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In-situ Magneto-Transport Measurements in a Transmission Electron Microscope

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Skyrmions are envisioned as nanoscale information carriers in future devices, since they can be electrically manipulated and detected. So far, topological Hall effect measurements on skyrmion samples are conducted on separate samples with different thicknesses and confinements as compared to samples for magnetic imaging in a transmission electron microscope (TEM) [1,2]. Such TEM-based magnetic characterization has proven extremely valuable for unveiling the details of skyrmionic spin textures, in particular, when it comes to exploring the three-dimensional structure of skyrmion tubes in extended volume samples [3]. The occurrence and nature of skyrmions depend strongly on the thickness and other geometrical confinements. However, since the latter influence, e.g., the demagnetizing field, the magnetic dipole interaction, and the stability of these topologically protected magnetic nano objects, a comparison of different types of samples is usually problematic. Accordingly, differences between samples impede a one-to-one correlation of magneto-transport data and TEM investigations, if not conducted simultaneously on an *identical* sample. Unfortunately to date, in-situ Hall measurements in a TEM are not yet available.

We have therefore devised a novel in-situ measurement platform that bridges this gap and allows for the first time for the conduction of in-situ magneto-transport measurements in a transmission electron microscope. A Protochips Fusion Select TEM holder with six electrical feedthroughs furnished with in-house made measurement chips is used to measure the Hall effect while simultaneously imaging the magnetic structure of a sample using Lorentz transmission electron microscopy (L-TEM) in-situ in a TEM. Chips with Si_3N_4 membranes and Au leads are lithographically structured from $Si_3N_4/Si/Si_3N_4$ sandwiches. These Au conducts are used to electrically contact focus ion beam (FIB) cut lamellae or thin films. A JEOL F-200 TEM (200kV, cold FEG) equipped with a Gatan Continuum electron energy loss spectrometer and a fast Gatan One View camera can then be used for a variety of magnetic characterization techniques including L-TEM, electron holography, differential phase contrast imaging (DPC) and/or measurement of the electron magnetic chiral dichroism (EMCD).

For proof-of-principal investigations, a 20 nm thin Ni film was deposited on an electron transparent Si_3N_4 membrane, integrated in a measurement chips, contacted by maskless lithography, and inserted in the Fusion Select holder. Four gold-plated spring contacts and feedthrough connectors provide for the electrical connection to the external Hall measurement setup. L-TEM was then used to image the magnetic domain pattern during in-situ Hall effect measurements in the TEM. The results of these proof-of-principle experiments are shown in Figs. 1(a-f). The magnetic field of the objective lens (OL) of the microscope was controlled to continuously magnetize the Ni film towards saturation. In good agreement with ex-situ reference measurements in a dedicated cryostat for state-of-the-art magneto-transport experiments, the L-TEM images reveal the coarsening of the magnetic domains upon increasing the field of the OL. As expected, this domain growth goes along with an increase of the Ni magnetization to saturation as probed by the simultaneously measured Hall voltage corresponding to the anomalous Hall contribution. These successful first measurements pave the way to previously unreported in-situ and operando Hall measurements in combination with high-resolution magnetic imaging in the TEM.

First investigations were then conducted to explore the long debated signature of topologically protected antiskyrmions in the Heusler compound $Mn_{1.4}PtSn$ on the (topological) Hall effect. For this, a TEM lamella was cut from a $Mn_{1.4}PtSn$ single crystal using focused ion beams, deposited on a measurement chip, and contacted. The characteristic stripe contrast in the in-situ L-TEM image in Fig 1(f) reveals the helical phase, which is the magnetic ground state of this material at room temperature [4], in zero external field (OL switched off). Our newly established setup then allowed us for the first time to follow in detail the field dependence of the Hall voltage (see insert) while simultaneously monitoring the field-induced creation and annihilation of antiskyrmions and non-topological bubbles in $Mn_{1.4}PtSn$ [5].

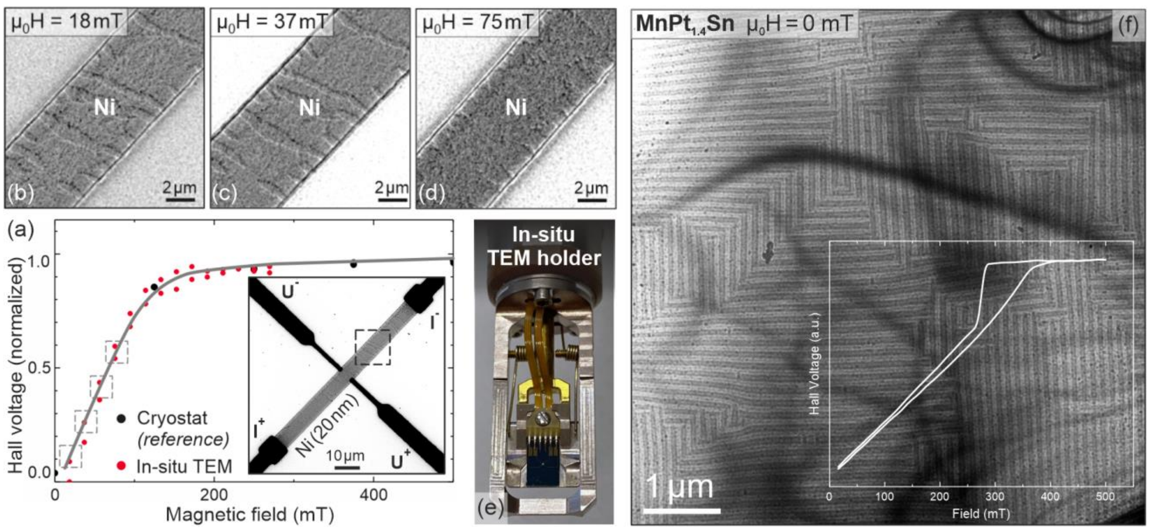

Figure 1. Hall measurements (a) and simultaneously recorded L-TEM images (b-c) reveal the domain growth upon magnetizing a 20 nm Ni test film in the magnetic field of the objective lens (OL). The in-situ Hall data are in good agreement with ex-situ reference measurements (insert in (a)). (e) Protochips Fusion Select holder; four of six spring contacts are used for the current supply and Hall voltage measurements. (f) L-TEM image of a $Mn_{1.4}PtSn$ sample revealing the ground state helical phase of this Heusler compound at $\mu_0 H_{OL}$ = 0 mT and in-situ measured field dependence of the Hall voltage (insert).

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