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Random interaction fields method: Magnetic phase transitions in the thin films

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ABSTRACT

In the framework of the random interaction fields method the properties of the magnetic thin films with non-magnetic layers are investigated. In this paper the evaluation of the interaction energy of Co layers and the oscillation period is carried out, depending on the thickness of the nonmagnetic layer Cu, assessing of the impact of the cobalt layer thickness on the average effective field RKKY interaction. Further, a possible explanation of the superparamagnetic properties of such systems is offered.

1. Introduction

In recent years, the physical phenomena in a periodic structures consisting of the alternating layers of different metals have been widely studied theoretically [1–3] and experimentally [4,5]. The interest in such systems is large because the thin film elements used in microelectronics are often representing multilayer system [6,7]. On the other hand, the metal films having different physical properties can be combined, then it is possible to obtain wires with fundamentally new physical properties which cannot be implemented in a homogeneous conductor. Thus, in particular, multilayers consisting of the alternating layers of magnetic and non-magnetic metals have giant magnetoresistance, which manifest themselves in changing the conductivity by tens of percent when there is the weak external magnetic field [8–10]. This effect is perhaps the most striking example of the unusual properties of nanostructured materials. The systems of Co/Cu and Co/Pd are most interesting in this field. Extremely low mutual solubility of the components of these systems allows us to obtain well-differentiated layers or other type of structure in the film version. The unusual magnetic properties, such as spin glass state [6] or quasicrystals [7], and size effects in ultrathin films [11,12] can be observed. It explains the increased interest and a huge amount of work on the films of Co/Cu and Co/Pd of different compositions which exist in the scientific journals. However, some experimental works have difficulties in interpreting results within existing theories, different experiments demonstrate various oscillation periods, etc.

Apparently, the direct exchange determines the Curie point and the temperature behavior of the spontaneous magnetization of Co, while relatively weaker RKKY interaction between spins of cobalt layers affects the relative orientation of the magnetization vectors and determines the energy of the interlayer interaction. In our view, many of the properties of such structures can be consistently explained using the random interaction fields method developed in our studies [13–18].

2. Evaluation of the interaction energy of cobalt layers and the oscillation period, depending on the thickness of the nonmagnetic layer

As was shown in [13–18], the distribution function of random fields $W(H)$ is "smeared" δ-function of the form

$$W(H)=\frac{1}{\sqrt{\pi}B}\exp\left(-\frac{[H-H_0(\alpha-\beta)]^2}{B^2}\right), \tag{1}$$

where the moments of the distribution function can be represented as

$$H_0=n\int \varphi\, dV, \tag{2}$$

$$B^2=2\sigma^2=2n\int \varphi^2\, dV. \tag{3}$$

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Here $(\alpha-\beta)$ is the relative magnetic moment per atom, φ is the "exchange field strength" acting on the selected atom from the neighboring atom, n is the volume concentration. "Exchange field strength" of alternating indirect Ruderman–Kittel–Kasuya–Yosida (RKKY) law is as follows:

$$\varphi = AF(x), \tag{4}$$

where $x = 2k_F R$ is the momentum of the electron on the Fermi surface

$$F(x) = \frac{x\ \cos(x) - \sin(x)}{x^4}, \tag{5}$$

the magnitude $A \approx 10^6$ Oe determines the intensity of the exchange interaction (estimation of the magnitude A is based on the evaluation of the Curie point $T_c \approx 200$ K).

Due to the long-range nature of the RKKY interaction, when a substantial contribution to the interaction comes from the atoms located at the distances larger than the lattice constant, the distribution of the interacting atoms in the volume can be considered as random. Then its moment can be determined as $H_0 = n\int \varphi(r)\,dV$, here r is the coordinate of the atom acting on the selected atom placed at the origin.

If the coordinate system is associated with the surface layer of Co thickness h, then the part of the average exchange field per atom Co, located at the origin, associated with the RKKY interaction should be calculated using the following formula:

$$H_0 = nA\int_{-h}^{0}\int_0^{\infty}\int_0^{2\pi} F(\rho,\varphi,z)\rho\,d\rho\,d\varphi\,dz + nA\int_d^{d+h}\int_0^{\infty}\int_0^{2\pi} F(\rho,\varphi,z)\rho\,d\rho\,d\varphi\,dz, \tag{6}$$

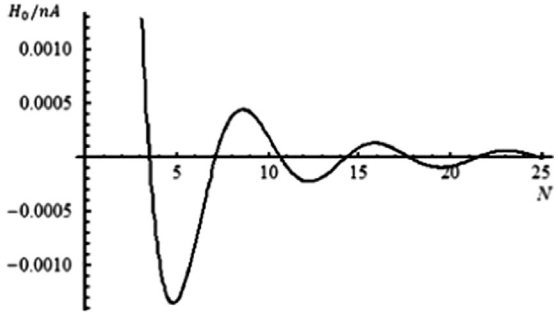

Fig. 1. Dependence of $H_0/nA(N)$ where N is the monolayers of Cu (1 monolayer=2 Å) at 1 monolayer of Co.

where ρ, φ, z are the cylindrical coordinates. It is possible to obtain simple results by assuming that the law of the RKKY interaction between the atoms through the Co–Co layer is either absent or is not very different from the law of interaction through the layer of copper. Then, considering only the interaction of the surface the atoms of Cu with the atoms Co Eq. (6) is transformed into the form

$$H_0 = nA\int_0^{\infty}\int_0^{2\pi} F\sqrt{\rho^2+d^2}\,\rho\,d\rho\,dz, \tag{7}$$

where n is number of atoms per unit surface layer Cu (Pd), d is the thickness of the layer Cu (Pd). The dependence of the magnitude H_0/nA on the thickness of Cu is shown in Fig. 1 (1 monolayer of Cu=2 Å) with a layer thickness of Co equal to 1 monolayer.

Note that the experimental curve can look quite differently at a certain step in increasing the thickness of the copper layer. For example, choosing N=2; 4; 4.5; 6; 6.5; 7; 8; 10, we obtain the dashed curve shown in Fig. 2a compared with experimental data obtained in [18], similar to Fig. 2b.

We can get to the points lying in the region of negative values of the exchange integral and can have oscillating antiferromagnetic ordering at such a discrete change of the intervals (Fig. 2a).

3. Estimation of influence the cobalt layer thickness on the average effective field RKKY interaction

In order to evaluate the influence of the cobalt layer thickness on the average effective field RKKY interaction, it is assumed that the main characteristics of the RKKY interaction in Co and Cu are comparable in the order of the magnitude. In this case, we use Eq. (6), which when integrated from d to $d+h$ functions $F(\rho, d)$ are identical in the region occupied by the copper and the cobalt.

Effect of Co layer should not be considered in the range of $-h$ to 0 when evaluating H_0, because the magnitude H_0 together with the direct exchange specifies a Curie point in a layer Co:

$$H_0 = A\int_d^{d+h}\int_0^{\infty}\int_0^{2\pi} F(\sqrt{\rho^2+z^2})\rho\,d\rho\,d\varphi\,dz. \tag{8}$$

The corresponding graph is shown in Fig. 3 in which the thicknesses of Co are 20 monolayers (smooth line), 10 monolayers (dotted line), and 5 monolayers (dashed line).

When comparing Figs. 1 and 3, it is seen that the order of the magnitude of the mean field of the exchange interaction between the layers and the oscillation period is not changed.

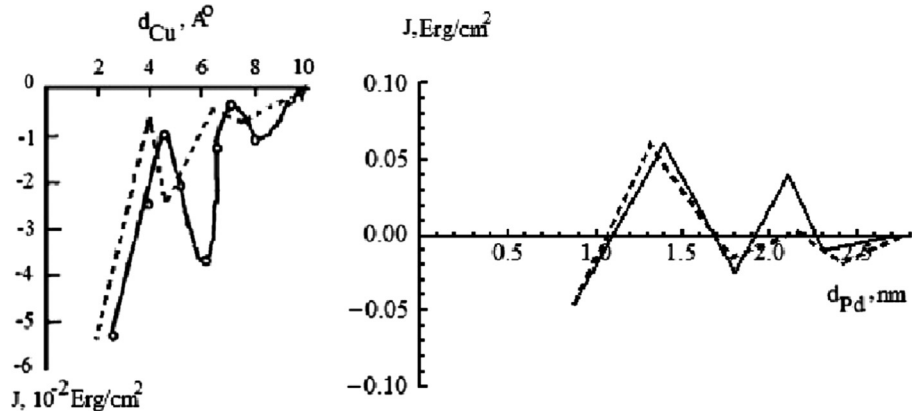

Fig. 2. (a) Plots of the dependence interlayer exchange interaction on the thickness Cu in the films CoCu. Black curve was obtained by means of the experimental data [18], dashed curve was obtained by means of the theoretical data in the framework of the random interaction fields method. (b) Plots of the dependence interlayer exchange interaction on the thickness Pd in the films CoPd. Black curve was obtained by means of the experimental data [19], dashed curve was obtained by means of the theoretical data in the framework of the random interaction fields method.