Anomalous metallic phase and magnetism in a high-mobility and strongly correlated 2D electron system

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Abstract

We report the transport properties of a low disorder two-dimensional electron system in the Si/SiGe heterostructure, where the strong *e*-*e* interaction causes the anomalous metallic temperature dependence of resistivity. The metallic behavior was observed even in a high magnetic field where spin degree of freedom is frozen.

Key words: two-dimensional electron system; magnetoresistance; metal-insulator transition

1. Introduction

It is well accepted that the Coulomb interaction is essential to the two-dimensional metal-insulator transition (MIT) [1,2]. The spins of electrons are expected to play important roles in such strongly correlated systems. A magnetic field applied parallel to the two-dimensional (2D) plane acts on the spins of electrons. Silicon inversion layers are ideal systems for studying on the spin effect using the parallel magnetic field [3,4] since the spin-orbit interaction is very small in the conduction band of silicon [5,6]. It was found that the parallel magnetic field suppresses the metallic behavior in Si-MOSFET's [7–9]. However, whether spin degree of freedom is essential for the metal-insulator transition is not clear yet. In the present work, we investigate the magnetoresistance in a very high-mobility silicon 2D electron system.

2. Samples and Measurements

A Si/SiGe heterostructure sample was grown by combining gas-source MBE and solid-source MBE. Details of the growth and characterization have been reported elsewhere [10,11]. The thickness of the strained silicon channel layer is 20 nm. It is sandwiched between relaxed $Si_{0.8}Ge_{0.2}$ layers and separated from a Sb-δ-doped layer by a 20 nm spacer. The electron density N_s can be controlled by varying the substrate bias voltage. It has a high mobility of $\mu = 66$ m^2/V s at zero substrate bias voltage ($N_s = 2.2 \times 10^{15}$m^{-2}) and $T = 0.36$ K. We could not measure the critical electron density $N_{\rm c}$ of the MIT due to large contact resistance in a low-$N_{\rm s}$ region. It was mounted on a rotatory thermal stage in a pumped ^{3}He refrigerator together with a GaAs Hall generator and resistance thermometers calibrated in magnetic fields.

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3. Results

3.1. $B = 0$ *metallic transport*

Fig. 1 shows metallic transport at $B = 0$. Fermi temperature is given by $T_{\rm F} = 2\pi\hbar^2 N_{\rm s}/k_{\rm B} m^* g_{\rm v} g_{\rm s}$, where $m^* = 0.19 m_e$ is the effective mass and $g_{\rm v} = 2$ is the valley degeneracy factor in silicon inversion layers. The spin degeneracy factor is $g_{\rm s} = 2$ for $B = 0$ and $g_{\rm s} = 1$ for a high magnetic field region where the spin polarization is completed.

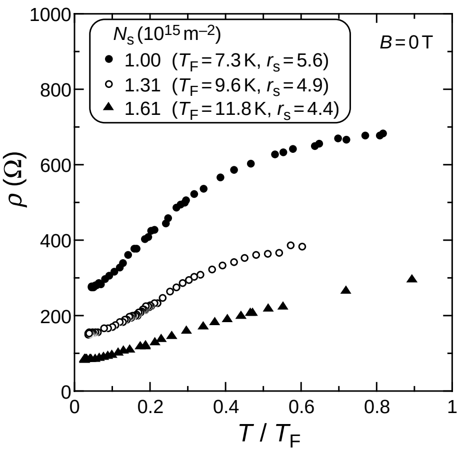

Fig. 1. Metallic temperature dependence of resistivity at $B = 0$. r_s represents the strength of the e-e interaction [9].

Das Sarma and Hwang calculated the metallic T-dependence of resistivity ρ in Si-MOSFET's based on the assumption that almost electrons are frozen due to impurities in the vicinity of the critical density N_c of the MIT and the density of free electrons responsible for the metallic transport is given by $N_s - N_c$ [12]. On the other hand, overall behavior shown in Fig. 1 is similar to that observed in Si-MOSFET's [1] while resistivities are much lower than the critical value ($\rho_c \sim 2h/e^2$) for the MIT. The result suggests that the distinct metallic T-dependence of ρ appears even for $N_s \gg N_c$.

3.2. *In a parallel magnetic field*

Magnetoresistance in a parallel magnetic field $B_{\|}$ for a low enough temperature ($T \ll T_F$) is shown in the inset to Fig. 2. The kink indicated by the arrow is associated with the critical magnetic field B_c for the spin polarization. As shown in Fig. 2, a sharp drop in ρ with decreasing temperature is observed even in the spin polarized state, while the metallic temperature dependence of ρ disappears for $B_{\|} > B_c$ in Si-MOSFET's [9]. The present result indicates that the metallic transport can appear even in the state where the spin degree of freedom is limited.

The strong $B_{\|}$-dependence of ρ due to the spin polarization was calculated by Dolgopolov and Gold [13], and Herbut [14]. They considered the screening effect on impurity potential in Si-MOSFET's and well reproduced the experimental $\rho(B_{\|})$ curve in Ref. [9]. The screening effect also explains the metallic T-dependence of ρ. A steep change in ρ should occur in the crossover regime of $T \sim T_F$ [12]. On the other hand, we found a sharp drop in ρ in rather low temperatures of $T/T_F < 0.2$ at $B_{\|} = 9$ T.

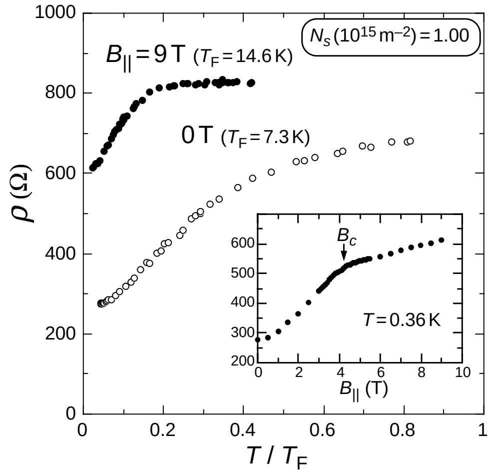

Fig. 2. ρ vs T/T_F data at $N_s = 1.00 \times 10^{15}$ m^{-2} for different magnetic states. The inset shows the $B_{\|}$-dependence of ρ at $T = 0.36$ K.

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