ISSN 1063-7826, Semiconductors, 2016, Vol. 50, No. 8, pp. 1049–1053. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © D.A. Pokhabov, A.G. Pogosov, M.V. Budantsev, E.Yu. Zhdanov, A.K. Bakarov, 2016, published in Fizika i Tekhnika Poluprovodnikov, 2016, Vol. 50, No. 8, pp. 1070–1074.

SEMICONDUCTOR STRUCTURES, LOW-DIMENSIONAL SYSTEMS, AND QUANTUM PHENOMENA

Nonequilibrium Chemical Potential in a Two-Dimensional Electron Gas in the Quantum-Hall-Effect Regime

D. A. Pokhabov[a, b]*, **A. G. Pogosov**[a, b], **M. V. Budantsev**[a], **E. Yu. Zhdanov**[a, b], **and A. K. Bakarov**[a, b]
[a] *Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences,*
pr. Akad. Lavrent'eva 13, Novosibirsk, 630090 Russia
[b] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia*
** e-mail: pokhabov@isp.nsc.ru*

Submitted February 2, 2016; accepted for publication February 10, 2016

Abstract—The nonequilibrium state of a two-dimensional electron gas in the quantum-Hall-effect regime is studied in Hall bars equipped with additional inner contacts situated within the bar. The magnetic-field dependence of the voltage drop between different contact pairs are studied at various temperatures. It was found that the voltage between the inner and outer contacts exhibits peaks of significant amplitude in narrow magnetic-field intervals near integer filling factors. Furthermore, the magnetic-field dependence of the voltage in these intervals exhibits a hysteresis, whereas the voltage between the outer contacts remains zero in the entire magnetic-field range. The appearance of the observed voltage peaks and their hysteretic behavior can be explained by an imbalance between the chemical potentials of edge and bulk states, resulting from nonequilibrium charge redistribution between the edge and bulk states when the magnetic field sweeps under conditions of the quantum Hall effect. The results of the study significantly complement the conventional picture of the quantum Hall effect, explicitly indicating the existence of a significant imbalance at the edge of the two-dimensional electron gas: the experimentally observed difference between the electrochemical potentials of the edge and bulk exceeds the distance between Landau levels by tens of times.

DOI: 10.1134/S1063782616080170

1. INTRODUCTION

The typical behavior of the magnetoresistance of a two-dimensional electron gas (2DEG) in the quantum-Hall-effect regime (QHE) consists in the appearance of the Hall-resistance quantization plateau and zeroing of the longitudinal resistance near integer filling factors. However, such a picture does not reflect some specific features arising in the QHE regime. In a number of experimental studies of the magnetization [1, 2], charge transport [3, 4], and local electrostatic potential [5, 6], hysteretic phenomena with varying magnetic field were detected near integer filling factors, which suggests that the 2DEG state is nonequilibrium in the QHE regime. So far, there is no unambiguous microscopic picture of these phenomena in publications; although, such behavior is most often explained by the appearance of long-living nonequilibrium currents in a 2DEG. Due to the absence of magnetoresistance in the QHE regime, ordinary magnetotransport measurements practically do not provide valuable information on the 2DEG state in this regime. However, as shown in [7–11], if 2DEG edges are brought closer, creating a narrow conducting channel, hysteretic phenomena can also be observed in the magnetoresistance. These results, along with the results of studying the spatial distribution of the local electrostatic potential [5, 6] allowed the conclusion that nonequilibrium currents flow in a submicrometer area along the sample perimeter.

In [11], it was assumed that the 2DEG in the QHE regime is divided into two subsystems, i.e., the "edge" and "bulk" which are not in equilibrium, i.e., the electrochemical potentials of the 2DEG bulk and edge differ significantly. The model based on this assumption explains the appearance of nonequilibrium currents at the 2DEG edge and a number of hysteretic phenomena observed in the 2DEG. However, the model does not allow to estimate the imbalance, i.e., the difference in the electrochemical potentials between the 2DEG edge and bulk remains unknown. In experiments on measuring 2DEG magnetization [1], the nonequilibrium 2DEG-magnetization amplitude in the QHE regime exceeds the Haas–van Alphen equilibrium magnetization by a factor of 20–60. If we attempt to explain these measurements within this model, the difference in the electrochemical potentials between the 2DEG edge and bulk states should be several tens of times larger than the distance between Landau levels $\hbar\omega_c$, where ω_c is the cyclotron frequency. Numerical estimations based on the data of magnetotransport measurements [10] yield a similar result and also allow the conclusion that the nonequi-

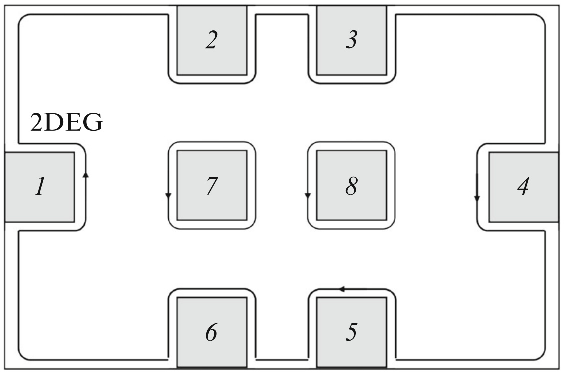

Fig. 1. Schematic representation of the samples.

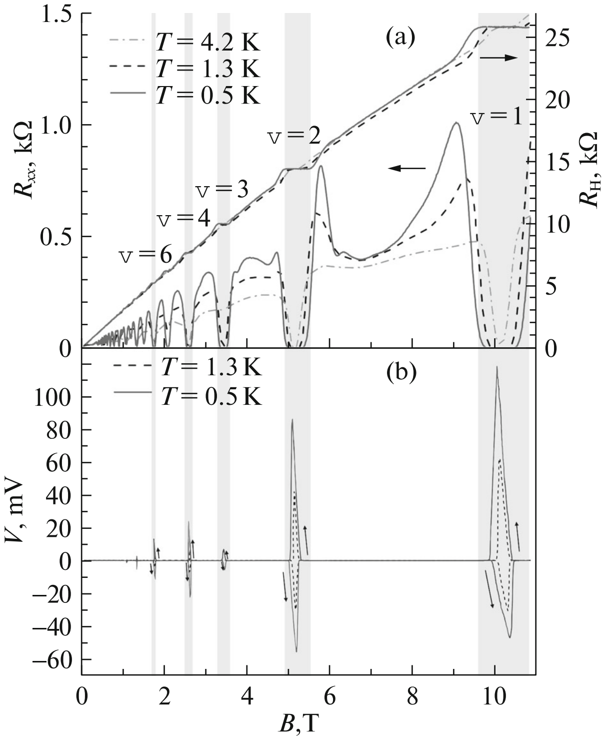

Fig. 2. (a) Longitudinal and Hall magnetoresistance of the sample. (b) Magnetic-field dependence of the voltage between the inner and outer contacts. The voltage hysteresis is observed against the background of the Hall-resistance plateau corresponding to integer even and odd filling factors.

librium between the edge and bulk can be several times larger than the cyclotron gap $\hbar\omega_c$. In this paper, we present the results of measurements of the potential difference between edge and bulk states in Hall bars equipped with both ordinary outer ohmic contacts (arranged along the bar perimeter) and additional inner ohmic contacts (located within the bars). Measurements were performed for various magnetic-field sweep directions in the absence of any external current and voltage sources. Similar measurements were discussed in [4]; however, the samples were shaped as a Corbino disk and did not allow comparative measurements of the magnetoresistance. The samples under study allow both conventional measurements of the magnetoresistance and measurements of the potential difference between 2DEG edge and bulk states. The results obtained are explained within the theory of quasi-elastic inter-Landau level scattering (QUILLS) [13], and the mechanism of intralevel transitions is considered.

2. EXPERIMENTAL

Experimental samples were fabricated based on GaAs/AlGaAs heterostructures grown by molecular-beam epitaxy and containing a 2DEG with an electron mobility of 0.8×10^6 cm^2/(V s) and a density of 1.8–2.2×10^{11} cm^{-2} at a temperature of 4.2 K. The 2DEG was located at a depth of 125 nm beneath the heterostructure surface. The geometry of experimental samples was set by photolithography. Samples 3 × 5 mm in size had Hall-bar geometry (Fig. 1). Ohmic potentiometric contacts were arranged along the sample edge (outer contacts *1*–*6*) and within the sample (inner contacts *7* and *8*). The contacts to the 2DEG were fabricated by Ge, Ni, and Au diffusion from a film 2000 Å thick, deposited onto the heterostructure surface, at a temperature of 420°C.

The measurements were performed in the temperature range from 0.5 to 4.2 K. The magnetic field was oriented perpendicularly to the 2DEG plane and was varied in the range of 0–11 T. The magnetic-field sweep rate was varied in the range of 0.01–0.04 T s^{-1}. To study the nonequilibrium 2DEG state, the voltage between various contact pairs was measured using a Keithley 2000 Multimeter with a high input resistance (>10 GΩ) during magnetic-field sweep without a transmission of current through the sample. The magnetoresistance was measured by the synchronous detection method in the linear response regime at an alternating current with an amplitude of 10 nA and a frequency of 7 Hz.

3. EXPERIMENTAL RESULTS

Figure 2a shows the results of 2DEG magnetoresistance measurements at various temperatures in the range from 0.5 to 4.2 K. The longitudinal magnetoresistance contains zeroings, and the Hall magnetoresistance has a plateau near integer filling factors, which suggests that the 2DEG is in the integer QHE regime. In this case, both the longitudinal and Hall magnetoresistance is independent of the magnetic-field sweep direction, i.e., does not exhibit hysteresis.

To study the nonequilibrium 2DEG state, the magnetic-field dependences of the voltage between various contact pairs were measured. The voltage between any pair of outer contacts remains zero in the

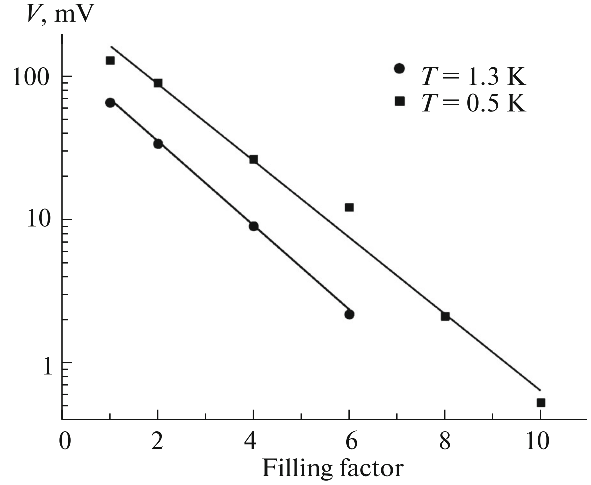

Fig. 3. Dependence of the hysteresis amplitudes on the filling factor at $T = 0.5$ K.

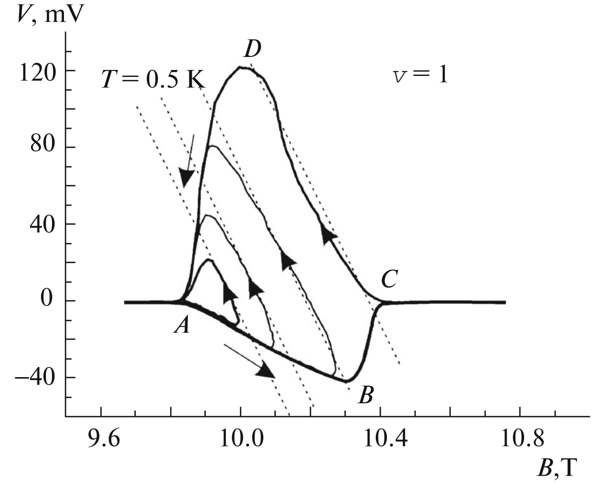

Fig. 4. Minor voltage hysteresis loops.

entire magnetic-field range. At the same time, the voltage between the inner and outer contacts exhibits peaks of significant amplitude in narrow magnetic-field ranges near integer filling factors (see Fig. 2b). Furthermore, the magnetic-field dependence of the voltage in these ranges exhibits hysteretic behavior with respect to the magnetic-field sweep direction. The observed hysteresis is independent of the sweep rate in the range from 0.01 to 0.04 T/s. The hysteresis amplitude has an exponential dependence on the filling factor (Fig. 3). The most pronounced hysteresis is observed at a filling factor of $\nu = 1$, at a temperature of 0.5 K. The voltage reaches $V_{\text{up}} \approx 50$ mV for the case of up-sweep of the magnetic field and $V_{\text{down}} \approx 150$ mV for the case of down-sweep of the magnetic field. The experimentally observed voltages suggest that the difference in the electrochemical potentials between the edge and bulk exceeds the distance between Landau levels by a factor of 5–15 ($\hbar\omega_c \sim 10$ meV, where ω_c is the cyclotron frequency). The difference between the amplitude voltages V_{up} and V_{down} for various sweep directions can be associated with differences in the electrostatic-potential profile at the 2DEG edge for different magnetic-field sweep directions, discussed in [11]. Another factor causing the difference between V_{up} and V_{down} can be the difference between the edge-state perimeters adjacent to the inner and outer contacts, respectively, i.e., the difference between the inner-contact perimeter and the perimeter of the entire sample. A more detailed explanation of the difference between the voltages V_{up} and V_{down} for different sweep directions requires further study.

The magnetic-field dependence of the voltage in the hysteresis region can be conditionally divided into four almost linear segments AB, BC, CD, and DA (see Fig. 4). The linearity of the magnetic-field dependence of the voltage is explained by the fact that the charge transferred between the edge and bulk is proportional to the change in the magnetic flux [12]. At the same time, a small hysteresis asymmetry with respect to integer filling factors is observed, which appears as the difference between the slopes dV/dB on the left (segment AB in Fig. 4) and on the right (segment BC) of the extremum (point B). As a rule, such behavior is associated with the presence of some electrical capacitance, i.e., the top gate [2], or capacitances specially connected between the 2DEG edge and bulk [4]. In the presence of such additional capacitance, the charge is redistributed not only from the 2DEG bulk to the edge, but also the additional capacitance is charged. In this case, the voltage is controlled not only by the charge transferred between the 2DEG edge and bulk, but also by the charge displaced to the capacitance. In the case at hand, the signal is limited by the parasitic capacitance (~0.1 pF) of the measuring device and the capacitance of cables used for measurements. In any case, the measured voltage is proportional to the difference in the electrochemical potentials between the edge and bulk states ($V \propto \Delta\mu$), and the absence of parasitic capacitance would lead to an even higher measured voltage.

The dependence of the magnetoresistance on the sweep prehistory was studied. To this end, the magnetic-field sweep terminated in the hysteresis region and then the sweep direction was reversed. It was found that minor-loop regions lying within the hysteresis loop (indicated by dotted lines in Fig. 4) have equal slopes dV/dB which are identical to the slope of the portion CD of the major loop, corresponding to the same sweep direction. As for the other regions of minor hysteresis loops, they completely coincide with the corresponding regions of the major loop ABCD. The curve slope at the hysteresis output is limited by the QHE breakdown. Most likely, two competing processes occur in the 2DEG in the QHE regime: on the

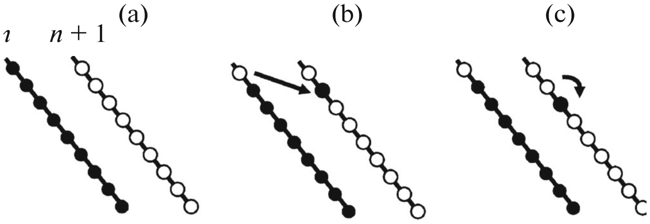

Fig. 5. Schematic representation of the electron transition between Landau levels at the edge and subsequent thermalization of the nonequilibrium electron to the 2DEG bulk.

one hand, the magnetic-field sweep redistributes the charge between the edge and the bulk, inducing the critical field of QHE breakdown [13] between the edge and the bulk; on the other hand, the nonequilibrium charge relaxes due to this critical field at the edge. Nonequilibrium charge-relaxation mechanisms are considered in more detail in the next section.

4. RESULTS AND DISCUSSION

The voltage between the inner and outer contacts observed in narrow magnetic-field intervals corresponding to the QHE regime clearly points to nonequilibrium between the 2DEG edge and bulk states. The appearing voltage points to a significant difference in the electrochemical potentials between the edge and bulk, which is several times larger than the distance between Landau levels. At the same time, the voltage sign indicates 2DEG edge depletion at up-sweep of the magnetic field and its overpopulation at down-sweep of the magnetic field. This experimental result is consistent with those obtained in [4] and with theoretical predictions of the microscopic nonequilibrium model proposed in [11].

4.1. Interlevel Transitions

The mechanism limiting nonequilibrium is probably the QHE breakdown accompanied by transitions between occupied and empty Landau levels at the sample edge. It should be taken into account that electrons are significantly redistributed between Landau levels with varying filling factor. For example, the transition from the filling factor $\nu = 1$ to $\nu = 2$ is accompanied by the transition of half of all 2DEG electrons ($\sim 10^7$ electrons) from the first Landau level to the second one. The rather large cyclotron gap ($\hbar\omega_c \sim 10$ meV at $\nu = 1$) complicates the direct transitions of electrons between bulk states at various Landau levels at low temperatures ($k_B T \sim 0.36$ meV at $T = 4.2$ K). Therefore, the transitions between Landau levels probably occur through edge states.

The theory of quasi-elastic inter-Landau level scattering (QUILLS) accompanied by energy and momentum transfer to phonon subsystem was constructed in [13], where it was found that the critical breakdown field has a characteristic value $\hbar\omega_c/el_B$, where e is the elementary charge, l_B is the magnetic length which is several tens of nanometers. Taking into account the experimental fact that the electric field between the 2DEG edge and bulk appears only in a narrow region along an edge of width $W_0 \sim 0.5$–1 μm [6, 10]; multiplying this width by the characteristic critical field and the electron charge, we obtain the difference in the electrochemical potentials $\Delta\mu \approx (W_0/l_B) \cdot \hbar\omega_c = (10\text{–}20)\hbar\omega_c$ which is in complete agreement with the experimentally observed nonequilibrium.

4.2. Intralevel Transitions

After the interlevel transition of the nonequilibrium electron, it is thermalized due to intralevel transitions from edge states to the 2DEG bulk (Fig. 5), which is accompanied by energy and momentum transfer to the phonon subsystem. Electron displacement across the edge by Δx causes a change in the electron-momentum component along the edge $\hbar\Delta q_y$ by

$$\hbar\Delta q_y = \hbar\Delta nx/l_B^2 = eB\Delta x, \tag{1}$$

where l_B is the magnetic length. This momentum is transferred to the phonon whose dispersion relation is given by

$$\Delta E = \hbar s\Delta q_y, \tag{2}$$

where s is the speed of sound.

Substituting Eq. (1), we obtain the dependence of the electron energy on the coordinate at the 2DEG edge,

$$\Delta E = \omega_c m^* s\Delta x, \tag{3}$$

where m^* is the effective mass and ω_c is the cyclotron frequency.

Taking into account that the electric field between the 2DEG edge and bulk arises only in a narrow region along the edge ~1 μm wide [6, 10], and substituting this value into Eq. (3), we obtain one more numerical estimation of the imbalance of the electrochemical potentials of the 2DEG edge and bulk, which is also several $\hbar\omega_c$,

$$\Delta\mu = \frac{m^* s}{\hbar}\Delta x\hbar\omega_c \cong 3\hbar\omega_c. \tag{4}$$

A change in the magnetic flux in the QHE regime changes the density of states at Landau levels, which in turn results in charge transfer between the 2DEG edge and bulk. Taking into account that the number of edge states is much smaller than the number of bulk states, even an insignificant charge redistribution between edge and bulk states leads to significant imbalance of the electrochemical potentials of the 2DEG edge and bulk. The nonequilibrium redistribution of electrons within the Landau level probably ceases as the critical

QHE breakdown field at the sample edge is reached (the model of interlevel transitions). Furthermore, an electric field is established at the edge, which is required to "thermalize" nonequilibrium edge electrons (the model of intralevel transitions). The considered models of interlevel and intralevel transitions confirm qualitative considerations and estimate the difference in the electrochemical potentials between the edge and bulk as $\Delta\mu \gg \hbar\omega_c$, which is in good agreement with the experimental results.

5. CONCLUSIONS

Direct measurements of the difference in the electrochemical potentials between various contact pairs in Hall bars equipped with additional inner contacts thermally alloyed into the 2DEG bulk were performed as functions of the magnetic field. The results obtained suggest that the nonequilibrium 2DEG state consists in a lack of equilibrium between the 2DEG edge and bulk and manifests itself as a difference in the electrochemical potentials between contacts thermally alloyed into the 2DEG edge and bulk. The experimentally observed difference in the electrochemical potentials between the 2DEG edge and bulk is huge (150 meV), which is tens of times higher than the distance between the Landau levels ($\hbar\omega_c \sim 10$ meV). A voltage between the edge and bulk appears in magnetic fields corresponding to the Hall plateau and changes sign as the magnetic-field sweep changes, i.e., exhibits hysteretic behavior. At the same time, additional magnetoresistance measurements showed that the behavior of the magnetoresistance is typical of the QHE in this case, and the potential difference regions arise exactly at Hall magnetoresistance-plateau centers. The formation of the potential difference between the inner and outer contacts is probably a consequence of the imbalance of electrochemical potentials between edge and bulk states, appearing in the 2DEG in the QHE regime due to nonequilibrium charge redistribution between the edge and bulk states. The proposed physical picture assuming strong ($\Delta\mu \gg \hbar\omega_c$) nonequilibrium between edge and bulk states significantly complements the conventional QHE picture and makes it possible to explain a number of hysteretic phenomena such as magnetization and magnetoresistance hysteresises observed in the QHE regime.

ACKNOWLEDGMENTS

We are grateful to M.V. Entin and A.A. Shevyrin for helpful discussions.

This study was supported by the Russian Foundation for Basic Research, projects nos. 16-32-00405 mol_a and 16-02-00579.

REFERENCES

1. A. Usher and M. Elliott, J. Phys.: Condens. Matter **21**, 103202 (2009).
2. N. Ruhe, G. Stracke, Ch. Heyn, D. Heitmann, H. Hardtdegen, Th. Schäpers, B. Rupprecht, M. A. Wilde, and D. Grundler, Phys. Rev. B **80**, 115336 (2009).
3. V. M. Pudalov, S. G. Semenchinsky, and V. S. Edelman, Solid State Commun. **51**, 713 (1984).
4. V. T. Dolgopolov, A. A. Shashkin, N. B. Zhitenev, S. I. Dorozhkin, and K. V. Klitzing, Phys. Rev. B **46**, 12560 (1992).
5. J. Huels, J. Weis, J. Smet, K. V. Klitzing, and Z. R. Wasilewski, Phys. Rev. B **69**, 085319 (2004).
6. T. Klaffs, V. A. Krupenin, J. Weis, and F. J. Ahlers, Physica E **22**, 737 (2004).
7. M. V. Budantsev, A. G. Pogosov, A. E. Plotnikov, A. K. Bakarov, A. I. Toropov, and Zh. K. Portal, JETP Lett. **86**, 264 (2007).
8. M. V. Budantsev, A. G. Pogosov, A. E. Plotnikov, A. K. Bakarov, A. I. Toropov, and Zh. K. Portal, JETP Lett. **89**, 46 (2009).
9. M. V. Budantsev, A. G. Pogosov, A. E. Plotnikov, A. K. Bakarov, A. I. Toropov, and Zh. K. Portal, JETP Lett. **89**, 92 (2009).
10. M. V. Budantsev, A. G. Pogosov, D. A. Pokhabov, E. Yu. Zhdanov, A. K. Bakarov, and A. I. Toropov, J. Phys.: Conf. Ser. **456**, 012005 (2013).
11. M. V. Budantsev, D. A. Pokhabov, A. G. Pogosov, E. Yu. Zhdanov, A. K. Bakarov, and A. I. Toropov, Semiconductors **48**, 1423 (2014).
12. R. B. Laughlin, Phys. Rev. B **23**, 5632 (1981).
13. L. Eaves and F. W. Sheard, Semicond. Sci. Technol. **1**, 346 (1986).

Translated by A. Kazantsev