One-Dimensional Plasmon Dispersion and Dispersionless Intersubband Excitations in GaAs Quantum Wires

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The energy and the wave-vector dispersion of single-particle and collective excitations of the one-dimensional (1D) electron gas in GaAs quantum wires have been determined by resonant inelastic light scattering. In the 1D quantum limit the intrasubband plasmon displays the linear dispersion characteristic of 1D free-electron behavior. Quantitative agreement is found with calculations based on the random-phase approximation. In contrast, collective 1D intersubband excitations appear as dispersionless and have a negligible shift from the single-particle energy. This mode exhibits the unique Landau damping expected for a 1D system with two occupied subbands.

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Recent progress in semiconductor fabrication enables the realization of systems in which free electrons are confined to one dimension (1D). Elementary excitations of the electron gas under reduced dimensionality in semiconductor nanostructures are a subject of growing experimental [1-7] and theoretical [8-13] interest. Electronic resonances in the far-infrared response [1,2], magnetoplasmon excitations [2,3,7], and large anisotropies in plasmon dispersions [6] have been measured in electron systems with many occupied 1D subbands. Inelastic light scattering is a powerful method for the investigation of collective and single-particle excitations of the electron gas because the energy and wave-vector dispersion of the excitations can be measured [14]. This technique was used by Egeler *et al.* [6] to study plasmons in systems with many occupied subbands where the mode dispersions exhibit features predicted for spatially periodic 2D electron gases [15]. Clear signatures of 1D behavior are expected in the 1D quantum limit, when the Fermi energy is comparable to the subband spacing and only the lowest subbands are occupied by electrons. Several theoretical studies have been made of the energies and dispersions of elementary excitations in quantum wires in this limit [10,12,16].

In this Letter, we report an experimental determination of wave-vector dispersions of excitations of the electron gas in the 1D quantum limit. The observation is made by resonant inelastic light-scattering measurements in GaAs/AlGaAs multiple quantum wires. For the first time, we find a clear signature of 1D behavior of the intrasubband plasmon. The mode exhibits a linear wave-vector dependence which is well described within the random-phase approximation (RPA). This linear dispersion is characteristic of the 1D electron gas. Single-quantum-wire behavior is demonstrated in the multiwire system because of weak Coulomb coupling between wires. Dispersionless intersubband charge-density excitations (CDE) are measured at the subband spacing. The spectral width of this mode exhibits the unique 1D features of vanishing Landau damping at finite wave vectors [16].

Modulation-doped multiple-quantum-well wires (QWW) were fabricated from a 250-Å-wide single GaAs/AlGaAs quantum well (SQW) using electron-beam lithography followed by low-energy ion bombardment [17]. The electron density and mobility of the two-dimensional (2D) electron gas are $n=3.2\times10^{11}$ cm^{-2} and $\mu=1.1\times10^{6}$ cm^2/V s, respectively. The 1D pattern consists of ~700-Å-wide lines with a period of $d=2000$ Å. Changes in the Fermi energy have been monitored by means of photoluminescence (PL) and photoluminescence excitation (PLE) measurements [17,18]. The energy spacing E_{01} between the two lowest 1D subbands was determined from light-scattering spectra of intersubband excitations as discussed below. At power densities of ~1 W/cm^2, we obtained a Fermi energy $E_F=5.8\pm0.5$ meV and intersubband spacing $E_{01}=5.2\pm0.5$ meV. The electron gas is therefore in a 1D quantum limit with only a slight occupation of the first excited subband.

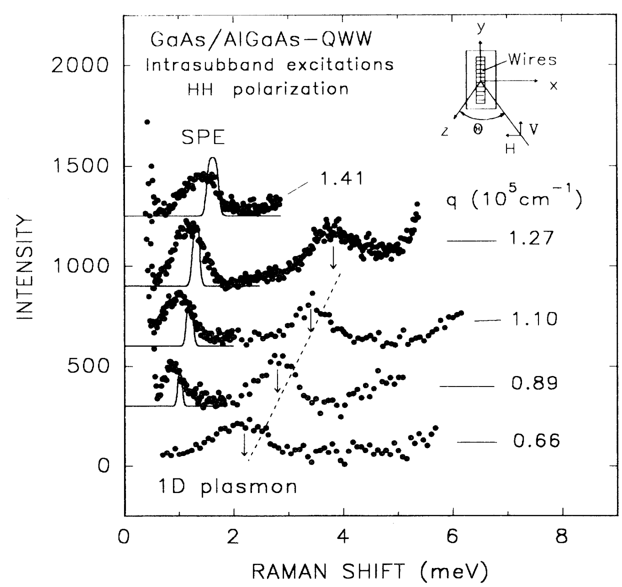

FIG. 1. Polarized light-scattering spectra of a multiple QWW sample at 1.8 K and for different wave vectors q along the wires. Solid curves correspond to the calculated functions $\mathrm{Im}\chi(\omega,q)$ of intrasubband SPE's. Inset: The scattering geometry.

Resonant inelastic light-scattering measurements were performed at 1.7 K using a tunable dye laser in the energy range of interband optical transitions from higher-lying valence to conduction subband states. Spectra were measured in a conventional backscattering geometry for different angles of incidence θ by rotating the sample around the y axis as shown in the inset of Fig. 1. In this scattering geometry the wave-vector component along the wires (x direction) is given by $q=(4\pi/\lambda)\sin\theta$, where λ is the wavelength of the incident light. Accessible wave vectors are in the range $(0.5-1.5)\times10^5$ cm^{-1} (roughly one-tenth of the Fermi wave vector). Incident and scattered light are linearly polarized parallel (H) or perpendicular (V) to the wires.

Figures 1 and 2 show polarized (HH) and depolarized (HV) light-scattering spectra for different wave vectors. Peak energies increase with increasing q. The strong dispersive behavior indicates that these bands are due to intrasubband excitations of the electron gas [14]. The higher-energy peaks observed only in HH polarization are assigned to the 1D plasmon of the wires. The bands at lower energy in HH spectra are interpreted as predominantly single-particle 1D intrasubband excitations (SPE), similar to the 2D case [14,19]. The broader HV spectra are a superposition of SPE and spin-density excitations (SDE).

For intrasubband SPE, light-scattering experiments measure the imaginary part of the dynamical polarizability function $\chi(\omega,q)$ [14]. In 1D, this function is a symmetric peak centered at $\hbar q v_F$ (v_F is the Fermi velocity) [16]. The solid curves in Figs. 1 and 2 represent calculations of $\mathrm{Im}\chi(\omega,q)$ using the density $n_0=(6.5\pm0.4)\times10^5$ cm^{-1} for the lowest subband. With this value of n_0 the calculated peaks at qv_F appear at slightly higher energy than the broad SPE spectra of Fig. 1. This n_0 was chosen because inclusion of a finite single-particle relaxation time shifts the peak positions by a few tenths of an meV to lower energies [19]. From this analysis we obtained $E_F=5.8\pm0.6$ meV and find a slight population of the second subband with Fermi energy $\sim$0.6 meV and density $n_1=(2.1\pm0.4)\times10^5$ cm^{-1}. In crossed polarization (see Fig. 2), the maximum peak position of the measured spectra is at lower energies because there is a contribution due to intrasubband SDE [19]. The calculated intrasubband SPE peaks (solid curves) coincide with the structure on the high-energy side of the depolarized spectra of Fig. 2. The energy shift of SDE's with respect to the SPE band is a measure of the exchange Coulomb interaction in the ground state of the electron gas. Exchange effects in 1D appear to be comparable to those reported in 2D [19].

In Fig. 3 we summarize the wave-vector dependence of the light-scattering peaks. The 1D intrasubband plasmon, which corresponds to oscillations of the charge density in the direction of the wires, exhibits an almost linear dispersion that extrapolates to a finite positive frequency at $q\approx0$. Similar q dependence has also been measured in a sample with smaller Fermi energy and wider wires (not shown in Fig. 3). The inset of Fig. 3 shows that the 1D system has markedly different behavior from the ex-

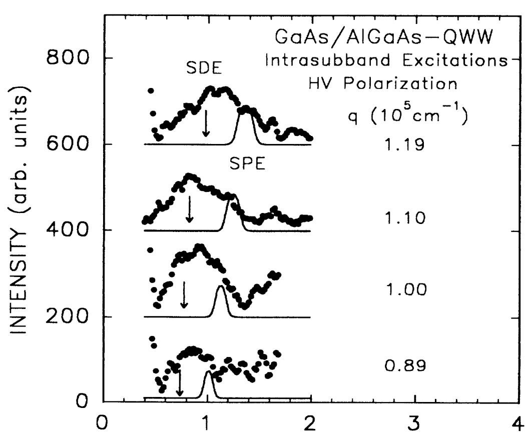

FIG. 2. Depolarized light-scattering spectra for different wave vectors q. Solid lines correspond to the calculated functions $\mathrm{Im}\chi(\omega,q)$ of intrasubband SPE's. Arrows indicate the position of SDE's.

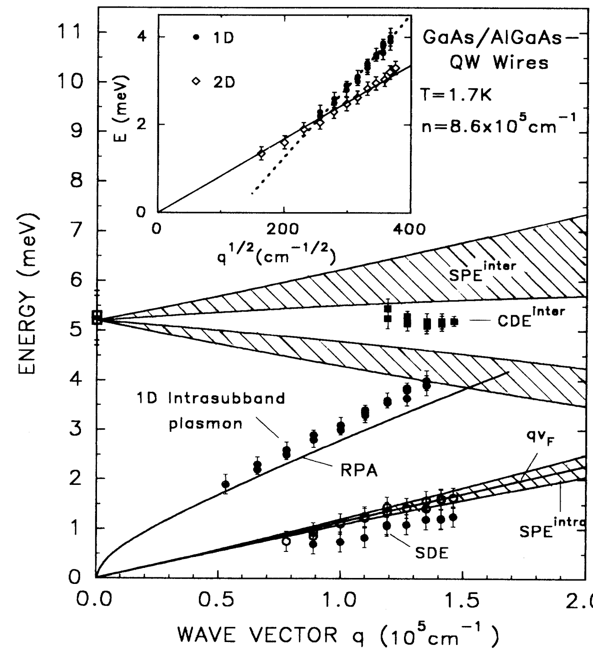

FIG. 3. Wave-vector dispersions of intrasubband and intersubband excitations of a 1D electron gas in the quantum limit. Solid dots represent intrasubband collective CDE's and SDE's. Open circles display the position of the peak at $\hbar q v_F$ of intrasubband SPE's. Squares correspond to data of 1D intersubband CDE's measured in VV polarization. The shaded areas indicate ranges of electron-hole pair excitations (SPE) given by the condition $\mathrm{Im}\chi(\omega,q)\neq0$. Inset: Comparison of the 1D intrasubband plasmon frequencies with those of a 2D electron gas with $E_F=3.8$ meV as a function of $q^{1/2}$.

pected $\omega_p \sim q^{1/2}$ dependence measured for 2D plasmons. The differences between the measured dispersion relations of 1D and 2D plasmons are larger than experimental uncertainty, as shown by the error bars. Classical considerations predict for isolated wires a linear dispersion with a logarithmic correction significant for vanishing q [12,16].

To give a quantitative interpretation, we consider the case of two occupied 1D subbands with linear electron densities n_0 and n_1, and we include the coupling among the intrasubband collective excitations of both subbands. In the RPA the intrasubband plasmon frequencies obtained by solving the coupled mode equation are [16]

$$\omega_\pm = \omega_0 q \left\{ \frac{n_0 f_{00} + n_1 f_{11}}{2n} \left[1 \pm \left(1 - \frac{4 n_0 n_1 (f_{00} f_{11} - f_{01}^2)}{(n_0 f_{00} + n_1 f_{11})^2} \right)^{1/2} \right] \right\}^{1/2}, \tag{1}$$

with $\omega_0 = (2ne^2/m^* \epsilon_L)^{1/2}$, $f_{ij}(q) = (\epsilon_L/2e^2) V_{ij}(q)$. Here $n = n_0 + n_1$ is the total linear electron density, e and m^* are the electron charge and effective mass, respectively, and ϵ_L is the background dielectric constant. The functions $V_{ij}(q)$ are the intrasubband matrix elements of the Coulomb interaction and $i,j = 0,1$ are the subband indices. In 1D these matrix elements depend on the spatial extension of the wave functions. This dependence, however, is very weak if $qa \leq 1$ (a is the wire width) [9,12]. This is the case here, so the f_{ij}'s have comparable values. Thus ω_+ corresponds to plasma oscillations of a single band with total density n. ω_- is expected to be smaller than ~ 0.5 meV and, therefore, is not observed.

Up to second order in q the single-band plasmon dispersion is [12,16]

$$\omega_+(q) = \omega_0 q \left\{ \frac{f_{00}(q)}{2} \left[1 + \left(1 + \frac{4k_F^2}{m^2 \omega_0^2} \frac{1}{f_{00}(q)} \right)^{1/2} \right] \right\}^{1/2}. \tag{2}$$

In the long-wavelength limit Eq. (2) can be approximated by $\omega_+ \sim \omega_0 q |\ln(qa/2)|^{1/2}$. For $qa \approx 1$, $\ln(qa/2)$ is slowly varying and ω_+ has a linear dispersion characteristic of 1D free-electron behavior.

The curves through the data points in Fig. 3 correspond to a fit using Eq. (2), with the electron density $n = (8.6 \pm 0.4) \times 10^5$ cm^{-1}. The matrix element $V_{00}(q)$ was calculated assuming harmonic-oscillator wave functions due to the confinement in the y direction, and the electron gas was assumed to be of zero thickness in the z direction [16]. In these experiments, Coulomb coupling between wires [16] is a minor effect because $1 < qd < 3$. The wire width a, defined as the FWHM of the ground-state harmonic-oscillator wave function, is found to be 330 Å from the experimental value of the intersubband spacing. The solid line in Fig. 3 represents the results of Eq. (2). The overall q dependence is well accounted for. There is a small discrepancy of $\sim 10\%$, which could indicate an underestimation of the electron density and the effect of the mode coupling. Equation (2) thus provides an excellent description of the 1D intrasubband plasmon dispersion.

The 1D intersubband CDE's also display remarkable behavior. Results obtained in the VV polarization are shown in Fig. 4. The modes appear dispersionless and exhibit a surprising q dependence of the bandwidths. For $q = 0$ there is a broadband at ~ 5.2 meV that partially overlaps a weak luminescence band. At larger wave vectors the bands are much sharper and appear at roughly the same energy. These striking results are explained by Landau damping effects. It is a feature of 1D that electron-hole pairs can be excited only with wave vectors parallel to the Fermi wave vector. Therefore, the slight occupation of the excited subband opens a gap in the energy spectrum of 1D intersubband pair excitations as shown in Fig. 3. The solid curves in Fig. 4 represent Landau damping as given by the imaginary part of the 1D intersubband polarizability function with random-phase ap-

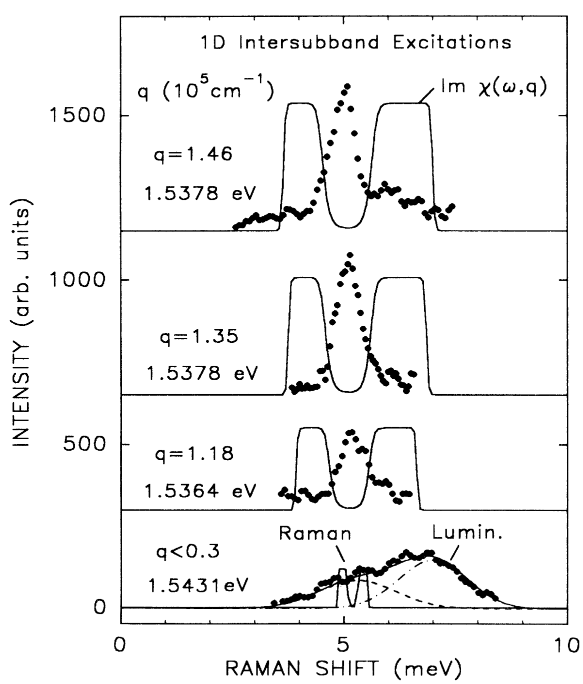

FIG. 4. Light-scattering spectra of 1D charge-density intersubband excitations measured at 1.8 K for different wave vectors q. The laser excitation energies are indicated. Solid curves represent the imaginary part of the 1D intersubband polarizability function calculated as described in the text.

proximation [16]. At finite q, this function has a minimum at E_{01} and maxima at $E_{01} \pm \hbar q v_F$. Undamped 1D intersubband CDE's exist with energy E_{01}. For $q \approx 0$, the two maxima in the loss function merge into a single peak at E_{01}, and the excitations are strongly damped. The spacing between the two lowest 1D subbands can be determined from these data [18]. For our low electron densities, the wire potential is nearly parabolic and the subband spacing depends weakly on density [20]. It is a general property of systems where the background potential is quadratic that the resonance frequencies of the electron gas are independent of the electron-electron interaction [13,21]. Thus the energy of intersubband CDE's is very close to E_{01}.

In conclusion, we have determined the wave-vector dispersion of 1D intrasubband and intersubband plasmons in quantum wires in which the higher subband is only slightly occupied. We have observed for the first time a plasmon dispersion with an almost linear dependence predicted by the RPA for 1D. The logarithmic correction to the linear dispersion sets in at very small wave vectors outside the range of our experiment. Further experiments in narrower wires would enhance the differences between 1D and 2D behavior. Intersubband charge-density excitations are dispersionless and have energy E_{01} as expected for a parabolic wire potential. These excitations also display the unique 1D features of Landau damping. In this way, we have provided new and interesting results of the collective behavior of the one-dimensional electron gas in the 1D quantum limit.

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