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Far-infrared response of one-dimensional electronic systems in single- and two-layered quantum wires

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The far-infrared (FIR) response of arrays of periodic single- and two-layered quantum wires has been investigated. The wire structures have been prepared by ultrafine deep-mesa etching of modulation-doped $Al_xGa_{1-x}As/GaAs$ heterostructures and two-layered quantum-well systems. Due to narrow geometrical dimensions (500 nm), quantum confinement arises and leads to the formation of one-dimensional electronic subbands with a typical energy separation of 1–3 meV. The FIR transmission spectra of the single- and two-layered quantum wire structures show one and two resonances, respectively. The resonance frequencies are observed at significantly higher energies compared to the one-dimensional subband separation. This implies that collective interactions have a strong influence on the excited transitions and leads to the conclusion that the FIR resonances in the one-dimensional electronic systems have predominantly the character of layer-coupled local plasmon modes.

Quantum-confined one-dimensional electronic systems (1DES) are currently the subject of increasing interest (e.g., Refs. 1–5). Starting from 2DES, e.g., Al_xGa_{1-x}-As/GaAs heterostructures, where the electrons are confined in z direction normal to the interface, these 1D systems can be realized by an additional lateral confinement, acting in x direction. It is thereby possible to induce quantum-confined discrete energy levels, E_x^i, and to restrict the free motion of the electrons to the y direction. From dc magnetotransport measurements on those samples typical values of 1–3 meV for the separation of these 1D subbands were found. However, in far-infrared (FIR) experiments on the same systems resonant excitations were observed at significantly higher energies.[4] We have recently demonstrated that 1DES can be realized in ultrafine deep-mesa-etched quantum-wire structures as sketched in Fig. 1.[5] This deep-mesa etching technique, in particular, enables fabrication of multilayer quantum-wire structures from multi-quantum-well systems. In this paper, we report FIR spectroscopy on 1DES

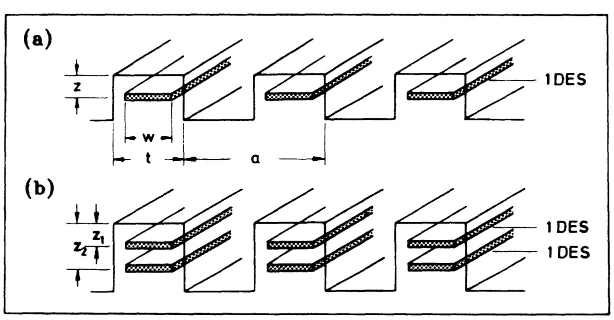

FIG. 1. Schematical configuration of 1DES in one-layered (a) and double-layered (b) quantum wires prepared by deep-mesa etching. The periodicity is a, the width of the etched wires is t, the lateral extent of the 1DES is w, and the distance between the 1DES and the surface is z_i.

in single-layered and two-layered quantum wires. In particular, the measurements on the two-layer systems give important insight into the nature of the FIR excitations in 1DES. From this, we conclude that the resonances have predominantly the character of local plasmon modes.

Two different types of structures will be discussed here. Their configurations are schematically shown in Figs. 1(a) and 1(b), and will be referred to in the following as sample A and B, respectively. For sample A we started from a modulation doped $Al_xGa_{1-x}As/GaAs$ single heterostructure, for sample B from a two-layered modulation-doped multi-quantum-well structure, both grown by molecular-beam epitaxy (MBE). A mask of periodic photoresist stripes was prepared by holographic lithography. Using an anisotropic plasma etching process, periodic rectangular profiles were etched all the way through the $Al_xGa_{1-x}As$ into the GaAs.

Magnetotransport measurements on these samples at low temperatures revealed well-resolved Shubnikov–de Haas (SdH) oscillations, which, in contrast to a 2DES, exhibited characteristic deviations from a linear $1/B$ dependence (B denotes the magnetic field perpendicular to the interface).[5] These deviations are a signature of the formation of 1D subbands[1] in our samples. From an analysis of the dc magnetotransport measurements, assuming that the confining potential can be described by a harmonic oscillator model, $V(x)=\frac{1}{2}m^*\Omega_0^2x^2$, we are able to characterize our 1DES by the following parameters: the constant energy separation $\hbar\Omega_0$ of the 1D subbands, the total 1D carrier density N_{s1D}, the spatial extent of the wave functions w defined at the Fermi energy $E_F=\frac{1}{2}m^*\Omega_0^2(w/2)^2$, and a local quasi-2D carrier density N_{s2D}, derived from the SdH period at high magnetic fields B. For sample A (sample B), we found: $\hbar\Omega_0=1$ (1.5) meV, $w=390$ (320) nm, $N_{s1D}=12$ (15) $\times10^6$ cm^{-1}, $N_{s2D}=4.2$ (6.5) $\times10^{11}$ cm^{-2}, and 12 (15) occupied 1D subbands at $B=0$. From electron microscopy, etching parameters, and MBE growth conditions we know the following parameters: grating periodicity $a=1100$ (1100) nm, geometrical width of the wires $t=550$ (550) nm, and etching depth 95 (280) nm. The distance between the sample surface and the electron sheets was $z=85$ nm ($z_1=60$ nm, $z_2=190$ nm). For sample B, we have checked very carefully that about the same carrier density was present in both layered quantum wires. For more detail, see Ref. 5.

The measurements were performed in a superconducting magnet cryostat, which was connected via a waveguide system to a Fourier transform spectrometer. The transmission $T(B)$ through the sample was measured at a temperature of 2.2 K at fixed magnetic fields B, oriented normally to the surface of the sample. The spectra were normalized to a spectrum $T(B_0)$, where B_0 was chosen in such a way that the reference spectrum $T(B_0)$ was flat in the frequency region of interest. The resolution of the spectrometer was set to 0.5 cm^{-1}. The characterization of the samples, i.e., the determination of Ω_0, N_{s1D}, and w (see above) was performed in the same experimental setup under the conditions as the FIR experiments.

Experimental spectra for sample A are shown in Fig. 2(a). At $B=0$, the spectrum exhibits one resonance at 30 cm^{-1}, which is only observed for radiation with the electric field polarized perpendicular to the grating wires. With increasing B, the resonance shifts to higher wave numbers and a resonance with exactly the same resonance frequency is also observed in the polarization parallel to the wires, gradually increasing in strength. For sample B in Fig. 2(b) two resonances at $\omega_{r1}=64$ cm^{-1} and $\omega_{r2}=34$ cm^{-1} are observed in perpendicular polarization at $B=0$. The high-energy resonance has a greater strength. Both resonances shift with increasing B to higher frequencies and again, with increasing B, for parallel polarization resonances occur with exactly the same resonance frequencies as for perpendicular polarization. The experimental resonance positions for sample B are plotted on a quadratic scale, ω_{ri}^2 vs B^2, in Fig. 3. From these graphs we find that the two resonances ω_{r1} and ω_{r2} obey the relation $\omega_{ri}^2(B)=\omega_{ri}^2(B=0)+\omega_c^2$, where $\omega_c=eB/m^*$ is the cyclotron resonance (CR) frequency. The same dependence was also found for the single resonance in sample A.

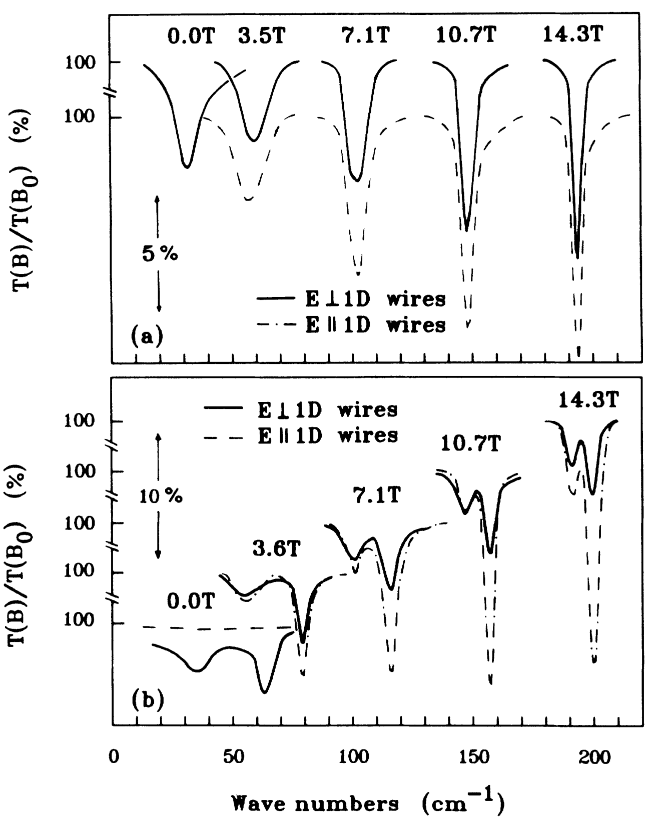

FIG. 2. Experimental FIR spectra, measured on a (a) one-layered and a (b) double-layered quantum wire structure at indicated magnetic fields B. Full lines and dash-dotted lines denote, respectively, polarization of the incident FIR radiation with the electric field vector perpendicular and parallel to the wires.

The most striking result is that these resonance frequencies ω_r in the FIR spectra are significantly higher in energy than one would expect from the 1D subband separation $\hbar\Omega_0$ which was determined from the dc magnetotransport measurements; i.e., at $B=0$, for sample A, $\hbar\Omega_0=1$ meV, $\hbar\omega_r=4$ meV; for sample B, $\hbar\Omega_0=1.5$ meV, $\hbar\omega_{r1}=8$ meV, $\hbar\omega_{r2}=4$ meV. From the 2DES it is known that the FIR intersubband resonance ω_r is shifted with respect to the one-particle transition due to the resonant screening effect of all electrons in the system. This collective so-called depolarization effect is characterized by an effective plasma frequency ω_d. If we use the 2D model also for the 1DES, i.e., $\omega_r^2=\Omega_0^2+\omega_d^2$, we find that the intersubband transition is strongly governed by the depolarization effect. For example, for sample A it is $\omega_d^2=\omega_r^2-\Omega_0^2=(4\ \text{meV})^2-(1\ \text{meV})^2=(3.9\ \text{meV})^2$. Thus, a very accurate model for the depolarization shift is necessary to determine the one-particle energy $\hbar\Omega_0$ from the FIR resonance.

In the following, we demonstrate that this strongly dominant collective contribution can be understood in terms of a "local" plasmon resonance, $\omega_d=\omega_{\text{pl}}$. The magnetic field dependence of the FIR resonances and, in par-

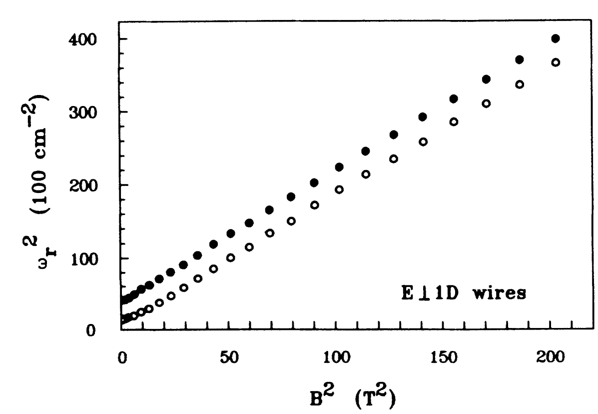

FIG. 3. Experimental resonance positions ω_r^2 vs magnetic field B^2, measured on the two-layered quantum wire structures for perpendicular polarization of the incident electric field with respect to the 1D wires.

ticular, the occurrence of two resonances for two-layered quantum-wire structures resembles a plasmon type of excitation. For a two-layered, homogeneous 2DES it is known that the collective-excitation spectrum at small wave vectors q consists of two branches.[6–8] A calculated plasmon dispersion for a two-layered homogeneous system is shown in Fig. 4. We have determined the dispersion from the zeros of the determinant in the Fresnel coefficient of the multilayered system, treating the electrons strictly two dimensionally, including retardation and the asymmetric geometry of the sample configuration. Whereas for widely separated electron sheets ($qd \gg 1$, $d = z_2 - z_1$) the plasmon branches are degenerate, for small distances ($qd \ll 1$) the coupling leads to a splitting of the plasmon dispersion. In this case the high-energy branch represents an "in-phase longitudinal oscillation" of both electron layers. The frequency of the lower-energy branch is determined by the strength of the coupling of the two electron sheets. This is the first observation of layer-coupled type of plasmon modes directly using FIR spectroscopy and also in the presence of a magnetic field. So far these modes have only been detected by Raman spectroscopy.[6,7] However, the resonances observed in our 1DES differ significantly from excitations in a homogeneous system in the following points. (a) Besides the plasmon resonance one would expect to observe the CR ω_c in a homogeneous system. This resonance is completely quenched in our microstructured sample, all observed resonances ω_{ri} are shifted with respect to ω_c. (b) When we calculate the plasmon frequency of a homogeneous system, using the average dielectric constant $\bar{\epsilon}=6.9$ for the microstructured region and the average 2D charge density $\bar{N}_{s2D} = N_{s1D}/a$, we find for sample A $\omega_p = 23$ cm^{-1} and for sample B $\omega_{p1} = 37$ cm^{-1} and $\omega_{p2} = 21$ cm^{-1}. Thus, the experimentally observed resonances ($\omega_r = 30$ cm^{-1}, and $\omega_{r1} = 64$ cm^{-1} and $\omega_{r2} = 34$ cm^{-1}), are significantly higher in energy compared to those of the homogeneous system.

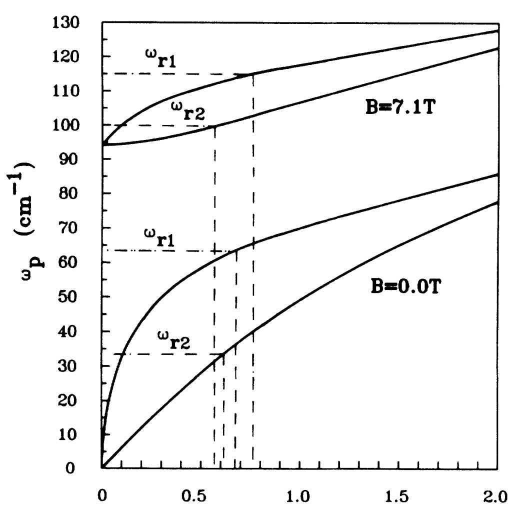

FIG. 4. Calculated plasmon dispersion for a two-layered homogeneous system at magnetic fields $B=0$ and $B=7.1$ T. The dash-double-dotted (dash-dotted) lines indicate the experimentally observed resonance energies for $B=0$ ($B=7.1$ T). The intersection with the dispersion is projected onto the q axis to determine quantized q values, $q=\pi/w_e$, of the local plasmons.

We explain this frequency shift by "localization" of plasmons in the following sense: Let us assume a single-layer "2DES" which is additionally confined in x direction on a width w. Then, in a very simple model, we can treat the 2D plasmon mode for the x direction as a "plasmon in a box." The continuous 2D plasmon dispersion $\omega_p^2 = (N_s e^2/2\epsilon\epsilon_0 m^*)q$ of a homogeneous system with a free wave vector q is now quantized in fixed values of $q = \pi/w_e$ and correspondingly, $\omega_{pl}^2 = N_s e^2/2\bar{\epsilon}\epsilon_0 m^* \pi/w_e$. Here $\bar{\epsilon}$ is the effective dielectric constant. The effective width w_e is given by $w_e = w(1+\alpha)$, where α takes account of the phase relation if the plasmon is "reflected" at the walls of the box. A similar model has also been applied to localized plasmons in density modulated Si-inversion layers.[9] This is of course a very rough model, which totally neglects Coulomb interaction with neighboring electron stripes and leaves α, so far, undetermined. However, this model explains our experimentally observed upward shift of the resonance frequency with decreasing w. It can also be applied to the two-layer case. This is demonstrated in Fig. 4, where the calculated plasmon dispersion of a homogeneous two-layered system, using the parameters of sample B, is plotted for $B=0$ and $B=7.1$ T. We adopt a strictly "local" model, i.e., we take the local 2D charge density in the wire, $N_{s2D} = 6.5 \times 10^{11}$ cm^{-2}, and the dielectric constant of the direct surroundings, $\epsilon = 12.8$, for GaAs and $Al_xGa_{1-x}As$. Projecting the experimentally observed resonance frequencies onto the dispersions we get values of q which are converted, via $w_e = \pi/q$, into the effective width. We find a value of $w_e \approx 500$ nm, which is comparable to the dimensions w and t. For $B=7.1$ T this evaluation depends, because of the flat plasmon dispersion, very sensitively on the value of the CR mass. We took the value of $m^*/m_0 = 0.0707$ from CR measurements on an unstructured reference sample. The good agreement between the experimentally observed splitting of the two plasmon modes and our calculation confirms our interpretation of layer-coupled plasmon modes and shows that the coupling of the modes is not very different in the microstructures compared to in the homogeneous samples.

A quantitative evaluation within this strictly "local" plasmon model is not always satisfactory. For example, for sample A we find that the observed resonance frequency is best described by an excitation halfway between the "local" plasmon and an "extended" plasmon. The latter is a better description when coupling between the different parallel wires becomes important. Then ω_p is governed by the grating periodicity $a = 2\pi/q$ and the averaged 2D charge density $\bar{N}_{s2D} = N_{s1D}/a$ of the system. This latter situation is, e.g., present in the experiments of Refs. 9 and 10 and is treated theoretically in Refs. 11 and 12. Indeed, sample A has been deduced to have wider electron channels and its smaller etching depth might also weaken the localization of the plasmons.

A strongly dominant collective contribution was also found in 1DES of GaAs systems with split-gate configuration.[4] In experiments on InSb systems[3] the 1D-subband separation and FIR resonance energy were much closer, presumably due to the suppression of the depolarization effect by a metal gate in the vicinity of the 1D channel. We emphasize, that the contribution of a dominant collective excitation in a microstructured system can be described by various models, such as a depolarization effect[4] or a geometrical resonance.[13] Note that for the one-layered system the frequencies for ω_d in Ref. 4 and our "local" plasmon frequencies ω_{pl} (using $w_e = w$), agree except for a factor of 1.3. They are, except for a factor 0.65, identical with the geometrical resonances considered in slightly wider structures (which have not been tested to be 1DES) in Ref. 13. We prefer the local plasmon model, since in this model the layer-coupled plasmon effect of multilayer quantum wires can easily be described. It also explains experiments in split-gate configuration, where a continuous transition from an extended plasmon to the local plasmon frequency is found, if via the split gate the system is changed from a density modulated system to a 1D system (see Ref. 4, Fig. 3). For the one-layered system our model of "plasmons in a box" is a simplified version of a calculation for a density-modulated system by Lai, Kobayashi, and Das Sarma.[11] In the latter calculation the coupling between different wires and the "boundary conditions" for the "reflection" of the plasmons (i.e., the determination of our α) are treated rigorously. Also, calculations assuming model 1D wave functions and, thus, taking better account of the one-particle contribution for one (Ref. 14) and two (Ref. 15) occupied 1D subbands have been reported. However, we believe that for a quantitative comparison with the experiment one should take into account the occupation of many 1D subbands, which have a strong influence on the FIR response of the samples discussed here.

In conclusion, we have investigated the FIR response of single and two-layered 1D quantum wire structures. The FIR resonance frequencies are significantly higher than expected from the 1D subband separation, indicating a strong collective contribution that can be described in a "local" plasmon model. This model in particular explains the experimentally observed shift of the resonance frequencies and the splitting of the layer-coupled local plasmon modes.

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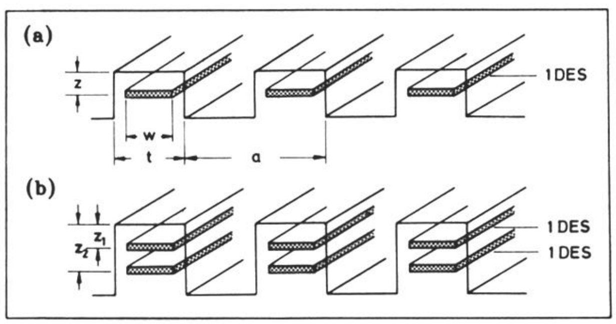

FIG. 1. Schematical configuration of 1DES in one-layered (a) and double-layered (b) quantum wires prepared by deep-mesa etching. The periodicity is a, the width of the etched wires is t, the lateral extent of the 1DES is w, and the distance between the 1DES and the surface is z_i.