Electron plasma resonances in wide parabolic quantum wells

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The far-infrared resonances of an electron plasma in wide parabolic quantum wells (PQW's) are investigated by Fourier transform spectroscopy. We report on recent experimental results employing different techniques to observe these dimensional resonances. First, we study their coupling to the cyclotron resonance in various wells of different curvature and width using tilted magnetic fields. Secondly, we observe the so-called plasma-shifted cyclotron resonance in Voigt-geometry. Finally, we demonstrate that the modes can also be observed directly, i.e. without the mediating help of a magnetic field by using a grating coupler technique. The results of the experiments are compared with each other and with the ones of existing theories.

The possible realization of artificial microstructures such as quantum wires, quantum dots [1] or parabolic quantum wells [2,3], has recently attracted considerable attention on parabolic confining potentials of different dimensions, both on the experimental as well as on the theoretical side. In this context, a generalization of Kohn's theorem [4] has been evaluated by different authors [5,6]. This theorem states, that for an electron system in the very specific case of a purely parabolic confining potential, radiation is only absorbed at the bare harmonic oscillator frequency Ω given by the curvature of the confining potential, independent of the electron–electron interaction. This is due to the fact that here the Hamiltonian can be separated in two parts, one only containing the coordinates of the center of mass (CM) of the system, and the other one only the relative coordinates of the interacting particles. The manybody wave function, too, separates into a CM dependent part and one containing only relative coordinates. A homogeneous radiation field in this case turns out to only act on the CM part. Thus the observed eigenfrequencies correspond to those of a single electron within the parabolic confining potential.

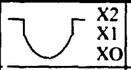
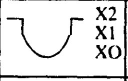
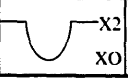
Here, we would like to report on our recent experiments on the far-infrared spectrum of wide parabolic quantum wells (PQW's). The bare harmonic oscillator frequency Ω is in this case simply given by the curvature of the grown parabola [5]. The measurements are performed at high magnetic fields $B < 16$ T and at low temperatures $T \geq 2$ K, using a rapid-scan Fourier spectrometer. Experimentally we detect the relative change in transmission $\Delta T/T$ through the sample by switching between a certain carrier density N_s and the depleted well. The carrier densities in our samples may be tuned by the use of a semitransparent NiCr gate and the application of a bias between this electrode and the electron system in the PQW [7,8]. The aim of this work is to demonstrate different experimental techniques for the observation of the electron plasma (or dimensional) resonances in a parabolic quantum well and to compare the obtained results. Classically speaking, the dimensional resonance in a PQW is the collective sloshing mode of the whole electron system in the direction of confinement, unaffected by the internal, self-consistent spectrum of the particles in the well. To excite this mode, the radiation field must have components in the direction of confinement (z-direction throughout this paper). The situation is thus analog to the intersubband-spectroscopy in heterostructures or conventional quantum wells. Consequently we employ similar techniques for the PQW case. First, we use tilted magnetic fields [5,9] to couple the cyclotron resonance (CR) to the dimensional resonance. For a single electron in the well (or due to Kohn's theorem also for the CM of a many electron system) the situation can be analytically calculated [10] by assuming the coupling of two harmonic oscillators of frequency ω_c and Ω. A finite angle θ between the sample normal and the magnetic field couples the motion in the xy-plane with the one in z-direction and leads to a characteristic splitting of the CR around $\omega_c \approx \Omega$. The two observable frequencies are then given by

$$\omega_{+/-} = \left(\tfrac{1}{2}\left(\omega_c^2 + \Omega^2\right) \pm \tfrac{1}{2}\left(\omega_c^4 + \Omega^4 + 2\Omega^2\left(\omega_x^2 - \omega_z^2\right)\right)^{1/2}\right)^{1/2}. \tag{1}$$

Here, ω_x and ω_z are the components of the CR on the x- and z-direction. In fig. 1 we show a representative result for such a tilted field experiment. The filled points represent the observed resonance positions, whereas the solid line is the result of the simple calculation (1) using $\Omega = 86$ cm^{-1} as expected from the curvature of the grown parabola. The two modes exchange oscillator strength as depicted by the open symbols and the dashed lines, respectively.

Table 1

Summary of the sample parameters presented here. The x_i in column 2 represent the Al mole fraction in the $Al_xGa_{1-x}As$ parabolic quantum wells at different locations. ω_{calc} depicts the resonance position as extracted from the curvature of the grown parabolae

PARABOLIC QUANTUM WELLS						
Sample	Type	XO	X1	X2	Width	ω_{calc}
PB25		0	0.1	0.3	75 nm	86 cm
PB26		0	0.2	0.3	200 nm	47 cm
PB48		0	--	0.3	130 nm	86 cm

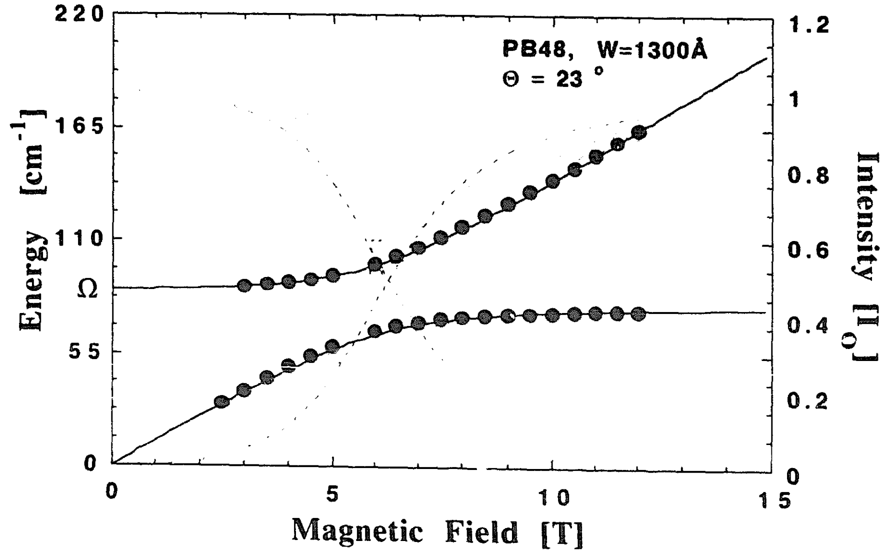


Fig. 1. Experimentally obtained resonance positions (filled circles) and intensities (open symbols) of the split CR under a tilt angle of 23°. The lines are the results of a simple harmonic oscillator model as derived in refs. [5,10] using an effective mass $m^* = 0.07m_0$, and $\Omega = 86$ cm^{-1} as expected from the growth.

If the magnetic field is directed parallel to the electron layer, i.e. $\theta = 90°$ (Voigt-geometry), only one line should be observed in the harmonic oscillator model. This line corresponds to the hybridization of Ω and ω_c, sometimes called the plasma-shifted cyclotron resonance [11], given by

$$\omega^* = \left(\omega_c^2 + \Omega^2\right)^{1/2}. \tag{2}$$

In fig. 2 we depict the typical result of such an experiment. The observed resonance positions nicely follow the model, and the intensity of the observed line can also be well explained taking the polarization of the incoming light to be parallel to the layers, i.e. perpendicular to the z-direction. The extracted bare oscillator frequency $\Omega = 47\ \text{cm}^{-1}$ again agrees very well with the one expected from the growth.

Finally, we would like to demonstrate the observability of dimensional resonances in a PQW by using a grating coupler technique. This technique has been previously successfully applied to the investigation of the intersubband resonance spectroscopy of quasi-two-dimensional electron system [12]. Highly conducting metal stripes (100 nm Ag) with a periodicity of several μm on the sample surface act as a diffraction grating for the incident long-wavelength radiation. In the near field of such a grating (i.e. in a distance of the order of the grating period) the normal incident light has electric field components also in z-direction, which in turn act to couple to the subband or dimensional resonance. In this way we are able to study the dimensional resonance directly, i.e. without the need of a magnetic field, and as a function of the numbers of carriers in the well. The result then is in fact a direct proof of Kohn's theorem for the case of a single parabolic confining potential. In fig. 3 we depict a typical result of such a grating coupler induced transmission spectrum. For comparison, however, the sample in this case is a quite narrow (75 nm) and shallow (75 meV) PQW with vertical sidewalls of approximately 150 meV energetical height [8]. These hard wall boundaries, together with the shallow well, represent a strong, but *intentionally induced* deviation from the ideal parabolicity of the quantum well. In this case also, deviations from the validity of Kohn's theorem are expected. The carrier density in the described experiment is such that the PQW is nearly completely filled so that the finite size of it becomes important. As a result not only a single line (the one of the bare potential) is observed, but additional sidelines appear. This appearance is unique to a strongly deformed PQW and is not observed on more ideal samples. The existence of such sidelines in

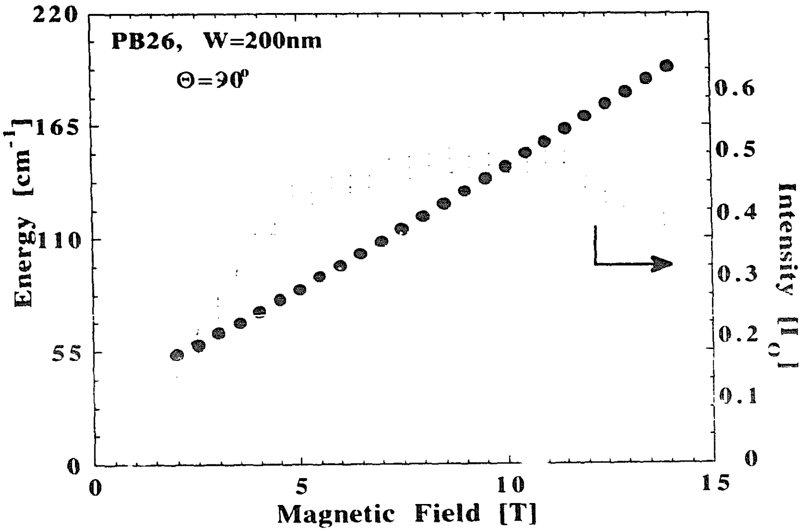


Fig. 2. Resonance positions (filled symbols) and intensities (open symbols) of the plasma shifted CR for a 200 nm wide PQW in Voigt geometry. The extracted resonance frequency at $B = 0$ T is in good agreement with the one expected from growth.

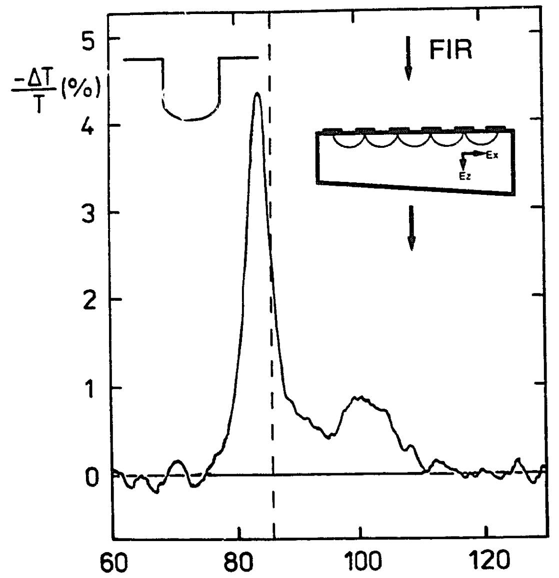


Fig. 3. Experimental spectrum of the dimensional resonance in a parabolic quantum well with vertical sidewalls. The left inset schematically shows the shape of the well. A grating coupler technique is used to directly measure this resonance. The dashed line represents the position of the resonance as expected from growth alone. A sketch of the sample geometry is depicted in the inset. Due to deviations from the ideal parabola in this specially designed sample more than one line is observed.

the spectra of 'imperfect' parabolic quantum wells has recently been predicted by Brey and coworkers [13] in a self-consistent calculation using the local density approach. They represent internal oscillations of the electron system, which occur due to the presence of the vertical sidewalls and the subsequent accumulation of charge near the boundaries of the PQW. The agreement between the data extracted (within the simple harmonic oscillator picture) from magnetic field experiments with those using a grating coupler is very poor, which is certainly due to the fact, that for the description of the coupling of the dimensional resonance and the CR, this model is no longer valid. It turns out [14], that here additional degrees of freedom of the system have to be taken into account, such as an internal 'Fermi pressure'. Details of the magnetic field behavior of such samples, however, are still under consideration and will be discussed elsewhere. For the 'ideal' samples PB26 and PB48, however, the agreement between the results of the observed resonance positions is excellent. This proves the result of the generalization of Kohn's theorem [4–6], that both the dimensional resonance in a PQW as well as the cyclotron resonance are indeed unaffected by particle–particle interactions. In fig. 4, finally, we compare those observed resonance positions for a PQW obtained using all three techniques mentioned above. The small, but reproducible scatter around the expected value is independent of the choice of the experimental technique and is thought to be due to a test of the local curvature of the parabola as a function of gate bias [8].

In summary, we have demonstrated different possibilities for the observation of dimensional electron plasma resonances in artificially created parabolic quantum wells. The validity of the generalization of Kohn's theorem has been demonstrated for various wells. In specially designed samples, however, deviations have been observed. The use of a grating coupler technique enables us to directly study the behavior of $\sigma_{zz}(\omega)$ without the mediating help of a magnetic field.

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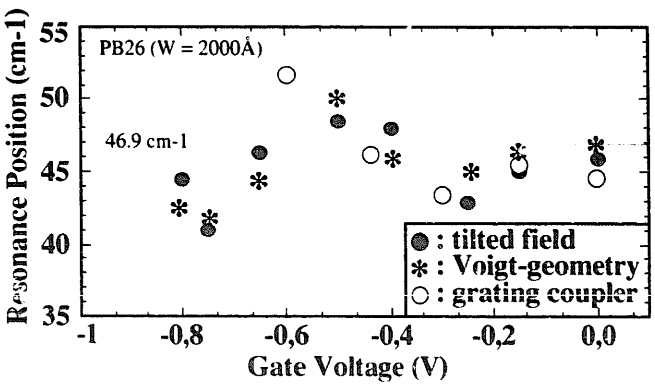

Fig. 4. Observed resonance positions from different experimental techniques. The inset shows the type of experiment used. The tilted field data have been obtained at a tilt angle of 23°. Within the experimental error, the agreement indicates the validity of Kohn's theorem in its generalized form both with and without magnetic field.

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