Magnetoresistance in Dilute $p$-Si/SiGe in Parallel and Tilted Magnetic Fields

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We report the results of an experimental study of the magnetoresistance $\rho_{xx}$ and $\rho_{xy}$ in two samples of $p$-Si/SiGe with low carrier concentrations $p=8.2\times10^{10}$ cm$^{-2}$ and $p=2\times10^{11}$ cm$^{-2}$. The research was performed in the temperature range of 0.3-2 K and in the magnetic fields of up to 18 T, parallel or tilted with respect to the two-dimensional (2D) channel plane. The large in-plane magnetoresistance can be explained by the influence of the in-plane magnetic field on the orbital motion of the charge carriers in the quasi-2D system. The measurements of $\rho_{xx}$ and $\rho_{xy}$ in the tilted magnetic field showed that the anomaly in $\rho_{xx}$, observed at filling factor $\nu=3/2$ is practically nonexistent in the conductivity $\sigma_{xx}$. The anomaly in $\sigma_{xx}$ at $\nu=2$ might be explained by overlapping of the levels with different spins $0\uparrow$ and $1\downarrow$ when the tilt angle of the applied magnetic field is changed. The dependence of $g$-factor $g^*(\Theta)/g^*(0^\circ)$ on the tilt angle $\Theta$ was determined.

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INTRODUCTION

In studied $p$-Si/Si$_{1-x}$Ge$_x$/Si the 30 nm wide asymmetrical quantum well is positioned in the layer of strained Si$_{1-x}$Ge$_x$, so threefold degenerated (not considering a spin) SiGe valence band is split into 3 subbands via strong spin-orbit interaction and a strain. Charge carriers are the heavy holes, related to the band which is formed from the atomic states with quantum numbers $L=1$, $S=1/2$, and $J=3/2$. As the result, there is a strong anisotropy of $g$-factor: $g^*_1 \cong 4.5$ when the magnetic field is perpendicular to the plane of the quantum well and $g^*_2 \cong 0$ when the magnetic field is oriented in the plane of the well [1].

One of the interesting phenomena observed in this object was the discovery of the so-called "reentrant Metal-to-Insulator transition" in a magnetic field at filling factor $\nu=3/2$ [2–5]. In Ref. [2] that anomaly was attributed to the presence of long-range potential fluctuations with amplitude comparable with the Fermi energy in this material. However, the author of [3–5] explained those magnetoresistance anomalies by crossing of Landau levels with different spin directions $0\uparrow$ and $1\downarrow$ when the magnetic field increases. In the present work the studies of magnetoresistance and Hall effect were conducted in tilted magnetic fields to determine the dependence of $g$-factor on the tilt angle and the possible causes of the anomalies in magnetoresistance and conductivity at filling factor $\nu=2$ in the sample $p$-Si/SiGe with $p=2\times10^{11}$ cm$^{-2}$.

EXPERIMENTAL RESULTS AND DISCUSSION

We report the results of an experimental study of the magnetoresistance $\rho_{xx}$ in two samples of $p$-Si/SiGe/Si with low carrier concentrations $p=8.2\times10^{10}$ cm$^{-2}$ and $p=2\times10^{11}$ cm$^{-2}$. The research was performed in the temperature range of 0.3-2 K in the magnetic fields of up to 18 T, parallel to the two-dimensional (2D) channel plane[6] at two orientations of the in-plane magnetic field $B_{||}$ against the current $I$: $B_{||} \perp I$ and $B_{||} \parallel I$. In the sample with the lowest density in the magnetic field range of 0-7.2 T the temperature dependence of $\rho_{xx}$ demonstrates the metallic characteristics ($d\rho_{xx}/dT > 0$). However, at $B_{||}=7.2$ T the derivative $d\rho_{xx}/dT$ reverses the sign. Moreover, the resistance depends on the current orientation with respect to the in-plane magnetic field. At $B_{||} \equiv 13$ T there is a transition from the dependence $\ln(\Delta \rho_{xx}/\rho_0) \propto B_{||}^2$ to the dependence $\ln(\Delta \rho_{xx}/\rho_0) \propto B_{||}$. The observed effects can be explained by the influence of the in-plane magnetic field on the orbital motion of the charge carriers in the quasi-2D system[7]. This result confirms that in the in-plane magnetic field $g^* \equiv 0$.

Magnetoresistance and Hall effect were measured in

FIG. 1: Dependence of $\Delta \rho_{xx}/\rho_0$ on $B_{||}$ at $T=0.3$ K for the sample with $p=8.2\times10^{10}$ cm$^{-2}$. $B_{||} \perp I$. 

\begin{align} 
\Delta \rho_{xx}/\rho_0 & \propto B_{||}^2 \\
\ln(\Delta \rho_{xx}/\rho_0) & \propto B_{||}.
\end{align}
tiled magnetic field of up to 18 T in the temperature range of 0.3-1.6 K in the linear regime at \( I = 10 \) nA. More detailed studies of the tilt effects were done on the sample with the density \( p = 2 \times 10^{11} \text{cm}^{-2} \) and mobility \( \mu = 7 \times 10^{3} \text{cm}^{2}/\text{Vs} \). These data allowed to calculate the dependence of \( \sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2) \) on the magnetic field at different angles \( \Theta \) between the 2D interface surface normal and the magnetic field orientation (\( \Theta = 0^\circ \) if \( B \) is perpendicular to the 2D interface). In Fig.2, \( \rho_{xx} \) and \( \sigma_{xx} \) traces are plotted versus normal component \( B_\perp \) for a number of the tilt angles.

FIG. 2: Dependence of \( \rho_{xx} \) (a) and \( \sigma_{xx} \) (b) on \( B_\perp \) at different tilt angles \( \Theta, T = 0.3 \) K.

As can be seen from the Fig.2 the maximum of \( \rho_{xx} \) at \( \nu = 3/2 \) increases with the increase of the tilt angle, which was interpreted by many researchers as a M-I reentrant phase transition. However, the dependence of \( \sigma_{xx} \) on the angle at \( \nu = 3/2 \) does not show any anomaly. Further in this work the analysis of the dependences of \( \sigma_{xx} \) on the magnetic field, temperature and the tilt angle will be presented. As can be seen from the Fig.3, \( \sigma_{xx} \) at \( \nu = 3 \) increases with increasing temperature (\( \Theta = 0^\circ \)) (a) as well as with increase of the tilt angle (\( T = 0.3 \) K = const) (b). Minimum of \( \sigma_{xx} \) at \( \nu = 3 \) is observed when the Fermi level lies between two spin split Landau levels \( 1 \uparrow \) and \( 1 \downarrow \). In the temperature range of 0.6-1.7 K \( \sigma_{xx} \propto \exp[-g^*\mu_B B/2k_BT] \), where \( g^* \) is the effective g-factor, \( \mu_B \) is the Bohr magneton, \( B \) is the total magnetic field, \( k_B \) is the Boltzmann constant.

The change of \( \sigma_{xx} \) in Fig.3a is associated with change of \( T \) at constant g-factor and \( B_\perp \). Yet the conductivity variation with the tilt angle (see Fig.3b) at constant \( T = 0.3 \) is \( \sigma_{xx} \propto \exp[-g^*(\Theta)\mu_B B_\perp/2k_BT] \), and here this
is g-factor that changes (decreases). If to build the dependencies $\sigma_{xx}(T)$ and $\sigma_{xx}(\Theta)$ and at $\sigma_{xx}$ being equal to associate the angle with a certain temperature $T'$ one may obtain the equation $g^*(0^+)/0.3 = g^*(\Theta)/T'$, i.e. $g^*(\Theta)/g^*(0^*) = T'/0.3$. Thus, one can determine the dependence of reduced g-factor on the tilt angle.

Another method for determining $g^*(\Theta)$ is to construct dependencies of $\sigma_{xx}$ magnitudes at $\nu=3$, 5, 7 and 9 on total magnetic field $B$ at different angles $\Theta$ (Fig.4a). Since $\sigma_{xx} \propto \exp[-g^*(\Theta)\mu_B B/2k_BT]$, then $\ln \sigma_{xx}(B) \propto g^*(\Theta)$ at $T=$const and different $\Theta$, which makes it possible to determine $g^*(\Theta)/g^*(0^*)$. Results of determination of g-factor using these methods are illustrated in Fig.4b. $\sigma_{xx}$ obeys to the activation law with $\Delta E/2k_BT \approx 1.6K$. We now consider changes of the conductivity oscillation traces near $\nu=2$ with $T$ and $\Theta$. Fig.5a shows that the position of the $\sigma_{xx}$ minimum at $\nu=2$ and $\Theta=0^0$ does not change in the magnetic field with temperature, and However, with the increase of the tilt angle the conductivity minimum increases and shifts in the direction of small magnetic fields until $\Theta \approx 60^0$ (Fig.5b). When the angle reaches the value of $\approx 59.5^0$, two oscillations appear on the curve: the former, which shifted to the left with the angle increase, and the new one which emerged at $B_\perp \approx 4$ T. With further increase of the angle this new oscillation shifts left and grows in amplitude while the former oscillation disappears. Fig.6a shows the new oscillation arising and a region of angles where both types of oscillations coexist. The explanation of this anomaly might be associated with the emergence of a ferromagnetic-paramagnetic transition due to the Landau levels crossing with the magnetic field tilt. Fig.6b demonstrates the possibility of such crossing. We used here the experimental data obtained in this work: the dependence of $g^*(\Theta)/g^*(0^*)$ on $\Theta$, $\Delta E=0.14$ meV is the gap between the levels $0\uparrow$ and $1\downarrow$ at $\Theta=0^0$. To enable Landau levels overlapping at $\Theta=(50-60)^0$ it is necessary that at $\Theta=0^0$ the system is in the ferromagnetic state, i.e. the energy of level $1\downarrow$ is higher than the one of $0\uparrow$, otherwise no crossing occurs (in this case $g^*(0) = 5$). It is worth noting that the results in Fig.6b are approximate, as a broadening of the levels (disorder in the system) was not taken into account.

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[1] E. Glaser, J.M. Trombetta, T.A. Kennedy, S.M. Prokes, O.J. Glmbocki, K.L. Wang and C.H. Chern, Phys. Rev. Lett. 65, 1247 (1990).

[2] S.I. Dorozhkin, C.J. Emeleus, T.E. Whall, G. Landwehr, and O.A. Mironov, JETP Lett. 62, 534 (1995).

[3] P.T. Coleridge, A.S. Sachrajda, P. Zawadzki, R.L. Williams, and H. Lafontaine, Sol. St. Com. 102, 755 (1997).

[4] M.R. Sakr, Maryam Rahimi, and S.V. Kravchenko, Phys. Rev. B 64, 161308 (2001).

[5] P.T. Coleridge, Sol. St. Com. 127, 777 (2003).

[6] I.L. Drichko, I.Yu. Smirnov, A.V. Suslov, O.A. Mironov, and D.R. Leadley, Phys. Rev. B 79, 205310 (2009).

[7] S. Das Sarma, E.H. Hwang, Phys. Rev. Lett. 84, 5596 (2000).