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PROPERTIES OF ELECTRON INSULATING PHASE IN SI INVERSION LAYERS AT LOW TEMPERATURES

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Phase boundary in the (H, N_s)-plane has been found for the metal-insulator transition in Si inversion layers at magnetic fields normal and parallel to the interface. Transport properties of an insulating phase have been investigated. These are qualitatively the same irrespective of both the value and the direction of the magnetic field.

Metal-insulator transition in a $2D$ electron gas of Si metal-oxide-semiconductor structures (MOSFET's) was investigated in detail in a number of experiments at temperatures $T > 1\,\mathrm{K}$ (see [1]). The results of experiments in the absence of the magnetic field were interpreted as Anderson localization in $2D$ electron system [2]. Some doubts in this interpretation have arisen lately. New features in the behaviour of an insulating phase have been found in recent experiments at lower temperatures [3]. Firstly, as the temperature decreases current-voltage characteristics become strongly non-linear. At high currents ($> 1\,\mathrm{nA}$) a voltage tends to saturate. Secondly, ac voltage generation was observed in the non-linear region of $I - V$ characteristics. Authors [3] argue that these effects contradict the model of single-particle conduction and support the formation of a pinned quantum electron solid.

In the pioneering works [4,5] it has been shown that normal magnetic field promotes an insulating phase. Competition between the integer quantum Hall effect (QHE) and the insulating phase has been found in high-mobility Si MOSFET's at low temperatures [6].

The results mentioned above are similar to those obtained on AlGaAs/GaAs heterostructures in a quantizing magnetic field: i) At small filling factors there has been observed an insulating phase which is interrupted by a fractional QHE state [7–14]. ii) Current-voltage characteristics of the insulating phase are strongly non-linear [10,12–14]. iii) At high currents it is possible to observe a noise signal [13]. In the majority of papers Wigner crystal is considered to be the origin for the effects.

Another interpretation has appeared as a result of studying the phase boundary between metal and insulator in the (H, N_s)-plane for $2D$ electron gas in Si MOSFET's [15]. (We consider a $2D$ electron system capable of conducting current in a weak electric field at zero temperature to be *metal*. In accordance with this definition the system with zero conductivity σ_{xx} and quantized value of σ_{xy} is a metal. In an insulating phase all the components of a conductivity tensor are equal to zero at $T = 0$.) This phase boundary has been found to be a straight line in the extreme quantum limit. The slope of this line is equal to $\partial N_s/\partial H \approx 1/2\frac{e}{hc}$, which presumably points to the percolation character of metal-insulator transition.

In present work we have investigated properties of an insulating phase of a $2D$ electron gas in Si MOSFET's: i) Phase boundary in (H, N_s)-plane between metal and insulator in normal and parallel magnetic field; ii) Current-voltage characteristics for the insulating phase at different temperatures.

Measurements were made on three Si MOSFET's from different wafers. Peak mobilities were $\mu_{peak} \sim 3 \times 10^4\,\mathrm{cm^2/Vs}$ at temperature $T = 1.3\,\mathrm{K}$. All samples were of the "Hall-bar" geometry ($0.25 \times 2.5\ \mathrm{mm^2}$ and $0.8 \times 5\,\mathrm{mm^2}$) with distances between the nearest potential probes $0.625\,\mathrm{mm}$ and $1.25\,\mathrm{mm}$ respectively. The results obtained for different samples were qualitatively similar.

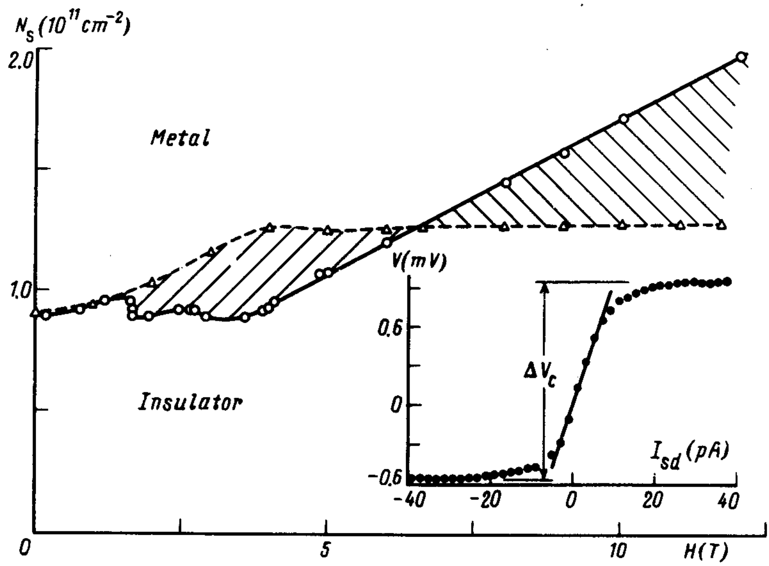

Fig.1. Phase boundaries at parallel (triangles) and normal (dots) magnetic fields. The inset shows $I - V$ characteristics measured at $H = 14\,\mathrm{T}$, $T = 60\,\mathrm{mK}$, $N_c - N_s = 0.77 \cdot 10^{10}\,\mathrm{cm^{-2}}$

Measurements were carried out in a dilution refrigerator TLM-400 with a base temperature of $\approx 25\,\mathrm{mK}$. To achieve maximum mobility, the samples were slowly (over 5 hours) cooled from the room temperature to $T = 1.3\,\mathrm{K}$ with a fixed voltage $V_g = 10$ V between the gate and the $2D$ layer. This procedure enabled us to obtain the most homogeneous distribution of electrons. When measuring the temperature dependences, the temperature at every point was stabilized to make sure that there were no temperature gradients in the mixing chamber. We obtained current-voltage characteristics by measuring the potential difference, V, between voltage probes when sweeping the source-drain current, I_{sd}. At temperatures below 1.3 K and at low electron densities, the contact resistances increased to very high values so that measurements with a standard Lock-in technique were no longer possible. All experimental results were obtained by a four-terminal dc technique using two KEITHLEY 614 DVM's as high-input-resistance preamplifiers. As at low N_s the resistance exceeded $10\,\mathrm{G\Omega}$, the source-drain current was set via a resistance of $150\,\mathrm{G\Omega}$.

The phase diagram including low magnetic fields is shown in Fig.1. A line separating metal and insulator phases was drawn through the points at which the longitudinal resistivity was equal to $100\,\mathrm{k\Omega}$. The phase boundary determined in this way is nearly independent of temperature. In the case of normal magnetic field (dots in Fig.1) it is in agreement with the results of two recent works [6,15]. In Fig.1 we also show a phase boundary for the same sample in a parallel magnetic field (triangles). At high magnetic fields ($H > 4\,\mathrm{T}$) the threshold electron density proves to be constant. In a weak magnetic field ($H < 1.5\,\mathrm{T}$) it does not depend on the orientation of magnetic field. At $H = 6.5\,\mathrm{T}$ the phase boundaries intersect

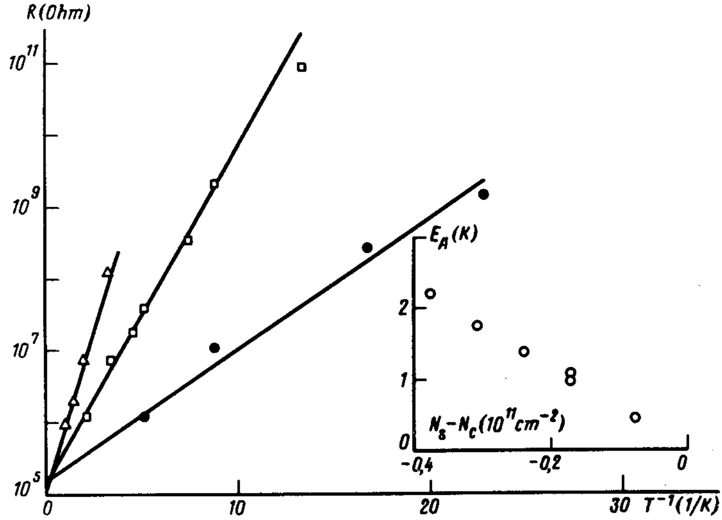

Fig.2. Arrhenius plots of resistance of the linear part of $I-V$ curve. $H = 14\,\mathrm{T}$, $N_c - N_s = 0.77\cdot10^{10}\,\mathrm{cm}^{-2}$; $1.73\cdot10^{10}\,\mathrm{cm}^{-2}$; $3.77\cdot10^{10}\,\mathrm{cm}^{-2}$. Activation energy vs electron density is displayed in the inset

each other, i.e., change of the magnetic field direction from parallel for the normal one causes the number of localized electrons to decrease at lower magnetic fields and to increase in the opposite case (see hatched regions in Fig.1).

Inset in Fig.1 displays current-voltage characteristics for an insulating phase. A shape of these characteristics is specific: At low currents a voltage is proportional to a current, while at high currents $> 0.1\,\mathrm{nA}$ one can observe a saturation of the voltage across a sample. The shape of $I-V$ characteristics is the same irrespective of both the point's location in (H, N_s)-plane and the direction of a magnetic field. However, when departing from the phase boundary the range of currents in which $I-V$ characteristics is linear becomes smaller and the difference ΔV_c between threshold voltages (see inset in Fig.1) rises in accordance with an overlinear law. Temperature dependences of the slope of the linear part of $I-V$ characteristics are shown in Fig.2 for different electron densities. These obey an Arrhenius law, the activation energy increasing with decreasing the electron density at a fixed magnetic field (inset in Fig.2). Absence of a jump of activation energy at the phase boundary indicates that this transition is not the first order one. As one can see from Fig.2 pre-exponential factors in the temperature dependence of resistance are the same, which points out the sample being "ideal" according to [1]. Long-range potential fluctuations are regarded to be absent in the "ideal" samples ([1]).

From works [16,17] it is expected that in the $(\sigma_{xy}, \sigma_{xx})$-plane there exists a line (separatrix) which separates regions with the different behaviour of conductivities when scaling a sample size. At sufficiently low temperature the experimental dependence of σ_{xx} on σ_{xy} should correspond to the separatrix. Fig.3 shows a part of this dependence at $\sigma_{xy} \le e^2/h$ when only one quantum level is filled with electrons. The separatrix has been found in the region of metal-insulator transition; experimental curves used for calculating the conductivities are demonstrated in the inset in Fig.3. The shape of the separatrix is similar to that obtained in [18] at larger σ_{xy} but the maximum value of σ_{xx} is three times as large.

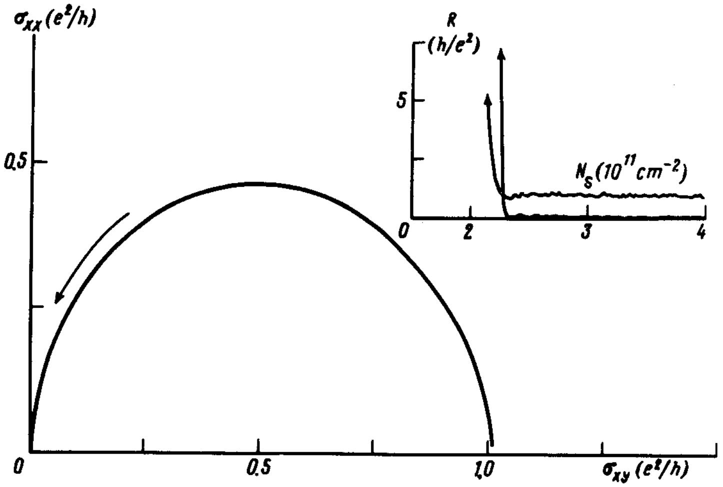

Fig.3. Dependence $\sigma_{xx}(\sigma_{xy})$ for the lowest quantum level. Experimental dependences of resistivities on the electron density obtained in the region of metal-insulator transition at $H = 14$T are shown in the inset

In paper [19] the mentioned dependence $\sigma_{xx}(\sigma_{xy})$ has been measured in the case when electron density slightly exceeds that at the phase boundary in the absence of a magnetic field. As filling factor decreases a part of experimental curve starting from the point (2,0) tends to the point (0,0) along an arc in the (σ_{xy}, σ_{xx})-plane. When decreasing the filling factor further the curve comes out of the point (0,0) to (1,0) drawing a smaller arc. On our samples we could observe the analogous behaviour in the region of oscillations of the phase boundary (Fig.1). It should be emphasized that this behaviour points out the disappearance of extended states of the completely filled lower Landau level and then their re-entrance as the number of electrons on the upper Landau level decreases.

As was mentioned above there exist three alternatives of the metal-insulator transition: i) Anderson localization in a short-range potential; ii) Percolation transition in a long-range potential; iii) The formation of a Wigner electron solid. Unfortunately the obtained experimental results do not enable us to determine unambiguously which mechanism really takes place.

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1. T.Ando, A.B.Fowler, and F.Stern, Rev. Mod. Phys. **54**, 437 (1982).
2. N.F.Mott, M.Pepper, S.Pollitt, et al., Proc. Roy. Soc. A **345**, 169 (1975).
3. S.V.Kravchenko, V.M.Pudalov, J.Campbell, and M.D'Iorio, Pis'ma Zh. Exp. Teor. Fis. **54**, 528 (1991) [JETP Lett. **54** (1991)].
4. S.Kawaji and J.Wakabayashi, Sol. St. Commun. **22**, 87 (1977).
5. M.Pepper, Phil. Mag. B **37**, 83 (1978).
6. M.D'Iorio, V.M.Pudalov, S.G.Semenchinsky, Phys. Lett. A **150**, 422 (1990).
7. R.L.Willett, H.L.Stormer, D.C.Tsui, L.N.Pfeiffer, K.W.West, and K.W.Baldwin, Phys. Rev. B **38**, 7881 (1988).
8. V.J.Goldman, M.Shayegan, and D.C.Tsui, Phys. Rev. Lett. **61**, 881 (1988).
9. E.Y.Andrei, G.Deville, D.C.Glattli, F.I.B.Williams, E.Paris, and B.Etienne, Phys. Rev. Lett. **60**, 2765 (1988).
10. R.L.Willett, H.L.Stormer, D.C.Tsui, et al., Phys. Rev. B **40**, 6432 (1989).
11. H.W.Jiang, R.L.Willett, H.L.Stormer, et al., Phys. Rev. Lett. **65**, 633 (1990).

12. V.J.Goldman, M.Santos, M.Shayegan, and J.E.Gunningham, Phys. Rev. Lett. **65**, 2189 (1990).
13. F.I.B.Williams, P.A.Wright, R.G.Clark, et al., Phys. Rev. Lett. **66**, 3285 (1991).
14. H.W.Jiang, H.L.Stormer, D.C.Tsui, L.N.Pfeiffer, and K.W.West, Phys. Rev. B **44**, 8107 (1991).
15. V.T.Dolgopolov, G.V.Kravchenko, and A.A.Shashkin, Pis'ma Zh. Exp. Teor. Fis. **55**, 146 (1991).
16. H.Levine, S.B.Libby, A.M.M.Pruisken, Phys. Rev. Lett. **51**, 1915 (1983).
17. D.E.Khmelnitskii, Pis'ma Zh. Exp. Teor. Fis. **38**, 454 (1983).
18. V.T.Dolgopolov, A.A.Shashkin, B.K.Medvedev, V.G.Mokerov, Zh. Exp. Teor. Fis. **99**, 201 (1991).
19. S.V.Kravchenko, J.A.A.J.Perenboom, and V.M.Pudalov, Phys. Rev. B **44**, 13513 (1991).