Magnetic thin films for high-density recording

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Abstract

Magnetic and magneto-optic recording technologies are continuing to evolve at a rapid pace resulting in longer playing times and more data being stored in ever decreasing volumes. Thin-film media are playing an important role in this process. Three different type of thin-film media are discussed here, namely, a hard disk application for data recording, metal-evaporated tape for audio/video applications and CoNi/Pt multilayer for application as a magneto-optic media for blue laser recording. The relationship between deposition parameters (evaporation and sputtering), structural parameters and magnetic and recording behaviour are discussed.

Keywords: Magnetic structures; Sputtering; Evaporation; Deposition process

1. Introduction

The invention of magnetic recording (at the end of the 19th Century) has developed to the present high-quality and very compact magnetic recording products. Magnetic recording spans audio, video and data storage applications in the form of tapes, floppy and hard disks in products such as digital video recorders, digital camera-recorders, audio equipment, electronic games, video telephones, fax machines and personal organisers. The market requirements include continued reduction in peripheral device size and power consumption while maintaining an exponential increase in capacity.

High-density recording depends on shortening the recording wavelengths, λ , or, in other words, making the recorded bitlength, bl , as small as possible. Also, for increasing areal density, the track width, tw , has to be made smaller.

A principle configuration of the recording geometry is given in Fig. 1. Here, a ring head is used which operates on a head, medium spacing (d) from the media in motion. The gap length of the head is g , the magnetic thickness of the recording medium is δ , the recorded bit length is bl and the track width is tw . A bit cell is defined as the distance between the recorded transitions, a , and is give by $bl = v/T$, where T is the bit duration in seconds, $1/T$ is the bit frequency in Hz and v is the head-to-medium speed in m s^{-1} . The bit cell area, ba , as recorded, has the dimension $tw \times bl$.

The digital storage of a bit in a moving medium beneath a soft magnetic head can be achieved by a current pulse in the recording head. The magnetic flux associated with the writing current travels the magnetic circuit of the head. The gap fringe flux penetrates the medium and magnetises small volumes of

Fig. 1. Recording parameters for the head and the medium with written track, tw , recording wavelength, λ , linear bit length, bl , and the recorded transition, a .

the material. In the case of longitudinal recording, the horizontal fringing field component is the most important. The ba should be small for high-density recording and a should be as sharp as possible. The change of the head current from one polarity to another produces a magnetisation that is not spatially sharp but varies over a distance from one direction to the opposite one. The transition length in longitudinal recording is mainly determined by the head field gradient and the demagnetising fields generated by the magnetostatic fields of the transition itself and the switching field distribution of the magnetic units in the medium; it is given by [1]:

$$a \cong [\{ 4M_r \delta (d + \delta/2) \} / (QH_c)]^{1/2}$$

where M_r = remanent magnetisation, δ = layer thickness, d = head-to-medium spacing, Q = a value related to the field gradient of an inductive head (0.75) and H_c = medium coercivity. For a small transition width, H_c should be large in relation to $M_r \times \delta$ (remanence thickness product) and d

Fig. 2. Typical configuration of (a) a commercial thin-film medium, and (b) an advanced multilayer medium for very high-density applications.

should be as small as possible (contact). The stored bit (transition) can be read by the head due to the flux changes in the head which give an induced voltage.

The development of thin-film media brought important advantages in relation to particulate media. The most important one is that the $M_r \times \delta$ (remanence thickness product) for metal thin films in the range of $\delta = 20\text{--}80\text{ nm}$ is about a factor of 10 times higher because of the high M_r value. Thin films can be easily tailored by changing the deposition parameters, material choice etc. Last, but not least, the grain size is 0.1 times the size of a particle in a particulate medium. The disadvantage of using thin film for very high-density longitudinal recording is that the transition, a , will form a zig-zag shape due to the strong demagnetizing fields. Such a transition shows not only this shape but it is also very irregular, depending on the average size distribution of the crystals and the intergranular (exchange) coupling. These effects can generate a lot of noise during the recording process. The main aim for tailoring the right thin-film morphology is to create magnetically uncoupled grains. Uncoupling of the exchange forces between the grains can be realised by physical separation due to controlling the nucleation and growth of the layer by means of sputter parameters, or by depositing an appropriate intermediate layer between the magnetic layer and the substrate. Another method is based on chemical phase separation or segregation mechanisms. The choice of the right combination of materials and deposition technologies is then very important.

In this paper a few thin-film recording media will be discussed: a sputtered hard disk used for data recording, an oblique evaporated tape for audio/video applications and, finally, a multilayer medium for magneto-optic recording applications.

2. Hard disk media

Sputtered hard disks of Co–Cr–X ($X = \text{Ni, Ta, Pt, C}$) for very high-density recording have been prepared and tested

over the years. The first disks with a density larger than 1 Gbit in^{-2} were reported by IBM (USA) [2] and Hitachi (Japan) [3]. The recording layers are deposited on a Cr underlayer which is deposited on the substrate. Sputtering is the most favourable deposition technology for preparing these disks. The most important process parameters for depositing a suitable magnetic layer are the composition, thickness and structure of the layer. The latter also depends on the structure of the Cr underlayer. The deposition parameters for both layers, such as substrate temperature, bias voltage and surface texture, are also very important.

A typical configuration of a commercial thin-film medium is given in Fig. 2(a). As can be seen, the medium consists of a substrate made of glass, aluminium, polyester, PET etc. A transition (intermediate, seed layer or underlayer) between the substrate and the magnetic (recording) layer and a covering (protective and/or lubrication layer). They all consist of different materials, chemical compositions, microstructures and thicknesses.

2.1. Choice of Co–Cr and Co ternary alloyed thin films

Promising thin-film media for magnetic recording consist of the materials Co–Cr–X ($X = \text{Pt, Ta, Ni}$). It is essential to deposit this alloy on a Cr underlayer in order to obtain the necessary in-plane orientation. A second element combined with Co has important consequences for the Curie temperature, T_c , of the alloy, at which the spontaneous magnetisation disappears. The T_c for Co is very high (1131°C), and provides a reasonable margin for the amount by which T_c usually decreases. It is also true, at least for bulk material, that adding Cr to Co can finally make the hcp structure unstable, and, at certain compositions, 2 crystal structures (fcc and hcp) may be present. Furthermore, it has been shown that even 2 different phases, one with a high Co-rich composition (ferromagnetic) and the other with a high Cr-rich content (paramagnetic) can be formed [4]. Consequently, adding Cr to Co has 2 important effects, namely reduction of the T_c

and reduction of the M_s . For recording applications these values should be optimised. The T_c must not be too close to room temperature, because then the magnetic behaviour becomes too sensitive to temperature variations. M_s should have a certain value because otherwise the information can not be read by the head. It is very difficult to understand the physics behind the reduction of M_s and T_c because they are very complicated and not completely known. However, the most useful model when Cr is added to Co is to consider that the magnetic moment of Co atoms is reduced by electron transfer to its 3d band from Cr. It has been shown experimentally that T_c drastically decreases with the Cr content and becomes paramagnetic just above about 22 wt.% at room temperature. This is not expected if Cr only acts as a simple diluent [5]. Also, the transfer of 4s electrons from Cr to the 3d shell of Co may lower the magnetic moment [6]. Furthermore, pure Cr is antiferromagnetic at room temperature and a ferromagnetic sublattice coupling also seems to be an acceptable explanation of the relatively strong decrease in T_c when compared with the other element X, which forms a hcp phase with Co [7]. Adding Cr to Co also gives an enhanced anisotropy field. Furthermore, with the variation of the Cr content, it is possible to adjust H_c .

Another favourable influence of Cr on the film morphology is the reduction of the column dimensions [8] and the appearance of the compositional separation. As previously mentioned, the latter has a great influence on the magnetic microstructure because it can lead to more or less magnetically uncoupled columns if the enhancement of Cr at the column boundaries becomes higher than about 27 at.%. Smaller grain size has the advantage of a lower surface roughness which results in a better head-medium interface. Last, but not least, the choice of Cr also improves the corrosion resistance and mechanical hardness of the Co-based medium, although in a few cases other elements have been added to increase these properties.

For further tailoring, longitudinal media ternary and quaternary alloys have been prepared and used as high density media [3,9]. Quaternary alloys Co–Cr–Pt–X (X = Ta, B, Ni, B) have also been reported, for instance in [10,11].

2.2. Texture, morphology and crystal structure

The c-axis orientation is very important for the magnetic anisotropy. The Co-based alloys used mostly have a hcp structure with the c-axis randomly in-plane, but it is also possible to create a tilted c-axis depending on the underlayer structure, e.g. [12]. On thick Cr underlayers the (10.1) Co–Cr–Ta orientation growth on the Cr (100) plane will finally lead to a tilted c-axis of 28° with respect to the substrate plane, but, for instance, the (11.0) of Co–Cr–Pt layers grow epitaxially on the Cr (100) resulting in a c-axis orientation of the magnetic layer in-plane. An optimised Cr thickness is found for this type of epitaxial growth. Besides randomly in-plane texture, oriented in-plane texture can also be made. In this kind of film the properties (H_c and M_r) in the various in-

plane directions (texture and non-texture directions) are different. The texture of the film can be supported by the texture of the substrate and the crystal lattice may be smaller in the texture direction than in the transverse direction. This may be the source of strain-induced magnetic anisotropy (magnetostriction). It is also found that the crystal is aligned in the texture direction [13].

As discussed previously, thin films should magnetically operate as individual particles. The exchange between the crystals should be broken or at least minimised. This can be realised by mechanical separation or by segregated crystal boundaries with non-ferromagnetic compositions. The Cr underlayer is responsible for the physical separation. Cr grows with a columnar morphology and has a rough surface structure [14]. It was reported that the dome-like surface roughness is in the order of tens of nanometers, depending on the thickness of the Cr layer. TEM observations [15] indicate, that in combination with a high Ar sputter-gas pressure, the Co–Cr–Pt layer shows physically separated crystal boundaries.

Fig. 3 shows a planar TEM observation from a Co–Cr–Pt film prepared at room temperature and at 150°C . The sample made at low surface diffusion shows a more decoupled grain structure than the one deposited at higher temperature. This is also reflected in the magnetic properties [16].

Fig. 3. TEM planar view of sputtered Co–Cr–Pt films prepared (a) at room temperature, and (b) at 150°C .

The crystal size depends on the argon gas pressure during sputtering, the substrate temperature and the bias voltage on the substrate. The method of deposition also has a large influence on the development of the 'grain' growth. It can be seen from TEM observations that the average crystal has a 10–50 nm diameter. Depending on the preparation conditions, the crystals can be mechanically separated (spacing about 4 nm) at the grain boundaries. Another magnetic separation of the crystals is achieved using segregated crystal boundaries with a non-ferromagnetic material. This has been shown already by Aspland [17] in CoP-plated disks. Grain size or columnar size is strongly influenced by the microstructure of the underlayer/substrate.

Many of the Co-X (=Cr, P)–Y (=Ta, Pt, Ni) thin-film media do have a hcp structure with the texture axis (c-axis) parallel or perpendicular to the substrate surface depending on the properties of the Cr underlayer. It is also possible for the films to have fcc phases.

The texture of a polycrystalline material can be simply defined as the crystallographic preferential orientation. In the case of a ferromagnetic thin film the orientation distribution of the column is of great importance because it determines the quality of the direction of the magnetic anisotropy.

Another influence on the orientation is caused by the pressure of sputter gas and a worsening background pressure. It has been shown that a small amount of residual N₂ gas in the process chamber causes the formation of the fcc phase which also destroys the well-oriented hcp structure. A higher Ar pressure usually means that the atoms are more scattered during their movement from target to substrate, and, consequently, their kinetic energy is reduced, with consequences for the surface diffusion.

Compositional separation at the grain boundaries influences the magnetic interactions of the individual grains. In principle, different origins for obtaining the compositional separation (CS) can be mentioned such as the deposition temperature, the geometry of the deposition process or magnetic inducement.

Most of the experimental results about CS have been published on Co–Cr media for perpendicular recording. But Maeda [18] also showed compositional separation is present in Co–Cr–X materials used for longitudinal recording. In [19] it was shown that the CS is suppressed by increasing the T_a content.

The microstructure of the thin-film medium has a great influence on the magnetic behaviour of the film. Is the magnetic behaviour of the layer continuous or particulate? Both qualifications refer to the degree to which exchange forces are able to extend throughout the medium. In a continuous medium the exchange forces are hardly disturbed by structural discontinuities such as crystal boundaries. From the magnetic point of view, even thin films may be considered particulate, showing distinct structural ferromagnetic units like crystals, columns, or clusters of crystals/columns separated by non-ferromagnetic materials or voids. Such kinds of microstructures may be influenced by the deposition methods

and the nucleation and growth process of the layers, as noted previously. If the thin film has a continuous microstructure in which there is an exchange between the magnetic units, then at a remanent magnetic state the layer consists of magnetic domains having their direction of magnetisation anti-parallel and separated by a domain wall. As can be understood, the magnetisation reversal in a thin-film medium is very strongly dependent on the microstructural properties. Depending on the morphology and chemical inhomogeneities of thin-film media the reversal takes place as follows:

- The reversal in one grain is strongly dependent on the CS structure in one grain.
- Exchange-coupled grains show a magnetic-domain structure which covers many grains and gives a reversal originating in domain-wall motion. The wall energy, influenced by crystalline anisotropy, magnetostatic energy at the wall, strain, chemical inhomogeneities and film surface properties, dominates the coercivity (H_c).
- Uncoupled grains, when reversed, are independently influenced by magnetostatic interactions. Here, the H_c is determined by the crystalline anisotropy of the grain, shape and strain anisotropy.
- Clusters of grains which are locally magnetically coupled can reverse in unison. These reversals are independent of other clusters, but magnetostatic coupling may influence their behaviour.

2.3. Magnetisation and coercivity

The relationship between the magnetisation and the composition is frequently presented by the Slater-Pauling curve which gives the relationship between the saturation magnetisation (M_s) and the homogeneous bulk Co–X [20,21]. In general, most papers reported that the M_s of sputtered and evaporated films, deposited at higher substrate temperatures, is found to be larger than that for bulk alloys having the same average chemical composition. Although in the literature various origins have been proposed, the most likely explanation is phase separation. Two hcp phases, which hardly occur in bulk Co–Cr material at low temperatures, cause compositional fluctuations along the grain boundaries as the film growth proceeds. In the random Co–Cr alloy, the Cr atoms are not distributed in the most suitable way for reducing the M_s of the alloy. Therefore, the maximum local content of Cr for this distribution is much higher than in the case where Cr–Cr bonds are not present. From measurements, M_s becomes 0 at about 25 at.% Cr. Consequently, 4 Cr NN (Nearest Neighbour) in a hcp lattice makes the final M_s zero.

The coercivity in a magnetic material is a very important parameter for applications but it is very difficult to understand its physical background. It may be varied from nearly zero to more than 2000 kA m^{−1} in a variety of materials. For thin-film recording media, values of more than 250 kA m^{−1} have been reported. The first point is that the coercivity is an extrinsic parameter and is strongly influenced by the microstructural properties of the layer, such as crystal size and

shape, composition and texture. These properties are directly related to the preparation conditions. Material choice and chemical inhomogeneities are responsible for the M_s of a material and this is also a parameter that influences the final H_c . If we only consider crystalline material, then the crystalline anisotropy field plays an important role. It is difficult to discriminate between all these parameters and to understand the coercivity origin in the different thin-film materials in detail.

2.4. Current research and the future

Disk manufacturers are using sputtering technologies for thin-film medium production. New substrate materials such as glass and ceramics now promise to replace aluminium. Substrate surfaces have to be prepared to create the right properties. Firstly, the surface roughness has to be controlled by texturing to roughen it in a controlled pattern. The final surface topology should then be smooth (small head/medium distance), but not too smooth in order to avoid stiction. An overcoat layer (carbon) has to be deposited. This layer has to be thin, hard, dense and as diamond-like as possible. Additionally, a thin fluorocarbon lubricant is applied to reduce disk friction.

In order to improve the disk media for future high densities ($> 10 \text{ Gbit in}^{-2}$), two approaches are proposed by Howard [22]; these are the evolutionary approach and the revolutionary approach. The first focused on gradual improvement of the hcp Co alloy media, discussed elsewhere in this paper. The revolutionary development of new media focuses on materials with higher anisotropies than the present hexagonal Co alloys. In the literature, sputtered BaF thin films, granular media and amorphous CoSm alloyed films on Cr underlayers are mentioned. The main reason for this is to provide more stable particles with smaller diameters. A few examples of both approaches will be given in more detail.

Quaternary Co-Cr-X-Y alloys have been proposed as suitable media for longitudinal high-density thin-film media. Underlayers (mostly Cr) are necessary for controlling the magnetic properties. Higher density in longitudinal recording requires thinner layers and smaller crystallites. A trend is that the layer thickness for hard disk applications must decrease to about 10–15 nm in order to obtain 10 Gbit in^{-2} density recording. The addition of Pt, Ta or Ni to Co-Cr in combination with a higher substrate temperature favours the enhancement of M_s and H_c .

Laminated media consist of several magnetic layers separated by a non-ferromagnetic interlayer [23–27]. The main aim of studying the laminated media structures for high-density recording is to improve the signal-to-noise ratio by reducing the medium noise. The linear density is determined by the macroscopic magnetic properties H_c and the remanence thickness product $M_r\delta$, while the medium noise is related to the individual grain structure and the exchange coupling between the grains.

Individual control of the parameters H_c and $M_r\delta$ in thin films was previously announced in 1979 by Maloney [28] proposing stacked Co-films. The increases in H_c and $M_r\delta$ in a 4-layer system consisting of a Cr underlayer (300 nm) / CoNiCr (35 nm) / Cr interlayer (12.5 nm) / CoNiCr (35 nm) have shown better read/write characteristics [29].

It has also been reported that the noise contribution in such a system can be reduced because the combined noise of the individual layers is lower than that of a thicker single layer [25]. The authors found that the total noise is the sum of the noise of the 2 individual layers plus a cross term. The key now is to design individual layers with low-noise behaviour. One of the advantages of the laminated technology is that the growth of the magnetic layer is interrupted at a very early stage; this provides a better opportunity to obtain uncoupled (exchange) crystals. This research is in progress using a variety of materials and deposition parameters. An important aspect is that the interlayer thickness should be thick enough to interrupt the exchange between the magnetic layers, but thin enough to retain magnetostatic coupling.

In comparison with common technologies, the manufacturing control of macromagnetic and micromagnetic properties will be more difficult during the laminated process [30].

The medium structure given in Fig. 2(a) has been modified to a more complicated one as given in Fig. 2(b). Promising media for high-density recording are multilayered structures consisting of a substrate (special glass, ceramics), seedlayer, underlayer, intermediate layer, first magnetic layer, interlayer(s), second magnetic layer, overlayer, overcoat and lubricant. Although more research has to be carried out, it is clear that the underlayer determines the orientation and grain-size of the first magnetic layer. At present, NiAl, MgO and GaAs are mentioned in the literature; these materials also improve the epitaxial growth of the Co-based magnetic layer. The interlayer materials between the 2 magnetic layers can be made of Al, Ag, Cr and Cu. The function is to change the texture of the second magnetic layer which influences the interaction between the grains and the noise performance.

Barium ferrite media ($\text{BaFe}_{12}\text{O}_{19}$) hcp particles have already been used as longitudinal media on tape, floppy and hard disk for a long time. The large anisotropy (the easy axis parallel to the hcp c-axis) is one of the main features, but, moreover, the magnetic decoupling of the particles plays an important role [31]. Ba ferrite thin films have already been prepared for the last 15 years. Preparation with the easy axis perpendicular, as well as in the longitudinal direction, has been reported. Relatively large H_c values and crystalline anisotropy have been mentioned. In the case of longitudinal recording experiments it was also announced that Ba ferrite thin films have shown mechanical hardness, chemical stability, good durability and corrosion resistance, but one of the largest problems was to control the grain size. Recently [32] it has been shown that an addition of Cr_2O_3 (0.1–1 vol.%) to $\text{BaFe}_{12}\text{O}_{19}$ and an annealing process can result in a reduction of the crystal size by a factor of 5–10 compared with pure Ba ferrite. In [33] similar effects have been published

about CoTi doping followed by an annealing process. Moreover, they also reported that with a multilayer structure consisting of pure Ba ferrite and CoTi-doped Ba ferrite, media with a variety of coercivities ($80\text{--}320\text{ kA m}^{-1}$) can be prepared without degradation of the other magnetic properties.

The most important point in this kind of research is to find a way to reduce the annealing temperature. This is, in fact, the question about how the crystallisation temperature of the Ba ferrite can be reduced and/or the grain growth restricted [22] to achieve the $8\text{--}10\text{ nm}$ decoupled grains needed for 10 Gbit in^{-2} .

Ultra-clean sputtering process: this was introduced by the group of Prof. M. Takahashi at the Tohoku University, Sendai, Japan [34]. Co–Cr–Ta films for LMR are sputtered at a pressure of less than 3×10^{-9} Torr, which is about 2 orders lower than in a standard production machine. The impurity level used in the process chamber is about 1 ppb (H_2O level), which is about 3 factors lower than the present systems. Ultra-clean sputtering has been applied for preparing Co–Ni–Cr and Co–Cr–Ta thin-film media for longitudinal recording. A typical thickness of the Co–Cr–Ta layer is 40 nm . The substrate material is NiP/Al together with an intermediate layer of Cr (50 nm).

Fig. 4 shows a plane-view TEM observation of such a layer having a $H_c = 188\text{ kA m}^{-1}$.

The crystal structure is almost perfect and another structure can be observed at the boundaries. It is suggested that Cr from the underlayer diffuses homogeneously into the grain bound-

ary by the presence of the clean top surface of the Cr underlayer metal during sputtering. In comparison with media fabricated by a standard process, anisotropy fields higher by a factor of 2 have been determined, which means that the intergranular coupling is smaller.

3. Metal evaporated tape

The incidence angle of the atomic flux plays an important role in the nucleation and growth process. Atoms arriving at an angle to the substrate usually show a different behaviour to those which approach perpendicularly. First of all, the shadowing effect plays an important role in the film formation. If there is no adatom (physically adsorbed atom), mobility and the sticking coefficient probability equal 1; an incoming atom is captured as soon as it touches the substrate or surface atom. Atoms already deposited and surface irregularities throw a shadow. No direct impingement is possible in these shadowed areas. When a non-zero adatom mobility occurs, which is normally the case due to the kinetic energy of the atoms and the substrate temperature, they can then move to energetically favourable positions, including the shadowed areas. Therefore, an increasing mobility will partly annul the shadowing effect. The degrees of shadowing and mobility are determined by the deposition conditions. The direction of the adatom movement is considered to have 2 contributors, namely the surface diffusion (responsible for the movement in all directions) and the angle-of-incidence effect which causes the atoms to have a momentum component parallel to the incidence plane [35]. This is true for the situation where the substrate is fixed in relation to the incoming flux. In [36] a study was made of the effect of the mobility of metal atoms on the structure of oblique-incidence films, and it introduced the mechanism of inhibited mobility. With this principle it is possible to give an explanation of the dependence of the preferred direction of growth of texture, angle of incidence, affinity of oxygen, substrate and source temperatures, melting point of the evaporated material and the background gas pressure. Most of the publications dealing with oblique-incidence magnetic films have been produced by the group of Japanese researchers; e.g. [37].

Besides columnar growth, there is another aspect of the morphology, namely columnar bundling [38]. Bundling is the growth of a column in the direction perpendicular to the evaporation plane. Bundling is also dependent on the incoming angle of the flux atoms (α_i), substrate temperature, deposition rate and gas pressure. The interest in obliquely-deposited films for magnetic-recording purposes is mainly created by the experimental results that enable the magnitude and direction of the magnetic anisotropy, the coercivity and a suitable squareness to be varied by modifying α_i . Recently, an overview paper has been published dealing with the oblique-incidence methods [39].

The coercivity is strongly influenced by the incoming angle of the deposited atoms — the better the columnar separation,

Fig. 4. TEM microstructure of an ultra-clean sputtered Co–Cr–Ta film (Courtesy of Dr. M. Kuwabara, Kobe Steel USA and Prof. Dr. M. Takahashi, Tohoku University, Sendai, Japan).

the larger the H_c , but the disadvantage of large angles is the very bad deposition-process efficiency.

There are 2 methods used to overcome the relatively low H_c , namely, using a Cr underlayer, and, deposition by varying the angle of incidence of the arriving metal atoms [40]. In order to produce the so-called ME (Metal Evaporated)-tape, modifications have been made to the oblique-incidence evaporation process in order to obtain a more efficient use of the evaporated material and a continuous evaporation over the total length of the substrate, i.e. hundreds of meters of tape have to be produced in 1 single run at a very high production speed. The most important modification is that the evaporation occurs over a range of angles, instead of 1 angle, whereby the incidence angle changes as the substrate passes along the vapour beam. This means that the direction of the elongated columns changes throughout the thickness of the tape. In [41] the properties of continuously varied incidence Co, Ni, Co–Ni and Fe tapes were investigated. Only at large angles of incidence was a suitable H_c obtained.

At such a high angle of incidence, however, the incoming vapour beam is almost parallel to the substrate and the deposition rate becomes very low; in addition, the packing fraction is strongly reduced.

Last, but not least, the corrosion resistance of this type of material is very poor. A partly oxidised medium is the solution; therefore, oxygen was added during deposition. The final composition of Co–Ni–O also gave the right magnetic medium properties. The H_c is strongly influenced by the O_2 value.

The morphology of the ME tape can be seen in Fig. 5. In the cross-sectional microstructure, prepared by ion milling, the so-called banana-shaped morphology is clearly visible. Due to the shadowing effect, the density of such a film is not very high and the micromagnetic behaviour is probably a mixture of domain-wall motion and rotation of the magnetisation. The structural analysis of the tape provides the following data. The thickness of the magnetic layer is about 130 nm and a regular structure composed of very fine fibres is observed (thickness 3–10 nm). The columns make an angle of 37° relative to the plane of the film. Auger Electron Spectroscopy has shown an average composition of $Co_{77}Ni_{10}O_{13}$ [42,43]. The substrate side seems to be less dense, which is to be expected from large shadowing at a high incidence angle. It is anticipated that the fibre-like structure consists of crystallites. A hcp Co phase and an Ni–O fcc phase were

found by X-ray diffraction. Moreover, an antiferromagnetic CoO phase was determined [44]. Consequently, the measured ME tape consists of structural and magnetic features over a variety of length scales depending on the material choice and deposition parameters.

The magnetic anisotropy of such a very complicated material has been analyzed [45] while a correlation between the anisotropy direction and the shape of the recording pulse has been discussed [43].

The films do not seem to be totally crystalline, but are partly amorphous, and several oxide and metallic phases have been observed. The oxygen addition leads to an increased oxide concentration at the top of the film which means more oxidation, but it also leads to a surface with a higher corrosion resistance. The oxidised state is important for the coupling between the fibres, columns and even within the fibres.

To study the relationship between the deposition angle, oxygen concentration and magnetic properties, as well as the recording performance, a mini roll coater was developed [44] and basic experiments were performed. Auger depth profiling showed that the Co/Ni ratio is constant over the total thickness of the film. The O_2 concentrations were enhanced at the top (30 nm) and the bottom (10 nm). With this setup we studied the relationship between the deposition rate, the magnetic properties and the structural features. We deposited 3 tapes with deposition rates of (a) 21, (b) 14, and (c) 7 nm s^{-1} . The magnetic easy axis was varied from (a) 23° to (c) 47° with respect to the film plane, and corrected for sheet demagnetisation. The columnar tilt angle relative to the substrate becomes larger for the stronger-oxidised films (in this case the one with the lowest deposition rate, sample (c)). This shows how the random surface diffusion is more strongly limited by the oxygen at low deposition rates, leading to columnar growths towards the normal as a result of the larger effect of the conserved momentum of the incoming atoms. The crystal size also varies with the deposition rate; it was 7 nm for the highest rate and 22 nm for the lowest rate.

At present, a lot of attention is given to oblique-deposited Co–O tapes [46,47]. These films have shown a hcp Co phase and CoO crystals of about 5 nm [46] which is the same size as the columnar diameter. The easy axis of magnetisation is about 30° from the normal to the film. The very small crystalline features and the relative sharp columnar structure [47] have shown sharp transitions at 100 kfrpi. In addition, very small magnetic irregularities were measured in these

Fig. 5. Cross-section of a CoNi(O) ME tape deposited in a commercial roll coater.

samples and these are the main reason for reducing medium noise.

The high linear bit densities and low noise are due to the magnetic microstructures available in ME tape. Smaller columns magnetically separated by CoO phases are very important for noise and sharp transitions. Moreover, the direction of the anisotropy, determined mainly by the shape of the columns, is very important. By comparison with in-plane media, the ME tapes discussed here all have an oblique anisotropy of about 30° out-of-plane.

Moreover, recently, multilayered structures were made in commercial Hi-8 mm tapes (Sony, TDK). These structures have shown different easy-axis directions due to the columnar orientation of the individual layers. In addition, the magnetic coupling between the layers is strongly influenced by the presence of oxygen at the interface.

4. Multilayers for magneto-optic recording

A schematic illustration of the principles of reading and writing data in MO (magneto-optical) recording is shown in Fig. 6.

Magneto-optical recording is a technique for information storage in which, just as in the case of magnetic recording, the data is stored in the form of small magnetic bits in a magnetic thin film. MO recording is a rewritable recording mode which means that the information can be written, read and then erased and used again. In contrast to magnetic recording, writing as well as reading takes place in an optical way. According to today's technology, reversed domains (areas with opposite magnetisation directions) are written in a magnetically saturated disk which rotates at 2000 rpm.

The domains (bits) are formed in the heated spot (diameter in the order of $0.5\text{--}1\text{ }\mu\text{m}$), addressed by a pulsed laser beam (wavelength = 800 nm, power = 10 mW, write pulse ≤ 100 ns) while a magnetic field (coil) is supplied; this field is lower than the room temperature coercive field (H_c) of the medium. The written information can be read back by detection of the rotation (Magneto-optic Kerr rotation θ_K) of the polarisation vector of the laser beam after reflection on the domain pattern with up and down magnetisation

directions. Before rewrite, the magnetisation in a track has to be reset in 1 direction; refer to Fig. 6.

The bit density is strongly dependent on the properties of the 'optical head' (spot size, wavelength and power) and the medium (reflectivity and Magneto-optic Kerr rotation). At present, 10^8 bits cm^{-2} can be stored. It is expected that the density will increase by a factor of 10 (to 10^9 bits cm^{-2}) by the year 2000. Nowadays, in commercial systems, the data-rate is $0.6\text{--}1.1$ MBytes s^{-1} and the average access time is 45 ms [48]. The present applications and the outlook ensure that MO recording is well qualified to compete with magnetic recording.

The bit density can be increased if the wavelength, λ , of the laser can be made smaller, because the diffraction-limited spot size is proportional to λ^2 . Consequently, the medium material should be changed because the current MO media (GdTb-FeCo alloy) are not suitable for recording at smaller wavelengths (blue laser recording).

The multilayer materials have better performance at smaller wavelength, lower costs and easier preparation than the current amorphous rare-earth-transition-metal alloys (RE-TM). The Co/Pt-type of multilayers are more resistant to oxidation and corrosion and have better performance at the shorter wavelengths that are required to further increase storage capacity. Furthermore, the CoNi/Pt-type has also shown lower Curie temperatures, independent of the method of deposition [49,50].

In the author's laboratory, multilayer structures were prepared in a UHV sputter machine. With this apparatus we prepared Co/Pd, Co/Pt and CoNi/Pt multilayers. All these materials have shown a strong perpendicular anisotropy, a rectangular hysteresis loop and an acceptable Curie temperature. Low signal-to-noise ratios were measured for CoNi/Pt layers having magnetic properties similar to Co/Pt multilayers, as prepared with the same evaporation unit.

The base pressure in the load lock is about 1×10^{-6} mbar and is reached within about 20 min. The sample can be transported from and to the process chamber by means of a UHV manipulator. The base pressure of this process chamber is now in the order of 1×10^{-9} mbar, but if suitable baking is installed a base pressure of 1×10^{-10} mbar should be within range. The substrate rests on a wafer carrier, which is put on a heatable, rotatable table. The table can be rotated by means of a stepper motor. The heating stage and the rotatable table can be adjusted in height with respect to the sputter guns, located at the top side of the process chamber. Three magnetron sputter guns are available.

During the deposition process, the guns are constantly active, and the table containing the sample is rotating between these 2 active guns. The thickness of the sublayers that compose the total multilayer are controlled by 2 pneumatically activated shutters. Typical sputter times for the sublayers are in the order of a few s. The whole system is computer controlled.

One of the disadvantages of Co/Pt multilayers is their relatively high Curie temperature (T_c) which is about 200°C

Fig. 6. Schematic representation of the MO read and write process [48].

Fig. 7. TEM picture of a CoNi/Pt multilayer structure.

higher than current commercially used RE–TM media ($T_c = 150^\circ\text{C}$). A lower T_c will increase the number of write/erase cycles that a disk can withstand before its recording performance is reduced. Also, the data rate will increase. In order to lower the T_c we studied CoNi/Pt multilayers made by evaporation [49] and sputtering [50].

The T_c is influenced by the magnetic layer thickness, the composition ($\text{Co}_x\text{Ni}_{1-x}$) and the non-magnetic layer thickness (P_t). A magnetic layer thickness series reveals perpendicular anisotropy up to 2 nm CoNi thickness. The multilayer composition was 23 nm P_t seedlayer + $17 \times (t \text{ nm CoNi}/1.5 \text{ nm } P_t)$ with t between 0.4 nm and 3.8 nm. The P_t seedlayer was deposited to improve the flatness and the orientation of the multilayer stack.

The microstructure of the multilayers is strongly influenced by the seedlayer thickness, the number of layers, sputter pressure etc. All films show a distinct multilayer structure. Fig. 7 shows a TEM cross-section observation of a CoNi/Pt multilayer.

As shown in Fig. 7, columnar structures from bottom to top are observed and in most of the layers curved structures can be seen. The columnar morphology and curvature become stronger with increasing thickness of the CoNi layer. One of the possible explanations is that the accumulation of the lattice strains, due to the lattice mismatch, can be relaxed mainly at the columnar boundaries for the samples with thicker CoNi layers. The measure of the curvature can be also influenced by bias sputtering which immediately refers to the nucleation and growth process of the multilayers. Both phenomena are not very well understood and have to be studied in more detail in this project. The relationship between these morphological features and the magnetostriction has to be determined. Also, interface roughness (a phenomenon which also influences the magnetic properties) has to be related to the anisotropy and the coercivity behaviour of the multilayer structure.

The magnetic microstructure was observed using Lorentz microscopy and Magnetic Force Microscopy (MFM). The observed domain width was found to be 60–80 nm. This is 3–4 times the columnar diameter of the multilayer obtained from TEM measurements [51].

By annealing CoNi/Pt multilayers we found that the structural and magnetic properties remained stable after annealing at 250°C for 2 h (this is approximately equal to the temperature needed for the writing process). A remarkable change is that H_c increases after 2 h annealing at 300°C while the magnetisation (M_s) and the effective perpendicular anisotropy (K_{eff}) decreased slightly. From 300°C to 400°C , M_s , H_c and K_{eff} decreased rapidly to zero [52].

5. Conclusions

Thin-film media thicknesses are becoming thinner and thinner and surface and interface properties are becoming more important. For hard disk media, the very small bit volumes will require extremely small grains and sufficient magnetic moment per bit. Very high densities also require extremely high coercivities which can only be obtained by optimising the crystal anisotropy and the magnetic decoupling of the grains. The second generation ME tape will be made by reactive deposition of Co in oxygen. Double-layered structures have been made to obtain better recording characteristics (lower noise) over a wider recording wavelength. Interlayer interactions are extremely important and are dependent on the deposition parameters. CoNi/Pt multilayers for blue laser recording have been prepared and optimised by seedlayer thickness and thickness of the magnetic and non-magnetic multilayer components. Even a multilayer thickness of 10 nm can be prepared with the right parameters for the Curie temperature, Kerr rotations and coercivity.

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