Pis'ma v ZhETF, vol. 74, iss. 5, pp. 300 – 303 © 2001 September 10

Cyclotron spin-wave in the 2D electron system

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Submitted 31 July 2001

The cyclotron spin-wave mode of a two-dimensional electron system have been investigated by inelastic light scattering. It is observed at small electron filling factors, $\nu \sim 0.1$, when the electron system is spin-depolarized. As long as the electron system becomes fully spin-polarized ($\nu > 0.2$) the cyclotron spin-wave disappears from the inelastic light scattering spectra. It reenters at electron filling factors $\nu > 1$. Over the range of electron filling factors of $1 < \nu < 2$ the cyclotron spin-wave energy is insensitive to both the experimentally accessible in-plane momenta and the electron concentration, whereas its inelastic light scattering efficiency is strongly influenced by the spin polarization of the electron system.

PACS: 73.40.Hm

Collective excitations in a two-dimensional electron system (2DES) under an external static magnetic field are usually classified as intra- and intersubband modes, associated with poles in the corresponding parts of charge- and spin-density response functions, the intra- and intersubband excitations being taken as non interacting (the long-wave approximation). The intersubband part of the excitation spectrum consists of principal intersubband modes, which are charge- and spin-density excitations (CDE and SDE) [1], intersubband Bernstein modes [2, 3], and out-of-phase or optical charge and spin-density excitations [4, 5]. The intrasubband excitations can in turn be separated in inter- and intra-Landau-level collective modes. The latter are the spin-wave mode and fractional excitations, originating from the nontrivial self-ordering of the 2DES in a partially filled Landau level (LL) [6, 7]. As to the inter-Landau-level (ILL) excitations, they are associated with electron transitions from LL n to LL $n+m$ with or without flipping the electron spin. Their energies are given by:

$$E(q) = m\hbar\omega_c + \delta S_z g\mu_B B + E_{\delta S_z}(q). \qquad (1)$$

Here, ω_c is the cyclotron frequency, $\delta S_z = -1, 0, 1$ and m are the excitation spin and momentum projections along the magnetic field axis [8]. At $q \to 0$, the $E_{\delta S_z}(q)$ term equals to zero for ILL excitations with $\delta S_z = 0$. It can however be significant for ILL excitations with $\delta S_z = -1, +1$ [9, 10]. Since there generally exist an infinite number of ILL excitations with different m, hereafter, the exemplar case of ILL excitations from the lowest Landau level with $m = 1$ will be considered. The theory of such excitations has been developed in Ref.[8] for integer and in Ref.[9, 11] for non-integer electron filling factors (ν).

When the electrons in the 2DES equally occupy the two spin states of the lowest LL, the ILL excitations can be classified as singlet and triplet states. The singlet state is the magnetoplasmon, which gives rise to a pole in the charge-density response function. The modes that constitute the triplet state are the two cyclotron spin-flip modes (SF, $\delta S_z = -1, 1$) and the cyclotron spin-wave mode (CSW, $\delta S_z = 0$), with its spin directed in the 2D plane. The magnetoplasmon can be described as an in-phase oscillation of the two spin subsystems of the 2DES involving inter-LL electron transitions, whereas the spin-wave mode is associated with the out-of-phase oscillations of the two spin subsystems. This classification is no longer valid, if the ground state of the 2DES has a different occupation for the two spin states. In that case both $\delta S_z = 0$ modes, the magnetoplasmon and the cyclotron spin-wave, give rise to poles in the charge-density response function, whereas only the cyclotron SF modes give rise to poles in the spin-density responce functions. Despite the mixed charge-spin character, the cyclotron spin-wave mode is not active in infrared absorption experiments, as it is a pure spin-density type excitation in the limit of $q \to 0$, whereas it becomes a pure charge density excitation only at $q \to \infty$ (the latter statement is not valid for a special case of odd noninteger filling factors, $\nu = 3, 5, 7, ...$, when both $\delta S_z = 0$ modes are of charge density type at all q [12]). Only recently, the cyclotron spin-wave mode was observed for the first time with the inelastic light scattering (ILS) technique in the limiting case of small non-integer filling factors ($\nu \ll 1$) [10]. Here, we report on the study of the cyclotron spin-wave at large ν, and demonstrate that at $\nu \sim 2$, namely, the cyclotron spin-density wave (*not the magnetoplasmon*) dominates inelastic light scattering in the vicinity of the cyclotron frequence.

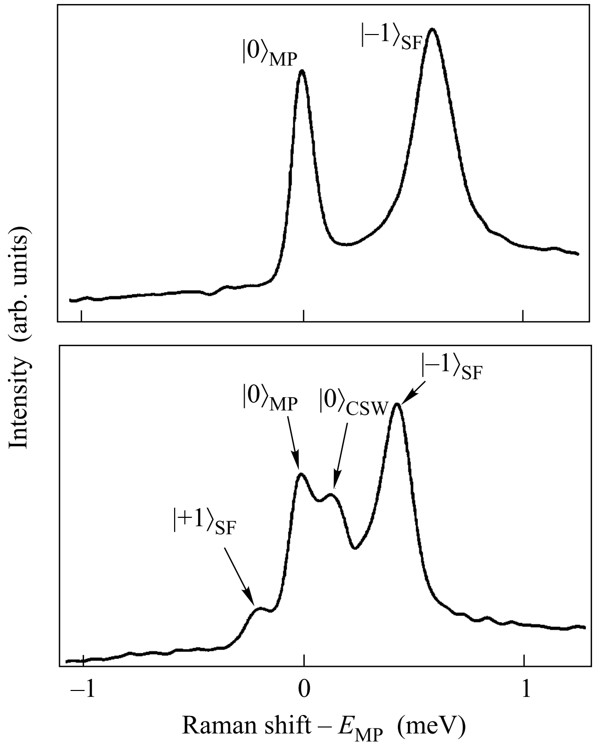

Fig.1. ILS spectra measured for a single 300 Å QW sample at the in-plane momentum of $0.4 \cdot 10^5\,\mathrm{cm}^{-1}$, the magnetic field, $B = 9.4$ T, and at $\nu = 0.12$ and at $\nu = 0.26$. The lines are classified by the spin projection of their corresponding modes along the magnetic field axis. The spin-triplet state consists of the cyclotron spin-wave ($|0>_{\rm CSW}$) and two spin-flip modes ($|-1>_{\rm SF}$, $|+1>_{\rm SF}$). The spin-singlet state is the magnetoplasmon ($|0>_{\rm MP}$). The energy is counted from the magnetoplasmon energy

Four different asymmetrically doped high-quality semiconductor heterostructures containing a single AlGaAs/GaAs quantum well (QW) with a width of $250 \div 300$ Å, electron concentrations in the dark of $1.6 \div 3.5 \times 10^{11}$ cm^{-2} and an electron mobility of $\sim 1.5 \div 7 \times 10^6$ cm^2/Vs were used for this study. The electron concentration (n_s) in the samples was continuously tuned using the opto-depletion effect, and was measured by means of in-situ luminescence [13]. A two-fiber optical system was utilized in measurements [3]. One fiber transmitted the pumping laser beam, and the other collected the scattered light out of the cryostat. The angles between the sample surface, pumping and collecting fibers were chosen to attune the in-plane momentum transferred to the 2DES via the ILS process. The in-plane momentum was $0.4 - 1.0 \cdot 10^5$ cm^{-1}. The scattered light was dispersed by a Ramanor U-1000 double grating monochromator and detected by a CCD camera. Taking into account the resonant nature of ILS in a magnetic field, the experimental spectra were recorded using a series of different photon energies of the pumping radiation.

Fig.1 shows a typical ILS spectrum taken at small ν and the fixed magnetic field of 9.4 T. Three lines are observed in the energy range of the cyclotron resonance (Fig.1). The lowest and the highest energy lines correspond to the $\Delta S_z = +1$ and $\Delta S_z = -1$ spin-flip modes, respectively (the negative g-factor of electrons in GaAs is taken into account), whereas the two central lines correspond to two possible $\Delta S_z = 0$ modes: the magnetoplasmon or cyclotron mode with zero spin, and the cyclotron spin-wave with its spin directed in the QW plane [10]. The inelastic cross-section of the spin-wave mode decreases when the spin polarization degree increases. At $\nu > 0.2$ only two modes are left in the spectra, characteristic of a spin-polarized 2DES: the $\Delta S_z = -1$ spin-flip mode and the magnetoplasmon (Fig.1).

The CSW mode reenters in the ILS spectra, as soon as the second electron spin state becomes populated. Fig.2 shows ILS spectra taken in the vicinity of the cyclotron frequency at different magnetic fields over the range of the electron filling factors, $1 < \nu < 2$. Two ILS lines are observed, which are identified as the cyclotron spin-wave and magnetoplasmon modes using the same "symmetry test" as in Ref.[10]: if one tilts the magnetic field, inter- and intrasubband modes possesing the same symmetry, should interact near their energy resonance. Such interactions were indeed observed in our experiment for the magnetoplasmon and the intersubband CDE, as well as for the spin-wave and the intersubband SDE. The latter interaction is clearly seen in Fig.2. Due to the coupling CSW and SDE, the CSW energy dicline from the corresponding energy calculated in the absense of mixing between inter- and intrasubband excitations (solid triangulars), whereas the magnetoplasmon energy intersects the SDE energy without an observable effect.

Having identified the cyclotron spin-wave mode we compared its dispersion properties with that of the magnetoplasmon (MP). The dispersions of the CSW and MP modes at 6 T are shown in Fig.3. In agreement with the theory of Ref.[9, 11], the CSW mode does not posses any appreciable dispersion at the experimentally accessible in-plane momenta. In contrast, the dispersion of the MP is easily observable. The MP energy demonstrates

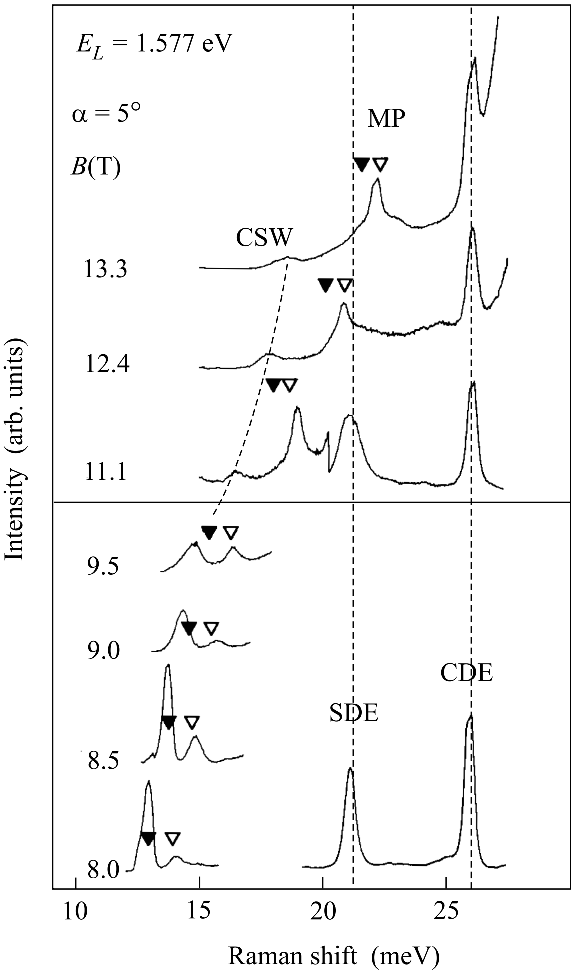

Fig.2. ILS spectra measured for a 250 Å QW sample with $n_s = 3.5 \cdot 10^{11}\,\mathrm{cm}^{-2}$ at different magnetic fields close to the resonance of the CSW and SDE energies. The simulated energies of the magnetoplasmon and cyclotron spin-wave at $q = 1.0 \cdot 10^5\,\mathrm{cm}^{-1}$ in the absence of interaction between inter- and intra-subband excitations are shown by open and solid triangles. The dotted lines are guides for the eyes

the familiar linear growth with increasing electron concentration. However, the experimentally observed linear slope of the magnetoplasmon energy is larger than the predicted one, and, as a consequence, the magnetoplasmon energy intersects the spin-wave energy at a finite electron concentration. Thus, at sufficiently large ν the MP energy exceeds the CSW energy, but at small ν the CSW energy exceeds that of the MP, see Fig.1. This result is in qualitative agreement with conclusions of Ref.[14, 15], where the influence of impurities on the spectrum of collective modes is considered. In a way, it resembles a similar experimental observation called "Collapse of the Hartree term" for intersubband counterparts of CSW and MP, intersubband SDE and CDE [16]. It is however to be stressed, that in an ideal translationally invariant 2DES the calculated CSW and SDE energies are always below that of MP and CDE, respectively [9, 11].

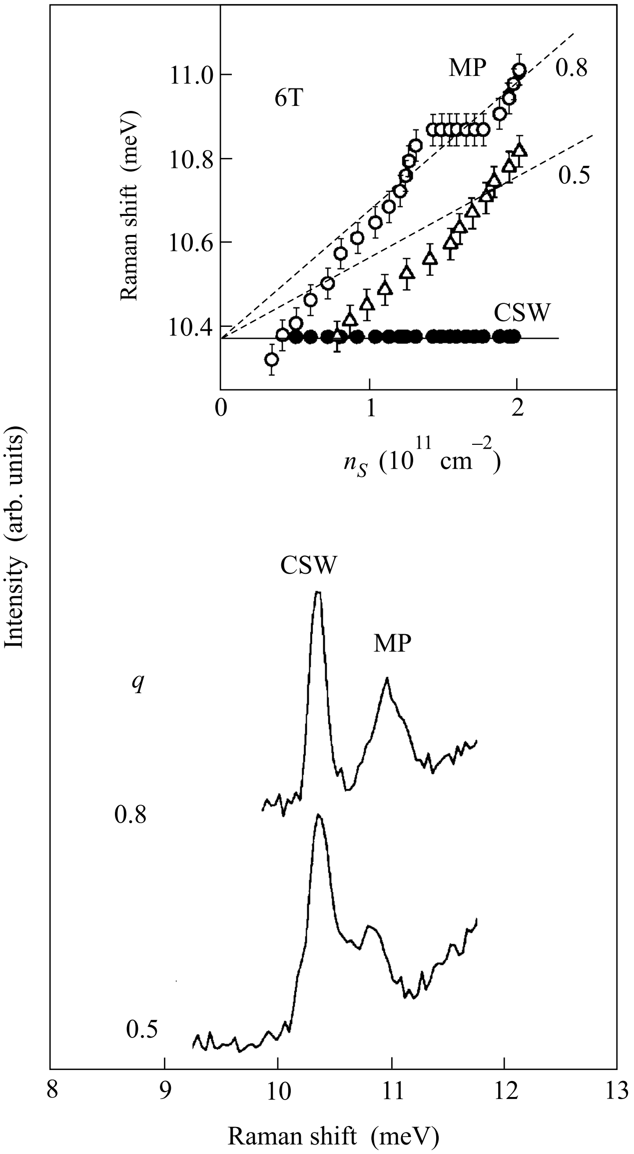

Fig.3. ILS spectra measured for a 250 Å QW sample with $n_s = 2 \cdot 10^{11}\,\mathrm{cm}^{-2}$ for two in-plane momenta, 0.5 and $0.8 \cdot 10^5\,\mathrm{cm}^{-1}$, and the magnetic field of 6 T. In the inset the MP and SW energies vs. the electron concentration are shown

The ILS cross-section of the CSW mode and the magnetoplasmon strongly depend on the relative population of the two spin states in the 2DES ground state. Fig.4 shows the electron filling factor and temperature dependence of the CSW and MP ILS cross-sections. When a single spin state is occupied ($\nu = 1$), only the MP mode is observed. The filling of the second spin state by increasing either the electron filling factor or the temperature is accompanied by the enhancement of the CSW

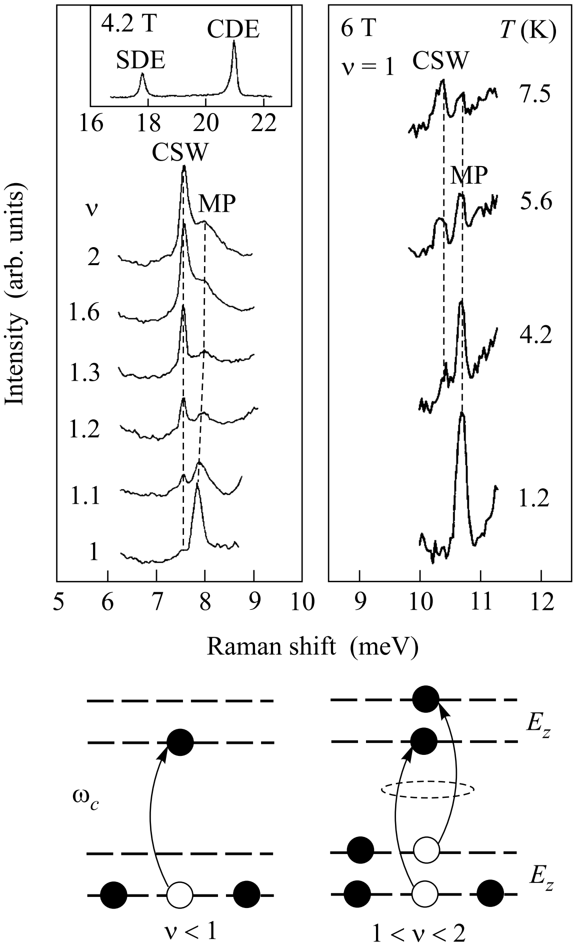

Fig.4. Left: ILS spectra measured for a 250 Å QW sample with the electron concentration in the dark of $2 \cdot 10^{11}$ cm^{-2} for a magnetic field of 4.2 T and different ν (ν is pointed at the left of the spectra). In the inset, the intersubband counterparts of the cyclotron spin-wave and the magnetoplasmon, spin- and charge-density excitations (SDE and CDE), for $\nu = 2$ are shown. Right: The temperature dependence of the relative ILS cross-sections for the cyclotron spin-wave and the magnetoplasmon for a magnetic field of 6 T and $\nu = 1$. The diagram at the bottom demonstrates an additional degree of freedom that allows the cyclotron spin-wave to exist. At $1 < \nu < 2$ two modes with $\delta S_z = 0$ can be constructed on the basis of two electronic transitions from the two spin states coupled by the Coulomb interaction, whereas at $\nu < 1$ there exists only the magnetoplasmon

ILS cross-section. At $\nu = 2$, namely, the dipole forbidden CSW mode dominates the ILS spectra, which is in contrast to the infrared absorption spectra where only the dipole allowed MP mode is generally observed [12]. The ILS from the cyclotron spin-wave mode can be thus employed to characterize the polarization properties of the 2DES's.

In conclusion, we studied the cyclotron spin-wave mode of 2DES in the case when electrons occupy the lowest LL. Being the out-of-phase oscillation of the two electron spin subsystems of 2DES the cyclotron spin-wave mode has zero oscillator strength at small in-plane momenta. Despite this fact it is active in the inelastic light scattering whenever the electrons fill more than one spin state. The energy of the cyclotron spin-wave lies at the cyclotron frequency, and does not change at the in-plane momenta used in the experiment. The last result is in perfect agreement with the theoretical predictions using Generalised Single Mode and Hartree-Fock approximation [8, 9, 11].

The financial support from the Volkswagen Stiftung, Russian Fund of Fundamental Research, INTAS (project # v99-1146), A. von Humbolt Stiftung (L. V. K.), and the German Israeli Foundation (J. H. S and V. U.) is gratefully acknowledged.

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