Evidence for a New Dissipationless Effect in 2D Electronic Transport

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In an ultraclean 2D electron system (2DES) subjected to crossed millimeterwave (30–150 GHz) and weak ($B < 2$ kG) magnetic fields, a series of apparently dissipationless states emerges as the system is detuned from cyclotron resonances. Such states are characterized by an exponentially vanishing low-temperature diagonal resistance and a classical Hall resistance. The activation energies associated with such states exceed the Landau level spacing by an order of magnitude. Our findings are likely indicative of a collective ground state previously unknown for 2DES.

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Scattering and dissipation are central issues in quantum transport in electronic systems. The integer and the fractional quantum Hall effects (QHE) [1] are the most remarkable dissipationless transport phenomena observed in a two-dimensional electron system (2DES), as it is subjected to strong perpendicular magnetic fields (B) and low temperatures (T). Such effects arise from the opening of energy gaps, with the underlying states related to the Landau level (LL) filling factor, $\nu = hn_e/eB$ (n_e is an electron density). While the integer QHE can be understood in terms of the electron localization in LL gaps, at integer ν, the fractional QHE stems from the formation of an incompressible quantum fluid with fractionally charged quasiparticles, at rational ν. In standard transport experiments, QHE exhibits an exponentially vanishing diagonal resistance, $R_{xx} \rightarrow 0$, and a quantized Hall resistance, $R_{xy} = (1/\nu)h/e^2$, as $T \rightarrow 0$.

The vanishing of R_{xx} in the QHE regime indicates complete suppression of scattering of electrons, much the same as in a case of charge superfluidity. Dissipationless effects have been proposed to exist, theoretically, in 2D electronic transport regimes other than the QHE. For example, Fröhlich superfluidity, the transport of a phase-coherent sliding charge-density wave [2], is an ideal dissipationless effect. Superfluidity of excitonic systems, such as those realized by optical pumping [3] or in a coupled two-layer electron-hole quantum well (QW) [4,5] have also been long-sought-after but remained experimentally elusive. More recently, evidence for excitonic superfluidity has been reported for a double electronic QW [6]. Observation of dissipationless transport in a new experimental regime, in addition to QHE, is of fundamental importance to correlation physics since it signals a novel ground state.

Until recently, magnetotransport in 2DES under the influence of a millimeterwave (MW) field has often revealed photoconductivity related to electron spin resonance [7] or long-wavelength magnetoplasmons [8], with a signal level of a few percent. With increased 2DES mobility, giant amplitude, oscillatory magnetoresistance was discovered by Zudov *et al.* [9,10] using MW excitation. While the underlying mechanism for such an effect has not been theoretically established, the period (in $1/B$) of the oscillations is believed to be determined by the ratio of the MW frequency, ω, to the cyclotron frequency, $\omega_c = eB/m^*$ ($m^* = 0.068\, m_0$ is the effective mass of conduction band electrons in GaAs). Specifically, the B positions of maxima and minima in the oscillatory structure were found to conform to

$$\frac{\omega}{\omega_c} \equiv \varepsilon = \begin{cases} j, & \text{max} \\ j + 1/2, & \text{min} \end{cases}, \quad j = 1, 2, 3, \ldots, \tag{1}$$

where j is the difference between the indices of the participating LLs. Phenomenologically, such oscillations resemble Shubnikov–de Haas (SdH) oscillations except that their period relates to ε rather than to ν. Similar oscillatory R_{xx}, but with an even greater amplitude, has been observed in transmission line experiments [11]. Most remarkably, both experiments have reported that at the minima ($\varepsilon = j + 1/2$), the R_{xx} was *reduced* as compared to its dark (i.e., without MW illumination) value indicating a suppression of scattering events for electron transport. Increasing sample mobility favors oscillation amplitude, and, therefore, the minima become progressively stronger under similar experimental conditions. Intuitively, one would wonder if the minima ultimately approach zero in a very clean 2DES.

In this Letter, we report on experimental evidence for dissipationless transport related to these minima observed in an ultraclean GaAs/Al$_x$Ga$_{1-x}$As QW sample. As the system is detuned from cyclotron resonance conditions ($\varepsilon = j$), a series of deep R_{xx} minima emerges at low temperatures. Transport in such states is characterized by an exponentially vanishing R_{xx} and a largely classical R_{xy}, as $T \rightarrow 0$. For stronger minima, the R_{xx} values are indistinguishable from zero within experimental uncertainty. Temperature-dependent R_{xx} shows an activated behavior with an energy scale exceeding the LL spacing by an order of magnitude.

Our samples [12] were cleaved from a $Al_{0.24}Ga_{0.76}As/GaAs/Al_{0.24}Ga_{0.76}As$ QW wafer grown by molecular beam epitaxy. The width of the QW was 300 Å and the electrons were provided by two Si sheets placed symmetrically above and below the QW at 800 Å. In this experiment the mobility, μ, and the electron density, n_e, were 2.5×10^7 cm^2/Vs and 3.5×10^{11} cm^{-2}, respectively. Such parameters were obtained by a brief illumination from a red light-emitting diode at $T \approx 1.5$ K. The specimens were $\sim$5 mm $\times$ 5 mm squares with eight In contacts diffused along the perimeter. The experiment was performed in a ^{3}He cryostat equipped with a superconducting magnet; the MW setup was of Faraday geometry (cf. inset, Fig. 1). Coherent, linearly polarized MWs were provided by a set of Gunn diodes (typical power is 10–40 mW, varied by a 60 dB calibrated attenuator) covering 30–150 GHz (1.5–7.5 K) frequency range. The radiation was sent down to the experiment via an oversized (WR-28) waveguide [13]. The specimen was immersed in the ^{3}He coolant kept at a constant temperature controllable from 0.5 to 6 K and monitored using a calibrated carbon glass thermometer. R_{xx} and R_{xy} were measured employing low-frequency lock-in technique, in sweeping B, at constant T, and under *continuous* MW illumination of fixed frequency and power.

In Fig. 1 we present typical data for the R_{xx} (left axis) and the R_{xy} (right axis) taken at $T \approx 1$ K under $f \equiv \omega/2\pi = 57$ GHz illumination. The MW power incident on the sample surface is estimated to be 100 μW. For comparison, we also plot the R_{xx} with no MW illumination (thin line) which reveals only SdH oscillations at $B \gtrsim 1.2$ kG. While both the R_{xx} curves converge as $B \to 0$, they are drastically different at $B \gtrsim 50$ G, as the sharp oscillatory structure emerges under MW illumination. The peaks are dramatically stronger than those in the $\mu = 3.0 \times 10^6$ cm^2/Vs samples previously studied [9,10]; R_{xx} is enhanced up to 5 times due to MWs. However, the most striking feature of the R_{xx} data is the emergence of wide, apparently *zero-resistance* (within experimental uncertainty) regions punctuated by those peaks. Typically, the values of the R_{xx} at the major minima are bound by ± 0.01 Ω, roughly the noise level in this experiment. In what follows we shall examine the R_{xx} and R_{xy} structures in the range of 0.3–2.0 kG, where their features are the strongest.

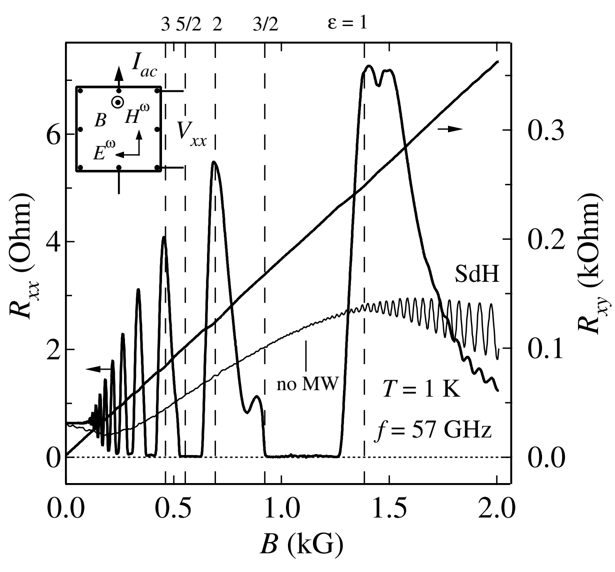

FIG. 1. Thick lines represent R_{xx} (left axis) and R_{xy} (right axis) under MW ($f = 57$ GHz) illumination at $T \approx 1$ K. Thin line shows R_{xx} with no MW illumination. Vertical dashed lines are calculated using Eq. (1) and are marked by ε on top axis. The inset depicts a sample layout, typical electrical connections, and orientations of current I, magnetic field B, electromagnetic wave fields E^ω and H^ω.

Vertical dashed lines in Fig. 1 were drawn in accordance with Eq. (1) for $j = 1, 2, 3$, and $f = 57$ GHz. While the positions of the major peaks can still be described by Eq. (1) for $\varepsilon = j$, their shapes are largely asymmetric, with a steeper left (lower-B) slope. The zero-resistance regions in such ultraclean samples are *not centered* around the $\varepsilon = j + 1/2$; they reside primarily on the higher-B side from those half-integers. In fact, such half-integers (3/2, 5/2, and 7/2) seem to represent a sharp boundary between the R_{xx} peaks and the neighboring minima. We interpret the dramatic shift of the minima positions with respect to Eq. (1) as an indication of modified energy spectrum due to electron-electron interactions, prevailing in ultraclean 2DES.

The widths of the zero-resistance regions, furthermore, encompass a large range of the filling factor ν. For instance, the strongest of such regions, 0.94 kG $< B <$ 1.27 kG, corresponds to a range of $155 \gtrsim \nu \gtrsim 115$ in this sample. Roughly the same widths ($\Delta\nu \approx 40$) were obtained for each of the other major minima. This fact reinforces our earlier conclusion [9] that the electronic transport here is controlled by ε rather than by ν. Notice that the SdH is absent in this weak B regime, indicating that LLs are strongly mixed and cannot be resolved at a macroscopic scale. The electron scattering times *between* LLs (especially for spin-related events), on the other hand, are found to be exceedingly long [7,9], thereby resulting in sharp R_{xx} structures.

Despite the drastic behavior in the R_{xx}, little change has been observed in the Hall resistance, R_{xy}. In $B <$ 2 kG, we have observed a classical R_{xy} trace, i.e., $R_{xy} = eB/n_e$, with $n_e \cong 3.5 \times 10^{11}$ cm^{-2}. This value is consistent within 1% with the n_e obtained from the SdH and the QHE at higher B, indicating that electrons are largely delocalized in this regime. While deviations from the linearity under MWs are noticeable, they appear to accompany only the R_{xx}-maxima but not the zero-resistance regions, and thus cannot be viewed as the precursors of the Hall plateaus. In fact, these deviations can be explained quantitatively by a trivial coupling between the components of the resistivity tensor, since δR, an increment in the R_{xx}, translates into a correction of $-\delta R/(\omega_c \tau)$ in the R_{xy} [14]. The absence of Hall plateaus and the apparent independence on ν present the main observational distinction from the QHE. Our findings thus represent, unequivocally, a new dissipationless transport effect in a clean 2DES.

We have repeated the experiment using different f and obtained similar results, as presented in Fig. 2. Typical traces recorded up to 2 kG for three selected frequencies of 35, 57, and 90 GHz are plotted against the normalized magnetic field axis, i.e., $1/\varepsilon = \omega_c/\omega$. Plotted in such a way, these traces largely collapse together, demonstrating that the observed transport behavior is generic over a wide range of frequencies. In the $f \lesssim 50$ GHz range, however, we observe additional R_{xx} maximum at $1/\varepsilon \approx 2$ and a minimum at $1/\varepsilon \approx 1.7$ (cf. the 35 GHz trace). Such features have already been visible in the previous data [9,10] but are much more pronounced here.

The following details are also worth noting. First, at all frequencies we have detected secondary peaks appearing on the higher-B shoulders of the main peaks. This is best observed for $j = 2$ (cf. vertical arrow in Fig. 2) but is also present for higher orders. Note that such peaks are consistently observed in large square samples and therefore cannot be explained by magnetoplasmon resonances previously seen in narrow Hall bars [8,9]. The B positions of such peaks shift concurrently with the main peaks, and thus do not exhibit the characteristic dispersion of the plasmon modes. Second, a close inspection of the data in lower-B range [cf. inset (a) in Fig. 2 for $f = 57$ GHz] reveals beats in R_{xx}; such beats were also observed at other frequencies.

The emergence of the zero-resistance regime dramatically depends on the MW power as well as the temperature. As an example, we present power-dependent R_{xx} at a constant $T \approx 1$ K, for $f = 57$ GHz, in inset (b) of Fig. 2. The incident power, P, on the sample surface was varied from 1 μW, when the oscillations start to appear, up to 100 μW, in 5 dB increments. As can be clearly seen, with increasing P, the R_{xx} at the major minima becomes progressively smaller and eventually reaches zero. The R_{xx} at the maxima was found to be linear with P within the P-range studied.

As far as the T dependence of the R_{xx} is concerned, transport at the minima is remarkably reminiscent of the QHE. In Fig. 3(a) we plot $R_{xx}(B)/R_{xx}(0)$ traces versus $1/B$(rather than B), recorded at a constant T (from 0.9 to 3.5 K), constant $P \approx 100$ μW, and $f = 57$ GHz. As typically observed in the QHE regime, zero-resistance regions first become narrower and eventually disappear with increasing T; the peaks diminish as well. Note that while the oscillatory structure disappears in the high-T limit ($T \gtrsim 4$ K), the $R_{xx}(B)$ is not restored to its dark value; it becomes essentially flat as opposed to the dark trace in Fig. 1.

At intermediate temperatures, the minima become sharply defined, allowing us to measure their B positions with a refined resolution. Surprisingly, the first few minima seem to form their own sequence, roughly periodic in

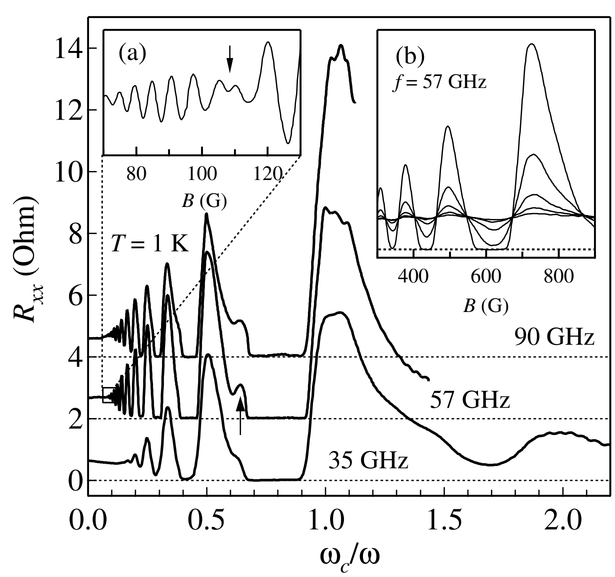

FIG. 2. R_{xx} ($T \approx 1$ K) under MW illumination for $f = 35$, 57, and 90 GHz are plotted against the ω_c/ω (vertically offset for clarity). The vertical arrow marks the secondary peak. Inset (a) expands the low-B part of the $f = 57$ GHz trace showing the beats at $B \lesssim 0.1$ kG. Inset (b) shows the R_{xx} at $f = 57$ GHz for different MW power from 1 μW to 100 μW in 5 dB increments.

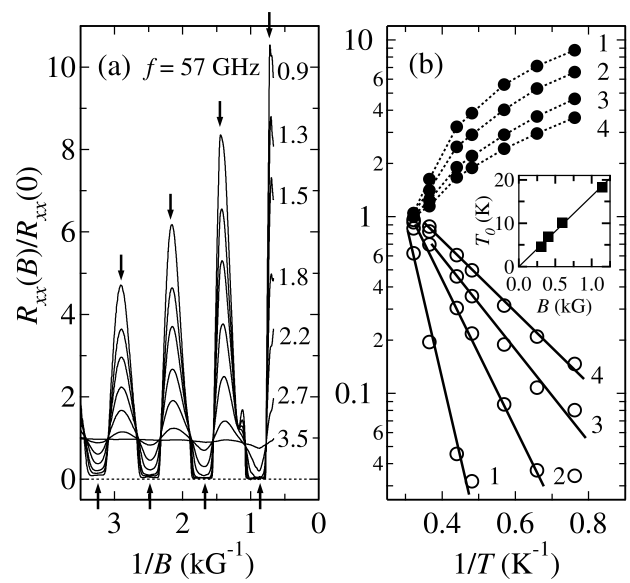

FIG. 3. (a) $R_{xx}(B)/R_{xx}(0)$ under MW ($f = 57$ GHz) illumination, plotted vs $1/B$ at different T from 0.9 to 3.5 K. Upward arrows mark positions of the minima suggesting a roughly periodic series in $1/B$. (b) $R_{xx}(B)/R_{xx}(0)$ at the minima series (open circles) and at the $j = 1$, 2, 3, and 4 maxima series (solid circles), as a function of $1/T$. Solid lines are fits to $R_{xx}(T) \propto \exp(-T_0/T)$. The inset shows the values of the fitting parameter T_0 as a function of B.

$1/B$, as marked by the upward arrows in Fig. 3(a). The period of the minima sequence is about 20% larger than that of the peaks. We may, without resorting to a specific theoretical model, take this as spectroscopic evidence that such minima occur at energy intervals about 20% blueshifted from the cyclotron transitions $j\hbar\omega_c$.

Using standard Arrhenius plot, we present in Fig. 3(b) the $R_{xx}(B)/R_{xx}(0)$ of the first four minima (open circles) and maxima (filled circles) on a logarithmic scale, versus $1/T$. All four minima conform to a general expression, $R_{xx}(T) \propto \exp(-T_0/T)$, over at least one decade in R_{xx}. We therefore conclude that the resistance in these regions vanishes exponentially with decreasing T.

Quantitatively, an unusually large energy scale appears to be associated with such minima. For example, for the first minimum we extract $T_0 \simeq 20$ K. This value exceeds both the MW energy ($\hbar\omega \simeq 3$ K) and the LL spacing ($\hbar\omega_c \simeq 2$ K) by about an order of magnitude. Furthermore, by deducing the T_0 at other minima, we observe a rough linearity between T_0 and B with a slope of $\simeq 18$ K/kG (cf. inset in Fig. 3). Overall, the T dependence of the R_{xx} in this regime cannot easily be reconciled with any simple model based on a single-electron spectrum in a weak magnetic field.

In conclusion, we have reported for the first time the evidence for a new dissipationless transport effect, experimentally observed in an ultraclean 2DES in crossed MW and weak B fields. By varying a single experimental parameter, namely, the mobility of the 2DES, we find a dramatic transition from SdH-like MW photoconductivity oscillations in a moderate-mobility 2DES to zero-resistance states in an ultraclean 2DES.

The exact nature of such extraordinary electronic transport is presently unclear. Among possible explanations we may consider the magnetoexcitations and their condensations in the 2DES promoted by MW pumping. There exist in this system at least three types of fundamental processes that need to be taken into consideration. The first is the cyclotron transitions between LLs separated by $j\hbar\omega_c$, which can be related to the B positions of the strong R_{xx} peaks observed previously [9,10], and confirmed again in this experiment. The second is spin-dependent cyclotron transitions, with energy shifts due to Zeeman splitting in a weak magnetic field. Such transitions become possible due to spin-orbital coupling effects, but are difficult to resolve because the bare g-factor in GaAs is rather small. However, it remains to be seen whether or not the beats seen in a very weak B are in effect a manifestation of such transitions. And the third, magnetoexcitons and magnetoplasmon modes [15] could be relevant although one must consider such entities in the weak magnetic field limit. A dense 2DES in a weak magnetic field, where many LLs are occupied, is believed to exhibit unique properties due to modified electron-electron correlations [16]. In particular, a 2D electron liquid must be favored in the ultraclean systems. Low-energy (on the MW scale) magnetoexciton formed between the excited electron and the hole created in the liquid, in a weak magnetic field, is an attractive candidate for considering the mechanism related to dissipationless transport. In principle, 2D excitonic condensates could exhibit superfluidity at low temperatures. Possible edge excitations and their condensates, which support dissipationless transport, would be interesting to examine in the context of our experiments.

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