Quantum interferometry and spin–orbit effects in a heterostructure with a 2D hole gas in a $Si_{0.2}Ge_{0.8}$ quantum well

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The magnetic-field dependence (up to 110 kOe) of the resistance of $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}/Si_{0.7}Ge_{0.3}$ with a 2D hole gas in a $Si_{0.2}Ge_{0.8}$ quantum well is measured in the temperature range 0.335–10 K and in a range of variation of the currents from 100 nA to 50 μA. Shubnikov–de Haas oscillations are observed in the region of high magnetic fields, and in the low-field region $H \leqslant 1$ kOe a positive magnetoresistance is observed which gives way to a negative magnetoresistance as the field is increased. This peculiarity is explained by effects of weak localization of the 2D charge carriers under conditions when the spin–orbit scattering time τ_{so} is close to the inelastic scattering time τ_{φ}, and it is evidence of a splitting of the spin states under the influence of a perturbing potential due to the formation of a two-dimensional potential well (the Rashba mechanism). Analysis of the weak localization effects gave the values of the characteristic relaxation times as $\tau_{\varphi}=7.2T^{-1}\times 10^{-12}$ s and $\tau_{so}=1.36\times 10^{-12}$ s. From these characteristics of the heterostructure studied, a value of $\Delta=2.97$ meV was obtained for the spin splitting. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1542476]

INTRODUCTION

The study of quantum interference and quantum oscillation effects in heterojunctions yields information about the characteristics of the charge carriers in two-dimensional electron systems. In some cases the behavior of the magnetoresistance of inversion layers in heterostructures in weak magnetic fields[1–4] attests to the existence of appreciable spin–orbit scattering, which has been linked to a lifting of the spin degeneracy in zero magnetic field in the absence of inversion symmetry in the crystal[5] or under the influence of an asymmetric electric field which forms a two-dimensional structure.[6] The lifting of the spin degeneracy in zero magnetic field leads to the formation of two electronic subsystems with nearly the same characteristic parameters. The existence of spin splitting in such objects has been confirmed by the finding of two effective masses for the charge carriers by the cyclotron resonance technique,[7] and also by the observation of beats of the Shubnikov–de Haas oscillations in different heterostructures.[8–13] The concepts of spin splitting have been used successfully to explain the positive magnetoresistance at low magnetic fields in the weak localization effect.[2–4]

In this paper we present the results of a study of weak localization effects and the interaction of charge carriers in a $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}/Si_{0.7}Ge_{0.3}$ heterostructure, which exhibits its spin–orbit effects (unlike the $Si/Si_{1-x}Ge_x/Si$ heterostructures with $x=0.13$ and 0.36 studied previously,[14,15] for which the spin–orbit effects could be neglected). This study included the investigation and analysis of the variation of the magnetoresistance at low and high magnetic fields (up to 110 kOe) in the temperature range 0.335–10 K for transport currents varying from 100 nA to 50 μA. The results made it possible to determine the following:

— the values of the effective mass m^* and quantum time τ_q of the charge carriers, on the basis of an analysis of the change in amplitude of the Shubnikov–de Haas oscillations upon a change in magnetic field and temperature;

— the temperature dependence of the dephasing time τ_{φ} and the spin–orbit scattering time τ_{so} by extracting the quantum corrections to the conduction, which are manifested in temperature and magnetic-field dependence of the conductivity;

— the temperature dependence of the electron–phonon relaxation time τ_{eph}, with the use of the electron overheating effect;

— the splitting Δ of the spin states, on the basis of data for the spin–orbit interaction time.

The simultaneous observation of Shubnikov–de Haas oscillations (which are ordinarily manifested only in pure and perfect samples) and quantum interference effects (the observation of which requires a rather high level of elastic scattering) in the same sample turns out to be entirely possible, as was noted in Refs. 14 and 15, since these effects are manifested at different values of the magnetic fields. The weak localization effect and electron interaction effects are manifested at low magnetic fields, where the magnetic length $L_H=(\hbar c/2eH)^{1/2}$ should be larger than the mean free path l. (The length L_H corresponds to the field value for which an area $2\pi L_H^2$ is threaded by one magnetic flux quantum $\Phi_0 = hc/2e$.) As the magnetic field is increased, the inequality $L_H<l$ comes to be satisfied, and magnetic quantization ef-

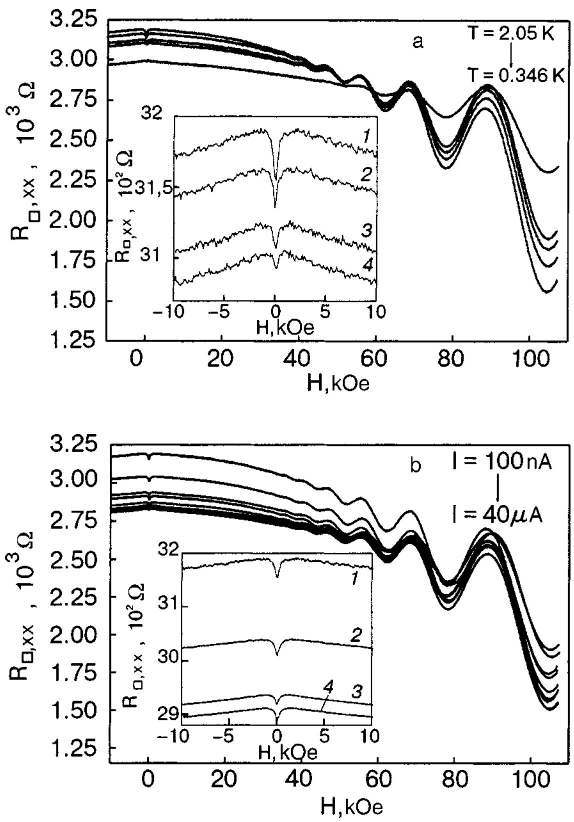

FIG. 1. Magnetic-field curves of the resistance $R_\square$ at different temperatures (a) and currents (b). a — $I=100$ nA, T [K]: 205, 1.738, 1.44, 0.754, 0.346. The inset shows the region of low magnetic fields for different T [K]: 0.36 (*1*), 0.754 (*2*), 1.44 (*3*), 1.738 (*4*). b — $T\approx 0.35$ K, currents: 100 nA, 300 nA, 1 μA, 2 μA, 5 μA, 10 μA, 15 μA, 28 μA, 40 μA. In the inset $I=100$ nA (*1*), 300 nA (*2*), 1 μA (*3*), 2 μA (*4*).

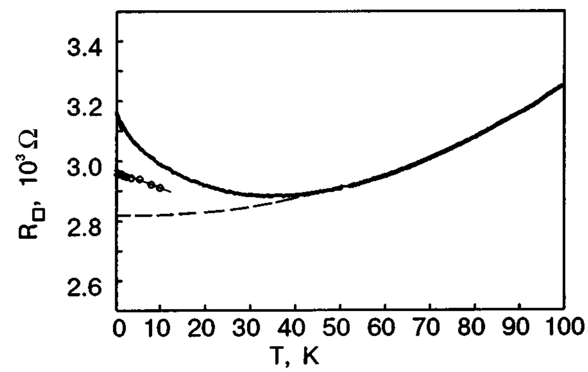

FIG. 2. Temperature dependence of the resistance $R_\square$. The solid curve shows the experimental data; the data points are the calculated values of the quantum correction due to the weak localization effect for the values of τ_φ and τ_{so} obtained from an analysis of the magnetoresistance curves. The dashed curve is the assumed temperature dependence of the ''classical'' resistance.

fects such as Shubnikov–de Haas oscillations can appear. An estimate of the mean free path in the sample gives a value $l\approx 300$ Å. This value of l and, accordingly, of L_H, corresponds to a magnetic field $H=3.6$ kOe. Analysis of weak localization effects can be carried out at fields less than that value.

1. EXPERIMENTAL RESULTS

The object of study was a $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}/Si_{0.7}Ge_{0.3}$ heterostructure obtained by molecular-beam epitaxy; a quantum well is formed in the $Si_{0.2}Ge_{0.8}$ region, which is 10 nm wide.[1)]

The carriers (holes) appear in the quantum well from a boron-doped layer located a distance ~10 nm from the well. From a crystallographic standpoint such a structure is a stressed pseudomorphic heterostructure. The stressed state is due primarily to the 4% difference in the lattice constants of germanium and silicon (5.65 and 5.43 Å, respectively). The electronic properties of the heterostructure are determined by the two-dimensional electron gas filling the potential well. The conducting region had a ''double cross'' configuration in the form of a narrow strip ~0.55 mm wide and ~2.25 mm long, with a distance of ~1.22 mm between the two pairs of narrow potential leads.

Figure 1 shows recordings of the magnetic-field-induced variation of the diagonal component of the sheet resistance (resistance per square) of the sample at different temperatures (Fig. 1a) and current values (Fig. 1b). The amplitude of the Shubnikov–de Haas oscillations decreases with increasing temperature and current. In the low-field region positive magnetoresistance is observed (see the inset to Fig. 1), with a characteristic initial segment of steep growth followed by a maximum and then a slow decline down to negative values. This form of the magnetoresistance curves is characteristic for the weak localization effect[16–20] under conditions such that τ_φ and τ_{so} are close in value. It is seen in the insets in Fig. 1 that the height of the maximum (above the zero-field value of the resistance) decreases rapidly with increasing temperature and current growth.

The temperature variation of the resistance of the sample in zero magnetic field (Fig. 2) confirms the assumption that one is seeing a manifestation of effects of weak localization and quasiparticle interaction: the minimum and the increase of the resistance with decreasing temperature T are due to the contribution of quantum corrections to the conductivity, which grow as the temperature is lowered.[18,21]

2. CALCULATION OF THE CHARACTERISTIC PARAMETERS OF THE CHARGE CARRIERS

The heterostructure under study has a hole type of conductivity, and the structure of its valence band is therefore important. In pure silicon there are two degenerate maxima in the valence band at the point $k=0$, where two bands with different values of the curvature touch; the corresponding values of the effective mass m^* are $0.49m_0$ and $0.16m_0$. The valence bands in germanium have an analogous structure with $m^*=0.28m_0$ and $0.04m_0$.

The form of the Shubnikov–de Haas oscillations (Fig. 1) attests to the fact that they are formed by a single dominant type of charge carrier. The proposed spin splitting of the bands was not in any way reflected in the form of the oscillations. For this reason the analysis of the oscillatory curves can be done in the standard way.

It is known that the Shubnikov–de Haas oscillations are described by the relation

$$\frac{\Delta\rho_{xx}}{\rho_{xx}^0}\propto\frac{\psi}{\sinh\psi}\exp\left(-\frac{\pi\alpha}{\omega_c\tau}\right)\cos\left(\frac{2\pi\varepsilon_F}{\hbar\omega_c}-\Phi\right), \qquad (1)$$

where $\psi=2\pi^2kT/(\hbar\omega_c)$, $\omega_c=eH/m^*c$ is the cyclotron frequency, $\alpha=\tau/\tau_q$, τ is the transport time, τ_q is the quantum scattering time, and Φ is the phase. If the Fermi energy for the two-dimensional electron gas is written in the form $\varepsilon_F=\pi\hbar^2n/m^*$ (n is the concentration of electrons (holes)), then, knowing the change in amplitude of the oscillations upon changes of the temperature and magnetic field, we can determine the unknown parameters m^*, n, and τ_q. For example, having constructed the dependence of $\ln([\Delta\rho(T)/\rho(0)][\sinh\psi(T)/\psi(T)])$ on $(\omega_C\tau)^{-1}=(\mu H)^{-1}$ (where μ is the mobility), by fitting the experimental data to a single straight line we can find α and then determine τ_q, and having constructed the dependence of $\ln(\Delta\rho(H)/\rho(0))$ on $\ln(\psi(H)/\sinh\psi(H))-(\pi\alpha/\mu H)$ and plotting all the experimental data on a single straight line, we can find m^*. The resulting value $m^*=0.16m_0$ apparently corresponds to heavy holes in the heterostructure under study. This value will be used in the calculations below.

The carrier concentration p_{SdH} found in an analysis of the Shubnikov–de Haas oscillations equals 1.46×10^{12} cm^{-2}. It is close to the value $p_H=1.36\times10^{12}$ cm^{-2} obtained from measurements of the Hall coefficient.

The values m^* and p_H can be used to find the elastic scattering time from the electrical conductivity of the channel, which gives a value $\tau=0.147\times10^{-12}$ s, and the mean free path of the holes, $l=310$ Å, and also the Fermi velocity v_F, mobility μ, diffusion coefficient D, and Fermi energy ε_F, by making use of the relations for a two-dimensional system: $v_F=(\hbar/m)(2\pi p_2)^{1/2}$, $D=v_F^2\tau/2$, $\varepsilon_F=\pi\hbar^2p_2/m$. The following values are obtained: $v_F=2.11\times10^7$ cm/s, $\mu=1590$ cm^2/(V·s), $D=32.7$ cm^2/s, and $\varepsilon_F=20.35$ meV.

3. ANALYSIS OF THE QUANTUM CORRECTIONS

In a two-dimensional system the contribution of the weak localization effect to the temperature dependence of the conductivity is described by the relation[17,22]

$$\Delta\sigma_T=-\frac{e^2}{2\pi^2\hbar}\left[\frac{3}{2}\ln\frac{\tau_\varphi^*}{\tau}-\frac{1}{2}\ln\frac{\tau_\varphi}{\tau}\right], \tag{2}$$

where τ is the elastic relaxation time of the electrons, $\tau_\varphi^{-1}=\tau_{\varphi0}^{-1}+2\tau_s^{-1}$, $(\tau_\varphi^*)^{-1}=\tau_{\varphi0}^{-1}+{}^4/_3\tau_{so}^{-1}+{}^2/_3\tau_s^{-1}$, $\tau_{\varphi0}$ is the phase relaxation time due to inelastic scattering processes, τ_{so} is the spin–orbit scattering time, and τ_s is the time for spin–spin scattering on magnetic impurities (in the object studied here there is no spin–spin scattering, so the time τ_s can be neglected, and in that case $\tau_{\varphi0}\equiv\tau_\varphi$). One can go from the resistance to the quantum corrections to the conductivity with the aid of the relation $-\Delta\sigma_T(T)=[R(T)R_\square(T_{\min})]^{-1}$, where $R_\square$ is the resistance per square of the two-dimensional system, and $T_{\min}$ is the temperature at which the minimum of the function $R(T)$ is observed and the contribution of the corrections is negligible.

In a two-dimensional system in a perpendicular magnetic field the change of conductivity due to the weak localization effect is described by the relation[23]

$$\Delta\sigma_H^L=\frac{e^2}{2\pi^2\hbar}\left[\frac{3}{2}f_2\left(\frac{4eHD\tau_\varphi^*}{\hbar c}\right)-\frac{1}{2}f_2\left(\frac{4eHD\tau_\varphi}{\hbar c}\right)\right], \tag{3}$$

where $f_2(x)=\ln(x)+\psi(1/2+1/x)$, ψ is the logarithmic derivative of the Γ function, and $D=(1/2)v_F^2\tau$ is the electron (hole) diffusion coefficient. The characteristic field $H_0^L=\hbar c/4eD\tau_\varphi$ corresponds to a change of the form of the function $f_2(x)$ from quadratic to logarithmic. For analysis of the variation of the quantum correction in the magnetic field one can use the relation $-\Delta\sigma_H(H)=[R(H)-R(0)]\times[R(H)R_\square(0)]^{-1}$; here $-\Delta\sigma_H(H)$ reflects the change in the magnetoresistance.

A computer fitting of the theoretical dependence (3), which contains two unknown fitting parameters, τ_φ and τ_φ^*, to the experimental data for the magnetoresistance allows one to find the values of τ_φ and τ_φ^* and then τ_{so}. This sort of fitting has turned out to be the most successful when an additional term proportional to H^2 is introduced. We assume that this term reflects the contribution of a correction due to the hole–hole interaction in the Cooper channel and corresponds to a repulsion between quasiparticles. Such a correction to the conductivity has been identified for $Si_{0.64}Ge_{0.36}$ heterostructures with a quantum channel.[14] The expression for the correction in the Cooper channel is given in Refs. 18, 22, and 23:

$$\Delta\sigma_H^C=-\frac{e^2}{2\pi^2\hbar}\lambda_H^C\varphi_2(\alpha);\quad \alpha=\frac{2eDH}{\pi ckT}, \tag{4}$$

where λ_H^C is the coupling constant. The characteristic field $H_0^C=\pi ckT/2eD$ corresponds to a change in the functional dependence of $\varphi_2(\lambda)$ from quadratic to logarithmic. This allows us to use the quadratic approximation for $\Delta\sigma_H^C$ at low magnetic fields ($H<H_0^C$).

Taking the Cooper correction into account at the lowest temperatures and at low currents can explain the temperature behavior of the maximum that arises on the $\Delta\sigma(H)$ curve in the weak localization effect under conditions when the elastic scattering time τ_φ is close to the spin–orbit scattering time τ_{so}. The magnetic field $H_{\max}$ corresponding to the maximum is somewhat higher than the characteristic field H_0^L and should increase weakly with increasing temperature (as a consequence of the decrease of τ_φ and τ_φ^* with increasing T). The weak decrease of $H_{\max}$ observed in this study (see Fig. 1) is due to fact that the Cooper correction falls off with increasing temperature as $1/T^2$. A rough estimate of the coupling constant λ_H^C at the lowest temperature of the experiment and at low current is 0.023. It follows from the calculations that the temperature dependence $\tau_\varphi(T)$ at $T>3$ K is described by the relation $\tau_\varphi\simeq7.2T^{-1}\times10^{-12}$ s. This is close to the analogous temperature dependence $\tau_\varphi=6.6T^{-1}\times10^{-12}$ s for p-Si/Si$_{1-x}$Ge$_x$/Si heterostructures with $x=0.13$ and 0.36.[14] A dependence of the form $\tau_\varphi\propto T^{-1}$ corresponds to the manifestation of electron–electron (in the present case hole–hole) scattering processes in disordered two-dimensional systems.[21,22] For the spin–orbit interaction time an average value of $\tau_{so}=1.36\times10^{-12}$ s is obtained.

Figure 3 shows the values obtained for τ_φ and τ_{so} as functions of temperature. The deviation of τ_φ from the relation $\tau_\varphi=7.2T^{-1}\times10^{-12}$ s at $T<3$ K is apparently due to the influence of spin effects. The positive magnetoresistance on the initial parts of the $R_\square(H)$ curve (Fig. 1) vanishes when the inequality $\tau_{so}<\tau_\varphi$ changes to the opposite, $\tau_{so}>\tau_\varphi$. Using the values found for the diffusion coefficient D and for

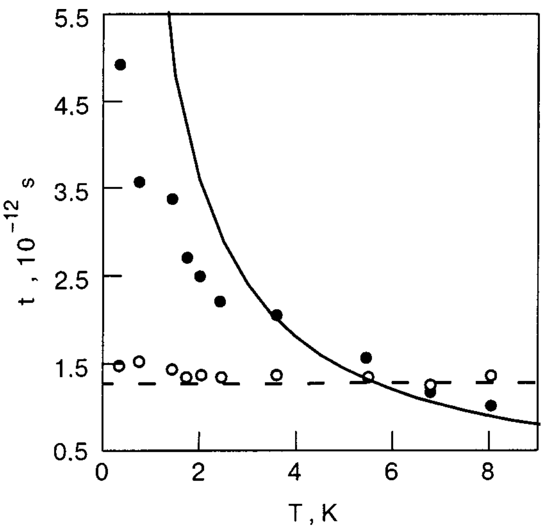

FIG. 3. Values of the dephasing time τ_φ (●) and spin–orbit scattering time τ_{so} (○) at different temperatures. The solid curve is a plot of $\tau_\varphi = 7.2T^{-1} \times 10^{-12}$ s.

$\tau_\varphi(T)$, we can estimate the characteristic fields H_0^L and H_0^C: at a temperature of 1 K they are 0.05 and 0.34 kOe, respectively. At magnetic fields exceeding these values by one or two orders of magnitude, the quantum corrections practically vanish, and the anomalous temperature dependence of the resistance vanishes accordingly.

We have satisfied ourselves that the values found for $\tau_\varphi(T)$ and τ_{s0} give a completely realistic description of the anomalous temperature dependence of the resistance of the sample (Fig. 2). The values calculated according to Eq. (2) for the localized correction $\Delta\sigma_T^L$ are shown by the data points in Fig. 2. The dashed curve reflects the assumed temperature variation of the ''classical'' resistance of the sample. It was obtained by extrapolating the functional dependence of the resistance on temperature from the region considerably above the minimum of the resistance. It is seen in Fig. 2 that a quantum correction due to the interaction in the Cooper channel is present in addition to the localization correction.

4. TEMPERATURE DEPENDENCE OF THE ELECTRON–PHONON SCATTERING TIME OF THE CHARGE CARRIERS

The electron–phonon interaction time τ_{eph} can be found with the aid of the electron overheating effect.[24] Under conditions of overheating the electron temperature T_e is elevated with respect to the phonon temperature T_{ph} under the influence of an electric field (current), and the transfer of excess energy from the electron to the phonon system is governed by the time τ_{eph}. A necessary condition for realization of the electron overheating effect is the unimpeded escape of phonons from the conducting layer into the surrounding crystal. This requirement is clearly met in the sample studied here.

A comparison of the change in amplitude of the Shubnikov–de Haas oscillations upon an increase in temperature and an increase in current (Fig. 4) allows one to find the value of T_e at each specified value of the current (the arrows in Fig. 4).

The time τ_{eph} can be calculated with the aid of the heat balance equation, which implies the relation[25]

$$(kT_e)^2 = (kT_{\mathrm{ph}})^2 + \frac{6}{\pi^2}(eE)^2 D\tau_{\mathrm{eph}}. \quad (5)$$

The electric field E is easily found from the values of the current I and resistance per square $R_\square$: $E = IR_\square / a$ (where a is the width of the conducting channel). The temperature of the crystal is used for T_{ph}. The values found for τ_{eph} with the use of Eq. (5) are referred to electron–phonon interaction temperatures T_{eph} under conditions of electron overheating, where to a first approximation the estimate $T_{\mathrm{eph}} = (1/2)(T_{\mathrm{ph}} + T_e)$ is valid.[15,26]

The observed temperature dependence observed of τ_{eph} has the form $\tau_{eph} = 1.1T^2 \cdot 10^{-8}$ and is close to the analogous dependence for $Si/Si_{0.7}Ge_{0.3}/Si$ heterostructures.[15] A dependence $\tau_{\mathrm{eph}}^{-1} \propto T^2$ is characteristic for two-dimensional electron systems[27] and is realized at low temperatures under conditions such that the wave momentum of the thermal phonon is sufficient to change the electron wave vector by the maximum amount $2k_F$.

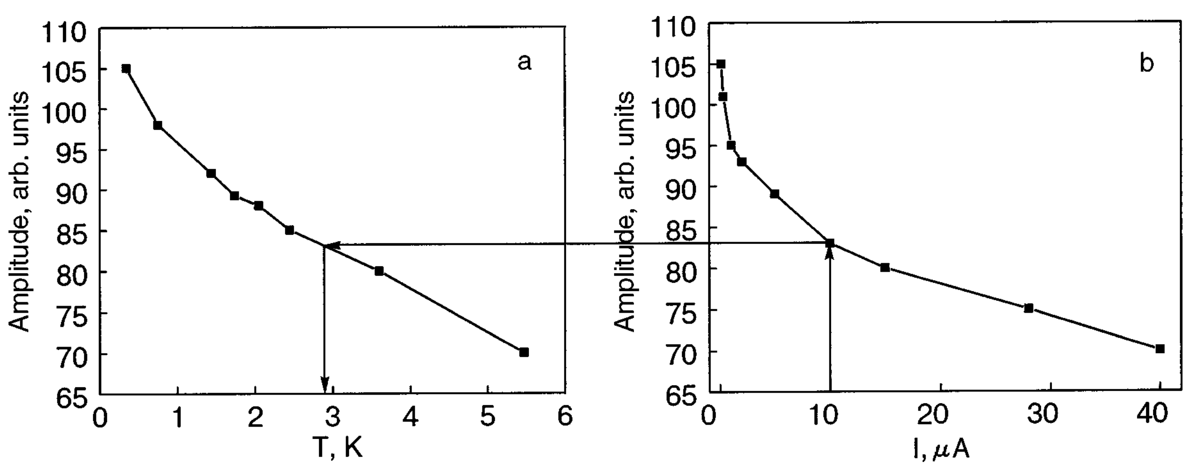

FIG. 4. Variation of the amplitude of the Shubnikov–de Haas oscillations as a function of temperature (a) and current (b).

It should be noted that it remains unclear why the resistance of the sample decreases so noticeably as the current is increased at zero magnetic field (see Fig. 1b): increasing the current from 100 nA to 10 μA leads to a decrease of $R_\square$ from 3150 Ω to 2850 Ω. The resistance remains unchanged as the current is increased further. It is seen in Fig. 4 that at a current of 10 μA the value of the overheating of the electron temperature is 3 K, which, according to Fig. 2, corresponds to a decrease of the resistance only to 3080 Ω. A probable cause of this disagreement might be the direct influence of the electric field on the quantum corrections. We note that the in-plane electric field in the two-dimensional structure was extremely small in these experiments, ranging from 0.066 V/cm at 100 nA to 0.65 V/cm at 10 μA.

The influence of electric field on the quantum localization correction has been considered in a number of theoretical papers.[25,28–32] According to Refs. 25, 31, and 32, a change in the value of the localization correction under the influence of electric field occurs only as a result of a change in the electron temperature (or the electron drift velocity). The absence of a direct influence of the electric field on the localization correction has been established in experiments on films of gold[33] and bismuth.[34] However, as was shown in Ref. 35, an electric field (with a strength of 10–30 V/cm) decreases the quantum correction due to the electron–electron interaction considerably, as a result of a decrease of the coupling constant λ. This decrease in λ is caused by a feature of the scattering in a two-dimensional electron system. In this conceptual framework the observed decrease of the resistance of the sample with increasing current in zero field, which is greater than the expected decrease of the resistance due to the electron overheating effect, is yet another indication of the presence of a contribution to the conductivity from the quantum correction due to the hole–hole interaction.

5. SPIN SPLITTING AND SPIN–ORBIT RELAXATION

Our analysis of the magnetoresistance curves of the $Si_{0.2}Ge_{0.8}$ quantum-well heterostructure has made it possible to determine the value of the spin splitting Δ on the basis of the value obtained for the spin–orbit scattering time τ_{so}.

The possibility of lifting the spin degeneracy in semiconductor crystals was first shown by Dresselhaus.[5] The cause of the lifting of the spin degeneracy in crystals lacking a center of inversion (in structures of the zinc blende, wurtzite, etc., types) is the asymmetric crystalline field. When the spin–orbit interaction is taken into account, the symmetry with respect to time inversion is broken. The value of the spin splitting is proportional to the cube of the wave vector, k^3 (the cubic Dresselhaus term). In Refs. 36–38 it was shown that the formation of a symmetric quantum well in such a crystal leads to additional lowering of its symmetry and to an additive contribution to the spin splitting which has a linear dependence on k (the linear Dresselhaus term). Another cause of lifting of the spin degeneracy was pointed out by Rashba.[6,39,40] In considering the properties of a two-dimensional electron gas, Rashba noticed that the appearance of an asymmetric quantum well in a crystal is due to the presence of a perturbing potential that acts along the normal to the plane of the two-dimensional gas and leads to lifting of the spin degeneracy. Spin splitting of this nature has a linear dependence on the magnitude of the wave vector (the linear Rashba term). We note that in the $Si_{0.2}Ge_{0.8}$ quantum-well heterostructure under study the spin splitting is due to the Rashba mechanism, since germanium and silicon are centrosymmetric crystals.

The spin–orbit scattering of electrons on impurities is the main mechanism for relaxation of the spin state under conditions where the spin degeneracy is lifted, for any type of spin splitting. Elliot[41] considered the spin relaxation mechanism under conditions such that the spin splitting is greater than the elastic scattering energy ($\hbar/\tau<\Delta$) (see also Ref. 42). There is a linear relation between the spin relaxation rate and the elastic scattering rate. D'yakonov and Perel'[43] considered the case when the impurity scattering energy is greater than the spin splitting ($\hbar/\tau>\Delta$). Scattering leads to "randomization" of the spin states, and the spin relaxation rate turns out to be proportional to the elastic scattering time.

From the carrier kinetic characteristics found for the heterostructure under study we can conclude that the main mechanism of spin relaxation is the D'yakonov–Perel' one. The value of τ obtained by us means that the inequality $\hbar/\tau>\Delta$ holds up to $\Delta\approx4.8$ meV. The spin–orbit relaxation time τ_{so} can be used to determine the value of the spin splitting from the relation[43]

$$\frac{1}{\tau_{so}}\approx\Omega_0^2\tau, \tag{6}$$

where the precession frequency $\Omega_0=\Delta/2\hbar$. The value of the spin splitting Δ calculated from Eq. (6) is 2.97 meV for the heterostructure under study.

Our results show that heterostructures based on the isovalent semiconductors Si and Ge can be of interest for creating electronic devices with controllable spin transport.[44]

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[1)]The sample was grown by the advanced Semiconductors Group, University of Warwick, Coventry, UK.

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