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Spin precession observation in quantum corrections to resistance of $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}$ heterostructure with 2DHG

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Abstract

The two-dimensional hole gas (2DHG) magnetoresistivity of a $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}$ heterostructure in a wide range of temperatures $T = 0.335$–20 K and transport currents $I = 100$–50 μA is measured. In the vicinity of zero magnetic field, a sharp and positive in sign feature on smooth negative magnetoresistance is observed at the lowest temperatures. The amplitude of this feature quickly fades with increasing temperature and transport current. For the analysis of the experimental data the theory of weak localization for 2DHG is applied.

The values of τ_{so} and τ_{tr} obtained are used for the first time to define zero magnetic field splitting in the hole energy spectrum for a $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}$ heterostructure: $\Delta = 2.97$ meV.

Keywords: Heterostructure; Spin splitting; Weak localization

1. Introduction

The spin-orbit interaction, which control spin splitting in the energy spectrum of a two-dimensional hole gas offers promise for the creation of devices in which not only charge transport but also spin transport as well can be realized [1]. It is found [2] that the spin splitting in the energy spectrum of bulk semiconductors (3D) in zero magnetic field is caused by the lack of inversion symmetry of their crystal lattices. The spin-splitting value turns out to be proportional to the cubed wave vector of charge carriers, $\sim k^3$ (the Dresselhaus cubed term). The formation of a symmetric quantum well in such a crystal is responsible for a further decrease in its symmetry [3] and gives rise to an additive contribution to the spin splitting which is linearly dependent on wave vector $\sim k$ (the Dresselhaus linear term) [4]. Generation of an asymmetric quantum well results in an extra spin splitting which also is in linear dependence on wave vector (the Rashba term) [5,6]. As shown in Ref. [7], the contributions of these linear terms to the resultant spin splitting cannot be considered additive.

The spin splitting in zero magnetic field gives rise to two electron subsystems similar in characteristic parameters. Examples of the splitting manifestation are: dramatic beats in Shubnikov–de Haas oscillations [8]; two effective masses of charge carriers revealed with the cyclotron resonance technique [9]; positive magnetoresistivity in low magnetic field in the weak localization effect [10] with increasing asymmetry of the two-dimensional potential well, etc.

2. Experimental results

The paper concerns the quantum interference and oscillation effects in the boron-modulation-doped $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}/Si_{0.7}Ge_{0.3}$ heterostructure in wide ranges of magnetic fields (up to 11 T), temperatures (down to 0.346 K) and transport currents (100–40 μA). The dependence $\rho(T)$ at $T \approx 40$ K exhibited a minimum resistance. A decrease in temperature caused the resistance to increase. The dependence $\rho(B)$ displayed a change from the positive to negative magnetoresistance with increasing magnetic field.

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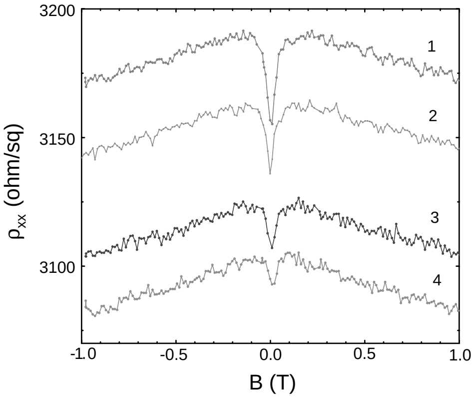

Fig. 1. Records of magnetoresistivity of the sample studied. Temperature (K): (1) 0.346, (2) 0.754, (3) 1.44, and (4) 1.738.

The increase in temperature up to $\sim$ 3 K or in transport current up to $\sim$ 40 μA caused the positive magnetoresistivity to disappear (Fig. 1). This behavior is indicative of contributions of the weak localization effects under strong spin–orbit interaction.

The analysis of the Shubnikov–de Haas oscillations made it possible to obtain the following values of charge carrier concentration and effective mass: $p_{\mathrm{SdH}} = 1.46 \times 10^{12}$ cm^{-2} (close to $p_{\mathrm{H}} = 1.36 \times 10^{12}$ cm^{-2} obtained from the measurements of the Hall coefficient) and $m^* = 0.16m_o$. Using the above values of m^* and p_{H} and the relationships for the 2D system: $\upsilon_{\mathrm{F}} = \hbar/m^*(2\pi p_2)^{1/2}$, $D = \frac{1}{2}\upsilon_{\mathrm{F}}^2\tau$ and $\varepsilon_{\mathrm{F}} = \pi\hbar^2 p_2/m^*$, we estimated elastic scattering time, τ, hole mean free path, l, Fermi velocity, υ_{F}, mobility, μ, diffusion coefficient, D, and Fermi energy, ε_{F}, as being equal to 0.147×10^{-12} s, 310 Å, 2.11×10^7 cm s^{-1}, 1590 cm^2 V^{-1} s^{-1}, 32.7 cm^2 s^{-1} and 20.35 meV, respectively. The analysis of the temperature dependence of quantum corrections in zero magnetic field, made by the theory in Ref. [11] permitted the times of energy and spin relaxations to be estimated. The relaxation times may be estimated more precisely by analyzing the magnetic field dependencies of resistance and using the above estimated values. Such an analysis was made by the theory [12] in magnetic fields of $\sim$ 0.3 T, because the weak localization effects manifested themselves in magnetic fields satisfying the inequality $L_{\mathrm{H}} > l$ where L_{H} is the magnetic length. For the sample studied this corresponds to the limiting value of magnetic field strength $H = 0.36$ T. We obtained the following relaxation times: $\tau_\varphi = 7.2 \times 10^{-12}$ T^{-1} s and $\tau_{\mathrm{so}} = 1.36 \times 10^{-12}$ s. The antilocalization effects (positive magnetoresistivity) disappear with increasing temperature where the inequality $\tau_{\mathrm{so}} > \tau_\varphi$ is met.

The main mechanism of spin relaxation in non-centrisymmetrical semiconductors and semiconducting structures is a D'yakonov–Perel (DP) mechanism [13]. A prerequisite to the realization of this mechanism is the predominance of impurity smearing over spin splitting ($\hbar\tau_{\mathrm{tr}}^{-1} > \Delta$). Our values of τ_{tr} offers the fulfillment of the above inequality up to $\Delta = 4.8$ meV. The spin relaxation time makes it possible to estimate the value of spin splitting by the relationship $\tau_{\mathrm{so}}^{-1} = \langle\Delta^2\rangle\tau_{\mathrm{tr}}/4\hbar^2$ [14] and to obtain $\Delta = 2.97$ meV for the sample studied.

An increase in transport current causes electron overheating to appear and positive magnetoresistivity to disappear as in the case of temperature increase. The effect of electron overheating was used to determine the temperature dependence of hole-phonon relaxation time $\tau_{\mathrm{pph}} = 11 \times 10^{-8}$ T^{-2} s.

Thus, relying on the analysis of weak localization in the $Si_{0.7}Ge_{0.3}/Si_{0.2}Ge_{0.8}/Si_{0.7}Ge_{0.3}$ heterostructure, we estimate the value of spin splitting in the energy spectrum of charge carriers. The observation of antilocalization testifies that the contribution of the Rashba term to the spin splitting is dominant [4]. The results of our investigation suggest that Si- and Ge-based heterostructures may be applied in spin transport-controlled electron devices.

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