IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Dynamic, *in situ* optical, magnetic and magneto-optical monitoring of the growth of Co/Au and Pd/Co/Au multilayer systems

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2005 J. Phys.: Condens. Matter 17 5313

(http://iopscience.iop.org/0953-8984/17/34/014)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 129.252.86.83
The article was downloaded on 28/05/2010 at 05:53

Please note that terms and conditions apply.

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **17** (2005) 5313–5326 doi:10.1088/0953-8984/17/34/014

Dynamic, *in situ* optical, magnetic and magneto-optical monitoring of the growth of Co/Au and Pd/Co/Au multilayer systems

W R Hendren, C Cassidy, R Atkinson, I W Salter and R J Pollard

School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK

E-mail: ronald.atkinson@qub.ac.uk

Received 9 March 2005, in final form 25 July 2005
Published 12 August 2005
Online at stacks.iop.org/JPhysCM/17/5313

Abstract

The growth of magnetron sputtered Co/Au and Pd/Co/Au superlattices on Au and Pd buffer layers, deposited onto glass substrates, has been monitored optically and magneto-optically in real time, using rotating analyser ellipsometry and Kerr polarimetry, at a wavelength of 633 nm. The magneto-optical traces, combined with *ex situ* and *in situ* hysteresis loops, provide a detailed and informative fingerprint of the optical and magnetic properties of the films as they evolve during growth. For Co/Au, oscillations in the polar magneto-optical effect developed during the deposition of Au overlayers on Co and these may be attributed to quantum well states. However, the hysteresis measurements show that the magnetic field required to maintain saturation magnetization throughout the experiment was larger than available *in situ*, introducing a degree of confusion concerning the interpretation of the data. This problem was overcome by the incorporation of Pd layers into the Co/Au structure, thereby eliminating variation in magnetic orientation during growth of the Au layers as a contributory factor to the observations.

1. Introduction

Recently, studies of multilayers of magnetic materials combined with a noble metal have revealed a variety of thickness dependent phenomena. In particular, several oscillatory effects associated with the changing thickness of noble metal overlayers have been observed in the magnetic anisotropy [1], magneto-optical effects [2, 3], and even strength of coupling between magnetic layers in the multilayer structure [4], and these are generally explained in quantum mechanical terms.

In a previous paper [2], *in situ* magneto-optical studies were reported on the Co/Au system. These contrasted with other published experiments, in that the structures grown were more sophisticated, with a multilayer consisting of up to ten bilayers, and the measurements were

 © 2005 IOP Publishing Ltd Printed in the UK

made dynamically during growth with magneto-optical data accompanied by a corresponding set of optical measurements. Furthermore, whilst studies done by others paid particular attention to the sharpness of the interfaces between layers, on which the magneto-optical oscillations were expected to be highly reliant, in our case no such precautions were taken and films were deposited using industrially compatible r.f. magnetron sputtering in an argon atmosphere at low deposition rates of around 0.3 Å s^{-1}. Nevertheless, clear oscillations in the linear polar magneto-optical effects were observed, during the growth of the Au layers, which persisted throughout the deposition.

Despite the clarity of the observations reported previously, some doubt existed in the interpretation of the data, which stemmed from uncertainty in the dynamic magnetization state of the growing samples. Hysteresis studies, done *ex situ* after the deposition, showed that the film was fully remanent and could easily be magnetized perpendicular to the film plane by the field applied *in situ* during the deposition process. However, it could not be assumed that this would also be true throughout the formation of the multilayer. Given that Au overlayer thickness affects magnetic anisotropy [1], and that the deposition conditions were not particularly conducive to quantum well states, it was possible that the observed oscillations were, at least partly, due to changes in the magnitude of the film magnetization and/or magnetic orientation. Consequently, it was felt necessary to confirm the interpretation of the observations by carrying out *in situ* magnetic measurements during growth and, if full magnetization was not always being achieved, develop a means by which the perpendicular magnetic anisotropy of the films could be assured.

In a follow-up publication to [2], *in situ* hysteresis studies were carried out on Co/Pd multilayers, where the Co layer was 3 Å thick [5]. Amongst other things, it was found that a Co layer deposited on Pd was always perpendicularly magnetized with 100% remanence. Accordingly, it was felt that by incorporating Pd into a Co/Au multilayer it might be possible to ensure perpendicular magnetization during the deposition of the Au layers, and to explore the impact of this on the observations of associated magneto-optic oscillations.

In this paper, the results of *in situ* optical (ellipsometric), magnetic and magneto-optical investigations into the growth of Pd/Co/Au multilayers are presented. First, and for comparison, we report some hysteresis studies on Co/Au, which confirm that the films were not completely magnetized in the direction perpendicular to the film plane until quite late in the multilayer deposition. Second, we report studies on 5 Å thick Co layers deposited on Pd that show a complementary magnetic behaviour to that of 3 Å Co on Pd [5]. Finally, the development of the magnetic, optical and magneto-optical properties of a trilayer-based Pd/Co/Au multilayer system will be discussed in detail.

2. Experimental details

Figure 1 shows a schematic diagram of the deposition chamber and associated monitoring equipment. The system achieved a base pressure of $\sim 1 \times 10^{-6}$ mbar using a turbo-molecular pump. Films were sputter deposited in an Ar atmosphere of $\sim 2.2 \times 10^{-3}$ mbar, at room temperature, onto glass substrates. Two r.f. magnetrons were used for the deposition of Au and Co and a dc magnetron was used for the deposition of Pd. The deposition rates were typically ~0.5 Å s^{-1}.

In situ optical and magneto-optical monitoring at 6328 Å was achieved using a fast, rotating analyser ellipsometer and a normal incidence Kerr polarimeter. The ellipsometer was used to record the development of the optical functions $\mathrm{Re}(r_p/r_s)$ and $\mathrm{Re}(r_s/r_p)$ during growth, where r_p, r_s are the *complex Fresnel amplitude reflection coefficients* for p- and s-*polarized* light, respectively. Measurements were made at a constant rate of 1 s^{-1} throughout

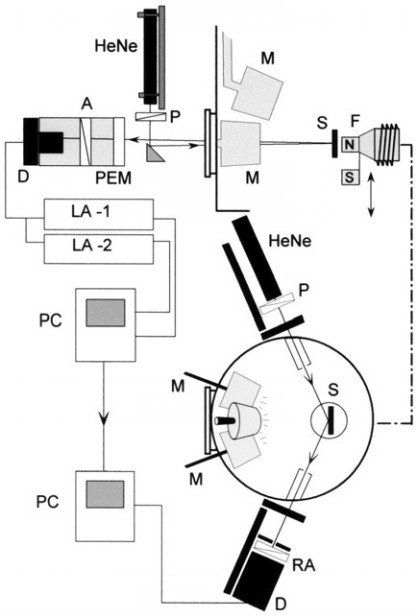

Figure 1. Schematic diagram of the deposition system. HeNe, helium–neon laser; A, analyser; P, polarizer; RA, rotating analyser; PEM, photoelastic modulator; M, magnetron; PC, computer; S, substrate; D, detector; LA-1, lock-in amplifier (50 kHz); LA-2, lock-in amplifier (100 kHz); F. field switch/electromagnet.

the deposition process, although the time required to complete a measurement was only 100 ms. The Kerr polarimeter, based on a photoelastic modulator (PEM) operating at 50 kHz, allowed the simultaneous measurement of both *Kerr rotation* and *ellipticity* with a precision better than ± 1 arcsec. The details of this technique may be found elsewhere [6]. All films were deposited in a reversible applied perpendicular field, supplied by either an arrangement of permanent magnets (± 0.15 T) or a manually operated, uncooled, electromagnet (± 0.2 T).

Two interconnected and synchronized computers co-ordinated the deposition parameters of all materials, including the control of magnetron shutters, magnetic field switching and the status of a quartz-crystal monitor. In addition, they controlled the operation of the ellipsometer and the Kerr polarimeter and all data collection during the deposition process.

3. Results

3.1. Hysteresis measurements on Co/Au multilayers

To begin with, it is appropriate to investigate how the magnetic behaviour of a Co/Au structure develops during growth and whether or not the *in situ*, static magnetic fields, used here and in previous work [2], were adequate to magnetize the films to saturation in a direction perpendicular to the film plane. Figure 2(a) shows the *in situ* magneto-optical measurements for 10 bilayers of Co(5 Å)/Au(37.5 Å) on a 125 Å Au buffer deposited on glass. This is the same structure as studied in [2]; however, it must be noted that, in the latter case, the static magnetic field applied during deposition and measured at the front surface of the substrate was 0.28 T, compared with 0.15 T for the experiment presented here. Despite this difference, figure 2(a)

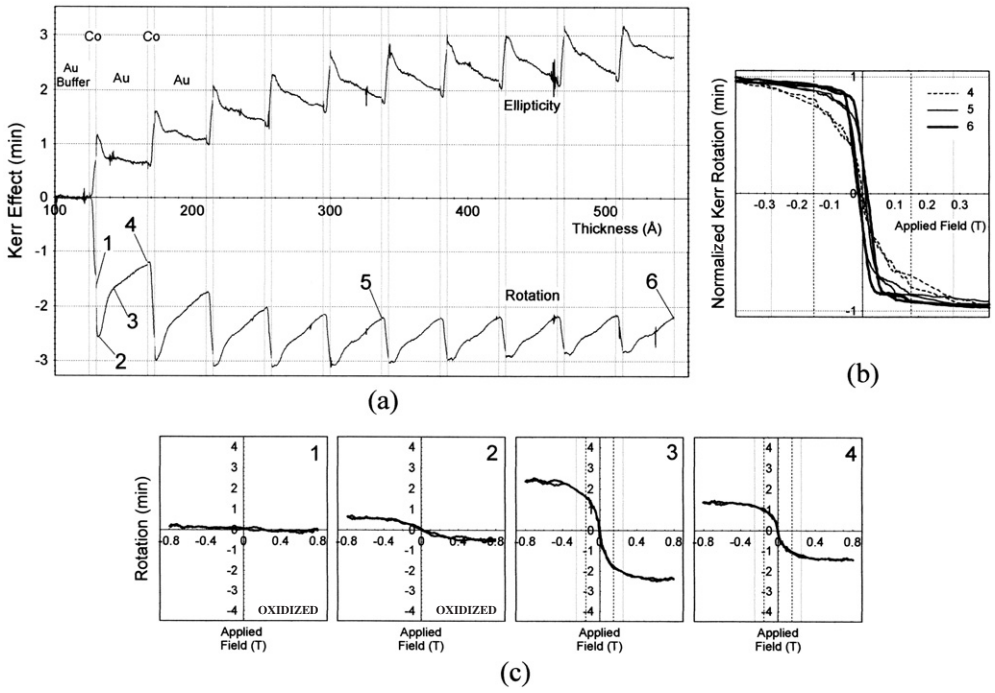

Figure 2. (a) MO growth curves for Co(5 Å)/Au(37.5 Å) multilayer on a Au(125 Å) buffer. (b) *Ex situ* polar hysteresis loops taken after one, five and ten bilayers (points 4–6 on (a)). (c) *Ex situ* polar hysteresis loops for a single bilayer: Au overlayer thickness = 0, 2, 12 and 37.5 Å (points 1–4 on (a)). The grey and dotted vertical lines in (b) and (c) represent ±0.28 and 0.15 T respectively.

compares well with previously reported results, with oscillations clearly discernible in the Kerr ellipticity during every Au deposition, and increasingly in the Kerr rotation as the number of periods in the multilayer increases. The reason for this observation is well understood and related to the developing optical properties of the structure as reported in [2].

Initially, the dependence of the magnetic behaviour of the film on the number of the bilayers was investigated by growing a series of samples with depositions terminating at the points indicated on figure 2(a) (1–6). The hysteresis loop of each sample was then measured, *ex situ*, using the polar magneto-optical Kerr effect (PMOKE). The results are summarized in figure 2(b), which illustrates the evolving perpendicular anisotropy as the number of bilayers increases. It is worth noting that the size of the field required to saturate the film magnetically is always larger than 0.28 T, even at the end of the experiment. This is a little different to the results of [2], where the film was easily magnetized and had 100% remanence when measured at the end of the tenth bilayer. The reason for the disparity is probably due to small differences in layer thickness, in particular that of the Co layers.

The hysteresis loops associated with the first bilayer (1–4) are shown in figure 2(c) and it is clear that the results are anomalous when compared to the magneto-optical effects observed *in situ*. Loops 1 and 2 have a much smaller magneto-optical signal than expected, whereas close examination of loops 3 and 4 reveals a slightly larger magneto-optical effect than recorded *in situ*. In the latter case, this is due to the inadequacy of the *in situ* applied field, as indicated by the dotted vertical lines at ±0.15 T. However, the Kerr rotations recorded at ±0.15 T during the hysteresis measurements are consistent with those observed *in situ*. For loops 1 and 2, the low

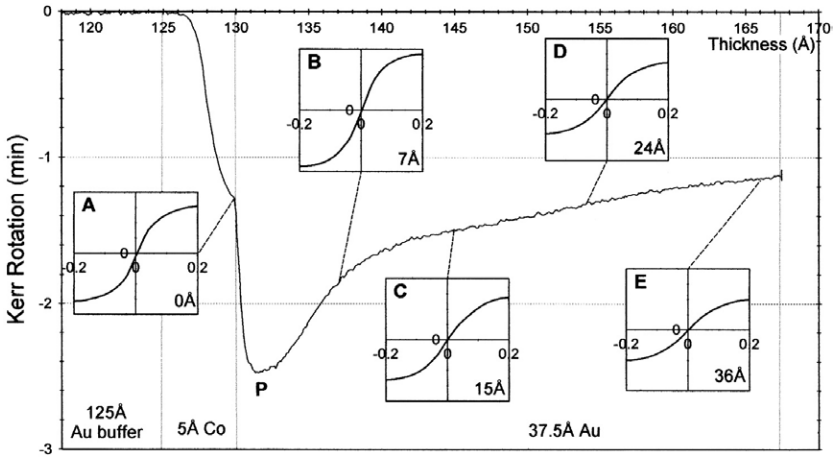

Figure 3. *In situ* hysteresis loops (A–E) taken at different stages during the growth of a Co(5 Å)/Au(37.5 Å) bilayer on a Au(125 Å) buffer. The loops are marked with the Au overlayer thickness and the same scale is used in each case.

magneto-optical effects are a direct result of the oxidation (or contamination) of the exposed Co layer and illustrate the need for the measurements to be made *in situ*. For this reason, an *in situ* study of how the magnetic hysteresis develops during the deposition of the Au in the first bilayer was undertaken, and the results are seen in figure 3. The loops were taken during a pause in the bilayer deposition, using an electromagnet capable of fields up to 0.2 T. Importantly, the loops demonstrate that the static *in situ* fields were always inadequate to saturate fully the magnetization of the film. It is possible that the peak (P) in the magneto-optical effect at 2 Å of Au coverage is indicating a point where the structure was fully magnetized and this interpretation would be consistent with the studies of others [1], which show an enhancement of perpendicular magnetic anisotropy for a Au overlayer of approximately this thickness. However, since no *in situ* loop was taken at this point, we cannot confirm this conclusively. Moreover, it will be seen later that this explanation alone is inadequate to account for this peak completely.

To summarize, this initial study confirms that the magnitude of the static magnetic field required to guarantee full perpendicular saturation magnetization is larger than that available *in situ*. Consequently, the interpretation of the observation of oscillations in the magneto-optical effects during the growth of Au overlayers could be confused if there is a dependence of the magnetic anisotropy on the thickness of the Au overlayer.

3.2. The effect of a Pd buffer layer on a Co/Au multilayer

In a previous paper [5], it was shown that a 3 Å Co layer grown on Pd has remarkably strong perpendicular magnetic anisotropy. In order to resolve the uncertainties concerning perpendicular magnetization in Co/Au, it was proposed that the Au buffer be replaced with Pd to increase the perpendicular magnetic anisotropy of the multilayer. However, to be useful in the context of our Co/Au investigations, the thickness of the Co layer would have to be 5 Å and, since the perpendicular contribution to the total magnetic anisotropy is mostly associated with interfacial effects, it was possible that some fraction of the thicker Co layer would be magnetized in the plane of the film.

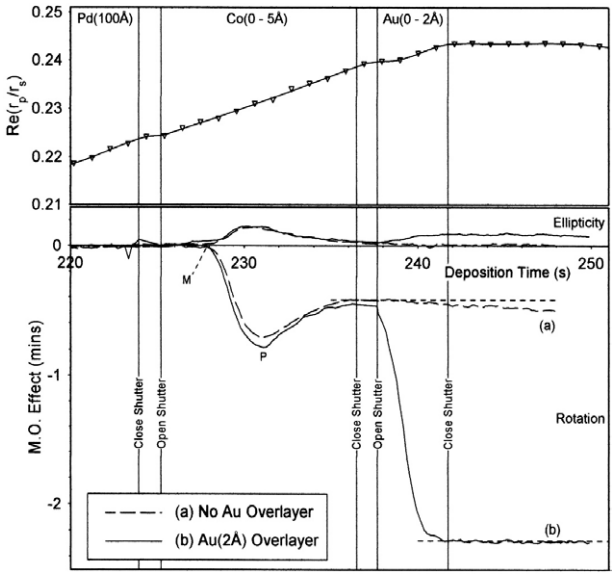

Figure 4. The magneto-optical developments observed during the deposition of 5 Å of Co onto 100 Å of Pd followed by (a) no further depositions (dashed traces); (b) the deposition of 2 Å of Au (solid traces). Also shown are the optical measurements for the latter experiment (top graph). The solid vertical lines mark the beginning and end of each deposition phase.

The magneto-optical effects observed during the growth of a Co(5 Å) layer on Pd(100 Å) are shown in figure 4. The figure compares two experiments: (a) where the Co layer is not covered by Au, and monitoring is continued for 10 s after the deposition ends (dashed traces); (b) the Co layer is followed by 2 Å of Au (solid traces). The evolving magneto-optical developments are seen most clearly in the Kerr rotation, which, at this stage, is the larger of the two parameters. The interpretation of the curve shapes is as follows. As the Co atoms are deposited, there is a delay in the manifestation of magneto-optical effects until a thickness of about 1.5 Å (marked M on the figure). During this stage, *in situ* ellipsometry (shown as $\mathrm{Re}(r_\mathrm{p}/r_\mathrm{s})$, in figure 4) confirms that Co is being deposited, and the absence of magneto-optical effects is interpreted as a paramagnetic or super-paramagnetic phase associated with the dispersed nature of the Co atoms on the surface. This observation is consistent with our previous studies on both Co/Pd [5] and Co/Au [2]. However, the thickness at which the magneto-optical effects are first observed is less than a monolayer and this is significantly less than that reported by others for the onset of ferromagnetism [7–9]. We believe that the appearance of magneto-optical effects at this early stage is explained in terms of a low density of nucleation sites and the mobility of the Co atoms which combine to form a small number of rapidly growing islands that become ferromagnetic much more quickly than if the film were to grow uniformly over the surface.

Whatever the case, once the magneto-optical effects appear, they increase rapidly to a maximum (P) at approximately 3 Å of Co where there is a turning point and the effects begin to decrease. If no material deposition follows the Co layer, as in case (a), the polar Kerr rotation is observed to steadily, but slowly, increase. However, if Au is deposited on top of the Co, case (b), there is an immediate and very spectacular increase in the magneto-optical response. After the Au layer is completed, the magneto-optical effects suffer no further change, even though the amount of Au deposited is so small it would not have provided a continuous monolayer.

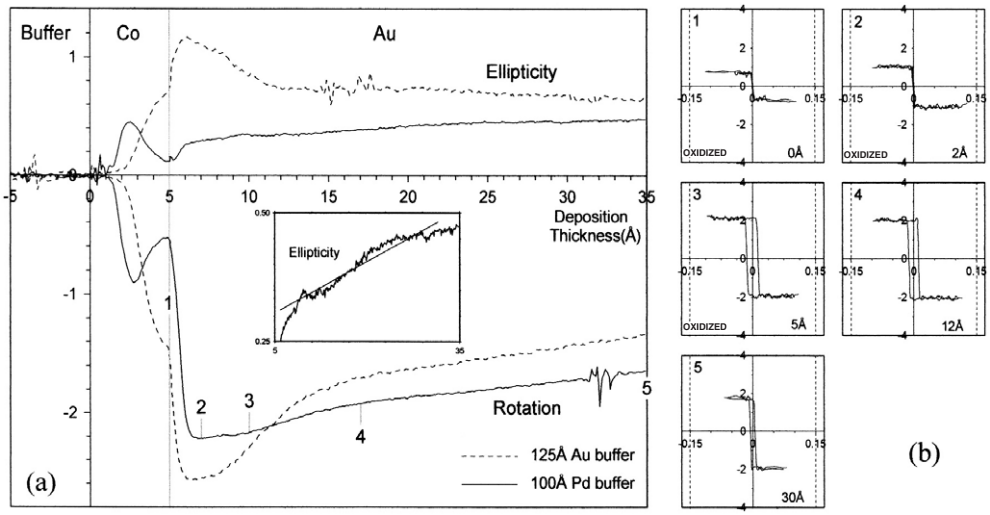

Figure 5. (a) Magneto-optical developments observed during deposition of Au(30 Å) on Co(5 Å)/Pd(100 Å). The MO trace of figure 2(a) (125 Å Au buffer) is shown for comparison. Thickness is counted from the start of the Co deposition. Inset: closer view of the ellipticity revealing possible oscillations. (b) *Ex situ* polar hysteresis loops taken on equivalent structures at various stages of growth. Dotted vertical lines on the hysteresis graphs indicate *in situ* field during growth.

It is concluded that, above 3 Å, the perpendicular anisotropy of the Co layer arising from interactions at the Co–Pd interface is gradually lost and the applied *in situ* static field is insufficient to keep the film fully magnetized. This results in a decrease in the polar magneto-optical effect. As mentioned in the previous section, a thin capping layer of Au increases perpendicular anisotropy. In this case, the Au deposition causes a restoration of the perpendicular anisotropy resulting in the dramatic increase in polar Kerr rotation. Interestingly, experiment (a) shows that, even without the Au, the polar Kerr rotation is observed to increase gradually, indicating some slower transient process such as a re-ordering of the surface or the formation of an alloy, and this causes a re-directing of the easy axis toward the perpendicular direction. Another possibility is that there is an increase in magneto-optical activity arising out of an increase in the magnetic moments of the Co and/or the underlying Pd atoms [5, 10]. However, we feel that the former is the better explanation for reasons that will become clear later.

In figure 5(a), the thickness of the Au overlayer has been increased to 30 Å. Also shown for direct comparison are the results of the corresponding experiment with a Au buffer (the first bilayer in figure 2(a)). It can be seen that there are many similarities between the two experiments but there are also crucial differences. First, the turning point observed during the growth of the Co layer on Pd is not seen when the Co is grown on Au. Second, both experiments show a distinct peak in the magneto-optical effects at approximately 2 Å of Au coverage, but this peak is much greater for a Au buffer layer and is obvious in both rotation and ellipticity. Third, as the Au layer thickness increases, the magneto-optical effects for the film with a Au buffer drop more rapidly than for the case of a Pd buffer, and at a Au layer thickness of 30 Å the film with a Pd buffer shows slightly larger rotation. Fourth, the ellipticity trace for the experiment involving a Pd buffer is very different to that for a Au buffer, and at first sight it would appear that there are no oscillations. However, if a different scale is used

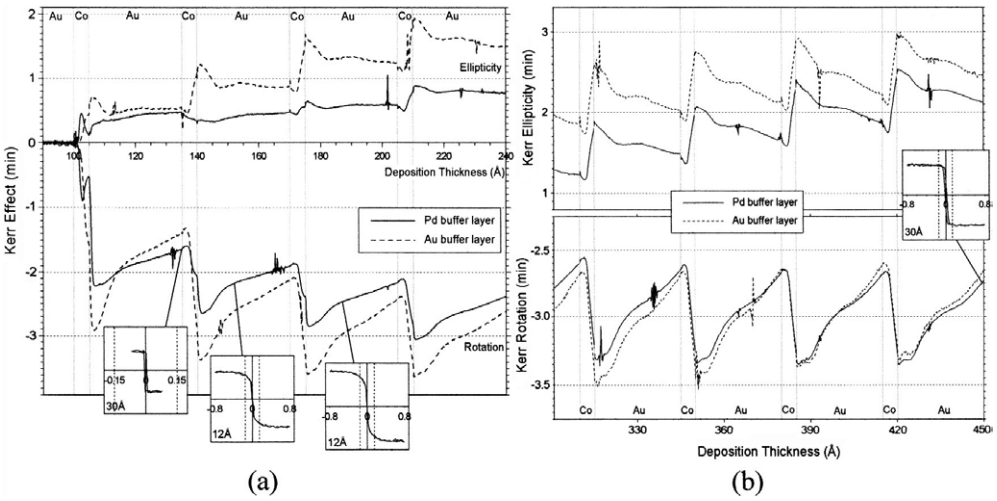

Figure 6. Comparison of identical Co/Au multilayers on different buffer layers: (a) an expanded view of the first four bilayers; (b) the final four bilayers. The *ex situ* polar hysteresis loops were taken on equivalent structures at the points indicated. The loops are labelled with the Au overlayer thickness and the dotted vertical lines indicate the *in situ* polar magnet field applied throughout the deposition.

(inset) there are discernible features in the ellipticity that suggest oscillations. Finally, it is worth noting when comparing these two cases that the observed magneto-optical behaviour is heavily influenced by the optical properties of the buffer layer [2], and Au and Pd are very different in this respect.

Initially, and to compare with the previous results, an *ex situ* hysteresis study was conducted using PMOKE, with loops taken at 2, 5, 12 and 30 Å of Au coverage. The results are shown in figure 5(b) with loops labelled 1–5. Comparison of the absolute magnitudes of the *in situ* magneto-optical measurements and *ex situ* loops shows that for films with Au overlayers of thickness 0–5 Å the *ex situ* magneto-optical effects were much reduced, and this is an effect of oxidation or contamination of the Co atoms. Beyond this initial phase and for 12 and 30 Å of Au, the *in situ* and *ex situ* measurements agree well, indicating that the Au coverage is sufficient to protect the Co layer. Nevertheless, in all cases the *ex situ* hysteresis loops are perpendicular and fully remanent in contrast to the results of Co deposited directly on Au, where none of the loops was perpendicular at this stage in the process.

From this study it is sensible to suppose that the *in situ* magneto-optical observations for a Co/Au bilayer on Pd correspond to a system fully magnetized in the perpendicular direction, certainly when Au coverage is 12 Å or more and quite possibly when thinner, although the issue is confused by the effect of oxidation. Clearly, the latter uncertainty can be removed by performing a similar study of hysteresis *in situ* and this will be discussed later, albeit in the slightly different context of Pd/Co/Au trilayer structures. For now, it is sufficient to note that the use of Pd as an underlayer has a beneficial effect since it ensures that the Co/Au bilayer system is perpendicularly magnetized.

A question that now arises is whether the influence of the Pd buffer extends beyond the first bilayer. In figure 6, the magneto-optical observations for up to ten Co(5 Å)/Au(30 Å) bilayers on Au and Pd buffers are compared, along with a number of *ex situ* PMOKE hysteresis loops, measured on equivalent structures with Pd buffers. The results for the first four bilayers, figure 6(a), show clear differences between the two cases in the development of both Kerr

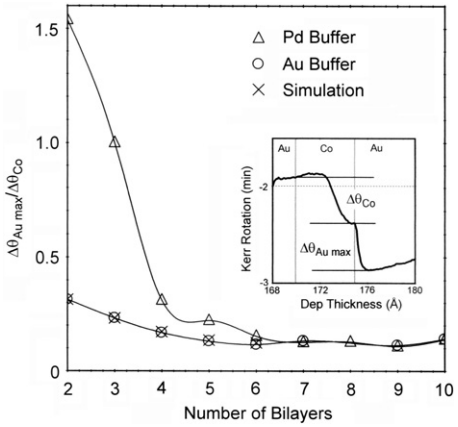

Figure 7. Using the ratio $\Delta\theta_{Au\,max}/\Delta\theta_{Co}$ to investigate the convergence of the magnetic behaviour of Co/Au multilayers on Pd and Au buffers, as the number of bilayers increases. A simulation confirms that the very different optical characters of the two buffer materials do not affect $\Delta\theta_{Au\,max}/\Delta\theta_{Co}$. See the inset for the definition of $\Delta\theta_{Au\,max}$ and $\Delta\theta_{Co}$.

rotation and Kerr ellipticity, and in the magnetic hysteresis. The *ex situ* hysteresis loops shown in figure 6(a) indicate that for the second and third bilayers there is a gradual loss of the perpendicular component of the magnetic anisotropy of the multilayer, and by the tenth bilayer (figure 6(b)) the loop is perpendicular again. This result implies that there is no strong, long-range, influence of the Pd buffer layer.

However, examining the development of the Kerr effects for bilayers 2–4 (figure 6(a)), it is noticeable that, when using a Pd buffer, the change in ellipticity is negative during the deposition of the second Co layer, but is progressively more positive for subsequent bilayers. This is in contrast to the large positive changes in Kerr ellipticity observed throughout the deposition of the Co/Au multilayer onto a Au buffer. For Kerr rotation, the increases seen during the deposition of the Co layers are much less for a Pd buffer than for a Au buffer; but the peak increase in rotation observed during deposition of the Au layers is noticeably greater for a Pd buffer than for a Au buffer. From the fourth bilayer onwards the magneto-optical traces for Co/Au on a Pd buffer look progressively more like those corresponding to a Au buffer, and by the last bilayer (figure 6(b)) the results are very similar, including the same oscillatory behaviour.

Clearly, the optical environments provided by the two buffer layers are very different and go some way towards explaining the differences in the magneto-optical developments, particularly ellipticity. Of course, as the number of bilayers increases, the optical influence of the buffers becomes less important, and one might expect the two sets of results to begin to look the same, as is observed. However, not everything can be explained on this basis and there are indications that the Pd buffer does indeed exert an influence well beyond the first bilayer. This is revealed by further analysis of the Kerr rotations as follows. The important parameters are the overall increase in rotation observed during a Co deposition, $\Delta\theta_{Co}$, and the peak increase in rotation in the early stages of the subsequent Au deposition, $\Delta\theta_{Au\,max}$, for each bilayer (see inset, figure 7). One would expect the ratio of these two to be unaffected by the optical behaviour of the buffer, since the optical effects that arise from the structure underneath will equally apply to both parameters. In figure 7, the ratio $\Delta\theta_{Au\,max}/\Delta\theta_{Co}$ for Au and Pd buffers is plotted against the number of bilayers, for bilayers 2–10. The third curve is a simulation of what should happen if the Au buffer were exchanged for Pd, and confirms the assertion made

above that $\Delta\theta_{\mathrm{Au\,max}}/\Delta\theta_{\mathrm{Co}}$ is independent of the buffer optics. The simulation was performed by, first, characterizing the Co/Au bilayers on the Au buffer, optically and magneto-optically, using the *in situ* measurements, and then recalculating the magneto-optical effects for the Co/Au bilayers with a Pd buffer. Although the simulation predicted that the magneto-optical effects would change with a different buffer layer (not shown), the $\Delta\theta_{\mathrm{Au\,max}}/\Delta\theta_{\mathrm{Co}}$ ratio did not change.

Comparison of the experimental curves in figure 7 show that, in spite of what was predicted, the Pd buffer layer has had a significant effect on $\Delta\theta_{\mathrm{Au\,max}}/\Delta\theta_{\mathrm{Co}}$, which is most obvious for the second and third bilayers. Furthermore, it is not until the seventh bilayer that the curves converge, after which the two cases fully correspond. Note also that there is a slight ripple running through the curves; this is a result of the oscillation in the Kerr rotation, which affects $\Delta\theta_{\mathrm{Au\,max}}$. Figure 7 presents clear evidence that the Pd buffer influences the magnetic behaviour of the multilayer well beyond the first bilayer. A physical explanation for this behaviour has not been investigated but we believe it may originate in structural effects rather than any exchange or magneto-static coupling.

3.3. Studies on Pd/Co/Au

In the previous section, it was shown that, in principle, Pd could be used to influence the magnetic anisotropy of a Co/Au bilayer toward a perpendicular easy axis. For a 5 Å thick Co layer, the magnetic hysteresis shows perpendicular magnetization with 100% remanence for a Au overlayer of 12 Å or more. The picture for thinner Au overlayers is confused because of deterioration of the Co but the indications suggest strong perpendicular magnetic anisotropy. It has also been shown that, although the Pd has a longer range influence, it can only be relied upon to ensure perpendicular magnetization for the bilayer deposited immediately on top, suggesting that the Co layer must be in direct contact with the Pd. Consequently, it was proposed that if a Pd layer were incorporated as part of a Co/Au multilayer, a perpendicular easy axis might be achieved throughout, regardless of the number of periods in the structure. The idea was investigated by monitoring the growth of up to ten trilayers of Pd(15 Å)/Co(5 Å)/Au(37.5 Å) deposited on a 90 Å Au buffer. The dimension of the Au buffer was chosen to be thick enough to ensure film continuity, whilst being thin enough to take advantage of some optical enhancement for the magneto-optical effects, which would be particularly beneficial during the first few trilayers. At 15 Å, the Pd layer is thick enough to form a continuous layer on the Au and allow any induced magnetic moments to develop fully [5].

To avoid the complications associated with *ex situ* magnetic measurements it was decided to perform an *in situ* study during the growth of the films. Figure 8(a) shows the Kerr effects observed during the deposition of a single Pd/Co/Au trilayer onto a Au buffer. The traces are similar to those seen when a Co/Au bilayer was deposited onto a Pd buffer, there being the usual delay in the appearance of Kerr effects followed by turning points after about 3 Å of Co and then again shortly after the start of the Au deposition. A clear oscillation is particularly noticeable in the Kerr ellipticity as the Au thickness increases (see inset).

The experiment was repeated but this time the deposition was arrested at regular intervals to allow hysteresis loops (1–9) to be taken, shown in figure 8(b). Throughout the growth of the Au layer, the loops indicate strong perpendicular anisotropy and the structure is easily magnetized by the *in situ* electromagnet. Of particular interest, however, is loop 1, taken on completion of the Co layer but before Au is added. First, the magnitude of the Kerr rotation for this loop is larger than for the later loops and this is not consistent with the magneto-optical trace. Second, there is evidence of transient behaviour during the time the loop was being taken.

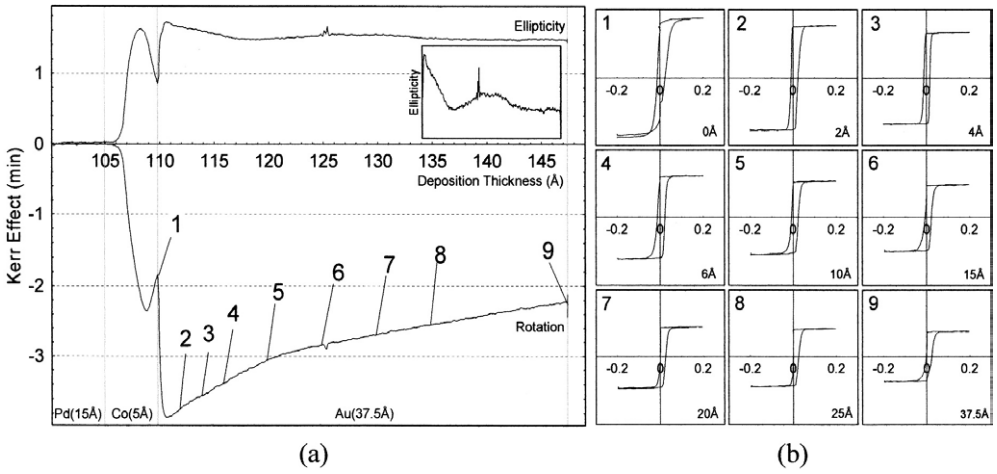

Figure 8. (a) The magneto-optical developments observed during the deposition of a Pd(15 Å)/Co(5 Å)/Au(37.5 Å) trilayer on a 90 Å Au buffer. A closer examination of the ellipticity reveals an oscillation (see inset). (b) *In situ* loops corresponding to the points in the Au overlayer deposition indicated in (a). The Au thickness is given with each loop.

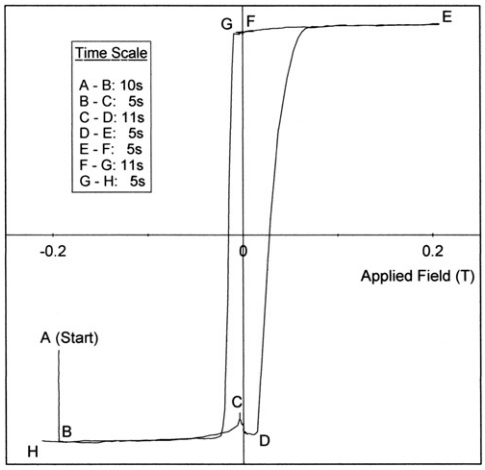

Figure 9. More detailed view of the first PMOKE hysteresis loop from figure 8(b).

This is more clearly illustrated by figure 9, which shows the hysteresis loop taken after the deposition of the Co layer. The loop is labelled indicating the changes in behaviour with time and initially these are rapid. In the 11 s delay between the end of the deposition and the start of data collection for the loop (A–B), the rotation has almost doubled. On reducing the magnetic field from the negative direction to zero (B–C), it is clear that the loop is not square. However, in the 10 s it takes to change the polarity of the current source (C–D), the remanence of the loop has increased significantly and appears to reach 100%. After this the changes in behaviour continue, with the switch characteristic observed as the magnetic field increases in the positive direction (D–E) being much less sharp than that seen when the field is reversed

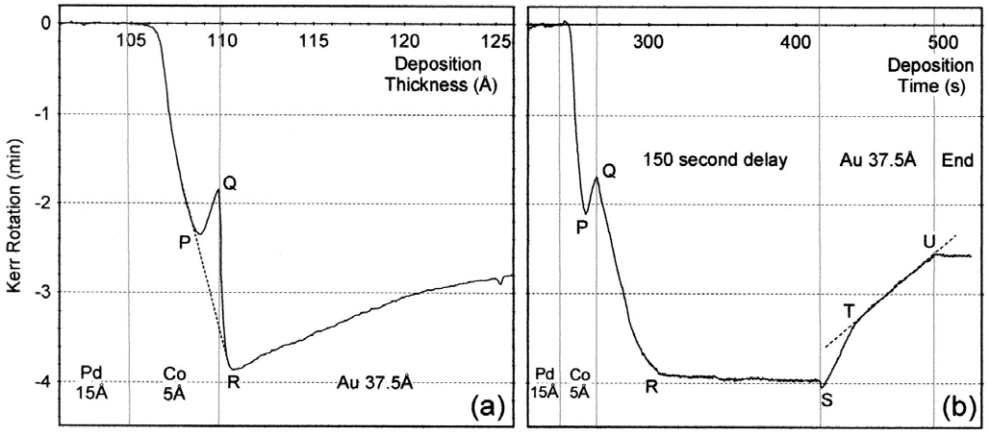

Figure 10. (a) Kerr rotation during the deposition of a Pd/Co/Au trilayer on a Au buffer layer; (b) Kerr rotation during the deposition of a Pd/Co/Au trilayer on a Au buffer layer with a 150 s delay after the Co layer.

during the return phase of the loop (G–H). The total time taken for the entire loop was only 52 s. This experiment implies that during the period immediately following the completion of the Co layer, the magnetic anisotropy of the layer goes through quite slow changes as the easy axis of the film reorientates from in plane to perpendicular. This sheds light on the development of the Kerr effects during the deposition of Co. We already know from our earlier studies that a 3 Å Co layer on Pd is perpendicular, but beyond this there is a reduction in the polar magneto-optical effects consistent with the film going from perpendicular to in-plane anisotropy. However, it has now been seen that the in-plane condition is only temporary, and if left the film will gradually become perpendicular again; this may take minutes rather than seconds and may depend in the physical structure of the underlying substratum.

When there is no delay between the end of the Co layer and the beginning of the Au layer, figure 10(a), there is a rapid increase in Kerr effects seen in the earliest moments of the Au deposition, consistent with a rapid onset of perpendicular anisotropy, as noted and discussed in the latter two sections. In order to explore this effect in more detail, an experiment was performed where a 150 s delay was inserted between the Co and Au depositions, and the trace of polar Kerr rotation was recorded throughout, figure 10(b). After the deposition of the Co, an initial increase in rotation occurs during a distinct period lasting about 50 s (Q–R). A similar transient was noted earlier for a Co layer on a Pd buffer, figure 4, but in this case, the increases in the rotation are much more striking. After this period, the rate of change in the Kerr rotation decreases dramatically, causing a knee in the trace, and the rotation increases slowly thereafter (R–S). This result is largely consistent with the hysteresis loop shown in figure 9, although in the latter case the process seems to have happened at an even greater pace, with most developments in the anisotropy having occurred in less than 40 s. Following on from the 150 s delay and during the subsequent deposition of the Au, there is now an almost imperceptible increase in rotation, which lasts for under a second (S). In fact, this feature is so small and transient it is uncertain whether it is real. With the Co magnetization already orientated perpendicular to the film plane there is little further reorientation that can be stimulated by the Au. More importantly, as the Au is deposited, the magneto-optic trace is dominated by a decrease in rotation, which starts almost immediately and is a consequence

of the non-contribution of the Au to magnetic effects and its intrinsic optical absorption. By comparing the two traces, figures 10(a) and (b), without and with the 150 s delay, it is also clear that the two cases reach the same maximum Kerr rotation, even though the perpendicular anisotropy in the Co is being stimulated by entirely different processes. In either case, the Au contributes nothing intrinsically to the magneto-optical effect and has no magnetic moment.

At this stage, we are in a position to explain, in a qualitative way, the magneto-optical traces that have been collected dynamically during deposition and that are fingerprints of the evolving magnetic properties of these multilayered structures. Moreover, we have repeatedly observed and confirmed the existence of oscillations in the magneto-optical effects during the deposition of Au on Co and have eliminated any possibility that these are related to variations in magnetic anisotropy. However, one peculiarity that remains unexplained occurs principally in the rotation, but is also discernible in ellipticity, and is most clearly illustrated in figure 10(b). To begin with, it is worth pointing out that a simple thin film calculation would indicate that, for these film thicknesses, the Kerr rotation should reduce in an almost linear manner throughout the whole of the Au deposition. However, figure 10 shows that the rotation decreases in two phases marked (S–T) and (T–U). These decreases are essentially linear, and certainly the latter rate of decrease (T–U) seems consistent with the optical absorption effects of the Au layer growing over, and obscuring, the Co [2]. However, the former decrease is much more rapid, implying either a greater optical absorption coefficient for Au or some other mechanism that rapidly reduces the magneto-optical activity, such as a stress-related reduction in the mean Co moment because of the presence of the Au atoms.

4. Summary

A comprehensive study has been made of the magnetic properties of Co/Au and Pd/Co/Au, bilayer and trilayer systems with Au and Pd buffer layers, deposited on glass substrates. Ellipsometry and normal incidence, magneto-optic, polar Kerr polarimetry have been used, *in situ*, to explore the dynamically evolving magnetic properties of these structures during deposition. Magnetron sputtering techniques were used to deposit the atomic-scale layers, so that the observations would be compatible with commercially relevant processes.

In situ and *ex situ* hysteresis studies on Co/Au multilayers showed that the structures were not fully magnetized in the perpendicular direction during growth, inevitably affecting the results of the magneto-optic monitoring. The use of a Pd buffer as a way to improve the perpendicular magnetic anisotropy of Co/Au was investigated and was found to induce strong perpendicular behaviour in a single Co/Au bilayer, and to continue having a discernible effect for further bilayers. The investigation was extended to Pd/Co/Au trilayer systems, where a more detailed *in situ* study showed continuous, fully remanent, perpendicular hysteresis throughout the deposition of Au overlayers and revealed some transient behaviour associated with the uncovered Co layer. These studies enabled us to confirm that magneto-optical oscillations, which were seen to develop during the growth of Au overlayers on Co, were not caused by an inadequate magnetizing field, and consequently were likely to be the same as those observed by others in similar magnetic multilayer systems which have a quantum mechanical origin.

Whilst the conclusions reported here are qualitative, they are based on quantitative observations of the dynamic optical and magneto-optical signatures that describe the various processes associated with the growth of the multilayered system. The details of these signatures can be understood in terms of the evolving optical and magnetic properties of the materials. However, one particular feature remains unclear, and this may be related to the effect that Au atoms have on the magnetization or magnetic moment of an underlying Co layer.

Acknowledgments

We wish to acknowledge the support of the EPSRC, UK, through the provision of ROPA grant no GR/R55429/01, and the Special EU Programmes Body through Invest Northern Ireland for funding Nanotec NI. CC wishes to acknowledge the support of Seagate Technologies.

References

[1] Engel B N, Wiedmann M N and Falco C M J 1994 *J. Appl. Phys.* **75** 6401
[2] Atkinson R, Didrichsen G, Hendren W R, Salter I W and Pollard R J 2000 *Phys. Rev.* B **62** 12294
[3] Mégy R, Bounouh A, Suzuki Y, Beauvillain P, Bruno P, Chappert C, Lecuyer B and Veillet P 1995 *Phys. Rev.* B **51** 5586
[4] Bounouh A, Beauvillain P, Bruno P, Chappert C, Mégy R and Veillet P 1996 *Europhys. Lett.* **33** 316
[5] Atkinson R, Didrichsen G, Hendren W R, Salter I W and Pollard R J 2001 *J. Phys.: Condens. Matter* **13** 691
[6] Sato K 1981 *Japan. J. Appl. Phys.* **20** 2403
[7] Lee J W, Jeong J R, Shin S C, Kim J and Kim S K 2002 *Phys. Rev.* B **66** 172409
[8] Sawada M, Hayashi K and Kakizaki A 2001 *Appl. Surf. Sci.* **169/170** 176
[9] Kim J, Lee J W, Jeong J R, Kim S K and Shin S C 2001 *J. Appl. Phys.* **89** 7147
[10] Yaresko A N, Uba S, Uba L, Perlov A Y, Gontarz R and Antonov V N 1998 *Phys. Rev.* B **58** 7648