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Edge-magnetoplasma excitations in GaAs-$Al_xGa_{1-x}As$ quantum wires

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We report the experimental observation of strongly localized edge collective excitations propagating around each individual wire in a modulation-doped GaAs-$Al_xGa_{1-x}As$ quantum-wire array. The excitations have been observed in radio-frequency experiments at magnetic fields in the vicinities of the filling factors ν=2 and 4. For other magnetic-field strengths or with rising temperature the high-finesse edge wave transforms abruptly into a very different type of excitation, i.e., into a strongly damped relaxation mode distributed all over the wire.

Currently there is a broad interest in the physics of semiconductor quantum wires.[1] Quantum wires have a width of the order of 100 nm, which is comparable to the Fermi wavelength and the electrons thus represent a quasi-one-dimensional electron system. The collective excitations in quantum wires have been studied experimentally in samples which were fabricated by using lithographic techniques on two-dimensional electron systems[2–6] (2DES) (for theoretical treatments see Ref. 7). These plasmons are strongly damped at low frequencies $2\pi f\tau < 1$ (τ is the momentum relaxation time), therefore the measurements are carried out at high f in far-infrared[2–4] or Raman[5,6] experiments. The plasmon dispersion is found to exhibit a strong anisotropy for different directions of the driving electric field reflecting two different excitations, i.e., propagating 1D plasmons parallel and standing-wave plasmons perpendicular to the wires.[4,5] Applying a magnetic field B perpendicular to the wire shifts the plasmon frequency without changing however the character of the excitation qualitatively.[2–4] Here we report very different collective excitations in quantum wires which, to our knowledge, have so far not been observed or predicted. We have studied in radio-frequency (rf) experiments the dynamic response of deep-mesa-etched GaAs-$Al_xGa_{1-x}As$ quantum-wire arrays. At high perpendicular magnetic fields and in the vicinities of the filling factors $\nu = 2$ and $\nu = 4$ ($\nu = hnc/eB$, n is the 2D electron density) we observe at low temperatures T well-pronounced resonances with a surprisingly small damping in spite of the condition $2\pi f\tau \simeq 5 \times 10^{-3} \ll 1$. The resonance frequency decreases when ν changes from 4 to 2 and does not depend on the direction of the driving electric field with respect to the wire axis. These excitations resemble edge magnetoplasmons in large area 2DES where the frequency is determined by the perimeter of the sample. (See, e.g., Refs. 8–15 for experiments and Refs. 16 and 17 for theory.) We explain the observed resonances as edge plasma waves propagating around each individual wire in the direction determined by the orientation of B. They are localized in a very small region close to the wire edge which is narrower than 100 nm. Moreover, outside the vicinity of integer filling factors or with rising T, we observe that the spectrum changes its shape and the character of the excitation transforms into a relaxation type of excitation thus that the frequency and damping strongly depend on the direction of the driving electric field with respect to the wire. We explain this by the increase of the localization region of the plasma excitation, which is governed by the diagonal conductivity σ_{xx},[14] and leads, with increasing σ_{xx}, to an overlap of the two excitation regions at the opposite sides of each wire. This results in the transformation of the strongly localized high-finesse edge plasma wave into a damped relaxation mode distributed all over the wire. The dispersion in this relaxation regime is in good agreement with calculations based on the local-capacitance approximation.[13]

Arrays of periodic quantum wires have been fabricated, starting from modulation-doped $Al_xGa_{1-x}As$-GaAs heterostructures, which consisted of a 10-nm-thick GaAs cap layer, a 50-nm-thick n-doped and a 25-nm-thick undoped spacer $Al_xGa_{1-x}As$ layer. A photoresist mask has been prepared by holographic lithography and the pattern was etched 200 nm into the heterostructure through the 2D electron layer using deep-mesa etching techniques.[3–5] We will extensively discuss one sample where the wires had a geometrical width $t = 540$ nm, a period $a = 1000$ nm, a length $L = 4.5$ mm, and the number of the quantum wire was about 7000. We have studied four wire arrays with the same dimensions which show essentially the same behavior and a series of arrays with geometrical wire widths ranging from 600 to 300 nm which will be discussed below. In the dark, the wires had no mobile electrons. With pulses from a red light emitting diode we could then increase the electron density. The actual width w of the electron channels was smaller than t, caused by a lateral edge depletion usually of 100 to 120 nm on either side of the wire.[3,4] To study the dynamic response we used a nonresonant rf measurement cell in which conventional 2D samples have been measured previously.[13,14] The quantum-wire sample was positioned, as sketched in Fig. 1, between two electrodes which act as transmitting

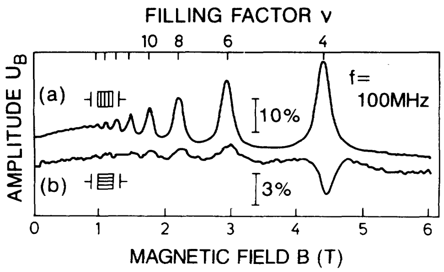

FIG. 1. Dependence of the rf signal U_B on the magnetic field B for different antenna positions at $T = 4$ K. U_B is normalized to 100% at B=0, the curves are shifted vertically, and the scale is given in the figure. (a) The applied electric field is perpendicular to the wire axis. (b) The applied electric field is parallel to the wire axis.

and receiving antennas. Using different antenna positions around the sample we could apply ac electric fields and, also, measure the response in different directions with respect to the wire axis. We have measured the normalized amplitudes of the signal, either in a sweep of B at constant f, $U_B = U(f = \text{const}, B)/U(f = \text{const}, B = 0)$, or at fixed B values in sweeps of f, $U_f = U(f, B = \text{const})/U(f, B = 0)$. As has been demonstrated before,[10] the real (plasmon frequency f_p) and imaginary (damping γ_p) parts of the response can be determined from the U_f spectrum using a linear-oscillator approximation with, depending on the sharpness of the resonance, 2–10% accuracy for f_p and 5% accuracy for γ_p.

As an example for original curves we show in Fig. 1 U_B curves for different antenna positions. The rf response, which was measured with similar results on four different samples with the same width t, exhibits an oscillatory behavior periodic in $1/B$. As seen from Figs. 1(a) and 1(b), the signals measured in different orientations of the antennas with respect to the wire direction, show a qualitative difference for B values lying in the vicinity of $\nu = 4$ in comparison to other B values. This directly reflects the anisotropy of the wire array, which is not expected for a 2D sample, and the special behavior near $\nu = 4$. A similar behavior as for $\nu = 4$ was also observed at higher B near $\nu = 2$.

For a full understanding of the dynamic excitations in the wire array we have investigated the whole three-dimensional U vs B and f space. In Figs. 2(a) and 2(b) we show the results taken at different B values near $\nu = 2$. The frequency dependence of the response at $\nu = 2$ is characterized by curve C in Fig. 2(a). As has been demonstrated before,[10,14] such U_f dependences indicate collective excitations with small damping. If we vary B, curve C gradually transforms into curves B or D and then into curves A or E. This change in the frequency spectrum indicates a transition from an oscillation to a relaxation regime. Figure 2(b) shows the f_p and γ_p values obtained from these U_f spectra by fits with the harmonic oscillator model. As expected, the damping of the excitations is small in the vicinity of $\nu = 2$. Note that only in a small B region the parameters f_p and γ_p determined for the two different directions of the driving electric field are very close to each other and exhibit similar B dependences. Outside this regime the γ_p values exceed the f_p values and both experimental values are very different for different directions of the electric field. (We cannot study in detail the relaxation signal for a driving field applied parallel to the wire axis because this lies at very high f.) Figure 2(c) shows data obtained in the vicinity of $\nu = 4$. At $T = 4$ K the f_p and γ_p values are nearly the same, indicating a moderate damping, where as at $T = 1.7$ K the f_p value increases while the γ_p value decreases with respect to $T = 4$ K. This indicates that for $\nu = 4$ a high-finesse collective excitation occurs only for $T = 1.7$ K.

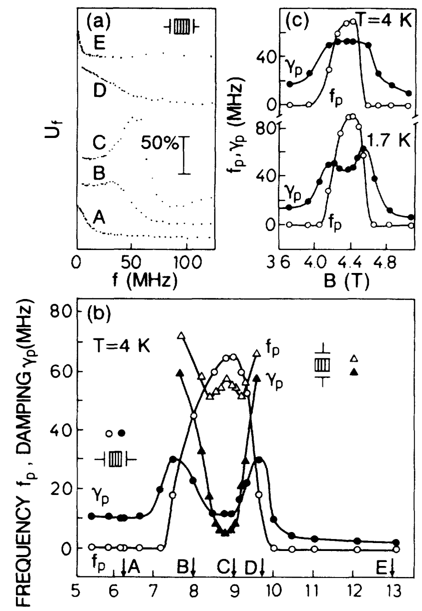

FIG. 2. (a) U_f spectra in the vicinity of $\nu = 2$ at $T = 4$ K. Capital letters correspond to different B values indicated by the arrows in (b). (b) f_p and γ_p values in the vicinity of $\nu = 2$ and $T = 4$ K for different directions of the exciting electric field. (c) f_p and γ_p values in the vicinity of $\nu = 4$ at different temperatures with electric field applied perpendicularly to the wire axis.

At low B the response of the quantum-wire sample is dominated by its imaginary part, as shown in Fig. 3(a). The frequency f_p is larger than zero only in the vicinity of integer ν values. Note that at low B the f_p values increase with decreasing ν in contrast to decreasing f_p at high B when the ν index changes from 4 to 2. The interesting finding in Fig. 3(a) is that the oscillatory B dependence of γ_p is in phase with the U_B dependence.

These results in Figs. 1, 2, and 3 clearly demonstrate two different regimes in the rf dynamic response of quantum-wire samples. In the first one, i.e., in the vicinities of $\nu = 2$ and $\nu = 4$ at $T = 1.7$ K and in the vicinity of $\nu = 2$ at $T = 4$ K, the response is governed by high-finesse collective excitations. Analyzing the phase in different positions around the sample[14] we find that these plasma waves change the direction of propagation when one changes the B orientation. The plasma frequency decreases when ν decreases. Further, there is an "out-of-phase" dependences of the f_p and γ_p values in the vicinities of $\nu = 2$ and $\nu = 4$, i.e., increasing f_p for decreasing γ_p and vice versa. Such a behavior is very

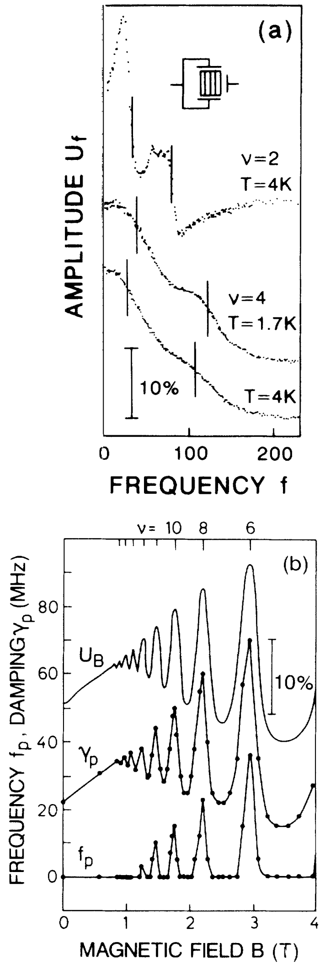

FIG. 3. (a) f_p and γ_p values at low magnetic fields and $T = 4$ K measured with electric fields applied perpendicular to the wire axis. The U_B dependence measured at $f = 30$ MHz in the same antenna geometry is also shown for comparison. (b) U_f spectra at $\nu = 2$ and 4 and different temperatures measured with a two-electrode transmitting antenna. Vertical lines show frequencies f_{p1} and f_{p2} for different excitation modes as determined from fits with the damped linear oscillator.

similar to that of rf edge magnetoplasma waves in large area 2D samples which have been extensively studied by various authors[9–17] and which have the dispersion

$$f_p = \frac{e^2 \nu m q}{\pi h \varepsilon} \ln\left(\frac{1}{ql}\right), \quad q = \frac{2\pi}{p}, \tag{1}$$

where q is the wave number, p the perimeter, m the mode index, and ε the effective dielectric constant. These excitations are localized within a width $l = \sigma_{xx}/\varepsilon f$ from the edge.[12,14,16] Since $l \propto \sigma_{xx}$ a variation of σ_{xx} with B or T leads to a variation of f_p and ν_p. For the large area 2D samples it was found that these localization lengths were, depending on temperature, filling factor, and sample quality, as small as about 50 nm.[12,14] Thus we conclude that the excitations observed in the wire arrays are edge plasma waves running around each individual wire in the direction governed by the magnetic field. Since the effective electrical wire width w, i.e., the geometrical width t minus the lateral depletion regimes, is $w \simeq$ 200–300 nm we also conclude that the excitations in the wires here are localized on a distance which is smaller than 100 nm, i.e., as observed on large area 2D samples.[12,14] Changing B or rising T results in the unique situation that with increasing σ_{xx}, and thus increasing l, for $l \sim w$, the two plasma excitation regions at the opposite sides of the wire begin to overlap. This causes a drastic change of the character of the excitation, which now becomes a relaxation type of excitation where the dynamic response represents a strongly damped charge oscillations distributed all over the wire. Thus these wire-edge plasmons are fundamentally different from the high frequency excitations observed in Raman and far-infrared experiments.[3–6] The latter consist of a center-of-mass oscillation perpendicular to the wire and freely propagating plasmons along the wires (or a superposition of both). The wire-edge plasmons here propagate over much longer length scales around the full circumference of each individual wire. They show a strong influence on the filling factor determined value of σ_{xx} and the unique crossover to the relaxation regime if the localization lengths exceed w.[18]

In the relaxation regime the neighboring wires act to each other as metal screens and we can use the local-capacitance approximation[13,16] to calculate the dispersion. For excitation with an electric field perpendicular to the wires and $l \gg w$ in this regime, we find that it is dominated by the imaginary part, $\gamma_p \propto dq^2/\rho_{xx}$, where ρ_{xx} is the diagonal resistivity and d is the distance between the wires. Note that this gives us, via $1/\rho_{xx}$, a very different B dependence, and stronger dependence on q, as compared to the edge-plasmon dispersion Eq. (1). This change in the character of the excitation nicely explains the experimentally observed very similar B dependences of γ_p and U_B at low B in Fig. 3(a), because the U_B signal is inversely proportional to ρ_{xx} at $f < f_p$. For excitation with an electric field parallel to the wires, where the relaxation occurs all along the full length of the wire, we find in analogy to the 2D result for metal-oxide-semiconductor system,[19] $\gamma_p \propto \Delta q^2 \sigma_{xx}$, where Δ is an effective distance to a screening electrode. Because of the different dependence of $1/\rho_{xx}$ and σ_{xx} on B in the relaxation regime we have a characteristic difference for the B dependence of f_p and γ_p in Fig. 2(b), in particular an increase of γ_p for parallel excitation as compared to the decrease for perpendicular excitation. We have so far no rigorous theory for wire-edge plasmons in the oscillatory regime, in particular a full treatment of interaction between neighboring wires in an array which certainly will have an effect on the plasmon frequency (see below). However, as shown experimentally by the unique behavior for the wire samples in comparison to the large area 2D samples, this interaction does not suppress the oscillations if l is smaller than w. Note also that ε in the localization length $l = \sigma_{xx}/\varepsilon f$ is determined only by the local surrounding on a scale of l. Thus l has in a wire a value similar to that of a 2DES.

We have additionally performed a systematic study on the rf reponse of wire arrays with different wire widths

t ranging from 600 to 300 nm. The samples were prepared from the same wafer; nevertheless we could not be absolutely sure that the conditions at the etched surface were exactly the same in the different fabrication processes. However the general trend is that as the wire width decreases the crossover from the high-finesse edge plasmon excitation to the relaxation regime occurs for smaller temperatures or smaller filling factors. If we use as a measure a Q factor $Q = f_p/\gamma_p$ we have for $\nu = 4$ $Q = 3$ for $t = 600$ nm, 2 (1.3) for 540 nm and 0.8 (0.2) for 420 nm at 1.7 (4.2) K. For $\nu = 2$ we find $Q = 10$ (10) for 600 nm, 8 (5) for 540 nm, and 4 (2.2) for 420 nm at 1.7 (4.2) K. For the arrays with widths $t = 300$–350 nm the response is practically governed only by the relaxation type behavior. So the experiments with varying wire width support our interpretation above that was derived from changing B and temperature.

It is now an interesting question whether in the high-finesse regime close to $\nu = 2$ and 4 the wire edge magnetoplasmons can also be described by the 2D plasmon formula, Eq. (1), using there $p = 2L$ for the wire. However, the absolute detemination of an edge plasma frequency is already in large area 2D samples a problem, since normally ε and in particular σ_{xx} in the Hall regime are not exactly known. If we use the parameters of the original 2D sample and apply Eq. (1) with $p = 2L$ we find that the calculated frequency is larger than the experimental wire edge plasmon frequency, roughly by a factor of 2.

Further information on a possible special dispersion for the wires can be deduced from higher-index modes. So far we have considered the excitation of the fundamental mode $m = 1$. If we use the two-electrode transmitting antenna shown in Fig. 3(b), the electric field has another symmetry with respect to the wire contour as compared to the "usual" (Fig. 1) antenna geometry. With this arrangement we can excite two edge modes with $q = \pi/L$ and $q = 2\pi/L$ ($m = 1$ and 2). At B values far from $\nu = 4$ and 2 the U_f spectra are similar to the values measured with the usual antenna geometry. When approaching the value $\nu = 4$ or $\nu = 2$ we observe indeed two resonances with frequencies f_{p1} and f_{p2}. The interesting observation is that the frequency ratio of these two resonances for $\nu = 2$ is $f_{p2}/f_{p1} = 2.4$. For a large area 2D sample one usually finds for this ratio 1.5 to 1.8. This indicates that the frequency of the wire-edge plasmons is quantitatively different from the 2D case. For the moment, without any accurate theory for this wire-edge magnetoplasmon, we do not know whether this is a property of the mode spectrum already for a single wire, or whether it arises from interaction with the closely spaced neighboring wires. For $\nu = 4$ in Fig. 3(b) we find that the frequency ratio depends on T. When T increases from $T = 1.7$ K to $T = 4$ K the f_{p2}/f_{p1} value increases from 3 to 4 and the γ_{p2}/γ_{p1} value increases from 2 to 3. This arises since for $\nu = 4$ the transition between the oscillation and the relaxation regimes occurs between $T = 1.7$ K and $T = 4.2$ K. Because of the different dispersions in these regimes this leads to increasing mode ratios.

In summary, we have observed at $\nu = 2$ and $\nu = 4$ rf wire-edge magnetoplasmons, i.e., edge collective excitations propagating around each individual wire in a quantum-wire array. These plasmons are localized within a very small distance from the wire edge that increases outside the vicinity of interger ν or rising T and, as a result, the high-finesse wire edge magnetoplasmon transforms into a relaxation mode which is distributed all over the wire and is strongly damped.

[1] For a recent review see, e.g., *Nanostructures and Mesoscopic Systems*, edited by W.P. Kirk and M.A. Reed (Academic Press, New York, 1992).

[2] W. Hansen, M. Horst, J.P. Kotthaus, U. Merkt, Ch. Sikorski, and K. Ploog, Phys. Rev. Lett. **58**, 2586 (1987).

[3] T. Demel, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. B **38**, 12 732 (1988).

[4] T. Demel, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. Lett. **66**, 2657 (1991).

[5] T. Egeler, G. Abstreiter, G. Weimann, T. Demel, D. Heitmann, and P. Grambow, Phys. Rev. Lett. **65**, 1804 (1990).

[6] A.R. Goni, A. Pinczuk, J.S. Weiner, J.M. Calleja, B.S. Dennis, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **67**, 3298 (1991).

[7] S. Das Sarma and W.Y. Lai, Phys. Rev. B **32**, 1401 (1985); Surf. Sci. **170**, 43 (1986); Q. Li and S. Das Sarma, Phys. Rev. B **40**, 5860 (1989); **41**, 10 286 (1990); Wei-ming Que and George Kirczenow, *ibid.* **37**, 7153 (1988); G. Eliasson, J.-W. Wu, P. Hawrylak, and J.J. Quinn, Solid State Commun. **60**, 41 (1986).

[8] V.A. Volkov, D.V. Galchenkov, L.A. Galchenkov, I.M. Grodnensky, O.R. Matov, and S.A. Mikhailov, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 510 (1986) [JETP Lett. **44**, 655 (1986)].

[9] S.A. Govorkov, M.I. Reznikov, A.P. Senichkin, and V.I. Tal'yanskii, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 380 (1986) [JETP Lett. **44**, 487 (1986)].

[10] L.A. Galchenkov, I.M. Grodnensky, and A.Yu. Kamaev, Fiz. Tekh. Poluprovodn. **21**, 2197 (1987) [Sov. Phys. Semicond. **21**, 1330 (1987)].

[11] E.Y. Andrei, D.C. Glattli, F.I.B. Williams, and M. Heiblum, Surf. Sci. **196**, 501 (1988).

[12] M. Wassermeier, J. Oshinowo, J.P. Kotthaus, A.H. MacDonald, C.T. Foxon, and J.J. Harris, Phys. Rev. B **41**, 10 287 (1990).

[13] I.M. Grodnensky, D. Heitmann, K. v. Klitzing, and A.Yu. Kamaev, Phys. Rev. B **44**, 1946 (1991).

[14] I.M. Grodnensky, D. Heitmann, and K. v. Klitzing, Phys. Rev. Lett. **67**, 1019 (1991).

[15] K.C. Ashoori, H.L. Störmer, L.N. Pfeiffer, K.W. Boldwin, and K. West, Phys. Rev. B **45**, 3894 (1992).

[16] V.A. Volkov and S.A. Mikhailov, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 450 (1985) [JETP Lett. **42**, 556 (1985)]; Zh. Eksp. Teor. Fiz. **94**, 217 (1988) [Sov. Phys. JETP **67**, 1639 (1988)].

[17] A.L. Fetter, Phys. Rev. B **32**, 7676 (1985); **33**, 3717 (1986); **33**, 5521 (1986).

[18] Of course the transition is not abrupt. We use the qualitative statement of high-finesse plasmons if the Q factor $Q = f_p/\gamma_p > 2$. In fact even in the intermediate regime at $T = 4$ K in Fig. 2(c) with $Q > 1$ oscillations are supported.

[19] A.V. Chaplik and A.O. Govorov, Poverhnost **12**, 5 (1987).