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Magnetic resonance and anisotropy in multilayer Co/Cu (111) system

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The angular dependences of FMR spectra for the multilayer system [Co (8 Å)/Cu (d_{Cu}) (111)]$_{20}$ are studied. The values of internal effective field are measured, and the parameters of spatial nonuniformities of the system as a function of copper nonmagnetic layer thickness are calculated. The parameters values are found to increase with a number of Cu layers. The dependences are treated qualitatively in terms of the model taking account of interface roughness. The degree of roughness is increasing with grown nonmagnetic layer thickness.

Исследованы угловые зависимости спектров ФМР в многослойной системе [Co (8Å)/Cu (d_{Cu}) (111)]$_{20.}$ Измерены значения внутреннего эффективного поля и рассчитаны зависимости параметров пространственных неоднородностей системы от толщины немагнитного слоя Cu. Обнаружено, что значения этих параметров возрастают по мере увеличения количества слоев меди. Качественное описание этих зависимостей выполнено в рамках модели, учитывающей шероховатость интерфейсов, степень которой увеличивается при увеличении толщины немагнитных слоев.

Development of working media for high-density magnetic recording is among practical uses of magnetic multilayer nanostructures. A necessary condition for such media is a single-axis anisotropy with the orientation of the film magnetic moment along the normal to its plane. It is therefore essential to understand the nature of the film magnetic anisotropy and to establish the components defining the resulting value and sign of magnetic anisotropy depending on the material composition, the layer thickness, deposition technique, heat treatment, etc. One of the efficient ways to this kind of information is to study the magnetic resonance because the anisotropy constant defines immediately the resonance frequency (or resonance field) and the resonance line width is very sensitive to internal inhomogeneities in the system. In epitaxial films, such inhomogeneities are mainly due to the roughness of layer interfaces.

The roughness can be controlled by selecting the film growth conditions (evaporation rate, substrate temperature, residual atmosphere in the chamber). Under steady growth conditions, the roughness depends also on the average thickness of the sputtered layer. It is obvious that when growing in the layer-by-layer mode, the roughness will be minimal if the layer thickness is a multiple of the lattice period for the condensed material in the direction normal to the film. In this work, the angular dependence of the magnetic resonance line position and width for a [Co/Cu]$_{20}$ multilayer system was investigated thoroughly. To vary the interface roughness, the Co layer thickness was kept constant ($d_{Co} = 8$ Å) while that of the Cu layers was changed at a step about 1–2 Å. The work purpose was to estimate the internal effective fields and the inhomogeneity degree in the samples as a function of the Cu layer thickness.

The samples were prepared by magnetron sputtering of Co and Cu targets onto mica (fluorophlogopite) in a vacuum setup, the residual atmosphere being ~10^{-6} Torr at Ar pressure of $1.3 \cdot 10^{-3}$ Torr. The thickness of the layers was measured using multiple-beam optical interferometry to within 2 %. The first Cu sublayer (50 Å) was sputtered directly onto the mica and then twenty Co/Cu bilayers were formed thereon. The upper Cu layer was 12.5 Å thick in each sample. The electron microscopic examinations have shown that the samples had a polycrystalline structure with the Cu planes (111) parallel to the substrate surface. No other preferential crystallographic directions were observed in the grains. The Cu and FCC Co layers were growing epitaxially one after another. Only one grain fits within the sample thickness, and the grain boundaries passed through the entire sample thickness essentially perpendicular to the mica surface. The grains are equiaxial in the sample plane. The grain size (80–100 Å) is independent of d_{Cu}. The small-angle X-ray diffraction analysis of the formed multilayer systems shows a good periodicity and homogeneity of the layer thickness. The resonance spectra were taken using a JEOL-XK spectrometer at room temperature in the 3-cm wavelength range and in magnetic fields up to 1.5 T. The samples (discs 3 mm in diameter) were placed in a rotator at the center of a cylindrical cavity operating at the H_{011} wavelength. The angular dependences of the resonance field and the resonance line width were measured while varying the external magnetic field direction with respect to the film surface. The resonance field and the line width exhibited no anisotropy in the film plane.

All the experimental samples contain the same number of cobalt layers with a nominally identical thickness. In accordance with the problem symmetry, the free energy of a system consisting of identical ferromagnetic layers with moments M can be written (the interlayer exchange being neglected) as

$$E = -HM\cos(\theta - \theta_H) + K_{eff} \cdot \cos^2\theta. \quad (1)$$

The first term takes into account the Zeeman interaction between the magnetic moments and the external field H; the second one describes the anisotropy energy; θ and θ_H are the angles between the normal to the layer plane n and the direction of the moments and external field, respectively.

In thin single-crystal layers of magnetically ordered metals, including Co, the effective magnetic anisotropy is often formed by contributions from different origins, primarily from the sample shape anisotropy related to the magnetic dipole energy of the film as $E_d = 2\pi M^2$, which is minimal when the magnetic moment is oriented in the sample plane, i.e. $\theta = \pi/2$. The other contributions can be competitive in sign with the magnetic dipole one. Nevertheless, the resulting anisotropy is

$$K_{eff} = K_A - 2\pi M^2. \quad (2),$$

where K_A is the uniaxial anisotropy parameter.

The effective internal field $H_i = 2K_{eff}/M$ determined by this parameter is negative for all the samples of our series.

The dependence of ferromagnetic resonance frequency on the external magnetic field [1] is

$$\left(\frac{\omega}{\gamma}\right)^2 = \{H\cos(\theta - \theta_H) + H_i\cos^2\theta\} \times \times \{H\cos(\theta - \theta_H) + H_i\cos2\theta\}, \quad (3)$$

where γ is the gyromagnetic ratio. For extremal orientations, this expression is transformed into the known Kittel equations:

$$\frac{\omega}{\gamma} = H_\perp + H_i \quad (4)$$

for the field along the normal to the film plane, $\theta_H = 0$ ($H > |H_i|$), and

$$\left(\frac{\omega}{\gamma}\right)^2 = H_\parallel(H_\parallel - H_i) \quad (5)$$

for the field in the film plane, $\theta_H = \pi/2$.

The $H_\parallel$, $H_\perp$ and H_i parameters describe quite adequately the angular dependence of the resonance field exhibiting an appreciable anisotropy (see Fig. 1).

The working frequency $\nu = 9.685$ GHz corresponds to the ratio $\omega/\gamma = 3.101$ kOe used in the calculations. The gyromagnetic ratio is $\gamma = g|e|/2mc$ (the effective g-factor of Co is 2.16). When calculating, the satu-

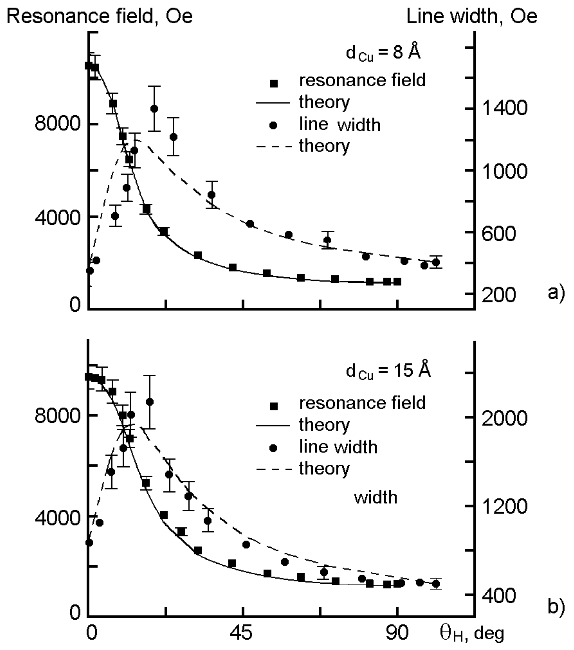

Fig. 1. Angular dependences of resonance field and line width for two samples with d_{Cu} = 8 Å (a) and d_{Cu} = 15 Å (b).

ration magnetization of a 8 Å thick Co layer (M = 1350 Gs) was taken equal to the average value obtained [2–5] for several series of multilayer Co/Cu samples with layer thickness close to 8 Å.

The resonance line width taken for our samples also exhibits a considerable anisotropy which can be attributed to the average-over-sample variation of the parameters of Eq.(3). In this case, the line width can be written as [6]

$$\Delta H(\theta) = \Delta H_0 + \frac{\partial H_r}{\partial \theta}|\Delta\theta| + \frac{\partial H_r}{\partial H_i}|\Delta H_i|, \qquad (6)$$

where H_r is the orientation-dependent resonance field at a fixed frequency; ΔH_0, the angle-independent term defined by the internal damping of the system; $\Delta\theta$, the scatter of the normal directions over the film; ΔH_i, the inhomogeneity of the effective field in the sample. The parameters ΔH_0, $\Delta\theta$ and ΔH_i were calculated by Eq.(6) for all samples. Their dependences on the Cu layer thickness are shown in Fig. 2, which also shows the corresponding dependence H_i from Eq.(3) for comparison.

The parameters of all the dependences demonstrate the oscillating variation with the thickness of Cu layers. Moreover, these oscillations fluctuate quite regularly with a period close to the interplanar spacing of the FCC Cu lattice in the [111] orientation. This means that the above dependences are based on a common mechanism possibly connected

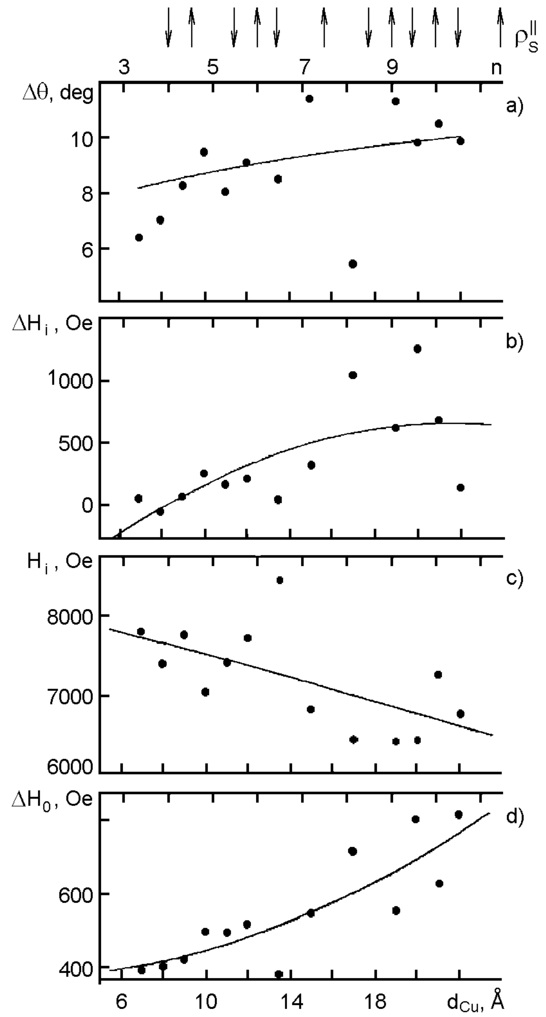

Fig. 2. Nonmagnetic copper layer thickness of the scatter in the normal orientations over the film $\Delta\theta$ (a); inhomogeneity of the effective field in the sample ΔH_i (b); effective internal field H_i (c) and the angle-independent parameter defined by the internal damping of the system ΔH_0 (d). Vertical lines correspond to the Cu layer thicknesses $d_{Cu} = nd_{(111)}$ where n is an integer. The solid line in Fig. 2(a) corresponds to the results from (7), those in Fig. 2(b, c, d) are polynomial approximations corresponding to minima of r.m.s. deviation. The arrows ↑ and ↓ indicate the positions of the maxima and minima of the relative resistivity in a saturation state $\rho_s^{\parallel}$ (in the magnetic field H = 15 kOe longitudinal to the layers [14]).

with changes in the roughness of the layer interfaces. The reason for that is as follows.

In the course of a metal layer condensation, its surface roughness increases with the layer thickness because the upper atomic plane accumulates the stacking faults of the lower atomic planes. As a result, the next layer of another metal is condensed onto the interface with a roughness predetermined by the underlying metal layer. In our multilayer system, the roughness of the Cu layer is imposed on the next upper magnetic Co layer, the roughness of the latter should oscillate against the background of its monotonous increase with increasing thickness of the Cu layers. This statement was supported quantitatively by numerical simulation of interface roughness for two- and multilayer films. The r.m.s. roughness parameter σ' was investigated as a function of the absolute and relative thickness in amorphous and crystalline multilayer structures [7]. The obtained dependence [7] was a power law $\sigma' \sim t^{\beta}$ ($\beta<1$), where t is the total condensation time.

The roughness degree is most often characterized by the ratio σ/ζ, where σ is the asperity height or the dent depth, and ζ is the average size of a flat region (Fig. 3). The asperities and dents cause changes in local directions of the normal n' to the plane. The orientations of the normal-related magnetic anisotropy axes also vary in different parts of the film. The average disorientation degree is characterized by the parameter $\Delta\theta$ of the equality $\sigma/\zeta = \mathrm{tg}\Delta\theta$. This model provides an adequate interpretation of the experimentally observed increase in $\Delta\theta$ with the Cu layer thickness. The solid line in Fig. 2(a) is based on the results from [7]:

$$\Delta\theta = A + k(d_{\mathrm{Cu}}/d_{\mathrm{Cu[111]}})^{\beta} \qquad (7)$$

for $A = 4°$, $\beta = 0.33$ and $k = 2.8°$

In all samples, $d_{\mathrm{Co}} = 8$ Å was selected practically equal to four interplanar spacings of the FCC structure for the [111] orientation which ensures the smallest inherent roughness of the magnetic layers. For the FCC Cu structure $d_{\mathrm{Cu[111]}} = 2.09$ Å, and a change with a step of 1–2 Å in the average thickness of the Cu layers must increase the interface roughness additionally. Therefore, the maxima and the minima of $\Delta\Theta$ correspond to the Cu layer thicknesses $nd_{\mathrm{Cu[111]}}$ where n is an integer (vertical lines in Fig. 2) or a semi-integer. The interface roughness may influence significantly the effective magnetic anisotropy (Eq.2) that for thin films is usually considered separating surface and bulk components. The surface anisotropy E_S is related to distortions in the spatial surroundings of atoms residing on a flat surface [8]. The roughness causes a decreased anisotropy at the magnetic crystalline surface [9] by $\Delta E_S/E_S \approx 2\sigma/\zeta$ because some surface atoms are positioned not on the plane but on the edges of the asperities and dents, i.e. in intermediate positions between the surface and bulk ones. The main volume contribution to the system energy which is affected by the interface roughness is the magnetic dipole energy E_d. Its quantitative dependence on the parameter σ/ζ was considered for some perfect configurations with periodical irregularities on both surfaces of a thin film [10–12]. The magnetic dipole anisotropy decreases nonlinearly with increasing roughness and the slope of this dependence drops at increasing σ/ζ. The roughness affects also the magnetoelastic anisotropy E_{ME} of the Co films. In our multilayer systems, the Co layers are under tension due to a slight disparity between the cobalt and copper lattice parameters (~2 %). To our knowledge, this effect in Co/Cu films has not been investigated either theoretically or experimentally.

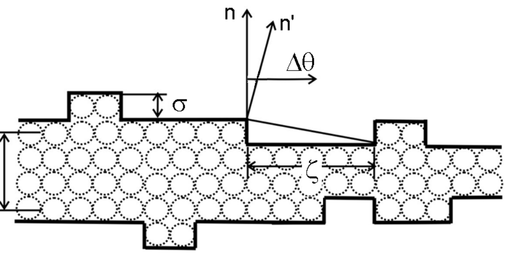

Fig. 3. Schematic image of a rough area in an epitaxial layer with average thickness d.

Taking into account the different signs of the anisotropy components, the resulting energy of the magnetic anisotropy of the film can be written as

$$E_a = E_v - (E_d - \Delta E_d) + (E_S - \Delta E_S) + E_{ME}, \quad (8)$$

where E_v is the roughness-independent bulk anisotropy. The different dependences of the terms in Eq.(8) on the parameter σ/ζ can account for the experimentally observed increase of K_A [13] and the decrease in H_i with the increasing thickness of the Cu layer.

The increase of ΔH_0 against its background oscillations (solid curve in Fig. 2c) with d_{Cu} also points to the increasing roughness of the layer surface. In metallic ferromagnetics, the resonance line width is defined to a large extent by scattering of conduction electrons on structural irregularities. In the model discussed, the interface roughness is a source of such scattering centers.

As mentioned above, the dependence $\Delta\theta(d_{\mathrm{Cu}})$ exhibits oscillations about the average value in Eq.(7) with a period close to the interplanar spacing of the Cu structure. Previous investigations of magnetic resistance versus the Cu layer thickness on the same series of samples [14] revealed oscillating behavior of another important parameter — the saturated state resistivity $\rho_s^{\|}$ in a magnetic field parallel to the measuring current. The extremes in the dependence $\rho_s^{\|}(d_{\mathrm{Cu}})$ are shown in Fig. 2 (arrows (↑) and (↓). The extremes of $\rho_s^{\|}$ and $\Delta\theta$ occur at similar d_{Cu}-values, which is another point in favor of the important role of roughness in the formation of scattering centers for conduction electrons.

To conclude, note that the used model treats the interface roughness as the only contributor to $\Delta\theta$. However, another source of internal inhomogeneities is possible in our multilayer system. Being granular in nature, the layers (see above) form a columnar structure in the film. The edge effects changing the orientations of magnetization at the lateral surfaces of the columns can also contribute to $\Delta\theta$, and this contribution is most likely independent of the Cu layer thickness, at least for rather large d_{Cu} values. The additional contribution forms a certain invariant component, which is the same in all the samples. That is why the dependence $\Delta\theta(d_{\mathrm{Cu}})$ in Fig. 2 (a) has a constant component $A = 4°$. The component above it increases with d_{Cu} and is thus dependent on the interface roughness. A similar constant component is observed in the dependence $\Delta H_0(d_{\mathrm{Cu}})$, where it is due to the corrugated lateral surfaces of the columns.

Thus, the dependence of the magnetic subsystem parameters in the multilayer Co/Cu (111) samples upon the thickness of the nonmagnetic layers can be attributed to the surface roughness of the Cu layers imposed toughly on the magnetic Co layers. The roughness-induced spatial inhomogeneities in the magnetic layers cause orientational disordering of the local anisotropy axes over the sample and result in a strong angular dependence of the FMR line width. The roughness has a significant effect on magnetic anisotropy modifying the parameters of its bulk and surface components. The inhomogeneities acting as scattering centers for conduction electrons define the natural damping of the system in dynamic susceptibility and hence the initial width of the FMR line.

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Магнітний резонанс та анізотропія у багатошаровій системі Co/Cu (111)

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Досліджено кутові залежності спектрів ФМР у багатошаровій системі [Co (8 Å)/Cu (d_{Cu}) (111)]$_{20}$. Виміряно значення внутрішнього ефективного поля та розраховано залежності параметрів просторових неоднорідностей системи від товщини немагнітного шару міді. Виявлено, що значення цих параметрів зростають зі збільшенням кількості шарів Cu. Якісний опис цих залежностей виконано у рамках моделі, що враховує шорсткість інтерфейсів, ступінь якої збільшується при збільшенні товщини немагнітних шарів.