Magnetoresistivity and Acoustoelectronic Effects in a Tilted Magnetic Field in $p$-$Si/SiGe/Si$ Structures with an Anisotropic $g$ Factor

I.L. Drichko,¹ I.Yu. Smirnov,¹ A.V. Suslov,² O.A. Mironov,³ and D.R. Leadley⁴

¹A.F. Ioffe Physico-Technical Institute of Russian Academy of Sciences, 194021 St. Petersburg, Russia
²National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA
³Warwick SEMINANO R&D Centre, University of Warwick Science Park, Coventry CV4 7EZ, UK
⁴Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

(Dated: November 25, 2010)

Magnetoresistivity $\rho_{xx}$ and $\rho_{xy}$ and the acoustoelectronic effects are measured in $p$-$Si/SiGe/Si$ with an impurity concentration $p = 1.99 \times 10^{11}$ cm$^{-2}$ in the temperature range 0.3-2.0 K and an tilted magnetic field up to 18 T. The dependence of the effective $g$ factor on the angle of magnetic field tilt $\theta$ to the normal to the plane of a two dimensional $p$-$Si/SiGe/Si$ channel is determined. A first order ferromagnet-paramagnet phase transition is observed in the magnetic fields corresponding to a filling factor $\nu = 2$ at $\theta \approx 59^\circ$-$60^\circ$.

PACS numbers: 73.23.-b, 73.43.Qt

INTRODUCTION

The rather interesting kinetic properties of $p$-$Si/SiGe/Si$ structures have been attracting attention of researchers for the last two decades [1-6]. The quantum well in $p$-$Si_{1-x}Ge_x/Si$ is located in the strained Si$_{1-x}$Ge$_x$ layer; therefore, the triply degenerate (without regard for spin) valence band of SiGe splits into three bands due to spin–orbit coupling and mechanical stresses. The charge carriers are represented by heavy holes, whose band is formed by atomic states with quantum numbers $L = 1$, $S = 1/2$, and $J = 3/2$. This should result in a strong anisotropy of the effective $g$ factor: $g^* \approx 4.5$ if a magnetic field is normal to the plane of the quantum well and $g^* \approx 0$ if a magnetic field is parallel to the plane of the quantum well [7].

In such structures in a magnetic field normal to the plane of the quantum well, the values of parameter $m^*$ and $g^*$ factor are such that the relationship $g^* \mu_B B \approx \hbar \omega_c$ holds true; here, $\mu_B$ is the Bohr magneton, $\omega_c = eB/m^*c$ is the cyclotron frequency, $e$ is the electron charge, $B$ is the magnetic field, $m^*$ is the effective hole mass, and $c$ is the velocity of light. As a result, resistivity $\rho_{xx}$ oscillations only with odd filling factors $\nu = 1, 3, 5, \ldots$ are experimentally observed in magnetic field $B$. $\rho_{xx}(B)$ oscillations at $\nu = 2$ are observed only in some samples. The specific features of conductivity in the magnetic field corresponding to $\nu = 2$ are comprehensively studied in this work.

The formation of pinned Wigner glass was revealed in $p$-$Si/SiGe/Si$ with a low impurity concentration ($p = 8.2 \times 10^{10}$ cm$^{-2}$) in the quantum limit in a perpendicular magnetic field [8], and a giant positive magnetoresistivity was observed in this structure in a parallel magnetic field [9]. This magnetoresistivity was caused by the interaction of the orbital motion of carriers in a wide quantum well with a parallel magnetic field.

An unusual phenomenon, namely, the so called re-entrant metal-insulator transition, was also found in this structure in a magnetic field at a filling factor $\nu = 3/2$ [1-6]. In [2], this anomaly was related to the presence of smooth large scale potential fluctuations with an amplitude comparable with the Fermi energy. In [3-5], however, this phenomenon was explained by the crossing of Landau levels with opposite spin directions ($0^\uparrow, 1\downarrow$) when the magnetic field strength changes.

In this work, we study magnetoresistivity, Hall effect, and acoustoelectronic effects in an tilted magnetic field to determine the dependence of the $g^*$ factor on the angle of magnetic field tilt to the normal to the plane of a two dimensional channel. With this dependence, we can analyze the possible cause of the anomalies in conductivity that appear at a filling factor $\nu = 2$ in a $p$-$Si/SiGe/Si$ sample with $p = 2 \times 10^{11}$ cm$^{-2}$. The asymmetric quantum well in this sample was 30 nm wide, and the sample structure was described in [9].

EXPERIMENTAL RESULTS

Magnetoresistivity $\rho_{xx}$ and $\rho_{xy}$ and the acoustoelectronic effects were measured in an tilted magnetic field up to 18 T in the temperature range 0.3-2.0 K in a linear current regime ($I = 10$ nA). A sample with an impurity concentration $p = 2 \times 10^{11}$ cm$^{-2}$ and a mobility of $7 \times 10^{4}$ cm$^2$/V·s was studied. The integer quantum Hall effect was observed in the sample in a magnetic field normal to the plane with two dimensional conductivity (Fig. 1).

Figure 2a shows $\rho_{xx}$ versus total magnetic field $B$ at various angles of inclination $\theta$ to the normal to the two dimensional layer surface at $T = 0.3$ K. At $\theta = 0^\circ$ in field $B \approx 5.2$ T, which corresponds to $\nu = 3/2$ the maximum of $\rho_{xx}$ is observed. It is seen that, as $\theta$ increases, the oscillation maxima and minima shift toward high magnetic fields and the value of $\rho_{xx}$ in the maxima at $\nu = 3/2$ in-
increases. Figure 2b shows the $\rho_{xx}(B_\perp)$ dependence near $\nu = 3/2$ for various $\theta$. Indeed, the anomaly described in the Introduction does occur near $B = 5.2$ T ($\nu = 3/2$): $\rho_{xx}$ increases more than five fold when angle $\theta$ increases from 0° to 70°. Figure 3 shows the dependences of $\rho_{xy}$ on the total magnetic field and its perpendicular component at $T = 0.3$ K and various angles of inclination $\theta$.

The conductivity was calculated at various angles of inclination $\theta$,

$$\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2).$$

The $\sigma_{xx}(B_\perp)$ dependence is shown in Fig. 4. It is interesting that anomalies do not occur in the $\sigma_{xx}(B_\perp)$ dependences at $\nu = 3/2$ ($\sigma_{xx}$ changes by 30% when tilt angle $\theta$ changes from 0° to 75°). Moreover, the positions of the $\sigma_{xx}$ minima in a magnetic field are independent of the tilt angle at $\nu = 1, 3$, and 5, whereas these minima begin to shift toward low magnetic fields at $\nu = 2$ and $\theta > 50°$. The explanation of this fact requires separate consideration.

Apart from the dc measurements, we also studied the acoustoelectronic effects in an tilted magnetic field at $T = 0.3$ K. The acoustic methods based on surf face acoustic waves make it possible to measure samples of a square or rectangular shape without application of electric contacts. To this end, a “hybrid” method is used: a surface acoustic wave propagates along the surface of the piezoelectric insulator LiNbO$_3$, and the structure to be studied is slightly pressed to the lithium niobate surface by a spring. A deformation wave propagating along the lithium niobate surface is accompanied by an electric field wave having the same frequency. The electric field penetrates into the channel with two dimensional conductivity, inducing high frequency currents and, correspondingly, wave energy absorption. In this experimental configuration, deformation is not transmitted into the sample.

![Diagram](image-url)

**FIG. 1:** $\rho_{xx}$ and $\rho_{xy}$ (in $\hbar/e^2$) vs. magnetic field at $T = 0.35$ K and $p = 1.99 \times 10^{11}$ cm$^{-2}$.

![Diagram](image-url)

**FIG. 2:** (a) $\rho_{xx}$ vs. total magnetic field at various angles of inclination $\theta$ to the normal to the sample surface at $p = 1.99 \times 10^{11}$ cm$^{-2}$ and $T = 0.3$ K ($B_\perp$ and $B_\parallel$ are the field components normal and parallel to the structure plane, respectively). (b) $\rho_{xx}(B_\perp)$ dependences at various angles $\theta$ and $T = 0.3$ K.

We measured the following acoustoelectronic effects: absorption coefficient $\Gamma$ and the change in the surface acoustic wave velocity at a frequency of 30 MHz in an tilted magnetic field up to 18 T for various angles of inclination at $T = 0.3$ K. The acoustoelectronic effects are governed by the high frequency conductivity of a two dimensional system [10]. If the system exhibits the quantum Hall effect and dc Shubnikov-de Haas oscillations in a magnetic field, similar oscillations are also observed in the acoustoelectronic effects.

Figure 5 shows absorption coefficient $\Gamma$ and the change in the surface acoustic wave velocity $\Delta V/V$ versus the total magnetic field at various angles of magnetic field tilt.

We measured the following acoustoelectronic effects: absorption coefficient $\Gamma$ and the change in the surface acoustic wave velocity at a frequency of 30 MHz in an tilted magnetic field up to 18 T for various angles of inclination at $T = 0.3$ K. The acoustoelectronic effects are governed by the high frequency conductivity of a two dimensional system [10]. If the system exhibits the quantum Hall effect and dc Shubnikov-de Haas oscillations in a magnetic field, similar oscillations are also observed in the acoustoelectronic effects.

Figure 5 shows absorption coefficient $\Gamma$ and the change in the surface acoustic wave velocity $\Delta V/V$ versus the total magnetic field at various angles of magnetic field tilt.
FIG. 3: $\rho_{xy}$ as a function of (a) a total magnetic field and (b) its normal component at $T = 0.3$ K and various angles of magnetic field tilt to the normal to the sample surface.

It is seen that the positions of oscillations shift toward high magnetic fields as the tilt angle increases and that the oscillation corresponding to $\nu = 2$ disappears at $\theta = 53^\circ$. This fact means that, at $\theta \approx 53^\circ$, the conductivity in the two dimensional channel increases strongly.

**DISCUSSION OF THE EXPERIMENTAL RESULTS**

If an effective $g$ factor is isotropic, its value in an tilted magnetic field is usually determined by the formula

$$g^* = \sqrt{g_\perp^2 \cos^2 \theta + g_\parallel^2 \sin^2 \theta}, \quad (1)$$

where $g_\perp$ is the $g$ factor in the magnetic field normal to the plane of the channel with two dimensional conductivity and $g_\parallel$ is the $g$ factor in the magnetic field parallel to this plane. For a strong anisotropy, where $g_\parallel = 0$ (as should be in the structure under study), we have $g^* = g_\perp \cos \theta$. In this case, when a magnetic field is inclined, the positions of the oscillation minima shift toward high magnetic fields but the oscillation amplitude is independent of the angle of magnetic field tilt. Such a situation took place in [11]. In our samples, the oscillation amplitude depends on angle $\theta$ at all filling factors; therefore, axial symmetry which is corresponded to Eq. (1) is likely to be violated in our sample. We use the dependences of conductivity $\sigma_{xx}$ on temperature and angle of magnetic field tilt $\theta$ at $\nu = 3$ in order to determine the angular dependence of the $g^*$ factor. As a function of the magnetic field at $\nu = 3$, $\sigma_{xx}$ is minimal when the Fermi level is located between two spin split Landau levels, $1\downarrow$ and $1\uparrow$. As
is seen from Fig. 6, $\sigma_{xx}$ at $\nu = 3$ grows with both temperature ($\theta = 0$) and angle of magnetic field tilt $\theta$ ($T = 0.3$ K). In this case, the temperature and angular dependences of the conductivity minimum can be expressed as

$$\sigma_{xx} \propto \exp\left[-g^* (\theta) \mu_B B/2kT\right],$$

where $B$ is the total magnetic field and $k$ is the Boltzmann constant. Therefore, if we plot the $\sigma_{xx}(T)$ and $\sigma_{xx}(\theta)$ dependences and attribute certain temperature $T'$ to every angle $\theta$ at the same $\sigma_{xx}$, we can obtain the expression

$$g^*(\theta = 0)/0.3 = g^*(\theta)/T',$$

or

$$\frac{g^*(\theta)}{g^*(\theta = 0)} = \frac{T'}{0.3},$$

Thus, we can determine the dependence of the reduced $g^*$ factor on tilt angle $\theta$. A similar procedure can also be performed for $\nu = 5$ but with a much lower accuracy.

Another method for determining $g^*(\theta)$ is related to the construction of the dependences of $\sigma_{xx}$ on total magnetic field $B$ for the oscillation minima at $\nu = 3, 5$, and $9$; various angles $\theta$; and $T = 0.3$ K. The conductivities were determined from the curves shown in Fig. 2. Since $\sigma_{xx} \propto \exp(-g^*(\theta) \mu_B B/2kT)$ as noted above, the $\ln \sigma_{xx}(B)$ dependences at various $\theta$ are described by linear functions. In this case, we have $\Delta(\ln \sigma_{xx})/\Delta B \sim g^*(\theta)$; therefore, we can determine the ratio $g^*(\theta)/g^*(\theta = 0)$. As is seen from Fig. 7, the slope increases with decreasing angle $\theta$. It turns out that the values of $g^*(\theta)/g^*(\theta = 0)$ determined by different methods at the same value of $\theta$ are similar; they are shown as points in Fig. 8 at $g^*(\theta = 0) = 6$ ($g^*(\theta = 0)$ is determined below). Figure 8 (curve) also shows the $g^*(\theta) = 6\cos \theta$ dependence. As follows from Fig. 8, the $g^*(\theta)$ dependence in the sample under study differs from the curve calculated by Eq. (1).

We now consider the $\sigma_{xx}(B_L)$ dependences of conductivity near $\nu = 2$ for various temperatures and angles $\theta$ (Figs. 9, 10).

As noted above, only odd minima are usually observed in Shubnikov-de Haas oscillations in experiment in Si/SiGe/Si samples in a magnetic field normal to the plane of a two dimensional channel. The only exception is the even minimum at $\nu = 2$, which is only observed in some samples, in particular, in the sample under study. It is generally accepted that the absence of oscillations with an even filling factor $\nu$ is caused by the relation $\hbar \omega_c \approx g^* \mu_B B$. When this equality holds true in magnetic fields corresponding to even $\nu$, the energies of the levels with different spin directions are the same in different Landau bands; therefore, oscillations with even $\nu$ are not observed. The value of $g^*$ calculated from this equality at $m^* = 0.21m_0$ is 4.7. However, as was shown in our experiment, we both observed a clear minimum of $\sigma_{xx}$ at $\nu = 2$ (Fig. 9a) and were able to measure its temperature dependence. The $\sigma_{xx}(T)$ dependence at $\theta = 0$ corresponds to an activation energy $E_a \approx 3.2$ K (0.28 meV), which means that levels $0$ and $1$ at $\theta = 0$ are close but noncoincident.

![Graph showing absorption coefficient $\Gamma$ and change in surface acoustic wave velocity $\Delta V/V$ vs. total magnetic field $B$ at various angles $\theta$.](image)

**FIG. 5**: Absorption coefficient $\Gamma$ and the change in the surface acoustic wave velocity $\Delta V/V$ vs. the total magnetic field at various angles of magnetic field tilt $\theta$ to the normal to the structure surface, $T = 0.3$ K, and $f = 30$ MHz.

![Graph showing $\sigma_{xx}(B_L)$ dependences at various angles $\theta$.](image)

**FIG. 6**: $\sigma_{xx}(B_L)$ dependences (a) at various angles of inclination $\theta$; $\nu = 3$, and $T = 0.3$ K and (b) $\sigma_{xx}(B_L)$ at various temperatures $\nu = 3$, and $\theta = 0$.

It is also seen from Fig. 9 that conductivity $\sigma_{xx}$ in the minimum at $\nu = 2$ and a varied magnetic field increases with both the temperature and angle. When the
temperature changes, the position of this oscillation minimum does not change along the magnetic field axis (Fig. 9a); however, as tilt angle increases, the conductivity minimum shifts toward low magnetic fields. As increases further, the amplitudes of the new oscillations increase and their minima shift toward low magnetic fields, and the former oscillations disappear. Both types of oscillations coexist in the angular range $59.5^\circ \leq \theta \leq 61^\circ$.

Figure 11 shows the $\sigma_{xx}(B_{\perp})$ dependences in the field range 2.5-5.2 T for various angles $\theta$ shifted at a step of $5 \times 10^{-6} \Omega^{-1}$ with respect to the curve with $\theta = 55.7^\circ$ (for clarity).

To analyze these anomalies, we use the idea employed in [3-5] to explain the specific features of electrical resistivity in Si/SiGe/Si at $\nu = 3/2$. They were related to the change of the relative position of spin-split (0↑, 1↓) Landau levels induced by the dependence of the $g^*$ factor of the magnetic field. This idea was developed earlier in theoretical works [12, 13] and was supported experimentally in GaAs/AlGaAs for $\nu = 4$ [14] and 2/3 [15]. It was assumed that the crossing of the Landau levels is accompanied by a first order paramagnet-ferromagnet phase transition [14, 15].

We now study the relative position of Landau levels 0↑ and 1↓ at $\nu = 2$ ($B_{\perp} = 4.15$ T) as a function of the angle of magnetic field tilt. To this end, we need to know the value of $g^*(\theta = 0)$. We choose $g^*(\theta = 0) = 6 \cos \theta$, (circles) experimental data at $\nu = 3$, and (squares) experimental data at $\nu = 2$.

When choosing the values of $g^*$ and $m^*$, we take into account that these levels should cross at $\theta = 60^\circ$, since the anomalies are observed experimentally at this angle.
FIG. 10: $\sigma_{xx}(B_{\perp})$ dependences at various angles $\theta$. (see Fig. 11). The calculation results are shown in Fig. 12. It should be noted that this calculation is a rough illustration of the possibility of the crossing of these levels. Here, we do not take into account the interaction between the levels, the disorder induced broadening of the levels, and the carrier distribution nonuniformity in a quantum well [16].

It should be noted that the $g^*(\theta)/g^*(\theta = 0)$ dependence was determined from the dependences of the spin gap energy on temperature and angle $\theta$ at $\nu = 3$. However, at a large spin splitting and $\nu = 3$, the order in the relative position of the Landau levels can also be broken. In this case, the energy determined in the angular range $0^\circ \leq \theta \leq 60^\circ$ differs from the spin gap. As a check, we also determined $g^*(\theta)$ from the $\sigma_{xx}(\theta)$ dependence at $\nu = 2$ in the angular range $0^\circ \leq \theta \leq 60^\circ$ (see the inset to Fig. 13). Since the dependence

\[ \sigma_{xx} \propto \exp \left( -\frac{\hbar \omega_c - g^* \mu_B B}{2kT} \right), \]

holds true in this angular range, the $\sigma_{xx}(\theta = 0)/\sigma_{xx}(\theta)$ ratio can be represented by the equation

\[
\frac{\sigma_{xx}(\theta = 0)}{\sigma_{xx}(\theta)} = \exp \left( -g^*(\theta = 0)\mu_B B + g^*(\theta)\mu_B B \right),
\]

which can be used to determine $g^*(\theta)$. The values of $g^*$ determined from this equation are shown as squares in Fig. 8. It is seen that the values of $g^*(\theta)$ determined by different methods are close, which means that the crossing of the Landau levels weakly distorts the spin gap at $\nu = 3$.

For the Landau levels to be intersected, we have to assume (as noted above) that the energy of level $0^\uparrow$ is higher than that of level $1^\downarrow$ in a magnetic field normal to the two dimensional layer, i.e., at $\theta = 0$. This means that a ferromagnetic order should be in the system, since two filled Landau levels with the same spin direction lie below the Fermi level. At $\theta \approx 60^\circ$, the levels intersect each other and, at $\theta > 60^\circ$, change their relative position, breaking the ferromagnetic order. In the angular range from $59.5^\circ$ to $61^\circ$, both states coexist.

Landau levels $0^\uparrow$ and $1^\downarrow$ intersect due to a strong dependence (decrease) of the $g^*$ factor on the angle of magnetic field tilt. At the point of crossing, we have $g^* \approx 2.37$. In this case, the value of filling factor $\nu$ calculated from the position of the oscillation minima in the magnetic field axis changes jumpwise. The $\nu(\theta)$ dependence is shown in Fig. 13. Both phases are seen to coexist in the angular range $59.5^\circ \leq \theta \leq 61^\circ$. However, the conductivity at the oscillation minima does not jump and reaches a maximum at the transition point. This dependence can easily be explained, since the activation energy at the transition point is minimal and increases on either side of this transition. This fact is also supported by
samples are ambiguous: in some samples, the resistivity anomaly exists and depends on the angle of magnetic field tilt \( \theta \); in other samples, this anomaly is absent; and in samples of a third group, this anomaly is independent of the tilt angle \([3]\). We think that the resistivity anomaly should be studied at \( \nu = 2 \), since point \( \nu = 3/2 \) has no physical meaning at a large spin splitting.

2. The ambiguity of the results obtained on different \( p\text{Si}/\text{SiGe}/\text{Si} \) samples is thought to be related to different dependences of the \( g^* \) factor on the angle of magnetic field tilt and, apparently, different absolute values of this factor, which is controlled by the quality of the sample and the hole concentration.

**CONCLUSIONS**

We studied the magnetoresistivity and the Hall effect of a \( p\text{-Si}/\text{SiGe}/\text{Si} \) structure with a quantum well and an anisotropic \( g^* \) factor in an tilted magnetic field.

At \( \nu = 2 \) and \( 3 \), we determined the dependence of the \( g \) factor on the angle of magnetic field tilt to the normal to the plane of a two dimensional channel and found the absolute value of the \( g^* \) factor for \( \theta = 0 \).

A high value of the \( g^* \) factor at \( \theta = 0 \) was shown to result in the fact that, in the magnetic field corresponding to \( \nu = 2 \), the energy of Landau level 0↑ is higher than the energy of level 1↓ and fully spin-polarized levels 0↓ and 1↓ lie below the Fermi level. This leads to a ferromagnetic order. When the angle of magnetic field tilt changes, the \( g^* \) factor decreases, the normal order of the Landau levels is restored at \( \theta \approx 59.5^\circ \), and the ferromagnetic order is broken. A first order ferromagnet-paramagnet phase transition occurs, which is indicated by a sharp jump in filling factor \( \nu \) and the coexistence of two phases at the transition point.

**ACKNOWLEDGMENTS**

I.L.D and I.Yu.S are grateful to Yu.M. Gal’perin, S.A. Tarasenko, L.E. Golub, V.T. Dolgopolov, E.V. Devyatov, R.V. Parfen’ev, and V.A. Sanina for useful discussions. We thank T. Murphy and E. Palm for their assistance in the experiments.

This work was supported by the Russian Foundation for Basic Research (project no. 080200852); Presidium of the Russian Academy of Sciences; program Spintronics, Department of Physical Sciences, Russian Academy of Sciences; and the state program for support of leading scientific schools (project no. NSh2184.2008.2). A portion of the work was performed at the National High Magnetic Field Laboratory (Tallahassee, FL, USA) which was supported by the National Scientific Foundation (NSF), cooperative agreement no. DMR0654118), by the State of Florida.

**REFERENCES**
1. S. I. Dorozhkin, Pis’ma Zh. Eksp. Teor. Fiz. 60 (8), 578 (1994) [JETP Lett. 60 (8), 595 (1994)].

2. S. I. Dorozhkin, C. J. Emeleus, T. E. Whall, G. Landwehr, and O. A. Mironov, Pis’ma Zh. Eksp. Teor. Fiz. 62 (6), 511 (1995) [JETP Lett. 62 (6), 534 (1995)].

3. P. T. Coleridge, A. S. Sachrajda, P. Zawadzki, R. L. Williams, and H. Lafontaine, Solid State Commun. 102, 755 (1997).

4. M. R. Sakr, Maryam Rahimi, S. V. Kravchenko, P. T. Coleridge, R. L. Williams, and J. Lapointe, Phys. Rev. B: Condens. Matter 64, 161 308 (2001).

5. P. T. Coleridge, Solid State Commun. 127, 777 (2003).

6. R. B. Dunford, E. E. Mitchell, R. G. Clark, V. A. Stadnik, F. F. Fung, R. Newbury, R. H. McKenzie, R. P. Starrett, P. J. Wang, and B. S. Meyerson, J. Phys.: Condens. Matter 9, 1565 (1997).

7. 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).

8. I. L. Drichko, A. M. Dyakonov, I. Yu. Smirnov, A. V. Suslov, Y. M. Galperin, V. Vinokur, M. Mironov, O. A. Mironov, and D. R. Leadley, Phys. Rev. B: Condens. Matter 77, 085 327 (2008).

9. I. L. Drichko, I. Yu. Smirnov, A. V. Suslov, O. A. Mironov, and D. R. Leadley, Phys. Rev. B: Condens. Matter 79, 205 310 (2009).

10. I. L. Drichko, A. M. Dyakonov, I. Yu. Smirnov, Yu. M. Galperin, and A. I. Toropov, Phys. Rev. B: Condens. Matter 62, 7470 (2000).

11. R. W. Martin, R. J. Nicholas, G. J. Rees, S. K. Haywood, N. J. Mason, and P. J. Walker, Phys. Rev. B: Condens. Matter 42, 9237 (1990).

12. G. F. Giuliani and J. J. Quinn, Phys. Rev. B: Condens. Matter 31, 6228 (1985).

13. S. Yarlagadda, Phys. Rev. B: Condens. Matter 44, 13101 (1991).

14. A. J. Daneshvar, C. J. B. Ford, M. J. Simmons, A. V. Khaetskii, A. R. Hamilton, M. Pepper, and D. A. Ritchie, Phys. Rev. Lett. 79, 4449 (1997).

15. V. T. Dolgopolov, E. V. Deviatov, V. S. Khrapai, D. Reuter, A. D. Wieck, A. Wixforth, K. L. Campman, and A. C. Gossard, Phys. Status Solidi B 243, 3648 (2006).

16. L. Yu. Shchurova, Ann. Phys. (Berlin) 18, 928 (2009).