induced intersubband electron transitions and from the temperature dependence of the signal height have determined the effective width of the conducting channel at one value of the gate bias.

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