Unusual remanent magnetization of granular Co/Cu

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Abstract

The magnetization measurements for annealed Co(6 Å)/Cu(14 Å) \times 15 multilayers, evaporated on Si (1 1 1) substrate, showed easy direction parallel to the film. The in-plane DC demagnetization remanence curve has a minimum with amplitude much higher than the saturation remanence for magnetic field applied perpendicular to the easy axis. This is explained as caused by a portion of the sample, having negative remanence.

Keywords: Remanent magnetization; Competing anisotropies; Fine particles

The Co/Cu system has been widely investigated, mainly after the discovery of the giant magnetoresistance effect in magnetic multilayers and subsequently in other kinds of systems including granular systems and multilayers composed of immiscible elements submitted to proper annealing treatment. The latter, in some cases, represent an intermediate state between multilayer and granular structures. Very recently, the correlation between giant magnetoresistance and magnetic interactions was investigated in such systems [1–3], as the interactions were estimated by using a technique, based on a comparison of the isothermal remanent magnetization curve, $M_r(H)$ and the DC demagnetization remanence curve, $M_d(H)$. The latter is measured by first saturating the sample in a positive field and then measuring the remanence $M_d$ after application of progressively larger negative fields. $M_r(H)$ is instead obtained by applying and removing the field $+H$ to the demagnetized state. $M_d(H)$ versus $M_r(H)$ plots for non-interacting uniaxial anisotropy particles should give a straight line; for randomly oriented spherical particles with cubic anisotropy these plots are nonlinear in a ‘positive’ sense with the curves concave downwards [4]. Ultra-thin films provide conditions where uniaxial and cubic anisotropies may co-exist. Recent studies on such systems [5,6] revealed some interesting features, e.g. the negative remanence of some particles.

In the present work some magnetic properties of Co(6 Å)/Cu(14 Å) \times 15 multilayers evaporated at room temperature on a Si (1 1 1) substrate and subsequently annealed under Ar atmosphere at 250°C for 1 h were investigated. Due to the very small Co layer thickness, these magnetic layers are discontinuous, composed of very fine Co grains. The X-ray diffraction indicates fcc structure with the [1 1 1] direction out of plane. Although bulk hcp Co is stable below the allotropic transformation temperature of about 420°C, there is no evidence of hcp Co phase in our samples; the fcc phase of fine Co particles is usually stable at ambient temperature (see, e.g. [7] and the references therein). Due to the small size of the Co particles and the high lattice coherency between the fcc Co phase and the Cu matrix, this Co phase could not be distinguished.

The magnetization measurements were performed using an alternating gradient magnetometer. The samples show an in-plane easy axis, which can be attributed, e.g. to strain, induced during the deposition. The in-plane hysteresis loops and the corresponding $M_d(H)$ curves for
the annealed sample for different magnetic field directions are plotted in Fig. 1. It can be seen, that the $M_d(H)$ curve for field perpendicular to the easy axis shows a very unusual behavior: there is a minimum with amplitude much higher than $M_0(\infty)$. By decreasing the angle between the in-plane easy axis and the field direction, a gradual decrease of the minimum depth is observed, and the remanence curve for field parallel to the easy axis does not show minimum. This effect can be explained considering a system of non-interacting single-domain particles whose anisotropy is made up of a cubic magnetocrystalline and an uniaxial components, with anisotropy constants $K_l$ (negative for fcc Co) and $K_u$, respectively. Let the direction cosines of the magnetization vector $\mathbf{M}$, of such a particle be $x_1$, $x_2$ and $x_3$ and those of the uniaxial anisotropy $l$, $m$ and $n$, referred to the cube axes. Neglecting the thermal activation effects and considering coherent magnetization rotations only, the total reduced (to 2$K_l$) free energy per unit volume of the particle is

$$
\eta(\gamma, \theta) = -\frac{K}{2|K_l|}(x_1m + x_2n)^2 - h \cos \phi.
$$

(1)

$h$ is the reduced magnetic field ($=HM/2|K_l|$), and $\cos \phi = \cos \gamma \cos \theta + \sin \gamma \sin \theta \cos (\theta - \phi)$. Here $\gamma$ and $\theta$ are the spherical coordinates of $\mathbf{M}$, and $\theta$ and $\phi$ are those of $\mathbf{H}$. $\phi$ is the angle between $\mathbf{M}$ and $\mathbf{H}$. The equilibrium magnetization direction can be calculated by minimizing $\eta$ for a given parameter set ($K_w/|K_l|$, $h$, $l$, $m$, $n$, $\theta$, $\psi$); the minimization procedure used is described elsewhere [4,6]. The system’s magnetization is given by the weighted average of the projections of the particles’ magnetizations along the field direction.

The experimental in-plane $M_d/M_0(\infty)$ versus $H/H_c$ curve measured perpendicular to the texture axis, as well as the corresponding model curve are shown in Fig. 2 [$H_c$ is the remanence coercivity, i.e. $M_d(H_c) = 0$]. In the calculation it is assumed that $[\bar{T} \bar{T} 2]$ is the easy axis in the (1 1 1) plane, and $K_u/K_l = 0.49$. This value is sufficiently high so the number of the minimum directions is reduced to two. A slight disorder of the particle orientations is introduced by taking into account the contribution of 1681 particles with $\theta \in (90^{\circ},110^{\circ})$ and $\psi \in (135^{\circ},155^{\circ})$, i.e. $\mathbf{H}$ is nearly perpendicular to $[\bar{T} \bar{T} 2]$ in the (1 1 1) plane.

As the model curve fits very well the experimental data, the minimum in the $M_d(H)$ curve can be attributed to the remanent magnetization contributions of some of the particles [5,6]: each of them has negative remanence for fields up to a certain value (the anisotropy field for the particle). For higher (negative) magnetic fields, the remanent magnetization is positive, resulting in an increase of the total $M_d(H)$. This phenomenon may appear when uniaxial and cubic anisotropies co-exist.

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References