V. M. Pudalov and S. G. Semenchinskiĭ. *Galvanomagnetic properties of a 2D electron layer in silicon under conditions of a quantized Hall resistance.* For a 2D electron layer in a quantizing magnetic field **H** directed perpendicular to the layer, the Hall resistivity exhibits a step behavior $\rho_{xy} = h/(\nu e^2)$ ($\nu = 1,2,\ldots$), and the diagonal component of the resistivity tensor vanishes, $\rho_{xx} \approx 0$, upon a change in the electron density in the 2D layer (Fig. 1).[1] The smallest deviations from these ideal relations which can be detected experimentally are $(\delta\rho_{xy}/\rho_{xy}) \lesssim 10^{-7}$, $\rho_{xx}^{\min} \lesssim 10^{-3}\ \Omega/\square$, determined primarily by instrumental limitations. It was found in the measurements of Ref. 2 that in the case of "large" deviations $\delta\rho_{xy}$ is related to ρ_{xx} by $|\delta\rho_{xy}| \approx 0.2\rho_{xx}$. Substituting in the value of $\rho_{xx}^{\min}$, we find an estimate of the same order of magnitude: $\delta\rho_{xy}/\rho_{xy} \sim 3\cdot 10^{-8}$. What restrictions of a physical nature are imposed on the accuracy of the quantization of the Hall resistance and on the minimum value of ρ_{xx} in a 2D layer?

In particular, experiments of this sort are carried out with metal-insulator-semiconductor (MIS) structures[1] consisting of a plane capacitor one of whose plates is a metal gate, while the other is a 2D electron layer induced near the surface of silicon through the application of a positive voltage V_g to the gate. The physical parameter in these experiments is the electron density in the 2D layer, n_s, or the change $Q_s = n_s eS$, while only V_g is monitored experimentally. It would be natural to assume that the charge of the 2D layer is always proportional to $V_g - V_t$, where V_t is the threshold voltage. Nevertheless, the effect of Landau quantization on the charging of the 2D layer requires experimental study.

In the experiments which we are describing here, the current (J_g) charging the capacitor formed by the gate and the 2D layer is measured as V_g or the magnetic field H is swept at a constant rate. A numerical integration of the results of these measurements over time yields the functions $Q_s(V_g)$ and $Q_s(H)$.

The experimental results show that at comparatively high temperatures, $T \gtrsim 1.5$ K, in a magnetic field $H \leqslant 85$ kOe the function $Q_s(V_g)$ is linear (Fig. 1a) and independent of the sign[3] of dV_g/dt, as expected. Clearly, by measuring the current J_g we can find the total charge on the MIS structure. On the other hand, knowing the density of possible states at the Landau level, $n_H = eH/ch$, we can determine the charge in the 2D layer alone for those values of V_g which correspond to the centers of the ρ_{xy} plateaus (curve 2 in Fig. 1). The two curves $Q_s(V_g)$ found in this manner coincide within the experimental error, $\sim 2\%$. This agreement means that all the charge introduced into the MIS structure goes to the 2D layer, so that there are no electron reservoirs other than the 2D layer in the structure.

At lower temperatures, we observe deviations of a hysteresis nature from the linear function $Q_s(V_g)$ near the values $\nu = n_s/n_H = 2,4,6,8,\ldots$, at which we observe the deepest minima in ρ_{xx} and flat plaeaus in ρ_{xy}. Figure 1(b) shows the behavior of $Q_s(V_g)$ near $\nu = 4$.

As V_g is increased in a certain region, the charge is below the "equilibrium value," while as V_g is decreased the charge is, on the contrary, higher than the equilibrium value. The maximum difference between these values of the charge during the forward and reverse sweeps of V_g increases rapidly with decreasing T, reaching (at $T = 0.4$ K) $\sim 10\%$ of the total charge in the 2D layer per Landau level ($n_g es$). This behavior of $Q_s(V_g)$ does not affect the values of ρ_{xy} (at least within 10^{-5}), the shape of the ρ_{xy} plateau, or that of the ρ_{xx} minimum. Measurements at various values of dV_g/dt show that as the hysteresis region is swept through more slowly it becomes narrower, and the deviations of the charge from its equilibrium value become smaller (Fig. 2). An extrapolation of the dependence of the width of the hysteresis region on dV_g/dt yields an estimate of the charging rate at which the anomaly disappears completely. At $T = 0.42$ K with $\nu = 4$, for example, this disappearance occurs if the time over which one Landau level is charged is $\tau_H = 100$ yr.

An analogous hysteresis of the charge of the 2D layer occurs as the magnetic field is varied.[4] If we hold the charge in the MIS structure constant, disconnecting the gate from the voltage source, we observe a hysteresis in the change in the gate potential with respect to the 2D layer as H is swept.[4]

Phenomenologically, long relaxation times of the

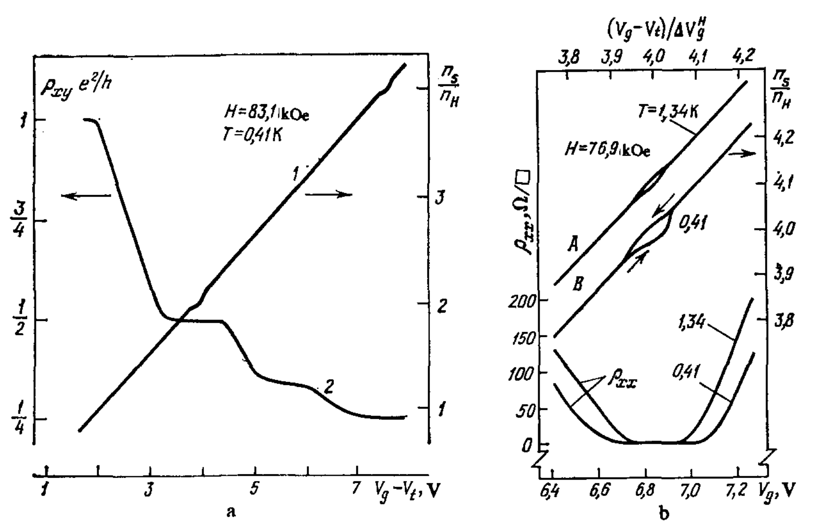

FIG. 1. The electron density in the 2D layer, n_s, and components of the resistivity tensor ρ_{ik} as functions of the gate voltage V_g ($dV_g/dt = 1$V/s). a—$\rho_{xy}(V_g)$ and $n_s(V_g)$ in a magnetic field of 83.1 kOe at $T = 0.41$ k; b—the parts of the $\rho_{xx}(V_g)/n_s(V_g)$ curves near $\nu = 4$ for two values of the temperature in a field of 76.9 kOe (for clarity, curve A is shifted upward; ΔV_g^H is the interval along the V_g scale between the centers of adjacent minima or plateaus).

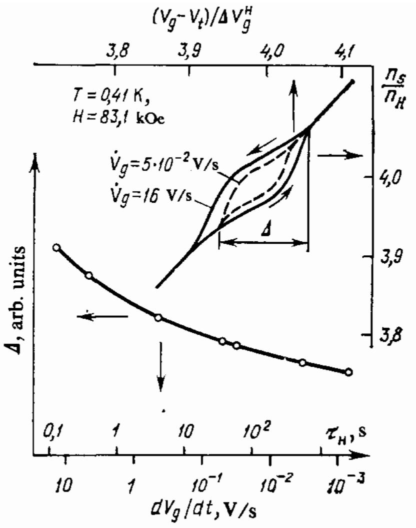

FIG. 2. Top right—Typical shape of the hysteresis loop for the recharging of the 2D layer, for two values of dV_g/dt; bottom—width of the hysteresis region versus the rate of change of the gate voltage. Here τ_H is the time required to fill one Landau level.

charge in the 2D layer can be linked with low electron drift velocities along the potential gradient because of the small component σ_{xx} of the conductivity tensor. The time constant of the charge relaxation can be estimated from $\tau \sim C_f/\sigma_{xx}$, where C_f is the capacitance of the part of the MIS structure with the nonequilibrium charge. The value $\tau \sim 10^9$ s leads to the estimate $\sigma_{xx} < 10^{-18}$ S, i.e., $\rho_{xx} < 10^{-11}\ \Omega/\Box$. Closed Hall currents arise in the 2D layer here and decay with the same time constant.

In summary, these experimental results show that vortex Hall currents can arise in a 2D electron layer, and the time scale over which these currents decay is comparable to that for the decay of currents excited in a superconducting ring. On the other hand, the estimate of ρ_{xx} which we find from the decay time of the vortex currents implies that the accuracy with which the quantization of ρ_{xy} occurs locally in the 2D layer may be $(\delta \rho_{xy}/\rho_{xy}) < 10^{-16}$.

[1]V. M. Pudalov and S. G. Semenchinskiĭ, Poverkhnost' No. 4, 5 (1985).
[2]V. M. Pudalov and S. G. Semenchinskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 173 (1983) [JETP Lett. **38**, 202 (1983)].
[3]V. M. Pudalov, S. G. Semenchinskiĭ, and V. S. Édel'man, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 474 (1984) [JETP Lett. **39**, 576 (1984)].
[4]V. M. Pudalov, S. G. Semenchinskiĭ, and V. S. Edelman, Solid State Commun. **51**, 713 (1984).