Magnetic and Magneto-Transport Characterization of (Ga,Mn)(Bi,As) Epitaxial Layers

Khrystyna Levchenko [1], Tomasz Andrearczyk [1], Jarosław Z. Domagała [1], Tadeusz Wosiński [1], Tadeusz Figielski [1] and Janusz Sadowski [1,2]

[1] *Institute of Physics, Polish Academy of Sciences, 02-668 Warszawa, Poland*
[2] *MAX-IV Laboratory, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden*

The ternary III-V semiconductor (Ga,Mn)As has attracted much attention as the model diluted magnetic semiconductor, which combines semiconducting properties with magnetism and offers a basis for developing novel spintronic devices. Substitutional Mn ions in (Ga,Mn)As become ferromagnetically ordered below the Curie temperature, T_C, owing to interaction with spin-polarized holes. The sensitivity of the magnetic properties, such as the Curie temperature and magnetic anisotropy, to the hole concentration allows for tuning those properties by low-temperature post-growth annealing, photo-excitation or electrostatic gating of the (Ga,Mn)As layers. In the present paper we investigate an impact of Bi incorporation into (Ga,Mn)As layers on their magnetic and magneto-transport properties. Incorporation of a small fraction of Bi, substituting As in GaAs, results in a large decrease in its band gap and the strongly increased spin-orbit coupling, accompanied by a giant separation of the spin-split-off hole band [1].

We have investigated (Ga,Mn)(Bi,As) layers, with 4% and 6% Mn contents and the Bi composition in the range from 0 to 1%, grown by the LT-MBE technique at a temperature of 230°C on semi-insulating (001)-oriented GaAs substrate. High-resolution X-ray diffraction characterization of the layers confirmed their high structural perfection and showed that all of them were grown pseudomorphically on GaAs substrate under compressive misfit strain. An addition of a small amount of Bi to the (Ga,Mn)As layers resulted in a distinct increase in their lattice parameter perpendicular to the layer plane and an increase in the in-plane compressive strain. Magnetic properties of the layers were examined using both the magnetic-field- and temperature-dependent SQUID magnetometry, showing the in-plane easy axis of magnetization in all the layers, typical for (Ga,Mn)As layers grown under compressive misfit strain. Incorporation of Bi into the (Ga,Mn)As layers results in decreasing their Curie temperature, which, however, can be enhanced during the low-temperature post-growth annealing performed in air at 180°C for 50 h. The main effect of the annealing is outdiffusion of self-compensating Mn interstitials. The T_C enhancement caused by the annealing is accompanied with a decrease in the coercivity of the layers, which results mainly from an increase in the hole concentration in annealed layers.

Magneto-transport properties of the layers were measured in samples of Hall-bar shape supplied with Ohmic contacts to the (Ga,Mn)(Bi,As) layers. Using a low-frequency lock-in technique we measured four-probe longitudinal magneto-resistance (MR) and planar Hall effect (PHE) as a function of in-plane magnetic field at liquid helium temperatures. The obtained results reveal a strong decrease in the hole concentration upon the addition of a small amount of Bi into the layers. The complex PHE dependence on applied magnetic field is discussed taking into account the magnetocrystalline anisotropy of the (Ga,Mn)(Bi,As) layers, which results from biaxial compressive strain in the layers.

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[1] Z. Batool, K. Hild, T. J. C. Hosea, X. Lu, T. Tiedje, and S. J. Sweeney, *J. Appl. Phys.* **111**, 113108 (2012).