Evidence for the influence of electron-electron interaction on the chemical potential of the two-dimensional electron gas

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It is shown experimentally that the interaction between electrons strongly influences the chemical potential of the two-dimensional (2D) electron gas. At sufficiently low temperatures and in high magnetic fields, regions of filling factor appear where (i) the chemical potential μ diminishes with increasing carrier density, i.e., the thermodynamic density of states is negative; (ii) the derivative $\partial\mu/\partial H$ (H is the magnetic field) is considerably higher than the maximum value for a noninteracting 2D electron gas. Using these results, we have estimated that the energy of the *e-e* interaction in Si inversion layers in a magnetic field is about 1 order of magnitude less than the classical Coulomb interaction calculated for Si metal-oxide-semiconductor field-effect transistors.

I. INTRODUCTION

The electron-electron (*e-e*) interaction plays an important role in two-dimensional (2D) electron systems, being responsible, e.g., for the fractional quantum Hall effect (QHE). In the case of the integer (IQHE), however, many assume that the *e-e* interaction only influences some features, while the whole picture can be described rather well on the basis of a simple one-particle model.

Recently, however, we have observed experimentally[1] in high-mobility Si metal-oxide-semiconductor field-effect transistors (MOSFET's) in the IQHE regime that the influence of the *e-e* interaction on the density of states is so drastic that the latter may become negative. This phenomenon was predicted theoretically by Efros[2] in 1988. According to Ref. 2, the negative sign of the density of states is the result of the interaction between quasiparticles belonging to the same energy level: In the limit where the effect of the Coulomb interaction dominates the effect of disorder, the thermodynamic density of states is of order

$$\frac{\partial n_s}{\partial\mu}\simeq-\frac{\epsilon}{e^2 l_H}\{\nu\}^{1/2}\quad\text{for }\{\nu\}\le\tfrac{1}{2}\tag{1a}$$

and, due to the electron-hole symmetry,

$$\frac{\partial n_s}{\partial\mu}\simeq-\frac{\epsilon}{e^2 l_H}(1-\{\nu\})^{1/2}\quad\text{for }\{\nu\}>\tfrac{1}{2}\ .\tag{1b}$$

Here, n_s is the carrier density, μ is the chemical potential, e is the elementary charge, ϵ is the dielectric constant, l_H is the magnetic length, and $\{\nu\}$ is the fractional part of the filling factor: $\{\nu\}\equiv\nu-\llcorner\nu\lrcorner$, with $\nu=2\pi n_s l_H^2$.

The thermodynamic properties of an interacting 2D electron gas in a high magnetic field have also been theoretically studied by MacDonald, Oji, and Liu,[3] who made predictions of the influence of the Coulomb interaction on the entropy, the chemical potential, the heat capacity, and the magnetization. In particular, they showed that when interactions are included, the rate of increase of the chemical potential with magnetic field at partial sublevel fillings is much higher than that for a noninteracting-electron gas, and that interaction causes a giant enhancement of the spin splitting when the chemical potential moves from an antiparallel-spin level to a parallel-spin level.

Our preliminary experiments[1] demonstrated the expected behavior of the thermodynamic density of states. In the present paper we communicate the results of measurements of the chemical potential, μ, of a 2D gas of interacting electrons. Measurements of μ were performed using two independent methods: integration of the inverse density of states obtained by measuring the magnetocapacitance, and by the floating-gate technique. In accordance with the theoretical predictions, our experiments have shown that at low temperatures and in high magnetic fields there appear filling-factor regions where (i) the chemical potential diminishes with increasing electron density, and (ii) the derivative $\partial\mu/\partial H$ is considerably higher than its maximum value for a noninteracting 2D electron gas.

A comparison of our data with calculations allows us to estimate that the energy of the *e-e* interaction in Si inversion layers in a magnetic field is about 10–20 times lower than the classical Coulomb interaction.

II. EXPERIMENT

The chemical potential of a 2D electron system in a magnetic field is equal to (Ref. 4)

$$\mu(H,n_s)=\mu(0,n_s)+\frac{e^2 S}{C_{cg}}[n_s(H)-n_s(0)]+e[V_g(H,n_s)-V_g(0,n_s)]\ ,\tag{2}$$

where S is the effective sample area, assumed to be independent of H and n_s, V_g is the gate voltage, and C_{cg} is the geometric capacitance of the capacitor channel gate. The chemical potential $\mu(0,n_s)$ at zero magnetic field is known to be[5]

$$\mu(0,n_s)=\frac{\pi\hbar^2}{2m^*}n_s=D_0^{-1}n_s \ , \tag{3}$$

where m^* is the effective mass of an electron and D_0 is the density of states at $T=0$ K and at zero magnetic field. The inverse thermodynamic density of states, obtained by differentiating (2), is equal to (to an accuracy of $\Delta C/C$, Ref. 6)

$$\left[\frac{\partial n_s}{\partial\mu}\right]^{-1}\simeq\frac{\pi^2\hbar}{2m^*}+e^2S\left[\frac{1}{C(H)}-\frac{1}{C(0)}\right]$$
$$\simeq D_0^{-1}+e^2S\frac{\Delta C}{C^2} \ , \tag{4}$$

where C is the capacitance of a metal-oxide-semiconductor (MOS) structure to be measured, and $\Delta C\equiv C(0)-C(H)$.

To find $\mu(n_s)$ for fixed H, one should integrate $(\partial n_s/\partial\mu)^{-1}$, obtained from capacitance measurements, over n_s. The latter is proportional to V_g to an accuracy of $\Delta C/C$. The data for $\Delta C(V_g)$ were measured directly in the experiments. Thus the only parameter that cannot be determined in present experiment is the effective mass, which is known to be $m^*\geq 0.19m_e$ (Refs. 5, 7, and 8) (m_e is the free-electron mass).

The experiments were performed on two Si MOSFET's: no. 1 ("Si 1-33A") and no. 2 ("Si 2-16B"). The maximum zero-magnetic-field mobilities of the electrons in these samples were 3.2 and 3 $m^2V^{-1}s^{-1}$ respectively, achieved at $n_s\simeq 4\times10^{15}$ m^{-2}. Similar results were obtained with other samples of similar mobility. All samples were of "Hall-bar" geometry (0.8×5 mm^2); the oxide thickness in the samples was about 2000 Å.

The capacitances were measured with an RC bridge in the frequency range 9–74 Hz. The results did not depend on frequency. The amplitude of the gate-voltage modulation, $2\leq U_{\sim}\leq 20$ mV [corresponding to a modulation of the carrier density $\Delta n\simeq(2-20)\times10^{12}$ m^{-2}] was rather small and did not noticeably influence the results. Two orthogonal components of the bridge imbalance signal, connected with changes of capacitance and conductivity of the sample, were measured simultaneously using two lock-in amplifiers.

To determine $\mu(H)$ directly, it is convenient to fix n_s and to measure the dependence of V_g on a magnetic field. This method (the so-called "floating-gate" technique[4]) is potentially more reliable than the ac method described above, as one does not need to assume a constant effective sample area and to take the value of the effective mass from other experiments. The gate was connected to a direct-current amplifier with an input resistance greater than 10^{14} Ω (which corresponds to a time of a structure discharge above 10^5 s): After setting V_g, the gate was isolated from the voltage source and the variations of V_g measured directly using the amplifier.

III. RESULTS

Figure 1 shows the chemical potential as a function of V_g ($\propto\nu$) calculated from $\Delta C(V_g)$. The excitation of eddy currents[9] makes it impossible to determine μ at filling factors close to $\nu=2$ at T below 4.2 K, and therefore $\mu(V_g)$ was interpolated in this region (dashed lines in Fig. 1) by taking into account the value of the energy gap determined by the floating-gate technique (see below). At $T=4.2$ K the $\mu(V_g)$ dependence is monotonous at all filling factors, except for the small ν region between $\nu=1$ and 2. Lowering the temperature leads to the appearance of several ν regions where the chemical potential diminishes with n_s. This diminution, $\Delta\mu$, depends on the sublevel involved and usually is of the order of 0.2–0.5 meV. The calculations of $\mu(V_g)$ have been done using the lowest known value of the effective mass, $m^*=0.19m_e$. If one uses a more realistic, higher value of m^* in the calculations of $\mu(V_g)$, $\Delta\mu$ will be larger.

All the investigated samples showed a similar behavior of the chemical potential; in particular, at T below 2–2.5 K there were always at least three filling-factor regions where the chemical potential diminished at increasing n_s: in the extreme quantum limit ($\nu<1$) and slightly above and below $\nu=2$. However, $\Delta\mu$ differed from sample to sample, even though the electron mobilities were close. It should be noted that with increasing magnetic field the effective sample area at low n_s can decrease slightly due to field-induced localization,[10] so it is possible that the real value of $\Delta\mu$ in the extreme quantum limit is even higher than that in Fig. 1.

The $\mu(H)$ dependence for Si MOSFET no. 2 obtained at $T=1.3$ K by the floating-gate technique is shown in Fig. 2 (upper curve). Although eddy currents do not allow one to determine μ in the vicinity of $\nu=2$, they do not affect the drop of the chemical potential. The dotted-dashed curve shows the calculated $\mu(H)$ for

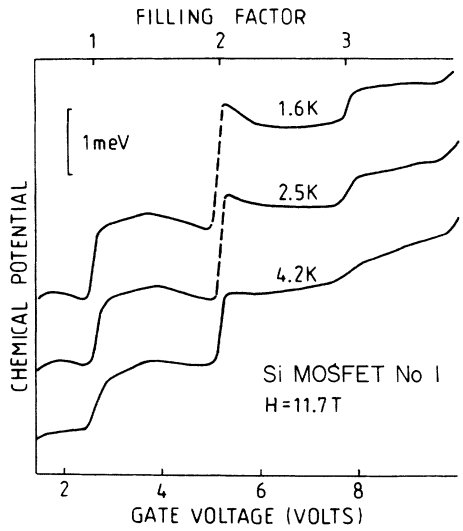

FIG. 1. The chemical potential of Si MOSFET no. 1 as a function of $V_g\propto\nu$ at three temperatures. The curves are shifted vertically for clarity.

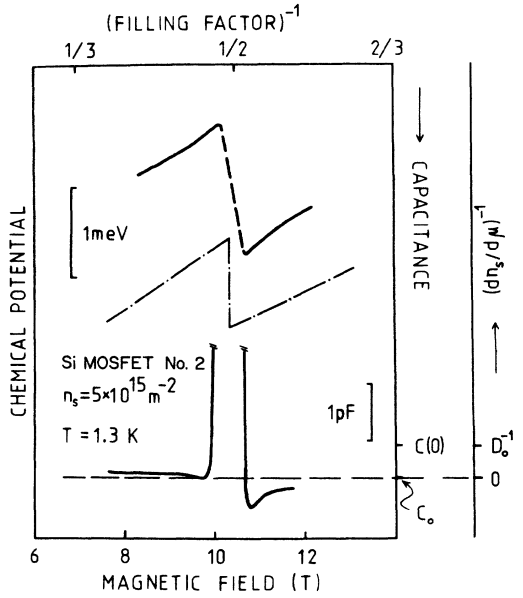

FIG. 2. The chemical potential (upper curve) and the magnetocapacitance (lower curve) as functions of $H \propto \nu^{-1}$. The dotted-dashed curve shows the calculated $\mu(H)$ dependence for a noninteracting gas at $T=0$ K and in the absence of disorder. The horizontal dashed line corresponds to the zero value of $(\partial n_s/\partial\mu)^{-1}$; C_0 is the capacitance at $\partial n_s/\partial\mu \to \infty$.

noninteracting 2D electrons at $T=0$ and in the absence of disorder (see next section). One can see that at $\nu<2$ the slope of the measured $\mu(H)$ dependence is nearly twice the maximum slope for the noninteracting gas. Capacitance measurements show that just at this region of ν the density of states becomes negative (lower curve in Fig. 2). At $2<\nu<3$, where $(\partial n_s/\partial\mu)^{-1}$ is close to zero, the measured slope is nearly equal to the calculated maximum one. In addition, the energy splitting at $\nu=2$ calculated for a noninteracting gas is considerably lower than the measured one, as has been observed previously.[11]

In closing this section it is worth mentioning that the unexpectedly high slope of the $\mu(H)$ dependence was also noticed in Ref. 12 for a 2D electron gas in the $GaAs/Al_xGa_{1-x}As$ heterostructure. However, the effect was not explained in that paper.

IV. DISCUSSION

In a high magnetic field the electron-energy spectrum in a 2D system is completely quantized, and the positions of energy levels in Si inversion layers at $T=0$ K and in the absence of scatterers and of the *e-e* interaction can be represented by the expression

$$E_i^0=\hbar\omega_c(\tfrac{1}{2}+N)\pm\tfrac{1}{2}g^*\mu_B H\pm\tfrac{1}{2}\Delta_v \ . \tag{5}$$

Here, $\omega_c=eH/m^*c$ is the cyclotron frequency, N is the Landau quantum number, g^* is the g factor assumed to be 2, $\mu_B=e\hbar/2m_e c$, and Δ_v is the valley splitting. In choosing a value of Δ_v, one could use the results of Ref. 13, according to which Δ_v would be less than 0.15 meV in the range of n_s and H considered here. On the other hand, experimental results[4] indicate that Δ_v is at least 0.2 meV and does not depend on n_s. We shall take $\Delta_v=0.2$ meV for further calculations and assume, for simplicity, Δ_v to be independent of H. The maximum value of $\partial\mu/\partial H$ for a noninteracting-electron gas is therefore approximately equal to

$$\left(\frac{\partial\mu}{\partial H}\right)_{\max} \simeq \frac{e\hbar}{m^*c}(\tfrac{1}{2}+N)\pm\tfrac{1}{2}g^*\mu_B \ , \tag{6}$$

where + and − correspond to antiparallel and parallel spin directions, respectively.

As mentioned above, the *e-e* interaction lowers μ. According to the results of Ref. 14, the energy of interacting electrons (per area) on the positive background is nearly equal to

$$E_{e\text{-}e}=-\frac{\alpha e^2}{2\pi\epsilon l_H^3}\{\nu\}^{3/2} \ , \tag{7}$$

where α is a positive dimensionless constant equal to

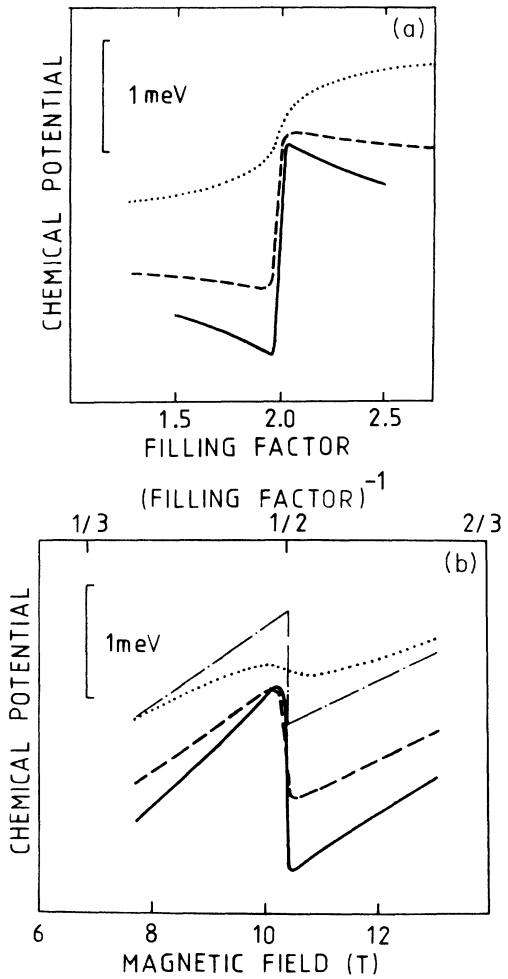

FIG. 3. (a) $\mu(\nu)$ dependences calculated for $\alpha=0$ (dotted curve), $\alpha=0.04$ (dashed curve), and $\alpha=0.06$ (solid curve); $T=1.5$ K, $\Gamma=0.1$ meV, $H=12$ T. (b) $\mu(H)$ calculated for $\alpha=0$ (dotted curve), $\alpha=0.04$ (dashed curve), and $\alpha=0.06$ (solid curve); $T=1.5$ K, $\Gamma=0.1$ meV, $n_s=5\times10^{15}$ m^{-2}. The dotted-dashed curve corresponds to $\alpha=0$, $\Gamma=0$, $T=0$ K.

0.782 for the classical interaction. To take account of the influence of scatterers, one can use the conventional Gaussian formula[5] for the one-particle density of states:

$$D_{1p}(E)=\frac{1}{2\pi l_H^2}\left[\frac{2}{\pi}\right]^{1/2}\Gamma^{-1}\exp\left[-2\frac{E^2}{\Gamma^2}\right]. \quad (8)$$

Here, Γ is the level broadening assumed, for simplicity, to be independent of ν, and E is the energy measured from the level center. For the estimates of Γ, we used results from Ref. 4 for Si MOSFET's with similar mobilities and have chosen Γ to be 0.1 meV. Taking into account the electron-hole symmetry, we calculated dependences $\mu(n_s)$ and $\mu(H)$ for different α. The results are represented in Figs. 3(a) and 3(b) by the dotted, dashed, and solid curves; the dotted-dashed curve in Fig. 3(b) shows the $\mu(H)$ dependence for $\alpha=\Gamma=T=0$. The regions of filling where $(\partial n_s/\partial\mu)^{-1}<0$ and $\partial\mu/\partial H>(\partial\mu/\partial H)_{\max}$ arise at $\alpha>0.035$. Approximate quantitative agreement between calculated and measured features of the chemical potential can be obtained by taking the parameter α to be 0.04–0.06, i.e., 10–20 times smaller than that calculated in Ref. 14.

In conclusion, we have found experimentally that at sufficiently low temperatures and in high magnetic fields filling-factor regions occur where the chemical potential of a two-dimensional electron gas diminishes with increasing carrier density, and the derivative $\partial\mu/\partial H$ is considerably higher than the maximum one for a noninteracting 2D electron gas. These results can be explained by the interactions between electrons. The estimated energy of the *e-e* interaction in Si inversion layers appears to be an order of magnitude less than the calculated classical interaction energy. To understand this lowering of interaction energy, novel experimental and theoretical studies are recommended.

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