Angle and Temperature Dependence of Magnetic Circular Dichroism in Core-Level Photoemission from Gd(0001)

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INTRODUCTION

Magnetic dichroism in core-level photoelectron emission from solids represents a promising new element-specific probe of surface and interface atomic structure and magnetic order. One way of measuring such effects is by using photoelectrons excited by circular polarized radiation, thus leading to magnetic circular dichroism (MCD) if the intensity with right-circular polarized (RCP) light is not equal to that with left-circular polarized (LCP) light. The spin-integrated photoelectron intensity in a certain emission direction also in general depends on the direction of the magnetization in a magnetic material. In fact, if the magnetization lies in a surface mirror plane, then inverting its direction can provide a second way of measuring MCD. Purely atomic theoretical models have been successful in explaining many aspects of such data [1]. By varying the emission direction one also probes the geometric structure of the sample. But such MCD in photoelectron angular distributions (MCDAD) then has to be interpreted also in terms of photoelectron diffraction. Measuring the temperature dependence of such MCD effects also provides a useful tool for studying magnetic transition temperatures. We have here studied such effects in core-level emission from Gd(0001).

EXPERIMENT

The experiments have been performed on beamline 9.3.2 [2a] using the advanced photoelectron spectroscopy/diffraction endstation [2b]. Photoelectron spectra were measured with a Scienta-200 electron analyzer, and with an overall photon-plus-analyzer energy resolution of about 1 eV. All spectra shown have been taken at a photon energy of about 450 eV yielding Gd 4d photoelectron energies of about 290-298 eV. The helicity of the photons can be chosen by moving an aperture above or below the plane of the storage ring, with the degree of circular polarization being about 80-85% [2a]. In the experiments presented here, we have largely used LCP light, but spot checks were also made to see if inverting magnetization in a mirror plane yielded the same effects as switching to RCP light.

The samples used were atomically thick films of Gd evaporated at room temperature onto a clean W(110) substrate. The thickness of the Gd films was chosen to be 100ML (≅300Å), as monitored by a quartz crystal microbalance, with final annealing at 700 K to insure monatomically flat surfaces. The cleanliness and crystalline order of the substrate and the final films were checked by x-ray photoelectron spectroscopy (XPS) and low energy electron diffraction (LEED), respectively. The Gd films have been studied with remanent in-plane magnetization, as induced by an in-situ magnetic field of about 200 G lying along a high-symmetry direction containing a mirror-plane of the crystal. During photoemission measurements, the light impinged on the sample at an angle of 20° relative to the surface. Photoelectrons were collected either in normal emission or in emission at 20° with respect to the surface normal, and the sample was rotated stepwise about its surface normal so as to vary the azimuthal emission angle. The geometry is shown as an inset in Figure 1; the photon incidence direction **q**, the surface normal **n**, and the photoelectron wave vector **k** all lie in a plane. The MCD measurements were performed by inverting the magnetization direction; this was done simply by rotating the sample by 180° around the surface normal. The angle varied in the angle-dependent spectra shown below (Φ_M) is thus also the angle between the magnetization directions and the plane defined by **q**, **n**, and **k**.

RESULTS

Figure 1 shows an example of Gd 4d core-level spectra taken with the two different orientations of the magnetization axis (here denoted as parallel (p) and anti-parallel (a)). Also shown is a normalized MCD difference or asymmetry curve obtained from these two spectra. This asymmetry curve agrees very well with a free-atom theoretical description by van der Laan et al. [1], although the present data better resolve the individual final states of the Gd^+ ion than the experimental results presented in this prior study. As an overall measure of the MCD effect, we

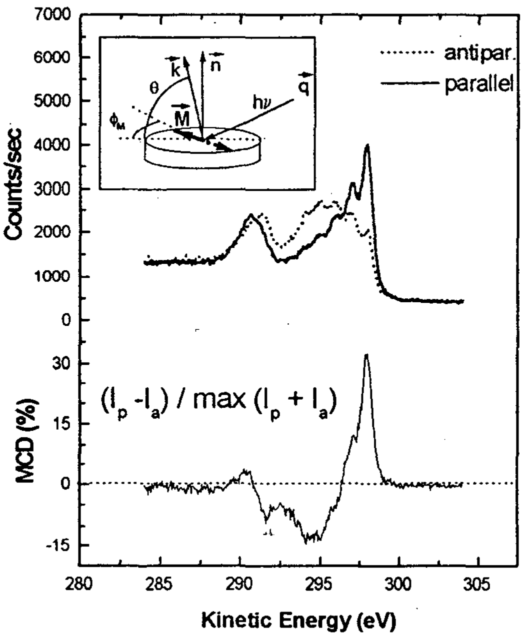

Fig.1: Gd 4d core-level photoemission spectra taken at a photon energy of 450 eV using left circular polarized light. The solid line spectrum was taken with the sample magnetization parallel to the azimuth of the light indicence direction (Φ_M=0°), and the dotted line spectrum with an antiparallel arrangement (Φ_M = 180°). The lower curve is the normalized difference or MCD asymmetry. The inset shows the experimental geometry.

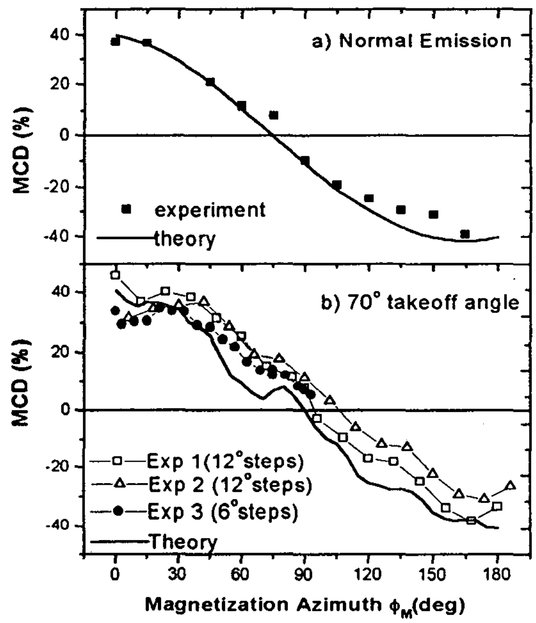

Fig.2: Angle dependence of the overall MCD effect for Gd 4d core-level emission. (a) Normal emission, (b) Electron takeoff angle = 70° (20° from normal). In both cases the solid lines show theoretical curves calculated for the respective cases. In (a) the calculation is for a free atom, in (b) it is for emission from an atomic cluster three layers thick in order to account for photoelectron diffraction effects.

have taken the difference between the maximum and minimum values of MCD curves such as that in the bottom panel of Fig. 1. For normal emission , Fig. 2(a) shows this overall MCD as a function of Φ_M. The same quantity for emission at 20° off normal is shown in Fig. 2(b).

The data in Fig. 2(a) basically exhibit a cosine-like behavior which would be expected from the free atom case, and there is excellent agreement with calculations based on such a free-atom model. However, the MCD behavior in Fig. 2(b) shows noticeable deviations from free-atom behavior, and this is reproducible over three different samples studied. The additional MCD modulations riding on the overall cosine-like curve are due to photoelectron diffraction. In order to learn more about the scattering processes involved, we have performed simulations using single-scattering and multiple scattering cluster calculations and including spin-orbit splitting and exchange splitting in the initial state [3]. The results of these calculations are shown in Fig. 2(b) as a dotted line. The theory well reproduces the additional modulations found in the experiment and clearly identifies them as diffraction features.

Turning now to the temperature dependent data, we note that the Curie temperature for bulk Gd material is about 293K. Thus, our samples were initially cooled to approximately 260K and then heated up to about 340 K in order to determine the manner in which the magnetic order disappears. Some preliminary results are shown in Fig. 3, where we plot the overall MCD asymmetry as a function of temperature for two runs on different samples. As temperature is increased, one clearly observes the decrease of the MCD signal to a negligibly small value when T_C has been exceeded, with the second run having a slightly higher transition temperature by about 10K. Shown also in Fig. 3 are magneto-optical Kerr effect (MOKE) measurements for two different annealing temperatures in preparing the Gd that span our choice of 700K [4]; these confirm the transition temperature seen in our first run, which is essentially the bulk value. Since MOKE penetrates a number of atomic layers into the sample, it is not surprising that it yields a bulk transition temperature for such a thick film. However, photoemission is a surface sensitive probe, so we might also expect to detect a surface-specific transition temperature, if it is in fact higher than that of the bulk by 20-60K, as has been proposed previously [5]. There may be some indication of this in the data for our second MCD run, which in fact had a cleaner surface, but further measurements will be necessary to confirm this suggestion.

CONCLUSIONS

For thick Gd(0001) films grown on W(110), we have obtained angle-dependent magnetic circular dichroism (MCD) data which vary by as much as ±35%. These data also reveal modulations of ~ ±5% which are verified as due to photoelectron diffraction effects by comparison with diffraction calculations. Additionally, we have measured the temperature dependence of the MCD amplitude. This clearly shows the bulk Curie temperature, and perhaps an indication of a higher surface Curie temperature. More investigations of these issues, from both experimental and theoretical viewpoints, are underway.

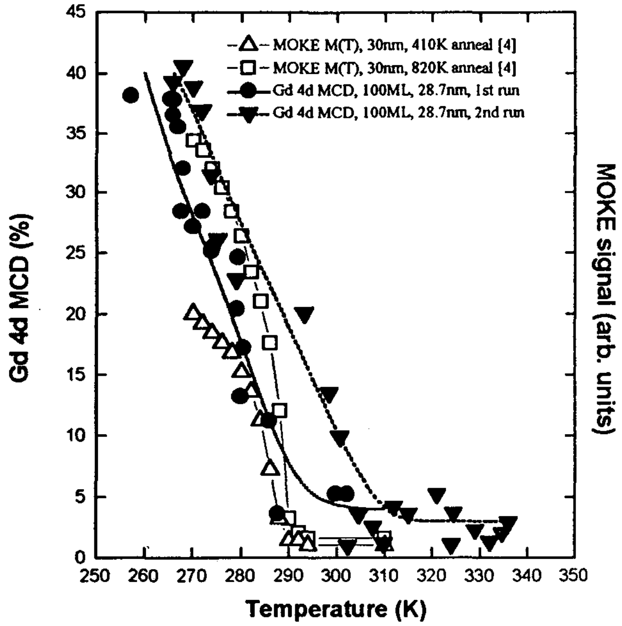

Fig.3: Temperature dependence of the MCD asymmetry for a takeoff angle of 70°. Shown are two different experimental MCD runs and MOKE measurements for comparison [4]. The sample surface in the first run was slightly contaminated, and shows a lower transition temperature by about 10K.

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