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Integer and fractional microwave induced resistance oscillations in a 2D system with moderate mobility

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ABSTRACT

We report on integer and fractional microwave-induced resistance oscillations in a 2D electron system with high density and moderate mobility, and present results of measurements at high microwave intensity and temperature. Fractional microwave-induced resistance oscillations occur up to fractional denominator 8 and are quenched independently of their fractional order. We discuss our results and compare them with existing theoretical models.

1. Introduction

It was established recently that electron transport in two dimensional (2D) layers exposed to microwave (MW) irradiation in the presence of a perpendicular magnetic field B demonstrates remarkable properties. Resonant transitions of electrons between Landau levels (LLs) lead to microwave-induced resistance oscillations (MIROs) whose period is governed by the ratio of the radiation frequency ω to the cyclotron frequency $\omega_c = eB/m^*$, where m^* is the effective mass of electrons [1]. For samples with ultrahigh mobility, these MIROs evolve into "zero-resistance states" (ZRS) [2]. The periodicity and the phase of MIROs are described theoretically by the displacement mechanism [3,4] and by the inelastic mechanism [5] of photoresistance. The inelastic mechanism, associated with a microwave-generated non-equilibrium oscillatory component of the electron distribution function, dominates at low temperatures T due to the large ratio of the inelastic scattering time $\tau_{in} \propto T^{-2}$ to quantum lifetime of electrons τ_q. Recently, it has been found that the inelastic mechanism also explains magnetoresistance oscillations in a two-subband system [6]. MIROs can also occur due to the "photovoltaic" mechanism describing combined action of the microwave and dc fields on both temporal and angular harmonics of the distribution function [7]. It has also been predicted that microwave excitation of the second angular harmonic of the distribution function, which is referred to as the "quadrupole" mechanism [7], should lead to an oscillatory contribution to the transverse (Hall) resistivity.

For high microwave intensity, the resistance has resonant features associated with the fractional ratios

$$\varepsilon = \omega/\omega_c = n/m, \quad (1)$$

where n and m are integers ($m \geq 2$). These fractional microwave-induced resistance oscillations (FMIROs) have been observed up to $\varepsilon = \frac{1}{4}$ [8] and explained by multiphoton absorption processes appearing in the strongly nonlinear regime. The FMIROs are described by two theoretical models: a simultaneous absorption of several photons [9] and a stepwise single-photon absorption [10]. In both cases the FMIROs corresponding to larger fractional denominators m (higher-order FMIROs) which progressively appear with increasing MW power.

2. Experimental results

In contrast to the previous studies [8] of 2D electron gas with low density ($n_s < 3.6 \times 10^{11}\,\mathrm{cm}^{-2}$) and ultrahigh mobility ($\sim 10^7\,\mathrm{cm}^2/\mathrm{V\,s}$), we investigate high-density electron gas with moderate mobilities $< 1.8 \times 10^6\,\mathrm{cm}^2/\mathrm{V\,s}$. The samples are 14 nm wide GaAs quantum wells from different wafers. In this paper we report on the results for the samples with electron density $n_s = 7.8 \times 10^{11}\,\mathrm{cm}^{-2}$ and mobility of $1.2 \times 10^6\,\mathrm{cm}^2/\mathrm{V\,s}$. We have used a VTI cryostat with a waveguide to deliver radiation down to the sample. The measurements were done at different intensities

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of MW radiation in the frequency range from 32 to 140 GHz. The resistance $R=R_{xx}$ was measured by using a standard low-frequency lock-in technique (13 Hz) under continuous MW illumination up to $T=15$ K.

Fig. 1 presents temperature dependence of magnetoresistance traces for a MW frequency $f=140$ GHz. We observe integer MIROs and cyclotron resonance (CR, MIRO $n=1$). In our high-density samples, we observe MIROs up to $n=4$ at $T=1.4$ K. With increasing temperature, amplitude and integer number n decrease until for $T\geq 10$ K only MIRO $n=2$ and CR appear. For lower frequencies, between 32 and 85 GHz, we also see FMIROs, which are better resolved at higher temperatures when they are not hindered by the Shubnikov-de Haas (SdH) oscillations. Fig. 2 shows the magnetoresistance for different frequencies at $T=6.5$ K and a constant MW electric field $E\simeq 7.5$ V/cm (the details on estimation of the electric field E can be found in Ref. [6]). First, we note that with decreasing frequency the CR amplitude becomes smaller and vanishes for 35 GHz. This can be attributed to the strong suppression of the Landau quantization by disorder, i.e. to the exponential smallness of the Dingle factor in the region of B corresponding to the CR.

All corresponding FMIRO positions in Fig. 2 are marked according to Eq. (1) with circles for each fractional feature. We observe high-order ($\varepsilon=\frac{1}{6}$, $\frac{1}{7}$, and $\frac{1}{8}$) fractional features for 45 and 55 GHz in the region where they are superimposed by SdH oscillations. With increasing MW frequency, these high-order FMIROs vanish first. At 85 GHz we still see the features with $\varepsilon=\frac{2}{3}$, $\frac{1}{2}$, and $\frac{2}{5}$. For 90 GHz all features are quenched, independently of their fractional order. A similar behavior has been observed for integer MIROs [11]. In contrast to Ref. [11] the mobility of the samples used in Ref. [12] is two times higher than in Ref. [11] which causes MIRO observation at 240 GHz.

We focus now on the power dependence of FMIROs for 45 GHz [Fig. 3(a)] and analyze also the temperature dependence of magnetoresistance (Fig. 4). The first observation is that FMIROs with different fractional ratio $\varepsilon=n/m$ are sensitive to different MW powers, see Fig. 3(b). The amplitude 2 A is extracted from the

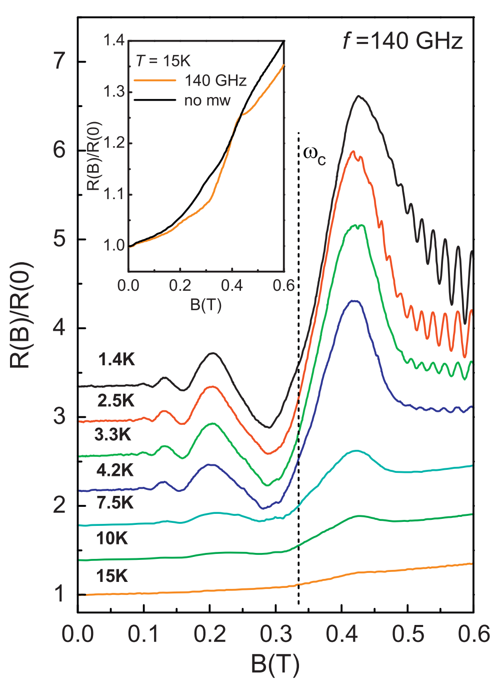

Fig. 1. Integer MIROs at 140 GHz in a high-density sample for different temperatures. We observe MIROs $n=1$, 2, 3, and 4. Cyclotron resonance ($n=1$) is visible up to 15 K. (Curves are shifted up for clarity, except the one for 15 K.)

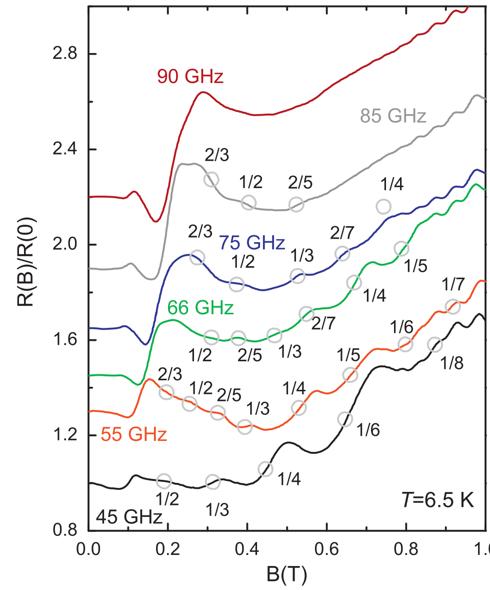

Fig. 2. Frequency dependence of FMIROs at $T=6.5$ K up to 90 GHz for the electric field $E=7.5$ V/cm. FMIRO features n/m are indicated according to Eq. (1). With increasing MW frequency, high-order FMIROs vanish, and for $f>85$ GHz all FMIROs are quenched, independently of their fractional order. (Curves are shifted up for clarity, except the one for 45 GHz.)

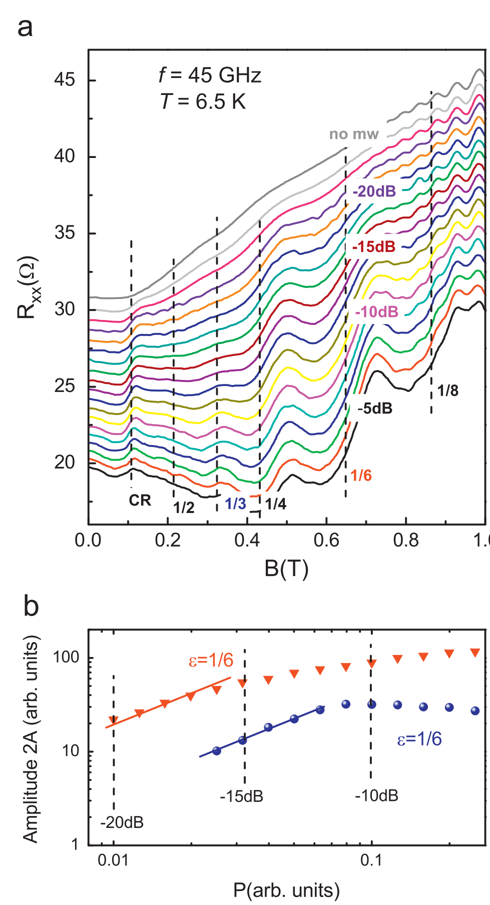

Fig. 3. (a) Power dependence for 45 GHz at $T=6.5$ K and (b) amplitude for chosen FMIROs (solid lines indicate linear power dependence). Different FMIROs are sensitive to different MW power. With decreasing MW power, the maxima for CR (FMIROs) shifts to higher (lower) magnetic fields.

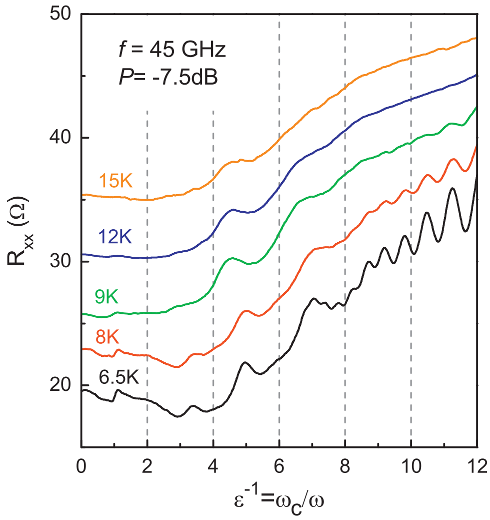

Fig. 4. Temperature dependence for 45 GHz (constant electric field 7.5 V/cm) at $T=6.5$ K. A shift of FMIRO maxima with increasing temperature is observed.

derivative dR/dB (peak to peak) and the solid lines in Fig. 3(b) indicate linear power dependence. The saturation for both FMIRO features occurs also at different MW power. As the power decreases, the maxima of FMIROs (CR) shift to lower (higher) magnetic fields. This phase shift for integer MIROs has already been predicted in Ref. [5]. Finally, we present in Fig. 4 temperature dependence of CR and FMIROs for $f=45$ GHz up to 15 K. Starting at 6.5 K, we find a shift of the FMIRO maxima to lower magnetic fields with increasing temperature. Note that the feature attributed to $\varepsilon=\frac{1}{4}$ still exists at 15 K whereas the CR feature is not visible any more.

3. Discussion and theoretical models

We now briefly discuss and compare the obtained results with already existing theories. Both MIROs and FMIROs survive with increasing temperature whereas FMIROs are favored at higher temperatures (around 6.5 K). The FMIROs observed in our experiments can hardly be ascribed to simultaneous multiphoton absorption processes [9] which require higher MW power. Therefore, the process of stepwise absorption seems to be more suitable [10]. In this model, the intensity of FMIROs with denominator m is proportional to the m th power of the squared Dingle factor $\exp(-2m\alpha)$, with $\alpha=\pi/\omega_c\tau_q$. As a consequence, we do not observe fractional features at the low-field side of cyclotron resonance. FMIROs should also damp exponentially faster than integer MIROs owing to a decrease of the quantum lifetime with increasing temperature. However, our results show that FMIROs weaken and disappear at the same temperature as integer MIROs, except for high power measurements (see Fig. 4, $T=15$ K). The occurrence of fractional resonances due to the stepwise absorption requires single-photon transitions between adjacent LLs. In the regime of separated LLs ($\alpha\equiv\pi/\omega_c\tau_q<2$ according to the self-consistent Born approximation) one has to satisfy the relation

$$\hbar\omega_c-2\Gamma<\hbar\omega<\hbar\omega_c+2\Gamma, \quad (2)$$

where $\Gamma=\hbar\omega_c[\arccos(1-\alpha)+\sqrt{(2-\alpha)\alpha}]/2\pi$ is the LL half-width. The lower limit of this restriction is violated for high-order FMIROs in our experiment. The FMIRO quenching at $f>85$ GHz independently of the fraction also disagrees with the stepwise absorption model.

In conclusion, we have studied integer and fractional MIROs in quantum wells with high density and moderate mobility for different temperatures, MW powers and frequencies. We have analyzed frequency, power and temperature dependence and found: (i) a quench of all fractional features for $f>85$ GHz, (ii) a linear power dependence of FMIROs for weak MW intensity as well as (iii) a phase shift with decreasing MW power and increasing temperature of FMIRO maxima. Both theoretical models, the simultaneous absorption of several photons and a stepwise single-photon absorption fail to explain our observed high-order FMIROs.

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