Observation of a Bloch-Grüneisen regime in two-dimensional electron transport

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(Received 18 September 1989)

We have observed a rapid decrease in the rate by which two-dimensional electrons in very high-mobility ($\mu \approx 10^7$ cm^2/V sec) GaAs-Al$_x$Ga$_{1-x}$As heterostructures are scattered by acoustic phonons as the temperature approaches $T = 0$. This precipitous drop in scattering rate is caused by strong phase-space restrictions for electron-phonon scattering. The characteristic temperature for this transition is not the Debye temperature of the GaAs host material, but the temperature at which phonons of twice the Fermi wave vector cease to be thermally excited.

The temperature dependence of the resistivity of a pure metal undergoes a smooth transition from a linear T dependence to a T^5 dependence as the temperature drops below the Debye temperature, Θ_D.[1] This transition reflects a change in the character of electron scattering by acoustic lattice vibrations. For temperatures $T \gg \Theta_D$, the motions of the ions is essentially independent and electron scattering becomes proportional to the square of the oscillation amplitude, which is linear in T. At temperatures $T \ll \Theta_D$, the correlation of the ionic motion can no longer be neglected and a description in terms of interacting electron and phonon waves is required. The ensuing phase-space restriction strongly reduces the possibilities for electron scattering which leads to the precipitous drop of the resistivity for $T \ll \Theta_D$.

The characteristic temperature scale for this transition is Θ_D because of the relative radius k_D of the Debye sphere compared to a typical k_F of the Fermi surface. In common three-dimensional (3D) metals $2k_F > k_D$ and acoustic phonons of all conceivable energies can contribute to the scattering of electrons. Yet, when the temperature drops below Θ_D, the higher-energy phonon modes are no longer thermally excited and they cease successively to contribute to the resistivity. This transition has been formulated analytically and is known as the Bloch-Grüneisen (B-G) theory for the resistivity of metals.[2] In a more general sense the temperature range in which electron-phonon scattering processes in any conductor are dominated by restraining k-space selection rules may be termed a B-G regime.

We have observed such a B-G regime of a different kind in the low-temperature transport of 2D electron systems in GaAs-Al$_x$Ga$_{1-x}$As heterostructures. The characteristic transition temperature is not related to Θ_D (~ 350 K in GaAs). In these low-density ($\sim 10^{11}$ cm^{-2}) 2D materials, the radius k_D of the Debye sphere greatly exceeds $2k_F$ and only a small fraction of acoustic phonons having wave vector $k_p \lesssim 2k_F$ can interact with the degenerate electron system[3] at any temperature. Therefore, the transition does not occur at Θ_D but rather at a temperature when phonons with wave vector $k_p \sim 2k_F$ cease to be thermally excited. Its characteristic temperature T_c is related to the sound velocity s according to $k_B T_c \approx 2k_F \hbar s$ which amounts to only a few K.

Our experiments were performed on 2D electron sys-

tems in molecular-beam epitaxy grown GaAs-(Al$_x$Ga$_{1-x}$)As heterostructures of unprecedent carrier mobility.[4] Sample A had an electron density of $n = 2.2 \times 10^{11}$ cm^{-2} with a peak mobility of 11.7×10^6 cm^2/V sec while sample B contained $n = 1.7 \times 10^{11}$ cm^{-2} electrons with a peak mobility of 7.2×10^6 cm^2/V sec. Those persistent values were achieved after a standard low-temperature illumination with visible light.[4] The samples were mounted with vacuum grease on a solid copper block equipped with a calibrated Ge thermometer (0.1–9 K) and a calibrated Si thermometer (4–300 K) in a charcoal-pumped ^{3}He refrigerator capable of reaching ~ 0.3 K. Between ~ 0.3 and ~ 2 K, the samples were immersed in liquid ^{3}He. Above ~ 2 K the sample resided in ^{3}He gas heated by the charcoal pump and by an extended copper tube surrounding the sample holder. The samples had the shape of a 4×4-mm square with small indium contacts diffused into the corners. The carrier density was determined with standard Hall measurements at base temperature and at our highest temperature of 40 K. The results of these Hall measurements and *in situ* low-temperature Shubnikov–de Haas data all agreed to within 5%. The resistivity of the samples was determined in the standard van der Pauw geometry using lock-in techniques and current values below 1 μA. For this current level no electron heating could be detected at base temperature. Data taken with 100 nA coincided with those at 1 μA current level.

Data were taken in rapid succession (~ 5 sec) while the system slowly drifted in temperature over the course of several hours. Our experiments focused on the temperature range below 40 K where acoustic-phonon scattering dominates and optical-phonon scattering is negligible. Four independent van der Pauw measurements, each with 90° rotation of the contact configuration, were taken successively and then averaged. Rather than determining the resistivity ρ of the specimens, we derived their mobility $\mu = (ne\rho)^{-1}$. This is the quantity which is generally referred to in 2D electron transport. The results of such measurements for sample A are shown as the lowest traces in Fig. 1. In the following we will analyze these data in terms of different electron scattering mechanisms.

There exists extended literature on electron-phonon scattering in 2D systems in GaAs-(Al$_x$Ga$_{1-x}$)As heterostructures.[5-19] For electronic transport limited by acous-
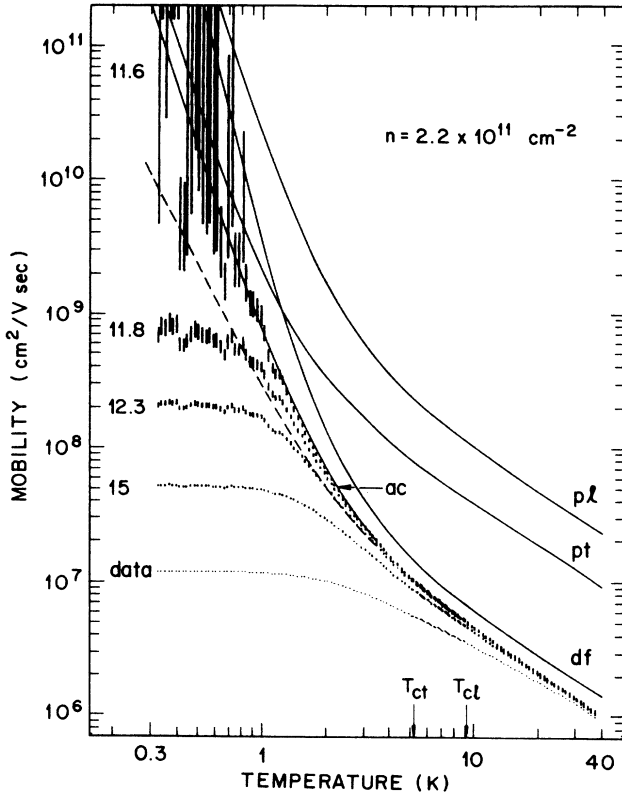
FIG. 1. Temperature dependence of mobility for 2D electron system in sample A. The lowest trace represents the experimental data points. Traces identified as 15–11.6 result from subtraction of all T-independent scattering contributions μ_i using $\mu_{ac}^{-1} = \mu_{data}^{-1} - \mu_i^{-1}$. The numbers represent the value of μ_i in 10^6 (cm^2/V sec). The full lines are the result of a numerical integration of Eq. (1) for piezoelectric longitudinal (pl), piezoelectric transverse (pt), and deformation-potential (df, $D = 11.5$ eV) acoustic-phonon scattering. The trace identified as "ac" is the sum $\mu_{ac}^{-1} = \mu_{df}^{-1} + 2\mu_{pt}^{-1} + \mu_{pl}^{-1}$ of all these acoustic-phonon contributions counting "pt" twice for two transverse phonon branches. The dashed trace is the same as ac but using a deformation potential $D = 6$ eV and neglecting screening [$S = 1$ in Eq. (1)]. At high temperatures ($T \gtrsim 5$ K) the ac trace and the dashed trace coincide with one another and with the data. They have been truncated for clarity. T_{ct} and T_{cl} are the onset temperatures for the B-G regime for transverse (t) and longitudinal (l) phonons.

tic phonons, the existing theories almost exclusively address the high-temperature regime where all potentially scattering phonons are thermally occupied. In this limit, the equivalent to the high-temperature regime of the B-G theory, the resistivity is linear in T leading to a T^{-1} dependence for the mobility. While there is some uncertainty as to the correct value for at least one of the parameters (the deformation potential D for GaAs), there is general agreement as to the T dependence. The only other processes contributing to electron scattering at those

temperatures are interactions with imperfections of the host material. They dominate at the lowest temperatures and arise from several sources: remote ionized impurities from the modulation-doping process, residual neutral and ionized impurities in the host, interface roughness at the GaAs-(Al_xGa_{1-x})As boundary, and randomness of the (Al_xGa_{1-x})As ternary compound. For ultrahigh mobility material such as shown in Fig. 1, little is known as to the relative contribution from these different scattering sources. However, it is clear that all these processes are temperature independent in a truly degenerate carrier system. We examined the onset of T dependence for such scattering processes in our 2D systems using an approximate expression given in Ref. 20 and found its effect to be inconsequential for our analysis.

Assuming Mathiessen's rule, the total mobility μ_{tot} within our temperature range is

$$[\mu_{tot}(T)]^{-1} = [\mu_{ac}(T)]^{-1} + \mu_i^{-1}.$$

With the mobility limit due to imperfections $\mu_i = \text{const} = C$, the total acoustic-phonon mobility μ_{ac} can be determined by subtracting a constant, although unknown, quantity from μ_{tot}^{-1}; i.e., $\mu_{ac}(T) = (\mu_{tot}^{-1} - C^{-1})^{-1}$. Since μ_{tot} at low T is vastly dominated by $\mu_i = C$, the correct value of C is very close to $\mu_{tot}(T_{min} \sim 0.3$ K). The actual determination of C is facilitated by two guiding principles: (i) within noise limits C cannot be smaller than μ_{tot} at any T and, (ii) if a subtraction yields a largely T-independent mobility at low temperatures, C requires further reduction. Figure 1 shows the result of such subtractions for sample A on a double logarithmic scale for different C values and a given uncertainty in the values of μ_{tot}. The top trace labeled 11.6 represents our optimum choice for C. A further decrease in the value of C by as little as a few 10^4 cm^2/V sec creates a majority of unrealistic negative values for μ_{ac} in the low-temperature regime.

The residual noise level in $\mu_{tot}(T)$ limits the precision to which one can attain a full representation of $\mu_{ac}(T)$ at these lowest temperatures. However, independent of any such uncertainties, as the temperature falls below $T \sim 5$ K, we observe a rapid increase of $\mu_{ac}(T)$ by several orders of magnitude, far beyond the high-temperature T^{-1} dependence. This steep rise in the phonon limited mobility represents the transition to a B-G regime in the electron transport of a 2D system. The characteristic temperatures for the onset of the transition are, indeed, in the range of $T_c = 2k_F \hbar s / k_B$ which assume values $T_{cl} = 9.1$ K, $T_{ct} = 5.3$ K for sample A where l and t indicate longitudinal and transverse sound velocities.[14]

The acoustic-phonon contribution to the low-temperature mobility of 2D systems has been addressed only briefly in the past.[15] Price has sketched the algebra required in the B-G regime. The mobility $\mu = e\tau/m^*$ is derived by evaluating the scattering rate τ_j^{-1} for all different phonon processes, j. In its general form the expression for τ_j^{-1} in 2D is[7,14,15]

$$\tau_j^{-1} = \frac{2\pi}{\hbar} \frac{1}{(2\pi)^2} \int dk^2 \int dq (1 - \cos\phi) S^2(Q) |I(q)|^2 |C_j|^2 \frac{1}{k_B T} \{Nf(E)[1 - f(E+\varepsilon)] + (N+1)f(E)[1 - f(E-\varepsilon)]\}.$$

(1)

$S(Q)$ represents a two-dimensional screening function[15] for a phonon with in-plane (x,y) wave vector Q. $I(q)$ is a form factor depending on the z component of the phonon which reflects the finite thickness of the 2D wave function usually parametrized[21] as

$$\rho(z) = \tfrac{1}{2}\beta^3 z^2 \exp(-\beta z).$$ (2)

$|C_j|^2$ is the scattering function for deformation-potential scattering $|C_{df}|^2$, longitudinal-piezoelectric $|C_{pl}|^2$ and transverse-piezoelectric scattering $|C_{pt}|^2$. $N = [\exp(\varepsilon/k_B T) - 1]^{-1}$ represents the Bose-Einstein distribution for phonons of energy ε and $f(E)$ is the Fermi distribution for

electrons of energy E. The integration has to be performed over all 2D electron k states weighted by the $(1 - \cos\phi)$ term which reflects the angular change in the electron momentum for each scattering event and over all perpendicular components of the phonon wave vector. The B-G transition is a consequence of the expression in square brackets. It strongly reduces the scattering rate at low temperatures when, for phonon absorption (first term), the phonon population dwindles and phonon emission (second term) becomes prohibited by a sharp Fermi distribution. For a degenerate system $(k_B T \ll E_F)$, all scattering events take place in a thin shell around the Fermi circle and Eq. (1) simplifies[15] to

$$\tau_j^{-1} = \frac{m^*}{\hbar^3 k_F}\frac{4}{(2\pi)^2}\int_0^\pi k_F d\phi \int_0^\infty dq(1 - \cos\phi)S^2(Q)|I(q)|^2|C_j|^2 G(\varepsilon),$$ (3)

$$G(\varepsilon) = 2\frac{\varepsilon}{k_B T}N(N+1),$$

where the effective mass m^* enters through the density of states at E_F. At high temperature $G(\varepsilon) \approx 2(k_B T/\varepsilon)$ and the integration simplifies considerably. The T dependence of $G(\varepsilon)$ carries through leading to the well-documented T^{-1} dependence of μ for acoustic phonon scattering in the high-temperature limit. The explicit dependences are given by several authors.[10-15] In the low-temperature limit using Eq. (3) Price has derived[15] temperature dependences as T^{-7} for deformation potential scattering and T^{-5} for piezoelectric scattering. The prefactors, relevant for the crossover from deformation potential limited to piezoelectric limited transport can also be derived analytically.[22]

For a comparison with our experimental results over the whole temperature range, we have numerically integrated Eq. (3) and reproduce the results in Fig. 1. We show the total theoretical acoustic-phonon limited mobility $\mu_{ac} = (\mu_{df}^{-1} + \mu_{pl}^{-1} + 2\mu_{pt}^{-1})^{-1}$ and its components using literature values for GaAs (Ref. 14) and a deformation potential of $D = 11.5$ eV. This model for the B-G regime in 2D systems agrees quite well with the experimental data over the whole temperature range. At high temperatures it approaches the expected T^{-1} dependence while at low temperatures it clearly reproduces the steep rise in the experimental results. A detailed comparison between experiment and theory at the lowest temperatures is somewhat complicated by the increasing noise level in the data and a residual ambiguity in the exact level of scattering from imperfections. However, from a sequence of theoretical fits to the data with slightly different values of C, we conclude that a purely deformation-potential limited low-temperature mobility with a T^{-7} dependence is not consistent with our results. The smaller negative exponent provided by the T^{-5} dependence of the piezoelectric interaction is required as also seen in low-T electron relaxation experiments.[23] Furthermore, only a combination of longitudinal and transverse phonons having different sound velocities and, therefore, different onset temperatures T_c is able to provide a good description of the data in the temperature range $1 \text{ K} \lesssim T \lesssim 8 \text{ K}$.

Our low-temperature data and their analysis also shed some light on a recent controversy in the literature.[19,20,24] It has been argued that high-temperature mobility data on 2D electron systems in GaAs can be explained within two competing theoretical schemes. Either one uses the traditional value for the deformation potential of $D \sim 6$ eV and neglects screening $[S(Q) = 1$ in Eq. (3)] completely[20] or one includes screening in an approximate two-dimensional analog of the Debye theory and adopts[14] $D \approx 13$ eV. Since there is independent recent evidence[18,19] for such an elevated value for D in GaAs, both models have their merits.

On the basis of mobility data in the high-T acoustic limit alone, one cannot differentiate between both models. Our data which extend into the B-G regime favor the model which requires the larger D value and includes screening. For comparison, we show in Fig. 1 the results for μ_{ac} using again Eq. (3) for all acoustic phonon processes but choosing $S = 1$ and $D = 6$ eV. At high T, this curve is indistinguishable from the result of the model we presented earlier. However, at low temperatures theory and experiments become incompatible since the neglect of screening has raised all exponents in $\mu_{ac}(T)$ by T^2. It appears, therefore, that theories on the scattering of 2D electrons by acoustic phonons in GaAs cannot neglect screening. Once screening is adopted an elevated value for D is required to describe our data. Whether such an enhanced deformation potential is unique to GaAs-Al$_x$Ga$_{1-x}$As heterostructures, or whether it also indicates a value more appropriate for bulk GaAs than the traditional $D \approx 7$ eV, remains unclear.[19]

Even within our experiments there remains some uncertainty as to the D value required to fit the data. This becomes evident when analyzing the data from sample B (not shown). It reproduces all features seen in sample A and the theoretical fit to the data is of the same quality as the fit for sample A. However, a deformation potential of $D = 13.5$ eV is required to fit the high-temperature data in the presence of screening and $D = 7$ eV when screening is neglected. The slight discrepancy between samples A and

B may actually derive from an insufficient knowledge of the z extent of the 2D electronic wave function[21] which enters Eq. (3) via $I(q)$ and linearly affects the high-T mobility.[14]

In conclusion we have observed a B-G regime in the two-dimensional electron scattering by acoustic phonons in GaAs-Al$_x$Ga$_{1-x}$As heterostructures. The transition temperatures of a few K arise from strong phase space limitations for electron-phonon scattering as phonons of wave vector $2k_F$ cease to be thermally excited. Theoreti-cal fits to our data indicate that a value $D \sim 11-13.5$ eV is required for the deformation-potential and that the effects of screening on the electron-phonon interaction need to be considered.

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$$\tau_{df}^{-1} = gD^2(\hbar s_l)^{-6}(3/2^7\pi)7!\zeta(7)(k_B T)^7 ,$$

$$\tau_{pl}^{-1} = g(eh_{14})^2(\hbar s_l)^{-4}(63/2^{13}\pi)5!\zeta(5)(k_B T)^5 ,$$

$$\tau_{pt}^{-1} = g(eh_{14})^2(s_l/s_t)^2(\hbar s_t)^{-4}$$

$$\times (3 + \tfrac{63}{8})/(2^{11}\pi)5!\zeta(5)(k_B T)^5 ,$$

$$g^{-1} = \rho s_l^2 k_F^3 m^* e^4/\epsilon^2 .$$

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