Floating up of the extended states of Landau levels in a two-dimensional electron gas in silicon MOSFET's

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(Submitted 17 June 1993; resubmitted 6 July 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **58**, No. 3, 215–219 (10 August 1993)

Phase diagram in H, N_s plane for a 2D electron gas in Si MOSFET's has been studied. It was found that transition to 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 center, in weak magnetic fields they float up and finally combine upon lowering the magnetic field.

In the energy spectrum of a two-dimensional electron gas (2DEG) in a quantizing magnetic field there exist extended states near the center 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 a 2D system are expected to be localized in accordance with the scaling hypothesis. Hence, in weak magnetic fields the extended states should float up without following the Landau levels and leave the Fermi sea in a decreasing magnetic field, as was shown in Ref. 2. The result that in a 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. The existence of extended states in 2DEG in a zero magnetic field, an obvious contraction of the scaling model, has recently been reported.[4] This result was obtained by solving the Schrödinger equation for short-range scatterers. Presumably it should be valid primarily 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 out of the Fermi sea in a decreasing magnetic field if the scaling hypothesis is valid. Secondly, they combine, with a possible upward shift in energy.[3] To determine the behavior of the extended states, the metal–insulator transition in 2DEG in Si MOSFET's has been studied in a wide range 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, which results in the quantum Hall effect (QHE). Since in the quantum Hall regime the dissipationless Hall current flows in 2DEG, should this state of the electron gas be assumed an insulator or a metal? At filling factors close to integer, the Fermi level is in a region of localized states. Below the Fermi level, there are the extended states of Landau levels capable of carrying the Hall current. (In the case of a 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 the electric field is absent, it seems reasonable to speak about the insulator. Properties of the so-called insulating

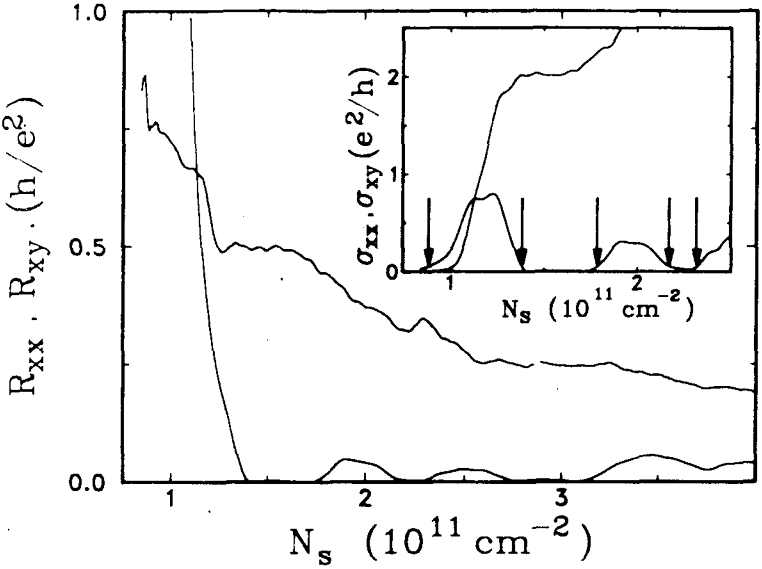

FIG. 1. Resistances R_{xx} and R_{xy} versus the electron density at $H = 3$ T. To allow for the admixture of R_{xx}, the Hall resistance was measured at each polarity of the magnetic field and then averaged. The conductivities calculated from this data are shown in the inset. Arrows mark the position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

phase, in particular, the charge transferred between sample contacts when the changing magnetic flux through the sample depends on the number of Landau levels below the Fermi level, i.e., the insulating phase, can be characterized by the Hall conductivity. When the Fermi level is located in the extended states of a Landau level, the conductivity σ_{xx} is finite and the 2D electron system demonstrates a metal behavior. Actually, the same definition was used in Ref. 5.

We believe that a metal phase is characterized by the conductivity $\sigma_{xx} > e^2/h$, when the 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 the conductivity which separates the metal and the insulator. We assume that the position of the metal–insulator transition is determined by $\sigma_{xx}^{-1} = 500$ kΩ. The choice of the boundary conductivity value qualitatively does not affect the experimental results.

Measurements were made on the Hall bar Si MOSFET's. Their size was 0.25 $\times$2.5 mm, with distances between the nearest potential probes 0.625 mm. The peak mobilities were $\mu_{\text{peak}} \sim 3 \times 10^4$ cm^2/(V · s) at a 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 Ref. 6, the nonlocal effects were not important in our samples. This conclusion follows from the fact that the values of σ_{xx} calculated from R_{xx} and R_{xy} are close to those measured in Corbino geometry samples.

In contrast with previous studies, our experiments were carried out with high-mobility samples in the 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

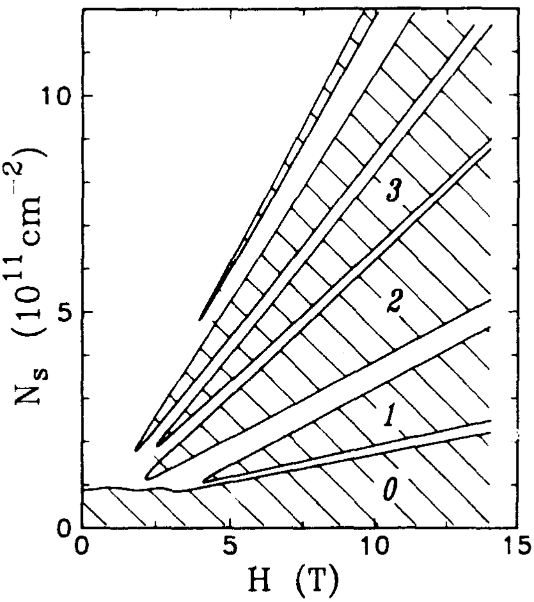

FIG. 2. Metal–insulator phase diagram. Digits indicate the values of the Hall conductivity in units e^2/h for different insulating phases.

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 2–40 nA, which corresponded to the linear regime.

Experimental traces R_{xx} and R_{xy} as a function of the electron density N_s are shown in Fig. 1. At high N_s we 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 with decreasing N_s. This behavior indicates that there is a transition to an insulating phase which is characterized by a zero Hall conductivity. At the initial stage of growth of R_{xx}, the Hall resistance does not change appreciably, becoming smaller compared with 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}. Accordingly, at the metal–insulator transition in Si MOSFET's in weak magnetic fields the Hall resistance remains near its classical value, which is similar to the case of AlGaAs/GaAs heterostructures in strong magnetic fields.[7,8] The inset of Fig. 1 shows plots of the calculated conductivities σ_{xx} and σ_{xy} versus the electron density. In this magnetic field the quantum Hall state, which is characterized by $\sigma_{xy}=e^2/h$, is not realized.

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

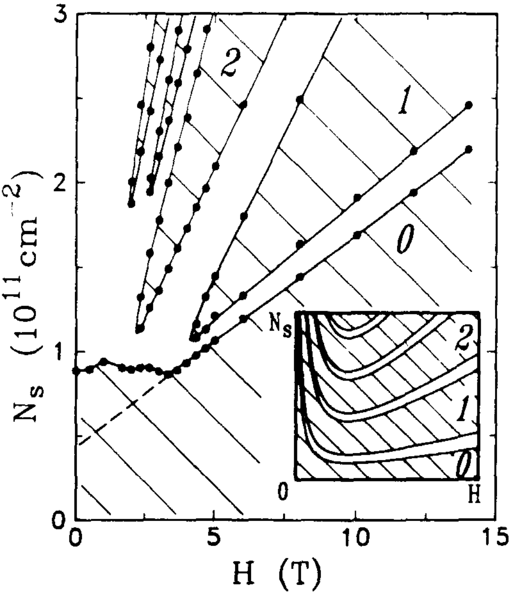

FIG. 3. Blow up of the lower part of the phase diagram. Dashed line is an extension of the straight line confining the insulating phase with $\sigma_{xy}=0$ at $H>4$ T. The sketch of the phase diagram expected from scaling theory is displayed in the inset.

In a wide range of magnetic fields the phase boundaries are straight lines within a high accuracy. Top part of the phase diagram corresponding to the QHE is basically trivial. The region of low electron densities is worth noting (see Fig. 3). As can be seen from Figs. 2 and 3, the low boundary separates the low-electron-density insulating phase and the metal phase, in which the insulator strips with nonzero σ_{xy} are embedded. These strips are directed along straight lines which run into the coordinate axis zero, with the slopes corresponding to integer filling factors. In turn, the insulator strips form a set of metal strips 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 extension of its lower boundary intersects the ordinate axis at a point pertaining to the density of electrons which are strongly coupled by positive ions at the interface[9] Si–SiO_2. Since in high magnetic fields the slope of this metal strip is close to $e/2hc$, the strongly coupled electrons do not affect the behavior of the rest, giving rise only to a parallel shift of the lower metal strip relative to the expected position. As can be seen in Fig. 3, the situation changes in weak magnetic fields: At $H=3.4$ T, the lower boundary strongly deviates from the extension of the 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. The lower boundary, moreover, tends to higher N_s when 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 neighboring Landau levels become contiguous at $H<H^*$. Although in this case we cannot find a boundary between them, we believe that below each insulating phase with nonzero σ_{xy} there is a corresponding number of metal strips which is determined by the value of σ_{xy}.

The behavior of the lower boundary suggests that in weak magnetic fields the extended states do not follow Landau levels but float up. Instead of leaving the Fermi sea (Fig. 3), however, they just combine in a decreasing magnetic field. It is interesting to note that despite the observed deviation of the lower boundary, the properties of the low-electron-density insulating phase were found to be similar in the whole range of magnetic fields.[10–13]

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

In conclusion, we have investigated a 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 the H, N_s plane is 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 the Fermi level when moving in the H, N_s plane; they leave the Fermi sea passing through the Fermi level. In weak magnetic fields the extended states do not follow the Landau levels but float up and combine in a decreasing magnetic field. The experimental results point out that there is a similarity between all the insulating phases which are characterized by different values of the Hall conductivity.

This work is supported by a grant 93-02-2304 from the Russian Foundation for Basic Research.

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