Effect of current in the channel of a metal-insulator-semiconductor structure on its charge when a quantized Hall resistance is present

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The charge on a metal-insulator-semiconductor structure, Q_S, has been studied for various gate voltages V_g and various currents in the channel, I_0, over the temperature interval $T = 0.42$–4.2 K in a magnetic field $H \approx 70$ kOe. The results show that Q_S depends on I_0, because the current is redistributed during passage through that region of V_g or H in which a plateau is observed on the Hall resistance ρ_{xy}. The relationship between Q_S and I_0 which has been found is used to explain the hysteresis which had been found previously in $Q_S(V_g)$, $Q_S(H)$, and $V_g(H)$. The results show that the hysteresis is due to the appearance of eddy currents, whose distribution also changes as V_g of H is varied.

How the current is distributed in the two-dimensional ($2D$) layer of charge carriers under conditions of a quantized Hall resistance has been under discussion for several years now.[1] Different authors have offered two alternative explanations of the current flow: 1) Current flows only along the edges of the sample, along the banks of the channel. 2) The current is distributed roughly uniformly over the cross section of the channel. Recent direct experiments[2,3] have shown that the actual current distribution in GaAs heterojunctions is not what was predicted earlier. As a magnetic field is varied, the current contracts into a filament near one bank of the channel at the beginning of the plateau on the quantized Hall resistance. This filament then moves toward the other bank, where it dissipates. This current distribution, which might be unexpected at first glance, can easily be explained in terms of a gradient of the carrier density in the samples. This explanation was offered in Ref. 4. A similar effect should also occur, according to Ref. 4, in the case of a $2D$ carrier layer near a conducting plane [e.g., in a metal-insulator-semiconductor (MIS) structure]. The density gradient required for an observation of the effect in this case would be produced by a current, even if the situation is uniform in the absence of a current.

To study the current distribution, Ebert *et al.*[2] and Zheng *et al.*[3] prepared samples with contacts inside the channel. Conclusions were drawn about the current distribution in this case from measurements of the potential difference between the contacts. In the case of an MIS structure, certain conclusions about the current distribution can also be reached without fabricating auxiliary contacts. It is sufficient to measure the charge Q_S on the structure as a function of the voltage between the contact to the channel and the gate, V_g.

In the present paper we derive a theory for the effect of the current distribution on the charge on an MIS structure, Q_S, and we also report an experiment carried out to observe an effect of the current on Q_S. We analyze the results of this experiment. We also report some new experimental results on the hysteretis observed in $Q_S(V_g)$ and $V_g(H)$ in Ref. 5. We offer an explanation for that effect.

RELATIONSHIP BETWEEN Q_S AND THE CURRENT DISTRIBUTION

As became clear after the observation of oscillations in the chemical potential μ_0 of a $2D$ layer as a magnetic field was varied,[5] μ_0 is not determined by the chemical potential of the electrons in the volume; it oscillates independently of the chemical potential. The period of the oscillations is the de Haas–van Alphen oscillation period, which is determined exclusively by the surface density (n_S) of electrons in the $2D$ layer.[6] We will therefore ignore the effect of the bulk electrons on μ_0. If there is no current in the $2D$ layer, the electrochemical potentials at various points in the layer must be identical; i.e., the condition $\mu_0 - e\varphi = \text{const}$ must hold, where e is the charge of an electron, and $\varphi = \varphi(r)$ is the potential of some point in the $2D$ layer in the electric field of the gate electrode, whose potential we set equal to zero. The quantity μ_0 is a function of n_S and also of the magnetic field H in the temperature T: $\mu_0 = \mu_0(n_S, H, T)$. We also note that n_S can be found in terms of φ from the formula for a plane capacitor: $n_S = \varkappa\varphi/4\pi de$, where $\varkappa$ is the dielectric function of the insulator, and d is its thickness. The latter equality of course holds only for the average value of n_S over some region with linear dimensions greater than d. If a current flows in the $2D$ layer, its density is determined by

$$\|\sigma_{ij}\| \nabla(\varphi - e^{-1}\mu_0) = \mathbf{j}. \tag{1}$$

Here $\mathbf{j} = \mathbf{j}(r)$ is the current density, $\nabla = (\partial/\partial x, \partial/\partial y)$, and $\|\sigma_{ij}\|$ is the $2D$ conductivity tensor.

Since μ_0 is a function of n_S and thus of φ, Eq. (1) can be rewritten as

$$\|\sigma_{ij}\| [1 - e^{-1}(\partial\mu_0/\partial\varphi)] \nabla\varphi = j. \tag{2}$$

In the absence of a magnetic field we would have $\mu_0 = 2\pi\hbar^2 n_S/4m^*$, where m^* is the effective mass of an elec-

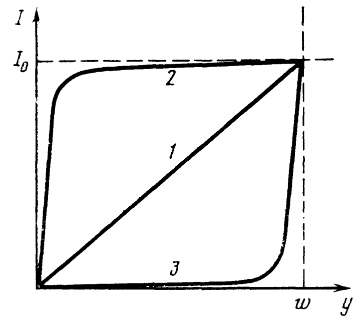

FIG. 1. The functions $I(y)$ for (1) a uniform distribution of the current over the channel, (2) the case in which the current is concentrated near the right bank, and (3) the case in which the current is concentrated near the left bank.

tron, and $\hbar$ is Planck's constant. We have taken into account a fourfold degeneracy in terms of the spin and the valleys here. In this case we have $e^{-1}(\partial\mu_0/\partial\varphi = \varkappa\hbar^2/8m^*e^2d$. At $d\sim 1000$ Å this ratio is on the order of 10^{-3}, so that we are justified in ignoring the term proportional to $\partial\mu_0/\partial\varphi$ in (2).

In a magnetic field the state density of electrons in Landau levels increases, while that in the gaps between levels decreases. A decrease in the state density can give rise to the inequality

$$e^{-1}(\partial\mu_0/\partial\varphi)\gtrsim 1, \tag{3}$$

which had hold only in a narrow interval $\Delta\mu_0$, less than the distance between Landau levels, $\Delta\varepsilon(H,n_S)$. In this case we can ignore the components $\sigma_{ij}, i\neq j$, of the conductivity tensor in comparison with the components σ_{ij}, $i\neq j$. If the current flows along the x axis, then we have $\mu_0=\mu_0(y)$ according to (1), and the change in μ_0 in the region from y_1 to y_2 is

$$\Delta\mu_0\sim\sigma_{xy}^{-1}e\int_{y_1}^{y_2} j_x(y)\,dy.$$

Substituting in $\nabla\mu_0=\Delta\varepsilon$ to find an upper estimate, we find that a current $I_0>|\sigma_{xy}e^{-1}\Delta\varepsilon|$ cannot flow through a region with a low state density. For the case $\sigma_{xy}\sim e^2/2\pi\hbar$, $\Delta\varepsilon\sim 1$ meV, we then find $I_0\lesssim 10^{-7}$ A. In the experiments which we will describe below we studied the behavior of MIS structures at currents $I_0\gtrsim 10^{-5}$ A. In this case, most of the current always flows where the state density is rather high, so that we can ignore the term proportional to $\partial\mu_0/\partial\varphi$ in (2) and assume

$$\|\sigma_{ij}\|\nabla\varphi=\mathbf{j}. \tag{4}$$

The conclusion which we have reached tells us that we must be extremely suspicious of experiments carried out to determine the energy density of electron states from an analysis of components of the conductivity tensor. A pronounced decrease in the state density in a gap between Landau levels could be "felt" only if a low current is flowing through the $2D$ layer, $I_0\lesssim 10^{-7}$ A, but even in this case the experiment would show only some average state density over an interval $\Delta\mu_0\sim e\sigma_{xy}{}^{-1}I_0$.

We now seek the charge on the MIS structure. We assume that a current I_0 is flowing in the x direction through a channel of width w, while $\mathbf{H}$ is directed along the z axis. In the plateau of the Hall conductivity we have $\sigma_{xx}\ll|\sigma_{xy}|$. We will therefore assume that the current density is a function of the coordinate y alone. For this case we find from (4)

$$n_s(y)=(\varkappa/4\pi de)\,[\varphi(0)+\rho_{xy}I(y)],$$
$$I(y)=\int_0^y j_x(y)\,dy. \tag{5}$$

Here $\varphi(0)$ is the potential at the right edge of the channel ($y=0$) and $\rho_{xy}=-\sigma_{xy}{}^{-1}$ is the Hall resistance. Integrating (5) over the width of the sample, we find

$$Q_S=Le\int_0^w n_S(y)\,dy=C_0w^{-1}\Big[\varphi(0)\,w+\rho_{xy}\int_0^w I(y)\,dy\Big], \tag{6}$$

where L is the length of the channel, and $C_0=\varkappa Lw/4\pi d$ is the capacitance of the MIS structure.

We assume that the gate voltage V_g is applied between the gate and a contact at the right bank of the channel: $V_g=\varphi(0)$. In the absence of a current, the charge would then be $Q_S=C_0V_g$, and a current would change it to

$$\delta Q_S=Q_S-C_0V_g=C_0\rho_{xy}w^{-1}\int_0^w I(y)\,dy. \tag{7}$$

The change δQ_S depends on the current distribution in the channel. If this distribution is uniform, the function $I(y)$ increases linearly from 0 at $y=0$ to I_0 at $y=w$ (Fig. 1). If ρ_{xy} is positive, a shift of the current toward the right bank of the channel increases δQ_S, while one toward the left bank reduces it. A change in the current distribution in the channel can thus be observed by measuring the dependence $Q_S(V_g)$.

EXPERIMENTAL PROCEDURE

The test samples are MIS structures fabricated on the (001) surface of a p-type silicon single crystal.[7] The dimensions of the structures are 5×0.8 mm; the thickness of the oxide layer is 2000 Å; and the capacitance is $C_0=700$ pF. For the samples selected for the experiments the maximum carrier mobility is $\mu_{max}=(30\text{–}40)\cdot 10^3$ cm^2/V·s) at $T=1$ K. The current is passed through the sample between the source and drain contacts along the channel.

In the experiments we measure the current which charges the gate, I_g, when the gate voltage V_g is varied. If V_g is varied at a constant rate we have

$$I_g=-dQ_S/dt=-(dQ_S/dV_g)(dV_g/dt)=\text{const}\cdot dQ_S/dV_g.$$

The quantity found directly from the experiment is thus the derivative dQ_S/dV_g. The arrangement for these measurements is shown in Fig. 2. The measurements are carried out in a static magnetic field directed perpendicular to the plane of the sample. In the experiments, V_g is varied at a rate between 10^{-3} and 10 V/s. The measured current I_g correspondingly varies from 10^{-12} to 10^{-8} A. The intrinsic noise of the current-to-voltage converter is less than 10^{-14} A.

In some of the experiments we measure the change in

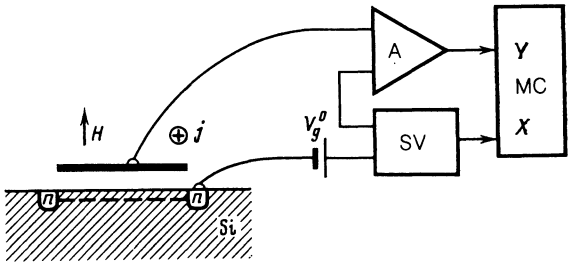

FIG. 2. Arrangement for measuring the gate charging current. A—Amplifier and current-to-voltage converter; SV—sawtooth voltage generator; V_g^0—source of the constant gate voltage; MC—multichannel storage.

the gate voltage V_g of a sample when the magnetic field changes, as was done in Ref. 6. The arrangement for those measurements differs from the arrangement in Fig. 2 only in that the sawtooth voltage generator is not included in the power circuit of the gate, and the current-to-voltage converter is replaced by an amplifying electrometer. In the analysis of the results of these experiments, a correction is made for the capacitance of the line connecting the sample to the amplifying electrometer.

The output signal from the measuring instrument is stored in digital form by a multichannel storage device. The channel numbers are changed at uniform time intervals upon a signal from an internal sweep generator. The time at which the sweep is triggered is synchronized with a certain phase of the sweep of V_g or if the magnetic field on the basis of a sync pulse from the sawtooth voltage generator. This measurement system makes it possible to build up the signal during repeated passes through a given interval of V_g or H (so that the signal-to-noise ratio is improved), to store the results in digital form on magnetic tape for a long time, and to carry out a preliminary analysis of the results, e.g., integration.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Effect of the current I_0 on Q_S

These experiments show that sharp anomalous features appear in dQ_S/dV_g (curve 1 in Fig. 3) near integer values of the occupation nunber of the Landau levels, $\nu = n_S/n_H$ ($n_H = eH/2\pi\hbar c$ is the surface state density at the Landau level) as the result of the current I_0 flowing through the channel. In the absence of a current, at $T \gtrsim 2$ K, we would have $dQ_S/dV_g = C_0$ except for a small decrease at $\nu = i$, caused by the decrease in the state density in the gap between Landau levels (curve 2 in Fig. 3).

On the curve of dQ_S/dV_g versus V_g we can distinguish three regions (Fig. 4b): 1) and 3) regions with $dQ_S/dV_g < C_0$; 2) region with $dQ_S/dV_g > C_0$. If we assume that at values of ν far from integer values the current in the channel is distributed uniformly over its width, then it follows from (7) that in region 1 the current collects near one bank of the channel. In region 2 it then moves toward the other bank. Later, in region 3, a uniform current distribution is restored. These changes in the current distribution agree

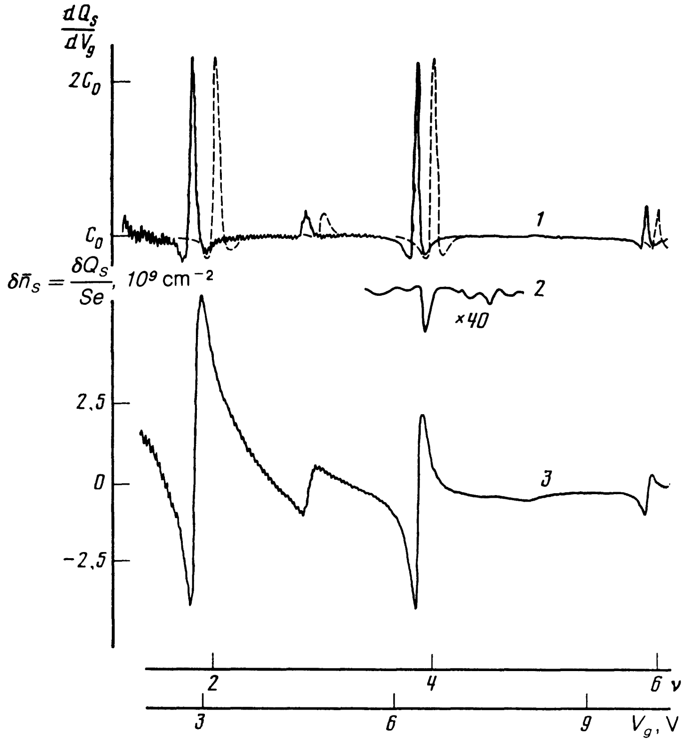

FIG. 3. The derivative dQ_S/dV_g (curves 1 and 2) and the average electron density $\delta\bar{n}_S$ (curve 3) versus the gate voltage V_g at $T = 2$ K, $H = 70$ kOe, and $n_H = 1.6 \cdot 10^{11}$ cm^{-2} Curves 1: solid—$I_0 = 20$ μA; dashed—$I_0 = -20$ μA. Curve 2: $I_0 = 0$, at an amplification 40 times greater. Curve 3: Result of an integration of curve 1, with $I_0 = 20\,\mu$A. The occupation numbers of the Landau levels, ν, at $I_0 = 0$ are also plotted along the abscissa.

well with those predicted in Ref. 4 for MIS structures.

To illustrate this point, let us assume that the direction of the current is the direction adopted as positive in (5). In this case the potential difference between the gate and edge of the channel ($y = w$) is always larger than that for any other point in the channel. It then follows that $n_S(y)$ has a maximum at $y = w$ [see (5)]. If $n_S(y)$ is markedly different from in_H for all $0 < y < w$, then we have $\rho_{xx}(y) \approx$ const, and the current is distributed uniformly over the channel. With increasing V_g, the carrier density in the channel approaches

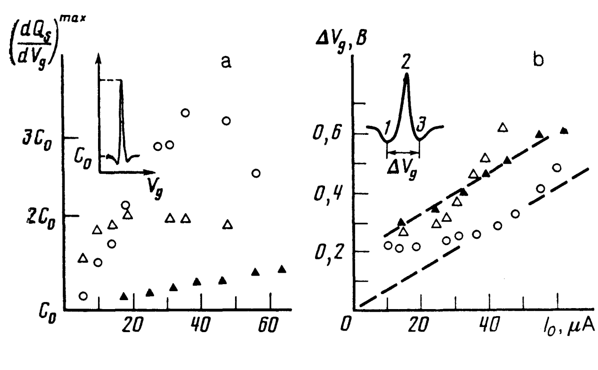

FIG. 4. Maximum value of dQ_S/dV_g versus the current I_0. b: Distance between minima versus the current I_0. ($H = 70$ kOe) ○—$\nu \approx 4$, $T = 2$ K; △—$\nu \approx 2$, $T = 2$ K; ▲—$\nu \approx 4$, $T = 4.2$ K. The slope of the dashed lines in Fig. 5 is $\rho_{xy} = 6453$ Ω ($\nu = 4$).

in_H. When the condition $n_S(w) \approx in_H$, $\rho_{xx}(y)$ becomes satisfied, $\rho_{xx}(y)$ has a minimum at $y = w$, and the depth of this minimum increases as $n_S(w)$ approaches in_H. These changes involve redistribution of the current: a current "filament" forms near $y = w$. The function $j(y)$ now has a maximum at $y = w$. The center of gravity of the current shifts away from the middle of the channel toward the left edge ($y = w$). According to (7), this shift should reduce δQ_S; i.e., we have $dQ_S/dV_g < C_0$. After $n_S(w)$ exceeds in_H, the current filament begins to move toward the left bank of the channel. The position Y at which the current density is at maximum is determined by the condition $n_S(Y) = in_H$, $dQ_S/dV_g > C_0$. The dissipation of the filament at the left edge of the channel is also due to the decrease in Q_S, since the center of gravity of the current moves to the right, toward the middle of the channel. The last minimum in dQ_S/dV_g should therefore occur when the condition $n_S(0) \approx in_H$ is satisfied.

Since $n_S(0)$ is independent of I_0, being determined by the given value of V_g, a change in the magnitude or sign of the current flowing through the channel should not displace one of the minima, while the position of the other minimum should depend strongly on the current, according to (5). For example, the minimum corresponding to $n_S(w) \approx in_H$ will lie to the left or right of the $n_S(0) \approx in_H$ minimum, depending on the current direction. This conclusion is confirmed experimentally. Comparison of the solid line in Fig. 3, drawn for the positive current direction, with the dashed line (which corresponds to the current of the other sign) shows that the position of one of the minima is indeed independent of the current direction. The position of the second minimum of dQ_S/dV_g with respect to the first depends on the sign of the current, as can be seen from Fig. 3. Figure 4b shows δV_g, the distance between minima, as a function of I_0.

Curve 3 in Fig. 3 is a record of the dependence of $\delta \bar{n}_S = \delta Q_S S$ on V_g, found by integrating the gate current I_g over time. The expected change in the charge in the channel as the current track moves from one bank to the other can easily be estimated for the limiting case of an infinitely thin filament. We assume that the current is flowing along the line $y = Y$. From (5) we then find

$$n_S(y)_{y>Y} - n_S(y)_{y<Y} = C_0 \rho_{xy} I_0 / Se.$$

It follows that as Y varies from 0 to w the change in Q_S is

$$\Delta Q_S = \Delta \bar{n}_S S = C_0 \rho_{xy} I_0.$$

Since the change in the charge occurs at a fixed value of V_g, the derivative dQ_S/dV_g should become infinite. Experimentally, however, ΔQ_S is about half the value of $C_0 \rho_{xy} I_0$, and dQ_S/dV_g does not exceed $4C_0$ (Fig. 4a). A possible explanation is that the width of the current track is comparable to the width of the sample. In this case, in calculating the maximum value of dQ_S/dV_g we need to take into account the nonzero current density at the edges of the sample and the change in the current distribution with respect to the maximum of $j_x(y)$ as the current track moves. For a rough estimate, however, we will assume that the current distribution about the peak does not change. According to Ref. 4, the maximum of $j_x(y)$ occurs at the point Y determined by the equality $n_S(Y) = in_H$. From (5) we can find $V_g = \varphi(0)$ for this case:

$$V_g = \frac{Se}{C_0} in_H - \rho_{xy} \int_0^Y j(y)\, dy.$$

As Y is varied by δy we have $\delta V_g = (dV_g/dy)dy = \rho_{xy} j(0)$. The change in the charge Q_S here can be estimated to be $\Delta Q_S(\delta y/w)$, where ΔQ_S is the maximum change in the charge (Fig. 5). We thus find

$$(dQ_S/dV_g)^{max} \sim \Delta Q_S / \rho_{xy} j^{min}(0) w,$$

i.e.,

$$j^{min}(0) \sim \Delta Q_S / [(dQ_S/dV_g)^{max} \rho_{xy} w].$$

Comparing $(dQ_S/dV_g)^{\max}$ (Fig. 4a) with $\Delta Q_S = \Delta \bar{n}_S S$ (Fig. 5), we reach the conclusion that we have $j^{\min}(0) \sim 2$ $\mu A/w$ for $\nu = 2$ and 4 and that this quantity is independent of I_0 at $I_0 \lesssim 20\,\mu$A. The independence of $j^{\min}(0)$ from I_0 means that the current distribution changes as I_0 increases. This result is in qualitative agreement with the results of Ref. 4, according to which the width of the current filament should decrease as the current is increased.

At high currents, $(dQ_S/dV_g)^{\max}$ begins to decrease, possibly because of heating of the electron gas. Furthermore, we do not rule out the possibility that we are seeing evidence of a breakdown effect here, similar to that observed in GaAs heterostructures.[8]

In all of the experiments described here we varied V_g, while holding H constant. Some analogous experiments wre carried out in which H varied. In those other experiments we measured the dependence $Q_S(H)$ at V_g = const or the dependence $F_g(H)$ for Q_S = const. The results of those other experiments also agree well with the model current distribution described above.

2. Time-varying effects at $I_0 = 0$

At temperatures $T < 2$ K, even if the current passed through the channel from the external current source is zero,

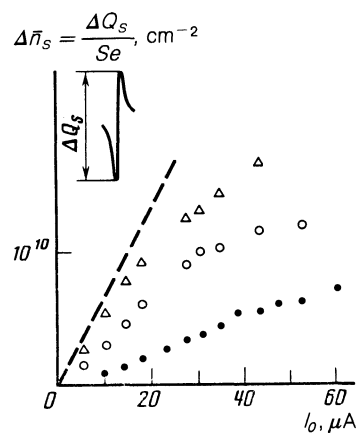

FIG. 5. Change in the average electron density, $\Delta \bar{n}_S = \Delta Q_S/Se$, near integer values of ν versus the current I_0. Δ—$\nu \approx 2$; ●—$\nu \approx 3$; ○—$\nu \approx 4$. The temperature is $T = 2$ K; $H = 70$ kOe.

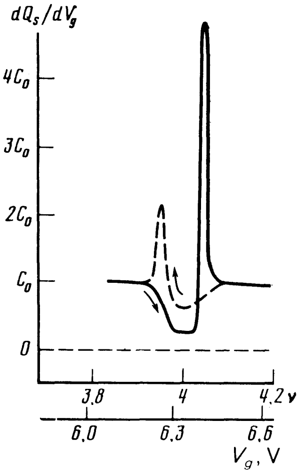

FIG. 6. Dependence of dQ_S/dV_g on V_g at $I_0 = 0$, $T = 0.42$ K, $dV_g/dt = 0.1$ V/s, and $H = 68$ kOe.

the derivative dQ_S/dV_g may not be equal to C_0 near certain integer values of ν. Figure 6 shows a representative curve of the dependence of dQ_S/dV_g on V_g near $\nu = 4$ for this case. In contrast with the case $I_0 \neq 0$ at a higher temperature, the dependence of dQ_S/dV_g on V_g is not an equilibrium curve; it is affected by the magnitude and sign of the sweep rate dV_g/dt. This dependence of dQ_S/dV_g is a consequence of the hysteresis in $Q_S(V_g)$, which was found and studied in Ref. 5.

In Ref. 5 it was also suggested that the hysteresis stems from the appearance of eddy currents in the channel. The effect of the current on the charge on the MIS structure observed in that study is an argument in favor of this explanation. The reason for the appearance of the current is a gradient in the density n_S in the channel. The time constant for the charging of the sample, $\tau \sim C_0/\sigma_{xx}$, increases sharply near integer values of ν because σ_{xx} is small in this density region. As a result, at the values $\nu = 2$, 4, 8, and 12—corresponding to the deepest minima of σ_{xx}—an equilibrium density cannot be established in the channel for the instantaneous value of V_g. The current in the channel is found from the expression

$$j_x(y) = \sigma_{xy} \partial\varphi(y)/\partial y = \sigma_{xy}(\partial n_S/\partial y) Se/C_0.$$

We assume that V_g varies monotonically and that n_S monotonically approaches in_H. Until the condition $n_S(y) = in_H$ becomes satisfied somewhere in the channel, the minimum of $\sigma_{xx}(y)$ will be near the contact, since $n_S(0)$ is closest to in_H. In the same region, the derivative $\partial n_S/y$ is at a maximum, so that $j_x(y)$ is also. After $n_S(0)$ exceeds in_H, the maximum of the current density moves away from the contact. The condition

$$\int_0^w j(y)\,dy = 0$$

means that the condition $n_S(0) = n_S(w)$ holds in any cross section of the channel. The charge distribution in the channel should therefore not change as the contact to the layer is moved from the right bank to the left. This statement means that the charge distribution is mirror-symmetric with respect to the middle of the channel, $y = w/2$. The current track, which moves from right to left as V_g is varied, will therefore meet at $y = w/2$ its "reflection," in which the current is flowing in the opposite direction. The currents then disappear, and a uniform charge density is reestablished in the channel. It is easy to see that the appearance of a current should correspond to a decrease in dQ_S/dV_g, and its motion away from the contact should correspond to an increase, as in the case $I_0 \neq 0$. This is precisely what we see on the curves in Fig. 6. In contrast with the case $I_0 \neq 0$, there is no second minimum of dQ_S/dV_g (Fig. 3) corresponding to disipation of the current filament after it has reached the other bank.

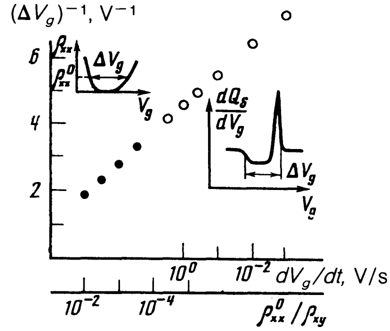

FIG. 7. Comparison of the dependence of the width of the $\rho_{xx}(V_g)$ minimum on ρ^0_{xx} (●) with the dependence of the width of the anomaly in the derivative dQ_S/dV_g on dV_g/dt (○) ($T = 4.2$ K, $\nu \approx 4$, $H = 68$ kOe).

What is the width of the anomalous in the capacitance along the V_g scale? The difference between the charge on the structure and the equilibrium value, $\delta Q_S = Q_S - C_0V_g$, can be estimated at small values of δQ_S from $\delta Q_S \sim \tau C_0 dV_g/dt$. If we determine the width of the anomaly from the values of V_g corresponding to a certain value of δQ_S, this width, ΔV_g, should correspond to the width of the ρ_{xx} minimum determined from the values of V_g corresponding to

$$\rho_{xx} = \sigma_{xx}\rho_{xy}^2 \sim (\rho_{xy}^2 C_0^2/\delta Q_S)(dV_g/dt).$$

The temperature dependence of ΔV_g should therefore be the same as that of the width of the $\rho_{xx}(V_g)$ minimum, while the dependence of ΔV_g on dV_g/dt should be the same as the dependence of the minimum of the width at $\rho_{xx} = \rho^0_{xx}$ on ρ^0_{xx}. This conclusion is verified by the experimental results; see Figs. 7 and 8. This model for the appearance and distribution of the currents is independent of the sign of dV_g/dt. A

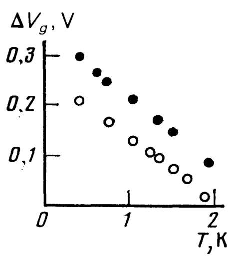

FIG. 8. Comparison of the temperature dependence of the width of the $\rho_{xx}(V_g)$ minimum $\rho^0_{xx} = 10^{-3}$ (●) and that of the width of dQ_S/dV_g anomaly at $dV_g/dt = 0.3$ V/s (○) ($H = 68$ kOe, $\nu \approx 4$).

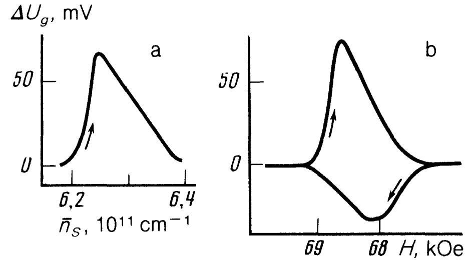

FIG. 9. a—Dependence of $\Delta U_g = V_g - Q_S/C_0$ on Q_S; b—dependence on H ($T = 0.42$ K). a) The sweep rate is $dV_g/dt = 0.1$ V/s; b) $dH/dt = 0.25$ kOe/s.

change in this sign should cause only a change in the sign of $j_x(y)$. Experimentally, on the other hand, we find that the effect is asymmetric. This asymmetry is quite evident in Fig. 6. As V_g is increased, the maximum value of dQ_S/dV_g is greater than during a decrease. This result apparently means that in the first of these cases the current which arises is greater than that in the second and/or contracts into a narrower filament. The reason for this asymmetry is not completely clear. If the anomalous dependence $Q_S(V_g)$ is governed by the presence of a current, determined externally, in the channel, and if there is no hysteresis, the amplitude of the effect should be independent of the current direction. A possibility is that the asymmetry at $I_0 = 0$ is due to an interaction of the magnetic field of the currents in the channel with the external magnetic field. The eddy current can be estimated from $I_B \sim \Delta U_g/\rho_{xy}$, where $\Delta U_g = V_g - Q_S/C_0$. Figure 9a shows ΔU_g as a function of Q_S as calculated from the curves in Fig. 6. It can be seen from this figure that we have $\Delta U_g^{\max} \sim 100$ mV. The energy of the current in a magnetic field is

$$E_H = \frac{1}{4\pi} MH \approx \frac{1}{4\pi c} I_B SH \sim \frac{1}{4\pi c} \Delta U_g^{max} SH \frac{1}{\rho_{xy}} \sim 10^{-2} \text{ erg},$$

or ~ 10 K per electron. In other words, this energy is (we wish to stress this point) comparable to the Fermi energy (~ 50 K). It can be shown that this energy is negative when V_g is increased or positive if it is reduced. In the former case the current will then tend to increase its magnetic moment M (in magnitude), while in the latter case it will tend to reduce it. The result may be a situation in which, in the former case, the current, tending to increase the area which it spans (and thus the value of $|M|$), flows through a thin filament along a bank, while in the latter case the width of the filament is greater, and $|M|$ is smaller.

As H is varied hysteresis effects are also observed in the curves of $V_g(H)$ at $Q_S = \text{const}$ or in the curves of $Q_S(H)$ at $V_g = \text{const}$ (Ref. 5). Figure 9b shows a $\Delta U_g(H)$ curve. The reason for the hysteresis is the appearance of eddy currents in the channel as a result of the changing field: $\operatorname{rot} j = c^{-i} \rho_{xx}^{-1}(dH/dt)$. The currents which arise cause a nonuniform density n_S; then the arguments above regarding $Q_S(V_g)$ are valid. The similarity of the $\Delta U_g(H)$ and $\Delta U_g(Q_S)$ curves is a strong argument in favor of the conclusion that in these two cases we are dealing with precisely the same mechanism for the appearance of hysteresis.

It can be seen from Fig. 10 that the presence of a current I_0, determined externally, in the channel suppresses the hysteresis. Since, as we have already mentioned, hysteresis arises when the time constant for the charging of the sample, $\tau \sim C_0/\sigma_{xx}$, becomes rather long, the decrease in the hysteresis may be regarded as a decrease in τ caused by I_0. This effect could be explained on the basis that the charge redistribution in the channel caused by the current I_0 leads to an increase in σ_{xx} over a large part of the area of the sample, while the dimensions of the region in which σ_{xx} is small (i.e., the dimensions of the region in which most of the current flows, according to Ref. 4) decrease. We can thus conclude that the width of the current track decreases with increasing current.

Consequently, most of the experimental results which have been found correspond at least qualitatively to the models for the current distribution in the channel discussed above. It should be noted, however, that there is one discrepancy between the model current distribution of Ref. 4 and the experimental results. This discrepancy is manifested as a difference between the experimental value of ΔV_g (the width of the dQ_S/dV_g anomaly) and the expected value in the case $I_0 \neq 0$. Let us assume that the current filament appears near the left bank of the sample at a certain carrier density $n_S(w) = in_H - \Delta n_S$. If the Landau levels are symmetric, the filament should then disappear at the right bank at a density $n_S(0) = in_H + \Delta n_S$. Using (5), we find

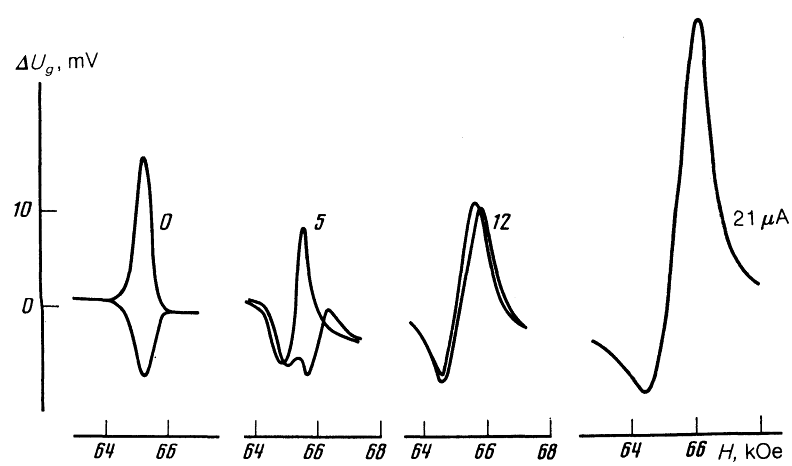

FIG. 10. Effect of the current I_0 on the hysteresis in the gate voltage at $T = 0.42$ K and at a rate of change of the magnetic field $dH/dt = 0.25$ kOe/s.

$\Delta V_g = \rho_{xy} I_0 +$ const. It can be seen from Fig. 4b that at $T = 4.2$ K the experimental dependence $\Delta V_g(I_0)$ agrees well with this result; we cannot say the same about the curves measured at $T = 2$ K. At that temperature, ΔV_g is essentially independent of I_0 over a large range of the current I_0. This behavior of $\Delta V_g(I_0)$ is puzzling. It may be a consequence of a change in the width of a Landau level (and thus in Δn_S) caused by the current I_0.

CONCLUSION

The results of the experiments which we have described here show that the current flowing through the channel of an MIS structure under conditions corresponding to quantization of the Hall resistance affects the relation between the charge on the structure, Q_S and the gate voltage V_g. We can conclude from the nature of the dependence $Q_S(V_g)$ that at the beginning of the ρ_{xy} plateau the current collects near one of the banks of the channel; as V_g of H is then varied, the current track moves toward the other bank, where it dissipates. This result is similar to the result found in Ref. 2 for a GaAs-Al_xGa_{1-x}As heterostructure, but there is the difference that a change in the sign of the current changes the direction in which the current filament moves. The difference apparently arises because the current redistribution in the heterostructure is an embedded density gradient, while in an MIS structure the density gradient is formed by the current itself, and a change in the direction of the current changes the sign of the density gradient.

The relationship which we have established between the current and the electron density gradient in the channel yields an explanation of the hysteresis observed on the curves of $Q_S(V_g)$, $V_g(H)$, and $Q_S(H)$ in Ref. 5. The apparent reason for the observed shapes of these curves is the formation of an eddy current along the perimeter of the channel and the subsequent collapse of this current as the middle of the channel. It should be noted here that Widom *et al.*[9] have proposed a different explanation for the hysteresis of $Q_S(V_g)$. They offered their own theory for the effect of the quantization of the Hall resistance, based on the appearance of so-called quantum eddies. They argue that the hysteresis in $Q_S(V_g)$ proves the existence of quantum eddies. Unfortunately, Widom *et al.*[9] did not predict the parametric dependence of the hysteresis so that their assertion could be tested experimentally. Nevertheless, that explanation of the hysteresis in $Q_S(V_g)$ is rather dubious. The experiments show that the hysteresis disappears at a current of about 20 μA through the channel (Fig. 10). The quantization of the Hall resistance has not yet disappeared at this current, as was shown in Ref. 7; it is observed even at higher currents. Consequently, the hysteresis in $Q_S(V_g)$ could not be regarded as a necessary concomitant of quantization of the Hall resistance, although the presence of a quantized Hall resistance is undoubtedly a necessary condition for the observation of hysteresis effects.

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