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Effect of disorder on phonon emissions from a two-dimensional electron gas in $GaAs/Al_xGa_{1-x}As$ heterostructures

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We report heating measurements in $GaAs/Al_xGa_{1-x}As$ heterostructures with tunable mobilities in the temperature range 100–710 mK. We find a power-law dependence on temperature for the phonon emission power $P=dT^b$. With decreasing mobility, the exponent b changes systematically from 5.15 ± 0.10 to 3.80 ± 0.02; the prefactor d increases by more than an order of magnitude. These results explicitly corroborate the prediction by Girvin [in Phys. Rev. Lett. **77**, 1143 (1996)] that the phonon emission changes character due to a disorder induced change in the screening from static to dynamic. [S0163-1829(97)51228-8]

The temperature (T) dependence of the electron-phonon scattering rate ($1/\tau_{e\text{-ph}}$) of a clean metal follows a T^α power law with $\alpha=3$ at temperatures below the Debye temperature.[1] The power law T^3 arises from the phonon phase space and the statically screened phonon matrix element. Since both the mean energy per phonon and the number of electrons which are sufficiently thermally excited to emit a phonon are proportional to T, this gives rise to a $T^{\alpha+2}=T^5$ dependence in the phonon emission power P in electron heating experiments below 1 K.[2] However, our understanding in disordered metals is limited due to widely varied results.[3–5]

In a clean two-dimensional electron gas (2DEG) with a density n trapped at the interface of a $GaAs/Al_xGa_{1-x}As$ heterojunction, Price[6] has obtained

$$P(W/m^2)=1.65\times10^6[T(\mathrm{K})]^5/\sqrt{n(m^{-2})} \qquad (1)$$

by taking into account the *statically screened* piezoelectric coupled phonon matrix element. This T^5 power law arises from the same physics as that in the case of clean metal and has been observed in a multi-quantum-well sample below 1 K (Ref. 7) and in heterostructures.[8,9]

Recently, in an attempt to explain the result $P\sim T^4$ observed in between quantum Hall plateaus in a 2DEG in high magnetic fields (B), Girvin predicted that the phonon emission power in a dirty sample is significantly enhanced.[9] This is due to the fact that electrons in a disordered medium cannot move fast enough to respond adiabatically to the electric field generated by phonons, and so the static screening approximation used in previous theoretical studies fails. The power law $P\sim T^4$ was derived by taking into account *dynamic screening* in dirty samples. To connect this theoretical prediction to the experiment, one needs to assume that the effective disorder seen by the 2DEG increases in high B, an assumption not intuitively clear (although the longitudinal conductivity σ_{xx} does reduce markedly in high B). Moreover, since it is also possible to explain the result of $P\sim T^4$ in between quantum Hall plateaus in terms of quantum critical dynamics with dynamic scaling exponent $z=1$ without involving electron-phonon interactions,[9] an explicit demonstration of the effect of disorder on phonon emission in a 2DEG is therefore lacking.

In this paper, we report heating measurements at $B=0$ in two $GaAs/Al_xGa_{1-x}As$ heterostructures in which the disorder is changed by varying the electron mobilities. The samples were grown using the molecular beam epitaxy (MBE) technique. The distance between the 2 DEG and the top surface is 650 Å. Two samples were mesa-etched into a standard Hall bar geometry with a channel width of 300 μm and a distance of 780 μm between the voltage probes. Ohmic contacts were made by alloying indium in ambient forming gas. The resistance of the samples was measured using low-frequency ac lock-in techniques. However, we have also checked that the results presented in this paper are the same for dc measurements. A dilution refrigerator was used for study in the temperature range $100<T<710$ mK.

Figure 1 shows the mobility μ as a function of n for the two samples studied. The density is measured by the low B Hall effect and the mobility is calculated by $\mu=1/(\rho ne)$ where ρ is the resistivity measured at $B=0$. All symbols represent data points measured at $T=300$ mK. The first sample (solid circles) has no free carriers when cooled down in complete darkness. We use a red light-emitting diode mounted on top of the sample to induce carriers into the 2DEG at low temperatures via the persistent photoconductivity effect.[10] The vertical bars in the low n region represent the mobility range for $100<T<710$ mK at a given n with the top side of the bar being the high T. In the high n regime, the mobility change within the same T range is smaller than the size of the symbol. The squares are data points for the second sample whose n is changed by applying negative voltage to a metallic gate located 350 μm away in the back of the sample. This sample has $n=1.6\times10^{11}$ cm^{-2} and $\mu=44\,800$ cm^2/V s at $T=300$ mK when cooled in the dark. The increasing μ with increasing n in both samples is due to increasing screening.[11] We see that our samples cover the μ range from 2200 to 44 800 cm^2/V s. We also notice that, unlike the Si sample in Ref. 12, the resistance in our samples always increases with decreasing T even at the highest n that we studied.

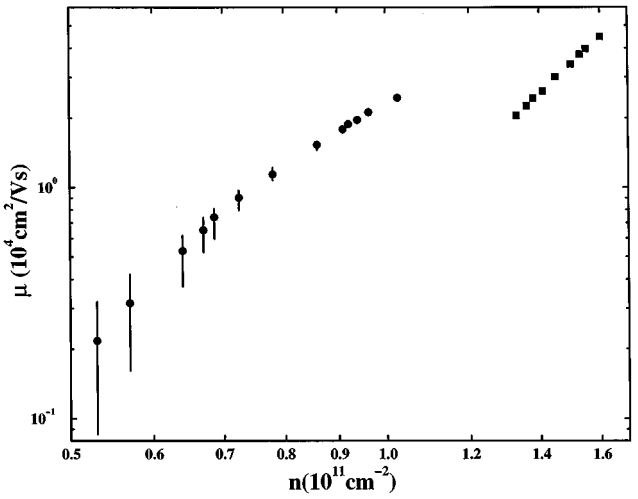

FIG. 1. Electron mobility μ at $T=300$ mK as a function of density n for two samples, the circles and squares. The vertical bars represent the μ range for $100<T<710$ mK. The density is changed by illuminating the sample with a red light-emitting diode (circles), and by applying a backgate voltage (squares).

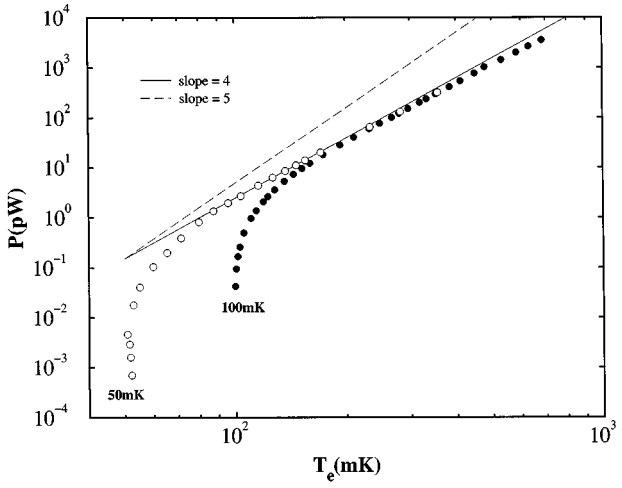

FIG. 2. The input Joule heating power $P=I^2R$ as a function of the effective temperature T_e at two lattice temperatures 50 and 100 mK for $n=0.53\times10^{11}$ cm^{-2}. The solid and dashed reference lines have a slope of 4 and 5, respectively.

At zero B, the disorder of the sample is characterized by the mobility. Theoretically, a sample is considered disordered if the electron mean free path (l_e) is shorter than the inverse of the thermal phonon wave vector $q=k_BT/\hbar s$ (i.e., $ql_e<1$), where s is the sound velocity and k_B the Boltzmann constant. In GaAs/Al_xGa_{1-x}As heterostructures, piezoelectric coupling to transverse phonons [$s=3070$ m/s (Ref. 14)] dominates the electron-scattering process when $T<1$ K.[13] For the highest n in Fig. 1, we find $1.26<ql_e<9.03$ for $100<T<710$ mK. On the other hand, $0.014<ql_e<0.36$ for the lowest n. Our samples, therefore, can change systematically from the clean limit to dirty limit in the T range studied, by tuning n.

We performed electron heating measurements for each n in Fig. 1. Let us take the case of the lowest $n=0.53\times10^{11}$ cm^{-2} to illustrate what we did. First, the T dependence of the resistance R between two voltage probes is measured with an excitation current of $I=0.6$ nA. This current is chosen so that there is no detectable heating in the sample. Second, we measure R as a function of I at a low fixed lattice temperature T_L. The effect of large I is to heat the 2DEG above T_L. The existence of an effective electron temperature T_e is expected since electron-electron scattering is so frequent in a degenerate semiconductor system that it keeps the system under quasi-equilibrium. Operationally, we use the T dependence of R as a thermometer with which the I dependence of R is compared. This is a standard method of deducing T_e of the heated 2DEG at a given I.[7]

In Fig. 2, we plot the power input $P=I^2R$ as a function of T_e on a log-log scale for the lowest n. The open and closed symbols are obtained at $T_L=50$ and 100 mK, respectively. We would like to mention that at other densities we only measured the data at $T_L=100$ mK. The data points merge into a single linear relation when P is larger than a characteristic value at each T_L. The solid and dashed lines, which have a slope of 4 and 5, respectively, are drawn for reference. We see that P has a power-law dependence on T with the exponent being close to 4.

By fitting the power-law $P=dT^b$ to all data points for $T_e>2T_L$, we can obtain the prefactor d and the exponent b. Figure 3 shows the exponent b as a function of μ for each n in Fig. 1. Each value is represented by a rectangle whose length is the μ range within the experimental T range, and

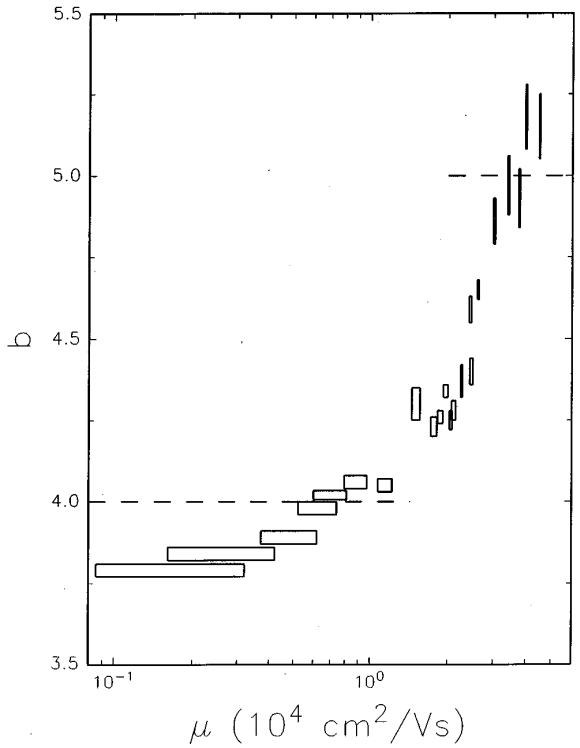

FIG. 3. The T exponent b in $P=dT^b$ as a function of mobility μ. The data are plotted as rectangles, whose length is the μ range for $100<T<710$ mK, and whose height is the uncertainty arising from the fitting procedure. The dashed lines at $b=4$ and 5 are drawn for reference.

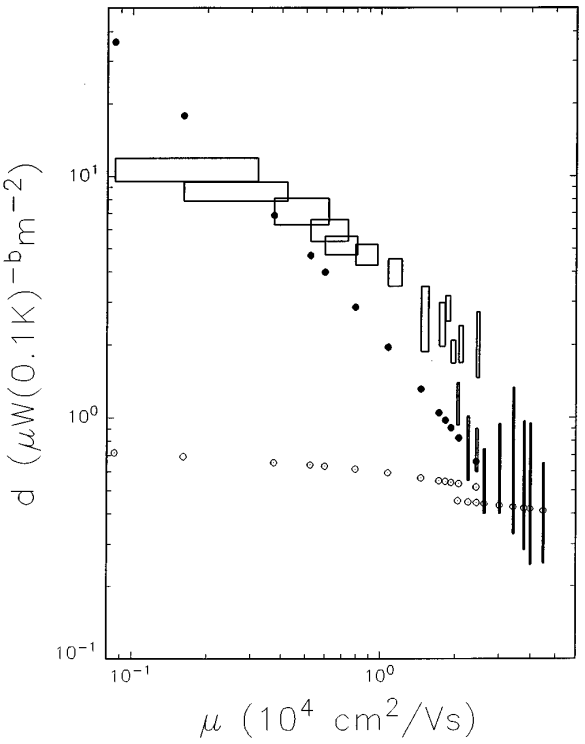

FIG. 4. The prefactor d in $P=dT^b$ as a function of mobility μ. The unit is chosen as such that d is equivalent to P at 100 mK. The data are plotted as rectangles, whose length is the μ range for $100<T<710$ mK, and whose height is the uncertainty arising from the fitting procedure. The open and closed circles are calculated from Eq. (1) and Eq. (2) at $T=100$ mK, respectively.

whose height is the uncertainty in b arising from the fitting procedure. On the high n side, the uncertainty in b is bigger since the T dependence of R is weaker, leading to larger uncertainty in deducing T_e. Within our experimental error, b systematically decreases from 5.15 ± 0.10 at high mobility to 3.80 ± 0.02 at low mobility. For comparison, we draw a horizontal dashed line at $b=5$ which is expected in a clean sample, and at $b=4$ which is the result observed in between quantum Hall plateaus at high B and expected in dirty samples at $B=0$.

The change of b from ~5 to ~4 can be viewed as the change from 3 to 2 in the T exponent α for $1/\tau_{e\text{-ph}}$. One may be tempted to attribute this to a reduction in the effective dimensionality of the phonons.[15,16] However, this requires large acoustic mismatch between the thin film and the substrate, which is not expected in the lattice matched structure grown by MBE. In addition, it is also unreasonable that the large acoustic mismatch, if any, depends on the mobility of the 2DEG.

In Fig. 4, we plot the prefactor d as a function of μ of each n in Fig. 1. Similar to Fig. 3, each result is represented by a rectangle whose length is the μ range, and whose height is the uncertainty in d due to the fitting procedure. We chose the units in such a way that the value of d is equivalent to the cooling power of the 2DEG per unit area at 100 mK. We see that as disorder increases, indicated by the decreasing μ, not only does b deviate from the clean limit value, but the prefactor d is enhanced by more than one order of magnitude.

The power law in Eq. (1) for a clean sample cannot explain the deviation of b from ~5 in our observation. Nor does it describe the dramatic enhancement of the cooling power. This is illustrated, in Fig. 4, by the open circles which are calculated from Eq. (1) for all n's in Fig. 1 at $T=100$ mK. When $\mu>25\,000$ cm^2/V s, the theoretical values fall within the experimental rectangles, indicating that the samples are in the clean limit. On the other hand, the data start to take off dramatically when $\mu<20\,000$ cm^2/V s, indicating that Eq. (1) cannot be applied to disordered samples.

For dynamically screened piezoelectric coupling in the regime where σ_{xx} in units of $(\Omega/\square)^{-1}$ is independent of the frequency and wave vector,[9]

$$P(W/m^2)=\frac{e^2}{h\sigma_{xx}}6.75\times10^{-2}[T_e(\mathrm{K})]^4. \tag{2}$$

Here e is the electron charge and h is the Planck constant. The power enhancement due to disorder (and thus poor screening) is built into the equation since σ_{xx} is expected to be small in dirty samples. We would like to mention that using static screening in the formalism for deriving Eq. (2) correctly reproduces the result in Eq. (1) in the high mobility region.[9] We calculate P at $T=100$ mK from Eq. (2) by using the experimentally measured $\sigma_{xx}(T=100$ mK) for the samples represented by the circle symbols in Fig. 1. The results are plotted as solid circles in Fig. 4. In contrast to the prediction from Eq. (1) (open circles), Eq. (2) (solid circles) produces a strong enhancement comparable to the experimental data. The quantitative discrepancy, however, is presumably due to the following. Our samples cover both the dirty and clean limit, and it is expected that Eq. (2) cannot describe the phonon emission in the whole mobility range that we studied. Even within the dirty limit, the strong T dependence of σ_{xx} due to localization in our low mobility samples may give rise to frequency-dependent σ_{xx}, which is neglected in the derivation of Eq. (2). One should therefore be cautious when comparing quantitatively the theoretical values with the experimental data in Fig. 4. We emphasize that in the quantum Hall transition region, σ_{xx} is not only small but largely T and frequency independent. In this regime, Eq. (2) is quantitatively very accurate.[9] Our experimental results call for a more detailed theoretical investigation of the phonon emission in the dirty limit where σ_{xx} depends strongly on T.

In summary, we carried out electron heating measurements in two GaAs/Al_xGa_{1-x}As heterostructures with varying mobilities. We observe that the phonon emission power obeys $P=dT^b$. With increasing disorder, b change systematically from 5.15 to 3.8, and d increases by one order of magnitude. Our results explicitly demonstrate that the phonon emission is characteristically different in the clean and dirty limits.[9]

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