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UNCONVENTIONAL METALLIC STATE IN TWO DIMENSIONAL SYSTEM WITH BROKEN INVERSION SYMMETRY

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We present a model that explains two phenomena, recently observed in high-mobility Si-MOS structures: (1) the strong enhancement of metallic conduction at low temperatures, $T < 2$ K, and (2) the occurrence of the metal-insulator transition in 2D electron system. Both effects are prescribed to the spin-orbit interaction anomalously enhanced by the broken inversion symmetry of the confining potential well.

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Introduction. Recently, in experiments with high mobility Si-MOS structures, a strong drop in resistivity $\rho(T)$ has been found [1] as temperature decreases below $\simeq 2$ K. This effect is evidently in disagreement with the conventional interpretation of the one-parameter scaling theory (OPST) [2], according to which all states in 2D system at zero magnetic field should be localized in the limit of $T \to 0$. The subsequent scaling analysis of the temperature and electric field dependencies of the conductivity [3] has revealed a critical behavior, typical for the metal-insulator transition. Finally, convincing evidence for the existence of the extended states in 2D system at zero field has been obtained in experiments in magnetic field, in studies of the quantum Hall effect to insulator transitions [4]. The extended states which in high magnetic field are located in the centre of the corresponding Landau bands, at decreasing field were found to remain in a finite energy range, giving rise to a mobility edge.

The experimental results thus suggest the existence of a true metallic state and of the metal-insulator (M-I) transition in 2D. These results are in apparent contradiction with the conventional OPST, and the origin of the metallic state remains puzzling. In this work, both experimental findings are explained as a consequence of the spin-orbit interaction enhanced by the broken inversion symmetry. The suggested model provides a good agreement with the experimental data on the temperature dependence of the resistivity $\rho(T)$.

Analysis of the experimental results. Fig.1 shows a set of the curves ρ vs T typical for the high-mobility samples [1], at different electron densities n_s. At $T \gtrsim 2$ K, the resistivity, ρ, increases slowly as temperature decreases, the latter is characteristic for the weakly localized regime. At lower temperature, ρ drops sharply for all curves belonging to the "metallic" range of densities, $n_s > n_c$.

The resistance drop is observed at densities in the range from n_c to $\approx 1.4n_c$. The critical density, n_c is sample dependent and is equal to $9.2 \cdot 10^{10}$ cm^{-2} for the sample shown in Fig.1. The drop in $\rho(T)$ diminishes with decreasing sample mobility, and is almost replaced by a conventional rise in ρ at $T \to 0$ in the sample with 8 times lower mobility, $\mu = 5000$ cm^2/Vs. The latter behavior is consistent with that reported in earlier studies on low-mobility samples [5].

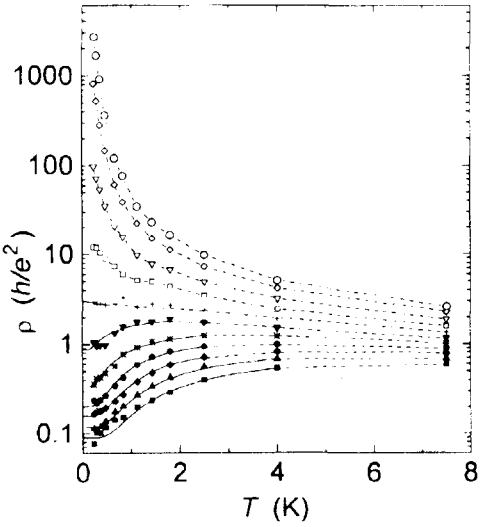

Fig.1. Typical temperature dependencies of the resistivity for a high-mobility sample [1, 3]. Electron density, from bottom to the top, is equal to 13.69, 12.81, 12.15, 11.50, 10.84, 10.18, 9.53 8.87, 8.21, 7.55, 7.12 $\cdot 10^{10}$ cm^{-2} [1, 3]. Solid lines - simulations, as discussed in the text

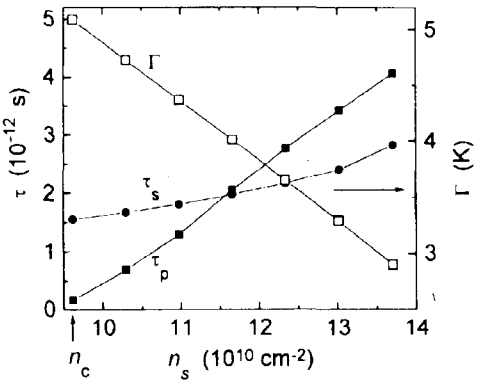

Fig.2. Level broadening, Γ, and relaxation times, as determined from the fit, Fig.1, in the vicinity of n_c

Empirical fit of the data. The $\rho(T)$- curves in Fig.1 may be fitted well by an empirical dependence which summarizes the scattering probabilities of two processes:

$$\rho(T) = \rho_0 + \rho_1 \exp(-T^*/T). \qquad (1)$$

The first term is independent of temperature, while the second one describes a scattering through an energy gap, $\Delta = k_B T^*$. The curves shown in Fig.1 by thick continuous lines were obtained using two fitting parameters for each density, ρ_1/ρ_0 and T^*.

Possible microscopic mechanisms. As seen from Fig.1, the characteristic temperature, T^*, is of the order of 2 K in high mobility samples. Searching for a proper microscopic mechanism, we find two small energy gaps intrinsic to Si-MOS structures at $H = 0$: the valley splitting $\Delta_v \approx 2.4$ K and the zero-field spin-gap $\Delta_s(H = 0) \approx 3.6$ K [6].

It seems attractive to link the resistance drop to the transitions between the two electron valleys, located close to the X-points in the Brillouin zone [7]. However, the intervalley "um-klapp" scattering would hardly occur, since it requires a combination of the reciprocal lattice vectors of the very high order. On the other hand, the phonon-induced intervalley transition would require participation of high energy phonons, $E_{ph} \sim 10^4$K, and is therefore unlikely at low temperatures. Electron tunneling, as the intervalley transition mechanism, would not lead to a strong temperature dependence of scattering.

Spin-orbit splitting and interaction effects. In the one-electron approximation, the spin-orbit interaction is described by the Hamiltonian [7]:

$$H_{so} = \frac{\hbar^2}{4m^2c^2}[\nabla V(\mathbf{r}) \times \mathbf{p}]\sigma, \tag{2}$$

where p and σ are the momentum and spin operators, correspondingly. For the 2D electron system in Si, the contribution of the bulk crystal potential in ∇V is small ($g^* \approx 2$), and the lack of inversion symmetry of the triangular confining potential $U(z)$ plays the major role.

This lifts the spin-degeneracy at zero magnetic field, and leads to the appearance of a linear term in the energy spectrum of 2D electrons [8]:

$$E^{\pm}(k) = \frac{\hbar^2 k^2}{2m^*} \pm \alpha k, \tag{3}$$

The corresponding spin-gap

$$\Delta_s = E^+ - E^- = 2\alpha k_F, \tag{4}$$

can be viewed as the difference in energy for the electron states with spin directed in the plane but to the left and right side with respect to $\mathbf{k}_F$, or, equivalently, along and opposite to the effective magnetic field $\mathbf{H}^* \sim (1/m^*c)\left[\mathbf{k_F} \times \nabla U\right]$ in the frame related to electrons moving in 2D plane with Fermi velocity.

We suggest that the empirically determined energy gap, Δ originates from Δ_s, and is equal to $p\Delta_s$ (where $p \sim 1$), whereas the temperature independent contribution to the resistivity, ρ_0, is related to the spin-independent scattering. Finite quantum relaxation time τ_q and the corresponding level broadening $\hbar/\tau_q$ should reduce the effective gap:

$$k_B T^* = p\Delta_s - \hbar/\tau_q. \tag{5}$$

Comparison of the model with the experimental results. The spin splitting $\Delta_s(H = 0) = 3.6$ K for the same Si-MOS structures was determined from the magnitude of the quantum oscillations of the chemical potential [6], extrapolated to zero field. It is clear from Eqs. (3) and (4), that this value corresponds to $E^-_{min} = -2m^*\alpha/\hbar^2$. With this result we obtain $\alpha = 1.79 \cdot 10^{-5}$ K·cm and the total energy spectrum becomes known.

In order to estimate the quantum level broadening, $\Gamma = \hbar/\tau_q$, the temperature dependence of the diagonal resistance was measured in the quantum Hall effect regime with Fermi energy adjusted to the Zeeman energy gap at $\nu = 6$ in the field of $H = 0.75$ T. As a result, we have obtained an estimate, $\Gamma = 2.8$ K for $n_s = 10.84 \cdot 10^{10}\text{cm}^{-2}$ (here we presumed the Gaussian level broadening and Γ to be the full width). Comparing the model effective energy gap, $\Delta = p\Delta_s - \Gamma$ with the empirical value, $T^* = 0.96$ K obtained in the fit at $n_s = 10.84 \cdot 10^{10}$ (the 5th curve from the bottom in Fig.1), we eventually find $p = 0.46$ [9].

The empirical energy gap, $k_B T^*$, decreases to zero at $n_s = n_c$, as seen in Fig.1. In the above model, Eq. (5), this occurs because (i) the level broadening increases, $\Gamma \propto 1/n_s$ and (ii) the spin splitting, $\Delta_s = 2\alpha k_F$, diminishes $\propto n_s^{1/2}$. The empirical fitting parameter Γ shown in Fig.2 vs electron density, rises indeed as density decreases. The total fit in Fig.1 is in surprisingly good agreement with the experimental data, despite the very simplified character of the above model.

As n_s decreases and approaches n_c, the resistance drop starts at lower temperatures. The weak decrease in $\rho(T)$ noticeable at $T > 4$ K is presumably due to

the weak localization corrections $\delta\rho \propto -\log(T/T_0)$ [10]. This effect was ignored in the above model and the $\rho(T)$ points corresponding to the negative $\partial\rho/\partial T$ were not fitted; these points are connected by dashed lines in Fig.1.

Fig.2 shows also two relaxation times: τ_p calculated from the mobility in the $T=0$ limit, and $\tau_q = \hbar/\Gamma$. It is noteworthy that both τ_p and τ_q diminish almost linearly as density decreases (but at $n_s > n_c$) and independently of each other. The momentum relaxation time τ_p provides the necessary resistivity value, $\rho \sim h/e^2$ at the critical density [1, 3], whereas τ_q provides the effective spin-gap equal to 0 at $n_s = n_c$. As a result, τ_p decays faster and becomes smaller than τ_q with decreasing n_s. At the critical density, μ is of the order of 0.1 m^2/Vs and $\Gamma \simeq 5K$, that corresponds to $\tau_p = 0.17 \cdot 10^{-12}$ s, and $\tau_q \simeq 1.5 \cdot 10^{-12}$ s. The conclusion on interception of the two curves, $\tau_q(n_s)$ and $\tau_p(n_s)$ is model independent, whereas the numerical values of $\tau_q(n_s)$ and the interception point depend on the model chosen for level broadening. For instance, the interception occurs at 11.5 or $13 \cdot 10^{10}$ cm^{-2} for Gaussian or Lorenzian broadening correspondingly.

Metal-Insulator transition at $H=0$: Spin-orbit interaction and symmetry effects. It is not only the low-temperature resistance drop but the total scaling behavior strongly depends on the symmetry. The corresponding universality classes of the symmetry for random systems were established by Dyson [11]. In the presence of the spin-orbit (SO) interaction, the orthogonal symmetry of the system is replaced by the symplectic symmetry. Correspondingly, the level-repulsion exponent in the random matrix statistics [11] changes from $\omega = 1$ to $\omega = 4$. It appears therefore, that states are less easily localized in systems with large ω.

The effect of the spin-orbit interaction on weak localization was studied both theoretically and experimentally [12]. For the strong localization regime, there have been suggestions [13] that M-I transition can occur in the presence of a strong SO interaction. The scaling function in 2D was found to behaves asymptotically like $\beta(G) \sim -a/G$ in the high conductance limit $G \gg 1$, with $a > 0$ in the orthogonal and $a < 0$ in the symplectic case [14]. The β-function in the symplectic case may thus become positive at sufficiently large G. As disorder increases and conduction G decreases, all states will be localized even in the symplectic case. The critical level of disorder and the critical conduction G_c correspond to the point at which $\beta(G_c) = 0$.

The behavior of the symplectic $\beta(G)$-function in 2D is qualitatively consistent with the experimental data presented in Fig.1, in the vicinity of n_c. As temperature, or broadening increases, the energy relaxation time τ_ϵ appears as a cut-off parameter and $1/\tau_\epsilon$ may become larger than the inverse spin relaxation time $1/\tau_\epsilon \gg 1/\tau_s$. Then the system would again behave as in the orthogonal symmetry case. The natural measure of the SO interaction strength is the spin-orbit gap Δ_s given by Eqs. (4) and (5), whereas as an estimate for disorder we adopted $\hbar/\tau_s \approx \hbar/\tau_q = \Gamma$. Thus, one may expect the M-I transition would manifest in those samples where $\Delta_s/\Gamma \geq 1$, which is also consistent with occurrence of the transition in the samples with peak mobility larger than 5000 cm^2/Vs [15].

Discussion. The above model explains why the resistance drop is seen only in low-disordered samples with large τ_q-values [15]. The effect is dependent also on the symmetry of the potential well. This provides a key for testing the driving mechanism. As for other systems, the zero field spin-gap in GaAs/Al(Ga)As is smaller by a factor of $10 \div 100$, due to the smaller g^*-factor value and much smaller ∇U [16]. Thus, even in ideal samples with zero broadening, the resistance drop may occur at temperatures $10 \div 100$ $\times$ lower than those for the Si-MOS

structures. In accord with this, no signatures of the resistance drop were revealed in recent measurements on GaAs/Al(Ga)As heterojunctions at temperatures down to 20mK [17].

Recently, there have been suggestions on other possible collective mechanisms, such as Coulomb interaction [18], spin-triplet pairing [19], and non-Fermi-liquid behavior [20]. However, the corresponding models are not developed yet to provide a comparison with the experimental data.

Summary. It seems likely that the recently observed metal-insulator transition in high-mobility Si-MOS structures is the first experimental manifestation of the spin-orbit interaction induced transition in 2D. The enhancement of the metallic conduction in these samples at low temperatures fits the same framework. Strong SO interaction energy relative to the level broadening, and broken inversion symmetry are favorable for the 2D metallic state. The Coulomb interaction in this model provides the small level broadening at density down to n_c. In the recent experiments [21, 22], the 2D metallic phase was found to be easily destroyed by the in-plane magnetic field; this is a strong evidence for the spin-related origin of the 2D metal.

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