Magnetoresistance and spin polarization in the insulating regime of a Si two-dimensional electron system

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We have studied the magnetoresistance in a high-mobility Si inversion layer down to low electron concentrations at which the longitudinal resistivity ρ_{xx} has an activated temperature dependence. The angle of the magnetic field was controlled so as to study the orbital effect proportional to the perpendicular component $B_\perp$ for various total strengths B_{tot}. A dip in ρ_{xx}, which corresponds to the Landau level filling factor of $\nu=4$, survives even for high resistivity of $\rho_{xx}\sim 10^8 \Omega$ at $T=150$ mK. The linear B_{tot} dependence of the value of $B_\perp$ at the dip for low B_{tot} indicates that a ferromagnetic instability does not occur even in the far insulating regime.

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I. INTRODUCTION

There has been great attention to the fundamental properties of strongly correlated two-dimensional (2D) electron or hole systems in the last decade, due in part to the discovery of the zero-magnetic-field metal-insulator transition (MIT).[1–3] The strength of the Coulomb interaction between the carriers is characterized by the Wigner-Seitz radius r_s, which is equal to the ratio of the Coulomb energy per electron to the Fermi energy. In the Fermi liquid theory, the effective mass m^*, the effective g-factor g^*, and the spin susceptibility $\chi^* \propto g^* m^*$ are renormalized by r_s, and they are expected to be enhanced as r_s increases.[4–6] The dimensionless parameter r_s can be written as $r_s = \pi^{1/2}(e/h)^2(m_b/\kappa\varepsilon_0)N_s^{-1/2}$ and controlled by changing the electron concentration N_s, where m_b is the band mass and κ is the average dielectric constant. The enhancement of the spin susceptibility with increasing r_s (decreasing N_s) has been observed in various 2D electron systems (2DESs) formed in Si metal-oxide-semiconductor field-effect-transistors (MOSFETs),[7–9] GaAs/AlGaAs,[10] Si/SiGe,[11] and AlAs/AlGaAs (Ref. 12) heterostructures. For 2DESs without disorder, the ferromagnetic transition is expected to occur at $r_s\sim 26$ before the Wigner crystallization at $r_s\sim 35$.[13] Recently, the divergence of χ^* at or near the MIT with $r_s\sim 9$ has been reported for Si-MOSFETs,[14,15] while the results in Refs. 9 and 16 do not support the occurrence of a ferromagnetic instability at the MIT. Another 2D Fermi liquid system, ^{3}He absorbed on graphite, also shows a tendency for χ^* to diverge as the system goes into localization.[17,18]

A possible ground state in the insulating regime of high-mobility Si-MOSFETs is a pinned Wigner crystal (WC) or glass. Pudalov *et al.* observed nonlinear dc conduction with a sharp threshold electric field in the insulating regime of Si-MOSFETs and attributed it to that of a pinned WC,[19] while it was also discussed in terms of the single particle localization picture taking into account a Coulomb gap.[20,21] Chui and Tanatar found from their Monte Carlo studies that the WC can be stabilized at r_s as low as 7.5 in the presence of a very small amount of disorder in the oxide layer.[22,23] In the WC at rather low r_s, exchanges among neighboring electrons are expected to occur frequently. The amplitudes of several types of ring exchanges in Si-MOSFETs were calculated[24,25] to be in the order of 0.1 K at $r_s\sim 8$ using the WKB method developed by Roger.[26] The strength of the ferromagnetic interaction, which arises from exchanges of an odd number of particles, is comparable to that of the antiferromagnetic interaction from exchanges of an even number of particles.[25] Furthermore, the valley degree of freedom in Si inversion layers makes the system more complicated.[27] It seems hard to predict theoretically the magnetic ground state of the WC in Si 2DESs.

In this work, we have performed systematic measurements of magnetoresistance of a high-mobility Si-MOSFET in order to study the electronic and spin states in the insulating regime. The perpendicular component $B_\perp$ of the magnetic field was controlled by rotating the sample for various total strengths B_{tot} so as to investigate the orbital effect independently of the Zeeman effect. We observed that a dip in the longitudinal resistivity ρ_{xx}, which corresponds to the Landau level filling factor of $\nu=4$, remains even in the far insulating regime where the Landau levels are expected to be smeared out. The value of $B_\perp$ at the dip shows a linear B_{tot} dependence in the low B_{tot} region below a kink indicating the onset of the full spin polarization. The results strongly suggest that a ferromagnetic instability does not occur in the insulating regime.

II. SAMPLE AND EXPERIMENTAL METHOD

We used a (001)-oriented Si-MOSFET sample with a peak electron mobility $\mu_{peak}=2.4$ m^2/V s at $N_s=4\times 10^{15}$ 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. Standard dc four-probe techniques were used to measure ρ_{xx} and the Hall resistivity ρ_{xy}. The potential probes were separated by 1.5 mm and the excitation voltage had been kept 0.4 mV to ensure that measurements were taken in the *I*-*V* linear regime. The electron concentration N_s was controlled by varying the gate voltage and determined from the Hall coefficient measured at $T=3$ K. The MIT is observed at the critical electron concentration $N_c=0.97\times 10^{15}$ m^{-2} in the absence of the magnetic field. It is estimated that $r_s=8.4$ at $N_s=N_c$ with $m_b=0.19m_0$ and $\kappa=7.7$.[28]

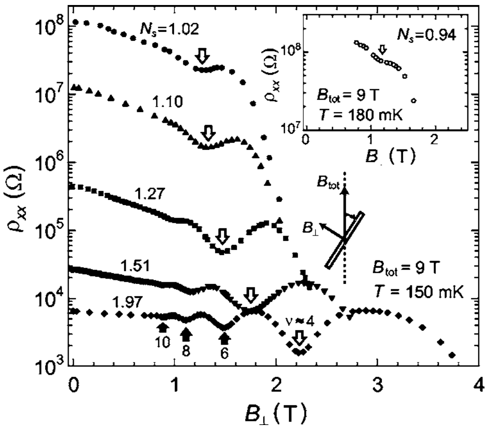

FIG. 1. Longitudinal resistivity as a function of $B_\perp$ at B_{tot} =9 T and T=150 mK for various N_s indicated in units of 10^{15} m^{-2}. The inset shows the data at T=180 mK for N_s=0.94 × 10^{15} m^{-2}.

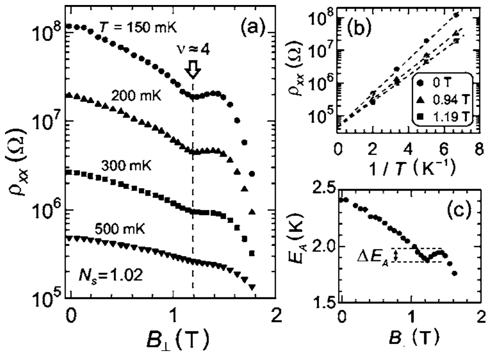

FIG. 2. Data in the insulating regime for B_{tot}=6 T and N_s =1.02 × 10^{15} m^{-2}. The electron spins are expected to be fully polarized (Ref. 8). (a) $B_\perp$ dependence of ρ_{xx} for various temperatures. (b) Arrhenius plots of ρ_{xx} for $B_\perp$=0, 0.94, and 1.19 T (at the dip). (c) Activation energy as a function of $B_\perp$.

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. The rotatory thermal stage was cooled via a silver foil linked to the mixing chamber and the temperature was accurately controlled by a heater on the stage.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the $B_\perp$ dependence of the longitudinal resistivity ρ_{xx} at B_{tot}=9 T for various N_s with a wide range of ρ_{xx}. As discussed later, the electron spins are expected to be fully polarized at B_{tot}=9 T for these values of N_s.[8] For N_s =1.97 × 10^{15} m^{-2}, minima in ρ_{xx} are observed at the Landau level filling factors $\nu \approx 4$, 6, 8, and 10, which correspond to the Shubnikov-de Haas (SdH) oscillations of the spin polarized system. Note that twofold valley degeneracy remains in Si(001) inversion layers. As N_s decreases, ρ_{xx} drastically increases and the dips at $\nu \approx 6$, 8, and 10 are smeared out. It is reasonable that the SdH oscillations disappear when a dimensionless parameter $\omega_c \tau$ becomes less than unity. Here ω_c is the cyclotron frequency and τ is the cyclotron scattering time. This condition can be rewritten as $\rho_\parallel \geqslant h/\nu e^2 (\approx \rho_{xy})$ if τ is replaced by the classical scattering time τ_c obtained from the resistivity $\rho_\parallel \equiv \rho_{xx}(B_\perp = 0)$. Measurements on low-mobility Si-MOSFETs[29] and GaAs/AlGaAs 2DESs (Ref. 30) have shown that τ is comparable or smaller than τ_c. Thus, in a simple picture, the SdH oscillations are not expected to appear for $\rho_\parallel \gtrsim 10^4 \Omega$. However, the dip at $\nu \approx 4$ remains for very high resistivity up to $\rho_{xx} \sim 10^8 \Omega$. Distinct ρ_{xx} minima at $\nu \approx$ integer in the insulating regime of high-mobility Si-MOSFETs have also been observed for $\nu \approx 1$ and 2 in perpendicular magnetic fields ($B_\perp = B_{tot}$).[31,32] It is well known that the usual SdH oscillations originate from the $B_\perp$ dependence of the density of states at the Fermi level ε_F. The longitudinal conductivity $\sigma_{xx} = \rho_{xx}/({\rho_{xx}}^2 + {\rho_{xy}}^2)$ has a minimum when ε_F lies in a gap between Landau levels. For $\rho_{xx} \ll \rho_{xy}$, a minimum in σ_{xx} leads to a minimum in ρ_{xx}. In the insulating regime with $\rho_{xx} \gg \rho_{xy}$, on the other hand, it leads to a maximum in ρ_{xx}, which is contrary to the experimental results for $\nu \approx$ integer.

Figure 2(a) shows the $B_\perp$ dependence of ρ_{xx} in the insulating regime for various temperatures. ρ_{xx} decreases drastically with increasing temperature even for the minimum at $\nu \approx 4$ while ρ_{xx} increases with T for minima in the usual SdH oscillations.[9] While the dip at $\nu \approx 4$ in Fig. 2(a) is gradually smeared out as T increases, the position of the dip does not depend on T. Figure 2(b) shows Arrhenius plots of ρ_{xx} for different $B_\perp$. The dashed lines are least-square fits to the experimental data and represent $\rho_{xx} = \rho_0 \exp(E_A/2T)$.[33] The $B_\perp$ dependence of ρ_{xx} at low temperature is attributed to a change in the activation energy E_A rather than that in the prefactor ρ_0. The obtained E_A is shown in Fig. 2(c) as a function of $B_\perp$. In the low $B_\perp$ region, E_A decreases almost linearly with increasing $B_\perp$. This might be associated with the delocalization effect of the magnetic field in the strongly localized regime. E_A shows a dip at $\nu \approx 4$. Although it might be a trace of the Landau level formation, the depth of the dip of $\Delta E_A \sim 0.1$ K is much smaller than the Landau level spacing of $\hbar\omega_c$=8.5 K at $B_\perp$=1.2 T expected from the band mass of m_b=0.19m_0. At this stage, the origin of ρ_{xx} or E_A minima at $\nu \approx$ integer observed in the insulating regime is not understood. We have investigated $B_\perp$ dependence of ρ_{xx} also for other 2D systems with high resistivity of $\rho_{xx} \gtrsim 10^6 \Omega$ at low temperatures down to 100 mK.[34] Dips at $\nu \approx 1$ and 2 are observed for GaAs hole systems with $r_s \approx 10$, while an insulating GaAs electron system with small $r_s (\approx 3)$ only shows a broad minimum resulting from negative magnetoresistance at low $B_\perp$ and positive one at high $B_\perp$ owing to the shrinkage of the electron wave function. Such $B_\perp$ dependence of ρ_{xx} in a GaAs 2DES was also observed in Fig. 2 of Ref. 35. The collective motion of electrons might cause the dips in ρ_{xx} at $\nu \approx$ integer observed in the insulating regime of the strongly correlated 2D systems.

The values of $B_\perp$ at ρ_{xx} minima depend on B_{tot}. Typical data in the low resistivity region are shown in Fig. 3(a). The positions of the ρ_{xx} minima at $\nu \approx 4$ and 6 in the SdH oscillations shift toward low-$B_\perp$ side as B_{tot} decreases. This can be explained as the result of a decrease in the fraction of "spin-up" electrons.[8,11,36–38] Similar behavior is observed in the insulating regime. In Figs. 3(b) and 3(c), the data for N_s=1.02 and 0.94 × 10^{15} m^{-2} are shown, respectively. The

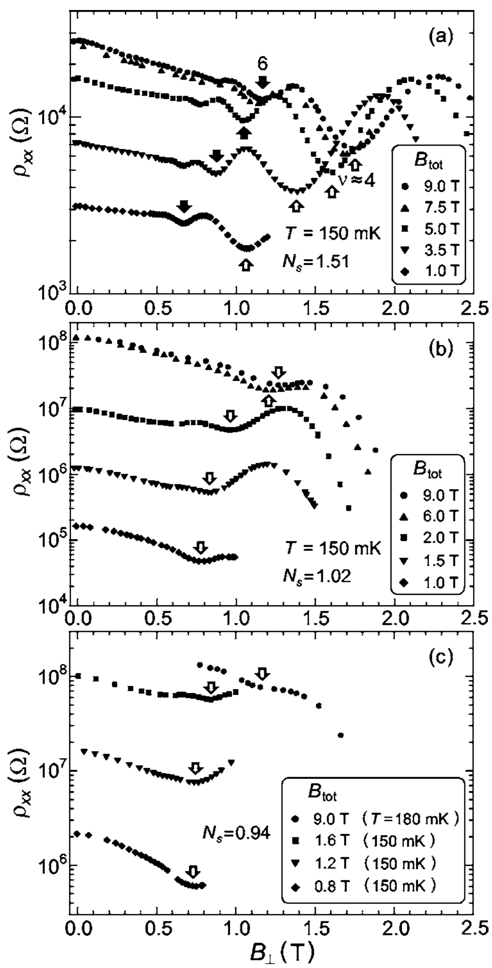

FIG. 3. $B_\perp$ dependence of ρ_{xx} for various B_{tot}. (a) Data in the low resistivity region with $N_s=1.51\times10^{15}$ m^{-2}. (b), (c) Data in the higher resistivity region with $N_s=1.02$ and 0.94×10^{15} m^{-2}, respectively.

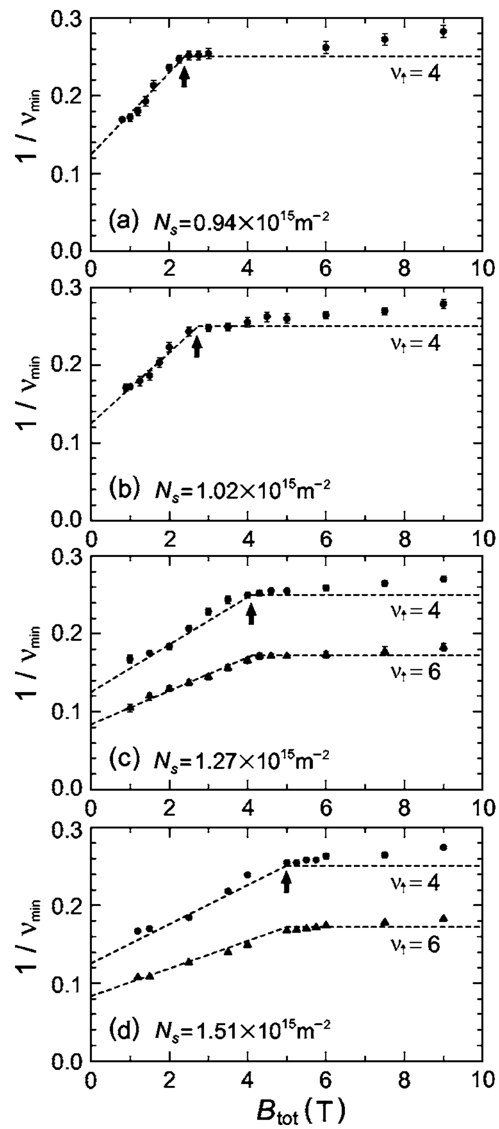

FIG. 4. Position of ρ_{xx} minima $1/\nu_{min}=eB_\perp/hN_s$. Data for (a) $N_s=0.94\times10^{15}$ m^{-2}, (b) 1.02×10^{15} m^{-2}, (c) 1.27×10^{15} m^{-2}, and (d) 1.51×10^{15} m^{-2} are shown. The arrows indicate B_c. The dotted lines represent $\nu_\uparrow=4$ or 6 (see text).

dip at $\nu\approx4$ shifts toward low-$B_\perp$ side as B_{tot} decreases. In Fig. 4, the positions of the ρ_{xx} minima determined taking into account the negatively $B_\perp$-dependent baseline are shown as $1/\nu_{min}=eB_\perp/hN_s$ for different N_s. Overall behavior for low N_s is similar to that for high N_s, i.e., $1/\nu_{min}$ increases almost linearly with B_{tot} before B_{tot} exceeds a critical value B_c indicated by arrows. We consider that B_c corresponds to the onset of the full spin polarization of 2D electrons. The dotted lines represent $\nu_\uparrow=4$ or 6 assuming that the spin polarization $P=2N_\uparrow/N_s-1$ increases linearly with B_{tot} for $B_{tot}\leqslant B_c$. Here $\nu_\uparrow$ and $N_\uparrow$ are the Landau level filling factor and the concentration of spin-up electrons, respectively ($\nu_\uparrow=hN_\uparrow/eB_\perp$). The SdH oscillations depending on $\nu_\uparrow$ are also observed in a Si/SiGe sample with much lower resistivity.[11] Although the reason for the survival of the dip in the far insulating regime is unclear, the dotted line for $\nu_\uparrow=4$ well reproduces the experimental results for $B_{tot}\leqslant B_c$. The B_{tot}-dependent behavior for $B_{tot}\leqslant B_c$ strongly suggests that the spin polarization is not completed and a ferromagnetic instability does not occur.

A gradual increase in $1/\nu_{min}$ with B_{tot} is observed above B_c for which the spin polarization is expected to be completed. Similar behavior is found for ρ_{xx} minima at $\nu\approx1$ and 2 in the insulating regime as shown in Fig. 5. We estimate that the change in N_s due to the B-dependent shift of the chemical potential of the 2DES for a fixed gate voltage is negligible (in the order of $10^{-3}N_s$). It seems possible that spin-down electrons occupy deep levels due to impurity potentials even at $B_{tot}=B_c$ and are gradually released into nontrapped states with an up-spin at higher magnetic fields. In the Si/SiGe sample,[11] the increase in $1/\nu_{min}$ with B_{tot} is not observed above B_c.

The critical magnetic field B_c is also obtained from a kink in a magnetoresistance curve in the in-plane magnetic field $B_\parallel$ since the $B_\parallel$ dependence of ρ_{xx} is associated with the spin polarization.[8,11,36–38] Figure 6(a) shows the data in the insulating regime. While ρ_{xx} has strong temperature dependence, the $B_\parallel$ dependence at a constant temperature shows a steep increase in the low $B_\parallel$ region and a saturation in the high $B_\parallel$ region. The critical magnetic field determined from the mag-

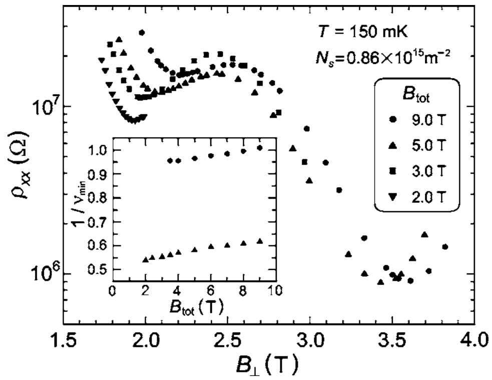

FIG. 5. $B_\perp$ dependence of ρ_{xx} at T=150 mK and N_s=0.86 $\times 10^{15}$ m^{-2} for various B_{tot}. ρ_{xx} minima at $\nu \approx 1$ and 2 are observed. The inset shows the position of the ρ_{xx} minima.

netoresistance curve is consistent with that obtained from Fig. 4 as shown later in Fig. 7. It also suggests that a ferromagnetic instability does not occur in the insulating regime. In Refs. 14 and 15, the authors claimed that B_c tends to vanish at an electron concentration close to the MIT at B =0 based on the analysis of the $B_\parallel$ dependence of ρ_{xx} obtained in the metallic side. However, the magnetoresistance in the far insulating regime was not studied.

In Fig. 6(b), we show the activation energy E_A determined from the Arrhenius temperature dependence of ρ_{xx}. If we assume E_A as an energy gap for an elementary excitation, the magnetization change due to the excitation can be obtained thermodynamically via the relation $\delta M = -\partial E_A / \partial B_\parallel$. A similar method was used for the study of the energy gap for the odd-integer quantized Hall states.[39] In our Si-MOSFET, the average distance of electrons from the Si/SiO_2 interface[28] is by one order of magnitude smaller ($\approx$3.8 nm) than the mag-

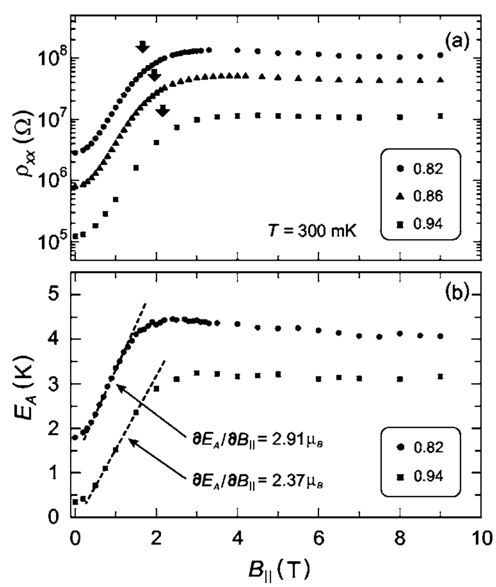

FIG. 6. (a) In-plane magnetic field dependence of ρ_{xx} for different N_s at T=300 mK. The arrows indicate B_c determined from ρ_{xx} vs $B_\parallel$ data obtained for various temperatures. (b) Activation energy determined from T dependence of ρ_{xx} for N_s=0.82 and 0.94 $\times 10^{15}$ m^{-2}.

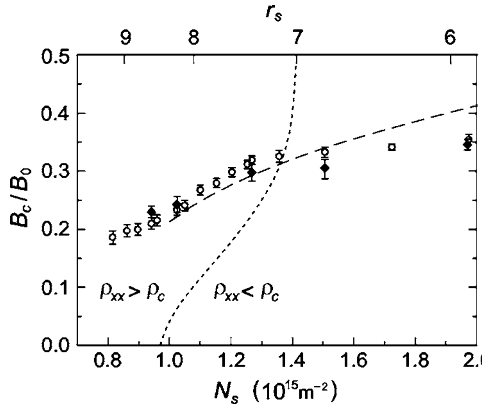

FIG. 7. B_c obtained from the B_{tot} dependence of $1/\nu_{min}$ (closed diamonds) and that from the $B_\parallel$ dependence of ρ_{xx} (open circles) are shown as a ratio to the noninteracting value B_0. The dashed curve is an estimation from the spin susceptibility obtained by Pudalov *et al.*[9] in the limit of small magnetic fields. The dotted curve represents the values of $B_\parallel/B_0$ for a tentative boundary in the $B_\parallel$-N_s plane determined from ρ_{xx} at T=150 mK. ρ_c=60 kΩ is the critical resistivity at N_s=N_c and B=0.

netic length $l_0=(\hbar/eB_\parallel)^{1/2}$ in the low $B_\parallel$ region where the steep increase in E_A is observed. Since $B_\parallel$ does not couple to the orbital motion of electrons in this case, δM should be attributed to electron spin flips. The slope $\partial E_A/\partial B_\parallel$ in the low $B_\parallel$ region is somewhat larger than $+2\mu_B$ expected from a single spin flip. Here, μ_B is the Bohr magneton and the bare g factor in silicon is close to two. The observed large $|\delta M|$ cannot be explained by a single particle picture.

Figure 7 shows B_c as a function of N_s. They are normalized by the noninteracting value $B_0=\pi\hbar^2 N_s/2\mu_B m_b$ with $m_b=0.19m_0$. If P increases linearly with B_{tot} below B_c, B_c/B_0 is equal to the inverse of the ratio of χ^* to noninteracting susceptibility χ_0. The dashed curve represents χ_0/χ^* obtained from the data by Pudalov *et al.*[9] The dotted curve represents the values of $B_\parallel/B_0$ for a tentative boundary in the $B_\parallel$-N_s plane on which ρ_{xx} at T=150 mK is equal to the critical resistivity ρ_c=60 kΩ for the MIT at B=0.[40] While the magnetic-field-induced MIT occurs in the intermediate N_s range, B_c/B_0 is in good agreement with χ_0/χ^* obtained in the metallic regime in the limit of small magnetic fields.[9] B_c/B_0 gradually decreases with decreasing N_s (increasing r_s) in the whole N_s range and the N_s dependence shows no distinct anomaly.

IV. SUMMARY

In summary, we have studied the low-temperature magnetoresistance in a high-mobility Si-MOSFET sample. Even in the far insulating regime with $\rho_{xx} \sim 10^8 \Omega$, we observed a dip in ρ_{xx} at $\nu \approx 4$ in the $B_\perp$ dependence at B_{tot}=9 T. The critical magnetic field for the onset of the full spin polarization determined from the B_{tot} dependence of the value of $B_\perp$ at the dip, which agrees with that from the magnetoresistance curve in the in-plane magnetic field, indicates that a ferromagnetic instability does not occur in the insulating regime.

It was found that $B_\perp$ dependence and $B_\parallel$ dependence of ρ_{xx} at low temperature in the far insulating regime are the results of those of the activation energy E_A in the Arrhenius temperature dependence. However, the origins of the dip in E_A at $\nu \approx$ integer and the steep increase in E_A with $B_\parallel$ for low $B_\parallel$ are not understood, while they might be associated with strong electron correlations. Further investigations are required.

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