Quantum Oscillations in the Thermal Conductance of GaAs/AlGaAs Heterostructures

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Magneto-oscillations have, for the first time, been observed in the thermal conductance of GaAs/AlGaAs heterostructures containing two-dimensional electron systems. The oscillations result from a modulation of the thermal-phonon lifetime via coupling to the Landau-quantized electrons confined in quantum wells near the sample surface. These thermal-conductance measurements provide a new avenue for study of both the high-field density of states and the electron-phonon interaction in these semiconductor systems.

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Intense effort has been devoted to the study of electrical transport at high magnetic fields in semiconductor heterostructures containing two-dimensional electron systems (2DES).[1] The thermoelectric properties of these systems have also been studied, if less extensively.[2] By contrast, the thermal conductivity of such layered systems[3] has received far less attention presumably because of the tiny magnitude of the electronic contribution (typically one part in 10^5 of the lattice conduction at 0.5 K). In addition to its direct contribution, however, the 2DES can influence the lattice conduction through the electron-phonon coupling in the system. This coupling, along with the other scattering mechanisms present, determines the mean free path of the phonons in the sample. At high magnetic fields the fully quantized Landau-level structure of the electronic density of states of the 2DES causes dramatic oscillations in the electron-phonon scattering rate and these are reflected in the thermal conductance. Furthermore, since the typical phonon wavelengths $\lambda/2\pi \simeq (100\ \text{Å K})/T$ are comparable with the cyclotron radius $l \simeq (250\ \text{Å T}^{1/2})/B^{1/2}$, the detailed structure of the electron-phonon matrix elements is accessible via the temperature dependence of these oscillations. Thus, thermal-conductance measurements provide a tool for examination of both the 2D density of states and the electron-phonon interaction in this relatively new class of semiconductor structures. In this Letter we report on our studies of the thermal conductance of GaAs/AlGaAs multilayer heterostructures. These measurements show striking magneto-oscillations arising from the coupling of lattice phonons to 2D electron systems.

The modulation-doped GaAs/AlGaAs heterostructures studied here (see Table I) are grown by molecular-beam epitaxy (MBE) on ⟨100⟩-oriented GaAs substrates and consist of alternating AlGaAs barriers and GaAs quantum wells which contain the 2DES. Both samples to be discussed show a well-developed quantum Hall effect at low temperatures. The samples are first cleaved into 1×8-mm^2 bars and then the substrate is chemically thinned with a bromine-methanol etch, until a total thickness of about 50 μm is achieved. Two small carbon resistance thermometers, cut from the same parent resistor, are mounted directly on the sample (substrate side) using GE 7031 varnish. At one end of the sample bar, a Constantan strain-gauge heater is varnished on to the substrate. The other end is indium soldered to a copper block in good thermal contact with the mixing chamber of a dilution refrigerator. Electrical contact to both the thermometers and the heater is made with very fine stainless steel or NbTi wires both of which have a negligible thermal conductance compared to the sample itself. This experimental arrangement is depicted in the inset to Fig. 1. With use of standard ac bridge techniques, the temperature difference between the two thermometers may be measured with high precision.

Figure 1(a) shows the temperature dependence of the thermal conductance of sample 2 at zero magnetic field. The data are reasonably well fitted by a $T^{2.65}$ power law. This is close to the T^3 law expected for boundary

TABLE I. Relevant physical parameters for both multilayer samples.

Sample	Length[a] (mm)	Width (mm)	Thickness (μm)	Number of periods	GaAs well (Å)	AlGaAs barrier[b] (Å)	2D density (cm^{-2})	Low-T mobility (m^2/V·s)
1	1.8	1.0	50	172	170	330	8.9×10^{11}	2.0
2	3.7	1.0	48	50	140	400	5.1×10^{11}	8.0

[a]Thermometer spacing, center to center.
[b]Including Si-doped central region. Al concentration 0.3.

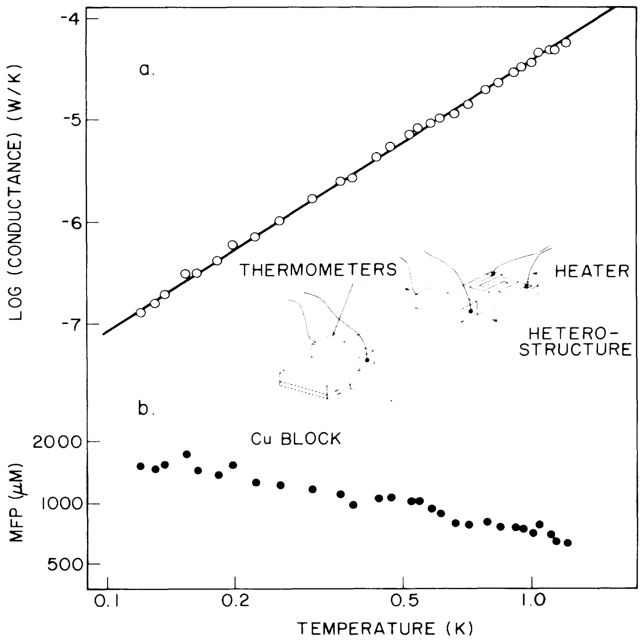

FIG. 1. (a) Thermal conductance at zero magnetic field of sample 2 vs temperature. Solid line represents $T^{2.65}$ power law. (b) Apparent mean free path deduced from $B=0$ conductance data on sample 2.

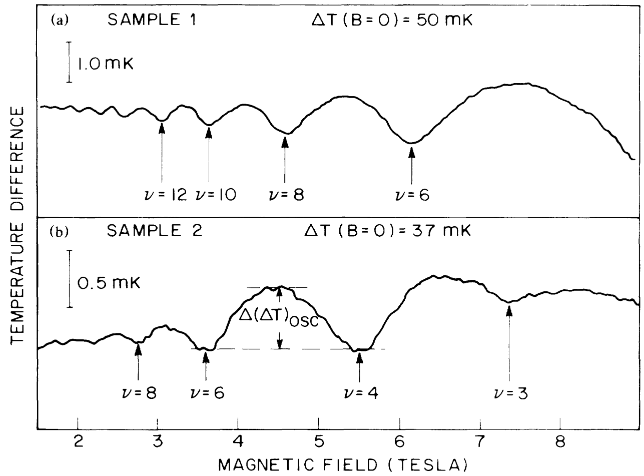

FIG. 2. (a) Thermal-conductance oscillations at 0.7 K for sample 1. Note the large vertical offset. Arrows indicate the "cusps" at which E_F lies in the Landau gap. (b) Thermal-conductance oscillations at 0.35 K for sample 2. The arrow at $\nu=3$ represents E_F in the spin gap of the $j=1$ Landau level.

scattering of phonons. With use of the kinetic formula for the thermal conductivity, $\kappa = C_{ph} c \lambda/3$, where C_{ph} is the lattice specific heat[4] of GaAs and c is an appropriate average phonon velocity,[5] the apparent phonon mean free path λ may be determined from the observed conductance and sample dimensions. Figure 1(b) shows this apparent mean free path (mfp) for sample 2. For the slab geometry employed here, the expected[6] diffuse boundary-scattering mean free path λ_B is 153 μm. The observed mfp much exceeds λ_B and implies a significant degree of specularity in the phonon-surface scattering. Assuming a uniform temperature gradient along the length of the bar, one can estimate[6] the degree of specularity to range from about 75% at 1 K to greater than 90% below 0.2 K. Klitsner and Pohl[7] have shown the uniform-gradient assumption to be unreliable for highly specular surfaces because of the large effects of the (presumably) diffuse regions of surface on which the thermometers and heater are mounted. For sample 2 the temperature jumps, for the same heat flux, of the individual thermometers relative to the copper mounting block are in a ratio of about 2.5:1, whereas geometrically one would expect about 5:1. This is consistent with a larger temperature gradient under the thermometers than between them. There the sample surface is clean and the specularity is very high, probably exceeding the estimates given above.

Application of a magnetic field perpendicular to the 2D electron planes (and the heat-flow direction) causes dramatic oscillations in the thermal conductance. Data for both samples are shown in Fig. 2. Note the large offset of the temperature difference; these oscillations are only a few percent of the total measured temperature drop between the thermometers. In the ideal case, a magnetic field **B** perpendicular to the 2DES splits the electronic spectrum into discrete Landau levels with energies

$$\epsilon_j = (j + \tfrac{1}{2})\hbar\omega_c \pm g\mu_B B. \qquad (1)$$

Here $j=0,1,2,\ldots$ is the Landau-level index, ω_c the cyclotron frequency, and μ_B the Bohr magneton. Since each Landau spin sublevel carries an orbital degeneracy eB/h, even integral values of the filling factor $\nu = N_s/(eB/h)$ imply that the Fermi level E_F lies in the gap between neighboring Landau levels. Odd values of ν place E_F in the much smaller spin gap within a given Landau level. The cusplike minima occurring in the temperature difference can be indexed with a sequence of even integer filling factors which imply a carrier density $N_s = 8.9 \times 10^{11}$ cm^{-2}. As there are no minima at odd values of ν, the spin splittings are not resolved for this sample. These results are consistent with Shubnikov–de Haas measurements on nearby segments of the same MBE wafer. The general shape of these oscillations resembles that expected for the density of states at the Fermi level for a 2D electron system.

The cusplike features are local minima in the temperature difference and therefore correspond to local maxima in the thermal conductance. Since these occur when the Fermi level is in a gap in the electronic density of states, the direct electronic contribution to the thermal conductance should be very small. Furthermore, the oscillation amplitudes remain a roughly fixed fraction of the total temperature drop between thermometers as the overall temperature is varied from around 1.0 to 0.15 K. Since one expects the electronic thermal conductance to be roughly proportional to T, its importance should increase, roughly as T^{-2}, relative to the lattice contribution as the temperature is reduced. These two observations appear to rule out simple parallel electronic and phonon thermal-conductance channels as the source of the oscillations. We propose instead that they result from a modulation of the effective phonon mean free path due to the electron-phonon coupling. This coupling will depend on the density of states in a way similar to the electronic specific heat and should therefore show analogous magneto-oscillations.[8]

For qualitative purposes, we model the multilayer heterostructure sample as a single-crystal bar with a layer of electrons residing near one, highly specular, surface. The presence of the 2D electron sheet will reduce this specularity through the finite probability for phonon absorption (and subsequent thermal reemission) by the electrons. This effective surface "roughness" may be modulated by applying a magnetic field perpendicular to the 2D plane. This causes the electronic density of states (DOS), on which the electron-phonon scattering rate directly depends, to oscillate as the Landau levels pass through the Fermi level, E_F. Reduced scattering occurs when an integral number of Landau levels are filled and E_F is in a gap. In this situation the temperature gradient will be relatively smaller than when the Fermi level is in the middle of a Landau level and the density of states is large. This effect is also observable when E_F resides in the much smaller spin gaps of the DOS as shown in Fig. 2(b) where data from sample 2 are displayed. The higher electron mobility of this sample results in the narrower Landau levels needed to resolve the (high-field) spin doublets. It is interesting to point out that thermal-conductance magneto-oscillations will be present in a bulk three-dimensional electron system as well. With a 2DES, however, the effect is enhanced by the complete quantization of electron states.

To determine the strength of the electron-phonon coupling, we have measured the temperature dependence of the oscillation amplitude for sample 2. This is defined [see Fig. 2(b)] as the maximum change in the observed temperature drop between two adjacent cusplike minima occurring at integral filling factors. To the extent that the DOS is much smaller in the gaps than at the peaks of the Landau levels, this amplitude measures the maximum electron-phonon scattering rate with E_F in the center of a particular Landau level. To see this, we assume the kinetic formula $\kappa = C_{ph}c^2\tau_{ph}/3$ for the conductivity and that the phonon lifetime τ_{ph} may be written as

$$\tau_{ph}^{-1} = \tau_0^{-1} + \tau_{eph}^{-1}(B), \quad (2)$$

where $\tau_{eph}^{-1}(B)$ is the electron-phonon scattering rate at magnetic field B and τ_0^{-1} is some residual, magnetic-field-independent phonon scattering rate. With the assumption of a uniform temperature gradient in the region between the thermometers and an electron-phonon scattering rate τ_{eph}^{-1} near zero when E_F is in the Landau gap, the amplitude of the oscillation in the measured temperature difference as the magnetic field is swept from one minima to the next is approximately

$$\Delta(\Delta T)_{osc} = \{3QL/(AC_{ph}c^2)\}(\tau_{eph}^{-1})_j, \quad (3)$$

where $(\tau_{eph}^{-1})_j$ is the maximum electron-phonon scattering rate with E_F in the jth Landau level, Q is the applied heat flux, and A and L are the sample cross-sectional area and thermometer spacing, respectively. We have assumed that only intra-Landau-level transitions are involved. This is an excellent approximation at the temperatures and fields used in the experiment since the Landau splittings greatly exceed the typical phonon ener- gies. Figure 3 shows the temperature dependence of $\Delta(\Delta T)_{osc}/Q$ for sample 2. These data represent the scattering rate at 4.5 T with E_F in the middle of the $j=2$ Landau level. The closely T^{-3} dependence of the data implies that, over this temperature range at least, $(\tau_{eph}^{-1})_2$ is essentially temperature independent since the lattice specific heat is proportional to T^3. This analysis of the oscillation amplitude yields $\tau_{eph} \simeq 20$ μs or, equivalently, a mean free path for electron-phonon scattering of approximately 7 cm. Given the expected[6] diffuse boundary-scattering mfp of 153 μm and that sample 2 has fifty layers of electrons, the probability of single-phonon absorption by any one of the 2D electron layers at 4.5 T is roughly 4×10^{-5}. Although not yet studied in as great detail, the oscillations at other mag-

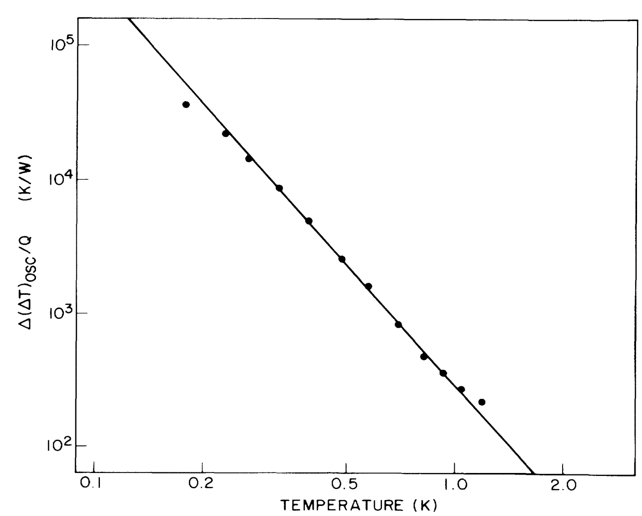

FIG. 3. Temperature dependence of $\Delta(\Delta T)_{osc}$ for sample 2 at 4.5 T in the $j=2$ Landau level. Solid line is a T^{-3} power law.

netic fields show broadly similar results.

The theoretical interpretation of these results is complicated by the presence of several distinct effects. Predicting the temperature dependence of $(\tau_{eph}^{-1})_j$, for example, requires consideration of both piezoelectric and deformation-potential scattering channels, screening, the wave-vector dependence of the matrix elements, and some knowledge of the broadening of the Landau levels. Analytical calculations of phonon lifetimes in semiconductor heterostructures containing 2D electron systems have not yet been performed, although considerable work has been done on the related problem of the acoustic-phonon–scattering limit to the zero-field mobility.[9] The presence of a large magnetic field not only produces a highly structural DOS and hence the thermal conductance oscillations, but also injects a new length scale into the problem, the cyclotron radius $l=(\hbar/eB)^{1/2}$. It is the product $q_{\parallel}l$, with $q_{\parallel}$ the in-plane component of the phonon momentum, that determines the electron-phonon matrix elements. In addition to an overall Gaussian dependence on $q_{\parallel}l$, the matrix elements contain polynomial factors which reflect the nodes in the Landau-level wave functions. In these experiments $q_{\parallel}l \simeq (2.5\ \mathrm{T}^{1/2})/\sqrt{B}$ and can therefore be scanned, via T or B, through the important range around $q_{\parallel}l \simeq 1$. This will show up directly in the temperature dependence of $(\tau_{eph}^{-1})_j$. Systematic variations of this temperature dependence between different Landau levels should reflect the differences in the structure of the wave functions. Calculations and additional experiments to explore these ideas are currently under way.[10]

In summary, we have measured the thermal conductance of multilayer GaAs/AlGaAs heterostructures containing two-dimensional electron systems. Magneto-oscillations of the conductance have been observed arising from the scattering of the phonons carrying the heat with the electrons residing near the sample surface. These oscillations provide a new tool for studying the electron-phonon coupling as well as the density of states in these structures.

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