Activated magnetoconductivity in the region of fractional quantization of the Hall resistance in a silicon metal-insulator-semiconductor structure

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That gap (ΔE) in the energy spectrum of interacting 2D electrons in a strong transverse magnetic field H which corresponds to a filling factor $\nu = 2/3$ has been determined from the temperature dependence of the diagonal component of the magnetoresistance tensor. The results reveal $\Delta E \sim \sqrt{H}$, in accordance with a theory which explains the fractional quantum Hall effect in terms of an electron-electron interaction.

A fractional quantum Hall effect in two-dimensional (2D) electron systems has been observed in GaAs-AlGaAs heterojunctions[1–4] and silicon metal-insulator-semiconductor (MIS) structures[5–7] with an anomalously high carrier mobility. The effect is seen as additional minima and plateaus on the curves of the components ρ_{xx} and ρ_{xy} of the magnetoresistance tensor in the region of fractional values of the filling factor of the Landau sublevel, $\nu = n_s h/eH$, where n_s is the density of 2D electrons, h is Planck's constant, and e is the electron charge. These structural features were explained by Laughlin[8,9] in terms of the condensation of 2D electrons into a new type of highly correlated, incompressible Fermi liquid. The groundstate energy of the system of interacting electrons has a minimum at $\nu = 1/3$ and, by virtue of the electron-hole symmetry, at $\nu = 2.3$. The change in the density in the region $\nu = 1/3$ can be described in terms of the creation of excitations: quasielectrons and quasiholes with a fractional charge $e^* = (1/3)e$. The incompressibility of the Fermi liquid means that there are no gap-free excitations in this system and thus suggests that there exist quasielectron and quasihole bands separated by energy gaps from the ground state. To determine the typical sizes of these gaps, we can study the activated magnetoconductivity in the region of fractional values of ν (Refs. 10 and 11).

The energy gaps at integer values of ν correspond to cyclotron, spin, and intervalley splittings and are determined in structures with a high carrier mobility from the temperature dependence of the diagonal component of the magnetoresistance tensor, $\rho_{xx}^{\min} \sim \exp(-W/kT)$ where W is the activation energy, and $\Delta E = 2W$ is the energy gap.[10] The activation energies in the region of fractional values of ν have been determined in heterojunctions by several teams of investigators,[11–14] but all these results have been obtained under different experimental conditions; they agree poorly with each other and with the theory, since it has not been possible to vary the density of 2D electrons at the heterojunctions over a broad range.

The system of 2D electrons in silicon MIS structures has the advantage over the system of electrons in heterojunctions that it is possible to vary n_s in a given structure

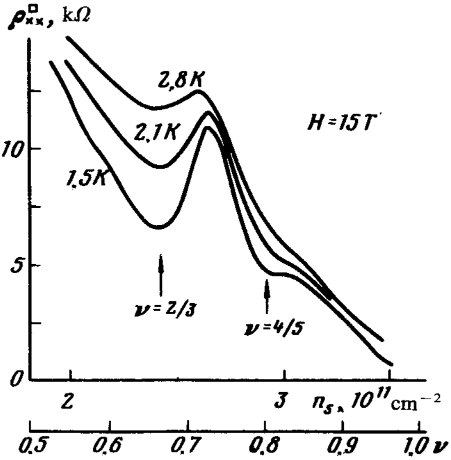

FIG. 1. Diagonal component of the magnetoresistance tensor, ρ_{xx}, versus the density of 2D electrons at various temperatures: $T = 1.51$ K, 2.10 K, and 2.82 K.

at a fixed value of the magnetic field and at fixed values of the other parameters [including the mobility μ_e, if the change in n_s occurs near the $\mu_e(n_s)$ maximum], in order to determine the activation energy for various values of ν. In this letter we are reporting a determination of the gap in the energy spectrum of 2D electrons in a silicon MIS structure for $\nu = 2/3$ and its dependence on the magnetic field under conditions such that all the other parameters of the system are fixed.

We studied a structure with a maximum 2D-electron mobility, $\mu_e = 3.6 \times 10^4$ cm^2/(V · s) (at a density $n_s = 3 \times 10^{11}$ cm^{-2} and a temperature $T = 1.5$ K). The behavior $\mu_e(n_s)$ and other parameters of this structure are described in detail in Ref. 7. The measurements were carried out in an ac regime at 20 Hz. The *I-V* characteristics turn out to be linear (so that there is no heating of the electron system) near fractional values of ν only at a measurement current $I_0 < 200$ nA.

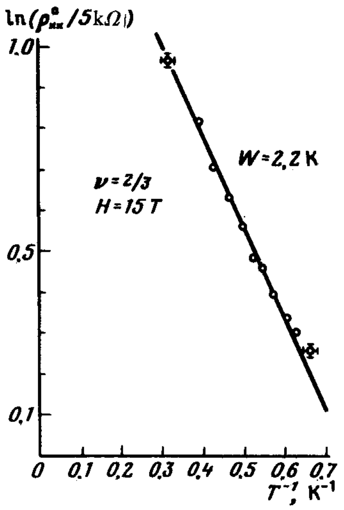

FIG. 2. Temperature dependence of ρ_{xx} at the minimum corresponding to $\nu = 2/3$ at $H = 15$ T.

Figure 1 shows curves of $\rho_{xx}(n_s)$ near $\nu = 2/3$ for $H = 15$ T and various temperatures. As the temperature is raised, the structural feature in ρ_{xx} (and also in ρ_{xy}) disappears. The same behavior of $\rho_{xx}(T)$ is observed at all the minima in ρ_{xx} observed in this MIS structure at the fractional values $\nu = 1/3$, 2/3, 4/3, 4/5, and 6/5. The activation nature of the magnetoconductivity near $\nu = 2/3$ is demonstrated by Fig. 2, which shows $\ln \rho_{xx}$ versus the reciprocal temperature. We see that the experimental points conform well to a straight line in these coordinates, which corresponds to the expected behavior $\rho_{xx}^{\min} \sim \exp(-W/kT)$. The low-temperature deviation agrees with the experimental result of Ref. 13, where it was shown that the dependence on $\ln \rho_{xx}$ on T^{-1} consists of two straight lines with different slopes, but it is the slope at the higher temperatures which corresponds to the activation energy W. For $\nu = 2/3$ at $H = 15$ T and $\mu_e = 3.5 \times 10^4$ cm^2/(V · s), the activation energy turns out to be $W = 2.2 \pm 0.1$ K. This value is substantially greater than the value found for $\nu = 2/3$ in heterojunctions: $W = 0.38$ K at $H = 9.6$ T (Ref. 11), $W = 1.2$ K at $H = 12$ T (Ref. 12), and $W = 0.9$ K at $H = 7.4$ T (Ref. 13). This result is due, in particular, to the circumstance that the effective dielectric constant which appears in the interelectron potential is[15] $\epsilon = (\epsilon_{\rm Si} + \epsilon_{\rm SiO_2})/2 = 7.7$ for silicon MIS structures ($\epsilon_{\rm Si}$ and $\epsilon_{\rm SiO_2}$ are the dielectric constants of silicon and its oxide), nearly twice the corresponding value for a GaAs-AlGaAs heterojunction.

On the other hand, the value which we find for W for $\nu = 2/3$ is substantially lower than the theoretical prediction $W_t = 6.6$ K at $H = 15$ T (Ref. 8). A possible reason for this circumstance is that the experimental value of $\Delta E = 2W$ corresponds to an energy gap that separates mobility thresholds, rather than corresponding energy levels. Evidence for this interpretation comes from the circumstance that the activation energy depends on the mobility of the 2D electrons in our experiments at a fixed magnetic field and increases with increasing μ_e. This question will be discussed, along with the corresponding experimental results, in a separate paper, but it is clear that the mobility of the 2D electrons did not change during the determination of the dependence $W(H)$. For our MIS structure for 2.1×10^{11} cm^{-2} $< n_s < 4.2 \times 10^{11}$ cm^{-2} at 1.5 K $< T < 3$ K, the change in μ_e does not exceed 3%: $\mu_e = (3.5 \pm 0.1) \times 10^4$ cm^2/(V · s)

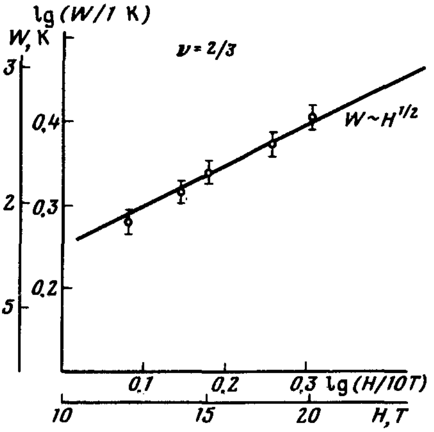

FIG. 3. Dependence of the activation energy W on the magnetic field for $\nu = 2/3$ and for a constant mobility of the 2D electrons, $\mu_e = (35 \pm 1) \times 10^3$ cm^2/(V · s). Line—The theoretical function $W \sim \sqrt{H}$.

(Ref. 7). Accordingly, for $\nu = 2/3$ it is possible to vary the magnetic field over the interval from 12 to 20 T, without changing any of the other parameters of the system of 2D electrons. Figure 3 shows the dependence $W(H)$ found under these conditions in full logarithmic scale. Shown for comparison in the same figure is a line with a slope of 1/2, in accordance with Laughlin's theory, in which we have $\Delta E \sim e^2/\epsilon l_H \sim \sqrt{H}$, where $l_H = \sqrt{\hbar/eH}$ is the magnetic length. We see that the experimental results are in good qualitative agreement with the theory and can be described by $W \cong 0.007 e^2/\epsilon l_H$.

The size found for the gap in the energy spectrum of 2D electrons in the region of fractional quantization of the Hall resistance and its dependence on the magnetic field indicate that the observed anomalies of the magnetotransport properties stem from effects of a Coulomb interaction of 2D electrons. These results agree with the suggestion of a condensation into a new type of highly correlated Fermi liquid.

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[1]D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[2]H. L. Störmer, A. Chang, D. C. Tsui, J. C. M. Hwang, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **50**, 1219 (1983).
[3]H. L. Störmer, D. C. Tsui, A. C. Gossard, and J. C. M. Hwang, Physica (Utrecht) **117B/118B**, 688 (1983).
[4]A. C. Gossard, Two Dimensional Systems, Heterostructures and Superlattices. Springer Series in Solid State Sciences, Vol. 53, 1984, p. 262.
[5]V. M. Pudalov and C. G. Semenchinskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 143 (1984) [JETP Lett. **39**, 170 (1984)].
[6]M. G. Gavrilov, Z. D. Kvon, I. V. Kukushkin, and V. B. Timofeev, Pis'ma Zh. Eskp. Teor. Fiz. **39**, 420 (1984) [JETP Lett. **39**, 507 (1984)].
[7]I. V. Kukushkin, V. B. Timofeev, and P. A. Cheremnykh, Zh. Eskp. Teor. Fiz. **87**, 2223 (1984) [Sov. Phys. JETP **60**, No. 6 (1984)].
[8]R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
[9]R. B. Laughlin, Surf. Sci. **142**, 163 (1984).
[10]K. Von Klitzing, G. Ebert, N. Kleimichel, H. Obloh, G. Dora, and G. Weiman, Proceedings of the Seventeenth International Conference on the Physics of Semiconductors, San Francisco, 1984.
[11]D. C. Tsui, H. L. Störmer, J. C. M. Hwang, J. S. Brooks, and M. J. Naughton, Phys. Rev. B **28**, 2274 (1983).
[12]A. M. Chang, M. A. Paalanen, D. C. Tsui, H. L. Störmer, and J. C. M. Hwang, Phys. Rev. B **28**, 6133 (1983).
[13]S. Kawaji, J. Wakabayashi, J. Yoshiro, and H. Sakaki, J. Phys. Soc. Jpn. **53**, 1915 (1984).
[14]G. Ebert, K. Von Klitzing, J. C. Maan, G. Remenyi, C. Probst. G. Weiman, and W. Schlapp, J. Phys. C **17**, L775 (1984).
[15]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

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