

# Chapter 1

## Introduction

Magnetism is the underlying effect of many technical achievements provided by science and industry during the last decades. In today's research focusing on nanotechnology and electronic data storage [1], interest in magnetism even increased, and future attempts in micro-design require a deeper knowledge of magnetic properties on the nanoscale.

In contrast to optical or acoustic phenomena, which in principle are accessible by human perception, magnetism cannot be directly sensed and its experimental investigation is restricted to indirect observation. This can be done by measuring the effect of magnetic order on other physical properties of a solid like electrical and thermal conductivity [2, 3], elasticity [4], heat capacity [5], sound attenuation [6] or lattice strains [7] – all these properties show anomalies at the magnetic phase transitions.

Another important access to magnetism is given by magneto-optical (MO) effects, which relate the optical properties and the magnetic state of a solid. In the visible light region MO effects are widely used to measure the average magnetization of thin samples (thickness  $\ll$  wavelength of the probing light) and therefore has become a standard tool in thin-film magnetism research [8]. Although MO effects in the visible-light region are quite small, refined optical methods not only yield sufficient contrast for distinguishing bits of opposite magnetization, but even allow one to observe details of magnetic domains in optical microscopes [8]. Most importantly, MO techniques are ideally suited for studying magnetization reversal processes in external magnetic fields, which is impossible with, e.g., electron microscopes involving slow cascade electrons that are strongly affected by the Lorentz force.

Besides all merits, conventional MO techniques lack element specificity, simply because electric dipole transitions in the visible-light region mainly take place between delocalized conduction-electron band states. This has become a severe limitation in analyzing compounds containing several magnetic elements, as required for information storage [1, 9] or permanent-magnet nanostructures [10]. In these advanced magnetic systems, lanthanide elements (mostly Tb) are used to achieve large perpendicular magnetic anisotropy [11], and large coercive fields [10].

Reliable element-specific information can be obtained by techniques that involve core-level transitions, e.g. by magnetic circular dichroism in x-ray absorption (XA) [12, 13]. In

the soft x-ray region, absorption signals are commonly detected by electron-yield methods [14], so that in general no large external magnetic fields can be applied, and hence only very few hysteresis loops have been recorded via electron yield. Alternative XA detection modes which do not employ electrons are either limited to specific samples that are suspended on transparent foils [13], or they suffer from saturation effects for all but highly diluted samples (fluorescence yield) [15]. Thus, to probe the field-induced magnetization reversal of a compound in an element-specific way, it is useful to employ x-rays in *reflection* like in conventional magnetooptics.

Resonant enhancement of x-ray scattering cross sections at inner-shell absorption thresholds [16,17] have been used for years to investigate the magnetic structure of lanthanide [18] and actinide [19] materials in the hard x-ray region (above 2 keV). The experimental demonstration of large changes in the specularly reflected x-ray intensity at the Fe  $L_{2,3}$  threshold [20] upon magnetization reversal initiated the ongoing search for magneto-optical (MO) effects in the *soft x-ray* region, [21–27] and for ways to apply them to element-specific studies of heteromagnetic systems [28–33].

Apart from their technological relevance in soft and hard magnetic films [10,11], lanthanide elements constitute a unique case in x-ray optics: the  $4d - 4f$  electric dipole transitions (the so-called giant resonances) are among the strongest in the periodic table [34]. They give rise to high absorptivity and reflectivity, corresponding to a very short x-ray absorption length which in the course of the present work were found to be comparable or even shorter than the lanthanide  $4d - 4f$  transition wavelength ( $l \approx 8$  nm). This unique situation is quite different from previously studied transition-metal (Fe, Co, ...)  $2p - 3d$  transitions [20,35], where the attenuation lengths are much longer than the wavelength, giving rise to complicated interferences when samples are structured on the nanometer scale [20].

Yet, in analyzing soft x-ray MO signals from thin films and multilayer systems with thicknesses comparable to the x-ray wavelength, previous investigations have shown [20,28,33] that a comparison with model calculations (based on the Fresnel equations) is needed [36] in order to extract layer-resolved sample magnetization profiles. Several experimental determinations of soft x-ray MO constants have been reported [23–25] for ferromagnetic transition metals in the region of the  $L_{2,3}$  thresholds, but none so far for the lanthanide elements.

The purpose of this thesis is to investigate MO effects of lanthanide elements in the soft-x-ray region. The results are compared with visible-light MO data in order to discuss their mutual compatibility. Special attention is paid to the element-specific behavior of heteromagnetic systems. The elements Gd and Tb are chosen as examples because of their similarity in lattice constants but widely different magnetic behavior.

The thesis is organized as follows: The first part is concerned with MOKE in the visible-light region and the description of the magnetic behavior of thin-film Gd and Tb metal. In particular, this part contains an introduction into the theoretical background including metal optics in the visible and soft x-ray region, a basic treatment of magnetooptics, and some general aspects of magnetism in lanthanides. A primer on magnetostriction is given in the second chapter. Details of the experiment [37] and the applied methods are presented

in chapter three. The fourth chapter discusses a comprehensive study of Tb and Gd films using visible-light MOKE, with particular emphasis on the dependence of the Tb film magnetization on sample preparation [38].

The second part of this work deals with MOKE in the soft-x-ray region, starting with magnetic soft-x-ray data of lanthanide elements at the  $N_{4,5}$  and  $M_{4,5}$  (XMOKE) thresholds presented in chapter five [39–41]. Special attention will be paid to hysteresis loops recorded at various photon energies, demonstrating the dependence of the reflected signal on light penetration depth and details of the magnetization reversal process. Calculations of the optical constants at the  $N_{4,5}$  and  $M_{4,5}$  thresholds of Gd give an insight into interference effects that appear in XMOKE signals from thin-film samples [42]. A critical comparison of XMOKE versus visible-light MOKE is presented in chapter six, followed by a conclusion with summary and outlook in chapter seven.

