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Conductivity corrections in a strongly correlated and disordered two-dimensional electron system

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We have measured the resistivity ρ of a dilute two-dimensional electron gas near the (111) silicon surface as a function of a temperature. Since the valley degeneracy in such structures g_v is 6, the dimensionless radius r_s approaches 50 at electron densities significantly larger than in previously studied (100)Si or p-AlGaAs/GaAs systems. We have observed a nonmonotonical behavior of $\rho(T)$, the resistivity slowly decreasing with the temperature decreasing for temperatures above $T\approx 1$ K and increasing at lower temperatures for electron densities corresponding to $\rho\sim h/e^2$, when the metal-insulator transition is expected. Such nonmonotonic behavior can be tentatively described by corrections to the conductivity due to electron-electron interaction with negative Fermi-liquid constant $F_0^\sigma\approx -0.25$.

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The nature of the ground state of a strongly correlated and disordered electron system continues to be an object of active study and speculation. Recently this interest has been further heightened by the observation of an anomalous temperature dependence of the conductivity in high mobility (100)Si metal-oxide-semiconductor field-effect transistors (MOSFET's).[1] In this system the conductivity grows by several times with the temperature decreasing under the condition of $E_F \gg kT$ and a practically total absence of the phonon scattering. However, the conductivity is expected to decrease with the temperature decreasing, becoming zero at $T=0$, in accordance with the prediction for systems with noninteracting particles.[2] The anomalous behavior of the conductivity observed in Ref. 1 is accompanied by a large value of the dimensionless radius r_s which is equal to the ratio of the Coulomb and the Fermi energies. The interaction strength can be characterized by the Fermi-liquid constant F_0^σ. Large interaction may drive the system close to the Fermi-liquid instabilities (superconductivity, superfluidity, ferromagnetism, etc.). For example, if $F_0^\sigma\approx -1$, the spin-exchange interaction leads to the ferromagnetic Stoner instability. Explicit expression of the parameter F_0^σ in terms of r_s is not possible. However, the Fermi-liquid constant can be derived from the comparison of some effective renormalized parameters (Pauli spin susceptibility) with phenomenological theory. Therefore the anomalous temperature dependence of the conductivity observed in Si MOSFETs,[1] and in various low-density two-dimensional systems,[3] has been tentatively ascribed to the precursor of the Fermi-liquid instability.[4,5] An alternative viewpoint is that the corrections to the conductivity due to the electron-electron interaction can be extended to the regime of a moderately large r_s within the assumption of the Fermi-liquid theory and thus explain the T dependence of a system with strong electron-electron interaction.[6] Finally, it is believed that the ground state of a two-dimensional (2D) electron in the clean limit is a Wigner crystal (WC), which occurs at $r_s=37\pm 5$.[7,8] In this case disorder may pin the Wigner crystal, and system is insulating at $T=0$. Motivated by this controversy, we have studied a 2D system with a large dimensionless parameter r_s and a strong disorder—the two-dimensional electron gas (2DEG) in Si MOSFET'S near the (111) Si surface. Since in a highly disordered system the Coulomb interaction and localization are equally important, it is expected that the results of this study can give an additional experimental support for either of the theoretical models mentioned above.

Parameter r_s can be written in the form $r_s = 16{,}6 g_v (m/0.38m_0)(10^{11}/n_s)^{1/2}$. Therefore for a 2D gas near the (111) Si surface, where $g_v=6$ and $m=0.38m_0$, we obtain $r_s=99{,}6(10^{11}/n_s)^{1/2}$. It has to be noted, however, that the problem of the valley degeneracy of 2DEG near the (111) Si surface is not yet resolved completely. The measurements of the Shubnikov–de Haas (SdH) oscillations indicated $g_v=2$ instead of 6, as is expected from the effective-mass approximation. It was assumed that the possible reason of such discrepancy may be the interaction effects in a multivalley 2D electron system in a strong magnetic field.[9] More recently the valley degeneracy in the absence of magnetic field has been determined from the thermopower measurements.[10] These measurements confirmed that $g_v=6$ at $B=0$ in accordance with the effective-mass approximation, therefore the observation of the valley degeneracy $g_v=2$ from the SdH

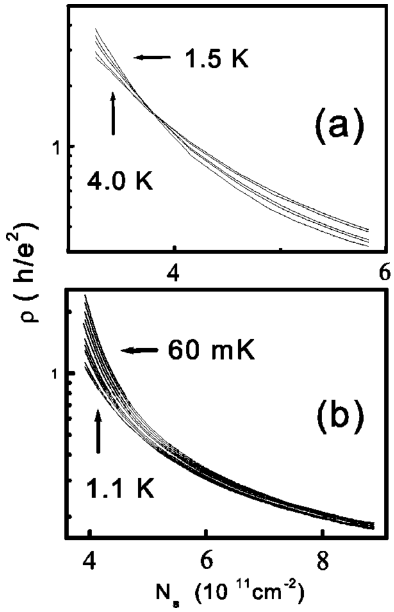

FIG. 1. Resistivity ρ versus electron density N_s in high-temperature region 1.4–5 K for sample MOS3: (a) the same dependence in low-temperature region 60 mK–1.1 K; (b) we may see the breakdown of the critical point at $N_s < 4\times10^{11}$ cm^{-2}.

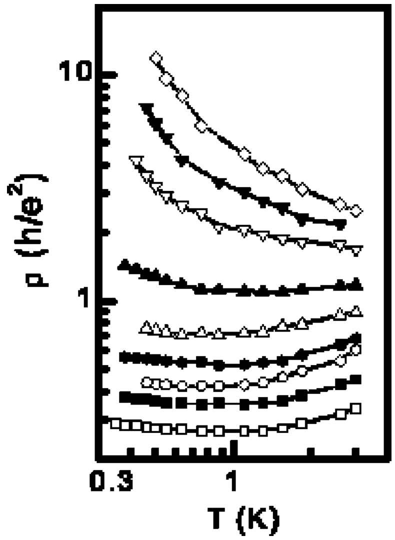

FIG. 2. Resistivity ρ versus the temperature at different values of N_s. $N_s(10^{11}$ cm^{-2}): squares, 6.44; full squares, 5.68; circles, 5.3; full circles, 4.92; up triangles, 4.54; full up triangles, 4.16; down triangles, 3.78; full down triangles, 3.55; diamonds, 3.4.

oscillations should be addressed to the problem of the transport in multivalley systems subject to a strong magnetic field. We will focus mostly on the results in zero magnetic field, therefore further we accept the value of $g_v = 6$.

In this paper we report the results of the measurements of the resistivity of 2DEG in Si MOSFET's fabricated on (111) silicon surface in the temperature range 4 K–60 mK. The resistivity in this system was found to show an insulating behavior at temperatures below 1 K. However, at higher temperatures we observed that the resistivity increases with the temperature decreasing. Such experimental behavior is consistent with the recent calculations of the conductivity corrections in a disordered system with Coulomb interaction, which can be characterized by the negative Fermi-liquid constant F_0^σ.[6]

The samples used in our experiments were silicon MOSFET fabricated on a (111) surface by means of conventional silicon technology. They have a Hall bar geometry with the width 400 μm and the same distance between the potentiometric contacts. The resistance has been measured in the temperature range from 60 mK to 4 K by a four terminal configuration with the frequency $f = 10.4$ Hz and the current $I \sim 1$ nA. We have investigated five MOSFET's with the maximum mobility about $\mu = 1500$–2000 cm^2/V s at $T = 4.2$ K. The mobility of the electrons near the (111) Si surface is usually smaller than in (100) Si MOSFET's. The main reason is the significantly larger number of the charged states on the (111)Si-SiO$_2$ interface in comparison with (100)Si-SiO$_2$. The mobility at low densities is determined by the charged centers at Si-SiO$_2$. We emphasize that the results of the measurements were very similar for all samples studied. Figure 1(a) shows the electron density dependence of the resistivity ρ for one of the sample MOS3 in the temperature range 1.1–4 K. Figure 1(a) unambiguously demonstrates a crossover point, when the sign of $d\rho/dT$ changes at $N_{sc} = 3.8\times10^{11}$ cm^{-2} and $\rho_c = 1.5h/e^2$. Naively, if one were to limit oneself only to the data at $T > 1.5$ K, one might have concluded that a metal-insulator transition occurs at $N_s = N_{sc}$, which is very similar to that reported in different two-dimensional systems.[3] However, to make a definite conclusion we should extend our measurements to a lower temperature. Figure 1(b) shows the same dependence $\rho_{xx}(T)$ for the temperature range 60 mK–1.1 K. One can see that for all electron densities N_s the resistivity increases when the temperature decreases. One does not find any change of sign of $d\rho/dT$ in this temperature range. Therefore the crossover point shown in Fig. 1(a) only mimics the metal-insulator transition, and the temperature dependence of the resistivity $\rho(T)$ should demonstrate nonmonotonic behavior. Figure 2 shows the dependence $\rho(T)$ for a wide range of density. One can see that for the electron density $N_s > 3.7\times10^{11}$ cm^{-2} the resistivity decreases with the temperature decreasing for temperatures above $T \approx 1$–2 K and increases at lower temperatures.

Now let us compare the experimental data with the theoretical models. It is worth noting that the nonmonotonic behavior of $\rho(T)$ has been observed in a two-dimensional hole gas in AlGaAs/GaAs heterostructures with an extremely high mobility and a large r_s.[11] However, this nonmonotonicity in $\rho(T)$ is different from what we find in our results: in addition to the minimum at $T \approx 1$–2 K the resistivity of the 2D holes exhibits local maximum at $T \approx 0.4$ K. This striking nonmonotonicity in $\rho(T)$ has been explained by the competition between the different scattering mechanism in the 2D hole gas.[12] It has been shown that the increase of $\rho(T)$ with T at low temperature is due to the screening effects, after which the system crosses over from a degenerate quantum to a nondegenerate classical regime, and therefore $\rho(T) \sim T^{-1}$ at $T > T_F \approx 0.4$ K. Finally at $T > 1$–2 K phonon scattering gives rise to a monotonical increase of the resistivity with T. Our system is very different from the 2D hole gas. First, the mobility in our samples is very low, therefore we can neglect the phonon scattering mechanism. Second, the Fermi temperature in our system corresponds to $T_F = 1.2(N_s/10^{11})$ K. Thus the Fermi temperature in Fig. 2 varies from 4.6 K ($N_s = 3.5\times10^{11}$ cm^{-2}) to 8.7 K ($N_s = 6.4\times10^{11}$ cm^{-2}), and quantum-classical crossover effects are not important in our samples at $T<4$ K. Finally, it is worth noting that the temperature averaging in the classical regime leads to a resistivity decreasing with temperature at $T>T_F$, which disagrees with our results shown in Fig. 2.

The mechanism which can in principle lead to the resistivity increasing with temperature is the temperature-dependent screening effect.[13] Recently the scattering processes contributing to the temperature dependence of the resistivity have been reexamined[6], because of the inconsistency in the calculations in the diffusive regime, when $T\tau/\hbar \ll 1$ (τ is elastic scattering time), and the ballistic regime, when $T\tau/\hbar \gg 1$. It has been recognized that the Altshuler-Aronov corrections to the conductivity at low temperatures ($T\tau/\hbar \ll 1$),[14] and corrections due to screening effects,[13] are the result of the same physical process—coherent scattering by Friedel oscillations.[6] The corrections to the conductivity corresponding to this process have been calculated for a wide temperature range and an arbitrary value of $T\tau/\hbar$ and for $E_F\tau/\hbar \gg 1$. The total correction to the conductivity is the sum of the charge channel, the triplet channel, and the single-particle localization corrections:

$$\Delta\sigma = \delta\sigma_C + \delta\sigma_T + \delta\sigma_{loc}. \tag{1}$$

The localization corrections can be written as

$$\delta\sigma_{loc} = -\frac{\alpha g_v p e^2}{2\pi^2\hbar}\ln\left(\frac{T_0}{kT}\right), \tag{2}$$

where p depends on the inelastic scattering process, which controls the dephasing scattering time $\tau_\varphi \sim T^{-p}$. For electron-electron scattering in the presence of disorder it has been shown that $p=1$.[14] The prefactor α depends on the ratio of intravalley and intervalley scattering rates and should lie between $1/g_v$ and 1, for fast and slow intervalley scattering consequently. The charge channel correction $\delta\sigma_C$ is given by[6]

$$\delta\sigma_C = \frac{\alpha g_v e^2}{\pi\hbar}\frac{T\tau}{\hbar}\left[1-\frac{3}{8}f\left(\frac{T\tau}{\hbar}\right)\right] - \frac{\alpha g_v e^2}{2\pi^2\hbar}\ln\left(\frac{E_F}{kT}\right), \tag{3}$$

and $\delta\sigma_T$ can be written as[6]

$$\delta\sigma_T = \frac{\alpha g_v e^2}{\pi\hbar}\frac{T\tau}{\hbar}\frac{3F_0^\sigma}{1+F_0^\sigma}\left[1-\frac{3}{8}t\left(\frac{T\tau}{\hbar},F_0^\sigma\right)\right] - 3\left(1-\frac{1}{F_0^\sigma}\ln(1+F_0^\sigma)\right)\frac{\alpha g_v e^2}{2\pi^2\hbar}\ln\left(\frac{E_F}{kT}\right). \tag{4}$$

The functions $f(T\tau/\hbar)$ and $t(T\tau/\hbar, F_0^\sigma)$ are given by dimensionless integrals in Ref. 6 and also shown in Fig. 5 and 6 of the same work.[6] As has been demonstrated from the measurements of the negative magnetoresistance in the weak-localization regime,[15] prefactor αg_v is a constant of order 1 due to the fast intervalley scattering. As it was also pointed out in Ref. 6, the corrections given by Eq. (1) demonstrate nonmonotonic behavior for the negative values of the Fermi-liquid constant F_0^σ in the range $-0.25 < F_0^\sigma < -0.5$. Such behavior leads to a minimum in the resistivity at $T\tau/\hbar \approx 0.4-1$ for $F_0^\sigma = -0.3$. In Fig. 2 we may see that the transition in the resistivity behavior from the anomalous nonmonotonic to insulating occurs at electron densities corresponding to $\rho \sim h/e^2$. In the transition point one should have $E_F\tau/\hbar \approx 0.5$ or $k_F l \approx 1$. Since the Fermi energy varies from 0.35 to 0.62 meV for the density range shown in Fig. 2, it is reasonable to assume that $\hbar/\tau \simeq 0.4$–0.5 meV. It is worth mentioning that for the electron densities corresponding to $\rho \ll h/e^2$ we also have $E_F\tau/\hbar \gg 1$, and the approximation of Ref. 6 is still valid. Figure 3 shows the fit obtained from Eqs. (1)–(4) to the experimental results for $N_s \geq 4.92 \times 10^{11}$ cm^{-2} assuming $F_0^\sigma = -0.25$ and $\hbar/\tau \approx 0.46$ meV. A good agreement with the expressions (1)–(4) is achieved. Comparison of resistivity for different electron densities also produced a quantitative agreement between theory and experiment.

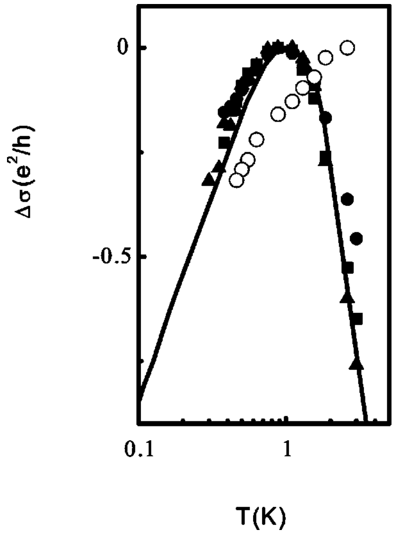

FIG. 3. Conductivity corrections $\Delta\sigma$ versus the temperature for different values of N_s. $N_s(10^{11}$ cm$^{-2})$: circles, 4.94; squares, 5.68; triangles, 6.44. Solid line: Eqs. (1)–(4). Open cicrles show conductivity corrections for the density $N_s = 3.55\times10^{11}$ cm$^{-2} < N_{sc}$.

Naively, for multivalley systems one would expect that the transition from weak to strong localization should occur at $\rho \sim h/g_v e^2$ and $k_F l \approx g_v$, which corresponds to $\rho \sim h/6e^2$ in our system. This is also consistent with the fact that if we calculate the level broadening from the mobility, we obtain the value of $\hbar/\tau$ which is six to ten times larger than estimated from the condition $E_F\tau/\hbar \approx 0.5$. It strongly disagrees with our observation of the resistivity increasing for $0.2h/e^2 < \rho < h/e^2$ (Fig. 2) at $T>1$ K. For large values of $\hbar/\tau \gg E_F$ the resistivity should demonstrate only insulating behavior. A fast multivalley scattering can explain such discrepancy. Since the intervalley scattering involves a transfer of a large momentum $1/a$, where a is the lattice constant of Si, the interface roughness can be responsible for such scattering,[16] in contrast to the transport scattering time, which is due to the charged interface states. Intervalley scattering is mostly elastic process, therefore it does not depend on the temperature. However, it may depend on the electron density. Since at low density the average distance of the electrons from the interface increases, intervalley scattering is suppressed. Unfortunately there is no available data about direct measurement of intervalley scattering near the (111) Si surface. However, some information can be obtained from the measurements of the negative magnetoresistance at low magnetic field. As we already mentioned above, the weak-localization corrections should be multiplied by prefactor αg_v. In high mobility (100) Si MOSFET's it lies between 1.1 and 1.6 with a tendency to increase with the density decreasing.[17] In low mobility (111) Si devices the prefactor is found to be close to 1 and does not vary with density, which corresponds to the fast intervalley scattering.[15] It also supports the assumption that the quality of the (111)Si-SiO_2 interface is generally worse than at (100)Si-SiO_2 interface. Therefore the weak-localization corrections in the system with strong intervalley mixing are identical to the corrections in a single valley system. Based on these arguments, we assume the presence of fast mulivalley scattering in our system, and just below the transition for $\rho \leqslant h/e^2$ we have $\hbar/\tau \leqslant E_F$.

As we have already mentioned above, the Fermi-liquid constant cannot be calculated from the first principles. However, for large value of r_s it is expected that the ferromagnetic state, which is characterized by $F_0^\sigma = -1$, may be a ground state for a dilute 2DEG in the presence of disorder.[7,18] Having no way to know which approximation is more realistic, we, however, may assume that our system is close to the ferromagnetic instability due to the large parameter r_s, and therefore the negative value of $F_0^\sigma = -0.25$ is not very surprising. For lower concentration we observed only a monotonic increase of the resistivity with the temperature decreasing. It could be explained by the mobility decreasing. At low electron density $T\tau/\hbar$ becomes very small, and therefore the conductivity is described by the Altshuler-Aronov corrections in the diffusive regime ($T\tau/\hbar \ll 1$), which leads to the logarithmic increase of the resistivity with the temperature decreasing. Figure 3 shows conductivity corrections for the density $N_s < N_{sc}$. However, it is pertinent to note that for this density the resistivity $\rho > h/e^2$ and the result of model[6] is no longer valid in this case. Therefore the resistivity behavior for lower electron density is consistent with insulating behavior because of the single-particle strong localization.

It has been found from a Monte Carlo simulation that at low density for clean systems at $r_s = 37 \pm 5$ the ground state of a 2DEG is a Wigner crystal.[7] An observation of a WC in a high mobility 2D hole gas had been claimed in Ref. 8. It appears to be difficult to distinguish between a WC and a single-particle localization from the temperature dependence of the resistivity, because in both cases $\rho_{xx}(T)$ grows with the temperature decreasing. In our samples $r_s = 37$ at $N_s = 7 \times 10^{11}$ cm^{-2}, and therefore one might consider explaining the resistivity growth at low density by the WC pinning. There is no consensus whether the disorder should destroy the WC or stabilize the WC phase. In our system the ratio between the Coulomb energy and the elastic broadening is around 10, and therefore it is expected that the disorder is small in comparison with the electron-electron interaction and may enhance Wigner crystallization.[19] In this paper we focus mostly on the nonmonotonic behavior of the resistivity and do not address the properties in the insulating phase.

In conclusion, we have observed nonmonotonicity in $\rho(T)$ of the 2DEG with large dimensionless parameter $r_s \approx 50$. We attribute such behavior to the temperature-dependent corrections to the conductivity due to the electron-electron interactions. From the comparison with theory[6] we derived the Fermi-liquid constant, which is responsible for the strength of the spin-exchange interaction. We found $F_0^\sigma \simeq -0.25$, which means that the system is not very far from the ferromagnetic Stoner instability.

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