Anticorrelation of compressibility and resistivity in a microwave-irradiated two-dimensional electron system

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We report our direct study of the compressibility on an ultrahigh mobility two-dimensional electron system ($\mu_e \sim 1{\times}10^7$ cm^2/V s) in GaAs/AlGaAs quantum wells under microwave irradiation. The field penetration current results show that the quantum capacitance oscillates with microwave-induced resistance oscillations, however, the trend is opposite with respect to the compressibility of equilibrium states in previous theoretical explanations. The anomalous phenomena provide a platform for study on the nonequilibrium system under microwaves. Moreover, the quantum capacitance indication for a multiphoton process around $j = 1/2$ is detected under an intensive microwave below 30 GHz.

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I. INTRODUCTION

The two-dimensional electron system (2DES) is a paradigmatic platform of condensed matter physics. In recent years, the ultraclean 2DES under microwave (MW) irradiation has emerged as a model system of nonequilibrium phenomena [1]. In particular, the magnetoresistance oscillates periodically [2,3] with $j = \omega/\omega_c$, in which ω is the microwave frequency, $\omega_c = eB/m^*$ is the cyclotron frequency, and m^* is the electron effective mass. Zero-resistance states (ZRS) may form at the dips of microwave-induced resistance oscillation (MIRO) around $j = n + 1/4$ (n is an integer) [4,5]. The MW-induced nonequilibrium states can also be probed by different techniques, including magnetoconductance in Corbino geometry [6] and contactless measurements with coplanar waveguides [7].

Various microscopic mechanisms of MIRO have been proposed, including the disorder-assisted inter-Landau-level transition (the “displacement” mechanism) [8], the microwave-induced nonequilibrium steady state (NESS) distribution (the “inelastic” mechanism) [9,10], the semiclassical model of microwave-driven time-dependent orbits [11], etc. [12–14]. It was argued that the inelastic mechanism is dominant especially for moderate microwave power [15]. Microwave-induced nonequilibrium distribution was observed in a two-subband 2DES with a geometric magnetocapacitance [16]. On the other hand, ZRS was attributed to the spontaneous

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formation of current domains in negative conductance states [8] irrespective of the microscopic origin of MIRO. The current domains are observed in experiments [17,18].

The compressibility is a thermodynamic signature of 2DES. In equilibrium the compressibility κ is proportional to the density of states (DOS) at the Fermi level, $\kappa = (1/n^2)(dn/d\mu)$, in which n is the carrier density and μ is the chemical potential. Based on near-equilibrium distribution, the compressibility in the MIRO regime is predicted to oscillate in phase with the resistance signal [19]. Experiments on very dilute (nondegenerate) electrons on liquid helium indicate that the transitions between the two sets of shifting Landau levels are incompressible [20]. An unpublished experiment based on the single electron transistor (SET) suggested the oscillatory properties of local compressibility [21], but the results contain irregularities and vary with the SET position and microwave frequency. Therefore, it is important to directly measure the compressibility of degenerate 2DES under microwave irradiation in order to clarify the nonequilibrium property.

In this paper, we adopt the penetrating current technique [22] to directly measure the compressibility of 2DES under microwave irradiation. The compressibility oscillates in phase with the Shubnikov–de Haas (SdH) effect of the resistivity in high magnetic fields. However, we find unexpectedly that the compressibility anticorrelates with the resistivity in the MIRO regime in low magnetic fields, i.e., the compressibility shows maxima at the resistivity minima, and vice versa, which is in sharp contrast to the behavior in the SdH regime and the theoretical prediction [19]. It thus calls for a more complete understanding of the nonequilibrium dynamics of the interacting 2DES.

II. METHOD

The wafer used in our experiments is a high-quality, *in situ* back-gated GaAs/$Al_{0.24}Ga_{0.76}As$ quantum well (QW) grown by molecular beam epitaxy [23]. The 30-nm-wide QW is located about 200 nm beneath the sample surface, and the highly n^+-doped *in situ* gate is 850 nm below the QW. The electron density and mobility are $n_e \sim 1.6\times10^{11}$ cm^{-2} and $\mu_e \sim 1.0\times10^7$ cm^2/V s below 4 K.

To fabricate a device for our study, we define an 800 μm$\times$800 μm square mesa with six arms by UV lithography and wet etching. Ohmic contacts are made by an 8/80/160/36 nm stack of Ni/Ge/Au/Ni metals. The alloy front gate is deposited on the device which is transparent for MW irradiation. The measurements are carried out in a ^{3}He refrigerator with a base temperature of 0.3 K, and the microwave is guided down to the base via a WR-28 waveguide.

The prototypical method of studying the quantum capacitance C_q is to directly measure the capacitance C between the 2DES and a gate electrode, $\frac{1}{C} = \frac{1}{C_q} + \frac{1}{C_g}$ (C_g is the geometric capacitance). But it is difficult to extract C_q from C, because $C_q \gg C_g$. Recent experiments reported (geometric) magnetocapacitance measurements [16,24], which are distinct from our study. In this paper, we adopt the penetrating current technique [22] to directly measure the compressibility of the 2DES, which has been successfully applied to the interacting two-dimensional systems in equilibrium [25–27]

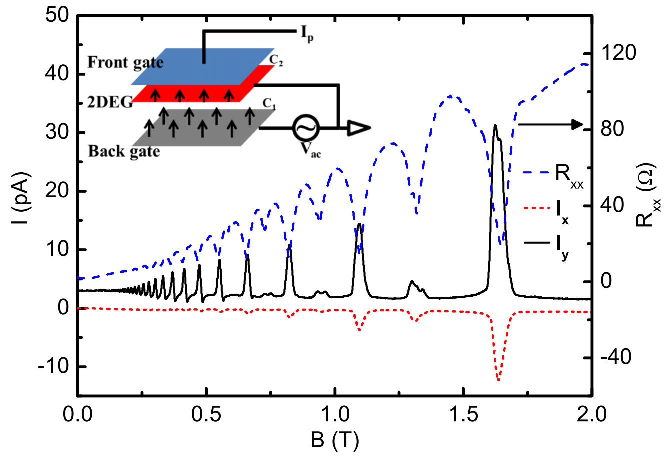

FIG. 1. Magnetoresistance, x component I_x, and (90° phase) y component I_y of the penetration current at 300 mK. The inset shows the sketch of the measurement setup.

[see the Supplemental Material (SM) of Refs. [1,2]]. The experimental setup with the sandwichlike device structure is illustrated in the inset of Fig. 1. The 2DES is grounded to screen the electric field. A 20-mV ac excitation V_{ac} is applied to the back gate, and the penetrating current I_p is detected from the front gate. According to Dultz and Jiang [26] (see SM of Ref. [1]), in the low-frequency limit, the in-phase component I_x is proportional to $-1/\sigma_{xx}$ (σ_{xx}: conductivity), and the 90° phase I_y ($I_y \equiv I_p$) is proportional to $1/C_q$ or $1/\kappa$.

III. RESULTS

We first present the results of the quantum capacitances of equilibrium states without microwave irradiation: the Shubnikov–de Haas (SdH) oscillations and the integer quantum Hall effects (IQHEs). Figure 1 shows the traces of I_x, I_y, and the magnetoresistance R_{xx} as a function of B (without irradiation) at 300 mK. The frequency of ac voltage V_{ac} is 91 Hz. The R_{xx} exhibits IQHE features and reaches minima at the integer fillings. Meanwhile, the current components I_x and I_y show maxima of their absolute values, which indicates that κ and σ_{xx} are approaching zero in the IQHE insulating regime. When the Fermi level is located in the gap between two adjacent Landau levels, the DOS tends to be zero, and the electron states become more incompressible ($\kappa\downarrow$). These experimental results can be easily explained with the classical theory of Landau levels. When the Fermi level is located in the center of a Landau level, I_y presents a minimum, and the compressibility reaches a maximum.

The method of the quantum capacitance study can be simplified [22,26] as shown in the inset of Fig. 1, where C_q is illustrated with the geometric capacitances C_1 and C_2. Based on the I-V characterization, we estimate the capacitances of $C_1 = 360$ pF and $C_2 = 45$ pF, and a reasonable estimation of C_q is 63 nF in the absence of magnetic fields. So far we have provided the proof for the validity and quality of our devices; I_x and I_y both meet the ac-frequency criteria of the quantum capacitance model [26] (see SM for Ref. [1]), and the details are shown in our SM [28].

We apply the penetrating current technique to the nonequilibrium states under microwave irradiation. Figure 2(a)

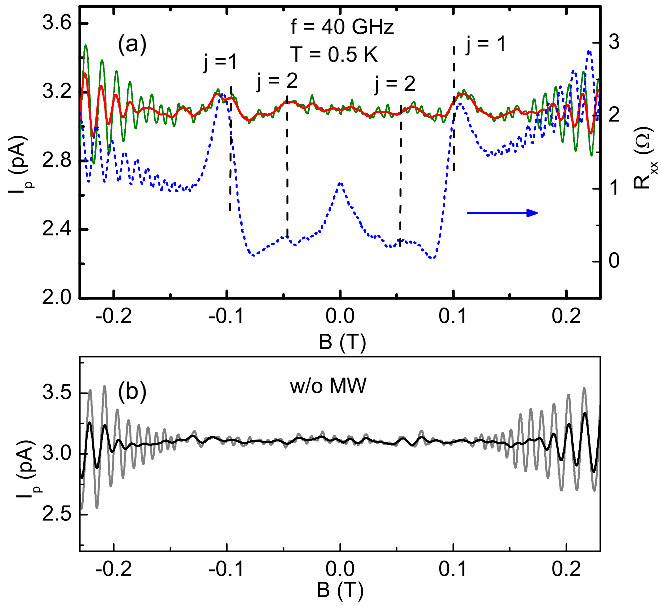

FIG. 2. (a) The magnetoresistance (blue dotted curve) and the penetrating current I_p under a 40-GHz MW. The red I_p curves indicate the smoothed results by the FFT method. (b) The penetrating current without MW is also shown (by the gray curve). The black I_p curves indicate the smoothed results by the FFT method.

presents the longitudinal resistance (blue dotted curve) under a 40-GHz MW at 0.5 K. R_{xx} shows strong MIRO features and a tendency to form ZRS. The feature of MIRO in our study is fully consistent with previous experiments.

Figure 2(a) also shows the penetrating current I_y with MW irradiation (the green curve). We notice that I_y oscillates weakly with magnetoresistance when the device is irradiated by MW. However, sharply different from the SdH oscillations, the current I_y exhibits opposite trends. It reaches maximal values at the maximum resistances of MIRO. On the contrary, at the maximal resistances of SdH oscillations, I_y reaches minima, which is consistent with the Landau level spectrum. In the low B MIRO regime at 40 GHz, C_q decreases at the resistance maximum, and increases at the R_{xx} minimum. Considering that the I_p signals are very small and noisy at low magnetic fields, we use the fast Fourier transform (FFT) method to filter out noise in order to highlight the MIRO signals. For the sake of comparison, the MR and I_p for the sample without MW are displayed in Fig. 2(b). It is evident that the averaged trace (envelope) in the MIRO regime is not weaker than the amplitudes in the SdH oscillation regime.

The specific features of MW-induced nonequilibrium are more visible if we comparatively study κ ($\propto 1/I_y$) and R_{xx} as shown in Fig. 3. The plot can be separated into two parts: the MIRO regime in weak magnetic fields and the SdH oscillation regime in high fields. The MIRO features dominate below 0.13 T, and the SdH oscillations are fully developed above 0.13 T. Qualitatively, the κ minima appear around the maximal resistances in the MIRO regime, whereas the maximal DOS exists at maximal MR in the SdH regime. Quantitatively, the amplitudes of $1/C_q$ oscillations ($j = 1, 2$) are at the same level as those of SdH oscillations. The $j = 1, 2$ amplitudes of κ are much larger than those at the onset of SdH oscillations.

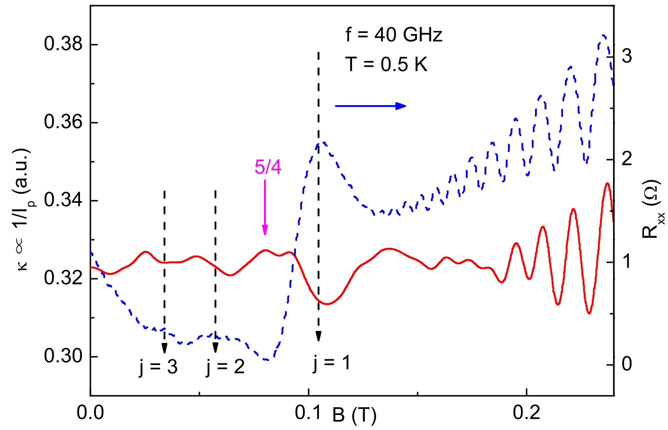

FIG. 3. The compressibility ($\kappa \propto 1/I_p$) and the magnetoresistance (blue dotted curve) under 40-GHz microwave: The minima exist around the integer $j \sim 1, 2, 3$.

The maximal κ around $j \sim 5/4$ is marked by the pink solid arrow. In general, the features are symmetric in B, repeatable with different samples and conditions, and vary linearly as a function of MW frequency. Therefore, the anticorrelation of the compressibility and the resistivity in the MIRO regime is the intrinsic property of the nonequilibrium 2DES and cannot be attributed to noise, etc.

In our device, the microwave is weakened by the metallic top gate to some degree. To compensate for this, the quantum capacitance signals can be strengthened by raising the MW power (P). The P-dependent penetrating currents at 30-GHz MW are shown in Fig. 4. At first sight, the relation between the magnetoresistance and the quantum capacitance for 30-GHz microwave is very similar to that for 40 GHz shown in Fig. 2. The amplitudes of SdH oscillations are weakened by MW power owing to the heating effect. The peak at $j = 1$ (marked by dashed lines) is strengthened at 8 and 12 dBm power. The peak position of I_p shifts slightly to higher B and the minimum position shifts slightly to lower B

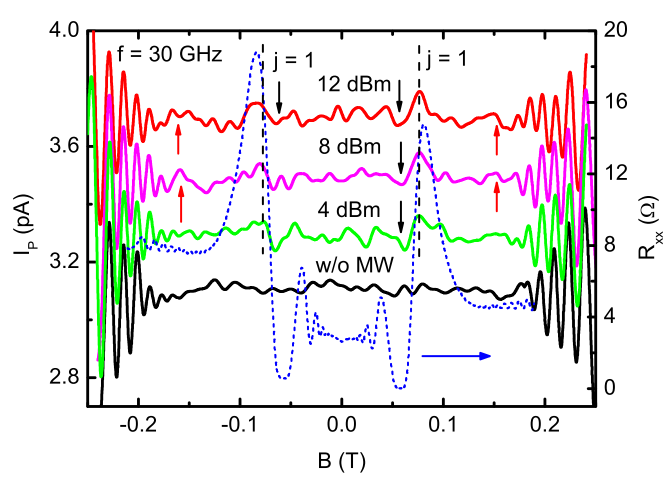

FIG. 4. Power-dependent I_p under 30-GHz MW: MW-off, 4, 8, and 12 dBm curves are in black, green, pink, and red, respectively. The black downward arrows mark the ZRS, the dashed lines mark the feature at $j = 1$, and the red arrows mark the multiphoton process at $j = 1/2$ at high power. R_{xx} is shown by the blue dotted curve.

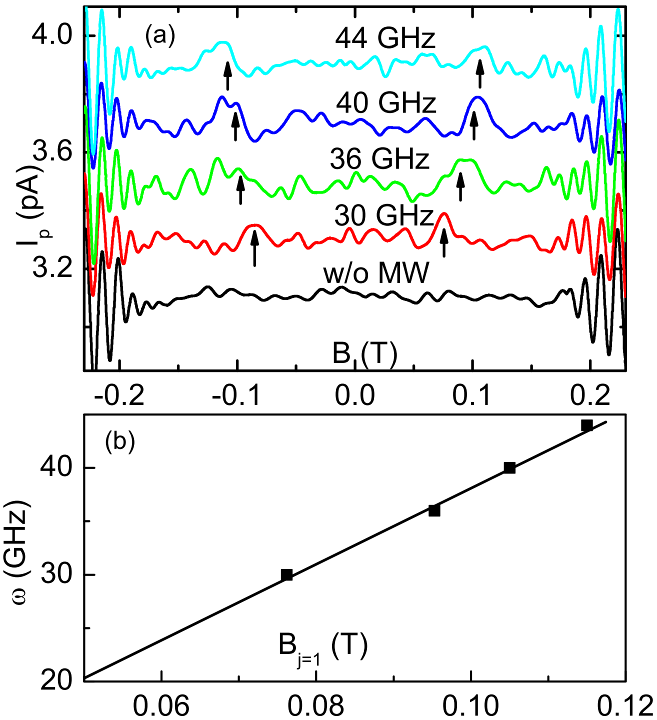

FIG. 5. (a) The frequency-dependent I_p at 30–44 GHz. The indications at $j = 1$ are marked by arrows. (b) The MW frequency vs B field of the $j = 1$ peak.

with power, which is in agreement with the P-dependent MR features [5], and can be explained by the enhancement and broadening of the resonance peak in high MW power. The C_q oscillations can be strengthened gradually by increasing MW power. However, at the highest power regime above 15 dBm, the C_q oscillations can be weakened by the heating effect on electrons.

In addition, in the traces of 8 and 12 dBm, we observe the indication of multiphoton processes at $j = 1/2$ [29], which is marked by red arrows in Fig. 4. This feature appears only under high MW power, and it cannot be detected in magnetoresistances in our gated devices. As far as we know, the multiphoton process for MIRO has only been reported below 30 GHz.

The penetrating currents for MIRO and ZRS at $f \sim 30$–44 GHz are presented in Fig. 5(a). The I_p traces are very symmetric with respect to magnetic fields. Each microwave-f curve exhibits a peak at $j = 1$ and a valley in the region of $j \sim 1$–2. With increasing MW frequency, the I_p expands along the B axis. In addition, as shown in Fig. 5(b), the $j = 1$ peak position in the magnetic field is proportional to MW frequency, which is in accordance with the magnetoresistance results quantitatively. Similar findings are obtained even for much higher frequency (∼102 GHz, see SM [28]). Although the guide of high-frequency power is less efficient, indications of the penetrating current are still clearly observed, especially for the minima around $j \sim 5/4$.

IV. SUMMARY AND DISCUSSION

To summarize, we have measured the compressibility (the quantum capacitance) of a 2DES irradiated by microwave. Our key finding is the anticorrelation of the compressibility and the DC resistance in the MIRO regime, which is in sharp contrast to their correlation in the SdH regime both in equilibrium and under microwave irradiation in higher magnetic fields.

The anticorrelation brutally violates the theoretical prediction that the compressibility would oscillate *in phase* with the resistance [10]. This prediction was made on the basis of the microwave-induced correction to the electron distribution $f(\epsilon) = f_T(\epsilon) + \delta f(\epsilon)$,

$$\delta f(\epsilon) \propto \partial_\epsilon f_T(\epsilon) \sin\frac{2\pi\epsilon}{\omega_c} \sin\frac{2\pi\omega}{\omega_c}, \quad (1)$$

in which $f_T(\epsilon)$ is the equilibrium Fermi distribution. It has been argued that the nonequilibrium steady state (NESS) characterized by the distribution $\delta f(\epsilon)$ is the major physical consequence of the microwave irradiation and is dominant in accounting for the MIRO, at least for a moderate microwave power [15]. However, our results suggest that it cannot explain the compressibility oscillation in the MIRO regime.

The discrepancy between the theory and our experiment cannot be remedied even if the electron Coulomb interaction is taken into account in the NESS. Because of the highly oscillatory feature of $\delta f(\epsilon)$ as a function of ϵ, its correction to the Coulomb exchange energy is thermally suppressed in the low-field MIRO regime by a Lifshitz-Kosevich factor in the same fashion as the SdH effect. Therefore, to fully understand the anticorrelation of the compressibility and the DC resistivity requires going beyond the NESS approximation. One possibility is that the nonequilibrium distribution may depend on the momentum and other quantum numbers except for the energy. Another possibility is concerned with the memory effect and the non-Markovian properties of the nonequilibrium dynamics of the interacting 2DES.

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