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Electronic Spin-Precession in Magnetic Nanostructures

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Spin-precession of electrons in magnetic nanostructures can be used to measure the spin torque, which is interesting for the development of magnetization reversal in nano-sized ferromagnets by spin injection [1]. To address this issue, we studied spin-precession of electrons during ballistic propagation through single-crystalline magnetic thin films by spin-polarized low-energy electron microscopy (SPLEEM). Using SPLEEM it is possible to observe a spin-dependent interference pattern produced by superposition of the two branches of a spin-polarized electron beam which are created by partial reflection at the film surface and partial reflection at the film-substrate interface. This kind of electronic Fabry-Perot interferometry shows reflectivity maxima for certain electron energies, corresponding to quantum resonances [2]. The electron energies at which quantum interference maxima and minima occur are spin-dependent for magnetic materials and give direct information on the energy- and spin-dependent phase-shift accumulated upon passage through the film. This result was utilized to determine the influence of different magnetic thin films on the polarization vector of spin-polarized electron beams. In particular, results for ultra-thin cobalt and iron films grown on W(110) are shown, which demonstrate the success of this new approach to determine electronic spin-precession by SPLEEM.

In our experiments ultra-thin magnetic films were grown on W(110) single crystals by evaporation from water-cooled electron beam evaporators. Growth temperature was optimized in order to promote the formation of several micron large, atomically flat islands, which cover multiple terraces of the underlying substrate (Fig. 1a). By observing the characteristic occurrence of quantum resonances in energy-dependent electron reflectivity measurements ranging from 0 eV to 22 eV above vacuum level, we were able to determine the exact local film thickness. The energy- and thickness-dependent reflectivity obtained by such energy scans was evaluated for spin-polarization of the incident electron beam parallel (spin UP) and anti-parallel (spin DN) to the magnetization of the film (Fig. 1b). Information on the corresponding phase-shifts φ_{UP} and φ_{DN} accumulated during electron transport within the film can be extracted directly from the positions of the reflectivity maxima and minima, since every intensity maximum (minimum) corresponds to a phase shift of an integer multiple of 2π (+1).

Basic quantum mechanics states that a perpendicularly polarized electron beam can be expressed as the coherent superposition of a spin-UP wave and a spin-DN wave (same amplitude, no relative phase shift) and that the spin-UP and spin-DN parts of electron wave-functions interfere independently [3]. This has been verified by energy-dependent reflectivity measurements using perpendicularly polarized electrons, where the reflectivity spectrum is found to be exactly the arithmetic average of the two curves plotted in Fig. 1b (not shown). Consequently, the amount of spin-precession can be deduced from the results of two independent experiments, i.e. one where the polarization of the incoming electron beam is oriented parallel to the magnetization of the film and another one where the polarization is anti-parallel (cf. Fig. 1b). The spin-precession angle is then exactly the difference between the energy-dependent phase-shifts $\varphi_{UP}(E)$ and $\varphi_{DN}(E)$.

We evaluated this phase-shift-difference at fixed electron energy for various film thicknesses and found almost perfect linear dependence. By measuring the slope of the corresponding linear regression line we could then determine the precession angle per atomic layer (Fig. 1c). This procedure removes all interface effects, which might influence the absolute value of the precession angle, and results in an experimental determination of a basic property of magnetic materials, i.e. the energy-dependent electronic spin-precession angle per atomic layer [4].

References
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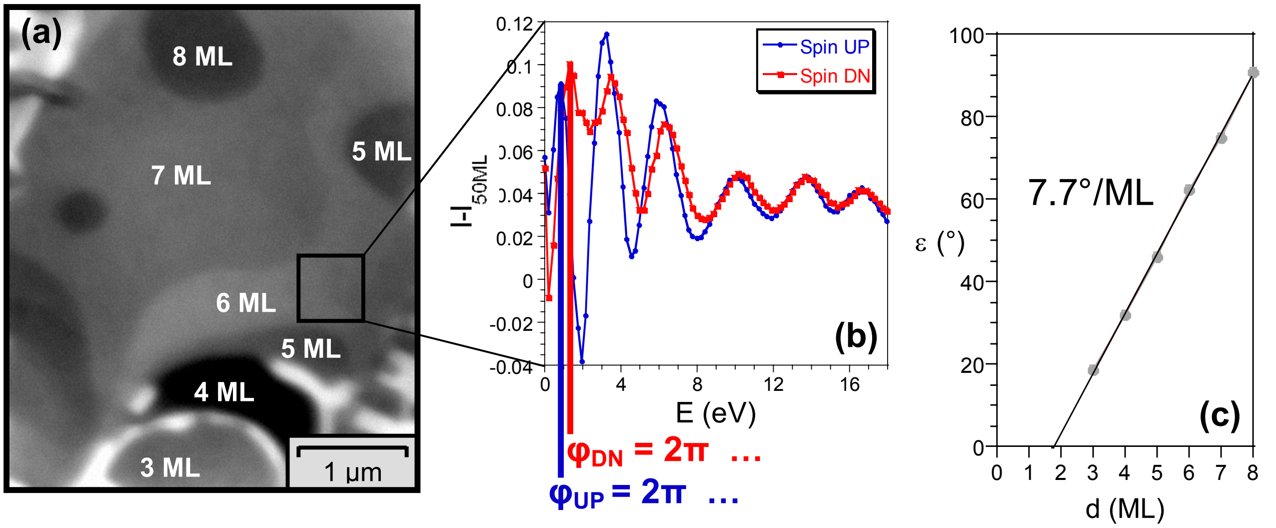

FIG. 1. (a) LEEM image of an atomically flat Co island grown on stepped W(110) (3.86 x 4.4 μm^2). Regions of different film-thickness show different reflectivity due to quantum size effects. (b) Energy-dependent reflectivity of a 6 ML thick Co film (normalized by subtracting the reflectivity spectrum of a 50 ML thick Co film). Spin UP/Spin DN curves show results for initial beam polarization parallel/anti-parallel to sample magnetization. Energy-dependent phase-shifts $\varphi_{UP}(E)$ and $\varphi_{DN}(E)$ determine spin-precession angle: $\varepsilon(E) = \varphi_{UP}(E) - \varphi_{DN}(E)$. (c) Experimentally obtained precession angle ε plotted vs. Co-film thickness for electron energies of 10 eV (above vacuum level) and 33% initial beam polarization. Electronic spin-precession angle per atomic layer is given as half of the slope of the plotted linear regression line and found to be 7.7°/ML.