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Description of spin reorientation transition in *Au*/*Co*/*Au* sandwich with *Co* film thickness within a simple phenomenological model of ferromagnetic film

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Simple phenomenological model of ferromagnetic film characterized by equal energies of surface anisotropies at two sides of a film (symmetric film) is considered. The model is used to describe a two-step spin reorientation transition (SRT) in *Au*/*Co*/*Au* sandwich with *Co* film thickness: the SRT from perpendicular to canted noncollinear (CNC) state at $N_\perp = 6.3$ atomic layers and the subsequent SRT from CNC to in-plane state at $N_\parallel = 10.05$ atomic layers. Analytic expressions for the stability criterion of collinear perpendicular and in-plane states of a film are derived with account of discrete location of atomic layers. The dependence of borders that separate regions corresponding to various magnetic states of a film in the (k_B, k_S)-diagram on film thickness N is established. $k_S(k_B)$ is surface (bulk) reduced anisotropy constant. The comparison of theory with experiment related to *Au*/*Co*/*Au* sandwich shows that there is a whole region in the (k_B, k_S)-diagram corresponding to experimentally determined values of threshold film thicknesses $N_\perp = 6.3$ and $N_\parallel = 10.05$. The comparison of this region with similar region determined earlier for a bare *Co*/*Au* film within the same model of asymmetric film and characterized by $N_\perp = 3.5$, $N_\parallel = 5.5$ shows that the intersection of these regions is not empty. Hence, both the SRT in *Au*/*Co*/*Au* sandwich and in bare *Co*/*Au* film with *Co* film thickness can be described within the same model using the same magnitudes of model parameters k_S, k_B. Based on this result we conclude that the energy of Neel surface anisotropy at free *Co* surface is negligible compared to the energy of *Co*–*Au* interface anisotropy. It is demonstrated that the destabilization of collinear states in symmetric film leads to occurrence of the ground CNC state and two novel metastable CNC states. These three CNC states exhibit different kinds of symmetry. In case of asymmetric film only ground CNC state occurs on destabilization of collinear states of a film.

1. Introduction

Variation of a film thickness can lead to the change in a balance between the bulk and surface anisotropy energies which in turn can lead to spin-reorientation transition (SRT) [1]. The polar SRT between the perpendicular and in-plane magnetic directions with film thickness has been discovered in bare *Co*/*Au*(111) films [2,3], in *Au*/*Co*/*Au* sandwich [4] and in bare *Fe*/*Cu*(001) film [5,6]. Bare *Ni*/*Cu*(001) films exhibit the reversed polar SRT from the in-plane to perpendicular orientation with film thickness [7,8]. Evaluation of the surface and bulk anisotropy constants from the comparison of experimental data with results of theoretical description of SRT is an important source of knowledge regarding magnetic anisotropy. The present work is devoted to analysis of canted noncollinear states that occur on destabilization of collinear perpendicular and in-plane states of symmetric and asymmetric films and to description of SRT in *Au*/*Co*/*Au* sandwich with *Co* film thickness.

In accordance with experimental data [4] at low thickness $N \le N_\perp = 6.3$ (N is the number of atomic layers in *Co* film in *Au*/*Co*/*Au* sandwich) *Co* film exhibits a collinear state characterized by perpendicular orientation of magnetization (⊥-state). At large thickness $N \ge N_\parallel = 10.05$ *Co* film exhibits a collinear state characterized by in-plane orientation of magnetization (∥-state). Both ⊥- and ∥-states are uniform across the film thickness. At the intermediate thickness $N_\perp < N < N_\parallel$ *Co* film exhibits a canted state characterized by an intermediate orientation of magnetization between the perpendicular and in-plane (∠-state).

In the present work the description of a two-step SRT ⊥ → ∠ → ∥ with *Co* film thickness in a *Au*/*Co*/*Au* sandwich is based on the account of the change in a balance between anisotropy energy of Co–Au interface and anisotropy energy of inner Co

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atomic layers. Numerous experiments with *Co* films had demonstrated that anisotropy energy of the interface between *Co* film and noble metal films *Co–Au, Co–Ag, Co–Cu, Co–Pd* always favors the perpendicular orientation of magnetization. It is described by the first-order anisotropy constant $K_S \sin^2\theta (K_S < 0)$ [9,10]. θ is orientation angle between vector magnetization and the film plane. This anisotropy is formed in a thin layer and thus it can be ascribed to the surface atomic layer of *Co* film adjacent to *Co–Au* interface. It follows from LEED experiments that *Co* films have cubic crystal structure [2–4] that is characterized by zero magnitude of the first-order anisotropy constant. Nevertheless, *Co* films exhibit bulk anisotropy described by the first-order anisotropy constant due to magneto-dipole interaction between atoms in each atomic layer parallel to the film plane. Contrast to *Co–Au* interface anisotropy it favors the in-plane orientation of magnetization.

Based of these facts one can suggest the following mechanism of a two-step SRT $\perp \to \angle \to \parallel$ in *Au/Co/Au* sandwich with *Co* film thickness. At small thickness $N \le N_\perp$ the interface anisotropy energy dominates in *Au/Co/Au* sandwich. As a consequence, the magnetization of *Co* film is oriented perpendicular to the film plane. Contrast to this, at large thickness $N \ge N_\parallel$ bulk anisotropy energy of inner atomic layers dominates in *Au/Co/Au* sandwich. As a consequence, the magnetization of *Co* film is oriented in-plane. At the intermediate thickness $N_\perp < N < N_\parallel$ the magnitudes of the interface and bulk anisotropy energies are comparable and thus due to the competition between them the canted state takes place in a *Co* film with the intermediate orientation of magnetization between the perpendicular and in-plane orientation.

These simple considerations regarding the mechanism of a two-step SRT in *Au/Co/Au* sandwich with *Co* film thickness are supported by the following comparison of experimental data related to *Au/Co/Au* sandwich [4] with experimental data related to bare *Co/Au* film [2,3]. The SRT in bare *Co/Au* film with film thickness is similar to the SRT in *Au/Co/Au* sandwich, i.e. it is again a two-step SRT$\perp \to \angle \to \parallel$. The only difference is the magnitude of the threshold thicknesses: $N_\perp = 3.5$, $N_\parallel = 5.5$. One can see that these magnitudes are approximately twice smaller than similar magnitudes related to *Au/Co/Au* sandwich: $N_\perp = 6.3, N_\parallel = 10.05$. Hence it is natural to assume that this difference is caused by the fact that contrast to bare *Co/Au* film there are two *Co–Au* interfaces in *Au/Co/Au* sandwich. Both interfaces tend to orient magnetization perpendicular to the film plane. Because of that the perpendicular state in *Au/Co/Au* sandwich exists at larger thickness compared to bare *Co/Au* film.

Before we formulate the analytical expression for theoretical model we have to pay attention to the following two points A and B:

A. It follows from experiment that the as grown *Co* film consists of domains. For example, the perpendicular state of a film is realized as a set of domains with opposite orientation of magnetization [2–4]. In the vicinity of SRT the size of these domains decreases [2–4,11–14]. At present the theory that describes this decrease is well developed [15–20]. The nature of SRT with thickness in *Co/Au* films has been investigated in Ref. [2]where the authors answered the question whether the out-of-plane remanence decrease is due to a breakup into domains or rather due to a rotation of magnetization from the out-of-plane toward the in-plane orientation. Monitoring the magnetization direction in a domain allowed the authors of Ref. [2]to unequivocally conclude that the magnetization crossover took place by continuous rotation. It was shown in a theoretical work [21] that the difference between the energies of a single-domain state and multi-domain state is very small. Because of that the application of relatively small external magnetic field can transform film from a multi-domain state to a single-domain state [11,12]. This single-domain state exists until the film is heated above the Curie point and then cooled without the application of external field. It was shown in experimental work [12] that *Co* film in a single-domain state experiences similar two-step SRT $\perp \to \angle \to \parallel$ but the magnitudes of parameters $N_\perp$ and $N_\parallel$ are shifted to slightly larger values. In the present work we describe the two-step SRT $\perp \to \angle \to \parallel$ in *Au/Co/Au* sandwich with *Co* film thickness in a single-domain state. Since, as it follows from experiment, the as grown *Co* film is in a multi-domain state in the present work we indeed investigate the SRT between perpendicular, in-plane, and canted states which are uniform in the film plane and metastable with respect to a multi-domain state of a film. One should distinguish these metastable states from the novel metastable canted noncollinear states discovered recently in our work [22] which are uniform in the film plane and nonuniform across the film thickness.

B. To the best of my knowledge at present the experimental evidence of dependence of magnetization orientation on the atomic layer index in *Co* film in a canted $\angle$-state is absent. Nevertheless I believe that in the interval of thicknesses $N_\perp < N < N_\parallel$ *Co* film is in the *canted noncollinear* (CNC) state, characterized by the dependence of magnetization orientation on the layer index. Indeed in *Co* the domain wall width is approximately equal to 30 lattice parameters [23], that is comparable with the magnitude of $N_\parallel, N_\perp \sim 10$. By this reason a considerable part of a domain wall can be placed across the *Co* film thickness. Therefore, one should not ignore the dependence of magnetization on the layer index. To describe this dependence one should take into account the finite magnitude of energy of exchange interaction between atomic layers.

The simplest phenomenological model of ferromagnetic film that is able to describe (A) single domain state of the perpendicular and in-plane phases of a film; (B) CNC state of a film in the intermediate phase; and (C) two-step SRT $\perp \to \angle \to \parallel$ with film thickness can be written as

$$\Psi = -JM^2 \sum_{n=1}^{N-1} \cos(\theta_n - \theta_{n+1}) + K_{1S} M^2 \sin^2\theta_1 + K_B M^2 \sum_{n=2}^{N-1} \sin^2\theta_n + K_{NS} M^2 \sin^2\theta_N. \tag{1}$$

Here the exchange interaction between atomic layers is assumed to be positive, isotropic and independent on the layer index $J_{n,n+1} \equiv J > 0$. Vector magnetizations of macroscopic atomic layers $\overrightarrow{M}_n$ are treated as classic vectors. The absolute value of $\overrightarrow{M}_n$ is assumed to be independent on the layer index. Vector magnetizations of all atomic layers belong to the same plane that is perpendicular to the film plane. Small rotation of $\overrightarrow{M}_n$ around the axis normal to the film plane leads to increase in the angles between $\overrightarrow{M}_n$ and $\overrightarrow{M}_{n\pm1}$which in turn leads to increase in the exchange energy. Hence, all the magnetizations $\overrightarrow{M}_n$ are kept in the same plane due to the energy of exchange interaction. First and second sides of a film are characterized by anisotropy constants K_{1S} and K_{NS}. Each inner atomic layer is characterized by the bulk anisotropy constant K_B that exists due to magneto-dipole interaction within each atomic layer. θ_n is orientation angle between $\overrightarrow{M}_n$ and the film plane. Experiments devoted to investigation of a two-step SRT $\perp \to \angle \to \parallel$ in *Au/Co/Au* sandwich were performed at room temperature. By this reason one should consider all parameters $(J, M, K_B, K_{S1}, K_{SN})$ in the expression for thermodynamic potential (1) to be determined at room