MAGNETIC PROPERTIES OF SPUTTERED CoCr FILMS AND MAGNETO-OPTICS OF RARE EARTH-TRANSITION METAL MULTILAYERS

By

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Abstract

The goal of the thesis is to make contributions to the development of two new technologies for data storage: perpendicular recording and magneto-optic recording. CoCr and rare earth-transition metal multilayers are the most suitable media for perpendicular recording and magneto-optic recording technologies, respectively. In part A of the thesis, magnetic properties of CoCr thin films produced by dc magnetron sputtering are studied for various deposition conditions. Dielectric constants and extraordinary Hall effect are also studied to provide information complementary to magnetic properties. In part B, new methods are developed for theoretical analysis of the magneto-optics of rare earth-transition metal multilayers, which can be used to optimize the readout of the recording system.

Part A

For dc magnetron sputtered CoCr films the perpendicular and parallel magnetic coercivities are found to be mainly controlled by the substrate temperature during film growth. Substrate temperatures between 180 and 300 C are necessary to fabricate CoCr thin films for recording media. Films produced in this manner have magnetic anisotropy constants ranging from \(-1.0\) to \(+0.5 \times 10^6\) erg/cc. The magnetic anisotropy has a complicated dependence on a large number of deposition parameters and can be best controlled by the dc sputtering power and the target-to-substrate distance. Based on microstructural analysis film properties are interpreted in terms of the adatom diffusion during film growth. It is found that high adatom mobility and low deposition rate promote positive magnetic anisotropy. The dielectric constants measured by ellipsometry are found to depend on the film thickness because of the change in film morphology during film growth. The effects of asymmetric sputtering are analyzed, and the relationship between the extraordinary Hall effect and the magnetic properties is investigated.

Part B

The 4x4 matrix method proposed by Lin-Chung and Teitler [P. J. Lin-Chung and S. Teitler, J. Opt. Soc. Am. A 1 703(1984)] is applied to the magneto-optics of the rare earth-transition metal multilayer system. Based on a plane wave model, the above method enables one to calculate the sensitivity of the readout to the layer thicknesses as well as effects of oblique angle of incidence, anisotropy in the nonmagnetic part of the dielectric constants and misalignment of the magnetization. Finally, an improved model is presented to take into account the fact that the reading laser is a strongly focused beam instead of
a plane wave. This new model is used to optimize the magneto-optic multilayer system. When the focal spot size of the reading laser beam is less than about three wavelengths, significantly different results are obtained from the focused beam and the plane wave models.
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Chapter 1
Introduction

1.1. Significance of Research on Magnetic Thin Films

With the popularity of computers it becomes more and more important to develop a means for fast storage and retrieval of large amount of data. Market studies\(^1\) have estimated that tens of billions of dollars are involved in the disk storage market. Kryder wrote\(^2\)

"The fact that the Santa Clara valley in California, regarded as the center of U. S. electronics industry, has been dubbed ‘Silicon Valley’ piques manufacturers of magnetic data-storage devices. After all, the companies based in the valley actually derive more of their revenue from magnetic devices than from semiconductor devices. A more appropriate sobriquet, the manufacturers suggest, would be ‘Iron Oxide Valley,’ after the commonest material from which magnetic-recording mediums are made."

The point is that magnetic data storage technology is as important and critical for today’s computer as semiconductor technology. A powerful computer system is useful only if it can access data in large volume and at high speed.

Research on the subject could be beneficial in terms of funding for universities. Good examples are the magnetics research centers at Carnegie Mellon University, the University of San Diego and Santa Clara University\(^3\).

The subject of magnetic thin films is also an interesting subject for pure research. The question of how a small region of a magnetic medium reverses its magnetization direction may sound like a classical problem. However, even today no quantitive prediction exists for magnetization reversal of most thin magnetic films\(^4\).
1.2. Media for Perpendicular Recording and Magneto-Optic Recording

In the most common recording media today, such as iron oxide, information is stored by impressing a bit pattern of magnetization on a thin film. The direction of magnetization is parallel to the magnetic film. As the storage density becomes higher, the magnetization is decreased due to the increasing demagnetization field to a point that the written pattern can no longer be distinguished (see Fig. 1.1). To decrease the demagnetization field one can reduce the film thickness; however the magnetic field on the surface becomes very weak and the readout of signal is difficult.

One way out of this difficulty to achieve higher density is to write a bit pattern with magnetization perpendicular to the film so that the demagnetization field of one bit pattern is actually favorable for the magnetization in the next bit pattern (see Fig. 1.2). A sharp region of magnetization transition is formed between adjacent bits and higher density can be achieved in this way. For the magnetization to have a stable direction normal to the film it must first overcome its own demagnetization field. In a simple model, a single, "perpendicular" magnetic domain in a homogeneous and perfectly smooth thin film has a demagnetization field of $4\pi M$, where $M$ is the magnetization intensity in emu units. The associated magnetostatic energy is $2\pi M^2$. To hold the perpendicular magnetization there must be an internal force in the domain that rotates it towards the film normal. This force is described by the anisotropy field and the associated energy is the anisotropy energy.

The usefulness of CoCr as a suitable perpendicular medium was discovered by Iwasaki in 1977. Subsequently, CoCr films produced by rf diode sputtering were studied by many workers and found to give rise to a strong anisotropy field which favors perpendicular magnetization. CoCr was chosen as the thesis project because of its potential applications in perpendicular recording technology. Another reason was that, at the start of the project, relatively little work had been done on CoCr produced by dc magnetron sputtering, which is a suitable deposition method for massive production because of the process controllability and the readiness to scale up from the experimental size.

The magneto-optic (MO) multilayer is another type of erasable recording medium which was proposed by Connel. The rare earth-transition metal (RE-TM) (e.g. TbFe) materials are antiferromagnetic with perpendicular magnetic anisotropy. Two dielectric layers sandwich the RE-TM layer, both to protect it and to optimize the optics of the multilayer system. Room temperature lies between the Curie temperature and the compensation tem-
perature of the RE-TM. As shown in Fig. 1.3, a focused laser heats up the bit and reduces coercivity of the region so that an external field can reverse the magnetization (writing). For reading, a laser with lower power is polarized in one direction and focused on the written bit. Depending on the direction of magnetization in the RE-TM layer, the reflected (transmitted) light will contain polarization in the other direction due to the polar Kerr effect (Faraday effect), which can be used to determine the recorded information.

The second part of the thesis is concentrated on the optimization of the optics of the MO multilayer system, which is critical for achieving high readout signal. Previous works were limited to plane wave model calculation. The present work considers the real case of focused beams.

1.3. Organization of the Thesis

Part A consists of chapters 2, 3 and 4 and it describes the experiments on CoCr films. Chapters 2 and 3 detail the process used to deposit the films and the characterization of the magnetic and structural properties. Answers are given to the question of how one can control the magnetic properties in terms of deposition parameters. Chapter 4 discusses the electronic properties of CoCr and describes the measurement of the dielectric constants and the extraordinary Hall effect of CoCr films. Due to the lack of availability of necessary apparatus and/or time limitations, no attempt was made to carry out a comprehensive investigation for the work described in chapter 4. However, some results are interesting and lead to better understanding of the films.

Part B includes chapters 5 and 6. In chapter 5, a new matrix method is used to calculate the optics of the MO multilayers for a plane wave model. In chapter 6 a model for the optics is presented, which takes into account the focal nature of the beams, and is used to optimize the MO films. Comparison is also made between the plane wave and the focused beam models.

Chapter 7 is an overall summary of the original contributions in this thesis. Figures are collected at the end of each chapter for convenience. Lengthy, but important, derivations and useful computer programs are presented as appendices.
Figure 1.1. Demagnetization fields in the conventional ("longitudinal") recording medium. The field depends on the thickness and the recording density.

Figure 1.2. Schematics of perpendicular recording.
Figure 1.3. Optics in the magneto-optic recording system from Kryder$^2$. 
Part A
Magnetic Properties of CoCr Films

Chapter 2
Sputtering of CoCr Films

2.1. Experimental Apparatus

Sputtering is a thin film deposition process in which Ar ions are accelerated towards a target made of material from which the films are to be made. The atoms of interest are ejected from the target by the energetic Ar ions and land on a substrate. To keep the current of Ar ions constant, the ions can be used to produce secondary electrons during target bombardment. The secondary electrons in turn ionize Ar atoms. In magnetron sputtering, magnets are installed near the target so that the secondary electrons travel in a cycloidal path and, thereby, are localized near the target surface. In this way, high sputtering efficiencies and high deposition rates can be achieved. Since less secondary electrons are needed with the use of magnetic field confinement, one can work at a lower Ar pressure; e.g. less than 3 mTorr. Besides a higher sputtering rate, magnetron sputtering also has the advantage of easy scale up to manufacturing size, mainly because the plasma is well confined to the target region and is not affected by other parts of the sputtering chamber.

Pure Co films cannot support perpendicular magnetization. As we mentioned in chapter 1, the demagnetization field of Co is much larger than its anisotropy field. There are two ways of getting around this problem. One is to reduce the magnetization $M$ (hence the demagnetization field) by adding other elements. The other is to deposit polycrystalline films so that the shape of the grains reduces the effective demagnetization field. Adding 18 to 22 atomic % Cr to Co gives an CoCr alloy which, in thin film form, can support perpendicular magnetization.\textsuperscript{7-11}

A planar dc magnetron sputtering system was used to deposit CoCr thin films. The main features of the sputtering coater are seen in Fig. 2.1. The target composition, 80 at.% Co and 20 at.% Cr, was selected on the basis of the best results previously reported.\textsuperscript{7-11} The target diameter was 15 cm. Magnets behind the target confined the erosion track to a 7 cm diameter ring. The vacuum system was pumped by a helium cryopump to a base pressure about $1\times10^{-6}$ Torr. The substrate holder assembly was designed such that the
substrates were uniformly heated directly from behind by a quartz halogen lamp, as shown in Fig. 2.2. The substrate temperature, $T_s$, was monitored by a thermocouple attached directly to the substrate. In order to obtain accurate measurement of $T_s$, a hole was drilled on one of the 6 glass substrates in Fig. 2.2, and the thermocouple was clamped between a glass washer and the glass substrate by a screw through the hole. About 20 minutes were required to reach a steady state value $T_s$ before sputtering. By adjusting the heating power, $T_s$ could be controlled to within 10 degrees C during sputtering.

It is well known that at small target to substrate distance, $d_{ts}$, the position of substrate for optimal film uniformity is slightly off center.\textsuperscript{12} For this reason, a substrate of 5 cm×5 cm is located 2.4 cm from the axis of the target. Corning 7059 glass is used as substrate material for most of the films. To study the effects of the substrate material on the film properties, NiCr(50 at.% Cr) and Ti films deposited on glass are also used as substrates for CoCr films. The choice of Ti is based on a previous work\textsuperscript{13}, which found Ti to be a good substrate material for CoCr. As discussed below, NiCr is shown to be better than Ti.

To optimize the film properties the sputtering parameters are varied in the following range: argon pressure $P_{Ar}$ from 1.5 to 10 mTorr; dc sputtering power from 150 to 900 watts; $d_{ts}$ from 5 to 10 cm; rf substrate bias from -200 to 0 volt; and $T_s$ from 25 to 350 C. A deposition rate of 100 nm/min for CoCr is typical for the above experimental conditions. Most of the films are sputtered to a thickness of 500 nm. Larger thicknesses do not give rise to any significant change in film properties.
2.2. Film Properties

The magnetization curves (M-H curve) of the deposited CoCr films are measured with a vibrating sample magnetometer (VSM). Depending on the deposition conditions, saturation magnetizations range from 350 to 450 emu/cc. For most films, both M-H curves with external field perpendicular and parallel to the film surface are measured, and the corresponding coercivities $H_{c\perp}$ and $H_{c\parallel}$ are determined. $H_{c\perp}$ and $H_{c\parallel}$ are found to range from 100 to 1400 Oe. By an optimal choice of the deposition parameters, values as high as 1800 Oe are obtained for $H_{c\perp}$.

The magnetic anisotropy of CoCr is measured by the torque magnetometer as shown in Fig. 2.3. It consists of two dials connected by a torsion wire. The difference between the readings of the two dials gives the torque experienced by the magnetic film sample. Detailed instructions for building such a magnetometer are provided by Cullity\textsuperscript{14}. The critical points include making the dials symmetric and choosing the proper diameter and length for the torsion wire. For CoCr films of thickness 500 nm and size 2.5 cm x 2.5 cm, a tungsten wire of 38 cm in length and 0.013 cm in diameter is suitable. The constant of torsion is measured to be 7.15 dyne-cm/degree.

Film orientation is referenced by the coordinate system in Fig. 2.2. The torque of a film is measured in a magnetic field of 13 kOe. It is found, in general, that the axis of the anisotropy is not normal to the film, which is not too surprising since the substrate is not located at a symmetric position with respect to the target. At large $d_{ts}$ (e.g. 9 cm) the anisotropy axis is not significantly different from the film normal. The torque data fit very well to the torque derived from the anisotropy energy of the form:

$$E_a = K_u sin^2(\alpha - \alpha_u) + K_2 sin^4(\alpha - \alpha_u)$$

where $\alpha$ defines the direction of the applied field with respect to the film normal in the torque measurement, and $\alpha_u$ gives the direction of the magnetic easy (or hard) axis specified with respect to the target (see Fig. 2.2).

The measured $K_u$ is typically -1 to 0.5 $10^6$ erg/cc, which is to be compared with $K_u = 4.5 \times 10^6$, and $K_2 = 1.5 \times 10^6$ erg/cc for a pure Co single crystal without contribution from the shape anisotropy. For CoCr, $K_2$ is typically 20% of $K_u$, but in some cases, $K_2$ can be larger than $K_u$. It is so far unclear what controls the ratio of the two quantities and how one can interpret it in terms of microstructural properties. However, a meaningful
quantity is $K_u + K_2$. It is an indication of the total anisotropy and seems to be better controlled than $K_u$ or $K_2$ individually. For example, we sputtered several films under the same condition and found that all the films have about the same value of $K_u + K_2$, however, the ratio of $K_u$ over $K_2$ can be quite different for the films.

Microstructural analysis has been made with a scanning electron microscope (SEM), transmission electron microscope (TEM) with transmission electron diffraction (TED) capability, x-ray diffractometer (XRD), and texture goniometer (TG). TEM and TED are found to be the most reliable and most reproducible of the above methods for the analysis of the sputtered CoCr films. About 100 nm of CoCr is deposited on a carbon coated copper grid for TEM and TED experiments. The grid is mechanically clamped to the glass substrate and the temperature of the grid is assumed to be the same as that of the substrate. Typical TEM and TED photographs are shown in Figs. 2.4 and 2.5. The grain size is determined as follows: the sizes of the bright spots (single crystals that diffract the electron beam) are measured and averaged for each TEM photograph. In the present study, the grain size is found to range from 20 nm to 70 nm. The crystal structure of CoCr determined by TED is found to be hcp. Since there has been reports of a transition from hcp to fcc phase for pure Co films\textsuperscript{15}, great care has been taken to analyse the TED results. So far, no phase transition has been found. A comparison of the predicted TED pattern for the hcp structure (see Fig. 2.6) generated by a computer program with the observed TED pattern in Fig. 2.5 is quite convincing. In the computer program the film is assumed to have c axes perpendicular to the film surface so that all the (hk0) diffraction peaks have strong intensities and the rest of the peaks have weak intensities. This preferred crystal orientation (or texture) is confirmed by XRD and TG methods as will be discussed later.

SEM provides a good indication of surface roughness and a reliable measurement of the thin film thickness. But cross section SEM does not reveal the grain structure in a reproducible manner and very much depends on how the film is fractured. For example two films deposited in one run of sputtering (one run can sputter 5 films) under identical conditions appear very different in SEM photos as shown in Fig. 2.7 and 2.8. Because of this problem most of the discussion on grain structure in this thesis is based on TEM and TED data.

In XRD and TG measurements only the (002) peak is detected. This is mainly due to the texture of the film (c axis perpendicular to film surface) and also because of the fine grains. TG is useful only when the films are well crystallized and have a well defined peak
of (002). For those films a $\theta_{50}$ value of 3.5 degrees is typical, where $\theta_{50}$ is defined such that $\theta \pm \theta_{50}$ corresponds to half the peak intensity for (002), and $\theta$ is the diffraction angle.

2.3. Effects of Substrate Temperature

At the beginning of the experiments, no substrate heating system was installed. For rf diode sputtering, the substrate heating is not critical since the substrate is bombarded by electrons and ions, and, therefore, significant substrate heating occurs. Hoffmann et al.\textsuperscript{16} studied the case of dc magnetron sputtering of CoCr and found that the coercivity increases with the substrate temperature. The present study provides more details on the effects of substrate heating for dc magnetron sputtering. When no substrate heating was provided, no matter how hard the author tried for all combinations of sputtering parameters other than $T_s$, almost all the CoCr films had the same magnetic properties. The films were nearly isotropic with a low coercivity of about 200 Oe, which is unsuitable for recording applications.

When a substrate heating system was installed films with larger coercivity could be obtained\textsuperscript{17}. As $T_s$ increased to about 180 C, a large increase in both $H_{c,\perp}$ and $M_{r,\perp}$ was observed as indicated in Fig. 2.9 and 2.10, where $M_r$ denotes the magnetic remanence. The sputtering parameters other than $T_s$ are as follows: $P_{Ar} = 3$ mTorr, dc power $W = 350$ watts and $d_{ts} = 9.0$ cm. The substrate was electrically floating. The film thickness was about 500 nm. This $T_s$ dependence is quite general and observed for films deposited with other sputtering parameters.

Fisher\textsuperscript{15,18} has recently reported the use of sputtered CoCr films for the production of commercial, longitudinal-type hard disks. As shown in Fig. 2.11, negative anisotropy required for longitudinal recording is achieved in the present study. However, it is clear from the scatter of data points in Fig. 2.11 that $T_s$ is not the best parameter to control the anisotropy constant.

TEM photographs of films deposited at $d_{ts} = 9.5$ cm, $T_s = 25, 210$ and 300 C, respectively, are given in Figs. 2.4, 2.12 and 2.13. The dependence of the grain diameter $d$ as a function of the substrate temperature is summarized in Fig. 2.14. The grain diameter is determined from TEM photographs in the following way. A line is drawn across the photograph. When we count across the line, each bright spot is considered as a grain and each dark spot is also a grain. The dimensions of the grains measured across the line give
the average grain diameter and the standard deviation. As can be seen from Fig. 2.14, for unheated substrates the film consists of fine grains (20 nm). As $T_s$ increases to 210°C, the grain size doubles. But as $T_s$ increases further to 300°C, the grain size becomes finer again. The latter behaviour is probably related to the fact that if the heating is too high, the perpendicular coercivity starts to drop as shown in Fig. 2.9. There seems to be a strong correlation between the coercivity and the grain size: larger grain size corresponds to larger coercivity. Recently, Khan et al.\textsuperscript{19} also found a similar relationship between the coercivity and the grain size for CoCr produced by rf sputtering. The difference in grain size seen in Figs. 2.4($T_s=25$°C) and Fig. 2.12($T_s=210$°C) can be interpreted in terms of Thornton's\textsuperscript{20} structural zone model as follows: At low $T_s$, because of low adatom mobility and the shadowing effect fine grains with voids at the grain boundaries develop; As $T_s$ increases, the grain sizes become larger and the grain boundaries fuse together. The explanation for the effect of heating at higher temperature (greater than 300°C) on the microstructure remains an unsolved problem.

How does one interpret the effect of substrate heating on the coercivities? There are two possible mechanisms. One possible mechanism is based on the observation that a larger coercivity is associated with a larger grain size. In the extreme of very fine grains separated by voids, the exchange interaction between electrons in different grains are weakened and there is week coupling between the magnetic moments of the grains. If the grain size and the coupling between grains are so small that thermal fluctuation can easily reverse the magnetic moment, the film will behave like a superparamagnet with low coercivity.\textsuperscript{21} The other possible mechanism is based on the assumption of segregation which is still controversial.\textsuperscript{19} It is well known to metallurgists that, upon heating, many solutes tend to segregate to the grain boundaries to reduce the free energy. Therefore, it is reasonable to think that the Cr atoms diffuse to the grain boundaries at high $T_s$ and, thereby, increase the compositional inhomogeneity. This inhomogeneity will in turn increase the coercivity since it is harder for the magnetic domain wall to move in the process of reversing its magnetization. Support of this interpretation is provided by Friedberg and Paul\textsuperscript{22} who have classified the coercivities of many alloys ranging from 0.002 Oe for supermalloy to 10 kOe for $Co_5Sm$ using a simple model in which the domain wall is blocked by planar defects such as grain boundaries, solute segregates, etc. The assumption of segregation is further supported by the observation that $M_s$ gets larger as $T_s$ is increased (Fig. 2.15), a point that will be discussed in more detail in chapter 4 in terms of the band structure of Co.
An attempt was made to obtain direct, experimental evidence for segregation of Cr at the grain boundaries with the use of an energy dispersive x-ray spectrometer. No variation in Cr content was observed by scanning the beam across the grains; however, because of the beam size (10 nm) was comparable to the grain size (about 40 nm), the EDXRS results were of little use. A composition analysis with higher resolution is required.

2.4. Demagnetization Field for CoCr Films

This section will discuss some observations made during the VSM and TM measurements and their relation to microstructure. In general, for a thin film, $K_u$ can be written as:

$$K_u = K_1 - 2\pi(N_\perp - N_\parallel)M^2$$  \hspace{1cm} (2.2)

where $N_\perp$ and $N_\parallel$ are the demagnetization factors in directions perpendicular and parallel to the film, respectively, and $K_1$ is the part of anisotropy constant internal to the grain (e.g. crystal anisotropy). The second term is the contribution from the microscopic shape anisotropy. For a single magnetic domain in a homogeneous and perfectly smooth thin film, the contribution from the shape anisotropy, or in other words, from the magnetostatic energy is $-2\pi M^2$ (i.e. $N_\perp = 1$ and $N_\parallel = 0$). Therefore, the shape anisotropy of this idealized model favours longitudinal magnetization. For a real film consisting of grains and voids, the contribution is smaller and one can obtain a film with positive macroscopic anisotropy. The above point is confirmed by plotting $M$ perpendicular to the film plane versus the magnetic field within the film: $H_{appl} = 4\pi N_\perp M$, where $H_{appl}$ is the applied field and the second term is the demagnetization field. If one sets $N_\perp = 1$ as in the idealized model, one gets an unphysical $M$-$H$ curve with a negative slope as shown in Fig. 2.16; i.e. this would mean that the effective demagnetization factor is less than unity.

Another interesting point is that, in the case of films deposited with $T_s$ greater than 200 C, a positive magnetic anisotropy necessarily means a large perpendicular coercivity, while the reverse does not hold. It is possible to support perpendicular magnetization even if the macroscopic magnetic anisotropy has a negative value. As seen in Fig. 2.17, the easy magnetization can be parallel to the substrate, but a significant coercivity in the perpendicular direction can be obtained.
2.5. Substrate Effects.

Three types of substrates, glass (Corning 7059), Ti-coated glass, and NiCr-coated glass, were used to investigate the effects of the substrate material on the magnetic properties of the CoCr films. Fig. 2.18 gives the coercivity, $H_{c\perp}$, for the perpendicular magnetization as a function of CoCr film thickness. In the case of glass substrate, the reduced value of $H_{c\perp}$ for small film thickness has been previously associated with the initial layer (about 100 nm) deposited, which has poor texture. As seen in Fig. 2.19, the initial layer effect is not observed in the case of Ti/glass and NiCr/glass substrates.

A possible explanation of this observation is that NiCr and Ti films have textures and crystal structures which are similar to those for CoCr so that no initial layer can develop. Similar results have been recently observed by Tanaka and Masuya for e-beam evaporated CoCr on Ti substrates.

TED experiment has been carried out to analyze the structure and texture of NiCr and the data are shown in Fig. 2.19. The first structural model used to analyze the TED data is fcc of Ni. It has been well known that hcp and fcc are two different ways of close packing spheres. Fig. 2.20 shows how to section the fcc lattice to form two-dimensional triangular lattices. If A, B and C represent different ways of stacking the two-dimensional triangular lattice upon each other, the stacking sequence of hcp is (...ABABAB...) and that of fcc is (...ABCABCABC...). Therefore, fcc has the same triangular lattice structure in the $(111)$ planes as hcp in $(002)$ planes. If NiCr has the the structure of fcc, its $(111)$ planes will match the $(002)$ planes of hcp of CoCr. Fig. 2.21 plots the theoretical reciprocal lattice constant $K_{\text{theo}}$ for fcc versus the experimental TED data $K_{\text{exp}}$.

The second structural model for NiCr is bcc of Cr. The fit of bcc to experimental data is presented in Fig. 2.22 in terms of the reciprocal lattice constants. Because of the similarity between fcc and hcp, the TED data are also fitted to the structure of hcp assuming that the $c$ axis is normal to the film (i.e. only the strong peaks indicated in Fig. 2.6 are seen in the TED data of NiCr). The fit to hcp as shown in Fig. 2.23 is much better than those for fcc (Fig. 2.21) and bcc (Fig. 2.22). We conclude that the sputtered NiCr film has the structure of hcp. It is also interesting to compare the nearest atomic distances for the following metals (taken from the periodic table) and alloyed films (determined from TED data of the present study):

Co(hcp): $a = 2.51 \, \text{Å}$
Cr(bcc): \( a' = 2.49 \, \text{Å} \)
Ni(fcc): \( a = 2.49 \, \text{Å} \)
Ti(hcp): \( a = 2.95 \, \text{Å} \)
CoCr(hcp): \( a = 2.52 \, \text{Å} \)
NiCr(hcp): \( a = 2.35 \, \text{Å} \)

where \( a \) is the lattice constant for the two-dimensional triangular lattice in hcp or fcc, and \( a' \) is the smallest lattice constant for bcc. One notices that the nearest atomic distance of NiCr(hcp) is smaller than those of Ni and Cr. One also finds that the match of NiCr lattice to CoCr lattice is better than that of Ti to CoCr.
Figure 2.1. Schematics of the dc magnetron sputtering system used to deposit CoCr films.
Figure 2.2. Details of the substrate holder assembly. The size of the substrate is 5 cm x 5 cm and the center of the substrate is located 2.4 cm from the axis of the target.
Figure 2.3. Torque magnetometer. The tungsten torsion wire has a length of 38 cm and a diameter of 0.013 cm.
Figure 2.4. A typical TEM photograph of a CoCr film. The sputtering parameters are as follows: $T_s = 25$ C, $P_{Ar} = 3$ mTorr, $W = 350$ watts, and $d_{ts} = 9.5$ cm. The sample is deposited on a carbon coated copper grid designed for TEM studies.
Figure 2.5. TED photograph for the same sample as in Fig. 2.4. The electron beam energy is 200 kV.
Figure 2.6. Predicted TED pattern for the hcp structure. The intensity of the rings are predicted assuming the film has an orientation with c axis normal to the film surface. The rings that have been seen in experiment and have been identified are labelled.
Figure 2.7. A typical cross section SEM photograph of CoCr sputtered on glass at $T_s = 200$ C, $P_{Ar} = 3$ mTorr, $W = 350$ watts and $d_{ts} = 8.0$ cm. The magnification is 40,000 and the dotted line at the lower right corner of the photograph represents $750$ nm.
Figure 2.8. Another SEM photograph of CoCr deposited on glass under the same condition as in Fig. 2.7 in the same run of sputtering. The magnification is 50,000 and the dotted line at the lower right corner represents 600 nm.
Figure 2.9. Dependence of the coercivity of CoCr deposited on glass on the temperature of the substrate, $T_s$, during film growth. The sputtering parameters other than $T_s$ are as follows: $P_{Ar}=3$ mTorr; $W=350$ watts, $d_{ts}=9.0$ cm. The CoCr film thickness is about 500 nm.
Figure 2.10. Ratio $M_r/M_s$ of CoCr deposited on glass as a function of $T_s$, where $M_r$ is the magnetic remanence and $M_s$ the saturation magnetization. The films are sputtered under the same condition as for Fig. 2.9. The film thickness is about 500 nm.
Figure 2.11. The anisotropy constants $K_u$ and $K_2$ of CoCr deposited on glass as a function of the substrate temperature $T_s$ during film growth. Sputtering parameters other than $T_s$ are given in Fig. 2.9.
Figure 2.12. TEM photograph of CoCr deposited at $T_s = 210$ C. The other parameters are the same as for the TEM photograph in Fig. 2.4.
Figure 2.13. The same as Fig. 2.12 except $T_s = 300$ C.
Figure 2.14. The grain size of CoCr, $d$, as a function of the substrate temperature, $T_s$. The films are deposited at different target to substrate distance $d_{ts}$. Other sputtering conditions are the same as for the TEM photograph in Fig. 2.4. The grain size is determined from TEM photographs.
Figure 2.15. The saturation magnetization of CoCr deposited on glass, $M_s$, as a function of the substrate temperature, $T_s$. The other sputtering parameters are given in Fig. 2.9. $M_s$ is determined by VSM measurement and the error is mainly due to the measurement of the film thickness and the area of the sample. The thickness is measured with a profilometer and/or cross section SEM.
Figure 2.16. The magnetization $M$ versus $H_{appl} - 4\pi NM$ for a film of CoCr deposited on glass at $T_a = 280$ C. Other parameters are the same as for Fig. 2.9. $N$ is the demagnetization factor. The curves correspond to $N_\perp = 1$ and $N_\parallel = 0$. 
Figure 2.17. Example of VSM result of CoCr on glass showing easy magnetization direction in the plane and a significant $H_{c\perp}$. The sputtering parameters are: $T_s = 210$ C, and other conditions are the same as for Fig. 2.9.
Figure 2.18. The substrate effects on perpendicular coercivity as a function film thickness. The growth temperature is 300 C and the target to substrate distance is 8 cm. The other parameters are the same as for Fig. 2.9. The lines between data points are used only as a guide to the eyes.
Figure 2.19. TED photograph of NiCr. The beam energy is 200 kV.
Figure 2.20. How to section the fcc lattice into the same two-dimensional triangular lattice as (002) planes of hcp lattice.
Figure 2.21. Fit of the TED data to the structure of fcc. $K_{\text{theo}}$ is the reciprocal lattice constant calculated for fcc. $K_{\text{exp}}$ is determined from the TED experiment. A best fit straight line through the origin is also shown.
Figure 2.22. Fit of the TED data to the structure of bcc. \( K_{\text{theo}} \) is the reciprocal lattice constant calculated for bcc. \( K_{\text{exp}} \) is determined from the TED experiment. Also shown is a best fit straight line through the origin.
Figure 2.23. Fit of the TED data to the structure of hcp. $K_{\text{theo}}$ is the reciprocal lattice constant calculated for hcp. $K_{\text{exp}}$ is determined from the TED experiment. The film is assumed to have a texture with c axis normal to the film surface so that only the (hk0) peaks are seen.
3.1. Effects of Sputtering Power and Target-Substrate Distance

The first stage of the study concentrated on the development of dc sputtering process for the fabrication of CoCr films, which would be useful for recording applications. As described in chapter 2 it was found that the perpendicular magnetic coercivity $H_{c\perp}$ is controlled mainly by the substrate temperature $T_s$ during film growth. The situation is more complicated for the magnetic anisotropy.

The anisotropy field $H_k$ is defined as $H_k = 2K/M_s$ and, in practise, is estimated from the M-H curve for a field direction parallel to film surface. Other workers\textsuperscript{25,26,27} have shown that $H_k$ is dependent on $T_s$, $P_{Ar}$, and the base pressure $P_b$. Usually low $P_b$ and $P_{Ar}$, and high $T_s$ promote positive anisotropy. One complication enters at this point. In general, when $H_k$ is estimated from M-H curve, one has assumed that the demagnetization factor is zero for magnetization parallel to the film. But this is not the case as was demonstrated in the last chapter. Therefore, $H_k$ estimated in this way does not indicate whether the film favors perpendicular or longitudinal magnetization. A more direct approach is to characterize the anisotropy with a torque magnetometer, as will be described in this chapter.

For the results to be reproducible, the Corning 7059 glass substrates are cleaned (or preconditioned, to be exact) with a method developed by Sullivan\textsuperscript{28}. First, the glass substrate is cleaned by methanol and wiped by lens paper. Then it is cleaned with trichloroethylene followed by methanol again. Finally it is blown dry by a $N_2$ gas flow. The experimental apparatus is shown in Figs. 2.1 and 2.2 and is described in section 2.1.

To obtain the lowest base pressure possible during sputtering the pump is not throttled. $T_s$ is fixed at 210 C to optimize $H_{c\perp}$, $P_{Ar}$ is kept at 3 mTorr, by the control of input Ar gas flow. A lower $P_{Ar}$ might be better for the magnetic anisotropy; but, it would make the plasma difficult to turn on. By varying the dc sputtering power, $W$, and the target-to-substrate distance, $d_{ts}$, sputtering rates ranging from 0.3 to 3.5 nm/sec are obtained. The deposition time is controlled so that all the films have a thickness of 500 ± 50 nm. The shortest $d_{ts}$ that can be used is about 5 cm. At this point, the substrate assembly starts to interfere with the plasma as is evident from the change of the target voltage caused by
the movement of the shutter.

After sputtering, the film orientation with respect to the target is marked. The reference coordinate system is shown in Fig. 2.2. The film is then measured with the torque magnetometer described in chapter 2. The data is fitted to the torque curve calculated from equation (2.1). M-H curves are measured by VSM for directions perpendicular and parallel to the film, and in some cases, other directions are also scanned. The film structure is characterized by XRD. Texture goniometer measurement is not always possible since some of the films are not well crystallized and do not show any peaks in XRD measurement. However, we introduce the ratio \( I_{(002)}/I_b \), where \( I_{(002)} \) and \( I_b \) are the intensities of the (002) reflection and the background intensity in the vicinity of (002) peak, respectively, which can be used as a measure of the degree of crystallization. TEM and TED are also used to give additional information on the microstructure. The (100) peak and other low intensity peaks are not seen above the background, except in the case of films with large \( I_{(002)}/I_b \) (\( \approx 60 \)).

Three sets of samples with \( d_{ts} \) equal to 9.5, 7.8 and 5.3 cm were sputtered and characterized. The anisotropy constant, \( K_u + K_2 \), discussed in the last chapter, as a function of the sputtering power, \( W \), is given in Fig. 3.1. For \( d_{ts} = 7.8 \) cm, it has the opposite dependence on \( W \) to that for \( d_{ts} = 5.3 \) cm. Compared to the corresponding \( H_{c\perp} \)'s in Fig. 3.2, which have large values for all three sets of data between \( W = 350 \) and \( W = 600 \) watts, the \( K_u + K_2 \) data is more complex.

The direction of the axis for the anisotropy, \( \alpha_u \) and \( I_{(002)}/I_b \) are presented in Figs. 3.3 and 3.4, respectively. One notices that, in general, \( |\alpha_u| \) increases with \( W \). All the easy axes \( (K_u + K_2 > 0) \) point away from the target center \( (\alpha_u < 0) \) and all the hard axes \( (K_u + K_2 < 0) \) towards it \( (\alpha_u > 0) \). One also finds that, at \( d_{ts} = 7.8 \) cm, the best crystallized film (i.e. with maximum \( I_{(002)}/I_b \)) has large values of \( K_u + K_2, H_{c\perp} \), and a small \( |\alpha_u| \).
3.2 The Roles of Adatom Diffusion and Covering Rate

In this section we attempt to interpret the complicated dependence of $K_u + K_2$ and $\alpha_u$ on the sputtering parameters. It is necessary to consider the effect of the stress anisotropy for the following discussion. It is well known\textsuperscript{20} that films of high melting point material ($T/T_m < 0.25$, where $T_m$ is the melting temperature) sputtered at low pressure (< 8 mTorr) can have internal compressive stress as high as $10^9$ Pa. This is a result of bombardment by energetic coating atoms and by Ar ions neutralized and reflected at the cathode. The stress anisotropy constant\textsuperscript{14} $K_\sigma(\sigma)$ is a function of the stress $\sigma$ and is the order of $10^6$ erg/cc for Co under a compressive stress of $10^9$ Pa, i.e. it is of the same order of magnitude as the measured total anisotropy. However, when the stress is along the c axis, $K_\sigma = 0$ due to the uniaxial symmetry, which is probably the reason why the effect of internal stress on anisotropy could not be measured before.\textsuperscript{25} We assume that the internal stress in the film is due to the bombardment of energetic particles coming from an angle with respect to the film normal. The induced stress anisotropy has an easy axis along the direction of the compressive stress\textsuperscript{14} for Co and we assume this is also the case for CoCr. For simplicity we further assume that the stress anisotropy only contribute to $K_1$ in equation (2.2). Then, we have

$$K_u + K_2 = K_1^0 + K_2^0 + K_\sigma - 2\pi (N_\perp - N_\parallel)M^2$$

(3.1)

where $K_1^0$ and $K_2^0$ arise from crystalline anisotropy.

The anisotropy constant can be related to the sputtering parameters in the following way: 1) $K_1^0 + K_2^0$ depends on the microstructure and texture of CoCr films; 2) the microstructure and texture are determined by the mechanism of film growth (e.g. adatom diffusion); 3) the film growth condition is controlled by the sputtering parameters of a specific sputtering system.

Regarding point 1) above we assume that $K_1^0$ and $K_2^0$ depend on the degrees of crystallization and texture. This assumption is supported by the findings of Hwang et al.\textsuperscript{25} and Ouchi and Iwaski\textsuperscript{30}. They found that $H_k = 2K_1/M_s$ increases as $\theta_{50}$ is reduced. Therefore, it is reasonable to assume that a high degree of crystallization promotes positive magnetic anisotropy. We note from the last term in (3.1) that compositional inhomogeneity and the shape of the grains also affect $K_u + K_2$, as discussed in section 2.4.

To study the dependence of the microstructure and texture on the film growth condition (point 2) above), we consider what happens to a sputtered atom landing on the
growing film. Upon arrival on the growing film, the sputtered atom diffuses with a kinetic energy much larger than the thermal energy before it loses its kinetic energy and reach thermal equilibrium with the substrate.\textsuperscript{31} We assume that the kinetic energy is equivalent to an effective temperature $T_{\text{eff}}$ for the diffusion constant $D$:

$$D \sim \exp\left(-\frac{Q_d}{k_b T_{\text{eff}}}\right)$$

(3.2)

where $Q_d$ is the surface diffusion activation energy (typically 0.5 eV) and $k_b$ is the Boltzmann's constant. This adatom diffusion process affects very much the morphology of the growing film. In Thornton's structure zone model,\textsuperscript{20} high adatom mobility results in well crystallized films with large grain size. Glocke et al.\textsuperscript{32} have modeled the growth of CoCr films and found that the preferential growth direction is along the $c$ axis because of the geometry of the unit cell of CoCr(hcp). In this study, we assume that the film is grown layer by layer in the direction of the $c$ axis.

To take the deposition rate into account in the study of adatom diffusion, we assume that the adatom is considered to be immobilized if it is covered by a layer of sputtered material of thickness $c$, where $c$ is the height of the hcp unit cell. The above assumption is based on the fact that the surface diffusion coefficient is much larger than the bulk diffusion coefficient.\textsuperscript{31} The time, $t_d$, available for the adatom to diffuse before it is covered by the incoming sputtered atoms can be expressed as

$$t_d = \frac{c}{R}$$

(3.3)

Within $t_d$ the adatom can diffuse over a distance, $s$:

$$s = \sqrt{2Dc/R}$$

(3.4)

In the following discussion we assume that, for the film to be well crystallized, the adatom must diffuse over a sufficiently long distance, $s$, before it is covered by the incoming atoms.

We now consider point 3) above. To study the relationship between the sputtering parameters ($d_{ts}$ and $W$) and the growth condition (i.e. the distance $s$), we note that the sputtering rate can be written as

$$R = Wg(d_{ts})$$

(3.5)

where the function, $g$, depends on the geometry of the sputtering system. The kinetic energy associated with each sputtered atom arriving on the substrate can be written as

$$E_k = E_0(W)\exp\left(-\frac{d_{ts}}{\lambda_e}\right)$$

(3.6)
where \( E_0(W) \) is the energy of an sputtered atom ejected from the target. It is determined by the cathode voltage which is a weak function of \( W \). For a sputtering voltage of 500 V, \( E_0 \) is estimated to be between 5 to 10 eV. Formulas for estimating the mean free path, \( \lambda_e \), have been given by Westwood. Including the effect of kinetic energy, we find \( \lambda_e = 3.1 \text{ cm} \) for the present study. During the film growth, the adatom diffusion is also promoted by the radiation from the target, plasma bombardment and neutral Ar atom impingement. The energy flux of the radiation and the energetic particles can be approximated as

\[
E_T = A \frac{W}{d_{ts}}
\]  

(3.7)

where \( A \) depends on the specific geometry and must be determined empirically for each experimental set-up. \( E_k \) in (3.6) and \( E_T \) in (3.7) cause the effective surface temperature \( T_{eff} \) to increase, which in turn enhances the adatom diffusion coefficient in equation (3.2).

Finally, \( s \) is related to \( W \) and \( d_{ts} \) through (3.4) and (3.5) as follows:

\[
s = \sqrt{\frac{2cD(W,d_{ts})}{Wq(d_{ts})}}
\]

(3.8)

where \( D(W,d_{ts}) \) is the given through (3.2), (3.6) and (3.7). Due to the large number of undetermined parameters in the above equations, it is impossible to make any quantitative predictions. However, the above formulas enable us to interpret the dependence of \( K_u + K_2 \) as follows.

At \( d_{ts} = 9.5 \text{ cm} \) and low power range (\( \approx 150 \text{ watts} \)) the sputtering rate is the lowest and the adatom has the longest \( t_d \) to diffuse \( (t_d \approx 1 \text{ sec} \) from (3.3)) before it is covered. At this \( d_{ts} \), it is assumed that \( E_k \) and \( E_T \) are too small to cause significant diffusion of adatoms to the nucleation sites. A small increase in \( W \) causes \( D \) to increase through the relations in (3.2), (3.6) and (3.7), which then results in a large increase in \( K_u + K_2 \) as shown in Fig. 3.1(\( d_{ts} = 9.5 \text{ cm} \)). When \( D \) is small, the films are not well crystallized, resulting in small \( I_{(002)}/I_b \) ratio and a negative anisotropy, in agreement with the data discussed above.

If \( d_{ts} \) is decreased and \( W \) made larger, \( R \) plays a more important role (e.g. if \( D=6 \times 10^{-14} \text{ cm}^2/\text{sec} \), as estimated by Hoffman et al., and \( R=30 \text{ Å/sec} \), we obtain \( s=9 \text{ Å} \), i.e., the adatom hardly has a chance to move around before it is covered). To interpret the power dependence of \( K_u + K_2 \) at \( d_{ts} = 7.8 \text{ cm} \), we assume that the substrate is still “outside” the plasma, and the effect of \( E_T \) in (3.7) to \( T_{eff} \) is less than that of \( E_k \) in
which has a weak dependence on $W$. The increase of $D(W, d_{ts})$ with $W$ is slower than that of $R$. As a consequence the diffusion distance, $s$, in (3.8) decreases with $W$. Therefore, we expect $I_{(002)}/I_b$ to decrease and $K_u + K_2$ to drop with increasing $W$, in agreement with the $d_{ts} = 7.8$ cm curves in Figs. 3.4 and 3.1.

To confirm the above point of view, TEM and TED measurements were made on films deposited at different sputtering powers at $d_{ts} = 7.8$ cm. TEM photographs for $W = 150$ and $W = 750$ watts are shown in Figs. 3.5 and 3.6, respectively. The data is in good agreement with the theory. At high $W$, the adatoms do not have sufficient time to diffuse and fine grains with relatively well defined grain boundaries are developed. As $W$ is reduced, larger grains with grain boundaries fused together are formed which is a result of longer adatom diffusion time. The TED data indicates that the $c$ axes of the films are normal to the film surface except for the film deposited at $W=150$ watts, which is the best crystallized film obtained (Fig. 3.7). The $c$ axis is found to be tilted away from the film normal in this case probably because it is much better crystallized and, therefore, more sensitive to texture measurement.

When $d_{ts} = 5.3$ cm, the substrate is almost in contact with the plasma, and the effect of $E_T$ to $T_{eff}$ is larger than that of $E_k$. The increase of $D(W, d_{ts})$ with $W$ is faster than that of $R$. Therefore, $s$ in equation (3.8) increases with $W$. This explains the increase of $K_u + K_2$ with power at the the above target-to-substrate distance.

TEM photographs corresponding to $W=150$, 350 and 750 watts, with $d_{ts} = 5.3$ cm, are presented in Figs. 3.8, 3.9 and 3.10, respectively. For $W=150$ and 350 watts, TEM results agree with the theory: As $W$ increase the adatoms are more activated by the plasma and larger grains with fused grain boundaries are seen at 350 watts. But something unexpected is seen for $W=750$ watts: The grains become finer and the grain boundaries are sharper again. A possible reason for this is that, at the small $d_{ts}$ used (5.3 cm), the surface heating is high and causes the Cr atoms to segregate and to form finer grains. The relatively large magnetic anisotropy in this case is likely due for the most part to the smaller demagnetization factor arising from the fine grains. This effect of overheating has been discussed in section 2.3.
3.3 Effects of Asymmetric Sputtering

The off-axis location of the substrate with respect to the target as shown in Fig. 2.2 enables one to study the effect of asymmetric deposition. Results in Fig. 3.3 indicates that the magnetic easy axis is tilted away from the center of the target and the hard axis towards it. This asymmetry in the magnetic anisotropy cannot be accounted for with crystalline anisotropy since it was shown in section 3.2 that most of the films have c axes normal to the film surfaces. Possible causes of the asymmetry in the anisotropy are: 1) stress anisotropy due to the bombardment of energetic coating atoms and Ar ions neutralized and reflected from the cathode; 2) shape anisotropy of grains grown towards the direction of the flux of the sputtered atoms. The following is a simple model to demonstrate how the compressive stress causes the axis of the total anisotropy to differ from the film normal and why \( \alpha_u \) changes sign when the total anisotropy \( K_u + K_2 \) does.

For simplicity we neglect the fourth order term, \( K_2 \sin^4(\alpha - \alpha_u) \) in (2.1) and assume the shape anisotropy part has the hard axis normal to the film surface. However, the method of derivation below applies to the most general case. From the geometry of the sputtering system in Fig. 2.2 we conclude that the impinging particles from the direction of \( \alpha < 0 \) are more energetic than those from other directions. If \( \alpha_\sigma (< 0) \) is the direction of the compressive stress which is along the direction of the flux of the impinging particles from the direction of \( \alpha < 0 \), then the total anisotropy energy can be expressed as

\[
E_\alpha = \left[ K_1^0 - 2\pi (N_\perp - N_\parallel)M^2 \right] \sin^2(\alpha) + K_\sigma \sin^2(\alpha - \alpha_\sigma) \tag{3.9}
\]

where the first term is due to the crystalline anisotropy and the shape anisotropy, and the second term arises from stress anisotropy. In the small angle approximation (3.9) becomes

\[
E_\alpha = \left[ K_1^0 - 2\pi (N_\perp - N_\parallel)M^2 \right] \alpha^2 + K_\sigma (\alpha - \alpha_\sigma)^2 \tag{3.10}
\]

Since \( K_\sigma > 0 \) (see Ref. 14), one can show that from (3.10) that the minimum (easy axis) or maximum (hard axis) occurs at

\[
\alpha_u = -K_\sigma \alpha_\sigma / K_u \tag{3.11}
\]

where \( K_u = K_1^0 - 2\pi (N_\perp - N_\parallel)M^2 + K_\sigma \). (3.10) and (3.11) indicate that if \( K_u > 0 \) then \( \alpha_u < 0 \) is an easy axis (minimum in \( E_\alpha \)) and similarly for \( K_u < 0 \). The above simple model for the origin and sign of \( \alpha_u \) agrees well with the experimental data.

It is important to note that \( \alpha_u \) is sensitive to the orientation of the film with respect to the target. If the substrate is not parallel to the target, \( \alpha_u \) changes significantly.
For example, one sample was intentionally misoriented from the parallel direction by +8 degrees, and with $W=350$ and $d_{ts} = 5.3$ cm; as a consequence $\alpha_u$ changed from -12 to -40 degrees while $K_u$ and $K_2$ remained unchanged. The effect of this large $|\alpha_u|$ to the M-H curve is shown in Fig. 3.11. One can see a significant difference when the applied field direction $\alpha$ changes from 45 to -45 degrees.

We conclude that the anisotropy constants can be controlled by the sputtering power and the target to substrate distance. It is important to orient the substrate during sputtering in order to control the easy (hard) axis orientation of the magnetic anisotropy. Once the films have been made, we should carry out some more experimental and theoretical studies on their physical properties such as the electronic states, dielectric constants and the Hall effect. Such a study is the task for the next chapter.
Figure 3.1. Anisotropy constant $K_u + K_2$ of CoCr on glass as a function of the sputtering power $W$ at various $d_{ts}$. Other parameters are: $P_{Ar} = 3$ mTorr, $T_s = 210$ C. The film thickness is $500 \pm 50$ nm. The lines are used only to identify the data sets.
Figure 3.2. Perpendicular coercivity $H_{c \perp}$ versus the sputtering power $W$ at various target-to-substrate distance $d_{ts}$. Other parameters are the same as for Fig. 3.1. The lines are used only to identify the data sets.
Figure 3.3. The orientation of the easy (hard) axis of the anisotropy $\alpha_u$ defined in equation (2.1) and Fig. 2.2 versus the sputtering power for the same sets of samples as in Fig. 3.1. The straight lines are used only to identify the data sets.
Figure 3.4. Ratio of (002) peak intensity $I_{(002)}$ to the background intensity $I_b$ from XRD versus the sputtering power $W$, for the same sets of samples as in Fig. 3.1. The lines are used only to identify the data sets.
Figure 3.5. TEM photograph for $W=150$ watts and $d_{ts} = 7.8$ cm. Other parameters are the same as for Fig. 3.1.
Figure 3.6. Same as Fig. 3.5 except $W=750$ watts.
Figure 3.7. TED photograph for the same sample as in Fig. 3.5.
Figure 3.8. TEM photograph for $W=150$ watts and $d_{ls}=5.3$ cm. Other parameters are the same as for Fig. 3.1.
Figure 3.9. Same as Fig. 3.8 except $W=350$ watts.
Figure 3.10. Same as Fig. 3.8 except $W=750$ watts.
Figure 3.11. M-H curve for a sample oriented +8 degrees from the usual direction parallel to the target surface during deposition (see also Fig. 2.2). $\alpha$ is the direction of the applied field defined in Fig. 2.2 in torque magnetometer measurement. Sputtering parameters are $d_{ts} = 5.3$ cm and $W=350$ watts.
4.1 Saturation Magnetization and Electronic States of CoCr

The saturation magnetization $M_s$ is observed to increase with increasing substrate temperature $T_s$: In Fig. 2.15 $M_s$ increases from 360 emu/cc at $T_s = 30 \, ^\circ\text{C}$ to 420 emu/cc at $T_s = 250 \, ^\circ\text{C}$.

Haines$^{34}$ has developed a model for the saturation magnetization and derived the following semiempirical formula:

$$M_s = M_{s0}(1 - C_{Cr})(1 - 4C_{Cr})$$

(4.1)

where $M_{s0}$ is the saturation magnetization for pure Co crystal and $C_{Cr}$ is the concentration (i.e. atomic percentage) of Cr. The model assumes: 1) Only Co atoms contribute to $M_s$; 2) Cr atoms are uniformly distributed and interact only with Co atoms; and 3) By transferring the outer electrons to the Co atoms, one Cr atom destroys the magnetic moment of 4 neighbouring Co atoms as estimated from the fact that bulk CoCr alloy becomes nonmagnetic at about $C_{Cr} = 25$ at. %. He further argued that the observed $M_s$ should be larger in thin films than in homogeneous bulk samples since the Cr atoms may not be uniformly distributed in the films, in which case the $(1 - 4C_{Cr})$ factor should be replaced by a larger value. The above model explains his data,$^{34}$ and fits to the values of $M_s$ in Fig. 2.15 for $C_{Cr} = 20$ at. %. A detailed study of the saturation magnetization as a function of $C_{Cr}$, film thickness and sputtering parameters other than $T_s$ was recognized as being worthwhile; however, such a study could not be fit into the timeframe allowed for the main scope of this thesis. We notice that there is no report of a detailed study of the electronic states to justify the semiempirical formula (4.1). In the following discussion we attempt to interpret (4.1) in terms of a previous band structure calculation$^{35}$ for pure Co crystals.

Singal and Das$^{35}$ calculated the band structure for pure Co crystals using a hybridized-tight-binding-plane-wave method and were able to predict the saturation magnetization. For future reference in this thesis, the electron density of states for majority- and minority-band states are reproduced in Figs. 4.1 and 4.2. Singal and Das$^{35}$ also derived the electron distribution in various bands as follows:

$$N_{3d}^\uparrow = 5.033, \quad N_{3d}^\downarrow = 3.490,$$

57
\[ N_{\text{free}}^\uparrow = 0.248, \quad N_{\text{free}}^\downarrow = 0.230 \]  

(4.2)

where '3d' and 'free' denote for 3d bands and free electron-like 4s bands, respectively, and the arrows refer to majority- and minority-bands. We conclude from (4.2) that, approximately, 1.5 electrons are needed to fill up the magnetic, 3d bands and, consequently, to destroy the magnetic moments. If a Cr atom transfers all of its 6 \((3d^5 4s^1)\) outer cell electrons to the 3d bands of Co, it can just make 4 Co atoms nonmagnetic. This explains the \((1-4C_{\text{Cr}})\) factor in Haines' model.

4.2 Dielectric Constants of CoCr Films

An automatic spectroscopic ellipsometer described in detail by Sullivan\(^{28}\) has been used to measure the dielectric constants of the CoCr films. It has been well known within the framework of the effective medium theory\(^{36-40}\) that the measured dielectric constants are very sensitive to the surface morphology as well as to the dielectric constants of the material itself. Qualitatively, for a rough surface (described by a terminology “microroughness”) or a material containing voids full of air or dielectric material (described by a terminology “porosity”) the depolarization effects due to the microroughness or porosity will reduce the absolute value of the measured \(\epsilon_1\) and \(\epsilon_2\), the real and imaginary part of the dielectric constants, respectively. In the present case air and chromium oxides and/or cobalt oxides fill the voids between the grains and reduce the absolute values of the measured dielectric functions.

Dielectric constants of CoCr sputtered on an unheated glass substrate, with \(P_{\text{Ar}} = 3\) mTorr, \(W=350\) watts and \(d_{\text{ts}} = 8\) cm were measured and presented in Figs. 4.3 and 4.4. Previous measurements on single crystal\(^{41}\) and thin film\(^{42,43}\) Co are also shown in the figures for comparison. \(|\epsilon_1|\) and \(|\epsilon_2|\) of CoCr films decrease as the films become thinner, indicating that larger microroughness or porosity are developed for smaller thickness.\(^{36-40}\)

Similar increase in microroughness or porosity with reduced thickness is observed for CoCr sputtered on unheated and heated \((T_s = 250\) C) NiCr coated glass as indicated in Figs. 4.5 and 4.6. To study the effect of substrates on the film morphology, the dielectric constants for CoCr deposited on heated \((at T_s = 250\) C) Ti coated glass are also presented in Fig. 4.7. To clarify the relation between dielectric constants and the surface morphology, SEM surface photographs are shown in Figs. 4.8, 4.9 and 4.10, respectively, for CoCr films on unheated NiCr coated glass with thicknesses of 230, 400 and 910 nm. A SEM
photograph for CoCr deposited on NiCr coated substrate at $T_s = 250$ C is also presented in Fig. 4.11.

Common to Figs. 4.3 to 4.7 is that the substrate does not affect the dielectric function (or the surface morphology) significantly if the films are thicker than about 500 nm. The SEM photographs in Figs. 4.8, 4.9 and 4.10 indicate that a rough surface develops into a smoother surface as the film thickness is increased. Further inspection reveals that high $T_s$ increases the surface microroughness as confirmed by SEM photographs in Fig. 4.11.

We interpret the increase in surface microroughness or porosity with reduced thickness as attributed to the growth of an initial layer with poor texture, as discussed in section 2.5. Since the preferential growth direction is parallel to the $c$ axis,\textsuperscript{32} grains with randomly distributed $c$ axes will give rise to a rough surface. As the $c$ axes become better aligned with larger thickness, a smoother surface results. As for the substrate effect, Inspection of data in Figs. 4.3 to 4.7 suggests that the NiCr substrate yields the smoothest CoCr film surface, or the weakest thickness dependence compared to other substrates under the same deposition conditions. We have found in section 2.5 that the similarities between the structure and texture of CoCr and NiCr weakens the thickness effect on the magnetic properties of CoCr films. The substrate effects on the dielectric function discussed above indirectly support the point of view regarding the effect of substrate on film growth as discussed in chapter 2.5.

Sullivan\textsuperscript{28} investigated the effects of substrate temperature on the surface morphology of Pd films, using ellipsometry techniques. He interpreted the increase in microroughness in terms of Thornton's\textsuperscript{20} structure zone model. According to the model, as the substrate temperature is increased, small grains combine and grow into larger ones at the T-zone as a consequence of increased adatom mobility. Larger grains will, of course, make the surface rougher as confirmed by SEM photograph in Fig. 4.11.

Let us consider the spectral dependence of the dielectric constants. From the above discussion, we conclude that the best samples for the study of the spectrum of the material are the thickest, unheated CoCr films because they yield the smoothest surfaces and the measured dielectric constants for those samples best represent the dielectric constants of the material. The first model that comes to mind is the Drude model of free electrons, which works well for noble metals\textsuperscript{44} up to 2 eV. If the Drude model is valid, plots of $-\varepsilon_1$ and $\varepsilon_2/2\lambda$ versus $\lambda^2$, respectively, should yield straight lines as the model suggests\textsuperscript{42}. 59
However, such plots as shown in Fig. 4.12 for a 870 nm thick CoCr film sputtered on unheated glass substrate do not give any hints of straight lines. One might think the long wavelength end could still be represented by Drude model, but the slope of the line at the long wavelength end for the plot of $-\varepsilon_1$ versus $\lambda^2$ yields an optical mass 360 times larger than the rest mass of the electron. We conclude that the Drude model is inadequate in the case of the above data and, therefore, the dielectric constants have a significant contribution from interband transitions. In the case of pure Co, it was found that the interband transition is the dominant mechanism\(^{42}\). Indeed the electron density of states in Fig. 4.2 indicates high density of states in the range of interest for this study. We also conclude from Figs. 4.3 and 4.4 that great care should be taken in the interpretation of measured dielectric constantes of Co and CoCr because they are very sensitive to the condition of the surface.

### 4.3 Anisotropy in Dielectric Constants.

As discussed in chapter 3, CoCr films sputtered at small $d_{ts}$ and located in an asymmetric position have a magnetic easy (hard) axis tilted away from the film normal. What is the direction of the optical axes?

In general the dielectric tensor for a material with magnetization $M = 0$ can be written as\(^{45}\)

$$
\varepsilon = A(\phi, \theta, \psi) \begin{pmatrix} 
\varepsilon_1^0 & 0 & 0 \\
0 & \varepsilon_2^0 & 0 \\
0 & 0 & \varepsilon_3^0 
\end{pmatrix} A^{-1}(\phi, \theta, \psi) 
$$

(4.3)

where $\varepsilon_1^0, \varepsilon_2^0$ and $\varepsilon_3^0$ are the three principal values of the dielectric tensor and $A$ is the rotation matrix given by Goldstein\(^{46}\) in terms of the three Euler angles: $\phi, \theta$ and $\psi$. The rotations defining the Euler angles\(^{46}\) are shown in Fig. 4.13.

CoCr samples 500 nm thick were deposited on glass substrates for measurement in the spectroscopic ellipsometer described in section 4.2. The deposition conditions were: $P_{Ar} = 3$ mTorr, $d_{ts} = 8$ cm and $T_s = 210$ C and the substrate is glass. An angle of 20 degrees is found between the magnetic easy axis and the film normal as shown in Fig. 3.3. Accurate measurement of the Kerr effect requires the installation of a magnet near the sample holder in the ellipsometer since the error due to the misalignment of the film sample with respect to the incident light is comparable to the Kerr effect. A detailed study of the Kerr effect in CoCr is out of the scope of the thesis. To avoid the complication due
to the Kerr effect (which is negligible in the study of spectral dependence), the sample is "demagnetized" with an AC magnetic field that decreases slowly in amplitude, i.e. the magnetic remanence is brought down to zero.

A special sample holder was made such that we can rotate the sample around the film normal without taking the sample off the holder. The sample is then rotated through the first Euler angle $\phi$ (see Fig. 4.13) about the film normal while the complex reflection ratio $\rho$ is measured at 2 eV. $\phi = 0$ correspond to such an orientation that the X-axis in Fig. 2.2 is in the plane of incidence. The complex reflection ratio, $\rho$, is defined as

$$\rho = \frac{r_p}{r_s}$$

$$r_p = \frac{E_p^r}{E_p^i}$$

$$r_s = \frac{E_s^r}{E_s^i}$$

where $E_s$ and $E_p$ are components of the electric field of the light perpendicular and parallel to the plane of incidence, respectively, and superscripts 'i' and 'r' denote for incident and reflected light, respectively. The result of $\rho$ as a function of $\phi$ is given in Fig. 4.14.

Using a new matrix technique that will be described in detail in the next chapter, we are able to calculate $\rho$ as a function of $\phi$ and fit the experimental data to the nine parameters of the dielectric tensor ($\phi$, $\theta$ and $\psi$; real and imaginary part of $\epsilon_1^0$, $\epsilon_2^0$ and $\epsilon_3^0$). In practice, only three or four parameters are needed to obtain a good theoretical fit to the data.

When the nature of the optical anisotropy is unknown a priori, the goal of the fit is to obtain a combination of the smallest number of uncorrelated unknown-parameters and a reasonable fit to the data. The first model is the isotropy model. The dielectric constant ($\epsilon_0$) obtained this way can be regarded as the average of the three principal values of the dielectric tensor. In the example of Fig. 4.14, over a dozen models with different number of parameters (usually 2 to 4) and different combinations have been tried. The best fit is as follow:

$$\epsilon_1^0 = \epsilon_0(1 + \delta_1 - i\delta_2)$$

$$\epsilon_2^0 = \epsilon_0(1 - \delta_1 + i\delta_2)$$

$$\epsilon_3^0 = \epsilon_0$$

$$\theta = \psi = 0, \phi = 35.3^\circ$$

where

$$\epsilon_0 = -14.17 + i20.21$$
Where \( \delta_1 \), \( \delta_2 \) and \( \phi \) are the fitting parameters. Therefore, such a sample can best be described as being slightly biaxial with one optical principal axis normal to the film. It is so far unclear how this biaxial model is related to the uniaxial magnetic anisotropy model described in the last chapter.

4.4 Extraordinary Hall Effect of CoCr Films

Extraordinary Hall effect is characterized by a Hall voltage in ferromagnetic materials about two orders of magnitude larger than that in nonmagnetic materials. This voltage is proportional to the magnetization of the ferromagnets and is a consequence of the spin-orbit coupling of the conduction electrons. We neglect the contribution from the ordinary Hall effect and express the Hall resistivity \( \rho_H \) as

\[
\rho_H = 4\pi R_s M
\]

(4.7)

where \( R_s \) is the spontaneous Hall coefficient and \( M \) is the magnetization of the sample.

It was well known that the experimental data of \( R_s \) can be related to that of the electrical resistivity, \( \rho_r \), by

\[
R_s \propto \rho_r^n
\]

(4.8)

where \((1 < n < 2)\). The theories of extraordinary Hall effect represent some of the most complicated and sophisticated theories in solid state physics. Early works include those of Karplus and Luttinger\(^{49}\), Smit\(^{50}\) and Luttinger\(^{51}\). The basic model is that the magnetically polarized electrons move under the influence of an external electric field and scattered by impurities and phonons. The spin-orbit coupling gives rise to a transverse current which is the origin of the extraordinary Hall effect.

Luttinger\(^{51}\) found that the Hall coefficient \( R_s \) can be divided into two parts. The first part is the higher order corrections to the Born approximation for the scattering of polarized electrons by impurities. This part is the skew scattering part and was found to be proportional to the density of the scattering centers and, therefore, to the electrical resistivity.\(^{51,52}\) The second part arises from the off diagonal elements of the density matrix describing the electronic states and does not have a classical analogue. The corresponding
Hall current was found to be independent of the density of the scattering centers. Therefore, this part of the Hall coefficient is proportional to the square of the resistivity and is often referred to as the side jump part. Irkhin and Shavrov used the same theoretical point of view as Luttinger and showed that, as the temperature is raised, phonon scattering becomes important and enhances the side jump part significantly. The exponent $n$ in (4.8) can be interpreted in terms of the above theories as follows: If $n = 1$ the mechanism of the extraordinary Hall effect is the skew scattering; if $n = 2$ the mechanism is the side jump.

In the present study ac Hall measurement was chosen since it was found that the dc measurement had a large noise level due to thermoelectric and thermomagnetic effects. The dc method was used to determine the sign of the Hall voltage. The ac Hall voltage was found to be independent of the ac current frequency in the range from 10 Hz to 1000 Hz. During the measurement the frequency was kept at 83 Hz. A photolithographic technique was used to make the CoCr film into the four point probe pattern and a transformer was used to match the impedance of the sample to that of the lock-in amplifier (Fig. 4.15). The applied magnetic field, $H$, was scanned from -10 to 10 kGauss. A cryostat shown in Fig. 4.16 was used to provide ±0.5 K temperature ranging from 4 K to 300 K.

Three 500 nm thick CoCr films deposited on glass substrate at $T_s = 100$, 210 and 300 C were studied. The other sputtering parameters are: $P_{Ar} = 3$ mTorr, $d_{ts} = 9$ cm and $W = 350$ watt. The resistivities of the above three films were found to be about 80 $\mu \Omega \text{cm}$. The measured Hall voltage as a function of the applied field appears very different for different samples. For example, $V_H$ versus $H$ plot for the film with $T_s = 300$ C in Fig. 4.17(a) appears very different from that with $T_s = 210$ C in Fig. 4.17(b). However, careful inspection shows that they both can be explained by the same equation, given below:

$$V_H = (R_0 + 4\pi R_s M/t)I$$  \hspace{1cm} (4.9)

where $R_0$ is the resistance due to the misalignment of the leads where the Hall voltage is picked up. Ideally, if $R_0 = 0$, the output signal would be like Fig. 4.18 and the highest sensitivity for the equipment would be achieved. When $4\pi R_s M/t > R_0$, the output will be like that in Fig. 4.17(a), and $4\pi R_s M/t < R_0$ yields an output like Fig. 4.17(b). If $R_0 \gg 4\pi R_s M/t$, a large off-set $V_H$ will decrease the sensitivity of the measurement of $\rho_H$. The above reasoning justifies the use of photolithographic technique to fabricate well aligned samples in order to optimize the sensitivity of the measurement.

The temperature dependence of the Hall effect in the above CoCr films was measured
using the cryostat in Fig. 4.16 from 4 K to 300 K. Fig. 4.19 gives $\rho_H$, at the state of saturation magnetization, as a function of the temperature for the three CoCr film samples. $\rho_H$ seems to increase with $T_s$ as seen from Fig. 4.19, which is a reminder of the dependence of $H_c$ on $T_s$ in Fig. 2.9. One possible explanation for the correlation of $\rho_H$ to $H_c$ is as follows: $H_c$ depends on Cr segregation as discussed in section 2.3. The Cr segregates act as scattering centers for the magnetically polarized electrons and the spin-orbit coupling of the scattered electrons gives rise to the extraordinary Hall effect.

McAlister and Hurd developed methods to determine the signs of the skew and the side jump part of the spontaneous Hall coefficient for various metals. They found that the sign for the side jump part varies from metal to metal. No explanations had been given for the signs of the side jump part. According to McAlister and Hurd, a pure Co single crystal has a negative Hall voltage. At temperatures greater than 78 K, $\rho_H$ increases with temperature, indicating a positive side jump contribution to $\rho_H$. The reason is that phonon scattering is more important at higher temperatures. From Fig. 4.19, one sees that the sign of Hall voltage is positive, which is different from pure Co. Since $\rho_r(T)$ increases with temperature due to scattering, Fig. 4.19 also implies that $\rho_H$ of CoCr has a positive side jump part, just like a pure Co single crystal. The explanation of the difference between the signs of $\rho_H$ for CoCr and Co remains a theoretical problem.

The electrical resistivity of the CoCr film with $T_s = 200$ C was also measured in the temperature range of 4 to 300 K and the following relation was deduced for the data:

$$R_s(T) \propto [\rho_r(T)]^n$$

$$n = 1.5 \pm 0.1 \quad (4.10)$$

This result indicates that both types of mechanism, skew scattering and side jump, contribute to the extraordinary Hall effect of CoCr. The relation (4.10) for CoCr is to be compared to that for Ni and Fe:

$$Ni: \quad R_s(T) \propto [\rho_r(T)]^{1.5}$$

$$Fe: \quad R_s(T) \propto [\rho_r(T)]^{2.0} \quad (4.11)$$

Further studies of CoCr films, such as a theoretical treatment of the extraordinary Hall effect would be very useful; however, as outlined in the introduction, we have decided to devote the remaining part of the thesis to another, equally important, subject related to emerging recording technologies: magneto-optic media.
Figure 4.1. Electron density of states for majority- and minority-band electron states, taken from Singal and Das\textsuperscript{35}. The Fermi energy and the occupied states (shaded area) are shown.
Figure 4.2. Combined electron density of states for both the majority- and minority band states obtained from Fig. 4.1.
Figure 4.3. Real part of the dielectric constants $\varepsilon_1$ for CoCr sputtered on glass. Sputtering parameters for the samples are: $T_s = 30$ C, $P_{Ar} = 3$ mTorr, $W = 350$ watts and $d_{ts} = 8$ cm. Data for single crystal Co are from Ref. 41. $\parallel$ and $\perp$ correspond to electric field parallel and perpendicular to the crystal c axis of Co, respectively. Data for film 1 and film 2 are from Ref. 42 and 43, respectively.
Figure 4.4. Imaginary part of the dielectric constants $\varepsilon_2$ for the same set of sample as in Fig. 4.3. Data for pure Co are also from the same sources given in the previous figure caption.
Figure 4.5. Dielectric constants for CoCr sputtered on unheated NiCr coated glass substrate. Deposition parameters are the same as those for Fig. 4.3.
Figure 4.6. Same as Fig. 4.5 except $T_s = 250$ C.
Figure 4.7. Same as Fig. 4.5 except $T_s = 250$ C and the substrate is Ti coated glass substrate.
Figure 4.8. SEM photograph of surface of 230 nm thick CoCr sputtered on unheated, NiCr coated glass substrate. The magnification is 50,000 and the dotted line at the lower right corner of the photograph represent 600 nm. Sputtering conditions are the same as for Fig. 4.3.
Figure 4.9. Same as Fig. 4.8 except the thickness is 400 nm.
Figure 4.10. Same as Fig. 4.8 except the thickness is 910 nm.
Figure 4.11. SEM photograph of surface of 900 nm thick CoCr sputtered on NiCr coated glass substrate at $T_s = 250$ C. Other sputtering parameters are the same as for Fig. 4.3.
Figure 4.12. Plots of $-\epsilon_1$ and $\epsilon_2/2\lambda$ versus $\lambda^2$, respectively, for the 870 nm thick sample in Figs. 4.3 and 4.4.
Figure 4.13. The rotations defining the Euler angles, taken from Goldstein\textsuperscript{46}.
Figure 4.14. Complex reflection ratio $\rho$ versus $\phi$ for a CoCr film, where $\phi$ is the first Euler angle defined in Fig. 4.13. The deposition conditions for the film are specified in text. The solid line and the dashed line are theoretical fits for the real and imaginary part of the complex reflection ratio, respectively.
Figure 4.15. Pattern of sample and circuit diagram for Hall effect measurement. Only two leads of the four point probe type of sample are used in the measurement. The applied magnetic field is along the film normal.
Figure 4.16. Schematics of the cryostat system for measurement of Hall voltage as a function of temperature ranging from 4 K to 300 K. He gas provides a thermal link between the sample and the liquid He reservoir. An electrical heater and a Si diode thermometer on the sample holder are used to control the sample temperature to ±0.5 K.
Figure 4.17(a). Hall voltage, $V_H$, as a function of the applied field, $H$, for CoCr deposited on glass substrate with $T_s = 300$ C. The other sputtering parameters are: $P_{Ar} = 3$ mTorr, $d_{ts} = 9$ cm and $W=350$ watts. The applied field scans from -10 to 10 kGauss, but only the magnitude of the field is recorded in this experimental setup.
Figure 4.17(b). Same as Fig. 4.17(b) except $T_s = 210$ C. This figure appears very different from Fig. 4.17(a) because of different values of $R_0$, where $R_0$ is the resistance due to the misalignment of the leads where the Hall voltage is picked up.
Figure 4.18. Predicted Hall voltage, $V_H$, as a function of the applied field, $H$, for an ideal sample with $R_0 = 0$. 
Figure 4.19. Hall resistivity of CoCr as a function of temperature for films deposited at different growth temperature $T_s$. Other sputtering parameters are given in Fig. 4.17(a). The lines are intended to help the reader separate the data sets.
Part B
Optics of Magneto-Optic Recording Media

Chapter 5
Use of the $4 \times 4$ Matrix Method for Magneto-Optic Multilayers

5.1. Plane Wave Model for Magneto-Optic Recording Media

Erasable multilayer magneto-optical recording media were proposed by Connell. The working principle of the system is that the optical interference of the multilayer medium enhances the reflectivity component induced by the polar Kerr effect in the magnetic layer and, therefore, increases the signal-to-noise ratio (SNR). In practice the recording medium consists of four layers on a substrate; the overcoat layer, which acts both as an anti-reflectance layer and a protection layer for the subsequent layers, the magnetic layer, which causes the polar Kerr effect, an intermediate phase matching layer, and finally a reflectance layer. Nakamura et al. studied experimentally the relation between the Kerr rotation angle and the thickness of the intermediate layer and found that by choosing the proper material and thickness for the phase matching layer, the Kerr rotation angle could be significantly enhanced. Mansuripur et al. derived the expression for the SNR and used an iterative formula to optimize the Kerr component of the reflectivity. If $n_i$ is the complex refractive index for the $i$th layer, then the iterative formula can be written as follows: \( r_i = \frac{r_{i-1,i} + r_{i+1}^T e^{2i\beta_i}}{1 + r_{i-1,i} r_{i+1}^T e^{2i\beta_i}} \) (5.1)

where $r_i^T$ is the contribution from the reflectivity of all the layers below the $i$th layer as shown in Fig. 5.1 and $\beta_i = 2\pi t_i n_i / \lambda$ is the film phase thickness for the $i$th layer assuming an $e^{-i\omega t}$ time dependence in the electric fields. The complex Fresnel reflectance coefficient, $r_{i-1,i}$, for the interface between the $(i-1)$th and the $i$th layer is given by:

\[ r_{i-1,i} = \frac{n_{i-1} - n_i}{n_{i-1} + n_i} \] (5.2)

for normal incidence. The magneto-optical effect can be calculated by considering different indices of refraction for left-handed and right-handed circularly polarized light in the magnetic layer. Gamble et al. have simplified the iterative formula by considering the Kerr effect only to first order and showed that the gain of an optimized multilayer system depends on the ratio $n''/n'$, where $n'$ and $n''$ are the real and imaginary parts of the index of refraction of the magnetic layer, respectively. This index of refraction is associated
with the nonmagnetic part of the matrix elements of the dielectric tensor (or the diagonal matrix elements in the case of an isotropic medium).

The iterative formula, however, is valid only for isotropic media, perpendicular magnetization and for normal incidence. Although it is usually sufficient to consider the above restricted situations, a more general solution may be required in order to characterize the recording medium with oblique incident light in cases such as ellipsometry studies. As well, in practice the magnetization may not be perfectly normal to the film and may affect the SNR and, similarly, some of the thin film layers may be anisotropic. However, an analytical solution for a more general case is very complicated algebraically even for the case of a bare substrate. Therefore, it is desirable to have a computational method to treat any arbitrary multilayer structure. Various methods have been described by Berreman, Yeh, and Lin-Chung and Teitler and the last method has been found to be the most convenient.
5.2. Implementation of the 4×4 Matrix Method

In general, light propagating through a medium has two eigenmodes (or two degrees of freedom) so that the electromagnetic field can be specified by two eigenpolarizations of the electric or magnetic fields, with a different index of refraction associated with each eigenmode. For a multilayer system the electromagnetic field for each layer has two additional degrees of freedom due to the reflected light and must therefore be described by four independent variables. The boundary conditions on the interface connect the four variables of adjacent layers and leads to the 4×4 matrix method. Yeh developed the 4×4 matrix algebra in a very compact form; however, his method requires the evaluation of the polarization vectors for the four eigenmodes to construct the matrix. This leads to computational difficulties in cases such as an isotropic medium where the two transmitting (or reflecting) modes are degenerate and the two associated polarization vectors are arbitrary. The expression for the polarization vectors of the eigenmodes given by Yeh can then not be normalized due to this degeneracy.

While the above special case can be handled separately, we find it more practical to implement the method of Lin-Chung and Teitler. In this method they chose the four components of the electromagnetic field to be the four independent variables and constructed a column matrix ψ (not to be confused with the third Eulerian angle):

\[
ψ = \begin{pmatrix}
E_x \\
H_y \\
E_y \\
-H_z
\end{pmatrix}
\]  (5.3)

for a right-handed Cartesian coordinate system where the z-axis is along the normal to the multilayer structure. This column matrix remains always well defined and can be determined from the matrix equation

\[
n_zψ = Δψ
\]  (5.4)

where \( n_z \) is the eigenvalue of the refractive index associated with the z component of the wavevector and the 4×4 matrix \( Δ \) is a function of the dielectric tensor of the medium.

For a magnetic medium the complex dielectric tensor can be separated into magnetic and nonmagnetic components:

\[
ε = ε^0 + ε^m
\]  (5.5)

where \( ε^0 \) is the nonmagnetic component of the dielectric tensor and was expressed by Yeh in terms of the three principal axis values \( ε_1^0, ε_2^0 \) and \( ε_3^0 \) (see also equation (4.3)).
The magnetic part of the dielectric tensor can be written as,

\[
\epsilon^m = \begin{pmatrix}
0 & \delta_x i & -\delta_y i \\
-\delta_x i & 0 & \delta_z i \\
\delta_y i & -\delta_z i & 0
\end{pmatrix}
\]  \hspace{1cm} (5.6)

where \( \delta_x, \delta_y \) and \( \delta_z \) are complex off-diagonal matrix elements responsible for the magneto-optical effects. Furthermore, \( \vec{\delta} \propto \vec{M} \), the magnetization vector.\(^{64}\)

After solving (5.4), the total field can be written as a linear combination of the four eigenvectors,\(^{63}\) or

\[
\psi = \Psi \phi
\]  \hspace{1cm} (5.7)

where \( \Psi \) is a 4×4 matrix consisting of the eigenvectors from (5.4) as columns and \( \phi \) is a weight vector chosen to be the electric field components.\(^{63}\) The matrix \( \Psi \) is calculated in a computer program as follows. After (5.4) is solved, the transmitting modes are separated from the reflecting modes by the signs of the real part of the eigenvalue \( n_z \). Then the ratio,

\[
C_p = \frac{|E_x|^2}{|E_x|^2 + |E_y|^2}
\]  \hspace{1cm} (5.8)

is evaluated for the four modes. The eigenvectors of the transmitting modes with the large and small \( C_p \) occupy the first and third columns, respectively. Similarly, the eigenvectors of the reflecting modes with the large and small \( C_p \) will occupy the second and fourth columns, respectively. Then all the columns are normalized such that \( \Psi_{11} = 1, \Psi_{12} = -1, \Psi_{33} = \Psi_{34} = 1 \). The above arrangements and normalizations, although not explicitly stated by Lin-Chung and Teitler\(^{63}\), are very important to ensure a smooth transition from anisotropic to isotropic layers.

The final result can be expressed in terms of the reflection matrix:

\[
\begin{pmatrix}
E_s^r \\
E_p^r
\end{pmatrix} =
\begin{pmatrix}
r_{ss} & r_{sp} \\
r_{ps} & r_{pp}
\end{pmatrix}
\begin{pmatrix}
E_s^i \\
E_p^i
\end{pmatrix}
\]  \hspace{1cm} (5.9)

relating the incident and the reflected electric fields.

The program was first tested on systems with known results: 1) substrate of isotropic nonmagnetic medium with oblique angle of incidence; 2) substrate of anisotropic non-magnetic medium with oblique angle of incidence, for which Lettington\(^{65}\) has given the analytical expression; 3) substrate of anisotropic and magnetic medium with oblique angle of incidence\(^{61}\); 4) multilayers of isotropic and nonmagnetic medium as described by equation (5.1); 5) isotropic medium with magnetization direction normal to the film as
calculated by the iterative formula in equation (5.1) for left-handed and right-handed circularly polarized light; and 6) The gain function calculated by Gamble et al.\textsuperscript{58}. In all cases the agreement was good to four significant figures.

5.3. Application to Quadrilayer Recording Medium

In order to optimize the Kerr component of the reflectivity with respect to the thickness of the dielectric layers of the recording medium, we have applied the above $4 \times 4$ matrix method to the magneto-optic multilayer structure\textsuperscript{66}. The multilayer structure is shown in Fig. 5.2, with an overcoat and phase matching layer consisting of SiO$_2$, and with MnBi and Al as the magnetic and the reflector layers, respectively. This system has been studied by Mansuripur et al.\textsuperscript{56} using the iterative formalism and their values for the complex refractive indices for these layers were used in our calculations, corresponding to a wavelength of 840 nm. In addition, we further investigate the effect of anisotropy, an oblique angle of incidence, and misalignment of the magnetization on the SNR of the optimized quadrilayer system.

We fix the magnetic layer thickness at 90 Å, which is typical for multilayer magneto-optical recording media. Mansuripur et al.\textsuperscript{56} and Gamble et al.\textsuperscript{58} have shown previously that the readout of the recording system is insensitive to the magnetic film thickness in this thickness region. To optimize the SNR one calculates $|r_{sp}|^2$ as a function of the thickness of the overcoat layer $t_c$ and that of the intermediate layer $t_i$ (Fig. 5.2), and presents the results in a contour plot shown in Fig. 5.3. The maximum of $|r_{sp}|^2$ occurs at $t_i \simeq 0.225\lambda_i$ and $t_c \simeq 0.238\lambda_c$, where $\lambda_i = \lambda/n_i$ and $\lambda_c = \lambda/n_c$ are the wavelengths of light in the intermediate and the overcoat layer, respectively. The maximum value of $2000 |r_{sp}|^2 \simeq 0.9$ and the values of $t_c$ and $t_i$ corresponding to the maximum are in reasonable agreement with those obtained Mansuripur et al.\textsuperscript{56} From Fig. 5.3 , we find that the maximum occurs at $t_i \simeq \lambda_i/4$ as predicted by Mansuripur et al.\textsuperscript{56}.

To study the sensitivity of $|r_{sp}|^2$ to the nonmagnetic component of the dielectric tensor of the magnetic layer, we vary the imaginary part of the refractive index of the magnetic layer while leaving the magnetic part (i.e. the $\delta$ vector) unchanged. The results are shown in the contour plots in Figs. 4 (a) and (b). We find that if $n''$ is reduced by $1/2$, $|r_{sp}|^2$ is increased by about a factor of 3 and the peak of $|r_{sp}|^2$ moves to lower $t_i$ and higher $t_c$ as shown in Fig. 5.4(a). If $n''$ is increased by $1/2$, $|r_{sp}|^2$ decreases by $2/3$ and the peak moves to higher $t_i$ and lower $t_c$, as seen in Fig. 5.4(b). The above trends
are consistent with the findings of Gamble et al.\textsuperscript{58} that the key factor to the gain of the recording system is the ratio of the imaginary part of the refractive index of the magnetic layer to the real part.

These contour plots can also be useful in recording disk structural design and can be fitted to experimental data when studying the effect of the thickness of the dielectric layers on the SNR.\textsuperscript{55,60} It can be seen from Fig. 5.4(b) that $|r_{sp}|^2$ is very sensitive to $t_i$ in the range from $\frac{3}{8}\lambda_i$ to $\lambda_i/2$, which is undesirable in system design as it is sometimes difficult to control this thickness.\textsuperscript{55,60}

We should point out that in some theories\textsuperscript{58,60} the intermediate layer is taken to be $\lambda_i/2$ thick, while Figs. 3 and 4 indicate that this value does not optimize $|r_{sp}|^2$. One notices that the gain function defined by Gamble et al.\textsuperscript{58} has such a special form that it is unchanged whether one uses $\lambda_i/2$ or $\lambda_i/4$ for the intermediate layer, provided the magnetic layer is thin enough. However, the thickness will affect $|r_{sp}|^2$. The gain function $G$ is defined as\textsuperscript{58}

$$G = \frac{|r_{ms}|^2}{|r_{ms}|^2 (1 - R)}$$

where $R = |r_T^2|^2$ and the subscript 'ms' denotes the corresponding quantity in the case of a substrate of the same magnetic material. One finds that in the case of $t_i = \lambda_i/2$, the system is not well matched, i.e. it does not have a minimum $R$, so that the increase in $R$ cancels the decrease in $|r_{sp}|$ in (5.10). Therefore one must be very careful in using the gain function as the criterion for optimization, since it is meaningful only when the system is well matched. To optimize the readout of the system, $t_i$ should be approximately $\lambda_i/4$ as predicted by Mansuripur et al.\textsuperscript{56}, with the exact value depending upon the dielectric constants and the thickness of the magnetic layer.

Based on the optimized quadrilayer system corresponding to Fig. 5.3, we vary the refractive index of the intermediate layer to study the effect of anisotropy and oblique angle of incidence. In Fig. 5.5 $|r_{sp}|^2$ is plotted as a function of the incident angle $\theta_0$ for different degrees of anisotropy as described by $K_i$, where

$$\epsilon_3^0 = K_1\epsilon_1^0$$

for the intermediate layer. Here we have chosen the principal axis of $\epsilon_3^0$ to be parallel to the $z$ axis. We find that the effect of the oblique angle of incidence is small up to about 45 degrees. This is expected since $|r_{sp}|$ is relatively insensitive to the phase mismatch in the
vicinity of the maximum as can be seen in Fig. 5.3. The anisotropy of the intermediate layer is quite significant as shown in Fig. 5.5.

Finally, we study the effect of misalignment of the magnetization vector \( \vec{M} \). Fig. 5.6 shows \( |r_{sp}|^2 \) as a function of \( \theta_m \), the angle between the direction of magnetization and the normal to the film in the case of normal incidence. The Kerr component of the reflectivity \( |r_{sp}| \) gradually decreases to zero at 90 degrees as expected. In practical situations, one treats the magnetization as having a Gaussian distribution with a distribution function

\[
f(\theta_m) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(\frac{\theta_m}{\sigma})^2}
\]

Fig. 5.6 shows \( \langle |r_{sp}|^2 \rangle \) averaged by the Gaussian distribution while varying the standard deviation, \( \sigma \), which is a measure of the misalignment. From these results, we find that even in the case of a very serious misalignment, the decrease in SNR is not significant.
Fig. 5.1. Schematic for the iterative formalism. $r_{i-1,i}$ is the Fresnel coefficient between $i-1$th and $i$th layer and $r_i^T$ is the contribution from the reflectivity of all the layers below the $i$th layer.
Fig. 5.2. The structure of a typical, quadrilayer magneto-optical disk. It consists of SiO$_2$ as the overcoat layer and the intermediate phase matching layer, MnBi, as the magnetic layer, and Al as the reflector. The refractive indexes are taken from Ref. 56, at a wavelength of 840 nm. The superscript '+' and '-' denote the refractive indices for left-handed and right-handed circularly polarized light, respectively.
Figure 5.3. Contour plot of $2000 | r_{op} |^2$ as a function of the thickness of the intermediate layer $t_i$ and that of the overcoat layer $t_o$. 
Fig. 5.4(a). Same as Fig. 5.3 except that the imaginary part of the reflective index, \( n'' \), is reduced by 1/2.

Fig. 5.4(b). Same as Fig. 5.3 except that the imaginary part of the reflective index, \( n'' \), is increased by 1/2.
Figure 5.5. Plot of $2000 \left| r_{sp} \right|^2$ as a function of the incident angle $\theta_0$, showing the effect of anisotropy. Based on the quadrilayer in Fig. 5.2, with optimized thicknesses for the layers, the principal axis value of the dielectric tensor, $e_0^0$, is varied for the intermediate layer. $K_i = e_0^0/e_1^0$ and $e_1^0 = e_2^0$, where $e_1^0$, $e_2^0$ and $e_3^0$ are the principal values of the dielectric tensor. We have chosen the axis of $e_3^0$ to be the film normal.
Figure 5.6. Dependence of $2000 \left| r_{sp} \right|^2$ on $\theta_m$, the angle between the direction of magnetization and the normal to the film. Also shown is $2000\langle \left| r_{sp} \right|^2 \rangle$ averaged over a Gaussian distribution as a function of the standard deviation of the distribution $\theta_\sigma$. 

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Chapter 6
Interaction of Focused Light Beams With Magneto-Optic Recording Media

6.1. Problems in Magneto-Optics Theories

For a long time it has been realized that the reading laser in a magneto-optic recording system is a strongly focused light beam instead of a plane wave (see Fig. 1.3), and, therefore, a Gaussian beam model, which has a Gaussian amplitude distribution, is expected. However, no one seems to have carried out a detailed, theoretical study for a Gaussian beam interacting with the magneto-optic multilayers, probably due to the lack of a practical approach for this problem.

Reviewing the literature on Gaussian beams, we found the following. In the 60's and 70's, most of the theoretical work were concerned with how a Gaussian beam was generated and how it propagates in space. The medium that interacts with the Gaussian beam was approximated as a lens. This approximation is good as long as the beam focus is not too small or the beam rays are nearly parallel to each other. Recently, researchers have started to look at the interaction of a Gaussian beam with a multilayer medium and found that there was a shift in both the position of the focal spot and the angle of reflection for the reflected beam. But, the treatment is based on paraxial approximation and the interest is in nonspecular phenomena.

For the ease of computation the Gaussian beam is often assumed to be a scalar field. This does not cause any difficulty in the paraxial approximation since light rays propagating parallel have only one field component. Simon et al. were the first to notice that, even in the paraxial approximation, the longitudinal component of the field in the direction of the beam axis, though small, is essential for a consistent description of the Gaussian beam.

To find out what happens beyond the paraxial approximation, one has to solve the wave equation under a realistic boundary condition. Such a task was accomplished by Takenaka et al. based on some previous works of others. This is the starting point of the present work. In order to make use of the beam field solution derived by Takenaka et al., we consider the following: First, it must be decomposed into plane waves so that the technique developed in the last chapter can be used. This turns out to be nontrivial task and requires a considerable amount of mathematical skill. Second, for a strongly focused light beam there is significantly large component with propagation vector in an
oblique angle of incidence, which implies that the field component parallel to the beam axis (longitudinal) is important. Therefore, one must include the longitudinal field in the theory, while Takenaka et al.\textsuperscript{71} only treated a scalar field. Third, the final result must be easy to apply for numerical studies so that optimization of a thin film system is possible.

6.2. Interaction of a Strongly Focused Beam With Magneto-Optic Medium

The goal is to derive an expression for the reflected or transmitted beam given the incident beam field. For a focused beam propagating in the \( +z \) direction, the wave equation and a realistic boundary condition for the incident beam are as follows:

\[
(\nabla^2 + k_0^2)E_x(r, \phi) = 0 \tag{6.1}
\]

\[
E_x(r, 0) = \exp(-r^2/w_0^2) \tag{6.2}
\]

(6.2) is regarded as realistic since it emphasizes the important fact that the energy of the focused beam is concentrated on a finite area with symmetric intensity distribution in the focal plane. The Fourier transform of the solution to (6.1) and (6.2) as the incident beam, and the expression for the beam field reflected from a magneto-optic multilayer recording medium, have been described in an article\textsuperscript{72} by the author for publication purposes. Since the article is up to date and quite self-contained, the author would rather include it as Appendix B than go through the nightmare of re-typing the mathematic equations.

This section discusses some points that are not included in Appendix B, but quite important to understanding the physics behind the equations therein. To demonstrate the importance of going beyond the paraxial approximation when the focal spot size is small, we plot the intensity of a Gaussian beam (corresponding to \( s=0 \) in equation (3) of Appendix B) in Fig. 6.1(a), which is to be compared to the solution to (6.1) and (6.2) as shown in Fig. 6.1(b). In both Figs. 6.1(a) and 6.1(b), a spot size \( w_0 = \lambda/2 \) is used.

Another interesting point is that one can never produce a beam that satisfies (6.1) and (6.2) exactly. This point is demonstrated as follows. In equation (11) of Appendix B, the spectrum of the beam field contains \( \delta(k_z + k_r^2/2k_0 - k_0) \) which relates the \( z \) component of the propagation vector \( k_z \) to the transverse components \( k_r = \sqrt{k_z^2 + k_\phi^2} \) as indicated by the solid and dashed line in Fig. 6.2. An exact solution to (6.1) and (6.2) requires a spectrum that extends to the whole range (both solid and dashed line in Fig. 6.2). However, a real light beam only propagates in one direction and can never have \( k_z < 0 \) (i.e. only the solid
line in the figure is realistic). This is not very discouraging since the \( k_z > 0 \) part of the spectrum represents a very good approximation to the solution to (6.1) and (6.2) which well justifies the effort.

To optimize the readout of the multilayer magneto-optic recording medium, one has to have an expression for the reflectance and transmittance for the focused beam. This is also included in another paper\textsuperscript{73} written for publication purposes and is presented in Appendix C.

The numerical integrations associated with equation (21) of Appendix B and (11) and (12) of Appendix C are quite time consuming. To minimize the cost of computation, the integrands in the above-mentioned integrals are approximated by polynomials of order 12. This concludes the major part of the thesis and an overall summary is presented next as the concluding chapter.
Figure 6.1(a). Contour plot of a Gaussian beam intensity near the focal spot. The beam propagates in the $+z$ direction and $r = \sqrt{x^2 + y^2}$. $z$ and $r$ are expressed in units of wavelength $\lambda$. 
Figure 6.1(b). Contour plot of the beam intensity near the focal spot, given by the solution to equation (6.1) and (6.2) in the text. $z$ and $r$ are in units of wavelength $\lambda$. 
Figure 6.2. Spectral range for a focused beam as indicated by the solid line and the dashed line. $k_z$ and $k_r$ are the longitudinal and transverse components of the wavevector, respectively, and $k_0 = 2\pi/\lambda$, where $\lambda$ is the wavelength. $\theta$ in the figure is the angle of incidence for a plane wave component with wavevector $(k_r, k_z)$. $k_z$ axis is assumed to be along the film normal.
Chapter 7
Summary

7.1. Summary of Part A

1. CoCr(20 at. % Cr) films with potential for perpendicular or longitudinal recording application have been fabricated using a dc magnetron sputtering technique. The magnetic coercivity of the films is found to increase with the substrate temperature, \( T_s \), during film growth. Temperature \( T_s \) in the range from 180 to 300 C is essential for the fabrication of films with high coercivities. Through microstructural analysis, an account has been given regarding the effects of substrate temperature on the microstructure. The basic theoretical model is that higher adatom mobility upon heating results in larger grain size and, possibly, Cr segregation to grain boundaries.

2. Sputtered NiCr films can be used as a substrate material to eliminate the effect of initial layer growth, which occurs with glass substrate. A NiCr underlayer was shown to give a higher perpendicular coercivity than Ti, which were previously reported. The improved magnetic property with NiCr(or Ti) substrate is attributed to the similarity of the structure and texture of NiCr(or Ti) to those of CoCr.

3. A broad range of magnetic anisotropy (-1.0 to 0.5 \(10^6\,\text{erg/cc} \)) has been obtained by varying the target-to-substrate distance and the sputtering power. The dependence of the anisotropy on the above two parameters is interpreted in terms of the adatom diffusion constant and the deposition rate. A balance between the two effects determines the anisotropy.

4. When the target-to-substrate distance is small or the deposition rate high, the effect of asymmetric sputtering becomes important. Asymmetry in both magnetic and optical axes of the CoCr films due to this effect has been analyzed.

5. Ellipsometry and SEM experiments indicate that CoCr film surface has larger microroughness as the film thickness is reduced. This microroughness is associated with the poor texture of the initial layer.

6. Models for the analysis of optical anisotropy measured by ellipsometry are described and demonstrated for CoCr produced by asymmetric sputtering. It is found that the
optical axes are not necessarily coincident with the axes of magnetic anisotropy.

7. The extraordinary Hall voltage for CoCr has been measured as a function of the applied magnetic field at temperatures ranging from 4 K to 300 K. The Hall voltage is found to be positive which is opposite to the sign for pure Co. The Hall resistivity increases with the growth temperature $T_s$. This increase is attributed to the scattering of conduction electrons by Cr segregation. The Hall resistivity is found to be related to the electrical resistivity by $\rho_H \propto \rho_r^{1.5 \pm 0.1}$, where both $\rho_H$ and $\rho_r$ are varied by the temperature.

7.2. Summary of Part B

8. A $4 \times 4$ matrix technique has been implemented which makes the analysis of optical anisotropy and calculation of optics for magneto-optic multilayers routine activities. The technique has been applied to ellipsometry data of CoCr with optical anisotropy and the calculation of readout from magneto-optic recording medium in a plane wave model. It also provides input data for a more realistic model calculation as described below.

9. Using a Fourier transform technique, the reflected beam field of a strongly focused light beam from magneto-optic multilayers is calculated and found to have an asymmetric distribution in intensity.

10. The reflectance and transmittance of a focused beam interacting with a multilayer system have been derived and used to optimize the readout of the magneto-optic recording medium. It is shown that when the spot size is less than about three wavelengths, significant difference arises between the plane wave model and the focused beam model.
Appendix A
A Computer Program for Reflection Matrix of Multilayer Systems

A.1. Purpose

The purpose is to calculate the reflection matrix for a plane wave of light reflected from a multilayer system. The structure and the dielectric tensor for each layer is totally arbitrary. The reflection matrix is defined as:

\[
\begin{pmatrix}
E_x^f \\
E_p^f
\end{pmatrix} = \begin{pmatrix}
\tau_{ss} & \tau_{sp} \\
\tau_{ps} & \tau_{pp}
\end{pmatrix} \begin{pmatrix}
E_x^i \\
E_p^i
\end{pmatrix}
\]  \tag{A.1}

The convention for definition of symbols is the same as those used throughout the previous chapters. Note that the axis for reflected p-component of the electric field is defined such that it has the same direction as the axis for the incident p-component at normal incidence. This definition is different from that of some other authors. To change to the convention of others, one just has to change the signs of \(\tau_{ps}\) and \(\tau_{pp}\).

The dielectric tensor for each layer can be written for a time dependent factor \(\exp(-i\omega t)\) as follows:

\[
\epsilon = A(\phi, \theta, \psi) \begin{pmatrix}
\epsilon_x^0 & 0 & 0 \\
0 & \epsilon_y^0 & 0 \\
0 & 0 & \epsilon_z^0
\end{pmatrix} A^{-1}(\phi, \theta, \psi) + \begin{pmatrix}
0 & i\delta_x & -i\delta_y \\
-i\delta_x & 0 & i\delta_z \\
i\delta_y & -i\delta_z & 0
\end{pmatrix}
\]  \tag{A.2}

\(\delta\) is proportional to the magnetization in the magneto-optic medium, and the reader is referred to section 4.3 for the definitions of the above symbols.

Comments are written in the computer program for those who want to understand it or improve it. The comments refer to equations appearing in three references as follows: ‘L’ for Lin-Chung (Ref. 63); ‘B’ for Berreman (Ref. 62); ‘Y’ for Yeh (Ref. 45). The subroutine is named ‘BERR’ in honour of D.W. Berreman (Ref. 62) who introduced the four components for the electromagnetic fields of the eigenmodes in a manner most convenient for application.
A.2. How to Use

IMPLICIT REAL*8(A - H,O - Z)
COMPLEX*16 RSS,RSP,RPS,RPP
CALL BERR(NLAYER, TH0, RSS, RSP, RPS, RPP)

In the calling program, a common area must be created to provide information about the structure and dielectric tensor for each layer before calling the subroutine 'BERR', as follows:

COMMON /CRYST/ ISO, EV, H, AN, PHI, THETA, PSI, ED, DELTA
INTEGER*4 ISO(6)
COMPLEX*16 ED(3,6), DELTA(3,6),AN(6)
REAL*8 EV, H(6), PHI(6), THETA(6), PSI(6)

- **NLAYER**: On entry it must be set to the number of layers above the substrate.
- **TH0**: On entry it must be set to the angle of incidence.
- **RSS**: Complex*16 variable. On entry it need not be specified. On exit it gives the first element of reflection matrix defined in (A.1) above. Similarly for RSP, RPS, RPP.
- **ISO**: If ISO(I)=0, the Ith layer(layers are numbered so that the 1st layer is the top layer and the substrate is (NLAYER+1)th layer) is isotropic and one only needs to specify H,AN for the layer. If ISO(I)=1, the Ith layer is optically anisotropic or magnetic, and one must specify H, PHI, THETA, PSI, ED, DELTA for the layer.
- **EV**: On entry it must be set to the photon energy of the incident light in unit of eV.
- **H**: On entry H(I) must be set to the thickness of the Ith layer in unit of Å.
- **AN**: On entry, if ISO(I)=0, AN(I) must be set to the complex refractive index for the Ith layer. It need not be specified if ISO(I)=1.
- **PHI**: On entry, if ISO(I)=1, PHI(I) must be set to the first Eulerian angle of the rotation matrix in (A.2) for the Ith layer. If ISO(I)=0, it need not be specified. Similarly for THETA, PSI, the second and third Eulerian angles, respectively.
- **ED**: On entry, if ISO(I)=1, ED(J,I) must be set to the Jth principle value of dielectric constants (see (A.2) above) for the Ith layer. If ISO(I)=0, it need not be specified.
- **DELTA**: On entry, if ISO(I)=1, ED(J,I) must be set to the Jth component (J=1,2,3 correspond to x,y,z component) of the vector $\delta$ in (A.2) for the Ith layer. If ISO(I)=0, it need not be specified.
SUBROUTINE BERR(N, THO, RSS, RSP, RPS, RPP)
IMPLICIT REAL*8(A - H, O - Z)
COMPLEX*16 RSS, RSP, RPS, RPP
C
COMMON /CRYST/ ISO, EV, H, AN, PHI, THETA, PSI, ED, DELTA
INTEGER*4 ISO(6)
COMPLEX*16 ED(3,6), DELTA(3,6), AN(6)
REAL*8 EV, H(6), PHI(6), THETA(6), PSI(6)
C
COMMON /PSI/BPSI, BPSIN, EIG
COMPLEX*16 BPSI(4,4), BPSIN(4,4), EIG(4)
C
COMPLEX*16 CTHO, CITHO, PHCON, AI, FT,
1 B(K), F(K, K), YM(K, K), YMDEL
PARAMETER (AI=(0.0D0, 1.0D0), PI=3.141592653589793D0)
C
PHCON=DCMPLX(O.DO, -2.DO*PI*EV/12400.DO)
C
INVERSE PSI0 AND INITIALIZE YMM FOR MATRIX MULTIPLICATION (L14)
DO 5 JJ=1, 2
DO 5 JJ=1, 2
YMM(JJ, JJ+2)=(O.DO, O.DO)
YMM(JJ+2, JJ)=(O.DO, O.DO)
5 CONTINUE
CTHO=DCMPLX(DCOS(THO)*0.5DO, O.DO)
CITHO=DCMPLX(0.5DO/DCOS(THO), O.DO)
YMM(1, 1)=(O.5D0, 0.DO)
YMM(1, 2)=CTHO
YMM(2, 1)=(-0.5D0, 0.DO)
YMM(2, 2)=CTHO
YMM(3, 3)=(O.5D0, 0.DO)
YMM(3, 4)=CITHO
YMM(4, 3)=(O.5D0, 0.DO)
YMM(4, 4)=-CITHO
C
CALCULATE PSI MATRIX (L2)
DO 200 LAYER = 1, N + 1
IF(ISO(LAYER).EQ.0) THEN
CALL ISOPSI(LAYER, THO)
ELSE
CALL ANIPSI(LAYER, THO)
END IF
C
IF (LAYER .LE. N) THEN
C CALCULATE THE PHASE FACTOR
DO 160 I = 1, 4
BK(I) = CDEXP(PHCON*EIG(I)*DCMPLX(H(LAYER), O.DO))
160 CONTINUE
C
C CALCULATE THE F MATRIX (L6)
DO 180 K = 1, 4
DO 180 I = 1, 4
FT = (O.00D0, O.00D0)
180 CONTINUE
F(I,K) = FT

190 CONTINUE

C MATRIX MULTIPLICATION (L11,14)
CALL CDMULT(YMM, F, YM, 4, 4, 4, 4)
CALL CDCOPY(YM, YMM, 4, 4, 4)
ELSE
CALL CDULT(YMM, BPSI, YM, 4, 4, 4, 4)
ENDIF

200 CONTINUE

YMDL = (1.D0, 0.D0)/( YM(1,1) * YM(3,3) - YM(1,3) * YM(3,1) )
RSP = -((YM(3,3)*YM(4,1) - YM(4,3)*YM(3,1)) * YMDL
RPS = (YM(2,3)*YM(1,1) - YM(2,1)*YM(1,3)) * YMDL / DCONC(THO)
RETURN
END

SUBROUTINE ANIPSI(LAYER,THO)
IMPLICIT REAL*8(A - H, O - Z)

COMMON /CRYST/ ISO, EV, AN, PHI, THETA, PSI, ED, DELTA
INTEGER*4 ISO(G)
COMPLEX*16 ED0(6), DELTA(3,6), AN(6)
REAL*8 EV, HO, PHI, THETA, PSI(6)

COMMON /PSI/BPSI, BPSIN, EIG
COMPLEX*16 BPSI(4,4), BPSIN(4,4), EIG(4)

COMPLEX*16 EE(3,3), AI, BM(6,6), BD, BA3(6), BA6(6), DD(4,6).
1
2
REAL*8 A(3,3), SOR(2,4), COMEX(4), VI(4,4), AR(4,4),
1
PARAMETER (AI=-0.0D0,1.0D0), PI=3.141592653589793D0
DATA BA3, BA6 /12*(0.0D0,0.0D0)/, BM /36*(0.0D0,0.0D0)/

ANX = DSIN(THO)

CALCULATE ROTATION MATRIX A (Y2)
SPHI = DSIN(PHI(LAYER))
CPI = DCON(PHI(LAYER))
SPSI = DSIN(PSI(LAYER))
CPSI = DCON(PSI(LAYER))
STHETA = DSIN(THETA(LAYER))
CTHETA = DCON(THETA(LAYER))
A(1,1) = CPSI * CPI - CTHETA * SPHI * SPSI
A(1,2) = -SPSI * CPI - CTHETA * SPHI * CPSI
A(1,3) = STHETA * SPHI
A(2,1) = CPSI * SPHI + CTHETA * CPI * SPSI
A(2,2) = -SPSI * SPHI + CTHETA * CPI * CPSI
A(2,3) = -STHETA * CPI
A(3,1) = STHETA * SPSI
A(3,2) = STHETA * CPSI
A(3,3) = CTHETA

C
C TRANSFER BY A MATRIX TO FORM DIELECTRIC TENSOR EE (Y1)

DO 30 II = 1, 3
DO 20 JJ = 1, 3
EE(II,JJ) = (0.0,0.0,0.0,0.0)
DO 10 K = 1, 3
EE(II,JJ) = EE(II,JJ) + A(II,K) * A(JJ,K) * ED(K,LAYER)
10 CONTINUE
20 CONTINUE
30 CONTINUE

EE(1,2) = EE(1,2) + A1 * DELTA(3,LAYER)
EE(2,1) = EE(2,1) - A1 * DELTA(3,LAYER)
EE(1,3) = EE(1,3) - A1 * DELTA(2,LAYER)
EE(3,1) = EE(3,1) + A1 * DELTA(2,LAYER)
EE(2,3) = EE(2,3) + A1 * DELTA(1,LAYER)
EE(3,2) = EE(3,2) - A1 * DELTA(1,LAYER)

C INPUT OPT CONST INTO BM MATRIX (=M MATRIX IN B3)

DO 40 J = 1, 3
DO 40 I = 1, 3
BM(I,J) = EE(I,J)
40 CONTINUE

DO 50 I = 4, 6
BM(I,I) = (1.0,0.0,0.0,0.0)
50 CONTINUE

C BA3 AND BA6 ARE USED TO EXPRESS THE EZ,HZ

C COMPONENTS OF THE TOTAL FIELD (B20,21)

BD = (1.0,0.0,0.0,0.0) / (BM(3,3) * BM(6,6) - BM(3,6) * BM(6,3))
BA3(1) = (BM(6,1) * BM(3,6) - BM(3,1) * BM(6,6)) * BD
BA3(2) = ((BM(6,2) - ANX) * BM(3,6) - BM(3,2) * BM(6,6)) * BD
BA3(4) = (BM(6,4) * BM(3,6) - BM(3,4) * BM(6,6)) * BD
BA3(5) = (BM(6,5) * BM(3,6) - (BM(3,5) + ANX) * BM(6,6)) * BD
BA6(1) = (BM(6,3) * BM(3,1) - BM(3,3) * BM(6,1)) * BD
BA6(2) = (BM(6,3) * BM(3,2) - BM(3,3) * BM(6,2) - ANX) * BD
BA6(4) = (BM(6,3) * BM(3,4) - BM(3,3) * BM(6,4)) * BD
BA6(5) = (BM(6,3) * BM(3,5) + ANX) - BM(3,3) * BM(6,5) * BD

C DD MATRIX IS USED TO ARRANGE (B15-18) INTO (B23)

DO 60 J = 1, 6
DD(1,J) = BM(5,J) + (BM(5,3) + ANX) * BA3(J) + BM(5,6) * BA6(J)
DD(2,J) = BM(1,J) + BM(1,3) * BA3(J) + BM(1,6) * BA6(J)
DD(3,J) = -(BM(4,J) + BM(4,3) * BA3(J) + BM(4,6) * BA6(J))
DD(4,J) = BM(2,J) + BM(2,3) * BA3(J) + (BM(2,6) - ANX) * BA6(J)
60 CONTINUE

C THE BDEL MATRIX FORMS EIGN EQUATION FOR (EX, HY, EY, -HX)
C OR (GAMMA1,GAMMA5,GAMMA2,-GAMMA4) (B23)

DO 70 I = 1, 4
BDEL(I,1) = DD(I,1)
BDEL(I,2) = DD(I,5)
BDEL(I,3) = DD(I,2)
BDEL(I,4) = -DD(I,4)
70 CONTINUE

C SOLVE EIGENVALUE PROBLEM (L1)

DO 80 I = 1, 4
DO 80 J = 1, 4
  AR(J,I) = DREAL(BDEL(J,I))
  AIJ(J,I) = DIMAG(BDEL(J,I))
80 CONTINUE
CALL DCEIGN(AR, AIJ, 4, 4, ER, EI, VR, VI, IERROR, 1, 1)
IF (IERROR .NE. 0) THEN
  WRITE (6,*) IERROR, 'TH EIGN VALUE NOT FOUND'
END IF
C C SORT EIGEN VALUE AND EIGEN VECTOR ACCORDING TO LINCHUNG'S
C CONVENTION:
C SORT MODES INTO INCIDENT(I1,I2) AND REglected(J1,J2) MODES
C ACCORDING TO THE SIGNS OF THE POSITIVE PART OF THE EIGNVALUES.
DO 90 1 = 1, 4
  SOR(1,1) = ER(1)
  SOR(2,1) = DFLOAT(I)
90 CONTINUE
CALL SSORT(SOR, 2, -4, 4)
11 I = SOR(2,1)
12 J = SOR(2,2)
J1 = SOR(2,3)
J2 = SOR(2,4)
C C CALCULATE EX**2/(EX**2+EY**2) FOR EACH MODE TO DETERMINE
C WHETHER EX IS ITS DOMINATE POLARIZATION
DO 100 1 = 1, 4
  COMEX(I) = (VR(1,I)**2 + VI(1,I)**2) / (VR(1,I)**2 + VI(1,I)**2 + VR(3,I)**2 + VI(3,I)**2)
100 CONTINUE
C C ARRANGE ORDER OF MODES ACCORDING TO THE
C SCHEME OF LINCHUNG (L12) BASED ON COMEX OF EACH MODE
IF (COMEX(I1) .GE. COMEX(I2)) THEN
  EIG(1) = DCMPLX(ER(I1), EI(I1))
  EIG(3) = DCMPLX(ER(I2), EI(I2))
  DO 110 I = 1, 4
    BPSKI(I) = DCMPLX(VR(I,I1), VI(I,I1))
  110 CONTINUE
  ELSE
  EIG(3) = DCMPLX(ER(I1), EI(I1))
  EIG(1) = DCMPLX(ER(I2), EI(I2))
  DO 120 I = 1, 4
    BPSKI(I) = DCMPLX(VR(I,I1), VI(I,I1))
  120 CONTINUE
  END IF
IF (COMEX(J1) .GE. COMEX(J2)) THEN
  DO 130 I = 1, 4
    BPSKI(I) = DCMPLX(VR(I,J1), VI(I,J1))
  130 CONTINUE
  ELSE
  DO 140 I = 1, 4
    BPSKI(I) = DCMPLX(VR(I,J1), VI(I,J1))
  140 CONTINUE
END IF
CONTINUE
EIG(4) = DCMPLX(ER(J1),EI(J1))
EIG(2) = DCMPLX(ER(J2),EI(J2))
END IF

NORMALIZATION ACCORDING TO (L12)
BPNO1=BPSI(1,1)
BPNO2=BPSI(1,2)
BPNO3=BPSI(3,3)
BPNO4=BPSI(3,4)
DO 150 I = 1, 4
 BPSI(I,1) = BPSI(I,1) / BPNO1
 BPSI(I,2) = BPSI(I,2) / BPNO2
 BPSI(I,3) = BPSI(I,3) / BPNO3
 BPSI(I,4) = BPSI(I,4) / BPNO4
150 CONTINUE

CALCULATE THE INVERSION OF BPSI
DO 170 I = 1, 4
 BPSIN(J,I) = BPSI(J,I)
170 CONTINUE
CALL CDINVT(BPSIN, 4, 4, DET, COND)
RETURN

SUBROUTINE ISDPSI(LAYER,THO)
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /CRYST/ ISO, EV, H, AN, PHI, THETA, PSI, ED, DELTA
INTEGER*4 ISO(6)
COMPLEX*16 ED(3,6), DELTA(3,6), AN(6)
REAL*8 EV, H(6), PHI(6), THETA(6), PSI(6)
COMMON /PSI/BPSI, BPSIN, EIG
COMPLEX*16 BPSI(4,4), BPSIN(4,4), EIG(4)

ANL=AN(LAYER)
CTH=CDSORT((1.DO.0.DO)- (DSIN(THO)/ANL)**2 )
EIG(1)=CTH*ANL
EIG(3)=EIG(1)
EIG(2)=-EIG(1)
EIG(4)=EIG(2)

DO 5 II=1,2
 DO 5 JJ=1,2
 BPSIN(JJ,II+2)=(0.DO.0.DO)
 BPSIN(JJ+2,II)=(0.DO.0.DO)
5 CONTINUE
BPSIN(1,1)=(0.5DO.0.DO)
BPSIN(1,2)=(0.5DO.0.DO)*CTH/ANL
BPSIN(2,1)=(-0.5DO.0.DO)
BPSIN(2,2)=BPSIN(1,2)
BPSIN(3,3)=(0.5DO.0.DO)
BPSIN(3,4) = (0.5D0, 0.0D0)/(ANL*CTH)
BPSIN(4,3) = (0.5D0, 0.0D0)
BPSIN(4,4) = -BPSIN(3,4)

C
DO 65 II = 1, 2
   DO 65 JJ = 1, 2
      BPSI(JJ, II+2) = (0.0D0, 0.0D0)
      BPSI(JJ+2, II) = (0.0D0, 0.0D0)
65 CONTINUE

BPSI(1,1) = (1.0D0, 0.0D0)
BPSI(1,2) = (-1.0D0, 0.0D0)
BPSI(2,1) = ANL/CTH
BPSI(2,2) = BPSI(2,1)
BPSI(3,3) = (1.0D0, 0.0D0)
BPSI(3,4) = (1.0D0, 0.0D0)
BPSI(4,3) = ANL*CTH
BPSI(4,4) = -BPSI(4,3)
RETURN
END
Appendix B
An Article on Reflected Beam
Fields of a Light Beam Focused on a
Magneto-Optic Multilayer Structure
ABSTRACT

General formalism for reflection of a strongly focused beam from magneto-optic multilayer thin films is established using the Fourier transform technique. It is most useful when the focused spot size is of the order of the wavelength, in which case the paraxial approximation is not valid. A significant asymmetry in the field distribution is found for the reflected beam at normal incident angle. This asymmetry can be explained in terms of contributions from plane wave components with different incident angles.
1. **Introduction**

It is often useful to focus a collimated beam to very small spot of the size of a wavelength. One such example is the new erasable magneto-optic recording technology\(^1\),\(^2\). Previous optics theories treat the incident laser beam in the recording system as plane waves\(^1\),\(^3\),\(^4\). Such a treatment is convenient in optimization of the recording media. However, a proper theory should take into account the fact that for strongly focused beams, even the Gaussian beam description is insufficient and one has to go beyond the paraxial approximation\(^5\).

Using a scheme proposed by Lax et al.\(^6\), Takenaka et al. were able to find the beam field distribution beyond the paraxial approximation\(^5\). Corrections to the fundamental Gaussian beam were expressed in terms of the complex-argument Laguerre-Gaussian beams. Zauderer\(^7\) later obtained the same correction terms using a perturbation expansion technique. It is interesting to study how a system of multilayer films responds to the beam fields mentioned above.

In this work, the incident beam is described by the beam fields derived by Takenaka et al.\(^5\). Fourier transform (F.T.) technique is used to decompose the beam field into plane waves so that the respond of the multilayer thin films to plane waves can be applied. The reflected beam obtained in this way, in general, has an asymmetric distribution over the beam cross section. It will be shown that this asymmetry arises from different responds of various plane wave components in the incident beam.
2. **Fourier Transform of Beam Fields Beyond Paraxial Approximation**

A model for a strongly focused beam can be described as follows. A collimated Gaussian beam is polarized in the \(x\) direction and then focused by a perfect lens down to a spot size \(w_0\) on the focal plane \(z = 0\) as shown in Fig. 1. The equation and boundary condition for the \(x\) component of the electric beam field is expressed in cylindrical system as

\[
(V^2 + k^2_0)E_x(r,z) = 0 \quad (1)
\]

\[
E_x(r,0) = e^{-r^2/w_0^2} \quad (2)
\]

where \(k_0 = \omega \sqrt{\mu_e}\) and a time dependent factor \(e^{-i\omega t}\) is depressed.

The solution for (1) and (2) was given by Takenaka\(^5\) as

\[
E_x(r,z) = \sum_{s=0}^{\infty} \sum_{p=0}^{s} \sum_{m=0}^{p} (-1)^m c_m^p (2s)^{1/2} w_0^{-2m} r^{-m} \psi_o^{(s)} e^{ik_0z} \quad (3)
\]

where

\[
c_m^p = \frac{p!}{(p-m)! m!} \quad (4)
\]

\[
c_o^{(0)} = 1
\]

\[
c_p^{(2s)} = \frac{(-1)^{s+p} (2s)!}{s(p-1)!(s-p)!(s+p)!}
\]

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\[ s = 1, 2, \ldots, p = 0, 1, \ldots, s. \quad (5) \]

where one has used the convention that a term containing a factorial of a negative number should be set to zero. And

\[ f = \frac{1}{k_o w_o} \]

\[ \gamma = \frac{1}{w_o^2(1 + iz/z_o)} \]

\[ z_o = k_o w_o^2/2 \quad (6) \]

\( \psi^{(0)} \) is the complex-argument Laguerre-Gaussian beam defined as

\[ \psi^{(0)}(r,z) = \sum_{j=0}^{n} (-1)^{n+j}(n!)^2 \frac{w_o^{2(n+1)} \gamma^{n+j+1} r^{2j} e^{-\gamma r^2}}{(n-j)!(j!)^2} \quad (7) \]

Fourier transform is defined by

\[ \hat{U}(k) = (2\pi)^{-3/2} \int \int \int \hat{E}(x,y,z)e^{-ik_x x - ik_y y - ik_z z} \, dx \, dy \, dz \quad (8) \]

where \( x^2 + y^2 = r^2 \) has been used and integration over all possible values of the variable is implied throughout this work.

From Appendix A, one finds

\[ \int r^2 e^{-\gamma r^2 - ik_x x - ik_y y} \, dx \, dy \]
Coefficient $Q^j_l$ is given in Appendix A and $k_r$ is defined as $k_r^2 = k_x^2 + k_y^2$.

F.T. requires the following relation:

\[
\sum_{q=l}^{n} \frac{(-1)^{n+q}(n!)^2}{(n-q)!(q)!} \cdot Q^q_l = \delta_{n,l} Q^n
\]

which is also derived in Appendix A. Using (9) and (10), the desired F.T. can be written as:

\[
U_x(k_r, k_z) = \sum_{s=0}^{\infty} \sum_{p=0}^{\infty} \sum_{m=0}^{\infty} (2\pi)^{-1/2} G(s, p, m) k_r^{2(s+p)} e^{-k_r^2 w^2/4} k_{z_o} \frac{d^m}{dk_b^m} \delta(k_b)
\]

where

\[
k_b = k_z + \frac{k_r^2}{2k_o} - k_o
\]

\[
G(s, p, m) = \int_{0}^{\infty} \int_{0}^{\infty} \int_{0}^{\infty} e^{-q^2 r^2/4} \delta(q - l) e^{-k_r^2 w^2/4} k_{z_o} \frac{d^m}{dk_b^m} \delta(k_b)
\]
and δ function is used such that:

\[
\int F(x) \frac{d^m}{dx^m} \delta(x-x_0) dx = (-1)^m \frac{d^m}{dx^m} F(x) \bigg|_{x=x_0}
\]  

(13)

3. Reflection from Magneto-Optic Multilayer Films

Using the 4x4 matrix technique\(^3,8\), one is able to find the reflectivity from a multilayer thin film system with arbitrary dielectric tensors. If the film system is placed a distance \(d\) from the focal plane, the spectrum for the reflected beam can be expressed in terms of reflection matrix for plane waves\(^3\):

\[
\begin{bmatrix}
U_s^r(k^r) \\
U_p^r(k^r)
\end{bmatrix} = e^{i2dkz} \begin{bmatrix}
r_{ss}(\hat{k}) & r_{sp}(\hat{k}) \\
r_{ps}(\hat{k}) & r_{pp}(\hat{k})
\end{bmatrix} \begin{bmatrix}
U_s(\hat{k}) \\
U_p(\hat{k})
\end{bmatrix}
\]  

(14)

where the superscript 'r' denotes the reflected beam and the direction of \(s\) and \(p\) components are defined in Fig. 2.

Since \(k_z = -k_z^r\), one needs to replace \(z\) in the inverse F.T. by \(z = -z\) (see Fig. 1). From Maxwell's equation: \(\nabla \cdot \vec{E} = 0\), one can relate \(U_z\) to \(U_x\) by:

\[
k_x U_x + k_z U_z = 0
\]  

(15)

Using (14), (15) and the coordinate system in Fig. 2, the spectrum of the reflected beam for the model of Fig. 1 can be expressed as
\[ U_z = e^{\frac{12\pi i k}{z}} U_x(R_x \cos^2 \phi_k + R_2 \sin^2 \phi_k + R_3 \sin \phi_k \cos \phi_k), \]

\[ v = x, y \]

\[ U_z = e^{\frac{12\pi i k}{z}} U_x(R_x \cos \phi_k + R_2 \sin \phi_k) \quad (16) \]

where

\[ R_x = r_{pp}, R_2 = r_{ss}, R_3 = -(r_{sp}/\cos \theta + r_{ps} \cos \theta) \]

\[ R_1^y = r_{sp}/\cos \theta, R_2^y = -r_{ps} \cos \theta, R_3^y = r_{pp} - r_{ss} \]

\[ R_1^z = r_{pp} \tan \theta, R_2^z = -r_{ps} \sin \theta \quad (17) \]

Usually, the reflection matrix is only a function of \( \theta \) and \( k \): \( R_j^y(k_r, k_z) = R_j^y(\theta, k) \). \( k_r, k_z \) can be related to \( \theta \) by

\[ \tan \theta = k_r/k_z \]

\[ k^2 = k^2_r + k^2_z \quad (18) \]

The inverse F.T. requires an integral
\[
\int e^{ibzo} R^\nu_j [ \frac{\delta}{\delta k_b} \delta(k_b) ] e^{i(k_z - k_0)z} \text{dk}_z \\
= (-1)^m e^{i(k_0 - k_0^2/2k_o)z} W^\nu_{jm}(k_r) \tag{19}
\]

where
\[
W^\nu_{jm}(k_r) = \frac{\delta}{\delta k_b} \left[ e^{ik_b(z - iz_o)} R^\nu_j(k_r, k_b + k_o - k_0^2/2k_o) \right]_{k_b=0} \tag{20}
\]

From (16) and (19), one finally obtains the reflected beam fields as follows:

\[
E^r_{\nu}(r, \phi, z^r) = 
\sum_{s=0}^{\infty} \sum_{p=0}^{\infty} \sum_{m=0}^{\infty} \frac{(-1)^m k}{2\pi} G(s, p, m) e^{ik_z' z^r} \\
\times \int_0^{k^2(s+p)} e^{-k^2/4\gamma'} \left\{ \frac{1}{2} (W^\nu_{1m} + W^\nu_{2m}) J_0(rk_r) \\
- \left[ \frac{1}{2} (W^\nu_{1m} - W^\nu_{2m}) \cos 2\phi + \frac{1}{2} W^\nu_{3m} \sin 2\phi \right] J_2(rk_r) \right\} \text{dk}_r, \\
\nu = x, y
\]

\[
E^z_{\nu}(r, \phi, z^r) = 
\sum_{s=0}^{\infty} \sum_{p=0}^{\infty} \sum_{m=0}^{\infty} \frac{(-1)^m k}{2\pi} G(s, p, m) e^{ik_z' z^r} \\
\times \int_0^{k^2(s+p)} e^{-k^2/4\gamma'} \left\{ (W^\nu_{1m} \sin \phi - W^\nu_{2m} \cos \phi) i J_1(rk_r) \right\} \text{dk}_r \tag{21}
\]
where $\phi$ is defined through

\[
x = r \cos \phi \\
y = r \sin \phi
\]  

(22)

and

\[
z' = z + 2d
\]

(23)

\[
\gamma' = \frac{1}{w_o^2[1 + 1(z + 2d)/z_o]}
\]

In (21) $J_0$, $J_1$ and $J_2$ are Bessel functions.

4. **Reflected Beams at Far Fields**

From (3) one can show that at $z \gg z_o$, only the first term in (21) (the Gaussian beam) is significant and behaves like $1/(z - iz_o)$. All the rest decays much faster. The question arises naturally: Can one neglect all other terms in (3) when calculating the reflected beams at far field? Or does the other beam fields mix with the Gaussian beam after interaction with the multilayer system?

At far field, the leading term is

\[
\hat{W}^y_{jm}(k_r) = [1(z + 2d - iz_o)]^m R^y_j(k_r, k_o - k_r^2/2k_o)
\]  

(24)
Since $R_j^{(k)}$ and $J_2^{(rk)}$ have upper bounds, the integrals in (21) can be written as

$$\left(z + 2d - iz_0\right)^m g(\phi) \int_0^\infty k_r^2(s+p) e^{-k_r^2/4z} \, k_r \, dk_r$$

$$= \frac{1}{2}(-2ik_o)^{s+p+1} g(\phi) (s+p)!/(z + 2d - iz_0)^{s+p-m+1}$$

where $g$ is a bounded function. One concludes immediately from (25) and (21) that only $s = 0$ (Gaussian beam) is important at far field. Therefore, in such a model the strongly focused beam can be approximated by a Gaussian beam at far fields.

It is interesting to find from (21) that, in general, the reflected beam has a significant dependence on $\phi$. This dependence will be less significant as the spot size gets larger, as expected. (21) has been applied to erasable magneto-optic multilayer recording media for system optimization and the details will be published elsewhere. One example is given below to demonstrate the asymmetry mentioned above.

A typical numerical aperture for the lens of the recording system is N.A. = 0.5. If one takes the diameter of the lens to be $\pi w(z)$ (99% criterion$^9$), where

$$w(z) = w_0 \sqrt{1 + (z/z_o)^2}$$

the estimated spot size is$^9$ $w_o = (\sqrt{3}/2) \lambda$, where $\lambda$ is the wavelength. For convenience $d$ is set to zero since it only introduces a shift in $z^r$ in the
The parameters $R_j^y$ are calculated from the same multilayer structure as in Ref. 3 with the thickness and refractive indexes listed in Table 1. The wavelength is that of a laser diode (0.830 µm).

With the system parameters specified above, the Gaussian beam ($s=0$ term in (21)) field intensity $2000 \cdot |E_y^r(r,\phi,z^r)|^2/|E_x(o,z^r)|^2$ for $z^r = 5 z_o$ is shown in Fig. 3 as a contour plot. The normalization factor is chosen so that the result can be compared to the results in Ref. 3.

The asymmetry arises from a non-vanishing $\omega^y_{3o}$ and $(\omega^y_{1o} - \omega^y_{2o})$ in (21). One can see from (17), that this is due to a nonzero angle $\theta$. For example, the contribution of $E_x$ to $E_y^r$ incident at $(\theta,\phi)$ will have opposite sign to that of $(\theta,-\phi)$ with a non-vanishing $r_{pp} - r_{ss}$.

The weakness of the model is that $d$ does not have any fundamental effects on the reflected beam, while in a recording system $d$ and the focused spot should be positioned on the bits. Therefore, a model including the variation of the dielectric constant of the magnetic layer in the x-y plane is necessary for a complete description of the recording system.

One of the authors (Z.L.) thanks Dr. T. Tiedje for interesting discussions.
Appendix A

The purpose is to evaluate the integral in (9). Define:

\[ u_o = \frac{ik}{2\gamma} x \]
\[ v_o = \frac{ik}{2\gamma} y \]
\[ u = x + u_o \]
\[ v = y + v_o \] \hspace{1cm} (A1)

The desired integral can be written

\[
I_p = \iint r \ e^{-\gamma r^2 - ikx - ik y} \ dx \ dy
\]

\[
= e^{-\frac{k^2}{4\gamma}} \iint (u^2 + v^2 + u_o^2 + v_o^2 - 2u_o u - 2v_o v)e^{-\gamma (u^2 + v^2)} \ dudv \] \hspace{1cm} (A2)

Introducing another set of variables:

\[ u = V \cos \phi \]
\[ v = V \sin \phi \]
\[ u_o = V_o \cos \phi_o \]
\[ v_o = V_o \sin \phi_o \] \hspace{1cm} (A3)

(A2) becomes
The summation is over all possible non-negative integers as bounded by the factorial. One notes:

\[ \int_0^{2\pi} \cos^{2k} \phi \, d\phi = 2 \sqrt{\pi} \Gamma(k + 1/2)/k! \]

\[ \int_0^{2\pi} \cos^{2k+1} \phi \, d\phi = 0 \]  \hspace{1cm} (A5)

Using (A5), (A4) becomes

\[ I_p = e^{-k^2/4\gamma} \sum_{j} \sum_{m} \frac{p!(-2)^m}{(p-j)! (j-m)! m!} \int \int \psi^{2p-2j+m} \psi_o^{2j-m} \times \cos^m(\phi-\phi_o) e^{-\gamma\psi^2} \, d\phi \, d\psi VdV \]  \hspace{1cm} (A4)

If one defines \( \lambda = j-k \) and exchanges the order of summation in (A6), one has

\[ I_p = e^{-k^2/4\gamma} \sum_{j} \sum_{k} \frac{(-1)^{j-k} \sqrt{\pi} 2^k \Gamma(\lambda+1)}{(p-j)! (j-2k)! (2k)! k!} \times \frac{1}{k^2(j-k)} \gamma^{(p+j-k+1)} \]  \hspace{1cm} (A6)

with
which is the desired coefficient.

(A7) and (A8) have been tested numerically for a large range of p and γ.

Given (A8), one can prove relation (10) as follows:

\[
\sum \frac{(-1)^{n+p} (n!)^2}{p (n-p)! (p!)^2} Q_p^k
\]

\[
= \sum \frac{(-1)^{n+p} \sqrt{2\pi} 2^{k-l} n! (k+1/2)}{(l-k)! (2k)! k!} \sum \frac{(-1)^{P-l} (p-l)(p-l-1)...(p-l-k+1)}{P^n} x^{P-l-k}
\]

One notices that

\[
\frac{d^k}{dx^k} x^{-l} (1-x)^n = \sum \frac{(-1)^{P-l} (p-l)(p-l-1)...(p-l-k+1)}{P^n} x^{P-l-k}
\]

and it can be readily shown that

\[
\frac{d^k}{dx^k} x^{-l} (1-x)^n \bigg|_{x=1} = 0, \ l < n \text{ and } k < n
\]

From (A8-11), one obtains
\[
\sum_{p=1}^{n} \frac{(-1)^{n+p} (n!)^2}{(n-p)! (p!)^2} q_p = \delta_{n,k} Q_n^n
\]

where

\[
Q_n^n = (-1)^n 2^{-2n} \pi
\]
References


Table 1
Parameters of thickness and refractive indexes of the magneto-optic multilayer thin films for the intensity calculation as shown in Fig. 3. Superscripts '+' and '-' denote for left-handed and right-handed circularly polarized light, respectively. The wavelength $\lambda = 0.830 \, \mu m$.

<table>
<thead>
<tr>
<th>Layer</th>
<th>refractive index</th>
<th>thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$n_c = 1.50$</td>
<td>$0.2375 (\lambda/n_c)$</td>
</tr>
<tr>
<td>2</td>
<td>$n^+ = 3.77 + 3.92,i$</td>
<td>110 Å</td>
</tr>
<tr>
<td></td>
<td>$n^- = 3.56 + 3.79,i$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$n_f = 1.50$</td>
<td>$0.225 (\lambda/n_f)$</td>
</tr>
<tr>
<td>4</td>
<td>$n_r = 2.00 + 7.00,i$</td>
<td>$&gt;500$ Å</td>
</tr>
<tr>
<td>substrate</td>
<td>$n_s = 1.50$</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Schematics of the model system and coordinate system for the beam fields. The incident beam propagates along +z direction.
Figure 2. Coordinate system of $p$ and $s$ light for incident and reflected plane wave components, respectively. Superscript 'r' denotes for reflected waves.
Parameters for the incident beam is described in text and those for the multilayer thin films are specified in Table 1. $w(z)$ is spot size defined in (26).
Appendix C
An Article on Optimization of Readout From Magneto-Optic Recording Medium
Abstract

Reflectance and transmittance of a light beam strongly focused on multilayer thin films are derived at far field. Using the Fourier transfer technique, the reflectance (transmittance) can be expressed in terms of the reflection (transmission) matrix for plane waves. The readout from magneto-optic multilayer films is optimized for a strongly focused beam. It is found that when the focal spot size $w_0$ is less than three wavelengths, the readout is significantly different from that calculated for plane waves.
Erasable magneto-optic recording technologies have received increasing amount of attention because of the high storage density.\textsuperscript{1} The magneto-optic recording medium consists of a thin layer of rare earth-transition metal alloy sandwiched between two dielectric layers. Mansuripur et al.\textsuperscript{2} have optimized the readout from the multilayer film system against the thicknesses of the cover and intermediate layers.\textsuperscript{2} As for the maximum readout, Mansuripur\textsuperscript{3} has derived a figure of merit as the upper bound. Using the $4 \times 4$ matrix technique, Li et al.\textsuperscript{4} were able to study the sensitivity of the readout with respect to the thicknesses of the dielectric layers. In all the above theories the incident wave was assumed to be a plane wave for convenience while in real recording systems, the reading laser beam is focused down to a spot size of the order of a wavelength, in which case even the conventional paraxial Gaussian beam theory failed to describe the beam fields properly.\textsuperscript{5,6} We are going to derive the reflectance and transmittance of a beam focused on the magneto-optic recording medium. Since the formalism is very general, it will also be useful for other thin-film designers dealing with strongly focused laser beams.

The model is as follows. A collimated Gaussian beam propagating in the $+z$ direction is polarized in the $x$ direction and then focused by a perfect lens on the focal plane $z = 0$. Assuming that the beam intensity on the focal plane has a Gaussian distribution with spot size $w_0$, Takenaka et al.\textsuperscript{5} expressed the beam fields in terms of a Gaussian beam and correction terms of increasing order in $1/k_0 w_0$, where $k_0 = \omega \sqrt{\mu e}$. Recently Li and Parsons\textsuperscript{6} were able to derive the $k$-space spectrum for the beam fields and expressed the reflected fields in terms of the reflection matrix for plane waves.

In the following reasoning, only reflectance is considered since the derivation of transmittance is completely analogous. The reflectance is given by:

$$R_\nu = \frac{\text{Re} \int |iE^r| \times (\nabla \times E^r)|_z dx dy}{\text{Re} \int |iE^t| \times (\nabla \times E)|_z dx dy},$$  

(1)

where only $E_x^r$ and $E_x^t$ are needed for $\nu = x$ and similarly for $\nu = y$. The surface integral is over a plane at far field, and the superscript $r$ denotes for the reflected light. Using a spherical coordinate system, $(k, \theta, \phi)$, the k-space spectrum for the reflected beam fields can be written as\textsuperscript{6}:

$$U_{\nu}^r = U_x r_{\nu}, \quad \nu = x, y, z,$n

(2)

$$r_\nu = R_1^\nu \cos^2 \phi + R_2^\nu \sin^2 \phi + R_3^\nu \sin \phi \cos \phi, \quad \nu = x, y,$n

$$r_z = R_1^z \cos \phi + R_2^z \sin \phi,$n

(3)

where $U_x$ is the spectrum for the incident field and $R_i^\nu$ is a function of the elements of the reflection matrix: $\begin{pmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{pmatrix}$ and is given by\textsuperscript{6}:

$$R_1^z = r_{pp}, \quad R_2^z = r_{se}, \quad R_3^z = -(r_{sp}/\cos \theta + r_{ps} \cos \theta),$$

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\[ R^y_1 = r_{sp}/\cos\theta, \quad R^z_2 = -r_{ps}\cos\theta, \quad R^y_3 = r_{pp} - r_{ss}, \]
\[ R^z_1 = r_{pp}\tan\theta, \quad R^z_2 = -r_{ps}\sin\theta. \]  

(4)

Taking advantage of the \( \delta \) function\(^6\) in \( U_z \), eq. (1) can be transferred into integration of the corresponding spectral functions with respect to \( dk_x dk_y \). The result is

\[ R_\nu = \frac{1}{2\pi I_0} \int e^{-k^2 w_0^2/2} [(k_0 - k^2 / 2k_0) | r_\nu |^2 - k_\nu Re(r_\nu^* r_z)] dk_x dk_y, \]  

with \( \nu = x, y, \) and

\[ I_0 = \int e^{-k^2 w_0^2/2} [k_0 - k^2 / 2k_0 + k^2 / 2k_0 - k^2 / 2k_0] k_r dk_r, \]  

(6)

where \( k^2 = k_x^2 + k_z^2 \) and integration over all possible value is implied. In \( r_\nu, k_z \) is no longer independent\(^6\) and must be expressed as \( k_z = k_0 - k^2 / 2k_0 \).

If the reflection matrix is independent of \( \phi \) (e.g. isotropic thin films), eq. (5) can be further written as:

\[ R_\nu = \frac{1}{8I_0} \int e^{-k^2 w_0^2/2} [(k_0 - k^2 / 2k_0) < | r_\nu |^2 > - k_r G_\nu] k_r dk_r, \]  

(7)

where \( \nu = x, y, \) and

\[ < | r_\nu |^2 > = 3 | R^x_\nu |^2 + 3 | R^y_\nu |^2 + | R^z_\nu |^2 + 2 Re(R^x_\nu R^z_\nu), \]

\[ G_x = Re(3R^x_L R^x_1 + R^x_R R^x_2 + R^x_R R^x_L), \]

\[ G_y = Re(3R^y_L R^x_2 + R^y_R R^x_1 + R^x_R R^y_L). \]  

(8)

Since a powerful technique has been developed for calculating the reflection and transmission matrices,\(^4,7\) (5) or (7) enable one to calculate the reflectance and transmittance of a light beam strongly focused on a thin film system with arbitrary structure and dielectric tensors.

For the readout \( \propto R_y \) of a magneto-optic medium with a magnetic moment \( \vec{M} \), \( \frac{1}{2}[r_y(M_z) - r_y(-M_z)] \) and \( \frac{1}{2}[r_z(M_z) - r_z(-M_z)] \) are used to eliminate a background arising from the diagonal matrix elements of the reflection matrix. The integrands in (7) are evaluated by the \( 4 \times 4 \) matrix technique\(^4,7\) for incident angle \( \theta \) ranging from \( 0^\circ \) to \( 87^\circ \).

For comparison purposes, the same film material studied by Mansuripur\(^3\) are considered (i.e., the intermediate and cover layers have refractive indices \( n_i = n_c = 2.0; \) TbFe has dielectric constants \( \epsilon = -1.4 + i28.3 \) and \( \epsilon' = 0.12 + i0.57 \) and substrate is Al; the wavelength \( \lambda = 8200 \) Å). We found that for plane waves, the optimal thickness for TbFe layer is 175 Å and the readout reaches a maximum 95% of the figure of merit\(^3\) at \( t_i = 0.175 \lambda_i \)
and \( t_c = 0.213 \lambda_c \), where \( t_i \) and \( t_c \) are the thicknesses of the intermediate and cover layers, respectively, and \( \lambda_i = \lambda/n_i, \lambda_c = \lambda/n_c \). The sensitivity of the readout power (scaled to \( 10^4 \times R_y \)) to \( t_i \) and \( t_c \) is shown as a contour plot in Fig. 1 for 175 Å thickness of TbFe layer.

To study the effect of the spot size on the readout, \( 10^4 R_y \) is shown as a function of \( w_0 \) in Fig. 2 for a film structure optimal for plane waves. When \( w_0 < 3\lambda \), \( R_y \) decreases significantly. The dependence of \( 10^4 R_y \) on \( t_i \) and \( t_c \) is also presented in Fig. 3 as a contour plot for a typical \( w_0 = \lambda/2 \) and the same TbFe layer thickness as for Fig. 1. In this case, not only is the maximum readout power reduced to 92% of the figure of merit, but the optimal \( t_i \) and \( t_c \) also shift 18% and 13%, respectively, to larger values than those of the plane wave model. Another interesting difference between Fig. 1 and Fig. 3 is that the readout is less sensitive to \( t_i \) and \( t_c \) for focused beams than for plane waves. The reason is that the distribution of plane wave components in the beam smoothes out the response of the film system to a single component.

In conclusion, the reflectance (transmittance) of a focused light beam has been calculated in terms of the reflection (transmission) matrix. A plane wave model calculation is insufficient if good accuracy is required. The small focal spot size makes it harder to reach the figure of merit derived by Mansuripur\(^3\).
References

FIG. 1. Contour plot of the readout (scaled to $10^4 R_y$) for a plane wave ($\lambda = 8200 \text{ Å}$) as a function of the intermediate and cover layer thicknesses $t_i$ and $t_c$ in units of $\lambda_i = \lambda/n_i$ and $\lambda_c = \lambda/n_c$, respectively, where $n_i$ and $n_c$ are the corresponding refractive indices. TbFe layer thickness is 175 Å.
FIG. 2. Reflectance $10^4 R_y$ as a function of the beam spot size $w_0$. The thicknesses for the layers are: $t_i = 0.175 \, \lambda_i$ and $t_c = 0.213 \, \lambda_c$ and TbFe layer thickness is 175 Å.
FIG. 3. Same plot as Fig. 3 except the incident wave is a focused beam with spot size $w_0 = \lambda/2$. 

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FIG. 3. Same plot as Fig. 3 except the incident wave is a focused beam with spot size $w_0 = \lambda/2$. 

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