"Skin effect" and observation of nonuniform states of a 2D electron gas in a metal-insulator-semiconductor structure

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A method is proposed for studying the spatial distribution of the conductivity σ_{xx} of a layer of a 2D electron gas in a field-effect transistor. Under conditions of the quantum Hall effect, spatially nonuniform distributions of σ_{xx} are found. It is shown that the presence of a transport current I under nonlinear conditions gives rise to a conductivity distribution which can be controlled by an electric field and which accounts for the formation of a filament of a Hall current.

The method which we are proposing here for studying metal-insulator-semiconductor (MIS) structures is based on measurements of the reactive and active components of the current which arises when an alternating voltage is applied between the gate of a field-effect transistor and a layer of 2D electrons (Fig. 1). This method makes it possible to measure local values of the conductivity and to study the spatial distribution of the conductivity. The distributed capacitance between the gate and the electron layer has the consequence[1] that even if the conductivity σ_{xx} is independent of the coordinates, an alternating current will be concentrated in a region with a scaled length $\lambda = (2\sigma_{xx}\omega^{-1}C^{-1})^{1/2}$ (a "skin effect"). Here C is the capacitance per unit area of the MIS structure. For samples with the geometry of a Corbino disk (Fig. 1), under the conditions of the quantum Hall effect, it is a simple matter to satisfy the inequality $\lambda \ll r_2 - r_1$. The dependence of the potential difference between the gate and the layer on the radius r in the case in which an alternating voltage is applied to an internal contact, with $I = 0$, is described by

$$U(r) = V_g + U_0 \exp[-(1+i)(r-r_1)\lambda^{-1} + i\omega t]. \quad (1)$$

The magnitude of the alternating current in the presence of a magnetic field is determined by the diagonal component of the conductivity tensor σ_{xx}:

$$I_\omega = U_0 \pi r_1 \omega G(1+i)\lambda(\omega). \quad (2)$$

If σ_{xx} is a function of the coordinates, then by measuring the dependence of both current components on the frequency we can draw conclusions about the spatial distribution of the conductivity.

In the present experiments we used two field-effect transistors with the Corbino geometry with an electron inversion layer at the (100) surface of silicon. The average electron density in the sample, n_s, was set, as usual, by the static voltage on the gate, V_g. It was determined from the position of the quantum oscillations of the conductivity. The electron mobility at the maximum at 4.2 K is $\mu_{max} = 2\times10^4$ cm^2/(V·s). The thickness of the silicon oxide layer is $d = 1.4\times10^{-5}$ cm, and the capacitance is $C = 2.4\times10^{-10}$ F/mm^2. The measurements were taken in a magnetic field $H = 10.6$ T at a temperature of 1.6 K. Figure 1 shows the general behavior of the reactive

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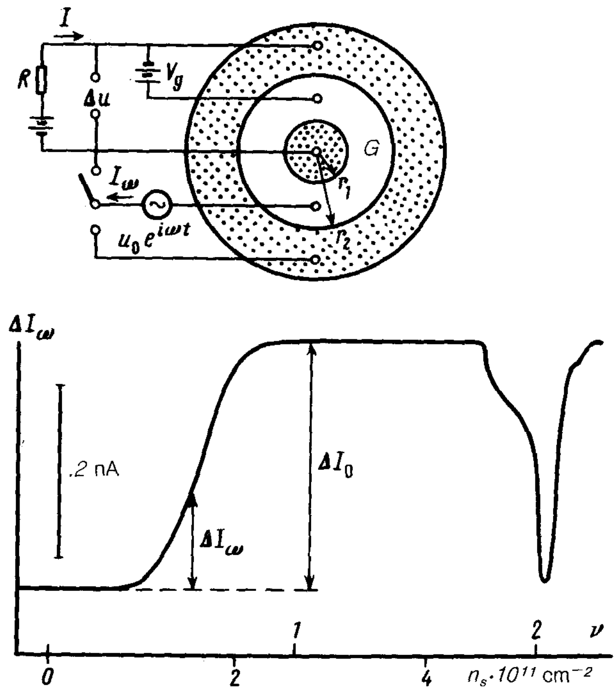

FIG. 1. Experimental arrangement and plot of the reactive component, ΔI_ω, of the current through the internal contact versus the electron density in the layer, n_s. Here $\nu = n_s/(eH/hc)$ is the filling factor of the Landau levels. The contacts to the layer are marked. G is the gate; $r_1 = 0.11$ mm; $r_2 = 0.34$ mm; $U_0 = 6\times 10^{-4}$ V; $\omega/2\pi = 920$ Hz. Sample No. 1.

component of the alternating current as a function of n_s. This particular choice of origin for the current scale makes it possible to eliminate all parasitic capacitances. The current ΔI_ω corresponds to the total capacitance of the sample. The dips on the $\Delta I_\omega(\nu)$ curve, which appeared near integer values $\nu \geqslant 2$, result from the dependence of U on the distance $r - r_1$; i.e., they result from the "skin effect."

Analysis of the frequency dependence of the imaginary and real components of the alternating current for both samples, under linear conditions, revealed that the conductivity distribution at densities n_s near integer values of the filling factor is nonuniform and depends on the history of the sample. As an example, we show the conductivity distribution near the external contact of sample No. 1 for various values of the average filling factor along the sample, found from an analysis of the curves in Fig. 2. For this sample, with $3.96 \leqslant \nu \leqslant 4.40$, there is a region of comparatively high

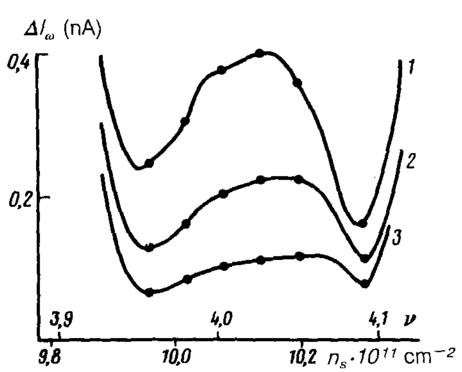

FIG. 2. Reactive component, ΔI_ω, of the current through the external contact versus ν near $\nu = 4$. 1—$\omega/2\pi = 15.6$ kHz; 2—$\omega/2\pi = 7.6$ kHz; 3—$\omega/2\pi = 3.5$ kHz. The points are the results of numerical calculations for the conductivity distributions described in the text. Sample No. 1.

conductivity $\sigma_{xx1} \geqslant 4 \times 10^{-9}$ S near the contact, bounded by a region with $\sigma_{xx2} \leqslant 1.5 \times 10^{-10}$ S. An important point is that the area of the high-conductivity region varies smoothly from 1.5×10^{-2} mm^2 at $\nu = 3.96$ to 3.2×10^{-2} mm^2 at $\nu = 4.04$. If we assume axial symmetry, we conclude that these results correspond to a change in the width of the region from 7 to 15 μm. At $\nu \approx 4.1$ (the maximum at the right in Fig. 2), the conductivity turns out to be uniform along a scale length of 20 μm ($\sigma_{xx} = 1.3 \times 10^{-9}$ S). Together, these results clearly contradict the edge-current model.[2] The appearance of a nonuniform distribution near integer values of the filling factor ν and the change in the geometry of the nonuniformity as ν is changed are apparently evidence of an amplification of the resultant potential relief in a sample under conditions of the quantum Hall effect because of a degradation of screening.

A nonuniform distribution of the conductivity along a coordinate could be caused artificially if a transport current of adequate magnitude flowed through the sample.[3-5] The nonuniform distribution of σ_{xx} would be accompanied by the simultaneous appearance of a filament of a Hall current. Let us assume as a starting point that in the absence of a transport current the conductivity σ_{xx} does not depend on the coordinates. For the Corbino geometry, the relationship between the transport current I and the potential difference (U) between the gate and the $2D$ layer (the gate is an equipotential) would then be

$$\frac{I}{2\pi r} = -\sigma_{xx}(U)\frac{dU}{dr}, \qquad U(r_2) = V_g. \tag{3}$$

The conductivity σ_{xx} is a function of the electron density or, equivalently, the potential difference[6] U:

$$\sigma_{xx} = \sigma_0 \, e^{-(\Delta/2kT)} \cosh\frac{U - V_g^0}{\nu_0 T}, \qquad \nu_0 = keD/C. \tag{4}$$

Here V_g^0 is the voltage corresponding to an integer filling factor, Δ is the energy separation of the mobility thresholds at adjacent Landau levels, and $D = \text{const}$ is the state density half way between the two Landau levels.

From (3) and (4) we easily find expressions for $\sigma_{xx}(r, I)$ and for the Hall current density $j_\varphi(r, I)$:

$$\sigma_{xx}(r, I) = \sigma_0 e^{-(\Delta/2kT)} \left[1 + \left(\sinh\frac{V_g - V_g^0}{\nu_0 T} - \delta \ln\frac{r}{r_2}\right)^2\right]^{1/2}, \tag{5}$$

$$j_\varphi(r, I) = \frac{I}{2\pi r}\, \sigma_{xy}\, \sigma_{xx}^{-1}(r, I); \qquad \delta = \frac{I e^{(\Delta/2kT)}}{2\pi \sigma_0 \nu_0 T}. \tag{6}$$

Since $\sigma_{xx}(r)$ has a minimum at the point

$$r = r_{\min} = r_2 \exp\left[\delta^{-1} \sinh\left(\frac{V_g - V_g^0}{\nu_0 T}\right)\right] \quad (r_1 \leqslant r_{\min} \leqslant r_2)$$

a filament of a Hall current j_φ, flowing in a circle, appears in the region $|r - r_{\min}|$

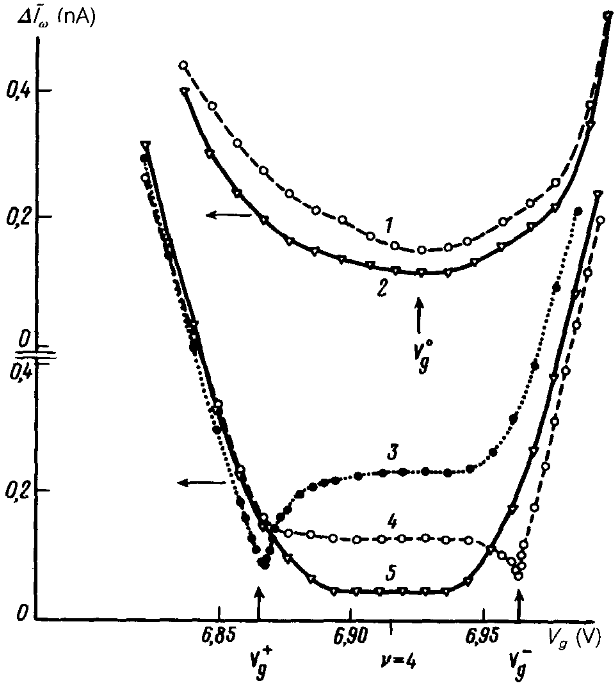

FIG. 3. Active component, $\Delta \tilde{I}_\omega$, of the current through the external contact (1,2) and through the internal contact (3–5) versus the voltage V_g. $\omega/2\pi = 80$ kHz. $U_0 = 5\times 10^{-4}$ V. 2, 5—$I = 0$; 1, 4—$I = -5\times 10^{-10}$ A; 3—$I = 5\times 10^{-10}$ A. Sample No. 2.

$\approx \delta^{-1} r_{\min}$. This filament moves through the sample as the voltage V_g is varied. The coordinate $r_{\min}$ at $r_1 < r_{\min} < r_2$ corresponds to that point in the sample in which the local value of the filling factor is an integer value. This effect is very nonlinear, so that at high currents I a nonuniform distribution $\sigma_{xx}(r)$ arises, regardless of the initial conductivity distribution. (An analogous effect in the configuration of a Hall-effect transistor with a long gate was analyzed in Ref. 4.)

The method outlined above makes it possible to directly identify the times at which the filament of Hall current is near one of the contacts. In this case, the alternating current I_ω has a minimum, which corresponds to a minimum of σ_{xx}. Figure 3 shows the results of measurements of the active component of the alternating current through the external and internal contacts. We might note that since the alternating voltage is small, $U_0 = 5\times 10^{-4}$ V, the alternating current does not cause any significant changes in the distribution $\sigma_{xx}(r)$. The Hall-current filament at $I > 0$ arises near the internal contact ($V_g = V_g^+$; curve 3 in Fig. 3) and arrives at the external contact at $V_g = V_g^0$. When the polarity of the current is reversed, the filament moves from the external contact ($V_g = V_g^0$) to the internal contact ($V_g = V_g^-$) (curves 1 and 4 in Fig. 3). These results agree completely with the predictions of expression (5) and are direct evidence of a filamentation of the Hall current.

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