Observation of Magnetoplasmons, Rotons, and Spin-Flip Excitations in GaAs Quantum Wires

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Inelastic light scattering spectra of the one-dimensional electron gas in GaAs quantum wires embedded in a strong perpendicular magnetic field show long-wavelength collective excitations and display multiple structures that indicate the magnetoroton density of states. The observed shift of the $q \sim 0$ intersubband magnetoplasmons from the cyclotron frequency is the signature of 1D behavior. At low temperatures spin polarization of the 1D system is revealed by the exchange enhancement of spin-flip excitations.

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With novel nanofabrication techniques carriers can be confined in narrow semiconductor quantum wires of less than 100 nm in width. The reduced dimensionality of quantum wires anticipates new and interesting problems [1]. Fundamental questions about the many-body behavior of the so formed one-dimensional (1D) electron gases in semiconductor quantum wires remain open. For example, it is not yet clear whether these systems are better described as Fermi liquids, or if a Tomonaga-Luttinger model is more appropriate for such strongly correlated electron gases [2]. The study of elementary excitations of 1D electron gases in the presence of magnetic fields is of increasing interest since this is a very important aspect of many-body physics [3]. A deep roton minimum in the wave vector dispersion has been predicted for 1D magnetoplasmons at wave vectors $q \gtrsim l/l_0 \approx 10^6$ cm^{-1}, where l_0 is the magnetic length [4]. Roton features are among the most significant manifestations of electron-electron interactions. They result from the interplay between direct and exchange terms of the electron gas. The depth of the minimum is determined by the strength of the exchange vertex corrections. Such terms represent an excitonic binding which is expected to be strongly enhanced by confinement to 1D. Long-wavelength magnetoplasmons (MP) in quantum wires have been investigated by far-infrared absorption spectroscopy [5–8]. Magnetoroton phenomena could be investigated by inelastic light scattering spectroscopy under conditions of breakdown of wave vector conservation [9].

This Letter reports the first inelastic light scattering observations of elementary excitations of the 1D electron gas of GaAs quantum wires in a large perpendicular magnetic field. Disorder-induced breakdown of wave vector conservation allows the measurement of large q excitations and yields a direct determination of the energies of critical point in the MP density of states. The evidence of magnetoroton minima is found in the multiple structures that occur in the light scattering spectra. The long-wavelength magnetoplasmons are shifted from the cyclotron energy ω_c by the effect of the confining potential of the quantum wires. At intermediate and high magnetic fields, when the Fermi energy is comparable to or smaller than the Zeeman splitting of the lowest magnetic subband, we observe spin-flip (SF) excitations that are blueshifted from the energy of the long-wavelength magnetoplasmons. In 2D the blueshift of the SF mode is evidence of enhanced exchange interactions in the spin-polarized state [10,11]. The observation of the blueshift of SF modes of the quantum wires is interpreted as evidence of the spin polarization of the 1D system and suggests a substantial enhancement of the spin gap of the lowest magnetic 1D subband.

To model the electron states of the quantum wires we consider a parabolic self-consistent potential along the y direction perpendicular to the magnetic field along z. For the purpose of the later discussion the exact shape of the potential is not essential. The energy levels are [12]

$$E_{n,k} = \left(n + \frac{1}{2} \right) \Omega_{01} + \frac{\hbar^2 k^2}{2m} , \qquad (1)$$

where $k \equiv k_x$ and $m = m^* (Q_{01}/E_{01})^2$. In 1D the frequency of the harmonic oscillator is $\Omega_{01}^2 = \omega_c^2 + E_{01}^2$, where $\omega_c = \hbar e B / m^* c$ is the cyclotron energy and E_{01} is the 1D intersubband spacing. The longitudinal mass for free electron motion along the wires is enhanced by the factor $(\Omega_{01}/E_{01})^2$. The confining potential of the wires lifts the degeneracy of the Landau levels so that the energy eigenvalues depend on the position of the center of the cyclotron orbits. Because of the large longitudinal mass at fields such that $\omega_c > E_{01}$ all electrons can be accommodated in the lowest spin-split magnetic subband and the system becomes spin polarized at relatively low fields.

The energy of magnetoplasma oscillations differs from the single-particle energy Ω_{01} because of collective effects due to Coulomb interactions. The long-wavelength intersubband magnetoplasmon energy can be written as [4,8,13,14]

$$\Omega^2(B) = \omega_c^2(B) + \omega_0^2(0) . \qquad (2)$$

Here, $\omega_0(q)$ is the energy of the 1D intersubband collective mode. It is shifted from the single-particle energy E_{01} (which includes the exchange self-energy Σ_{MP}) by the well-known *depolarization* (or Hartree) term and the *ex-*

citonic shift of vertex corrections due to exchange [15,16]. In the extreme magnetic quantum limit, when the system is spin polarized, we also need to consider excitations associated with SF transitions between the two lowest magnetic 1D subbands. These excitations have not been discussed for 1D systems. In analogy with the 2D case we assume a mode dispersion that contains the exchange self-energy Σ_{SF}, the excitonic term, and the Zeeman splitting $\Delta_Z = g\mu_B B$ [10,11]. In the spin-polarized state a strong exchange enhancement is expected such that $\Sigma_{SF} > \Sigma_{MP} \gg \Delta_Z$. This would result in a sizable blueshift of the SF mode [10,11].

The quantum wire samples were prepared from a modulation-doped 250 Å wide single GaAs/AlGaAs quantum well (QW) using electron-beam lithography followed by low-energy ion bombardment [17]. The starting 2D electron density was 2.3×10^{11} cm^{-2}. The pattern consists of 1000 Å wide lines repeated with a period of 2000 Å. Here we present results of a sample bombarded for 4 min with oxygen ions accelerated to 300 V. The result is a very low 1D electron density $n = 5.6 \times 10^5$ cm^{-1} and a small intersubband spacing $E_{01} = 2.5$ meV. This corresponds to a FWHM of 500 Å of the harmonic oscillator wave function for the ground state. The total 1D density can be determined by fitting the 1D intrasubband plasmon dispersion with the random phase approximation expression [17], while the subband spacing is inferred from spectra of intersubband single-particle excitations [18]. Consequently, the Fermi energy is $E_F = 2.7$ meV and the electron gas is in the 1D quantum limit with only a slight occupation of the first excited subband. The resonant inelastic light scattering measurements were done at 1.4 K by inserting the sample in the cold bore of a superconducting magnet with silica windows for optical access. Spectra were measured in backscattering geometry with ~ 1 W/cm^2 incident power density from a tunable dye laser.

Figure 1(a) shows spectra of 1D intersubband excitations for different magnetic fields. The peak energies and spectral linewidths increase with increasing B. At fields larger than 4.5 T additional structure is clearly apparent from the spectra, as shown in Fig. 1(b). Four well-defined intensity maxima are identified. The one at the lowest energy is assigned to the long-wavelength MP mode at Ω. The highest energy peak is assigned to the $q \approx 0$ SF excitation as discussed below. The blueshift of the SF mode from Ω reveals spin polarization in the 1D system for $B \geq 6$ T. The other two structures in the spectra of Fig. 1(b) are interpreted as the roton and the maximum in the dispersion of magnetoplasmons. These features are the critical points of the MP dispersion shown schematically in the inset to Fig. 2. Such large q

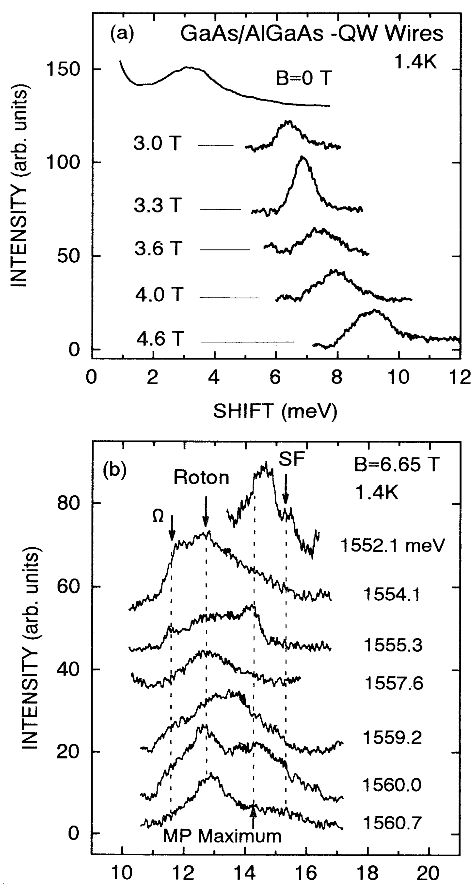

FIG. 1. Resonant elastic light scattering spectra of 1D magnetoplasmon excitations (a) for different magnetic fields and (b) at 6.65 T and for different incident photon energies.

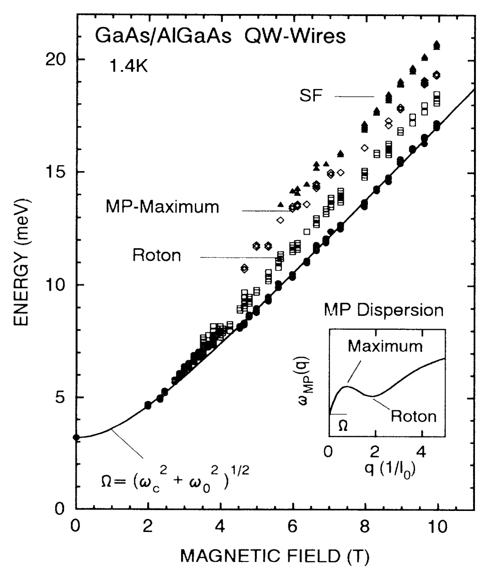

FIG. 2. Measured peak energy positions (symbols) as a function of magnetic field. The inset displays schematically the magnetoplasmon wave vector dispersion.

excitations are active in light scattering because of the breakdown of wave vector conservation caused by disorder [9,19]. The spectral changes observed with changes in incident photon energy are caused by well-known resonant enhancements of the scattering cross section. The peak positions are plotted in Fig. 2 as a function of the magnetic field.

At low and intermediate magnetic fields $B \leq 7$ T, where the longitudinal mass enhancement factor is $(\Omega_{01}/E_{01})^2 \leq 20$, free electron behavior in the quantum wires differs significantly from that in 2D systems. The signature of 1D behavior is seen clearly in the shift of long-wavelength MP mode from ω_c. The solid line in Fig. 2 represents the prediction of Eq. (2) using the experimental value of $\omega_0 = 3.2$ meV obtained from the zero field data. A similar behavior has also been reported in infrared absorption experiments [5,8]. It is important to emphasize that in the case of the quantum wires, ω_0 is the energy of collective 1D intersubband excitations measured at $B=0$. The small discrepancies in the peak positions from Ω at about 4 T could be evidence of Landau damping effects which exist in 1D at low fields when the mass enhancement is small. For simplicity the solid line in Fig. 2 has been obtained with $m^* = 0.068 m_0$. A more sophisticated fit should include the effects of band nonparabolicity on the cyclotron mass [6]. Such analysis indicates an increase in ω_0 at large fields.

We consider next the other spectral features observed at $B \leq 7$ T. In this regime the calculation for 2D electron gases at filling factor $\nu=1$ do not account quantitatively for the measured energies of the roton and MP maximum [10,11]. The calculated 2D values are typically 30% smaller than the measured ones. To interpret the roton and the MP maximum we consider the wave vector dispersion relation of 1D magnetoplasmons. The calculations by Yang and Aers [4], within the time-dependent Hartree-Fock approximation (HFA), is in qualitative agreement with the experiment. In particular, the calculation accounts well for the energy difference between the MP maximum and Ω, which is a measure of the contribution from the depolarization or Hartree term. There are, however, some significant quantitative discrepancies. They occur in Ω and in the depth of the roton minimum. Such discrepancies could possibly arise from overestimates of the strengths of enhanced vertex corrections and from not taking into consideration the finite size of the wave function along the z direction.

The results of Figs. 1(b) and 2 show that 1D intersubband spin-flip excitations are observed at low temperatures in the range 6 T $\leq B \leq$ 8 T. The SF mode exhibits a large blueshift from Ω. This is considered evidence that in this field range the 1D system becomes spin polarized and the blueshift Σ_{SF} is a measure of the enhancement of the exchange self-energy by spin polarization. This effect also results in an enhancement of the spin gap of the lowest state [10,11,15]. We find that in the wires the shift Σ_{SF} is typically 15% larger than the calculated 2D value, assuming a filling factor $\nu=1$. These results indicate an increase of exchange in 1D and present the first evidence that suggests an enhanced spin gap in the 1D electron system.

For magnetic fields $B > 8$ T the mass enhancement is such that the electron gas is effectively in a spin-polarized quasi-2D limit. In this regime SF modes are prominent in the light scattering spectra. Figure 3(a) shows spectra taken at 8.95 T and 1.4 K. In Fig. 3(b) we show the dispersions calculated at $\nu=1$ for a 2D electron gas where the finite z extent of the wave function has been taken into account [11]. At these large fields there is a very good agreement between the energies of the measured features and the predicted positions of the critical points with the HFA calculations. This supports the assignment of the high-energy structures observed at lower magnetic fields.

The observation of spin polarization, through the enhancement of a blueshifted SF mode, speaks for a relatively large spin gap and for a small smearing of the Fermi surface. This is additional evidence that the 1D electron gas in the quantum wires is adequately described as a Fermi liquid [20]. It has been shown that impurity scattering can suppress Luttinger liquid behavior in 1D by damping out low-energy plasmons and restoring the Fermi surface [21]. Further evidence of the effects of disorder is found in the remarkably different behaviors in light scattering by magnetic excitations in the quantum wires compared to the 2D case. In the latter, due to the screening of the weak residual disorder in the metallic state, magnetoroton critical points and SF excitations are

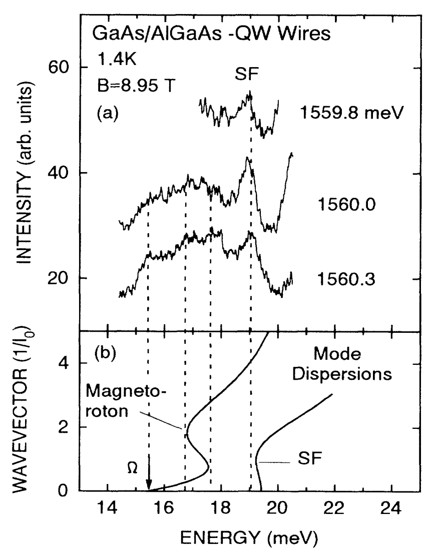

FIG. 3. (a) Resonant light scattering spectra of spin-flip excitations at 8.95 T. (b) Mode dispersions of a 2D electron gas at filling factor $\nu=1$ after Ref. [11].

observed only at the integral values of ν when the 2D electron systems become insulating [11]. In the results presented here, on the contrary, magnetoroton structures and SF excitations are observable over a wide range of magnetic fields. Thus the disorder potential, mainly caused by quantum wire imperfections, is not being efficiently screened by the 1D electron gas.

In summary, using inelastic light scattering we have measured magnetic excitations of the 1D electron gas in GaAs quantum wires. We have observed for the first time features associated with a roton minimum in the wave vector dispersion of 1D magnetoplasmons, in qualitative agreement with results of the time-dependent Hartree-Fock approximation. Spin-flip excitations have been measured at intermediate and large magnetic fields. Spin polarization is revealed in the blueshift of SF excitations due to enhancement of the exchange interaction. This observation represents, to the best of our knowledge, the first indication of an enhancement of the spin gap of the magnetic 1D subbands.

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