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Zero-resistance states in bilayer electron systems induced by microwave irradiation

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Abstract. We experimentally demonstrate the existence of microwave-induced zero-resistance states (ZRS) in bilayer electron systems created in wide quantum wells. In contrast to single-layer two-dimensional electron systems, ZRS are developed from the strongest magneto-intersubband oscillation peaks inverted by microwave radiation. Our experimental work is discussed within the theories of microscopic mechanisms of photoresistance, and the calculations reveal that the condition for absolute negative resistivity correlates with the appearance of ZRS.

1. Introduction

Exposing a two-dimensional electron system (2DES) to microwave (MW) irradiation leads to the appearance of zero dissipative resistance (zero-resistance states, ZRS) for samples with high electron mobility [1]. This phenomenon is closely related to microwave-induced resistance oscillations (MIROs) [2]. Both MIROs and ZRS occur at low magnetic fields before Shubnikov-de Haas (SdH) oscillations are developed, and are governed by the ratio of the radiation frequency ω to the cyclotron frequency ω_c. Since their discovery, properties of ZRS and MIROs have been experimentally investigated in numerous works including dependence on temperature, MW power (see Refs. [1, 2] as well as Ref. [3] and references therein), and MW field polarization [4].

MW-induced vanishing resistance has attracted attention of theorists who suggested several mechanisms responsible for both MIROs and ZRS. The so-called displacement mechanism which accounts for a spatial displacement of electrons along the applied dc field under scattering-assisted microwave absorption has been predicted by Ryzhii in the 70s [5] and found again by Durst *et al.* [6]. Later on, the so-called inelastic mechanism, based on inelastic-scattering-controlled oscillatory contribution to the electron distribution function, has been developed by Dmitriev *et al.* [7]. Both these mechanisms can lead to absolute negative resistivity, which causes the instability of homogeneous current flow and spontaneous breaking of the sample into domains [8] giving rise to vanishing dissipative resistance R_{xx}.

Until now, all studies of MIROs and ZRS have been carried out in high-mobility 2D systems with one populated subband. Recently, the observation of MIROs in 2D systems with more than one populated subband, formed by two or more coupled quantum well layers, has demonstrated that MW-induced oscillation phenomena are not restricted to single-layer systems [9, 10, 11] but there is no evidence for MW-induced ZRS neither in bilayer nor in other systems. This raises the question whether vanishing dissipative resistance appear only in a one-subband system or might occur in multilayer or in quasi-three-dimensional (3D) electron systems.

2. Experimental observation

Our samples are wide GaAs quantum wells (w=45 nm) with a high electron density of $n_s \simeq 9.1\times10^{11}$ cm^{-2} and a mobility of $\mu \simeq 1.9\times10^6$ cm^2/V s. We have studied samples in both Hall bar (length $L\times$ witdh W=250 μm $\times$ 50 μm) and van der Pauw (3 mm $\times$ 3 mm) geometry. Our system forms a bilayer configuration due to charge redistribution, when two quantum wells near the interfaces are separated by an electrostatic potential barrier, illustrated in the inset of Figure 1(a). The two lowest subbands are separated by the energy Δ_{SAS} = 1.4 meV, extracted from the periodicity of magneto-intersubband (MIS) oscillations [12] which appear as a result of a consecutive alignment of Landau levels of different subbands as the magnetic field increases. The measurements of the resistance have been performed in a cryostat with a variable temperature insert, and we used special probes to deliver MW radiation down to the sample and to control the orientation of linear MW polarization in the temperature range from 1.4 to 6.5 K.

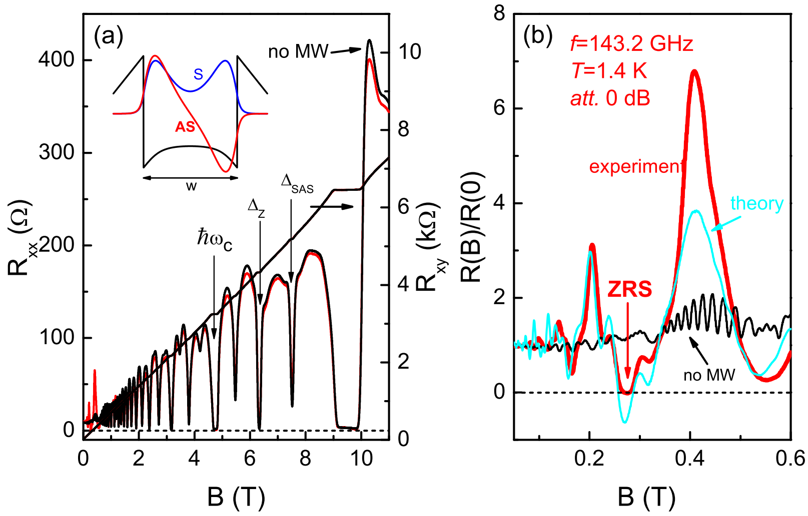

Figure 1. (Color online) (a) Longitudinal resistance and quantum Hall effect in a high-mobility bilayer system, with and without MW excitation (energy gaps are labeled). For MW frequency of 143.2 GHz (red trace) at a temperature of 1.4 K, zero resistance appears in the region of the inverted MIS oscillation peak at $B \simeq 0.27$ T. Inset: wide quantum well with symmetric (S) and antisymmetric (AS) wave functions. (b) Expanded view of the low-field data showing $R_{xx} \to 0$ in the vicinity of 0.27 T.

In Figure 1(a), we show measurements of longitudinal and Hall resistance with and without MW irradiation (no MW). For high magnetic field we have labeled corresponding energy gaps $\hbar\omega_c$, Δ_Z (Zeeman gap), and Δ_{SAS}. We observe MIS oscillations for $B < 1$ T thereby confirming bilayer nature of our system. Under a MW irradiation of 143.2 GHz, we find enhanced and inverted MIS oscillations for $B < 1$ T whereas in high magnetic fields MWs only damp SdH oscillations due to heating of the electron gas [9]. The Hall resistance in Figure 1(a) remains essentially unaffected. In the region of small magnetic fields, see Figure 1(b), we observe a profound ZRS for $B \simeq 0.27$ T developed from an inverted MIS oscillation peak. This behavior is distinct from the one in single-layer systems where ZRS occur at $\omega/\omega_c = j + 1/4$ (j is an integer).

3. Experimental analysis and theoretical model

A detailed study in the whole frequency range to our disposal (35 to 170 GHz) reveals that, in total, four inverted MIS oscillation peaks evolve into ZRS, as presented in Figure 2. Corresponding ZRS are marked with roman numbers from (I) to (IV).

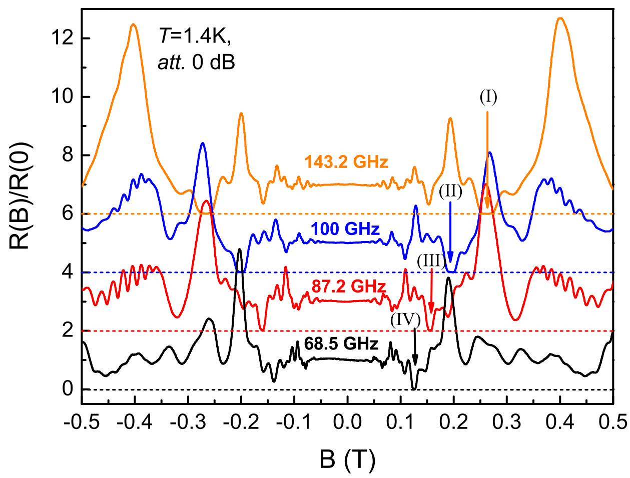

Figure 2. (Color online) Normalized magnetoresistance for positive and negative magnetic field exposed to MW irradiation from 68.5 to 143.2 GHz for highest intensity (attenuation 0 dB). ZRS can be observed for four inverted MIS oscillations, denoted with peak (I) to peak (IV). Traces are shifted up for clarity except the one for 68.5 GHz. Dashed lines mark R_{xx}=0.

A decrease in MW frequency leads to the appearance of ZRS at lower magnetic fields, because the conditions for inversion of MIS oscillations are determined by MW frequency [9]. For each frequency, only the strongest inverted MIS peak, closest to the cyclotron resonance $\omega = \omega_c$, evolves into a ZRS; the other inverted MIS peaks do not reach zero resistance. In contrast to single-layer systems, the regions where ZRS occur are narrow and strongly sensitive to MW frequency. An overview of ZRS is presented in Figure 3 showing the frequency regions where each of the inverted MIS peaks evolves into a ZRS. The width of ZRS correlates with the MIS peak width, which implies that the regions of ZRS are narrower for lower frequencies.

We focus now on the MIS oscillation peak (I) which exhibits a profound ZRS at $B = 0.27$ T. In Figure 4(a) the evolution of magnetoresistance exposed to a MW irradiation of 143 GHz for several chosen temperatures from 1.4 to 6.5 K is presented. As we approach ZRS by lowering temperature, the amplitude of $R(B)/R(0)$ rapidly decreases. A fit to exponential dependence $R \propto \exp(-E_{ZRS}/T)$, see the Arrhenius plot shown in Figure 4(b), gives us E_{ZRS}=7 K, which is of the same order of magnitude as in single-layer systems [1].

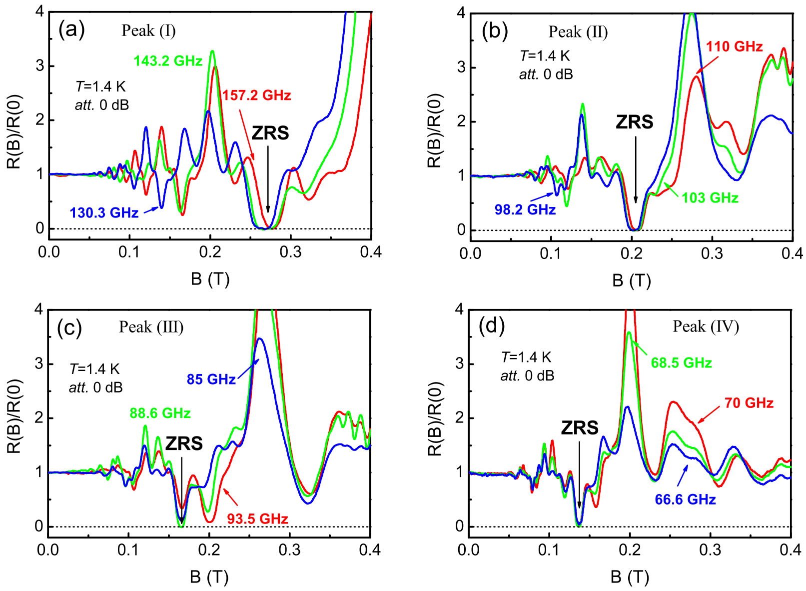

Figure 3. (Color online) Regions of ZRS in bilayer electron systems: (a) for peak (I), (b) for peak (II), (c) for peak (III), and (d) for peak (IV). With decreasing MW frequency, the frequency region for existence of ZRS becomes smaller.

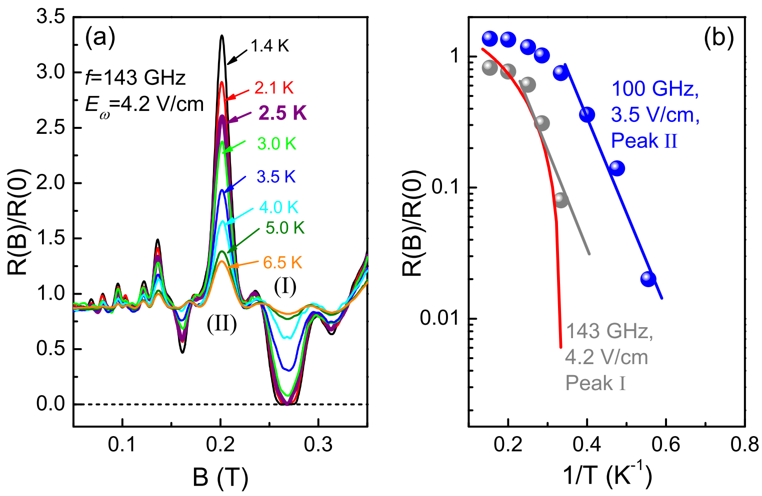

Figure 4. (Color online) (a) Temperature dependence of longitudinal resistance from 1.4 to 6.5 K. The ZRS first narrows at 2.1 K and vanishes for $T > 2.5$ K. (b) $R(B)/R(0)$ for 100 GHz [ZRS, peak (II)] and 143 GHz [ZRS, peak (I)]. The solid lines are fits to $R \propto \exp(-E_{ZRS}/T)$. The red trace is a theoretical calculation.

We analyze our experimental results within the models of displacement and inelastic mechanisms of photoresistance generalized (see Refs. [9, 10]) to the two-subband case. The inelastic mechanism is found to be the dominant contribution under conditions of our experiment, while the displacement mechanism becomes essential only at higher MW power or at $T > 4$ K [13]. The effective electron temperature, which depends on MW power, frequency, and magnetic field, has been determined by assuming energy relaxation of electrons due to their interaction with acoustic phonons. By analyzing dark magnetoresistance data at different temperatures, we have extracted the quantum lifetime and transport scattering time of electrons in our sample [13]. The inelastic relaxation time, which characterizes the strength of the inelastic mechanism, is determined from theoretical estimates [7]. The MW electric field strength at 0 dB attenuation, E_ω=4.2 V/cm, is found by fitting the theory to experimental traces. As a result, the calculated magnetoresistance at 143.2 GHz in Figure 1(b) reproduces experimentally observed features. In particular, the negative resistivity around $B = 0.27$ T can be the reason of inhomogeneous current pattern (domains) which is responsible for ZRS in this region of magnetic fields.

4. Conclusion

We have demonstrated the evidence of MW-induced ZRS for 2DES which are different from conventional single-layer electron systems. Theoretical calculations have shown that this phenomenon can be explained by the absolute negative resistivity under MW irradiation governed by the inelastic mechanism of photoresistance. Our results are the first step to generalization of ZRS phenomenon for the systems beyond the single-subband case, since we show that the additional intersubband scattering leading to MIS oscillations is not a hindrance for observation of ZRS in bilayers. These results also open the possibility for experimental and theoretical studies of ZRS in quasi-3D systems.

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