Magnetic anisotropy and how it can be controlled

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The magnetic properties of ferromagnetic epitaxial layers and nanostructures often deviate from that of their bulk counter parts [1, 2, 3]. A most intriguing aspect is the change of the easy magnetization direction away from that of the respective bulk sample [4, 5].

Experiments have revealed that this change of the easy magnetization direction can be induced and controlled by several processes. An adsorbate layer on top of a ferromagnetic film [6], lattice strain [4] and also a variation of temperature [7] have been found to drive a corresponding change of the magnetic anisotropy. Also, electron confinement, which gives rise to so-called quantum well states, has been proposed to change the magnetic anisotropy [8].

It is the goal of my lecture to elucidate the underlying physical principles of the resulting reorientation of the easy magnetization direction, which is often described by the term *spin-reorientation transition* (SRT). Based on experimental observations, the relevant principles regarding symmetry and magnetic anisotropy and the electronic origin of the magnetic anisotropy will be discussed [1]. We focus on the contribution of the spin-orbit interaction to the magnetic anisotropy, and mention only briefly the role of dipolar interactions.

We extend our discussion by addressing not only the change of the magnetic anisotropy as such, but we also comment on the implication for the magnetization reversal of nanostructures. We discuss our recent low temperature spin-polarized scanning tunnelling microscopy studies on nm small Co islands with some thousand atoms. These studies reveal high switching fields of order 1—2 T, and this implies a significantly enhanced magnetic anisotropy as compared to bulk Co [9].

Starting from the concise description of ferromagnetic properties by Kittel [10], the decisive expressions for a mathematical description of magnetic anisotropy in cubic and hexagonal systems will be introduced. The ideas will be extended to include the coupling between lattice strain and magnetic anisotropy, as given by the expressions of the magnetoelastic coupling.

Recent measurements on the magnetoelastic properties of epitaxially strained ferromagnetic layers will be presented to discuss the impact of the non-bulklike magnetoelastic properties on the magnetic anisotropy of epitaxially strained films. This aspect of the talk tackles the important issue of how the almost inevitable lattice strain of the nanostructure or ferromagnetic film couples to the magnetic anisotropy [4, 10]. The experimental results are discussed in view of recent theoretical work on the magnetic anisotropy and its strain dependence. The agreement between experiment and theory is even today still surprisingly poor when it comes to magnetoelastic effects. Thus more work on an admittedly experimentally and theoretically demanding topic is called for [11].

We extend the discussion of magnetic anisotropy to systems, where a SRT can be triggered by modifying the surface and / or thickness of a ferromagnetic layer. The film thickness dependence of a SRT will be discussed in view of combined magnetic and stress and structural investigations [12]. These studies show that the variation of film strain with film thickness is of utmost importance to characterize a thickness-driven SRT properly. The change of strain with film thickness is accessible by stress measurements with sub-monolayer sensitivity [3, 4, 13], and the crucial difference between pseudomorphic and non-pseudomorphic growth in view of the epitaxial lattice misfit strain will be elucidated.
For films of a fixed thickness of several monolayers, we present examples which demonstrate that both interfaces and surfaces influence the resulting magnetic anisotropy. Combined magnetic and highly accurate structural investigations by surface sensitive diffraction techniques will be presented which identify that a structural relaxation at an interface, and its change upon adsorbate coverage, may play a crucial role for the corresponding adsorbate-induced SRT [6]. These studies identify that not only the lack of bonding partners at a surface, but also the corresponding structural relaxation is a decisive aspect for the understanding of the role of interfaces for the magnetic anisotropy. The link between strain-induced lattice distortion, layer-wise structural relaxation and magnetic anisotropy will be elaborated in view of recent theoretical work.

A short excursion at the end of my lecture will address the aspect of switching the magnetization direction of a nanostructure, and how it is related to the magnetic anisotropy. The concepts of superparamagnetism and blocked magnetization will be introduced [14]. Experimental studies by in-field spin-polarized scanning tunneling microscopy of the magnetization reversal of individual Co nanoislands are presented [9], and the magnetic switching field is extracted as a function of temperature and island size. A simple magnetization reversal mechanism based on the coherent rotation of all spins [15, 16] does not give a favourable description of our data. Short comings of this model and a possible way towards an appropriate description of the magnetization reversal are discussed.

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