

BASIC MAGNETIC PROPERTIES OF AMORPHOUS ALLOYS

著者	Mizoguchi Tadashi
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	1978
number	Supplement
page range	117-129
year	1978
URL	http://hdl.handle.net/10097/27956

BASIC MAGNETIC PROPERTIES OF AMORPHOUS ALLOYS

Tadashi Mizoguchi

Faculty of Science, Gakushuin University

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

ABSTRACT

The present state of knowledge and understanding of the basic magnetic properties of amorphous alloys is reviewed. It covers magnetic moment, exchange interaction and temperature dependence of the magnetization for both categories; metal-metalloid and rare earth-transition metal amorphous alloys. It is pointed out that the effect of electron transfer on the magnetic moment of transition metal atoms and the effect of fluctuation of exchange interaction on the temperature dependence of the magnetization is characteristic in amorphous alloy systems.

I. INTRODUCTION

Amorphous metals and alloys so far obtained can be classified into three categories which are closely related to preparation methods.

- 1) Amorphous pure metals and alloys which can be obtained by evaporating on a cooled substrate. The amorphous state in this case is sustained by a substrate and stable only at low temperature.
- 2) Metal-metalloid alloys prepared by rapid quenching from the liquid state. They are sometimes called metallic glasses or glassy alloys. They can be also prepared by electrodeposition, chemical deposition from aqueous solution, sputter deposition and evaporation.
- 3) Rare earth-transition metal amorphous alloys prepared by sputter deposition or evaporation. Other metal-metal amorphous alloy systems, e.g. Cu-Zr etc. may also included in this category.

The structure of the amorphous state[1] seems, in most cases examined so far, to be reasonably described as a random dense packing of hard spheres (RDPHS) model. The state is apparently stabilized by a mixture of atoms with appropriately different sizes, and also by a mixture of metallic bonding and some covalent bonding or electron transfer. Since transition metals and rare earth metals are good candidates for elements of amorphous alloys, the magnetism is inevitably important and interesting.

The basic magnetic properties of amorphous alloys are reviewed in the following sections, which cover magnetic moment, exchange interaction and temperature dependence of magnetization for both categories; metal-metalloid and rare earth-transition metal amorphous alloys.

II. MAGNETIC MOMENT

Many experimental studies of ferromagnetism in amorphous solids employed alloys of 3d transition metals with about 15~30 at.% of light metalloid elements of group IIIA, IVA and VA (B, C, Si, Ge and P). These small metalloid atoms are supposed to occupy relatively larger holes in the dense random packing structure of the metal atoms, transferring electrons to the unfilled d holes of the transition metals. This accounts for the reduction of magnetization of these amorphous alloys as compared to the corresponding metallic crystalline alloys without metalloid elements.

Let us consider a simple situation of the electron transfer. If up-spin electrons are full in d-states of the transition atom, M, and transferred electrons from metalloid atoms, G and E, flow into the d holes of down-spin states in $M_{1-x-y}G_xE_y$ alloy, the average magnetic moment per formula of this alloy can be expressed as follows,

$$(\bar{\mu}/\mu_B) = m(1-x-y) - nx - py \quad (2.1)$$

where m is an original number of the down-spin holes of the 3d atom, n and p are numbers of transferred electrons from G and E atoms, respectively.

Concentration dependence of the magnetic properties of amorphous Fe-B-P alloys were studied by Durand et al. [2,3]. The average magnetic moment of $Fe_{1-x}B_x$ and $Fe_{1-y}B_y$, which were extrapolated from those of $Fe_{1-x-y}B_xP_y$ alloys, were expressed as follows, respectively;

$$(\bar{\mu}/\mu_B) = 2.37 - 3.7x \quad (2.2)$$

and

$$(\bar{\mu}/\mu_B) = 2.33 - 3.9y \quad (2.3)$$

If we apply Eq.(2.1) to these relations we get the moment of Fe extrapolated to $x \rightarrow 0$ and $y \rightarrow 0$ in the amorphous phase as about $2.35\mu_B$ and the numbers of transferring electrons from B and P to Fe are 1.3 and 1.6, respectively.

Detailed experimental study was done by Mitera et al. [4] on amorphous $Fe_{0.8-x}G_xE_{0.2-x}$ alloys, where G represents B, C, Si, Ge or P, and E represents B or P. The average magnetic moment of Fe atoms showed linear dependence on x as expected from Eq.(2.1). Assuming $m = 2.35$ for iron, the number of transferred electrons to iron from B, C, Si, Ge or P is derived with Eq.(2.1) as about 1.07, 1.32, 0.94, 0.64 or 1.64, respectively. There are clear trends that lighter metalloid and higher valence metalloid atoms transfer more electrons to transition metal atoms ($n_C > n_{Si} > n_{Ge}$, $n_C > n_B$ and $n_P > n_{Si}$).

The saturation magnetization of amorphous $Fe_{1-x}B_x$ binary alloys [5,6,7] was found to decrease with decreasing x for small x (<0.15). This inclination suggests that the magnetic moment of iron in iron rich

amorphous alloys may involve low spin states. This is also suggested in an experimental study done by Felsch[8] on amorphous iron films containing small amount of Si, O or Ge prepared by evaporation on a cold substrate.

The average magnetic moments, $\bar{\mu}$, of the 3d transition metal atoms were studied in quasibinary amorphous $(T_{1-x}M_x)_{80}B_{10}P_{10}$ ferromagnetic alloys, where T represents Fe or Co, M represents V, Cr, Mn, Fe, Co or Ni. They are plotted in Fig.1 as a function of the average outer electron concentration, N, of metallic atoms, along with corresponding crystalline data (broken lines) on the so-called Slater Pauling curve which extends over both bcc and fcc phases with some anomalies in the Invar region[9,10]. Though the electron transfer from the metalloid atoms reduces the magnetic moment of the quasibinary Fe-Ni and Fe-Co amorphous alloys compared to the Slater Pauling curve, the average magnetic moment, $\bar{\mu}$, decreases with increasing N with the slope of -1, which does not conflict with a simple rigid band model. Taking into account the screening effect this composition dependence of the average magnetic moments is explained by the complementary spatial aspect that Fe, Co or Ni has about 2, 1 or $0\mu_B$, respectively.[36,37].

The transition metals such as Mn, Cr and V which have fewer 3d electrons than Fe reduce greatly the net moment of these amorphous alloys when they replace a part of Fe atoms. If Fe moment is assumed to be unchanged by the replaced transition metal atoms, they seem to couple antiparallel to Fe with the magnetic moment of about 3, 4 and $5\mu_B$ for Mn, Cr and V, respectively. Roughly speaking, the atomic moment of the 3d elements can be considered to increase linearly from 0 for Ni to $5\mu_B$ for V with decreasing atomic number in these amorphous alloys. Randomness of the potential may help localization of 3d electrons, which are fully polarized by sufficiently large intra-atomic exchange interaction.

It is interesting to point out that the behavior of the magnetization of Fe and Co base amorphous alloys resembles that of Co and Ni base metallic crystalline alloys, respectively. This shift may be attributed to the forced insertion of electrons into the 3d states of the transition metals in this amorphous alloys.

The magnetic moments of dilute 3d atoms in some amorphous alloys were obtained from the Curie-Weiss susceptibility. In an amorphous $Pd_{80}Si_{20}$, 3d atoms of Cr, Mn, Fe and Co have 3.6, 5.7, 5.9 and $4.4\mu_B$ effective moment, respectively[11,12]. In an amorphous $Cu_{57}Zr_{43}$ alloy, which shows temperature independent Pauli paramagnetism in itself, all 3d atoms (V, Cr, Fe, Co and Ni) except Mn were found to lose their localized moment[13,14]. Only Mn impurity gives the well behaved Curie-Weiss susceptibility with an effective moment of about $1.6\mu_B$.

For rare earth-transition metal amorphous alloys, the magnetic moment of heavy rare earth atoms couples to that of transition metals (Fe and Co) ferrimagnetically. So the magnetization is sensitive to a slight change of composition. For example, a 2% composition difference around $Gd_{25}Fe_{75}$ gives a change of the net magnetization by a factor of about 2.

An extensive survey of RFe_{1-x} amorphous alloys[15], where R represents Gd, Tb, Dy, Ho, Tm, Yb or Lu, indicates a decrease of Fe moment with increasing R content, x, with the rate dependent on the effective rare earth spin (g-1)J, as;

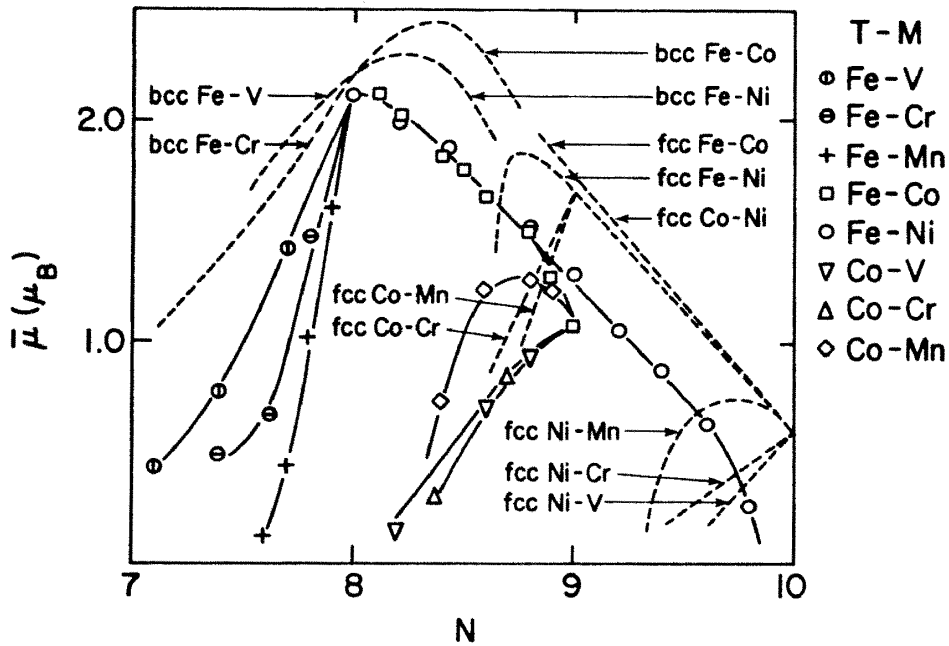


Fig. 1. The average magnetic moment, $\bar{\mu}$, of 3d atoms in quasi-binary amorphous $(T_{1-x}M_x)_{80}B_{10}P_{10}$ ferromagnetic alloys as a function of the average outer electron concentration, N , of the metallic atoms, along with that for crystalline alloys (broken lines).

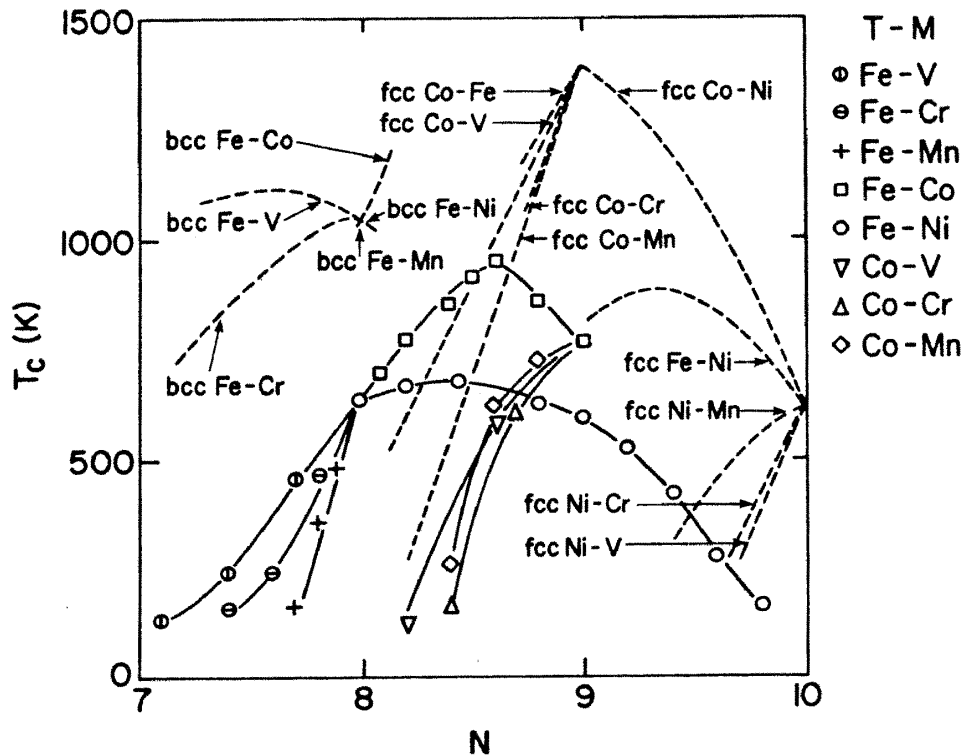


Fig. 2. The Curie temperature of quasibinary amorphous $(T_{1-x}M_x)_{80}B_{10}P_{10}$ alloys as a function of the average outer electron concentration of the metallic atoms, along with that for crystalline alloys (broken line).

$$(\mu_{\text{Fe}}/\mu_{\text{B}}) = 2.2 - [x/(1-x)][3.2 - 0.7(g-1)J]. \quad (2.4)$$

Considerable reduction of Fe moment in the R-Fe amorphous alloys (for example, $\mu_{\text{Fe}} = 0.7\mu_{\text{B}}$ for $\text{Gd}_{0.33}\text{Fe}_{0.67}$) can be attributed to the charge transfer from the R atom with the addition of moment induced by R.

The magnetic moment of Co in amorphous $\text{R}_x\text{Co}_{1-x}$ ($0.12 \leq x \leq 0.67$), where R represents nonmagnetic Y, La and Zr, decreases proportionally to $(x_0 - x)^{1/2}$ with increasing x[16]. The critical concentration at which the Co moment disappears ($x_0 = 0.5$ for Y and La, $x_0 = 0.4$ for Zr) in the amorphous phase is much higher than in the crystalline phase. Fitting the data to a simple charge transfer model, it is found that Y and La contributes about 1.4 electrons to the Co d state while Zr contributes 2.2.

Amorphous Co-Gd-Mo thin films are of particular interest because of their potential application to the bubble magnetic materials. Thin films of good quality are fabricated by rf bias sputter deposition in an Ar plasma which usually results in the incorporation of some amounts of Ar in the film. Extensive experimental studies were done in IBM Research Center and other places[17,18].

In order to get magnetic moments of atoms from magnetization, we need to know the density or the number of atoms, N, per unit volume in the amorphous alloys. It is estimated as[19];

$$N = 0.95 / \sum_i x_i v_i \quad (2.5)$$

where x_i is the composition and v_i is the volume per atom of the i-th species. These volume were taken to be 11.14, 32.84, 15.38 and 53.37, all in unit of \AA^3 , for Co, Gd, Mo and Ar. Assuming the gyromagnetic factor, g, for Co and Gd to be 2.22 and 2.00 and the Gd spin to be 7/2, the Co spin value was found to be expressed as[19];

$$S_{\text{Co}} = 0.775 - 0.848(x_{\text{Gd}}/x_{\text{Co}})^{1.5} - 1.688(x_{\text{Mo}}/x_{\text{Co}}). \quad (2.6)$$

This is shown in Fig.3.

The local environment in an amorphous solid differs site by site because of the random arrangement of atoms, in contrast to the regular crystalline lattice. Therefore the magnetic moment of atoms is not expected to be identical on every site but has a distribution in a certain range, which may be observable through hyperfine interactions.

Combined NMR and MÜssbauer experiments were performed on amorphous $\text{Fe}_{79}\text{P}_{21-x}\text{B}_x$ alloys by Raj et al.[20]. The distributions of hyperfine field at ^{57}Fe nuclei generally lei between about 160 and 330KG, with a maximum at about 260KG at room temperature. The distributions have structures which suggest the similar short range atomic configuration, at least in the nearest neighbor shell, in the amorphous alloy to that observed in their crystalline counterparts. The center of gravity of the spectra shifts linearly to higher values with increasing B content. This implies a linear variation of the Fe hyperfine field with the average Fe moment with the slope of $126\text{KG}/\mu_{\text{B}}$.

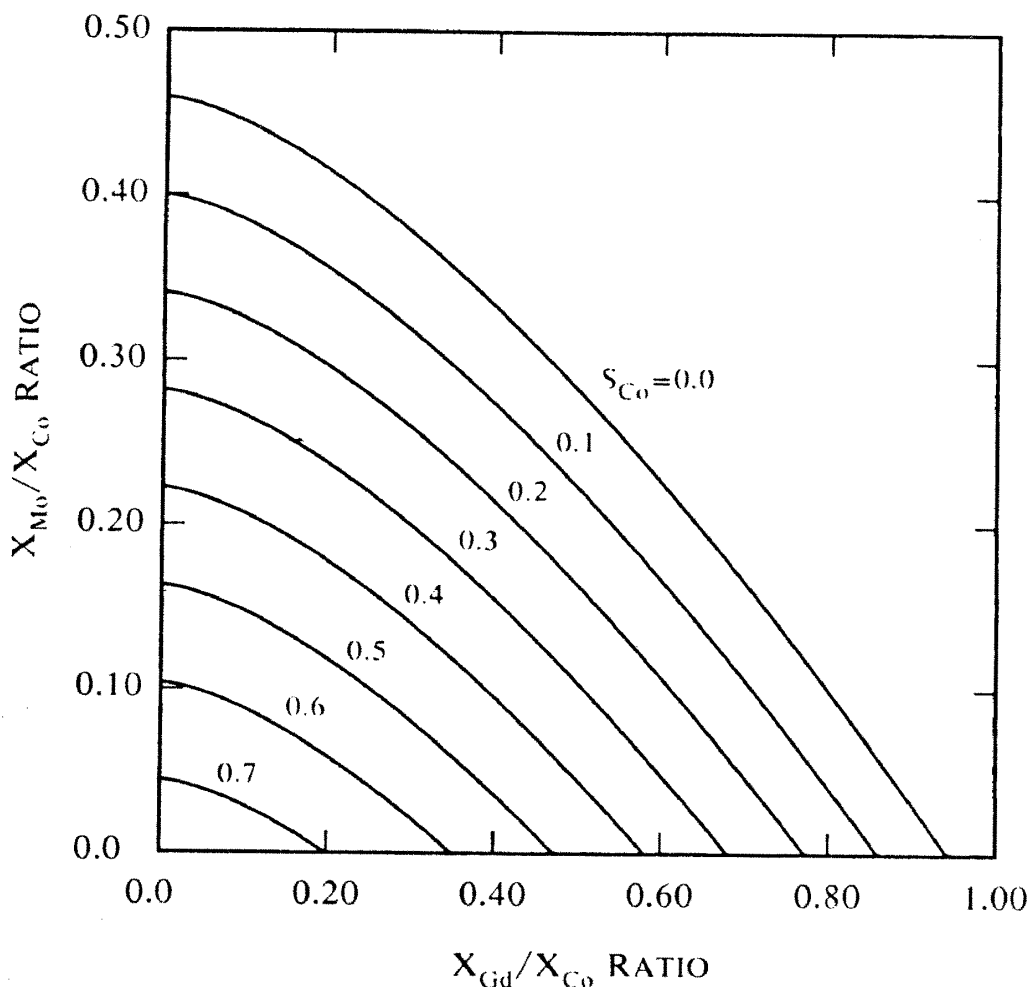


Fig. 3. Countour plot of the Co spin value, S_{Co} , with increasing x_{Gd}/x_{Co} and x_{Mo}/x_{Co} ratio in amorphous $Co_{1-x}Gd_x$ - $Co_{1-x}Mo_x$ -Ar alloy films prepared by rf sputter deposition [19].

The spin-echo NMR signals in these amorphous alloys are observed in the frequency range of 20~60 MHz. From an analysis of the NMR data, the hyperfine field at the B nuclei is found to range from 24 to 26KG increasing with B content with the half width of less than 8KG, while that at P nuclei seems to have broader distribution between 20 and 35KG for the higher P concentration alloys.

NMR of Co was observed in amorphous ferromagnetic Co-P[21,23] and $Co_{70}B_{20}P_{10}$ [22] alloys. The hyperfine interaction in Co-P was also investigated by means of inelastic incoherent spin-flip scattering of neutrons[24]. The mean value of the hyperfine splitting is, in first order, proportional to the magnetic moment of Co.

The hyperfine field distributions of Co and Fe were studied by NMR and Mossbauer experiments in amorphous $(Fe_{1-x}Co_x)_{80}B_{10}P_{10}$ alloys[25]. The peak of the hyperfine field distribution at Co dose not shift with x, while that for Fe shifts to higher value with small x and then become constant for $x > 0.3$

III. EXCHANGE INTERACTION

The long range magnetic ordering can be realized in amorphous solid in spite of the lack of long range atomic ordering. In fact many iron and cobalt based amorphous alloys show ferromagnetism. In the molecular field approximation, the Curie temperature of a ferromagnet is expressed as;

$$T_c = (2/3k)s(s+1) \sum J_{ij} = (2/3k)s(s+1)J(0) \quad (3.1)$$

where k is the Boltzman constant and the Fourier transform of the exchange interaction is generally defined as;

$$J(q) = \sum J_{ij}(r_j - r_i) \exp[q(r_j - r_i)]. \quad (3.2)$$

Let us examine experimental data obtained so far. The Curie temperature, T_c , of the quasibinary transition metal amorphous alloys, ($T_{1-x}M_x$)₈₀B₁₀P₁₀, are plotted in Fig. 2, along with corresponding T_c of metallic crystalline alloys, in which hcp Co has the highest Curie temperature. Taking into account the change of the spin value, we find that the total exchange interaction, $J(0) = \sum J_{ij}$, acting on a Co atom in the amorphous Co₈₀B₁₀P₁₀ is slightly higher than that in hcp Co ($J(0)_{\text{amr}}/J(0)_{\text{cry}} \approx 1.1$). However this is not the case for Fe. the exchange interaction, $J(0)$, of Fe in the amorphous Fe₈₀B₁₀P₁₀ is less than 2/3 of that in bcc Fe. If only the nearest neighbor interaction is important, we should take into account the difference of coordination numbers in amorphous ($z \approx 12$) and bcc phase ($z = 8$), which reduce the nearest neighbor interaction in amorphous phase to roughly half of that in bcc phase. [36,37].

There is a significant discrepancy between the Curie temperature of crystalline bcc alloys and that of fcc alloys as seen in Fig. 2, suggesting the complexity of the effect of crystalline structure on T_c . On the other hand, in amorphous alloy systems, the T_c is a smooth function of the alloy composition in the whole range. It may be interpreted with a pair interaction model as the first approximation. The exchange interaction between Fe and Co seems to be most strong in this amorphous alloy system.

Becker et al. measured the composition dependence of T_c [27] in (Fe_xNi_{1-x})₈₀B₂₀ alloy. Assuming the pair interaction model they found $T_{\text{Fe-Fe}}$, $T_{\text{Fe-Ni}}$ and $T_{\text{Ni-Ni}}$ to be 651K, 1055K and -175K, respectively, while corresponding interaction in fcc crystalline Fe-Ni alloy are -170K, 1400K and 630K, respectively.

The Curie temperature of amorphous Fe_{0.8G}E_{0.2-x}, where G and E represent metalloid atoms, shows systematic change corresponding to the magnetic moment of Fe [4]. The total exchange interaction, $J(0) = \sum J_{ij}$, between Fe atom in Fe_{0.8G}E_{0.1} (where G=B or P and E=B, C, Si, Ge^{IV} or P) is derived with Eq.(3.1) from observed T_c and the magnetic moment, $\mu_{\text{Fe}} = g\mu_B$, (assuming $g = 2$). It increases monotonically with increasing magnetic moment of iron as shown in Fig. 4.

The series of amorphous rare earth-iron alloys RFe₂ (where R=Gd, Tb, Dy, Ho, Er and Y) have been studied by Rhyne [26]. The observed T_c exhibits a smooth decrease from 500K for GdFe₂ to 0 for YFe₂ with decreasing De Gennes factor, $G = (g-1)^2 J(J+1)$, of the rare earth atom. this behavior of T_c of the amorphous alloys should be compared to that of the

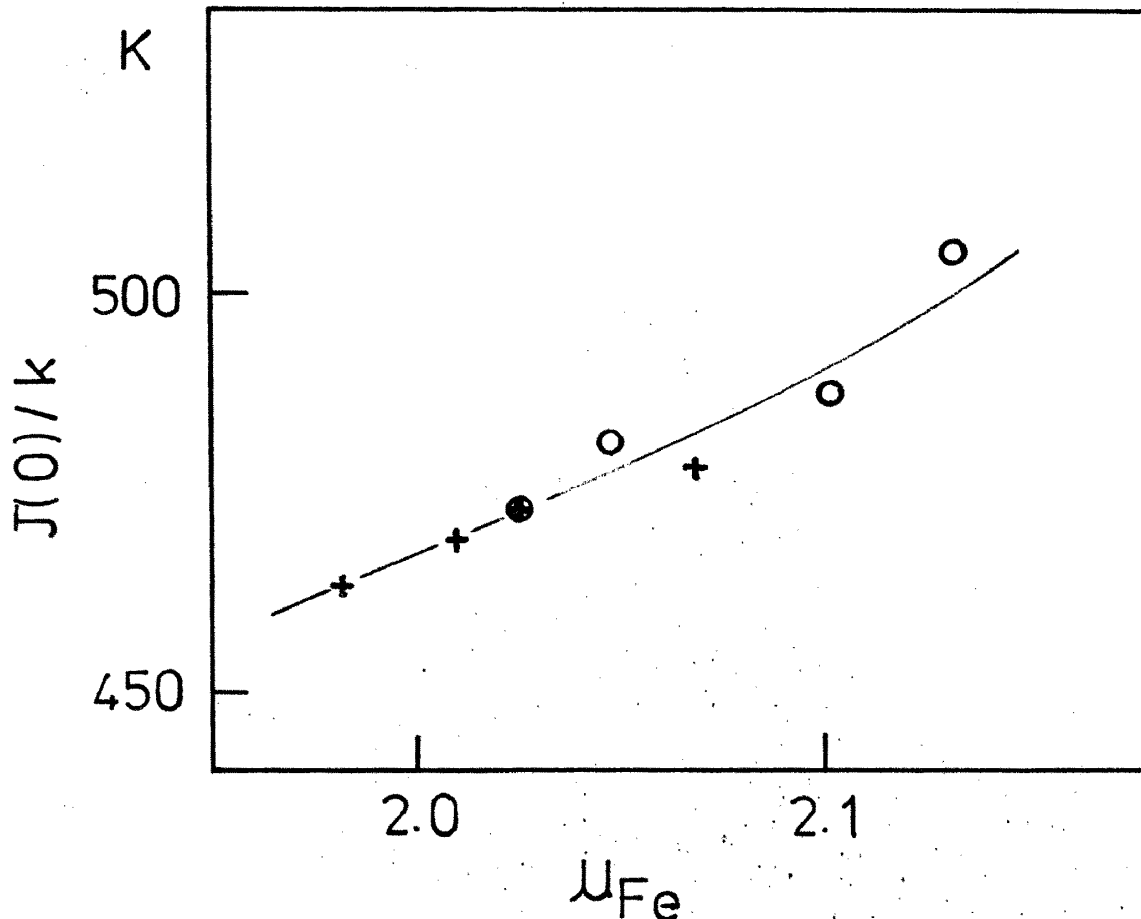


Fig. 4. The total exchange interaction $J(0)/k = \sum J_{ij}/k$ between Fe atoms versus the magnetic moment μ of Fe in amorphous $Fe_{0.8}G_{0.1}E_{0.1}$ alloys, where $G=B$ (open circles) or P (crosses) and $E=B, C, Si, Ge$ or P .

corresponding crystalline Laves phase compounds, for which YFe_2 has T_c of 535K and which shows a much weaker dependence on G .

A two sublattice molecular field calculation gives an adequate fit to the observed T_c in the crystalline Laves RFe_2 compound with the exchange constant of $J_{Fe-Fe}^c = 832K$, $J_{R-Fe} = -137K$ and $J_{R-R} = 98K$. The fit for the amorphous alloys is less satisfactory and yields $J_{Fe-Fe} = 0$, $J_{R-Fe} = -129K$ and $J_{R-R} = 73K$. It is quite puzzling that J_{Fe-Fe} anomalously vanishes in amorphous $R-Fe$ alloys. There are other works in which T_c of amorphous YFe_2 was reported as finite ($\sim 120K$) [15].

It is interesting that for RFe_2 system T_c in the amorphous state is lower than that in the crystalline state while for RCo_2 system the situation is reversed. For example, T_c for crystalline compounds vary between 0K for YCo_2 and 409K for $GdCo_2$, whereas T_c is higher than 450K for all amorphous $R_{0.33}Co_{0.67}$ alloys.

Gangulee and Kobliska analyzed the temperature dependence of the saturation magnetization of amorphous Co-Gd-Mo-Ar alloy films in terms of the mean field theory of two subnetwork ferrimagnet. The temperature dependence of the spin value is assumed to obey the Brillouin function as

$$\bar{S}_i(T) = S_i B_{S_i}(H_i, T) \quad (3.3)$$

where the mean field experienced by an i -atom may be expressed as

$$H_i = H_a = \sum_j 2J_{ij} z_i x_i x_j \bar{S}_j(T) / u_B g_i \quad (3.4)$$

where H_a is the externally applied field and z_i is the coordination number of an i -atom. Assuming the Gd-Gd exchange interaction energy to be $2.7 \cdot 10^{-23}$ Joule, they found a somewhat weak correlation of the Co-Co exchange interaction energy, J_{Co-Co} , with the x_{Gd}/x_{Co} ratio as:

$$J_{Co-Co} = [2.301 - 2.498(x_{Gd}/x_{Co})] \times 10^{-21} \text{ joule.} \quad (3.5)$$

However this correlation was poor (the confidence level of 65%) with the root mean square deviation of $1.2 \cdot 10^{-22}$ Joule. It does not seem reasonable to assume the unique exchange interaction parameter J_{Co-Co} for various states of Co atoms which have different magnetic moments in these amorphous alloys.

The Co-Gd exchange interaction energy, J_{Co-Gd} did not correlate at all with Co, Gd or Mo concentration but depend on the Ar concentration as:

$$J_{Co-Gd} = -[2.519 + 6.169x_{Ar}] \times 10^{-22} \text{ Joule} \quad (3.6)$$

The reason for this correlation is not clearly understood, but it may be caused by structural changes associated with increasing substrate bias voltage during fabrication.

For heavy rare earth- transition metal (Fe and Co) system, two sub-network ferrimagnetic structure seems to be consistently stabilized since the exchange interaction between atoms of same species is positive and that of different species is negative.

Generally speaking, however, theoretical treatment of a stable spin configuration in amorphous solid is much more difficult than in regular crystalline lattices which have translational symmetry. In the case of crystalline Bravais lattice, the most stable spin configuration is, in general, a screw structure of the wave vector Q , where Q is defined as the q which gives the maximum in $J(q)$ in Eq.(3.2). The ferro or antiferromagnetic state is realized for $Q=0$ or $Q=K/2$, respectively, where K is a reciprocal lattice vector.

For an amorphous phase, the above discussion can not be applied straight-forwardly except in the case of $Q=0$. It should be noted that in amorphous alloy $J(q)$ in Eq.(3.2) depends not only q but also i , that is, the origin in the summation. Therefore a vector Q differs from site to site not only in magnitude but also quite randomly in direction. These situation very likely prevent a coherent ordering of spin system except in the case of ferromagnetic ordering.

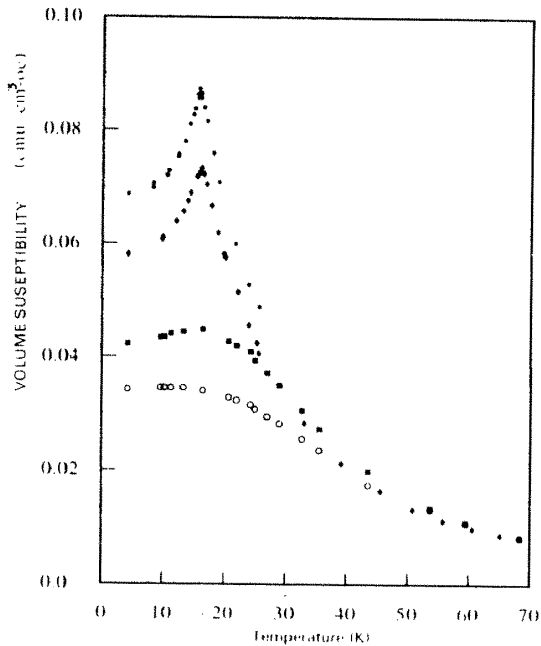


Fig. 5a. Magnetic susceptibility of amorphous $Gd_{0.37}Al_{0.63}$ vs temperature in fields of 0.12, 9.0, 3000 and 60000e.

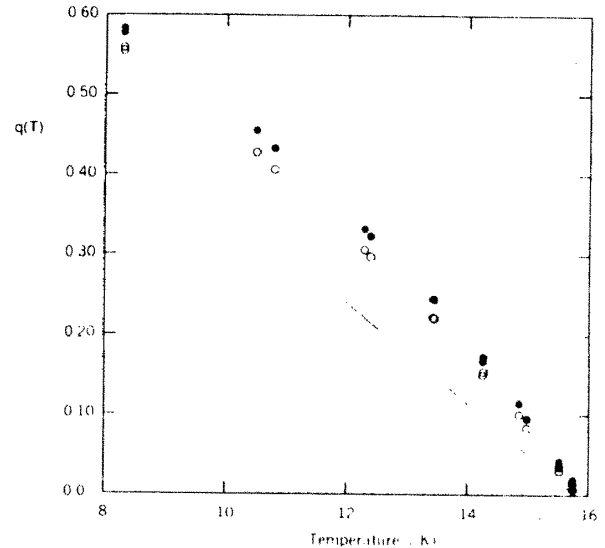


Fig. 5b. Spin glass order parameter, $q(T)$, extracted from the data of Fig. 5a. The solid line is the mean field theory prediction for $q(T)$.

Edwards and Anderson [28] have proposed that there exists the second order transition from paramagnet to a random, but rigid spin state which called "spin glass" when a system involve a certain portion of negative exchange interaction. To detect the presence of such a state they introduce a new type of order parameter, $q(T)$, which has the interpretation

$$q(T) = \langle |\langle S_i \rangle_T|^2 \rangle_r \quad (3.7)$$

In Eq.(3.7), the thermally averaged local moment, S_i , is squared to remove any dependence on the local orientation before carrying out spatial averaging, denoted by the angular bracket $\langle \rangle_r$.

Amorphous films of composition $Gd_{0.37}Al_{0.63}$ are found to exhibit a transition to a spin glass state below 16K [29,30]. In this amorphous alloy the RKKY interaction between Gd spins distributes over both positive and negative side even for nearest neighbor pairs. The susceptibility maximum at 16K, when measured in dc fields of 10~0.10e, sharpens into an asymmetric cusp as shown in Fig. 5a. Using the theory of Sherrington and Kirkpatrick, the spin glass order parameter, $q(T)$, is extracted from the observed cusp. As shown in Fig. 5b, it has the qualitative appearance predicted by mean field theory, but its onset is slightly steepened, just as occurs in conventional magnetic transitions.

The fluctuation of exchange interactions makes characteristic effect on the temperature dependence of the magnetization of amorphous alloys, even in a ferromagnetic state. It causes a faster decrease of the reduced magnetization with reduced temperature compared to the case without fluctuations. In fig. 6 the temperature dependence of the magnetization for an

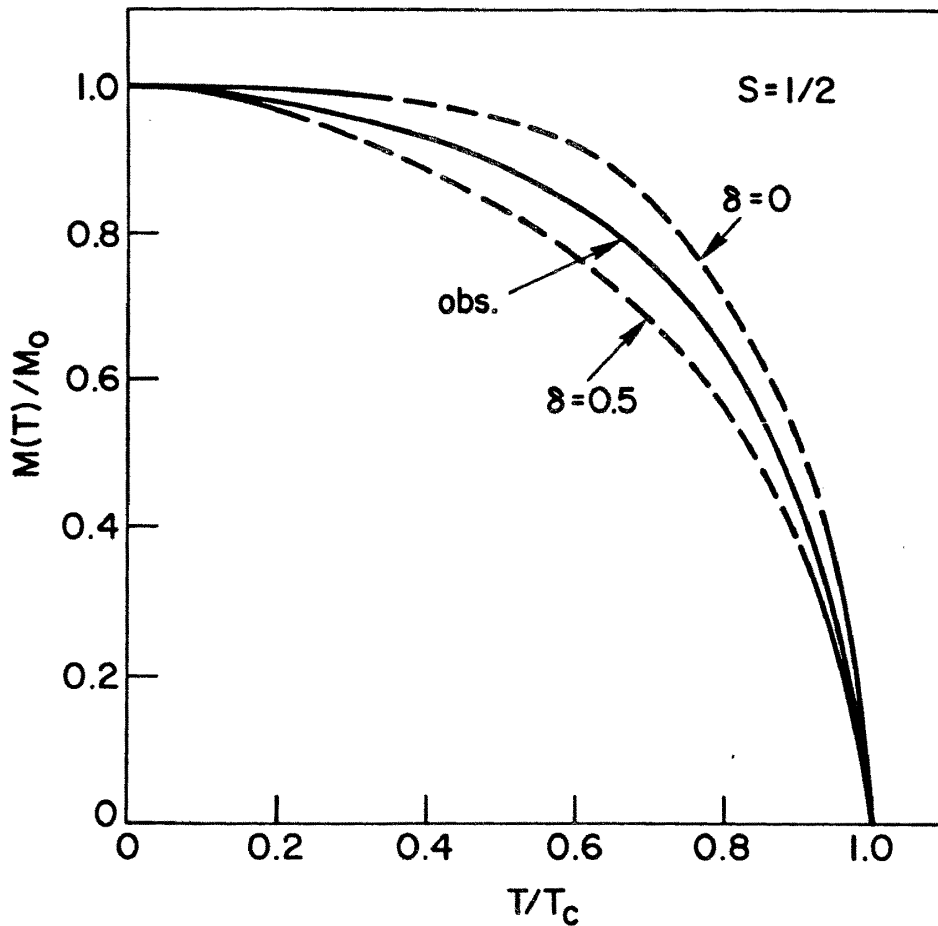


Fig. 6. The reduced magnetization $M(T)/M(0)$, for an amorphous $\text{Co}_{70}\text{B}_{20}\text{P}_{10}$ versus the reduced temperature T/T_c , with the expected curves from the molecular field approximation.

amorphous $\text{Co}_{70}\text{B}_{20}\text{P}_{10}$ alloy is shown with the expected curve from the molecular field approximation. A measure of the deviation of the exchange integral from the average can be estimated from the overall temperature dependence [31]. For this alloy $\delta = (\langle \Delta J^2 \rangle)^{1/2} / \langle J \rangle \sim 0.3$ [32].

At low temperatures the spin wave excitation describe a reduction of magnetization as;

$$M(T) = M_0 (1 - BT^{3/2} - CT^{5/2} - \dots) \quad (3.8)$$

As is well known the constant B is related to the quadratic spin wave stiffness constant D through

$$B = 2.612 (g\mu_B/M_0) (k/4D)^{3/2} \quad (3.9)$$

Low angle inelastic neutron scattering experiments and low temperature magnetization measurements were performed on an amorphous ferromagnet of $(\text{Fe}_{93}\text{Mo}_7)_{80}\text{B}_{10}\text{P}_{10}$ alloy [33]. The comparison between the calculated B from $D = 85.0 \text{ meV}\text{\AA}^2$ and observed one gives $B(\text{cal})/B(\text{obs}) = 3.12 \times 10^{-5} \text{ K}^{-3/2} / 4.5 \times 10^{-5} \text{ K}^{-3/2} \sim 0.7$. Although Eq.(3.9) is well satisfied for bcc Fe and fcc Ni [34], the poor agreement found above is characteristic of

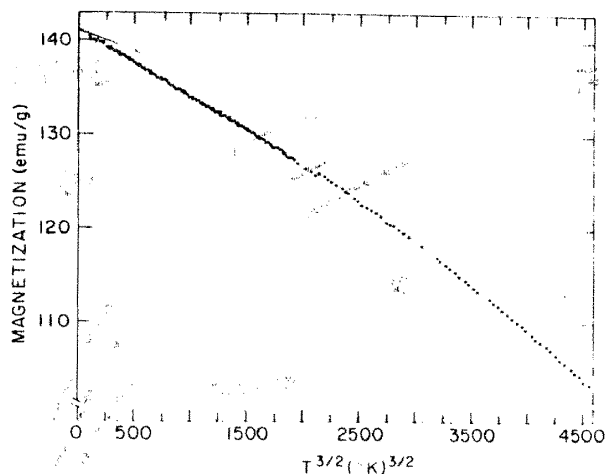


Fig. 7. The low temperature magnetization of amorphous $(\text{Fe}_{93}\text{Mo}_7)_{80}\text{B}_{10}\text{P}_{10}$ alloy versus $T^{3/2}$. A solid line indicates the slope, B, calculated from the quadratic spin wave stiffness constant, D, obtained from the inelastic neutron scattering experiment [33].

the amorphous ferromagnets studied thus far by inelastic neutron scattering. The fact that $B(\text{obs}) > B(\text{cal})$ apparently means that the spin waves contribute only about 70% of the low frequency excitation density of state. Presumably the remaining low frequency excitations are more or less localized in character because of the fluctuation of the exchange interactions in the amorphous alloy.

Near the Curie temperature, that is, in the critical region, thermal fluctuation of spins become dominant. It is interesting to examine whether a clear magnetic phase transition occurs in an amorphous alloy system where, more or less, the static fluctuation of exchange interaction and also of magnetic moments exists.

A detailed experimental study for an amorphous $\text{Co}_{70}\text{B}_{20}\text{P}_{10}$ showed that there was a definite second order transition in this amorphous ferromagnet with the critical indices $\beta = 0.402 \pm 0.007$, $\gamma = 1.342 \pm 0.025$ and $\delta = 4.39 \pm 0.05$ [35]. A clear peak of the specific heat was also observed at T_c . The amorphous alloy can be an isotropic ideal ferromagnet in the critical region in which the fluctuation of the magnetization becomes long ranged so that the microscopic randomness may be averaged out. The dynamic fluctuation melts out the static fluctuation or microscopic heterogeneity in the critical region.

ACKNOWLEDGMENTS

The author is indebted to Dr. A. Gangulee and Dr. Mitera for sending him a preprint prior to the publication.

REFERENCES

1. G. S. Cargill III, in Solid State Physics (F. Seitz, D. Turnbull and H. Ehrenreich, eds.), Academic Press, New York, Vol. 30 1975
2. J. Durand, IEEE Tran. on Magnetics MAG12 (1976) 945
3. J. Durand and M. Yung, in Amorphous Magnetism (ed. R. A. Levy and R. Hasegawa, Plenum Press, 1977) p275.
4. M. Mitera et al. to be published.
5. R. Hasegawa, R. C. O'Handley, L. E. Tanner, R. Ray and S. Kavesh Appl. Phys. Letters 29 (1976) 219
6. M. Takahashi et al.
7. K. Fukamichi, M. Kikuchi, S. Asakawa and T. Masumoto, Solid State Comm. 23 (1977)
8. W. Felsch, Z. Physik 219 (1969) 280.
9. S. Chikazumi, T. Mizoguchi and T. Yamaguchi, J. Appl. Phys. 39 (1968) 939
10. T. Mizoguchi, J. Phys. Soc. Japan 25 (1968) 904.
11. R. Hasegawa, J. Appl. Phys. 41 (1970) 4096
12. R. Hasegawa and C. C. Tsuei, Phys. Rev. B2 (1970) 1631.
13. T. Mizoguchi and T. Kudo, AIP Conf. Proc. 29 (1976) 167.
14. F. R. Szofran et al.
15. N. Heiman, K. Lee and R. I. Potter, AIP Conf. Proc. 29 (1975) 130
16. N. Heiman and N. Kazama, IBM Research Report RJ2042 (1977)
17. P. Chaudhari, J. J. Cuomo and R. J. Gambino, IBM J. Res. Develop. 17 (1973) 66
18. R. Hasegawa, J. Appl. Phys. 46 (1975) 5263
19. A. Gangulee and R. J. Kobliska, submitted to J. Appl. Phys.
20. K. Raj et al. in Amorphous Magnetism II (Plenum 1977) p221.
21. J. Durand, M. F. Lapierre and C. Robert, J. Phys. F. Metal Phys.
22. T. Mizoguchi, AIP. Conf. Proc. 34 (1976) 286
23. K. Raj et al. presented at Int. Topical Conf. on Structure and Excitation of Amorphous Solids (1976)
24. A. Heidemann, Z. Physik B20 (1975) 385.
25. K. Sato, H. Miyajima and T. Mizoguchi, to be published.
26. J. J. Rhyne, AIP Conf. Proc. 29 (1976) 182.
27. J. J. Becker et al. IEEE Trans. MAG13 (1977) 988.
28. S. F. Edwards and P. W. Anderson, J. Phys. F5 (1975) 965.
29. T. Mizoguchi, T. R. McGuire, R. J. Gambino and S. Kirkpatrick, Proc. Int. Conf. Magnetism (1976 Amsterdam) p783.
30. T. Mizoguchi, T. R. McGuire, S. Kirkpatrick and R. J. Gambino, Phys. Rev. Letters 38 (1977) 89.
31. K. Handrich, Phys. Stat. Solids 32 (1969) K55.
32. T. Mizoguchi, AIP Conf. Proc. 34 (1976) 286
33. J. D. Axe, G. Shirane, T. Mizoguchi and K. Yamauchi, Phys. Rev. B15 (1977) 2763.
34. F. Keffer, in Encyclopedia of Physics (Springer, Berlin, 1966) Vol 18-2 p. 49.
35. T. Mizoguchi and K. Yamauchi, J. de Physique 35 (1974) C4-287.
36. T. Mizoguchi, K. Yamauchi and H. Miyajima, in Amorphous Magnetism (h. D. Hooper and A. M. deGraaf, eds.) Plenum Press, New York, 1973 p. 325
37. T. Mizoguchi, K. Yamauchi and H. Miyajima, Proc. Int. Conf. on Magnetism (1973 Moscow) TOM2 p. 54.