Tunable Planar Hall Effect in (Ga,Mn)(Bi,As) Epitaxial Layers

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Motivation

In quest of more efficient spintronic materials, which are both useful for spintronic applications and interesting for physical phenomena investigations, we have focused on the quaternary (Ga,Mn)(Bi,As) compound [1,2]. Incorporation of a small amount of heavy Bi atoms into epitaxial layers of (Ga,Mn)As (regarded as the prototype dilute ferromagnetic semiconductor (DFS) combining semiconducting properties with magnetism [3]) results in a strong enhancement of the spin-orbit interaction in the valence band owing to a large relativistic correction to the band structure. This, in turn, modifies essentially certain magnetoelectric properties of the material. The enhanced spin-orbit interaction is especially favourable for spintronic materials as it enables to tune electrically the magnetization direction through the spin-orbit torque effect. In the present paper we report on our study of the planar Hall effect in (Ga,Mn)(Bi,As) epitaxial layers and its sensitivity to the in-plane magnetic anisotropy in the layers.

Layer growth and characterization

We have investigated 50 nm thick (Ga,Mn)(Bi,As) layers, with 6% Mn and 1% Bi contents, and reference (Ga,Mn)As layers, grown on semi-insulating (001)-oriented GaAs substrate under biaxial compressive misfit strain by the low-temperature molecular-beam epitaxy (LT-MBE) technique, at the substrate temperature of 230°C. After the growth the samples were subjected to a low-temperature annealing treatment carried out in air for 50 h at 180°C. An incorporation of a small amount of Bi into the (Ga,Mn)As layers causes a distinct expansion of their lattice parameter perpendicular to the layer plane and an enhancement of the in-plane compressive strain [4].

SQUID magnetometry measurements [2] revealed that incorporation of Bi into the (Ga,Mn)As layer resulted in a distinct broadening its magnetization hysteresis loops and a decrease in the Curie temperature. At low temperatures both the (Ga,Mn)(Bi,As) and (Ga,Mn)As layers display the ⟨100⟩ in-plane easy magnetization axes and hard axes along two magnetically non-equivalent in-plane ⟨110⟩ crystallographic directions, where the [110] direction is noticeably harder than the [-110] one.

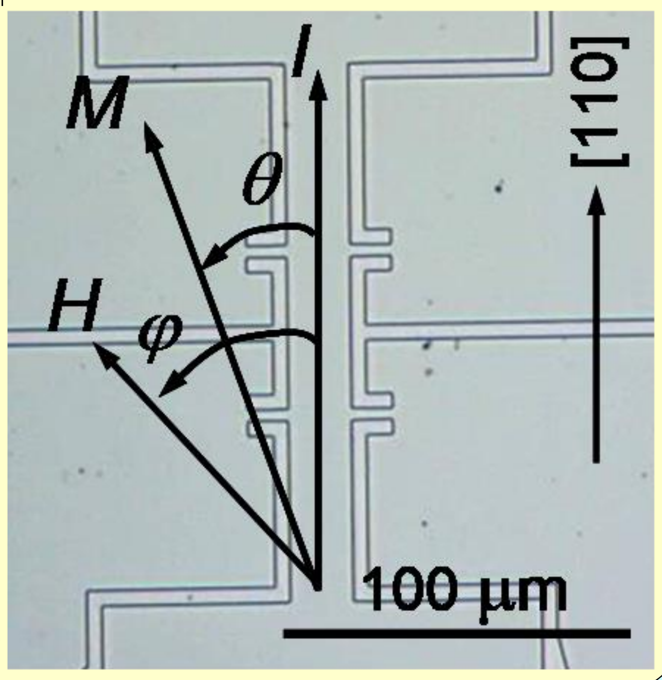
Planar Hall Effect

So-called planar Hall effect (PHE) is an interesting phenomenon arising due to the spin-orbit interaction in conducting ferromagnetic materials. PHE consists in developing a spontaneous transverse voltage in ferromagnetic layers with in-plane magnetization as a result of flowing longitudinal current. PHE resistivity in a single domain ferromagnetic layer can be described by the formula [5,6]:

$$\rho_{xy} = -\tfrac{1}{2}(\rho_{\perp} - \rho_{\parallel})\sin 2\theta, \qquad (1)$$

where $\rho_{\parallel}$ and $\rho_{\perp}$ are the resistivities for the in-plane magnetization vector oriented parallel and perpendicular to the current flow, respectively, and θ stands for the angle between the current direction and the magnetization vector *M*.

The PHE resistivity has been measured with micro-Hall-bars, tailored from the layers by means of electron-beam lithography patterning and chemical etching, while sweeping an in-plane magnetic field, *H*, applied at various angles, φ, with respect to the current, *I*, as shown in **Fig. 1**.



Results and discussion

The up and down sweep of an in-plane weak magnetic field causes non-monotonic changes of the PHE resistivity whose shape depends on the field orientation with respect to the Hall-bar axis. As an example, **Fig. 2** presents a record of changes of the PHE resistivity normalized to zero-field longitudinal resistivity, ρ_0, measured for the (Ga,Mn)(Bi,As) layer at the liquid helium temperature under magnetic field perpendicular to the Hall-bar axis, i.e. along the [-110] crystallographic direction at $\varphi = 90°$.

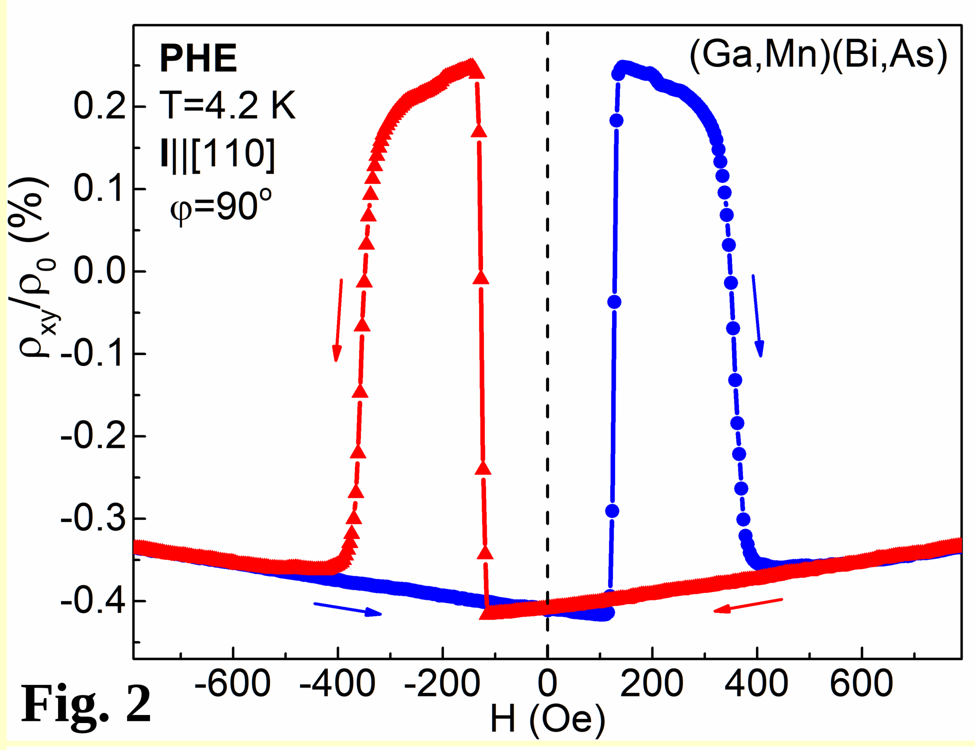


Fig. 2

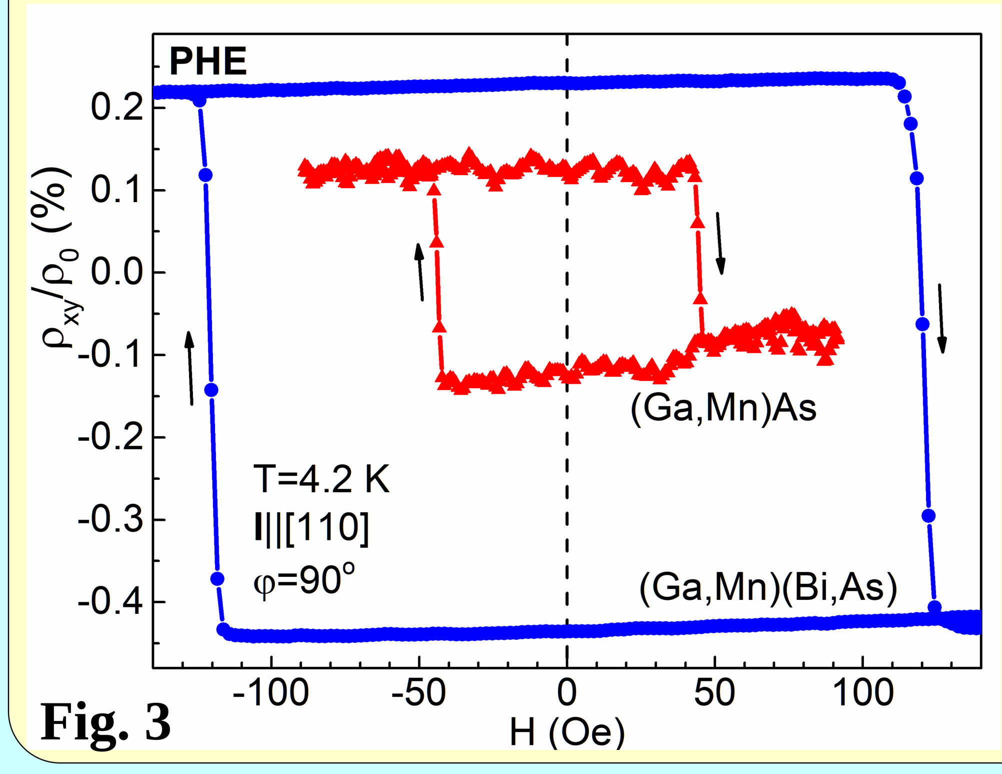


Fig. 3

The double-hysteresis-loop behaviour results from a field-induced reorientation of the magnetization vector in the Hall-bar by 360° between the four equivalent easy axes oriented along in-plane ⟨100⟩ directions. According to Equation (1) the low values of $\rho_{xy} = -\tfrac{1}{2}(\rho_{\perp} - \rho_{\parallel})$ appear at the θ angles of 45° and 225° and the high values of $\rho_{xy} = \tfrac{1}{2}(\rho_{\perp} - \rho_{\parallel})$ appear at the θ angles of 135° and 315°. The difference between the high and low values corresponds to the amplitude of PHE resistivity and equals $\rho_{\perp} - \rho_{\parallel}$.

The PHE resistivity record, obtained while sweeping the magnetic field in a narrower range displays single-hysteresis-loop dependence, as shown in **Fig. 3**, resulting from magnetization vector rotation by 90° between two in-plane ⟨100⟩ easy axes.

In **Figs. 4** and **5** we present the PHE resistivity records measured while sweeping the field applied at the φ angle values of 40° and 50°, i.e. the values of 5° smaller and 5° larger, respectively, with respect to the one corresponding to the [010] easy axis. In the case of $\varphi = 40°$ the rotation of magnetization vector in the Hall-bar by 360° occurs in the counter-clockwise direction, while for $\varphi = 50°$ that rotation occurs in the opposite, clockwise direction. In the former case, when starting from the positive field value, the first transition of the magnetization vector between the easy axes occurs by overcoming the [-110] crystallographic direction, while in the latter case it occurs by overcoming the magnetically harder [110] one, thus requiring a distinctly larger value of coercive field, as shown in **Fig. 4**. Consequently, the single hysteresis loops, obtained while sweeping a magnetic field in a narrower range (**Fig. 5**), differ significantly in their width depending on the applied φ angle. For the (Ga,Mn)(Bi,As) layer the width of the PHE resistivity hysteresis loop recorded at $\varphi = 50°$ becomes by about 25% larger than that recorded at $\varphi = 40°$. For the reference (Ga,Mn)As layer the respective difference is smaller and amounts to about 15%.

Magnetization vector rotation between the easy axes in these layers occurs through nucleation and propagation of 90° domain wall existing over a narrow magnetic field range in the vicinity of the coercive field [7].

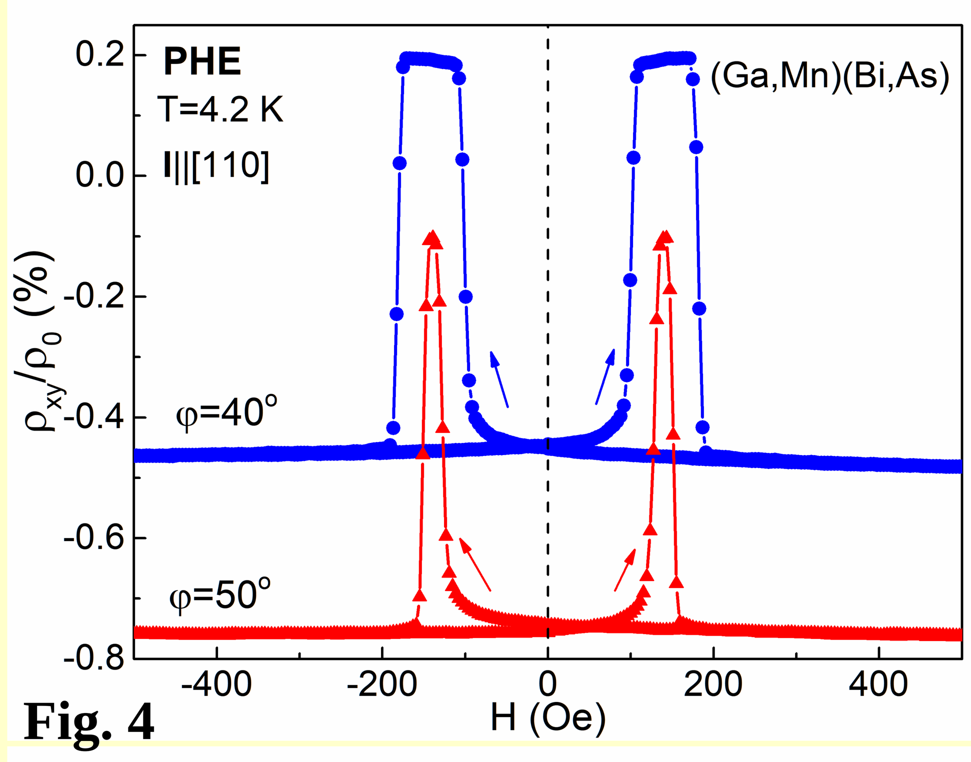


Fig. 4

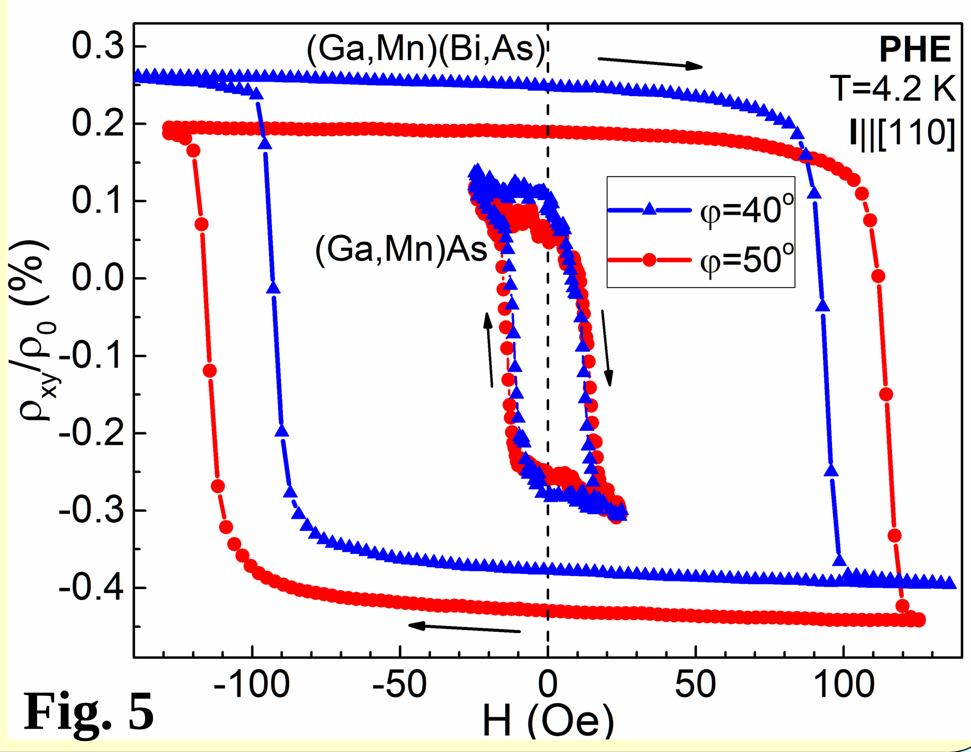


Fig. 5

Conclusions

Small addition of heavy Bi atoms to (Ga,Mn)As DFS results in significantly larger coercive fields and distinctly stronger uniaxial anisotropy between the perpendicular ⟨110⟩ crystallographic directions. Incorporation of just 1% Bi into (Ga,Mn)As layer causes an essential enhancement of the amplitude of PHE resistivity, by a factor of 2 to 3, as a result of increased strength of the spin-orbit coupling. The two-state behaviour of the PHE resistivity at zero magnetic field (shown in **Figs. 3** and **5**), which may be tuned by the applied field orientation, provides its usefulness for applications in nonvolatile memory elements. The quaternary (Ga,Mn)(Bi,As) ferromagnetic semiconductor appears also to be a promising material for studying the operation of novel spintronic devices, such as the recently proposed magnetoelectric spin-orbit logic device [8], requiring the high-spin-orbit-coupling materials.

References

[1] K. Levchenko, T. Andrearczyk, J.Z. Domagala *et al.*, *J. Supercond. Nov. Magn.* **30**, 825 (2017).
[2] K. Levchenko, T. Prokscha, J. Sadowski, *et al.*, *Sci. Rep.* **9**, 3394 (2019).
[3] T. Dietl and H. Ohno, *Rev. Mod. Phys.* **86**, 187 (2014).
[4] T. Andrearczyk, K. Levchenko, J. Sadowski *et al.*, *Materials* **13**, 5507 (2020).
[5] T.R. McGuire and R.I. Potter, *IEEE Trans. Magn.* **11**, 1018 (1975).
[6] H.X. Tang, R.K. Kawakami, D.D. Awschalom and M.L. Roukes, *Phys. Rev. Lett.* **90**, 107201 (2003).
[7] U. Welp, V.K. Vlasko-Vlasov, X. Liu, J.K. Furdyna and T. Wojtowicz, *Phys. Rev. Lett.* **90**, 167206 (2003).
[8] S. Manipatruni, D.E. Nikonov, C.-C. Lin *et al.*, *Nature* **565**, 35 (2019).