Spin Degree of Freedom in a Two-Dimensional Electron Liquid

Tohru Okamoto,[1] Kunio Hosoya,[1] Shinji Kawaji,[1] and Atsuo Yagi[2]
[1]*Department of Physics, Gakushuin University, Mejiro, Toshima-ku, Tokyo 171-8588, Japan*
[2]*NPC, Ltd., Shiobara-cho, Tochigi 329-2811, Japan*
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We have investigated correlation between spin polarization and magnetotransport in a high mobility silicon inversion layer which shows the metal-insulator transition. Increase in the resistivity in a parallel magnetic field reaches saturation at the critical field for the full polarization evaluated from an analysis of low-field Shubnikov–de Haas oscillations. By rotating the sample at various total strength of the magnetic field, we found that the normal component of the magnetic field at minima in the diagonal resistivity increases linearly with the concentration of "spin-up" electrons. [S0031-9007(99)09119-X]

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A metal-insulator transition (MIT) observed in Si metal-oxide-semiconductor field-effect transistors [1,2] (Si-MOSFET's) and other systems [3–6] attracts a great deal of attention since it seems to contradict an important result of the scaling theory by Abrahams *et al.* [7] that the conductance of a disordered two-dimensional (2D) system at zero magnetic field goes to zero for $T \rightarrow 0$. In the metallic phase in Si-MOSFET's with high peak electron mobilities of $\mu_{\mathrm{peak}} \gtrsim 2\ \mathrm{m}^2/\mathrm{V\,s}$, the diagonal resistivity ρ_{xx} shows a sharp drop with decreasing temperature from about 2 K [1]. Recent experiments [8,9] show that magnetic fields applied parallel to the 2D plane suppress the low temperature metallic conduction in Si-MOSFET's. Since the parallel magnetic field does not couple the orbital motion of electrons, this fact suggests an important role of the spin of electrons. However, the mechanism of the conduction in the anomalous metallic phase is not clear yet.

The 2D systems that show the MIT [1–6] are characterized by strong Coulomb interaction between electrons. The mean Coulomb energy per electron $U = (\pi N_s)^{1/2} e^2/4\pi\varepsilon_0\kappa$ is larger than the mean kinetic energy $K = \pi\hbar^2 N_s/m^*$ by an order of the magnitude around the critical point for the MIT. Here, N_s is the electron concentration, κ is the relative dielectric constant at the interface, and m^* is the effective mass of electron. It is estimated that $U = 120$ K, $K = 14$ K, and the ratio $r_s = U/K = 8.3$ for $\kappa = 7.7$ and $m^* = 0.19 m_e$ at $N_s = 1 \times 10^{15}\ \mathrm{m}^{-2}$ in Si-MOSFET's. The ground state of the insulating phase of high mobility Si-MOSFET's is considered to be a pinned Wigner solid (WS) [10,11]. Magnetic field dependence of the thermal activation energy observed for various angles of the magnetic field was essentially explained by a model based on magnetic interactions in the pinned WS [12,13]. Although the quantum fluctuations change the 2D system into a liquid at higher N_s, electron-electron (*e-e*) interaction is expected to be still important.

In the conduction band of silicon, the spin-orbit interaction is negligible and the spin polarization $p = (N_\uparrow - N_\downarrow)/N_s$ can always be given in the direction to the magnetic field. Here $N_\uparrow$ and $N_\downarrow$ are the concentrations of electrons having an up spin and a down spin, respectively ($N_s = N_\uparrow + N_\downarrow$). In the present work, we investigate the low temperature conduction in a high mobility Si-MOSFET for various values of p.

The Si-MOSFET sample used has a peak electron mobility of $\mu_{\mathrm{peak}} = 2.4\ \mathrm{m}^2/\mathrm{V\,s}$ at $N_s = 4 \times 10^{15}\ \mathrm{m}^{-2}$ and $T = 0.3$ K. It has a Hall-bar geometry of total length 3 mm and width 0.3 mm. The estimated SiO_2 layer thickness is 98 nm. The diagonal resistivity ρ_{xx} as well as the Hall resistivity ρ_{xy} were obtained from the linear relationship in the *I-V* characteristics using a four-probe dc method. The source-drain current and the potential difference across the two potential probes separated by 1.5 mm were limited below 10 nA and 0.4 mV, respectively. The sample was mounted on a rotatory thermal stage in a dilution refrigerator together with a GaAs Hall generator and a RuO_2 resistance thermometer calibrated in magnetic fields [13].

As shown in Fig. 1, the MIT is clearly observed in a zero magnetic field. The critical value of ρ_{xx} at the MIT is 55 kΩ. It is close to $\rho_c \sim 2h/e^2$ reported by Kravchenko *et al.* [1]. A high magnetic field of 9 T parallel to the 2D plane drastically increases ρ_{xx} and eliminates the positive temperature dependence even in the low-ρ_{xx} region [14]. The disappearance of the MIT due to the parallel magnetic field seems to resemble that induced by increasing disorder reported by Popović *et al.* [2].

In noninteracting degenerate 2D Fermi gases, the spin polarization p increases linearly with the total strength B_{tot} of the magnetic field for $p < 1$ and reaches $p = 1$ at the critical magnetic field of $B_c = 2\pi\hbar^2 N_s/\mu_B g_v g^* m^*$. Here, μ_B is the Bohr magneton ($=\hbar e/2m_e$). The valley degeneracy g_v is 2 on the (001) surface of silicon and the effective g factor g^* is 2.0 in the conduction band in silicon [15]. According to Landau's Fermi liquid theory, the *e-e* interaction changes the effective g factor and mass of electrons (or quasiparticles) into enhanced values denoted by g_{FL} and m_{FL}, and reduces the critical magnetic field.

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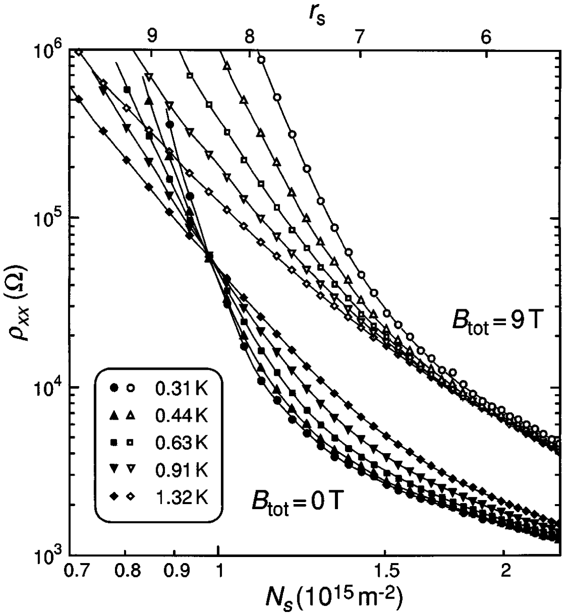

FIG. 1. Diagonal resistivity as a function of electron concentration for different temperatures in a zero magnetic field (closed symbols) and in a parallel magnetic field of 9 T (open symbols).

The product of g_{FL} and m_{FL} in (001) Si-MOSFET's can be determined from the Shubnikov–de Haas oscillations in tilted magnetic fields [16]. Figure 2 shows the diagonal conductivity $\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2)$ divided by eN_s for various angles of the magnetic field to the 2D plane. The normal component $B_\perp$ of the magnetic field is fixed at 0.80 T. The upper abscissa is given by a half of the Landau level filling factor $\nu = N_s\phi_0/B_\perp$ ($\phi_0 = h/e$) taking into account the valley degeneracy $g_v = 2$. We ignore the valley splitting energy since no indication is observed at ν = odd. For $B_{tot} = 0.80$ T, σ_{xx}/eN_s takes minima at even numbers of $\nu/2$ where the Fermi energy is located at the middle of a gap between Landau levels having different Landau quantum numbers and spin indexes. This energy gap $\Delta E_{even} = \hbar eB_\perp/m_{FL} - g_{FL}\mu_B B_{tot}$ decreases with B_{tot}, and the minima in σ_{xx}/eN_s at even numbers of $\nu/2$ fade away at higher B_{tot} due to the level broadening. On the other hand, the spin splitting $\Delta E_{odd} = g_{FL}\mu_B B_{tot}$ increases with B_{tot} and the minima in σ_{xx}/eN_s at odd numbers of $\nu/2$ become clearer. We have evaluated the critical angle θ_c of the magnetic field to the 2D plane where ΔE_{odd} becomes equal to ΔE_{even} from comparing the depth of the minimum in σ_{xx}/eN_s at an odd-number of $\nu/2$ with the average of those at $\nu/2 - 1$ and $\nu/2 + 1$ for various values of B_{tot}. We assumed that the level broadening is a smooth function or independent of ν. Thus we have $g_{FL}m_{FL} = m_e B_\perp/B_{tot} = m_e \sin\theta_c$.

In Fig. 3, we show the ratio of $g_{FL}m_{FL}$ to g^*m^* in the noninteracting system. The enhancement factor $\alpha = g_{FL}m_{FL}/0.38m_e$ increases monotonically with the strength of the e-e interaction. Results on much lower mobility samples measured in higher magnetic fields by Fang and Stiles [16] are also plotted. No $B_\perp$ dependence is found between our results at 0.8 and at 1.2 T. We believe that these values of $B_\perp$ are small enough and $g_{FL}m_{FL}$ was determined in the limit of $B_\perp = 0$. While $B_\perp$ may cause a small oscillation of the effective g factor with the maxima g_{FL}^{max} at $\nu/2$ = odd and the minima g_{FL}^{min} at $\nu/2$ = even [17], $g_{FL}m_{FL}$ determined from the critical angle for $\Delta E_{odd} = \Delta E_{even}$ is related to the average of g_{FL}^{max} and g_{FL}^{min}. The present method cannot be used in the large-r_s region where $g_{FL}m_{FL}/m_e$ exceeds unity ($\alpha > 2.63$). We use a simple extrapolation function

$$\alpha - 1 = 0.2212 r_s + 0.003\,973 r_s^2 \qquad (1)$$

represented by the solid line in Fig. 3. The critical

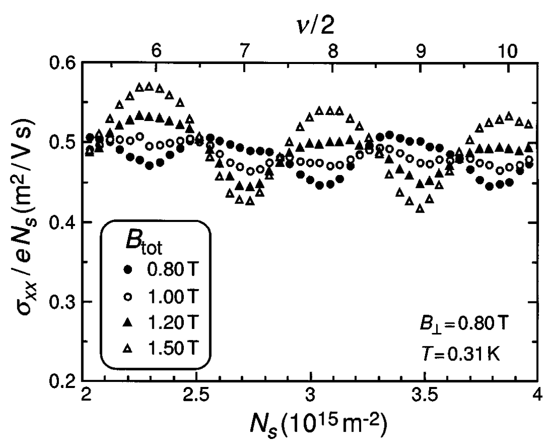

FIG. 2. Shubnikov–de Haas oscillations at $B_\perp = 0.80$ T and $T = 0.31$ K for various B_{tot}.

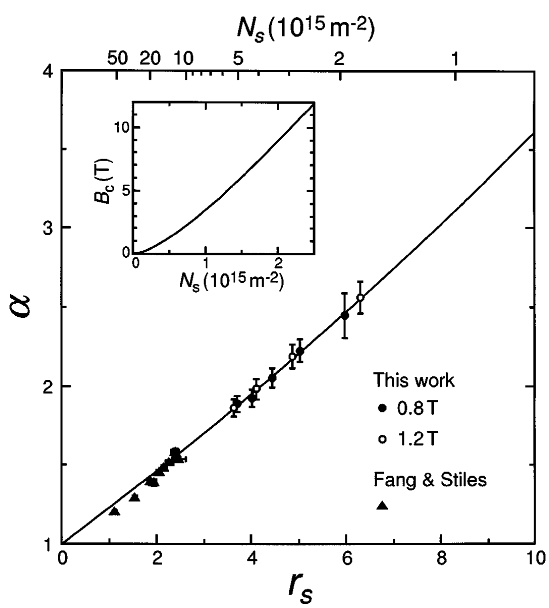

FIG. 3. The enhancement factor $\alpha = g_{FL}m_{FL}/0.38m_e$ vs the strength of the electron-electron interaction. The inset shows the critical magnetic field B_c calculated using Eq. (1).

magnetic field $B_c = 2\pi\hbar^2 N_s/\mu_B g_v g_{\rm FL} m_{\rm FL}$ is calculated using (1) as shown in the inset to Fig. 3.

In Fig. 4, ρ_{xx} at $T = 0.21$ K in the parallel magnetic field ($B_\perp = 0$) is shown. The diagonal resistivity ρ_{xx} increases with $B_{\rm tot}$ in the low-$B_{\rm tot}$ region, but it takes almost constant values in the high-$B_{\rm tot}$ region. The saturation of ρ_{xx} occurs around $B_{\rm tot} = B_c$ at which the spin polarization is expected to be completed. The result indicates that the mixing of the different spin states causes the reduction of ρ_{xx} in the low-$B_{\rm tot}$ region. The dashed line represents the critical value of ρ_{xx} at the MIT. It was tentatively determined from the sign of the change in ρ_{xx} from $T = 0.21$ to 0.91 K. The positive temperature dependence of ρ_{xx} below 1 K was not observed for $B_{\rm tot} > B_c$. The positive T dependence of ρ_{xx} in the low-$B_{\rm tot}$ region may arise from the scattering related to the spin degree of freedom.

The most important finding has been obtained by rotating the sample in the magnetic field. Results at $N_s = 1.46 \times 10^{15}$ m^{-2} are shown in Fig. 5. We focus on the ρ_{xx} oscillation that appears in the low-$B_\perp$ region, while the $\rho_{xx}(B_\perp)$ curves for different $B_{\rm tot}$ approach each other in the higher-$B_\perp$ region (not shown in Fig. 5) and converge on a single curve for $B_\perp/N_s\phi_0 > 0.5$ with two deep minima at $B_\perp/N_s\phi_0 = 0.5$ ($\nu = 2$) and $B_\perp/N_s\phi_0 = 1.0$ ($\nu = 1$) as reported by Kravchenko *et al.* [18]. Unlike ordinary Shubnikov–de Haas oscillations that show ρ_{xx} minima at fixed points with $\nu =$ integer, the ρ_{xx} minima indicated by the black arrows and the white arrows in Fig. 5 shift toward the high-$B_\perp$ side as $B_{\rm tot}$ increases. Such peculiar behavior was also observed for lower N_s down to 1.02×10^{15} m^{-2}.

In Fig. 6, the positions of the ρ_{xx} minima for various N_s are shown. Both $B_\perp$ and $B_{\rm tot}$ are normalized by $N_s\phi_0$ and B_c, respectively. The closed (open) symbols correspond to the black (white) arrows in Fig. 5. The value of $B_\perp/N_s\phi_0$ increases linearly with $B_{\rm tot}/B_c$ for $B_{\rm tot}/B_c < 1$, but saturates for $B_{\rm tot}/B_c > 1$ where the spin polarization is expected to be completed. We link this behavior to the concentration $N_\uparrow$ of electrons having an up spin. Assuming that a change in p by $B_\perp$ is negligible in the low-$B_\perp$ region, we have $N_\uparrow/N_s = (1 + B_{\rm tot}/B_c)/2$ for $B_{\rm tot}/B_c < 1$ and $N_\uparrow/N_s = 1$ for $B_{\rm tot}/B_c > 1$. All the data are distributed along the solid line or the dashed line on which the number of the flux quantum per "spin-up" electron takes a constant value of $B_\perp/N_\uparrow\phi_0 = 0.265$ or 0.172.

One may attribute the observed ρ_{xx} minima to the Shubnikov–de Haas oscillation produced by spin-up electrons. Actually, the effective Landau level filling factor of spin-up electrons $N_\uparrow\phi_0/B_\perp$ at the ρ_{xx} minima is close to an even number of 4 or 6. Note that we have the valley degeneracy $g_v = 2$ in this system. It is expected that ρ_{xx} also takes minima at even numbers of the effective Landau level filling factor of spin-down electrons. However, we observed no feature even for $N_\downarrow\phi_0/B_\perp = 2$ represented by the dotted line in Fig. 6. The disappearance of ρ_{xx} minima related to spin-down electrons implies that spin-down electrons do not contribute to the conduction owing to localization or large scattering rate. If that is the case, one should accept an unusual negative dependence of the mobility of spin-up electrons on the carrier concentration $N_\uparrow$ since the value of ρ_{xx} steeply increases with the spin polarization. The ρ_{xx} minimum at $B_\perp/N_\uparrow\phi_0 \approx 0.265$ appears even in the

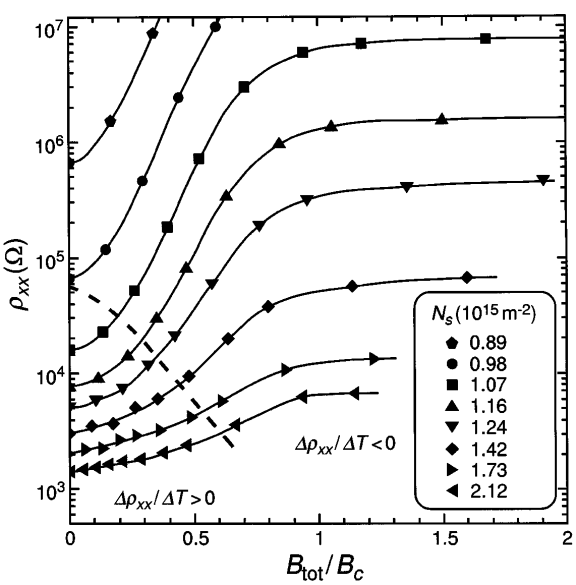

FIG. 4. Resistivity vs $B_{\rm tot}/B_c$ at $T = 0.21$ K and $B_\perp = 0$ for various N_s. The dashed line represents the critical value of ρ_{xx} at the MIT determined from temperature dependence between 0.21 and 0.91 K.

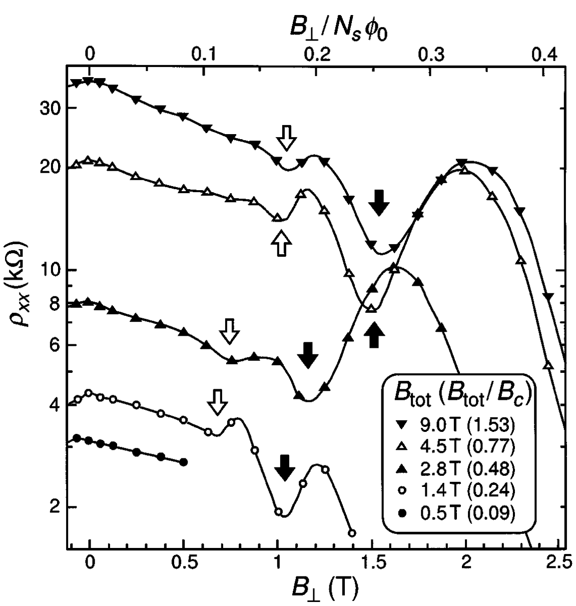

FIG. 5. Diagonal resistivity vs normal component of the magnetic field at $T = 0.31$ K and $N_s = 1.46 \times 10^{15}$ m^{-2} for several values of $B_{\rm tot}$.

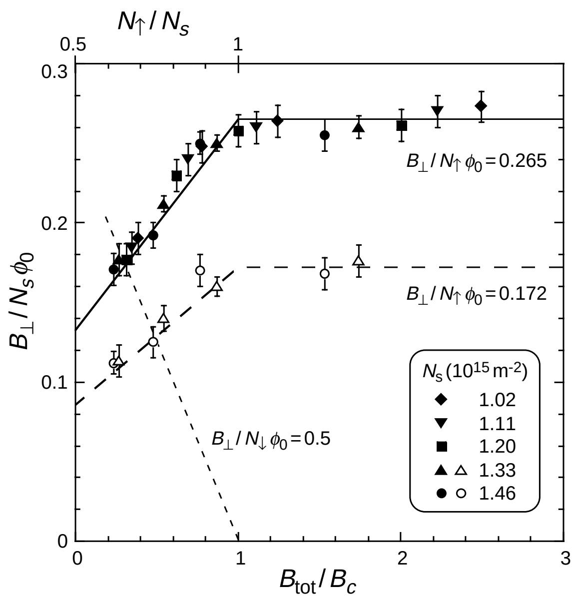

FIG. 6. Positions of the ρ_{xx} minima for various N_s are plotted. The solid and dashed lines represent $B_\perp / N_\uparrow \phi_0 = 0.265$ and $B_\perp / N_\uparrow \phi_0 = 0.172$, respectively. The dotted line represents $B_\perp / N_\downarrow \phi_0 = 0.5$.

insulating region with $\rho_{xx} \sim 10^6\ \Omega$, where the Landau level separation is considered to be entirely smeared out by the level broadening. Further consideration is required to explain the results consistently.

Finally, we also propose a quite different interpretation of the ρ_{xx} minima. In previous work [12,13], we investigated the activation energy in the insulating phase which depends on $B_\perp$ and $B_{\rm tot}$. Oscillatory behavior linked with $B_\perp / N_s \phi_0$ was explained using a model based on the Aharonov-Bohm effect on the exchange of electrons localized in the pinned Wigner solid [19]. This model may be partly applied to the present case if one assumes that spin-up electrons are localized and form an ordered state in the real space like a Wigner solid. Then, the $B_{\rm tot}$ dependence of ρ_{xx} can be understood as a result of the change in the concentration of spin-down electrons which carry the charge. While we at this stage do not identify the origin of the ρ_{xx} minima specifically, we consider that the effect of the magnetic flux on the system of spin-up electrons can cause an oscillatory perturbation in the mobility of spin-down electrons through some interactions.

In summary, we have studied the magnetotransport in a high mobility Si-MOSFET at electron concentrations around the MIT. The relationship between the resistivity and the spin polarization indicates that the mixing of the different spin states is important for the metallic conduction. We also found the ρ_{xx} minima in the $B_\perp$ dependence, which should be related to the concentration of "spin-up" electrons.

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