Magnetic Structure of Laves Phase [111]-Grown Superlattice: [50 $ErFe_2$/ 100 YFe_2]$_{40}$

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Introduction

There is a long history of research into the rare earth - transition metal (R-T) intermetallic compounds in bulk form, based on the idea that the R and T atoms will interact to give useful properties. The R and T magnetic moments couple ferromagnetically when R is a light rare earth and antiferromagnetically when R is a heavy rare earth and magnetic interactions are possible that will raise the ordering temperature of the elemental rare earths - which have large localized moments - to above room temperature. This is the basis for the permanent magnet compounds RT_5 and R_2T_{17}, which are widely used in electric motors and other magnetomechanical devices.

Magnetic multilayer films of these compounds have become a subject of research due to their possible applications as permanent magnets [1]. The successful growth of $DyFe_2$/ YFe_2 superlattices with [110] growth direction, which have magnetic moments aligned largely perpendicular to this direction, has demonstrated unusual exchange spring behavior as well as the existence of spin-flop phases in Y-rich materials [2], [3]. The direction of the moments depends on the composition of the superlattice. $ErFe_2$/YFe_2 [110] superlattices have also been grown and have the magnetic moments aligned largely along the growth direction. Magnetization measurements show that in an applied field they also show exchange spring behavior [4].

Recently it has become possible to grow RT_2, single layers and superlattices with [111] growth direction [5]. This is of interest as the [111] growth system also allows other R-T compounds such as RT_3 and R_2T_{17} to be produced. Magnetization measurements on the $ErFe_2$/YFe_2 superlattice system using a SQUID magnetometer show that the easy axis of magnetization is along this growth direction and suggest that it is difficult to rotate the Er moments away from the easy axis by applying a perpendicular field.

Experimental Arrangements

The superlattice discussed in this report has composition [50 $ErFe_2$/ 100 YFe_2]$_{40}$ and was prepared in the Balzers facility, Oxford using molecular beam epitaxy (MBE). $ErFe_2$ and YFe_2 have the face centred-cubic $MgCu_2$ structure and the super-lattice has the [111] direction as the growth direction. The notation used for the structure is [t_1Å $ErFe_2$/ t_2Å YFe_2]$_N$ where t_1 is the thickness of the $ErFe_2$ layer, t_2 is that of the YFe_2 layer and N is the number of layers. It was grown as detailed in ref. [5]. X-ray diffraction measurements [5] have shown that this sample is composed of two epitaxial domains: one with the [111] direction parallel to the growth direction, the other with this direction anti-parallel to the growth direction.

Polarized neutron reflectivity and unpolarized neutron diffraction measurements were carried out on the C5 spectrometer. The sample was oriented with the growth direction ([111] direction) horizontal and perpendicular to the incoming neutron beam and with the $[11\bar{2}]$ or $[\bar{1}\bar{1}2]$ direction parallel to the beam. A vertical magnetic field was applied, perpendicular to both the superlattice growth direction and the beam direction. The diffraction measurements were taken at the (111), (220), and (113) Bragg reflections at fields starting at -7.5 T and increasing up to 6 T, field cooled at -7.5 T, at temperatures of 100 K and 200 K. Reflectivity measurements were taken at fields between 0 T and 6 T, also at 100 K and 200 K. Theoretical calculations of the reflectivity were produced using the `Polly: Polarised Neutron Reflectivity' program developed by S.Langridge at the Rutherford Appleton Laboratory, Oxfordshire, UK.

Erbium and Yttrium have very similar neutron scattering lengths: 7.79 fm and 7.75 fm respectively. Consequently, the subsidiary peaks due to the superlattice will not be visible unless the $ErFe_2$ and YFe_2 layers have different magnetizations.

Results and Discussion

Reflectivity

Figure 1 shows the polarized neutron reflectivity of a [50 $ErFe_2$/ 100 YFe_2]$_{40}$ superlattice. This was measured at 100 K with an applied field of 3 T perpendicular to the neutron beam and to the growth direction of the sample.

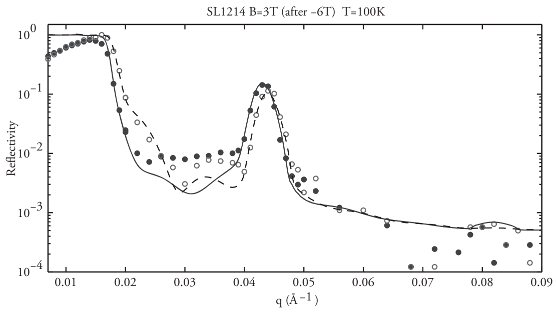

Fig. 1 Reflectivity of a [50 $ErFe_2$/ 100 YFe_2]$_{40}$ superlattice at 100 K and 3 T (after -6 T). Filled circles show the up-up measurement, open circles show the down-down measurement. Theoretical calculations are shown as a solid line (up-up) and a dashed line (down-down).

The features are typical of all of our neutron reflectivity measurements on this sample. The filled circles show the up-up measurement, the open circles show the down-down measurement. The up-down and down-up measurements were also recorded and showed that there was no spin-flip scattering. The first order superlattice peak can be clearly seen at $q \approx 0.043$ Å. However, the second order peak, expected at $q \approx 0.081$ Å, is not observed in this or in any of the reflectivity measurements taken. This absence should not be due to structural imperfections in the superlattice, as x-ray reflectivity measurements on this sample show several orders of superlattice peaks.

A model is necessary for the magnetization profile of the sample that produces no spin-flip intensity and also reduces the intensity of the second reflectivity superlattice peak. One such model, shown schematically in figure 2, is that of a magnetic exchange spring forming in the soft YFe_2 layers while the magnetic moment of the strongly anisotropic $ErFe_2$ layer remains aligned along the growth axis of the superlattice.

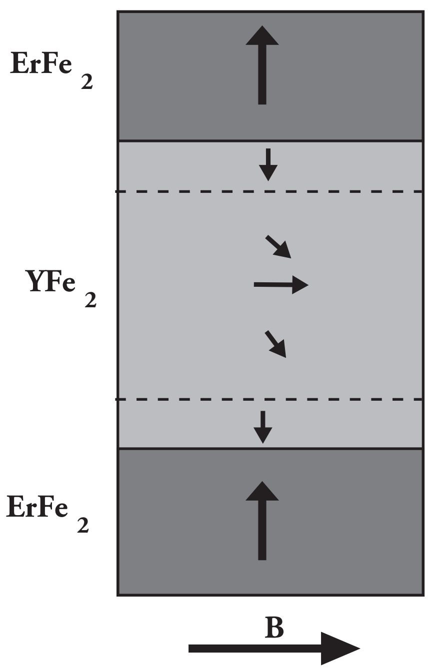

Fig. 2 Schematic diagram of the proposed magnetization of the superlattice.

In our model, the magnetic moments of the YFe_2 layers are anti-aligned with those of the $ErFe_2$ layers (along the [111] growth direction) for 12 Å from the $ErFe_2/YFe_2$ interface due to the strong coupling between the Fe moments in both compounds. Further into the YFe_2 layers the magnetization rotates away from the [111] direction towards the direction of the applied magnetic field. In the largest applied fields the magnetization at the center of the YFe_2 layers becomes parallel to the applied field; for smaller applied fields the magnetization is still at an angle to the applied field.

Diffraction

Figure 3 shows the integrated intensities of the scattering from the (111), (220) and (113) Bragg reflections at 100 K in applied magnetic fields of between 0 T and 6 T. The intensities are normalized to their values at 0 T. As the nuclear structure factors are constant, changes in these intensities are attributed to variation in the magnitude and direction of the magnetization of the sample. The magnetic structure factor is at a maximum for q perpendicular to the magnetization and at a minimum for q parallel to the magnetization.

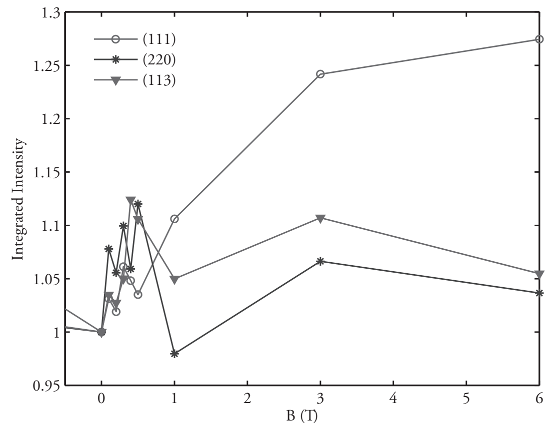

Fig. 3 Integrated intensities of the (111), (220) and (113) Bragg reflections at 100 K.

The intensity of the (111) reflection increases as the field is increased. This suggests a rotation of the sample magnetization away from the [111] direction. A reduction in the intensities of the (113) and (220) reflections can be seen at B = 1 T. This indicates that the magnetization of the sample rotates through the [113] and [220] directions as the field increases from 0.5 T to 3 T. As the sample contains two domains, both of these directions lie between the [111] direction and the direction of the applied magnetic field.

Conclusions

Polarized neutron reflectivity and unpolarized neutron diffraction measurements have been made on a $[50\ ErFe_2/100\ YFe_2]_{40}$ superlattice sample with a [111] growth direction. The reflectivity data suggests a model for the magnetization in which the magnetic moments in the $ErFe_2$ layers are aligned with the growth direction and those in the YFe_2 layers form exchange springs, rotating away from the growth direction towards the direction of the applied magnetic field (the [112] direction).

Diffraction measurements were made around the (111), (220) and (113) Bragg reflections. Analysis of the integrated intensity of these Bragg reflections shows that the magnetization of the superlattice rotates away from the [111] growth direction as the applied field increases and goes through the [113] and [220] directions as the field reaches ~ 2 T. As these two axes lie between the [111] and $[11\bar{2}]$ directions, this diffraction data supports the model, suggested by the reflectivity measurements, of exchange springs in the YFe_2 layers which rotate from the [111] direction towards the $[11\bar{2}]$ direction.

References

[1] J. M. D. Coey. Permanent magnetism. Solid State Commun., 102:101, 1997.

[2] M. Sawicki, G. J. Bowden, P. A. J. de Groot, B. D. Rainford, J.-M. L. Beaujour, R. C. C. Ward, and M. R. Wells. Exchange springs in antiferromagnetically coupled $DyFe_2$ – YFe_2 superlattices. Phys. Rev. B, 62:5817, 2000.

[3] M. J. Bentall, R. A. Cowley, W. J. L. Buyers, Z. Tun, W. Lohstroh, R. C. C. Ward, and M. R. Wells. Magnetic structures of laves phase superlattices. J. Phys.: Condens. Matter, 15:4301, 2003.

[4] K. N. Martin, K. Wang, G. J. Bowden, A. A. Zhukov, P. A. J. de Groot, J. P. Zimmermann, H. Fangohr, and R. C. C. Ward. Exchange spring driven spin flop transition in ErFe2 / YFe2 multilayers. App. Phys. Lett., 89:132511, 2006.

[5] S. R. Jones, A. Dunhill, R. A. Cowley, and R. C. C. Ward. Structure of epitaxially grown rare-earth intermetallics using x-ray diffraction: RT2, RT3, RT5, and R2T17. Phys. Rev. B, 77:214110, 2008.