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PERCOLATION METAL–INSULATOR TRANSITION IN 2D ELECTRON GAS OF SI MOSFET UNDER THE ULTRA–QUANTUM LIMIT CONDITION

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The metal-insulator transition in 2D electron gas of Si MOSFET has been investigated. In strong magnetic fields the phase boundary in H,N_s-plane has been found to be a straight line with slope $\nu_c = 0.53 \pm 0.01$, which is sure to indicate the percolation character of transition.

The problem of metal-insulator (MI) transition in two-dimensional ($2D$) electron systems has attracted considerable attention recently [1,2]. A single-particle localization state and a pinned electron solid are discussed as two possible states of non-metallic phase. The MI transition at quantizing magnetic fields is of particular interest because the transition into Wigner crystal has to occur from quantum liquid state. Numerous experimental works are devoted to the investigation of the MI transition in $2D$ electron gas in GaAs/AlGaAs heterostructures at filling factors $\nu < 1$ in extremely high magnetic fields (e.g.,[3–6]). In these papers the attention was paid largely to the search for Wigner crystal. In high-mobility $2D$ systems on the base of Si MOSFET the authors [7] argued the formation of Wigner crystal in the vicinity of $\nu = 1,5,\ 2,5$ at low magnetic fields ($H < 4$ T). *In the present paper the experimental study of the MI transition on Si MOSFET* samples has been performed at high magnetic fields ($H > 4$ T) in the range of filling factors $\nu < 1$. It has been found that this transition is the percolation one.

The measurements were carried out on high-mobility Si MOSFETs which had the peak mobility $\mu_p \simeq 3 \cdot 10^4$ cm^2/Vs at $T = 1,3$ K. The samples had the geometry of Hall-bar with sizes 250×2500 μm^2 and 800×5000 μm^2. These samples were identical with those used in experiments [7]. The results presented below were obtained on three samples fabricated from two different wafers. Four-terminal dc measurements of resistivities $\rho_{xx}(N_s)$ and $\rho_{xy}(N_s)$ were carried out at fixed magnetic fields and temperature $T = 25$ mK, the source-drain current being in the range $1 \div 5$ nA. The signal was detected by a voltmeter with high input resistance ($R_{in} \sim 10^{14}\Omega$). Due to the high value of R_{in} we managed to carry out measurements in high magnetic fields at low electron densities where probe resistances were so large that in previous experiments this region was not accessible for investigations.

In the experiment we registered the difference of signals measured at two directions of current. In this way we excluded a parasitic chaotic signal independent of the current direction. The typical experimental dependences are shown in Fig.1. One can see that at some electron concentration N_s^c the non-dissipative current through the lower quantum level disappears and the resistivity ρ_{xx} grows abruptly. In high magnetic field the rise of ρ_{xy} starts at lower concentrations than that of ρ_{xx} so that the intersection point of these curves is close to 26 kΩ.

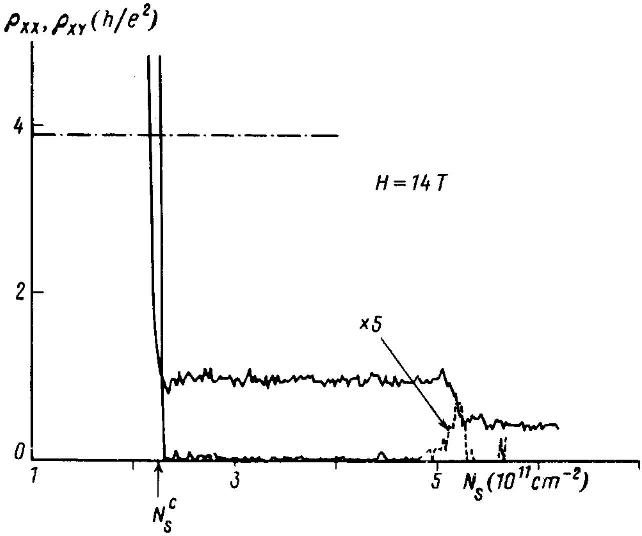

Fig.1. Typical experimental dependences of resistivities ρ_{xx}, ρ_{xy} on the electron concentration. Dashed-dotted line marks the resistance value 100 kΩ. The peak in ρ_{xx} at $\nu \simeq 1.5$ is enlarged by a factor of 5.

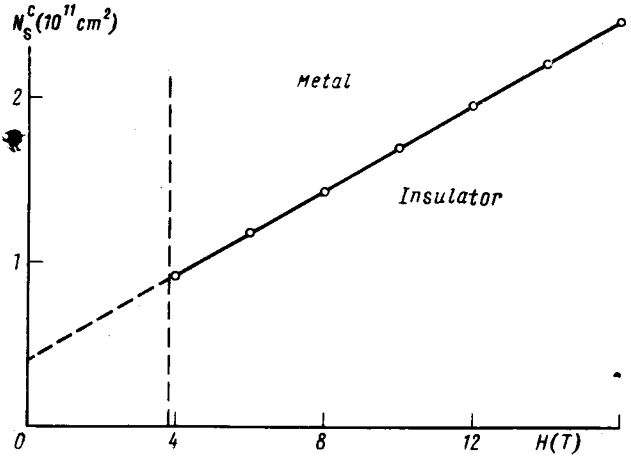

Fig.2. Change of the critical concentration with magnetic field. The solid line separates metal and insulator phases.

All the experimental dependences were obtained in decreasing electron concentration, i.e., at the transition from metallic to insulator phase. We hope that the concentration N_s^c obtained in such a way is the equilibrium one.

The value of resistance corresponding to MI transition is not known so the critical concentration cannot be determined unambiguously. We considered N_s^c to be the concentration at which the resistivity ρ_{xx} was equal to 100 kΩ. In the wide range of magnetic fields the dependences N_s^c vs H for all the samples used are straight lines. Fig.2 shows the dependence $N_s^c(H)$ obtained on one of samples. A vertical line confines the region of magnetic fields at which the measurements were performed. The phase boundary throughout this region is located at $\nu < 1$. In zero magnetic field the MI transition occured at $N_s^c = 8,6 \cdot 10^{10}$ cm^{-2}.

It is convenient to measure the straight line slope in dimensionless units $\nu_c = \frac{hc}{e}(\partial N_s^c/\partial H)$. The value of ν_c corresponds to the fraction of area occupied by $2D$ electrons if one electron occupies the area $2\pi l^2$ (where l is the magnetic length). The dependences $N_s^c(H)$ obtained on different samples were practically identical, the average value of slope being equal to $\nu_c = 0,53 \pm 0,01$.

In our opinion the phase boundary in H, N_s-plane being a straight line with the specific value of the slope points out the percolation character of MI transition. The fact that the resistivity ρ_{xx} starts to grow at higher electron concentration than ρ_{xy} does not contradict this statement.

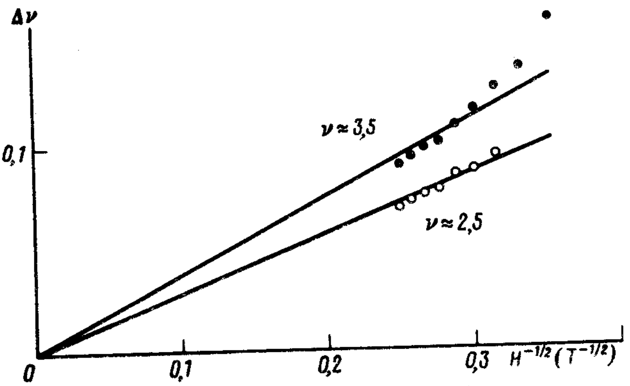

Fig.3. Behaviour of half-widths of peaks in ρ_{xx} measured on ac in changing magnetic field.

Two alternatives of the percolation MI transition are possible. The first one is the transition in long-range potential with the characteristic scale $L \gg (N_s^c)^{-1/2}$. In this case one should expect that the transition curve $N_s^c(H)$ will be a straight line with the slope $\nu_c = 0,5$ [8]. The straight line intersects the ordinate axis at the concentration which one can interpret as the number of electrons strongly coupled with positive ions at the interface $Si - SiO_2$. The concentration of these ions determined in such a way is equal to $3,5 \div 4 \cdot 10^{10}$ cm^{-2}. On the other hand the concentration of positive ions found independently on similar samples [9] was $2 \cdot 10^{10}$ cm^{-2}. The values obtained coincide satisfactorily. If one suppose for example that the long-range potential is connected with the presence of positive ions at the interface then its scale will be of the order of $L \sim 500 Å$. In this case in a magnetic field $16T$ an electron lake contains about 10 electrons. For this approach to be valid the coupling energy of electron with ion is necessary to exceed the cyclotron energy (the coupling energy is about 40 meV while in a field 16 T the cyclotron energy is 10 meV).

There is an independent way to check the existence of electron lakes. If percolation picture is valid for all lower quantum levels one can estimate the width of peaks of ρ_{xx} as $\Delta\nu \sim l/L \propto H^{-1/2}$. The experimental dependences $\Delta\nu(H)$ are shown in Fig.3 for two filling factors. The expected dependence coincides with the experimental one at least in the highest magnetic fields. Having determined the value of slope we can estimate a scale of potential $L \sim 800$ Å.

Thus the picture of long-range potential explains the experiment satisfactorily. Yet it is clear that a positive ion at the interface cannot keep an electron lake beside itself. We do not see other reasons for the existence in our samples of potential fluctuations due to the presence of 'frozen' charge $Q \gg e$ on the area L^2. Therefore we will consider the second alternative of the percolation transition.

In this case one should suppose that at low concentrations $N_s < N_s^c$ the localized electrons are distributed casually over the whole sample plane. A potential relief for such a distribution of electrons can be created by the roughness of $Si - SiO_2$ interface [1,9]. The percolation problem in this system is very close to the site problem in $2D$ lattice. If electrons occupy only the lowest Landau level the local electron density cannot exceed the fixed value $(1/2\pi l^2)$. The last statement is valid for lattices with one site per unit cell. As known [10] the critical concentration for lattices with one site per unit cell (triangular and squared) equals $x_c = 0.5$ and $x_c = 0.59$ respectively. In strong magnetic field an electron state occupying an area $2\pi l^2$, the percolation transition corresponds to the condition $\nu_c = x_c$, which is in agreement with the experiment. In used magnetic fields the electrons localized on the impurity ions do not affect the percolation condition ($a^* = \bar{\epsilon}\hbar^2/me^2 < l$) and lead only to the shift of phase boundary along y-axis.

In conclusion, the straight line dependence $N_s^c(H)$ we observe in the experiment is sure to point out the percolation character of MI transition but does not enable us to determine unambiguously the scale of potential relief.

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