Strongly Enhanced Hole-Phonon Coupling in the Metallic State of the Dilute Two-Dimensional Hole Gas

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We have studied the temperature dependent phonon emission rate $P(T)$ of a strongly interacting ($r_s \geq 22$) dilute 2D GaAs hole system using a standard carrier heating technique. In the still poorly understood metallic state, we observe that $P(T)$ changes from $P(T) \sim T^5$ to $P(T) \sim T^7$ above 100 mK, indicating a crossover from screened piezoelectric (PZ) coupling to screened deformation potential (DP) coupling for hole-phonon scattering. Quantitative comparison with theory shows that the long range PZ coupling between holes and phonons has the expected magnitude; however, in the metallic state, the short range DP coupling between holes and phonons is *almost 20 times stronger* than expected from theory. The density dependence of $P(T)$ shows that it is *easier* to cool low-density 2D holes in GaAs than higher density 2D hole systems.

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Hot carrier effects in semiconductors have been a subject of interest for device applications as well as for probing electron- or hole-phonon interactions [1]. In the low temperature Bloch-Gruneisen regime, hot carrier effects are particularly useful for studying inelastic electron- or hole-phonon scattering, because direct transport measurements require extremely high sample mobility [2]. Price provided the first theoretical study of hot two-dimensional (2D) electrons in high mobility GaAs heterostructures, considering the phonon emissions via deformation potential (DP) and piezoelectric (PZ) coupling [3]. The theory was extended further by other authors [4,5(a)], and has found excellent support from various heating experiments on 2D electrons with modest densities ($\sim 10^{11}$ cm^{-2}) [4–8].

The carrier heating phenomena in high mobility 2D systems with very low carrier densities has received recent attention [9,10], particularly in the context of the 2D metallic transport and the metal-insulator transition (MIT) [11]. As first discovered by Kravchenko and coworkers in silicon metal-oxide-semiconductor field-effect-transistors (Si-MOSFETs), the apparent metalliclike resistivity of various low-density 2D systems challenges the celebrated noninteracting scaling theory of localization for Fermi liquids [11]. However, because the $T = 0$ conductivity determines if the ground state of the system is metallic, it is critical to study the metalliclike behavior at the lowest possible temperatures. In the low temperature regime, the electron-phonon scattering time becomes very long and self-heating of carriers in a driving electric field poses a serious problem in interpreting experimental data [9]. To understand the carrier-phonon coupling of dilute 2D systems in the anomalous 2D metallic state, in this Letter we present a study of the energy relaxation of a dilute metallic 2D hole system (2DHS) in response to a driving electric field down to very low temperatures ($\sim$27 mK). Note that it is not *a priori* known if the standard weak-interaction theories of hot carriers [3,4,5(a)] would also apply to the anomalous 2D metallic state, since the strongly correlated 2D metal may not be a Fermi-liquid state [11].

Our energy relaxation measurements suggest that the dilute metallic 2D holes in our GaAs quantum well (QW) is cooled by emitting phonons. For all the densities studied, the T dependent phonon emission rate $P(T)$ exhibits either a T^5 or T^7 power law, with a crossover at $\sim$100 mK. The T^5 and T^7 power laws of $P(T)$ are interpreted as arising from the screened PZ or DP coupling, respectively, for hole-phonon coupling. The crossover at 100 mK suggests the two mechanisms have comparable magnitude at that temperature. Comparing our data with existing theories, we find that the T^5 part of $P(T)$ below 100 mK shows excellent quantitative agreement with weak-interaction theories. The T^7 part of $P(T)$, however, is about *three hundred* times larger in magnitude than the expected value for normal DP hole-phonon coupling. This indicates that the short range DP coupling strength between 2D holes and phonons is enhanced by almost a factor of 20 in the anomalous 2D metallic state. It follows that high mobility dilute 2D holes in GaAs are cooled via DP- instead of PZ-coupled phonon scattering at temperatures down to 100 mK, contrary to conventional experience drawn from higher density samples [3–8]. We suggest many-body effects as a possible origin of this more than an order of magnitude enhancement of hole-phonon coupling in the dilute limit.

Our experiments were performed on a high mobility low-density 2DHS in a 10 nm wide GaAs quantum well

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(QW) similar to those in previous studies [12]. The sample was symmetrically doped with a density of 1.3×10^{10} cm^{-2} from doping. The hole density p was tuned by a backgate about 0.15 mm below the QW. The ungated sample has a low temperature hole mobility, $\mu \approx 5 \times 10^5$ cm^2/Vs. The sample was prepared in the form of a Hall bar, with an approximate total sample area 0.2 cm^2. With the relatively large sample area, four-wire transport measurement can be realized with dissipation power down to fW/cm^2 for sample resistance in the kΩ and above range. The sample was driven with 8 Hz square wave voltage ranging from μVs to mVs in amplitude. During the experiments, the sample was immersed in the ^{3}He/^{4}He mixture in a top-loading dilution refrigerator [13].

We studied heating effects for five different hole densities in the sample from 1.2 to 1.9×10^{10} cm^{-2} deep in the metallic state where the low T resistivity is less than 0.1 h/e^2 for all the densities. Using an effective hole mass $m^* = 0.36m_e$, we obtain $22 \leq r_s \leq 28$ for this density range, where r_s is the ratio between the interparticle Coulomb energy and the Fermi energy. During the experiment and following previous experiments on electron-phonon coupling [6,8,10] the sample resistance was used as a self-thermometer for the overheated holes. In Fig. 1(a), the T dependence of R_{xx}, the longitudinal resistance is shown on a semilog plot, where the resistivity ρ_{xx} would be roughly R_{xx} divided by three. The data in Fig. 1(a) were obtained with negligible Joule heating power (<5 fW) on the sample to ensure good thermal equilibrium between holes and the lattice. The 2D holes were then purposely overheated by increasing the current through sample, with the lattice or substrate being held at a fixed temperature T_L. Figure 1(b) shows the resulting Joule heating power $P = I^2R_{xx}$ dependence of the sample resistance R_{xx} for $T_L =$ 27 mK. Except at very low power, the resistance increases as the power is increased, indicating the hole gas being heated up. Using the $R_{xx}(T)$ curve in Fig. 1(a) as a thermometer for the hot holes, one can deduce the hot hole temperature T_H for given R_{xx} and power P in Fig. 1(b). In this way, we obtain P (i.e., energy relaxation rate) vs T_H from the $R_{xx}(P)$ data in Fig. 1(b), as shown in the main panel of Fig. 2. For the clarity of presentation, we only include data for three densities.

We discuss some important qualitative features in the energy relaxation rate P vs hot hole temperature T_H data of Fig. 2. First, $P(T)$ follows T^5 dependence and crosses over to a T^7 dependence above ~100 mK. The exponent of the power law dependence of $P(T)$ can be used to distinguish the type of carrier-phonon coupling. If the carriers emit acoustic phonons via screened PZ or DP coupling, then the energy relaxation $P(T)$ will have a T^5 or T^7 dependence. The T^5 dependence we observe below 100 mK is consistent with the acoustic phonon emission via screened PZ coupling, similar to previous theories and experiments on 2D electrons in GaAs [3–8]. The T^7 suggests the dominance of screened DP coupling for phonon emission above 100 mK for dilute 2D holes. Interestingly, this crossover in power law dependence of $P(T)$ was predicted by theory to happen around 2 K for long time [3], but has never been observed experimentally. We shall see that an order of magnitude enhancement in the DP coupling strength can move the crossover temperature down to ~100 mK, as in our case. Secondly, the $P(T)$ curves for different densities show that it takes more power to warm up holes with lower density to a given temperature, i.e., it is easier to cool 2D holes with lower density. This is illustrated in the inset of Fig. 2, in which we plot the power/cm^2 needed to warm

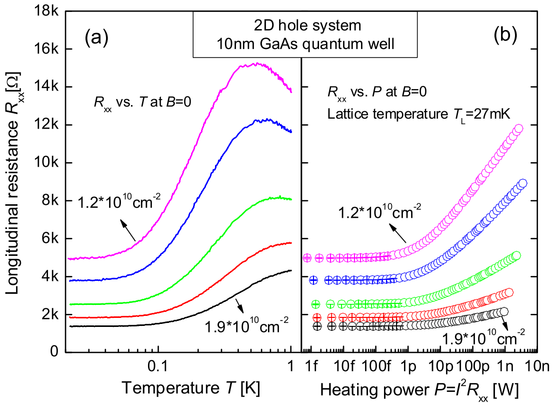

FIG. 1 (color online). (a) Longitudinal resistance R_{xx} vs T at zero magnetic field of 2D holes in a 10 nm wide GaAs quantum well. The data were obtained with less than 5 fW heating power on the sample. (b) Variation of R_{xx} against heating power $P = I^2R_{xx}$ with lattice held at $T_L = 27$ mK. The densities are 1.2, 1.3, 1.5, 1.7, and 1.9×10^{10} cm^{-2} from top to bottom in both (a) and (b).

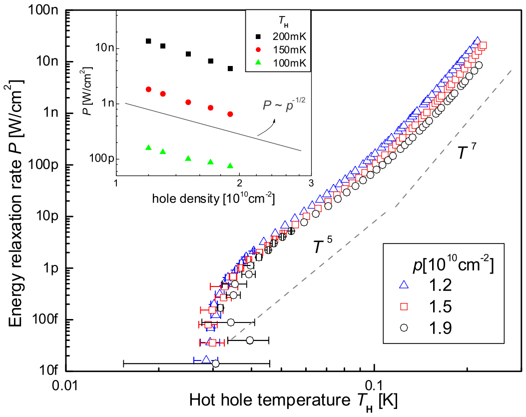

FIG. 2 (color online). The energy relaxation rate P vs hot hole temperature T_H with the lattice held at $T_L = 27$ mK, created from data in Fig. 1(b) using $R_{xx}(T)$ in Fig. 1(a) as a thermometer for hot holes. The dashed lines represent T^5 and T^7 behavior to be compared with the data. The inset plots the power per cm^2 needed to heat up holes to 100, 150, and 200 mK with $T_L =$ 27 mK vs hole density p, which is consistent with a $1/\sqrt{p}$ dependence.

holes from 27 mK to $T_H = 100$, 150, or 200 mK against the hole density. Assuming the formalism of hot electrons theories in Ref. [3,4] is also applicable to holes with appropriate substitution of parameters (carrier effective mass, DP constant, etc.), the energy relaxation rate through acoustic phonon emission for clean 2D holes in GaAs is [14]

$$P = [15 \times (T_H^5 - T_L^5) + 0.06 \times D^2 \times (T_H^7 - T_L^7)]/\sqrt{p} \quad (1)$$

On the right hand side of Eq. (1), the first/second part is the acoustic phonon emission rate through screened PZ-DP coupling. In Eq. (1), P is in units of $\mu\mathrm{W/cm}^2$, T_H and T_L are in units of Kelvin, hole density p is in units of 10^{10} cm^{-2}, and the DP constant D is in units of eV. Equation (1) predicts that the energy relaxation rate is inversely proportional to the square root of density, and therefore lower density holes can sustain higher heating power. This result is simply related to the fact that the Fermi degeneracy restricts the phonon-scattering probability and the Fermi temperature is lower in more dilute 2DHS. In the inset of Fig. 2 we draw a gray line representing the $P \propto 1/\sqrt{p}$ dependence, which is consistent with the data.

Now we compare the energy relaxation rate $P(T)$ data with existing theories quantitatively. The best estimate of the deformation potential constant D for hole-phonon scattering in GaAs is around 6 eV [15]. With $D = 6$ eV, Eq. (1) predicts that below 2.6 K the holes mostly relax by emitting acoustic phonons via screened PZ coupling. However, our data suggest that it is the DP coupled phonon emission that is responsible for the energy relaxation above 100 mK. We find that it is possible to fit our $P(T)$ data to Eq. (1) with D as the only fitting parameter. The best fitted D equals 105 eV for all the densities studied between 1.2 and 1.9×10^{10} cm^{-2}. In other words, standard theories of hot carriers in the Bloch-Gruneisen regime can explain our data with an *unaltered* PZ coupling and an *eighteen times enhanced* DP coupling. In Fig. 3(a), we plot the $P(T_H)$ for density 1.3×10^{10} cm^{-2} at three lattice temperatures: 27, 54, and 104 mK. The black lines are the theoretical curves according to Eq. (1) with $D = 105$ eV, which have good agreement with data. In Fig. 3(a), we also draw red and blue dotted lines to show the absolute (with $T_L = 0$) magnitudes of PZ and DP contributions to energy relaxation rate.

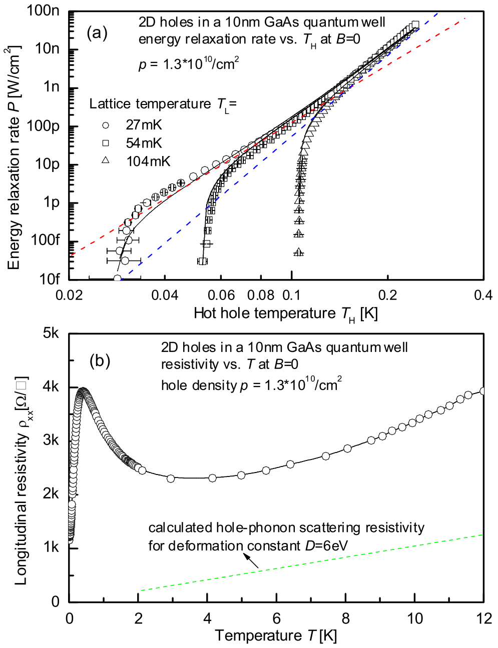

FIG. 3 (color online). (a) The temperature dependent energy relaxation rate of 2D holes with density $p = 1.3 \times 10^{10}$ cm^{-2}. Data are shown for three different lattice temperatures, $T_L = 27$, 54, and 104 mK. The black solid lines are according to Eq. (1) with an enhanced deformation potential constant $D = 105$ eV. The red and blue dotted lines are, respectively, the PZ coupling contribution $(15 \times T_H^5/\sqrt{p})$ and DP coupling contribution $(0.06 \times 105\ \mathrm{eV}^2 \times T_H^7/\sqrt{p})$ of the energy relaxation rate. (b) Resistivity $\rho_{xx}(T)$ over an extended temperature range for the 2D holes in (a) at zero magnetic field. The dotted green line depicts the hole-phonon-scattering induced resistivity in the high temperature equipartition regime with deformation potential constant $D = 6$ eV according to [16,17]. After adding a resistivity offset induced by impurity scattering, the hole-phonon scattering for $D = 6$ eV in the equipartition regime accounts for the $T > 4$ K experimental data satisfactorily.

The anomalously large deformational potential constant of 105 eV fitted from our energy relaxation rate data is most likely due to other hole-phonon coupling mechanisms in the dilute regime, instead of an unrealistically large DP constant. In contrast to electrons [2], the mobility of the 2DHS is not high enough to allow separating of phonon-scattering from impurity scattering to deduce the DP constant D in the Bloch-Gruneisen regime. However, it is possible to estimate D from the phonon-scattering induced resistivity [denoted as $\rho_{\mathrm{ph}}(T)$ hereafter] in the high temperature equipartition regime [16,17]. In Fig. 3(b) we show the resistivity $\rho_{xx}(T)$ at $B = 0$ over an extended temperature range up to 12 K for the 2DHS with $p = 1.3 \times 10^{10}$ cm^{-2}. Above 4 K, the resistivity has a positive temperature coefficient caused by phonon-scattering in the equipartition regime. We also calculated $\rho_{\mathrm{ph}}(T)$ with $D = 6$ eV in this regime according to Refs. [16,17] and included the result as a green dotted line in Fig. 3(b). It is known that in the high T equipartition regime, DP coupling accounts for most ($\sim 80\%$) of $\rho_{\mathrm{ph}}(T)$ [16,17]. Note that 6 eV for the DP constant gives a slope that is consistent with the observed slope of $\rho_{xx}(T)$. If the DP constant were 105 eV, the theoretical curve for $\rho_{\mathrm{ph}}(T)$ would be way out of scale in Fig. 3(b), as $\rho_{\mathrm{ph}}(T) \propto D^2$ [16,17]. We also briefly comment on the nonmonotonic peak around $T = 0.5$ K of $\rho_{xx}(T)$ at lower temperatures. This first increasing and then decreasing resistivity of dilute 2D systems with reducing temperature was attributed to the degeneracy of the systems in which the Fermi temperatures are very low [18]. To be consistent with this classical-quantum crossover scenario, we expect to observe the energy relaxation rate $P(T)$ changing from T^5 (or T^7) into a linear T dependence for $T > 0.5$ K [3]. Unfortunately, our sample could not sustain larger current to check this power law crossover in $P(T)$ around 0.5 K.

Jain, Jalabert, and Das Sarma (JJD) proposed a mechanism for energy relaxation rate enhancement of electron gas where new low-energy phonon modes are involved [19–21]. These new phonon modes are supposed to be due to coupling between quasiparticle excitations and longitudinal *optical* (LO) phonons. Including the extra energy loss of hot electrons through these novel phonon modes, a slightly enhanced effective DP constant of 16 eV in experiment [22] could be explained [19–21]. Note that the experiments by Manion *et al.* were performed on 2D electrons with 50 times higher density, and at much higher temperatures, relevant to the excitation energy scales in JJD theory, as opposed to our low T Bloch regime study. Moreover, JJD theory predicts a greatly enhanced energy relaxation rate in *optical* phonon-scattering, while our data are consistent with enhanced *acoustic* phonon-scattering via DP coupling. With the detailed temperature and density dependences to be further calculated in the JJD model into the density and temperature ranges of our experiment, the relevance between the many-body effects and renormalized LO phonon modes [19–21] with our data remains to be seen.

Finally, we discuss some relevance of our results to the much debated 2D metallic state problem [9,11]. First, it is striking that the hot carrier theories for weakly interacting systems appear to account for important features (i.e., the $T^{5,7}$ and the $1/\sqrt{p}$ dependences of energy relaxation rate P) of our data. Within the two-temperature model, the energy relaxation rate is related to the specific heat C of the 2D holes and the hole-phonon-scattering rate τ_{ph}^{-1} as $P(T_H) = \int_{T_L}^{T_H} C \times \tau_{\mathrm{ph}}^{-1} dT$. The power law dependence of $P(T_H)$ we observed is consistent with a linear T dependent specific heat and $T^{3,5}$ dependence of τ_{ph}^{-1} for our dilute holes in the metallic state. Linear T dependent $C(T)$ is a strong indication of Fermi liquid, in contrast to some non-Fermi-liquid models of the 2D metallic state where $C(T)$ might have a nontrivial T dependence [11]. Next, our measurements provide evidence that the minute energy loss through emitting phonons at low T poses a more severe problem on performing experiments on samples with higher carrier density, lower resistance, and smaller area.

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