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著者	Mizoguchi Tadashi
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FERRIMAGNETISM IN AMORPHOUS ALLOYS

Tadashi Mizoguchi

Faculty of Science, Gakushuin University

1-5-1 Mejiro, Toshimaku, Tokyo 171 Japan

ABSTRACT

The characteristic aspects of ferrimagnetism in amorphous alloys, the subnetwork magnetization, anisotropy from dipolar interactions and exchange stiffness are discussed.

INTRODUCTION

Ferrimagnetism can be realized without frustration even in amorphous binary alloys in which there is no long range atomic ordering, if the exchange interaction between different kinds of magnetic atoms is negative and those among same kinds of atoms are positive. The heavy rare earth metal - transition metal (RE-TM) systems, e.g., Gd-Co and Gd-Fe, are examples of amorphous ferrimagnetic alloys so far well known. Addition of non-magnetic other elements, e.g., Mo, in these systems makes no essential change in the magnetic ordering.

The net saturation magnetization M_s , the magnetic anisotropy energy K_u , and the exchange stiffness constant A are the important physical quantities of amorphous ferrimagnetic alloys which have been intensively investigated because of their potential application to magnetic bubble devices.

Some characteristic aspects of amorphous ferrimagnet, as a typical example of which we can refer amorphous GdCoMo alloy film, will be described briefly in the following.

SUBNETWORK MAGNETIZATION

The net saturation magnetization is sensitive to an alloy composition in the ferrimagnetic system where the magnetic

moments of different kinds of atoms comple antiparallel.

For example, 2% composition difference around $Gd_{25}Fe_{75}$ gives a change of the net magnetization by a factor of about 2.

The temperature dependence of the net magnetization is peculiar. Some of them show a compensation of the magnetization at a certain temperature, T_{comp} , below the Neel temperature.

Phenomenologically Neels molecular field theory of ferrimagnetism may be applicable to the amorphous ferrimagnets [1], although it may not be a good approximation.

The direct observation of the temperature dependence of a subnetwork mangetization has been done in a limited temperature range using polar Kerr rotation which is due mostly to the Co atoms in $GdCoMo$ alloys [2].

Ferromagnetic resonance gives us the effective g factor. In two subnetwork ferrimagnet, the net magnetization is expressed as follows.

$$\begin{aligned} M &= M_1 - M_2 \\ &= g\mu_B \bar{S}N \end{aligned} \quad (1)$$

where \bar{S} is the averaged spin, that is

$$\bar{S} = S_1(N_1/N) - S_2(N_2/N) \quad (2)$$

and $N = N_1 + N_2$ denotes the number of atoms per unit volume. As each subnetwork magnetization is expressed as

$$M_i = g_i \mu_B S_i N_i, \quad (i = 1, 2) \quad (3)$$

we get the Wangsness' expression [7],

$$g = (M_1 - M_2) / [(M_1/g_1) - (M_2/g_2)]. \quad (4)$$

If g_1 and g_2 are assumed to be temperature independent, the subnetwork magnetizations derived from the observed g values and the net magnetization are

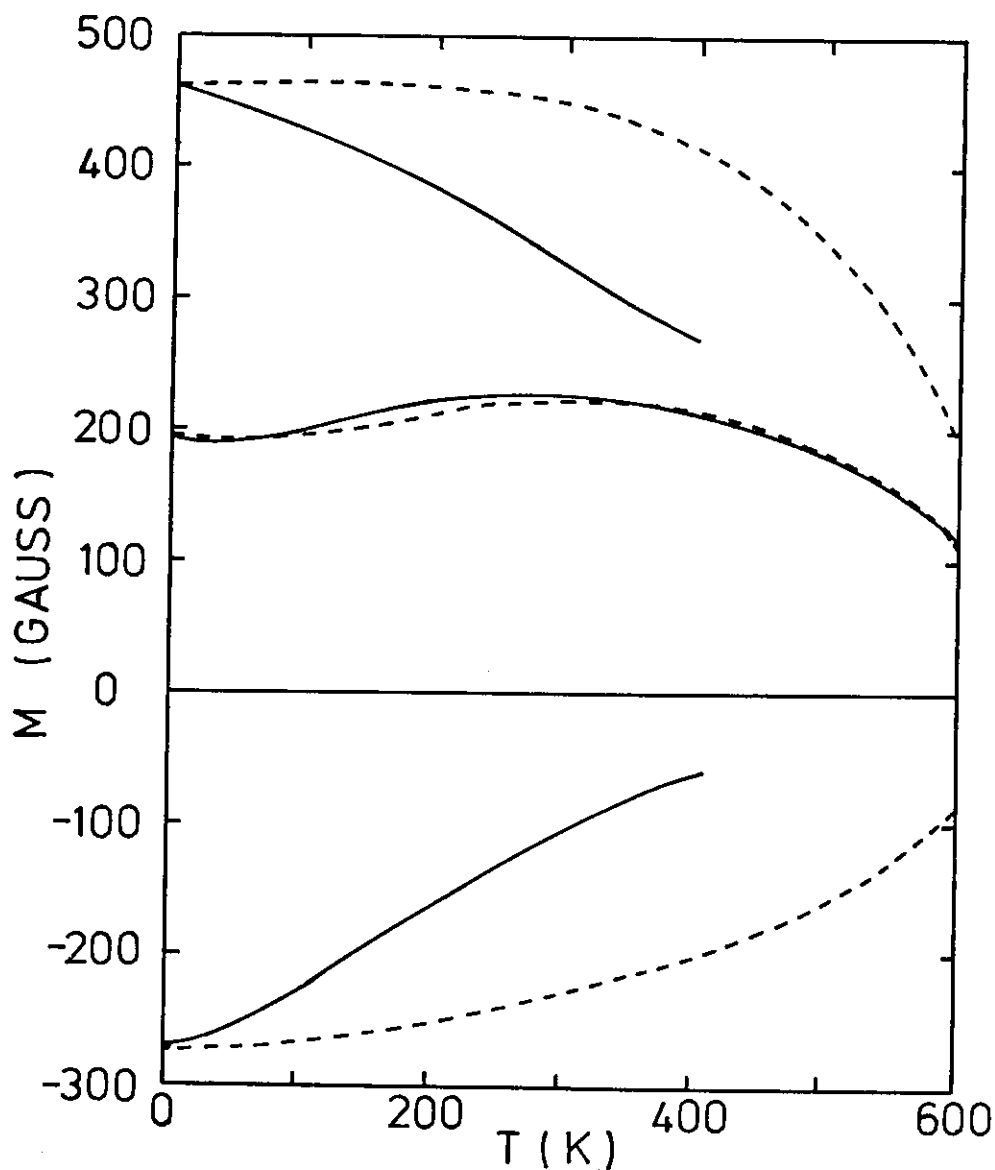


Fig. 1. The temperature dependence of the net magnetization M , and the subnetwork magnetizations M_{Co} and M_{Gd} in amorphous $\text{Gd}_{6.9}\text{Co}_{74}\text{Mo}_{12.8}\text{Ar}_{6.3}$ alloy derived with Eq. (5) and, (6) (solid lines), or with the molecular field approximation (broken lines).

$$M_1 = [g_1(g - g_2) / (g_1 - g_2)g]M, \quad (5)$$

$$M_2 = [g_2(g - g_1) / (g_1 - g_2)g]M. \quad (6)$$

The temperature dependence of the subnetwork magnetizations thus obtained are shown in Fig. 1, together with that from the molecular field approximation (MFA) for an amorphous GdCoMo alloys, in which the net magnetization seems to be well represented by the MFA. For an amorphous GdFe alloy the MFA can not reproduce even the net magnetization so well [3].

ANISOTROPY FROM DIPOLAR INTERACTIONS

Magnetic anisotropy in rare earth metal transition metal amorphous alloys has been the subject of many investigations in recent years. Anisotropy in these materials is closely related to their preparation conditions and must be due to some deviation from isotropy in arrangements of atoms in the amorphous alloys, although convincing evidence for atomic-scale structural anisotropy in amorphous RE-TM films has not yet been obtained by diffraction techniques. The magnetic anisotropy occurring in many of the amorphous films may include additive or competing contributions from several of the mechanisms.

It has been shown that classical magnetic dipolar interactions can make significant contributions to magnetic anisotropy in amorphous ferrimagnetic alloys with slight structural anisotropies on either atomic or microstructural scales [5].

The atomic scale structural anisotropy may be expressed by the anisotropic atomic distribution function with spherical harmonic as follows,

$$P_{IJ}(\vec{r}) = (N_J/N)R_{IJ}(r)[1 - p(3\cos^2\theta - 1) + \dots] \quad (7)$$

and

$$P_{II}(\vec{r}) = (N_I/N)R_{II}(r)[1 + (z_{IJ}/z_{II})p(3\cos^2\theta - 1) + \dots], \quad (8)$$

where θ is the angle between \vec{r} and the normal of the film,

and p is a measure of the anisotropy in distribution of IJ pairs, which, for simplicity, is assumed to be zero beyond nearest-neighbor distances. z_{IJ} is the average number of J -type atoms in nearest neighbor coordination shells of I -type atoms, etc. $(N_J/N)R_{IJ}(r)$ is the isotropic part of $P_{IJ}(\vec{r})$.

Classical dipolar interactions in ferrimagnetic spin configuration give the uniaxial anisotropy energy with this slight structural anisotropy. In cases of alloys with equal atomic radii, D , it is expressed simply as follows,

$$K_u = (3/5)p(zc_1c_2/ND^3)(|M_1/c_1| + |M_2/c_2|)^2, \quad (9)$$

where z is the number of nearest neighbors, and c_i denotes the concentration. In this equation $(ND^3)^{-1}$ can be expressed in terms of the "packing fraction" of the amorphous structure and is 0.7 for amorphous metallic alloys [4]. Since the net magnetization in this ferrimagnet is $M = M_1 - M_2$, $Q = K_u/2\pi M^2$ can be larger than unity with reasonably small p values.

Magnetic anisotropy arising from an internal shape effect, i.e., from anisotropically shaped composition heterogeneities in amorphous ferrimagnets have a very similar expression to the Eq. (9).

Accounting for magnetic anisotropy observed experimentally in bias-sputtered GdCo-based alloy films solely in terms of pair ordering and classical dipolar interactions requires $p \approx 0.015$. Accounting for the anisotropy solely in terms of composition inhomogeneities requires $\Delta x \approx 0.1$ for $V = 0.5$, where V is the volume fraction of inhomogeneities and Δx is the composition difference between the inhomogeneities and their surroundings.

Although such atomic-scale structural anisotropy will be very difficult to detect with currently available experimental techniques, composition inhomogeneities of this magnitude should be easily detectible in X-ray, electron, or neutron small-angle scattering experiments. Results of small-angle X-ray scattering experiments on micron-thick sputtered GdCo-based films indicate that occurrence and characteristics of microstructural inhomogeneities depend critically on substrate

vias. Although intense anisotropic small-angle scattering is present for nonbiased films, scattering from biased magnetically anisotropic films is weak and isotropic and can be attributed to formation of small Gd-oxide clusters during film growth, apparently unrelated to magnetic anisotropy. Although no evidence for anisotropic composition inhomogeneities is seen in X-ray scattering experiments on micron-thick bias-sputtered GdCo-based films, such inhomogeneities may be present in oxygen-doped evaporated Gd-Co films and in some annealed Gd-Co films prepared by evaporation and by zero-bias sputtering. Magnetic anisotropy in GdCo-based film probably involves spin-orbit interaction as well as classical magnetic dipolar interactions.

EXCHANGE STIFFNESS

The exchange stiffness constant is related to the exchange interaction between various atomic pairs. It may be estimated roughly from the Curie temperature, or can be obtained from the width of stripe domains in a film which has sufficient perpendicular anisotropy. Spin wave resonance gives us direct information about the exchange stiffness. In an amorphous $\text{Gd}_{6.9}\text{Co}_{7.4}\text{Mo}_{12.8}\text{Ar}_{6.3}$ alloy film, the spin wave dimensional resonances have been observed over a wide temperature range from 16K up to 400K.

The temperature dependence of the coefficient of spin wave dispersion relation D is shown in Fig 2. In a ferrimagnet the exchange stiffness constant A is related to D as follows,

$$A = D[(M_1/g_1) - (M_2/g_2)]/2\mu_B \quad (10)$$

The macroscopic theory of spin waves extended to a two-subnetwork ferrimagnet gives the following relation,

$$2A = \alpha_{11}M_1^2 + \alpha_{22}M_2^2 + 2\alpha_{12}|M_1M_2|, \quad (11)$$

where

$$\alpha_{ii} = (Nr_i^2)^{-1} \int dr^3 J_{ii}(\vec{r}) x^2, \quad (12)$$

$$\alpha_{12} = (Nr_1 r_2)^{-1} \int dr^3 J_{12}(\vec{r}) x^2 \quad (13)$$

and x denotes one of the components of vector \vec{r} .

In Fig. 3, the temperature dependence of A normalized at 0K is compared with those of M_{Co}^2 , $M_{Co}M_{Gd}$, and M_{Gd}^2 derived from the molecular field approximation and those from the observed g values in FMR experiments with Eq.(5) and (6). The molecular field (MF) approximation does not seem to give an accurate temperature dependence of the subnetwork magnetization, since the observed A is far from the combination of them with positive coefficients α_{11} , α_{12} , and α_{22} .

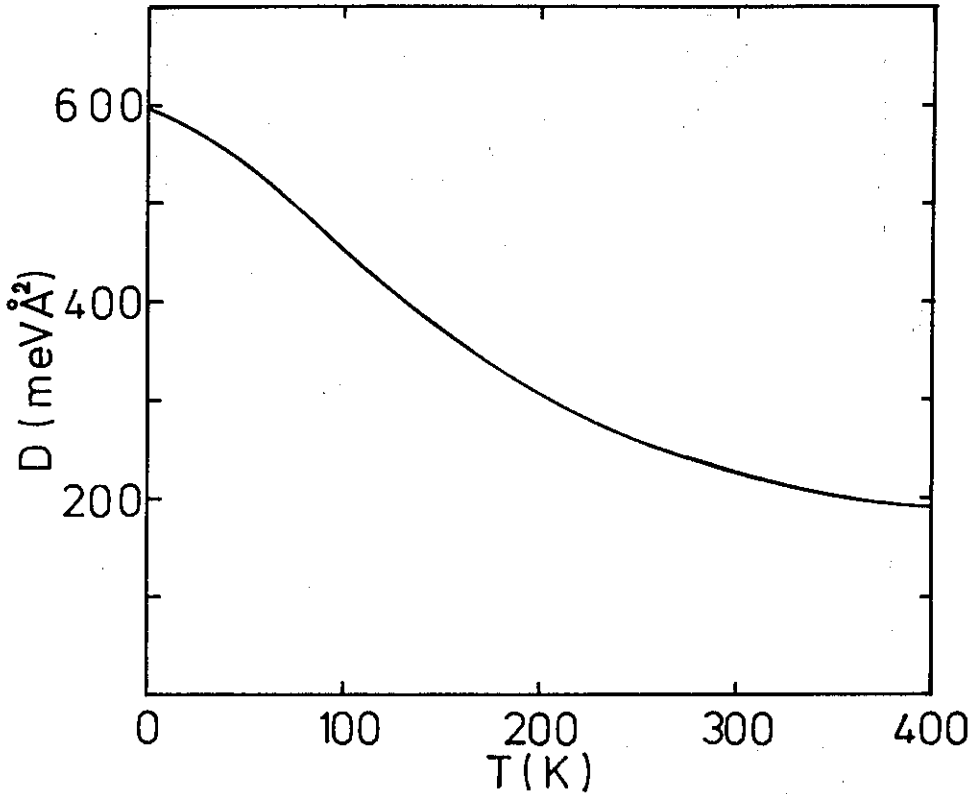


Fig. 2. The temperature dependence of the coefficient of the spin wave dispersion relation, D .

The temperature dependence of A fits quite well to that of M_{Co}^2 which is obtained from the observed g value with Eq. (5). This suggests that the exchange interactions between Co atoms is dominant in this ferrimagnetic alloy as suggested by previous works [1].

It would be interesting to discuss the range of exchange interaction in the metallic amorphous alloy. Let us think about a simplified case, where we take into account only the dominant Co-Co exchange interaction and neglect others in the first approximation.

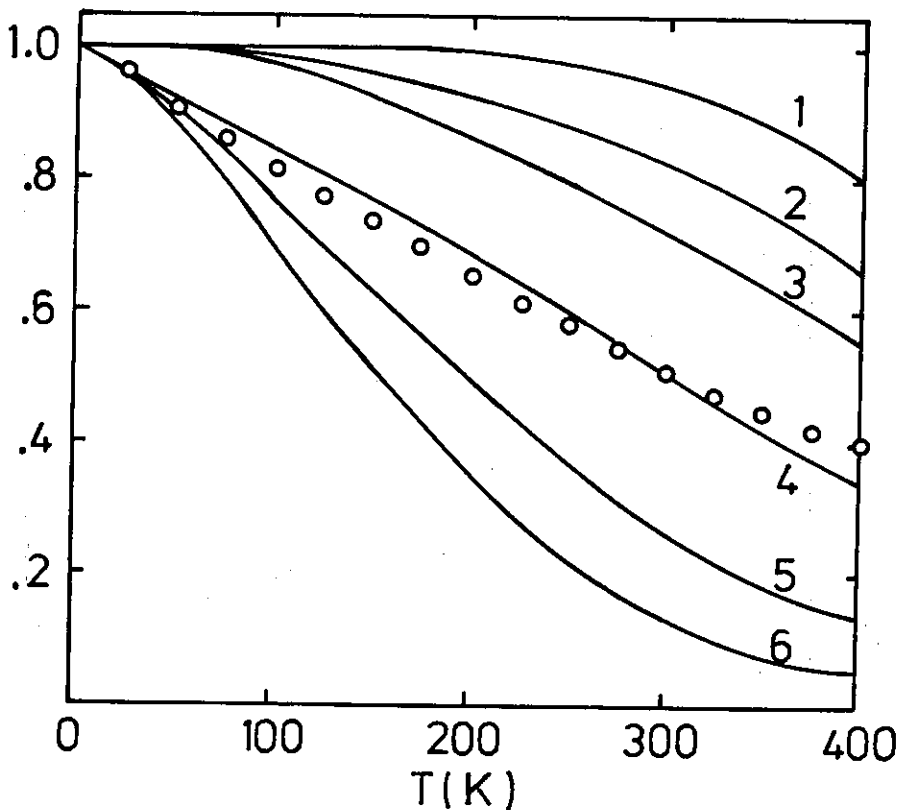


Fig. 3. The normalized temperature dependence of the exchange stiffness constant, A (open circles), and that of M_{Co}^2 , $M_{\text{Co}} M_{\text{Gd}}$ and M_{Gd}^2 derived with the molecular field approximation (1, 2, 3, respectively) or derived from observed effective g values (4, 5, 6, respectively).

Then we can estimate the second moment of the exchange interaction from the observed exchange stiffness constant A in this amorphous alloy as follows,

$$\begin{aligned} \int J_{11}(r) x^2 dr^3 &= \alpha_{11} \gamma_1^2 N \\ &= 2A \gamma_1^2 N / M_1^2 \\ &= 8.78 \times 10^{-29} \text{ erg cm}^2. \end{aligned} \quad (14)$$

On the other hand we estimate the exchange integral from the Curie temperature in the MF approximation

$$\begin{aligned} \int J_{11}(r) dr^3 &= 3kT_c / 2c_1 s_1 (s_1 + 1) \\ &= 2.32 \times 10^{-13} \text{ erg} \end{aligned} \quad (15)$$

The characteristic range of the exchange interaction, R_{ex} can be related to the square root of the ratio of Eq. (14) to Eq. (15) as follows,

$$\begin{aligned} R_{\text{ex}} &= [3\langle x^2 \rangle]^{1/2} \\ &= [3 \int J_{11}(r) x^2 dr^3 / \int J_{11}(r) dr^3]^{1/2} = 3.37 \times 10^{-8} \text{ cm}. \end{aligned} \quad (16)$$

The distance between the nearest neighbor Co atoms in amorphous Gd-Co alloys was estimated from the first peak of the radial distribution function as about 2.5\AA [4]. Taking into account the underestimation of the exchange integral in Eq. (15) in the MF approximation, we may consider that the nearest neighbor exchange interactions are dominant in the amorphous alloy. The short mean free path of conduction electrons in amorphous alloys may suppress the long range exchange interaction of the RKKY type [6].

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