Chapter 6

Discussion: XMOKE versus MOKE

MOKE is one of the traditional methods for the investigation of magnetism [93, 174]. The observed Kerr rotation contains contributions from all atomic layers within the absorption depth. When a light wave enters matter it is damped and shifted in phase, and a magneto-optical experiment usually is sensitive only to a certain phase for which the Kerr amplitude is allowed to interfere with the regularly reflected amplitude [93]. The penetration depth of visible light ($\lambda = 400..700$ nm) in metals is typically 20 nm, which – compared to the wave length – is relatively short and the observed Kerr rotations are small ($\sim 0.1°$). Under these conditions phase and amplitude of the complex Kerr rotation change only little within the absorption length (l_{abs}), and the contributions from each layer to the MO-signal are approximately equal [93].

On an absolute scale the absorption at the core level excitation thresholds $N_{4,5}$ and $M_{4,5}$ is huge ($l_{abs} \approx 3$ nm in the $4d \rightarrow 4f$ maximum of Gd). Compared to the wave length of the incident light ($\lambda \approx 7.9$ nm), the relative absorption length is much larger in the soft x-ray region ($l_{abs} \approx 0.6 \cdot \lambda$) as compared to the visible-light region ($l_{abs} \approx 0.03 \cdot \lambda$). Thus the Kerr rotation is strong compared to the wave damping inside the medium, and there are strong changes in phase and amplitude as the light enters the magnetic medium. In MO experiments one measures the Kerr rotation which fits to the phase of the experimental setup, and which gives the image of the magnetization at a certain depth inside the sample [93]. In XMOKE, in order to establish conditions comparable to the visible-light case, one can e.g. reduce the sample thickness. Thin systems are usually difficult to measure since there are only few absorbers giving only a small signal which sometimes is hard to detect. But working in the soft-x-ray region, one still finds a reasonable singal due to the strong absorption. MOKE in the soft-x-ray region is thus an appropriate method for the investigation of thin magnetic systems on the nanometer scale.

An example, which nicely characterizes the difference between MOKE and XMOKE, is shown in Fig. 6.1. The magnetic hysteresis loops of a Gd metal film recorded at $\lambda = 633$ nm and at $\lambda = 8.67$ nm ($h\nu = 143.1$ eV) have different shapes: XMOKE shows a higher "coercive" field and the hysteresis loop is asymmetric. The higher coercive field arises from the strong light absorption by the sample, whereas the asymmetry is due to interference effects of the Kerr contributions from different depths of the sample. Both

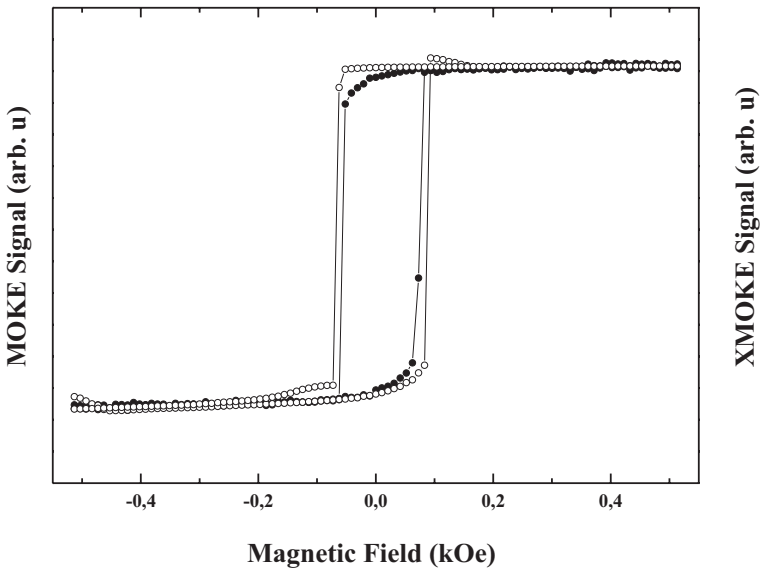

Figure 6.1. Magnetization versus field of an 8-nm-thick Gd film on W(110) at 20 K. (○) at $h\nu = 143.1$ eV ($\theta = 24°$) compared to (●) with laser light ($\lambda = 633$ nm, $\theta = 30°$). Both data sets are recorded from the same sample at the same temperature (~ 30 K).

effects are connected with the particular domain wall movement along the *c*-axis, which is characteristic for the system Gd/W(110), see section 5.2.1.

In the visible-light region, the reflectivity of a metallic sample is normally due to excitations of electrons in the conduction band. The associated electron states depend strongly on the overlap of the electron wave functions and are thus affected by thermal contraction: as a consequence, the MO-signal in the visible-light region should be temperature dependent, even if the magnetization does not change.

The lattice parameters of the crystalline sample and the magnetization are coupled by magnetostriction. Thus, the temperature-dependent lattice contraction, which influences the MOKE signal, reflects magnetostriction, however, in a rather complex way. Up to now magnetostriction has only been investigated by x-ray diffraction or stress measurements in thin samples ($\sim$ 0.2 mm) [175–177]. However, the thickness required for the latter, which reveals directly the magnetoelastic constants, is a severe limitation to the range of available substrates. Therefore reflectivity measurements of magnetostrictive effects, which are especially important in rare-earth materials (section 4.3), are an interesting approach for investigating samples grown on thick crystals.

Above the plasmon-frequency (~ 10 eV), the metal reflectivity decreases rapidely and at ~ 50 eV, the conduction band becomes transparent [75]. In the x-ray region, the reflectivity of the sample arises from transitions between localized core levels, i.e. no contributions from the conduction band will be involved. The atomic-like core levels have practically no overlap, and they are not affected by thermal contraction. Thus, the XMOKE signal will not be temperature dependent, and in the absence of optical effects, a measurement of the XMOKE signal for only one direction of magnetization will be sufficient to describe the

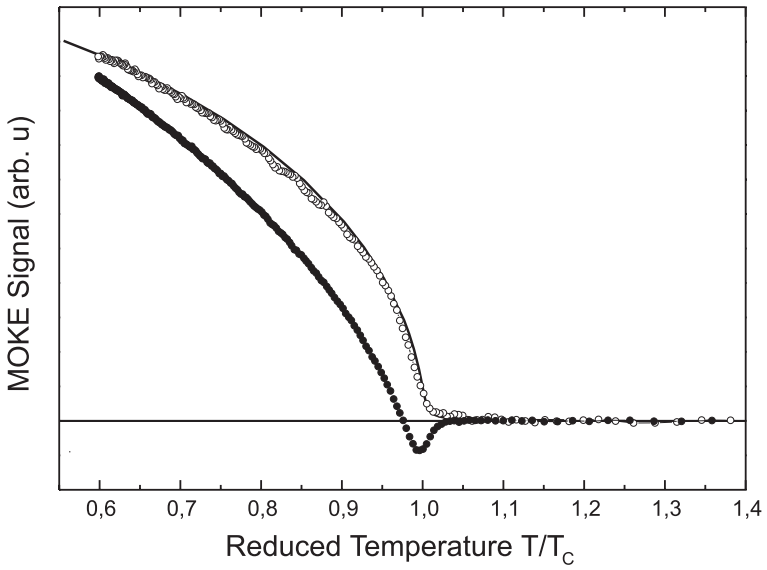

Figure 6.2. XMOKE at 136-eV photon energy: Temperature-dependent magnetization of 10-nm Gd/W(110) at $\theta = 10°$ (○) and $\theta = 30°$ (●), compared to the theoretically expected (mean-field) behavior for $J = 7/2$ (solid line).

behavior of the magnetization with temperature.

The energy of resonant absorption transitions depend on the core-level binding energies and are different for each element. In resonance, the absorption is strong; off-resonance it is weak. Tuning the photon energy to the resonance of one element in a system of several magnetic components, the MO signal (magnetic contrast) arises mainly (or even uniquely) from this particular element, depending on how well the transition energies are separated. In cases where the transition energies lie close together, a partial separation may only be obtained by choosing appropriate photoexcitation energies where the absorption by one of the elements is particularly strong. Elements of sufficiently separated absorption thresholds permit element-specific studies of alloys and – to some extent – also of multilayer systems (section 5.1)

The transparency of a sample in the x-ray region can change substantially upon magnetization reversal. The substrate is visible (or invisible) depending on the magnetization of the film, i.e. the degree of interference with the substrate changes with the film magnetization. Similar effects may come up when changing the angle of incidence, i.e. the length of the optical path through the sample to the substrate. The substrate is seen only for steep angles but it becomes invisible for shallow angles. As an example, the temperature-dependent magnetization recorded with XMOKE at a fixed energy ($h\nu = 136$ eV) and different angles (variation of the penetration depth) is shown in Fig 6.2. At small angles (10°), the signal shows a behavior comparable to the mean-field model (for $J = 7/2$), which is known to describe the magnetization curve of Gd quite well [153]. At larger angles (30°) the effective light-penetration depth is almost tripled, and the signal is obviously affected by interference effects (see dip around T_C in Fig. 6.2).

In summary, the observed results show that XMOKE spectra may suffer from difficulties that occur when the wave length approaches the characteristic dimensions of the film thickness. Yet, when wave length and absorption length are both much larger than the sample thickness ($\lambda >> d$, $l_{abs} >> d$), the phase of the light wave can be assumed to be constant over the sample thickness and no magnetization-depending interference occurs; in this limiting case the XMOKE signal is proportional to the average magnetization of the sample.