Effect of the current on the plateau width in the quantum Hall effect

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The effect of the current on the width (Δ) of the plateaus with indices $i = 2,4,6,8$ in the quantum Hall effect has been studied in magnetic fields up to 13.7 T in a silicon metal-oxide-semiconductor structure at $T \simeq 1.6$ K. The width of the plateaus can be described as a function of the current by $\Delta^{i} = \Delta_0^{(i)}(1 - I/I_{cr}^{(i)})$. The role played by localization effects is discussed.

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In two-dimensional electronic systems (at low temperatures and in strong magnetic fields), the curves of the Hall resistivity ρ_{xy} vs the density of two-dimensional carriers $N_s, \rho_{xy}(N_s)$, exhibit some relatively broad plateaus where ρ_{xy} takes on quantized values:

$$\rho_{xy}^{(i)} = \hbar / ie^2, \quad i = 1, 2, \ldots, \tag{1}$$

and ρ_{xx} and σ_{xx} are vanishingly small. This "quantum Hall effect" is observed, in particular, in inversion layers in metal-oxide-semiconductor (MOS) structures.[1] Despite the fair number of studies of the effect, several questions have not been finally resolved; in particular, it is not clear just which factors determine the plateau width Δ. The effect of the temperature has been studied in some detail,[2–4] but the data on the effect of the current are incomplete and contradictory, since the various investigators have usually restricted their detailed studies to a single plateau. In the present experiments we studied the dependence $\Delta^{(i)} = \Delta^{(i)}(I)$ for four plateaus, with $i = 2,4,6,8$ [see Eq. (1)].

The n-type MOS structures had dimensions of 1200×400 μm; the Si substrate was in the (100) orientation; and the thickness of the oxide layer was 1300 Å. The carrier mobility at 4.2 K was $\mu = (1.5\text{–}1.8) \times 10^4$ cm^2/Vs). Potential and Hall contacts were applied to the samples at separations of 400 μm. Measurements were taken by a dc potentiometric method at $T \simeq 1.6$ K in magnetic fields up to 13.7 T at carrier densities in the range $N_s = (3\text{–}30) \times 10^{11}$ cm^{-2}. The positions and widths of the plateaus were reproducible from experiment to experiment. As the current was raised from 0.5 to 60 μA, we observed a smooth decrease in the widths of all the plateaus studied (Figs. 1a and 1b). Following Ref. 4, we took the boundary of the ith plateau to be that gate voltage V_g which corresponded to the value $|\rho_{xy} - \rho_{xy}^{(i)}|/\rho_{xy}^{(i)} = 10^{-3}$. The current was used as a parameter. It can be seen from Fig. 1b that in a first approximation the dependence $\Delta^{(i)} = \Delta^{(i)}(I)$ can be approximated by

$$\Delta^{(i)} = \Delta_0^{(i)} \left(1 - I/I_{cr}^{(i)}\right). \tag{2}$$

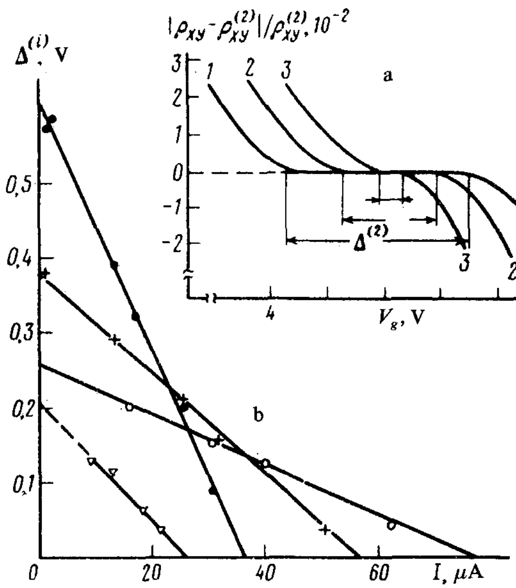

FIG. 1. a: Effect of the current on the width Δ of a plateau ($i = 2$) in the Hall resistivity when ε_F lies between (0↑ −) and (0↓ +) at $T \simeq 1.6$ K with $B = 13$ T. 1—$I = 1$ μA; 2—$I = 14$ μA; 3—$I = 31$ μA. b: Measured widths $\Delta^{(i)}$ of the plateaus which arise when ε_F lies between the following. ●—(0↑ −) and (0↓ +), $i = 2$; +—(0↓ −) and (1↑ +), $i = 4$; ∇—(1↑ −) and (1↓ +), $i = 6$; ○—(1↓ −) and (2↑ +), $i = 8$, for various currents, $T \simeq 1.6$ K, $B = 13.7$ T.

If a magnetic field is imposed in the direction perpendicular to the two-dimensional electronic system, the constant state density converts into a discrete series of Landau levels with $E_M = (M + \frac{1}{2})\hbar\Omega_c, M = 0,1, ...$ At $B = 13$ T the distance between the levels is $\hbar\omega_c \approx 8$ meV. In n-channel silicon MOS structures, the Landau levels are fourfold degenerate—in the spin and in the valley.[5] In field that lift this degeneracy the level splits into four levels, each of which can hold eB/h electrons (at $B = 13$ T, $eB/h \simeq 3 \times 10^{11}$ cm^{-2}). The magnitude of the spin splitting, $\Delta_s = g\mu_B B$, depends on the level index M, since g—the electron factor in the inversion layer in the MOS structure—decreases substantially with increasing[5] N_s, and Δ_s correspondingly decreases from ≈ 3 meV at $M = 0$ to 2 meV at $M = 2$. The valley splitting increases with increasing density in proportion to[6] N_s, and at $N_s = 3 \times 10^{12}$ cm^{-2} we have $\Delta_v \sim 1.5$ meV.

The level broadening and the localization of states in the level "tails" apparently play a decisive role in the quantum Hall effect. A plateau arises in the Hall resistivity when the Fermi level ε_F lies in the region of the localized states between the corresponding levels. The level broadening is determined primarily by the random distribution of inhomogeneities in the system, in particular, at the Si/SiO_2 boundary; according to theoretical estimates for a silicon MOS structure,[8] this broadening is 1–2 meV. The localized states are at the tails of the level, beginning at a certain energy E_C, called the "mobility angle."[7] Comparison of the values of $\Delta_0^{(i)}$ shows that the decrease in E_c (i.e., in the degree of localization) with increasing level index plays an important role.

For example, a calculation of the distances between the levels responsible for the second and fourth plateaus yields ≈ 3 and 4–5 meV, respectively, while we have $\Delta_0^{(2)} > \Delta_0^{(4)}$ (Fig. 1b). At high values of the plateau index i, it is difficult to estimate the width $\Delta_0^{(i)}$, because it is determined by various combinations of $\hbar\Omega_c$, Δ_s, and Δ_v; it is also determined by the general trend toward a decrease in the degree of localization with increasing level index (cf. $\Delta_0^{(6)}$ and $\Delta_0^{(8)}$ in Fig. 1b).

The decrease in the plateau width with increasing current evidently results from a delocalization caused by the electric field. It can be seen from Fig. 1b that the dependence $\Delta^{(i)}(I)$ is strongest for $i = 2$, where the localization effects are most obvious.

We have used the model outlined above to analyze all the data available in the literature on the effect of the current on the quantum Hall effect in silicon MOS structures.[3,4] In all cases, the dependence $\Delta^{(i)} = \Delta^{(i)}(I)$ is described by Eq. (2). The value of $I_{cr}^{(2)}$ for the results reported by Pepper and Wakabayashi[3] is about 25 times smaller than the value that we found, possibly because their samples had a lower mobility. The value found for $I_{cr}^{(4)}$ from the data of Pudalov and Semenchinskiĭ[4] is about 30% smaller than ours, perhaps because their results were obtained in a weaker field ($B \simeq 9$ T).

It is clear that the plateau width Δ can be used as a measure of the quality of MOS structures.

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