Effects of Rashba spin splitting and exchange interaction in electron spin resonance in narrow-gap quantum well heterostructures

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Abstract. We report an electron spin resonance (ESR) study in *n*-type narrow-gap quantum well (QW) heterostructures. By using the Hartree-Fock approximation based on the 8 $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian the many-body theory of the ESR in narrow-gap QWs is developed. We have discovered significant enhancement of the ESR g-factor and its low-magnetic-field divergence in both in asymmetric and symmetric QWs which is caused by the exchange interaction in 2D electron gas (2DEG). The ESR energies estimated for 2DEG in asymmetrical InAs/AlSb QWs are compared with the experimental results obtained by electrically detected ESR technique.

1. Introduction

The electron-electron (*e-e*) and Zeeman interaction in the two-dimensional (2D) electron system in a strong perpendicular magnetic field at low temperatures leads to a rich variety of many-body phenomena that do not have analogues in three-dimensional systems [1]. The experimental observation of the effects of an *e-e* interaction in these states is complicated due to a number of symmetry restrictions. The latter include the Kohn theorem, which states that the *e-e* interaction in an ideal translationally invariant system does not affect the cyclotron resonance (CR) energy in 2D electron gas (2DEG) [2]. According to a similar theorem for 2D systems with a rotational invariance in spin space (the Larmor theorem) the *e-e* interaction does not enter into the energy of ESR in such systems [3].

Since typical narrow-gap QW heterostructures based on InSb, HgTe and InAs are characterized by pronounced spin-orbit interaction (SOI), which leads to breaking of rotational symmetry in spin space, and nonparabolicity of the electronic subbands, resulted from perturbation of translational invariance by electric potential of crystal lattice, the both theorems should be violated in these structures [4, 5]. Our earlier studies [5-10] have shown the SOI and mixing between |*S*>- and |*P*>-states in the Γ_6, Γ_7 and Γ_8 bands to largely influence the *e-e* interaction effects such as quasiparticle and ESR g-factor enhancement in 2DEG. In this paper we extend the limits of our previous work [5] to a theoretical and experimental study of ESR in symmetric and asymmetric InAs/AlSb QWs.

2. Theory

To take into consideration SOI and the mixing of the conduction band (Γ_6) with the light- and heavy-hole bands (Γ_8) and with the split-off band (Γ_7) exactly, the 8-band **k·p** Hamiltonian [6] as a single-particle kinetic energy operator is used. It directly takes into consideration the influence of nonparabolicity, lattice-mismatch deformation and SOI on electron energy spectrum. Many-body corrections to ESR energies were obtained in the Hartree-Fock approximation (HFA) [5]. The Coulomb Green function was obtained by solving the electrostatic problem in three-layered system with different permittivity values in QW and in barriers [6]. As all calculations in this paper are performed for InAs/AlSb QW heterostructures [7, 11], we take into account the ‘built-in’ electric field of ionized donors in single-particle Hamiltonian.

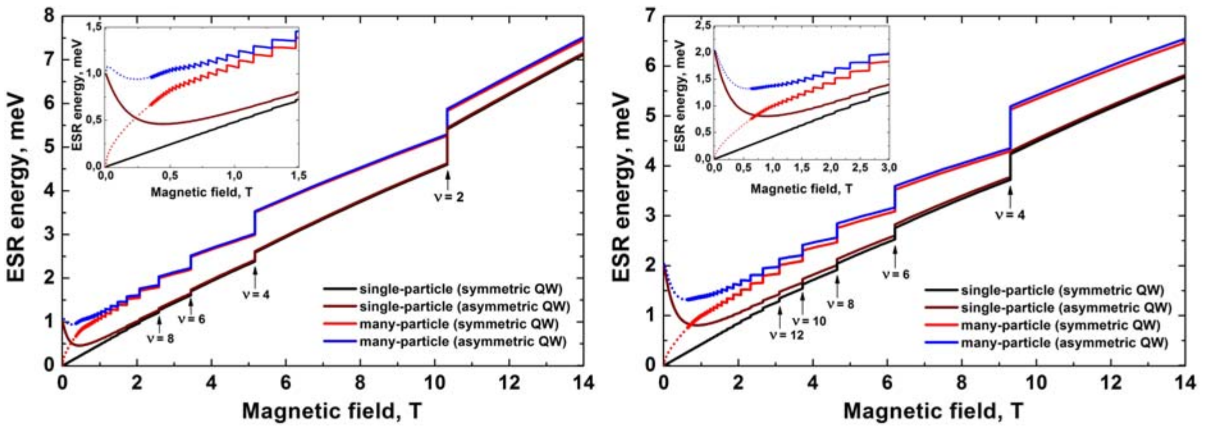

Figure 1: ESR energy in a 15 nm wide InAs/AlSb QW with symmetric and asymmetric profile versus magnetic field at different values of 2DEG concentration: $5 \cdot 10^{11}$ cm^{-2} (right panel) and $9 \cdot 10^{11}$ cm^{-2} (left panel). The insets show the results of calculations in weak magnetic fields. Red and blue dotted curves correspond to the zero-field values interpolated by using (1) and (2).

Fig. 1 illustrates the ESR energy calculations versus magnetic field in InAs/AlSb heterostructures with a 15 nm wide QW for different values of the 2DEG concentration. Black and brown curves correspond to the single-particle approximation in a symmetric and asymmetric QW. Red and blue curves are for the ESR energies calculated with allowance for the *e-e* interaction within HFA in QW with a symmetric and asymmetric profile, respectively. The arrows indicate the magnetic field values corresponding to the even-valued filling factors of Landau levels (LLs). The features observed at even-valued LL filling factors appear due to the electronic subband nonparabolicity in InAs/AlSb QW [5-10]. As the magnetic field increases, the Fermi level ‘jumps’ from one pair of spin-split Landau levels to the lower-lying pair with a greater spin-splitting. This causes a sharp rise of the spin-splitting energy at the Fermi level, followed by an abrupt change in the ESR energy. It is seen that the single-particle ESR energy in a symmetric QW is determined by the Zeeman splitting of LLs, demonstrating a linear dependence on magnetic field in the region of weak magnetic fields.

The Rashba spin splitting in an asymmetric QW leads to distortion of the monotonic dependence of single-particle ESR energy on magnetic field and appearance of a pronounced minimum in the low magnetic fields region. In this case the spin splitting at the Fermi level is determined by two contributors: the Rashba- and the Zeeman splitting [11]. As the magnetic field increases from zero, the ESR energy quickly drops, going smoothly over to the Zeeman splitting. Note that for high LL indices n (in weak magnetic fields) the single-particle ESR energies can be obtained analytically [12]:

$$E_{ESR} \approx \left[\left(\hbar\omega_C - g_{(1e)}\mu_B B\right)^2 + \Delta_R^2\right]^{1/2} - \hbar\omega_C , \quad (1)$$

where $g_{(1e)}$ is a single-particle g-factor [5, 6], $\omega_C = eB/m^*c$, m^* and Δ_R are the Rashba splitting and the electron effective mass at the Fermi wavevector in a zero magnetic field, respectively. Thus, the 'single-electron' ESR energy decreases linearly with B in weak magnetic fields.

Strong SOI and mixing between $|S>$- and $|P>$-states in the conduction and valence bands in the InAs/AlSb QWs leads to violation of Larmor theorem applicability conditions in symmetric and asymmetric QW. It is clear that *e-e* interaction in narrow-gap QW causes considerable enhancement of ESR energy that at low magnetic fields is more than twice its single-electron value. The Rashba spin splitting in the asymmetric QWs resulted in a noticeable effect on the many-body ESR energy in weak magnetic fields only. The behavior of many-body ESR energy in asymmetric QWs at low magnetic fields strongly depends on a magnitude of the Rashba spin splitting. We note that when the latter is weak in a zero magnetic field, the field dependence of ESR energy is monotonically increasing, whereas at high values of Rashba splitting we observe a monotonically decreasing curve in the region of low magnetic fields [10]. It can be shown that HFA corrections to ESR energy at *integer* LL filling factors in symmetric [5] and asymmetric [10] narrow-gap QWs have a square-root dependence on the magnetic field:

$$\Delta_{ESR}^{(e-e)} = C\sqrt{B}\,, \tag{2}$$

where constant C is independent of magnetic field, it is defined by quantum numbers of the upper fully filled LL [5, 10].

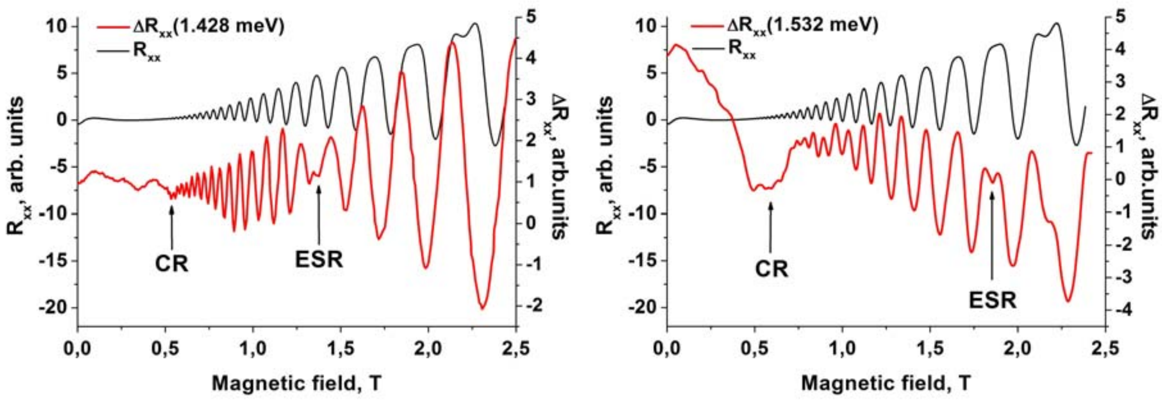

Figure 2: Shubnikov-de Haas oscillations and change in the resistance due to microwave-illumination as a function of applied magnetic field at different BWT photon energy: 1.428 meV (left panel) and 1.532 meV (right panel). The magnitude of current in the measurements was 50 μA. Features attributed to CR and ESR are labeled.

3. Experiment

ESR measurements have been carried out at 4.2 K using electrical detection technique [3]. As a radiation source the backward-wave tube (BWT) which covers the range of 250-500 GHz is used. The measurements were performed on a sample T340 with a QW width of 15 nm. The 2DEG concentration and mobility in the sample at $T = 4.2$ K were $7.65 \cdot 10^{11}$ cm^{-2} and $4.5 \cdot 10^5$ cm^2/V·s, respectively. Fig. 2 is a typical change in magneto-resistance in the sample T340 induced by BWT radiation. Magnetic field was oriented perpendicular to the sample plane. Features attributed to CR and ESR, are clear observed. The experimental values are presented in Fig. 3 by symbols. One can see a good agreement between theoretical predictions and experimental data if the asymmetric built-in electric field of the surface donors in GaSb cap layer [7, 13, 14] resulting in the Rashba spin splitting [15] is taken into account. A small discrepancy between calculated curve and experimental data is attributed, in our opinion, to the influence of dynamic polarization (Overhauser shift [16]) on the ESR line shape and position. In addition, we demonstrate that exchange interaction leads to the low-magnetic-field divergence of many-body ESR g-factor in symmetric QWs. In asymmetric QW it increases the Rashba splitting induced divergence of the g-factor under low magnetic fields. In high magnetic fields the contribution of the exchange enhancement to ESR energy and g-factor decreases with a growing magnetic field (see Fig. 3).

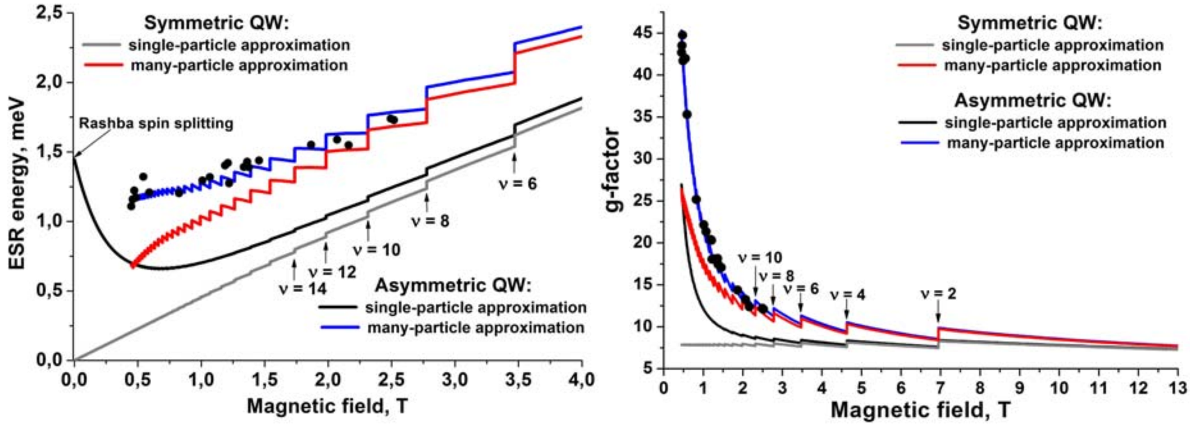

Figure 3: ESR energy (left panel) and g-factor (right panel) in a 15 nm wide InAs/AlSb QW with symmetric and asymmetric profile calculated for 2DEG concentration of $7.65 \cdot 10^{11}$ cm^{-2}. The symbols are experimentally data in T340 sample. Magnetic fields corresponding to even-valued LL filling factors are indicated by arrows.

This work demonstrates that ESR can serve as a tool to probe the *e-e* interaction effects in narrow-gap QWs. We hope that our results will stimulate further experimental studies of ESR in narrow-gap QW heterostructures and will provide an in-depth understanding of the physical mechanisms responsible for the exchange enhancement of ESR energy in 2DEG.

4. Acknowledgements

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