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Peculiarities of temperature behavior of magnetization in Co/Ge/Co films

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Abstract

In Letter the results of experimental and theoretical investigations of magnetic properties in trilayer Co/Ge/Co films are represented. The temperature dependences of films, being two phases in respect of magnetism, are studied. Experimental results are explained in the frameworks of impurity model, when the hexagonal cobalt grains are considered as quasi-Ising particles distributed chaotically and dissolved within an isotropic matrix of cubic cobalt. The fields of magnetization rise on the $T-H$ plane are determined.

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Interest to film materials in a *transition metal/semiconductor* system is caused, first of all, by possible practical application in spintronics devices [1]. But the investigation of physical properties presents no smaller interest in respect to problems of fundamental physics of solid state and magnetism. The possibility of control for properties of such structures by picking out of active layer and spacer materials and also creation of mesostructure required (granularity, modulation of active elements concentration and so on) permits not merely to construct new materials, but to reveal new physical phenomena.

Granular multilayer films are of interest in connection with existing in them large magneto resistive effect [2], as compared with films having homogeneous magnetic layers. General regularities of resistive properties of granular films are understudied on the whole, but the influence of magnetic structure on electron transport mechanisms in such systems is weakly studied. Also the question about mechanisms responsible for forming of magnetic state in such films is left in abeyance.

Earlier, it was found by us in trilayer Co/Ge/Co films that at magnetic layer thickness more 5 nm the hexagonal phase (hcp) is appeared together with the metastable cubic face-centered one (fcc). At the same time the ratio depends on both semiconducting layer thickness and magnetic layer one [3]. In the first case at the cobalt thicknesses $5 \leqslant t_{Co} \leqslant 10$ nm the hexagonal phase portion rises with increasing of germanium thickness t_{Ge}. In the last case in all films investigated by us at every semiconducting spacer thickness the portion of hexagonal phase rises with increasing of total magnetic layer thickness. The semiconducting interlayer is peculiar catalyst under forming of cubic cobalt phase, inasmuch as, the direct correlation is observed between structure of the germanium interlayer and it of cobalt close-fitting. These results were earlier obtained by transmission electron microscopy (TEM) and confirmed by nuclear magnetic resonance measurements (NMR). It turned out, that the hexagonal cobalt is uniformly distributed on film volume as grain in the form of like spherical. Consequently, with respect to magnetic structure we have situation, when the strongly anisotropic magnetic particles (hexagonal cobalt) are distributed in practically isotropic medium (cubic cobalt).

Exactly, the present investigation is given up to study of peculiarities of magnetic behavior in such system.

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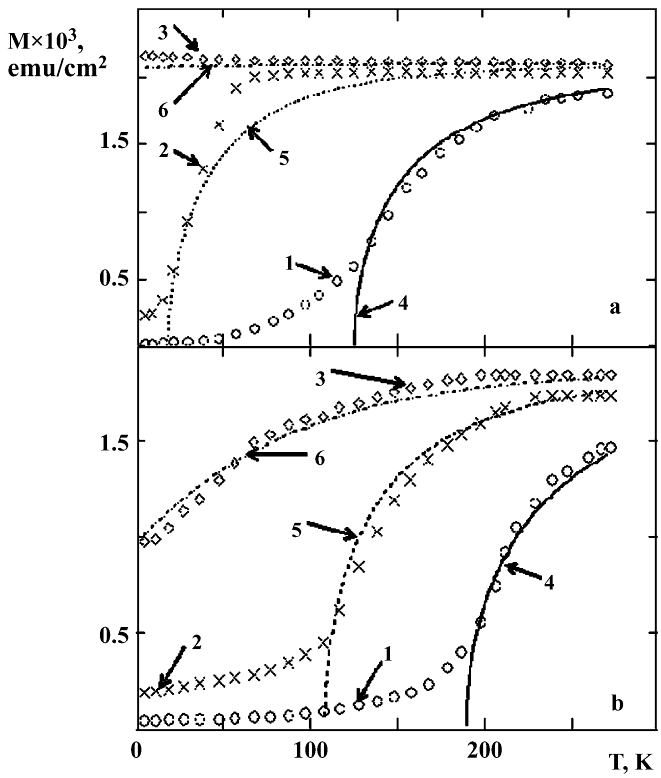

Fig. 1. Temperature dependences of magnetization of films 1 and 2 of composition Co/Ge/Co measured in different magnetic fields. Points are experiment; curves are calculations in formula (5). 1, 2—$H = 50$ Oe; 2, 5—$H = 200$ Oe; 3, 6—$H = 800$ Oe.

Temperature dependences of magnetization in low magnetic fields of such films are found unusual. Procedure of experimental data getting is expounded in paper [3]. Here note only, that before receiving of every experimental curve, from the beginning the sample was demagnetized and in zero magnetic fields was cooled to liquid helium temperature. Then magnetic field was switched on and, at this field fixed, the sample was heated. In Fig. 1 the magnetization dependences $M(T)$ are represented for films Co–Ge system with different thicknesses of magnetic and nonmagnetic layers (film 1—$t_{Co} = 12$ nm, $t_{Ge} = 2.4$ nm; film 2—$t_{Co} = 13.2$ nm, $t_{Ge} = 3.74$ nm) and, correspondingly, with different volume ratios of hexagonal and cubic phases $(q/(1-q))$. It is seen that in low magnetic field the magnetization is practically equal to zero up to some temperature (T_c), above that the sharp rise of magnetization and approaching to saturation are began. Such behavior is typical for all films investigated of this system. The difference is only in the fact that the rise of magnetization is occurred at different temperatures and magnetization values are different.

To analyze temperature properties of magnetization the model is proposed, when the strong anisotropic magnetic particles are solved in isotropic matrix and exchange coupled with it (expansion of Stoner–Wolhfarth model [4]). In Fig. 2 the model structure of film magnetic layer are represented. Here the direction of external magnetic field is chosen as Z-axis. In the general case for such situation the magnetic energy can be

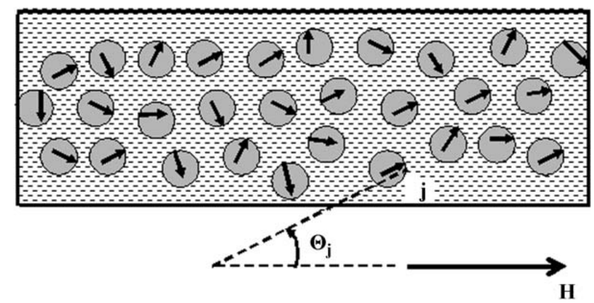

Fig. 2. Sketch of mesostructure of magnetic layer with strong anisotropic grains (spheres with arrows inside) in external magnetic field and orientation of grain anisotropy axes.

wrote in form

$$E = -tM_0 H\cos\varphi - H\sum_j \mu_j \cos\alpha_j - \lambda M_0 \sum_j \mu_j \cos(\varphi-\alpha_j) - \sum_j D_j \cos^2(\Theta_j - \alpha_j), \quad (1)$$

where $M_0 = M_0(H)$ is magnetization of matrix in given magnetic field, φ is angle, determinative the magnetization direction, α_j is angle between direction of magnetic moment of jth grain and external magnetic field, $\mu_j = \mu_j(T,H)$ is granular magnetic moment, depending on temperature an magnetic field, λ is constant of exchange coupling between matrix and particle, $D_j > 0$ is grain constant of anisotropy, t is effective thickness of magnetic layer. Summation is made on all grains of system.

The matrix magnetization is determined as $M = M_s\cos\varphi_0$, where M_s and φ_0 are magnetization of saturation and equilibrium angle, respectively. One can wait that the contribution from granular subsystem will be small. Estimation of these will be made later. Equilibrium angles are found from conditions of energy minimum:

$$\frac{\partial E}{\partial\varphi} = tM_0 H\sin\varphi + \lambda M_0\sum_j \mu_j \sin(\varphi-\alpha_j) = 0, \quad (2a)$$

$$\frac{\partial E}{\partial\alpha_j} = H\mu_j\sin\alpha_j - \lambda M_0\mu_j\sin(\varphi-\alpha_j) - D_j\sin\bigl[2(\Theta_j-\alpha_j)\bigr] = 0, \quad (2b)$$

under the stipulation that $(\partial^2 E/\partial\psi^2)_0 > 0$, $\psi = \{\varphi, \alpha\}$.

It is obvious that this system is not analytically solvable without simplifying assumptions. Now let us remember, that the energy of magnetic crystallographic anisotropy of the hexagonal cobalt is well above then it of the cubic cobalt. In low magnetic fields range the inequality $D_j \gg (H\mu_j, \lambda m\mu_j)$ is right. Under such conditions every particle, numbered by j index, behaves similar to quasi-Ising particle with local axis of anisotropy determined by Θ_j angle. As a zero approximation, neglecting by small items, from (2b) it follows, that $\alpha_j \cong \Theta_j$. To determine the φ angle we receive expression

$$\sin\varphi = \frac{1}{tM_0}\sum_j \mu_j \sin\Theta_j. \quad (3)$$

Next step consists in averaging-out of expression (3) on all directions of granular anisotropy axes. Also, for simplicity we