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To cite this version:
J. Borchers, G. Nieuwenhuys, M. Salamon, C. Flynn, R. Du, et al.. MAGNETIC STRUCTURE AND MAGNETOSTRICITION OF EPITAXIAL Er FILMS. Journal de Physique Colloques, 1988, 49 (C8), pp.C8-1685-C8-1686. 10.1051/jphyscol:19888764 . jpa-00229008

HAL Id: jpa-00229008
https://hal.science/jpa-00229008
Submitted on 4 Feb 2008

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MAGNETIC STRUCTURE AND MAGNETOSTRICTION OF EPITAXIAL Er FILMS

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Abstract. — The magnetism of epitaxial Er films up to 1 μm thick differs from bulk Er in that no ferromagnetic transition is observed. Above a critical field that depends on temperature and film thickness the magnetization saturates at the bulk value. Both neutron scattering and magnetization data show lock-in transitions, but at lower temperatures than in the bulk.

We have demonstrated in recent years [1] and in a paper on Er/Y at this conference [2], that rare-earth multilayers, grown with crystalline perfection by molecular-beam epitaxy, have properties distinctly different from the bulk elements. Here we show that many of the property changes are consequences of the epitaxy itself, rather than of the multilayer structure.

Er films of various thicknesses were grown epitaxially by first growing a layer of (110) Nb on sapphire, then a 300 Å film of (0001) Y, and finally Er films ranging in thickness from 400 Å to 9500 Å. All of the samples show excellent crystalline Bragg peaks, with c- and a-axis lattice parameters within 0.6 % of those of bulk Er. Nonetheless, even the thickest films are magnetically distinct from the bulk. The Er samples are not lattice matched to Y (2 % difference). Dislocations formed during film growth permit the samples to relax toward bulk lattice parameters. However, the films remain clamped to the substrate, as a result of which no magnetoelastic deformation is possible in the growth plane without irreversible damage to the sample.

Bulk Er orders in a sinusoidal c-axis modulated (CAM) structure at 89 K, with a phase advance of approximately 52.5° per Er plane. Below 50 K, a basal plane spiral appears, the c-axis modulation becomes more square-wave-like and the CAM and spiral undergo a series of phase transition to unique lock-in states [3]. The lines in figure 1 indicate the phase advance per Er layer for the lock-in states, with the x's indicating the temperatures at which they first appear on cooling (nomenclature of Ref. [3]). At 20 K, the c-component of the magnetization becomes ferromagnetic, while the spiral remains.

While some features of bulk Er are observed in epitaxial Er films, there are significant differences. Most notably, no c-axis ferromagnetic phase is observed to the lowest temperatures studied (4.2 K). The results of a neutron scattering study of the CAM structure in two representative thin films of 1750 Å (circles) and 9500 Å (triangles) are shown in figure 1. Both samples show a variation of wave vector with temperature, and each seems to pass through several of the lock-in states of bulk Er. However, the CAM structure persists below 10 K in each case. Each lock-in state appears at a lower temperature in the thin films than in the bulk and, further, the films fail to follow the entire sequence of lock-in states observed in the bulk.

The presence of lock-in transitions is also evident in magnetization data. In figures 2a and 2b, we show, respectively, the magnetization of a 1750-Å and a 9500-Å film, each cooled in a field of 2 kOe. Both films show a small maximum at TN = 85 K, indicating the onset of the CAM phase, followed by oscillations in magnetization. The saturation magnetization of both samples is 230 ± 10 emu/g, comparable to that of bulk Er, and appears abruptly above a temperature-dependent critical field. The number, amplitude, and position in temperature of the oscillations depend sensitively on film thickness and growth conditions. A 4000 Å film grown under slightly different conditions (and with an a-axis lattice parameter identical to bulk Er) shows only a smooth increase in magnetization under the same measurement conditions.

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Neutron scattering data were taken on the 9500 Å film in a 2 kOe field at temperatures corresponding to the extrema in figure 2b. The minima at 10 K and 32 K are consistent with the 1/2 and 3/11 lock-in states, while the maximum at 20 K has a phase advance close to the 5/10 state. The observed phase advances appear to be systematically 0.3° larger than those of the lock-in states reported by Gibbs et al. The maximum in magnetization observed at 38 K is puzzling. It corresponds to a phase advance of 50.5°, which is not one of the expected lock-in states. What is more, this state appears to be particularly stable in an applied field. At 30 K, the structure changes from the 48.4°-phase advance to the 50.5° advance at an applied field near 10 kOe; at still higher applied fields (> 35 kOe), the CAM structure is destroyed and the full bulk magnetic moment is observed.

The so-called antiferromagnetic next nearest neighbour Ising (ANNNI) model was explicitly invented to explain the behaviour of Er. More recently, the model has extended to include a magnetic field [4]. The already rich phase structure of the ANNNI model becomes even more complicated in the presence of a field. We have considered a simple model of Ising spins on a cubic lattice with ferromagnetic coupling \( J_0 \) between neighboring spins on a horizontal plane, \( J_1 \), between neighboring spins on successive planes, and an antiferromagnetic interaction \( J_2 \), between spins on next-neighbour planes. The ratio \( p = -J_2/J_1 \) controls the magnetic phase diagram. For \( p < 0.25 \), the system is ferromagnetic; for \( p > 0.5 \), the ground state is the antiferromagnetic \((22)\) state (two up, two down). We have solved the coupled equations for a 264-layer system and calculated the Gibbs free energy for all possible starting configurations. In figure 3, we plot the magnetization of the lowest energy state as a function of temperature at various magnetic fields for \( p = 0.55 \). At low fields (triangles), the magnetization has a maximum at 0.4 \( T_N \). Doubling the field \((x's)\) leads to a ferromagnetic low-temperature state without intermediate phases. This behaviour is qualitatively, and even semiquantitatively, similar to that observed in Er films.

Why, if the ground state of ANNNI systems is antiferromagnetic, does Er have a ferromagnetic ground state? We have, in the ANNNI model, ignored the important contribution of magnetostriction, which possibly decreases \( p \) and thus favors ferromagnetism in Er. The minimization of the magnetoelastic energy in bulk Er results in \( c \)-axis contraction and concomitant expansion in the basal plane. However, the \textit{clamped} epitaxial condition restricts the magneto-elastic energy gain with the result that exchange energy is more important in epitaxial Er films. The ferromagnetic phase can be induced by an applied field in a completely reversible process. This suggests that no plastic deformation takes place. The critical internal fields required to induce ferromagnetism at 10 K decreases from 8 kOe for a 860 Å film to 3 kOe for a 9500 Å film. While we have not yet determined whether this decrease is continuous or occurs as a step at a well defined thickness, it is clear that films up to 1 µm in thickness are still mostly clamped and behave differently from bulk Er. Further studies are underway to understand the relationship to bulk behaviour.

Acknowledgments

This work was supported in part by the National Science Foundation through Grant No. DMR-8521616. One of us (GN) acknowledges hospitality of the University of Illinois Department of Physics.