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ABSTRACT

Quantum effects in p-type $Si_{0.2}Ge_{0.8}/Ge/Si_{0.2}Ge_{0.8}$ heterostructure with an extremely high mobility of charge carriers $\mu_H = 1367000\ \mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$ have been comprehensively studied. An analysis of Shubnikov–de Haas oscillations yielded effective mass of charge carriers, which proved to be very low, $m^* = 0.062m_0$, and the value of fluctuations of hole density along the channel $\delta p = 3.5\cdot 10^9\ \mathrm{cm}^{-2}$. The fractional Hall effect (filling numbers 8/3, 7/3, 5/3, 4/3) observed at temperatures up to 5 K has been discovered in strong magnetic fields. The studies of quantum interference effects related to weak localization and electron-electron interaction between charge carriers, which have been conducted in such a high-mobility system for the first time, enabled calculation of spin splitting $\Delta = 1.07$ meV and the Fermi-liquid coupling constant $F_0^\sigma = -0.12$, which agree with results obtained earlier.

1. INTRODUCTION

The study of the contribution of quantum effects to electric conductivity of quasi-two-dimensional conducting systems as a function of temperature and external magnetic field is essential because it yields information on sign, effective mass, density of charge carriers, and times of their elastic, inelastic, and spin relaxation.[1,2] These studies are also of importance for practical applications as they can be employed in 2D superconductors used in modern electronics elements.[3,4]

As a result of disorder related to scattering processes, quantum corrections to conductivity occur that are due to weak localization of electrons (WL)[5,6] and electron-electron interaction (EEI).[7,8,9] Then, low-temperature electric resistivity of a 2D system exhibits a specific response to changes in temperature and magnetic field. The existing theory describes well the diffusion relaxation regime,[4,5,6,7,8,9,10] ballistic and intermediate relaxation regimes.[11,12] It provides an adequate interpretation of the anomalous behavior of low-temperature resistivity in 2D electron systems and information about phase and spin relaxation of electrons and parameters of interaction between them. Objects for experimental studies where WL and EEI quantum-interference effects have been observed include thin metal films,[13,14] inversion layers,[15,16] δ-layers,[17,18] heterostructures in semiconductors,[19,20] *etc.*

Dependence of conductivity on magnetic field B is related in weak magnetic fields with suppression of weak localization, while in strong magnetic fields Shubnikov–de Hass (SdH) oscillations emerge. The study of characteristics of 2D conducting systems provides information about a number of important characteristics of charge carriers (density, effective mass, relaxation times, *etc.*).

The development of various 2D conducting systems with highly mobile free charge carriers had led to new experimental studies of magnetic-oscillation and quantum-interference effects being conducted.[21,22] The point is that for the quantum-interference effects to be manifested, certain degree of disordering is required in objects under study, while the objects where these effects are most strongly pronounced usually feature low mobility of electrons. At the same time, the high-mobility systems that feature high purity enable the investigation of subtler effects that are indistinguishable in a "dirty" system. We present here studies of quantum effects in a system that features super-high mobility of hole-type charge carriers. We obtained effective masses of holes that proved to be very low and the value of fluctuations of carrier density along the channel. The fractional Hall effect (filling numbers 8/3, 7/3, 5/3, 4/3) observed at temperatures of up to 5 K has been discovered in strong magnetic fields. We have studied quantum interference effects for the first time in SiGe systems with high mobility of charge carriers: weak localization and effects of interaction between charge carriers. Relaxation times, value if the spin splitting, and Fermi-liquid interaction constant have been calculated.

2. OBJECT OF INVESTIGATION

The p-type SiGe heterostructure with pure Ge quantum well was studied. It consists of a layer of fully strained pure germanium (20 ± 1) nm thick sandwiched between two unstrained layers with composition $Si_{0.2}Ge_{0.8}$. A layer with the same composition doped with boron with a concentration of $1.4 \cdot 10^{18}\ \mathrm{cm}^{-3}$ was placed above the germanium quantum well at a distance of (26 ± 1) nm from where it was filled with free charge carriers because of the tunneling effect. The structure of the sample and the results of its structural analysis are described in Refs. 23 and 24.

The diagonal R_{xx} and non-diagonal R_{xy} components of resistivity as a function of temperature and magnetic field strength were measured using the standard look-in technique in magnetic fields up to 12 T and in a temperature range of 1.45–10 K.

3. MAGNETOQUANTUM EFFECTS

Fig. 1 shows experimental dependences ρ_{xx} (B) and ρ_{xy} (B) at low temperatures (ρ is the resistivity of a square area in the 2D electron system).

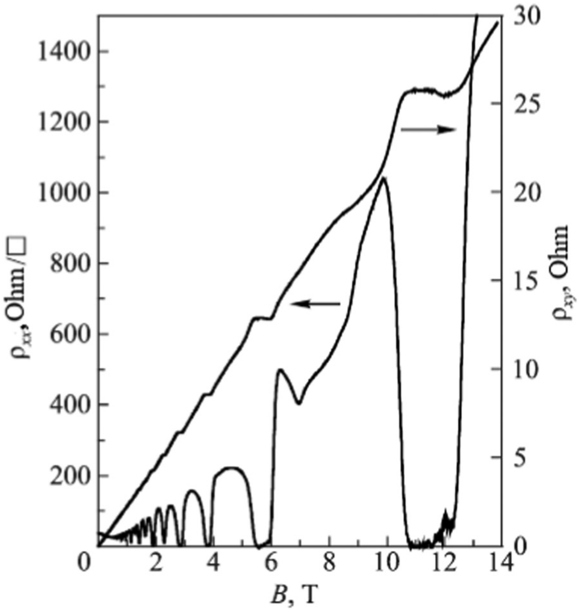

FIG. 1. Resistivity ρ_{xx} and ρ_{xy} as a function of magnetic field at T = 1.28 K.

As was noted earlier, experimental studies of SdH oscillations of a conducting system enable determination of the effective mass of free charge carriers. In this study, we perform calculations similar to those described in Refs. 25 and 26. The most detailed studies were conducted for a magnetic-field range of 1.2–2.5 T. In weak magnetic fields, the effect of quantum interference (described below) is of significance. In stronger magnetic fields, Sh-dH oscillations experience Zeeman splitting, a phenomenon that significantly complicates the analysis. The calculation are based on a theoretical model[27] according to which changes in resistivity of a 2D conducting system in case of pronounced magnetoquantum effects and homogeneous broadening of the Landau levels are described by the formula

$$\rho_{xx} = \frac{1}{\sigma_0}\left[1 + 4\sum_{s=1}^{\infty}\left(\frac{\Psi s}{\mathrm{sh}\Psi s}\right)\exp\left(-\frac{\pi s}{\omega_c \tau_q}\right)\cos\left(\frac{2\pi s \varepsilon_F}{\hbar\omega_c} - \Phi\right)\right], \quad (1)$$

where $\Psi = 2\pi^2 k_B T/(\hbar\omega_c)$ sets the temperature and magnetic-field dependences of the oscillation amplitude, $\omega_c = eB/m^*$ is the cyclotron frequency, τ_q is the quantum time of relaxation of charge carriers that characterizes broadening of the Landau levels, Φ is the phase, and ε_F is the Fermi energy. The calculations and theoretical arguments employ the complete set of experimental data on specimen resistivity as a function of temperature and magnetic field strength.

To determine the effective mass of free charge carriers, data are presented as dependence of $\ln\left[\frac{\Delta R}{R_0}\frac{\mathrm{sh}\Psi}{\Psi}\right]$ on $\frac{1}{\omega_c \tau}$ or $\frac{1}{\mu B}$, where μ is the mobility of charge carriers (the quantity in the exponent in the oscillating component of Eq. (1) is transformed into $-\pi\alpha/(\omega_c\tau)$, where $\alpha = \tau/\tau_q$ and τ is the transport relaxation time). Equation (1) was used to determine the effective mass $m^* = 0.062 m_0$ [solid line in Fig. 2(a)], where m_0 is the free-electron mass and $\alpha = 72$ [Fig. 2(b)].

Similar calculations were performed in Refs. 23 and 24; however, as a more detailed analysis showed, in weak magnetic fields [Fig. 2(a)], experimental values deviate from theoretical dependence (1). It was shown in Ref. 28 that nonlinearity in the coordinates defined above may be due to changes in density of free charge carriers and their Fermi energy as a result of natural local inhomogeneity of the conducting quantum channel. As a result, the oscillation extrema occur at different magnetic fields in different areas of the sample. In this case the observed amplitude of the oscillations decreases compared to that in a homogeneous sample. This corresponds to an additional effective broadening of the Landau levels referred to as “inhomogeneous broadening.” To obtain a numerical description of this broadening, an additional term with exponent $-(\pi\delta\varepsilon_F/\hbar\omega_c)^2$ should be added in the formula for oscillation amplitude (1), as a result of which the exponential factor in (1) takes the form[28]

$$\exp\left[-\frac{\pi}{\omega_c \tau_q} - \left(\frac{\pi^2 \hbar \delta n}{m^* \omega_c}\right)^2\right]. \quad (2)$$

Results of the calculations made with consideration of (2) are presented as a dashed line in Fig. 2(a).

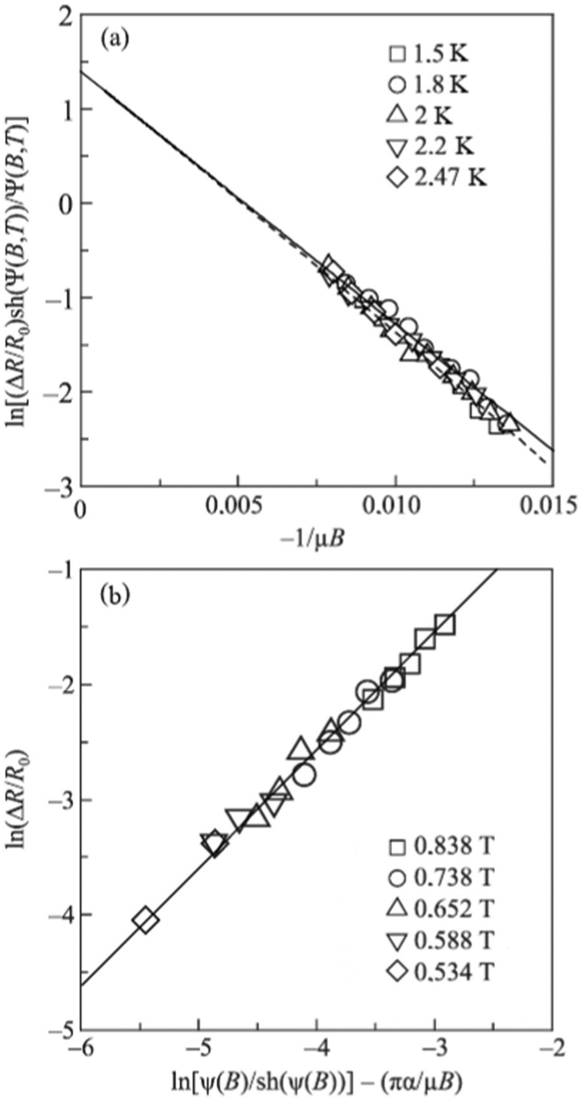

FIG. 2. Parameters m^* and α calculated using theoretical model.[27] Solid curve (a) is plotted in accordance with formula (1) and the dashed line is plotted with consideration for the exponential factor that takes into account “inhomogeneous” broadening of the Landau levels.[28] Solid line (b) corresponds to a tilt of 45°.

Numerical estimates were used to find density fluctuation $\delta p = 3.5 \cdot 10^{9}\ \mathrm{cm}^{-2}$ that makes ~1.25% of the average carrier density $p_H = 2.8 \cdot 10^{11}\ \mathrm{cm}^{-2}$ obtained from measurements of the Hall coefficient. It should be noted that similar calculations using correction (2) were made in Ref. 28 for a series of InP/In$_{0.53}$Ga$_{0.57}$As samples with density of electrons in a range of $p_H = (1.7–2.16) \cdot 10^{11}\ \mathrm{cm}^{-2}$ and mobility $\mu_H = 38100–83800\ \mathrm{cm}^2/(\mathrm{V} \cdot \mathrm{s})$, and in Refs. 25 and 29, for (Si$_{0.3}$Ge$_{0.7}$/Ge/Si$_{0.3}$Ge$_{0.7}$ and Si/Si$_{0.87}$Ge$_{0.13}$/Si) samples with hole type of conductivity and density of charge carriers $p_H = 5.81 \cdot 10^{11}\ \mathrm{cm}^{-2}$ and $p_H = 1.89 \cdot 10^{11}\ \mathrm{cm}^{-2}$ and mobilities $\mu_H = 46800$ and $11700\ \mathrm{cm}^2/(\mathrm{V} \cdot \mathrm{s})$, respectively. The density fluctuation values obtained in Ref. 28 $\delta p = (9.5–9) \cdot 10^{9}\ \mathrm{cm}^{-2}$ make 5.6–4.2% of the total charge carrier density, and the values obtained in Refs. 25 and 29 $\delta p = 2.7 \cdot 10^{9}\ \mathrm{cm}^{-2}$ make 6.5 and 2.1%, respectively. As follows from Eq. (2), the effect of the second term in the exponential factor decreases in the range of strong magnetic fields. The obtained density fluctuation of the order of 1% (of the total density of holes) is indicative of the exceptional purity of the quantum channel in the system under study, while observation of “inhomogeneous broadening” of the Landau levels only became possible owing to the record-setting high mobility of charges: $\mu_H = 1367000\ \mathrm{cm}^2/(\mathrm{V} \cdot \mathrm{s})$.

An interesting result of the performed studies was a discovery of the fractional quantum Hall minima on the magnetoresistance curves [Fig. 3(a)]. It should be noted that the discovery of this

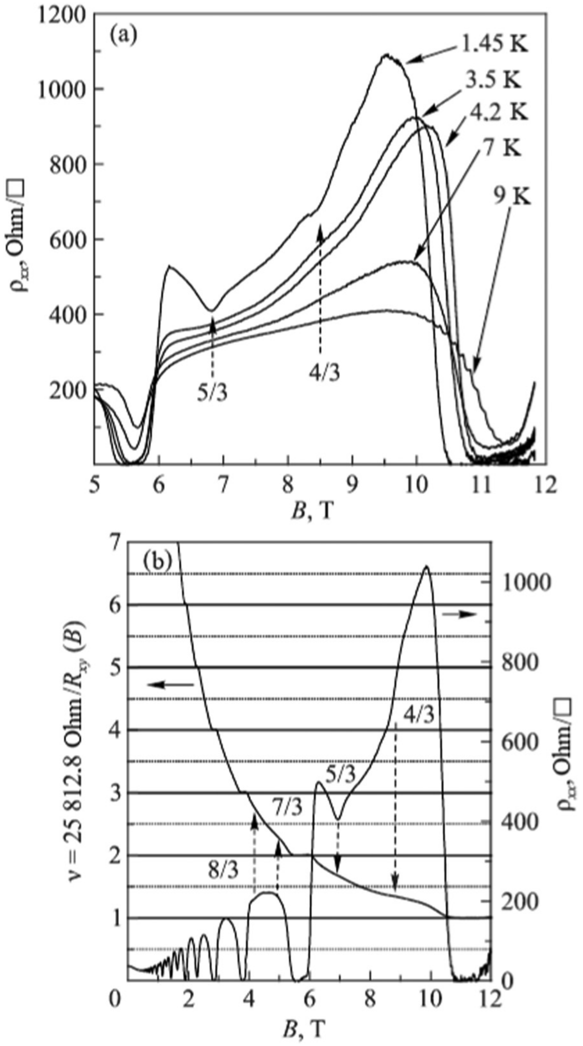

FIG. 3. Dependence of ρ_{xx} and ρ_{xy} on magnetic fields. Arrows indicate positions of extrema with fractional values of the filling factor.

effect in a similar system has already been reported in Ref. 30; however, this effect was discovered in our study at weaker magnetic fields and significantly higher temperatures [Fig. 3(b)].

4. QUANTUM-INTERFERENCE EFFECTS

Experiments have shown that field dependence of magnetoresistance in weak magnetic fields is described by a curve with a maximum [Fig. 4(a)], an indication of manifestation of WL and EEI effects. It should be taken into account that the WL effects are primarily observed in the diffuse regime of interaction between charge carriers. ($k_BT\tau/\hbar < 1$). The EEI effects may be manifested in both diffuse, intermediate and even ballistic ($k_BT\tau/\hbar > 1$) regimes.[11]

To describe experimental results for ultra-weak magnetic fields ($B < 0.05$ T), we used a technique proposed in Ref. 31 that is based on a theoretical model.[32] This model was developed to describe undeformed and deformed bulk *p*-type superconductors and structures containing quantum wells on their basis. The model takes into account that the valence band in $\mathrm{A^{III}B^{V}}$, Si, Ge semiconductors and heterostructures on their basis is formed due to strong spin-orbit interaction, and the total angular momentum proves to be related to particle quasi-momentum. As a result of this, the times of spin and momentum relaxation are of the same order of magnitude. Apart from this, in the heterostructures that contain an internal gradient of potential, spin-orbit processes in the directions perpendicular and parallel to the heterostructure occur in different ways. According to this theoretical model, the correction to the conductivity of a 2D p-type system that is due to the WL effect is described by the following formula:

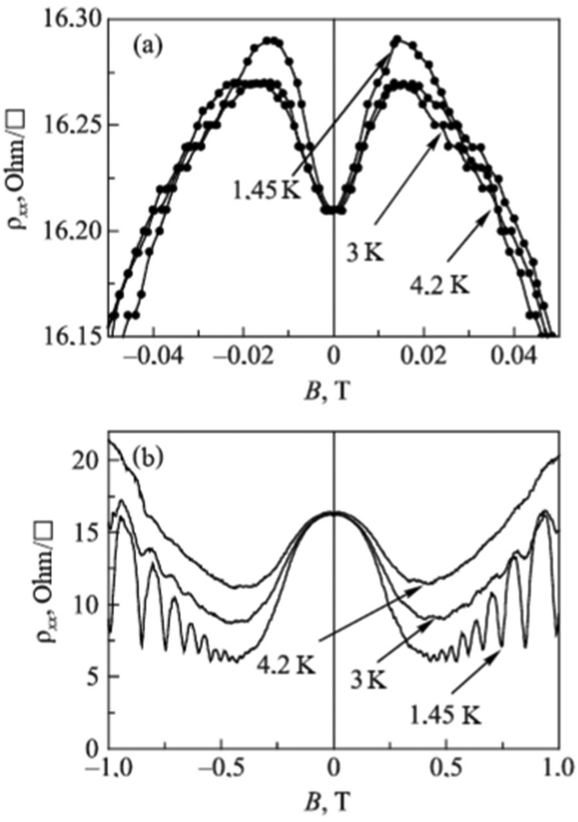

FIG. 4. Resistivity ρ_{xx} as a function of magnetic field.

$$\delta\sigma_{xx}^{WL}(B) = \frac{D_i^0}{D_a^0}\frac{e^2}{4\pi^2\hbar}\left[2f_2\left(\frac{4eDB}{\hbar}\frac{\tau_\varphi\tau_{||}}{\tau_\varphi+\tau_{||}}\right)\right. \\ \left. +f_2\left(\frac{4eDB}{\hbar}\frac{\tau_\varphi\tau_\perp}{\tau_\varphi+\tau_\perp}\right)-f_2\left(\frac{4eDB}{\hbar}\tau_\varphi\right)\right], \qquad (3)$$

where $f_2(x) = \ln(x) + \Psi\left(\frac{1}{2}+\frac{1}{x}\right)$ (here Ψ is the digamma function), τ_φ is the phase relaxation time, $\tau_{||}$ and $\tau_\perp$ is the time of longitudinal and perpendicular spin relaxation, respectively; the preferred axis is the normal to the quantum-well plane and $D = v_F^2\tau/2$ is the diffusion coefficient. The D_i^0/D_a^0 ratio characterizes the degree of strain in the structure; used as a fitting parameter it proved to be 200 for the system under study. Figure 5 shows numerical description of experimental data by means of Eq. (3) using τ_φ, $\tau_{||}$, and $\tau_\perp$ as fitting parameters. The obtained phase relaxation time τ_φ may be approximated by the function $\tau_\varphi \cong 8.7\cdot10^{-14}T^{-0.4}$s similar to that obtained for heterostructures with $\mathrm{Si_{0.2}Ge_{0.8}}$ and $\mathrm{Si_{0.05}Ge_{0.95}}$ quantum wells.[33] The times of longitudinal and transverse spin relaxation do not depend on temperature and are $\tau_{||} = 2\cdot10^{-14}$ s and $\tau_\perp = 3.2\cdot10^{-14}$ s, respectively.

As a result of lifting of the spin degeneracy in semiconductors and heterojunctions, two electron spin subsystems with similar parameters emerge. Lifting of the spin degeneracy appears because of either an asymmetric crystalline field that exists in a single semiconductor crystal without the inversion center (Dresselhaus model[34] or the effect of a non-uniform perturbing potential related to the emergence of an asymmetric potential well when the heterostructure is created (the Rashba model.[35,36] In the system we study, spin splitting is determined by the Rashba mechanism, since Si and Ge are centrally symmetrical crystals.

Spin-orbit relaxation in systems with split spin states is primarily driven by the Dyakonov–Perel mechanism.[37] Spin splitting Δ is equivalent to a magnetic field affecting spin as a result of which spin experiences precession with a frequency Ω_0. A change in the direction of electron momentum results in rotation of the precession axis. If

$$\Omega_0\tau \ll 1, \qquad (4)$$

spin relaxation is given by the formula

$$\tau_\perp^{-1} \approx \Omega_0^2\tau, \qquad (5)$$

where the precession frequency $\Omega_0 = \Delta/2\hbar$. Equation (5) yields the spin splitting $\Delta = 1.07$ meV, a value commensurable with that obtained in Ref. 38.

Effects of electron-electron interaction in the system under study were calculated using a theoretical model[11,12] in accordance

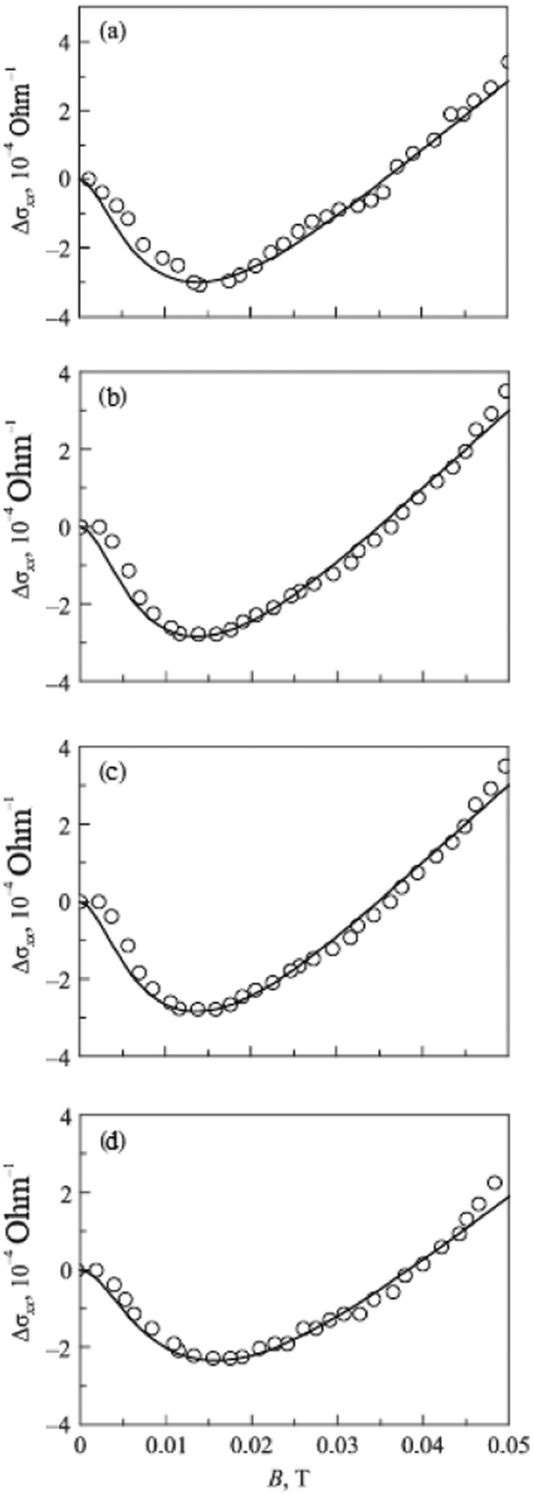

FIG. 5. $\Delta\sigma_{xx}$ as a function of the magnetic field at temperatures 1.42 (a), 2 (b), 3 (c), and 4.2 (d) K. Solid lines correspond to theoretical model.[11]

with the procedure described in Ref. 31. In particular, the monotonous component of magnetoresistance [Fig. 4(b)] may be described, as shown in Refs. 39 and 40, by the formula

$$\rho_{xx}(B, T) = \frac{1}{\sigma_0} - \frac{1}{\sigma_0^2}[1 - (\omega_c\tau)^2]\Delta\sigma_{xx}^{EEI}(T), \tag{6}$$

which, provided $\omega_c\tau \gg 1$ (here ω_c is the cyclotron frequency), may be transformed into the following formula (in the studied sample, the condition $\omega_c\tau = 1$ also holds at a magnetic field of $B = 0.00726$ T)

$$\frac{\rho_{xx}(B, T) - \rho_0}{\rho_0} = \frac{1}{\sigma_0}\mu^2 B^2 \Delta\sigma_{xx}^{EEI}(T). \tag{7}$$

If the monotonic component of magnetoresistance in weak magnetic fields is described by Eq. (7), the correction associated with electron-electron interaction $\Delta\sigma_{xx}^{EEI}(T)$ may be identified [see Fig. 6(a)]. This correction was calculated similar to[31] for the case of Coulomb interaction of holes with scattering centers. The quantum well is free from impurity atoms because acceptor boron atoms are concentrated in the layer separated from the quantum well. The ratio $\frac{k}{k_F} = 0.03$ is small for the case under study. According to,[11] the relative change in resistance in the magnetic field is described by the formula

$$\frac{\Delta\rho(B)}{\rho_0} = -\frac{(\omega_c\tau)^2}{\pi k_F l}[G_F(k_B T\tau/\hbar) - G_H(k_B T\tau/\hbar; F_0^\sigma)]. \tag{8}$$

The analytic form of the functions $G_F(k_B T\tau/\hbar)$ and $G_H(k_B T\tau/\hbar; F_0^\sigma)$ is presented in Refs. 11 and 12. The theoretical curve plotted according to Eq. (8) is compared with experimental data. The experimental value is best described [see Fig. 6(b)] if $F_0^\sigma = -0.12$; however, given this value, the corrections calculated according to Eq. (6) need to be increased by a factor of 40. It should be noted that this specific result has already been earlier. For example, it was shown in Ref. 12 in calculating corrections to interaction in ballistic regime for the *n*-type Si/SiGe heterostructure, that the calculated value of $\Delta\sigma_{xx}^{EEI}(T)$ is 5 times larger than that theoretically predicted in Ref. 11 for the case $\omega_c\tau \gg 1$Z. The case under study, similarly to that analyzed in Ref. 41, apparently corresponds to a larger extent to the case of "mixed disorder" described in Ref. 12. The fact is that the ionized boron admixtures that can serve as scattering point centers are removed from the quantum well; this, in turn, significantly reduces their scattering of the free carriers concentrated in the quantum channel. However, owing to their very presence, the long-range scattering potential may affect system conductivity. The conductivity is also affected by scattering on the short-range potential of scattering centers in the conducting channel and roughness of quantum well boundaries.

The "mixed disorder" is characterized in Ref. 12 by a random "white noise" potential with a characteristic time τ_{wn} and a random smooth potential with transport relaxation time τ_{sm} and condition $(k_F D)^2 \gg 1$ (for the system under study $(k_F D)^2 = 16.2$). In case of scattering on pointlike defects, theory[12] predicts a correction to

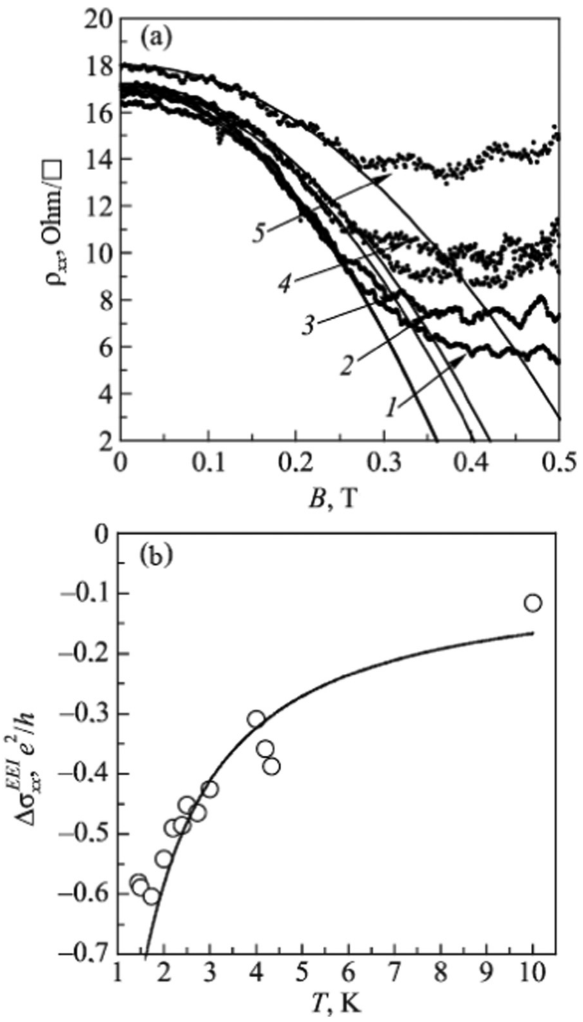

FIG. 6. (a) An example of identifying the interaction correction to the conductivity: 1.42 (1), 1.8 (2), 2.2 (3), 2.7 (4), 4.3 (5) K. Solid lines are drawn according to Eq. (7). (b) Change in the interaction correction with an increase in temperature. Solid line—calculation according to Eq. (9).

resistivity of the form

$$\frac{\Delta\rho_{xx}}{\rho_0} = \frac{(\omega_c\tau)^2}{\pi k_T l}\nu V_0 G_0^{\mathrm{mix}}\left(\frac{k_B T\tau}{\hbar}, \frac{\tau_{sm}}{\tau}\right), \tag{9}$$

where

$$\nu V_0 = 6\left(\frac{F_0^\sigma}{1+F_0^\sigma} + \frac{1}{2}\right), \quad G_0^{\mathrm{mix}}(x) = c_0 4\left(\frac{\tau_{sm}/\tau}{x}\right)^{1/2}, \quad x \gg 1.$$

Here, F_0^σ is the Fermi-liquid interaction constant $c_0 = 0.276$.

Calculated results are displayed in Fig. 6(b). Quantities τ_{sm}/τ and F_0^σ were used as fitting parameters. The best correspondence between the calculated curve and experimental data is provided by the values $\tau_{sm}/\tau = 3$ and $F_0^\sigma = -0.12$.

5. CONCLUSION

We have comprehensively explored quantum effects in conductivity of SiGe p-type heterostructure with pure germanium quantum channel. Studying of SdH magnetoquantum oscillations of the conductivity enabled us to calculate the effective mass of free charge carriers equal to $m^* = 0.062m_0$ that feature a record-setting high mobility [$\mu_H = 1367000\ \mathrm{cm^2/(V \cdot s)}$] and estimate fluctuation of their density along the channel $\delta p = 3.5 \cdot 10^9\ \mathrm{cm^{-2}}$ that makes ~1.25% of their average density $p_H = 2.5 \cdot 10^{11}\ \mathrm{cm^{-2}}$. The fractional Hall effect with filling numbers 8/3, 7/3, 5/3, and 4/3 was observed in strong magnetic fields as temperature was increased up to 5 K.

The quantum interference effect on conductivity of the system has been examined in weak magnetic fields. In particular, based on the analysis of weak-localization effects we calculated the times of phase and spin relaxation; then, we used the latter value to determine that the spin splitting in the system under study is $\Delta = 1.07$ meV, a value commensurable with the results obtained earlier.[38] The effects of interaction between charge carriers in the explored system were calculated in accordance with the "mixed disorder" model from theory[12] that allowed us to successfully describe experimental results and obtain the Fermi-liquid interaction constant $F_0^\sigma = -0.12$. It should be noted that it is the first time that the manifestation of this type of interaction was observed using the technique described above.

REFERENCES

[1] Y. M. Galperin, *Quantum Transport* (Lund University press 1998).
[2] R. Winkler, *Spin-Orbit Coupling Effects in Two- Dimensional Electron and Hole Systems* (Springer-Verlag, New York, 2003).
[3] J.-B. Waldner, *Nanocomputers and Swarm Intelligence* (ISTE, London 2007).
[4] *Nanoelectronics Devices, Circuits and Systems*, edited by B. K. Kaushik (series editor) (Elsevier 2018).
[5] P. W. Anderson, E. Adrahams, and T. V. Ramakrishnan, Phys. Rev. Lett. **43**, 718 (1979).
[6] B. L. Altshuler, D. E. Khmel'nitskii, A. I. Larkin, and P. A. Lee, Phys. Rev. B **22**, 5142 (1980).
[7] B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).
[8] B. L. Altshuler, A. G. Aronov, A. I. Larkin, and D. E. Khmel'nitskii, ZhETF **81**, 768 (1981).
[9] B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interactions in Disordered Systems Modern Problems of in Condensed Matter Science*, edited by A. L. Efros and M. Pollak (Amsterdam, North-Holland 1985).
[10] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **53**, 287 (1985).
[11] I. V. Gornyi and A. D. Mirlin, Phys. Rev. Lett. **90**, 076801 (2003).
[12] I. V. Gornyi and A. D. Mirlin, Phys. Rev. B **69**, 045313 (2004).
[13] B. L. Altshuler, A. G. Aronov, M. E. Gershenson, and Yu. V. Sharvin, "Quantum effects in disordered metal films," Sov. Sci. Rev. **A9**, 223 (1987).
[14] D. J. Bichop, R. C. Dynes, and D. C. Tsui, Phys. Rev. B **26**, 773 (1982).
[15] C. Wan and P. Sheng, Phys. Rev. B **66**, 075309 (2002).
[16] A. Shimkunas, P. Mauger, G. F. Rempfer, L. Almaraz, T. Dixon, N. Katan, and H. Walitzki, J. Vac. Sci. Technol. B **24**, 1413 (2006).
[17] V. Y. Kashirin, Y. F. Komnik, Vt. B. Krasovitsky, O. A. Mironov, O. N. Makarovsky, C. J. Emeleus, and T. E. Wall, Fiz. Nizk. Temp. **22**, 1166 (1996) [Low Temp. Phys. **22**, 891 (1996)].

[18] B. V. Y. Kashirin, Y. F. Komnik, O. A. Mironov, C. J. Emeleus, and T. E. Wall, Fiz. Nizk. Temp. **22**, 1174 (1996) [Low Temp. Phys. **22**, 897 (1996)].

[19] P. T. Coleridge, R. Stoner, and Fletcher, Phys. Rev. B **39**, 1120 (1989).

[20] G. Stöger, G. Brunthaler, G. Bauer, K. Ismail, B. S. Meyerson, J. Lutz, and F. Kuchar, Semicond. Sci. Technol. **9**, 765 (1994).

[21] T. Zhou, J. Zhang, Y. Xue, B. Zhao, H. Zhang, H. Jiang, and Zh. Yn, Phys. Rev. B **94**, 235449 (2016).

[22] L. Wang, M. Yin, A. Khan, S. Muhtadi, F. Asif, E. S. Choi, and T. Datta, Phys. Rev. Appl. **9**, 024006 (2018).

[23] O. A. Mironov, A. H. A. Hassan, M. Uhlarz, S. Kiatgamolchai, A. Dobbie, R. J. H. Morris, J. E. Halpin, S. D. Rhead, P. Allred, M. Myronov, S. Gabani, I. B. Berkutov, and D. R. Leadley, Phys. Status Solidi C **11**, 61 (2014).

[24] O. A. Mironov, A. H. A. Hassan, R. J. H. Morris, A. Dobbie, M. Uhlarz, D. Chrastina, J. P. Hague, S. Kiatgamolchai, R. Beanland, S. Gabani, I. B. Berkutov, M. Helmi, O. Drachenko, M. Myronov, and D. R. Leadley, Thin Solid Films **557**, 329 (2014).

[25] Y. F. Komnik, I. B. Berkutov, and V. V. Andrievsky, Fiz. Nizk. Temp. **32**, 109 (2006) [Low Temp. Phys. **32**, 82 (2006)].

[26] I. B. Berkutov, V. V. Andrievsky, Y. F. Komnik, Y. A. Kolesnichenko, R. J. H. Morris, D. R. Leadley, and O. A. Mironov, Fiz. Nizk. Temp. **38**, 1455 (2012) [Low Temp. Phys. **38**, 1145 (2012)].

[27] A. Isihara and L. Smrčka, J. Phys. C **19**, 6777 (1986).

[28] S. D. Bystrov, A. M. Kreshchuk, L Tuan, S. V. Novikov, T. A. Polyanskaya, I. G. Savel'ev, and A. Y. Shik, Semiconductors **28**, 55 (1994).

[29] I. B. Berkutov, V. V. Andrievsky, Y. F. Komnik, O. A. Mironov, M. Mironov, and D. Ledley, Fiz. Nizk. Temp. **35**, 188 (2009) [Low Temp. Phys. **35**, 141 (2009)].

[30] O. A. Mironov, N. d'Ambrumenil, A. Dobbie, D. R. Leadley, A. V. Suslov, and E. Green, Phys. Rev. Lett. **116**, 176802 (2016).

[31] I. B. Berkutov, Y. F. Komnik, V. V. Andrievsky, O. A. Mironov, M. Myronov, and D. R. Leadley, ФНТ **32**, 896 (2006) [Low Temp. Phys. **32**, 683 (2006)].

[32] N. S. Averkiev, L. E. Golub, and G. E. Pikus, Pis'ma Zh. Eksp. Teor. Fiz. **113**, 1429 (1998). [JETP **86**, 780 (1998)].

[33] D. R. Leadley, V. V. Andrievsky, I. B. Berkutov, Y. F. Komnik, T. Hackbarth, and O. A. Mironov, J. Low Temp. Phys. **159**, 230 (2010).

[34] G. Dresselhaus, Phys. Rev. B **100**, 580 (1955).

[35] E. I. Rashba and V. I. Sheka, Solid State Physic, Akad. Nauk SSSR, **2**, 162 (1959) (in Russian).

[36] Y. A. Bychkov and E. I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 66 (1984) [JETP Lett. **39**, 78 (1984)].

[37] M. I. Dyakonov and V. I. Perrel, Zh. Eksp. Teor. Fiz. **60**, 1954 (1971). [Sov. Phys. JETP **33**, 1053 (1971)].

[38] V. V. Andrievskii, I. B. Berkutov, T. Hackbarth, Y. F. Komnik, O. A. Mironov, M. Myronov, V. I. Litvinov, and T. E. Whall, in *Molecular Nanowires and Other Quantum Objects*, edited by A. S. Alexandrov, J. Demsar, and I. K. Yanson, NATO Science Series, II Mathematics, Physics and Chemistry (Kluwer Academic, Norwell, 2004), Vol. 148, p. 319.

[39] K. K. Choi, D. C. Tsui, and S. C. Palmateer, Phys. Rev. B **33**, 8216 (1986).

[40] G. M. Minkov, O. E. Rut, A. V. Germanenko, A. A. Sherstobitov, V. I. Shashkin, O. I. Khrykin, and V. M. Daniltsev, Phys. Rev. B **64**, 235327 (2001).

[41] E. B. Olshanetsky, V. Renard, Z. D. Kvon, J. C. Portal, N. J. Woods, J. Zhang, and J. J. Harris, Phys. Rev. B **68**, 085304 (2003).

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