JOURNAL OF NANO- AND ELECTRONIC PHYSICS | *ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ*
Vol. **4** No 2, 02043(3pp) (2012) | Том 4 № 2, 02043(3cc) (2012)

Magneto-Strain Effect in Double-Layer Film Systems

Z.M. Makukha, S.I. Protsenko, L.V. Odnodvorets, I.Yu. Protsenko*

Sumy State University, 2, Rymsky-Korsakov Str., Sumy, 40007, Ukraine

(Received 17 April 2012; revised manuscript received 23 May 2012; published online 04 June 2012)

For the first time a theoretical study of magnetodeformation effect (MSE) in double-layer film materials is presented, taking into account the previous results obtained for single-layer films. When creating the elementary theory one derives the well-known coefficient for longitudinal strain coefficient (SC, γ) for a double-layer film system of the type, "biplate", without taking into account the possible processes of mutual diffusion of atoms. The MSE is quantified by the magnetic coefficient of the SC $\beta_{\gamma B} = (1/\gamma)\cdot(\partial\gamma/\partial B)$, which describes the change of the film's electrical resistance under its deformation in the external magnetic field. In the finite ratio for MSE, considered by the appropriate index for three possible orientations of the magnetic field relative to the direction of the flow of electric current (which coincides with direction of the longitudinal SC) the right-hand-side consists of the following values: γ_R, ρ (resistivity), $\beta_{\rho B}$ (magnetic coefficient of resistivity) and second-order partial derivative ρ with respect to strain and magnetic field. The latter is not calculated from the first principles but is measured experimentally. Analyzing the ratio for the limiting cases for $\beta_{\gamma B}$, when $d_1 >> d_2$ and $d_1 << d_2$, leads to predicting as to how the SC depends on the size of the magnetic field.

Keywords: Longitudinal strain coefficient, Magneto-strain effect, Magnetic coefficient of the resistivity, Magnetic coefficient of the gauge factor.

PACS numbers: 46.25 Hf, 75.80.+q

1. INTRODUCTION

Efficacy of nanodimension thin film materials as sensitive elements of temperature sensors, pressure, strain, magnetic field, and others (see, [1]) allows the author [2] to develop the concept of designing a multifunctional sensor, including the strain sensor and a magnetic field sensor, the principle of the latter may be based on the magnetodeformation effect (MSE). Currently, there is a limited number of known works devoted to the study of MSE. In particular, Ref. [3] studied the peculiarities of the magnetic field effect on the strain coefficient in bulk amorphous alloys based on Fe, which are explained in terms of the so-called ΔE effect caused by the influence of magnetic ordering on the elastic properties of the material (this effect is directly related to magnetostriction phenomenon). In this case, as in the case of diamond films [4], the coefficients of longitudinal and transverse strain coefficient decrease in the external magnetic field. The reduction in strain coefficient is due to the change in the structure factor and Young's modulus under the action of magnetic field in metal films [3] or in case of diamond film the strain and magnetic field depend on the energy band gap [4]. The effect of magnetostriction and magnetoresistance in pseudo spin-valve structures of Co/Au/Co, deposited on polymide substrate to create sensors sensing elements of mechanical stress, was studied by the authors work [5]. Along with this, according to our preliminary data, the coefficient of longitudinal strain coefficient of Co and Ni films, measured perpendicular to the orientation of the magnetic field relative to the film's surface, increases by 1.5-1.7 times for a magnetic field of 0.1 T.

Therefore, the purpose of our work is to use a phenomenological theoretical model of magneto-strain effect in double-layer film systems, which may be a basis for a multifunctional sensor for both strain and magnetic field.

The model is a phenomenological approach developed in [6], where it was proposed within the phenomenological approach, that the theoretical correlation between coefficients of longitudinal magnetic strain coefficient and SC, which is expressed in terms of resistance of single-layer metal films. It allows a qualitative analysis of the possible dependence of SC on the magnitude of external magnetic field the magneto-strain effect (MSE).

Quantitatively, the effect can be characterised by the so-called magnetic strain coefficient, which describes the change in the electrical resistance of the film during its strain in the external magnetic field $\beta_{\gamma B} = (1/\gamma)\cdot(\partial\gamma/\partial B)$.

2. THEORETICAL ANALYSIS

The analysis conducted in [6] on the magneto-strain effect in a single layer metal film can be extended to the case of two-layer film systems, and that's the purpose of the present work. When using the elementary theory we have used equation for longitudinal SC of two-layer films, satisfying the "biplate" condition [7]:

$$\gamma = \gamma_1 + \gamma_2 - \frac{d_1\mu_1 + d_2\mu_2}{d_1 + d_2} - \frac{\gamma_1\rho_1 d_2 - \rho_1 d_2\mu_2 + \gamma_2\rho_2 d_1 - \rho_2 d_1\mu_1}{\rho_1 d_2 + \rho_2 d_1}, \quad (1)$$

where d_i, μ_i and ρ_i are the thickness, Poisson 's ratio, and resistivity of the i-layer ($i = 1, 2$), respectively.

After differentiating equation (1), we obtain the equation for the magnetic field induction, $\beta^k_{\gamma B}$, where we have not taken into account the terms proportional to the size of magnetostriction, $M^k_i = d\ln d_i / dB$, where the upper index k corresponds to the longitudinal, transverse or perpendicular direction:

* protsenko@aph.sumdu.edu.ua

$$\beta^k_{\gamma B} = \beta^k_{\gamma 1B}\cdot\gamma_1 + \beta^k_{\gamma 2B}\cdot\gamma_2 - \frac{\gamma_1\rho_1 d_2\left(\beta_{\gamma_1 B}+\beta_{\rho_1 B}\right)+\gamma_2\rho_2 d_1\left(\beta_{\gamma_2 B}+\beta_{\rho_2 B}\right)}{\left(\rho_1 d_2+\rho_2 d_1\right)} + \frac{\beta_{\rho_1 B}\rho_1 d_2\mu_2+\beta_{\rho_2 B}\rho_2 d_1\mu_1}{\left(\rho_1 d_2+\rho_2 d_1\right)} +$$
$$+\frac{\left(\beta_{\rho_1 B}\rho_1 d_2+\beta_{\rho_1 B}\rho_2 d_1\right)\left(\gamma_2\rho_2 d_1+\gamma_2\rho_2 d_1\right)}{\left(\rho_1 d_2+\rho_2 d_1\right)^2} - \frac{\left(\beta_{\rho_1 B}\rho_1 d_2+\beta_{\rho_2 B}\rho_2 d_1\right)\left(\rho_1 d_2\mu_2+\rho_2 d_1\mu_1\right)}{\left(\rho_1 d_2+\rho_2 d_1\right)^2} \qquad (2)$$

The value for $\beta_{\gamma B}$ for a single-layer film was previously obtained by the author [6] and it is as follows:

$$\beta^k_{\gamma B} = \frac{1}{\gamma_R}\left(-\beta^k_{\rho B}\cdot\frac{1}{\rho}\frac{\partial\rho}{\partial\varepsilon}+\frac{1}{\rho}\frac{\partial^2\rho}{\partial\varepsilon\partial B}\right) = \frac{\gamma_R-1-2\mu_f}{\gamma_R}\left(-\beta^k_{\rho B}+\frac{1}{\gamma_R-1-2\mu_f}\cdot\frac{1}{\rho}\frac{\partial^2\rho}{\partial\varepsilon\,\partial B}\right), \qquad (3)$$

where γ_R is the value of SC, which is expressed in terms of the electrical resistance. The magnetic coefficient of resistivity for a two-layer film can be represented as follows:

$$\beta^k_{\rho B} \cong \left[\left(\frac{\partial\rho_1}{\partial B}\rho_2\left(d_1+d_2\right)+\frac{\partial\rho_2}{\partial B}\rho_1\left(d_1+d_2\right)\right)\left(\rho_1 d_2+\rho_2 d_1\right)-\rho_1\rho_2\left(d_1+d_2\right)\left(\frac{\partial\rho_1}{\partial B}d_2+\frac{\partial\rho_2}{\partial B}d_1\right)\right]^{-1} \cong$$
$$\cong\left[\rho_1\rho_2\left(d_1+d_2\right)\left(\rho_1 d_2+\rho_2 d_1\right)\right]^{-1} \cong \frac{\beta^k_{\rho_1 B}\rho_2 d_1+\beta^k_{\rho_2 B}\rho_1 d_2}{\rho_1 d_2+\rho_2 d_1} \qquad (4)$$

The equation (4) in the limiting cases takes the following form: for $d_1 \to \infty$ and $d_2 \to \infty$, $\lim\limits_{d_1\to\infty}\beta_{\rho B} \cong \beta^{\infty}_{\rho_1 B}$; and for $d_2 \to \infty$ and $d_1 = const$, $\lim\limits_{d_2\to\infty}\beta_{\rho B} \cong \beta^{\infty}_{\rho_2 B}$, where the index «∞» denotes the asymptotic value $\beta_{\rho B}$.

The equations (2) and (4) are considerably simplified in the two limiting cases:

$$\text{for } d_2 << d_1,\ \beta^k_{\gamma B} \cong \beta^k_{\gamma_1 B}\gamma_1 + \beta^k_{\rho_2 B}\mu_1; \qquad (2')$$

$$\text{and for } d_2 >> d_1,\ \beta^k_{\gamma B} \cong \beta^k_{\gamma_2 B}\gamma_2 + \beta^k_{\rho_1 B}\mu_2. \qquad (2'')$$

3. LIMITING CASES

Note that equation (2) and its limiting cases are reatively easier to compare with the experimental results if $\gamma >> 1$, when equation (3) is simplified to the form:

$$\beta^k_{\gamma B} \cong -\beta^k_B + \frac{1}{\gamma\rho}\cdot\frac{\partial^2\rho}{\partial\varepsilon\partial B} \qquad (3')$$

Analysis of formula (3') suggests that the strain coefficient, when implementing MSE, is determined by competition of two mechanisms: a reduced resistance in a magnetic field and its increase due to the deformation processes. In case when $\beta^k_B < 0$, the gauge factor in magnetic field will increase if $\partial^2\rho/\partial\varepsilon\partial B > 0$ (it is observed in metallic Co and Ni films). When the inequality $\left|\partial^2\rho/\partial\varepsilon_{l,t}\partial B\right| > \left|\beta_B\right|$ is satisfied the coefficient of longitudinal and transfer strain coefficient will be reduced in an external magnetic field, as is the case in amorphous metallic alloys [3] or diamond films [4] in relatively strong fields.

It should be emphasized that because the value of SC significantly decreases with increasing thickness of the film, then on the settlement of relations for the limiting cases of formula (2) one must use the relation (3) or (3') for a thick or thin film, respectively. Specifically, equations (2) – (2''), (3) and (3') lead to predicting qualitatively the field-dependence of double-layer SC film systems. In particular, in (2') the value of SC of double-layer film will increase with increasing external magnetic field under the conditions:

if $\beta^k_{\gamma_1 B} > 0$ and $\beta^k_{\rho_2 B} > 0$ or $\beta^k_{\gamma_1 B} > 0$, then $\beta^k_{\rho_2 B} < 0$, but $\beta^k_{\gamma_1 B} > \left|\beta^k_{\rho_2 B}\right|$;

if $\beta^k_{\gamma_1 B} < 0$ and necessarily the condition $\beta^k_{\gamma_1 B} > 0$ and $\beta^k_{\rho_2 B} > \left|\beta^k_{\gamma_1 B}\right|$.

Similar conditions occur in case (2''). If, $d_1 \cong d_2$ as $\gamma_{1,2} \sim 1$, then the analysis should make calculation for the ratio (2) taking into account the ratio (3) and the possible options of the sign of $\beta^k_{\gamma B}$ and $\beta^k_{\rho B}$. This analysis will assist in developing other types of sensing elements for standard magnetoresistance strain sensors, one of which was proposed in [8] and was used by the authors of work [5].

4. CONCLUSIONS

Phenomenological model of magneto-strain effect in two-layer film systems that contain identity of individual layers (type biplate) was first proposed. Analyzed limiting cases of models that allow to establish sign of the magnetic SC, which makes it possible to operate this value. The results can be used to develop multifunctional sensors of magnetic field and strain.

ACKNOWLEDGEMENTS

The authors are gratefully acknowledge by Dr. C.J.Panchal and Dr. M.S. Desai for discussion of the results and useful advice. This work is done within framework of scientific and technical project between Sumy State University (Sumy, Ukraine) and M.S.University of Baroda (Vadodara, India).

Магніто-деформаційний ефект в двошарових плівкових системах

З.М. Макуха, С.І. Проценко, Л.В. Однодворець, І.Ю. Проценко

Сумський державний університет, 2, вул. Римського-Корсакова, Суми, 40007, Україна

Вперше представлені результати теоретичних досліджень магніто-деформаційного ефекту (МДЕ) в двошарових плівкових матеріалах з урахуванням попередніх результатів, отриманих для одношарових плівок. При створенні елементарної теорії отримані співвідношення для коефіцієнта поздовжньої тензочутливості (КТ, γ) для двошарової плівкової системи типу "біпластина", без урахування можливих процесів взаємної дифузії атомів. Кількісною характеристикою МДЕ є магнітний коефіцієнт КТ, який дорівнює $\beta_{\gamma B} = (1/\gamma)\cdot(\partial\gamma/\partial B)$, яка описує зміну електричного опору плівки при її деформації в зовнішньому магнітному полі. В кінцеве співвідношення для МДЕ входять величини γR, ρ (питомий опір), βρB (магнітний коефіцієнт питомого опору) та друга похідна ρ по деформації і магнітому полю. Остання величина не розраховується, а вимірюється експериментально. Аналіз співвідношення для граничних випадків для $\beta_{\gamma B}$, коли $d_1 >> d_2$ і $d_1 << d_2$, дозволяє розрахувати величину КТ при певних значеннях магнітного поля.

Ключові слова: коефіцієнт поздовжньої тензочутливості, магніто-деформаційний ефект, магнітний коефіцієнт опору, магнітний коефіцієнт коефіцієнта тензочутливості.

Магнито-деформационный эффект в двухслойных пленочных системах

З.Н. Макуха, С.И. Проценко, Л.В. Однодворец, И.Е. Проценко

Сумский государственный университет, 2, ул. Римского-Корсакова, Сумы 40007, Украина

Впервые представлены результаты теоретических исследований магнито-деформационного эффекта (МДЭ) в двухслойных пленочных материалах с учетом предыдущих результатов, полученных для однослойных пленок. При создании элементарной теории получены соотношения для коэффициента продольной тензочувствительности (КТ, γ) для двухслойной пленочной системы типа "бипластина", без учета возможных процессов взаимной диффузии атомов. Количественной характеристикой МДЭ является магнитный коэффициент КТ, равный $\beta_{\gamma B} = (1/\gamma)\cdot(\partial\gamma/\partial B)$, который описывает изменение электрического поля пленки при деформации во внешнем магнитном поле. В конечное соотношение для МДЭ входят величины γ_R, ρ (удельное сопротивление), $\beta_{\rho B}$ (магнитный коэффициент удельного сопротивления) и вторая производная ρ по деформации и магнитному полю. Последняя величина не расчитывается, а определяется экспериментально. Анализ соотношения для граничных случаев для $\beta_{\gamma B}$, когда $d_1 >> d_2$ и $d_1 << d_2$, позволяет рассчитать величину КТ при определенных значениях магнитного поля.

Ключевые слова: коэффициент продольной тензочувствительности, магнито-деформационный эффект, магнитный коэффициент сопротивления, магнитный коэффициент коэффициента тензочувствительности.

REFERENCES

1. S. Tumanski, *Thin film magnetoresistive sensors*, (Bristol and Philadelphia: Institute of Physics Publishing: 2000).
2. L.S. Martin, L.C. Wrbanek, G.C. Fralick, *Thin film sensors for surface measurement*, (Cleveland: Ohio: 2001).
3. M.P. Semen'ko, M.I. Zakharenko, Yu.A. Kunyts'kyi, A.P. Shpak, *Usp. Fiz. Met.* **10** №4, 331 (2009) (Ukr.).
4. W.L. Wang, K.J. Liao, C.G. Hu, S.X. Wang, C.Y. Kong, H.Y. Liao, *Sensors Actuat. A* **108**, 55 (2003).
5. B. Anvarzai, V. Ac, S, Luby, E. Majkova, R. Senderak, *Vacuum* **84**, 108 (2010).
6. S.I. Protsenko, *J. Nano- Electron. Phys.*, **1** No 2, 5 (2009).
7. S.I. Protsenko, I.V. Cheshko, D.V. Velykodnyi, I.M. Pazukha, L.V. Odnodvorets, I.Yu. Protsenko, O.V. Synashenko, *Usp. Phys. Met.* **8** №4, 247 (2007). (Ukr.).
8. T. Duenas, A. Sehrbrock, M. Lohndorf, A. Ludwig, J. Wecker, P. Grunberg, *J. Magn. Magn. Mater.* **242 – 245**, 1132 (2002).