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Structure and Magnetic Anisotropy of Amorphous Gd-Co Films

Abstract: It is found that the structure of amorphous Gd-Co films, as revealed by x-ray diffraction, is correlated with the magnitude of bias voltage present during the sputter deposition. Films sputter deposited with zero bias voltage typically show one broad peak in an x-ray diffraction spectrum, and films sputter deposited with −100 volts bias show two broad peaks with a shoulder between them. These structural differences appear to be related to the perpendicular magnetic anisotropy in these films.

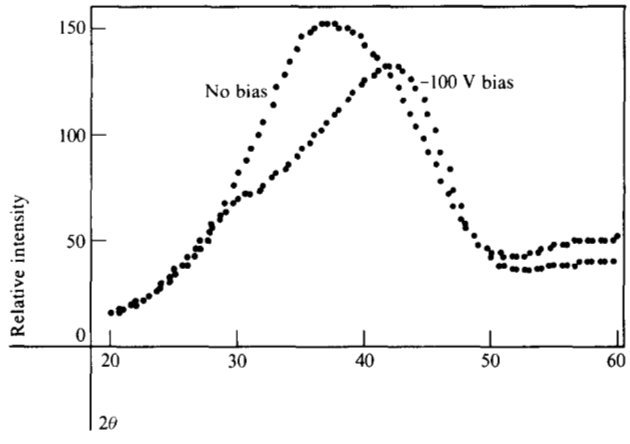
Introduction

The existence of stable magnetic bubble domains in thin films depends on the presence of uniaxial anisotropy, the easy axis of magnetization being perpendicular to the film plane. It was found by Chaudhari et al. [1] that amorphous Gd-Co films prepared by sputter deposition, with bias applied to the substrates, possess such an anisotropy. Sputter deposited Gd-Co prepared under the same conditions, but with no bias voltage applied to the substrate, was not observed to have any significant perpendicular magnetic anisotropy. Subsequently, Heiman and co-workers [2–4] reported the existence of perpendicular magnetic anisotropy in a number of other rare earth-transition metal alloys prepared by thermal evaporation. The exception to the general behavior appeared to be Gd-Co, for which no easy axis of magnetization perpendicular to the film plane was observed when prepared by thermal evaporation [5].

The origin of the magnetic anisotropy in amorphous Gd-Co has been of fundamental interest from the beginning. Chaudhari et al. [1] considered magnetocrystalline, stress induced, pair-ordering, and shape origins for the anisotropy. Magnetocrystalline anisotropy was ruled out [1] because of an upper limit of 15 Å in the extent of atomic ordering [6]; stress was ruled out because the anisotropy appears to be independent of substrate and is observed unaltered in free-standing films [1]. Gambino et al. [7] later suggested, on the basis of radiation damage and magnetic annealing experiments, that the atomic-pair-ordering mechanism was the most likely mechanism for the anisotropy. Shape anisotropy cannot be the predominant source of the observed magnetic anisotropy because its theoretical upper limit is $K_u = 2\pi M_s^2$, whereas typically observed anisotropies in amorphous Gd-Co are several times greater. However, it is difficult to rule out shape anisotropy entirely because it is such a frequently occurring phenomenon both theoretically [8] and experimentally [9].

The focus of the study reported here is to investigate by x-ray diffraction the structural differences between magnetically isotropic and anisotropic films. We utilize the dependence of magnetic anisotropy on substrate bias in sputter-deposited amorphous Gd-Co and find that a substantial difference exists in the x-ray diffraction of Gd-Co films sputter deposited with and without a sub-

Figure 1 The x-ray diffraction by amorphous $GdCo_3$, taken with $Cu_{K\alpha}$ radiation, shows the diffraction patterns for material sputter deposited with and without substrate bias.



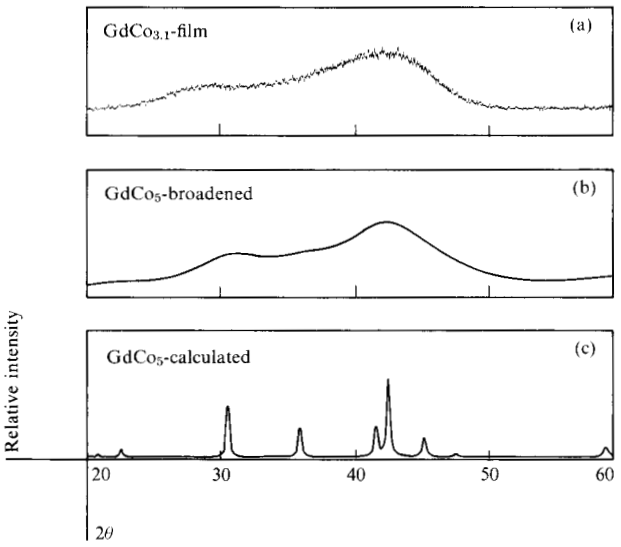


Figure 2 Comparison of the x-ray diffraction (a) for −100 V bias sputtered $GdCo_{3.1}$ with (b) the calculated diffraction pattern based on $GdCo_5$ having an 11 Å structural coherence length, and with (c) the calculated $GdCo_5$ powder pattern.

strate bias voltage. Since the structural differences correlate with the degree of magnetic anisotropy, they may be directly related.

Experimental results

Films of Gd-Co were rf sputter deposited in an argon pressure of 25μm with bias voltages from 0 to −100 volts. Film thickness ranged from 1000 Å to several μm. The substrates were fused silica and the films were not overcoated. Film compositions in the range $GdCo_2$ to $GdCo_{4.7}$ were made using targets of several compositions.

The results of x-ray diffractometer measurements taken in reflection with $Cu_{K\alpha}$ radiation are shown in Fig. 1. Because the absorption coefficient for $Cu_{K\alpha}$ radiation for films in this composition range is several μm, only the thicker films were used for x-ray analysis. As Fig. 1 shows, a film prepared with no bias voltage shows one peak in x-ray diffraction, and a film prepared with −100 V bias from the same target exhibits a double peaked x-ray diffraction band.

It is well known [10] that substrate bias during sputter deposition can cause compositional changes in the film. However, compositional changes alone cannot account for the observed changes in x-ray diffraction because essentially the same differences are observed between films sputtered with bias and with no bias over the entire composition range used in this study. For all compositions, the zero bias sample thus exhibits a single broad peak centered at within a few degrees of 37° in 2θ, while the bias sputtered sample invariably has a maximum at or slightly below 45° and there is a distinct secondary peak or shoulder at 30°.

Another known effect of substrate bias is to cause the incorporation of Ar into the Gd-Co film. In our films the Ar content varies from < 1 at.% for zero bias to > 7 at. % for −100 V bias, as determined by electron microprobe. The nature of the structural incorporation of Ar is not known, but a simple consideration of the relative x-ray scattering efficiencies of Gd, Co, and Ar indicates that the x-ray diffraction differences in Fig. 1 cannot be due to Ar scattering but must instead reflect structural differences in the Gd and Co atomic arrangements [11].

Discussion

Figure 2 shows a comparison of three diffraction patterns. Figure 2(a) is the experimental diffraction pattern for the film of Fig. 1, which was prepared with a substrate bias of −100 V. Figure 2(c) is a calculated diffraction pattern for polycrystalline $GdCo_5$ with large crystallite size and random crystallite orientations. Figure 2(b) was obtained by simply increasing the line width of the pattern in Fig. 2(c) until it began to resemble the experimental pattern. The line width shown in Fig. 2(b) corresponds to a crystallite size of 11 Å as calculated from the Scherrer formula. This value is smaller than the experimental upper limit for the crystallite size mentioned above.

$GdCo_5$ was chosen for this atomic model because it has the smallest unit cell of the Co-rich phases of Gd-Co. For example, the unit cell of $GdCo_3$ is much larger than the 11 Å coherence length. Another reason is that, with some variations, it can be considered a basic building block for most of the Co-rich phases (i.e., Gd_2Co_7, $GdCo_3$, etc.; cf. Ref. 12). Because of the building block nature of the $GdCo_5$ unit cell, many of the elementary intense x-ray diffraction lines of $GdCo_5$ occur also with the other phases at nearly the same value of 2θ. Thus the significance of the relatively good agreement in Fig. 2 is that a simple model of short-range structural order can give promising agreement with experiment for the Gd-Co system. It must be pointed out, however, that it is generally not possible to prove that a particular atomic model is unique. No such microcrystalline model for the zero-bias x-ray diffraction was been found, possibly because of a higher degree of structural randomness on an atomic scale.

Whether or not x-ray patterns such as shown in Fig. 1 represent truly amorphous structure, i.e., structure with random atom positions, or crystalline structure with very small crystallite size, is a long standing problem. Electron diffraction results have shown that if the Gd-Co films are microcrystalline, the crystallite size must be

less than 15 Å [4,6] (consistent with 11 Å of Fig. 2c). For crystallite sizes below this value, the problem is still unresolved.

In addition to short range order, there must be also a preferred direction to this order, according to this model, if there is to be uniaxial magnetic anisotropy. This preferred direction may be growth induced, i.e., it occurs during film formation, as does preferred orientation during the growth of crystalline film. Evidence for such a growth-induced preferred direction has been found by Heiman et al. [3] in experiments on thermally evaporated "amorphous" Ho-Co films evaporated at various angles of incidence, in which it was found that the axis of magnetic anisotropy always pointed in the direction of the incident vapor beam. Heiman and Lee [13] have also reported Mössbauer spectroscopy results on amorphous rare earth-iron films possessing uniaxial anisotropy. Their spectra show an electric field gradient similar in magnitude to that of the crystalline alloys but with a definite preferred orientation that is symmetric about the incident beam direction.

In summary, then, differences in x-ray diffraction patterns by amorphous Gd-Co films with and without magnetic anisotropy have been found in this study. On the basis of these data we suggest that the effect of substrate bias during sputter deposition is to produce a short range atomic arrangement that is more highly ordered. Such short range order is consistent with the similarities of the diffraction patterns for bias sputtered GdCo and the broadened $GdCo_5$ model illustrated in Fig. 2, and may be responsible for the uniaxial magnetic anisotropy in those films through the growth-induced anisotropy mechanism.

References and notes

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