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Optical and magneto-optical characterization of TbFeCo and GdFeCo thin films for high-density recording

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Abstract
Thin, optically semi-infinite films of amorphous TbFeCo and GdFeCo, suitable for magneto-optical recording, have been deposited by DC magnetron sputtering onto glass. Ellipsometric techniques have been used to determine the complex refractive index and complex magneto-optical parameter of the films in the wavelength range 400–900 nm, thus characterizing the materials. A review of the literature is presented and shows that the results for the TbFeCo films compare favourably with published results obtained from measurements conducted *in situ*, with the films protected with ZnS barrier layers. It is found that GdFeCo and TbFeCo are optically very similar, but magneto-optically the materials are quite different.

1. Introduction

It has been pointed out that designs for magneto-optical media should include an optical and magneto-optical perspective to ensure an optimum signal-to-noise ratio [1]. Typically, such designs involve a mirror, a magnetic layer and a dielectric layer. This concept is particularly suited to conventional magneto-optical recording where data is written to and read from a single layer of magnetic material, usually the amorphous rare-earth–transition metal (RETM) alloy TbFeCo. More recently, the need for higher areal bit densities has seen the pursuit of techniques which allow bits to be stored at a size and spacing much smaller than the diffraction limit of the laser used for reading and writing. The writing of data below this limit is more easily achievable than distinguishing between the bits when reading. Several solutions have been advanced, all of which separate the layer used for storing the data and the layer used

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Table 1. Optical and magneto-optical constants for optically semi-infinite TbFeCo and GdFeCo films determined at room temperature.

	TbFeCo				GdFeCo			
λ (nm)	n'	n''	Q'	Q''	n'	n''	Q'	Q''
400	2.32	2.92	0.0187	0.002 90	2.33	2.85	−0.0129	0.003 52
420	2.36	2.98	0.0195	0.002 71	2.36	2.89	−0.0149	0.003 92
460	2.50	3.13	0.0207	0.001 87	2.50	3.04	−0.0167	0.004 43
500	2.66	3.27	0.0221	0.008 01	2.65	3.18	−0.0182	0.005 08
540	2.83	3.39	0.0237	−0.000 528	2.81	3.30	−0.0197	0.006 01
580	3.00	3.50	0.0251	−0.001 99	2.97	3.41	−0.0210	0.007 12
620	3.13	3.60	0.0262	−0.003 54	3.11	3.51	−0.0222	0.008 34
660	3.28	3.69	0.0273	−0.005 22	3.25	3.60	−0.0232	0.009 69
700	3.42	3.77	0.0281	−0.006 92	3.39	3.68	−0.0240	0.011 2
740	3.54	3.84	0.0288	−0.008 53	3.52	3.75	−0.0247	0.012 7
780	3.67	3.91	0.0293	−0.010 2	3.64	3.82	−0.0252	0.014 2
820	3.79	3.98	0.0297	−0.011 7	3.76	3.89	−0.0255	0.015 8
860	3.90	4.05	0.0300	−0.012 9	3.87	3.95	−0.0259	0.017 1
900	4.01	4.11	—	—	3.97	4.01	—	—

for read-out. Consequently, these new media involve two or more magnetic layers, which are typically TbFeCo for storage and another amorphous RETM alloy, GdFeCo, for read-out.

Although the new structures are more complicated, it is still important to consider their optical and magneto-optical performance. This is particularly true of MAMMOS media [2], which tend to be among the simplest and optically resemble conventional media with the storage layer being included in the mirror. In order to achieve an optimized design, the layers which compose the media must first be characterized, i.e. the complex refractive indices ($n = n' + \mathrm{i}n''$) and magneto-optical parameters ($Q = Q' + \mathrm{i}Q''$) must be determined. The magneto-optical parameters of the storage layer are not so important, as this layer should not play any role in read-out. However, it seems that the optical and magneto-optical data that are found in the literature are for thin films of TbFeCo, i.e. the material most commonly used for storage. As far as the authors are aware, no such studies have been published on GdFeCo thin films though some observations of magneto-optical effects do exist [3]. It is the purpose of this paper to fill this gap in the available data. We will first review previously published studies on TbFeCo and compare them with our own. Then our results for GdFeCo will be presented in both graphical and tabulated form for the convenience of those wishing to make use of the numerical data (table 1).

2. Experimental details

Films of amorphous TbFeCo and GdFeCo were deposited from commercially manufactured targets onto glass substrates using DC magnetron sputtering at an argon pressure of 5 mTorr. The vacuum system was evacuated by a turbomolecular pump and a cryo-pump providing a typical pressure just prior to deposition of approximately 10^{-7} Torr. The compositions of the films were estimated using EDAX to be $Tb_{22}Fe_{65}Co_{13}$ and $Gd_{30}Fe_{43}Co_{27}$. In most cases, ZnS layers were deposited to act as barriers to the glass and the ambient. Deposition rates were calibrated using a mechanical stepper and were 4 Å s^{-1} for TbFeCo, 4.5 Å s^{-1} for GdFeCo and 1.7 Å s^{-1} for ZnS.

Optical measurements from 400 to 900 nm were carried out using a rotating analyser ellipsometer at 50°, 60° and 70° [4]. The complex refractive indices were then determined

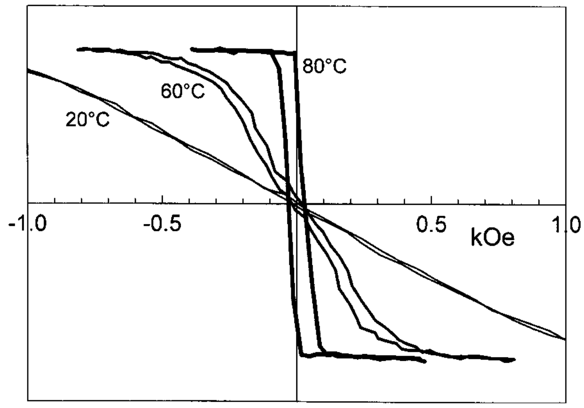

Figure 1. Magnetic hysteresis of the GdFeCo film showing the in-plane-to-perpendicular transition at 80 °C.

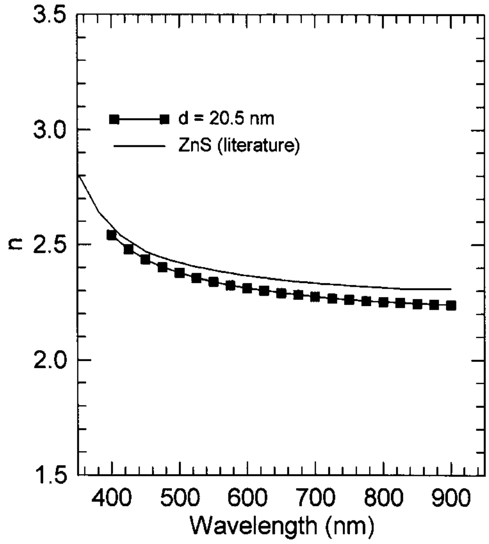

Figure 2. The refractive index of ZnS compared to those in the literature [9].

using a minimization routine based on the Levenberg–Marquart method [5] and the classical optical characteristic matrix model for thin films and multilayers [6, 7]. Using a photoelastic modulator-based Kerr polarimeter [8], the polar magneto-optical effects, Kerr rotation and Kerr ellipticity were measured spectroscopically from 400 to 860 nm. The optical and magneto-optical measurements together made it possible to determine the complex magneto-optical parameter.

The dependence of the magnetic properties of the films on temperature was observed using the magneto-optical Kerr effect. It was found that, for the TbFeCo films, the compensation temperature was below 20 °C and the Curie temperature was 260 °C. The GdFeCo films exhibited an in-plane-to-perpendicular transition around 80 °C (figure 1), a compensation temperature of 150 °C and a Curie temperature greater than 300 °C.

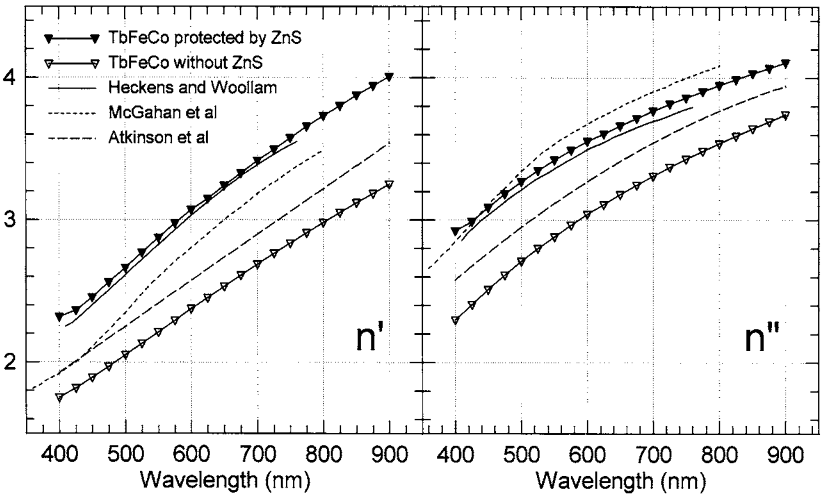

Figure 3. Comparison of refractive indices of TbFeCo determined by the authors with those previously published [10–13].

3. Optical measurements

The thickness of the RETM layers was in excess of 140 nm and therefore could be considered optically semi-infinite. Consequently, the ellipsometric measurements were affected by the RETM layer and the top dielectric layer only. The measurements were particularly sensitive to the optical thickness of the top layer and some effort went into characterizing this beforehand. A single film of ZnS was deposited onto glass with the same deposition time and power as were used for the layers deposited onto the RETM films. The film was then studied using ellipsometry and the refractive index determined. The results compared well with those found in the literature (figure 2) [9]. The thickness of the ZnS preferred by the minimization routine was 20.5 nm which is close to the expected thickness of 20 nm.

Figure 3 shows the complex refractive index of TbFeCo as determined by the authors (marked with filled triangles) compared to other data found in the literature. The experiments of Heckens and Woollam [10] were carried out *in situ* during deposition. McGahan *et al* [11] and Atkinson *et al* [12, 13] protected the TbFeCo with Si_3N_4 layers and SiO_2 layers respectively. The reported compositions were $Tb_{18.01}Fe_{71.56}Co_{8.76}$ $Ta_{1.67}$ for Heckens and Woollam; $Tb_{20.33}Fe_{71.71}Co_{7.96}$ for McGahan *et al*; $Tb_{27}Fe_{62}Co_{11}$ for Atkinson *et al*. The differences among the sets of data are significant, with the spread of results being 0.4–0.5 in the index of refraction, n', and 0.3 in the extinction coefficient, n''. There is no clear trend that could be linked to the differences in composition. Our results are among the highest and are very close to the *in situ* measurements of Heckens and Woollam. Also included is the refractive index of TbFeCo without a ZnS top layer measured within an hour of deposition in normal ambient conditions. Clearly, these curves are much depressed relative to all the other results and emphasize the detrimental effect of the atmosphere after even a short period.

The degree of agreement between the optical constants determined by us and those measured *in situ* from the literature confirms the reliability of our method, which was also applied to the GdFeCo films. The refractive indices for GdFeCo are shown in figure 4. The results for an unprotected film and a film covered with ZnS are compared to the corresponding curves for TbFeCo. As can be seen, it was found that the optical behaviour of the GdFeCo differed from that of the TbFeCo by only a small amount in the extinction coefficient, n''.

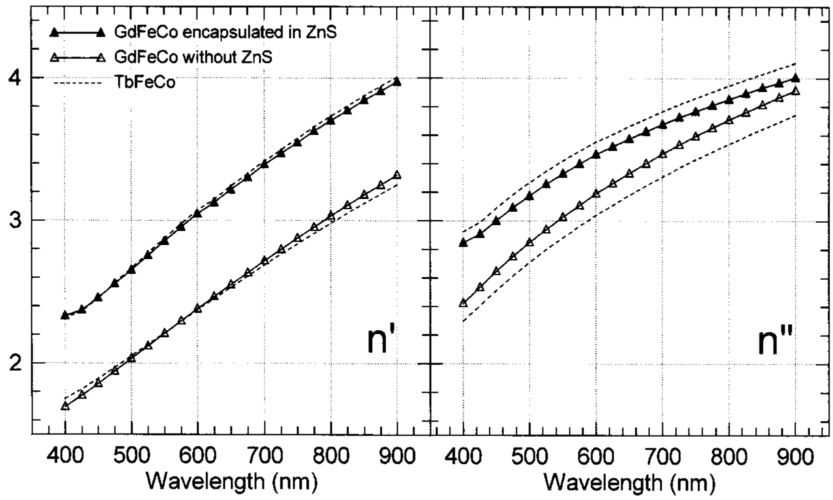

Figure 4. The refractive index of GdFeCo compared to that of TbFeCo.

4. Magneto-optical measurements

The permittivity tensor for a magneto-optical material in the polar configuration, in the preferred sign convention [14], is

$$[\varepsilon] = \begin{bmatrix} \varepsilon_{xx} & -\varepsilon_{xy} & 0 \\ \varepsilon_{xy} & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{xx} \end{bmatrix} = \varepsilon_0 n^2 \begin{bmatrix} 1 & -\mathrm{i}Q & 0 \\ \mathrm{i}Q & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where n is the complex refractive index and Q is the complex magneto-optical parameter defined by

$$Q = \mathrm{i}\frac{\varepsilon_{xy}}{\varepsilon_{xx}}.$$

Q is a measure of the magnitude of the first-order magneto-optical effects and is proportional to the magnetization of the lattice or sublattices that give rise to them. For both the alloys of interest, it is expected that the magneto-optical effects over the visible spectrum will be dominated by contributions from the transition metal sublattice [15]. The interaction of the electromagnetic radiation with the magnetization of the material is through spin–orbit coupling and, for this reason, the material is said to be gyromagnetic. At normal incidence, in the polar orientation, light will propagate in a gyromagnetic material as two counter-rotating circularly polarized modes with different effective refractive indices $n_\pm = n(1 \pm Q/2)$. Consequently, there is an overall change in polarization state that is magnetization dependent.

Where there is only a single magnetic layer in a multilayer structure, the determination of the magneto-optical parameter for the layer is a relatively simple process, since the complex Kerr rotation, Θ_K, becomes a product of Q and a purely optical function, f, for the whole multilayer. Consequently, if all the layers in the stack are optically characterized, the optical function may be determined using a magneto-optical multilayer model [7, 16] with Q set to unity. The magneto-optical parameter may then be calculated from the measured complex Kerr rotation by dividing by f.

The results of the analysis for TbFeCo, both protected by a ZnS layer and for a single unprotected film, are shown in figure 5(a) compared to the other published data. The magneto-optical parameters for the unprotected film are close to those of Atkinson *et al* which were

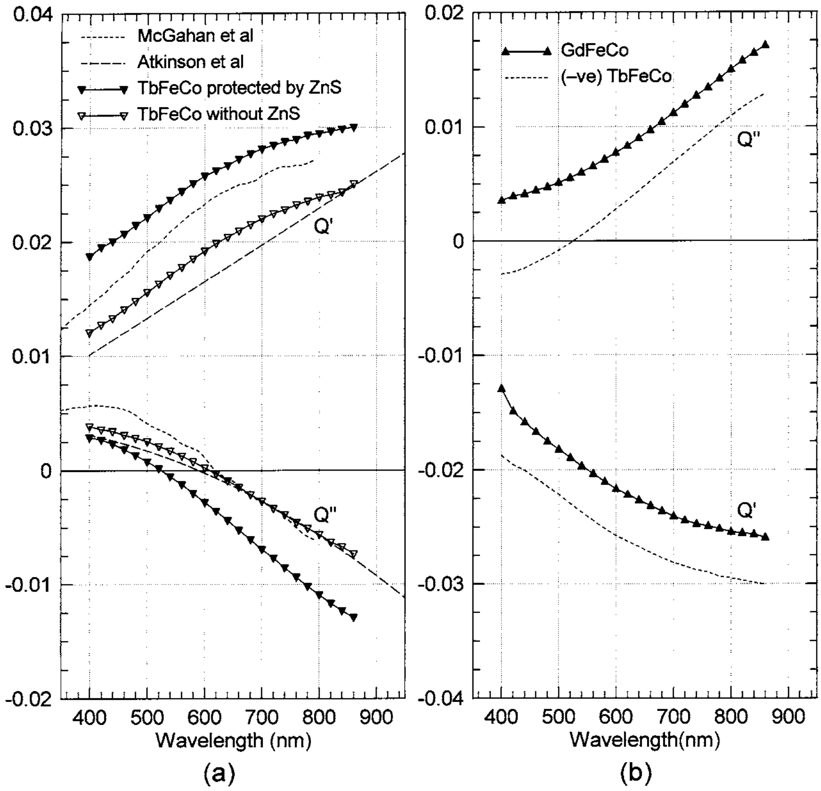

Figure 5. The magneto-optical parameter, Q, for (a) TbFeCo compared with those previously published in [11, 12] and for (b) GdFeCo compared to the negative of those for TbFeCo.

obtained for films capped with SiO_2. For the protected film, the curves are significantly elevated. Comparison with the unprotected film suggests that the effect of exposure to the atmosphere is to suppress the magneto-optical activity, probably via the formation of a dead layer on top.

The magneto-optical dispersion for the GdFeCo films with a ZnS protective layer is shown in figure 5(b). It is compared with the negative of the corresponding TbFeCo curve, the difference in sign being due to GdFeCo measurements being taken below the compensation temperature and the TbFeCo measurements being taken above the compensation temperature. Although the trends in the curves for the two materials are similar, the constants themselves are quite different, the results for GdFeCo being larger for Q'' and smaller for Q'. The moduli of the magneto-optical parameters are compared in figure 6. TbFeCo is more active than GdFeCo, corresponding to the transition metal content of the alloys. This is unfortunate, since it is GdFeCo that is used as a read-out layer in the new magneto-optical recording media.

In practice, data are read at an elevated temperature, not room temperature, and a reduction of the magneto-optical effects on heating has already been reported [3]. Therefore, the magneto-optical behaviour of GdFeCo was investigated at 80 °C where the magnetic orientation of the material becomes perpendicular. As expected, the magneto-optical activity was found to be lower, but only slightly, and this had a corresponding effect on Q as shown in figure 7.

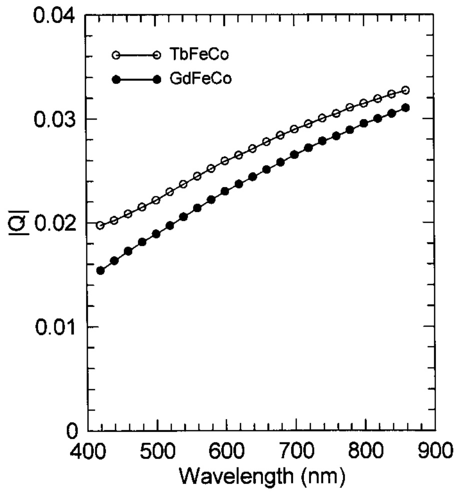

Figure 6. The modulus of the magneto-optical parameter, for TbFeCo and GdFeCo.

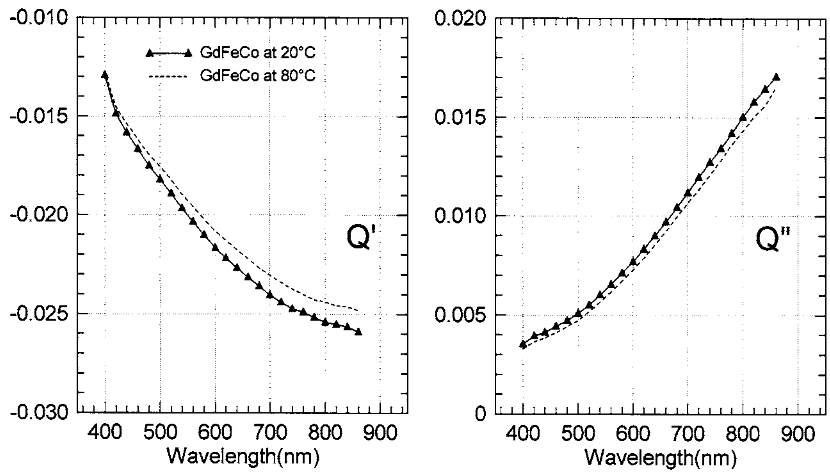

Figure 7. Comparison of the magneto-optical parameter for GdFeCo at room temperature and that at 80 °C.

5. Summary

Films of amorphous TbFeCo and GdFeCo, thick enough to make them optically semi-infinite, were deposited on glass substrates using conventional DC magnetron sputtering. Using well-established ellipsometric techniques, the materials were examined optically and magneto-optically, *ex situ*, and the relevant characteristic material constants were determined. When using ZnS as a barrier, the optical constants found for TbFeCo were close to previous published data obtained from *in situ* measurements. There are no similar data in the literature on GdFeCo for comparison, but our optical results for GdFeCo were similar to those for TbFeCo.

The magneto-optical results showed a higher Q for TbFeCo when compared to data published already. The GdFeCo films were slightly less active than the TbFeCo films, in accordance with the transition metal content, which is lower for the GdFeCo. At higher temperatures, the GdFeCo exhibited reduced magneto-optical effects, but at the temperature of transition between in-plane and perpendicular magnetic anisotropy, the reduction was small.

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