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Amorphous GdCoCr Films for Bubble Domain Applications

Abstract: Amorphous GdCoCr films of various composition ratios made by rf bias sputtering are investigated for their applicability as bubble domain supporting materials. Film compositions around $Gd_{0.13}Co_{0.65}Cr_{0.22}$ have temperature-insensitive magnetizations between 240 K and 350 K with $T_{comp} \approx 120$ K and $T_c \approx 630$ K. Reduction of the Cr content from 21.8 to 20.3 at. percent causes an increase of the magnetization by a factor of three. Thermal cycling of these films between 290 K and 570 K does not change the magnetization noticeably, nor does annealing for up to six days at 520 K.

The films are found to be very susceptible to contamination by the residual oxygen present in the vacuum chamber during sputtering. Films contaminated with 3 to 13 at. percent oxygen have coercivities around 800 A/m (10 Oe), whereas films which were oxygen-free according to microprobe investigations show coercivities less than 80 A/m (1 Oe).

Introduction

Amorphous GdCo films suitable for bubble domain applications [1] can be made with an easy magnetic direction perpendicular to the film plane and low saturation magnetization. The rare earth and the transition metal spins couple antiferromagnetically [2]. The necessary low saturation magnetization for bubble domain applications is achieved by adjusting the film composition such that the compensation point is either slightly above or slightly below the operating temperature range. This brings about large variations in magnetic properties with temperature in the operating range. Substitution of Co by a nonmagnetic species offers the possibility of tailoring a less temperature-sensitive film composition. Molybdenum as the nonmagnetic component has been investigated [3]. The dependence of the magnetization, the compensation temperature and the Curie point on the Mo content was found to be very large; e.g., 20% Mo addition lowers the Curie temperature to 35 K [4]. Previous experiments [5] gave indications that GdCoCr could be an attractive alternative to GdCoMo with a less pronounced reduction of the Curie temperature for increasing Cr content.

Some properties of the GdCoCr system are reported in this note.

Experimental methods

The GdCoCr films were made by rf bias sputtering analogous to the technique described in [1] for the GdCo film preparation. The ternary targets were made by arc melting the mixture of the single constituents onto a Mo backing plate. The target diameter was either 51 mm or 127 mm. The Co/Gd ratio of the films could be adjusted by varying the bias voltage as already described for pure GdCo films in [1].

The Co/Cr ratio, however, turned out to be constant within the bias voltage range that was suited to adjust the Co/Gd ratio. This indicates that the resputtering yields of Co and Cr are approximately equal in the bias voltage range suitable to adjust the Co/Gd ratio, whereas the resputtering yields of Co and Gd differ sufficiently to allow the observed variation of the Co/Gd ratio for different bias voltages. Various Cr contents in the films could be obtained only by varying the Cr content of the target.

The composition of the GdCoCr films was determined by microprobe analyses with typical accuracy of five percent and precision of two percent at 95 percent confidence level. A vibrating sample magnetometer was used to determine the magnetic properties. It could be equipped with a liquid helium dewar to span the temperature range between 4.2 K and 350 K. Also, an oven attachment to the magnetometer could be used, within which the samples could be heated in an air or He atmosphere up to 1050 K. H_c measurements were also done with a magneto-optic Kerr effect hysteresisgraph.

Experimental results

In Fig. 1 the transition and the compensation lines at room temperature are plotted for the GdCoCr system. Below the transition line the film compositions are ferrimagnetic. Above the transition line they are paramagnetic. For ferrimagnetic compositions at the left of the

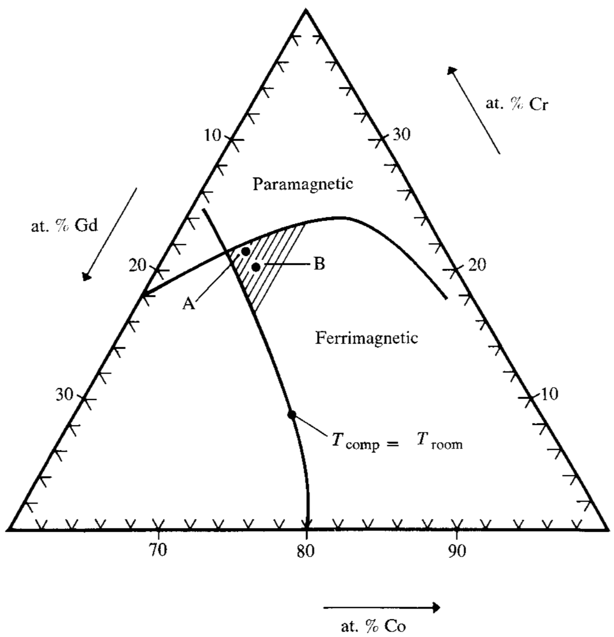

Figure 1 Composition diagram showing compensation line and magnetic transition line at room temperature for amorphous GdCoCr films. Compositions A and B are referred to in the text.

compensation line the compensation temperature T_{comp} is above room temperature. For compositions to the right of the compensation line T_{comp} is below room temperature; in this Co-dominated region, decreasing Gd content causes decreasing compensation temperatures.

For increasing Co/Gd ratios, the transition line moves toward higher Cr content, until at an approximate composition of $Gd_{0.06}Co_{0.70}Cr_{0.24}$ the transition line bends over, and for further increasing Co/Gd ratios, moves towards lower Cr content. This indicates that Cr not only has a diluting effect on the Co sublattice but also takes part in the magnetic coupling mechanism. As the transition line is approached from the GdCo side the anisotropy favoring that magnetization which is perpendicular to the film plane decreases. Also the anisotropy decreases for decreasing Gd/Co ratios in Co-rich films. For Co-dominated films with less than about 2 to 3 at. percent Gd, no perpendicular magnetization was found.

Films having temperature-insensitive, low-saturation magnetizations in a temperature range around room temperature can be expected to exist in the Co-dominated ferrimagnetic region of the phase diagram of Fig. 1. Their compensation temperature T_{comp} must be low enough and their Curie temperature T_c considerably higher than room temperature, such that the saturation magnetization has its maximum between T_{comp} and T_c around room temperature and stays essentially constant over the operating temperature range of about 50 to 100 degrees K. For bubble applications the maximum saturation magnetization $4\pi M_s$ should be around or less than 0.1 tesla (1000 gauss).

We find that film compositions close to the corner in the shaded area of the phase diagram meet these requirements. They resemble a balance between the demands for a large temperature range between T_{comp} and T_c centered around room temperature (requiring a sufficiently large deviation of the film composition from transition and compensation line), a low saturation magnetization (requiring a high Cr content), and a high perpendicular magnetic anisotropy (requiring a high Gd/Co ratio).

The M_s vs T curves for compositions A and B are shown in Fig. 2. Film A shows $4\pi M_s \approx 0.1100$ tesla at room temperature. The value of $4\pi M_s$ is constant within 3.5 percent between 240 K and 350 K. The Curie temperature has been extrapolated to be about 630 K; the compensation temperature lies at 120 K.

Composition B has essentially the same Gd content, but 1.5 at. percent less Co has been replaced by Cr. Here the saturation magnetization is constant over a much wider temperature range. This is due to the wider temperature range between T_{comp} and T_c. The $4\pi M_s$, however, is too high for bubble domain applications.

As mentioned previously, the Cr content of the films cannot be varied by bias voltage variations during the sputtering process, but can be adjusted only by a change in the target composition. The very high dependence of the saturation magnetization of GdCoCr films on the Cr/Co ratio, as found for compositions A and B, demands extremely narrow tolerances on the composition of various targets to be used for fabrication of films with similar magnetic properties.

GdCoCr films are found to be very susceptible to oxygen contamination. Films made at about 2×10^{-2} Torr Ar pressure in a sputtering system which had been evacuated into the 10^{-6} Torr range, prior to the Ar pressure adjustment, held typically 3 to 13 at. percent oxygen as detected by microprobe analysis.

The accuracy and precision of the microprobe analysis for oxygen contamination detection was 50% for 3 at.% O and 10% for 13 at.% O. Only films made at background pressures in the 10^{-8} Torr range were essentially free of oxygen. The coercivity of the oxygen contaminated films ranged around 800 A/m (10 Oersteds), whereas for oxygen-free films H_c of less than 80 A/m (1 Oe) has been determined by Kerr effect measurements.

The quality factor $Q = Ku/(2\pi M_s^2)$ of amorphous GdCoCr films was generally less than four. Attempts to increase the anisotropy to get a higher quality factor by annealing the films under an applied saturating magnetic field of 1.27×10^6 A/m (16 k Oe) perpendicular to the film plane were unsuccessful. The annealing time was typically five hours. Various annealing temperatures up to 620 K were used. The annealing was done in an atmosphere of helium. A possible explanation is that at low temperatures, where the magnetization could effectively assist the anisotropy-generating annealing procedure, the temperature is too low to activate diffusion processes necessary to rearrange the film atoms for higher magnetic anisotropy.

Temperatures high enough for the necessary diffusion processes to take place are, on the other hand, too close to the Curie temperature, and thus the film magnetization is too small to initiate preferred orientation of the film atoms for increased anisotropy.

Ion radiation damage has been successfully used to induce perpendicular magnetic anisotropy in binary GdCo films [6]. Attempts to increase the perpendicular anisotropy In GdCoCr films by using ion radiation damage under applied saturating fields were unsuccessful. In these experiments the film samples were bombarded with up to 5×10^{15} Ar ions per cm^2 at 2.8 MeV energy. We have indications that in these experiments a considerable film temperature increase by the impinging high energy ion beam could not be avoided.

The saturation magnetization of the GdCoCr films also was found to be very stable against temperature treatments. No effect of heatup cycles to 570 K for about two hours on the saturation magnetization and its temperature dependence was found. A 520 K anneal for six days in vacuum increased the magnetization only by about five percent.

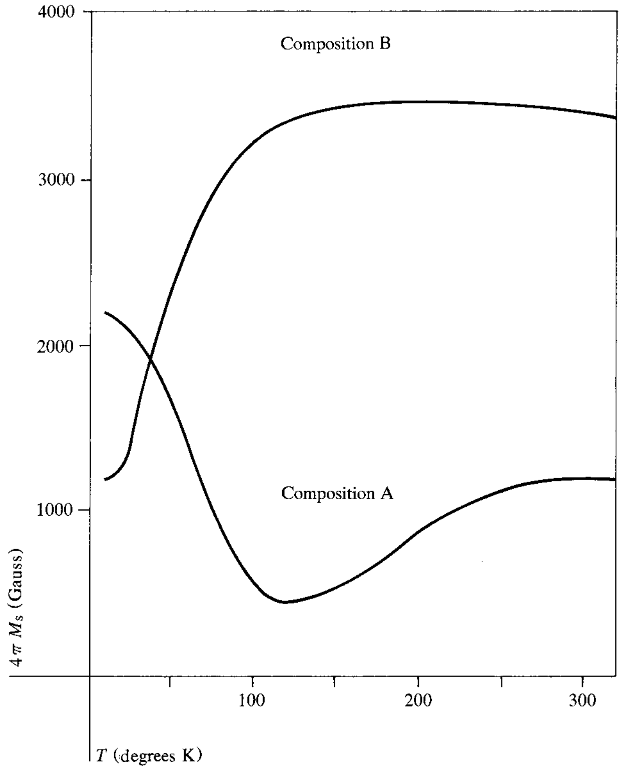

Figure 2 Temperature dependence of $4\pi M_s$ for amorphous GdCoCr films.
A: $Gd_{0.132}Co_{0.65}Cr_{0.218}$
B: $Gd_{0.133}Co_{0.664}Cr_{0.203}$

Summary

The transition line between ferrimagnetic and paramagnetic compositions in the amorphous GdCoCr system is determined for room temperature. The compensation line bends away from the CoCr axis for increasing Cr content. Co-dominated film compositions close to the intersection of the compensation and transition lines are found suitable for bubble domain applications. The saturation magnetization of amorphous $Gd_{0.132}Co_{0.65}Cr_{0.218}$ films stays constant within 3.5 percent in a temperature range of about 100° K around room temperature. Films in this composition region show a very high dependence of $4\pi M_s$ on the Cr/Co ratio. This very high dependence, together with the course of the transition line, indicates that Cr not only has a diluting effect on the magnetic Co sublattice, but also influences the magnetic coupling mechanisms in these films in a manner not yet determined.

Films with compositions near the transition line or the CoCr axis exhibit decreasing perpendicular magnetic anisotropy.

Thermal annealing and radiation damage by ion implantation under applied saturating perpendicular magnetic fields apparently do not cause a change in the magnetic anisotropy. The saturation magnetization is stable against thermal cycling up to 570 K and also is unchanged within five percent after six days of 520 K annealing in vacuum.

GdCoCr strongly getters oxygen during film preparation. 3 to 13 at. percent O in the films cause H_c to increase to about 800 A/m, whereas essentially oxygen-free films have coercivities less than 80 A/m.

This work was done by the author during a limited stay at the IBM Thomas J. Watson Research Center. Various additional measurements and investigations remain to be done: The temperature dependence of the bubble-domain-related properties like K_u, l-parameter, bubble collapse field, etc., still are to be measured. Further investigations to determine the reason for the strong dependence of $4\pi M_s$ on the Cr content should be made. Also the annealing behavior of the films should be investigated further.

The results reported here, however, especially the low temperature dependence of the magnetization, together with the low H_c of oxygen-free films, show amorphous GdCoCr films to be potentially attractive for bubble domain applications and should stimulate further research on this material.

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