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Temperature dependence of magnetisation and paramagnetism of ferromagnetic–antiferromagnetic superlattices

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Abstract. Using the mean-field approximation, the spontaneous magnetisation and paramagnetic susceptibility of localised spin ferromagnetic–antiferromagnetic superlattices, in which the antiferromagnetic films possess an odd number of the atomic planes which are parallel to the interfaces of the superlattices, are calculated numerically. A study of the spontaneous magnetisation as a function of temperature shows that the superlattices display five kinds of magnetism, and the compensation point appears for some values of the parameters J_{ab}, J_a and J_b. The calculation for the paramagnetic susceptibility shows that this system displays a paramagnetism that is similar to ferromagnetic, antiferromagnetic or ferromagnetic paramagnetism, depending upon J_{ab}, J_a, J_b and the period of the system.

1. Introduction

In the last few years, the studies of superlattices constructed by alternating films of different magnetic materials have attracted the attention of scientists. Experimentally, various magnetic superlattices have been synthesised [1–4]. Theoretically many studies and calculations of superlattices described through the use of various models, have been made by different methods [5–13]. Some interesting properties have been found, such as the RKKY interaction in the magnetic–non-magnetic superlattices [14, 15], the spin restructure and twist states in some superlattices [11, 13], and the effect of quantum fluctuation in the antiferromagnetic superlattice [16]. Of these articles, only a very small number are dedicated to the study of spontaneous magnetisation, and in particular there has not been any calculation of the paramagnetism of magnetic superlattices. In [6, 17] the Ginsburg–Landau formulation was used to discuss the critical temperature and magnetisation of superlattices constructed of alternating films of two different ferromagnetic materials. Recently in [18] the susceptibility and the compensation point of the ferromagnetic–ferromagnetic superlattice with antiferromagnetic coupling between two different ferromagnetic films were discussed. For ferromagnetic–antiferromagnetic superlattices [7, 12, 13], which are more complex magnetic superlattices, there still has been no discussion about the magnetisation and paramagnetism; therefore we shall discuss these subjects.

2. Model and method

We shall discuss the superlattice in [7], and let N_b, the number of the atomic planes in

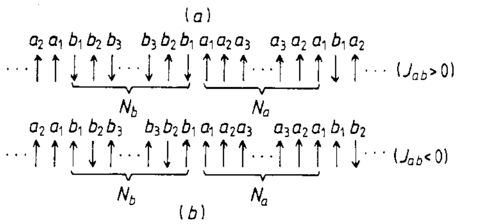


Figure 1. Ground-state spin configurations in a zero external field where $a_1, a_2, a_3, \ldots$ $b_1, b_2, b_3, \ldots$ represent indexes of the inequivalent atomic planes, respectively, N_b is an odd number and $N_a + N_b$ is the period of the superlattice: (*a*) antiferromagnetic interface coupling; (*b*) ferromagnetic interface coupling.

the antiferromagnetic films, be an odd number. For simplification, let $N_b = N_a$, the number of the atomic planes in the ferromagnetic films. The Heisenberg model Hamiltonian for this system is

$$H = 2\sum_{\langle ij \rangle} J(i,j) \boldsymbol{S}_i \cdot \boldsymbol{S}_j - h \sum_i \boldsymbol{S}_i \tag{1}$$

where

$$J(i,j) = \begin{cases} J_a & \text{in the ferromagnetic films} \\ J_b & \text{in the antiferromagnetic films} \\ J_{ab} & \text{between the ferromagnetic and antiferromagnetic films} \end{cases}$$

and where the sum in the first term is over site i and nearest neighbour j, and h is a reduced external field. In the following calculation, let $s_a = s_b = \frac{1}{2}$. Because the atoms in the same plane are equivalent, we use one magnetic moment to represent them; at the same time, one can note that the atoms in the two atomic planes which have the same distance to the middle atomic plane, in a magnetic film, are equivalent. In addition, the directions of the moments of the nearest-neighbour atoms in the antiferromagnetic films are opposite. Figure 1 shows the ground-state spin configurations ($h = 0$).

According to the mean-field approximation an atomic moment in the ith plane in the supercell is

$$M(T,i) = \mu_B B(y_i) \qquad y_i = (1/kT)\mu_B(H_0 + H_m) \tag{2}$$

where k is the Boltzmann constant, and H_0 and H_m are the external field and the effective field, respectively, acting on the ith atomic plane. $B(y)$ is the Brillouin function.

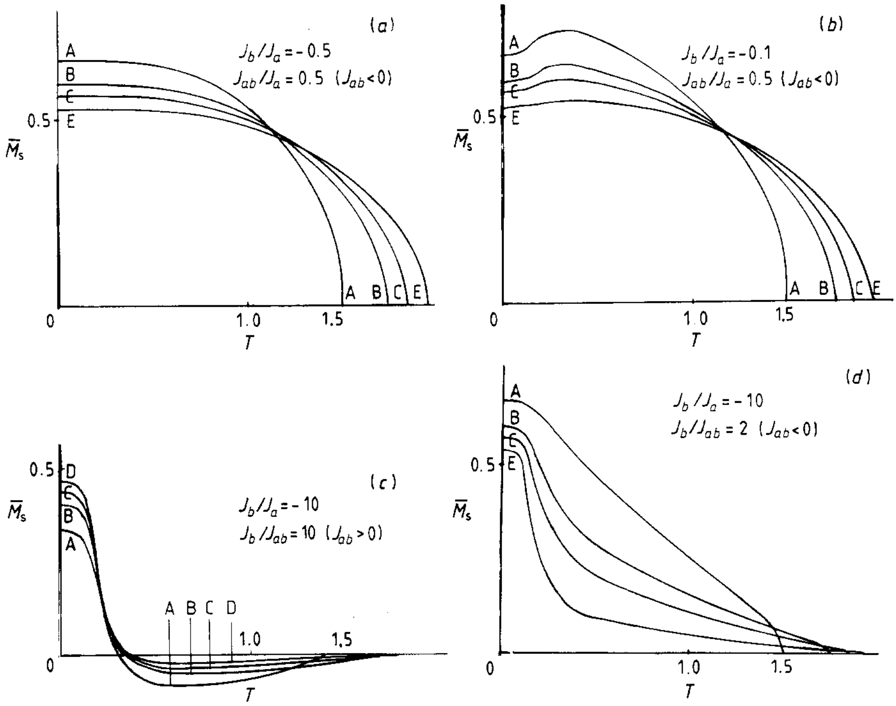
In the ferromagnetic film in the supercell,

$$\begin{aligned} y_{a1} &= (\mu_B/kT)[H_0 + (2J_a/\mu_B^2)M(T,a_2) + (2J_{ab}/\mu_B^2)M(T,b_1)] \\ y_{a2} &= (\mu_B/kT)[H_0 + (2J_a/\mu_B^2)M(T,a_3) + (2J_a/\mu_B^2)M(T,a_1)] \\ y_{a3} &= (\mu_B/kT)[H_0 + (2J_a/\mu_B^2)M(T,a_4) + (2J_a/\mu_B^2)M(T,a_2)] \\ &\vdots \\ y_{(N_a+1)/2} &= (\mu_B/kT)[H_0 + (4J_a/\mu_B^2)M(T,(N_a-1)/2)]. \end{aligned} \tag{3}$$

In the antiferromagnetic film,

$$\begin{aligned} y_{b1} &= (\mu_B/kT)[H_0 + (2J_b/\mu_B^2)M(T,b_2) + (2J_{ab}/\mu_B^2)M(T,a_1)] \\ y_{b2} &= (\mu_B^2/kT)[H_0 + (2J_b/\mu_B^2)M(T,b_3) + (2J_b/\mu_B^2)M(T,b_1)] \\ y_{b3} &= (\mu_B/kT)[H_0 + (2J_b/\mu_B^2)M(T,b_4) + (2J_b/\mu_B^2)M(T,b_2)] \\ &\vdots \\ y_{(N_b+1)/2} &= (\mu_B/kT)[H_0 + (4J_b/\mu_B^2)M(T,(N_b-1)/2)]. \end{aligned} \tag{4}$$

Substituting (3) and (4) into (2) gives $(N_a + N_b)/2 + 1$ simultaneous equations.



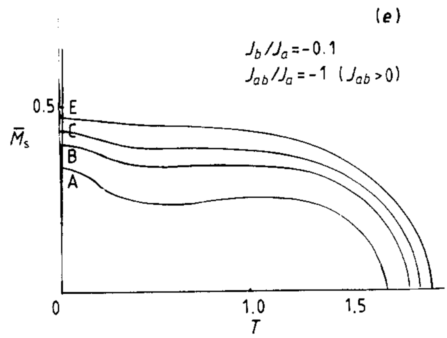


Figure 2. Spontaneous magnetisation as a function of temperature for typical cases: curves A, $N_a = N_b = 3$; curves B, $N_a = N_b = 5$; curves C, $N_a = N_b = 7$; curve D, $N_a = N_b = 13$; curves E, $N_a = N_b = 15$, where we take an arbitrary unit for temperature and $\bar{M}_s$ is the relative spontaneous magnetisation, (*a*)–(*e*) have the same scales.

Finding the solutions of these equations, one can obtain the temperature and period dependences of the paramagnetic susceptibility and spontaneous magnetisation of the system.

3. Results and discussion

3.1. Spontaneous magnetisation

Using $\bar{M}_s$ to represent the magnetisation, according to the temperature dependence of $\bar{M}_s$, we obtain five types of $\bar{M}_s$ curves and these are shown in figure 2. The curves of $\bar{M}_s$ in figures 2(*a*)–2(*c*) are typical ferrimagnetic-type curves; Q type, P type or N type.

(i) The curves in figure 2(*a*) are Q type, and every curve is similar to those of bulk ferromagnets. It is of interest to note that $\bar{M}_s$ increases with decrease in the period in the lower-temperature region and decreases with decrease in the period in the higher-temperature region.

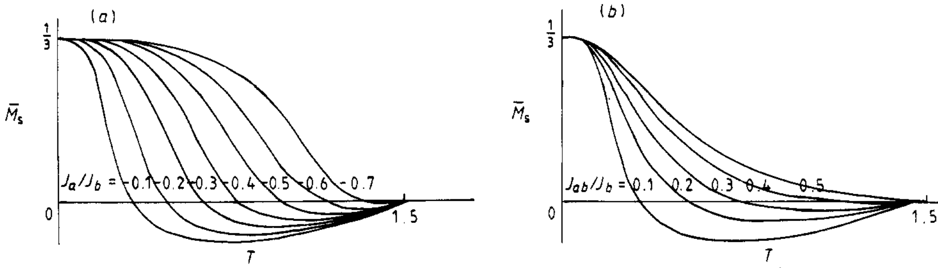


Figure 3. for $N_a = N_b = 3$, we plot the change in the spontaneous magnetisation as a function of temperature with (*a*) $|J_b/J_a|$ (where $J_{ab}/J_b = 0.1$) and (*b*) J_b/J_{ab} ($J_{ab} > 0$, $J_b > 0$) (where $J_a/J_b = -0.1$). From this figure, one can find the change in the compensation point with the parameters J_a, J_b and J_{ab}.

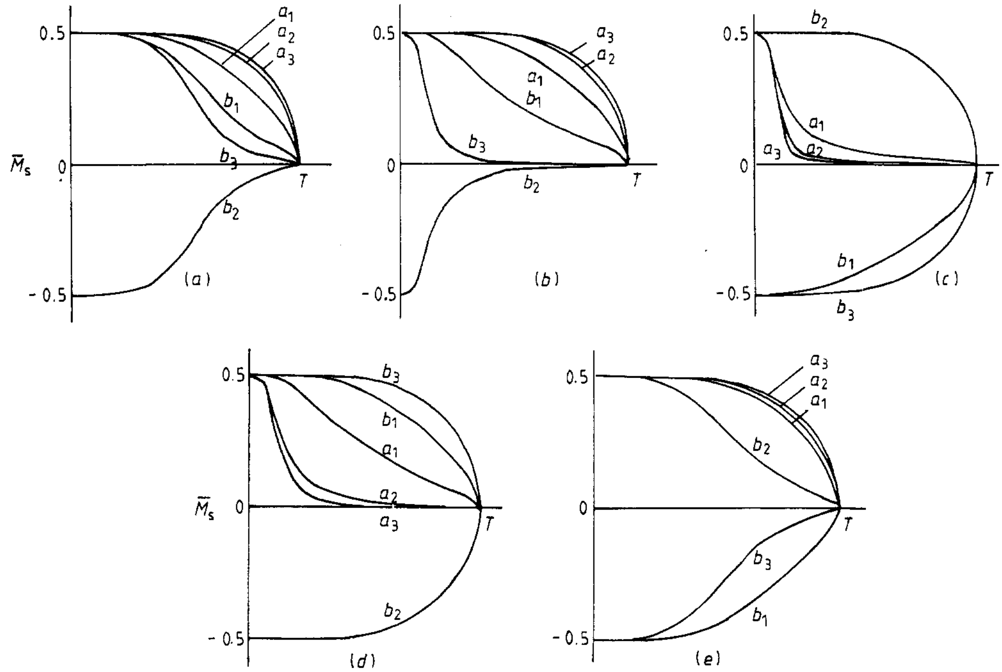


Figure 4. Sublattice magnetisations for the typical cases in figure 2, where $N_a = N_b = 5$.

(ii) As $|J_b/J_a|$ decreases, the curves of $\bar{M}_s$ change from Q type to P type as figure 2(*b*) shows. The maximum of $\bar{M}_s$ for a given period is located at a temperature $T \neq 0$. In a similar way to in figure 2(*a*), $\bar{M}_s$ increases as the period increases in the higher-temperature region and decreases as the period increases in the lower-temperature region.

(iii) If $|J_b/J_a| > 1$ and the interface coupling is antiferromagnetic ($J_{ab} > 0$), a compensation point may appear. For example, taking $|J_b/J_a| = 10$ and $J_b/J_{ab} = 10$, we obtain figure 2(*c*) which shows that there is a compensation point for $\bar{M}_s$ in every curve. In order to discuss the relation between the compensation point and $|J_b/J_a|$ or J_b/J_{ab}, we draw figure 3 for $N_a = N_b = 3$. Figure 3(*a*) shows that the compensation point seems to increase proportionally with increasing $|J_b/J_a|$ until it disappears or is equal to T_c. The change in the compensation point with J_b/J_{ab} is shown in figure 3(*b*). One can note that, the larger the values of $|J_b/J_a|$ and J_b/J_{ab}, the more likely it is that a compensation point will

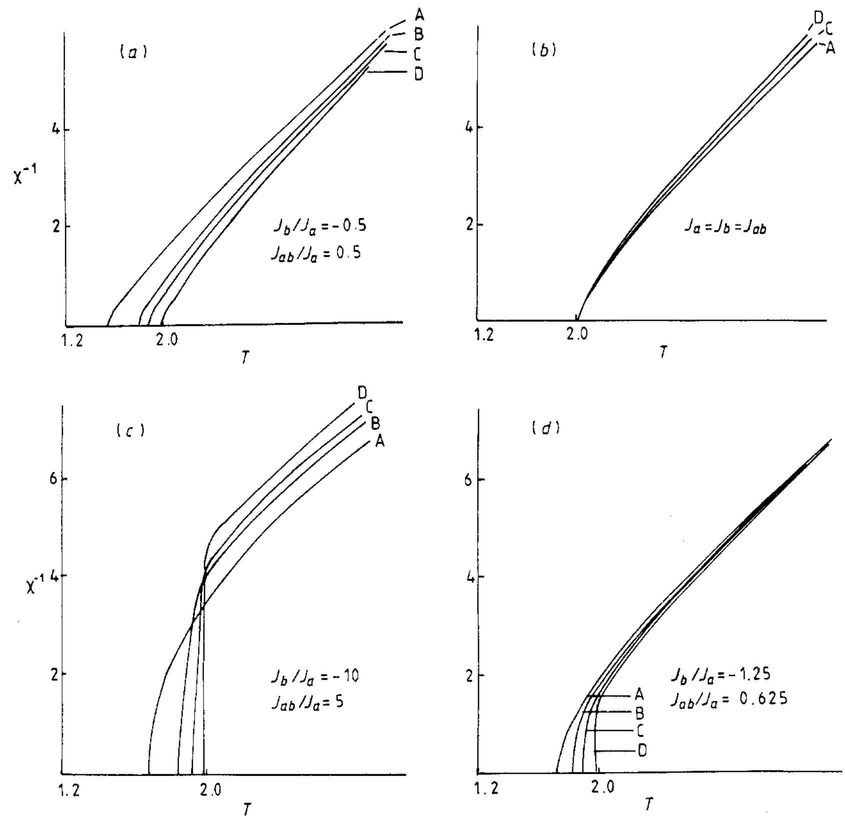


Figure 5. Paramagnetic susceptibilities as temperature functions for the case $h \to 0$: curves A, $N_a = N_b = 3$; curves B, $N_a = N_b = 5$; curves C, $N_a = N_b = 7$; curves D, $N_a = N_b = 15$.

appear. In figures 2(*c*) and 3, if $|J_b/J_a| \leq 1.25$ and $J_b/J_{ab} \leq 2$, it is almost impossible for a compensation point to appear for the superlattice with any period ($N_a = N_b$ is odd). In addition, the compensation point changes slowly with the period as figure 2(*c*) shows.

(iv) The curves in figure 2(*d*) and 2(*e*) for smaller periods are different from those of typical ferrimagnets. $\bar{M}_s$ for the superlattices with smaller period in figure 2(*e*) is very interesting. As the temperature rises from zero, firstly $\bar{M}_s$ decreases, next increases slowly and then decreases to zero. One knows the period dependence of $\bar{M}_s$ from figures 2(*d*) or 2(*e*).

In order to investigate the micromagnetism of the system, we show the temperature dependences of the sublattice magnetisations in figures 4(*a*)–4(*e*) which have the same parameters as figures 2(*a*)–2(*e*), respectively, except for the period, which is equal to 10 ($N_a = N_b = 5$) because there are five types of curve in figure 2. At the same time, this shows the micromagnetism of the superlattices.

3.2. Paramagnetic susceptibility

When $T > T_c$ and $h \to 0$ (very small), the Brillouin functions in equation (2) can be expanded in series and non-linear terms are neglected; then all the terms in the equations are differentiated with respect to h, and the susceptibility of every atomic plane in the supercell can be obtained as a function of temperature. Employing χ^{-1} to represent the reciprocal of the average susceptibility, we show the temperature dependence of χ^{-1} for a few typical cases in figure 5. From figures 5(a) and 5(b), one knows that the curves of χ^{-1} are straight lines approximately for the cases where $|J_b/J_a|$ is smaller than or close to unity. This indicates that the ferromagnetic films make a main contribution to the susceptibility. From figures 5(c) and 5(d) one knows that, as $|J_b/J_a|$ increases, the system with a given period displays firstly ferrimagnetic and then antiferromagnetic paramagnetism for longer periods, but mainly ferrimagnetic paramagnetism for shorter periods.

In this paper, we have discussed and calculated the spontaneous magnetisation and paramagnetism of the ferromagnetic–antiferromagnetic superlattices in which antiferromagnetic films have an odd number of the atomic planes; we obtained five types of magnetisation curve. It is interesting that, for some parameter values, the spontaneous magnetisation increases with decrease in the period in some temperature regions, but decreases with decrease in the period in other temperature regions, and there can be a compensation point for a given period. The paramagnetism depends mainly on the rate exchange interaction in the ferromagnetic and antiferromagnetic films in the supercell and on the period.

References

[1] Cable J W, Khan M R, Felcher G P and Schuller I K 1986 *Phys. Rev.* B **34** 1643
[2] Du R, Tsui F and Flynn C P 1988 *Phys. Rev.* B **38** 2941
[3] Borchers J, Salamon M B, Du R, Flynn C P, Erwin R W and Rhyne J J 1988 *J. Appl. Phys.* **63** 3458
[4] Weller D, Alvardo S F, Gudat W, Schroder K and Campagna M 1985 *Phys. Rev. Lett.* **54** 1555
[5] Ma H R and Tsai C H 1985 *Solid State Commun.* **55** 499
[6] Tilley D R 1988 *Solid State Commun.* **65** 657
[7] Hinchey L L and Mills D L 1986 *Phys. Rev.* B **33** 3329
[8] Dobrzynski L, Djafari-Rouhani B and Puszkarski H 1986 *Phys. Rev.* B **33** 3251
[9] Albuquerque E L, Sarmento P F and Tilley D R 1986 *Solid State Commun.* **58** 41
[10] Zhou Y F and Lin T H 1989 *Phys. Lett.* **134A** 257
[11] Camley R E and Tilley D R 1987 *Phys. Rev.* B **37** 3413
[12] Herman F, Lambin P and Jepsen O 1985 *Phys. Rev.* B **31** 4394
[13] Hinchey L L and Mills D L 1986 *Phys. Rev.* B **34** 1689
[14] Salamon M B, Sinha S, Rhyne J J, Cunhingham J E, Erwin R, Borchers J and Flynn C P 1986 *Phys. Rev. Lett.* **56** 259
[15] Erwin R W, Rhyne J J, Salamon M B, Borchers J, Sinha S, Du R and Flynn C P 1987 *Phys. Rev.* B **35** 6806
[16] Diep H T 1989 *Phys. Lett.* **138A** 69
[17] Fishman F, Schwabb F and Schwenk D 1987 *Phys. Lett.* **121A** 192
[18] Camley R E and Tilley D R 1989 *Phys. Rev.* B **39** 12316