The structure and magnetization of gadolinium/molybdenum multilayers

1996 J. Phys.: Condens. Matter 8 685

(http://iopscience.iop.org/0953-8984/8/6/009)

J. Phys.: Condens. Matter **8** (1996) 685–697. Printed in the UK

The structure and magnetization of gadolinium/molybdenum multilayers

J V Harkins and P E Donovan

Physics Department, Birkbeck College, Malet Street, London WC1E 7HX, UK

Received 11 September 1995, in final form 5 December 1995

Abstract. Gadolinium/molybdenum multilayers have been prepared by dc magnetron sputtering and their structure has been investigated by transmission electron microscopy and low-angle x-ray diffraction. The in-plane magnetization of a series of multilayers with the same molybdenum layer thickness but different gadolinium layer thicknesses has been measured in fields up to 7 T at temperatures between 5.5 K and 250 K. The magnetic behaviour of the multilayers has been interpreted on the basis of a simple model of their magnetic structure. The interfaces between the gadolinium and molybdenum layers have significant roughness which increases as the layer thicknesses increase, and this roughness affects the magnetic behaviour of the interface regions, preventing the gadolinium moments near the interfaces from aligning with the applied field.

1. Introduction

Magnetic multilayers offer the possibility of investigating a number of important problems in fundamental magnetism, including interface anisotropy, interlayer coupling and two-dimensional magnetic behaviour. To date, most investigations of magnetic multilayers containing rare-earth elements have concentrated either on systems in which both components are rare earths [1] or on rare-earth/transition metal multilayers in which the transition metal is magnetically ordered [2]. There have been relatively few investigations of the behaviour of magnetic rare earths interlayered with a non-magnetic transition metal [3]. We are studying multilayers composed of a rare-earth metal and the refractory non-magnetic transition metals of the chromium or vanadium groups. Our previous investigation of gadolinium/tungsten (Gd/W) multilayers showed that there was a very large enhancement of the magnetization of Gd/W multilayers with thin (<4 nm) gadolinium layers [4]. In this paper we describe the results of structural and magnetic measurements on gadolinium/molybdenum (Gd/Mo) multilayers. Molybdenum is chemically and structurally similar to tungsten, and like tungsten it does not mix or form compounds with the rare-earth metals [5] and remains paramagnetic at all temperatures.

2. Experimental procedure

Gadolinium/molybdenum multilayers were prepared by dc magnetron sputtering onto glass substrates measuring 21 mm^2 in a UHV vacuum chamber with base pressure below 2×10^{-10} Torr. The molybdenum sputter target was cut from a piece of 99.9% Mo foil purchased from Goodfellow Cambridge Limited, Cambridge, UK. The gadolinium sputter

0953-8984/96/060685+13$19.50

target was purchased from the Ames Laboratory, Illinois, USA. The substrates were carefully cleaned and then coated with a thin layer of amorphous carbon to improve the flatness and continuity of the sputtered layers. The substrates were mounted on a computer-controlled rotating table, which positioned them under each source for a pre-set time to deposit the required quantity of each metal. All of the specimens were deposited at ambient temperature in an atmosphere of 99.99% argon at a pressure of 5×10^{-2} Torr. Multilayers prepared for x-ray and magnetization measurements consisted of 50 bilayers with additional base and capping layers of molybdenum. Additional samples for examination by transmission electron microscopy (TEM), consisting of 10 bilayers without base or capping layers, were deposited under identical conditions directly onto amorphous carbon support films mounted on 3 mm diameter microscope grids.

The structure of the multilayers was characterized by low-angle x-ray diffraction in a Bede Scientific GXR1 reflectometer running in coupled $\theta/2\theta$ mode with Cu Kα radiation. The layer thicknesses in each multilayer were determined by matching the angles and relative intensities of the experimental x-ray diffraction peaks to simulated diffraction patterns of model multilayer structures produced using the Bede Scientific REFS software package, which is based on the analysis of Parratt [6]. The bulk densities of molybdenum and gadolinium were used in the simulations. Multilayer specimens deposited on microscope grids were examined in a JEOL 100C electron microscope operating at 100 kV.

The magnetization of each multilayer and substrate was measured using a Quantum Design MPMS SQUID magnetometer in applied fields up to 7 T with the field direction in the plane of the layers. Measurements were made at 5.5, 10, 20, 50, 80, 150, 200 and 250 K. The multilayer was then removed from the substrate by gentle abrasion with diamond paste (6 and 1 μm grade), followed by an ultrasound bath in ethanol, and the background magnetization of the substrate and holder were measured under identical conditions. This background measurement was then subtracted point-for-point from the first measurement to give the magnetization of the multilayer.

Gd/Mo multilayers have been prepared with bilayer thickness, Λ, between 2.2 and 13.6 nm and with individual layer thicknesses between 0.6 and 12.0 nm. Here we describe the structure and magnetization of a series of five multilayer specimens in which all the multilayers had the same pre-set time for molybdenum deposition, producing (within experimental uncertainty) the same molybdenum layer thickness, d_{Mo}, of approximately 1.4 nm, but each multilayer had a different gadolinium layer thickness, d_{Gd}. The properties of multilayers with different molybdenum thicknesses have been described elsewhere [7].

3. Results

3.1. Structure

X-ray measurements on all of the Gd/Mo multilayers showed several orders of Bragg reflection from the bilayer periodicity, indicating that the layer structure is well defined and regular. However, the total thickness of these multilayer specimens was too large for Kiessig fringes between the Bragg reflections to be resolved. As shown in figure 1, the number of reflection orders increased with Λ. The values of Λ, d_{Mo} and d_{Gd} determined from the x-ray measurements for each multilayer studied here are given in table 1. As previously discussed [4], Λ could generally be determined to within 0.02 nm, but the accuracy of the individual layer thickness determinations was poorer except in the few cases where one layer thickness was a sub-multiple of the other and the x-ray pattern showed intensity 'beats'. This is because the intensities of the Bragg reflections are affected not only by

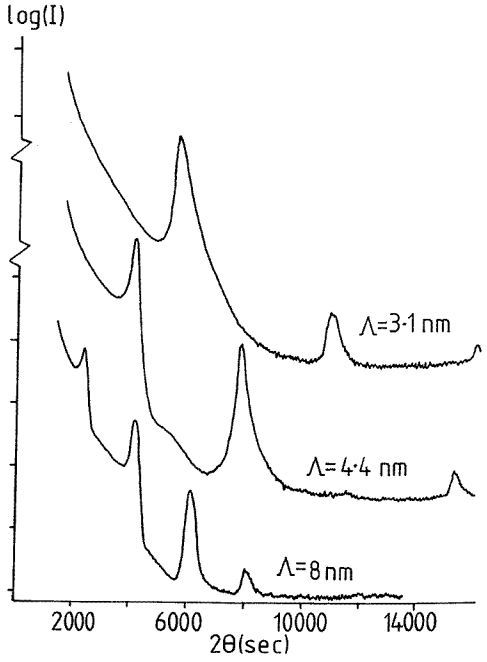


Figure 1. Low-angle x-ray diffraction patterns of three Gd/Mo multilayer specimens with different values of Λ. The curves have been displaced vertically for clarity. The $n = 3$ diffraction peak is absent in the multilayer with $\Lambda = 4.4$ nm, where the optical thickness of the Mo is half that of the Gd.

the thicknesses of the two different types of layer but also by other factors including the roughnesses of the layer interfaces, specimen curvature and the presence of a surface oxide layer. The REFS software allows these effects to be included in the simulations, and we have found that very accurate matches between experiment and simulation can be made provided that the specimen consists of fewer than about 10 layers. However, the specimens examined here consisted of 102 layers, and each of the layer interfaces could, in principle, have a different roughness, so the number of adjustable parameters in a full simulation is extremely large. Because of this we did not consider it worthwhile to make a detailed simulation study. Instead we performed simulations using a single rms roughness value for every layer interface and examined the effect on the simulated reflectivity of changing this single roughness value and of changing the proportions of the two materials. In this way we could arrive at an estimate of the individual layer thicknesses and an estimate of the average roughness, but we could not determine these parameters absolutely. The estimated uncertainties in the individual layer thicknesses obtained in this way are also given in table 1.

Table 1. Layer thicknesses of Gd/Mo multilayer specimens determined from x-ray reflection measurements.

Specimen	Λ (nm)	d_{Mo} (nm)	d_{Gd} (nm)
1	2.45 ± 0.05	1.55 ± 0.15	0.80 ± 0.15
2	3.137 ± 0.002	1.75 ± 0.10	1.40 ± 0.10
3	3.452 ± 0.002	1.35 ± 0.10	2.20 ± 0.10
4	4.440 ± 0.015	1.50 ± 0.15	2.95 ± 0.15
5	7.995 ± 0.008	1.65 ± 0.10	6.35 ± 0.10

It was noticeable that fewer reflection orders were generally observed for Gd/Mo than for Gd/W multilayers of comparable Λ [4]. This is partly due to the fact that the x-ray contrast

is lower in the Gd/Mo system than in Gd/W, so the Bragg reflections are less intense and for a given background intensity fewer peaks are observed. However, the simulations indicated that reduced contrast alone is not sufficient to account for the observations and that the Gd/Mo multilayers have significantly rougher layer interfaces than in Gd/W, leading to more rapid damping of the reflected intensity at high Bragg angles. Comparing the experimental x-ray patterns with simulations indicated that an average rms roughness value of 0.3 nm was appropriate for Gd/Mo multilayers with individual layer thicknesses of less than 5 nm, increasing to 0.4 nm for layer thicknesses up to 10 nm. The experimental x-ray reflectivity of Gd/W multilayers could be simulated well using average rms roughness values less than 0.1 nm for all layer thicknesses up to 10 nm. However, it should be emphasized that these roughness values are approximate. A more detailed x-ray study of interface roughness in Gd/Mo multilayers consisting of fewer layers is currently in progress.

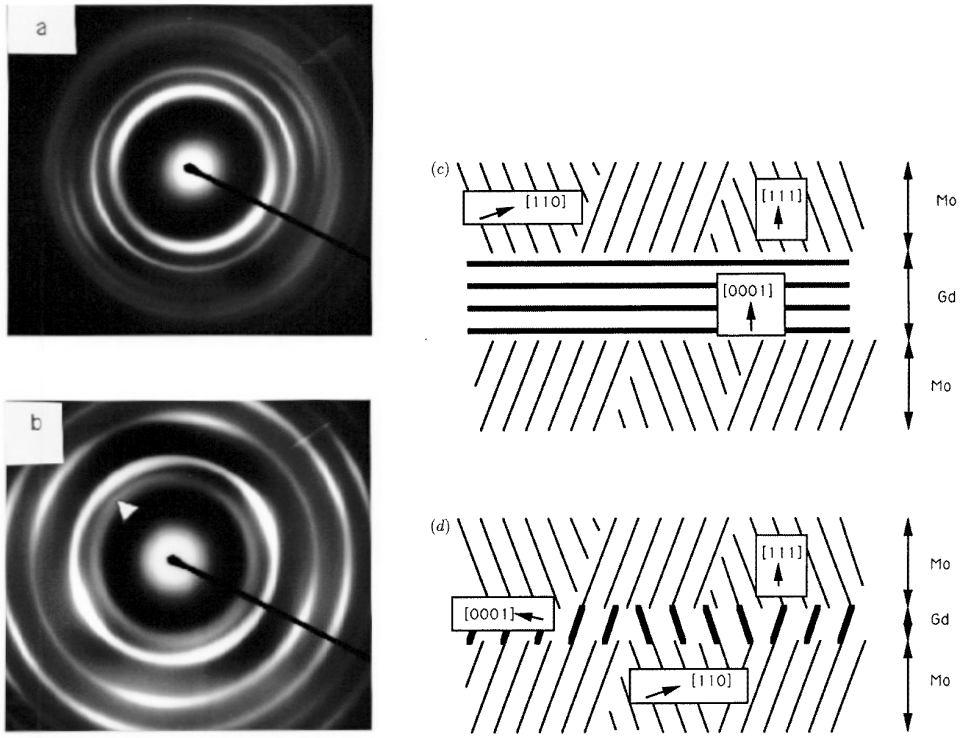


Figure 2. The preferred crystallographic orientation (texture) in Gd/Mo multilayers. (a) A TEM diffraction pattern from a multilayer with 1.5 nm Mo layers and 3.5 nm Gd layers, tilted by 15° from the horizontal. The diffraction rings from both the Mo and the Gd vary in intensity, showing that both metals have texture. (b) A TEM diffraction pattern from a multilayer with 1.5 nm Mo layers and 0.8 nm Gd layers, tilted by 40° from the horizontal. A weak Gd 0002 reflection has appeared (arrowed) in association with a strong Mo 110 reflection. (c) A schematic diagram showing the texture observed in multilayers with d_{Gd} greater than 1 nm. (d) A schematic diagram showing the texture observed in the multilayer with 0.8 nm Gd layers.

TEM showed that the layers are polycrystalline. Both gadolinium and molybdenum were found to have their equilibrium crystal structures. Weak, diffuse diffraction rings from metal oxide could also be seen in some specimens but the diffracted beams from the

pure metals were always much more intense, indicating that the amount of oxide present was relatively small. Attempts were made to measure the diameter of the oxide crystals by forming dark-field images with a small objective aperture centred on the most intense oxide diffraction ring, but the dark-field images obtained showed only a weak intensity distributed over the whole specimen and no individual oxide crystals could be resolved. These observations are consistent with the presence of a thin, uniform oxide film composed of small crystallites (<2 nm diameter) on the surface of the specimen.

Pure molybdenum sputtered onto carbon films was found to grow with randomly oriented crystals, but when the molybdenum is deposited onto gadolinium in a multilayer it develops a preferred orientation (texture). This is illustrated in figure 2. The nature of the texture was analysed by tilting the multilayer specimens in the microscope and observing the changes in relative intensity of the reflections in the electron diffraction patterns as a function of tilt angle. This showed that the molybdenum crystals were growing with the [111] crystal direction preferentially normal to the plane of the layers ([111] fibre texture). In a material like molybdenum with a cubic crystal structure this texture implies that the (111) crystallographic plane lies preferentially parallel to the plane of the layers, which is an unusual texture for a bcc material in which the (111) plane is not close packed. Preferred orientation in metal films usually favours close-packed crystal planes parallel to the substrate [8].

In pure sputtered films of gadolinium the crystals were observed to grow with the hexagonal *c*-axis preferentially normal to the layer plane ([0001] fibre texture). This texture was also observed in relatively thick (>3 nm) gadolinium layers in the multilayers. However, in the multilayer with the thinnest gadolinium layers (0.8 nm) a different texture was observed. In the untilted specimen, i.e. with the electron beam parallel to the layer normal, no diffracted beams from the gadolinium were visible in the diffraction pattern, and it seemed possible that the thin gadolinium had adopted an amorphous structure like that observed in Gd/Fe multilayers with thin layers [10]. However, on tilting the specimen by approximately 40° well-defined 0002 reflections from the gadolinium appeared, as shown in figure 2(b), in association with strong 110 reflections from the molybdenum. The thin gadolinium layers are therefore crystalline, and there is an orientation relationship between the gadolinium and the molybdenum such that $(0001)_{Gd}$ is parallel to $(110)_{Mo}$ but these planes are inclined at an angle to the plane of the layers. The two textures observed, in thin (0.8 nm) and thick (>3 nm) gadolinium layers, are illustrated schematically in figures 2(c) and 2(d).

The in-plane diameters of the crystals of each component in the multilayer were measured from dark-field images formed using a small objective aperture centred on a diffraction ring from each metal in turn. The average in-plane diameter was found to be approximately 45 nm for molybdenum crystals and 15 nm for gadolinium crystals. The crystal size did not vary significantly with layer thickness over the range of thickness examined.

3.2. Magnetization

The magnetization curves of the multilayers measured at 5.5 K are shown in figure 3. All of the curves are of similar shape, with an initial high-susceptibility region followed by a gradual transition to an approximately linearly increasing region at higher fields. All of the multilayers show an open hysteresis loop at low fields, but the remanent magnetization is very small. None of the specimens reached saturation in the maximum applied field of 7 T.

The total Gd content of each multilayer was calculated from the x-ray data shown in

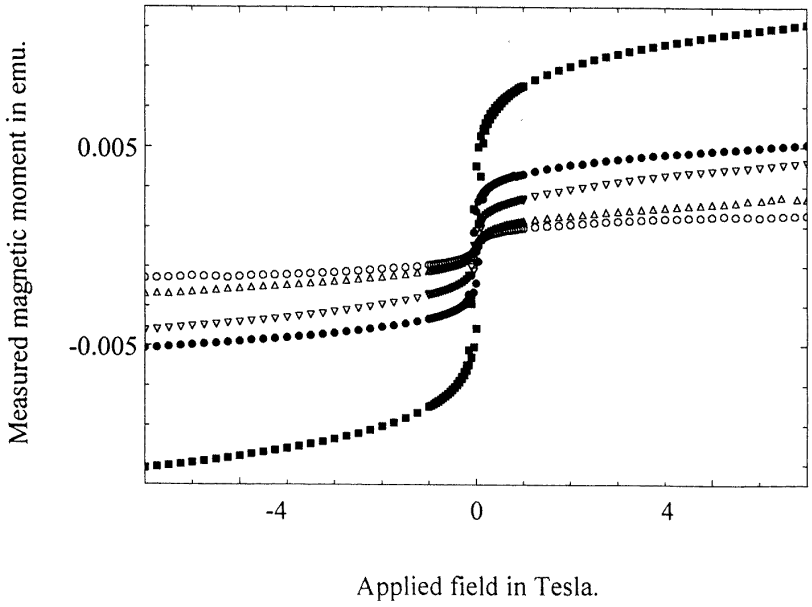


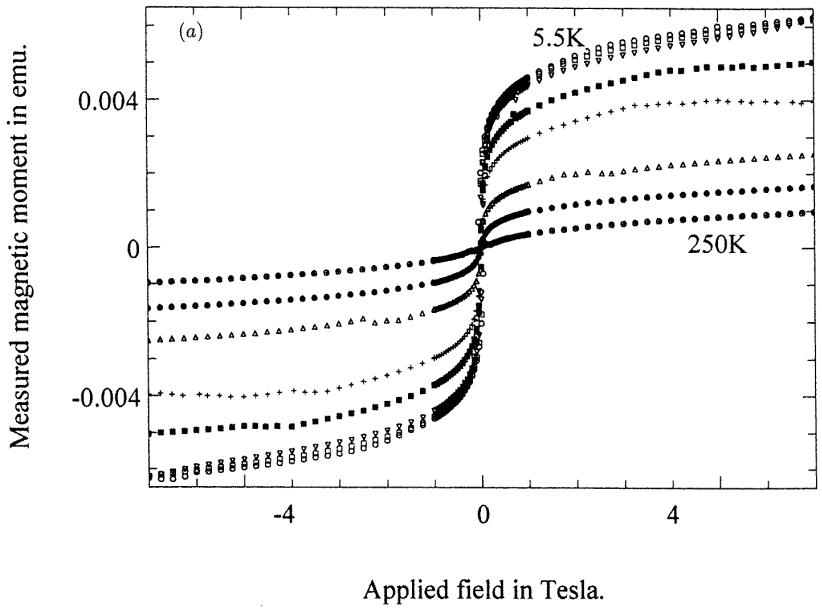
Figure 3. The magnetization of the multilayers measured at 5.5 K, showing a rapid initial rise followed by a slow increase at high fields. The symbols refer to the following gadolinium layer thicknesses: open circles: 0.8 nm; upward-pointing triangles: 1.4 nm; downward-pointing triangles: 2.2 nm; closed circles: 2.95 nm; solid squares: 6.35 nm.

table 1 and the expected saturation moment, M_E, of each multilayer was then calculated assuming the bulk metallic gadolinium moment of 7.63 μ_B per atom [10]. In all cases the maximum observed magnetic moment, M_{OBS}, of the multilayers is less than the expected value, i.e. we see no evidence for magnetization enhancement as was observed in Gd/W multilayers [4]. The ratio M_{OBS}/M_E decreases as the thickness of the Gd layers is reduced, i.e. the gadolinium layers become harder to saturate within the plane as their thickness decreases.

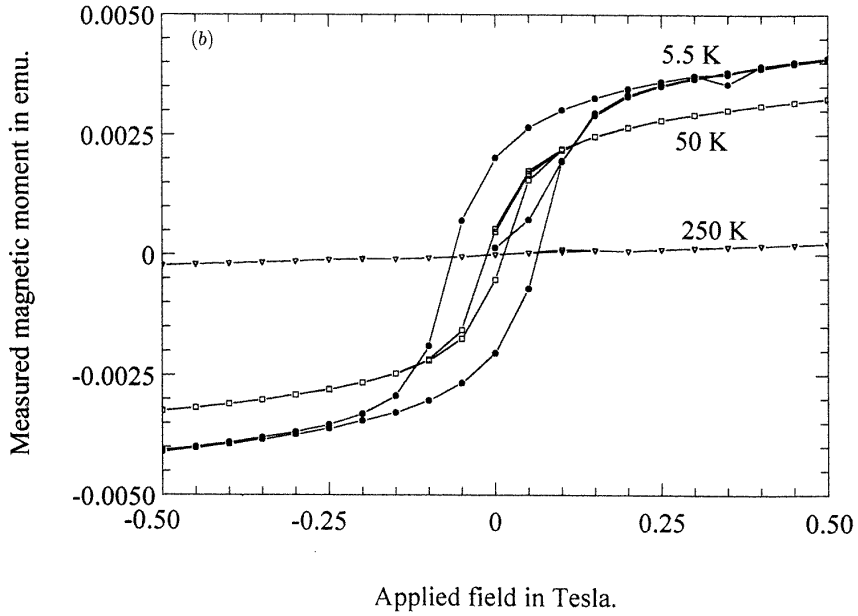
Table 2. Estimated ordering temperatures and thicknesses of the gadolinium layer centre and interface regions determined from magnetization measurements (the symbols are defined in text).

Specimen	Θ_P (K)	M_{centre} (nm)	M_P (nm)	M_M (nm)
1	35 ± 10	0.27	0.43	0.1 ± 0.15
2	75 ± 10	0.35	0.70	0.35 ± 0.10
3	135 ± 10	0.79	1.08	0.33 ± 0.10
4	195 ± 15	1.34	0.94	0.67 ± 0.15
5	> 250	2.84	2.11	1.40 ± 0.10

The magnetization of the multilayer with 2.2 nm Gd layers is shown as a function of temperature in figure 4. At temperatures of 150 K and above there is no hysteresis and the magnetization is linear with applied field, indicating that the Gd layers in this specimen are above their ferromagnetic ordering temperature. The ordering temperature of each multilayer has been estimated by using Curie–Weiss plots of the reciprocal susceptibility in



(*a*)



(*b*)

Figure 4. The magnetization of the multilayer with 2.2 nm Gd layers: (a) complete magnetization curves as functions of the temperature, showing the steady decrease in high-field moment with increasing temperature (the symbols refer to the following temperatures: open circles: 5.5 K; open squares: 10 K; downward-pointing triangles: 20 K; solid squares: 50 K; crosses: 80 K; upward-pointing triangles: 150 K; solid circles: 200 K); (b) the low-field part of the magnetization curves at 5.5, 50 and 250 K, illustrating the transition with increasing temperature from the typical open hysteresis loop characteristic of ferromagnetic order to a linear paramagnetic response.

the field region 0.1 to 0.3 T to determine the paramagnetic Curie temperature, Θ_P, and the results are given in table 2. The paramagnetic Curie temperature is expected to be close to, though not identical to, the ferromagnetic Curie temperature T_C [11]. All of the multilayers were found to have paramagnetic Curie temperatures significantly lower than that of bulk gadolinium, and the value of Θ_P decreases with decreasing d_{Gd} as predicted theoretically for thin magnetic layers [12]. In this investigation we have not determined the ferromagnetic Curie temperature. To do this it would be necessary to measure the susceptibility in much smaller temperature intervals close to the ordering temperature [13].

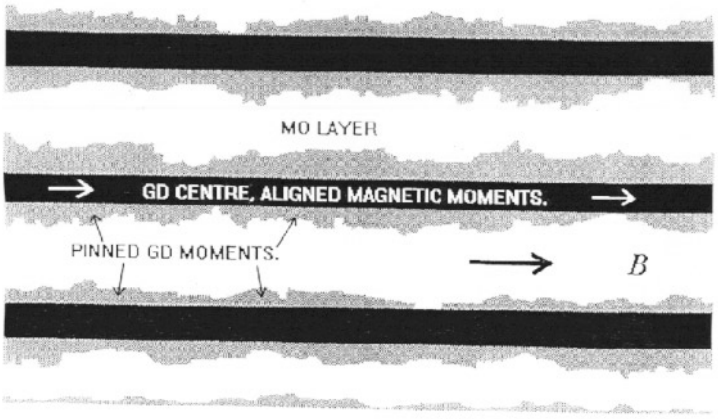


Figure 5. A schematic diagram of the model magnetic structure of the multilayers. Each gadolinium layer consists of a central region (dark shading) in which the moments align with the applied field, $\boldsymbol{B}$, and two interface regions (grey shading) in which the moments are not aligned.

4. Modelling

4.1. The thickness dependence of the magnetization

We have modelled the magnetization curves of the Gd/Mo multilayers by considering each Gd layer to be made up of three regions. We consider the initial rapid rise in magnetization at low applied fields to be associated with the Gd atoms in the centre of each Gd layer, whose moments can be aligned relatively easily by an external field. The slower, approximately linear, increase at higher fields is attributed to the Gd atoms close to the boundaries between each Gd and Mo layer. In these 'interface regions' the Gd moments require a large applied field for alignment. This model of the magnetic structure is illustrated schematically in figure 5. A similar model of the magnetic structure of thin layers has been used by other researchers [14].

In analysing the magnetization curves we have defined the boundary between the low-field region, corresponding to the layer centres, and the high-field region, corresponding to the interfaces, to be 0.3 T. This value of field was chosen because it marks the end of the rapidly rising part of the experimental 5.5 K magnetization curves of all of the specimens (see figure 3).

Using this model, we have estimated the thickness of the central region of each Gd layer from the measured moment of the multilayer at 0.3 T. We find that the thickness of

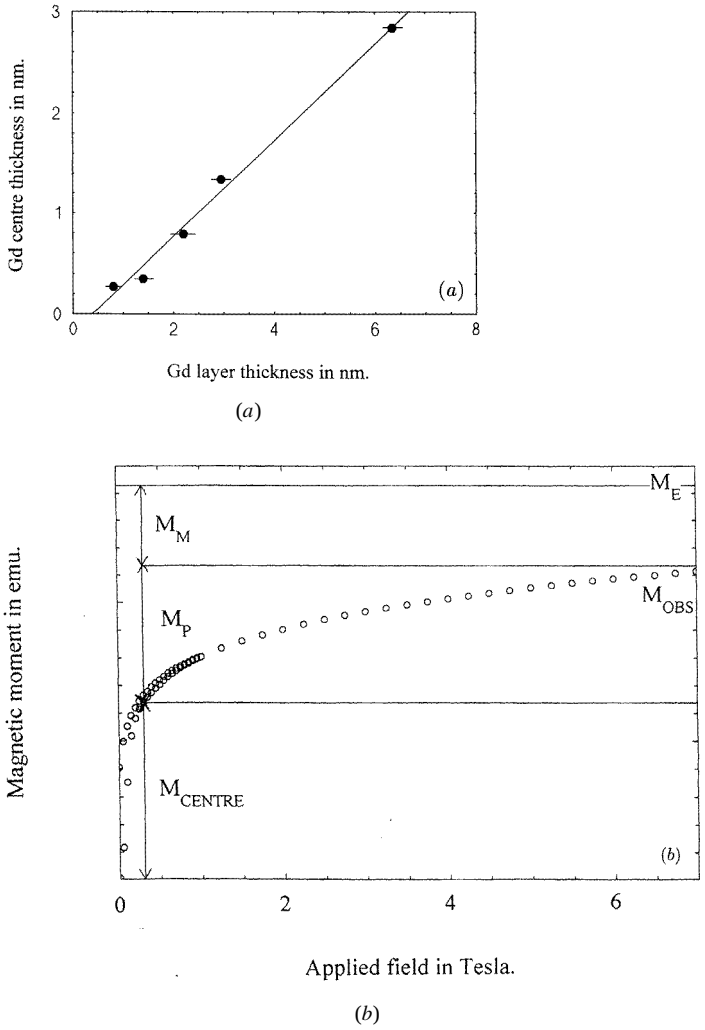


Figure 6. (a) The thickness of gadolinium layer centres as a function of total gadolinium layer thickness. The uncertainties in the total layer thickness are indicated by error bars. The line is a least-squares-fit to the data. (b) The magnetization curve, showing the relationship between the various parts of the curve and the components of the moment discussed in the text.

the layer centres increases approximately linearly with the total thickness of each Gd layer. This is shown in figure 6. A least-squares fit to the data indicates that the thickness of the central region becomes zero at a total layer thickness of about 0.5 nm, which corresponds to approximately twice the effective diameter of the Gd atom calculated from the lattice parameter of gadolinium metal. This provides support for our model, since in a flat film with a thickness of two atomic diameters every atom would be at an interface. The gradient of the least-squares-fit line in figure 6 is close to 0.5, indicating that above the minimum thickness of two atomic diameters about half of the additional Gd is in the layer centres. The thickness of the interface regions thus increases with the total Gd thickness. This point is discussed further below.

We assume that the total moment of the interface regions is the difference between the

moment of the central region, reached at 0.3 T, and the expected moment, M_E, calculated from the total Gd layer thickness. However, none of our multilayer specimens reached M_E in the maximum applied field. We have therefore chosen to consider two separate components of the interface moment. The first component is the difference between the 0.3 T moment and the moment observed at the maximum available field, M_{OBS}. We call this observed high-field moment, which is associated with pinned moments which cannot rotate at low field, M_P. The second component, M_M, the 'missing' moment, is the difference between M_{OBS} and M_E. The relationship between these components of the total moment of the multilayer and the magnetization curve is shown schematically in figure 6(b). The magnitude of the 'missing' moment, M_M, increases with Gd layer thickness. M_M also increases with Mo layer thickness in the series of multilayers with constant d_{Gd} [7]. The total inferred interface moment, $M_P + M_M$, increases with Gd thickness. The numerical values of the Gd layer centre thickness, M_P and M_M, for each multilayer, are summarized in table 2. To allow easy comparison of their relative magnitudes for the different specimens the magnetization values M_P and M_M are presented in table 2 as equivalent thicknesses of gadolinium, using the conversion factor of 7.63 μ_B per Gd atom.

4.2. The temperature dependence

The same model of the magnetism of the gadolinium layers has been used to analyse the temperature dependence of the magnetization of the multilayers. The first point which should be noted is that since the Curie–Weiss plots were made using the susceptibility at fields below 0.3 T the ordering temperatures in table 2 refer to the centres of the Gd layers. In the specimens with thin Gd layers Θ_P shows a linear dependence on both the total Gd layer thickness and the thickness of the layer centres, suggesting that the Gd layers should approach the bulk ordering temperature of 293 K when their total thickness is about 4 nm and their centre thickness is about 2 nm. This prediction agrees with results reported for Gd/Y single-crystal multilayers, in which an ordering temperature of 285 K was found for a gadolinium thickness of ten atomic layers (about 3 nm) [15]. We find that the Gd/Mo multilayer with 6.35 nm gadolinium layers (4.95 nm centre thickness) is clearly still ferromagnetically ordered at 250 K, but we have no measurements at temperatures higher than this.

The form of the temperature dependence of the layer centre moment is illustrated in figure 7. This shows the centre moment of each multilayer divided by its value at the lowest measuring temperature of 5.5 K. The magnetization decreases with increasing temperature for all the multilayers, as expected, falling off more quickly for thin Gd layers and qualitatively following the general form of temperature dependence predicted by spin-wave theory for thin magnetic films [12].

For each multilayer the high-field susceptibility between 4 and 6 T was found to be independent of temperature within experimental uncertainty, and therefore it was not possible to use Curie–Weiss plots to estimate an ordering temperature for the interface regions.

5. Discussion

Our analysis of the low-field portion of the magnetization curves of Gd/Mo multilayers shows that part of each gadolinium layer is ferromagnetically ordered with an ordering temperature which depends on the layer thickness, as predicted by theory. It is more difficult to determine the magnetic state of the 'interface regions' in which the atomic moments

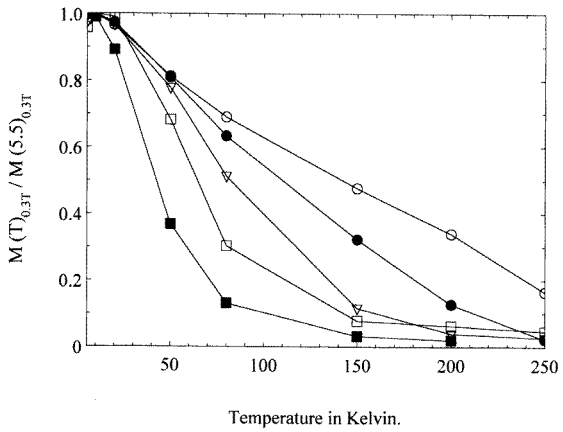


Figure 7. The Gd layer centre moment of each multilayer as a function of temperature, divided by the 5.5 K moment. Symbols refer to the following Gd layer thicknesses: solid squares: 0.8 nm; open squares: 1.4 nm; open triangles: 2.2 nm; closed circles: 2.95 nm; open circles: 6.35 nm. Lines through the symbols are a guide to the eye. The dependence of the moment on layer thickness at low temperatures is qualitatively in agreement with the predictions of spin-wave theory.

require a large external field to produce alignment. In itinerant magnetic metal multilayers, for example Ni/Cu, Fe/W, Fe/V, Fe/Nb and Co/Ti, intermixing produces a magnetically 'dead' (less magnetic or non-magnetic) layer at each interface [16]. In gadolinium metal the 4f electrons which are responsible for most of the atomic moment are localized core electrons and do not mix with the electrons of the spacer component, so it is not possible to form a dead interface layer. We assume, therefore, that every gadolinium atom in the multilayer, including those in the interface regions, carries a magnetic moment. The interface regions may then be in one of two possible magnetic states: either a paramagnetic state, in which the exchange interaction between different gadolinium atoms is insufficient to produce ferromagnetic alignment, or else a 'hard' ferromagnetic state in which the moments are ordered but cannot align with the applied field. Either of these states may occur near the interfaces in a magnetic multilayer. Reduced exchange near the layer interfaces might be caused by roughness or intermixing, both of which would reduce the number of gadolinium–gadolinium nearest neighbours, or by changes in the conduction band susceptibility due to hybridization with the molybdenum conduction band [17]. On the other hand ferromagnetically aligned atomic moments might be pinned by coherency strain, inhomogeneous strains due to crystal defects or interface roughness [18]. On the basis of the results of this investigation we are not able to determine whether the interface regions are paramagnetic or ferromagnetic.

The thickness of the interface regions in our multilayers increases with d_{Gd} and also with d_{Mo} [7]. This behaviour differs from that reported for MBE-grown single-crystal Gd/Y multilayers [14], in which a single Gd atomic layer at each interface was magnetically pinned regardless of the total layer thickness. The observed increase in M_M with increasing d_{Gd} or d_{Mo} shows that in Gd/Mo multilayers the interface regions are becoming magnetically harder as well as thicker, and our observations of the structure of the multilayers indicate that this behaviour is related to an increase in interface roughness. Our x-ray reflection results demonstrate that the rms roughness of the interfaces in Gd/Mo increases with increasing d_{Gd} and d_{Mo}. The relatively high rms roughness of Gd/Mo compared to Gd/W

is likely to be related to the fact that the Mo crystals grow with a non-close-packed crystal plane parallel to the plane of the layers, while the tungsten crystals in Gd/W have no preferred orientation [19]. Close-packed crystallographic planes, such as the (0001) plane in gadolinium, present a smooth, flat surface on the atomic scale whereas non-close-packed planes are atomically rough. The intrinsic atomic-scale roughness of the Mo(111) plane will be amplified as further Mo atoms are deposited at random positions on the growing molybdenum layer, and the rough molybdenum film will then form a rough base for the next gadolinium layer, so the roughness increases up through the layer stack [20].

Roughness of the molybdenum layers is probably responsible for the difference in texture that we observe between very thin (0.8 nm) and thicker Gd layers. Since the average thickness of a 0.8 nm Gd layer is comparable to the measured Mo layer roughness it follows that each thin Gd 'layer' will actually consist of non-uniform gadolinium regions with low connectivity. The gadolinium crystals cannot adopt their usual preferred orientation (the close-packed (0001) plane parallel to the layer plane) until the average Gd thickness is large enough to form a connected film over substantial areas. The low connectivity of very thin gadolinium layers must contribute to their low observed ordering temperature and their rapid decrease in magnetization with increasing temperature.

6. Conclusions

Gd/Mo multilayers have been prepared by dc magnetron sputtering with good layer regularity and compositional separation, but x-ray reflectometry indicated that the average rms layer roughness is high, increasing from 0.3 nm for 1 nm layers to 0.4 nm for 10 nm layers. TEM showed that the layers are polycrystalline, with preferred orientation in both materials. The nature of the preferred crystallographic orientation in the gadolinium layers depends on the layer thickness, changing between 0.8 and 3 nm.

Each gadolinium layer has been modelled as three magnetic regions: a central, magnetically 'soft' region and two magnetically 'hard' interface regions. As the Gd layer thickness increases the thicknesses of both the central region and the interface regions increase and the interface regions become magnetically harder. This behaviour is linked to the increase in interface roughness. The central regions of the gadolinium layers are ferromagnetically ordered with an ordering temperature proportional to layer thickness. The interface regions may be either paramagnetic or ferromagnetically ordered with strong pinning. We are unable to distinguish between these two possibilities on the basis of our experiments.

Acknowledgments

This research was supported by EPSRC grants GR/J37256, GR/H27823 and GR/K03456. The electron microscopy was carried out in the Electron Microscopy Unit, Department of Crystallography, Birkbeck College. The authors would like to thank G Akuetey, J Munn, A K Petford-Long and Professor K A McEwen for assistance and advice.

References

[1] For reviews see:
Majkrzak C F, Kwo J, Hong M, Yafet Y, Gibbs D, Chien C L and Bohr J 1991 *Adv. Phys.* **40** 99
Rhyne J J, Salamon M B, Flynn C P, Erwin R W and Borchers J A 1994 *J. Magn. Magn. Mater.* **129** 39
Also see papers given at *ICM'94*:

1994 *J. Magn. Magn. Mater.* **140–144** 769–84
[2] For example:
Zuberek R, Fronc K, Szymczak H, Nabialek A, Stobiecki T and Sokulski J 1995 *J. Magn. Magn. Mater.* **139** 157
Dufour C, Cherifi K, Marchal G, Mangin P and Hennion M 1993 *Phys. Rev.* B **47** 14 572
Motokawa M and Dohnomae H 1991 *J. Phys. Soc. Japan* **60** 1385
Wang Y J and Kleeman W 1991 *Phys. Rev.* B **44** 5132
Hosoito N, Yoden K, Mibu K, Shinjo T and Endoh Y 1989 *J. Phys. Soc. Japan* **58** 1775
Shan Z S, Sellmyer D J, Jaswal S S, Wang Y J and Shen J X 1989 *Phys. Rev. Lett.* **63** 449
[3] Raquet B, Sdaq A, Broto J M, Rakoto H, Ousset J C, Baudry A, Boyer P and Luche M C 1995 *J. Magn. Magn. Mater.* **140–144** 629
[4] Heys A, Donovan P E, Petford-Long A K and Cywinski R 1994 *J. Magn. Magn. Mater.* **131** 265
[5] Baenziger N C and Moriarty J L 1961 *Acta Crystallogr.* **14** 948
[6] Parratt L G 1954 *Phys. Rev.* **95** 359
[7] Harkins J V and Donovan P E 1996 *J. Magn. Magn. Mater.* at press
[8] Mayer H 1955 *Wissenschaftliche Verlagsgesellschaft (Physik Dünner Schichten 2)* (Stuttgart: Teubner)
[9] Morishita T, Togami T and Tsushima K 1985 *J. Phys. Soc. Japan* **54** 37
[10] Roeland L W, Cock G J, Muller F A, Moleman A C, McEwen K A, Jordan R G and Jones D W 1975 *J. Phys. F: Met. Phys.* **3** L233
[11] Koehler W C 1972 *Magnetic Properties of the Rare-earth Metals* ed R J Elliott (London: Plenum) ch 3
[12] Glass S J and Klein M J 1958 *Phys. Rev.* **109** 288
[13] Arrott A 1957 *Phys. Rev.* **108** 1394
[14] Kwo J, Gyorgy E M, DiSalvo F J, Hong M, Yafet Y and McWhan D B 1986 *J. Magn. Magn. Mater.* **54–57** 771
[15] Majkrzak C F, Cable J W, Kwo J, Hong M, McWhan D, Yafet Y, Waszczak J V, Grimm H and Vettier C 1987 *J. Appl. Phys.* **61** 4055
[16] (Ni/Cu): Zheng J, Ketterson J B, Falco C M and Schuller I K 1981 *J. Appl. Phys.* **53** 3150
(Fe/W): Xiao J Q and Chien C L 1991 *J. Appl. Phys.* **70** 6415
(Fe/V): Hosoito N, Kawaguchi K, Shinjo T, Takada T and Endoh Y 1984 *J. Phys. Soc. Japan* **53** 2659
(Fe/Nb): Mattson J E, Sowers C H, Berger A and Bader S D 1992 *Phys. Rev. Lett.* **68** 3252
(Co/Ti): Van Leeuwen R, England C D, Dutcher J R, Falco C M, Bennett W R and Hillebrands B 1990 *J. Appl. Phys.* **67** 4910
[17] Freeman A J 1972 *Magnetic Properties of the Rare-earth Metals* ed R J Elliott (London: Plenum) ch 6
[18] O'Handley R C and Sun S W 1992 *J. Magn. Magn. Mater.* **104–107** 1717
[19] Petford-Long A K, Donovan P E and Heys A 1992 *Ultramicroscopy* **47** 323
[20] Nevot L, Pardo B and Corno J 1988 *Revue Phys. Appl.* **23** 1675