Enhanced resonant coupling between one- and two-dimensional energy states in quantum wires

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250-nm narrow quantum wires have been prepared by deep-mesa etching of modulation-doped $Ga_xIn_{1-x}As$ heterostructures. The far-infrared response of these quantum wires is strongly governed by collective excitations. In tilted magnetic fields B we observe a resonant coupling of these collective wire modes to "two-dimensional" (2D) energy states, i.e., states that arise from the confinement in the original 2D system. We can qualitatively explain this coupling, in particular the observed anisotropy with respect to the tilt directions, within a one-particle model. Quantitatively, however, the coupling appears drastically enhanced in the 1D quantum wires as compared to the coupling in 2D systems.

With modern lithographic techniques it has become possible to fabricate quantum wires, one-dimensional electronic systems (1DES) with quantum confined energy levels. Starting from 2DES in modulation-doped semiconductor heterostructures, where the electrons are already confined in the growth direction (z direction), electrons are further confined by lateral potentials on a submicrometer scale in the y direction. The electronic properties of these systems have been studied with different methods, e.g., transport and magnetocapacitance[1–4] or far-infrared (FIR) spectroscopy.[5–9] In this article we report about FIR experiments in tilted magnetic fields B to explore interaction between "2D" and "1D" energy levels, i.e., states arising from the original vertical confinement in the z direction and from a lateral confinement in the y direction, respectively. The FIR response of the quantum wires is strongly governed by confined plasmon excitations. In tilted magnetic fields we observed a strong coupling of these plasmon modes with "2D" energy levels. This coupling was found to be anisotropic for different tilt directions with respect to the wire. Qualitatively we can explain this coupling and the anisotropy within a one-particle model. Quantitatively, however, the coupling is drastically enhanced in the 1D quantum wires as compared to resonant-subband-Landau-level coupling (RSLC) (Refs. 10 and 11) in 2DES.

Quantum wires have been prepared by deep-mesa etching of modulation-doped $Ga_xIn_{1-x}As$ heterostructures that were grown lattice matched ($x=0.47$) by molecular-beam epitaxy on semi-insulating InP:Fe substrates and consisted of 500-nm $Ga_xIn_{1-x}As$, with the active layer at the interface near a 34-nm $Al_yIn_{1-y}As$ spacer and 56-nm Si-doped $Al_yIn_{1-y}As$ ($y=0.48$). The cap layer was 2-nm $Ga_xIn_{1-x}As$. Starting from a holographically prepared photoresist mask, we fabricated arrays of quantum wires, with geometrical width $t=250$ nm and with period $a=400$ nm, on 4×5-mm^2 samples by a 140-nm-deep etching into the active layer.[9] The samples were characterized by magnetic depopulation[1] and had, assuming a parabolic lateral confining potential, a 1D subband spacing of 2 meV.[9] The local 2D electron density in the wires could be varied via the persistent photoeffect from $N_s=(2-3)\times10^{11}$ cm^{-2}. FIR transmission experiments were performed in a superconducting magnet cryostat that was connected to a Fourier transform spectrometer. The sample could be tilted continuously such that there was either a magnetic-field component B_x parallel to the wires, which will be called "longitudinal" tilting in the following, or a component B_y perpendicular to the wires in the original 2D plane ("transverse" tilting). The temperature was 2.2 K and the spectral resolution was set to 0.5 cm^{-1}.

Figure 1 shows experimental transmission spectra for p-polarized radiation (i.e., the exciting FIR electrical-field vector is perpendicular to the wires) at four different longitudinal tilt angles α (measured with respect to the surface normal) and the same B_z component. These spectra show clearly that, in spite of the same normal component B_z, the resonance frequency and also the amplitude decreases with increasing α. Experimental resonance positions for longitudinal tilts are depicted in Fig. 2. From the double-quadratic plot we find that for $\alpha=0°$ the resonance frequency obeys the relation $\omega_r^2(B)=\omega_{r,B=0}^2+\omega_c^2$ with the cyclotron-resonance frequency $\omega_c=eB/m^*$, as was observed earlier.[8,9] With increasing α the dependence of ω_r^2 on ω_c^2 is increasingly suppressed below the linear dependence observed at $\alpha=0°$ and this suppression is anisotropic, i.e., stronger for longitudinal tilts than for transverse tilts. This is also clearly demonstrated in Fig. 3, where we have plotted the resonance frequencies versus the tilt angle α at different B_z values.

How can we explain these observations? The optical response of quantum wires for perpendicular magnetic field $B=(0,0,B_z)$ is now relatively well understood.[6–9] In currently available quantum wires the effective one-particle energies of electrons are strongly determined by Coulomb interaction and self-consistent screening and the resulting separation of the 1D subband energies is significantly smaller than the energy spacing in the bare, external confining potential.[12] With FIR dipole excitation, however, it is not possible to couple to transition between these screened single-particle energy levels. Rath-

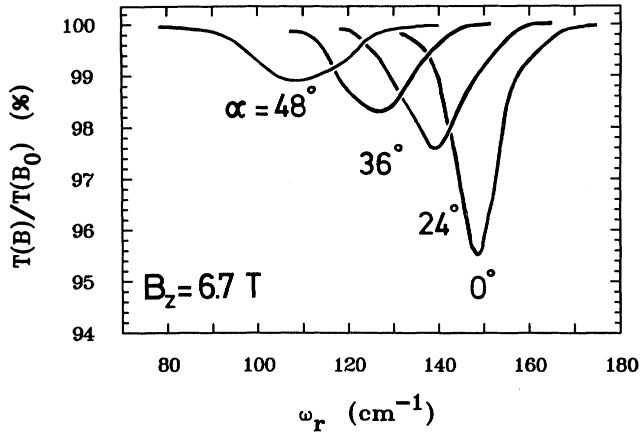

FIG. 1. Normalized transmission spectra of p-polarized FIR radiation through a $Ga_xIn_{1-x}As$ quantum wire sample at different longitudinal tilt angles α. The resonances decrease with increasing α drastically in intensity and resonance frequency in spite of a constant normal component B_z of the magnetic field.

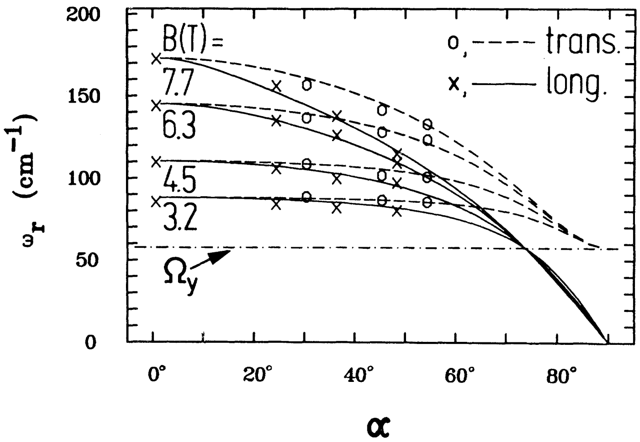

FIG. 3. Tilt angle dependence of the resonance frequencies for different normal components B_z. Open circles denote transverse tilts; multiplication signs denote longitudinal tilts. Dashed (solid) lines are fits using Eq. (1) [Eq. (2)] with $\Omega_z=270$ nm ($\Omega_z=200$ nm) for the transverse (longitudinal) tilt. Ω_y is indicated by the dash-dotted line.

er, the FIR response is strongly governed by collective effects giving the resonances the character of a local, confined plasmon mode.[8] For example, for our quantum wires we determine from magnetotransport[9] a screened energy separation of 2 meV, whereas the resonance frequency is 57 cm^{-1} (7 meV). Actually it has been shown for quantum wells,[13] wires,[14] and dots[15] that for a parabolic confinement the dipole excitation only couples to the rigid center-of-mass (c.m.) motion of all electrons. The excitation occurs at the eigenfrequency of the bare confining potential and might be interpreted as the oscillation of a single particle with a charge Ne and a mass Nm^* in the bare potential, where N is the total number of electrons.

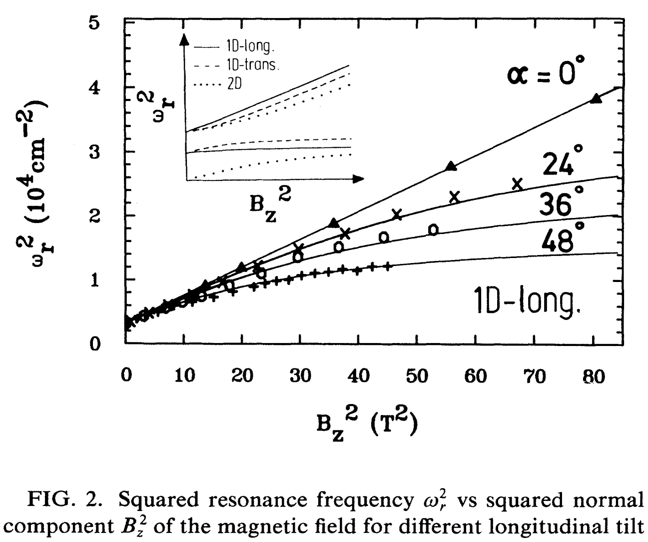

FIG. 2. Squared resonance frequency ω_r^2 vs squared normal component B_z^2 of the magnetic field for different longitudinal tilt angles α. Solid lines have been calculated [Eq. (2)] with $\Omega_z=200$ cm^{-1}. The inset shows the calculated dispersions ω_r^s vs B_z^2 according to Eqs. (1) and (2) with 1D confinement ($\Omega_y=0.75\Omega_z$) and without (2D: $\Omega_y=0$) for $\alpha=35° < \alpha_c$.

It is tempting to apply this "single-particle model" also to our case of tilted magnetic fields. In particular, if we assume for a moment that instead of the actual triangular confinement potential in the z direction of the heterostructure the confinements in both the z and the y direction are parabolic, $V_z(z)=0.5m^*\Omega_z^2z^2$ and $V_y(y)=0.5m^*\Omega_y^2y^2$, respectively, we can calculate the single-particle energies analytically for arbitrary tilt angles. We give the results here for the special cases of a purely transverse tilting, Ω_t, and a purely longitudinal tilting, Ω_l, to demonstrate directly the anisotropy:

$$2\Omega_{t\pm}^2=(\Omega_z^2+\omega_y^2+\Omega_y^2+\omega_z^2) \pm\sqrt{(\Omega_z^2+\omega_y^2-\Omega_y^2-\omega_z^2)^2+4\omega_y^2\omega_z^2}\ , \tag{1}$$

$$2\Omega_{l\pm}^2=(\Omega_z^2+\omega_x^2+\Omega_y^2+\omega_z^2) \pm\sqrt{(\Omega_z^2+\omega_x^2-\Omega_y^2-\omega_z^2)^2+4(\Omega_y^2+\omega_z^2)\omega_x^2}\ , \tag{2}$$

with $\omega_i=eB_i/m^*$ ($i=x,y,z$). This energy spectrum is sketched in the inset of Fig. 2 and can be interpreted as a resonant interaction of two hybrid subband-Landau modes, one of frequency $(\Omega_y^2+\omega_z^2)^{1/2}$ and another of frequency $(\Omega_z^2+\omega_i^2)^{1/2}$, with $i=x$ and $i=y$ for the longitudinal and transverse tilt, respectively. The inset of Fig. 2 shows that the "splitting" between the modes becomes smaller if we add 1D confinement to the 2D case ($\Omega_y=0$). In the 1D case, the longitudinal tilt, which couples the motion in the confined directions, leads to a larger splitting than the transverse tilt. The latter couples the motion in one confined direction with the unconfined x direction. Note that in tilted magnetic fields the Hamiltonian still contains only parabolic terms for the potential. Thus the decoupling of the c.m. motion from internal motion for dipole excitation is still valid also for the more complex energy spectrum in Eqs. (1) and (2).

In our experiments we observe the low-frequency branches Ω_-, and indeed find the anisotropy that is predicted by the single-particle theory. For a quantitative comparison, we know from the experiments $\Omega_y=57$ cm^{-1} and the mass of $0.045m_0$ (for our densities). We have fitted the experimental dispersions in Figs. 2 and 3 with the only free parameter, Ω_z, and find that $\Omega_z=200$ cm^{-1} for longitudinal tilting and $\Omega_z=270$ cm^{-1} for transverse tilting describe the experimental results very well. Interestingly, the theory predicts that for longitudinal tilting the dispersions for different B cross each other at the energy Ω_y and at the angle $\alpha_c=\arccos(\Omega_y/\Omega_z)$. ($\alpha_c$ is 73° for our sample). For the transverse case this behavior is different. With increasing α the dispersions do not cross and extrapolate for $\alpha=90°$ to Ω_y. This behavior yields indeed a consistent extrapolation of the experimental dispersion into the α regime that is not accessible in our experimental setup. From the resonant interaction sketched in the inset of Fig. 2 we also understand the experimentally observed decrease of the amplitude of the lower branch in Fig. 1 with increasing B. This is a direct manifestation of the expected transfer of oscillator strength from the lower to the higher of the interacting modes sketched in the inset of Fig. 2. Unfortunately, for the available B in our setup, the higher branch is hidden by the reststrahlen regime of the InP substrate.

The single-particle model seems to give a very good description and understanding of the observed phenomena. However, within the strict model of a parabolic confinement one would expect that the dispersions for both tilt directions are determined by the same value of Ω_z. Moreover, one would expect that in the 2D case ($\Omega_y=0$) the frequency lowering of the Ω_- dispersion should be even slightly larger as compared to the wires (see inset of Fig. 2). This is, however, not observed on our 2D reference samples. Actually, from tilted-field experiments on the 2D samples (this is the well-known RSLC experiment to determine intersubband resonance energies[10,11]) we find at least up to tilt angles $\alpha=45°$ a linear increase of the resonance frequency with B (except for the small effect of nonparabolicity) and no resonant interaction in the accessible frequency regime.

From this we must conclude that the coupling in quantum wires is drastically enhanced as compared to the 2DES and is differently enhanced depending on the tilt direction, as follows from the different fit values of Ω_z for transverse and longitudinal tilts. This points to the limitations of our single-particle approach. This ansatz can be justified rigorously only (i) for a dipole excitation, i.e., for a spatially homogeneous exciting FIR field, and (ii) only for parabolic confinement. In all other cases we immediately have coupling of the c.m. motion with internal motions. In the actual array of quantum wires with period a the local plasmon oscillation induces Fourier components of the FIR fields near the electron system with wave vectors $q_m=m2\pi/a$, $m=0,\pm1,\pm2,\ldots$. The field components $m\neq0$ decay exponentially away from the boundary and are *not* dipolelike. Most importantly, they have nonzero z components, E_{zm}, of the total electric FIR field. It has been shown experimentally by Oelting, Heitmann, and Kotthaus[16] for 2DES in Si-MOS (metal-oxide-semiconductor) systems and theoretically by Das Sarma[17] and recently by Broido and Kempa[18] that the resonantly enhanced E_z component, which is an intrinsic property of the in-plane plasmon excitation, leads to a strong resonantly enhanced interaction with 2D intersubband resonances (ISR), i.e., an anticrossing behavior. We believe that the resonantly enhanced E_z component of the local plasmon resonance in the quantum wires is important for the drastically enhanced interaction observed here. (These arguments also hold for a single quantum wire where we have a continuous Fourier spectrum and would exist even if the bare confining potentials were perfectly parabolic.)

Thus for a more quantitative understanding one needs a combination of previous calculations. (i) Plasmon-ISR interaction, which has been treated for 2DES and $B=0$ (Refs. 17 and 18). This interaction is governed by a Coulomb matrix element that involves the electron wave functions of the lowest (occupied) and first excited (unoccupied) 2D subbands. [It is actually the question of what is the "2D" ISR in a wire with a density profile $N_s(y)$. In a local model this would imply $\Omega_z=\Omega_z(y)$. Such a behavior has been observed in density modulated Si-MOS systems[19] where different ISR corresponding to different local densities were observed. Obviously, such a local description is not applicable here.] (ii) A treatment of the "local-field corrections" for the Fourier components $m\neq0$, which have been considered in calculations for 2D arrays of quantum wires (neglecting coupling to 2D ISR), e.g., in Ref. 20. These ingredients must be embedded in a self-consistent treatment of the 3D density profile of the quantum wires to explain their dynamic response in the resonant situation of tilted magnetic fields.

In conclusion, for quantum wires in tilted magnetic fields a strong resonant coupling of the confined plasmon modes with 2D levels is observed. A single-particle model explains qualitatively the tilt-angle dependence and anisotropy. Quantitatively, however, the coupling in the quantum wires is drastically enhanced with respect to similar interactions in 2DES.

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