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ANISOTROPIC BAND STRUCTURE OF A PARABOLICALLY CONFINED ELECTRON SYSTEM SUBJECTED TO AN IN-PLANE MAGNETIC FIELD

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The anisotropy of the effective mass in a wide electron layer confined in a parabolic potential well has been determined from plasmon resonance experiments for the case of an in plane magnetic field. For this system, the resulting band structure can be described in terms of a hybridization of the electrical and the magnetic confinement and free motion in the plane of the electron system. The effective mass shows a strong anisotropic behavior along the two principal directions with respect to the magnetic field. For a purely parabolic confining potential one can derive analytical expressions for this anisotropy which are in excellent agreement with the experimental results. Similarities to the collective excitation spectra of one-dimensional quantum wires are discussed.

The collective excitation spectrum of an electronic system contains valuable information as it is one of its most fundamental properties. For two-dimensional electron systems (2DES) as realized in space charge layers in semiconductors the study of plasmonic (intrasubband-) excitations as well as intersubband-transitions have proven invaluable in the characterization and understanding of these systems[1]. More recently[2], also the collective excitations in quasi-one-dimensional electron systems (Q1DES, quantum wires)[3,4] and quasi-zero-dimensional (Q0DES, quantum dots)[5] have attracted very much attention. On the other hand, the collective intersubband-like excitations of wide electron layers in so-called parabolic quantum wells (PQW) which form a quasi-three-dimensional electron system[6..9] (Q3DES) has led to the generalization of Kohn's theorem[10]. Subsequently, this theorem has been very successfully applied to explain many experimental observations also on Q1DES and Q0DES. It states that in a purely parabolically confined electron system long-wavelength radiation couples only to the center of mass coordinates and its motion. Relative coordinates and thus particularly electron-electron interactions in such systems do not affect the resonance frequency of the observed transitions.

Here, we report on the investigation of the collective excitations of a wide electron system in a PQW at finite wave vector[9]. If such a system is subjected to an in-plane magnetic field the resulting band structure is very closely related to the one of a 1D quantum wire in a perpendicular magnetic field. The reason is that 1D quantum wires in most cases can be described in good approximation by an external parabolic confining potential. The main advantage of a PQW, however, is the exact knowledge of the shape of the potential which allows to directly deduce analytical expressions for the expected spectrum of the collective excitations. Moreover, the case of an ideal parabolic quantum well in a parallel magnetic field is particularly simple and can be quantized in analytical form[11,12].

Referring the reader to a more detailed description of the growth procedure and fundamental properties of a PQW in refs. 6..9, we give here only a short list of the parameters for the sample used in the present experiment: Our sample is a parabolic $Al_xGa_{1-x}As$ quantum well of width W=200nm and energetical depth of Δ_1=150meV. It has additional vertical sidewalls of height Δ_2= 75meV. The curvature of the parabolic part of the well corresponds to the potential of a positive background density $n^+=2\cdot 2.10^{16}cm^{-3}$. On top of the sample we have a semitransparent NiCr gate and an Ag grating coupler of periodicity a=2µm. Ohmic contacts are made to the electron system by alloying In at T=430°C in reducing atmosphere. By application of a bias between the gate and the electron system[13] we can change the carrier density in the well from

$N_S=0$ to $N_S=2.6\cdot10^{11}cm^{-2}$. The grating coupler provides a plasmon wave vector $q = 2\pi/a = \pi\cdot10^6$ m^{-1}.

As has been shown before[14,15], a quasi 3DES confined in a PQW can support intra-subband excitations that for small q resemble the well known surface plasmon[16] of a 2DES. Its dispersion is given by

$$\omega_p^2 = \frac{N_s e^2 q}{2m_p\bar{\varepsilon}(q)\varepsilon_0} \qquad (1)$$

where $\bar{\varepsilon}(q)$ denotes an effective dielectric constant containing sample parameters and geometry, and m_p an effective plasmon mass. The other symbols have their usual meaning. For our sample $\hbar\omega_p \cong 15cm^{-1}$, depending on the carrier density in the well. The sample is mounted in Voigt geometry in the center of a superconducting solenoid providing magnetic fields up to 15T parallel to the plane of the electron system. It is held at a temperature of T=4.2K. The experiment are performed in transmission using a rapid scan Fourier transform spectrometer under normal incidence of unpolarized far infrared radiation (FIR). Experimentally we determine the relative change in transmission

$$-\frac{\Delta T}{T} = \frac{T(0)-T(N_s)}{T(0)} \qquad (2)$$

which is proportional to the real part of the dynamic conductivity $\tilde{\sigma}(\omega)$ of the electron system. The geometry of our experiment is depicted in Fig. 1. Here, both principal orientations of the plasmon wave vector with respect to the magnetic field are already sketched. By rotating the sample by $\pi/2$ we can excite surface plasmons with q being either parallel or perpendicular to the magnetic field.

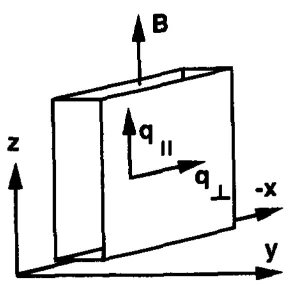

Fig. 1. Sketch of the geometry of the experiment. The unpolarized far-infrared radiation is incident in y-direction, the magnetic field is directing parallel to the electron layer (x-y-plane). The plasmon wave vector q is defined by use of a metal grating on top of the sample, and can direct either parallel or perpendicular to the magnetic field.

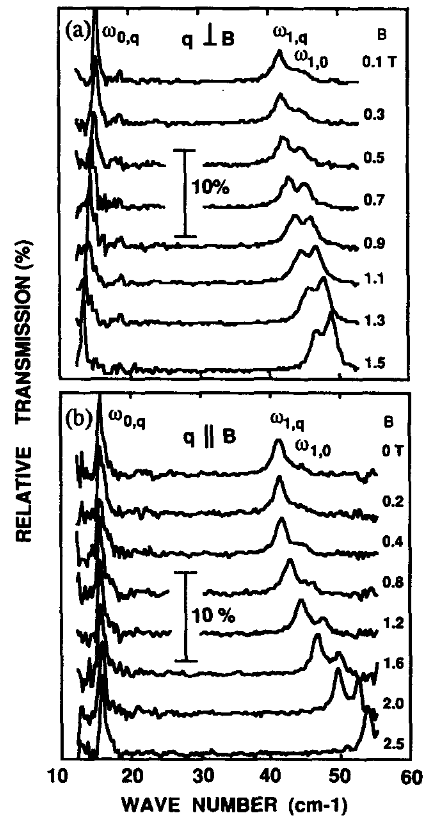

Fig. 2. Typical spectra as obtained in transmission and Voigt geometry for different magnetic fields B. Both cases of q being perpendicular (a) and parallel (b) to B are depicted. In both experiments we observe three resonances, which are related to the intra-subband plasmon at finite wave vector (0,q), the inter-subband plasmon at finite wave vector (1,q), and the inter-subband plasmon at zero wave vector (1,0). The latter is also called plasma shifted cyclotron resonance. In (a) the resonance (0,q) has a characteristic negative magnetic field dispersion, whereas (1,q) and (1,0) follow the dispersion for a magneto-electric hybrid excitation as described in the text. In contrast to (a), for parallel configuration (0,q) has no magnetic field dependence as expected from the simple model (b).

Typical spectra for both orientations of the plasmon wave vector with respect to the magnetic field are shown in Fig. 2. Here, we plot the observed relative change in transmission vs. energy for different magnetic fields. In perpendicular geometry, i.e. the plasmon wave vector being normal to the magnetic field (Fig.2a) we observe basically three resonances. The lower frequency mode $\omega_{0,q}$ around 16cm^{-1} at low B is identified with the surface plasmon and exhibits a *negative* dispersion with the magnetic field, which is a unique feature of an edge magnetoplasmon type of oscillation[17,18]. The higher frequency modes $\omega_{1,q}$ and $\omega_{1,0}$ are the grating coupler induced intersubband-type excitation[9] and the plasma shifted cyclotron resonance[7,8] at q=0, respectively. The oscillator strength of the latter is zero for zero magnetic field and then increases as the field increases[8], which can be clearly seen in the figure. This excitation is formally identical to the magneto-electric subband hybrid in a 1D quantum wire. For parallel geometry (Fig. 2b), we also observe three oscillations, but $\omega_{0,q}$ now has no significant magnetic field dependence. This striking difference contains information about the magnetic field induced anisotropy of the effective band structure that we like to discuss in this Communication.

Using the coordinate system of Fig.1 and omitting the spin, the initial eigenenergy equation for a PQW subjected to an in-plane magnetic field reads[12]

$$\left[\frac{1}{2m^*}\left(\vec{p}+e\vec{A}\right)^2+\frac{m^*\omega_{1,0}^2}{2}y^2\right]\psi=E\psi \qquad (3)$$

where $m^*\omega_{1,0}^2/2$ characterizes the parabolic potential in growth (y-) direction. This frequency is given by the bare external potential of the PQW and due to Kohn's theorem independent of the number of electrons in the well. It has been shown before[6..10] that this frequency $\omega_{1,0}$ for q=0 is solely determined by the *curvature* of the external parabolic potential and is given by

$$\omega_{1,0}^2=\frac{8\Delta_1}{W^2m^*} \qquad (4)$$

where Δ_1 is the energetical height of the parabolic part of the potential, and W its width in confining direction. At finite wave vector q, the mode exhibits a dispersion[14,15] which is determined by the quantity qd, d being the width of the *electron system* in the direction of confinement:

$$\omega_{1,q}^2=\frac{\omega_{1,0}^2}{2}(1+e^{-2qd}) \qquad (5)$$

Taking $\vec{A}=-(By,0,0)$ and separating the variables in the usual way one obtains form (3)

$$\left(\frac{-\hbar^2}{2m^*}\frac{d^2}{dy^2}+\frac{m\Omega^2}{2}\tilde{y}^2\right)f(\tilde{y})=\tilde{E}f(\tilde{y}) \qquad (6)$$

where $\Omega^2=\omega_{1,q}^2+\omega_c^2$ is the effective hybrid frequency, $\tilde{y}=y-y_0$ with $y_0=\hbar k_x\omega_c/m^*\Omega^2$. The resulting energy dispersion then turns out to be given by

$$E=\hbar\Omega(n+1/2)+\frac{\hbar^2k_x^2}{2m^*}\frac{\omega_{1,q}^2}{\Omega^2}+\frac{\hbar^2k_z^2}{2m^*} \qquad (7)$$

This dispersion describes a harmonic oscillator-like quantization in the confining direction of the parabolic potential with a characteristic frequency Ω, representing the intersubband-type collective excitation that obeys Kohn's theorem. The free motion in the plane of the Q3DES is represented by the quasi-momenta k_x and k_z. Eq. (7) has exactly the same form for a 1DES in parabolic approximation (quantum wire) if one replaces the term containing k_z by a 2D subband energy, since it is also confined in this direction. The term containing k_x is then related to so-called one-dimensional plasmons propagating along the wire[4]. The hybrid oscillator term is governed by the 1D intersubband plasmon. The interesting fact for a PQW, however, is the occurrence of an anisotropic band structure in the plane of the electron system with respect to the direction of the magnetic field. The same anisotropy has been observed before, although as a much weaker effect, for high quality 2DES on GaAs/AlGaAs heterostructures[19]. The theoretical description in that case, however, is rather complex and not straightforward[20]. Using eq. (7) one can define a very simple expression for the effective mass for a PQW and the geometry under consideration

$$m_\perp:=m^*\left(1+\frac{\omega_c^2}{\omega_{1,q}^2}\right) \quad and \quad m_\parallel:=m^* \qquad (8)$$

in the plane of the electron system. The subscript symbols for m* indicate the direction with respect to the magnetic field. With increasing magnetic field the 'perpendicular' effective mass increases quadratically. The effective mass parallel to the magnetic field, respectively, remains unaltered and is given by m*. Using this expression for the plasmon mass we obtain the magnetic field dispersion of the surface plasmon.

$$\omega_{0,q}^2(q_\perp)=\omega_p^2\left(1+\frac{\omega_c^2}{\omega_{1,q}^2}\right)^{-1} \quad ; \quad \omega_{0,q}^2(q_\parallel)\equiv\omega_p^2 \qquad (9)$$

The result is shown in Fig. 3, where we plot the extracted resonance positions of $\omega_{0,q}$ for both principal orientations of q as a function of the magnetic field. For high magnetic fields (B>3T) we are not able to follow the negative dispersion of $\omega_{0,q}(q_\perp)$ since we are approaching the noise limit of our spectrometer close to $10cm^{-1}$. The magnetic field independent resonance $\omega_{0,q}$ for q ∥ B, however, does not deviate significantly from its low field behavior up to B=15 T. This part of the data has been omitted in the plot for clarity. Note that no fit parameter has been used since all quantities can be measured independently. From cyclotron resonance[7,8] in Voigt-geometry one can

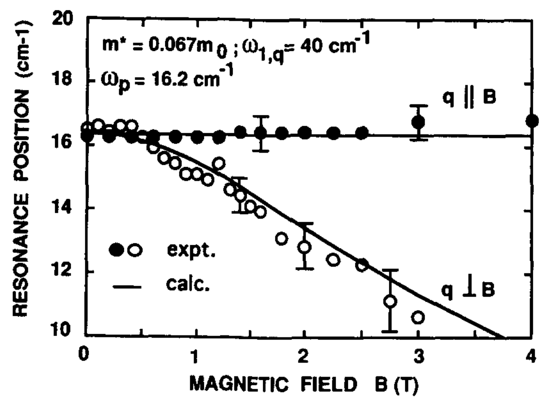

Fig.3. Resonance positions as extracted from Fig. 2 for both orientations of the plasmon wave vector q with respect to B. They reflect the magnetic field induced anisotropy of the plasmon mass. Symbols represent the experimental data, whereas the solid lines are the result of the simple model as described in the text. The parameters used are given in the inset.

extract m*. Plasmon resonance experiments[14] in Faraday geometry, i.e. the magnetic field directing normal to the sample surface are used to extract $\omega_{0,q}$. The q=0 resonance $\omega_{1,0}$ can be determined by tilted field experiments[3,6,8], where no grating coupler is needed to exite it.

In summary, we have investigated the collective excitations of a parabolically confined electron system subjected to a magnetic field perpendicular to the gradient of the confinement. The magnetic field induces a strong anisotropy of the effective band structure, which is reflected in the magnetic field dispersion of a finite q plasmon parallel to the electron layer. The resulting band structure is formally identical to the one of a 1DES as confined in a quantum wire in harmonic approximation. The orientation where q is normal to the magnetic field results in an edge magneto-plasmon type excitation that in a 1DES is propagating along the wire and usually is referred to as a 1D plasmon.

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