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Magnetoresistance in a stripe-shaped two-dimensional electron gas

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Abstract

We measure large positive magnetoreistance in a nonplanar stripe-shaped two-dimensional electron gas (2DEG) in magnetic field up to 28 T. If the applied magnetic field is quasi-parallel to the substrate, the effective magnetic field becomes essentially nonuniform and sign alternating, because the orbital motion of 2DEG is sensitive to only the normal component of magnetic field. We find that the shape of the magnetoresistance traces is dramatically changed, when magnetic field becomes exactly parallel to the substrate plane. We attribute such behaviour of the magnetoresistance to the formation of snake-like orbits which are channelling along the stripes. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recent theoretical developments of the transport properties of a two-dimensional electron gas (2DEG) have focused on a situation when the sign of the magnetic field alternates [1]. The formation of the magnetic edge states, sometimes called snake states due to the characteristic shape of the classical analogue trajectories, has been predicted in such sign alternating magnetic field [2]. These magnetic edge states can form bound and quasi-bound states in a magnetic cluster (magnetic dot) and lead to the sharp resonances in the conductivity of the mesoscopoic system with magnetic dots and antidots [3].

Several alternative techniques have been proposed to obtain 2DEG subjected by the sign alternating magnetic field with zero mean, such as magnetic superlattices by the patterning of ferromagnetic materials on the top of AlGaAs/GaAs heterojunction [4] and nonplanar 2DEG grown by a molecular beam epitaxy [5]. In this work we study large positive magnetoresistance in a nonplanar stripe-shaped 2DEG in magnetic field up to 28 T. Such large positive magnetoresistance in

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tilted field can be explained by the formation of the magnetic barriers across the current flow. However, we find that the magnetoresistance in exactly parallel magnetic field is smaller than at tilted field. We subtract the magnetoresistance curves at tilt angle $\Theta = 0°$ (parallel field) and 5° and obtain broader peak at $B = 15\,T$. We attribute such resonance in the magnetoresistance to the formation of snake-like orbits which are channelling along the stripes.

2. Results and discussion

Samples were fabricated by employing the overgrowth of GaAs and AlGaAs materials by molecular beam epitaxy on prepatterned (1 0 0) GaAs substrate. Atomic force microscope image shows periodical lattice of stripes with periodicity 1 μm and small corrugation height 300 Å. Details of the sample preparation are reported in Ref. [5]. The average periodicity $d = 1\,\mu m$ is coincident with the antidot lattice periodicity before overgrowth. The corrugation height h varies between 100 and 300 Å. The patterned area was $140 \times 140\,\mu m^2$. After regrowth, the HEMT structure was processed into Hall bars, and the nonplanar surface was situated on the one side of Hall bar. The distance between the voltage probes was 100 μm and the width of the bar was 50 μm. The Hall voltage of the planar 2DEG was used to measure tilt angles with a precision of 1–2°. The mobility of 2DEG is $(200\text{–}300) \times 10^3\,cm^2/V\,s$ and density $n_s = 5.4 \times 10^{11}\,cm^{-2}$. We studied three samples with identical parameters.

The magnetoresistance oscillations as a function of the perpendicular component of the magnetic field for different angles between magnetic field and normal to the substrate plane is shown in Fig. 1. We see that the magnetoresistance increases with angle and the amplitude of the oscillations decreases. The large positive magnetoresistance in periodic array of the ferromagnetic stripes also has been observed in the tilted field experiments [6]. Periodical magnetic field leads to the commensurability oscillations with amplitude, which is proportional to the square of the magnetic field modulation magnitude. The increase of the amplitude of a periodic stray in tilted magnetic field leads to the increase of the magnetoresistance bump, which belongs to the last commensurability peak. In our nonplanar structures cyclotron diameter is much smaller than the period of magnetic lattice, therefore large magnetoresistance cannot be explained by the enhanced drift velocity mechanism, as in the case of the commensurability oscillations.

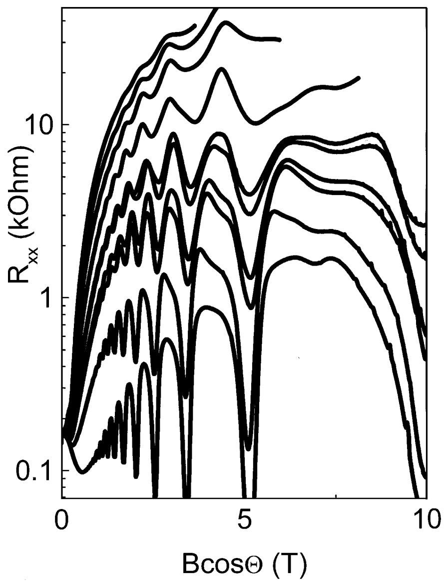

Fig. 1. Magnetoresistance as a function of the magnetic field component perpendicular to the substrate, for different angles θ between the applied magnetic field and the normal to the substrate: $\theta = 90°$, 53°, 45°, 35°, 30°, 28°, 25°, 20°, 18°, 15°, $T = 1.5\,K$.

Classical positive magnetoresistance in the presence of the wide magnetic barrier, when R_c is much smaller than the barrier width, has been calculated in Ref. [7]. It was argued that the magnetoresistance of the sample with multiple barriers in series is equal to the number of sidewalls $M = 200$ (twice the number of barriers) multiplies the magnitude of the resistance in one barrier, which is determined by the Hall resistance, because in strong magnetic field the Hall resistance mainly limits the current. In tilted magnetic field we find that the resistance across the stripes increases from 160 to 40000 Ω at $B = 28\,T$, a ratio of 260. The classical effects predict magnetoresistance in the order of $R \approx M \times B_{eff}/(n_s e) \approx 0.5\,M\Omega$. From experiments we find that

$B_{eff} \approx 0.16\,T$, which is in order of magnitude smaller than we estimate from the corrugation height h: $B_{eff} \approx (h/d)B_{ext} \approx 2\,T$. Generally, electrons drift in magnetic barriers without dissipation, and resistance, as in the case of the ballistic wires in series is determined by the resistance of the single wire. However, in this case the magnetoresistance should be 10 times smaller than we find in experiment. Therefore, we assume that dissipation occurs near some corners of the barriers region, and we have intermediate case between really diffusive and drift regime.

Fig. 2 shows the magnetoresistance in quasi-parallel magnetic field and exactly parallel field, when magnetic field becomes sign alternating with zero mean. We did not find any commensurability oscillations in this regime. The fluctuations in the corrugation height can be responsible for the suppression of the commensurability oscillations. However, we see that the shape of the magnetoresistance curve is changed in fluctuating field with zero average. We subtract the magnetoresistance curves at tilt angle $\Theta = 0°$ (parallel field) and $5°$ and obtain broader peak with maximum at $B = 15\,T$, which is shown in Fig. 3

We attribute such difference in the magnetoresistance to the formation of the snake-like orbits which are channelling along the stripes. In parallel B the amplitude of the magnetic field fluctuations due to the sample corrugation is large enough to bind electrons between maxima and minima of the field and create snake-like trajectories. For the small applied magnetic field the average cyclotron radius $\bar{R}_c$ is larger than the periodicity. In this situation electron experience chaotic motion and magnetoresistance is small. In high magnetic field, when $R_c < d/2$ (see Fig. 3) snake-like trajectories are formed. Considering realistic profile of the surface, we find that the amplitude of the magnetic field fluctuations approaches 8% of the external field. For $B_{ext} \approx 5$–$6\,T$ (region a in Fig. 3) it corresponds $B_N^{max} \approx 0.4$–$0.5\,T$, and cyclotron radius approaches 0.25–0.3 μm $\sim d/4$ in agreement with the value of the magnetic field, when resistance starts to grow significantly. In the region b we have $R_c < d/8$, and electrons located between maxima and minima of magnetic field follow rapid cyclotron orbits that slowly drift along contours of constant field. These trajectories have mean velocity in the opposite directions to the snake-like orbits. In the region c $R_c < d/16$, and drift orbits mainly contribute to the conductivity.

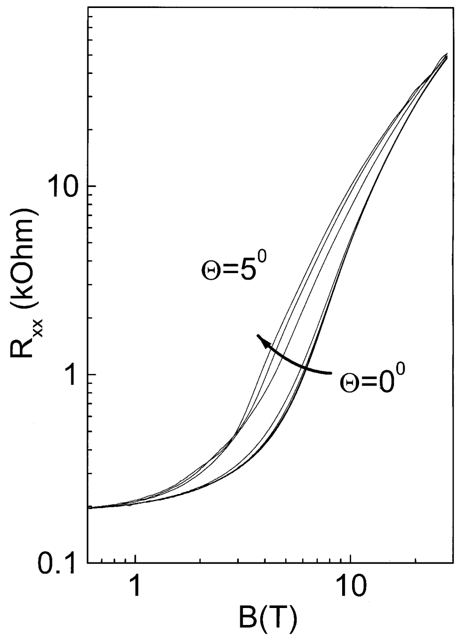

Fig. 2. Magnetoresistance of the stripe-shaped 2DEG for different angles in quasi-paralell magnetic field ($\Theta = 0$–$5°$).

As was shown in Ref. [2] the conductance of the snake states is given by

$$\sigma = (2^{3/2}e^2/\pi h)(k_F \Lambda)^{3/2} \sim \nabla B^{-1/2}, \qquad (1)$$

where $\Lambda = (h/e\,\nabla B)^{1/3}$, ∇B is the gradient of the magnetic field. In our case $\nabla B \sim B_{ext}$, and the magnetoresistance due to the snake states R_{snake} is proportional to $B_{ext}^{1/2}$. For the drift trajectories the magnitude of the drift velocity is given by

$$v_{drift} = eR_c^2 B_0/2mc, \qquad (2)$$

for a sufficiently small field gradient $\nabla B = B_0 y$. Therefore the magnetoresistance due to the drift orbits R_{drift} is proportional to the external magnetic field $R_{drift} \sim B_{ext}$, as has been shown in Ref. [7] for wide magnetic barriers. Total resistance R_{tot} for ballistic wires in series is not additive, and determined by the largest resistance. Thus, in our case in the region a, when $R_c < d/4$, the only snake states contribute to the magnetoresistance, and in

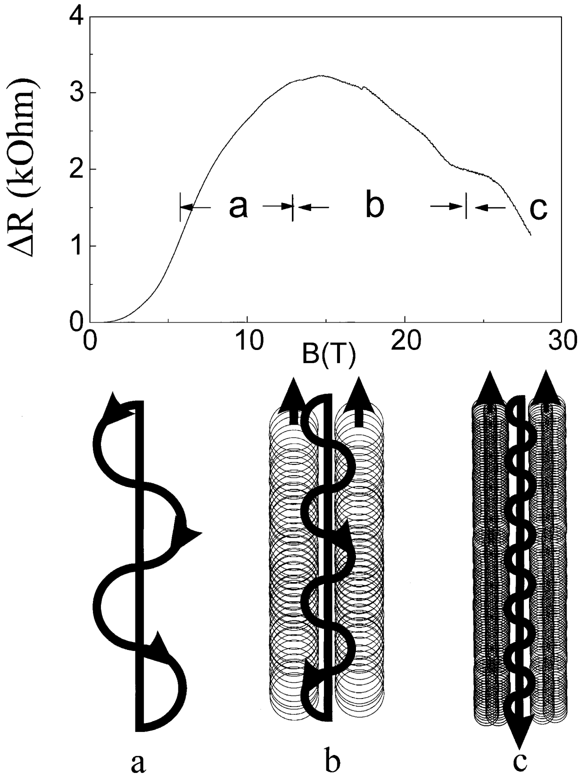

Fig. 3. Subtraction of the magnetoresistance curves at $\Theta = 5^\circ$ and 0° and schematic view of electron trajectories in different regions of the magnetic field.

the region c magnetoresistance results from the drift trajectories, and $R_{tot} \sim B_{ext}$, as we see in experiment. In tilted magnetic field, the magnetoresistance is mainly due to the drift trajectories, therefore the difference $\Delta R = R(\Theta = 5^\circ) - R(\Theta = 0^\circ)$ shown in Fig. 3 is determined by the snake orbits. However, from Eq. (1) we obtain $R_{snake} \approx 400\,\Omega$ at $B = 10\,\mathrm{T}$, which is seven times smaller, than observed value (Fig. 3). Therefore, as we already mentioned above, in our samples we have intermediate between ballistic and diffusive regime. It is very likely that the energy dissipation occurs in the region near the sides of the sample, when the snake trajectories scatter to the drift orbits. It is worth to note, that from comparison of the expected value of the magnetoresistance and experimental data we can estimate $R_{total} \approx 10R_{drift}$. Thus, the energy dissipation occurs, when electron travels $M/10 \approx 20$ times from one side of the sample to another.

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References

[1] D.K.K. Lee, J.T. Chalker, D.Y.K. Ko, Phys. Rev. Lett. 72 (1994) 1510.
[2] J.E. Muller, Phys. Rev. Lett. 68 (1992) 385.
[3] H.S. Sim, K.H. Ahn, K.J. Chang, G. Ihm, N. Kim, S.J. Lee, Phys. Rev. Lett. 80 (1998) 1501.
[4] H.A. Carmona, A.K. Geim, A. Nogaret, P.C. Main, T.J. Foster, M. Henini, S.P. Beamont, M.G. Blamire, Phys. Rev. Lett. 74 (1995) 3009.
[5] G.M. Gusev, A.A. Quivy, J.R. Leite, A.A. Bykov, N.T. Moshegov, V.M. Kudryashov, A.I. Toropov, Yu.V. Nastaushev, Semicond. Sci. Technol. 14 (1999) 1114.
[6] A. Nogaret, S. Carlton, B.L. Gallagher, P.C. Maan, M. Henini, R. Wirtz, R. Newbury, M.A. Howson, S.P. Beamont, Phys. Rev. B 55 (1997) R16037.
[7] I.S. Ibrahim, V.A. Schweigert, F.M. Peeters, Phys. Rev. B 56 (1997) 7508.