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Thickness dependences of coercivity in three layer films obtained by chemical deposition

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Abstract. The change of the coercivity H_C of three-layer films obtained by chemical deposition depending on the thickness of the nonmagnetic interlayers and magnetic layers are presented. Structures with magnetically identical soft layers, as well as with significantly different H_C values were investigated. It was established that in both cases thecoercivity decreases with the interlayer thickness increasing by an exponential law. It is consistent with a change in the displacement field of the hysteresis loop. The observed changes in the parameters of the hysteresis loop are associated with the roughness of the interfaces.

1. Introduction

Magnetic hysteresis or the magnetization delay from the external field which is observed in ferromagnets can be caused by various reasons. The value of the coercivity may vary in a wide range in the same compounds. In single-domain particles the basis of its occurrence is irreversible processes of magnetic moment rotation. In this case the magnitude of the coercivity is determined by the magnetic anisotropy of the particle which may include crystallographic, magnetoelastic parts, as well as anisotropy associated with the shape of the particle. In the presence of domain walls the magnitude of the magnetic hysteresis is associated with the height of potential barriers that prevent their movement. The above mechanisms are well studied and allow obtaining both highly and low coercive magnetic materials in a targeted manner. Three-layer films containing two magnetic layers with an intermediate nonmagnetic interlayer are the simplest multilayer structures in which spin-dependent effects take place. For this reason such systems are the most promising for creating spin-valve devices. In such systems a significant decrease of the coercivity is observed with a change in the thickness of the interlayer which causes both scientific and applied interest. For the first time a decrease of H_C from the thickness of the interlayer was observed in multilayer films in which 48 Ni layers were separated by Cu layers [1]. Then a similar effect was found in three-layer films containing two layers of $Ni_{80}Fe_{20}$ with a silicon [2] and silicon oxide layer [3], as well as in permalloy films with a carbon layer [4]. The mechanisms responsible for the decrease of H_C in such structures are largely unclear. There is only a qualitative explanation based on the presence of Neel double walls. Their appearance is associated with the minimization of the energy of stray fields, which leads to a general decrease in the energy of the domain walls [5, 6].

This paper represents the investigation of the coercivity changes in three-layer films obtained by chemical deposition depending on the thickness of the nonmagnetic and magnetic layers. It is shown that the anomalous change of H_C in the region of small thickness of the interlayer is due to the heterogeneity of the interfaces between the layers. The obtained results are considered within the Neel's model of the orange peel typeroughness.

2. Samples and experimental results

Three-layer films were obtained by chemical deposition of two magnetic layers of Co-P alloys separated by an intermediate non-magnetic Ni-P layer [7]. Their structure is shown in figure 1. Pd and SnO_2 sublayers play a technological role for the chemical reduction of Co and P ions on a glass substrate.

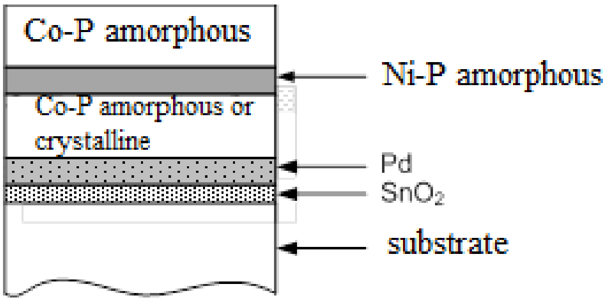

Figure 1. The structure of the samples.

The magnetic soft and hard layers were produced from amorphous and crystal Co-P respectively.The coercivity of the hard layer H_C (h) is 700-900 Oe. The deposition of soft layer was carried in uniform magnetic field of 1 kOe, by which uniaxial anisotropy was established. The morphology of the films was determined by using an atomic force microscope. The thickness of the layers was determined by the deposition time at a known deposition rate which was established using X-ray analysis. The coercivity wasdetermined on a vibrating sample magnetometer and a NANOMOKE magnetooptical installation at room temperature.

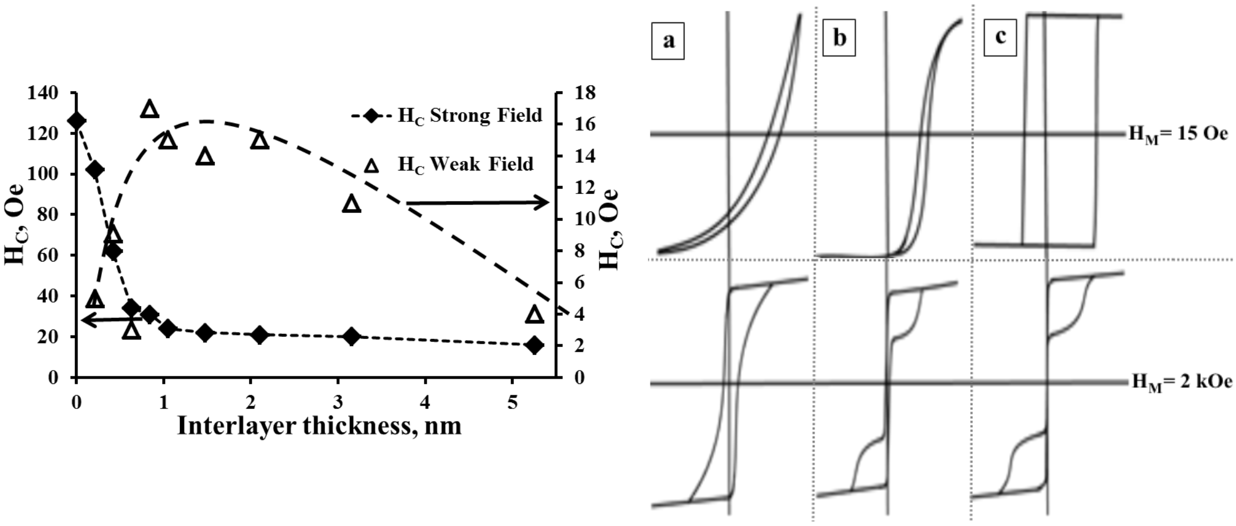

Figure 2. The coercivity dependence of asymmetric films on the interlayer thickness at H_M are 15 Oe and 2 кOe. The thickness of the magnetic soft and hard layers is 35 nm. A view of the hysteresis loops corresponding to these values magnetic field are shownforinterlayer thicknesses: a) 0; b) 0.6; c) 2 nm.

In this work three-layer films of two types were investigated. In samples of the first type or asymmetric films containing magneticallyhard and soft layers the type of hysteresis loops and their characteristics depend on the amplitude of the magnetic field H_M. If $H_M < H_C$(h)the change in the coercivity of the soft layer$H_C$from the thickness nonmagnetic layer d occurs non-monotonously, as shown on figure 2.

As follows from figure 3, the dependence of the displacement field H_D on the interlayer thickness is similar of the coercivity change during magnetization reversalin strong fields. H_D drops sharply when d changes from 0 to 1-2 nm.

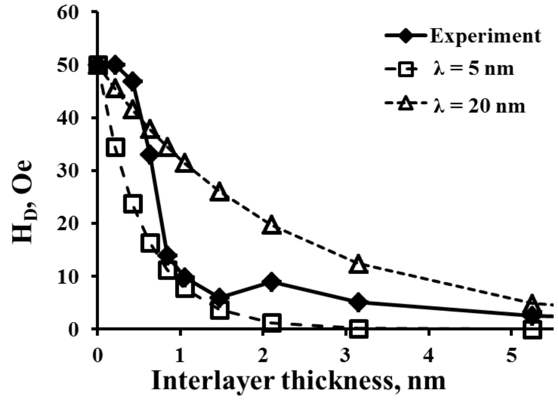

Figure 3. The dependence of the displacement field on the interlayer thickness. The dotted lines are the theoretical dependencies for different of the roughness wavelengths.

In samples of the second type or symmetric films that contain two identical soft magnetic layers, the center of the hysteresis loop shifts in the presence of interlayer, as well as in the case of asymmetric samples (figure 4). At the same time, the values of H_D and H_C change non-monotonously. H_C decreases from 7.5 to 0.5 Oe with increasing of the interlayer thickness from 0 to 1–4 nm and it grows monotonously with further growth of the interlayer thickness. H_D changes sign and then reaches zero values in the specified area of the interlayer thickness.

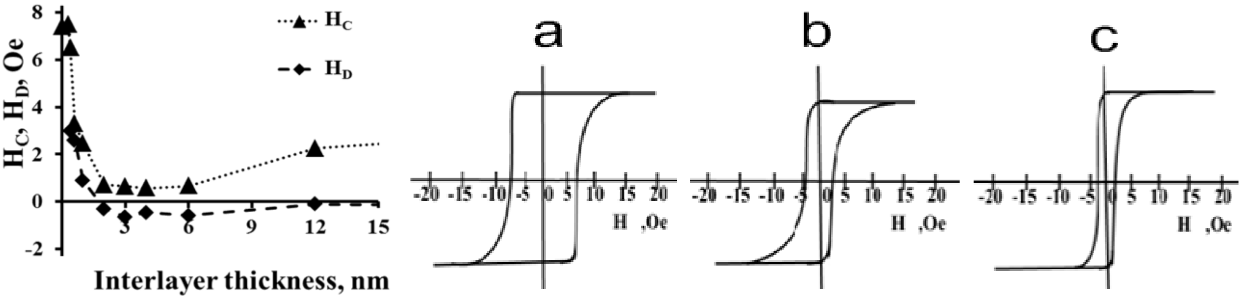

Figure 4. The dependence of coercivity of symmetric films on the nonmagnetic layer thickness. The thickness of the magnetic layer is 35 nm. A view of the hysteresis loops is shown for the interlayer thickness: a) 0; b) 0.6; c) 2 nm.

If the interlayer thicknessis fixed the increase of the magnetic layer thickness leads to decrease of the film coercivity,it reaches 0.05 Oe at t_s= 180 nm (figure 5).

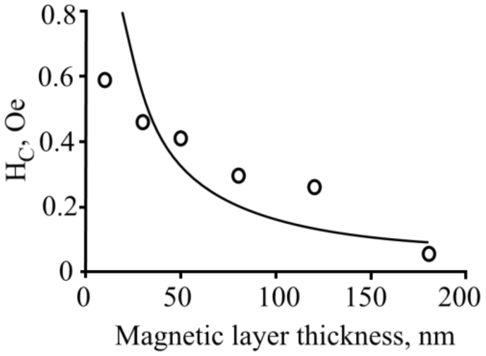

Figure 5. The coercivity dependence of symmetric films on the magnetic layer thickness. The interlayer thickness is 2 nm. The theoretical curve is a solid line.

3. The discussion of the results

The coupling energy J_{int} between magnetic layers

$$J_{int} = H_0 M_S t_S, \tag{1}$$

where H_0 is the coupling field, M_S is the saturation magnetization of the soft layer, t_s is its thickness. In the presence of a nonmagnetic interlayer this may be due to several physical mechanisms:

- RKKY interaction or indirect exchange through a metal layer,
- direct interaction during the diffusion of magnetic atoms through local pinholes,
- undulation of boundaries or roughness such as orange peel (Neel mechanism [8]),

The RKKY interaction is caused by conduction electrons in the metal interlayer which leads to antiferromagnetic exchange between the magnetic layers. As it shown in [9] the presence of such exchange in three-layer Co/Cu /Co films leads to an anomalous increase of the coercivity and then its decline in the thickness range of the nonmagnetic interlayer 1-2 nm.

The two remaining mechanisms are caused by the imperfection of the layers surface. The coupling energy has a positive sign for both of them; therefore, they are difficult to distinguish experimentally.

In Neel's model the roughness of the orange peel type is caused by a periodic wavy surface structure on both sides of the interlayer, as it shown on figure 6.

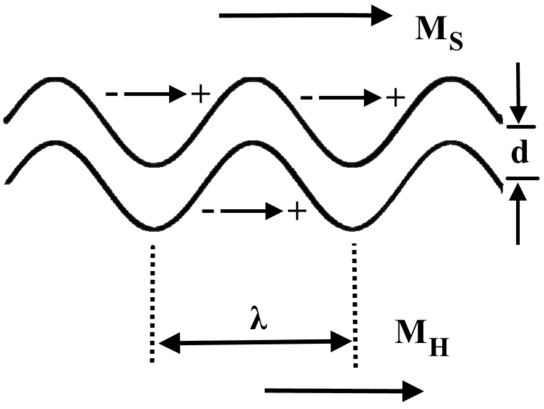

Figure 6. The emergence of magnetostatic charges in the uneven interface of the Neel's model [10, 11, 12].

The coupling field for such change in roughness for thick films is determined by the expression [8]:

$$H_o = \pi^2 h^2 M_h / \sqrt{2}\lambda t_S \left[1 - \exp\left(-2\sqrt{2}\pi 2 t_S\right)\right] \tag{2}$$

where λ, h are the wavelength and amplitude of roughness, M_h are the magnetization of the hard layer.

As noted above the changes of the coercivity from the interlayer thickness inasymmetric films as well as in symmetric films coincide with a displacement field change of the hysteresis loop. The established fact agrees with the results of [13], in which three-layer CoFeB films with a non-magnetic interlayer of Cr, Ta were studied. The authors of this work used the orange peel model to interpret the obtained data and established the correspondence between the coercivity and the coupling field defined by the equation (2).

For the three-layer films studied by us, the interface irregularities are determined of the surface morphology of the Co-P films. Its AFM image and cross-section are shown in figure 7.

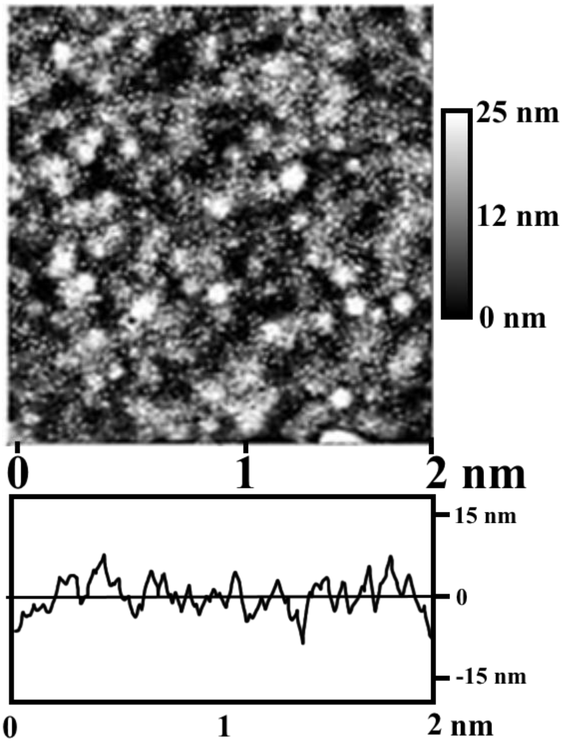

Figure 7. AFM surface morphology and cross section of Co-P films.

In Co-P films the average grain sizeis ~ 20–30 nm measured in the horizontal plane using the "Grain size" film thickness analysis program, the amplitude of the roughness is 5–7 nm [14]. Figure 3 shows the theoretical displacement field curves found by equation (2) for various values of λ. Qualitative agreement with the experimental dependence is observed at $\lambda \sim 5$ nm which differs significantly from the average grain size observed by AFM. This indicates that in our case, besides the coupling of the orange peel type, it is necessary to take into account direct interaction. As noted above, from the analysis of hysteresis loops for films with different magnetic layers it is followed that the magnetic layers are connected by direct interaction in the region of the small interlayer thickness. Its cause is the roughness of the lower layer, which induces pinhole in the interlayer.

We also note the following results.The observed differences of the thickness dependence of the coercivity in weak and strong magnetic fields indicate the presence of several mechanisms of magnetization reversal. From the obtained data it can be established that the decisive influence of the coupling energy on the coercivity manifests in the case if the magnetization reversal of the film is due to the displacement of the domain walls.

The interaction between the layers for symmetric films, as in the case of asymmetric samples, is detected by the change in the shape of the hysteresis loop. In the absence of an interlayer the hysteresis loop is rectangular which is characteristic to homogeneous films. The appearance of the step with the displacement of the hysteresis loop in the presence of an interlayer reveals the difference of the coercivity of the upper and lower layers. This causes the hysteresis loop to shift. We can conclude that the magnetization reversal of three-layer films of the symmetric type with small of the interlayer thicknesses is carried to the same scenario as in the case of asymmetric samples. According to formula (2) the change of the coercivity of a three-layer film, determined by the coupling field, should be inversely proportional to the thickness of the magnetic soft layer or ~ $1/t_S$. The curve calculated from this dependence is shown in figure 5. It is in qualitative agreement with experimental data.

4. Conclusion

The obtained data establish a correlation between the coercivity and the displacement field in three-layer films which indicates the decisive influence of interlayer interaction on the processes of magnetization reversal of such structures at small interlayer thicknesses. The description of the changes in the parameters of the hysteresis loop based on the Neel model allows us to explain qualitatively the effect of the interlayer roughness on the magnetization reversal processes. However, it is necessary to take into account the direct interaction to fully explain the observed changes of the hysteresis loop parameters and more research of the magnetic structure is needed.

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