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 the H, N_s plane was found to be a straight line with the slope $\nu_c = 0.53 \pm 0.01$, which strongly suggests 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 nonmetallic phase. The MI transition at quantizing magnetic fields if of particular interest because the transition into Wigner crystal must occur from a quantum liquid state. Many experimental studies have been 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., Refs. 3–6). In those papers, attention was focused largely on the search for a Wigner crystal. In high-mobility 2D systems on the base of Si MOSFET the authors[7] suggested that the Wigner crystal forms in the vicinity of $\nu = 1, 5, 2, 5$ at low magnetic fields ($H < 4$ T). Our experimental study of the MI transition on Si MOSFET samples was performed at high magnetic fields ($H > 4$ T) in the range of filling factors $\nu < 1$. It was found that this transition is a percolation transition.

The measurements were carried out on high-mobility Si MOSFETs, which had the peak mobility $\mu_p \simeq 3\times10^4$ cm^2/Vs at $T=1.3$ K. The samples had the geometry of a Hall bar with dimensions $250\times2500\ \mu$m^2 and $800\times5000\ \mu$m^2. These samples were identical to those used in other experiments.[7] The results presented below were obtained with three samples fabricated from two different wafers. Four-terminal dc measurements of the 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 was in the range 1–5 nA. The signal was detected by a voltmeter with a high input resistance ($R_{\text{in}}\sim10^{14}\ \Omega$). Because of the high value of R_{in}, we carried out measurements in high magnetic fields at low electron densities, where the probe resistances were so large that in previous experiments this region was not accessible for investigations.

In the experiment we recorded the difference in the signals measured for two directions of the current. In this way we excluded the 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 nondissipative current through the lower quantum level disappears and the resistivity ρ_{xx} increases abruptly. In a 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.

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 concentration.

The value of the resistance corresponding to the MI transition is not known so the critical concentration cannot be determined unambiguously. We assumed N_s^c to be the

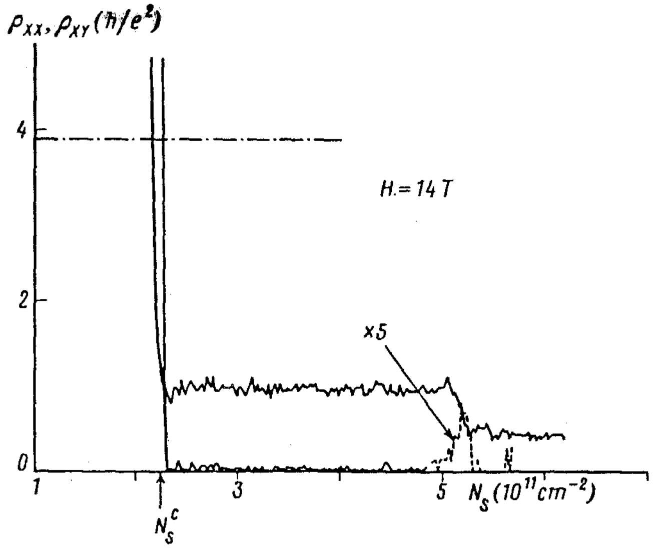

FIG. 1. Typical experimental dependences of resistivities ρ_{xx}, ρ_{xy} on the electron concentration. The dot-dashed line represents a resistance of 100 kΩ. The peak in ρ_{xx} at $\nu\simeq1.5$ is enlarged by a factor of 5.

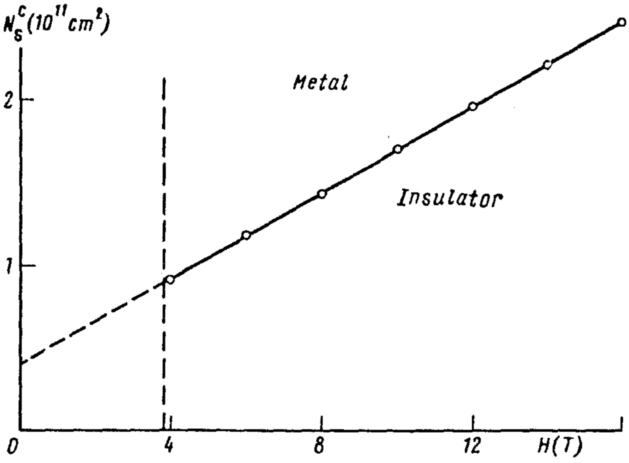

FIG. 2. Change in the critical concentration with magnetic field. The solid line separates metal and insulator phases.

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. Figure 2 shows the dependence $N_s^c(H)$ obtained for one of the 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 occurred at $N_s^c = 8.6 \times 10^{10}$ cm^{-2}.

It is convenient to measure the straight line slope in dimensionless units $\nu_c = (hc/e)(\partial N_s^c/\partial H)$. The value of ν_c corresponds to the fraction of the 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 for different samples were nearly identical, and the average value of the slope was $\nu_c = 0.53 \pm 0.01$.

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

Two alternatives of the percolation MI transition are possible. The first one is the transition in a 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[8] $\nu_c = 0.5$. The straight line intersects the ordinate 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 3.5–4$\times 10^{10}$ cm^{-2}. On the other hand, the concentration of positive ions found independently with similar samples[9] was 2×10^{10} cm^{-2}. The values obtained coincide satisfactorily. If it is assumed, 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 16-T magnetic field an electron lake contains about 10

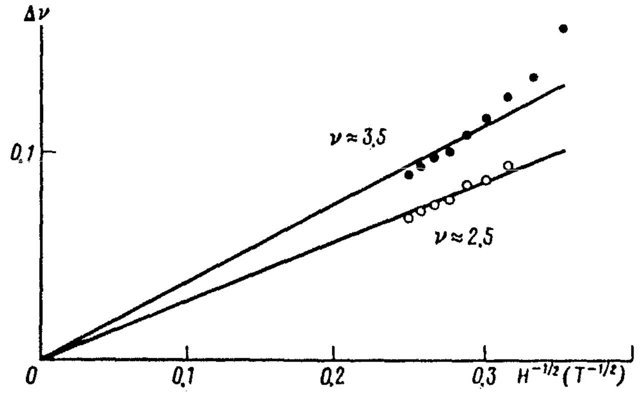

FIG. 3. Behavior of the half-widths of the peaks in ρ_{xx} measured with ac in a changing magnetic field.

electrons. For this approach to be valid the coupling energy of the electron and the ion must exceed the cyclotron energy (the coupling energy is about 40 meV, while in a 16-T field the cyclotron energy is 10 meV).

There is an independent way to check the existence of electron lakes. If the percolation picture is valid for all lower quantum levels, one can estimate the width of the peaks of ρ_{xx} as $\Delta \nu k \sim l/L \propto H.^{-1/2}$ 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 the slope we can estimate the scale of the potential $L \sim 800$ Å.

Thus the picture of the 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 the potential fluctuations due to the presence of 'frozen' charge $Q \gg e$ in the area L^2. Therefore, we will consider the second alternative of the percolation transition.

In this case one should assume that at low concentrations $N_s < N_s^c$ the localized electrons are distributed randomly over the whole sample plane. A potential relief for such a distribution of electrons can be created by the roughness of the Si–SiO$_2$ interface.[1,9] The percolation problem in this system is very close to the site problem in a 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 we know,[10] the critical concentration for lattices with one site per unit cell (triangular and squared) is $x_c = 0.5$ and $x_c = 0.59$, respectively. In a strong magnetic field in which an electron state occupies 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 magnetic fields used by us the electrons localized at the impurity ions do not affect the percolation condition $(a^* = \varepsilon\hbar^2/me^2 < l)$ and lead only to the shift of the phase boundary along the y axis.

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

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