XRES from an $Er_{0.8}Tb_{0.2}$ Thin Film

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Introduction

The magnetism of nanostructured materials fascinates scientists because of its relevance to understanding the influence of surfaces, interfaces, and electronic confinement. Applications of these materials in electronic devices open revolutionary windows because of the spin nature of their electrons.

Artificial superlattices containing rare-earth materials exhibit a variety of astonishing magnetic phenomena [1 and references therein]. Most noteworthy is the effect of interlayer exchange coupling (i.e., the formation of a coherent magnetic structure), even though nonmagnetic spacer layers separate the magnetic layers. Introducing spacer layers with a different magnetic structure leads to even more complex phases [2].

The ground state of the pure elements is mainly determined by the subtle balance among the RKKY interaction, crystal field anisotropy, and magnetoelastic energy [3]. In a superlattice containing Er and Tb, the anisotropies are fairly different. Bulk Tb exhibits two ordered magnetic phases. For both ordered states, the magnetic moments are aligned within the basal plane of the hexagonal lattice because of the strong crystal field anisotropy. The helix phase is stable between 230 and 220K. Below 220K, the magnetic structure is simply ferromagnetic. Er, in contrast, shows a series of different ordered phases below 81K, with a preferred orientation along the c-direction. At temperatures below 20K, the c-axis component becomes ferromagnetic, while the basal plane component remains in a modulated structure.

The pure materials show strong magnetostriction when they become ferromagnetic, exemplifying the influence of the magnetoelastic energy. It is evident that the epitaxial strains in a superlattice affect the magnetic structure. In a superlattice containing Er and Tb, magnetic proximity effects and the competing anisotropies affect the magnetic ground state. In our work, we are investigating the magnetic structure of a series of [Er|Tb] superlattices with different compositions in order to systematically study the influence of the different contributions. Part of the study is a comparison with a thin alloyed film. The objective is to compare the effect of statistical site occupation to the artificial superstructure.

Methods and Materials

The thin film was grown by molecular beam epitaxy (MBE) on a sapphire substrate. The recipe given in Ref. 1 was followed to evaporate a 250-Å of Nb buffer onto the substrate. The alloy was deposited by co-evaporation of Er and Tb, and the substrate temperature was held at 580°C to ensure the mixing of the Er and Tb. In addition, the sample was annealed for 20 minutes at 700°C. The total thickness of the film was 6000 Å. Finally, to protect the sample against oxidation, a 250-Å Y cap layer was evaporated.

Preliminary neutron scattering experiments revealed three magnetic phases (Fig. 1). Below 112K, magnetic moments align in a helix (H). At lower temperatures, the c-axis component also adopts a modulated magnetic order, referred to as tilted helix (TH). At 34K, the c-axis component becomes ferromagnetic, forming the cone phase, as known from bulk Er.

To study the magnetic behavior of the film specific elements, we measured the x-ray resonant exchange scattering (XRES) from the specimen. When the energy of the incoming photons was tuned to the absorption edge of the elements, the resonant enhancement of the magnetic scattering provided information about the magnetic state of the respective material only. The

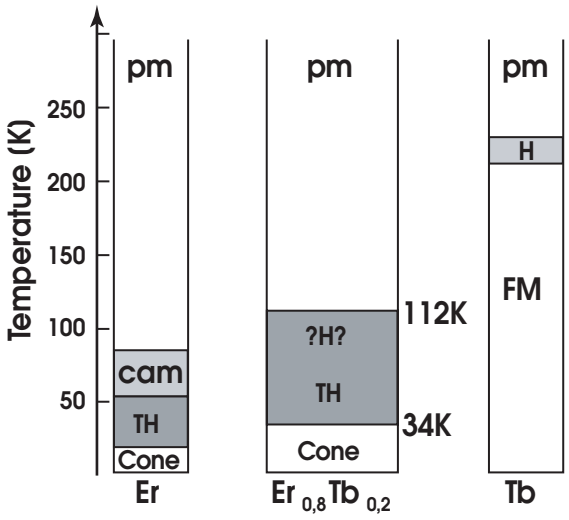

FIG. 1. Schematic phase diagram for the pure elements and the $Er_{0.8}Tb_{0.2}$ alloy thin film as deduced by neutron scattering. (Abbreviations are described in the text.)

sample was mounted to a closed-cycle cryostat. The sample temperature could be varied between 6 and 300K at an accuracy of better than 1K. A vertical scattering geometry was chosen. In order to suppress the dominant charge scattering, the polarization of the scattered photons was analyzed. We chose a vertical scattering geometry to analyze the polarization in σ-π' geometry (i.e., we measured the component of the scattered light that was rotated by the resonant magnetic scattering process). In contrast, charge scattering left the polarization state unchanged. The charge scattering was suppressed by 95% at the Er L_{III} edge and by more than 99% at the Tb L_{III} edge. The high efficiency at the Tb edge could be achieved by using an Al(222) crystal. At the Er edge, we employed a pyrolitic graphite crystal using the (0006) reflection.

Results

We measured the reflection (0002 – τ^*) due to magnetic modulation as a function of temperature and incoming photon energy. The propagation vector τ^* was calculated from the reflex position with respect to the position of the central Bragg reflection, deduced from longitudinal scans in reciprocal space along the (000Q_z) direction. The temperature dependence implies an incommensurate magnetic structure for all temperatures, which contrasts with the observation of lock-in transition in pure erbium (in bulk [4], thin films [5], and bulk alloys [6]).

The integrated intensities have been measured performing rocking scans across the reflections. The magnetic reflections are very intense; the counting rate for the different energies varies between 20,000 and 50,000 counts per second. The temperature dependence of the correlation length is deduced from the width of the magnetic reflections. The lateral correlation length ζ_{xy} is deduced from the width of the rocking scans. For the given scattering geometry, the angle can be transformed into a reciprocal space coordinate. Between 23 and 60K, the correlation length decreases. For the same temperatures, the integrated intensity exhibits two kinks (Fig. 2).

The phase transition to the cone structure cannot be identified easily by the magnetic scattering data. However, the c-axis lattice constant changes drastically at a temperature of 34K (Fig. 3), which is the Curie temperature as determined by neutron diffraction. Since the magneto-elastic energy drives the ferromagnetic phase transition [3], this identifies the phase transition.

XRES is not a direct measure of the magnetic moment. Instead, it probes the density of states above the Fermi level, which is exchange-split for magnetically ordered materials and leads to a polarization of the electrons. The strength depends on matrix elements for virtual transitions from electronic

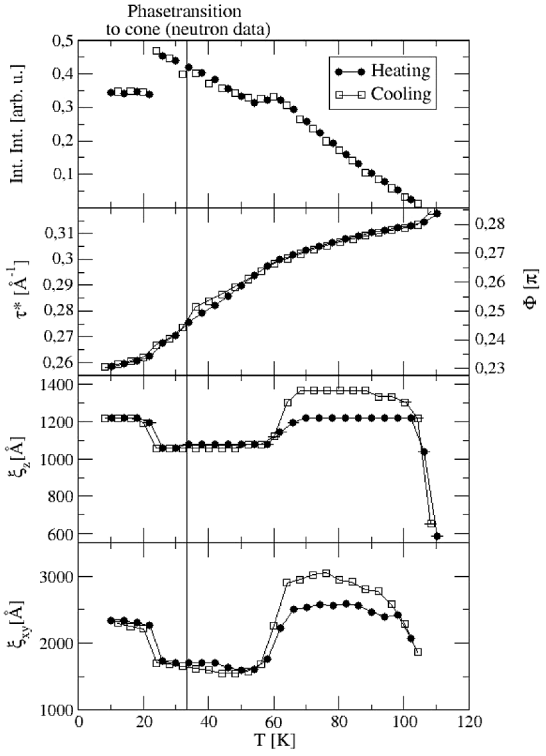

FIG. 2. Temperature dependence of the (0002 – τ^*) reflection. The energy E = 7.518 keV (Tb L_{III}). The correlation lengths were deduced from the width of the longitudinal scans (ζ_z) and from the width of the rocking curves. Since the rocking curve is approximately a linear scan in reciprocal space perpendicular to (000Q_z), the angles were transformed to reciprocal lattice coordinates to determine ζ_{xy}.

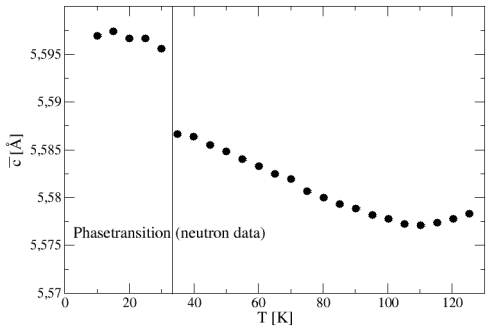

FIG. 3. Lattice parameter as a function of temperature. The lattice parameter is deduced from the position of the (0004) reflection after the scale has been fixed by measuring the (0002) and the (0004) reflection at room temperature.

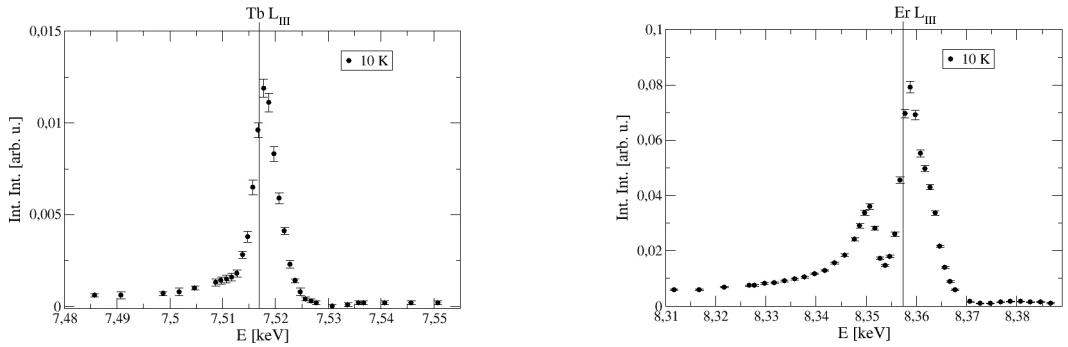

FIG. 4. Energy dependence of the (0002 – τ^*) reflection close to the Tb L_{III} and the Er L_{III} absorption edge at 10K. The inflection point of the fluorescence defines the absorption edge.

core states into these unoccupied states. Since the band polarization due to the modulation of the basal plane component persists to the lowest temperatures, a possible change of the matrix elements defining the strength of the resonance may account for the observed effects.

The energy dependence of the (0002 - τ^*) reflection is shown in Fig. 4. The maximum resonance enhancement is slightly above the absorption edge, whose position is defined by the inflection point of the fluorescence yield measured for this particular sample. This points to the fact that the core electrons are excited mainly by the dipolar transition into the 5d conduction band, as is known for bulk Er and Tb [7, 8]. At the Er edge, the weaker peak below the edge could be related to a quadrupolar transition probing the 4f states.

Discussion

The magnetic properties of Er_xTb_{1-x} alloys as bulk material were studied in 1971 [6]. The phase sequence is identical to that shown by the data for the thin film. The phase transition temperatures are slightly reduced for the thin film, particularly for the transition to the cone state. The reduction of the Curie temperature might be due to epitaxial strains, which change the magnetoelastic energy. It is this energy contribution that is the driving force of the ferromagnetic phase transition. The effect occurs also in superlattices containing nonmagnetic yttrium, which has a larger lattice constant than the heavy rare-earth metals [3].

The XRES experiment measures the polarization of the conduction band electrons. The high intensities allow for a detailed study in a relatively short time. The propagation vector of the spin density wave in the thin film is smaller than it is in pure erbium, but clearly larger than it is in bulk alloy of the same composition [6]. The temperature dependence of the intensity in the XRES experiment and the lack of commensurate magnetic structures are not yet understood.

Acknowledgments

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