A study of uranium-based multilayers: II. Magnetic properties

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Abstract

SQUID magnetometry and polarized neutron reflectivity (PNR) measurements have been employed to characterize the magnetic properties of U/Fe, U/Co and U/Gd multilayers. The field dependence of the magnetization was measured at 10 K in magnetic fields up to 70 kOe. A reduction in the magnetic moment was found for all systems. Magnetic ‘dead’ layers of ∼15 Å were determined for U/Fe and U/Co samples, indicative of chemically diffuse interfaces. For very thick layers, magnetic moments close to the bulk values were expected. For the U/Gd system, a large reduction in the magnetic moment, constant over a wide range of Gd layer thicknesses, was found (∼4 \(\mu_B\) compared with 7.63 \(\mu_B\) for the bulk metal). A possible explanation for this behaviour, consistent with observations of the structure of these multilayers, is that the Gd moments are pinned at the boundaries of column-like crystallites within the Gd layers. A study of the effective anisotropy and of a finite-size scaling behaviour of the U/Gd system is also presented. PNR data were collected in a field of 4.4 kOe for U/Fe and U/Co samples (at room temperature) and for U/Gd samples (at 10 K). Model calculations of the reflectivities used inputs extracted from the structural survey carried out on these systems, combined with data from the bulk magnetization measurements.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The fabrication of artificially layered heterostructures on a nanometre length scale has enabled us to explore the electronic interactions of dissimilar materials in close proximity to one another [1]. Magnetic multilayers represent a class of materials where the surface and interface effects contribute a major component of the properties of the sample as a whole, where the ability to tailor these effects and thus the sample properties, by careful control of the growth conditions, make this a very attractive route to study the properties of condensed matter [2]. This article focuses on the magnetic properties exhibited by multilayers, in particular the combination of a ferromagnetic component with uranium. Uranium is a light-actinide element; it is a paramagnetic metal at room temperature and below with a near temperature-independent susceptibility [3]. It is the first element in the period with an appreciable number of electrons in the 5f band, which has an itinerant character, close to the limit of localization [4]. In fact, ferromagnetism has been predicted at the surface of \(\alpha\)-U [5]. We are interested in any interfacial effects that might arise from hybridization of the U 5f electronic band with the electronic states of the ferromagnetic element and investigate the presence of any long-range collective phenomena.

A study of the structural and magnetic properties of the U/Fe system has been reported previously [6, 7]. However,
The magnetization measurements were carried out in Quantum Design MPMS (magnetic property measurement system) SQUID magnetometers at UCL and at the Clarendon Laboratory, Oxford. The data were taken using both the DC and the reciprocating sample option (RSO) in no-overshoot mode, which enables a slow stabilization of the field, an important consideration when measuring ferromagnetic signals with a large diamagnetic background, as in our case, due to the relatively thick sapphire substrates. Measurements of the magnetization as a function of applied field were recorded up to 70 kOe, at 10 K, well below the Curie temperatures of iron, cobalt and gadolinium (1043 K, 1388 K and 296 K, respectively).

2. Bulk magnetization

2.1. Experimental method

The magnetization measurements were carried out in Quantum Design MPMS (magnetic property measurement system) SQUID magnetometers at UCL and at the Clarendon Laboratory, Oxford. The data were taken using both the DC and the reciprocating sample option (RSO) in no-overshoot mode, which enables a slow stabilization of the field, an important consideration when measuring ferromagnetic signals with a large diamagnetic background, as in our case, due to the relatively thick sapphire substrates. Measurements of the magnetization as a function of applied field were recorded up to 70 kOe, at 10 K, well below the Curie temperatures of iron, cobalt and gadolinium (1043 K, 1388 K and 296 K, respectively).

2.2. U/TM field dependence

Figure 1 presents the saturation magnetization, \( M_{\text{sat}} \), plotted as a function of \( t_{\text{Fe,Co}} \); panel (a) describes the variation of the absolute magnetization, whereas (b) plots the values of magnetic moment per atom. The data in panel (a) were fitted to a linear relationship, which is then presented in panel (b) in units of \( \mu_B \)/atom. At large values of \( t_{\text{Fe,Co}} \) (inset of figure 1(b)) \( M_S \) tends towards the expected bulk moment values for Fe and Co of 2.2 \( \mu_B \) and 1.7 \( \mu_B \), respectively. The limited number of data points (figure 1(a)) implies some uncertainty in the extremal values of \( M_S \), although it is clear that values close to those of the bulk would be achieved with very thick layers. Values of the saturation magnetization in \( \mu_B/Fe, Co \), as determined by polarized neutron reflectivity, are also plotted in figure 1(b); these measurements are described later in the text.

The linear fit to \( M_{\text{sat}} \) described in figure 1(a) shows a direct proportionality between the increase in Fe or Co layer thickness and the saturation magnetization. The intercept of this line with the \( x \)-axis is an indication of the thickness at which there will be no magnetic moment, a magnetic ‘dead’ layer. However, this distinct separation of a non-ferromagnetic component and a ferromagnetic one is an unrealistic description of the Fe and Co layers. Mössbauer measurements on the U/Fe system [7] can be interpreted in terms of an iron layer comprising three components, Fe\(_\text{amorphous}\), which is paramagnetic, Fe\(_\text{bcc}\) carrying the bulk moment, and a non-magnetic Fe component likely to be present in a U–Fe alloy, where the spin up and spin down 3d bands of the iron can be equally populated; this alloy will be present at both U | Fe and Fe | U interfaces, since one of the principal factors for the formation of these alloy regions is that of chemical interdiffusion, a process independent of the sputtering sequence.

A consideration of the interfacial structure from x-ray diffraction data [8] and results from Mössbauer spectrosocopy [7] suggest that the centres of the layers are composed of bulk-like Fe, provided the Fe layers are thicker than the crystalline limit, \( \sim 20 \ \text{Å} \) [8], and then a U–Fe alloy region will be formed at the interfaces. These interfaces will then include components of non-magnetic Fe, where the concentrations of
Fe in U are low, and hence the coordination number of Fe is low. Across the interface from U to Fe, as the concentration of Fe atoms increases, paramagnetic Fe will be found and then ferromagnetic Fe as crystallites of \textit{bcc} Fe form. This result is supported by the x-ray diffraction data presented in paper I \cite{8}, which shows that for sample SN72, $[U_{23}/Fe_{17}]_{10}$, there is no visible intensity from any \textit{bcc} Fe component; however, a small magnetic moment is still present. This result suggests that the interface is a complicated mixture of Fe components. The similar atomic size (10.3 Å for Co compared with 11.5 Å for Fe) and diffusion properties of cobalt are likely to result in a similar interfacial structure and this is supported by the results shown in figure 1.

Although it is not wholly accurate to assign a ‘dead’ layer thickness, it is a useful tool to compare the extent of the interfaces. In the case of U/Fe and U/Co the values are very similar, 15 ± 2 Å and 16 ± 2 Å, respectively. The formation of such interfaces in transition metal multilayers is not uncommon and has been reported in Ni/Cu \cite{9}, Fe/W \cite{10}, Fe/V \cite{11}, Fe/Nb \cite{12} and Co/Ti \cite{13} systems. A schematic representation of a U/TM bilayer is shown in figure 2. The U/Gd interfaces are sharper than those for U/Fe or U/Co multilayers \cite{8} and do not include such a significant region of interdiffusion. In this case, the magnetic ‘dead’ layer is expected to be small.

2.3. \textit{U}/Gd field dependence

A study of the structural properties of uranium multilayers \cite{8}, suggests that the U/Gd interfaces are sharper than those for U/Fe or U/Co multilayers and do not include such a significant region of interdiffusion. In the U/TM systems a critical thickness for the onset of crystalline TM layers of $t_{\text{TM}} \sim 20$ Å was observed; no such critical thickness was apparent for the U/Gd system. Thus, for the case of U/Gd multilayers the magnetic ‘dead’ layer is expected to be small.

The saturation magnetization values, $M_{\text{sat}}$, are plotted in figure 3 for samples with $t_{0} \sim 25$ Å. The field was applied in the plane of the multilayers, $H_{\text{para}}$. A linear relationship is found between the saturation magnetization and the gadolinium layer thickness. The $x$-axis intercept of the fitted line gives the thickness of the magnetic ‘dead’ layer, which in this case is $3 \pm 1$ Å. The inset in panel (b) shows the extrapolated form of the saturation magnetization for large values of $t_{\text{Gd}}$, towards a value of 4.3 $\mu_{B}$. Figure 3(b) also includes saturation magnetization data obtained from polarized neutron reflectivity data (PNR), described in section 3.

There are some important observations to be made from figure 3. First, the magnetic ‘dead’ layer of $3 \pm 1$ Å is significantly thinner than that observed in the U/TM systems. Second, whereas for the U/TM multilayers $M_{\text{sat}}$ tended towards the bulk moment value for very thick TM layers (see inset of figure 1(b)) the saturation magnetization extrapolated for large values of $t_{\text{Gd}}$ in U/Gd multilayers tends towards a value of 4.3 $\mu_{B}$, significantly reduced from the bulk metal value of 7.63 $\mu_{B}$. This indicates that the reduction in magnetic moment is not confined simply to the interface regions, but is an effect arising from the bulk of the Gd layers. Significantly reduced values of the ordered gadolinium moment have been observed in other multilayer systems, such as Gd/Mo \cite{14}, Gd/V \cite{15} and Gd/Cr \cite{16}. The possible mechanisms for this phenomenon were discussed for the Gd/Mo system \cite{14} in.
The magnetic anisotropy energy, $K_{\text{eff}}$, can be determined from the difference in area of the magnetization loops (perpendicular minus parallel); this relationship holds for all directions of the magnetic easy axis. The sign convention adopted for $K_{\text{eff}}$ denotes that a positive $K_{\text{eff}}$ indicates a perpendicularly oriented magnetic easy axis. The magnetic anisotropy energy or effective anisotropy is primarily a combination of magnetic dipolar (favouring an in-plane alignment) and magnetocrystalline anisotropies, stemming from the long-range magnetic dipolar and spin–orbit interactions, respectively. These contributions can be resolved into volume, $K_V$, and surface, $K_S$, contributions to give,

$$K_{\text{eff}} = K_V + 2K_S/t_{\text{Gd}}$$

(1)

$K_V$ is dominated by the magnetic dipolar or shape anisotropy, whereas the lowered symmetry at the interface leads to a dominant spin–orbit effect and therefore surface anisotropy. A plot of the ferromagnetic layer thickness, $t$, versus $tK_{\text{eff}}$ should yield a linear function, where the gradient of the line can be used to calculate the volume anisotropy term and the $y$-intercept gives twice the surface term.

Although this treatment of the anisotropy of multilayer systems has become commonplace, we note that there are several important assumptions concerning this extraction of the volume and surface contributions from the effective anisotropy. It is assumed that the anisotropy, localized at the interface region, influences the magnetic moments within the bulk of the layer; this is only true if the anisotropy is much smaller than the intralayer exchange, i.e. when the layer is thinner than the exchange length, which is of the order of 50 Å. Also, the validity of the separation of the effective anisotropy into surface and volume terms becomes questionable when the layers are very thin and are almost entirely comprised of interface region.

Table 1 gives $H_{\text{C}}^{\text{para}}$, $H_{\text{C}}^{\text{perp}}$, and $K_{\text{eff}}$ for selected U/Gd samples. Figure 5(a) shows a plot of $t_{\text{Gd}} K_{\text{eff}}$ as a function of the gadolinium layer thickness and as a function of the uranium layer thickness. Panel (b) of figure 5 presents the coercive field values as a function of $t_{\text{Gd}}$ with the applied magnetic field parallel and perpendicular to the plane of the sample.

In bulk dhcp gadolinium a small uniaxial anisotropy acts to align the spins parallel to the $c$-axis between the magnetic ordering (Curie) temperature, $\sim$296 K, and the spin re-orientation transition temperature at $\sim$230 K [18]. The direction of growth of the gadolinium layers in these U/Gd multilayers is primarily [00.1] [8] so that the uniaxial anisotropy might act to align the moments out of the plane of the film. However, figure 5(a) clearly shows that for all Gd thicknesses investigated, a negative effective anisotropy was measured. This indicates an in-plane alignment of the magnetic moments. A linear fit to the data yields values for $K_V$ and $K_S$ of $-1.2 \pm 0.3$ MJ m$^{-3}$ and $0.28 \pm 0.2$ mJ m$^{-2}$, respectively, which are smaller than those obtained for the U/Fe system ($K_V = -1.8$ MJ m$^{-3}$ and $K_S = 2.0$ mJ m$^{-2}$) [19]. Our
Figure 5. (a) $t_{\text{Gd}}K_{\text{eff}}$ as a function of $t_{\text{Gd}}$ (solid black squares, left-hand axis) and as a function of $t_U$ (solid red circles, right-hand axis). The solid black line is a linear fit to the data. (b) Coercive field values as a function of $t_U$, with the applied magnetic field parallel to the plane of the sample, $H_{C,\text{para}}^{\text{eff}}$ (left-hand y-axis, solid red circles) and perpendicular, $H_{C,\text{perp}}^{\text{eff}}$ (right-hand y-axis, open blue circles). Dashed lines are guides to the eye.

values are comparable to those obtained for other Gd thin film systems, such as Gd grown on W, where values of between 0.47 and 1.9 mJ m$^{-2}$ and $-1.5$ to $-0.95$ MJ m$^{-3}$ have been reported for $K_S$ and $K_V$, respectively [20, 21].

The volume term includes contributions from the magnetocrystalline anisotropy, the shape (dipolar) anisotropy and a volume magnetoelastic anisotropy, whereas the surface term is comprised of a surface magnetoelastic effect and a Néel type surface anisotropy, concerned with the symmetry breaking at the interface. The negative slope of the fitted line in figure 5(a), for U/Gd with constant $t_U$, is a result of the competing shape anisotropy (acting to align the moments within the plane of the film) and surface anisotropy terms (perpendicular alignment). The fitted line extrapolates to a ($t_{\text{Gd}}K_{\text{eff}} = 0$) thickness of $\sim 5$ Å; thus a [U$_{25}$/Gd$_{35}$]$_N$ sample might exhibit perpendicular magnetic anisotropy (PMA). The variation from linearity at large values of $t_{\text{Gd}}$ is consistent with the observation of increased interfacial roughness, which is known to affect the anisotropy [22, 23]. The effect of varying $t_U$ on $K_{\text{eff}}$ is of a smaller magnitude, however there is a minimum in the anisotropy coincident with the minima of the coercive field data, shown in panel (b).

Figure 5(b) shows the variation in coercive field for different U layer thicknesses for both field directions. A minimum in $H_{C,\text{para}}^{\text{eff}}$ can be observed at $t_U \sim 20$ Å. As $t_U$ becomes thinner $H_{C,\text{para}}^{\text{eff}}$ changes very little, whereas $H_{C,\text{perp}}^{\text{eff}}$ shows a dramatic increase. For thicker U layers the situation is reversed; $H_{C,\text{perp}}^{\text{eff}}$ changes very little, but $H_{C,\text{para}}^{\text{eff}}$ shows a marked increase. This could be a consequence of the increased strain, a possible explanation for the decrease in $M_{\text{sat}}$ seen in figure 4 and consistent with the observation of the anisotropy data in figure 5(a).

2.5. Temperature dependence

The temperature dependence of the magnetization has been measured for a number of U/Gd multilayer samples with different gadolinium layer thicknesses. Zero field cooled measurements were made between 5 and 375 K in an applied field of 1 kOe with the field applied in the plane of the multilayers. For the purpose of this study $T_C$ was taken as the point at which spontaneous magnetization begins to be observed (i.e. the maximum in the second derivative of the susceptibility).

Figure 6(a) shows the temperature-dependent magnetization curves for a selection of U/Gd multilayers. The variation in lineshapes as a function of the gadolinium layer thickness suggests that the Gd layers consist of regions that have different Curie temperatures, specifically a difference in the behaviour of the centre of the layers and the interface. The dramatic difference between the sample grown at elevated temperature and a sample of similar composition, suggests that it may be strains at the interface region that cause a change in the onset of magnetization, since it is likely that the high temperatures allow the interfacial strain to relax, accommodating dislocations. Panel (b) presents the Curie temperatures for each of these samples as a function of $t_{\text{Gd}}$. The gadolinium layer thickness in this case is given in units of monolayers (1 ML = 2.9 Å [8]). Such a decrease in $T_C$ is well known in thin film systems and can be described by a finite-size scaling relationship [24]:

$$\frac{T_C(\text{bulk}) - T_C(t_{\text{Gd}})}{T_C(\text{bulk})} = C_0 \times \frac{t_{\text{Gd}}}{t_{\text{Gd}}}$$

where $C_0$ is an arbitrary constant, which includes contributions from interlayer coupling effects and $\lambda = 1/\nu$, where $\nu$ is the
This yields values for $\lambda$ solid line in figure 6(b) is the result of fitting to equation (2); this effect in thin films implies a layer-by-layer growth. The finite-size scaling effect and asserted that an observation of temperature of gadolinium grown on tungsten [24] reported interfaces. A similar study of the thickness-dependent Curie requires a coherent multilayer growth with little diffusion at the interfaces. This gives a value for the critical exponent, $\nu$, of 0.64, which is consistent with the 3D Ising model (0.63) [29] and with the relationship observed for the Gd/W thin films [24].

For the U/Gd multilayers with the thinnest gadolinium layers, the observed $T_C$ (90 K) is much higher than that expected from the finite-size scaling behaviour. This has also been observed in the Gd/W system [24] [30] and has been related to the cross-over from 3D to 2D magnetic behaviour, where theory predicts $\nu = 1.00$ in the 2D regime. Sample SN124, grown at a temperature of 600 K, also exhibits a $T_C$ that is higher than that expected. For the Gd/W system [24], higher than expected $T_C$ values were attributed to the accommodation of misfit dislocations and the presence of large inhomogeneous strains, caused by steps and other defects at the interface. The observation of a higher than expected Curie temperature for the U/Gd sample grown at elevated temperature is consistent with these ideas.

3. Polarized neutron reflectivity (PNR)

Neutrons are an extremely useful tool to study simultaneously the chemical and magnetic structure, since they interact with both the nuclei and atomic moments. By aligning a polarized neutron beam normal to the scattering plane and parallel to the sample surface, polarized neutron reflectivity can be used to determine the spin-flip (SF, $R^{+-}$ and $R^{-+}$) and non-spin-flip (NSF, $R^{++}$ and $R^{--}$) reflectivities, provided the magnetic field is applied along the quantization direction of the neutron. The difference between the NSF reflectivities is proportional to the magnetization along the field direction, whereas the difference in SF reflectivities is proportional to the square of the magnetization perpendicular to the applied field. Thus, PNR can be used to determine the layer thicknesses and roughnesses, the average magnetic moment per atom, the orientation of the magnetization and the distribution of magnetization in magnetic multilayers.

3.1. Experimental method

PNR measurements were carried out on the CRISP reflectometer of the ISIS time-of-flight neutron source at the Rutherford Appleton Laboratory. U/Fe and U/Co samples were measured at room temperature and PNR data were collected in the specular geometry over a typical $Q$ range of 0.005–0.20 Å$^{-1}$, in an applied magnetic field of 4.4 kOe, large enough to saturate the magnetization within the plane of the film. U/Gd samples were cooled in zero field to 10 K, well below their Curie temperatures. Only the NSF reflectivity was measured. The xPOLLY programme [31] was used to calculate polarized neutron reflectivities, which were fitted to the experimental data.

3.2. Results

This section presents the experimental data and calculated reflectivities for a selection of U/Fe, U/Co and U/Gd samples. The layer thickness and roughness parameters were fixed at values obtained from x-ray reflectometry. For the case of the U/TM multilayers the large roughnesses accounted for the diffusion at the interfaces, responsible for the magnetic ‘dead’ layer observed in the bulk magnetization. To analyse the PNR results, the ferromagnetic layers were separated into regions which exhibit a magnetic moment per atom equivalent to the bulk metal, placed at the centres of the layers, and regions with no magnetic moment, at the interfaces. Although it is clear that the layers will not have such discrete sections, it was not possible to distinguish more complex magnetization distributions from the PNR data.

The average magnetization per atom may be accurately determined, by closely monitoring the splitting of the two spin channels at the critical edge, the angle at which the
Figure 7. Panels (a) and (c) present the polarized neutron reflectivity data measured in the specular geometry at 300 K and 4.4 kOe for samples SN71, [U$_9$/Fe$_{34}$]$_{30}$ and SN118, [U$_9$/Co$_{34.5}$]$_{20}$, respectively. Experimental data and fitted, calculated curves are shown as black points (curve) for the R$^{++}$ channel and red points (curve) for the R$^{--}$. The asymmetry for these two samples is shown in panels (b) and (d); red points represent the data and the solid blue line, the fitted calculation.

Table 2. The thicknesses of the three components of the transition metal layers for a selection of U/Fe and U/Co samples, determined from the fitted PNR results.

| Sample  | Composition      | $t_{TM1}$ (±1 Å) | $t_{TM2}$ (±1 Å) | $t_{TM3}$ (±1 Å) |
|---------|------------------|------------------|------------------|------------------|
| SN71    | [U$_9$/Fe$_{34}$]$_{30}$ | 8.0              | 22.5             | 3.5              |
| SN74    | [U$_{32}$/Fe$_{27}$]$_{30}$ | 8.5              | 16.2             | 2.5              |
| SN75    | [U$_{35}$/Fe$_{27}$]$_{30}$ | 7.5              | 15.0             | 4.5              |
| SN116   | [Co$_{42}$/U$_{19}$]$_{20}$ | 11.0             | 24.0             | 7.0              |
| SN117   | [U$_9$/Co$_{34.5}$]$_{18}$ | 8.0              | 39.0             | 4.3              |
| SN118   | [U$_9$/Co$_{34.5}$]$_{20}$ | 8.0              | 22.5             | 4.0              |

neutron beam no longer undergoes total external reflection. In this region of the reflectivity curve the splitting of the two spin channels is sensitive to the magnetization of the whole sample. The values for the average magnetic moment per atom determined in this way are shown in figures 1(b), 3(b) and 4.

Figure 7(a) shows the normalized non-spin-flip reflectivity from sample SN71, [U$_9$/Fe$_{34}$]$_{30}$. The solid lines represent the calculated reflectivities for both spin channels. Panel (b) displays the asymmetry, determined from the difference divided by the sum of the reflected intensities. Figures 7(c) and (d) present similar results for the U/Co sample, SN118, [U$_9$/Co$_{34.5}$]$_{20}$.

A model, describing a multicomponent ferromagnetic layer in U/TM multilayers has been proposed in an earlier investigation of U/Fe multilayers [7], but a new interpretation of these components was given in paper I [8] (UTM$_\text{alloy}$ | TMA$_\text{amorphous}$ | TM$_\text{bulk}$ | TMU$_\text{alloy}$) and is shown in figure 2. Table 2 gives the thicknesses for a three-component ferromagnetic transition metal layer. TM1 represents a combination of the UT$_{\text{alloy}}$ and TM$_{\text{amorphous}}$ regions and carries no magnetic moment. It has a density that is 5% reduced from that of the bulk material. The central region of the layer, TM2, has equivalent magnetization and density properties to those of the bulk. TM3 includes the TM$_{\text{alloy}}$. The calculated reflectivities and asymmetries only reproduce the experimental data well when TM1 is greater than TM3, a trend observed for all U/TM samples investigated and consistent with the current description of the growth of U/TM multilayers [8]. The sum of the thickness of layers TM1 and TM3 gives the magnetic ‘dead’ layer thickness, $\sim 12$ ± 2 Å, which is close to the value determined by SQUID magnetometry (15 ± 2 Å and 16 ± 2 Å for U/Fe and U/Co, respectively).

Figure 8 shows the experimental data and fitted model for the NSF reflectivity of sample SN63, [U$_{25}$/Gd$_{33}$]$_{20}$. The U/Gd samples were modelled by a simple bilayer structure. Figure 2(b) showed that the saturation magnetization did not vary significantly for a wide range of Gd layer thicknesses, indicating a constant distribution of the magnetization within the Gd layers. It is clear from figures 8(a) and (b) that the calculated reflectivities for the NSF channels do not adequately reproduce the data far away from the Bragg peak positions. In particular, the experimental R$^{--}$ intensity is significantly larger in this region than that calculated. This results in a large asymmetry in the calculated case, but very little splitting of the NSF channels in the experimental data. The saturation magnetizations, determined from the splitting of the channels in the vicinity of the critical edge are consistent with SQUID magnetometry measurements. These measurements indicated an even distribution of the magnetic moment through the Gd layers (figure 3(a)). Attempts to introduce a complex
interfacial structure, as was successful for the U/TM samples, did not result in any improvement in the fit for the U/Gd multilayers.

4. Conclusions

The magnetic properties of U/TM (Fe and Co) and U/Gd multilayers have been determined by a combination of SQUID magnetometry and polarized neutron reflectivity measurements. These results are consistent with ideas developed in paper I [8], concerning the structure and interfacial properties of U/TM and U/Gd systems.

Magnetization measurements on U/Fe multilayers, grown on sapphire substrates with Nb buffer and capping layers, exhibited similar magnetic properties to those grown on glass [7]. This indicates that the predominant effects in this system arise from the interfaces between the two elements. Qualitatively similar effects were reported on the U/Co system. Extrapolated to large values of $t_{Fe}$ and $t_{Co}$, the saturation magnetization is found to be close to that of the bulk metals. The presence of a magnetic ‘dead’ layer ($\sim 15$ Å) for U/TM multilayers was inferred from both SQUID magnetometry and PNR measurements. However, it was possible to determine a further degree of complexity concerning the TM layers from the PNR data. The experimental data were well modelled by slicing the TM layers into regions with no magnetic moment, on either side of a central bulk-like region. The thicknesses of these slices were consistent with the structural description of the U/TM interfaces developed in paper I [8].

For the U/Gd multilayers, the magnetic moment measured by SQUID magnetometry and PNR was found to be substantially lower than that of bulk gadolinium. However, the mechanism for this reduction is clearly different from that observed in U/TM multilayers. The magnetically ‘dead’ layer observed for the U/Gd system is $3\pm 1$ Å, too small to account for such a large loss in magnetization. This reduction was constant across a wide range of Gd layer thicknesses and cannot be an effect confined to the U/Gd interfaces. A column-like growth, capable of producing the necessary strains and resultant defects in order to pin large numbers of Gd moments is the most likely explanation for this reduction. This picture is consistent with observations of the roughness and crystalline properties described in paper I [8] and with the PNR results.

For U/Gd samples, neither a simple layer structure nor a segmented layer model reproduce the observed experimental data in the PNR experiments. Intensity is observed in the R$^{--}$ channel that is much greater than that expected from model calculations. This effect can be attributed to the large reduction in saturation moment. The pinned moments at the boundaries of column-like gadolinium grains give rise to diffuse scattering, which could contribute to the additional intensity observed. Off-specular measurements will be employed to investigate the diffuse scattering and dichroism measurements will be used to explore any polarization of the U 5f states.

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