Thin films of Heusler compounds

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Thin film and devices using Heusler compounds are important for many applications such as spintronics, new permanent magnets and quantum computing. Since 2014 our thin film laboratory has been in function. First thin films are sputtered and characterized. For spintronics and permanent magnets we are searching for hard magnetic materials. Manganese-rich Heusler-compounds with large out of plane magnetization and large saturation magnetization have been designed for new magnets whereas a high magneto crystalline anisotropy and low magnetic moment for future magnetic random access technologies (MRAM) and spin torque oscillators for wireless communication. Films of topological Heusler compounds are tested whether they show a large spin Hall effect, large enough for spin switching in MRAM devices or as a basic material for SQUIDs.

Recently, we decided to explore the properties of thin film Heusler compounds. Many important applications in spintronics depend on the interface properties and quality and our know-how can help to improve spintronics devices via interface engineering. Additionally, single crystal thin films allow for the investigation of intrinsic and extrinsic materials properties which are not available in polycrystalline samples such as the magneto crystalline anisotropy. Finally new ways of tuning such as strain, gating etc. will be possible and compounds which are not stable as bulk materials might be possible.

New Mn2-based Heusler Compounds

We worked first on Mn_3Ga and $Mn_{2-x}Y_xGa$ (with Y=3d metals) films to verify and extended results, at the beginning in collaboration with the Tohoku University, Bielefeld University and IBM Almaden, well established collaboration partners. Especially the thickness dependence of the tetragonal electrode is of importance for future electronic devices. We could establish the already with a few nanometers an out of plane magnetized electrode can be realized [1]. Since the tunnel magneto resistance (TMR) values are still low at room temperature it is important to investigate the thin film quality (structure and magnetization) and the interface with MgO. Magnetization measurements and careful transmission electron microscopy investigation has enabled us to identify the in-plane component of the Mn-rich Heusler films, observed by many groups. The polycrystalline films have the tetragonal c-axis oriented primarily perpendicular to the film plane but some fraction of the sample exhibiting the c-axis in the film plane [2]. Via forward scattering in hard X-ray photoelectron spectroscopy (HAXPES) we were able to investigate the structure of buried Mn–Ga films [3] and with core level spectroscopy [4]. Differences in the angular distributions of electrons emitted from Mn and Ga atoms revealed that the structure of $Mn_{62}Ga_{38}$ changes from the disordered L10 towards the ordered D022 for increasing annealing temperatures. The improvement of the structural order of the $Mn_{62}Ga_{38}$ layer is accompanied by an improvement of the structure of the overlying MgO layer [3]. The core level investigation via HAXPES indicated the formation of Ga-O bonds at the interface between the oxygen of MgO and the Gallium of $Mn_{62}Ga_{38}$. Additionally we can conclude that the MnGa layer is the terminating layer at the interface, which was predicted to show no resonant tunneling. The deposition of few monoatomic layers of Mg on top of Mn–Ga film suppresses the oxidation of Gallium and increase the TMR slightly.

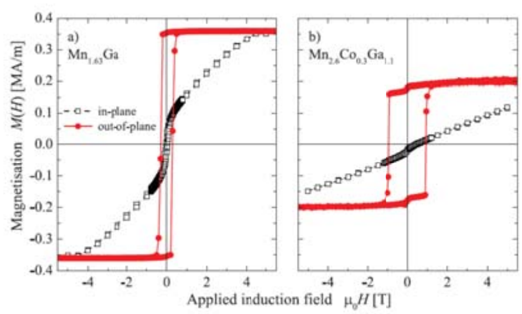

Fig. 1: Static magnetic properties at 300 K for (a) Mn–Ga and (b) Mn–Co–Ga films. The addition of Co results in a drop of the magnetization accompanied by an increase in both the coercive field and the anisotropy field [5].

Especially the thin films of the doped Mn_2Ga are special interested since we can realize huge coercitivity [4,5] by doping with other magnetic elements and a significant coercitivity with a large moment [patent to be submitted]. With time-resolved magneto-optical Kerr effect (TR-MOKE) we have probed the high frequency dynamics of Mn–Ga and Mn-Co-Ga. The ferromagnetic resonance frequency extrapolated to zero-field is found to be 125 GHz with a low Gilbert damping, α, of 0.019 [6]. A huge anisotropy field of 4.5 T was measured, corresponding to an effective anisotropy density of 0.81 MJm^{-3}. An even larger anisotropy field was found for the substituted $Mn_{2.6}Co_{0.3}Ga_{1.1}$ film. Only in the high field laboratory in Rossendorf with a pulsed magnetic fields up to 60 T it was possible to determine the field strength required to saturate the film in the plane. The effective anisotropy energy density for nearly compensated $Mn_{2.6}Co_{0.3}Ga_{1.1}$ is determined to be 1.23 MJ m^{-3} [6].

Mn_2RhSn with the non-collinear magnetic structure and the two systems Mn-Pt-Sn and Mn-Pt-Ga and Mn-Pt-Sn were identified by theory and bulk investigations as new materials for spintronics devices.

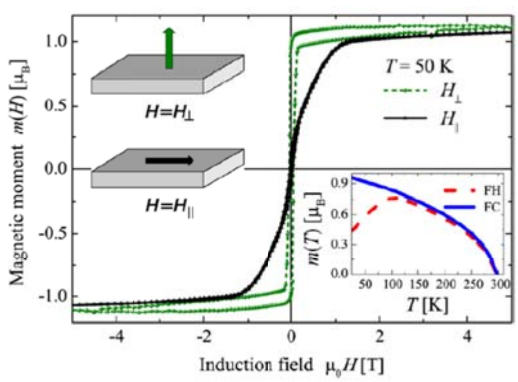

Fig. 2: Magnetic properties of Mn_2RhSn thin films. Shown are the in-plane (H∥) and out-of-plane (H⊥) magnetic hysteresis loops measured at 50 K.
The inset shows the temperature dependence of the magnetization measured in an induction field of μ_{0H} = 0.1 T.

Epitaxial thin films of Mn_2RhSn were grown on an MgO (0 0 1) substrate by magnetron co-sputtering of the elements. The measured saturation magnetization corresponds to a magnetic moment of 1 μ_B in good agreement with the bulk sample. The magnetization measurements revealed an out-of-plane anisotropy energy of 89 kJ m^{-3}, which makes these materials interesting for zero field Skyrmions as predicted by theory [5]. The lattice parameter of the compound has a very small mismatch with MgO, which makes it promising for TMR devices [5].

In the ternary system Mn-Pt-Ga we were able to sputter films of compensated ferrimagnets with a similar composition as the bulk sample. An even larger out-of-plane anisotropy energy was found for the compensated film, measured in the high field laboratory [to be published].

Hexagonal MnPtGa thin films could be prepared by DC magnetron sputtering on an MgO (001) substrate. The hexagonal structure arises from the cubic structure via a distortion along the 111 direction; most of the hexagonal manganese-rich-compounds are antiferromagnetic some are ferrimagnetic. However, due to the structural anisotropy a large magnetic anisotropy was realized in the thin-film sample [patent submitted].

Thin films of Mn-Pt-Sn were grown by co-sputtering. The temperature dependence of the magnetization shows signs of a spin reorientation between two non-collinear phases in the $Mn_{2-x}PtSn$ film at 100 K, which can be a hint for a skyrmionic phase. The susceptibility shows the typical Skyrmion-kink. With Lorenz TEM we see Skyrmions showing up during the reorientation process [to be published].

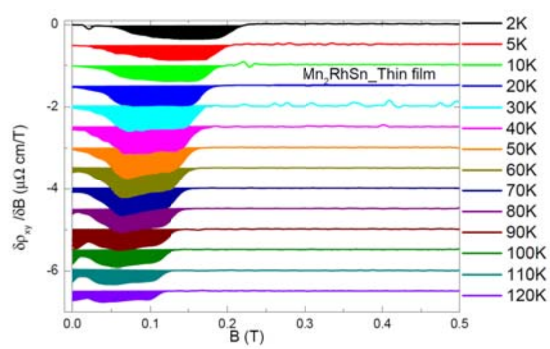

Fig. 3: Topological Hall effect of the Mn_2RhSn films in zero field.

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