Charge relaxation in two-dimensional electron gas under quantum Hall effect conditions

N. B. Zhitenev
Institute of Solid State Physics, 142432, Chernogolovka, Moscow District, Russia

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Time evolution of the Hall current in a two-dimensional electron gas with a gate in the quantum Hall regime was studied. It was found that current rise time t_1 is much shorter than the time t_2 of the current redistribution along the whole sample. After a time t_1 the net current flows in a narrow strip along the boundary. The value of the net current does not change during the redistribution. The nonequilibrium occupation of the edge channels was found to change the value of the rise time.

The Hall current and the potential distribution in the plane of the two-dimensional electron gas (2DEG) in the quantum Hall effect regime have been widely discussed (e.g., Refs. 1–5). In a number of papers,[1,2] it was assumed that the total current flows in the edge channels (*EC*). In Ref. 3 it was shown that local and nonlocal resistances under the quantum Hall effect conditions do not depend on the current distribution. The Hall current density is determined by a local electric field. Nonvanishing electric field has been observed in the 2DEG plane by an electrooptic method.[5] Since in a bulk of 2DEG the delocalized states exist below the Fermi level,[6] the current flows both in the bulk and in the *EC*. However, it is possible to push the Hall current to the boundary of 2DEG due to the peculiarities of electrodynamics in a strong magnetic field.

The time evolution of a Hall current in 2DEG after applying potential difference between contacts was studied in Refs. 7 and 8. The appearance of a Hall potential can be described as a motion of a jump in the electrochemical potential along the 2DEG edge in a narrow strip from the source to the drain contact. Stationary electrochemical potential at the boundary is established behind the front. This process can also be described in terms of a wave packet of edge magnetoplasmons (EMP).[9] As soon as the Hall potential has risen, the charge and current become stronger localized near the edge than in the stationary case. Therefore, the current dynamics should be especially sensitive to the boundary properties. The aim of this work is to study the current redistribution and to find the possible influence of the scattering between *EC* on the current dynamics.

The method used in the present experiment is like that employed in previous studies.[7,8] A voltage pulse was applied to the source and the current I_d was measured in the drain circuit. Any pair of contacts could be used as the source and drain. The difference consists in the presence of a metal gate close to 2DEG. By applying a voltage between the gate and 2DEG it is possible to change the electron concentration. On the other hand, the presence of the gate offers new chance to study the current dynamics. The potential difference between the gate and the drain contact is held constant. Applying the voltage pulse to the source results in the change of the concentration of 2D electrons in accordance with the potential distribution in 2DEG with

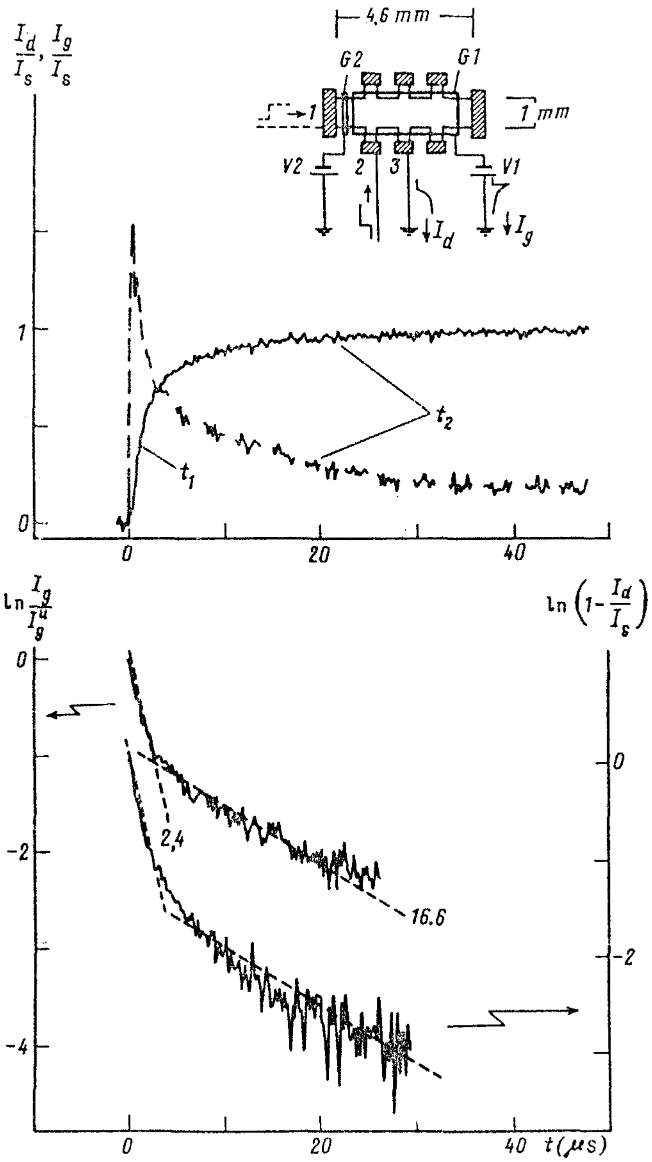

FIG. 1. Top: Typical time dependences of the drain (solid) and the gate (dashed) currents normalized to the stationary drain current value are shown. Sample 1, $n_s = 2.45\times10^{11}$ cm^{-2}, filling factor $i = 2.6$; $T = 4.2$ K, source—probe 2, drain—probe 3, edge length below gate 1.15 mm. Bottom: The same dependences illustrate the existence of two times. I_g^u maximal value of the gate current. The inset shows the operation of the sample 1.

respect to the gate. Some charge enters the 2DEG and produces a Hall field. The same charge leaves the gate as a second plate capacitance plate. By measuring the gate current I_g as a function of time one can determine excessive charge that appears in the 2DEG plane. The inset in Fig. 1 shows the setup for the measurements. The gate also screens the Coulomb interaction of charges in the 2DEG plane, which results in a reduction of the EMP velocity[9] and in an increase of the relative influence of the boundary potential.[10]

Two AlGaAs/GaAs samples with evaporated Al gates were used in the measurements. Sample 1 (shown in the inset in Fig. 1) has two gates, $G1$ and $G2$, sample 2 has only one gate, $G1$. The electron densities are 2.45×10^{11} cm^{-2} before and 4.12×10^{11} cm^{-2} after illumination; the mobility is about 2×10^5 cm^2/Vs. The distance between the 2DEG and the gates is 1700 Å. The stationary drain current I_s is in the range 1–5 μA.

Typical time dependences of I_d and I_g are shown in Fig. 1 (top) for the filling factor $i=2.6$. To extract the characteristic times, these traces are approximated by exponentials. The results of the corresponding fitting are shown in Fig. 1 (bottom). Two times are clearly seen for each dependence; they are observed at any filling factor. Dependences of short (t_1) and long (t_2) times on the magnetic field are shown in Fig. 2. The dips in t_1 and the peaks in t_2 appear at integer filling factors. The short time t_1 is proportional to the distance between the contacts along the boundary of the 2DEG, where the electrochemical potential is changed due to the pulse. The stationary potential at this boundary equals the source potential (under conditions of Figs. 1 and 2, this is the shortest boundary connecting probes 2 and 3). The same behavior of the rise time was observed in the case without the gate.[8] The relative amplitude of the slow process is roughly proportional to t_2^{-1}. To reliably determine the large t_2, we measured the time dependence of the change in the gate charge.

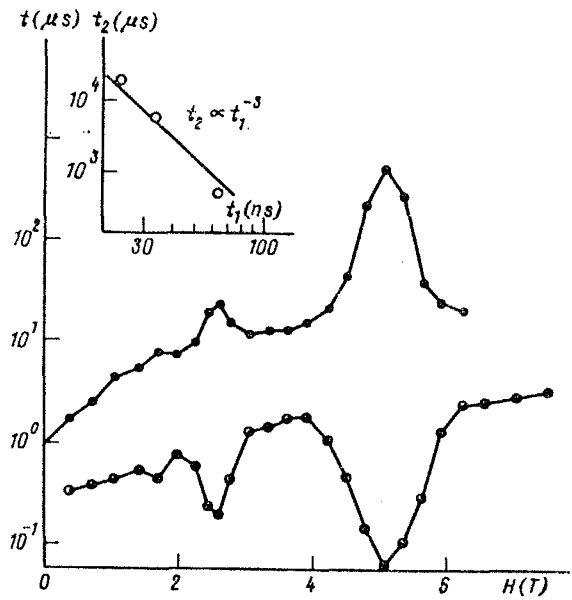

FIG. 2. Dependences of t_1 (O) and t_2 (●) on the magnetic field. Solid lines are guides to the eye. All conditions are the same as in Fig. 1. Inset—Times t_1 and t_2 for three different temperatures (0.4, 1.5, and 4.2 K) at the filling factor $i=2$.

These results can be interpreted in the following way. After applying a voltage pulse the jump in the electrochemical potential (or a wave packet of the EMP) runs along the edge. It reaches the drain after a time t_1. During this time, the equilibrium electrochemical potential is set in a narrow strip. It is accomplished by charging this strip (fast process in the dependence of I_g). The total current practically reaches its stationary value. A part of the current flows into the 2DEG plane (slow process in the dependence of I_g), where the equilibrium charge should be accumulated. This long time is also displayed in the I_d dependence.

It was shown in Refs. 11 and 12 that the charge propagation in a gated 2DEG, without a boundary, is described by the diffusion equation with the diffusion constant

$$D = \frac{\sigma_{xx}}{C} = \sigma_{xx}\left(\frac{1}{e^2\nu} + \frac{4\pi d}{\epsilon_d}\right), \tag{1}$$

where C and d are the capacitance and the distance between the 2DEG and the gate, respectively; ϵ_d is a dielectric constant, and ν is the density of states at the Fermi level. Hence the characteristic charging time of the 2DEG plane is

$$t_2 = \frac{L_y^2}{D} = \frac{L_y^2 C}{\sigma_{xx}}, \tag{2}$$

where L_y is the width of the sample. The EMP velocity in a gated system was calculated in Ref. 9:

$$V = \frac{2\sigma_{xy}}{\epsilon}\left(\ln\left(\frac{d}{\delta}\right) + 1\right), \quad d \gg \delta \tag{3}$$

$$V = \frac{2\sigma_{xy}}{\epsilon}\left(\frac{d}{\delta}\right)^{1/2}, \quad d \ll \delta \tag{4}$$

where δ is the width of a charged strip. There are several characteristic lengths and the value of δ is determined by the largest one: a magnetic length, a characteristic length of boundary roughness, and a length l_σ describing a charge departure from the boundary into the bulk of 2DEG due to a nonzero σ_{xx}. In Ref. 9, l_σ was calculated in the case without a gate: $l_\sigma = \sigma_{xx} t_1$. It should be assumed that in the case with a gate, the relation $l_\sigma = (\sigma_{xx} t_1/C)^{1/2}$ is satisfied in accordance with (2) (if $l_\sigma \gg d$). The connection between t_1 and t_2 follows from Eqs. (2) and (4): $t_2 \sim t_1^{-3}$. The times t_1 and t_2 are shown in the inset in Fig. 2 for three different temperatures at a filling factor of 2. The dependence $t_2(t_1)$ is close to the expected one, which proves that δ is determined by l_σ. Usually δ is estimated from a value of the velocity of the EMP. This method is unreliable because of an uncertainty in the effective dielectric constant in the experiment, and because of the low sensitivity of the velocity to the value of δ. Our technique makes it possible to measure the velocity and the value of δ separately. Measuring the charge which enters into 2DEG during t_1 and assuming that this charge is accumulated in the strip of width δ, one can estimate δ. At a filling factor of 2, this evaluation yields $\delta = 1.9\ \mu$m at $T = 0.4$ K. Substituting this value of δ and $\epsilon = \epsilon_{\text{GaAs}}$ in (4), we have $t_1 = 30$ ns, which is close to the experimentally observed value of 24 ns. It should be noted that $\delta \approx 1\ \mu$m, which is close to our value, was estimated in Ref. 10 by studying

EMP in a system with a compressed gate. It was assumed in Ref. 10 that δ is determined by boundary roughness.

The Hall current flows in the strip of width δ at the time $t \gtrsim t_1$, because there is no electric field in the 2DEG plane as a result of screening by the gate. The charge diffuses from the boundary to the plane during $t_2 \gg t_1$. It leads to a penetration of the electric field into the plane and to a redistribution of the Hall current along the entire sample. The net value of the current is established after a time t_1 and does not change during the redistribution.

It is believed that in the 2DEG without a gate the charge relaxation takes place in a similar manner, although there is no net charge entering into the 2DEG plane. Charges rapidly appear at the edge and slowly penetrate into the plane. The jump in the electrochemical potential occurs at the velocity $V_1 = 2\sigma_{xy}/\epsilon \cdot (\ln(a/\delta) + 1)$, where a is the front size of the jump in the initial disturbance.[7] The Hall current

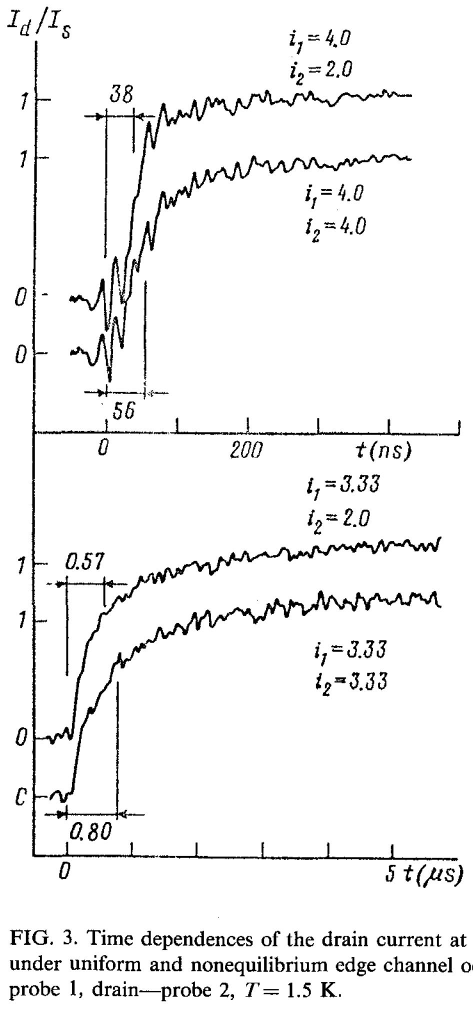

FIG. 3. Time dependences of the drain current at integer (top) and noninteger (bottom) filling factor i_1 under uniform and nonequilibrium edge channel occupations. Sample 1, $n_s = 4.12 \times 10^{11}$ cm^{-2}, source—probe 1, drain—probe 2, $T = 1.5$ K.

localizes near the boundary, but not as strongly as in the case with the gate, because an electric field penetrates into the plane. The charge departs from the boundary with a velocity $V_2 = 4\pi\sigma_{xx}/\epsilon$ (Ref 11). The last process which results in the equilibrium field and current distribution was not displayed on the time dependence of the drain current.[8]

Since the strip with δ (and the jump velocity) is determined by the diffusion of the charge from the boundary to the plane, the time t_1 should be sensitive to the change in the effective σ_{xx} near the edge. The scattering between EC is strongly reduced in comparison with the scattering in the plane.[13] Therefore, an influence of nonequilibrium occupation of the EC can affect the value of t_1. It is possible to redistribute a charge in such a way that the charge value in the outer EC is increased as compared with the uniform case. If an equilibration length is sufficiently large, the mean diffusion constant should diminsh.

For creation of nonequilibrium occupation an additional gate $G2$ (Fig. 1) was used. The edge length below $G2$ (0.15 mm) is much less than that below $G1$ (0.82 mm, probe 1—source, probe 2—drain). If the filling factor i_2 below gate $G2$ is an integer, the time t_1 is determined by the motion of a jump below $G1$ for any filling factor i_1. By decreasing the concentration below $G2$ it is possible to inject the charge preferably into the outer EC below $G1$. An influence of nonequilibrium occupation on t_1 was actually observed for low filling factors. The dependences of I_d on the time are shown in Fig. 3 for integer (top) and noninteger i_1 (bottom) under a uniform occupation and under conditions with preferable occupation of most outer EC below $G1$. A decrease in the time t_1 is clearly seen. Such a rapid decrease in t_1 cannot be attributed to the change in the jump that passes below $G2$. It means that average strip width below $G1$ diminishes. Hence a value of the equilibration length does not vanish in comparison with the source—the drain distance. For a quantitative determination of the relaxation times between EC further investigations are needed. So far, all of the experimental information on the scattering at the boundary is extracted from an analysis of the Hall and longitudinal resistances. Observed nonlocal effects in the EMP velocity makes it possible to propose another approach for studying the scattering processes.

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[1]M. Buttiker, Phys. Rev. B **38**, 9375 (1988).
[2]B. J. van Wees, E. M. M. Willems, C. J. P. M. Harmans *et al.*, Phys. Rev. Lett. **62**, 1981 (1989).
[3]S. Komiyama and H. Hirai, Phys. Rev. B **40**, 7767 (1989).
[4]P. C. van Son and T. M. Klapwijk, Europhys. Lett. **12**, 429 (1990).
[5]P. F. Fontein, P. Hendriks, F. A. P. Blom *et al.*, Proc. EP2DS-9, Nara, 531 (1991).
[6]V. T. Dolgopolov, N. B. Zhitenev, and A. A. Shashkin, Europhys. Lett. **14**, 255 (1991).
[7]V. T. Dolgopolov, N. B. Zhitenev, P. S. Kop'ev, and V. M. Ustinov, Zh. Eksp. Teor. Fiz. **97**, 2030 (1990) [Sov. Phys. JETP **70**, 1147 (1990)].
[8]N. B. Zhitenev, V. T. Dolgopolov, B. K. Medvedev, and V. G. Mokerov, Phys. Lett. **A148**, 225 (1990).
[9]V. A. Volkov and S. A. Mihailov, Zh. Eksp. Teor. Fiz. **94**, 217 (1988) [Sov. Phys. JETP **67**, 1639 (1988)].
[10]J. Cole, G. A. G. Jones, J. E. F. Frost *et al.*, J. Phys.: Cond. Matter **4**, 3955 (1992).
[11]A. O. Govorov and A. V. Chaplik, Poverhnost **12**, 5 (1987).

[12]S. I. Dorozhkin, A. A. Shashkin, and V. T. Dolgopolov, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 189 (1986) [JETP Lett. **44**, (1986)].
[13]T. Martin and S. Feng, Phys. Rev. Lett. **64**, 1971 (1990).

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