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CONDENSED MATTER

Electron Spin Resonance under Conditions of a Ferromagnetic Phase Transition

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The spin resonance of two-dimensional conduction electrons in a ZnO/MgZnO heterojunction in tilted magnetic fields is studied near the filling factor $\nu = 2$. The analysis of the spin resonance intensity at various ν values indicates that a phase transition accompanied by drastic change in the spin polarization occurs in a two-dimensional electron system at a certain angle near $\nu = 2$. For ν values larger than a certain critical value ν_c, an intense spin resonance is observed, clearly demonstrating that the system turns out to be in a spin-polarized state. For $\nu < \nu_c$, the resonance amplitude drops by more than an order of magnitude, and the spin polarization of the ground state decreases significantly. In the immediate vicinity of the transition, the spin resonance is broadened significantly and split into several independent peaks. Such behavior of the resonance can most likely be explained by the division of the system into domains with different spin polarizations.

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The quantum Hall effect (QHE) is one of the most striking phenomena in modern condensed matter physics. Although this effect was discovered several decades ago [1], it is still actively studied largely because the quantum Hall effect has been well studied only under rather limited conditions. Thus, the physics of this phenomenon is incompletely clear in a regime where the characteristic energy of the electron–electron interaction exceeds the splitting between the Landau levels, i.e., the cyclotron energy. Such regime could be observed in two-dimensional electron systems with a small cyclotron splitting due to the large effective mass of charge carriers. In this work, we study the spin properties of one of these structures, namely, ZnO/MgZnO heterojunctions [2, 3], near even filling factors in the quantum Hall effect regime.

The strong electron interaction significantly modifies almost all physical properties of a two-dimensional electron system, including spin ones. A striking example of such changes is the transition of the system from the paramagnetic to ferromagnetic state already in zero magnetic field. A similar effect was first proposed by Stoner [4] and was later confirmed by numerical calculations [5]. By analogy, the transition of the ground state of the system near even filling factors from nonmagnetic to fully spin polarized is possible under strong interaction conditions in the QHE regime. In this case, a feature appears in the longitudinal magnetoresistance of the two-dimensional electron channel, as well as in its magneto-optical properties. In this work, we study such a transition using an alternative experimental technique of electron spin resonance (ESR), which is one of the most productive approaches to studying the spin physics in various material systems, including low-dimensional semiconductor structures [6–8]. It is shown that the spin polarization undergoes a drastic modification during such a transition, and the system is divided into domains.

Electron spin resonance in the QHE regime is considered as the transition of an electron from the lower spin-split Landau sublevel to the upper sublevel upon absorption of a photon. An excited electron and a hole remaining at the lower sublevel form a bound state, a spin exciton [9]. Earlier, such excitation was actively studied in ZnO/MgZnO heterojunctions also in the QHE regime near a ferromagnetic transition near even filling factors, using Raman scattering [10–15]. This approach has a number of significant differences from the ESR technique. In particular, Raman scattering implies resonant inelastic scattering of light and, thus, the amplitude of the detected signal may depend on the wavelength of the exciting laser (see, e.g., Fig. 2 in [11]). Moreover, the significantly limited resolution of existing Raman spectrometers hardly allows following the evolution of the width and shape of the resonance line corresponding to the spin exciton in ZnO/MgZnO structures [10]. The ESR technique is free of this drawback, which makes it possible to study resonance lines of a submillitesla width with a high accuracy and, as will be shown below, to resolve the contribution of the domain structure to the shape of the ESR lines. The wavenumbers k of the used electromagnetic radiation are also different. At Raman scattering, the typical k values are $0.1/l_b$, where $l_b = \sqrt{\hbar/eB}$ is the magnetic length. In ESR, the characteristic kl_b values are 10^{-5}–10^{-4}, which allows studying the properties of the system on a much larger scale. Thus, despite the considerable number of Raman scattering studies of spin excitons in ZnO/MgZnO heterojunctions, the ESR study of the spin properties of such material systems is urgent and interesting.

The experiments were carried out on a high-quality ZnO/MgZnO heterojunction grown by molecular beam epitaxy. The sample had a square shape with ohmic contacts to the two-dimensional system located along the edges of the sample in the van der Pauw geometry (see the inset of Fig. 1a). Indium soldering and annealing was used to form contacts to the two-dimensional layer. The low-temperature two-dimensional electron density and mobility were $n = 2.1 \times 10^{11}$ cm^{-2} and $\mu = 4 \times 10^5$ cm^2/(V s). The sample was mounted inside the He-3 pot of a cryostat, and the tilt angle θ between the normal to the plane of the sample and the external magnetic field could be varied. The measurements were carried out in liquid He-3, the vapor of which was evacuated, so that the sample temperature was $T = 0.5$ K. Microwave radiation was supplied to the sample through an oversized waveguide. The radiation sources were frequency multiplication units coupled to a microwave generator.

Spin resonance of two-dimensional conduction electrons was detected by the change in the longitudinal magnetoresistance of the sample R_{XX} at the microwave radiation absorption. This approach was first proposed in 1983 [6]. In this case, ESR was detected as a peak in R_{XX} when the magnetic field was slowly swept at a fixed frequency of microwave radiation. To increase the signal-to-noise ratio, a double lock-in detection technique was used, the principle of which was described in detail in our previous works [16–18]. We note that the shape and amplitude of the observed resonance peaks did not depend on the sweep rate of the magnetic field, which means that the dynamic nuclear polarization effect [7] is insignificant under experimental conditions.

The typical magnetoresistance R_{XX} of the sample measured at $\theta = 35°$ is given in Fig. 1a. The positions of the first few minima of the Shubnikov–de Haas oscillations are marked in Fig. 1a. A sharp peak appears near even filling factors at certain angles θ. This effect is clearly seen in Fig. 1b, which shows the longitudinal resistance of the sample at different tilt angles $\theta = 0°$, 22.5°, 35° near $\nu = 2$. The feature in R_{XX} observed at $\theta = 22.5°$ marked by the arrow in Fig. 1b is shown in Fig. 1c on a magnified scale and at a significantly lower sweep rate of the magnetic field. The appearance of the described peak is usually associated with a ferromagnetic phase transition arising from crossing of spin-split Landau sublevels with different spin indices and projections (see Fig. 1d). Tilted magnetic fields favor this crossing because an increase in the tilt angle θ at a fixed filling factor leads to an increase in the splitting between the spin sublevels and does not change the cyclotron gap between the Landau levels. Such a model is undoubtedly a significant simplification, since all the effects of the electron–electron interaction are taken into account only by renormalizing the effective mass and Landé g-factor of the electron. The spin and cyclotron splitting energies, which determine the order of the levels, turn out to be significantly renormalized and very strongly depend on the two-dimensional electron density n [10, 19, 20]. Consequently, the angle at which the ferromagnetic transition is observed is determined by the density n, and at low densities, such a transition occurs already at $\theta = 0°$. It is assumed that the system in the transition region is divided into domains with different spin polarizations, the boundaries between which effectively scatter conduction electrons. Therefore, the longitudinal resistance of the system increases. The appearance of such a peak in R_{XX} makes it possible to establish the position of the transition in the magnetic field and the two-dimensional electron density, but does not allow one to directly follow the evolution of the spin polarization of the system and the formation of the domain structure or to estimate the scale of these domains.

We consider the behavior of ESR near the described ferromagnetic transition. Figures 2a and 2b show typical ESR peaks measured near $\nu = 2$ on different sides of the transition at $\theta = 22.5°$. The characteristic Landé g-factors determined from the positions of the ESR peaks are $g \approx 1.96$ and are essentially one-particle by virtue of the Larmor theorem. The corresponding microwave frequencies are indicated near resonance peaks. It is clearly seen that the shape of the peaks is far from Lorentzian. Under such conditions, the signal approximation by any formula does not make sense; for this reason, an integral approach was used to characterize the ESR intensity. The nonresonant background signal was approximated by a polynomial in a certain magnetic field range around the ESR peak; the resonance line itself did not enter this region. Taking into account the background, we integrate the absolute value of the amplitude only over the resonant contour. The applicability of this approach was tested on the ESR peaks obtained near odd filling factors, which had the Lorentzian shape.

The final dependence of the integral spin resonance amplitude obtained at $\theta = 22.5°$ is shown by empty blue circles in Fig. 2c. The horizontal arrows mark the points corresponding to the peaks in Figs. 2a and 2b. The vertical arrow indicates the position of the peak at R_{XX} shown in Fig. 1c. It is clearly seen that the

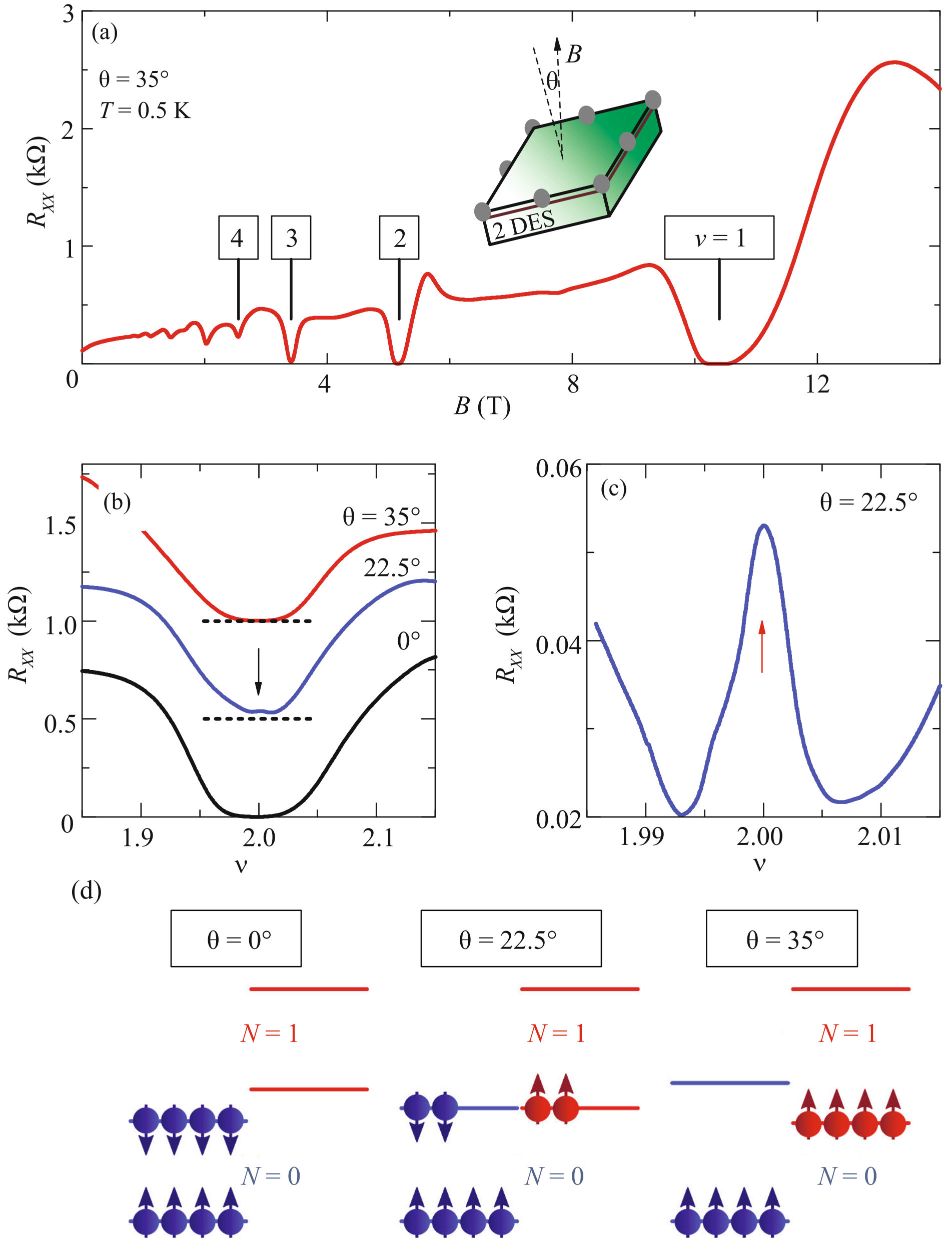

Fig. 1. (Color online) (a) Typical magnetic field dependence of the longitudinal resistance of the two-dimensional channel at a field tilt angle of $\theta = 35°$, a two-dimensional electron density of $n = 2.1 \times 10^{11}$ cm^{-2}, and a sample temperature of 0.5 K. The inset shows the schematic image of the sample and its orientation with respect to the external magnetic field. (b) Minimum of Shubnikov–de Haas oscillations near $\nu = 2$ at three different tilt angles of the magnetic field, $\theta = 0°$, 22.5°, 35°. (c) Feature marked by the arrow in panel (b) near the filling factor $\nu = 2$ at $\theta = 22.5°$. (d) Expected order of the Landau levels and their filling at different tilt angles θ.

ESR intensity on different sides of the phase transition differs by an order of magnitude; thus, it can be concluded that the spin polarization of the system undergoes drastic changes during such a transition. Indeed, in the nonmagnetic state, where the spin polarization of the system is zero, the electron transitions between the two spin sublevels are suppressed because of the absence of free positions on the upper sublevel (see Fig. 1d). The suppression of ESR in the nominally nonmagnetic phase becomes even more obvious if we compare the dependence of the ESR amplitude on the filling factor for a larger tilt angle of $\theta = 35°$ shown in Fig. 2c. As expected [10], the state of the system at this tilt angle should be ferromagnetic in a wide vicinity of $\nu = 2$. An extremely weak ESR peak was observed at zero tilt angle. We note that a large number of small ferromagnetic domains can serve as effective scatterers

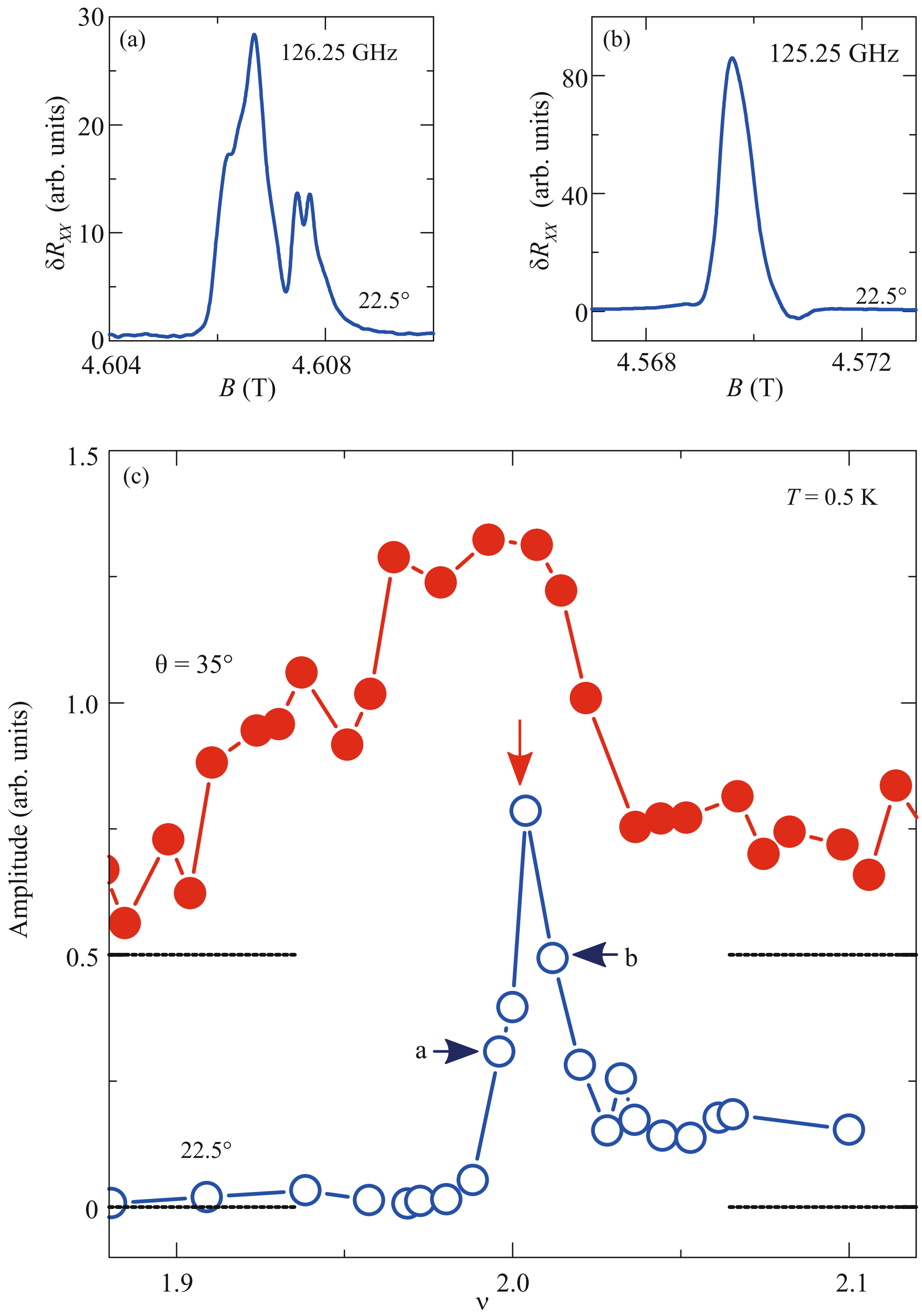

Fig. 2. (Color online) (a, b) Typical ESR peaks measured near the filling factor $\nu = 2$ on different sides of the ferromagnetic transition and at electromagnetic radiation frequencies of $f = 126.25$ and 125.25 GHz, respectively. The tilt angle of the field was $\theta = 22.5°$. (c) Integral ESR amplitude versus the filling factor at two tilt angles $\theta =$ (blue empty circles) 22.5° and (red filled circles) 35°. Data for $\theta = 35°$ are shifted upward for clarity, and the horizontal straight line segments set the zero position for them. The red vertical arrow indicates the position of the feature in the resistance observed near $\nu = 2$, and the horizontal arrows indicate the points corresponding to the peaks in panels (a) and (b). The sample temperature was $T = 0.5$ K.

of spin excitations and additionally suppress ESR in the nominally paramagnetic phase.

We consider now how the domain structure with the characteristic size ξ affects the ESR peaks. The presence of inhomogeneities in the spin density of such a scale allows the nonconservation of the momentum at a scale of $\hbar/\xi$. Because of the quadratic dispersion of the spin wave $E = g\mu_B B + \alpha(kl_b)^2$, broadening of resonance peaks and even their splitting into several independent peaks should be expected. Such behavior was observed in the experiment. Here, $g\mu_B B$ is the magnitude of the one-particle Zeeman splitting, g is the Landé g-factor, μ_B is the Bohr magneton, and k is the wavenumber, which is $k \sim 1/\xi$ under conditions of the formation of domains. Thus, the peak broadening δB can be estimated as $\delta B = \frac{\alpha(l_b/\xi)^2}{g\mu_B}$. From experimental data, we estimated $\delta B \sim 2$ mT, and the α value was obtained in [21, 22]. Taking into account these values, the typical domain size is $\xi \sim 100 l_b \sim 1$ μm. We note that such ESR splitting is not observed in the nominally ferromagnetic phase, which indicates a well-ordered phase. In addition, such splitting is absent near odd filling factors, the ground state of which is a quantum Hall ferromagnet, which means that the observed change in the ESR shape is not associated with the inhomogeneity of the two-dimensional density in the sample.

To summarize, spin resonance of two-dimensional conduction electrons in a ZnO/MgZnO heterojunction in tilted magnetic fields has been studied in the quantum Hall effect regime near $\nu = 2$. Analyzing the evolution of the spin resonance intensity with a change in the filling factor of the system, we have found that the ground state of the system at a certain tilt angle of the magnetic field undergoes a phase transition accompanied by a drastic change in the spin polarization. In this case, intense spin resonance is observed in the ferromagnetic state, the amplitude of which significantly decreases in the paramagnetic phase. In the immediate vicinity of the transition, the spin resonance is broadened and is split into several independent peaks. This behavior of the resonance is most likely due to the division of the system into domains with different spin polarizations.

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