ЖЭТФ, 2012, том 142, вып. 3 (9), стр. 542–546

MAGNETORESISTIVITY IN A TILTED MAGNETIC FIELD IN p-Si/SiGe/Si HETEROSTRUCTURES WITH AN ANISOTROPIC g-FACTOR. PART II

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Received October 25, 2011

The magnetoresistance components ρ_{xx} and ρ_{xy} were measured in two p-Si/SiGe/Si quantum wells that have an anisotropic g-factor in a tilted magnetic field as a function of the temperature, field, and tilt angle. Activation energy measurements demonstrate the existence of a ferromagnetic–paramagnetic (F–P) transition for the sample with the hole density $p = 2 \cdot 10^{11}$ cm^{-2}. This transition is due to the crossing of the $0\uparrow$ and $1\downarrow$ Landau levels. However, in another sample, with $p = 7.2 \cdot 10^{10}$ cm^{-2}, the $0\uparrow$ and $1\downarrow$ Landau levels coincide for angles $\theta = 0$–70°. Only for $\theta > 70^\circ$ do the levels start to diverge which, in turn, results in the energy gap opening.

1. INTRODUCTION

Magnetotransport measurements on dilute p-Si/SiGe/Si structures, with two-dimensional hole gas (2DHG) densities about 10^{11} cm^{-2}, have revealed an unusual phenomenon at the filling factor $\nu = 3/2$, the so-called “re-entrant” metal-insulator transition [1–6]. This phenomenon manifests itself as an additional peak of the magnetoresistance $\rho_{xx}(T,\theta)$ at $\nu = 3/2$. The peak demonstrates an insulator-type behavior, i. e., its magnitude increases with decreasing the sample temperature [3, 5].

The authors of Ref. [2] explained this appearance by the presence of smooth long-range potential fluctuations having a magnitude comparable to the Fermi energy. But in Refs. [3–5], the magnetoresistance anomaly was attributed to a crossing of Landau levels (LLs) with different spin directions $0\uparrow$ and $1\downarrow$ as the magnetic field increased. It appears that some p-Si/SiGe/Si systems show a magnetoresistance anomaly at $\nu = 3/2$ that depends on the tilt angle between the magnetic field and sample normal [6], whereas in other p-Si/SiGe/Si systems, this anomaly is not manifested at all [4]. The third set of p-Si/SiGe/Si systems have such anomaly in ρ_{xx} at $\nu = 3/2$, but it is independent of the tilt angle [3].

In our earlier article [7], we analyzed *the conductivity* at $\nu = 2$ in tilted magnetic fields in a sample with $p = 2 \cdot 10^{11}$ cm^{-2} and demonstrated the presence of a ferromagnetic–paramagnetic (F–P) transition at a tilt angle of about 60°. We note that we did not observe any significant variation of the conductivity at $\nu = 3/2$; instead, a resistivity peak of the reentrant-transition type occurred in this region of the filling factor. We therefore focused our research on the $\nu = 2$ region, i. e., the vicinity of the F–P transition. The magnetoresistance components ρ_{xx} and ρ_{xy} for the p-Si/SiGe/Si structure were measured in a tilted magnetic field, from which the conductivity σ_{xx} was calculated together with its dependence on the temperature T, the magnetic field, and the tilt angle θ. Such an approach allowed us to approximately calculate values

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of the LL energies, rather than just providing a qualitative description of the phenomenon, as was presented in Refs. [1–6]. The F–P phase transition seen at $\nu \approx 2$, $T = 0.3$ K, and $\theta \approx 60°$ is the result of a crossing of the $0\uparrow$ and $1\downarrow$ LLs. This transition is characterized by a jump in the filling factor and by the coexistence of both phases in the transition region. An F–P transition was previously reported in p-Si/SiGe/Si at $\nu = 4$, 6 in a tilted magnetic field by the authors of Ref. [8].

The present paper is a continuation of our previous article [7] and has three aims: (i) to study the dependence of the energy gap between LLs $0\uparrow$ and $1\downarrow$ on the magnetic field tilt angle θ to provide further confirmation of the crossing of these levels, in the p-Si/SiGe/Si sample with $p = 2 \cdot 10^{11}$ cm^{-2}; (ii) to investigate the conductivity anisotropy in this sample, by measuring the conductivity at different orientations of the magnetic field component in the sample plane with respect to the current, $B_\parallel \parallel I$ and $B_\parallel \perp I$, and comparing this with the theoretical model proposed in [9]; (iii) to measure the magnetoresistance in a tilted magnetic field for another p-Si/SiGe/Si sample with a lower density $p = 7.2 \cdot 10^{10}$ cm^{-2} and compare it with the experimental data obtained by other groups on similar samples [3, 4, 6], with the hope of clearing up the inconsistency of the previous results mentioned above.

2. EXPERIMENT AND DISCUSSION

In this research, we studied two p-Si/SiGe/Si systems grown on a Si (100) substrate that consisted of a 300 nm Si buffer layer followed by a 30 nm $Si_{(1-x)}Ge_x$ layer, 20 nm undoped Si spacer, and 50 nm layer of B-doped Si with a doping concentration of $2.5 \cdot 10^{18}$ cm^{-3}. One sample had $x = 0.08$, yielding $p = 7.2 \cdot 10^{10}$ cm^{-2}, and the second had $x = 0.13$, with $p = 2 \cdot 10^{11}$ cm^{-2}. Both samples had a hole mobility of about $1 \cdot 10^4$ cm^2/Vs at liquid-helium temperatures.

In the sample with $p = 2 \cdot 10^{11}$ cm^{-2}, we measured the temperature dependence of the conductivity at different tilt angles θ over the temperature range 20 mK to 1 K, from which we were able to determine the activation energy ΔE at various angles via the slope of the Arrhenius curves: $\ln \sigma_{xx} \propto 1/T$. The dependence of the activation energy on the tilt angle θ is shown in Fig. 1, where it can clearly be seen that the activation energy achieves a minimum at $\theta \approx 60°$. The conductivity $\sigma_{xx}(\theta)$ at the minima of oscillations at $\nu \approx 2$ also shows a maximum as a function of the tilt angle at $\theta \approx 60°$, as shown in the inset to Fig. 1.

It is worth noting that when the measurements are performed with the magnetic field normal to the sample plane, the energy gap related to $\nu = 2$ is about 3.2 K (0.28 meV). We are therefore justified in extracting the energy gap value from the temperature range 200 mK–1 K. When the tilt angle approaches 60°, the size of the energy gap is very small, due to the LLs crossing. Hence, although the actual gap value obtained here is subject to considerable uncertainty, the observation of a minimum of the energy gap value at about 60° qualitatively supports our model.

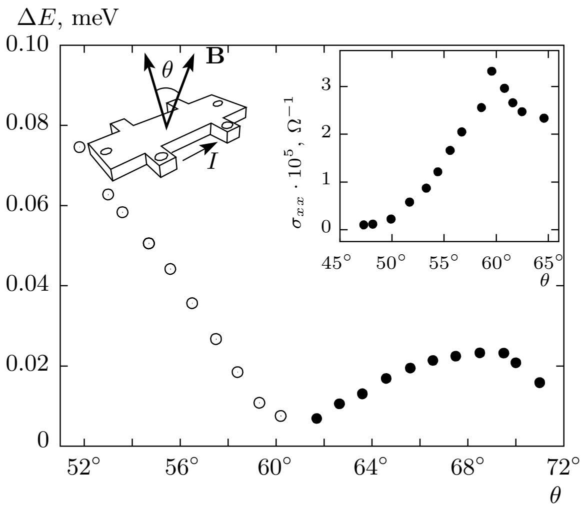

Fig. 1. Dependence of the activation energy on the tilt angle θ. Inset: Dependence of the conductivity σ_{xx} on θ at $\nu \approx 2$; $T = 0.3$ K

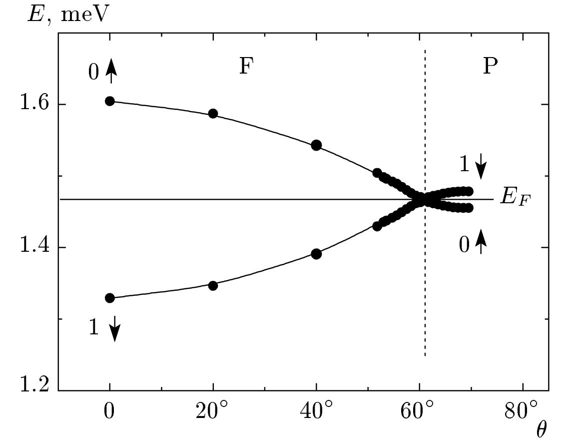

Fig. 2. Energies of the LLs $0\uparrow$ and $1\downarrow$ vs. the angle θ for the sample with $p = 2 \cdot 10^{11}$ cm^{-2}

These facts confirm that the observed F–P transition is indeed associated with the crossing of the LLs $0\uparrow$ and $1\downarrow$ at 60°. Now, knowing the activation energy dependence on θ and using the value $\Delta E = 0.28$ meV found in Ref. [7] for $\theta = 0$, we can obtain a more accurate angle dependence of the energies of the levels $0\uparrow$ and $1\downarrow$. It is presented in Fig. 2.

The F–P transition is expected to be accompanied by the formation of ferromagnetic domains. According to Ref. [9], the domain formation should be manifested in an anisotropy of the magnetoresistance, i. e., the value of the magnetoresistance in a tilted field should depend on the orientation of $B_{\|}$, the in-plane projection of the magnetic field, with respect to the current. For example, an anisotropy in the region where LLs cross has been reported in several papers for GaAs/AlGaAs [10] and n-Si/SiGe [11, 12] heterostructures.

We tilted the sample in the two possible orientations, keeping the field projection ($B_{\|} \parallel I$) parallel and ($B_{\|} \perp I$) perpendicular to the current, but did not observe any anisotropy of the magnetoresistance in the vicinity of the transition. Figure 3 illustrates the dependence of the conductivity on the normal component of the applied magnetic field $B_{\perp}$ at different angles and for both orientations of the in-plane projection of B relative to the current.

As seen in Fig. 3, the curves for the different directions of the in-plane projection of the magnetic field ($B_{\|} \parallel I$ and $B_{\|} \perp I$) virtually coincide, i. e., in our case, the anisotropy of the conductivity is absent with a high degree of accuracy.

We also carried out similar studies at $T = (20–200)$ mK for the lower-density p-Si/SiGe/Si sample with $p = 7.2 \cdot 10^{10}$ cm^{-2}. The dependence of the resistivity ρ_{xx} on the magnetic field for different tilt angles is shown in Fig. 4. We particularly note that at tilt angles θ from 0 to 70°, the oscillations corresponding to $\nu = 2$ are extremely weak. They only start manifesting themselves for $\theta > 70°$. At $\nu = 3/2$, a maximum of resistance appears similar to the one we observed in the other sample, with a magnitude that depends strongly on the tilt angle.

Yet the oscillations at $\nu = 2$ are clearly visible in another way of measuring the magnetoresistance: when the sample is rotated in a fixed total magnetic field, the perpendicular field component $B_{\perp}$ causes oscillations at the angles determined by the concentration of charge carriers in the sample. Figure 5 shows such an angle dependence of the magnetoresistance measured at several fixed magnetic fields, where the oscillation related to $\nu = 2$ can be seen to move from a tilt of about 9° at 10 T to 5° at 18 T. It corresponds to $B_{\perp} = 1.7$ T in each case, as shown in the inset to Fig. 5 [13]. The field value $B = 1.7$ T for $\nu = 2$ is slightly different from the

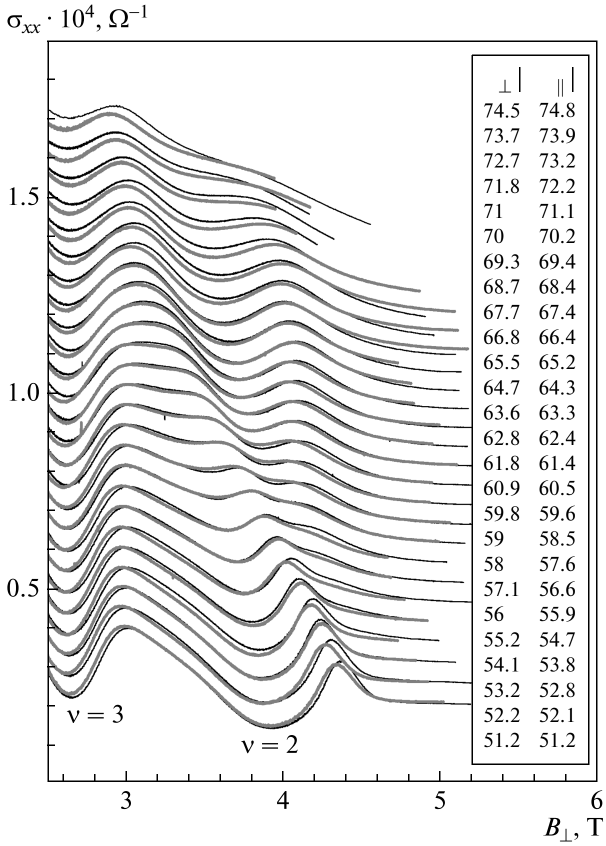

Fig. 3. Dependences of the σ_{xx} on the normal magnetic field component for different tilt angles shown for two orientations of the magnetic field $B_{\|} \parallel I$ and $B_{\|} \perp I$ at $T = 0.3$ K. The curves for each angle are shifted by $5 \cdot 10^{-6}\Omega^{-1}$ for clarity

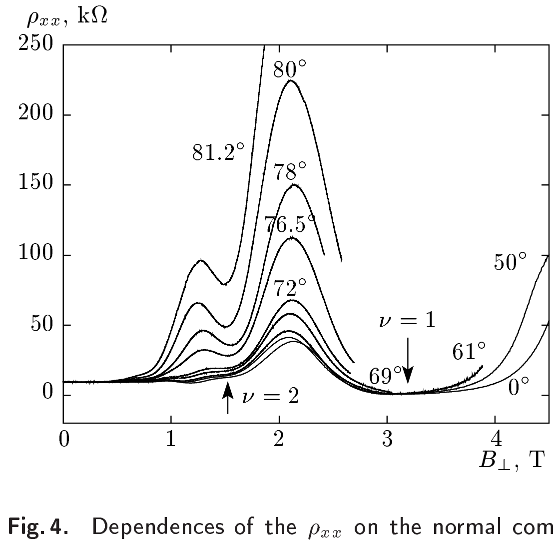

Fig. 4. Dependences of the ρ_{xx} on the normal component of the magnetic field for different tilt angles, $T = 0.2$ K

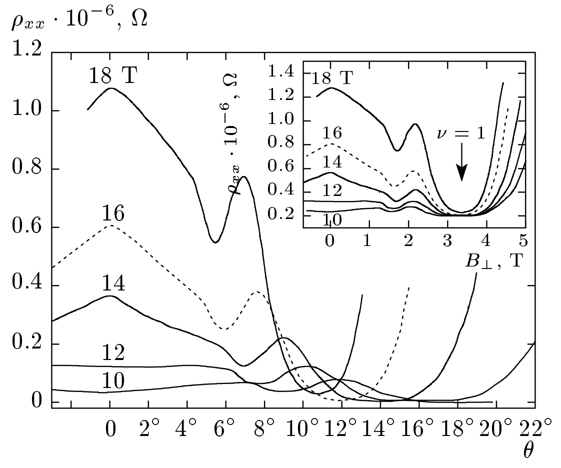

Fig. 5. Resistance ρ_{xx} as a function of the field tilt angle with respect to the plane of the 2D layer at different values of the total magnetic field, $T \approx 0.4$ K. Inset: ρ_{xx} as a function of the normal component of the magnetic field B

data shown above. This difference is probably a result of an ageing of the sample because the experiments in Ref. [13] were done much earlier.

The dependence of the conductivity σ_{xx} on the normal component of the magnetic field $B_\perp$ is shown in Fig. 6 at different tilt angles, with $B_\parallel \parallel I$. Since the oscillations of ρ_{xx} at high tilt angles are observed against a background of high resistance with $\rho_{xx} \gg \rho_{xy}$, it turns out that $\sigma_{xx} \sim 1/\rho_{xx}$, and therefore minima in ρ_{xx} correspond to maxima in σ_{xx}, as observed at $B_\perp \approx 1.5$ T in Fig. 6.

The absence of oscillations at magnetic fields corresponding to $\nu = 2$ in the range of angles (0–70)° indicates that the $0\uparrow$ and $1\downarrow$ LLs coincide. In our opinion, these oscillations appear for $\theta > 70°$ because the levels begin to diverge, resulting in the energy gap opening up. Apparently, the gap opening in the sample with $p = 7.2 \cdot 10^{10}$ cm^{-2} is associated with the angle dependence of the g-factor. The g-factor in this material is anisotropic [1] and depends on the magnetic field tilt angle relative to the sample surface normal. If the g-factor had an axial symmetry, we could write

$$g^* = \sqrt{g_\perp^2 \cos^2\theta + g_\parallel^2 \sin^2\theta},$$

where $g_\perp$ is the g-factor with the magnetic field perpendicular to the 2DHG and $g_\parallel$ is with the magnetic field parallel to the 2DHG. For strong anisotropy, when $g_\parallel = 0$ (as it should be in our structure) this reduces to $g^* = g_\perp \cos\theta$. However, if such a dependence of the

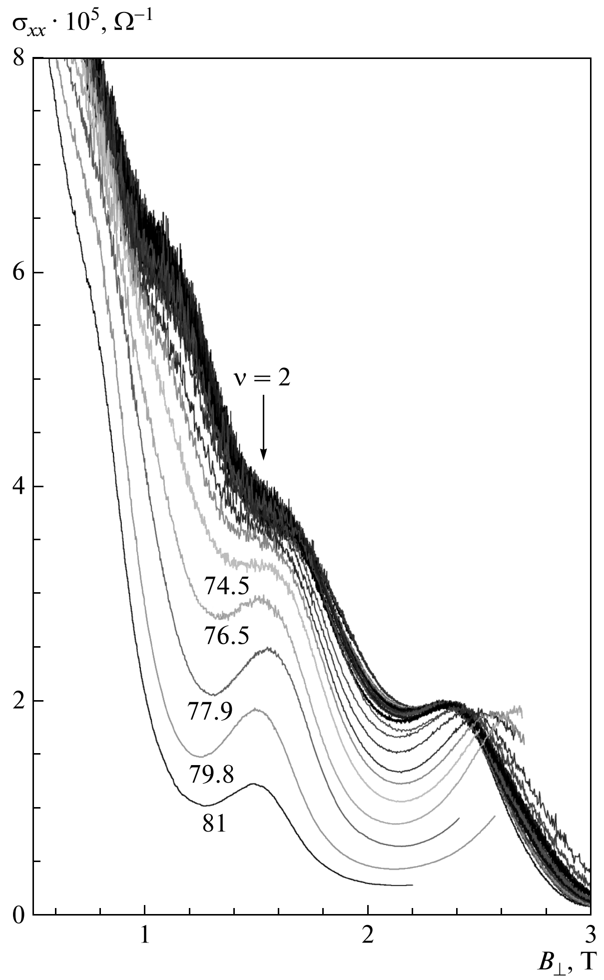

Fig. 6. Dependences of the σ_{xx} on the normal component of the magnetic field for different tilt angles for the sample with $p = 7.2 \cdot 10^{10}$ cm^{-2}; $T = 0.2$ K

g-factor were to occur, then the F–P transition should not be observed.

Unfortunately, we are unable to make reliable calculations and determine the width of the gap appearing in the sample with $p = 7.2 \cdot 10^{10}$ cm^{-2} due to the large magnetoresistance produced by the parallel magnetic field in this sample [13]. It should be noted that the values of $\rho_{xx}(B)$ and $\sigma_{xx}(B)$, on whose background the oscillations develop, strongly depend on the magnetic field, and the greater the angle is, the stronger this dependence. Hence, it does not seem to be possible to reliably separate the small oscillations at $\theta > 70°$ from the smooth background of $\rho_{xx}(B)$, which is about 10^6 Ohms. (Such problem for the sample with $p = 2 \cdot 10^{11}$ cm^{-2} did not arise because the overall change $\rho_{xx}(B)/\rho_{xx}(0)$ in a parallel magnetic field of

18 T did not exceed a factor of 4, and the in-plane resistance was only about 10^4 Ohms.)

Thus, the complete F–P transition in the sample with $p = 7.2 \cdot 10^{10}$ cm^{-2} is not observed in tilted fields. In a wide range of angles $\theta = (0–70)^\circ$, the $0\uparrow$ and $1\downarrow$ LLs are still coinciding, and only for $\theta > 70^\circ$ is there a gap in the hole energy spectrum arising as a result of a divergence of the LLs.

3. CONCLUSION

The ferromagnetic–paramagnetic transition is observed in a p-Si/GeSi/Si sample with $p = 2 \cdot 10^{11}$ cm^{-2} at a magnetic field corresponding to the filling factor $\nu \approx 2$. It appears as a result of a change in the relative position of the $0\uparrow$ and $1\downarrow$ LLs as a function of the tilt angle θ. This fact was first demonstrated in Ref. [7] and is confirmed in this paper by measurements of the energy gap dependence on the angle θ. For this sample, we also demonstrate the absence of anisotropy of σ_{xx} with respect to the magnetic field projection onto the sample plane, despite such an anisotropy having been proposed in Ref. [9]. At the same time, in the sample with $p = 7.2 \cdot 10^{10}$ cm^{-2}, the ferromagnetic–paramagnetic transition is not observed. In a wide range of angles $\theta = 0–70^\circ$, the LLs $0\uparrow$ and $1\downarrow$ coincide, and only for $\theta > 70^\circ$ does a gap open in the hole spectrum as a result of the LLs diverging.

The ambiguity in the results observed by various authors [1–6], as well as ourselves, on different p-Si/GeSi/Si samples is, in our opinion, due to dissimilar dependences of the g-factors on the magnetic field tilt angle. This is caused by different levels of disorder in all these samples, because disorder can lead to the axial symmetry breaking.

The authors are grateful to E. Palm, T. Murphy, J. H. Park, and G. Jones for their help with the experiments. This work was supported by the RFBR grant 11-02-00223, a grant of the Presidium of the Russian Academy of Sciences, the "Spintronika" Program of the Branch of Physical Sciences, RAS. The NHMFL is supported by the NSF through Cooperative Agreement No. DMR-0654118, the State of Florida, and the US Department of Energy.

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