Spectroscopic method for determining the size of the Coulomb gap in the energy spectrum of an incompressible Fermi liquid of 2D electrons

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An anomalous behavior has been observed for the spectral position of an emission line during the condensation of a gas of 2*D* electrons into an incompressible Fermi liquid. A spectroscopic method is proposed for an independent determination of the energy gaps in the spectrum of excitations: quasielectrons and quasiholes.

1. A question pertinent to research on the quantum Hall effect in 2*D* electron systems is an experimental determination of the size of the Coulomb gaps in the energy spectrum of incompressible Fermi liquids which arise at fractional values of the filling factor of the Landau levels: $\nu = hn_S/eH = p/q$, where n_S is the concentration of 2*D*

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electrons, e and h are the universal constants, H is the magnetic field, p and q are integers, and q is odd.[1,2] According to the theoretical ideas,[3] the elementary excitations in an incompressible Fermi liquid are quasiparticles with fractional charge, $e^* = e/q$. In this model, the appearance of an additional electron (at $\nu = p/q$) is equivalent to the creation of q excitations: quasielectrons. A decrease in the number of electrons by one is equivalent to the creation of q quasiholes. An important point is that these excitations are separated by an energy gap from the ground state, and the sizes of the gaps may themselves differ from the quasielectrons, Δ_e, and the quasiholes, Δ_h (Ref. 4). The gaps in the spectrum of an incompressible Fermi liquid have previously been measured by studying the temperature dependence of the magnetotransport coefficients at $\nu = p/q$: the magnetoresistance ρ_{xx} and the conductivity σ_{xx} (Ref. 5). During thermal activation of excitations at the mobility edge, we have $\sigma_{xx} \sim \rho_{xx} \sim \exp(-W/kT)$, so that the activation energy W and the total gap in the spectrum, Δ_G, can be found from the corresponding temperature dependences: $\Delta_G = \Delta_e + \Delta_h \approx 2W$ (Refs. 5 and 6). If the Coulomb gaps are small, the condensation of a gas of $2D$ electrons occurs at such low temperatures that the activation processes begin to be strongly masked by a hopping conductivity with a variable hopping length.[7] Under such conditions the behavior $\sigma_{xx}(T)$ and $\rho_{xx}(T)$ cannot be described by an Arrhenius law, and a determination of the Coulomb gaps by the method outlined here becomes unreliable. We obviously need other, independent methods for measuring these properties.

As we have reported previously,[8] the spectra of the radiative recombination of $2D$ electrons (e) with nonequilibrium holes (h) make it possible to directly determine the state density of $2D$ electrons in a transverse magnetic field and to measure the cyclotron, spin, and intervalley splittings. In the present letter we report the use of that method to measure the Coulomb gap in the spectrum of an incompressible Fermi liquid.

2. In the experiments we use a ring-geometry MIS transistor fabricated on the (001) surface of p-type Si (boron concentration of 7×10^{14} cm^{-3}) with a maximum mobility of $2D$ electrons $\mu^* = 32\times10^3$ cm^2/(V·s) at $T = 1.5$ K and $n_S = 3.5\times10^{11}$ cm^{-2}. The mobility reaches $41\cdot10^3$ cm^2/(V·s) at $T = 0.35$ K and $n_S = 2.7\times10^{11}$ cm^{-2}. The emission spectra are measured in a photon counting mode. A magnetic field up to 8 T is produced by a superconducting solenoid in an optical cryostat. To reach a temperature of 0.35 K, we use a He^3 device. The ac magnetoconductivity is measured at a frequency of 20 Hz. The electron system is not heated in the source-drain field $E_{SD} \leqslant 3\times10^{-3}$ V/cm. In some special cases in which we wished to raise the electron temperature to 3–5 K, we applied a static electric field $E \geqslant 1$ V/cm. The electron temperature in this case was determined from the $\sigma_{xx}(T)$ calibration curve measured for the given ν as the lattice temperature was varied. Other experimental details are described in Refs. 8 and 9.

3. Figure 1a shows curves of $\sigma_{xx}(\nu)$ measured in a magnetic field $H = 8$ T at $T = 0.35$ and 1.5 K. At $T = 0.35$ K we can clearly see minima of σ_{xx} at the fractional values $\nu = 4/3$, 5/3, 7/3, and 8/3. These minima are consequences of a condensation of the gas of $2D$ electrons into an incompressible Fermi liquid. As the temperature is raised, the minima in $\sigma_{xx}(\nu)$ gradually disappear, but the structural features in

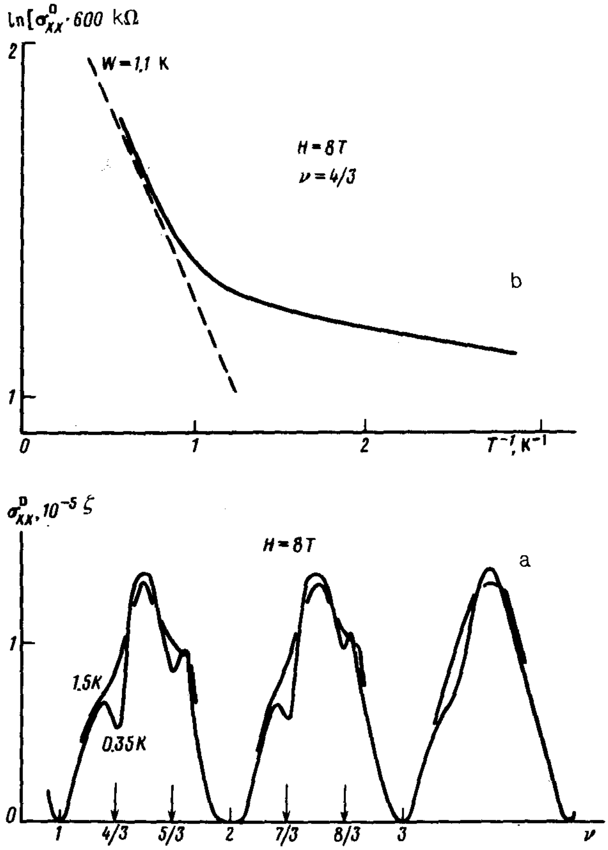

FIG. 1. a—Magnetoconductivity σ_{xx} versus the filling factor ν from measurements at $H = 8$ T and two temperatures: 1.5 K and 0.35 K; b—temperature dependence of the magnetoconductivity measured at $\nu = 4/3$ and $H = 8$ T in the coordinates $\ln\sigma_{xx}$, T^{-1}. The slope of the plot of $\ln\sigma_{xx}$ versus T^{-1} at high temperatures is shown by the dashed line.

$\sigma_{xx}(\nu)$ at these fractional values of ν are observed up to $T = 1.7$ K. Figure 1b shows, in the coordinates $\ln\sigma_{xx}$, T^{-1}, the temperature dependence $\sigma_{xx}(T)$ measured for $\nu = 4/3$ at $H = 8$ T. We see that the dependence cannot be described by a simple linear law. This result means that the magnetoconductivity is not a consequence of thermally activated processes alone in the temperature interval studied. A similar deviation from linearity on this dependence at low tempertures has been observed[6] in GaAs/AlGaAs heterojunctions. The reason for this behavior is that at low temperatures the hopping conductivity mechanism is more effective than the thermally activated mechanism. Consequently, the slope of the plot of $\ln\sigma_{xx}$ versus T^{-1} can give us the activation energy W only at high temperatures.[6] It follows from Fig. 1b that the activation energy is $W = 1.1 \pm 0.05$ K for $\nu = 4/3$ at $H = 8$ T. A similar analysis of the dependence $\sigma_{xx}(T)$ for $\nu = 7/3$ at $H = 8$ T yields $W = 0.95 \pm 0.05$ K.

4. Under conditions of nonequilibrium $e - h$ excitation, the depletion layer disappears, and boron atoms which have captured nonequilibrium holes appear directly

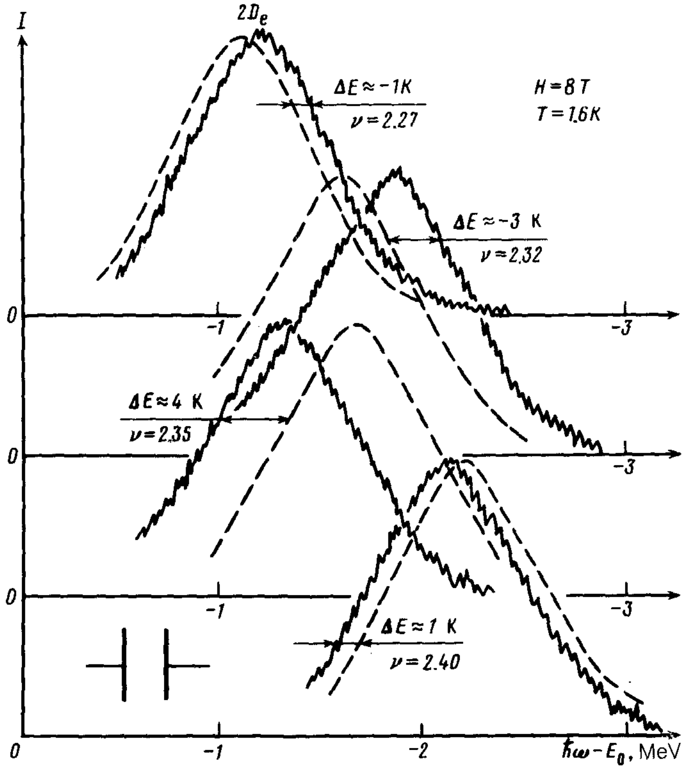

FIG. 2. Spectra of the radiative recombination of $2D$ electrons (the $2D_e$ line) measured at $T = 1.6$ K and 4 K (dashed lines) for various values of ν: 2.27, 2.32, 2.35, and 2.40 ($H = 8$ T). Here ΔE is the difference between the spectral positions measured for the line at $T = 1.6$ K and 4 K; $E_0 = 1.0885$ eV.

behind the $2D$ channel.[9] The wave function of the $2D$ electrons penetrates into the semiconductor. Consequently, a radiative recombination is possible because of an overlap of the wave functions of the $2D$ electrons and the nonequilibrium holes which have become bound to the cores of boron atoms near the interface.[10]

Figure 2 shows spectra of the radiative recombination of $2D$ electrons with nonequilibrium holes from measurements at $H = 8$ T and $T = 1.6$ K for the same MIS transistor as was used to find the dependence $\sigma_{xx}(\nu)$ (Fig. 1a). Under the conditions indicated ($T = 1.6$ K and $2.27 < \nu < 2.40$), many of the $2D$ electrons are delocalized, and the width of the Landau level does not exceed[8] 3 K.

The shape of the emission spectrum thus reflects the distribution of nonequilibrium holes with a width ≈ 10 K and is insensitive to changes in the state density of $2D$ electrons. Since the nonequilibrium holes populate only the ground state, with angular momentum $J_z = -3/2$ at $T = 1.6$ K and $H = 8$ T, optical transitions involving electrons with a spin $S_z = -1/2$ are forbidden, and in the spectra we observe the emission of $2D$ electrons with[8] $S_z = +1/2$. This method can thus be used to study only events that occur at $\nu > 2$.

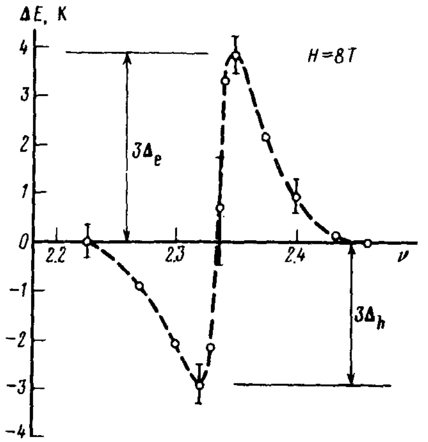

FIG. 3. The difference (ΔE) between the spectral positions of the $2D_e$ line measured at $T = 1.6$ K and 4 K versus the filling factor ν near $\nu = 7/3$ at $H = 8$ T.

It can be seen from Fig. 2 that as ν varies from 2.27 to 2.4, the shape of the $2D_e$ line remains essentially the same, but its spectral position varies in a nonmonotonic way. To see how the condensation of $2D$ electrons is manifested in the energy position of the $2D_e$ line, we compare the observed emission with the spectra measured under conditions such that an incompressible Fermi liquid does not arise [i.e., in structures with a low electron mobility[11] or at high temperatures ($T > \Delta_G$)]. The spectral position measured for the $2D_e$ line at $T = 4$ K ($T = 4K > \Delta_G$) varies in a monotonic way with ν, showing no structural features at $\nu = 7/3$. The difference ΔE in the energy positions of the $2D_e$ lines measured at $T = 1.6$ and 4 K (Fig. 2) is, in our opinion, a measure of the effect of the interaction of the $2D$ electrons as they condense into an incompressible Fermi liquid. Figure 3 shows the dependence $\Delta E(\nu)$ measured at $H = 8$ T. We see that ΔE is nonzero only near $\nu = 7/3$, so that the anomalous behavior of the energy position of the $2D_e$ line is due to a condensation of a gas of $2D$ electrons. The value of ΔE is negative and reaches a minimum at a value of ν slightly smaller than $\nu = 7/3$; it then changes sign and reaches a maximum at a value of ν slightly above $\nu = 7/3$. This behavior can be explained on the basis that the number of $2D$ electrons is reduced by one in a recombination event. In the model of an incompressible Fermi liquid, this reduction is equivalent at $\nu \leqslant 7/3$ to the creation of three excitations, quasiholes of charge $(1/3)e$, while at $\nu > 7/3$ it is equivalent to the absorption of three quasielectrons. During the absorption of the three quasielectrons, the energy of the emitted photon increases by $3\Delta_e$, while in the production of three quasiholes it decreases by $3\Delta_h$. It follows from Fig. 3 that at $H = 8$ T and $\nu = 7/3$ we have $3\Delta_e = 4 \pm 0.3$ K and $3\Delta_h = 3 \pm 0.3$ K. The resulting Coulomb gap measured by a spectroscopic method under these conditions agrees well with the value of $\Delta_G = \Delta_e + \Delta_h$ found independently by means of thermal-activation measurements with the same MIS structure and also with other structures with a similar electron mobility.[11] Accordingly, the spectroscopic method which we have been discussing here makes it possible, in principle, to separately measure the Coulomb gaps for quasielectrons and quasiholes. It can also be used to determine how the scale size of the energy gaps varies with the magnetic field, disorder, and the temperature.

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