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FLOATING UP OF THE EXTENDED STATES OF LANDAU LEVELS IN A TWO-DIMENSIONAL ELECTRON GAS IN SILICON MOSFET's

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Phase diagram in H, N_s plane for a 2D electron gas in Si MOSFET's has been studied. It has been found that transition into a low-electron-density insulating phase occurs only if all the extended states have passed, leaving Fermi sea, through the Fermi level. In contrast to the case of high magnetic fields when the extended states of each Landau level follow its centre, in weak magnetic fields they float up and finally combine all together when decreasing magnetic field.

In energy spectrum of a two-dimensional electron gas (2DEG) in quantizing magnetic field there exist extended states near the centre of a Landau level, as was proved experimentally by direct measurements of the Hall conductivity [1]. In the absence of a magnetic field all the electron states in 2D system are expected to be localised in accordance with the scaling hypothesis. Hence, in weak magnetic fields the extended states should float up without following Landau levels and leave Fermi sea when decreasing magnetic field, as was shown in [2]. The result that in the weak magnetic field the extended states are shifted up with respect to the middle of a Landau level was obtained in calculations [3] and treated as an effect of the mixing of Landau levels. Recently in paper [4] there has been made a statement about the existence of extended states in 2DEG in a zero magnetic field which obviously contradicts the scaling model. This result has been obtained by solving Schrödinger equation in the case of short-range scatterers. Presumably it should be valid, in first turn, for silicon MOSFET's because of a short-range fluctuation potential in these samples.

There are two possibilities for the extended states of Landau levels in the case of weak magnetic fields. First, the extended states are pushed up out of Fermi sea when decreasing magnetic field if the scaling hypothesis is valid. And second, they combine all together with a possible shift up in energy [3]. To determine behaviour of the extended states the metal-insulator transition in 2DEG in Si MOSFET's has been studied in a wide region of electron densities.

Dissipative conductivity in the 2D system at sufficiently low temperatures is known to tend to zero not only with decreasing electron density but also at integer filling factors resulting in the quantum Hall effect (QHE). Since in quantum Hall regime the dissipationless Hall current flows in 2DEG there emerges a question: should one consider this state of the electron gas to be insulator or metal? At filling factors close to integer the Fermi level is in a region of localised states. Below Fermi level there are the extended states of Landau levels capable of carrying Hall current. (In the case of Hall bar sample the Hall current is carried also by the extended edge states at the Fermi level.) As long as charge transfer in the direction of electric field is absent it seems reasonable to speak about the insulator. Properties of a so-defined insulating phase, in particular, the charge transferred between sample contacts when changing magnetic flux through the sample depend on the number of Landau levels below the Fermi level, i.e., the insulating phase can be characterised by Hall conductivity value. When the Fermi level is located in extended states of a Landau level the conductivity σ_{xx} is finite and the 2D electron system demonstrates a metal behaviour. Actually the same definition was used in work [5].

We believe that a metal phase is characterised by the conductivity $\sigma_{xx} > e^2/h$ when temperature tends to zero. In an insulating phase σ_{xx} is negligibly small compared to e^2/h. Hence, there is a boundary value of conductivity separating the metal and insulator. We regarded that the position of metal-insulator transition is determined by $\sigma_{xx}^{-1} = 500$ kΩ. Choice of the boundary conductivity value qualitatively did not influence the experimental results.

Measurements were made on Hall bar Si MOSFET's. They had dimensions 0.25×2.5 mm^2 with distances between the nearest potential probes 0.625 mm. Peak mobilities were $\mu_{peak} \sim 3 \times 10^4$ cm^2/Vs at temperature $T = 1.3$ K. The measured resistances R_{xx} and R_{xy} were used to calculate the conductivity σ_{xx}. We believe that in contrast to work [6] non-local effects were not significant in our samples. This follows from the fact that the values of σ_{xx} calculated from R_{xx}, R_{xy} were close to those measured on Corbino geometry samples.

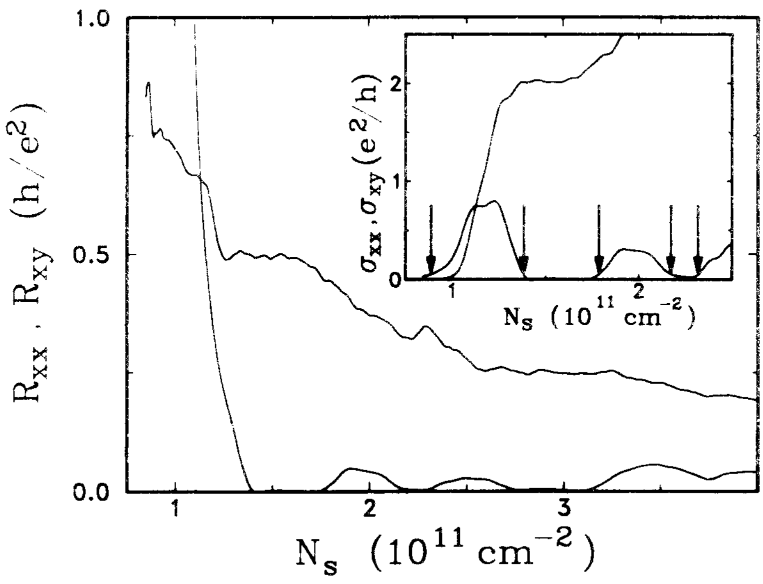

Fig.1. Resistances R_{xx}, R_{xy} against electron density at $H = 3$ T. To allow for the admixture of R_{xx} the Hall resistance was measured at both polarities of magnetic field and then averaged. The conductivities calculated from this data are shown in the inset. Arrows mark the position of metal-insulator transitions

In contrast to previous works our experiments were carried out on high-mobility samples in a range of low electron densities (down to $\sim 8 \times 10^{10}$ cm^{-2}) at a temperature of ≈ 25 mK. 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 an electrometer as high-input-resistance amplifier. Currents through the sample were in the range from 2 to 40 nA and corresponded to the linear regime.

Experimental traces R_{xx}, R_{xy} as a function of the electron density N_s are displayed in Fig.1. At high N_s one can see a series of plateaus in R_{xy} accompanied by zeros in R_{xx} while at low electron densities the resistance R_{xx} tends to infinity in decreasing N_s. This behaviour indicates the transition into an insulating phase that is characterised by zero Hall conductivity. At initial stage of the growth in R_{xx} the Hall resistance does not change appreciably becoming small compared to the longitudinal resistance. It is evident that when $R_{xx} \gg R_{xy}$ the measurements of R_{xy} are not reliable because of a possible admixture of R_{xx} into the measured value. Measuring the Hall resistance at different polarities of magnetic field one can partly remove the admixture of R_{xx}. So, at the metal-insulator transition in Si MOSFET's in weak magnetic fields the Hall resistance remains close to its classical value, which is similar to the case of AlGaAs/GaAs heterostructures in strong magnetic fields [7,8]. The inset in Fig.1 shows the calculated conductivities σ_{xx}, σ_{xy} against electron density. In this magnetic field the quantum Hall state characterised by $\sigma_{xy} = e^2/h$ is not realized.

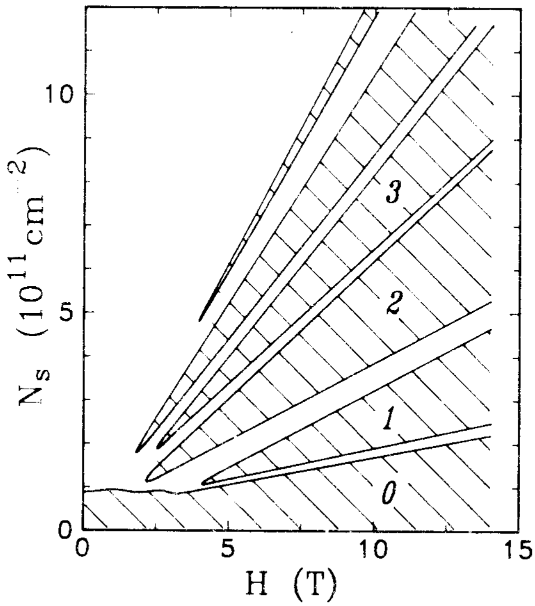

Fig.2. Metal-insulator phase diagram. Digits indicate the values of the Hall conductivity in units e^2/h for different insulating phases

Marking the position of metal-insulator transitions in different magnetic fields we obtain metal-insulator phase diagram in the H, N_s plane presented in Fig.2. One can see from figure that each insulating phase is surrounded by the metal phase. It means that not until the extended states pass through the Fermi level does transition into an insulating phase occur.

In a wide range of magnetic fields the phase boundaries are straight lines with high accuracy. Top part of the phase diagram corresponding to the QHE is more or less trivial. It is the region of low electron densities that attracts our attention (see Fig.3). As seen from Figs.2, 3 the lower boundary separates the low-electron-density insulating phase and the metal one in which the insulator

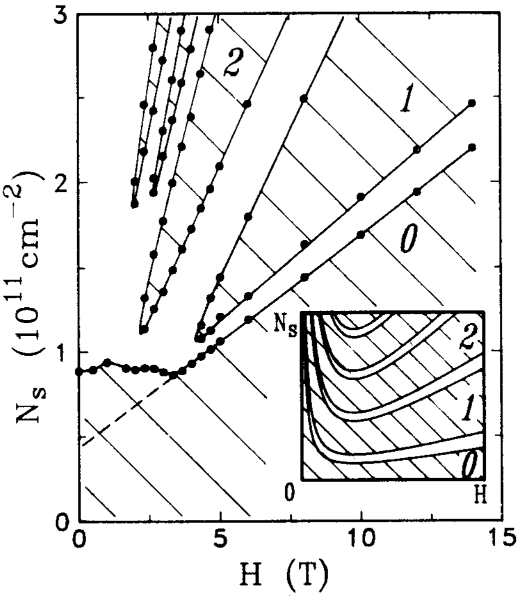

Fig.3. Blow up of the lower part of the phase diagram. Dashed line is an extention of straight line confining the insulating phase with $\sigma_{xy} = 0$ at $H > 4$ T. Sketch of the phase diagram expected from scaling theory is displayed in the inset

strips with non-zero σ_{xy} are embedded. These strips are directed along straight lines coming into coordinate axis zero with the slopes corresponding to integer filling factors. In turn, the insulator strips form a set of metal ones with the analogous geometry so that at high enough magnetic fields the extended states are centered in each Landau level, as was expected.

However, there is a metal strip between the insulating phases with $\sigma_{xy} = 0$ and $\sigma_{xy} = e^2/h$ that is specific. The extention of its lower boundary intersects the ordinate axis at a point pertaining to the density of electrons strongly coupled by positive ions at the interface Si-SiO_2 [9]. Since in high magnetic fields the slope of this metal strip is close to $e/2hc$ the strongly coupled electrons do not affect the behaviour of the rest, giving rise only to a parallel shift of the lower metal strip relative to the expected position. As seen from Fig.3 the situation changes in weak magnetic fields: at $H = 3.4$ T the lower boundary strongly deviates from the extention of straight line confining the zero-Hall-conductivity insulating phase in high magnetic fields, i.e., the extended states *leave* the lowest Landau level. In other words, it is the value of H at which the lowest Landau level enters the region of extended states. Moreover, the lower boundary tends to higher N_s whenever it intercepts the expected position of the higher Landau levels. Since there exists the minimum magnetic field, H^*, for each insulating phase with $\sigma_{xy} \neq 0$ the extended states of neighbouring Landau levels become contiguous at $H < H^*$. Though in this case we cannot find a boundary between them we argue that below each insulating phase with non-zero σ_{xy} there is the corresponding number of metal strips which is determined by the value of σ_{xy}.

The behaviour of the lower boundary means that in weak magnetic fields the extended states do not follow Landau levels but float up. However, instead of leaving Fermi sea (Fig.3) they just combine all together when decreasing magnetic field. It is interesting that despite the observed deviation of the lower boundary, properties of the low-electron-density insulating phase have been found to be similar in the whole range of magnetic fields [10–13].

The experimental results are in agreement with the statement made in [4] about the existence of extended states in 2D system in a zero magnetic field. Nevertheless final conclusions cannot be drawn because, in principle, there is a possibility that phase diagram could change when lowering temperature further.

In conclusion, we have investigated metal-insulator phase diagram in a 2DEG of Si MOSFET's in a wide range of electron densities. At low temperatures, the phase boundary in H, N_s plane was assumed to be determined by a fixed value of σ_{xx}. Since the metal phase surrounds every insulating phase the extended states do not disappear below Fermi level when moving in the H, N_s plane; they leave Fermi sea passing through the Fermi level. In weak magnetic fields the extended states do not follow Landau levels but float up and combine all together when decreasing magnetic field. The experimental results point out similarity between all the insulating phases characterised by different values of the Hall conductivity.

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