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*CONFERENCES AND SYMPOSIA*

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# Mesoscopic and strongly correlated electron systems "Chernogolovka 97"

## 6. Superconductor – metal – insulator transitions

The sixth session of the conference included the following presentations:

(1) **Shahar D** (Department of Electrical Engineering, Princeton University) "Duality and the quantum hall effect";

(2) **Pudalov V M** (Institute for High Pressure Physics, Troitsk, Russia) "The metal – insulator transition in a two-dimensional system at zero magnetic field";

(3) **Paalanen M** (Helsinki) "Superconductor – insulator transition in an isolated Josephson junction";

(4) **Gantmakher V F** (Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia) "Superconductor – insulator transitions and insulators with localized pairs";

(5) **Gold A** (Laboratoire de Physique des Solides, Universite Paul Sabatier, Toulouse, France) "Superconductor – insulator transition in the disordered Bose condensate: a discussion of the mode-coupling approach";

(6) **Frydman A, Price E P, Dynes R C** (Department of Physics, University of California, San Diego, La Jolla, CA92093) "Mesoscopic Phenomena in Disordered Superconductors";

(7) **Samoĭlov A V, Fu C C, Yeh N -C** (Department of Physics 114-36, California Institute of Technology, Pasadena CA 91125), **Beach G, Vasquez R P** (Department of Physics 114-36, California Institute of Technology, Pasadena CA 91125, Center for Space Microelectronic Technology, JPL, California Institute of Technology, Pasadena, CA 91109) "Giant spontaneous Hall effect and metal – insulator transition in $La_{1-x}Ca_xCoO_3$ ($0.2 \leqslant x \leqslant 0.5$)";

(8) **Lavrov A N** (Institute of Inorganic Chemistry, Siberian Branch of RAS, Novosibirsk, Russia), **Gantmakher V F** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Russia) "Low-temperature resistivity of underdoped cuprates";

(9) **Zaikin A D** (Institut Fuorperphysik, Universitat Karlsruhe, Karlsruhe, FRG; I E Tamm Department of Theoretical Physics, P N Lebedev Physics Institute, Moscow, Russia), **Golubev D S** (I E Tamm Department of Theoretical Physics, P N Lebedev Physics Institute, Moscow, Russia; Physics Department, Chalmers University of Technology, S-41296 Goteborg, Sweden), **van Otterlo A, Zimányi G T** (Physics Department, University of California, Davis, CA 95616, USA) "Quantum fluctuations and dissipation in thin superconducting wires".

Parers 2, 4, 5, 6, 8 and 9; are published below. For the contents of paper 1 see cond-mat/9708239

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## The metal – insulator transition in a two-dimensional system at zero magnetic field

V M Pudalov

### 1. Introduction

The one parameter scaling theory (OPST) of localization [1] is considered as one of the milestones of contemporary condensed matter physics. This theory gives a clear physical picture of localization. Particularly, according to the conventional interpretation of the OPST, there is no quantum diffusion in 2 dimensions, and thus, no true metallic state and no metal-insulator transition. All the states of the electrons in 2d systems are expected to be localized, strongly or, at least, weakly. On the experimental side, a large body of data on quasi-2D systems, which are usually considered in support of the OPST, support in fact not the 'weak localization' and not the 'one parameter scaling theory', but only the concept of 'quantum corrections' to the classical diffusion. On the theoretical side, the numerous attempts to prove the one parameter scaling have so far met with major difficulties (for the review see [2]).

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 on insulator transitions [3] and of the global phase diagram [4]. The extended states, which in high magnetic field $H$ are centered in the corresponding Landau bands, were found experimentally to coalesce 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 [3]. Fig. 1 shows the critical density $n_c$, which separates the quantum Hall effect phases (with a nonzero number of extended states, $s_{xy}$) and the insulating phase (with $s_{xy} = 0$) [3, 5]. The boundary $n_c(H)$, by definition, thus displays the location of the lowest extended state. It is seen that the critical density, as well as the critical energy, $E_c \propto n_c$, remains finite as $H$ approaches 0.

This behavior could not be expected in the framework of the one-parameter scaling theory (OPST) [1], where the extended states are anticipated to 'float up' in energy as $H \to 0$ [6]. The experimental findings thus prove the existence of a metal – insulator transition, whereas the predicted floating would evidently correspond to complete localization. In subsequent direct studies [7, 8], the conductivity in high-mobility Si-MOS structures in a zero magnetic field was found to scale with the temperature and electric field [9], and the scaling parameter demonstrated a pronounced critical behavior appropriate for a metal-insulator transition. Moreover, the temperature dependence of the resistivity, in high

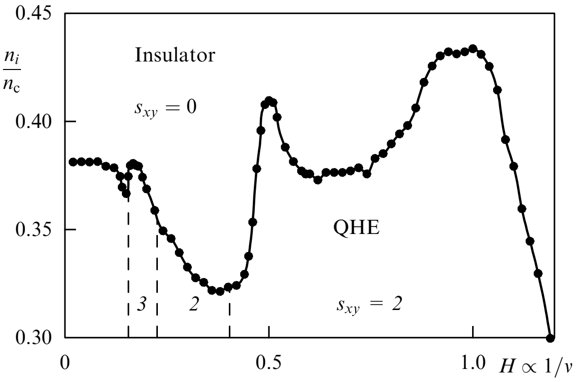


**Figure 1.** Phase diagram for the QHE-I transitions [3]. The experimental data, taken at $T = 35$ mK, show the inverse critical density $n_c$ normalized to the impurity density $n_i = 3 \times 10^{10}$ cm$^{-2}$, vs. the magnetic field in units of the inverse filling fact or $1/\nu = (He/hc)/n_s$.

mobility Si-MOS structures, shows an exponentially strong drop at temperatures below about 2K, which clearly indicates metallization rather than localization [7]. Similar behavior was found recently in high-mobility Si-SiGe heterostructures: both, in a 2d electron system [10] and in a 2d hole system [11].

The experimental findings thus raised a few questions such as: (i) what is the origin of the unforeseen M – I transition, (ii) whether or not the one parameter scaling theory (OPST) is correct in predicting the absence of the metallic state in two dimensions [1], (iii) is the concept of quantum corrections to the classical diffusion [12, 13] applicable to the anomalous 2D metallic state?

Here we report the new experimental evidence for the origin of the M – I transition in Si-structures, and test the applicability of the weak localization corrections. Particularly, we have observed that the magnetic field applied in the 2D plane destroys the metallic state and restores the localized regimes. Over the existence range of the metallic state, we have found *three distinct types* of magnetoresistance related to the quantum corrections due to interference and interactions [12, 13].

Four-terminal transport measurements were performed on five Si-MOS structures: Si-15A with peak mobility $\mu = 4.1$ m$^2$ (V s)$^{-1}$, Si-2Ni ($\mu = 3.8$), Si-22 ($\mu = 2.6$), Si-43 ($\mu = 1.7$), and Si-39 ($\mu = 0.5$). Figure 2 shows the temperature dependence of resistivity, typical for high mobility samples [7]. At carrier densities higher than $n_c$, the resistance *increases* with $T$, while at lower densities it *decreases*. In the 'metallic' range of densities, the resistivity for all four high mobility samples shows a strong drop, by a factor of $3 - 6$, at $T \leqslant 2$ K. The lowest mobility sample Si-39 does not display a decrease in $\rho$ apart from a few percent in the range 4 down to 0.02 K.

It has been shown [14] that the temperature dependence of the resistivity in the 2D metallic phase may be well described by an empirical law

$$\rho(T) = \rho_1 + \rho_2 \exp\left(-\frac{\Delta}{kT}\right), \tag{1}$$

where $\rho_1$ is related to scattering at $T = 0$, while the second term is associated with an energy gap, $\Delta$.

Application of the magnetic field in the 2D-plane causes the resistivity to increase dramatically, more than 30 times, as shown in Fig. 2. Upon a further increase in magnetic field, the

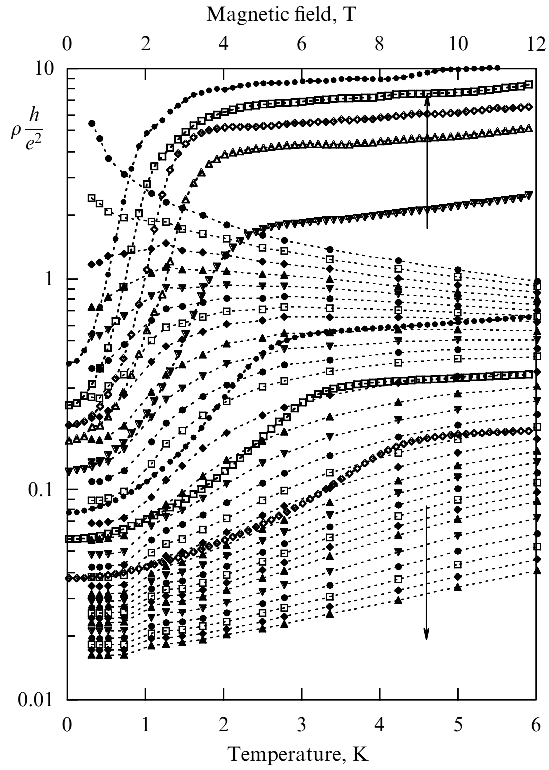


**Figure 2.** Resistivity vs temperature at $H = 0$ (filled symbols) and vs. parallel magnetic field at $T = 0.29$ K (empty symbols) [15]. Sample Si-15A. Different symbols correspond to the densities from 0.83 to $3.72 \times 10^{11}$ cm$^{-2}$.

resistivity saturates. This behavior was found in all high mobility samples [15, 16]. The saturation level $\rho^*(H = 12.5\,\mathrm{T}, T \to 0)$ at high $n_s$ 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. Comparison of the two dependencies, $\rho(H)$ and $\rho(T)$, reveals their remarkable similarity at high densities. Both the temperature and in-plane field destroy the metallic state and restore the weakly or strongly localized regimes. However, at $n_s < 2 \times 10^{11}$ cm$^{-2}$ and closer to $n_c$, the rise in the resistivity with magnetic field becomes 10$\times$ larger than with temperature. Since the parallel field couples to the 2D electrons via their spins, our results point out the spin-related origin of the unusual metallic state, and of the energy gap, $\Delta$.

The effective energy gap in Eqn (1), $\Delta$, is expected to diminish linearly with the in-plane field:

$$\Delta = \Delta_s(n_s) - g^* \mu H - \Gamma, \tag{2}$$

where $\Gamma$ is the broadening of the corresponding spin-polarized subbands [14]. Figure 3 shows that $T \log[\rho(H)]$ indeed rises with the magnetic fields with the rate $\sim$1 K/T at low field, which is close to the expected value, $g^* \mu = 1.33$ K/T.

The linear decrease in $\Delta$ saturates at a certain field $H_{\mathrm{sat}}$, plotted in Fig. 3 as a function of $n_s$. The saturation field may be related to the complete spin polarization of the 2D system, which occurs when $\Delta \approx E_F = g^* \mu H$. The slope $\mathrm{d}H_{\mathrm{sat}}/\mathrm{d}n_s$ should thus be $\mathrm{d}E_F/\mathrm{d}n_s = 7.3 \times 10^{-11}$ K cm$^2$. This is consistent with the measured slope $\mathrm{d}H_{\mathrm{sat}}/n_s \approx 6 \times 10^{-11}$ K cm$^2$, shown in Fig. 3.

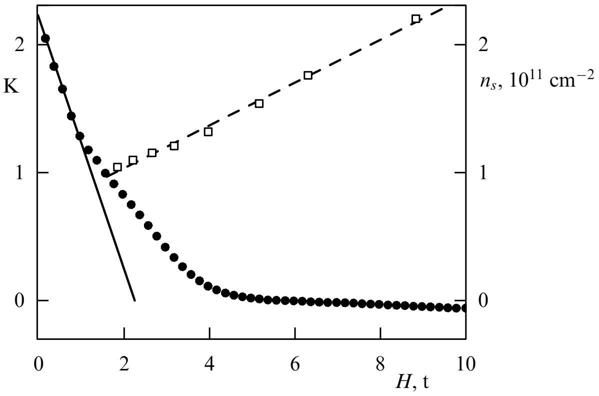


**Figure 3.** Activation energy (left axis) vs. parallel magnetic field calculated from Fig. 2 for $n_s = 1.32 \times 10^{11}$ cm$^{-2}$. Saturation magnetic field vs. electron density (right axis) [19].

## 2. Weak localization corrections

In the weak perpendicular field, $H < 0.1$ T, all high mobility samples exhibited weak magnetoresistance, as in the earlier data [17]. The narrow peak in $\rho(H)$ seen in Fig. 4 is sensitive only to the normal component of the field, and missing when the field is aligned with the 2D plane within 1/20 degree. Its magnitude, $\delta\rho(H)$, does not vary much with the density over the range $(1.2 - 7.0) \times 10^{11}\,\mathrm{cm}^{-2}$ , and is consistent with a logarithmic temperature dependence. The peak shape $\rho(H)$ is fitted well by the known expression [13] using the digamma function. Therefore, we attribute this peak to the orbital single-particle quantum interference correction [18].

At higher fields, $H > 0.2$ T, and at high density, $n > 4 \times 10^{11}\,\mathrm{cm}^{-2}$, the positive parabolic magnetoresistance, independent of the field orientation, dominates. This indicates the spin-related origin of the positive magnetoresistance component. The lower curve in Fig. 4 shows that the narrow peak $\rho(H)$ persists to mK-temperatures, whereas the parabolic magnetoresistance is overwhelmed by the fast emerging oscillatory effects.

As the density decreases, the negative magnetoresistance grows, takes over the positive one, and eventually becomes so large that it prevents observation of the quantum interference peak. The negative magnetoresistance persists to the insulating range of densities (curves *1* and *2*), where it has been studied in detail and attributed to electron tunneling in the slowly varying potential. The negative magnetoresistance is not seen for a parallel field and is therefore related to the orbital electron motion.

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 [12, 13]. 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 higher than the critical density at the M – I transition which is $n_c = 9.0 \times 10^{10}\,\mathrm{cm}^{-2}$ for Si-15A and Si-2Ni, and $n_c = 10.2 \times 10^{10}\,\mathrm{cm}^{-2}$ for Si-22. Therefore, the spin-effects and, partly, the Coulomb effects govern the resistivity in the metallic phase. The transition between the two regimes occurs not due to a weakening of the Zeeman component, but rather due to the growth of the Coulomb-component, their competition is pronounced in a wavy magnetoresistance pattern at the intermediate density, as shown in Fig. 4.

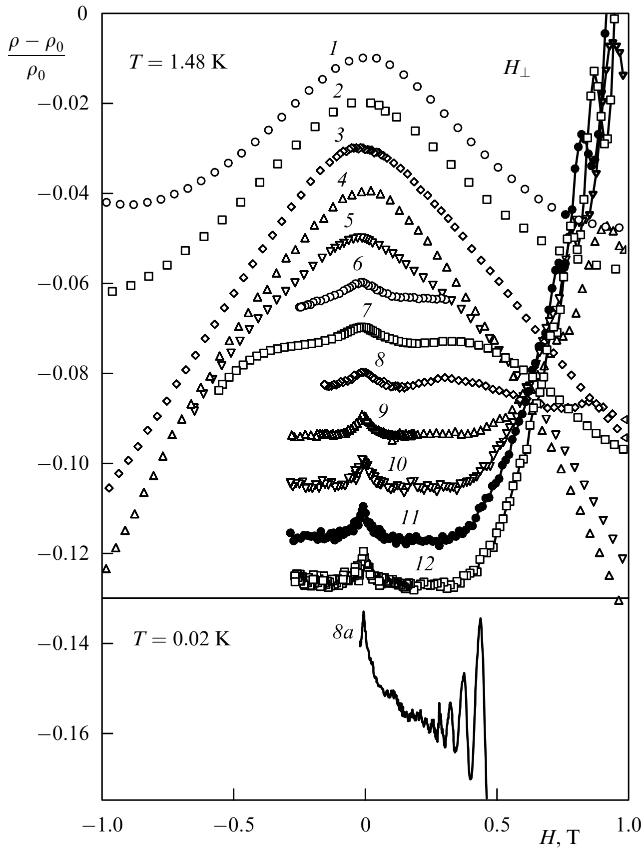


**Figure 4.** Normalized magnetoresistance vs. perpendicular magnetic field, measured for the sample Si-2Ni at $T = 1.48$ K. The curves labeled *1* to *12* correspond to the density values from 0.90 to $7.09 \times 10^{11}$ cm$^{-2}$. The curves are shifted vertically by 0.01 relative to each other. The lower curve *8a* was taken at the same density, $2.6 \times 10^{11}$ cm$^{-2}$, as curve *8*, but at $T = 21$ mK [15, 19].

The persistence of the quantum corrections to the conductivity over the range of existence of the metallic state seems to justify the applicability of the quantum corrections approach to the unusual 2D metal. On the quantitative side, the positive magnetoresistance shown in Figs 3 and 4 becomes unexpectedly large in the vicinity of the M – I transition, at $k_F l \sim 1$.

The magnetoresistance measurements discussed above reveal the partial quantum corrections, $\sigma_i$, to the conductivity, which are of the localization sign, $\mathrm{d}\ln\sigma_i/\mathrm{d}T > 0$. However, the conductivity in total does continuously display the delocalizing trend, $\mathrm{d}\sigma/\mathrm{d}T < 0$. This was tested to hold in the total temperature interval 2 K down to 16 mK, for the studied high-mobility samples, over the density range 1.5 to $11 \times 10^{11}\mathrm{cm}^{-2}$, i.e. in the range where $\sigma = 10$ to $\approx 100(e^2/h)$. In terms of the one-parameter scaling, this means that the scaling function $\beta(G)$, crosses zero only once, and remains positive for $G$ up to 100, at least.

## 3. Discussion

Considering the possible features in which the high mobility Si-MOS structures differ from GaAs/Al(Ga)As structures, where the mobility edge has not yet been found, we would like to note the following: (i) the Coulomb interaction energy $E_{ee} = e^2/\varkappa r$ is higher in Si-MOS structures than in GaAs samples by a factor of 1.7 at the same electron density, or by a factor of 5 at the same Fermi energy; (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 Lorentzian field $H^*$ seen by electrons; the corresponding spin-orbit gap at zero field is $\sim$3.6 K [14]. These effects associated with the broken inversion symmetry of the confining potential are much less pronounced in GaAs/Al(Ga)As heterojunctions and are almost absent for rectangular potential wells.

It is known that the universality class of the symmetry of the 2D system strongly affects its scaling behavior. The above spin-related mechanism should result in the breaking of spin-rotation SU(2) symmetry either completely or partially, and should correspondingly lead either to symplectic or another novel symmetry [20]. This may be important if the relevant energy gap, $\Delta = g^* \mu H^*$ is larger than $\Gamma = h/\tau$, the spin-level broadening. The estimated $\Delta/\Gamma$ -ratio $\sim 3$ for Si-15A and Si-2Ni, while $\sim 1$ for the sample Si-39, which does not exhibit the well pronounced M – I transition.

In conclusion, we suggest that the metallic state and M – I transition in the high mobility Si-MOS structures is a consequence of both the spin and the Coulomb interaction effects, where the former are enhanced by the broken inversion symmetry. Apparently, this is in agreement with a very recent observation of the M – I transition in the 2D hole system in Si – SiGe heterostructures [11] which exhibits strong spin-orbit coupling. In this context we also wish to emphasize that the Coulomb interaction was predicted by Finkel'stein [21] to overwhelm the localization trend in the cooperon channel and to lead the drop in resistivity upon lowering $T$, whereas the spin-related effects favor this drop to start earlier at higher temperatures. Recently it was also proposed that the ground state of the unconventional 2D metallic state is a spin-triplet paired state [22], and that the M – I transition may be a manifestation of non-Fermi-liquid behavior [23].

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# Superconductor – insulator transitions and insulators with localized pairs

V F Gantmakher

## 1. Introduction

Among the various scenarios of superconductor – insulator transitions (SIT) is a specific one proposed by Fisher [1]: a field-induced and field-tuned transition in two-dimensional superconductors. It supposes, at $T = 0$, the existence of delocalized Cooper pairs and localized vortices (superconductor) below the transition, at fields $B < B_c$, and of localized pairs and delocalized vortices (insulator) above it, at $B > B_c$. Several experimental studies [2, 3] apparently support this model describing the experimental data near the transition in terms of scaling relations [1]. As a consequence of the approach of [1 – 3], an insulator should be supposed to exist with localized Cooper pairs and the magnetic field structured into vortices. The properties of such insulators have still not been addressed. However, some experimental observations do point to localized pairs [4]. In particular, negative magnetoresistance in some three-dimensional materials, when superconductivity is alternated with insulating behavior, is one such indication [5]. This negative magnetoresistance results from destruction of the gap in the spectrum of localized electrons by the magnetic field, which affects single-particle tunneling [6].

Still, our knowledge of localized pairs is rather poor. The existing studies leave some doubts. The amorphous Mo – Ge films from [3] display only a 5% increase of resistance for a ten-fold decrease in temperature in the high-magnetic-field limit and behave not like an insulator, but more like a metal with a small quantum correction to the resistance. The measurements with In – O films [2] were made in the quasireentrant region (see below, next section).

Hence, additional experimental observations are desired. In this study, two experiments are described, both related to the problem. First, the existence of the scaling variable [1]

$$x = \frac{(B - B_c)}{T^{1/y}} \tag{1}$$

is re-examined by analyzing magnetotransport in amorphous $In_2O_x$ films ($y$ is the product of two critical exponents from the theory [1]). Our measurements do not reject the possibility of the field-induced phase transition but lead to more general scaling relations.