Critical behaviours of a ferrimagnetic alternating superlattice with disordered interfaces

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The phase diagrams and magnetic properties of a ferrimagnetic multilayer system consisting periodically of L layers of spin-1/2 A atoms, L layers of spin-1 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, are investigated by the use of an effective field method within the framework of a single cluster theory. The effects of the disorder in the interface, the bulk and interface anisotropies and different coupling constants on the magnetic properties are examined in details. A number of characteristic features such as the possibility of a compensation point are found.

Keywords: Phase diagram; Ferrimagnetic system; Multilayer system; Disordered Interface.

1. Introduction

In recent years, the study of magnetic multilayer systems (superlattices, films, etc.) 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 have been produced and extensively studied [1-3]. They can show a compensation point when their thickness are not very great [1,2]. Also, a systematic study of EuTe/PbTe superlattices [4], shows considerable changes of the Néel temperature depending on the number of monolayers of EuTe and PbTe in a supercell. 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 analysis of the experimental data reveal that in the region between the two components of the layered systems, the two types of magnetic atoms are mixed randomly to give an alloy-like disordered interfaces [2,5]. Furthermore, many experimental data indicate that the magnetic anisotropy on the interface is usually different from that in the bulk multiple layers [6]. Therefore, it is reasonable to assume that the existence of a disordered interface and different anisotropies can modify the magnetic properties of the multilayer systems. In order to explain the experimental data, the transition temperature T_c and the magnetization of Tb/Fe ferrimagnetic multilayer have been examined using mean field theory (MFT) [2,3], by including disordered interfaces of the type A_PB_{1-P}.

On the theoretical side, many efforts [7-10] have been directed to clarify the magnetic properties of Heisenberg or Ising multilayer systems, consisting of only spin-1/2 atoms. With different bulk properties. Some recent works [11,15] have investigated the role of disordered interfaces in the bilayer system consisting periodically of two

magnetic layers A and B where A and B can possess different bulk properties.

The aim of this work is to investigate the magnetic multilayer Ising system, consisting periodically of L layers of spin-1/2 A atoms, L layers of spin-1 B atoms and a disordered interfaces characterized by a random arrangement of A and B atoms like a two-dimensional A_PB_{1-P} alloy. This study is done within the framework of an effective field theory based on the use of a probability distribution technique [16], which is superior to the MFT.

II. Formalism

We consider a superlattice consisting periodically of L layers of A atoms, a disordered interface layer A_PB_{1-P} of A and B atoms randomly mixed, and then L layers of B atoms. For simplicity, we restrict our attention to the case of a simple cubic structure. Let the A and B atoms have different spins (S_A=1/2 and S_B=1 respectively). The Hamiltonian of the system is given by:

$$H=-\sum_{i,j} J_{ij} S_i^z S_j^z - D_0 \sum_i \left(S_i^z\right)^2 - D \sum_i \left(S_i^z\right)^2 \delta_{iB} \xi_i$$

Where the first sum runs over all pairs of nearest neighbors J_{ij} is the exchange interaction taking the values J_{AA} , J_{BB} and J_{AB} between A-A, B-B and A-B pairs of atoms. D_0 and D are the uniaxial single-ion anisotropy constants on the B layer and disordered interfaces respectively. ξ_i is a random variable on the disordered interfaces which can take

the value of unity or zero, depending on whether the site i, is occupied by an A (or B) atom.

The purpose of the paper is to study the phase diagrams of such a system, using the effective field theory based on the use of a probability distribution technique that correctly accounts for the single site kinematics relations [16,17]. This method provides results which are superior to those obtained within the MFT approximation.

For the system under consideration, the application of this method leads to the layer magnetizations:

•For the A layers

$$\sigma_1=\langle F\left(NJ_{AA}\sigma_{10}+N_0J_{AA}\sigma_{20}+N_0\left(J_{AA}\xi\right.\right.$$
$$=\langle F\left(X_1\right)\rangle \quad , \qquad (2)$$

For $2 \le n \le L-1$

$$\sigma_n=\langle F\left(NJ_{AA}\sigma_{n0}+N_0J_{AA}\sigma_{n-1,0}+N_0J_{A}\right.$$
$$=\langle F\left(X_2\right)\rangle \quad , \qquad (2)$$
$$\sigma_L=\sigma_1$$

For the interface

$$\sigma_I=\langle F\left(N_0J_{AA}\sigma_{L0}+N_0J_{AB}S_{10}+N\left(J_{AA}\xi\right.\right.$$
$$=\langle F\left(X_3\right)\rangle \quad , \qquad (3)$$
$$m_I=\langle G_1\left(N_0J_{AA}\sigma_{L0}+N_0J_{AB}S_{10}+N\left(J_{AA}\right.\right.$$
$$=\langle G_1\left(X_4\right)\rangle \quad , \qquad (3)$$
$$q_I=m_I\left(G_1\to G_2\right) \quad ,$$

•For the B layers

$$m_1=\langle G_1\left(NJ_{AA}S_{10}+N_0J_{BB}S_{20}+N_0\left(J_{AB}\right.\right.$$
$$=\langle G_1\left(X_5\right)\rangle \quad , \qquad (4)$$

For $2 \le n \le L-1$

$$m_n=\langle G_1\left(NJ_{BB}S_{n0}+N_0J_{BB}S_{n-1,0}+N_0J_{B}\right.$$
$$=\langle G_1\left(X_6\right)\rangle \quad ,$$
$$m_L=m_1$$

with

$$G_1(X)=\frac{2\sinh(\beta X)}{2\cosh(\beta X)+\exp(-\beta Y)} \quad , \qquad (5)$$

$$G_2(X)=\frac{2\cosh(\beta X)}{2\cosh(\beta X)+\exp(-\beta Y)} \quad ,$$

$$\mathrm{F(X)}=\frac{1}{2}\tanh(\beta \mathrm{X}) \quad ,$$

$$Y=\begin{cases} D & \text{in the interface} \\ D_0 & \text{in the bulk} \end{cases} ,$$

To perform the averaging on the right-hand sides of Eq. (2-4), we follow the general approach described in Refs. [16, 17] and obtain the layer magnetizations.

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

$$m=p\sigma_I+(1-p)\,m_I \qquad (6)$$

Thus, the total magnetization in the system is:

$$M_T=\frac{1}{(2L+2)N_A}\left(\sum_{i=1}^{L}\sigma_i+2m+\sum_{i=1}^{L}m_i\right) \qquad (7)$$

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

We are interested in the calculation of the longitudinal ordering near the transition temperature. The usual argument that the layer longitudinal magnetization m_{nz} tends to zero as the temperature approaches its critical value, allows us to consider only terms linear in m_{nz} on approaching a critical temperature. This leads to:

$$\sigma_1=A_{1,1}\sigma_1+A_{1,2}\sigma_2+A_{1,2L+3}\sigma_I+A_{1,2L+4}m_I$$

…

$$\sigma_n=A_{n,n-1}\sigma_{n-1}+A_{n,n}\sigma_n+A_{n,n+1}\sigma_{n+1}$$

… (8)

$$\sigma_L=A_{L,L-1}\sigma_{L-1}+A_{L,L}\sigma_L+A_{L,L+1}\sigma_I+A_{L,L+2}m_I$$
$$\sigma_I=A_{L+1,L}\sigma_L+A_{L+1,L+1}\sigma_I+A_{L+1,L+2}m_I+A_{L+1,L+3}m$$

$$m_I=A_{L+2,L}\sigma_L+A_{L+2,L+1}\sigma_I+A_{L+2,L+2}m_I+A_{L+2,L+3}m$$

…

$$m_p=A_{p,p-1}m_{p-1}+A_{p,p}m_p+A_{p,p+1}m_{p+1}$$

…

$$m_{2L+2}=A_{2L+2,2L+1}m_{2L+1}+A_{2L+2,2L+2}m_{2L+2}+A_{2L+}$$

Which can then be written as

$$M\vec{m}_z=0 \qquad (9)$$

Where $\vec{m}_z$ is a vector of components $(\sigma_1,\ldots\sigma_2,\ldots.\sigma_L,\sigma_I,m_I,m_1\ldots..m_p,\ldots.$,

The critical temperature T_C/J_{AA} is obtained from the equation

$$\det(M)=0 \qquad (10)$$

T_C/J_{AA} depends on $R_1=J_{BB}/J_{AA}$, $R_2=J_{AB}/J_{AA}$, D/J_{AA} , $D($.

From the many solutions of Eq.(10), we choose the one corresponding to the highest possible transition temperature [18].

On the other hand, the compensation temperature T_{comp} , if it does exist in the system with $J_{AB}\leq 0$, can be determined from:

$$M_T = 0 \text{ with } T_{comp} \quad T_c \qquad (11)$$

Where T_C is the critical temperature.

III. Results and discussions

We have first taken $D=D_0$ and studied the variation of the critical temperature with the anisotropy D_0 for $R_1=0.2$, $R_2=-1.5$ and for various values of the parameter p. In fig 1, we show the phase diagrams of the system for p=0.3, 0.5, 0.7 and 0.995. (Solid lines) and the compensation temperature (broken lines). We can see that the transition temperature increases from a saturation value for a large negative anisotropy to reach a saturation value for a large positive anisotropy. This saturation values depends on p, and the increase of T_c is smaller when p is greater. On the other hand, it is seen that the compensation temperature does not exist for any value of D, it exist only in a limited interval. This interval is smaller when p decreases (when the concentration of the spin 1/2 atoms in the interface is smaller). It is also noted that T_{comp}, when it exists, increases with D.

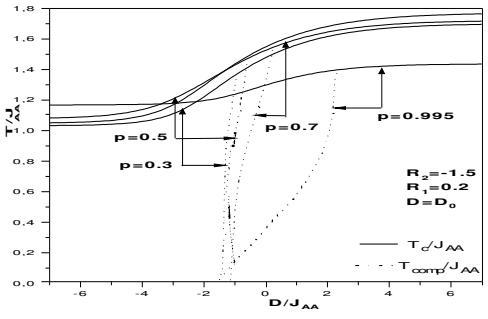

Fig.1: The variation of the critical temperature T_C/J_{AA} (solid line) and compensation temperature T_{comp}/J_{AA} (doted line) versus D of the system with $D=D_0$, $R_2=-1.5$ and $R_1=0.2$. The number accompanying each curve is the value of p.

In order to study the effect of the exchange interactions in the interface ($R_2=J_{AB}/J_{AA}$) and in the bulk ($R_1=J_{BB}/J_{AA}$) on the phase diagrams, we represent in fig 2 the phase diagrams for $R_1=0.2$, p=0.5 and for different values of R_2 (-1.5, -1 and –0.5) and in fig 3 we give the phase diagrams for a fixed values of R_2=-1.5, p=0.2 and for different values of R_1 (0.995, 0.7 and 0.5). We can see that the phase diagrams are topologically the same. That is, T_c increases from a saturation value for large negative values of D, to reach another saturation value for large positive values of D. The smaller saturation value of T_c (for D < 0) is independent on R_1 and R_2. In contrast, the greater one (for D > 0) depends strongly on R_1 and R_2, and it increases when we increase R_1 and $|R_2|$. In fig 2, we see also that the system can exhibit a compensation temperature, which exist only in a limited interval of D, which is more narrow when $|R_2|$ is smaller.

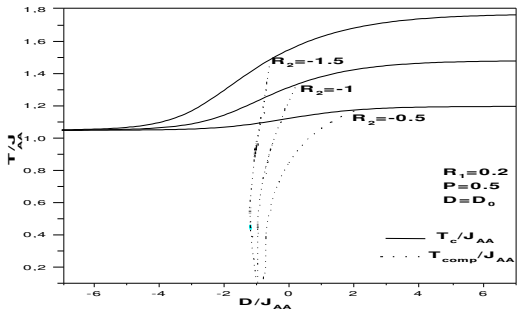

Fig. 2: The variation of the critical temperature T_C/J_{AA} (solid line) versus D of the system with $D=D_0$, $R_2=-1.5$, p=0.2. The number accompanying each curve is the value of R_1.

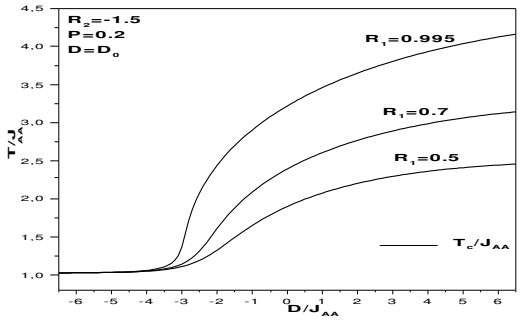

Fig.3: The variation of the critical temperature T_C/J_{AA} (solid line) and compensation temperature T_{comp}/J_{AA} (doted line) versus D of the system with R1= 0.2, p=0.5, $D=D_0$. The number accompanying each curve is the value of R_2.

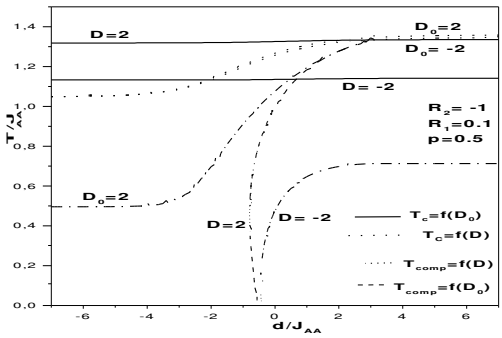

Fig.4: The variation of the critical temperature T_C/J_{AA} (solid line) and compensation temperature T_{comp} $/J_{AA}$ (doted line), for the system with R_2=-1, R_1=0.1, p=0.5,versus D taking D_0=2 and –2 and versus D_0 taking D=2 and –2.

In order to study the effects of the interface anisotropy and bulk one, we show in fig.4 the phase diagrams in the (T_C/J_{AA}, d) plane but taking ($D \neq D_0$), R_2=-1, R_1=0.1 and p=0.5, first we plot T_C=f(D_0) for D=2 and –2. It is clear that, the transition temperature is independent of D_0 (solid lines) but depends on D (T_C (D=2)=1.135 and T_C (D=-2)=1.317). Thus, one can conclude that the critical temperature of this system relays more on the interface anisotropy (D). In contrast, as we can see, the compensation temperature depends on both anisotropies, but these dependencies are slightly different. That is for D=2 and –2, T_{comp} increases from 0 for D_0=-0.59 and D_0=-0.42, to reach a saturation value for large positive anisotropy D_0. For D_0=2, T_{comp} increases from a minimum saturation value for large negative D to reach a maximum saturation value for large positive anisotropy D.

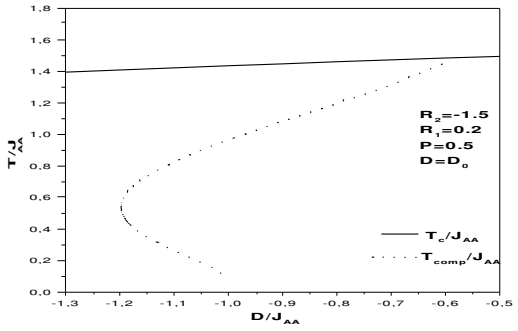

Fig.5: The variation of the critical temperature T_C/J_{AA} (solid line) and compensation temperature T_{comp}/J_{AA} (doted line) versus D for R_2=-1.5, R_1=0.2, p=0.5 and $D=D_0$.

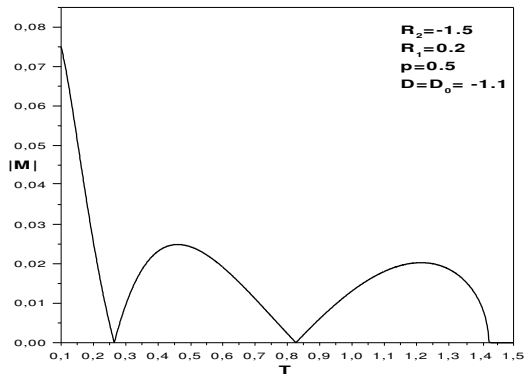

Fig.6: The temperature dependence of |M| for $D=D_0$=-1.1, R_2=-1.5, R_1=0.2 and p=0.5.

In order to show that this system can exhibit two compensation point we have replanted, in an enlarged scale, the curves of T_c and T_{comp} as a function of D, for R_2=-1.5, R_1=0.2 and p=0.5 (see fig 5). It is seen, that we can have two compensation points in a certain interval of D [-1.2, -0.6]. For example, for D=-1.1, the two compensation temperatures are: T_{comp1}=0.26 and T_{comp2}=0.82. These results are confirmed in fig 6, which presents the variation of the magnetization with temperature.

IV. Conclusion

In this work, we have shown that the phase diagrams have qualitatively the same shapes. T_C depends strongly on R_1, R_2 for large positive value of D and depends on the interface anisotropies. The compensation temperature depends on both anisotropies. It exists only in a limited interval of D.

We have also shown that this system may have two compensation points.

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