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INSTABILITY OF THE TWO-DIMENSIONAL METALLIC PHASE TO PARALLEL MAGNETIC FIELD

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We report on magnetotransport studies of the unusual two-dimensional metallic phase in high mobility Si-MOS structures. We have observed that the magnetic field applied in the 2D plane suppresses the metallic state, causing the resistivity to increase dramatically by more than 30 times. Over the total existence range of the metallic state, we have found three distinct types of the magnetoresistance, related to the corresponding quantum corrections to the conductivity. Our data suggest that the unusual metallic state is a consequence of both spin- and Coulomb-interaction effects.

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Recently, convincing evidence for the existence of a 2D-metallic state in Si-MOS structures at zero magnetic field has been obtained in studies of the quantum Hall effect to insulator transitions [1] and of the Global Phase Diagram [2]. The extended states, which in high magnetic field H are centred in the corresponding Landau bands, were found experimentally to merge and remain in a finite energy range as H approaches 0, thus providing direct transitions from the high-order quantum Hall effect states to the insulator [1]. This behavior could not be expected in the framework of the one-parameter scaling theory (OPST) [3], where the extended states are anticipated to "float up" in energy as $H \to 0$ [4]. The experimental findings thus prove the existence of a mobility edge, whereas the predicted floating would evidently correspond to complete localization. In subsequent direct studies [5, 6], the conductivity in high-mobility Si-MOS structures in zero magnetic field was found to scale with temperature and electric field, and the scaling parameter demonstrated a pronounced critical behavior appropriate for a metal-insulator transition.

The observations of the metal-insulator transition at zero magnetic field in two dimensional system raised two major questions: (i) what is the origin of this unforeseen transition, and (ii) whether or not the one parameter scaling theory [3] is correct in predicting the absence of the metallic state in two dimensions. The majority of experimental data on 2D-system, in fact support the results of calculations of the "quantum corrections" to the classical diffusion [7–9] rather than the scaling theory in total.

Recently, the strong influence of the in-plane magnetic field on the resistivity has been found in Si/SiGe superlattices [10] as well as in high mobility Si-MOS structures [11]. In the current work we report the new experimental evidence for the origin of the metal-insulator transition in Si-structures, and test the applicability

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of the weak localization corrections. We have observed that the magnetic field applied in the 2D-plane destroys the metallic state and restores the weakly or strongly localized regimes. Over the existence range of the metallic state, we have found *three distinct types* of the magnetoresistance related to the corresponding quantum corrections due to interference and interactions [7,8].

The magnetotransport measurements were performed by a 4-terminal dc-technique. Four Si-MOS structures were studied: Si-15A with peak mobility (at 0.3 K) $\mu = 41,000$ cm^2/Vs, Si-2Ni with $\mu = 38,000$, Si-22 with $\mu = 26,000$, and Si-39 with $\mu = 5,000$. While the first three samples exhibited the metal-insulator transition [5, 6] and a sharp drop in resistance at $T < 2-3$ K, the latter low-mobility sample does not show a substantial decrease in resistance.

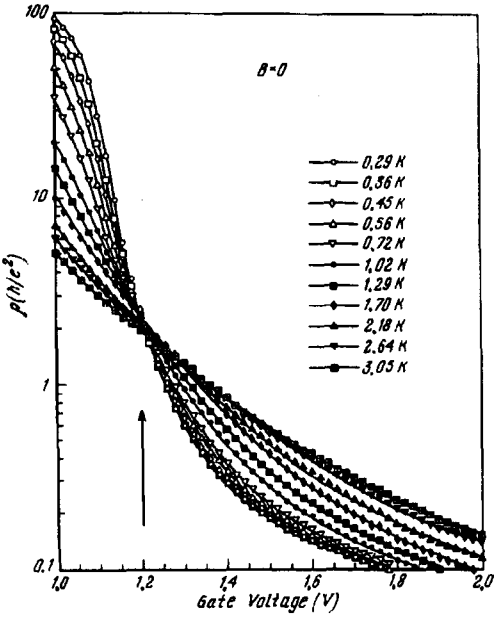

Fig.1. Resistivity vs gate voltage measured on sample Si-22. Different symbols correspond to 11 temperature values. The electron density is related to the gate voltage by $n = 1.205 \times 10^{11}(V_g - 0.4)$, where n is in cm^{-2} and V_g in Volts

Fig. 1 shows a set of resistivity curves at different temperatures, typical for high mobility samples [5]. At carrier density higher than the critical density, n_c (indicated by an arrow), the resistance *increases* with temperature, while at lower densities it *decreases*. The interception point is slightly dependent on temperature. The corresponding separatrix between the metallic and insulating sets of $\rho(T)$-curves in Fig. 2 is rising as T decreases.

Fig. 2*a* represents the "metallic" (or high density) part of the $\rho(T, n_s)$-plot and shows a strong drop (by 5×) in the resistivity below ~ 2 K. As T approaches 0, $\rho(T)$ saturates and does not show a tendency to increase, down to at least 14 mK. The lowest mobility sample Si-39 does not display a decrease in ρ apart from a few percents in the range 4 to 0.02 K; the latter behavior agrees completely with OPST.

Effect of the magnetic field parallel to the 2D-plane. The application of an in-plane magnetic field results in a dramatic increase of the resistance, more than 2 orders of magnitude, as seen in Fig.2*b*. At high fields, the resistance

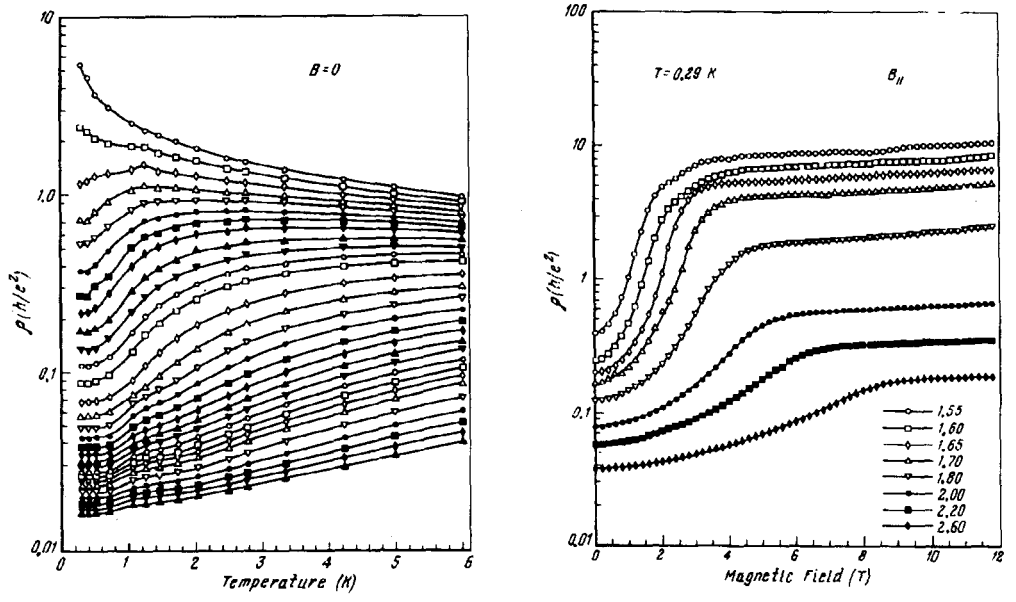

Fig.2. Resistivity vs temperature for the metallic range of densities, measured on sample Si-15A at zero field. Different curves correspond to electron densities between 0.83 and 3.72×10^{11} cm^{-2}. (*b*) Resistivity vs parallel magnetic field, measured at $T = 0.29$ K on sample Si-15A. Different symbols correspond to the gate voltages from 1.55 to 2.6 V, or, equivalently, to the densities from 1.01 to 2.17×10^{11} cm^{-2}

saturates. This behavior was found in all three high mobility samples, in agreement with the results of Ref. [11].

At high electron densities, the saturation level $\rho^*(H = 12.5\,\mathrm{T},\ T \to 0)$ seems similar to the saturation level at high temperatures and zero field, $\rho^*(H = 0, T = 6\,\mathrm{K})$, i.e. to the resistivity anticipated in the OPST-like behavior. Thus, the magnetic field simply destroys the metallic state. Comparison of the two plots, Figs. 2*a* and 2*b* reveals a remarkable similarity between the effect of the temperature and of the magnetic field on the resistivity at high densities. Both factors destroy the metallic state, and restore the weakly or strongly localized regimes. At densities lower than 2×10^{11} and closer to the critical density n_c, the magnetic field also gives rise to an additional $10\times$ larger positive magnetoresistance.

It has been noticed earlier [12] that the temperature dependence of the resistivity of the 2D-metallic phase may be well described by an empirical law $\rho(T) = \rho_1 + \rho_2 \exp(-T^*/T)$, where ρ_1 is related to scattering at $T = 0$, while the second term is associated with an energy gap, $\Delta = kT^*$. Since the parallel field does not affect orbital electron motion, the magnetic field may couple to the 2D-electrons only via their spins. Our results therefore, point out the spin - related origin of the unusual metallic state, and of the energy gap, Δ.

Weak localization corrections. In the weak perpendicular magnetic field, $H < 0.1\,\mathrm{T}$, all three high mobility samples exhibited the weak magnetoresistance, similar to the earlier reported data [12]. The narrow peak in $\rho(H)$ seen in Fig.3 is sensitive to the normal component of the field and is missing when the field is aligned with the 2D-plane within ± 7 min. Its amplitude does not vary much with

the density in the range $(9-100)\times 10^{10}$ cm^{-2}. These features allow us to attribute the narrow peak to the orbital single-particle quantum interference correction. At higher fields, $H > 0.2$T, and at high density, $n > 4 \times 10^{11}$ cm^{-2}, the positive parabolic magnetoresistance dominates, both in parallel and perpendicular field orientation. This indicates the spin-related origin of the positive magnetoresistance component. In the perpendicular field, the negative magnetoresistance grows as the density decreases, takes over the positive one, and eventually becomes so large that prevents the observation of the quantum interference peak. The negative magnetoresistance persists to the insulating range of densities, where it was explained by a field effect on the tunneling conductance [14]. The negative magnetoresistance is not seen for a parallel field and is therefore related to the orbital electron motion.

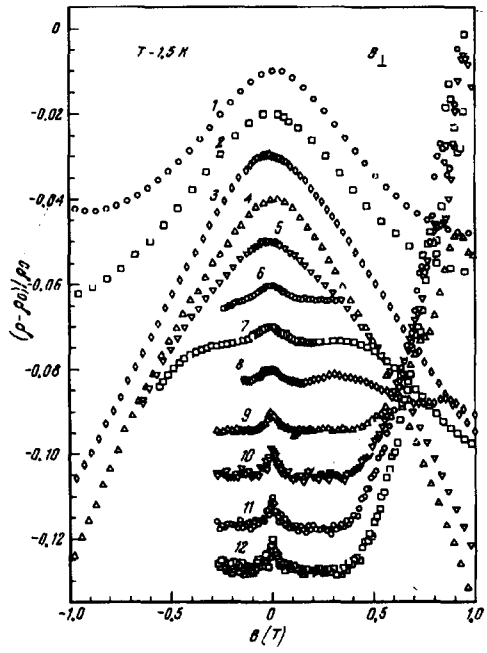

Fig.3. Normalized magnetoresistance $(\rho(H) - \rho(0))/\rho(0)$ vs perpendicular magnetic field for different densities on sample Si-2Ni at $T = 1.48$ K. The curves labeled 1 to 12 correspond to the density values of 0.90, 0.96, 1.12, 1.34, 1.56, 2.01, 2.12, 2.67, 3.77, 4.88, 5.98, and 7.09×10^{11} cm^{-2}. The curves were shifted vertically by 0.01 to each other

The positive parabolic magnetoresistance is usually considered as a quantum correction due to the interaction associated with the Zeeman splitting, while the negative magnetoresistance is associated with a correction due to electron-electron correlations [7,8]. The transition from the spin-dominant to the Coulomb dominant interaction occurs at the density $n^* \approx 2.8 \times 10^{11}$ for Si-15A and Si-2Ni, and $n^* = 1.7 \times 10^{11}$ for Si-22. These values are noticeably higher than the critical density at the mobility edge which is $n_c = 9.0 \times 10^{10}$ for Si-15A and Si-2Ni, and $n_c = 10.2 \times 10^{10}$ for Si-22. Therefore, the spin-effects and, partly, the Coulomb-effects govern the resistivity over the existence range of the metallic phase.

The persistence of the quantum corrections to the conductivity over the total range of existence of the metallic state (see Fig. 3) seems to justify the applicability of the quantum corrections approach to the unusual 2D-metal. On the quantitative side, if we attribute the positive magnetoresistance (shown in Fig. 2*b*) to the Zeeman-interaction term in the quantum corrections, than we come up with the

conclusion that the interaction-related quantum corrections are "blowing up" in the vicinity of the metal-insulator transition giving rise to the enhancement factor up to about $10^2\times$ to the $\Delta\rho(H)/\rho$ values. This is not surprising since the relevant theoretical calculations were done in the limit of $k_F l \gg 1$ where the corrections are small, whereas in the vicinity of the metal-insulator transition, at $k_F l \sim 1$, the quantum corrections may become large.

Discussion. Considering the possible features in which the high mobility Si-MOS structures differ from other systems, like GaAs/Al(Ga)As where the mobility edge was not found [15], we would like to note the following: (i) the Coulomb-interaction energy $E_{ee} = e^2/\kappa r$ is higher in Si-MOS structures than in GaAs samples (at the same interelectron distance, r) by a factor of 1.7 due to the smaller dielectric constant $\kappa = 7.7$ at the Si/SiO_2 interface [1], (ii) the Si/SiO_2 interface is characterized by a very strong asymmetry of the confining potential in the z-direction. The latter results in a large effective Lorenzian field H^* seen by electrons; the corresponding spin-orbit gap at zero field was found to be equal to ≈ 4K [12]. These effects associated with the broken reflection symmetry of the confining potential are much less pronounced in GaAs/Al(Ga)As heterojunctions and are apparently absent in the rectangular potential wells.

It is known that the inclusion of the spin changes the universality class of the 2D-system. The corresponding scaling consideration is based only on the symmetry arguments and should not depend much on the particular microscopic mechanism. The above spin-related mechanism may be important if the relevant energy gap, $\Delta = g\mu H^*$ is larger than $\Gamma = h/\tau$, the spin-level broadening. It appears, that the Δ/Γ -ratio is ≈ 3 for Si-15A and Si-2Ni, while $\Delta/\Gamma \approx 1$ for the low-mobility sample Si-39, which exhibits normal scaling behavior and no metal-insulator transition.

Thus, based on the data presented here we suggest that the metallic state and metal-insulator transition in the high mobility Si-MOS structures may be a consequence of both the spin- and the Coulomb-interaction effects. The former ones are enhanced by the broken reflection symmetry of the confining potential well, while the latter provide the necessary large relaxation time at the low electron density range.

Recently, some alternative suggestions on the origin of the unusual 2D-metallic state in Si-MOS structures were made, namely that it may be induced by Coulomb-interaction [16], or by spin-triplet pairing [17], or that it might be a manifestation of non-Fermi-liquid behavior [18].

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