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The spin-flip scattering effect in the spin transport in silicon doped with bismuth

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Abstract. Spin transport of conduction electrons in silicon samples doped with bismuth in the $1.1 \cdot 10^{13} - 7.7 \cdot 10^{15} \text{ cm}^{-3}$ concentration range was studied by the Hall effect measurements. The dependence of the Hall voltage magnitude on the magnetic field is the sum of the normal and spin Hall effects. The electrons are partially polarized by an external magnetic field and are scattered by the bismuth spin-orbit potential. Spin-flip scattering results in the additional electromotive force which compensates the normal Hall effect in strong magnetic fields.

1. Introduction

Silicon doped with donors having a large spin-orbit potential (such as Bi or Sb) is an attractive material for semiconductor spintronics due to a possibility of realization of the spin transport in these structures. Furthermore, the weaker spin-orbit interaction in silicon provides a longer lifetime of the excited spin state in comparison with A_3B_5 compounds.

In a recent paper [1], we have shown that a deviation from the linear dependence of the Hall resistance in the magnetic field in the temperature range 10 - 80 K is the manifestation of the spin Hall effect. The deviation decreases with rise of bismuth concentration as well as with temperature increasing. We have previously reported that the Elliott-Yafet mechanism [2,3] prevails in the spin-lattice relaxation of conduction electrons in silicon doped with bismuth. So, these results were explained by spin-dependent and spin flip scattering induced by heavy bismuth impurity centres.

In this work, we experimentally demonstrate how doping with bismuth affects the galvanomagnetic properties of silicon and propose the theoretical model of spin-flip scattering which explains the experimental results.

2. Samples and experimental technique

Natural silicon samples doped with bismuth in the $1.1 \cdot 10^{13} - 7.7 \cdot 10^{15} \text{ cm}^{-3}$ concentration range were prepared by the floating-zone growth process in the Leibniz Institute for Crystal Growth (Berlin, Germany).

The contribution of spin-dependent scattering to the Hall electromotive force (EMF) was studied with the Hall technique using a measuring system with a Janis Research CCS-300S/202 Cryostat.



3. Experimental results and discussion

The experimental dependencies of the Hall voltage on the magnetic field represent the sum of the normal and the spin Hall effects at $T = 30$ K (figure 1). Furthermore, the spin Hall effect compensates the normal one in the strong external magnetic field. It is easy to see that increasing the concentration of impurities leads to increasing the contribution of the spin Hall effect.

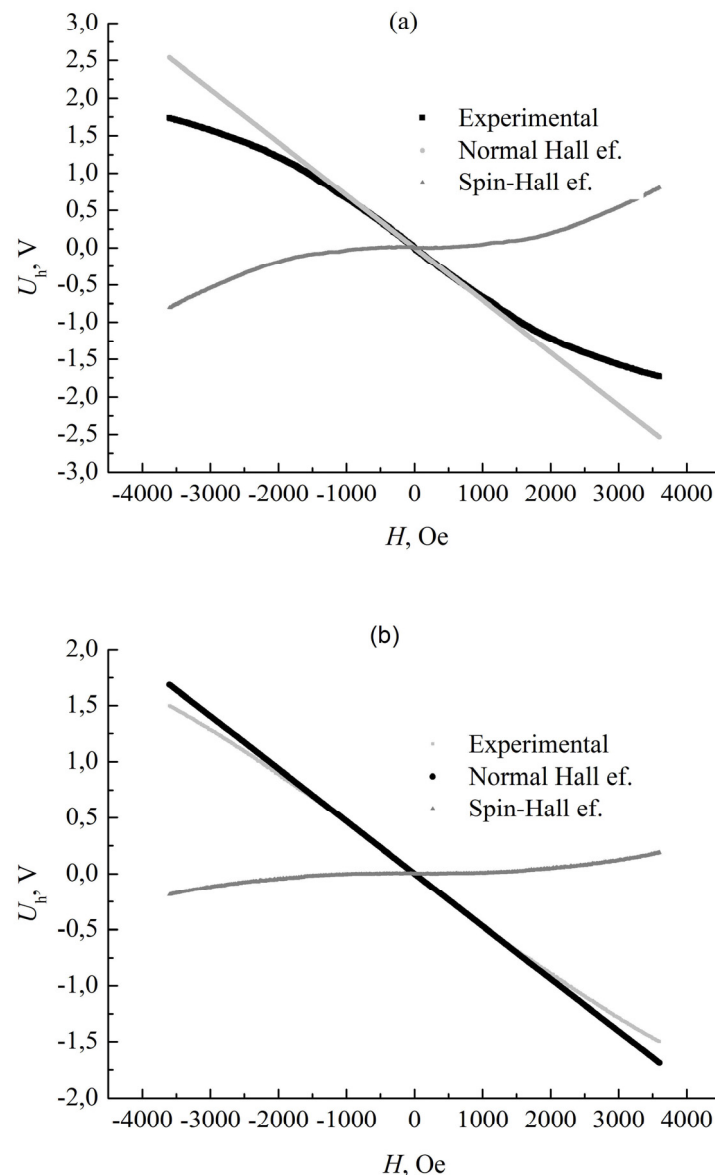


Figure 1. The dependencies of the Hall voltage on the magnetic field at $T = 30$ K. (a) - $N_d = 7.7 \cdot 10^{14} \text{ cm}^{-3}$, (b) - $N_d = 2.4 \cdot 10^{13} \text{ cm}^{-3}$.

Polarization of conduction electrons is necessary for an appearance of the electromotive force due to the spin Hall effect. Our samples are not ferromagnetic, therefore, only the mechanism of spin polarization by the magnetic field is obvious. We calculated the contribution of the spin Hall effect, taking into account only the polarization of carriers by the magnetic field and using the formulas presented in [4]. The calculation results are presented in figure 2. It is easy to see the linear

dependence of the Hall voltage on the magnetic field which is quite a good description of the experimental dependence in the weak magnetic field. However, the experimental dependence is growing faster than the theoretical one with increasing magnetic field. Thus, there is another mechanism of carriers polarization which is associated with spin-dependent scattering induced by heavy bismuth impurity centres.

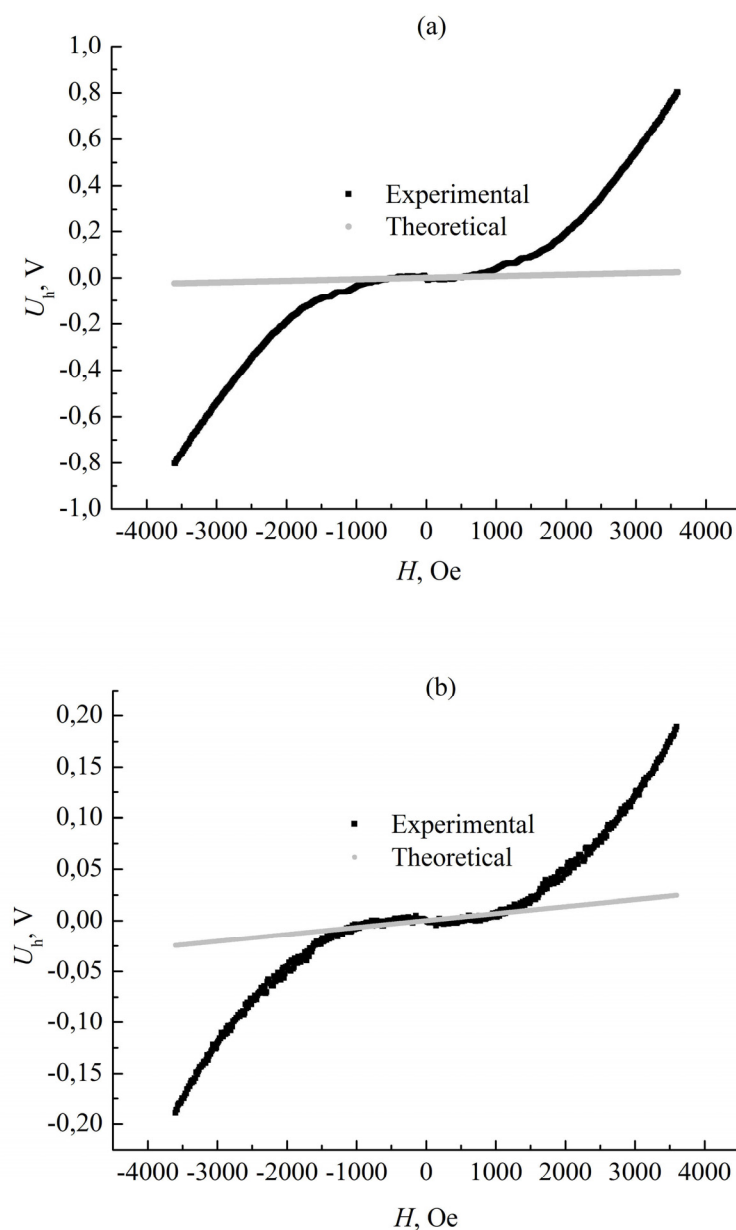


Figure 2. The theoretical and experimental dependencies of the Hall EMF on the magnetic field at $T = 30 \text{ K}$. (a) - $N_d = 7.7 \cdot 10^{14} \text{ cm}^{-3}$, (b) - $N_d = 2.4 \cdot 10^{14} \text{ cm}^{-3}$.

We offer the following model of the spin-flip scattering induced by heavy bismuth impurity centres: electrons are scattered through the polarized Bi donor and change the spin orientation in accordance with the direction of the donor polarization (figure 3).

The time variation of the changing of the spin-up carrier density polarized due to spin-flip scattering $\frac{dn_{\uparrow}^{\text{flip}}}{dt}$ has the form:

$$\frac{dn_{\uparrow}^{\text{flip}}}{dt} = CN_{\uparrow}n_{\downarrow}W_{\downarrow\uparrow}, \quad (1)$$

where C is constant, N_{\uparrow} is the spin-up donor concentration, n_{\downarrow} is the spin-down electron concentration, $W_{\downarrow\uparrow}$ is the probability of electron spin flip from the position \downarrow to \uparrow . The similar expression can be written for the opposite direction of the spin of the free carriers and donors.

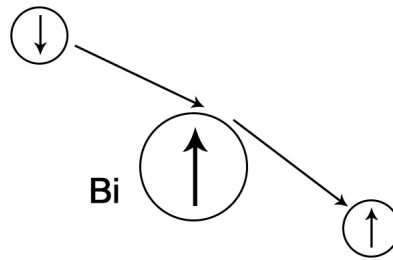


Figure 3. The schematic representation of the spin-flip mechanism of polarization of the conduction electrons.

Taking into account the coupling of the probability of electron spin flip with the relaxation time, the change of the concentration of free carriers with spin up due to spin-flip scattering can be written as:

$$\Delta n_{\uparrow}^{\text{flip}} = CNn \left(\frac{1}{4} - \left(\frac{e \frac{g\mu_B H}{kT} - 1}{e \frac{g\mu_B H}{kT} + 1} \right)^2 \right) \left(\frac{1}{\tau_{\uparrow}} - \frac{1}{\tau_{\downarrow}} \right) \Delta \tau, \quad (2)$$

where $\Delta \tau$ is the integration time, N is the donor concentration, n is the full concentration of the free carriers, g is the g-factor, H is the magnetic field strength, μ_B is the Bohr magneton, k is the Boltzmann constant, T is temperature, τ_{\uparrow} and τ_{\downarrow} are the life times of the spin-up and spin-down electrons, respectively.

The electromotive force according to [4] has the form:

$$V_{\text{SH}} = 4\pi R_{\text{SH}} L j_x \mu_B (n_{\uparrow} - n_{\downarrow}) \quad (3)$$

where R_{SH} is the spin Hall constant, L is the sample length, j_x is the current density which has three terms in our structures:

$$j = j_{\text{dr}}^0 + \Delta j + \Delta j^{\text{flip}}, \quad (4)$$

where the first term is the drift current density, the second one is the change of current density due to the magnetic field, the third one is the change of current density due to the spin-flip scattering. The concentrations of electrons with specific spin orientations also have three components:

$$\begin{aligned} n_{\uparrow} &= n_{\uparrow}^0 + \Delta n_{\uparrow} + \Delta n_{\uparrow}^{\text{flip}} \\ n_{\downarrow} &= n_{\downarrow}^0 - \Delta n_{\downarrow} - \Delta n_{\downarrow}^{\text{flip}} \end{aligned} \quad (5)$$

where the first terms are the initial concentrations of the carriers with a certain spin, the second ones are the changes of the electron concentrations due to the magnetic field, the third ones are the changes of the electron concentrations due to the spin-flip scattering

Then, the expression for the EMF spin Hall effect can be represented as:

$$V_{SH} = 8\pi R_{SH} L e v_x \mu_B \left(2n^2 \frac{e}{e} \frac{\frac{g\mu_B H}{kT} - 1}{kT + 1} + n^2 N \frac{1}{\tau_s} C(2\Delta\tau v_x) \frac{e}{e} \frac{\frac{g\mu_B H}{kT} - 1}{kT + 1} \left[\frac{1}{4} - \left(\frac{\frac{g\mu_B H}{kT} - 1}{e \frac{g\mu_B H}{kT} + 1} \right)^2 \right] \right) \quad (6)$$

where v_x is the velocity of the free carriers.

Then, the total Hall electromotive force appearing in our samples has the form:

$$V_H = R_H L H e n v_x - V_{SH}, \quad (7)$$

where the first term is the normal Hall effect, R_H is the constant of the normal Hall effect. Figure 4 shows the theoretical dependencies of the Hall voltage on the magnetic field at $T = 30$ K.

It is easy to see from the equation (6) and figure 4 that the spin-flip process (gray) gives a cubic contribution and a nonlinear dependence of the Hall EMF on the magnetic field. As a result, the form of the theoretical dependence repeats the experimental one.

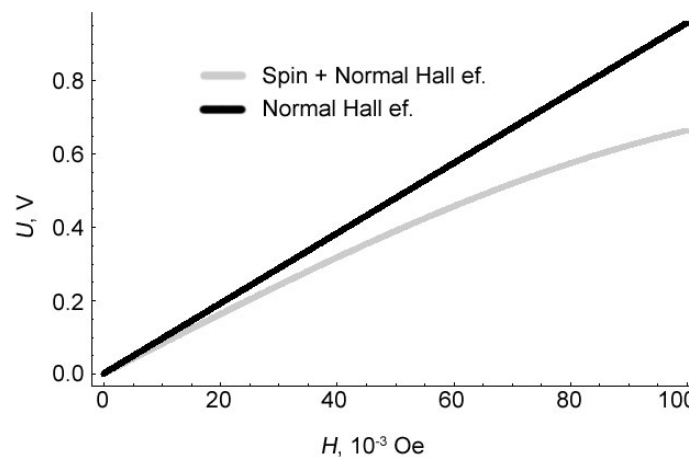


Figure 4. The theoretical dependencies of the Hall voltage on the magnetic field at $T = 30$ K.

4. Conclusion

The dependence of the Hall voltage magnitude on the magnetic field is the sum of the normal and spin Hall effects. The electrons are partially polarized by an external magnetic field and are scattered by the bismuth spin-orbit potential. Spin-dependent scattering results in the additional electromotive force which leads to a nonlinear dependence of the Hall EMF on the magnetic field. The spin-flip scattering of electrons in bismuth makes a significant contribution to the electromotive force spin Hall effect.

5. References

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