Observation of Microwave-Induced Zero-Conductance State in Corbino Rings of a Two-Dimensional Electron System

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Using Corbino samples we have observed oscillatory dc conductance in a high-mobility two-dimensional electron system when it is subjected to crossed microwave and magnetic fields. At the strongest of the oscillation minima the conductance is found to be vanishingly small, indicating a macroscopic insulating state associated with this minimum. With increasing voltage bias, a crossover from Ohmic to electron-heating regime is observed.

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Interesting new phenomena in dc transport can arise in a high-mobility two-dimensional electron system (2DES) when it is subjected to microwave (MW) radiation [1–4]. Giant MW photoconductivity oscillations (in $1/B$, the inverse magnetic field) were first observed in a 2DES in $GaAs/Al_xGa_{1-x}As$ heterostructures with a mobility $\sim 3 \times 10^6$ cm^2/Vs [1,2]. In samples of a very high mobility (typically $> 1 \times 10^7$ cm^2/Vs), it was subsequently found that the major oscillation minima can develop into a "zero-resistance state" (ZRS) under sufficient MW excitations [3,4]. The ZRS exhibits an exponentially small diagonal resistance and an essentially classical Hall resistance at low temperatures. The origin of the oscillations and the mechanism leading to ZRS are of considerable current theoretical interest [5–12]. Several models based on oscillatory density of states and negative dc response of the 2DES to a driving ac field are proposed [6–9], possibly providing a simple and physically transparent mechanism for the oscillations. In fact, the ideas of negative photoconductivity in semiconductors can be traced back to much earlier theoretical work [13,14]. The ZRS, it follows, is thought to result from an instability caused by the negative response and consequent redistribution of electric currents [7,8]. In particular, inhomogeneous phases consisting of density fluctuation and electrical current (or electrical field) domains could be formed in a 2DES [7–9,11]. Other models consider either the electron orbital dynamics and the formation of a sliding charge-density wave [5], or an interplay between the bulk and edge magnetoplasmon modes which could lead to oscillations [12]. A classical mechanism based on nonparabolicity of the electron dispersion is proposed in Ref. [10].

A general feature of the 2DES transport is that the resistivity and conductivity are fundamentally related; their relation in the microwave-induced dc transport is the subject of this work. It is well known [15] that, in the quantized Hall effects, a vanishing diagonal resistivity (ρ_{xx}) is equivalent to a vanishing conductivity (σ_{xx}) and these two quantities relate to each other by

$$\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2) \approx \rho_{xx}/\rho_{xy}^2 = (n_e e/B)^2 \rho_{xx}, \quad (1)$$

where n_e is the electron density. Experimentally, it remains unclear whether Eq. (1) holds for the microwave-induced effect. This question is relevant, in particular, when considering the theoretical proposal of the underlying inhomogeneous phases.

In this Letter, we report on a MW-induced electronic state of vanishing dc *conductance* observed in Corbino samples of a high-mobility 2DES. Corresponding to ZRS, such a state may be termed a "zero-conductance state" (ZCS). The experiments demonstrate that, regardless of the presence of the MW fields, the conductance and resistance are invertible according to Eq. (1), up to a scaling factor; hence, the observed ZCS is equivalent to ZRS. Macroscopically, the 2DES behaves like an insulator in the ZCS regime. Such an observation from a topologically distinct sample may impose new constraints on theoretical models.

Our samples were cleaved from a $Al_{0.24}Ga_{0.76}As/GaAs/Al_{0.24}Ga_{0.76}As$ quantum well (QW) wafer grown by molecular beam epitaxy. The width of the QW is 25 nm and the electrons are provided by Si δ-doping layers 80 nm above and below the QW. After illumination by a red light-emitting diode at $T \approx 1.5$ K, the electron density, n_e, and mobility, μ, reached 3.55×10^{11} cm^{-2} and 12.8×10^6 cm^2/Vs, respectively. The Corbino samples, with an inner diameter $d_1 \approx 0.5$ mm and an outer diameter $d_2 \approx 3.0$ mm, were made on a $\sim$4 mm $\times$ 4 mm square. Ohmic contacts were made of indium. To compare the conductance measurement with a resistance measurement, a $\sim$4 mm $\times$ 4 mm square sample (from the same wafer) was made with eight indium contacts placed along the perimeter. The measurements were performed in a sorption-pumped ^{3}He cryostat equipped with a superconducting magnet; the magnetic field was

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calibrated using a low temperature Hall sensor. The microwaves were generated by Gunn diodes and guided down to the sample (Faraday configuration) via an oversized (WR-28) waveguide. Except for the I-V characteristics, the conductance or resistance traces were recorded employing a low-frequency (2.7 Hz) lock-in technique while the sample was immersed in ^{3}He liquid and under continuous microwave irradiation of fixed frequency, f, and power, P.

The diagonal conductance, $G_{xx} = I/V$, of the Corbino sample was obtained by measuring the current (I) passing through the 2DES, while applying a voltage (V) between the inner and outer contacts. Here x denotes the direction along the radius. A typical bias of $V \sim 1$ mV was used for the measurements.

Without the MWs and while sweeping the magnetic field, the G_{xx} trace shows sequentially, in Fig. 1(a), a Drude conductance around $B = 0$, sharp Shubnikov–de Haas (SdH) oscillations at $B \gtrsim 1.5$ kG, and vanishing conductance at the integer quantum Hall effect (IQHE) minima at $B \gtrsim 10$ kG. The trace is strictly symmetrical with respect to $B = 0$, indicating that the recorded G_{xx} is essentially free of mixture with the Hall conductance. Altogether, such standard dc magnetotransport data attest exceptional quality of the Corbino sample. We note that at this temperature a residual conductance in the IQHE remains measurable. For example, at Landau level filling factor $\nu = 4$, its value is typically $\lesssim 5 \times 10^{-7}$ S, which is $\sim 10^{-7}$ of the conductance at $B = 0$. Finite residual conductance in the IQHE is commonly attributed to thermally activated conduction [16] or variable-range hopping conduction [17].

Figure 1(b) shows a G_{xx} trace with the MW frequency $f = 57$ GHz and an incident power $P \approx 10\ \mu$W on the sample surface. Notice that the temperatures marked in both 1(a) and 1(b) are those measured in the ^{3}He liquid. Strong MW-induced conductance oscillations up to 5 orders are observed. The peaks are marked by $\varepsilon \equiv \omega/\omega_c = 1, 2, 3, \ldots$, where $\omega_c = eB/m^*$ is the cyclotron frequency, $m^* = 0.068\, m_e$ is the GaAs conduction band electron mass, and $\omega = 2\pi f$.

Our central finding from such measurements, however, concerns the vanishing-conductance state observed at the strongest oscillation minimum, around $B = \pm 1.05$ kG. Such a state spans a wide range of Landau level filling factors, $\nu = n_e h/eB$, from $\nu \sim 160$ to $\nu \sim 120$. Similar to the resistance measured in the ZRS, the conductance in the ZCS is found to be thermally activated. The temperature-dependent conductance at $B = 1.05$ kG (the center of the strongest minimum), corresponding to two different MW power levels, is shown in Fig. 2. The activated conductance spans almost one decade and can be reasonably fitted by an exponential dependence $G_{xx} \propto \exp(-T_0/T)$, with an activation energy $T_0 \approx 4.5$ K (9.3 K) for $P \approx 10\ \mu$W (100 μW). Comparing the value 9.3 K with the $T_0 \approx 20$ K measured under a similar magnetic field and MW power, but in the ZRS of a cleaner sample [4], we interpret that the activation energy in this regime strongly correlates with the sample mobility.

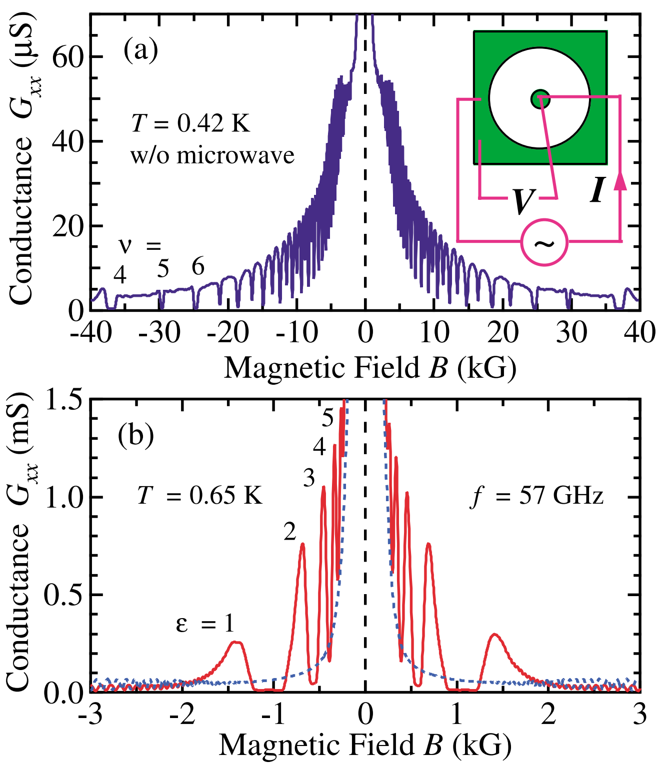

FIG. 1 (color online). (a) Magnetoconductance of a Corbino sample (without MW irradiation) is shown to exhibit sharp SdH oscillations at low magnetic field and vanishing IQHE minima at high magnetic field. The inset depicts the geometry of the sample and the measurement circuit. (b) The conductance oscillations observed in the Corbino sample with microwave irradiation. A vanishing-conductance state at the first minimum is observed. A trace without MW irradiation (dotted line) is also presented for comparison.

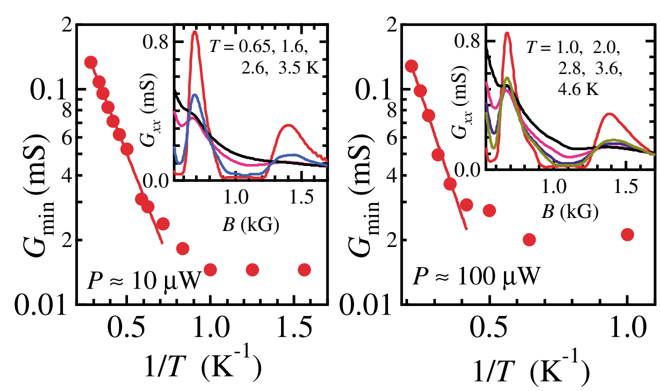

FIG. 2 (color online). The conductance at the center of the first minimum for $f = 57$ GHz with $P \approx 10\ \mu$W (left panel) and $P \approx 100\ \mu$W (right panel), plotted against $1/T$. The insets show the conductance traces around the minimum at selected temperatures. Solid lines represent fits to $G_{xx}(T) \propto \exp(-T_0/T)$.

On the other hand, we observed a drastic departure from the activated behavior in the lower temperature regime $T < 1$ K (2 K) for power level $P \approx 10\ \mu$W (100 μW). In particular, the conductance becomes flat at reduced temperatures, rendering a residual conductance, $G_{xx} \lesssim 2 \times 10^{-5}$ S, at the lowest T of the experiment, $T \approx 0.65$ K. Whether or not such a residual conductance is intrinsic in the ZCS regime is an open question. In our experiment it could be partially attributed to a parallel conduction channel excited by MWs in the sample material. In fact, we observed an enhanced residual conductance at $\nu = 4$ IQHE (from 5×10^{-7} S to 22×10^{-7} S) due to the same MW irradiation.

It is interesting to compare the residual *conductivity* in the ZCS with the conductivity quantum e^2/h. Considering the geometric factor of the Corbino sample and assuming a uniform distribution of the electric current passing through the contacts, we estimate a residual conductivity $\lesssim 6 \times 10^{-6}$ S, which is much less than e^2/h. We therefore conclude that the 2DES behaves like an insulator in the ZCS regime.

In order to compare the MW-induced conductance oscillations with the resistance oscillations, we calculate a diagonal conductance (G'_{xx}) from a diagonal resistance (R_{xx}) measured on a square sample, using the inversion relation $G'_{xx} \approx R_{xx}/\rho_{xy}^2 = (n_e e/B)^2 R_{xx}$. The quantity which can be directly compared between different samples is not the conductance but the conductivity. Since the conductivity is proportional to the conductance, we can normalize the conductance to a specific point B_0 (e.g., the first maximum of the oscillations), and compare the normalized conductances g_{xx} [$\equiv G_{xx}(B)/G_{xx}(B_0)$]. Figure 3 displays both the g_{xx} measured from the Corbino sample and the g'_{xx} converted from R_{xx} measured on a square sample. The R_{xx} of the square sample, measured under the same conditions as the G_{xx} ($T = 0.65$ K, $f = 57$ GHz, $P \approx 10\ \mu$W), is also shown in Fig. 3. Excellent agreement between the g_{xx}'s clearly demonstrates that, under MW irradiation the dc conductance and resistance remain invertible up to a scaling factor.

We have also measured the *I-V* characteristics in the ZCS regime. In order to establish a constant bias voltage (V) across the contacts of the Corbino sample, a dc voltage was applied and the dc current (I) was measured using a current amplifier. The signal was then averaged using a pair of B sweeps with alternating bias polarity. Under the same experimental conditions the conductance traces measured in this way are nearly identical to that measured using a low-frequency lock-in technique (quasi-dc, shown in Fig. 1). The inset of Fig. 4 shows G_{xx} (dc) traces around the ZCS minima taken with different bias voltages. Notice that the G_{xx} is shown on a logarithmic scale; similar to that found in quasi-dc measurements, a small residual conductance ($G_{xx} \lesssim 1.5 \times 10^{-5}$ S, at 1 mV) can be seen at low temperatures. On this scale the ZCS minimum exhibits a reproducible doublet shape.

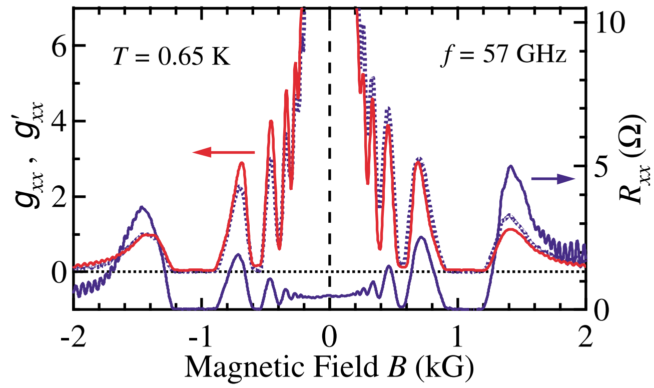

FIG. 3 (color online). The measured g_{xx} (normalized conductance, as defined in the text) of a Corbino sample is shown together with a g'_{xx} (dotted line) inverted via Eq. (1) from R_{xx} measured on a square sample. An excellent agreement between the measured g_{xx} and g'_{xx} is found.

Linear electrical transport is observed in ZCS in a large range of bias up to 10 mV in this sample. In Fig. 4 we present an *I-V* curve measured on ZCS for a MW frequency $f = 57$ GHz, along with a G_{xx}-V curve. A linear *I-V* regime can be found for small bias, $V < 10$ mV, followed by a nonlinear regime, $V > 10$ mV, where a marked increase of conductance is observed.

Before discussing the origin of the nonlinear regime it is useful to estimate the electrical field strength in the bulk of the 2DES. Note that the electrical field, E_x, along the radius of the Corbino ring, depends on the radial position; in our samples the E_x on the inner perimeter is about 6 times of that on the outer perimeter. The top

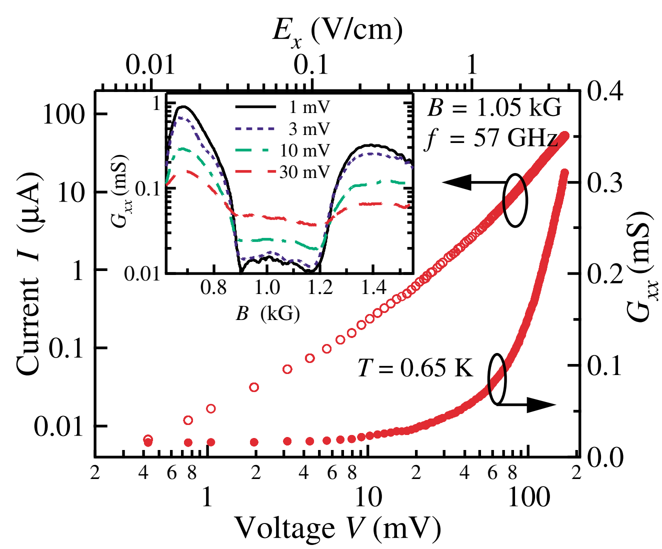

FIG. 4 (color online). Current, I (left axis) and the deduced conductance, G (right axis) at the first minimum as a function of applied bias voltage V. Microwave power is approximately 10 μW. Top axis shows an estimate for maximum (close to the inner perimeter of the Corbino sample) electric field, E_x. The inset shows conductance traces at selected bias voltages.

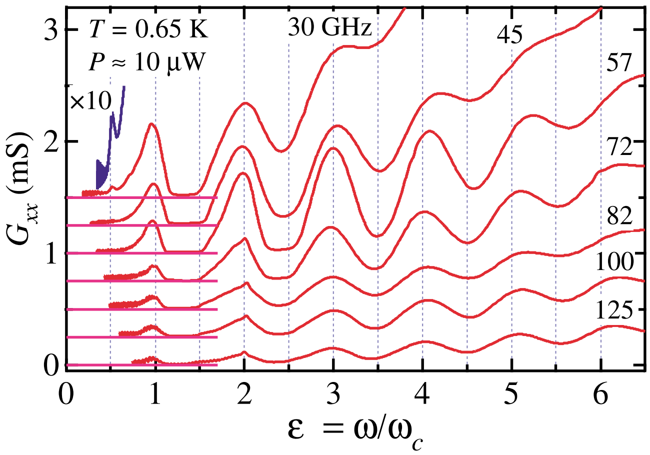

FIG. 5 (color online). The conductance oscillations of the Corbino sample for selected MW frequencies with roughly the same $P \approx 10\ \mu$W and $T \approx 0.65$ K (for clarity, traces are vertically shifted in steps of 0.25 mS), plotted against $\varepsilon = \omega/\omega_c$ with $m^* = 0.068\, m_e$. For all frequencies, strong oscillations and the vanishing-conductance state are observed.

axis of Fig. 4 shows the estimated maximum E_x (i.e., on the inner perimeter).

Our data at large bias, $V > 10$ mV, can be interpreted as due to an electron-heating effect in the presence of a bias E_x approaching 1 V/cm. One of the possible mechanisms for such a heating effect is the Zener tunneling between Landau orbits at a low magnetic field, relevant to the ZCS regime. We have observed Zener tunneling effect [18] at a magnetic field ~1 kG where the conductance of a 2DES exhibits sharp peaks due to the opening of new scattering channels. Such tunneling events take place at a characteristic electrical field of ~1 V/cm. It appears possible that Zener tunneling between Landau orbits occurs in some part of the Corbino sample giving rise to the nonlinear conductance. Variable-range hopping conductance can also be promoted by an increasing E_x [17].

In addition, we have measured the conductance at different MW frequencies (from 25.5 to 130 GHz) but at roughly the same MW power $P \approx 10\ \mu$W (on the sample surface) and the same temperature $T \approx 0.65$ K. Selected conductance traces against $\varepsilon = \omega/\omega_c$ are shown in Fig. 5. Strong oscillations as well as the ZCS are observed at all MW frequencies. The period and the phase of the oscillations seen here are consistent with those observed in ZRS [4,19]. We also notice a trend in which the strength of the oscillations, as measured by the peak height, is decreasing with increasing frequency. Such an observation can be partially accounted for by the number of photons incident on the 2DES. Since the MW power is roughly the same, the number of photons is inversely proportional to the MW frequency, leading to a diminishing of the oscillations at higher f. For $f < 40$ GHz, an additional maximum at $\varepsilon \approx 1/2$ is observed; an example can be seen on the $f = 30$ GHz trace. Such additional peaks have been previously seen in the ZRS experiments [4] and could be attributed to multiple-photon processes [19].

In conclusion, we have observed a MW-induced vanishing-conductance state in a high-mobility 2DES of Corbino geometry. Combining both the ZCS (in a Corbino sample) and ZRS (in a Hall bar sample), we present evidence for a new dissipationless 2D electronic transport effect induced by microwaves. While the effect is driven by an ac field, the dc conductivity and the resistivity are found to be invertible using the standard dc transport tensor relation. The electrical transport in ZCS regime is Ohmic in the small bias limit; at larger bias, the transport is dominated by electron heating. Such observation indicates that the ZCS is remarkably robust, a fact which is consistent with an unusually large energy scale associated with the effect. How such macroscopic properties relate to the theoretical models, especially to the proposed inhomogeneous phases [7–9,11], is an open subject for experimental and theoretical work.

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