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The magnetic properties of a ferrimagnetic bilayer system with disordered interfaces

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Abstract. A calculation is presented via the standard mean-field theory for the magnetic properties (transition temperature, compensation temperature, and magnetization curve) of a ferrimagnetic multilayer system, consisting periodically of two layers of spin-$\frac{1}{2}$ A atoms, two layers of spin-$\frac{3}{2}$ B atoms, and a disordered interface in between that is characterized by a random arrangement of A and B atoms of A_pB_{1-p} type and a negative A–B coupling. The consequences of the disordered interfaces and different anisotropies between the bulk and interface for the magnetic properties are examined. A number of characteristic behaviours, such as the possibility of two compensation points, are found for the magnetic properties.

1. Introduction

The study of magnetic multiple layers is of current interest because they are expected to have new and possibly useful properties for technological applications. In particular, rare-earth (RE)/transition-metal (TM) ferrimagnetic multilayers with different thicknesses have been produced. They can show a compensation point when their thicknesses are not very great [1, 2]. A material with a compensation temperature slightly higher than room temperature may be a good candidate for magneto-optic storage media. On the other hand, detailed analyses of the experimental data reveal that the interface of multiple layers consists of mixed layers: the two types of magnetic atom constituting the bilayer are randomly mixed to give an alloy-like disordered interface [3]. Furthermore, many experimental data indicate that the magnetic anisotropy on the interface is usually different from that in the bulk multiple layers.

On the theoretical side, much attention has been paid to the investigation of magnetic properties in an idealized multilayer system without any disordered interface [4–7]. However, most of the works are based on Heisenberg or Ising multilayer systems consisting of only spin-$\frac{1}{2}$ atoms. They have coupling constants of different magnitudes within each layer. The effects of disordered interfaces and magnetic anisotropies in a multilayer system have been little examined.

In recent works, the effect of disordered interfaces with alloying type A_pB_{1-p} on the transition temperature and magnetization has been investigated for a bilayer system consisting of two magnetic layers A and B where A and B can possess different bulk properties [8–10]. In fact, the transition temperature T_c of the bilayer Ising system with disordered interfaces has been studied in [8] and [9] when the spin S_A of the A atoms is fixed at $S_A = \frac{1}{2}$ and the spin S_B of the B atoms is a half integer ($S_B = \frac{1}{2}$ in [8] and $S_B = \frac{3}{2}$ in [9]) on the basis of the effective-field theory (EFT), superior to the standard mean-field theory (MFT) [11]. The temperature dependences of total magnetization in the bilayer spin-$\frac{1}{2}$ Ising system with disordered interfaces have been examined in [10] within the framework of the EFT, paying attention to the importance of ferromagnetic and antiferromagnetic coupling between the A and B atoms. In particular, the T_c and magnetization in Tb/Fe ferrimagnetic multilayers have been examined via the MFT in [2] by including the disordered interface of A_pB_{1-p} type, in order to explain the experimental data. However, the role of anisotropies in disordered interfaces and bulks on magnetizations have not been investigated in these works.

The aim of this work is to study via the MFT the magnetic properties (T_c, compensation temperature T_{comp}, and magnetization curves) of a ferrimagnetic bilayer system consisting of two spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ Ising ferromagnetic layers with different bulk properties and disordered interfaces, and having an antiferromagnetic coupling between the A and B atoms, in order to clarify the effects of disordered interfaces and anisotropies on the magnetic properties. We find some outstanding features of T_{comp} behaviour due to the structural disorder characterized by the concentration p of A atoms, depending on the values of anisotropies and exchange couplings in disordered interfaces and bulk layers of the system.

2. Formulation

We consider a bilayer system consisting of two ferromagnetic layers with different elements A and B, and disordered interfaces of the type A_pB_{1-p} where p is the concentration of A atoms. For simplicity, we restrict our attention to the case of the simple cubic Ising-type structure. The two-dimensional cross-section is depicted in figure 1. The Hamiltonian of the system is given by

$$H = -\sum_{(ij)} J_{ij} S_i^z S_j^z \xi_i \xi_j - D_0 \sum_i (S_i^z)^2 - D \sum_i (S_i^z)^2 \delta_{iB} \xi_i \tag{1}$$

where the first summation runs over all pairs of nearest neighbours, the spin operator S_i^z takes the usual Ising variable ($S_i^z = \pm\frac{1}{2}$) on the A atoms ($S_A = \frac{1}{2}$) or the spin-$\frac{3}{2}$ operator on the B atoms ($S_B = \frac{3}{2}$) and J_{ij} is the exchange interaction taking the value $J_A(= J_{AA})$, $J_B(= J_{BB})$, or $J_{AB}(= J_{BA})$ between the A–A, B–B, and A–B pairs of atoms. ξ_i is a random variable on the disordered interface, which can take the value of unity or zero, depending on whether the site is occupied by an A (or a B) atom. Performing the random configurational average denoted by $\langle\cdot\rangle_r$, the average value of ξ_i has a restriction

$$\langle\xi_{i=A}\rangle_r + \langle\xi_{i=B}\rangle_r = 1 \tag{2}$$

where $\langle\xi_{i=A}\rangle_r = p$ is the concentration of A atoms. D_0 is the anisotropy constant of B atoms in the B layers and the last term in (1) represents the contribution of anisotropy D for the B atoms on the disordered interfaces.

Within the standard MFT, the averaged magnetizations per site in the system are respectively given by

$$\sigma = \langle\langle S_{i=A}^z \rangle\rangle_r = \tfrac{1}{2}\tanh((\beta/2)E_\sigma) \tag{3}$$

for the A layers,

$$\sigma_I = \langle \delta_{iA}\xi_i \langle S_i^z \rangle\rangle_r / \langle \delta_{iA}\xi_i \rangle_r = \tfrac{1}{2}\tanh((\beta/2)E_{\sigma I}) \tag{4}$$

$$m_I = \langle \delta_{iB}\xi_i \langle S_i^z \rangle\rangle_r / \langle \delta_{iB}\xi_i \rangle_r = F(E_{mI}) \tag{5}$$

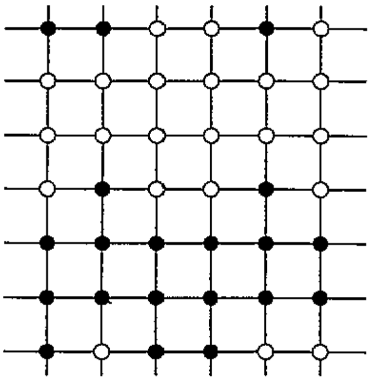

Figure 1. Part of the two-dimensional cross-section through the magnetic bilayer system consisting of the two magnetic A and B layers ($S_A = \frac{1}{2}$ and $S_B = \frac{3}{2}$) and disordered interfaces of the type A_pB_{1-p}. p is the concentration of A atoms in the interface.

for the disordered interfaces and

$$m = \langle\langle S^z_{i=B}\rangle\rangle_r = f(E_m) \tag{6}$$

for the B layers, where $\beta = 1/k_BT$, $\delta_{i\alpha}$ (α = A or B) is the Kronecker δ function and the functions $F(x)$ and $f(x)$ are defined by

$$F(x) = \tfrac{1}{2}[3\sinh(3\beta x/2) + \exp(-2D\beta)\sinh(\beta x/2)]/[\cosh(3\beta x/2) + \exp(-2D\beta)\cosh(\beta x/2)] \tag{7a}$$

for the B atoms in the disordered interfaces and

$$F(x) = \tfrac{1}{2}[3\sinh(3\beta x/2) + \exp(-2D_0\beta)\sinh(\beta x/2)]/[\cosh(3\beta x/2) + \exp(-2D_0\beta)\cosh(\beta x/2)] \tag{7b}$$

for the B atoms in the B layers. The parameters E_σ, $E_{\sigma I}$, E_{mI}, and E_m are defined by

$$\begin{aligned} E_\sigma &= 5J_A\sigma + pJ_A\sigma_I + (1-p)J_{AB}m_I \\ E_{\sigma I} &= 4pJ_A\sigma_I + 4(1-p)J_{AB}m_I + J_A\sigma + J_{AB}m \\ E_{mI} &= 4pJ_{AB}\sigma_I + 4(1-p)J_Bm_I + J_{AB}\sigma + J_Bm \\ E_m &= 5J_Bm + pJ_{AB}\sigma_I + (1-p)J_Bm_I. \end{aligned} \tag{8}$$

The averaged magnetization m_T per site in the interface is consequently given by

$$m_T = p\sigma_I + (1-p)m_I. \tag{9}$$

Thus, the total magnetization $\mathcal{M}$ in the system is

$$M = \mathcal{M}/3N = \sigma + m_T + m \tag{10}$$

where N is the number of magnetic atoms in each layer.

In order to obtain the transition temperature T_c, it is necessary to solve the coupled equations (3)–(6). For this purpose, expanding the right-hand sides of these equations and considering only terms linear in σ, σ_I, m_I, and m, we have the matrix equation of the type

$$\mathcal{N}\begin{pmatrix}\sigma\\ \sigma_I\\ m_I\\ m\end{pmatrix}=0 \tag{11}$$

and the T_c of the bilayer system can be determined from

$$\det\mathcal{N}=0 \tag{12}$$

by selecting the highest solution in it. On the other hand, the compensation temperature T_{comp}, if it does exist in the system with $J_{AB} < 0$, can be obtained by introducing the condition

$$M=0 \tag{13}$$

into the definition (10).

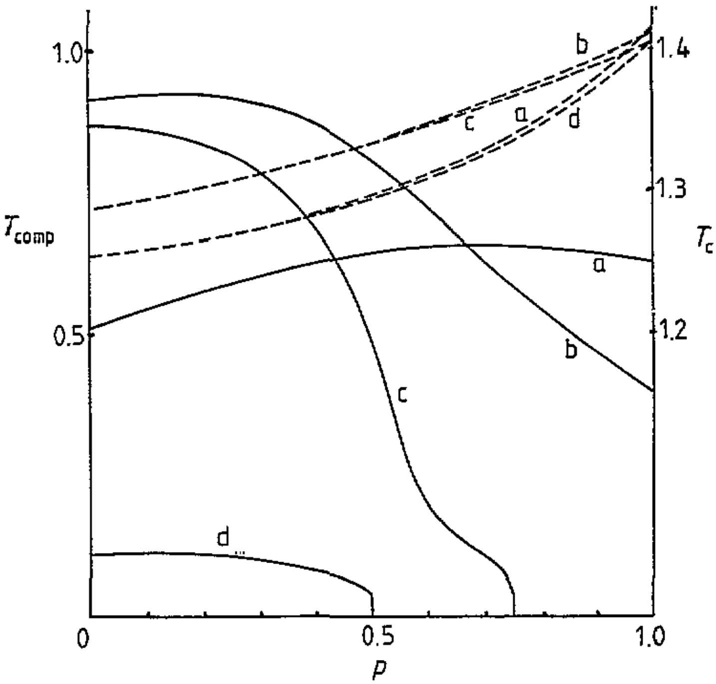

Figure 2. The phase diagram (T_{comp} (solid line) and T_c (dashed line) versus p) of the bilayer system with fixed values $J_B/J_A = 0.05$ and $J_{AB}/J_A = -0.3$, when the pair values $(D_0/J_A, D/J_A)$ are changed: (0.5, −3.0) for curves a, (0.0, 0.5) for curves b, (−3.0, 0.5) for curves c, and (−3.0, −3.0) for curves d.

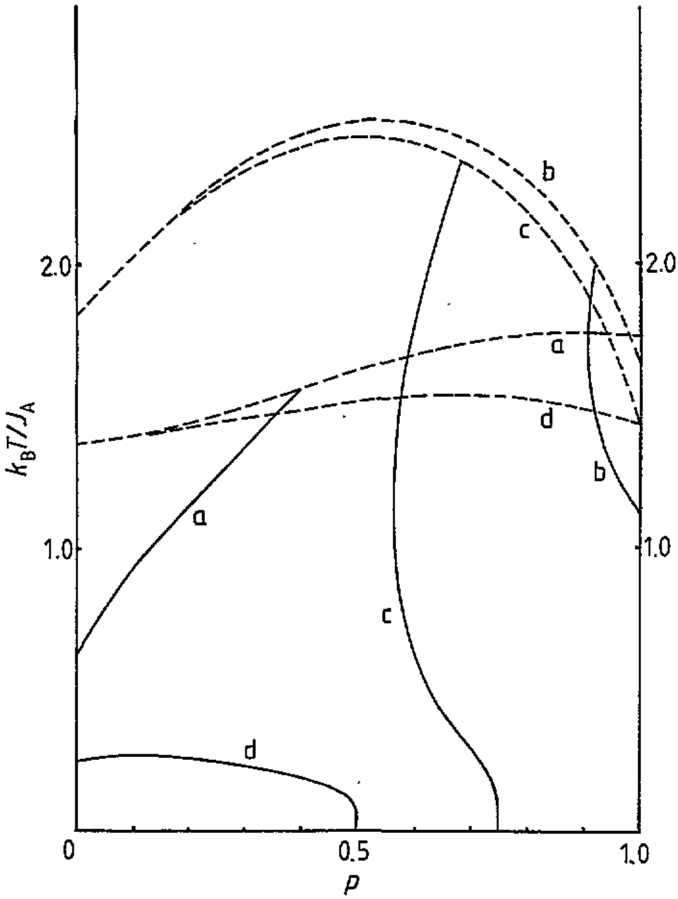

Figure 3. The phase diagram (T_{comp} (solid line) and T_c (dashed line) versus p) of the bilayer system with fixed values $J_B/J_A = 0.05$ and $J_{AB}/J_A = -1.5$, when the pair values $(D_0/J_A, D/J_A)$ are changed in the same way as those of figure 2: $(0.5, -3.0)$ for curves a, $(0.0, 0.5)$ for curves b, $(-3.0, 0.5)$ for curves c and $(-3.0, -3.0)$ for curves d.

3. The phase diagram

Equations (3)–(6) are solved numerically in the linear limit to give T_c and also to determine T_{comp} for some typical sets of values J_B/J_A, J_{AB}/J_A, D_0/J_A, and D/J_A in the ferrimagnetic system with $J_{AB} < 0$. Here, in order to relate our results to real systems, such as RE/TM multilayers, let us take $J_A > J_B > 0$, assuming that A and B atoms are respectively TM and RE atoms. On the other hand, as discussed in [8] and [9], the behaviour of T_c versus p in the system strongly depends on the ratio of $|J_{AB}/J_A|$. Therefore, in order to obtain the phase diagrams (T_c and T_{comp} versus p curves) as well as the magnetization curves (see the next section), we have taken the following sets of fixed values:

$$J_B/J_A = 0.05 \qquad J_{AB}/J_A = -0.3 \qquad \text{or} \qquad -1.5$$

corresponding to reasonable practical values in the multilayer experiments. For each set, the phase diagram (or magnetization curve) is obtained numerically by selecting typical values of D_0/J_A and D/J_A and selecting the value of p.

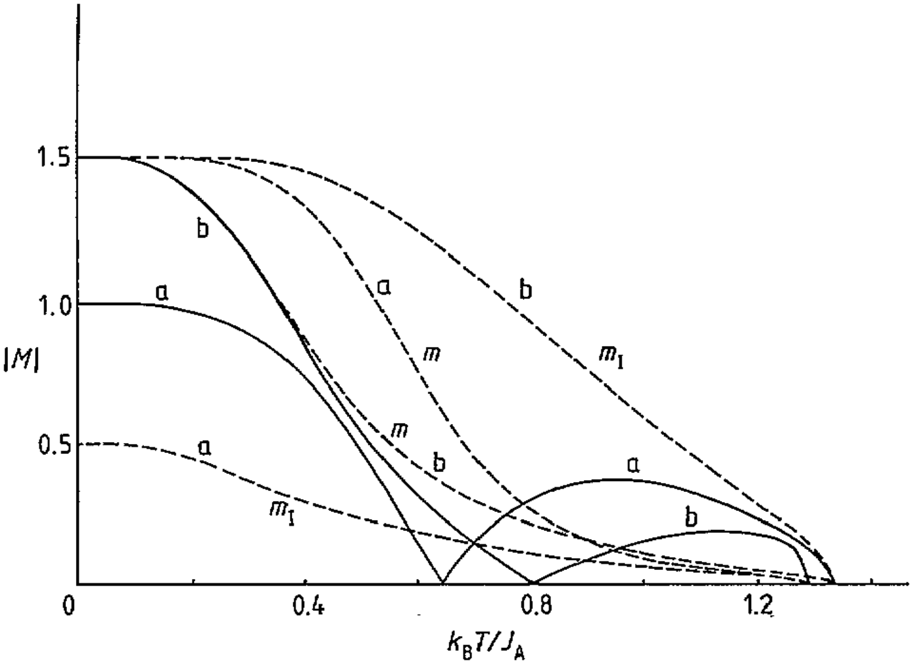

Figure 4. The temperature dependences of $|M|$ (solid lines) as well as m_I and m (dashed lines) for the bilayer systems labelled a and b in figure 2 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -0.3$ and the two sets of values $(D_0/J_A, D/J_A)$, namely (0.5, −3.0) for curves a and (0.0, 0.5) for curves b, when the value of p is fixed at $p = 0.5$.

Figure 2 shows the phase diagram of the bilayer system with $J_B/J_A = 0.05$, when $J_{AB}/J_A = -0.3$ and typical pair values $(D_0/J_A, D/J_A)$ are selected. Solid and dashed lines represent the T_{comp} and T_c curves, respectively. Figure 2 curves (a–d) are presented for the pair values $(D_0/J_A, D/J_A) = (0.5, -3.0)$ for curves labelled a, (0.0, 0.5) for curves b, (−3.0, 0.5) for curves c, and (−3.0, −3.0) for curves d.

As shown in the figure, the T_{comp} curves of the system may exhibit a variety of characteristic behaviours as a function of p (or the structural disorder on the interface), although the T_c curves take the standard forms due to the weak A–B coupling ($J_{AB}/J_A = -0.3$). In particular, the T_{comp} curve labelled c shows a particular feature near $p = 0.75$ and reduces to zero at $p = 0.75$, since at $T = 0$ K the spins of B atoms are in the $S_i^z = \pm\frac{3}{2}$ state at the disordered interface since $D/J_A = 0.5$ and in the $S_i^z = \pm\frac{1}{2}$ state on the B layers since $D_0/J_A = -3.0$, and hence from (9) and (10) $M = -\frac{1}{2}-\frac{1}{2}p+\frac{3}{2}(1-p)+\frac{1}{2} = \frac{1}{2}(3-4p)$. Also, the T_{comp} curve labelled d reduces to zero at $p = 0.5$, since at $T = 0$ K the spins of B atoms in the B layers and interfaces are both in the $S_i^z = \pm\frac{1}{2}$ state due to large in-plane anisotropies ($D_0/J_A = D/J_A = -3.0$) and $M = -\frac{1}{2}-\frac{1}{2}p+\frac{1}{2}(1-p)+\frac{1}{2} = \frac{1}{2}(1-2p)$. On the other hand, the T_{comp} curves labelled a and b do not reduce to zero in the whole range of p; for curve b the spin directions of B atoms in the B layers and interfaces are both in the $S_i^z = \pm\frac{3}{2}$ state at $T = 0$ K due to the perpendicular anisotropies ($D_0/J_A = 0.0$, $D/J_A = 0.5$). For curve a, at $T = 0$ K $M = -\frac{1}{2} - \frac{1}{2}p + \frac{1}{2}(1-p) + \frac{3}{2} = \frac{3}{2} - p$, due to $D_0/J_A = 0.5$ (perpendicular to the B layers) and $D/J_A = -3.0$ (in plane at the interfaces). Thus, these results clearly indicate that the behaviour of T_{comp} heavily depends on the anisotropy constants of B atoms in the bulk and interface.

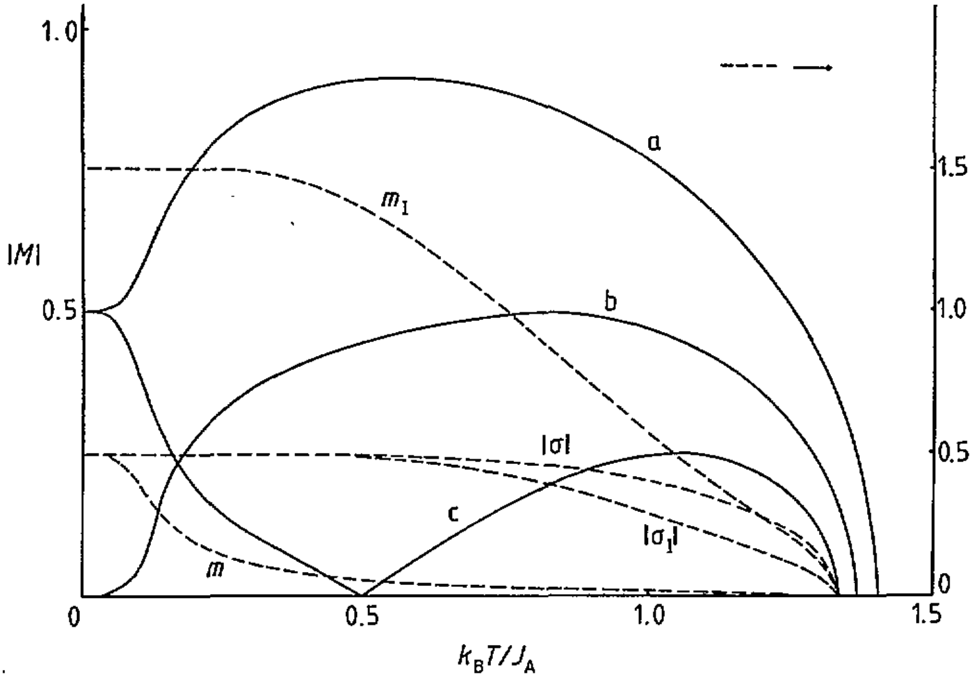

Figure 5. The temperature dependences of $|M|$ (solid lines) as well as $|\sigma|$, $|\sigma_1|$, m_1, and m (dashed lines) for the bilayer system labelled c in figure 2 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -0.3$, and the pair values $D_0/J_A = -3.0$, $D/J_A = 0.5$, when three values of p are selected: $p = 1.0$ (curve a), $p = 0.75$ (curve b), and $p = 0.5$ (curve c). The dashed lines are obtained for $p = 0.5$.

Now, as discussed in [8] and [9], the existence of disordered interfaces plays a major role for the behaviour of T_c, when the interaction $|J_{AB}|$ takes a large value in comparison with J_A and J_B. Then, the T_c value becomes larger in the region $0 < p < 1$ than those for the two pure ($p = 0.0$ and $p = 1.0$) interfaces. Therefore, for the case of strong negative A–B coupling ($J_{AB}/J_A = -1.5$) the phase diagram of the system with $J_B/J_A = 0.05$ is presented in figure 3 by selecting the same pair values (D_0/J_A, D/J_A) as those of figure 2. The solid and dashed lines also represent the T_{comp} and T_c curves, respectively.

As depicted in figure 3, the T_c curves become larger in the region $0 < p < 1$ than those of the two pure interfaces, especially for curves b and c. Similar behaviour has been obtained in previous works [8,9] for the case of strong A–B interaction ($|J_{AB}|$). On the other hand, the T_{comp} versus p curves may exhibit some outstanding features, which are clearly different from the corresponding results of figure 2.

(i) The T_{comp} curves for the systems labelled a, b, and c terminate at their T_c curves, although the T_{comp} curve labelled d is independent of the T_c curve, like those of figure 2. As a result, the compensation point (or points) for a, b, and c can be obtained for the restricted regions of p in contrast to the corresponding T_{comp} curves of figure 2.

(ii) The T_{comp} curve of the system labelled b or c has two solutions in a certain range of p. For instance, the result of the system labelled c indicates that two compensation points can be obtained in the region of $0.565 < p < 0.68$.

Now, the findings (i) and (ii) reflect the fact that the strong exchange coupling ($|J_{AB}/J_A| = 1.5$) in the disordered interfaces dominates the total magnetic behaviour of

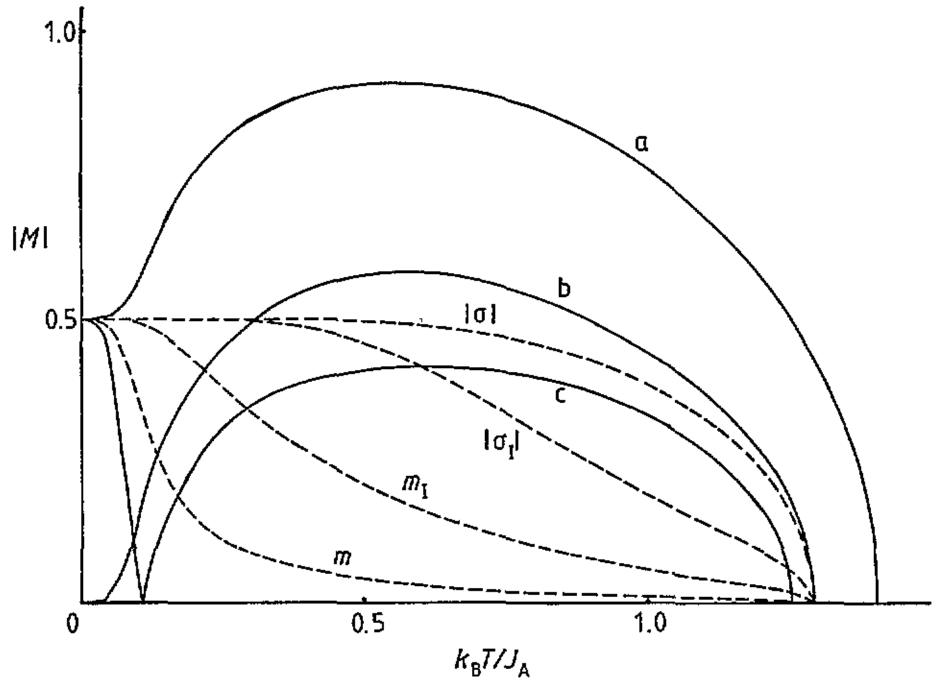

Figure 6. The temperature dependences of $|M|$ (solid lines) as well as $|\sigma|$, $|\sigma_I|$, m_I, and m (dashed lines) for the bilayer system labelled d in figure 2 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -0.3$, and the pair values $D_0/J_A = D/J_A = -3.0$, when three values of p are selected: $p = 1.0$ (curve a), $p = 0.5$ (curve b), and $p = 0.0$ (curve c). The dashed lines are obtained for $p = 0.5$.

the bilayer system. In fact, the T_{comp} in a bulk ferrimagnetic alloy of A_pB_{1-p} type normally has an end point on the T_c line, if it does exist. It also represents the total magnetic properties of the bilayer system being strongly affected by the existence of disordered interfaces with the strong coupling $|J_{AB}|$. On the other hand, the behaviour of T_{comp} for curve d in figure 3 is clearly different from the others and has a form similar to the correspoonding one in figure 2. This is due to the fact that both spins of B atoms in the bulk and interface layers are firmly fixed in the $S_i^z = \pm\frac{1}{2}$ state, since $D_0/J_A = D/J_A = -3.0$, and hence the effect of the strong $|J_{AB}|$ on T_c and T_{comp} is weaker than for the others. In other words, the results of figure 2 indicate that the compensation point is not affected by the weak exchange coupling ($|J_{AB}/J_A| = 0.3$) in the disordered interfaces and results from the exact cancellation between σ, σ_I, m_I, and m due to their different temperature dependences inherent to the bilayer system.

4. The magnetization curve

Let us in this section study the temperature dependences of magnetizations σ, σ_I, m_I, m, and the mean bulk-like magnetization M in the bilayer system by solving the coupled equations (3)–(6) numerically. Then, some typical values of p have been selected from the systems of figures 2 and 3, in order to obtain the magnetization curves.

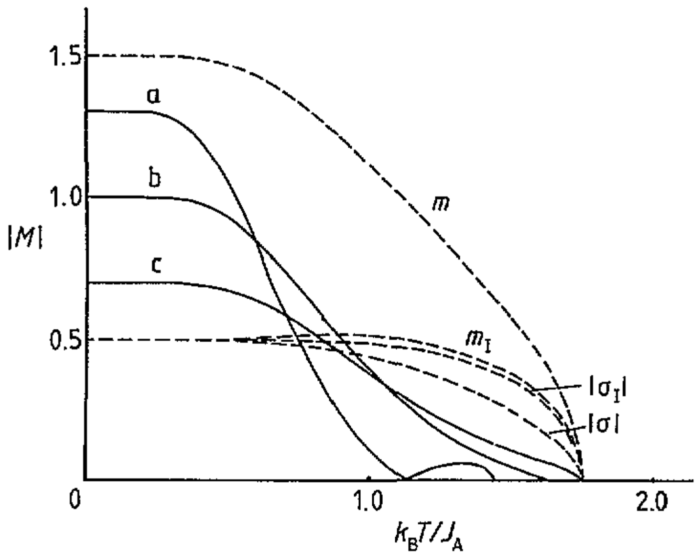

Figure 7. The thermal variations of $|M|$ (solid lines) as well as $|\sigma|$, $|\sigma_I|$, m_I, and m (dashed lines) for the bilayer system labelled a in figure 3 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -1.5$, and the pair values $D_0/J_A = 0.5$, $D/J_A = -3.0$, when three values of p are selected: $p = 0.2$ (curve a), $p = 0.5$ (curve b), and $p = 0.8$ (curve c). The dashed lines are obtained for $p = 0.8$.

(i) The case of the bilayer system with $J_{AB}/J_A = -0.3$ and $J_B/J_A = 0.05$ in figure 2: figures 4–6 present the results of the four systems labelled a–d in figure 2, when some characteristic values of p are selected from the phase diagram.

In figure 4, the temperature dependences of $|M|$ (solid lines), m, and m_I (dashed lines) are depicted for the two systems labelled a and b in figure 2 with two sets of pair values $(D_0/J_A, D/J_A)$, namely (0.0, 0.5) and (0.5, −3.0), when the value of p is fixed at $p = 0.5$. Each total magnetization M can express a compensation point below T_c ($T_{comp} < T_c$), as predicted in figure 2. Here, notice the different behaviours of m and m_I for the two systems, depending on whether the anisotropy D_0 or D is perpendicular (positive) or in plane (negative): for the dashed curves a, m_I is clearly modified by the large in-plane anisotropy ($D/J_A = -3.0$) at the disordered interfaces to $m_I = \frac{1}{2}$ at $T = 0$ K, although m takes the saturation value $m = \frac{3}{2}$ due to the perpendicular anisotropy ($D_0/J_A = 0.5$) in the bulk layers. In contrast, the m and m_I for the dashed curves b have the saturation value $m = m_I = \frac{3}{2}$ at $T = 0$ K owing to $D_0/J_A = 0.0$ and $D/J_A = 0.5$.

In figure 5, three results for $|M|$ (solid lines) are presented for the bilayer system labelled c in figure 2 with the pair values ($D_0/J_A = -3.0$, $D/J_A = 0.5$), selecting three values of p, namely $p = 1.0$ (curve a), $p = 0.75$ (curve b), and $p = 0.5$ (curve c). According to the Néel classification [12], the solid curves a, b, and c correspond respectively to the P-type, L-type, and N-type forms. In the figure, the dashed lines represent $|\sigma|$, $|\sigma_I|$, m_I, and m for the case of $p = 0.5$. Then, m takes the saturation value $m = \frac{1}{2}$ at $T = 0$ K, since $D_0/J_A = -3.0$.

Figure 6 shows the three results for $|M|$ (solid lines) for the bilayer system labelled d in figure 2 with large in-plane anisotropies ($D_0/J_A = D/J_A = -3.0$), when three values of p are selected, namely $p = 1.0$ (curve a), $p = 0.5$ (curve b), and $p = 0.0$ (curve c). Again, the dashed lines represent $|\sigma|$, $|\sigma_I|$, m_I, and m for the case of $p = 0.5$. Here, m and m_I take the saturation value $m = m_I = \frac{1}{2}$ at $T = 0$ K because $D_0/J_A = D/J_A = -3.0$.

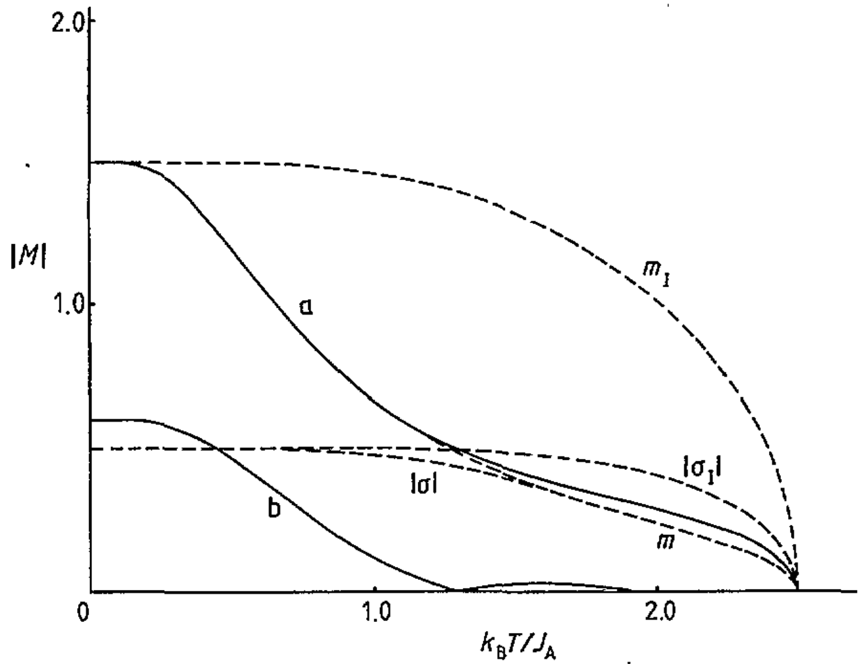

Figure 8. The thermal variations of $|M|$ (solid lines) as well as $|\sigma|$, $|\sigma_I|$, m_I, and m (dashed lines) for the bilayer system labelled b in figure 3 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -1.5$ and the pair values $D_0/J_A = 0.0$, $D/J_A = 0.5$, when two values of p are selected: $p = 0.5$ (curve a) and $p = 0.95$ (curve b). The dashed lines are obtained for $p = 0.5$.

(ii) The case of the bilayer system with $J_{AB}/J_A = -1.5$ and $J_B/J_A = 0.05$ in figure 3: figures 7–10 present the results for the four systems labelled a–d in figure 3, selecting some typical values of p in the phase diagram.

Figure 7 shows the thermal variations of $|M|$ (solid lines) for the bilayer system labelled a in figure 3 with $D_0/J_A = 0.5$ and $D/J_A = -3.0$, when three values of p are selected, namely $p = 0.2$ (curve a), $p = 0.5$ (curve b), and $p = 0.8$ (curve c). Comparing the solid curve a in figure 4 with the solid curve b in figure 7, the compensation point cannot be obtained in figure 7 although the value of p is $p = 0.5$ in both systems. This is consistent with the prediction of figures 2 and 3 (phase diagrams). The dashed lines represent $|\sigma|$, $|\sigma_I|$, m_I, and m for the system with $p = 0.8$. The saturation value of m at $T = 0$ K is $m = \frac{3}{2}$ and the saturation value of m_I is $m_I = \frac{1}{2}$ because $D_0/J_A = 0.5$ and $D/J_A = -3.0$. In particular, one should notice that the magnetization curve of $|\sigma_I|$ is larger than that of $|\sigma|$ in the whole temperature region. This phenomenon expresses another fact, that the strong A–B coupling ($J_{AB}/J_A = -1.5$) *in the disordered interfaces dominates the total magnetic* behaviour of the bilayer system. In fact, similar phenomena have been observed for the surface magnetism in a semi-infinite magnetic system with a strong surface interaction in comparison with an interaction in the bulk [13].

In figure 8, the temperature dependences of $|M|$ (solid lines) for the bilayer system labelled b in figure 3 with $D_0/J_A = 0.0$ and $D/J_A = 0.5$ are depicted by selecting two values of p, namely $p = 0.5$ (curve a) and $p = 0.95$ (curve b). The dashed lines represent $|\sigma|$, $|\sigma_I|$, m_I, and m for the case of $p = 0.5$. When selecting $p = 0.915$ in curve b of figure 3, for instance, we can find the two compensation points in the $|M|$ curve, although

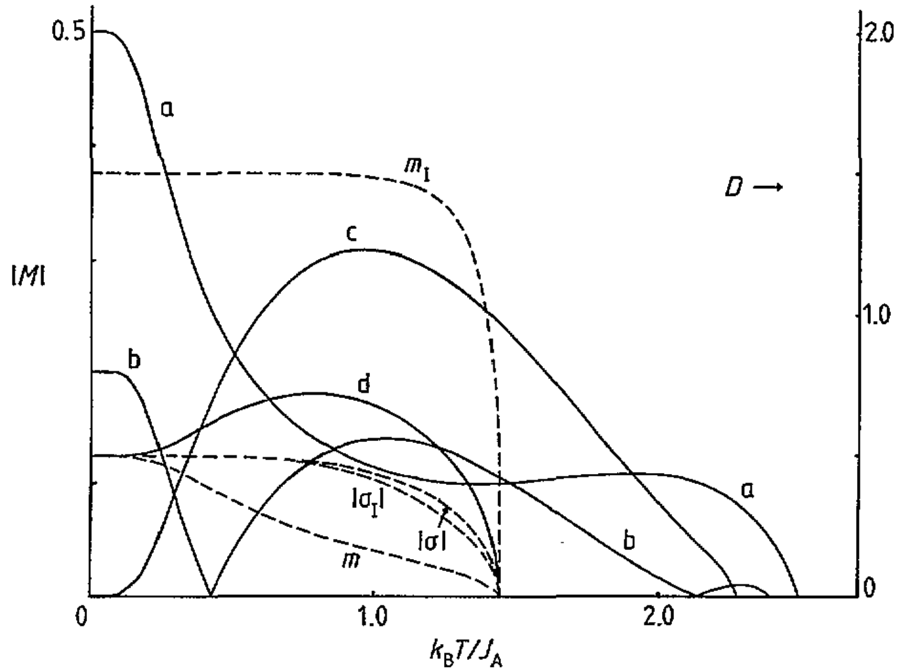

Figure 9. The thermal variations of $|M|$ (solid lines) as well as $|\sigma|$, $|\sigma_I|$, m_I, and m (dashed lines) for the bilayer system labelled c in figure 3 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -1.5$ and the pair values $D_0/J_A = -3.0$, $D/J_A = 0.5$, when four values of p are selected: $p = 0.5$ (curve a), $p = 0.65$ (curve b), $p = 0.75$ (curve c) and $p = 1.0$ (curve d). The dashed lines are obtained for the bilayer system with a pure ($p = 1.0$) interface.

this is not given.

Figure 9 shows the thermal variations of $|M|$ (solid lines) for the bilayer system labelled c in figure 3 with $D_0/J_A = -3.0$ and $D/J_A = 0.5$, when four typical values of p are selected, namely $p = 0.5$ (curve a), $p = 0.65$ (curve b), $p = 0.75$ (curve c), and $p = 1.0$ (curve d). Here, one should notice that the $|M|$ curve labelled b can clearly express the two compensation points below T_c, as predicted in curve c of figure 3. However, the situation is completely different from that of the spin-$\frac{1}{2}$ bilayer system with disordered interfaces [10]; the possibility of two compensation points could not be obtained in [10], since anisotropies D_0 and D were not included. Furthermore, the $|M|$ curve labelled a at first decreases rapidly from the saturation value, and with increasing T it shows a broad minimum and maximum below T_c. As far as we know, these findings have not been reported except in some recent related works [2, 14]. In the figure, the dashed lines again represent $|\sigma|$, $|\sigma_I|$, m_I, and m for the bilayer system with a pure ($p = 1.0$) interface. Then, m takes the saturation value $m = \frac{1}{2}$ at $T = 0$ K due to the large in-plane bulk anisotropy ($D_0/J_A = -3.0$), although $m_I = \frac{3}{2}$ owing to the perpendicular anisotropy ($D/J_A = 0.5$) in the disordered interfaces. In contrast to the features of $|\sigma|$ and $|\sigma_I|$ in figures 7 and 8, the value of $|\sigma|$ for this case becomes larger than that of $|\sigma_I|$ in the whole temperature region.

Finally, the temperature dependences of $|M|$ (solid curves) for the bilayer system labelled d in figure 3 with $D_0/J_A = D/J_A = -3.0$ are depicted in figure 10, selecting three values of p, namely $p = 0.0$ (curve a), $p = 0.5$ (curve b), and $p = 0.8$ (curve c). They also exhibit the N-type, L-type, and P-type forms for a, b, and c. The dashed lines then represent

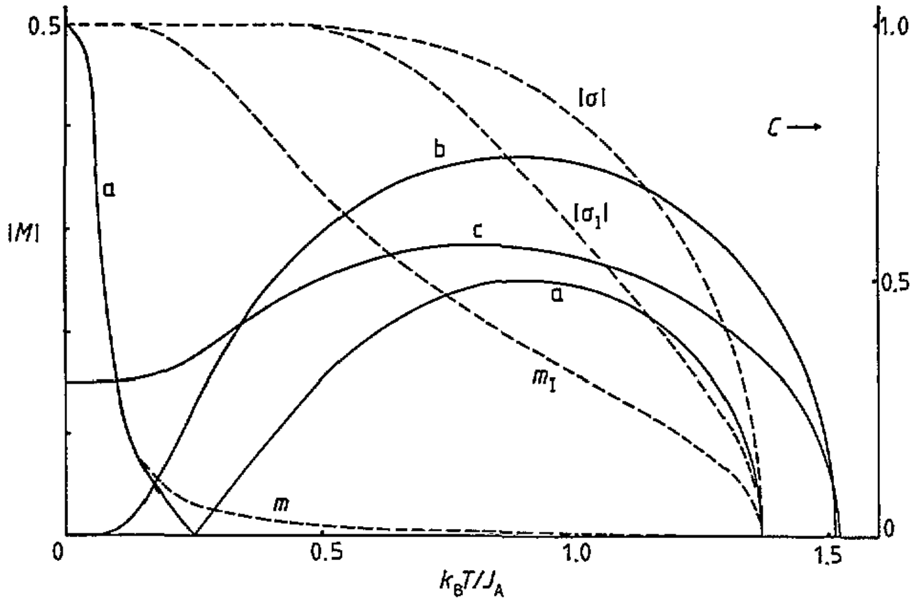

Figure 10. The thermal variations of $|M|$ (solid lines) as well as $|\sigma|$, $|\sigma_I|$, m_I, and m (dashed lines) for the bilayer system labelled d in figure 3 with $J_B/J_A = 0.05$, $J_{AB}/J_A = -1.5$ and the pair values $D_0/J_A = D/J_A = -3.0$, when three values of p are selected: $p = 0.0$ (curve a), $p = 0.5$ (curve b), and $p = 0.8$ (curve c). The dashed lines are obtained for the bilayer system with a pure ($p = 0.0$) interface.

$|\sigma|$, $|\sigma_I|$, m_I, and m for the system with a pure ($p = 0.0$) interface. Because of the large in-plane anisotropies, m and m_I take the saturation value $m = m_I = \frac{1}{2}$ at $T = 0$ K, but the value of m_I is larger than that of m in the whole temperature region. This phenomenon corresponds to the $|\sigma|$ and $|\sigma_I|$ features in figures 7 and 8, although $|\sigma| > |\sigma_I|$, as in the case of figure 9.

5. Conclusions

In this work, we have investigated the phase diagram and component magnetizations in a spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ bilayer system $(A)_2(A_pB_{1-p})(B)_2$ with a disordered interface (or the system depicted in figure 1) on the basis of the standard mean-field theory. We have shown that the existence of a disordered interface may significantly affect the total magnetic properties (transition temperature, compensation temperature, and magnetizations) of the bilayer system. The results have also clarified the outstanding effects of the ferrimagnetic A–B coupling in the disordered interface and different anisotropies between the bulk and interface in the magnetic properties, as shown in figures 2–10. In particular, for the case of strong A–B ferrimagnetic coupling ($J_{AB}/J_A = -1.5$) we have found that the system with in-plane bulk and perpendicular interface anisotropies can acquire the possibility of two compensation points for a certain domain of values of the random concentration parameter p that characterizes the disorder in the interface. From the experimental point of view, perpendicular anisotropy is possible for the surface and interface magnetism while the bulk anisotropy is in plane. Thus, the possibility of two compensation points may be of experimental interest for the future research of magnetic multilayer systems. Furthermore, the results obtained in this work may give a key to the mystery of whether the role of disordered interfaces and anisotropies must be taken into account in analysing the experimental data of real systems, such as RE/TM multilayer films.

Finally, it may be worth commenting on the present experimental and theoretical situations in the research of multilayer systems. Experimentally, it is well known that in the region between the two components of layered systems the two types of magnetic atom are mixed randomly to give an alloy-like disordered interface. From the theoretical point of view, the effects of the disordered interface on the magnetic properties, particularly within the Ising model, have been little examined, except for some special cases [8, 10] consisting of spin-$\frac{1}{2}$ ($S_A = S_B = \frac{1}{2}$) atoms. On the other hand, it is normally believed from experimental evidence that the magnetic anisotropy in the disordered interfaces may be different from those of the layered systems. As far as we know, however, the effects of both properties, namely different anisotropies and disordered interfaces, on the magnetic properties in a multilayer system have not been discussed theoretically. In this work, we have examined both roles in the magnetic properties in a ferrimagnetic bilayer system with disordered interfaces. As shown in figures 2–10, the obtained results exhibit many unexpected features. They may be of future experimental and theoretical interest in the research of magnetic multilayered systems.

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