THE CONTRIBUTION TO THE SCATTERING OF ELECTRONS IN THE MAGNETORESISTANCE OF MULTILAYERS OF NONMAGNETIC METALS

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The semiphenomenological model that describes the scattering of electrons in the implementation of the phenomenon magnetoresistance (MR) three-layer film based on non-magnetic metals were proposed. The quantitative characteristic of the MR is so-called magnetic resistance coefficient $\beta_B = d\ln R/dB$, the value of which on the field dependence not only of the mean free path of the electrons, and a specular parameter and transmission parameters at the grain boundary and interfaces.

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INTRODUCTION

When interpreting the results of studies electrical properties for polycrystalline films should be considered as surface and grain-boundary scattering of electrons. In the consideration to multi-layer film appears an additional mechanism of electron scattering at the interfaces, which also causes contribute to the electrical properties. Research received by the authors strain effect (see, for example [1]) indicate that the experimental results agree much better with billing based on classical models, given the so-called deformation results in electrocarried parameters, i.e., the dependence of strain not only the bulk mean free path (λ_0), but the specular parameter (p), transmission parameters at the grain boundary (r) and interfaces (Q_{ij}) of electrons. This semiphenomenological model for strain effect was proposed us [2] and tested in [3].

The idea of deformation effects proved very productive and the authors of [4] (see also [1]) extended to the case of them on the thermal coefficient of resistance (TCR) for two- and three-layer film systems. They introduced for consideration by analogy with [2], the so-called temperature effects in the above electron transport parameters. Obviously, it is obvious that this approach that allowed understanding the role of different processes of electron scattering effects in strain coefficient and TCR, may be proposed in the case of magnetoresistance (MR) of non-magnetic metals.

We have proposed a model for semiphenomenological model for MR films of the nonmagnetic metals, which, by analogy with [2, 4], takes into account the indirect influence of an external magnetic field not only λ_0, but p, r and Q_{ij}. This is precisely the new idea that will more accurately describe the physical processes in multilayers that lead to changing the settings electron transport and, consequently, the magnitude of MR. The basic requirement which is presented in this case, the film systems – is most probably an identity polycrystalline layers. This condition is almost satisfying film system based on V and Ni [3], or Cr, Cu and Sc [4].

EXPERIMENT

As in works [2, 4, 5] two- or three-layer film systems we simulate a parallel connection of film thickness d_i (i = 1, 2, 3) with a total resistance R:

$$\frac{1}{R} = \frac{a}{l}\left(d_1\sigma_{01}F_1 + d_2\sigma_{02}F_2 + d_3\sigma_{03}F_3\right), \qquad (1)$$

where a, l – width and length of the film system; σ – conductivity of bulk material; $F_i \equiv \frac{\sigma_i}{\sigma_{0i}}$ – Fuchs function (σ_i – conductivity of film).

The quantitative characteristics of the action magnetic induction (B) may be appropriate magnetic coefficients:

$$\beta_B^K = \frac{\partial \ln R}{\partial B},\ \beta_{0i}^K = -\frac{\partial \ln\lambda_{0i}}{\partial B},\ \beta_{pi}^K = -\frac{\partial \ln p_i}{\partial B},$$

$$\beta_{ri}^K = -\frac{\partial \ln r_i}{\partial B} \text{ and } \beta_{Qij} = -\frac{\partial \ln Q_{ij}}{\partial B},$$

where index "K" corresponds to three field orientations relative to the electric current: 1 (parallel), 2 (transverse) and 3 (perpendicular).

The physical nature of magnetic coefficients is that the Lorentz force causes a change λ_0, and magnetostrictive effects – change of p, r and Q_{ij}. In accordance with the ratio (1) magnetic resistance coefficient β_B^K can in semiphenomenological approximation represented as:

$$\beta_B^K \equiv \frac{d\ln R^K}{dB} = A_1\left(-\alpha_{B1}^K - \frac{\partial \ln\sigma_{01}^K}{\partial B} - \frac{\partial \ln F_1^K}{\partial B}\right) + \ldots$$

$$+A_3\left(-\alpha_{B3}^K - \frac{\partial \ln\sigma_{03}^K}{\partial B} - \frac{\partial \ln F_3^K}{\partial B}\right), \qquad (2)$$

where $A_i = \frac{d_i\sigma_{0i}F_i}{d_1\sigma_{01}F_1 + d_2\sigma_{02}F_2 + d_3\sigma_{03}F_3}$;

$\alpha_{Bi}^K = \frac{\partial \ln d_i}{\partial B} \cong 0$ – magnetostrictive coefficient;

$-\frac{\partial \ln\sigma_{0i}^K}{\partial B} = \beta_{0Bi}^K$, where index "0" means a bulk sample.

The derivatives of Fuchs function on the magnetic field (for example, F_1^K), can be represented as follows:

$$\frac{\partial \ln F_1^K}{\partial B} = \frac{\partial \ln F_1^K}{\partial \ln k_1}\frac{\partial \ln k_1}{\partial B} + \frac{\partial \ln F_1^K}{\partial \ln m_1}\frac{\partial \ln m_1}{\partial B} +$$

$$+ \frac{\partial \ln F_1^K}{\partial \ln k_1}\frac{\partial \ln k_i}{\partial \ln p_i}\frac{\partial \ln p_1}{\partial B} + \frac{\partial \ln F_1^K}{\partial \ln k_1}\frac{\partial \ln k_1}{\partial \ln k_2}\frac{\partial \ln k_2}{\partial B} +$$

$$+ \frac{\partial \ln F_1^K}{\partial \ln k_1}\frac{\partial \ln k_i}{\partial \ln r_i}\frac{\partial \ln r_1}{\partial B} + \frac{\partial \ln F_1^K}{\partial \ln m_1}\frac{\partial \ln m_i}{\partial \ln r_i}\frac{\partial \ln r_1}{\partial B} +$$

$$+ \frac{\partial \ln F_1^K}{\partial \ln m_1}\frac{\partial \ln m_1}{\partial \ln m_2}\frac{\partial \ln m_2}{\partial B} + \frac{\partial \ln F_1^K}{\partial \ln m_1}\frac{\partial \ln m_1}{\partial \ln m_2} \text{ x}$$

$$\text{x } \frac{\partial \ln m_2}{\partial \ln r_2}\frac{\partial \ln r_2}{\partial B} + \frac{\partial \ln F_1^K}{\partial \ln k_1}\frac{\partial \ln k_1}{\partial \ln Q_{12}}\frac{\partial \ln Q_{12}}{\partial B} +$$

$$+ \frac{\partial \ln F_1^K}{\partial \ln k_1}\frac{\partial \ln k_1}{\partial \ln k_2}\frac{\partial \ln k_2}{\partial \ln Q_{12}}\frac{\partial \ln Q_{12}}{\partial B}, \qquad (3)$$

where $k_i = \frac{d_i}{\lambda_{0i}}$ and $m_i = \frac{L_i}{\lambda_{0i}}$ – reduced thickness of i-layer and average size of crystallites (L_i).

After substituting in ratio (2) and similar relations for $\frac{\partial \ln F_2^K}{\partial B}$ and $\frac{\partial \ln F_3^K}{\partial B}$ taking into account the obvious equation:

$$\frac{\partial \ln F_i^K}{\partial \ln m_i} \cong \frac{\partial \ln F_i^K}{\partial \ln k_i} \cong 1 - \frac{\beta_{Bi}^K}{\beta_{0Bi}^K};$$

$$\frac{\partial \ln m_i}{\partial \ln m_k} \cong \frac{\partial \ln k_i}{\partial \ln k_k} = \frac{\beta_{0Bi}^K}{\beta_{0Bk}^K};$$

$$\frac{\partial \ln m_i}{\partial B} = \frac{\partial \ln k_i}{\partial B} = \alpha_{Bi}^K + \beta_{0Bi}^K \cong \beta_{0Bi}^K,$$

obtain a working formula for the drag coefficient of a three-layer non-magnetic film system:

$$\beta_B^K = A_1\left\{\beta_{0B1}^K - \left(1 - \frac{\beta_{B1}^K}{\beta_{0B1}^K}\right)\left[\left(2\beta_{0B1}^K + \beta_{p1}^K\frac{\partial \ln k_1}{\partial \ln p_1} +\right.\right.\right.$$

$$\left. + \beta_{r1}^K\frac{\partial \ln m_1}{\partial \ln r_1} + \beta_{Q12}^K\frac{\partial \ln k_1}{\partial \ln Q_{12}}\right) +$$

$$+ \left(2\beta_{0B2}^K + \beta_{p_2}^K \cdot \frac{\partial \ln k_2}{\partial \ln p_2} + \beta_{r_2}^K \cdot \frac{\partial \ln m_2}{\partial \ln r_2} +\right. \qquad (4)$$

$$\left.\left.\left. + \beta_{Q_{21}}^K \cdot \frac{\partial \ln k_2}{\partial \ln Q_{21}}\right)\cdot\frac{\beta_{0B1}^K}{\beta_{0B2}^K}\right]\right\} + \ldots + A_3\left\{\beta_{0B1}^K - \left(1 - \frac{\beta_{B3}^K}{\beta_{0B3}^K}\right)\right. \text{x}$$

$$\text{x}\left[\left(2\beta_{0B3}^K + \beta_{p3}^K\frac{\partial \ln k_3}{\partial \ln p_3} + \beta_{r3}^K\frac{\partial \ln m_3}{\partial \ln r_3} + \beta_{Q32}^K\frac{\partial \ln k_3}{\partial \ln Q_{32}}\right) +\right.$$

$$+ 2\beta_{0B2}^K + \beta_{p_2}^K \cdot \frac{\partial \ln k_2}{\partial \ln p_2} + \beta_{r_2}^K \cdot \frac{\partial \ln m_2}{\partial \ln r_2} +$$

$$\left.\left. + \beta_{Q_{23}}^K \cdot \frac{\partial \ln k_2}{\partial \ln Q_{23}}\right)\cdot\frac{\beta_{0B3}^K}{\beta_{0B2}^K}\right].$$

Note that the right side of relation (4) are two groups of terms that are directly (β_{0Bi}^K), and indirectly (β_{pi}^K, β_{ri}^K, β_{Qij}^K, $\frac{\partial \ln k_i}{\partial \ln p_i}$, $\frac{\partial \ln m_i}{\partial \ln r_i}$ and $\frac{\partial \ln k_i}{\partial \ln Q_{ij}}$, where i = 1–3) contribute to the value β_{Bi}^K and β_B^K.

To determine these parameters is necessary to obtain two groups of values λ_0 , p, r and Q_{ij} at two values of the magnetic field B_1 and B_2 (can be taken $B_1 = 0$). You can use the experimental dependences of TCR the thickness of one-layer films at B_1 and B_2, which must be processed within the lineralized value model and anisotropic scattering Tellier and Tosser [6]. This allows you to calculate the number of terms and factors the right side of (4), including:

$$\beta_p^K = -\frac{1}{p(B_1)}\frac{p(B_2) - p(B_1)}{(B_2 - B_1)};$$

$$\beta_r^K = -\frac{1}{r(B_1)}\frac{r(B_2) - r(B_1)}{(B_2 - B_1)};$$

$$\frac{\Delta \ln k}{\Delta \ln p} = -\frac{p(B_1)}{p(B_2) - p(B_1)}\frac{d/\lambda_0(B_2) - d/\lambda_0(B_1)}{d/\lambda_0(B_1)};$$

$$\frac{\Delta \ln m}{\Delta \ln r} = -\frac{r(B_1)}{r(B_2) - r(B_1)}\frac{L/\lambda_0(B_2) - L/\lambda_0(B_1)}{L/\lambda_0(B_1)}.$$

In articles [3, 4] presented a detailed procedure for testing theoretical models of TCR and strain coefficient considering temperature and deformation effects.

Note also that the relation (4) for β_B^K the three-layer film is relatively easy to extend to the case of arbitrary number of layers.

CONCLUSIONS

Semiphenomenological approach developed here, can qualitatively understand the role of electron scattering processes on the outer surfaces, interfaces and grain boundaries in the magnetoresistance effect. Obviously, their contribution is more significant when the foil system will consist of layers of magnetic metals or alloys cause a domain boundaries as the emergence of new terms on the right side of (4) associated with an additional mechanism of electron scattering. The presence of granular state will cause a new mechanism of electron scattering and a corresponding increase in magnitude MR.

Available with the trajectories of electrons with different geometry measurement MR presenting us in [7]. The results of our previous studies [7, 8] to a large extent confirm this qualitative conclusion. In particular, according to [7], the value of β_B in perpendicular geometry measurement of film Pd, Fe and Pd/Fe/S (S – substrate) thickness of 10 nm has the following values: $\beta_B^{Pd} \simeq -1.4\cdot10^{-2}$ T^{-1} (or 1.4%/T); $\beta_B^{Fe} \simeq -(2.5\ldots5.0)\cdot10^{-2}$ T^{-1}; $\beta_B^{Pd/Fe} \simeq -2\cdot10^{-2}$ T^{-1}, respectively.

In the transition to multilayers $[Fe/Cu/Fe]_n/S$ (n = 3...9) [8] value β_B varies – (3.0…8.7) %/T. If multilayers $[Fe/Cr/Fe]_n/S$ (n = 3...7) [8] value β_B varies – (0.7...7.7)% / T. Thus, the presence of a magnetic layer in the film system may make the change β_B on the several units % / T.

This is evidenced, for example, the results of [9], according to which a dilute granular solid solutions of atoms Co in Cu matrix at T = 300 K the value β_B^K increases approximately 7.5 times (from $0.5\cdot10^{-3}$ to $3.7\cdot10^{-3}$ T^{-1}) at the increasing the concentration of Co from 13 to 19 at.%, which can be explained by an additional spin-dependent scattering of electrons on the Co granules.

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ВКЛАД ПРОЦЕССОВ РАССЕИВАНИЯ ЭЛЕКТРОНОВ В МАГНИТОСОПРОТИВЛЕНИЕ МНОГОСЛОЙНЫХ ПЛЕНОК НЕМАГНИТНЫХ МЕТАЛЛОВ

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Предложена полуфеноменологическая модель, которая описывает процессы рассеивания электронов при реализации явления магнитосопротивления (МС) трехслойной пленки на основе немагнитных металлов. Количественной характеристикой МС является так называемый магнитный коэффициент сопротивления $\beta_B = d\ln R/dB$, величина которого определяется полевой зависимостью не только средней длины свободного пробега электронов, а и коэффициентов зеркальности внешних поверхностей пленки, прохождения границы зерен и интерфейсов.

ВНЕСОК ПРОЦЕСІВ РОЗСІЮВАННЯ ЕЛЕКТРОНІВ У МАГНІТООПІР БАГАТОШАРОВИХ ПЛІВОК НЕМАГНІТНИХ МЕТАЛІВ

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Запропонована напівфеноменологічна модель, яка описує процеси розсіювання електронів при реалізації явища магнітоопору (МО) тришарової плівки на основі немагнітних металів. Кількісною характеристикою МО виступає так званий магнітний коефіцієнт опору $\beta_B = d\ln R/dB$, величина якого визначається польовою залежністю не тільки середньої довжини вільного пробігу електронів, а і коефіцієнтів дзеркальності зовнішніх поверхонь плівки, проходження межі зерен та інтерфейсів.