Electrical Anisotropy of Thin Metal Films Growing on Dielectric Substrates

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Abstract. Electrical properties of conductive thin films, that are produced by vacuum evaporation on the dielectric substrates, and which properties depend on their thickness, usually are anisotropic i.e. they have uniaxial anisotropy. If the condensate grow on dielectric substrates on which plane electrical field **E** is created the transverse voltage $U_\perp$ appears on the boundary of the film in the direction perpendicular to **E**. Transverse voltage $U_\perp$ depends on the angle γ between the applied magnetic field **H** and axis of light magnetisation. When electric field **E** is applied to continuous or grid layers, $U_\perp$ and resistance R of layers are changed by changing γ. It means that value of $U_\perp$ is the measure of anisotropy magnitude. Increasing voltage U_0, which is created by **E**, $U_\perp$ increases to certain magnitude and later decreases. The anisotropy of continuous thin layers is excited by inequality of conductivity tensor components $\sigma_0 \neq \sigma_\perp$. The reason of anisotropy is explained by the model which shows that properties of grain boundaries are defined by unequal probability of transient of charge carrier.

Keywords: thin films, uniaxial anisotropy, and conductivity.

1 Introduction

In [1,2,3] magnetoresistance effect, which was investigate by mean Kerr microscopy and magnetic force microscopy is considered. In this paper we continued studies [4,5,6] of the magnetic anisotropy of thin metal films by

measuring transverse voltage. We investigated the influence of plain Hall effect on anisotropy of thin metal films as well.

We observed that there exists uniaxial anisotropy of conduction in the thin continuous films of conductive materials that are grown on dielectrical substrates. When electric field $\mathbf{E}$ is applied to such films, the difference of potentials $U_\perp$ (transverse voltage) appears between opposite boundaries of the film in the orthogonal direction to the $\mathbf{E}$. The magnitudes of $U_\perp$ and film resistance depend on the direction of $\mathbf{E}$.

The Hall plain effect influences the resistance and voltage $U_\perp$ of ferromagnetic films [4,7,8]. When the effect of dimensions is valid the magnetic and electric properties of the films are an isotropic [4,5,9]. During magnetisation process of the ferromagnetic films the hysteresis $U_\perp(\mathbf{H})$ is proportional to the hysteresis $B(\mathbf{H})$.

In this paper we demonstrate that anisotropy of electric and magnetic properties of thin metal films is exited by inequality of conductivity tensor components $\sigma_0 = \sigma_\perp$ and the transverse voltage can be used as a measure of anisotropy magnitude. In addition anisotropy of thin ferromagnetic films is caused by plain Hall and magnetoresistive effect.

2 Experimental Details

Our experimental films which have circle shape with electric contact that are laid round the film boundary (fig.1) were grown by thermal evaporation in vacuum from such substances as Ag, Cu, Sn, Co, Fe, Ni and CoNi on glass, quartz and ceramic substrates. That creates possibility to measure easily dependence $U_\perp$. The films were deposited at rate v=(0.5÷12) nm/s with pressure p=(10^{-5}÷10^{-3}) Pa. The conditions of the evaporation process were maintained within these limits: pressure of the remaining gas, condensation rate v=(0.5÷12) nm/s, temperature of the substrate T_p=(10÷350)^{o}C. The first batch of the samples was formed by growing of the layer upon influence of electric field E=(1÷20) V/cm; the second batch − upon an influence of the magnetic field of H=(0÷9) kA/m. The growth of the films was controlled by the amount of charges in the vapor stream and magnitude of substrate potential [6,10].
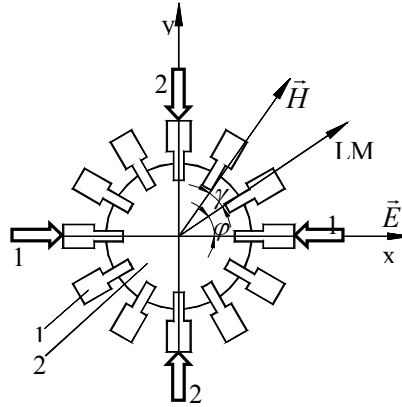
Fig. 1. Charts of the measurement for potential differences:
1 – contacts, 2 – substrate

The evaporated films were investigated by measuring transverse voltage $U_\perp$, transverse current $I_\perp$ and transverse resistivity $R_\perp$ between two samples connected to the boundaries of the films. At the same time another two samples were investigated when the angle between direction of the field **E** and the axis AA of anisotropy is variable. Longitudinal voltage $U_\parallel$, current $I_\parallel$, and resistance $R_\parallel$ are measured in the direction of the applied electric field **E**. Furthermore, the named above magnitudes were measured while effecting the film by the constant magnetic field **H** by the angle γ between **H** and axis of light magnetisation LMA. These magnitudes were measured by magnetooptic system MPKF determining the dependence of magnetic induction B and γ [6].

3 Results and Discussion

Chart of the measurement are presented in the fig.1. During these measurements the vector of the applied electrical field had the angle γ with AA. $U_\perp$ and $R_\perp$ dependencies on φ for nonmagnetic and ferromagnetic materials are given in the fig. 2. The transverse voltage could be characterized by the dependence $U_\perp \approx U_{\perp m} sin(2\varphi \pm \varphi_0)$, where $U_{\perp m}$ is maximal value of $U_\perp(\varphi)$ and φ_0 is an initial value of the angle φ.

The LMA of ferromagnetic films always coincides with AA. The degree of magnetic anisotropy S depends on the transverse voltage $U_\perp$ by $U_{\perp m}=kS+b$,

where k and b are coefficients depending on the conditions of film deposition [4]. If a magnetic field **H** is applied as well, then there appears the difference of values $\Delta U_\parallel$ and $\Delta U_\perp$ that depends on this magnetic field. The $\Delta U_\parallel$ and $\Delta U_\perp$ are functions of the magnitude of the **H** and the angle γ between **H** and LMA. Typical dependencies of values $\Delta U_\parallel$ and $\Delta U_\perp$ of the angle γ are presented in the fig. 3.
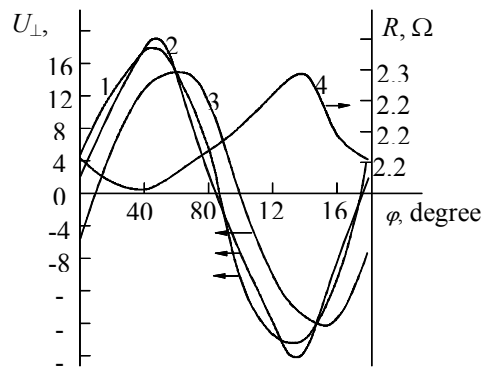
Fig. 2. Transverse voltage $U_\perp$ and resistance $R_\parallel$ dependencies on the angle between electric field vector **E** and anisotropy axis: 1 – Au, 2 – Ag, 3, 4 – Sn
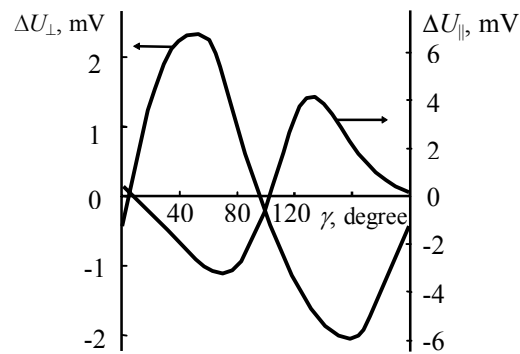
Fig. 3. Dependencies of transverse voltage change $\Delta U_\perp$ and longitudinal voltage change $\Delta U_\parallel$ in ferromagnetic films on the angle between applied magnetic field vector and anisotropy axis

Reversal magnetisation process of the ferromagnetic films enables to obtain $U_\perp(\mathbf{H})$ and $B(\mathbf{H})$ dependencies for various values of γ (fig. 4). Values of

both functions are proportional. When **E** and **H** are applied, then the transverse and longitudinal voltages are given by expressions

$$U_\perp^\Sigma = U_\perp(\mathbf{E},\ \varphi) + \Delta U_\perp(\mathbf{H, E},\ \varphi,\ \gamma), \tag{1}$$

$$U_{II}^\Sigma = U_\perp(I_{\|},\ R_{\|}) + \Delta U_{\|}(\mathbf{H, E},\ \varphi,\ \gamma), \tag{2}$$

where function $\Delta U_{\|}(\mathbf{H, E},\ \varphi,\ \gamma)$, expresses anisotropic magnetoresistant and function $\Delta U_\perp(\mathbf{H, E},\ \varphi,\ \gamma)$ – plain Hall effect. Then the ratio $U_\perp^\Sigma / U_{II}^\Sigma$ is expressed by

$$\Delta U_\perp^\Sigma / \Delta U_{II}^\Sigma = c_3 \mathrm{tg}^3(2\gamma - \gamma_0) + c_2 \mathrm{tg}^2(2\gamma - \gamma_0) + c_1 \mathrm{tg}(2\gamma - \gamma_0) + c_0 \tag{3}$$

where coefficients $c_0,\ c_1,\ c_2,\ c_3$ have been found by least squares method.

Properties of the films are described by the model of anisotropic conductivity and by model of charge dispersion into boundaries [4], [11].
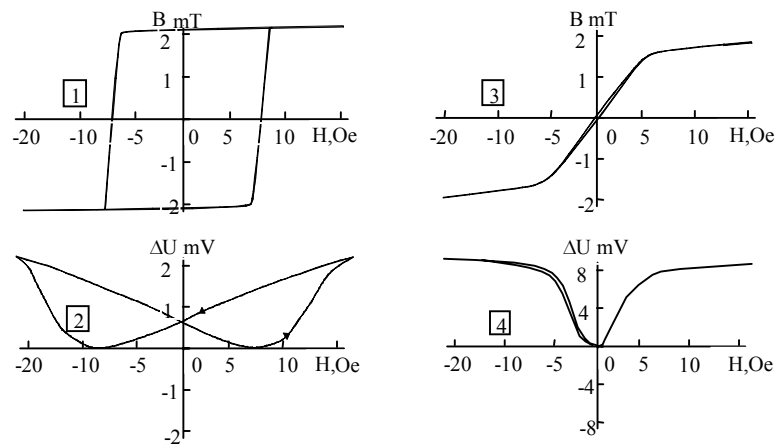

Fig. 4. Typical demagnetization hysteresis (1, 3) and transverse voltage change (2, 4) dependencies on the magnitude of applied magnetic field **H.** The angle between **H** and light magnetisation axis is 80° (1,2) and (3,4) when this angle is 180°

4 Models of Film Anisotropy

The resistance $R_{\|}$ measured parallel to the anisotropy axis is less than resistance $R_\perp$ measured in the orthogonal direction. The following model describes

dependence of transverse voltage on anisotropy magnitude. In this model we made premise that the grains have the shape of rectangular parallelepiped.

The quantities $U_\perp(E,\gamma)$ and $U_\parallel(I_\parallel,R_\perp)$ can be calculated if the tensor of the electrical conductivity σ is known. On the other hand σ can be calculated on the basis of the mathematical model [12]. As shown in [11], a distribution of electric field potential $\varphi(x,y)$ in the rectangular domain is expressed by the boundary value problem. Moreover, the solution φ of this problem on the boundary of the domain can be presented in an analytical way ($1 \le t \le 1/k$):

$$\varphi(x) = 2a\frac{A(\alpha,k,t)}{A(\alpha,k,t)}, \quad x = \frac{A(\alpha,k,t)}{A(\alpha,k,t)}, \tag{4}$$

where

$$A(\alpha,k,t) = \int_1^t (\tau - k\tau^2)^{\alpha-1}(\tau-1)^{-\alpha}\,\mathrm{d}\tau, \quad \alpha = \frac{1}{\pi}\arccos\frac{-\sigma_{12}}{\sqrt{\sigma_{11}\sigma_{12}}} \in]0;1[\,, \tag{5}$$

and the parameter $0 < k < 1$ is defined as a root of the uniquely solvable equation

$$\frac{A_\alpha(1-k)}{A_\alpha(k)} = \frac{b}{a}\sqrt{\frac{\sigma_{11}}{\sigma_{22}}}\;. \tag{6}$$

One can shown that the current

$$I_\parallel = 2\varphi_0\sqrt{(\sigma_{11}\sigma_{22} - \sigma_{12}^2)}\,\frac{A(0.5, 1-k, \kappa)}{A(0.5, k, \kappa)} \tag{7}$$

and that there exist a unique correspondence between the three quantities $(\alpha;k;I_\parallel)$ and $(\sigma_{11};\sigma_{12};\sigma_{22})$, so that the problem of finding the tensor σ is equivalent to the determination of quantities α, k and $I_\parallel$.

Let's go over to search for these quantities: a) current $I_\parallel$ is measured as a result of experiment; b) k is defined basing on equality (6); c)α is found by the measured potential φ on the side of rectangle not occupied by electrodes of supplying voltage. Namely, let $I_\parallel$ and $I_\perp$ be the quantities of currents flowing via the region when voltages either $2\varphi_0$ or $2\varphi_\perp$ are applied to the sides of the

rectangle a, b or $a_\perp$, $b_\perp$ respectively. Starting from the formulas of transformation of the tensor, we obtain that, if in the first case the conductivity is characterised by tensor σ or by the parameters α, k, then in the second case it is characterized by tensor

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix}$$

and the parameters $\alpha_\perp = 1 - \alpha$, $k_\perp = 1 - k$. Then we obtain that the relation of currents

$$\frac{I_\parallel}{I_\perp} = \left(\frac{A(0.5, 1 - k, 1/k)}{A(0.5, k, 1/k)} \right)^2 \tag{8}$$

represents an equation relative to one unknown quantity k, whereas the existence and uniqueness of its solution for any given $I_0, I_\perp, \varphi_0, \varphi_\perp$ are guaranteed by monotonous increasing of the right-hand side of (8). The next step of calculating the components of σ is to find the values of the parameter t, corresponding to the experimental value of potential φ_e at the point (x, b). For this we turn to the representation $\varphi(t)$ of (1) and get the equation for t

$$\varphi = 2\varphi_\parallel \frac{A(0.5, k, t)}{A(0.5, k, \kappa)} - \varphi_\parallel . \tag{9}$$

The determination of the last unknown α goes on according to the second equation (1) analogously to the above-mentioned method. If α, k are already found and the integrals $A(\alpha, k, t)$ calculated, then, from (5)–(7) it is easy to obtain the following formulas for calculating the components of the tensor σ:

$$\sigma_{11} = c \frac{a}{b} \frac{A(\alpha, 1 - k, t)}{A(\alpha, 1 - k, \kappa)}, \ \sigma_{12} = -c \cos(\pi \alpha), \ \sigma_{22} = \frac{c}{\sigma_{11}}, \tag{10}$$

here $c = I_\parallel A(0.5, k, \kappa)/2A(0.5, 1 - k, \kappa)$. The quantities $\Delta U_\perp(\mathbf{H}, \mathbf{E}, \varphi, \gamma)$ and $\Delta U_\parallel(\mathbf{H}, \mathbf{E}, \varphi, \gamma)$ can be calculated if the Hall mobility $\mu_H B$ and the specific resistivity ρ are known. On the other hand $\mu_H B$ and ρ can be calculated on the basis of the mathematical model represented in [13].

5 Conclusions

Light magnetisation axis of ferromagnetic films always coincides with axis of anisotropy. The transverse voltage value can be calculated when electrical conductivity of material and coefficients of magnetoresistive conductivity are given or are obtained by measurements. Function $\Delta U_{\perp}(\mathbf{H},\mathbf{E},\varphi,\gamma)$ expresses plain Hall effect and function $\Delta U_{\parallel}(\mathbf{H},\mathbf{E},\varphi,\gamma)$ expresses anisotropic magnetoresistive effects. Their ratio depends only on the angle γ. Transverse voltage is a measure of conductivity and magnetic anisotropy.

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