

Nonequilibrium currents in the quantum Hall effect regime spatially resolved by transport experiment

M V Budantsev^{1,2}, A G Pogosov^{1,2}, D A Pokhabov^{1,2},
E Yu Zhdanov^{1,2}, A K Bakarov¹ and A I Toropov¹

¹ Institute of Semiconductor Physics, SB RAS, Novosibirsk, Russia

² Novosibirsk State University, Novosibirsk, Russia

E-mail: budants@isp.nsc.ru

Abstract. Eddy currents in a constriction placed in a two-dimensional electron gas (2DEG) have been experimentally studied. The constrictions fabricated by the electron-beam lithography demonstrate quantum Hall effect in high magnetic field. Pronounced hysteresis of magnetoresistance is observed at Hall plateaus corresponding to integer filling factors $\nu = 1, 2$ and 4 of a macroscopic 2DEG. The dependence of magnetoresistance hysteresis on the constriction width is obtained. The dependence contains the threshold value of width that points to the edge nature of eddy currents and enables us to determine the eddy currents area width, which is about $0.5 \mu\text{m}$.

1. Introduction

A two-dimensional electron gas (2DEG) in the quantum Hall effect (QHE) regime demonstrates nonequilibrium state, manifested itself in hysteretic behavior of different 2DEG characteristics, such as magnetization [1], charge [2, 3], local electrostatic potential [4, 5] as a function of magnetic field in condition of $\sigma_{xx}=0$. For a long time this nonequilibrium state remained unnoticed in transport experiments. Recently this state has been revealed and investigated in conventional magnetoresistance measurements in the simple system — 2DEG with a constriction [6, 7, 8, 9, 10].

Such unusual behavior is explained by long-lived nonequilibrium currents of magnetization, induced in a 2DEG, that are often referred to as eddy currents. The term “eddy currents” designates currents induced in a conductor by sweep of the magnetic field. However it has been shown in Refs. [11, 12] that the same currents, responsible for the nonequilibrium magnetization of a 2DEG, can be induced by the sweep of the gate voltage as well as the sweep of the magnetic field. Therefore in Refs. [11, 12] they are referred to as “nonequilibrium currents”. This term is more general and emphasizes their nonequilibrium nature.

One of the most important unsolved problems is the problem of eddy currents spatial distribution. In the QHE regime the 2DEG bulk is occupied by incompressible electron liquid and the magnetic field sweep induces charge transfer between the bulk and the edge [13] that in its turn establishes radial electric field which generates large azimuthal eddy currents in disk-shaped 2DEG. In Ref. [14] these eddy currents are assumed to be distributed over the whole plane of a 2DEG, while Ref. [5] where the distribution of local electrostatic potential has been experimentally studied points rather to the edge nature of eddy currents.



It has been shown that the magnetoresistance of a constriction placed in the 2DEG bath demonstrates hysteretic behavior in magnetic field. The dependence of hysteresis of the magnetoresistance on the constriction width has been experimentally studied. It has been found that the hysteresis vanishes at certain critical width. This points to the edge nature of eddy currents. The obtained experimental results allow us to define the width of the area, where eddy current is located. This area width has been found to be about $0.5 \mu\text{m}$.

2. Experimental details

Experimental samples have been fabricated on the basis of GaAs/AlGaAs heterojunction, containing a 2DEG grown by means of molecular-beam epitaxy. The heterostructure with 2DEG is presented in Figure 1. The electron mobility is $0.8 \times 10^6 \text{ cm}^2/(\text{V}\cdot\text{s})$ and the 2DEG density is $1.8 \div 2.2 \times 10^{11} \text{ cm}^{-2}$ at 4.2 K.

GaAs	15 nm	
Al _x Ga _{1-x} As	20 nm	δ-Si
Al _x Ga _{1-x} As	40 nm	δ-Si
Al _x Ga _{1-x} As	50 nm	2DEG
x=0.3		
GaAs - substrate		

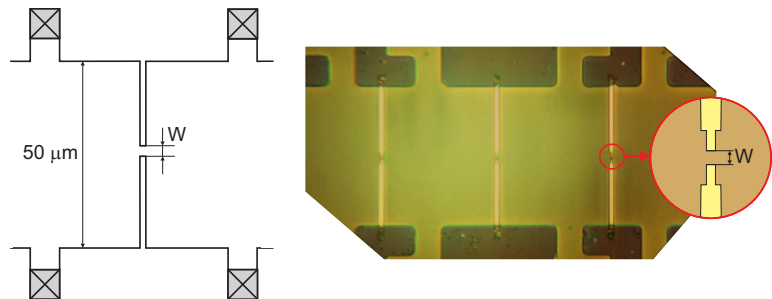


Figure 1. Heterostructure GaAs/AlGaAs with a 2DEG.

Figure 2. Schematic representation and microphotography of the Hall bar with the constrictions.

Constrictions of different widths have been fabricated by means of electron-beam lithography with following plasma-chemical etching on the Hall bar of $50 \mu\text{m}$ width. Six constrictions having lithographic widths in a range $W = 0.8 \div 1.3 \mu\text{m}$ have been fabricated. The microphotography of the sample is represented in Figure 2. Such samples allow measuring the Hall resistance of the macroscopic 2DEG as well as longitudinal magnetoresistance of constrictions. All the constrictions have a length $0.6 \mu\text{m}$ which is much less than the electron mean free path at given 2DEG parameters.

The measurements were carried out by means of lock-in technique in the linear response regime on the alternating current of the magnitude 10 nA and the frequency 7 Hz at temperature of 0.48 K. The magnetic field was directed perpendicularly to the 2DEG plane and covered a range $0 \div 11 \text{ T}$. The magnetic field sweep rate in the experiment was 0.01 T/s .

3. Experimental results and discussion

All the constrictions have low resistance ranged from $0.2 \text{ k}\Omega$ to $0.8 \text{ k}\Omega$ at zero magnetic field and demonstrate QHE regime in high magnetic field.

The minima of the constriction magnetoresistance is shifted to the lowest field relative to the centers of the Hall plateau of a macroscopic 2DEG (Fig. 3). It can be attributed to the difference between the electron density in the constrictions and that of the macroscopic 2DEG. This difference reached 10%.

The hysteresis of magnetoresistance of all the constrictions have been observed at the filling factors $\nu = 1, 2$ and 4 of the macroscopic 2DEG (Fig. 3). The hysteresis is practically independent on sweep rate. The increase of sweep rate in 30 times does not cause any significant change in the hysteresis [7].

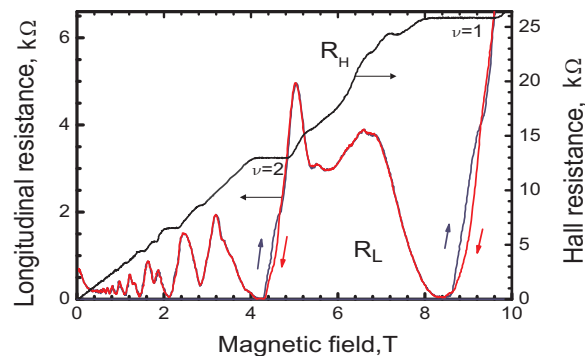


Figure 3. The longitudinal and Hall resistance in the constriction of width 1 μm as a function of the magnetic field. Arrows indicate the magnetic field sweep direction.

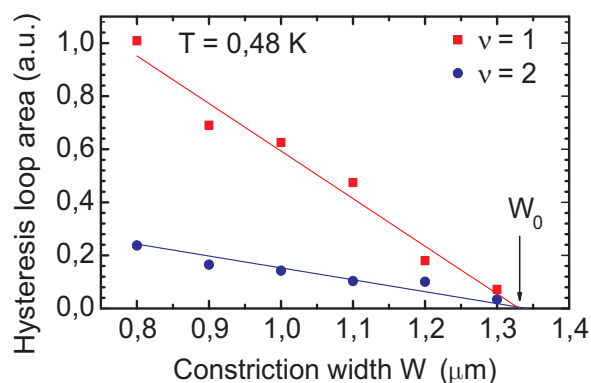


Figure 4. The hysteresis loop area as a function of the constriction lithographic width at the filling factors $\nu = 1$ and 2.

Figure 4 shows the hysteresis loop area as a function of the lithographic constriction width at filling factors $\nu = 1$ and 2. The experimental points are well fitted by straight lines. One can see that the loop area decreases with increasing width and vanishes at certain critical width. Moreover these critical widths coincide for both filling factors and is about 1.35 μm . Note that the slope of the dependence for $\nu = 1$ is 4 times steeper than that for $\nu = 2$ with a good accuracy.

The nonequilibrium state is not observable in transport measurements in a wide Hall bar. A constriction brings together the opposite 2DEG edges and makes eddy currents propagating in opposite directions to interact. If the eddy currents are distributed over the whole plane of a 2DEG, we would not observe such the clear cut-off in the dependence. The found threshold width points to edge nature of eddy currents.

To estimate lateral width of eddy currents the depletion width W_{depl} should be determined. The effective width of the conductive channel is $W_{eff} = W - 2 \times W_{depl}$. Due to the fact that the electron mean free path ($\sim 5 \mu\text{m}$) is much larger than the constriction length (0.6 μm) the constrictions could be considered as quantum point contacts and their conductance could be found from the equation:

$$G = \frac{2e^2}{h} \cdot \frac{k_F \times W_{eff}}{\pi}. \quad (1)$$

Taking into account the constrictions resistance at zero magnetic field it has been found that the effective width W_{eff} is about 0.4 μm less than the lithographic width W for all the

constrictions (Fig. 5). Thus the depletion layer width W_{depl} is about $0.2 \mu\text{m}$.

The constriction of critical width W_0 contains two counter propagating eddy currents each of them has width W_{EC} and two depletion layers of width W_{depl} :

$$W_0 = 2 \times W_{depl} + 2 \times W_{EC}. \quad (2)$$

This gives $W_{EC} \approx 0.5 \mu\text{m}$ for the studied samples.

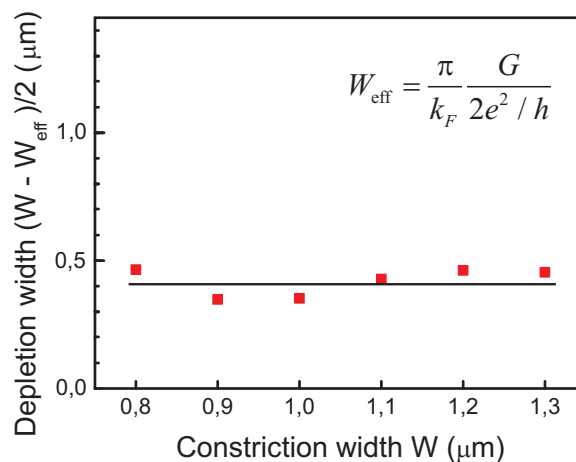


Figure 5. The depletion width calculated from zero-field conductance by the given formula as a function of the constriction lithographic width W .

It is well known that magnetic field sweep generates azimuthal electric field, which in its turn in the condition of $\sigma_{xx} = 0$ induces the charge transfer between the bulk and the edge [13, 3]. Thereby, the area of incompressible liquid is changed: it increases with decreasing the magnetic field and decreases with increasing the magnetic field. A constriction can be sensitive to such changes. Two different cases can be realized in the constriction at the same magnetic field:

(i) The area of incompressible liquid increases at down magnetic field sweep direction (Fig. 5 (a)). Edge currents in a constriction move away from each other, the backscattering is suppressed resulting in the resistivity decrease.

(ii) The area of incompressible liquid decreases at up magnetic field sweep direction (Fig. 5 (b)). Edge currents in a constriction move toward each other, the backscattering increases resulting in the resistivity increase.

This can be considered as a topological transition. At $\partial B / \partial t < 0$ the edge current transmits through the constriction forming the single loop and incompressible liquid forms simply connected space, while at $\partial B / \partial t > 0$ edge current scatters in the constriction and incompressible liquid splits into two spaces divided by compressible strip in the constriction.

It should be noted that the measurements of hysteresis of conductance of quantum point contact [10] have been carried out in a tunnel regime. The QHE is not realized in the mentioned case. The hysteresis is observed on the background of large magnetoresistance. In this case there are no topological transitions in the constriction. Such measurements are not able to provide the information about spatial distribution of eddy current since eddy current does not transmit through the constriction.

The range of widths of the constrictions studied in present paper allows us to establish the edge nature of NECs and determine eddy currents area width.

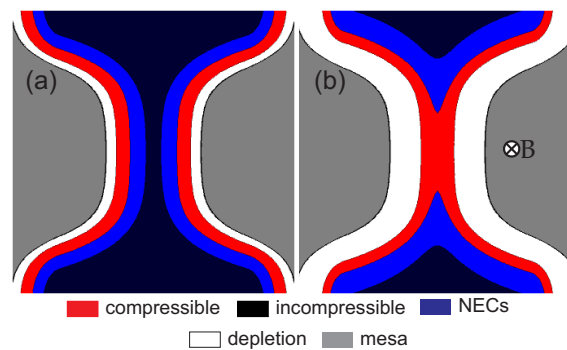


Figure 6. The schematic representation of Hall liquid structure in the constriction at down (a) and up (b) magnetic field sweep direction.

4. Conclusions

The original and simple method of study eddy currents induced in a 2DEG in the QHE regime has been suggested. This method is based on conventional measurements of magnetoresistance of constriction placed in a 2DEG bath. It has been shown that the constriction width is a critical parameter responsible for the observation of the hysteresis. The hysteresis of magnetoresistance as a function of the constriction width has been studied. The found critical width points to edge nature of eddy currents. The results obtained in present paper as well as in Ref. [5] are the experimental evidence of the fact that eddy currents are induced in a narrow area along the edge rather than distributed over the whole plane of the 2DEG as it proposed in Ref. [14]. The found width of area in which the eddy currents are induced is about $0.5 \mu\text{m}$.

Acknowledgments

The work is supported by RFBR (grant 12-02-00532), Program of DNIT RAS (project 3.2), Program of Presidium of RAS (grant 24.19).

References

- [1] Usher A, and Elliott M 2009 *J. Phys.: Condens. Matter* **21** 103202
- [2] Pudalov V M, Semenchinsky S G and Edelman V S 1984 *Sol. St. Commun.* **51** 713
- [3] Dolgoplov V T, Shashkin A A, Zhitenev N B, Dorozhkin S I and von Klitzing K 1992 *Phys. Rev. B* **46** 12560
- [4] Huels J, Weis J, Smet J, von Klitzing K and Wasilewski Z R 2004 *Phys. Rev. B* **69** 085319
- [5] Klaffs T, Krupenin V A, Weis J and Ahlers F J 2004 *Physica E* **22** 737
- [6] Budantsev M V, Pogosov A G, Plotnikov A E, Bakarov A K, Toropov A I and Portal J C 2007 *JETP Lett.* **86** 264
- [7] Budantsev M V, Pogosov A G, Plotnikov A E, Bakarov A K, Toropov A I and Portal J C 2009 *JETP Lett.* **89** 46
- [8] Budantsev M V, Pogosov A G, Bakarov A K, Toropov A I and Portal J C 2009 *JETP Lett.* **89** 92
- [9] Budantsev M V, Pogosov A G, Pokhabov D A, Zhdanov E Yu, Bakarov A K, Toropov A I and Portal J C 2011 *AIP Conf. Proc.* **1399** 601
- [10] Pioro-Ladriere M, Usher A, Sachrajda A S, Lapointe J, Gupta J, Wasilewski Z, Studenikin S and Elliott M 2006 *Phys. Rev. B* **73** 075309
- [11] Ruhe N, Stracke G, Heyn Ch and Heitmann D 2009 *Phys. Rev. B* **80**, 115336
- [12] Ho L H, Taskinen L J, Micolich A P, Hamilton A R, Atkinson P and Ritchie D A 2010 *Phys. Rev. B* **82**, 153305
- [13] Laughlin R B 1981 *Phys. Rev. B* **23** 5632
- [14] Matthews A J, Kavokin K V, Usher A, Portnoi M E, Zhu M, Gething J D, Elliott M, Herrenden-Harker W G, Phillips K, Ritchie D A, Simmons M Y, Sorensen C B, Hansen O P, Mironov O A, Myronov M, Leadley D R and Henini M 2004 *Phys. Rev. B* **70** 075317