Low-frequency magnetoplasma excitations in GaAs/AlGaAs quantum wires

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Plasma resonances in the rf range have been observed in quantum-wire structures in a strong magnetic field near integer values of the Landau-level filling factor ($\nu=2$ and $\nu=4$). The frequency of these resonances at $\nu=2$ is lower than that at $\nu=4$. The Q factor decreases with increasing temperature and/or with increasing distance from an integer value of ν. The experimental results show that these resonances can be associated with excitations similar to edge magnetoplasmons in an ordinary 2D system.

Lattices of quantum wires fabricated from structures with a 2D electron gas have recently been the subject of active research. The electron energy spectrum in these lattices is a quasi-2D spectrum because the transverse motion of the conduction electrons is quantized in the wire inversion layers with a thickness on the order of 100 nm which form beside the heterojunction.[1-3] One-dimensional subbands are usually arranged quasiequidistantly with a typical spacing of 1–5 meV ($\hbar\Omega$). The motion of the electrons in the wires in a strong magnetic field directed perpendicular to the heterojunction ($\omega_c \gg \Omega$, where ω_c is the cyclotron frequency) is rendered two-dimensional, and the wires constitute 2D strips with an electron density which varies over the width.[3,4] The dynamic response of quantum wires to an external electric field has been studied experimentally by measuring the far-IR absorption or Raman scattering.[5-7] In the absence of a magnetic field, absorption of transverse radiation is observed at a frequency $\Omega_\perp$, which is usually greater than Ω, and which corresponds to the excitation of the fundamental transverse plasma mode in the wire.[5-7] The absorption frequency increases in a magnetic field: $\Omega_\perp^2(B)=\Omega_\perp^2(0)+\omega_c^2$ (Refs. 5 and 7). A 1D plasmon has also been observed in wires in the far-IR region on the basis of Raman scattering.[6] Its dispersion with respect to the magnetic field, measured from the absorption,[7] has turned out to be negative. This feature is characteristic of edge magnetoplasmon excitations in 2D systems.[8-10] All the wire excitations which have been observed so far lie at $\omega\tau \gg 1$, where τ is a characteristic parameter of the impurity broadening of the Landau levels in quantizing ($\omega_c\tau \gg 1$) magnetic fields. In this letter we are reporting first results on the dynamic response of quantum wires in the rf range, with $\omega\tau \ll 1$.

The test samples were periodic lattices of quantum wires fabricated on the surface of a heterostructure consisting of a GaAs protective cover layer (10 nm thick), a

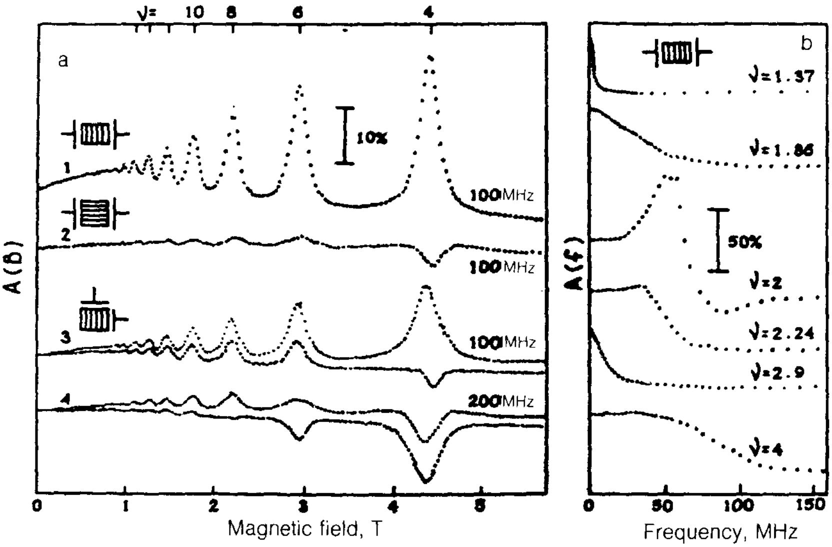

FIG. 1. a: Magnetic-field dependence of the response, $A(B)$, for several positions of the electrodes with respect to the sample, normalized at $B=0$. *1*—External electric field directed across the wires; *2*—along the wires; *3*, *4*—asymmetric arrangement of electrodes. b: Frequency dependence, $A(f)$, normalized to the response from the substrate.

doped AlGaAs layer (50 nm), an undoped AlGaAs layer (a spacer, 25 nm), a GaAs layer (1 μm), and a GaAs substrate (0.4 mm). A stripe photoresist mask was fabricated by holographic lithography. Stripes with a period $a=1000$ nm and a width $t=540$ nm[6,7] were formed by plasmachemical etching of the exposed surface to a depth of 200 nm (through the 2D layer). The number of the stripes was ≈ 7000, and their length $L=4.5$ mm. The electron conductivity, which was not exhibited when the sample was cooled to 4 K, was increased by illumination through the frozen photoconductivity mechanism. The formation of lateral depletion layers (with a thickness of 100–120 nm[6,7]) kept the width of the resulting electron wire channels, W, smaller than the dimension t.

The dynamic response of the quantum wires was measured by means of a nonresonant rf measurement cell,[10] in which the sample was placed between exciting and receiving electrodes. The response was measured for several positions of the electrodes with respect to the sample (Fig. 1), so that the electric field could act on the wire along different directions. We measured the magnetic-field and frequency dependence of the response, $A(B)$ and $A(f)$, where $A(B)=U(f=\text{const}, B)/U(f=\text{const}, B=0)$ and $A(f)=U(f, B=\text{const})/U(f, B=0)$ (U is the voltage amplitude on the receiving electrode at a constant amplitude on the exciting electrode; $\underset{\sim}{U}$ corresponds to the case in which a substrate of pure GaAs is in place of the sample in the cell).

These measurements showed that there are two regions of the magnetic field. In the first, which is near $\nu=2$ and $\nu=4$, we observed excitations in the quantum wires

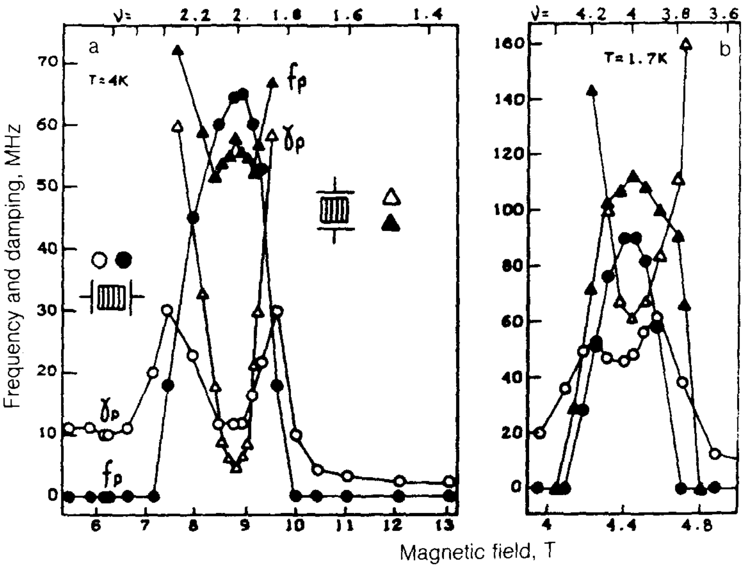

FIG. 2. Resonant frequency $f_p(B)$ and damping rate $\gamma_p(B)$ of excitations observed in longitudinal (open and filled circles) and transverse (triangles) external electric fields. *a*—Near $\nu=2$ at $T=4$ K; *b*—near $\nu=4$ at $T=1.7$ K.

with $f_p > \gamma_p$ $(\omega_p/2\pi = f_p - i\gamma_p)$. In the second, which was the complement of the first, we observed some strongly damped excitations $(f_p < \gamma_p)$. The difference between the Q values for the excitations in the two regions clearly demonstrates the frequency dependence of the response (Fig. 1b). Comparison with calculations based on the linear-oscillator approximation[11] makes it possible to reconstruct the field dependence $f_p(B)$ and $\gamma_p(B)$ for the observed resonances (Fig. 2). In the first magnetic-field region, these curves behave identically for two different orientations of the wires with respect to the electrodes (Fig. 2). With distance from an integer value of ν, the resonant frequency decreases, while the damping of the excitation increases. There is some difference in absolute value here, which we attribute to a difference in the "screening" effect of the electrons in the measurements in the two cases.

The resonances which we observed in the first magnetic-field region should be linked with excitations of an edge-magnetoplasmon-like nature (a particular case of these excitations is that of edge magnetoplasmons localized near the edge of the 2D system). The only low-frequency $(\omega < \omega_c)$ magnetoplasma excitations known in a 2D system which can be slightly damped, even under the condition $\omega\tau \ll 1$, are edge-magnetoplasmon-like excitations localized at irregularities. In the case of a bounded irregularity, they are characterized by a "rotation" in the plane of the 2D layer, in the direction specified by the orientation of the magnetic field.[8,11] The low-frequency region of excitations is present, and an edge-magnetoplasmon-like "rotational" nature is indicated by the following behavior.

Figure 1a shows plots of $A(B)$ which are oscillatory. When the electrodes are positioned asymmetrically with respect to the sample, the plots of $A(B)$ and $A(-B)$, i.e., measured for opposite directions of the magnetic field, are very different in the first magnetic-field region (curve *3* or *4* in Fig. 1a). In the case of a symmetric arrangement, they always coincide (curve *1* or *2* in Fig. 1a). This behavior of the response, which was observed in various samples, would be expected in the case of intrawire excitations characterized by a rotation in the plane of the 2D layer, in the direction specified by the orientation of the magnetic field, in agreement with the interpretation of the observed resonances as edge-magnetoplasmon-like excitations.

The decrease in the Q factor of the excitations with increasing distance from an integer value of ν and/or with an increase in the temperature from $T=1.7$ to 4 K (Figs. 2 and 3) can be explained on the basis of an increase in $\mathrm{Re}\sigma_{xx}$. The decrease in the resonant frequency with decreasing integer value of ν (Fig. 2) can be attributed to a decrease in σ_{xy}. In a 2D system under the condition $\mathrm{Re}\sigma_{xx} \ll \mathrm{Im}\sigma_{xx}$, for example, a calculation yields an expression for the resonant frequency of an edge magnetoplasmon which is proportional to the dissipationless component σ_{xy}, while the expression found for the damping rate is proportional to the ratio $\mathrm{Re}\sigma_{xx}/\mathrm{Im}\sigma_{xx}$.[8] The resonant frequencies and the damping of excitations observed in quantum wires in the range $\omega \tau \sim 0.005$ in the present study have a similar behavior. The range was estimated on the basis of the appearance of the first $(\omega_c\tau \sim 1)$ oscillation in the response, at $B \sim 1$ T $(T=4$ K). Here we made use of the fact that the suppression of the oscillations is due primarily to a τ broadening of the Landau levels, not a thermal broadening [at a much lower temperature, $T=1.7$ K, the field dependence $A(B)$ reveals the appearance of a first oscillation at essentially the same value of the magnetic field, $\sim$ 0.8 T]. The oscillatory nature of the resonant frequency in the damping of the excitations as ν is varied (Fig. 2), which is unlike the monotonic dependence in the far IR region,[7] is thus determined by the frequency range $\omega\tau \ll 1$ in our case.

There are two possibilities for the distribution of excitations within the wires. The first is that the excitation is localized near the edges of the wires, over a distance much shorter than their width (in Ref. 12, for example, the localization depth of edge magnetoplasmons near the edge of an ordinary 2D sample was clearly smaller than the half-width of the wires). In this case the resonances should be linked with the excitation of a mode which constitutes an in-phase propagation of edge magnetoplasmons with wavelengths equal to $2L$ along the perimeters of all the wires. The second possibility is that the excitation in the wires instead has a bulk distribution and that the resonances are associated with a mode characterized by in-phase rotations of the electric vector in the wires, which is elliptically polarized in the plane of the 2D layer.[13] The nature of the distribution of the excitation is a topic for further research.

In the second magnetic-field region we observe a sharp drop in the Q factors of the resonances and the appearance of an additional difference between the damping rates for the two directions of the external electric field. This effect is due to an increase in $\mathrm{Re}\sigma_{xx}$. In an ordinary 2D system, in the case of a strong damping of edge magnetoplasmons, the response is expressed by means of 2D-charge spreading modes,[14] so we attribute the low-Q resonances excited in the lattice of quantum wires to a spreading. Figure 3 shows curves of $f_p(B)$ and $\gamma_p(B)$ for a leakage mode excited by a transverse electric field; these plots oscillate as ν is varied. At integer values of ν, each

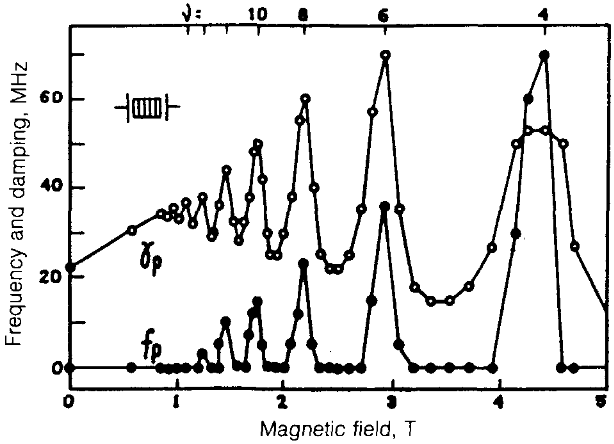

FIG. 3. Resonant frequency $f_p(B)$ and damping rate $\gamma_p(B)$ of excitations observed in a transverse electric field at $\nu \geqslant 4$ $(T=4\ \mathrm{K})$.

plot has local maxima, whose amplitude increases with increasing magnetic field. This effect is reminiscent of the oscillations in the quantity $1/\rho_{xx}$. For spreading with a stronger damping, excited by a longitudinal electric field, f_p and γ_p could be determined at the peripheries of the $\nu=2$ and $\nu=4$ regions (Fig. 2), in which γ_p is strongly damped as an integer value of ν is approached. The behavior here is reminiscent of that of $\mathrm{Re}\sigma_{xx}$.

The damping rates for both modes were estimated in Ref. 13. For the spreading mode excited by Hall currents themselves induced by a transverse electric field, the expression $\omega_p \sim -i \cdot 8\delta/\epsilon L \rho_{xx}$ was derived, where $\delta = W/a$ and $\epsilon = (1+\epsilon_{\mathrm{GaAs}})/2$. For the other mode, excited by a longitudinal electric field, an expression which describes a stronger damping was derived: $\omega_p \sim -i \cdot 8\sigma_{xx}/\epsilon W$. The magnetic-field dependence in each expression agrees with the experimental results. The low-Q excitations observed in the second magnetic-field region in quantum-wire lattices are thus indeed associated with fundamental modes of the longitudinal and transverse spreading of a 2D space charge.

In summary, this study has yielded the first observation of resonances in the rf range in quantum wires which are associated with edge-magnetoplasmon-like excitations which transform, with increasing temperature and/or with increasing distance from an integer value of ν $(\nu=2$ or $\nu=4)$, into relaxation modes of the spreading of a 2D charge.

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