Interface and magnetic characterization of ultrathin EuO films with XMCD

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We present work done on EuO films with thicknesses varying from 10 to 60 Å grown as a stepped wedge on Si/Cr(20 Å)/Cu(90 Å) and capped with Y(20 Å)/Al(80 Å). The films were characterized by x-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD) at the europium M_5 and copper L_3 edges. The films' high quality and consistent magnetic properties were confirmed by SQUID magnetometry, which revealed a constant saturation moment independent of film thickness. XAS at the Cu L_3 edge showed that the bottom Cu electrode is metallic (oxidation free). We report an XMCD intensity of 52% (±4.3), in close agreement with theoretical calculations.
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I. INTRODUCTION

In spin filtering tunneling junctions, the ferromagnetic barrier, sandwiched between two nonmagnetic electrodes, plays a critical role. With its simple FCC rock-salt structure, the ferromagnetic insulator EuO is a very attractive candidate for spin-filtering tunnel junctions.[1] It has high T_C (69 K) which can be raised to 150 K by doping.[2,3] Moreover, EuO can be used as a model system to examine other spin-filter tunnel junctions.[1] Since the tunneling current depends exponentially on the thickness of the barrier, thinner barriers are essential components of the structure. However, reducing the thickness of the barrier also decreases the magnetic properties essential to the spin filtering process.[4]

In this paper we report successful fabrication of ultrathin EuO films with an average XMCD values of 52%. We utilized x-ray characterization techniques and SQUID magnetometry to validate the quality of the samples and examine the magnetic properties of the EuO films.

II. EXPERIMENTAL

The 10–60 Å thick EuO films used in this study were grown using thermal reactive evaporation where pure Eu is deposited in the presence of molecular oxygen. The basic structure of the samples is Cr/Cu/EuO/Y. The samples were deposited on HF etched Si substrate and then capped with Al protective layer.[5] The bottom electrode, a lattice matching 90 Å thick Cu layer, promotes proper growth of EuO. The 20 Å Cr seed-layer is essential for the deposition of uniform Cu layer.

For interface uniformity, wedge samples where the thickness of the EuO film was varied such that it formed a stair-step structure substantially reduced the sample-to-sample variation inherent in samples grown in different sessions. This approach provides further control over the interfaces between the electrodes and the tunneling barrier.

X-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD) were acquired in the sample current mode at beamline 4.0.2 of the Advanced Light Source. The XMCD measurements were performed with an angle of incidence of 60 degrees at 18 K with 90% circular polarized light in the presence of a 0.5 T magnetic field applied parallel to the photon propagation direction. These techniques are element specific, allowing the oxidation state of both the bottom Cu electrode and the intervening EuO layer to be determined independently.

The use of a Cr/Cu buffer layer underneath the EuO barrier resulted in considerable improvement in the magnetic properties of the EuO films. Even though, the choice of other metals simplifies the growth process substantially, determining the degree of polarization of the tunneling current through the structure becomes a challenge. Santos et al.[6] developed an indirect approach for determining the polarization of the tunneling current from transport measurements.

III. RESULTS AND DISCUSSION

Figure 1 shows a typical XMCD spectra for 20 Å EuO film. The XMCD spectrum (panel c), which provides the magnetic sensitivity, is the difference between the aligned (solid line) and anti-aligned XAS spectra. From the XAS spectra (panel b), we can fingerprint the available oxides of europium by comparing the measured spectra to the references shown in Fig. 1 (panel a).

XAS measurements done on the Cu $L_{2,3}$ edges (not shown), when compared to a reference spectra of pure metallic Cu,[7] show no obvious difference. Any CuO present is therefore below our detection limit of a few percent. This indicates that the bottom electrode is metallic and no copper oxide layer is present between the metallic electrode and the EuO.

The measured XMCD values extracted from the actual spectra are shown in Table I (forth column). When reporting, however, the effect of experimental conditions

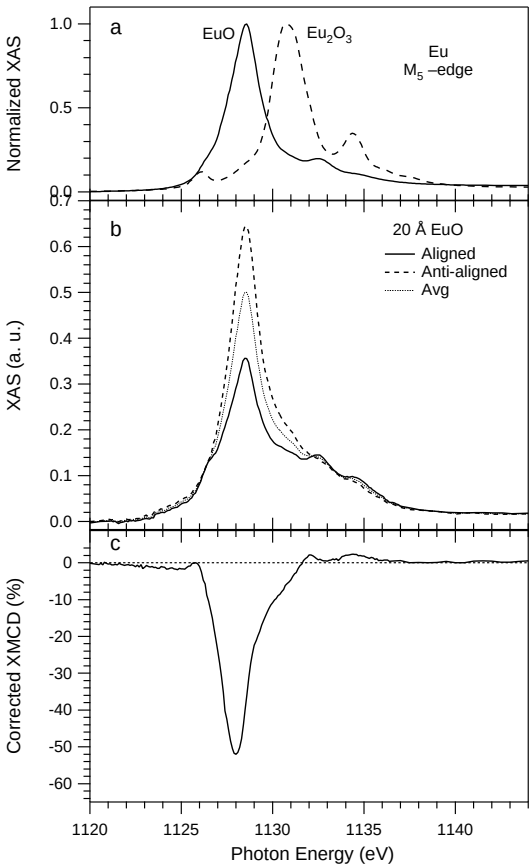

FIG. 1: (Panel a) Reference XAS spectra for the two common oxides of europium used to identify the relative presence of the two oxides. (Panel b) X-ray absorption spectra for a 20 Å EuO sample grown Si in the anti-aligned (solid) and aligned (dashed) configurations at the M_5 edge ($3d_{5/2}$). (Panel c) The corrected XMCD signal at 18 K (corrections described in text).

must be taken into account. The standard experimental procedure in XMCD experiments used to account for incomplete polarization and angle of incidence is to divide the measured value (shown in column 4 of Table I) by the product of degree of polarization P and sine of the incidence angle (1/P*sin θ_{inc}).[8,9]

Thickness	EuO Fraction (%)	Moment Correction	XMCD (%) Raw	XMCD (%) Corrected
10 Å	.93	.76	27.3	54.5
20 Å	.87	.89	29.1	52.7
30 Å	.89	.95	34.7	57.5
40 Å	.90	.95	33.5	54.8
50 Å	.91	1.00	30.2	46.7
60 Å	.90	1.00	30.5	47.6

TABLE I: Correction factors used to determine the XMCD value for different thicknesses of the EuO stair-step sample. Details of the analysis are described in the text.

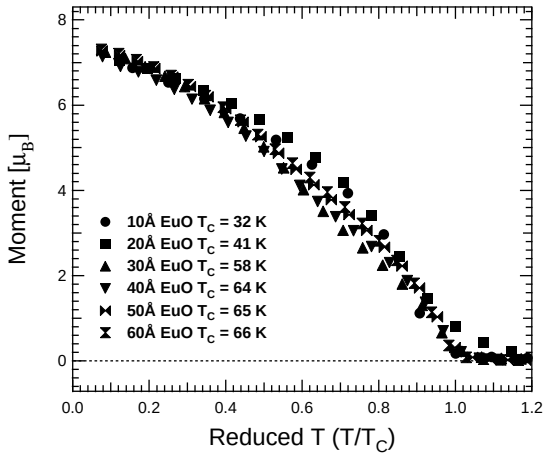

FIG. 2: Moment of different thicknesses of EuO films from 10–60 Å measured by SQUID magnetometry plotted against reduced temperature. The curves for all thicknesses follow the same trend indicating the quality and consistent magnetic property of the individual EuO films.

When comparing experimental XMCD values to theoretically calculated XMCD values, additional factors need to be taken into account. In this case, the measured XMCD intensity must be corrected for the presence of nonmagnetic phase and for the reduced moment from the finite temperature where the measurement was done. The presence of non-ferromagnetic Eu_2O_3 reduces the observed XMCD of that element proportionally by the amount of non-ferromagnetic phase. This is one of the attractive features of an XMCD measurement, the XMCD signal comes only from the element in the ferromagnetic phase. The non-ferromagnetic phase does not distort the XMCD spectrum, it only reduces its intensity by a dilution effect. This can be account for by dividing the measured spectra by the atomic percentage of the element in the ferromagnetic phase (see Table I, second column).

The XMCD signal is directly proportional to the moment of the sample. These measurements were done in an applied field but at a finite temperature. At that temperature, the magnetization of the EuO films is smaller than the zero temperature magnetization which in turn reduces the measured XMCD. The XMCD values can be adjusted for the impact of reduced magnetization by dividing the measured XMCD signal by the degree of magnetization of the sample (see Table I, third column). The degree of magnetization is determined from temperature dependent SQUID magnetometry measurements (shown in Fig. 2) by dividing the measured moment at 18 K for a given film thickness by the moment of the extrapolated saturation moment (M_{SAT}) at 0 K. Figure 2 displays the normalized moment as a function of reduced temperature to highlight the high quality of the wedge structure and to demonstrate that the moment reduction is exclusively due to a thickness dependent variation in the curie tem-

perature. The moments are all normalized to the 60 Å film value at low T.

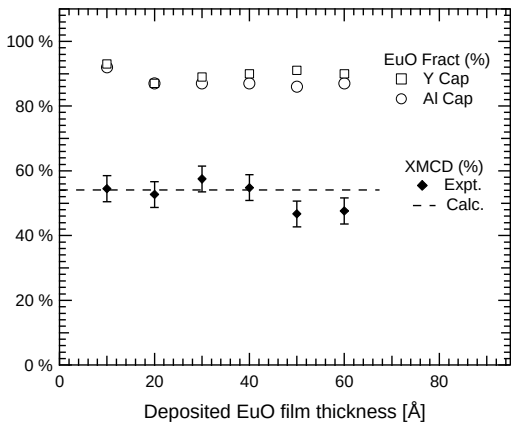

FIG. 3: Fraction of EuO for the Al capped (open circle) and Y capped (open square) and the corrected XMCD intensity for yttrium capped EuO wedge. The measured XMCD, averaging at 52.3 (±4.2)%, is in close agreement with theoretically expected value (shown by the dashed line) for ultrathin EuO films.

The XMCD values obtained after these adjustments are shown in Table I (Corrected). These values are in good agreement with the theoretical value of the XMCD[10] and are graphically reproduced in Fig. 3. Ott et al.[3] reported a corrected XMCD value of 11% for 600 Å undoped EuO film sample. Similarly, Holroyd et al.[11] reported XMCD signal of 28% for a 50 Å thick EuO film after correction of incomplete polarization and incidence angle. Neither included corrections for finite temperature moment reduction. It is hard to determine the T_C correction value because the measurement were reported to be performed near 30K. For comparison purposes, the same procedures for finite temperature correction used in this work can be applied to these earlier measurements and we would extract a value of 33% and 42%, respectively. Still, the XMCD value shown in Fig. 3 are higher.

The fact that the XMCD values of these materials remains constant (after correction) further demonstrates that the quality of these films can be maintained to these low thickness values. In spin-filter tunnel junctions, it has been shown that the T_C decreases when thickness of the ferromagnetic barrier is reduced.[4] Using thinner tunneling barriers, while desirable to decrease the resistance across the junction, it leads to decreased T_C and decreased exchange splitting (ΔE_{ex}) which are essential parameters for spin filtering.[4] However, as recently shown by Santos et al. even at such thicknesses (25 Å EuO film), the exchange splitting is sufficient and near 100% spin-polarized tunneling current was observed.[6]

IV. CONCLUSION

By using element specific x-ray techniques and appropriate structures, we examined the magnetic properties of the ultrathin EuO films. Magnetometry measurements show a normalized saturation moment close to bulk value for all film thicknesses. The XMCD measurements confirm this. Furthermore, the EuO films exhibit excellent stoichiometry (90% EuO) resulting in excellent magnetic properties. The average XMCD value of 52% we observed is considerably higher that previous reported values for bulk or thin EuO film.[3,11]

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