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THE CONTROL OF MICROSTRUCTURAL FEATURES OF THIN FILMS FOR MAGNETIC RECORDING

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Abstract

Extrinsic magnetic properties play a major role in determining the performance of magnetic thin films used as magnetic recording media. These extrinsic properties are the ones which are largely determined by the microstructure of the thin magnetic films. In this paper we discuss various ways that the crystallographic texture of thin films can be controlled. We begin with a discussion of the origin of crystallographic texture of underlayers. Next, the origin of crystallographic texture of magnetic thin films by means of epitaxy with the underlayer is discussed. The control of other microstructural features such as grain size and perfection by means of underlayers and interlayers is briefly introduced. Examples from recent research are included.

Introduction

In the field of Engineering, it is well known that the way a material is *produced* determines to a large extent the *performance* of the material. Engineers often change process variables in the hope that the resulting material will *perform* better. Materials Scientists and Engineers add another dimension to this approach by emphasizing that the *performance* of materials depends on their *microstructure* which in turn depends on the way in which the material was *produced*. This inter-relation among:

Processing
Microstructure
Performance

is the basic paradigm for Materials Science and Engineering. Properties of materials which depend on microstructure (and hence the method of processing) are known as *extrinsic* properties, while properties which are insensitive to microstructure are usually called *intrinsic* properties. By understanding the inter-relation among processing, microstructure and properties (and hence, performance), Materials Scientists or Materials Engineers can better develop high performance materials by understanding which microstructural features should be changed for improved performance. After this has been determined, the method of processing the materials can be chosen so as to produce the microstructure which yields the maximum improvement in the material's performance.

In this paper we review some of the ways by which important microstructural features of thin films can be controlled by processing variables. Of particular interest to us will be the control of the *crystallographic texture* of thin films used as magnetic longitudinal recording media. Other important microstructural features such as *grain size*, *film morphology, compositional inhomogeneity* and crystallographic *defects* will not be emphasized.

The process variables in the production of thin magnetic films by rf-sputtering include the temperature of the substrate, the sputtering power, the argon pressure, the amount of substrate bias as well as the possible use of underlayers, intermediate layers, interlayers and overlayers. All of these are important but can not be included in this review. In this paper we will emphasize the role that *underlayers* and *interlayers* play in the development of the crystallographic texture and grain size of thin magnetic films and only briefly discuss the role of the other process variables.

Development of Crystallographic Texture

In order to produce a thin film of a cobalt based alloy (*hcp*, $P6_3/mmc$) with its c axes in or near the plane of the film, an underlayer must be used (1-9). This is so because an *hcp* phase will usually *grow* with its c axis perpendicular to the film plane, unless it is forced to do otherwise during the initiation of its formation on the substrate. All crystalline materials have preferred *growth* directions when produced as thin films. These are invariably the directions perpendicular to the *closest packed planes* of the structure in question. Hence the planes parallel to the film usually will be the closest packed ones. For the *hcp* structure these are the basal (0001) planes. For the *bcc* structure (for example Cr, V) the closest packed planes are the {110}; hence the {110} planes tend to be in the plane of film with the bcc structure for growth controlled textures. Table 1 summarizes the growth textures for several common structures. It should be noted that it is the *structure* which determines the crystallographic growth texture, not the Bravais Lattice (10). For example the DO_3 structure (of Sendust, for example) has a growth texture of {110} even though it is based on the FCC Bravais

TABLE 1
Growth Textures of Selected Structures

Structure	Space Group	Thin Film Texture
bcc	$(Im\bar{3}m)$	{110}
fcc	$(Fm\bar{3}m)$	{111}
hcp	$\left(P\frac{6_3}{m}mc\right)$	{0001}
B2	$(Pm\bar{3}m)$	{110}
DO_3	$(Fm\bar{3}m)$	{110}
B1	$(Fm\bar{3}m)$	{100}
A4	$(Fd\bar{3}m)$	{110}
B3	$(F\bar{4}3m)$	{110}

Lattice. This is because the structure itself is based on the bcc structure, being a crystallographic derivative of it (11). Although a preferred crystallographic texture usually develops during the growth of films, other crystallographic textures can be obtained if the initiation stage of the thin film formation is controlled. Two ways of doing this will be discussed in this paper.

Most Co-based alloy thin films used for magnetic recording are deposited on underlayers. The crystallographic texture of the Cr underlayer controls the subsequent crystallographic texture of the Co-based alloy. We first discuss the formation of the underlayer crystallographic texture, followed by a discussion on the development of the crystallographic texture of the magnetic film.

The Underlayer Crystallographic Texture

Most of the underlayers that are currently used in the manufacture of thin films for magnetic recording are Cr thin films. Cr thin films deposited at room temperature tend to develop the {110} crystallographic texture. As discussed above, this crystallographic texture forms during the growth of the film. Underlayers with this crystallographic texture will produce Co-alloy thin films with their c-axis near the plane of the film.(9,12) See below.

However, by carefully controlling the processing variables, Cr films with a {200} in plane crystallographic texture can be produced. This change in crystallographic texture has been explained by Feng *et al.* (13) in terms of a model which emphasizes the role of surface and interface energies during the nucleation stage of the Cr thin films. They have shown that if the relative values of the substrate surface energy (S2), Cr/substrate interfacial energy (S12) and Cr surface energy (S1) are such that the nuclei tend not to wet the substrate surface, the nuclei will form with their {002} planes parallel to the film plane (See Figure 1B). If, however, the relative surface and interfacial energy values produce nuclei that promote the wetting of the substrate, the Cr films will tend to have the {110} in plane crystallographic texture (Figure 1A). This model assumes that the closest packed {110} planes of Cr have lower surface energies than the {200} planes. Thus, when the nuclei of Cr first form they will tend to maximize the amount of {110} surface area. This model also explains the recent observation of Cheong *et al.* (14) that fcc thin films of Co alloys formed at elevated temperatures have {200} in plane crystallographic textures rather than the expected {111} crystallographic texture which is the one that formed during growth.

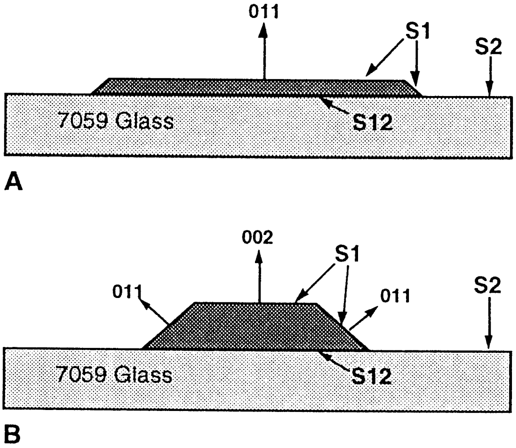

Figure 1. Schematic of the formation of nuclei of Cr with relative surface and interfacial energies that produce (A) wetting, (B) non-wetting nuclei. Case B will produce the (002) Cr crystallographic texture in order to minimize the Cr surface energy.

Hence, the mechanisms involved in the control of the crystallographic texture of the Cr underlayer depends on both the energetics and kinetics of the film formation.

Co-alloy Magnetic Thin Film Crystallographic Texture

The most common way by which the initial crystallographic texture of the magnetic film is controlled is by epitaxy with its underlayer. For epitaxy to arise between a magnetic film and its underlayer one or two directions in the film must have good atomic matching with directions or planes of the underlayer. When this occurs, specific planes of atoms in the film orient themselves with respect to specific underlayer planes. Thus, if the underlayer has a crystallographic texture, the magnetic film will start off with a crystallographic texture that is controlled by the crystallographic texture of the underlayer.

Co Alloys / Chromium Underlayers. Table 2 summarizes some of the observed crystallographic relationships between Co-alloy films and their Cr underlayers. These have all been observed by means of electron microdiffraction (15).

Each of these crystallographic relationships can be understood in terms of epitaxy. Figures 2-4 show various atomic arrangements of Co planes and Cr planes as well as depicting how closely the planes match. In Figure 2 the epitaxial relationship that is commonly observed in films produced on substrates at room temperature is displayed. In this case the c axis of the hexagonal Co alloy is out of the plane by about 29°. The Co alloy has the $(10\bar{1}1)$ crystallographic texture. Figure 3 displays the epitaxial relationship that is usually observed when the Co-alloy and Cr underlayer are deposited on heated substrates, yielding the $(11\bar{2}0)$ crystallographic texture of the Co alloy. In this case the c axis of the Co alloy lies in the plane of the film. Figure 4 displays another epitaxial relationship that places the c axis entirely in the plane of the film. This yields a $(10\bar{1}0)$ Co alloy texture. It can be seen that each of the orientation relationships in Figures 2-4 have a good match with respect to atomic dimensions and also with respect to the areal density of atoms above and below the interface. The importance of both of these features is demonstrated by Figure 5, in which a very good dimensional match between the $(10\bar{1}0)$ planes of a Co alloy is seen to exist with the (110) planes of Cr. However, since the Cr (110) plane has twice the number of atoms in it as the Co$(10\bar{1}0)$, the interfacial energy will be large and this epitaxial relationship is not favored.

Co Alloys / Other Underlayers. If other underlayers are to be used to control the crystallographic texture of the Co layer film, they must have some interplanar spacings that are similar to those of Co alloys. Let us focus on the important spacings of the (0001) planes of Co alloys. These have a spacing of c in the Co alloys, where c is the lattice parameter of the hexagonal cell along the six fold axis. For the Co alloys used in magnetic re-

TABLE 2
Crystallographic Relations of Co Grains with their Underlying Cr Grains

$(10\bar{1}1)$Co	//	(110)Cr
$(11\bar{2}0)$Co	//	(002)Cr
$(10\bar{1}0)$Co	//	(112)Cr
$(10\bar{1}0)$Co	//	(113)Cr
$(11\bar{2}0)$Co	//	(111)Cr

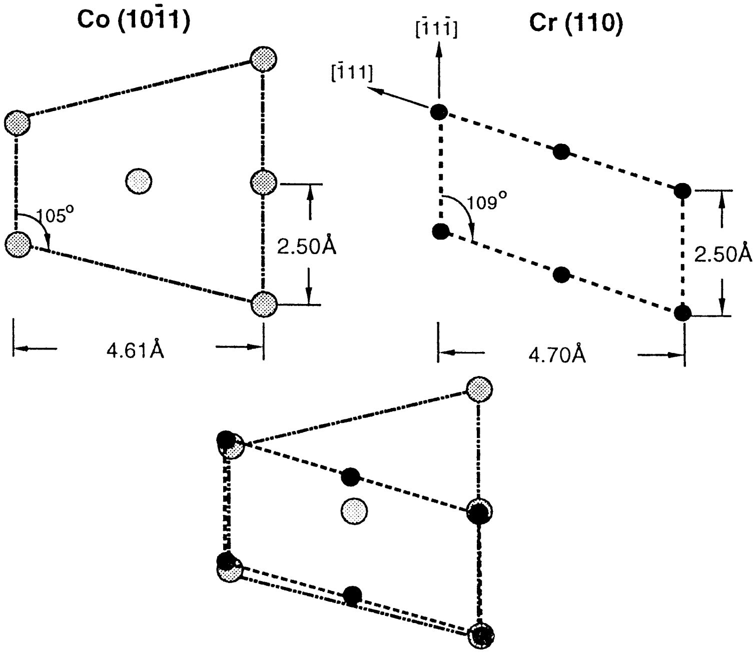

Figure 2. Schematic of the atomic positions for the (10$\bar{1}$0) planes of an hcp Co-alloy and the (110) planes of bcc Cr.

cording c is approximately 4.06Å. As can be seen from Figures 3 and 4, this distance is quite close to the value 4.08Å, which is twice the {110} interplanar spacing of Cr. This is the basic reason that the c axis of Co can be made to lie in the plane of the film for Cr underlayers with {002} or {112} crystallographic textures.

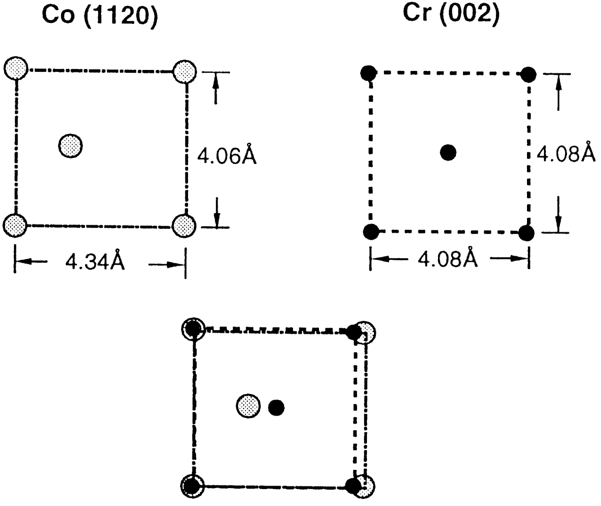

Figure 3. Schematic of the atomic positions of the (11$\bar{2}$0) planes of an hcp Co-alloy and the (002) planes of bcc Cr.

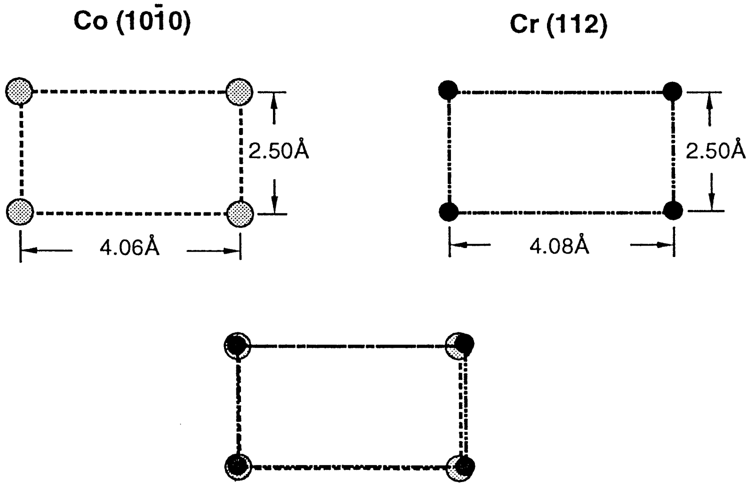

Figure 4. Schematic of the atomic positions for the (10$\bar{1}$0) planes of an hcp Co-alloy and the (112) planes of bcc Cr.

What other materials have spacings of planes approximately 4.06Å? The first one to be discussed is NiAl. NiAl is an intermetallic alloy with the B2 structure, shown in Figure 6. It can be seen that its structure is closely related to the *bcc* structure, being a crystallographic derivative of it. Its lattice parameter is nearly identical to that of Cr, so we would expect similar orientation relationships between it and Co based alloy thin films. Lee *et al.* (16) have presented results on the use of NiAl as underlayers.

Several other materials also have planes with approximately 4.06Å spacing, two of which are MgO and GaAs. MgO has the cubic B1 structure (NaCl) with lattice parameter of 4.21Å. Hence its {200} planes have nearly the desired spacing. GaAs has the cubic B4 structure (Zinc-Blende) with a lattice parameter of 5.65Å. Its {110} planes have a 3.995Å spacing. See Figure 7. These materials could be used as underlayers for Co

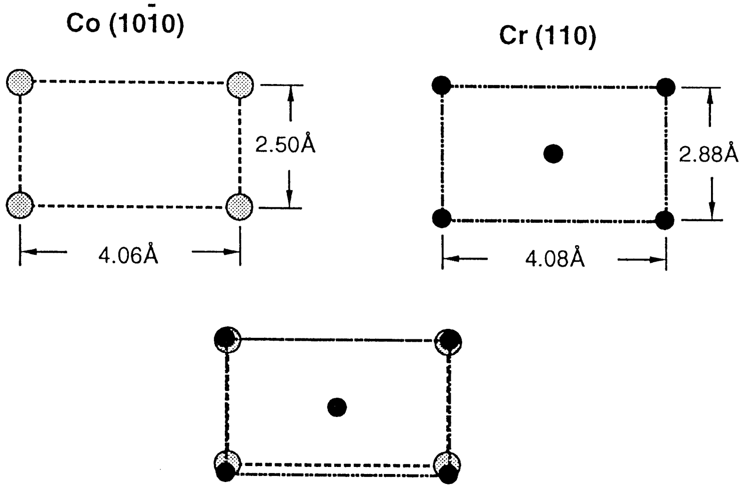

Figure 5. Schematic of the atomic positions for the (10$\bar{1}$0) planes of an hcp Co-alloy and the (110) planes of bcc Cr. Note the extra Cr atom.

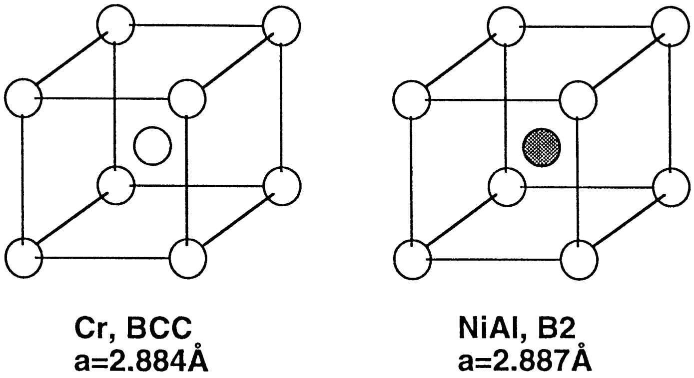

Figure 6. Unit cells of the crystal structures for Cr (A2, bcc) and NiAl (B2).

alloy films. In fact, since both of them are available in single crystal form they have been used to produce so-called bi-crystals of Co films that have two mutually perpendicular variants (17, 18).

Cheong *et al.* (19) have sputter deposited MgO thin films followed by deposition of Cr to obtain highly textured {200} Cr film. When a Co alloy is subsequently sputtered, a film with strong $\{11\bar{2}0\}$ crystallographic texture results. See Figure 8.

In addition to controlling (and enhancing) the crystallographic texture of the magnetic Co thin films, these other underlayer materials may give rise to other microstructural features which affect the Co alloy films. For example, Lee *et al.* (16) have shown that sputter deposited NiAl has a grain size that is nearly 50% smaller than sputter deposited Cr. This will give rise to Co films with smaller grain size, which should yield better signal to noise ratios in their recording performance.

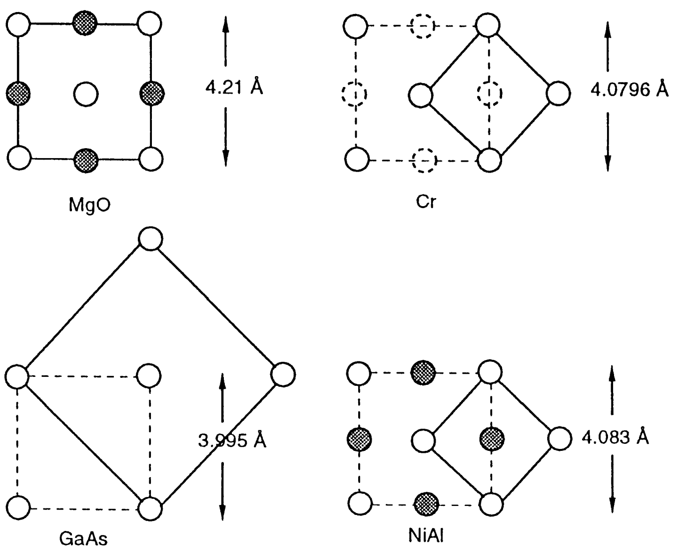

Figure 7. Projections of atomic positions on {100} planes of MgO, Cr, GaAs and NiAl.

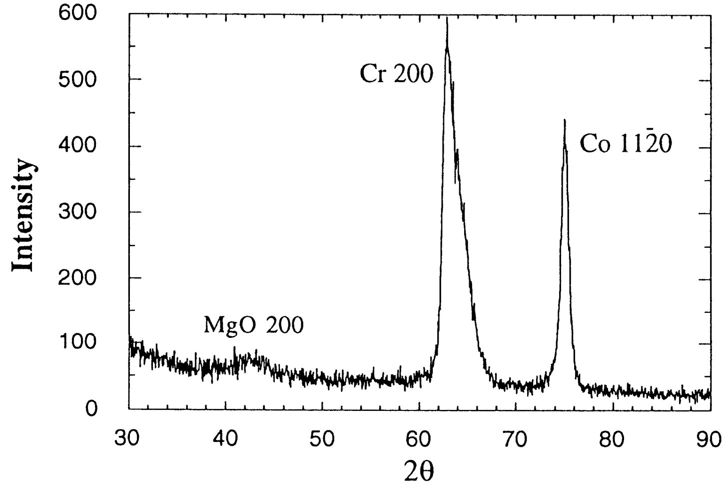

Figure 8. X-ray diffraction pattern of CoCrTa film on Cr intermediate deposited on a thin sputter deposited layer of MgO at room temperature.

Interlayers

Another configuration of magnetic thin films for recording is shown schematically in Figure 9. Here, an interlayer of a non-magnetic material is deposited between two magnetic layers. Feng *et al.* (20) have used a variety of interlayers. The interlayer may form epitaxially on the first magnetic layer. If this happens and if the second magnetic layer forms epitaxially on the interlayer, the two magnetic layers will have similar crystallographic texture. Wong and Laughlin (21) have shown that by using a Cr interlayer the grains in the two magnetic layers grow in a columnar fashion. In Figure 10 both bright field and dark field cross-section images of a CoNiCr/Cr/CoNiCr/Cr film are displayed. The dark field was imaged from a reflection that was common to both the Cr and the CoNiCr films because of epitaxy. The continuous nature of the image shows that the

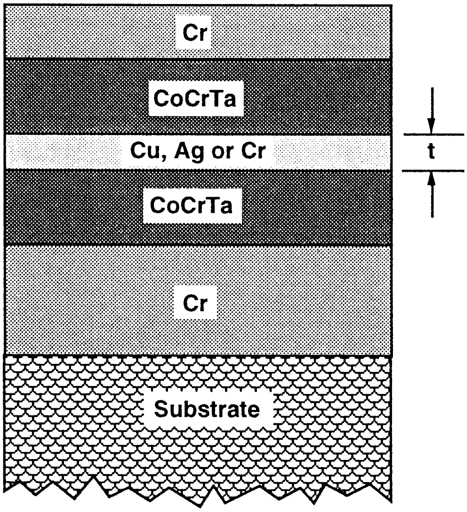

Figure 9. Schematic of thin film configuration using an interlayer (20).

Figure 10. Cross-sectional TEM image of a CoNiCr/Cr multilayer thin film. (a) Bright Field, (b) Dark Field.

top CoNiCr film has the same crystallographic orientation as the lower one. However, in this case the interlayer does "break up" the magnetic films in the sense that a smaller effective grain size of the magnetic material exists in the vertical direction. Using interlayers that do not form epitaxially on the first magnetic layer introduces the possibility that the second magnetic layer will be of different crystallographic texture than the first. Feng *et al.* (20) are currently studying this possibility.

The Control of Other Microstructural Features

The crystallographic texture is not the only feature of the Co-alloy film which can be controlled by underlayers and/or interlayers. Features such as grain size and grain perfection can also be controlled by manipulating the microstructure of the underlayer by processing techniques such as applying a bias during sputtering. The key to understanding this control of microstructure is the observation that many microstructural features of the magnetic Co-alloy films are often "passed on" to them from the underlayer (or interlayer) by means of epitaxy.

For example, Figure 11 is a schematic of a single grain of Cr with its (002) plane being the plane of the film. It is possible for the Co alloy that is deposited on top of it to form two distinct orientations with respect to this grain (see Wong *et al.* (22)). Since the (002) plane of Cr has four fold symmetry, the (0002) planes of the Co alloy may form parallel to either of the mutually perpendicular (110) and $(1\bar{1}0)$ Cr planes. This degeneracy will occur if the rate of formation of the Co nuclei is fast enough to form several nuclei before the lateral growth covers the Cr grain. Faster sputtering rates favor this situation. Thus for every grain of Cr there may be several grains of the Co film as depicted schematically in Figure 11, and shown in Figure 12. Here the large Cr grain has many (110) oriented CoNiCr grains on it.

If a Cr interlayer is sputtered on top of the Co alloy film its grain size will be approximately the same as that of the Co film. This occurs since the (002) plane of Cr has a higher symmetry than the $(11\bar{2}0)$ plane of the hcp Co phase, and no degeneracy is possible. However when the second Co alloy layer is sputtered on the

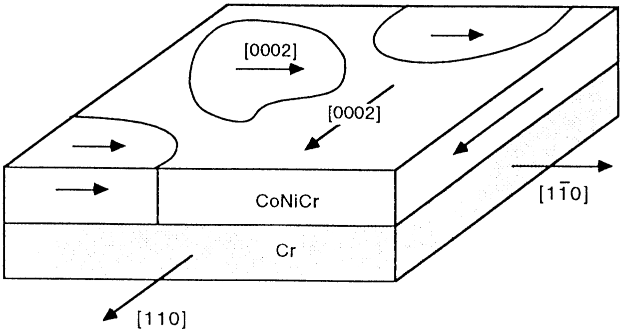

Figure 11. Schematic showing how two variants of a Co alloy can form on a single grain of Cr. The Cr has a [001] normal.

Cr interlayer its grain size may be reduced for the same reaons the initial Co film's grain size is smaller than the Cr underlayer. Thus, the magnetic film formed with an interlayer may have two different grain sizes, which will be of importance in determining its recording performance.

Another microstructural feature that can be controlled is the perfection of the grains. Figures 13a and 13b show atomic resolution transmission electron micrographs of two Cr films which were produced with and without an applied substrate bias during deposition. The film formed with an applied bias (Figure 13a) shows a higher degree of crystal perfection compared to the one formed without bias (Figure 13b). The grain size of the films is similar. However, the film formed without bias has much more substructure within the grains. This substructure consists of a large number of subgrains which are regions within a grain that are slightly misoriented with respect to each other. When the Co alloy is deposited on these underlayers the substructure will be replicated to a degree causing differing amounts of perfection to exist within the Co alloy grains. This will affect the magnetic properties of the Co alloy film.

Finally, the use of underlayers and interlayers affect the properties of the Co alloy films by means of interdiffusion. Feng *et al.* (23) have studied the effects of various sputtering conditions on the magnetic properties of pure Co films sputtered on Cr underlayers. After deposition, the films were annealed for various times at increasing temperatures. The resulting changes in the magnetization, coercivity and squareness ratio of the films were interpreted in terms of the diffusion of Cr atoms into the magnetic Co films along the grain boundaries. This not only changed the composition of the magnetic film (and hence its "intrinsic" properties) but

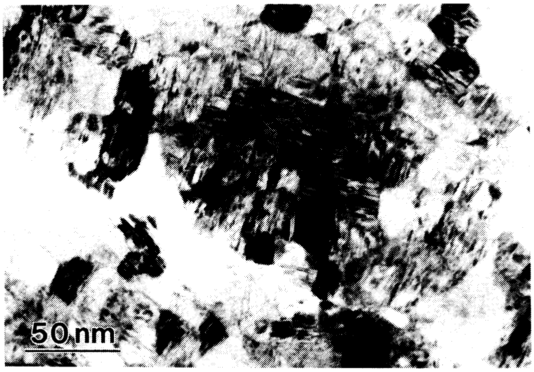

Figure 12. Plane view of several perpendicular variants of CoCrTa on Cr underlayer.

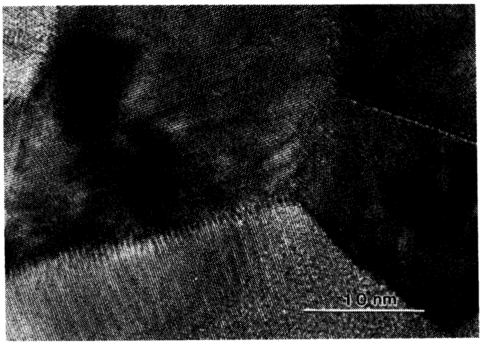

Figure 13a. High resolution TEM plane view of Cr thin film deposited with bias.

also increased the magnetic grain isolation, causing changes in extrinsic properties like coercivity and squareness ratio. Thus changing the composition of the films by interdiffusion also affects the overall recording performance of magnetic films.

Summary

We have discussed some of the mechanisms involved in controlling the crystallographic texture of thin films. If the film's crystallographic texture is developed during the growth stage, the film will usually exhibit a crystallographic texture in which the closest packed planes of the structure are in the plane of the film. If, however, the initiation process controls the crystallographic texture of the film, other crystallographic textures can be obtained. This may be due to epitaxy with an underlying film, or it may be due to the relative values of the surface and interfacial energies of the film and substrate. Other microstructural features such as grain size, grain perfection and even composition can also be controlled by a careful manipulation of the processing variables. In conjunction with the use of underlayers and interlayers this allows for the production of magnetic films with a variety of microstructures and hence with various extrinsic magnetic properties.

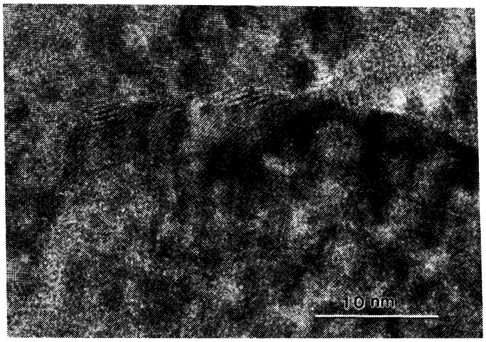

Figure 13b. High resolution TEM plane view of Cr thin film deposited without bias.

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