Surface Science 196 (1988) 501–506
North-Holland, Amsterdam

LOW FREQUENCY COLLECTIVE EXCITATIONS IN THE QUANTUM-HALL SYSTEM

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Received 24 June 1987; accepted for publication 22 August 1987

We report the observation of low frequency collective excitations of the two-dimensional electron system in a GaAs/GaAlAs heterojunction in a magnetic field. The excitations are present for temperatures less than 2 K and fields corresponding to filling factors between $\nu = 1/2$ and $\nu = 7$. Their dispersion relation is linear in the wave vector k, and shows no evidence of a gap. These modes vanish between the Hall plateaus and elsewhere their propagation velocity follows a $H^{-1}\ \ln(\alpha H)$ field dependence. The features of these modes are consistent with a propagating perimeter wave in a quantum 2D Coulomb system.

1. Introduction

The discovery of the quantum Hall effect [1] has generated much interest in the excitation spectrum of the 2D electron system in a magnetic field. The nature of the spectrum depends on the region of phase diagram explored.

In the classical regime [2], $k_B T \gg \hbar\omega_c$, $\hbar^2 n/m^*$, the collective excitation are by now fairly well understood. Here $\omega_c = eH/m^*c$ is the cyclotron frequency, H is the magnetic field and n, m^* are the electronic surface density and effective mass respectively. Thus, in the weakly correlated (liquid) phase, the spectrum consists of a single, mostly longitudinal, cycloplasmon branch [3] which has a gap of ω_c at $k=0$:

$$\omega_+ = (\omega_c^2 + \omega_l^2)^{1/2} , \tag{1}$$

where $\omega_l = (2\pi ne^2/\epsilon m^*)^{1/2}k^{1/2}$ is the unscreened plasmon frequency, and ϵ is the dielectric constant of the medium. When the correlations are strong and the system crystallizes, the appearance of shear elasticity [4] gives rise to an additional, mostly transverse, excitation branch:

$$\omega_- \approx \omega_l\omega_t/\omega_c \propto k^{3/2}, \quad \omega_c \gg \omega_l, \omega_t, \tag{2}$$

where $\omega_t = \beta(n^{1/2}e^2/\epsilon m^*)^{1/2}k$, is the frequency of the shear mode in the absence of a magnetic field, and [5] $\beta = 0.245$. For fixed k, ω_- decreases with magnetic field and vanishes for $k=0$. This lower excitation branch, which indicates elastic response to shear, is considered to be the signature of the 2D electron crystal.

In the dense quantum regime which concerns us here, $k_BT \ll \hbar^2 n/m^* < e^2n^{1/2}/\epsilon$, the electrons form a quantum liquid which exhibits the quantum Hall effect in magnetic fields until the Landau length, $l_c = (\hbar c/eH)^{1/2}$, becomes about 5 times smaller than the interelectronic distance. Beyond this field, corresponding to filling factors $\nu = 2\pi nl_c^2 < 1/7$, and for temperatures $k_BT \ll e^2n^{1/2}/\epsilon$ one expects [6] the formation of the Wigner crystal. This has not yet been observed directly but approximate theoretical calculations [7] predict that its excitation spectrum would consist of the same two branches, ω_+ and ω_-, that are present in the classical crystal. At intermediate and low fields where the quantum Hall effect is observed, $\nu > 1/7$, theoretical treatments of the problem [8–10] predict a gap in the spectrum at $k=0$ of order $\sim e^2/l_c$ for $1/7 < \nu < 1$, while for $\nu > 1$ the gap is of order $\sim \omega_c$.

In a finite sample, in the presence of a perpendicular magnetic field, a collective boundary excitation is expected to appear, which propagates around the perimeter within a strip of width $l_s = (\omega/\omega_c)k^{-1}$. Here l_s is the magnetic screening length, and the wave vector k is determined by the length of the perimeter. The perimeter waves have recently been observed in a classical 2D-electron system [11,12]. They are the dynamic manifestation of the Hall effect as can be seen from the dispersion relation

$$\omega = \frac{4\sigma_{xy}k}{\epsilon} \ln\left[\frac{\omega_c}{\omega_p}\right], \quad \omega \ll \omega_c. \tag{3}$$

Here σ_{xy} is the Hall conductivity, $\omega_p = (2\pi ne^2/\epsilon m^*)^{1/2}(k \,\mathrm{tgh}\, kd)^{1/2}$ is the screened plasmon frequency, and d is the electrostatic screening length. The details of the screening are accounted for in the logarithmic term. For the quantum system it is useful [13] to rewrite eq. (3) in terms of the filling factor ν:

$$\omega = \frac{4e^2}{\epsilon h} k\nu \ln\left[\frac{c_p m}{nh\nu}\right]. \tag{4}$$

Our experiments revealed low frequency excitations in the quantum regime over a wide range of frequencies and temperatures, consistent with perimeter waves [14].

2. Experiment

We designed an experiment capable of detecting both longitudinal and transverse modes of the 2D electron system for filling factors $\nu \geq 1/10$ and for low frequencies $\omega \ll \omega_c$.

Our samples were GaAS/GaAlAs heterojunctions of effective mass $0.07m_e$, and dielectric constant $\epsilon = 12$ and of dimensions $0.8 \times 0.6 \times 0.05$ cm^3. We measured two samples of densities 7.8×10^{10} and 4×10^{11} cm^{-2} and mobilities 1.5×10^5 and 0.9×10^5 cm^2 V^{-1} s^{-1} respectively. The front of the sample, located 1000 Å from the electron layer, was placed flat on top of a 50 Ω meander transmission line, which is part of a broadband (10–1500 MHz) swept spectrometer. The coupling between the transmission line and the electrons allows probing of the electronic properties without contacts. This technique simplifies sample preparation, and enables the investigation of low density samples for which Ohmic contacts with the electron layer cannot be made reliably. As explained in ref. [4], in presence of a magnetic field the meander line can excite both longitudinal and transverse modes, by means of the field it creates in the electron layer, derivable from the potential

$$V = V_0 \sum_s \mathrm{e}^{-k_s d} \mathrm{e}^{\mathrm{i}(k_s x - \omega t)} ,$$

where V_0 is the effective potential on the transmission line and d is its distance from the electron layer. The wave vectors of these excitations are imposed by the half period of the meander $\lambda = 16\mu = k_L^{-1}$, and thus can assume a series of discrete values $k_s = \omega a/c + sk_L$, $s = 0, 1, 2, ...$, where $a = 100$ is the aspect ratio of the meanders, and $\omega a/c \ll k_L$. In order to improve our signal we used phase sensitive detection locked on a low frequency (<1 kHz) modulation of the electronic density upon applying a potential between an electrode located on the back of the sample and the transmission line. Although there were no contacts on this sample, we nevertheless could determine the density in situ from a direct RF absorption measurements at a fixed frequency of ~ 8 MHz, located far below all resonances of the system, which gave a direct measurement of the magnetoresistance $\rho_{xx}(H)$.

To ensure good thermal contact and temperature control down to the lowest temperatures, the sample and the transmission line together with a thermometer and a heater, were mounted in the dilute phase inside the mixing chamber of our dilution refrigerator. Our refrigerator could attain temperatures of ~ 80 mK in fields up to 24 T.

3. Results

We measured the RF power absorbed by the electrons in the frequency range 10–1000 MHz for a sequence of magnetic field values between 0–24 T. In the range of filling factors $\nu > 1/2$ we found a series of up to seven sharp resonances ($Q \approx 20$)

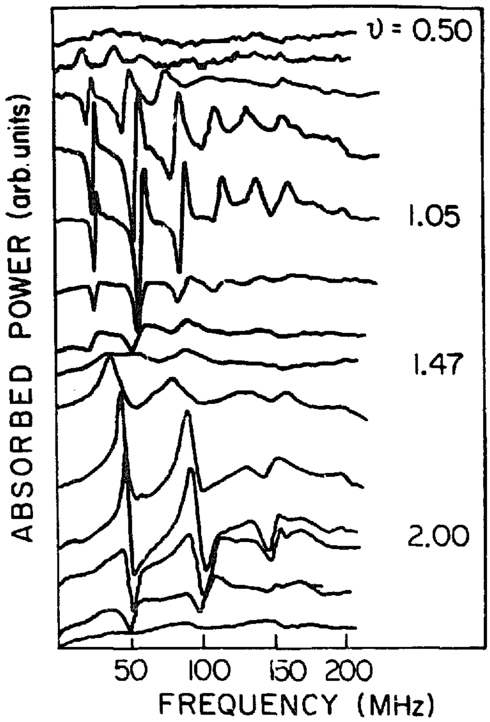

Fig. 1. Absorbed power versus frequency for filling factors ranging between 0.5 and 2.

which appear in an aproximately harmonic frequency sequence fig. 1. Their fundamental frequency ω_0, shows a plateau structure at integral filling factors ν falling off towards zero and decreasing in intensity on each side. For magnetic field values when the Fermi energy is close to half integer filling factor ν, the resonances could be made to decrease in frequency and vanish by heating the sample. The temperature increase that produced this effect varied from ~ 20 mK for very small deviations away from half-integer ν, to ~ 2 K near integer ν.

As illustrated in fig. 2, the mode frequencies on the plateaus have the field and wave vector dependence consistent with that of perimeter waves:

$$\omega_\nu = Bk\nu \ln(\alpha/\nu) , \tag{5}$$

where $B = 9$ MHz and $\alpha = 34$ and 90 for the samples of densities 7.8×10^{10} and 4×10^{11} cm^{-2} respectively, also in accord with the density dependence of perimeter waves.

To remove ambiguity about the domain of wave vector involved ($s = 0, 1, 2, ?$), we inserted a 12 μm Kapton sheet between the meander line and the sample so that it is subjected only to the low wave vector ($s = 0$) induction field; all the resonances disappeared. Either the modes are excited by the $s \geq 1$ ($k \geq 4000$ cm^{-1}) field or, if they are of low wave vector they must have vanishing amplitude at the position of the line which covers an area of 2×0.5 mm^2 in the center of the 8×6 mm^2 sample. But conceivably the modes were excited by the low wave vector fringe fields on the edge of the 2D electron gas, via its capacitive coupling to the line. We therefore

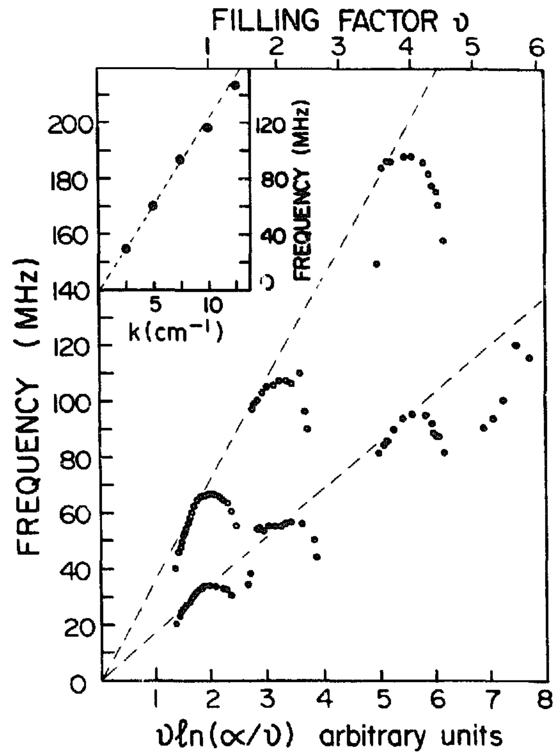

Fig. 2. Frequency of fundamental (●) and first harmonic (○) versus $\nu\ \ln(\alpha/\nu)$. The frequencies of the fundamental and four harmonics as a function of wave vector are plotted in the insert.

replaced the meander by a straight strip line some 250 μm wide which ran from edge to edge of the sample; those resonances we describe here returned, so we must conclude that they are of low wave vector and of vanishing amplitude in 2D bulk. Suspicion lies heavily on perimeter waves. To exclude all uncertainty we reduced the perimeter by 30% by cutting the sample in two. The resonance frequencies increased.

We plotted eq. (4) as a hashed line in fig. 2 by using $n=7.8\times10^{10}\ \mathrm{cm}^{-2}$, $k=2.2\ \mathrm{cm}^{-1}$ which correspond to the density and circumference of our sample, $\epsilon=6$ the average dielectric constant, and $d=10\ \mu$m, an adjustable screening length. The agreement is quite good. We conclude that the excitations described here are indeed perimeter waves in the quantum electron gas. These modes are localized within a narrow strip of several microns (or less) on the perimeter of the sample, and are a direct probe of the current carrying extended states in the quantum Hall system. The decrease in frequency and broadening as well as the temperature dependence observed for half-integer ν are consequences of the increase in dissipation near half-filled Landau levels.

Acknowledgements

We would like to thank N. Andrei, P. Coleman, C. Itzykson and E.E. Mendez for stimulating discussions and J. Verner, P. Pari and C. Heyer-Chaleil for expert technical help. We acknowledge with pleasure the help of G. Deville and of our Grenoble colleagues, in particular A. Benoit and T. Tholence of CRTBT. This work was supported in part by NATO Grant 86-0801. The experiment was done under the hospices of the Max-Plank Institute and SNCI in Grenoble, France, and the Francis Bitter National Magnet Laboratory, MIT, Cambridge, USA.

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