ELSEVIER

Journal of Magnetism and Magnetic Materials 162 (1996) 131–138

journal of magnetism and magnetic materials

Fundamental optical and magneto-optical constants of Co/Pt and CoNi/Pt multilayered films

R. Atkinson [a,*], S. Pahirathan [a], I.W. Salter [a], P.J. Grundy [b], C.J. Tatnall [b], J.C. Lodder [c], Q. Meng [c]

[a] *Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast, BT7 1NN, Northern Ireland, UK*
[b] *Department of Physics, Salford University, Salford, M5 4WT, UK*
[c] *MESA Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*

Received 9 April 1996; accepted 30 April 1996

Abstract

A study has been made of the optical and magneto-optical properties of several Co/Pt and CoNi/Pt multilayered films that were fabricated by magnetron sputter deposition. Spectroscopic rotating analyzer ellipsometry and Kerr polarimetry were carried out to determine the fundamental optical and magneto-optical constants over the spectral range 320–860 nm. The constants determined were the complex refractive index and the first-order magneto-optic Voigt parameter. A total of seven films were examined and excellent reproducibility was observed in the measured material constants. These have been used to discuss the spectral dependence of the figure-of-merit, for each material, associated with the detection of the polar Kerr effect.

Keywords: Multilayers; Magneto-optics; Optical constants

1. Introduction

There is currently great interest in the magnetic and magneto-optical properties of multilayered media [1,2] because of their many potential commercial applications. Their properties are also of fundamental interest since the materials often exhibit new physical characteristics not observed in the bulk materials. In this paper we present a comparative study of the optical and magneto-optical properties of Co/Pt and CoNi/Pt thin films whose main applications are related to the magneto-optic information storage industry. For the CoNi/Pt films the atomic ratio of Co:Ni was 1:1. In the past there have been a number of studies of the magneto-optical properties of these materials, though often, these tend to be confined to simple measurements of Kerr rotation θ_k and sometimes Kerr elipticity ϵ_k ($\hat{\theta} = \theta_k + i\epsilon_k$). Combined with the reflectivity R, usually of a very thick film, to form a figure-of-merit $\theta_k\sqrt{R}$ or $|\hat{\theta}_k|\sqrt{R}$, these parameters are often used to judge the potential of the material for magneto-optical readout of magnetically stored information.

Strictly speaking, from an optical point of view, the potential of any magnetic medium can only be properly assessed and compared to other materials if measurements are made of the fundamental optical

---

[*] Corresponding author. Fax: +44-1232-438918: email: ronald.atkinson@qub.ac.uk.

and magneto-optical constants. These constants are the complex refractive index ($\hat{n} = n + \mathrm{i}k$) [3] and the magneto-optic Voigt parameter ($\hat{Q} = Q_1 + \mathrm{i}Q_2$) [4]. Together, these quantities form the complete permittivity tensor [4] that fully describes the optical and first-order magneto-optical properties of the medium. Moreover, in the correct combination these constants form a reliable figure-of-merit, that is a true material constant and which allows one to compare and judge absolutely the potential of the medium for magneto-optic readout. From this point of view alone, the determination of these constants is of great importance.

In addition however, these parameters are also crucially important from the point of view of exploiting the full potential of the medium. Usually this can only be done by incorporating a thin film of the medium in an optical environment such as a trilayer [5] or quadrilayer [6] structure. In order to design such structures it is necessary to have reliable values for the basic constants $\hat{n}$ and $\hat{Q}$ for without these, correct layer thicknesses cannot deduced. It should also be mentioned that these parameters may, in principle, be related to the electronic transitions within the material that give rise to the observed macroscopic optical and magneto-optical properties. From this point of view their determination is of considerable benefit to the spectroscopist and theoretical modeller of magneto-optic media.

Here we present the results of an ellipsometric determination of the fundamental constants of several Co/Pt and CoNi/Pt multilayers prepared by dc magnetron sputtering. The fundamental constants are used to compare the potential of each medium for magneto-optic readout through a properly formed figure-of-merit and the results are contrasted with expectations based on the more usual use of the parameter $|\hat{\theta}_k|\sqrt{R}$.

2. Experimental

2.1. Preparation of multilayers

2.1.1. Co/Pt

The Co/Pt samples, deposited on glass substrates, were fabricated in a UHV-compatible vacuum system using balanced d.c. magnetron sputtering. The sputtering gas was Ar at 3 mTorr and the base pressure of the system was $< 2 \times 10^{-7}$ Torr. The deposition rates of the Co and Pt were ~ 0.6 and 1.14 Å/s respectively in a PC controlled deposition sequence.

2.1.2. CoNi/Pt

CoNi/Pt multilayers were prepared on Si(100) substrates using a magnetron sputtering system at a constant Ar pressure of 12 mTorr. The individual layer thickness d_{CoNi} and d_{Pt} were estimated from the product of the deposition time and deposition rate and confirmed by low and high angle XRD measurements. The composition of the CoNi layer (50/50 at%) was determined by measuring a thick deposited CoNi layer using EDX. All multilayers were prepared on a Pt buffer layer.

2.2. Optical and magneto-optical measurements

The real and imaginary parts of the refractive index were determined over the wavelength range 320–860 nm using an automatic rotating analyzer spectroscopic ellipsometer. All measurements were made at an angle of incidence of 70° at the air film interface. Inversion of the ellipsometric functions, to obtain $\hat{n}$, was carried out taking into account the magnetic film thickness, substrate type and, in the case of the CoNi/Pt, the presence of the Pt buffer layer. In most cases the magnetic layers were sufficiently thick compared with the optical skin depth (≈ 20 nm) that these factors had little influence on the computed values of n and k. Only for sample, CoNi/Pt-F43, was film thickness a significant parameter and since this was taken into consideration for the evaluation of n and k, the resulting data is no different than that obtained for thicker films.

Measurements of the Kerr rotation and associated ellipticity were determined at near normal incidence ($< 3°$) using a Kerr polarimeter identical in operating principle to the ellipsometer. This instrument also incorporates an electromagnet capable of producing magnetic fields in excess of 1.5 T in order to switch films in the polar orientation. Both the ellipsometer and the Kerr polarimeter are automatic and PC driven. Combining the optical and the polar complex Kerr data the magneto-optic parameter $\hat{Q}$ is determined directly making use of the 4×4 [7]

matrix approach for calculating the magneto-optical effects and again taking into account finite film thicknesses, buffer layers and the optical properties of the substrate. The sign convention for the Kerr rotation measurements and the magneto-optic parameter is the preferred scheme described in detail elsewhere [8].

3. Results

3.1. Structure and magnetic properties

The physical data corresponding to the films and associated magnetic properties is summarized in Table 1. All films showed low angle X-ray diffraction peaks associated with the periodicity of the multilayer structure. Examples of these, determined at Queen's University, are shown in Fig. 1. From the positions of these peaks the period of each sample was determined and is seen to compare well with the intended values determined from the thicknesses of the Co (or CoNi) (d_{Co}) and Pt (d_{Pt}) sub-layers. It should be noted that the total film thickness given in Table 1 is designed thickness and includes all the layers in a particular sample, including any buffer layer.

Hysteresis loops of all the samples were determined by an M.O. loop plotter and in the case of the CoNi/Pt films additionally by VSM. Typical loops are illustrated in Fig. 2, where the Co/Pt and CoNi/Pt magnetic layer thicknesses are 79.5 nm and 26.9 nm, respectively. The CoNi/Pt films clearly have good squareness compared with the Co/Pt, though the latter also becomes square for films having $d_{Co} < 0.5$ nm and fewer than 20 bilayer periods

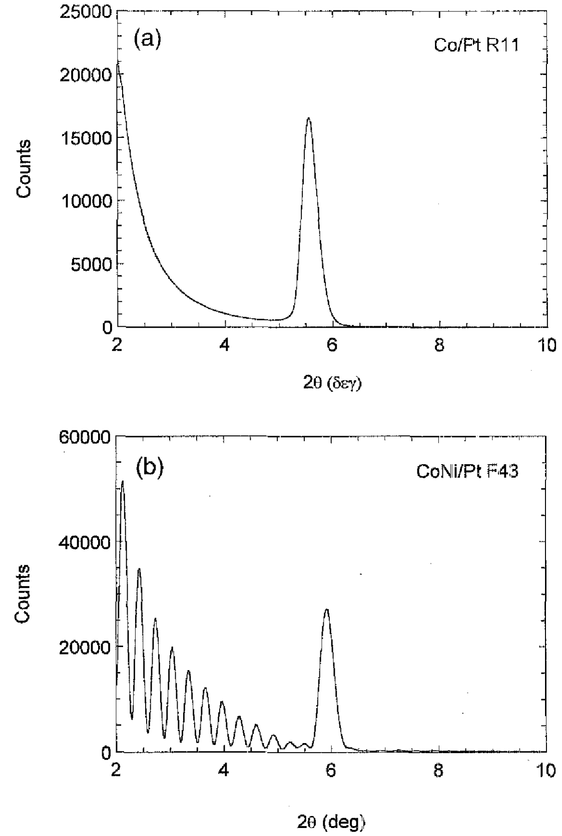

Fig. 1. Low angle X-ray diffraction patterns for (a) Co/Pt and (b) CoNi/Pt multilayers.

Table 1
Physical parameters for Co/Pt and CoNi/Pt multilayers

Material	Film number	Total film thickness (nm)	Coercivity H_c (kOe)	Saturation field H_s (kOe)	Squareness ratio M_r/M_s	d_{Co}/d_{Pt}	Period (nm)	Number of bilayers	M_s (emu/cc)
Co/Pt	R11	99.0	0.14	1.09	0.15	0.4/1.1	1.59	66	495
Co/Pt	R25	79.5	0.15	1.07	0.17	0.4/1.1	1.57	53	545
Co/Pt	R32	60	0.14	1.05	0.18	0.4/1.1	1.58	40	542
CoNi/Pt	F43	27.9 (1 Pt) [a]	0.35 (0.3) [b]	1.4 (0.9) [b]	1.0	0.58/1	1.49	17	303
CoNi/Pt	F44	53.3 (26.4 Pt) [a]	0.41 (0.58) [b]	1.4 (1.14) [b]	1.0	0.58/1	1.49	17	288
CoNi/Pt	F45	79.7 (52.8 Pt) [a]	0.42 (0.69) [b]	1.2 (1.3) [b]	1.0	0.58/1	1.52	17	307
CoNi/Pt	F46	53.1 (1 Pt) [a]	0.30 (0.25) [b]	1.41 (1.67) [b]	0.81 (0.88) [b]	0.58/1	1.44	33	305

[a] Indicates thickness of platinum buffer layer.
[b] Indicates results obtained by VSM.

[9]. The squareness of the CoNi/Pt multilayers is enhanced by the Pt buffer layer and a similar effect would be observed in Co/Pt systems prepared under similar conditions. Here, the canting of the Co/Pt loops is also exaggerated by the relatively large number of bilayers included in the film compared with the corresponding CoNi/Pt film in Fig. 2.

The coercivity of the CoNi/Pt is about a factor of two greater than that of the Co/Pt. This fact is also reflected in the fields required to saturate the films, typically 1 kOe for the Co/Pt and 1.4 kOe for the CoNi/Pt. It is also worth noting that the magnetisation of the Co/Pt samples is about one-and-a-half times larger than that of the CoNi/Pt. Increased coercivity and anisotropy field would also result for Co/Pt from 'tailored' deposition conditions using, for instance, increased Ar pressure and the presence of an underlayer.

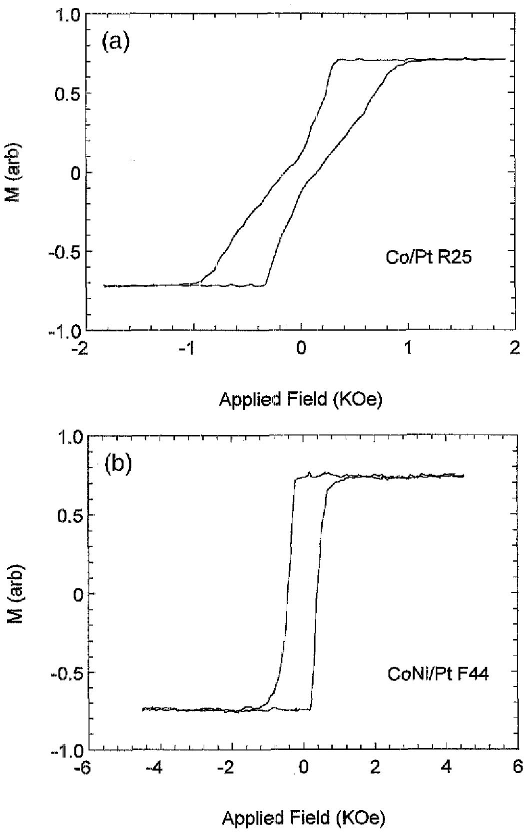

Fig. 2. M.O. hysteresis loops of (a) Co/Pt and (b) CoNi/Pt multilayer of magnetic layer thicknesses 79.5 nm and 26.9 nm, respectively. Probe wavelength = 633 nm.

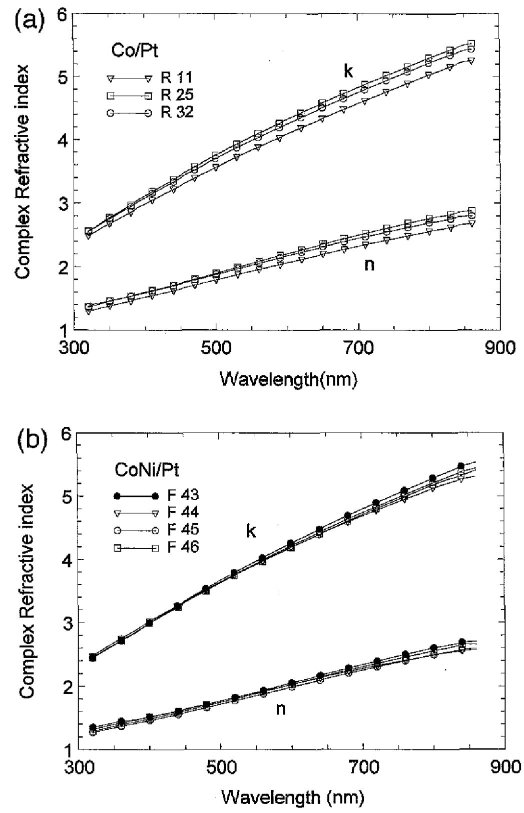

Fig. 3. Dispersion of the complex refractive index $\hat{n}$ ($= n + ik$).

3.2. Optical and magneto-optical measurements

The dispersion of the complex refractive indices of the two sets of films are shown in Fig. 3. It is quite clear that there is very little variation in the values of these constants between different samples of a given type. In addition, there is little difference between the two types of material. This is not surprising since the optical constants of Co and Pt are not too dissimilar. Consequently, one would not expect a very strong dependence of n and k on the ratio of the sub-layer thicknesses of the films. Nevertheless, the consistency in the values is encouraging and is a useful indicator as to the reproducibility of the film properties. It is worth noting that the ratio k/n shows little variation over the spectral region of interest being approximately equal to two. This is an important point in relation to the figure-of-merit that will be discussed later.

In Fig. 4 we show the complex polar Kerr rotations for each sample. It is clear that there is excellent agreement between films in the case of the Co/Pt and this strongly suggests good control over the sputter deposition parameters. In the case of the CoNi/Pt films it appears, at first sight, that there are significant variations in the properties of the medium. However, the differences between the samples merely reflects the differing film thicknesses. In particular, sample CoNi/Pt F43 is much thinner (26.9 nm) than the rest of the films of this type and consequently the Kerr rotations are influenced by the Pt buffer layer and the interference effects in the film itself.

This point is illustrated quite clearly in Fig. 5, where we see the real and imaginary parts of the complex magneto-optic parameter. There is no significant variation in the real and imaginary values of Q between films, either for the Co/Pt, or the CoNi/Pt samples. This, of course, is as it should be since we do not expect to see any thickness dependence of a material constant. There is, of course a significant difference between the Q-values for the two different media and this is to be expected since both the presence of the Ni and the different ratios of sub-layer thicknesses will influence the magneto-optical properties of the two media. In addition, the reduced magnetisation of the CoNi/Pt, compared with the Co/Pt, will influence the magnitude of magneto-optic effect. Nevertheless, the consistency of the magneto-optic parameter is very good for each particular set and confirms the reproducibility of both fabrication techniques.

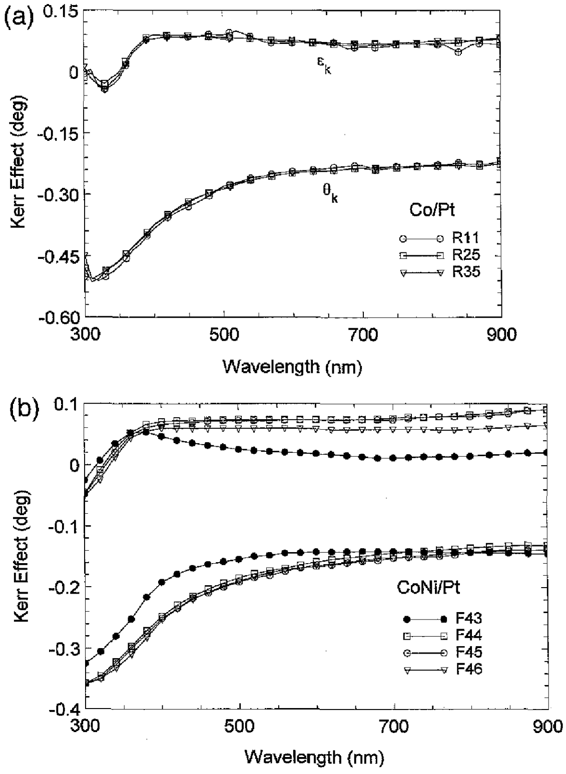

Fig. 4. Dispersion of the complex Kerr rotation $\hat{\theta}$ ($= \theta_k + i\epsilon_k$).

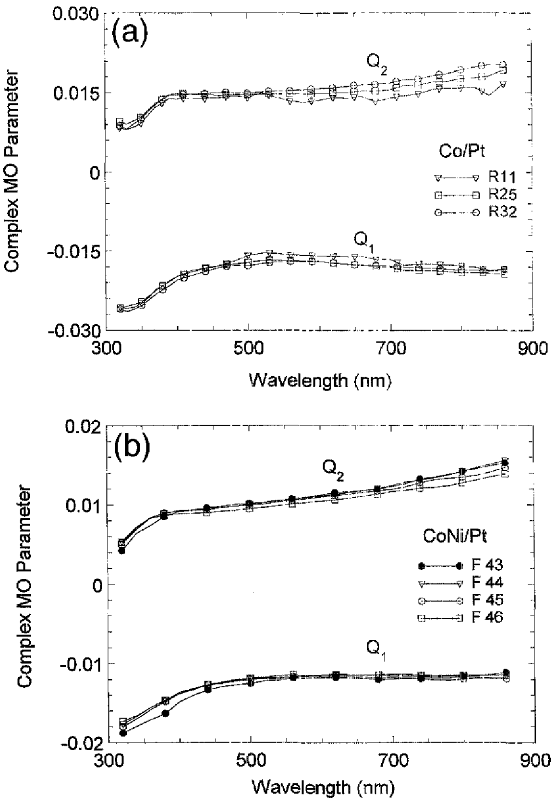

Fig. 5. Dispersion of the complex magneto-optic Voigt parameter $\hat{Q}$ ($= Q_1 + iQ_2$).

In order to provide a usable record of the optical and magnet-optical constants of these two materials we provide a numerical listing of the dispersion for $\hat{n}$ and $\hat{Q}$ in Table 2. The results shown in this table

Table 2
Dispersion of the optical ($n + ik$) and magneto-optical ($Q_1 + iQ_2$) constants of Co/Pt and CoNi/Pt multilayers

Wavelength	Co/Pt				CoNi/Pt			
(nm)	n	k	Q_1	Q_2	n	k	Q_1	Q_2
320	1.343	2.532	−0.0258	0.0088	1.306	2.456	−0.0180	0.0049
350	1.431	2.732	−0.0249	0.0098	1.382	2.661	−0.0165	0.0075
380	1.507	2.926	−0.0219	0.0135	1.447	2.856	−0.0151	0.0088
410	1.597	3.130	−0.0196	0.0145	1.518	3.069	−0.0137	0.0092
440	1.679	3.311	−0.0185	0.0144	1.590	3.260	−0.0129	0.0093
470	1.767	3.494	−0.0176	0.0146	1.669	3.453	−0.0124	0.0097
500	1.856	3.671	−0.0169	0.0145	1.750	3.639	−0.0121	0.0099
530	1.946	3.842	−0.0165	0.0149	1.832	3.817	−0.0119	0.0102
560	2.034	4.005	−0.0166	0.0145	1.915	3.989	−0.0117	0.0105
590	2.121	4.163	−0.0165	0.0147	2.001	4.161	−0.0116	0.0109
620	2.205	4.323	−0.0168	0.0150	2.082	4.320	−0.0116	0.0112
650	2.290	4.476	−0.0171	0.0152	2.164	4.478	−0.0116	0.0115
680	2.368	4.620	−0.0174	0.0151	2.243	4.629	−0.0117	0.0118
710	2.446	4.762	−0.0176	0.0157	2.320	4.777	−0.0117	0.0122
740	2.524	4.906	−0.0180	0.0162	2.394	4.920	−0.0117	0.0128
770	2.597	5.046	−0.0183	0.0170	2.464	5.061	−0.0118	0.0132
800	2.671	5.184	−0.0185	0.0176	2.536	5.204	−0.0117	0.0137
830	2.733	5.311	−0.0188	0.0177	2.597	5.324	−0.0116	0.0142
860	2.787	5.407	−0.0188	0.0186	2.632	5.424	−0.0115	0.0148

are the means of the measurements on all the films illustrated in Figs. 3 and 5.

4. Discussion and figure-of-merit

The value of the availability of the optical and magneto-optical constants of these materials may now be appreciated by using them to consider and compare the potential of Co/Pt and CoNi/Pt for magneto-optic readout using differential detection of the Kerr effect [10]. As already pointed out, this is often done in terms of the parameter $\theta_k \sqrt{R}$. In this case however, we use $|\hat{\theta}_k|\sqrt{R}$ which implies best performance after external phase compensation for the removal of the Kerr ellipticity. It is a simple matter to compute this parameter using the data given in Table 2. This has been done and the results are shown in Fig. 6. The conclusion from these curves is that these particular Co/Pt films would produce greater magneto-optic signals than would the CoNi/Pt and that the performance would improve significantly, for both media, towards the shorter wavelengths. This is the usual conclusion for this type of material, using films of semi-infinite thickness with measurements at the air/film interface. However, the most reliable figure-of-merit that should be used in this situation is given by [11]

$$\text{F.O.M.} = |\hat{Q}|(\Gamma + \Gamma^{-1})/4, \text{ where } \Gamma = k/n. \tag{1}$$

Briefly, this F.O.M. is a material constant and is a measure of how well a medium will perform magneto-optically, after it has been incorporated in a trilayer or quadrilayer system to optimize the polar Kerr effect at normal incidence. This parameter has

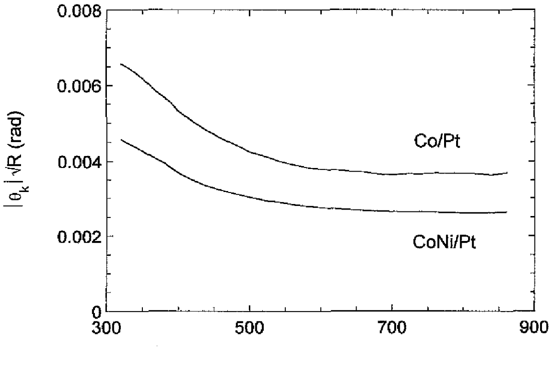

Fig. 6. Dispersion of the figure-of-merit $|\hat{\theta}_k|\sqrt{R}$.

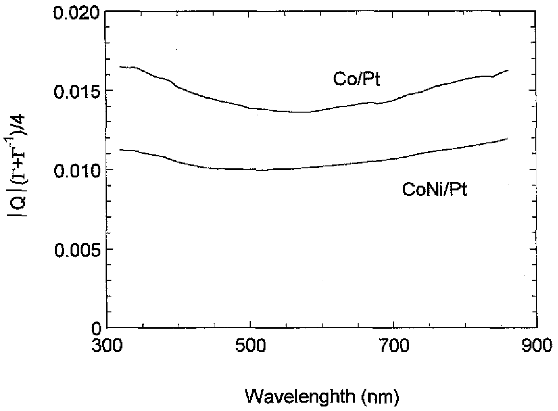

Fig. 7. Dispersion of the preferred figure-of-merit $|Q|(\Gamma+\Gamma^{-1})/4$.

also been computed and is shown in Fig. 7. Again the best performance is exhibited by the Co/Pt material. However, it is now clear that variation of performance of both materials, over the spectral region 320–860 nm, is quite small there being little difference in the F.O.M. at the two extremes. The approximately uniform spectral dependence of performance of these materials is, at first sight, surprising since there are quite large variations in the optical constants and the magneto-optic Kerr effect, especially at short wavelengths, as can be seen in Figs. 3 and 4. However, it is the ratio Γ and the modulus of magneto-optic parameter $|Q|$ that determine performance through Eq. (1) and, as may be deduced from Table 2, these two parameters do not vary much with wavelength. The above conflicting conclusions, regarding spectral performance, illustrate the consequence of attaching too much importance to the parameter $|\hat{\theta}_k|\sqrt{R}$.

In order to demonstrate that the conclusions regarding the spectral variations of performance of Co/Pt and CoNi/Pt are correct, we have used the data of Table 2 to design trilayer systems [5] that maximize the Kerr rotation for zero associated ellipticity and a reflectance into an incident medium of 10%. This has been done for both materials at the extremes of the wavelength range, namely at 320 and 860 nm. The results of the optimum designs are given in Table 3. Each system consists of three, precisely determined layers. First, the magnetic layer of thickness d_1, then a dielectric spacer layer of thickness d_2 followed by an opaque aluminium reflector layer. The thickness of the aluminium layer (> 70 nm), being opaque to maximize its reflectance, does not affect the performance of the trilayer. With the film thicknesses given in Table 2, the material will exhibit its optimum performance for the given reflectivity and design wavelength for the system. If the $|\hat{\theta}_k|\sqrt{R}$ parameter is now calculated using $R = 0.1$, and the optimized Kerr rotation from Table 3, one sees that, relatively speaking, there is very little difference between the performance at long and short wavelengths as, predicted in Fig. 7. In fact, for the CoNi/Pt the best performance is observed at 860 nm.

On the basis of the measurements presented we may conclude that, in terms of magneto-optic readout using the polar Kerr effect, the Co/Pt material performs better than the CoNi/Pt. Likewise we may also conclude that the coercivities and squareness of the hysteresis loops of the CoNi/Pt system are to be preferred to those of Co/Pt particularly for thicker films. However, it should be noted that these conclusions are confined to these particular samples only.

It has been shown quite recently (Meng et al.

Table 3
Trilayer designs based on Co/Pt and CoNi/Pt (thickness d_1), SiO_2 spacer (thickness d_2) and opaque aluminium. (Incident medium assummed to be transparent with refractive index 1.52)

Material	Wavelength (nm)	Reflectance (R)	d_1 (nm)	d_2 (nm)	θ_k (deg)	$\theta_k\sqrt{R}$ (rad)
Co/Pt	320	0.1	11.3	46.5	2.61	0.014
	860	0.1	9.6	156.7	2.54	0.014
CoNi/Pt	320	0.1	11.5	45.9	1.78	0.010
	860	0.1	9.6	169.4	1.86	0.010

[12]) that the magneto-optic effect in CoNi/Pt can be optimised with respect to the thickness of the Pt sub-layer. Indeed, when this has been done it appears that the magneto-optic performance of the multilayer is then very similar to that, described here, for the Co/Pt system. This observation is also supported by recent, dynamic, in-situ magneto-optical studies of the growth of Pt and Co multiple layers on Pt buffer layers (Atkinson et al. [13,14]). Here evidence was seen of the decreasing magnitude of the magnetic polarisation of Pt atoms with distance from an interface with Co. It is therefore clear that the thickness of the Pt sub-layers is a very important factor in determining M.O. performance of the whole multilayer system. Both authors, above, concluded that, from a magneto-optical point of view, the optimum thickness for the platinum is between 0.6 and 0.7 nm. It is also worth pointing out that the rate of change in M.O. performance with platinum layer thickness is greatest at $d_{Pt} \approx 1$ nm [15]. Consequently, at this value of d_{Pt} small errors in the thickness of the platinum layers will have a large effect on the Kerr rotations and hence the Q-values of the medium. Furthermore, it should be noted that the magnetisation of the CoNi/Pt films is smaller than that within the Co/Pt. We have observed that reduced magnetisation within Co/Pt films is accompanied by small Kerr effects. Consequently, we may assume that where CoNi/Pt films can be produced with increased magnetisation the M.O. activity may be significantly larger than that reported here. In addition, the presence of the Ni in combination with the Co causes a modification to the magneto-optic behaviour of the whole system. In a future article we intend to report more fully on the optical and magneto-optical properties of CoNi alloy and its effect on the performance of the CoNi/Pt system.

In contrast, the optical constants n and k of these materials are relatively insensitive to the sub-layer thicknesses, providing that these do not attain extreme values. Thus the n and k values reported here will, for practical purposes, be representative of most Co/Pt and CoNi/Pt multilayered media. In addition, in the case of Co/Pt this conclusion also extends to its alloys [16] and may very well therefore also apply to the alloys of CoNiPt.

We also note that magnetic parameters such as coercivity and hysteresis loop squareness, and their variation with thickness can be very dependent on type and condition of the substrate medium as well as on the deposition procedures. In this respect it is worth noting that in the course of fabricating several trilayer systems based on Co/Pt, and the designs given here, a sample was produced at the University of Salford that had a coercivity in excess of 2000 Oe. At the time of writing the cause of this very large coercivity has not been fully explored.

Acknowledgements

All of the authors are grateful for the support of the European community through the CAMST (II) organisation and the Universities of Salford and Belfast additionally acknowledge the support of the EPSRC grants GR/J27332 and GR/J29749.

References

[1] W.B. Zeper, F.J.A.M. Greidanus and P.F. Carcia, IEEE Trans. Magn. 25 (1989), 374.
[2] S. Hashimoto, Y. Ochiai and K. Aso, J. Appl. Phys. 67 (1990) 2136.
[3] E.D. Palik, Handbook of Optical Constants of Solids (Academic Press, New York, 1985).
[4] R. Atkinson, R. Gamble, G.P. Gu and P.H. Lissberger, Thin Solid Films 162 (1988) 89.
[5] R. Atkinson, J. Magn. Magn. Mater. 124 (1993) 178.
[6] R. Atkinson, I.W. Salter and J. Xu, J. Magn. Magn. Mater. 102 (1991) 357.
[7] Z.-M. Li, B.T. Sullivan and R.R. Parsons, Appl. Opt. 27 (1988) 1334.
[8] R. Atkinson and P.H. Lissberger, App. Opt. 31 (1992) 6076.
[9] S.J. Greaves, R.J. Pollard and P.J. Grundy, J. Magn. Magn. Mater. 121 (1993) 532.
[10] K. Egashira and T. Yamada, J. Appl. Phys. 45 (1974) 3643.
[11] R. Gamble, P.H. Lissberger and M.R. Parker, IEEE Trans. Magn. 21 (1985) 1651.
[12] W.P. van Drent, Q. Meng, J.C. Lodder, Th.J.A. Popma, and T. Suzuki, J. Appl. Phys. 79 (1996) 6190.
[13] W.R. Hendren, Ph.D. Thesis, The Queen's University of Belfast, Belfast, Northern Ireland, UK (1995).
[14] R. Atkinson and W.R. Hendren, Presented at MORIS '96, to appear in J. Magn. Soc. Jpn.
[15] Q. Meng, W.P. van Drent, J.C. Lodder and Th.J.A. Popma, J. Magn. Magn. Mater. 156 (1996) 296.
[16] S. Hashimoto, Y. Ochiai and K. Aso, J. Appl. Phys. 67 (1990) 26.