Measurement of the inversion-layer charge of a metal-insulator-semiconductor structure in a quantizing magnetic field

V. M. Pudalov, S. G. Semenchinskiĭ, and V. S. Édel'man
All-Union Scientific-Research Institute of the Metrological Service, State Committee on Standards; Institute of Problems of the Technology of Microelectronics and Especially Pure Materials, Academy of Sciences of the USSR

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Under conditions corresponding to the quantum Hall effect, the charge (Q_s) of the 2D layer is proportional to the gate voltage V_g in a first approximation. As the magnetic field is varied, the charge Q_s (at $V_g = \text{const}$) or the gate potential V_g (at $Q_s = \text{const}$) changes abruptly upon transitions of the Fermi level from one Landau level to another. The magnitude of the change corresponds to the energy splitting of the Landau levels.

In order to interpret experimental results on metal-insulator-semiconductor structures we need to know how the quasiparticle density n_s (or the charge $Q_s = n_s eS$) in a two-dimensional (2D) layer is related to the external parameters: the magnetic field H and the gate voltage V_g (e is the electron charge, and S is the area of the 2D

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layer). In the absence of direct measurements of the charge, the customary approach has been to simply assume the behavior[1,2]

$$n_s(V_g) \propto V_g - V_t ,\qquad n_s(H) = \text{const} , \tag{1}$$

where $V_t \approx 0.1 - 1$ V is a threshold voltage determined by the state of the particular structure.[1,2] These assumptions agree reasonably well with measurements of the Shubnikov–de Haas effect in the semiclassical region.[3] In strong fields and at low temperatures, however, i.e., under the conditions corresponding to observation of the quantum Hall effect, we can expect deviations from (1) for a 2D layer near those values of V_g or H at which the Fermi level ϵ_F switches from one Landau level to another, changing by an amount $\pm\Delta\epsilon$. This well-known factor should lead, in particular, to quantum oscillations of the capacitance between the gate and the 2D layer.[4] The related variations in n_s are small; specifically, their amplitude $\delta n_s/n_H \sim \Delta\epsilon/(eV_g)$ is on the order of 0.2% for the typical experimental conditions $H = 10^5$ Oe, $\Delta\epsilon \sim 1$ meV, and $V_g = 5$ V (n_H is the state density at the Landau level[1]). We might also expect that the width of the corresponding region along the V_g or H scale would be small: $\delta V_g \sim \Delta\epsilon/e \sim 10^{-4}$ V_g, $\delta H \sim HkT/(2\nu\epsilon_F) \sim 5\times 10^{-3}$ H (for these estimates we have set $T = 1K$ and $\nu \equiv n_s/n_H = 4$).

Several recent theoretical papers,[5–7] however, have attempted to explain the quantum Hall effect by assuming stepped functions $n_s(V_g)$ and $n_s(H)$, instead of (1). Physically, stepped functions might be caused by effects such as a tunneling of carriers through a potential barrier at a heterojunction[5,6] or the leakage of carriers from the 2D layer to the source and drain contacts.[7]

It is clear that there is a need for direct measurements of the functions $n_s(V_g)$ and $n_s(H)$ under the conditions of the quantum Hall effect. This letter reports the first results of such experiments.

1. Measurement of $Q_s(V_g)$. We studied silicon metal-insulator-semiconductor structures with a surface in the (100) orientation. Because of the large area of the channel (0.8×5 mm^2), the capacitance between the gate and the 2D layer was $\sim 7\times 10^{-10}$ F, so that it was possible to directly measure the current (I_g) recharging this capacitance as H or V_g is swept at a constant rate. The change in the charge at the gate was found through a numerical integration of the current: $Q_g = \int I_g(t)\,dt$. The change in the charge of the inversion layer over the interval over which V_g or H is swept is evidently $Q_s \approx -Q_g$. Special measurements of the capacitance of the gate with respect to the contacts of the metal-insulator-semiconductor structure in the absence of an inversion layer ($V_g = 0$) showed that this capacitance is less than 3% of the capacitance of the gate and the inversion layer. The equation written above thus holds within this error. All the results reported below refer to the density interval $\nu = 1$–4. A typical value of the resistivity ρ_{xx} at the minimum for these particular samples is $< 10^{-3}$ $\Omega/\square$ at $T = 1$ K, $H = 90$ kOe, and $\nu = 4$.

Figure 1 shows the behavior $n_s(V_g)$ found in measurements taken as the voltage V_g was swept at a rate ~ 1 V/s in the absence of a current in the channel. Shown for

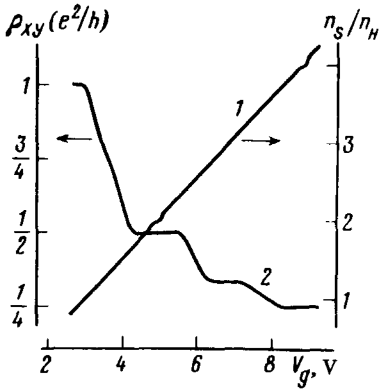

FIG. 1. 1—The carrier density in the 2D layer, n_s; 2—the Hall resistivity ρ_{xx} versus the gate voltage V_g. The magnetic field is $H = 83.1$ kOe, the temperature is $T = 0.41$ K, and the gate voltage is swept at $dV_g/dt \cong 1$V/s.

comparison here is the dependence $\rho_{xy}(V_g)$ [on which we see plateaus with $\rho_{xy} = h/(\nu e^2)$ at $\nu = 1, 2, 3, 4$ and a tendency toward a plateau at $\nu = 4/3$], measured as a current of 1 μA was flowing through the channel. In a first approximation, the function $Q_s = en_s(V_g)S$ is linear, in agreement with (1) and with the present understanding that the carriers of a 2D layer localize at potential fluctuations, giving rise to the quantum Hall effect.[1] On the other hand, it can be seen from this circumstance that conventional measurements of ρ_{xx} and ρ_{xy} cannot tell us about the charge state of the 2D layer. As the temperature is lowered, < 1.4 K, we find small charge variations $\delta Q_s/(en_H S) \sim 2\%$ (at $T = 0.4$ K) near the centers of the ρ_{xy} plateaus on the $Q_s(V_g)$ curves; these small charge variations are unsteady (Fig. 1). This effect is of independent interest, and we will not discuss it further here.

2. Measurement of $V_g(H)$. In these experiments the gate of the metal-insulator-semiconductor structure was charged to a potential V_g with respect to the 2D layer and then disconnected from the voltage source. Figure 2 shows the variations in the voltage V_g between the gate and the contact to the 2D layer measured by an electrometer as the magnetic field was swept out at 85 Oe/s. As expected, there is a discontin-

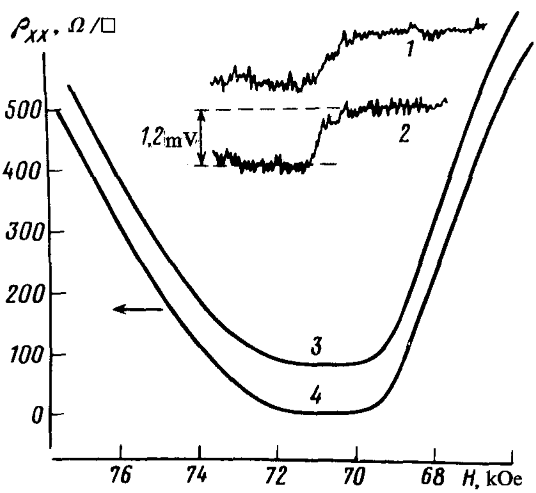

FIG. 2. 1, 2—Change in the potential V_g of a "detached" gate after charging to $V_g = 7$ V; 3, 4—change in the resistivity ρ_{xx} versus the magnetic field near $\nu = 4$; 3—"detached" gate ($n_s = $ const); 4—gate connected to the voltage source ($V_g = $ const). 1—$T = 1.48$ K; 2—$T = 1.05$ K; 3, 4—$T = 0.4$ K. For clarity, curve 3 has been displaced upward by 82 Ω/□.