Muon-Spin-Relaxation Study of Ferromagnetism in (Ga,Mn)(Bi,As) Dilute Magnetic Semiconductor

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GaAs-based ternary compound (Ga,Mn)As, in which a few percent of Ga lattice atoms have been substituted by Mn impurities, has become a prototype dilute ferromagnetic semiconductor, which exhibits spintronic functionalities associated with collective ferromagnetic spin ordering [1]. As demonstrated in our recent investigations [2], the replacement of a small fraction of As atoms by much heavier Bi atoms in (Ga,Mn)As layers results, owing to increased spin-orbit coupling, in a strong enhancement of magneto-resistive effects in the quaternary (Ga,Mn)(Bi,As) compound, favourable to its spintronic applications.

In the present study we have investigated spatial homogeneity of ferromagnetic phase in the (Ga,Mn)(Bi,As) layers using muon-spin-relaxation (μSR) spectroscopy at the Paul Scherrer Institute. μSR spectroscopy is a unique technique, which enables to study local, on the nanometer scale, magnetic properties of thin layers of materials making use of a beam of low-energy (keV), fully spin-polarized, positive muons.

We have investigated 50-nm thick (Ga,Mn)(Bi,As) layers, with 6% Mn and 1% Bi contents, grown by the low-temperature MBE technique on either GaAs substrate or the same substrate covered with (In,Ga)As buffer layer. Reference (Ga,Mn)As layers were also grown under the same conditions. High-resolution X-ray diffraction characterization of the layers proved their high structural perfection and showed that all of them were grown pseudomorphically – under compressive misfit strain on GaAs substrate and under tensile misfit strain on the (In,Ga)As buffer. Mn and Bi contents in the layers were determined with secondary ion mass spectrometry (SIMS). Magnetic properties of the layers were examined using superconducting quantum interference device (SQUID) magnetometry, showing the in-plane and out-of-plane easy axis of magnetization in the layers grown under compressive and tensile misfit strain, respectively, and the Curie temperatures in the (Ga,Mn)(Bi,As) layers by about 20% lower than those in the corresponding (Ga,Mn)As layers. μSR spectroscopy measurements, performed in the 4 K–250 K temperature range under either in-plane or perpendicular-to-the-plane magnetic field configuration, confirm the magneto-crystalline anisotropy of the layers and their Curie temperatures. Most importantly, the μSR spectroscopy results clearly demonstrate that below the Curie temperature ferromagnetism in our (Ga,Mn)(Bi,As) layers develops almost homogeneously in the full volume fraction of the layer, similarly as in the reference (Ga,Mn)As layers. The quaternary (Ga,Mn)(Bi,As) compound proves its usefulness as a novel dilute magnetic semiconductor displaying properties advantageous for spintronic applications.

[1] T. Dietl and H. Ohno, *Rev. Mod. Phys*. **86**, 187 (2014).
[2] K. Levchenko, T. Andrearczyk, J.Z. Domagala, J. Sadowski, L. Kowalczyk, M. Szot, R. Kuna, T. Figielski and T. Wosinski, *J. Supercond. Nov. Magn.* **30**, 825 (2017).