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Supersonic transport in GaAs/AlGaAs heterostructures

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Phonon-induced magneto-resistance oscillations [1], originating from electron scattering on thermal acoustic phonons carrying twice the Fermi momentum, can yield information on the sound velocity of the material hosting a two-dimensional electron gas (2DEG). Here, we report on a distinct peak in the current dependence of the differential resistivity *at zero magnetic field*. We associate this peak with a supersonic transition, occurring when the electron drift velocity becomes equal to the sound velocity. In contrast to phonon-induced oscillations, this peak is detectable over a wide temperature range as it does not rely on thermal excitation of phonons carrying large momenta.

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Magnetotransport properties of two-dimensional electron gases (2DEG) subject to weak magnetic fields and low temperatures have received considerable attention over the last decade [2], owing to discoveries of an array of fascinating phenomena [1, 3–24]. One such phenomenon is known as phonon-induced resistance oscillations (PIRO) [1, 25–36], which are understood in terms of resonant electron-acoustic phonon interactions, made possible a selection rule dictating electron backscattering [1]. In this scenario, even though phonons of many different energies are present, *only* the most energetic phonons that electrons can scatter off drive the effect. Such phonons carry twice the Fermi momentum and, as a result, their energy is equal to $2\hbar k_F v_{\rm s}$, where $v_{\rm s}$ is the sound velocity, $k_F = \sqrt{2\pi n_e}$, and n_e is the electron density. Due to absorption or emission of such $2k_F$ phonons, electron undertake *indirect* transitions between Landau levels, separated by $\hbar\omega_{\rm c}$, where $\omega_{\rm c}$ is the cyclotron frequency. Owing to such transitions, the longitudinal resistivity acquires an oscillatory correction, controlled by a parameter $\epsilon_{\rm ph} = 2k_F v_{\rm s}/\omega_{\rm c}$ According to Refs. 34, 36, in a typical 2DEG, PIRO are described by

$$\frac{\delta\rho_{\rm ph}}{\rho_0} \simeq \frac{2g^2 k_B T\tau}{\pi\hbar\sqrt{\epsilon}_{\rm ph}}\lambda^2 \cos\left[2\pi(\epsilon_{\rm ph} - 1/8)\right] , \qquad (1)$$

where ρ_0 is the resistivity at $B = 0$, g is the dimensionless electron-phonon coupling constant, τ is the transport lifetime, $\lambda = \exp(-\pi/\omega_{\rm c}\tau_{\rm q})$ is the Dingle factor, and $\tau_{\rm q}$ is the quantum lifetime. According to Eq. (1), one important practical application of PIRO is the determination of the sound velocity $v_{\rm s}$ of the host crystal.

It is important to mention that Eq. (1) describes a contribution only from a single phonon mode, whereas Ref. 30 identified important contributions from three modes: transverse (TA) mode polarized along $\langle 001\rangle$ (out of plane) direction ($v_T \approx 3.35$ km/s) and two longitudinal (LA) modes polarized along $\langle 100\rangle$ ($v_L \approx 4.73$ km/s) and $\langle 110\rangle$ ($v_l \approx 5.24$ km/s) directions. In a typical 2DEG with $n = 2\times 10^{11}$ cm^{-2}, the characteristic temperatures at which these modes become populated up to momentum $2k_F$ are rather close to each other: $T_T \approx 6$ K, $T_L \approx 8$ K, and $T_l \approx 9$ K. Nevertheless, since $v_T < v_L, v_l$, it is sometimes possible to realize PIRO originating primarily from a single mode which can be well described by Eq. (1) with $v_{\rm s} = v_T$ [36]. However, the requirements for such a realization are rather strict. First, one needs to use ultra-high mobility 2DEG where PIRO can be observed at T significantly lower than T_L and T_l, needed to minimize contributions from the LA phonons. Second, since PIRO quickly decay at low T due to both decreased population of the TA phonon mode and increased degeneracy of the 2DEG, observation of such single-mode PIRO is always limited to a very narrow temperature range. Most often, PIRO appear only at $T \gtrsim T_T$ and, a result, contain contributions from several phonon branches. This results in a PIRO waveform more complex than predicted by Eq. (1) precluding reliable determination of $v_{\rm s}$.

In this Rapid Communication we report on a nonlinear transport measurements of a 2DEG hosted in a GaAs/AlGaAs heterostructure at currents high enough to accelerate the charge carriers to the speed of sound. At magnetic fields above $B \approx 0.5$ kG, the differential resistivity reveals Hall field-induced resistance oscillations (HIRO) [4, 37–44], which gradually decay as the drift velocity approaches the sound velocity. Concurrent with the disappearance of HIRO the data reveal a distinct peak whose position is independent on B and which persists *all the way to* $B = 0$. We associate this peak with a transition that occurs when the drift velocity becomes equal to the sound velocity, i.e. at the current density $j = en_e v_{\rm s}$, $v_{\rm s} \approx v_l$. In contrast to PIRO, this "supersonic" peak is detectable over a much wider temperature range, as its emergence does not require thermal excitation of phonons carrying large momenta. It would be interesting to see whether or not this experimental technique can be used to obtain the sound velocities in other 2D materials.

Our samples are lithographically defined Hall bars of

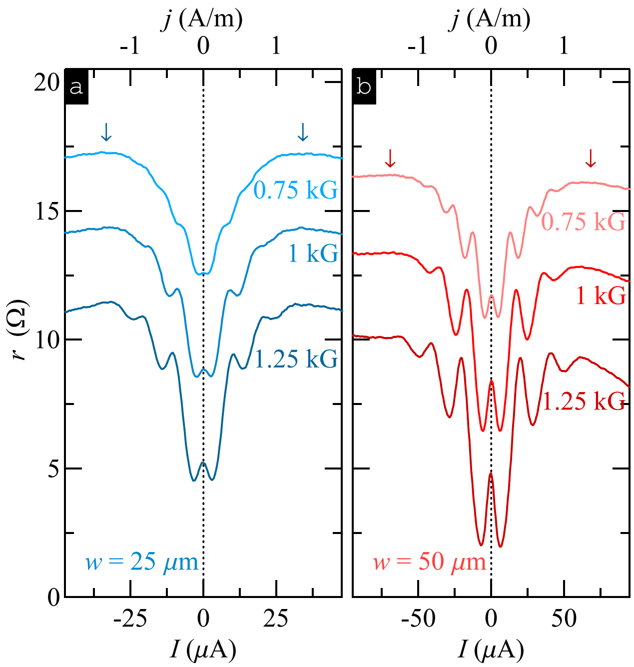

FIG. 1. (Color online) Differential resistivity r versus current I (bottom axis) and j (top axis) measured at fixed $B = 0.75$, 1, and 1.25 kG, as marked, in Hall bars of width (a) $w = 25$ μm and (b) $w = 50$ μm at $T = 1.5$ K. The traces are vertically offset for clarity, bottom to top, by 3 Ω.

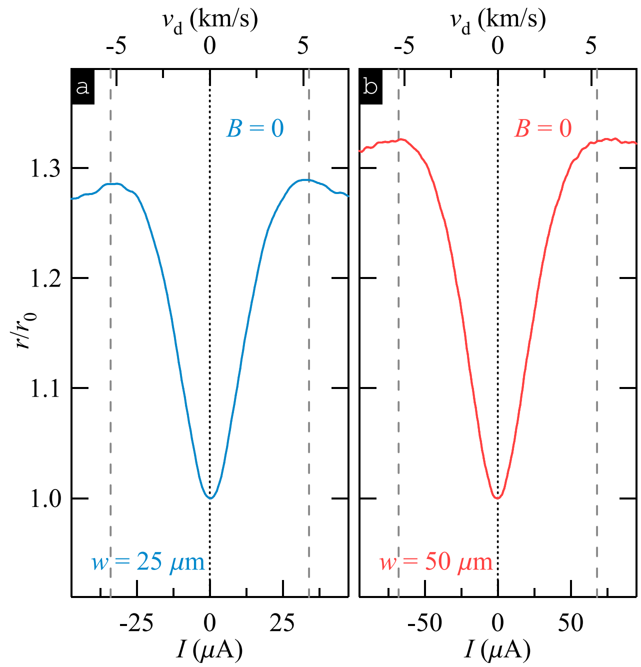

FIG. 2. (Color online) Normalized differential resistivity r/r_0 (r_0 is the resistivity at $I = 0$) versus current I (bottom axis) and v_d (top axis) measured at $B = 0$ in Hall bars of width (a) $w = 25$ μm and (b) $w = 50$ μm at $T = 1.5$ K. Vertical dashed lines are drawn at $v_d = 5.2$ km/s.

widths $w = 25\,\mu$m and $w = 50\,\mu$m fabricated from a GaAs/AlGaAs heterostructure (EA0761). The density $n_e = 1.6 \times 10^{11}$ cm^{-2} and the mobility $\mu = 4.6 \times 10^6$ cm^2/V s were obtained after a brief low temperature illumination. Transport measurements were performed using a low-frequency lock-in technique. The differential resistivity r was recorded as a function of direct current I up to 125 μA at various B, including $B = 0$, and at T from 1.5 to 14 K. The resistivity ρ was measured at temperatures T from 0.5 to 5.0 K.

In Fig. 1 we present the differential resistivity r as a function of current I (bottom axis) and current density $j = I/w$ (top axis) at $B = 0.75$, 1, and 1.25 kG, as marked, measured in Hall bars of width (a) $w = 25\,\mu$m and (b) $w = 50\,\mu$m at $T = 1.5$ K. The traces are vertically offset for clarity by 3 Ω. At small I, r exhibits a zero-bias peak [45] which becomes more pronounced with increasing B [46] and is stronger in the wider Hall bar. At higher I, the data reveal pronounced HIRO [4, 37–44], which are known to originate from electron transitions between Hall field-tilted Landau levels due to electron backscattering off of disorder. The probability of such transitions depends on the ratio between the cyclotron diameter $2R_c$ and the spatial separation between the levels and, as a result, is a periodic function of $\epsilon_{dc} \equiv 2eE_H R_c/\omega_c \sim j/B$, where E_H is the Hall field. At $2\pi\epsilon_{dc} \gg 1$, the differential resistivity is given by [40]

$$\frac{r}{\rho_0} = \frac{16\tau}{\pi\tau_\pi}\lambda^2 \cos 2\pi\epsilon_{dc}\,, \qquad (2)$$

where τ_π is the characteristic time between backscattering events.

The HIRO gradually decay with increasing I and disappear at $I \gtrsim 30$ μA ($\gtrsim 60$ μA) in a Hall bar of width $w = 25$ μm (50 μm). Concurrent with the disappearance of HIRO, the smooth part of r develops a broad maximum. This maximum occurs at roughly the same current density $j \approx 1.3$ A/m in both samples and its position does not change with B. The observed maximum is a manifestation of a supersonic transition [28], which occurs when the electron drift velocity becomes equal to the sound velocity v_s, i.e., when $j = j_s \equiv e n_e v_s$. Indeed, using the speed of LA phonon mode in GaAs, $v_s = 5.2$ km/s, we find $j_s \approx 1.3$ A/m, in agreement with the position of the observed maxima (cf. ↓). The disappearance of HIRO near $j \approx j_s$ contradicts both Eq. (2), which dictates no decay with increasing j [40], and a recent theoretical prediction of even stronger I-periodic oscillations in the supersonic regime, $v_d > v_s$ [47]. The observed decay of HIRO can be attributed to the current-induced increase of electron temperature which can be quite significant [41].

In Ref. 28, the appearance of the maximum near $v_d = v_s$ was attributed to the opening of an extra scattering channel which allows electron transitions within a single Landau level due to absorption or emission of acoustic phonons. Such scattering becomes possible when the angle between the Landau levels and the normal to the 2DEG becomes equal to one half of the opening angle

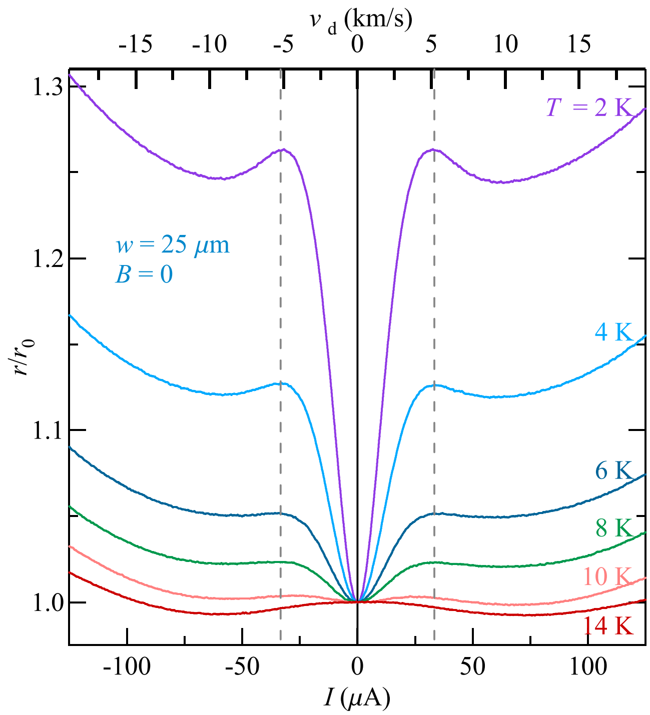

FIG. 3. (Color online) Normalized differential resistivity, r/r_0 versus I (bottom axis) and $v_{\rm d}$ (top axis) measured in a $w = 25\,\mu$m Hall bar at $B = 0$ and various temperatures from 2 to 14 K, as marked. Vertical dashed lines are drawn at $v_d = 5.2$ km/s.

of the acoustic phonon dispersion cone. Indeed, absorption of a phonon with momentum q_x results in a displacement of the electron guiding center by $\Delta y = q_x \ell_B^2$, where $\ell_B = \sqrt{\hbar/eB}$ is the magnetic length, accompanied by an energy gain of $\hbar q_x v_{\rm s} = e v_{\rm s} B \Delta y$. This gain is matched by the electrostatic potential of the Hall field, $eE_H \Delta y = e v_{\rm d} B \Delta y$, when $v_{\rm d} = v_{\rm s}$, regardless of Δy [28].

Since the condition $v_{\rm d} = v_{\rm s}$ does not contain B, the natural question arises as whether or not the supersonic transition can be detected in the absence of Landau quantization, e.g., at $B = 0$. To investigate this, we present in Fig. 2 the normalized differential resistivity r/r_0 versus current I (bottom axis) and v_d (top axis) measured in Hall bars of width (a) $w = 25\ \mu$m and (b) $w = 50\ \mu$m at $B = 0$ and $T = 1.5$ K. Remarkably, both traces reveal a maximum which occurs when $v_{\rm d} \approx 5.2$ km/s, as shown by vertical dashed lines. This maximum appears to be even more pronounced than the one observed at finite B (cf. Fig. 1), demonstrating that Landau quantization is not essential for the observation of the supersonic transition. We thus conclude that the sound velocity can be obtained from nonlinear transport measurements performed at $B = 0$.

It is interesting to investigate the temperature range allowing the detection of such supersonic transition in our 2DEG. In Fig. 3 we present r/r_0, where r_0 is the resistivity at $I = 0\ \mu$A, as a function of I (bottom axis) and $v_{\rm d}$ (top axis) measured in a $25\,\mu$m-wide Hall bar at $B = 0$ and various T from 2 to 14 K, as marked. We observe that at all temperatures below ≈ 10 K, r initially increases with current and then peaks at $v_{\rm d} \simeq v_{\rm s}$. Further increase in current results in a decrease of r until one reaches $v_{\rm d} \simeq 10$ km/s, after which r increases again. The supersonic peak can be clearly seen at any $T < 10$ K, although the nonlinearity gradually decreases with T. While the exact origin of this decrease is not clear, it appears possible that it occurs due to increased electron-electron scattering which is known to suppress the transport phenomena due to both non-equilibrium effects [42, 48] and resonant interaction with acoustic phonons [31]. Indeed, at $T \gtrsim 10$ K the peak is no longer present and r becomes a weak, initially decreasing function of I. Taken together, the data demonstrate that the supersonic peak is readily detectable in a wide T range.

As discussed in the introduction, an alternative way to obtain $v_{\rm s}$ is based on the analysis of PIRO waveform [1]. Since PIRO rely on resonant interaction between electrons and acoustic phonons carrying momentum $2k_F$, the effect cannot be observed at temperatures much lower than the Bloch-Grüneisen temperature $T_{\rm BG} = 2k_F v_s/k_B$, which is typically several kelvin. This is because the number of such phonons drops exponentially with decreasing temperature [49]. It is also known that with increasing T, electron-electron interactions result in enhancement of the quantum scattering rate [31, 42, 48], leading to suppression of the PIRO amplitude [31]. As a result, PIRO are observed in a rather narrow temperature range, and are often not pronounced enough for accurate determi-

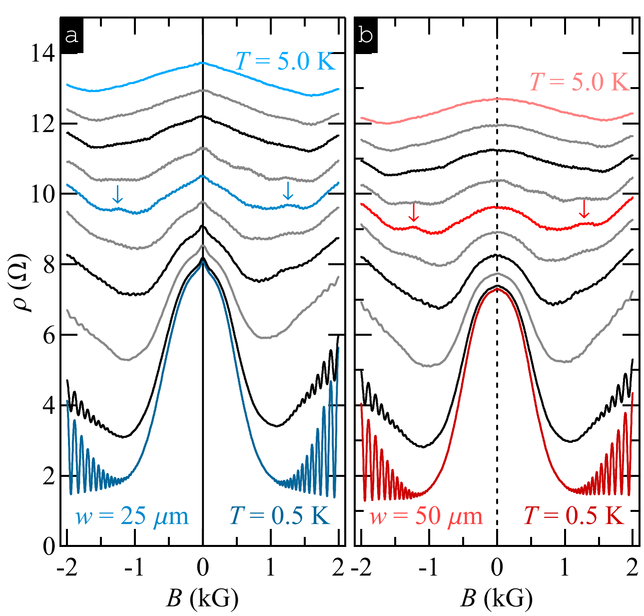

FIG. 4. (Color online) Magnetoresistivity $\rho(B)$ measured at different T from 0.5 to 5 K, in steps of 0.5 K, in Hall bars of width (a) $w = 25\ \mu$m and (b) $w = 50\ \mu$m. The traces are *not* vertically offset for clarity. Weak PIRO maxima are marked by ↓.

nation of v_s. In addition, there exists an uncertainty in the PIRO phase, as it can deviate from "1/8" appearing in Eq. (1), which further complicates the situation [35, 36, 47].

In Fig. 4 we present the magnetoresistivity $\rho(B)$ measured at different T from 0.5 to 5 K, in steps of 0.5 K, in Hall bars of width (a) $w = 25$ μm and (b) $w = 50$ μm. At low T, $\rho(B)$ exhibits strong negative magnetoresistance [50–54] followed by Shubnikov-de Haas oscillations. At $T \approx 3$ K, both data sets reveal weak additional maxima, marked by $\downarrow$, which quickly disappear both at lower and higher T. While these maxima clearly originate from PIRO, their use for reliable determination of v_s does not appear to be feasible in our samples at any temperature. In contrast, nonlinear transport measurements performed at $B = 0$, see Fig. 2 and Fig. 3, readily reveal the supersonic peak from which v_s can be easily determined.

In summary, we have observed a distinct peak in the differential resistivity measured in GaAs/AlGaAs Hall bars at zero magnetic field. We associate this peak with the supersonic transition, occurring when the drift velocity becomes equal to the sound velocity, a condition corresponding to the current density $j = en_e v_s$, where v_s is equal to the LA phonon mode polarized along $\langle 110 \rangle$ direction. Compared to PIRO, which, in some cases, can also be used to obtain the sound velocity, the supersonic peak is easily detectable over a much wider temperature range, as its emergence does not require thermal excitation of phonons carrying large momenta. It will be interesting to see if this experimental technique can be applied to material systems other than 2DEG in GaAs.

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