CHARGE RELAXATION IN TWO-DIMENSIONAL ELECTRON GAS UNDER QUANTUM HALL EFFECT CONDITIONS

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Time evolution of the Hall current in a two-dimensional electron gas with gate in the quantum Hall regime was studied. It was found that current rising time t_1 is much less then the time t_2 of current redistribution over the whole sample. After t_1 net current flows in a narrow strip along the boundary. Value of net current does not change during the redistribution. An influence of non-equilibrium occupation of the edge channels on the value of rising time was observed.

Hall current and potential distribution in a plane of two-dimensional electron gas (2DEG) in the quantum Hall effect regime are widely discussed (e.g. [1-5]). In a number of papers (e.g. [1,2]) it was assumed that the whole current flows in edge channels (*EC*). In [3] it has been shown that both local and nonlocal resistances under the quantum Hall effect conditions are independent of 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 delocalized states exist below the Fermi level [6], 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 peculiarities of electrodynamics in strong magnetic field.

Time evolution of a Hall current in 2DEG after applying potential difference between contacts has been studied in [7,8]. The appearance of a Hall potential can be described as a motion of a jump of electrochemical potential along the 2DEG edge in a narrow strip from source to drain contact. Stationary electrochemical potential on 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 charge and current are stronger localized near the edge than those in the stationary case. Therefore the current dynamics should be especially sensitive to boundary properties. The aim of this work is to study the current redistribution and to find the possible influence of scattering between *EC* on current dynamics.

A method used in present experiment is like that employed in previous works [7,8]. A voltage pulse was applied to the source and current I_d was measured in drain circuit. Any pair of contacts could be used as 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 gate presence offers new chance in studying of current dynamics. The potential difference between the gate and the drain contact is held constant. Applying voltage pulse to source results in the change of the concentration of $2D$ electrons in accordance with establishing potential distribution in 2DEG with respect to the gate. Some charge enters in the 2DEG and produces the Hall field. The same charge leaves the gate as a second plate of capacitance. By measuring the gate current I_g as a function of time one can determine excessive charge appearing in the 2DEG plane. The inset of Fig.1 provides a scheme of measurements. The gate also screens the Coulomb interaction of charges in the 2DEG plane, which results in reducing the EMP velocity [9] and increasing the relative influence of boundary potential [10].

Two AlGaAs/GaAs samples with evaporated Al gates were used in measurements. Sample 1 (shown in inset in Fig.1) had two gates $G1$ and $G2$, sample 2 had a gate $G1$ only. Electron densities were $2.45 \cdot 10^{11}$ cm^{-2} before and $4.12 \cdot 10^{11}$ cm^{-2} after illumination, mobility was about $2 \cdot 10^5$ cm^2/Vs. The distance between the 2DEG and gates was 1700Å. Values of the stationary drain current I_s were in the range of $1 - 5$ μA.

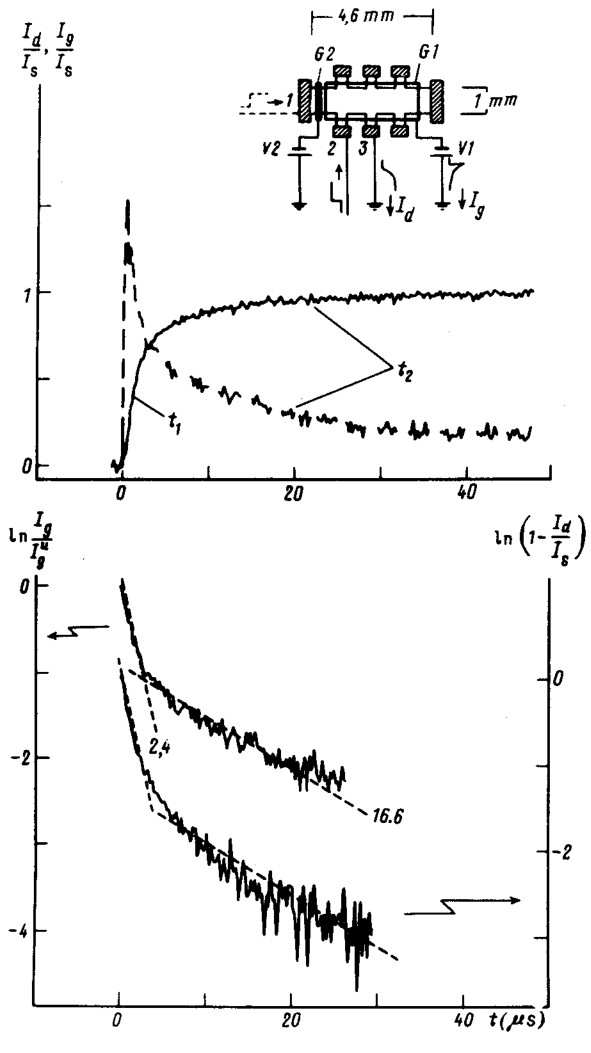

Fig.1. Top: typical time dependences of drain (solid) and gate (dashed) currents normalized on stationary drain current value are shown. Sample 1, $n_s = 2.45 \cdot 10^{11}$ cm^{-2}, filling factor $i = 2.6$; $T = 4.2$ K, source - probe 2, drain - probe 3, edge length below gate 1.15 mm. Bottom: the same dependences are treated to illustrate the existence of two times. I_g^u- maximal value of gate current. The inset depicts the operation of the sample 1

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

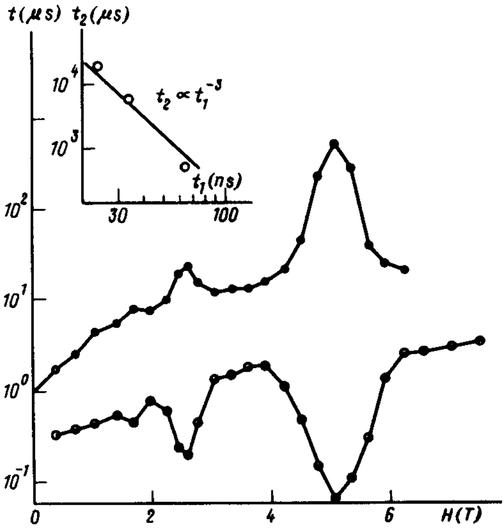

Fig.2.

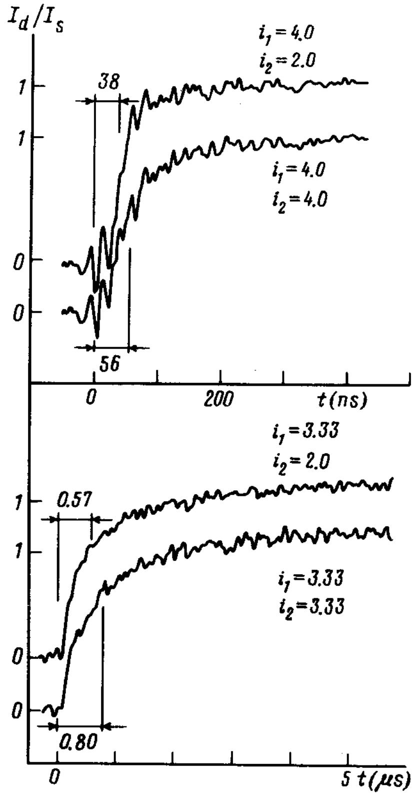

Fig.3.

Fig.2. Dependences of t_1 (o) and t_2 (•) on magnetic field. Solid lines are guides to the eye. All conditions are the same as on fig.1. Inset - times t_1 and t_2 for three different temperatures $(0.4, 1.5, 4.2K)$ at filling factor $i = 2$

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

These results can be interpreted in the following way. After applying a voltage pulse the jump of electrochemical potential (or, by other words, a wave packet of the EMP) runs along the edge. It reaches the drain after 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 whole 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 equilibrium charge should be accumulated. This long time is also displayed in I_d dependence.

It has been shown in papers [11,12] that the charge propagation in a gated 2DEG without boundary is described by diffusion equation with 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 capacitance and distance between the 2DEG and the gate respectively, ϵ_d is a dielectric constant, ν is the density of states at the Fermi level. Hence 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 a sample width.
The EMP velocity in a gated system was calculated in [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 nonzero σ_{xx}. In [9] l_σ was calculated in the case without gate: $l_\sigma = \sigma_{xx}t_1$. It should be supposed that in case with gate relation $l_\sigma = (\sigma_{xx}t_1/C)^{1/2}$ is fulfilled in accordance with (2) (if $l_\sigma \gg d$). The connection between t_1 and t_2 follows from equations (2) and (4): $t_2 \sim t_1^{-3}$. Times t_1 and t_2 are shown in inset in Fig.2 for three different temperatures at filling factor of 2. 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 velocity of the EMP. Such way is unreliable because of an uncertainty in effective dielectric constant in the experiment and low sensitivity of the velocity to value of δ. By our technique it is 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 the width δ one can estimate δ. At filling factor of 2 this evaluation yields $\delta = 1.9\mu m$ at $T = 0.4$ K. By substituting this value of δ and $\epsilon = \epsilon_{GaAs}$ in (4) we have $t_1 = 30ns$ which is close to the experimentally observed value of $24ns$. It should be noted that $\delta \approx 1\mu m$, which is close to our value, has been estimated in work [10] by studying EMP in a system with compressed gate. It was assumed in [10] that δ was determined by boundary roughness.

The Hall current flows in the strip of the width δ at time moment $t \gtrsim t_1$ because there is no any electric field in 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 electric field in the plane and to a redistribution of Hall current over the whole sample. The net value of the current is practically established after time t_1 and does not change during the redistri bution.

It is believed that in the 2DEG without gate the charge relaxation takes place in a similar manner, although there is no net charge entering into 2DEG plane. Charges rapidly appear at the edge and slowly penetrates into the plane. The jump of electrochemical potential runs with velocity $V_1 = 2\sigma_{xy}/\epsilon \cdot (\ln(a/\delta) + 1)$ where a - front size of jump in initial disturbance [7]. The Hall current localizes near boundary not so stronger as in the case with the gate, because an electric field penetrates into plane. The charge departs from the boundary with velocity $V_2 = 4\pi\sigma_{xx}/\epsilon$ [11]. The last process resulting in equilibrium field and current distributions was not displayed on time dependence of the drain current [8].

Since the strip with δ (and the jump velocity) is determined by diffusion of charge from the boundary to the plane, time t_1 should be sensitive to changing in effective σ_{xx} near the edge. Scattering between EC is strongly reduced in compare with the one in the plane [13]. Therefore an influence of nonequilibrium occupation of the EC can reveal in the value of t_1. It is possible to redistribute charge so that the charge value in outer EC is increased in compare with the uniform case. If an equilibration length is sufficiently large, mean diffusion constant should diminish.

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

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