

Microwave magnetoelectric effect in structures based on ferromagnetic metals

Alexander Tatarenko^{1,*}, Oleg Sokolov¹, Sergey Ivanov¹, Mirza Bichurin¹, and Yaojin Wang²

¹Novgorod State University, Veliky Novgorod, 173020, Russia

²Nanjing University of Science and Technology, 200 Xiaolingwei, Nanjing, China

Abstract. The results of a theoretical calculation of the resonant magnetizing field values for ferromagnetic resonance in thin films of nickel, iron and cobalt for frequencies of 3, 10, 30 GHz for various orientations of this field are presented. Analytical dependences of the ferromagnetic line shifts on the electric field strength are obtained for two-layer magnetoelectric composites in which PZT, PMN-PT or PZN-PT disks are used as piezoelectrics on which thin films of Ni, Fe or Co are deposited.

1 Introduction

In connection with the development of spintronics, interest in the magnetoelectric (ME) effect in nanostructures has increased. The ME effect in multiferroics in the terahertz range based on various manganites has recently been studied [1]. It is of interest to study the magnetoelectric effect in the ferromagnetic resonance (FMR) region in nanostructures based on ferromagnetic metals [2]. This paper presents the results of studies of the features of FMR in thin films of nickel, iron, and cobalt (film thickness ~ 50 nm). The objects of theoretical research were two-layer ME composites, in which PZT, PMN-PT or PZN-PT disks with a thickness of 0.5 mm was used as piezoelectric materials, on which thin films of Ni, Fe or Co were deposited. The values of the resonance bias field for frequencies of 3, 10, 30 GHz with different orientations of this field are calculated. Cases are considered when the magnetizing field is perpendicular to the plane of a thin metal film and also directed in the plane of a thin metal film along or perpendicular to easy magnetization axis. The main attention is paid to the theoretical study of the FMR line shift in two-layer ME composites based on thin films of ferromagnetic metals under the influence of an electric field.

1.1 Calculation methods of the FMR line shift in two-layer magnetoelectric composites

The calculation method for the FMR line shifting in two-layer ME composites consists of two stages. First, the values of the resonant magnetizing field are calculated at frequencies of 3, 10, 30 GHz for various orientations of this field. So, cases were considered when the magnetizing field is perpendicular to the plane of a thin metal film, and also directed in the

* Corresponding author: alexandr.tatarenko@novsu.ru

plane of a thin metal film along or perpendicular to the axis of easy magnetization. Then, two-layer ME composites based on thin films of ferromagnetic metals Ni, Fe or Co are examined. In case when a constant electric field directed perpendicular to the plane of the disk to influence at ME composites, the FMR line shifts as a result of the microwave ME effect [3]. The calculated dependences of the FMR line shift on the electric field strength were obtained by using the method of effective demagnetizing factors. The use of layered structures based on nanofilms of ferromagnetic metals will allow to proceed to further miniaturization of devices and design a number of new nanoelectronic microwave devices [4].

2 FMR in a ferromagnetic metal nanofilm

Let us consider a ferromagnetic metal nanofilm to which a constant magnetizing field is applied perpendicular to the plane of the film. We assume that the magnitude of this field is sufficiently large and the ferromagnetic metal film is uniformly magnetized to saturation. We direct the axis 3 along H_0 , then H_0 has components $(0, 0, H_0)$, and the equilibrium magnetization has components $(0, 0, M_0)$. Axis 1 is directed along the axis of easy magnetization of the nickel (iron) film.

The equation of the motion of magnetization in a ferromagnetic metal nanofilm under the action of a high-frequency magnetic field h in the presence of a constant magnetic field H , taking into account dissipation is

$$\frac{\partial \vec{M}}{\partial t} = \gamma \left[\vec{M} \times \frac{\partial W}{\partial \vec{M}} \right] + i\omega\alpha \frac{[\vec{M}_0 \times \vec{m}]}{M_0} \quad (1)$$

where the full magnetization consists of the equilibrium and high-frequency components

$$\vec{M} = \vec{M}_0 + \vec{m} \quad (2)$$

and the density of free energy is

$$W = -\vec{M} \cdot \vec{H} + \frac{1}{2\mu_0} \sum N_{11}^i M_1^2 + \frac{1}{2\mu_0} \sum N_{22}^i M_2^2 + \frac{1}{2\mu_0} \sum N_{33}^i M_3^2 + \frac{1}{\mu_0} \sum N_{12}^i M_1 M_2 \quad (3)$$

Then we write the dissipative term component wise

$$i\omega\alpha \frac{[\vec{M}_0 \times \vec{m}]}{M_0} = \frac{i\omega\alpha}{M_0} \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ 0 & 0 & M_0 \\ m_1 & m_2 & m_3 \end{vmatrix} = \frac{i\omega\alpha}{M_0} (-\vec{i}M_0 m_2 + \vec{j}M_0 m_1) = i\omega\alpha (-\vec{i}m_2 + \vec{j}m_1) \quad (4)$$

The magnetic field strength also consists of two components

$$\vec{H} = \vec{H}_0 + \vec{h} \quad (5)$$

Then we find the derivatives of free energy with respect to the components of magnetization

$$\begin{aligned} \frac{\partial W}{\partial M_1} &= -h_1 + \frac{1}{\mu_0} \sum N_{11}^i M_1 + \frac{1}{\mu_0} \sum N_{12}^i M_2 \\ \frac{\partial W}{\partial M_2} &= -h_2 + \frac{1}{\mu_0} \sum N_{22}^i M_2 + \frac{1}{\mu_0} \sum N_{12}^i M_1 \\ \frac{\partial W}{\partial M_3} &= -H_0 - h_3 + \frac{1}{\mu_0} \sum N_{33}^i M_3 \end{aligned} \quad (5)$$

Next, let's us write the equation of motion for the components

$$\begin{aligned}
 i\omega m_1 &= \gamma \left[m_2 \frac{\partial W}{\partial M_3} - (M_0 + m_3) \frac{\partial W}{\partial M_2} \right] - i\alpha\omega m_2 \\
 i\omega m_2 &= \gamma \left[(M_0 + m_3) \frac{\partial W}{\partial M_1} - m_1 \frac{\partial W}{\partial M_3} \right] + i\alpha\omega m_1 \\
 i\omega m_3 &= \gamma \left[m_1 \frac{\partial W}{\partial M_2} - m_2 \frac{\partial W}{\partial M_1} \right]
 \end{aligned} \tag{6}$$

Linearizing these equations and preserving only the first-order terms of smallness in them, we obtain a system of two linear inhomogeneous equations for two unknowns m_1, m_2

$$\begin{aligned}
 \left(i\omega + \gamma \frac{M_0}{\mu_0} \sum N_{12}^i \right) m_1 + \left[\gamma \left(H_0 + \left\{ \sum N_{22}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) + i\alpha\omega \right] m_2 &= \gamma M_0 h_2 \\
 \left[\gamma \left(H_0 + \left\{ \sum N_{11}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) + i\alpha\omega \right] m_1 + \left(-i\omega + \gamma \frac{M_0}{\mu_0} \sum N_{12}^i \right) m_2 &= \gamma M_0 h_1
 \end{aligned} \tag{7}$$

Having solved this system, we can write the form of the high-frequency magnetic susceptibility tensor

$$\chi = \begin{pmatrix} \chi_{11} & \chi_{12} & 0 \\ \chi_{21} & \chi_{22} & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{8}$$

Where components of this tensor are

$$\begin{aligned}
 \chi_{11} &= \frac{-\gamma M_0 \left[\gamma \left(H_0 + \left\{ \sum N_{22}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) + i\alpha\omega \right]}{D} \\
 \chi_{22} &= \frac{-\gamma M_0 \left[\gamma \left(H_0 + \left\{ \sum N_{11}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) + i\alpha\omega \right]}{D} \\
 \chi_{12} &= \chi_s - i\chi_a \\
 \chi_{21} &= \chi_s + i\chi_a \\
 \chi_s &= \frac{\gamma^2 M_0^2}{\mu_0 D} \sum N_{12}^i \\
 \chi_a &= \frac{\gamma M_0 \omega}{D}
 \end{aligned} \tag{9}$$

and

$$\begin{aligned}
 D &= \omega^2 (1 + \alpha^2) - \omega_0^2 - i\gamma\alpha\omega \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) \\
 \omega_0^2 &= \gamma^2 \left(H_0 + \left\{ \sum N_{11}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) \left(H_0 + \left\{ \sum N_{22}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) - \gamma^2 \left(\sum N_{12}^i \frac{M_0}{\mu_0} \right)^2
 \end{aligned} \tag{10}$$

We will be interested in the imaginary parts of the complex components of high-frequency susceptibility $\chi''_{11}, \chi''_{22}, \chi''_a$

$$\chi''_{11} = -\alpha\gamma M_0 \omega \frac{\omega^2(1+\alpha^2) - \omega_0^2 + \gamma^2 \left(H_0 + \left\{ \sum N_{22}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right)}{\left[\omega^2(1+\alpha^2) - \omega_0^2 \right]^2 + \gamma^2 \alpha^2 \omega^2 \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right)} \quad (11)$$

$$\chi''_{22} = -\alpha\gamma M_0 \omega \frac{\omega^2(1+\alpha^2) - \omega_0^2 + \gamma^2 \left(H_0 + \left\{ \sum N_{11}^i - \sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right) \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right)}{\left[\omega^2(1+\alpha^2) - \omega_0^2 \right]^2 + \gamma^2 \alpha^2 \omega^2 \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right)}$$

$$\chi''_a = \frac{\alpha\gamma^2 M_0 \omega^2 \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right)}{\left[\omega^2(1+\alpha^2) - \omega_0^2 \right]^2 + \gamma^2 \alpha^2 \omega^2 \left(2H_0 + \left\{ \sum N_{11}^i + \sum N_{22}^i - 2\sum N_{33}^i \right\} \frac{M_0}{\mu_0} \right)}$$

Demagnetizing factors associated with sample shape

$$N_{11}^F = N_{22}^F = 0 \quad (12)$$

$$N_{33}^F = 1$$

Demagnetizing factors associated with uniaxial magnetic anisotropy

$$N_{11}^a = -\frac{\mu_0 H_a}{M_0} \quad (13)$$

$$N_{22}^a = N_{33}^a = 0$$

The resonant values of the constant magnetizing field H_0 , found numerically in Maple for the microwave frequency $f=10$ GHz for the χ''_{11} , χ''_{22} , χ''_a , coincide with each other to an accuracy of 1 A/m and with the value found from the condition

$$\omega^2 = \omega_0^2 \quad (14)$$

In view of (10), from (14) we find the resonance value of the constant magnetizing field H_0

$$H_0 = \frac{\gamma M_0 \left(2\sum N_{33}^i - \sum N_{11}^i - \sum N_{22}^i \right) + \sqrt{\gamma^2 M_0^2 \left[\left(\sum N_{11}^i - \sum N_{22}^i \right)^2 + 4 \left(\sum N_{12}^i \right)^2 \right] + 4\mu_0^2 \omega^2}}{2\gamma\mu_0} \quad (15)$$

Substituting (12), (13) into (15), we obtain the values of the constant magnetizing field for nickel $H_0 \approx 4439, 6850, 13745$ Oe at resonant frequencies $f=3, 10, 30$ GHz, respectively. For iron we obtain the values of the constant magnetizing field for nickel $H_0 \approx 2414, 4824, 11720$ Oe at same frequencies, respectively.

We similarly consider the case when a constant magnetizing field is directed in the film plane along the axis of easy magnetization of the nickel (iron) film. For nickel, we have $H_0 \approx 98, 1973, 8626$ Oe and for iron $H_0 \approx 381, 2672, 9530$ Oe at the same frequencies, respectively.

For the case when a constant magnetizing field is directed in the plane of the film perpendicular to the axis of easy magnetization of the nickel (iron) film, For nickel, we have $H_0 \approx 483, 2317, 8942$ Oe and for iron $H_0 \approx 730, 2986, 9831$ Oe at the same frequencies, respectively.

For cobalt, there are only demagnetizing factors associated with the shape of the sample

$$N_{11}^F = N_{22}^F = 0 \quad (16)$$

$$N_{33}^F = 1$$

Therefore, from (15) we have the constant magnetizing field for cobalt $H_0 \approx 15500, 17830, 24497$ Oe at resonant frequencies $f=3, 10, 30$ GHz, respectively.

Similarly, we consider the case when the constant magnetizing field is directed in the plane of the cobalt film, and the values obtained are $H_0 \approx 69, 730, 5102$ Oe at resonant frequencies $f = 3, 10, 30$ GHz, respectively.

3 FMR line shift under an applied electric field

First, we write (14) without taking into account the effective demagnetizing factors arising from the action of the electric field strength E

$$\omega^2 = \gamma^2 \left(H_0 + \left\{ \sum_{i \neq E} N_{11}^i - \sum_{i \neq E} N_{33}^i \right\} \frac{M_0}{\mu_0} \right) \left(H_0 + \left\{ \sum_{i \neq E} N_{22}^i - \sum_{i \neq E} N_{33}^i \right\} \frac{M_0}{\mu_0} \right) - \gamma^2 \left(\sum_{i \neq E} N_{12}^i \frac{M_0}{\mu_0} \right)^2 \quad (17)$$

Now we write (14), taking into account the small correction δH_E associated with small effective demagnetizing factors arising from the action of the electric field strength E

$$\omega^2 = \gamma^2 \left(H_0 + \delta H_E + \left\{ \sum_{i \neq E} N_{11}^i - \sum_{i \neq E} N_{33}^i + N_{11}^E - N_{33}^E \right\} \frac{M_0}{\mu_0} \right) \times \quad (18)$$

$$\times \left(H_0 + \delta H_E + \left\{ \sum_{i \neq E} N_{22}^i - \sum_{i \neq E} N_{33}^i + N_{22}^E - N_{33}^E \right\} \frac{M_0}{\mu_0} \right) - \gamma^2 \left(\left\{ \sum_{i \neq E} N_{12}^i + N_{12}^E \right\} \frac{M_0}{\mu_0} \right)^2$$

Subtract (17) from (18) and save in the obtained equation only the terms of the first order of smallness in $\delta H_E, N_{11}^E, N_{22}^E, N_{33}^E, N_{12}^E$

$$\frac{M_0}{\mu_0} Q_2 (N_{11}^E - N_{33}^E) + \frac{M_0}{\mu_0} Q_3 (N_{22}^E - N_{33}^E) - \frac{M_0}{\mu_0} Q_4 N_{12}^E + Q_1 \delta H_E = 0 \quad (19)$$

where

$$Q_1 = 2H_0 + \left\{ \sum_{i \neq E} N_{11}^i + \sum_{i \neq E} N_{22}^i - 2 \sum_{i \neq E} N_{33}^i \right\} \frac{M_0}{\mu_0}$$

$$Q_2 = H_0 + \left\{ \sum_{i \neq E} N_{22}^i - \sum_{i \neq E} N_{33}^i \right\} \frac{M_0}{\mu_0} \quad (20)$$

$$Q_3 = H_0 + \left\{ \sum_{i \neq E} N_{11}^i - \sum_{i \neq E} N_{33}^i \right\} \frac{M_0}{\mu_0}$$

$$Q_4 = 2 \sum_{i \neq E} N_{12}^i \frac{M_0}{\mu_0}$$

From this condition we find the shift of the resonance line

$$\delta H_E = \frac{M_0 \left[Q_2 (N_{33}^E - N_{11}^E) + Q_3 (N_{33}^E - N_{22}^E) + Q_4 N_{12}^E \right]}{\mu_0 Q_1} \quad (21)$$

Next, we find the demagnetizing factors for ferromagnetic metal/piezoelectric structures associated with the action of a constant electric field. Consider the case when a constant electric field is directed along axis 3.

We substitute the previously found demagnetizing factors (12) and (13) into (20)

$$Q_1 = 2H_0 - H_a - \frac{2M_0}{\mu_0} \quad (22)$$

$$Q_2 = H_0 - \frac{M_0}{\mu_0}$$

$$Q_3 = H_0 - H_a - \frac{M_0}{\mu_0}$$

$$Q_4 = 0$$

Formulas (22) are valid for nickel and iron, and in order to use them for cobalt it is necessary to put $H_a = 0$

Consider the mechanical equilibrium of our structure. It is convenient to write the boundary conditions for a free sample in the form of a disk in cylindrical coordinates

$${}^m T_3 = {}^p T_3 = 0 \tag{23}$$

$${}^m_t {}^m T_{rr} \Big|_{r=R} + {}^p_t {}^p T_{rr} \Big|_{r=R} = 0 \tag{24}$$

$${}^m_t {}^m T_{\theta\theta} \Big|_{r=R} + {}^p_t {}^p T_{\theta\theta} \Big|_{r=R} = 0$$

where R is the radius of the disk.

The components of the stress tensor in rectangular coordinates are expressed in terms of the components of the stress tensor in cylindrical coordinates as follows

$$T_1 = \cos^2(\theta) T_{rr} + \sin^2(\theta) T_{\theta\theta} \tag{25}$$

$$T_2 = \sin^2(\theta) T_{rr} + \cos^2(\theta) T_{\theta\theta}$$

Multiplying (24) by $\cos^2(\theta)$, $\sin^2(\theta)$ and using (25), we obtain

$${}^m_t {}^m T_1 \Big|_{r=R} + {}^p_t {}^p T_1 \Big|_{r=R} = 0 \tag{26}$$

$${}^m_t {}^m T_2 \Big|_{r=R} + {}^p_t {}^p T_2 \Big|_{r=R} = 0$$

Given the quasistationary nature of the task, we can write

$${}^m_t {}^m T_1 + {}^p_t {}^p T_1 = 0 \tag{27}$$

$${}^m_t {}^m T_2 + {}^p_t {}^p T_2 = 0$$

In view of (23), the material equations for the ferromagnetic phase

$$S_1 = {}^m s_{11} {}^m T_1 + {}^m s_{12} {}^m T_2 \tag{28}$$

$$S_2 = {}^m s_{12} {}^m T_1 + {}^m s_{11} {}^m T_2$$

and for piezoelectric

$$S_1 = {}^p s_{11} {}^p T_1 + {}^p s_{12} {}^p T_2 + d_{31} E \tag{29}$$

$$S_2 = {}^p s_{12} {}^p T_1 + {}^p s_{11} {}^p T_2 + d_{31} E$$

Solving together (27), (28) and (29), we find

$${}^m T_1 = {}^m T_2 = \frac{d_{31} {}^p_t E}{{}^p_t ({}^m s_{11} + {}^m s_{12}) + {}^m_t ({}^p s_{11} + {}^p s_{12})} \tag{30}$$

Part of the free energy associated with the presence of stresses arising from the action of an electric field on a piezoelectric

$$\Delta W_{ME} = -\frac{3\lambda_s}{2M_0^2} ({}^m T_1 M_1^2 + {}^m T_2 M_2^2 + {}^m T_3 M_3^2) \tag{31}$$

From this conditions we find effective demagnetizing factors arising from the action of the electric field E

$$N_{11}^E = -\frac{3\mu_0 \lambda_s}{M_0^2} {}^m T_1 \tag{32}$$

$$N_{22}^E = -\frac{3\mu_0 \lambda_s}{M_0^2} {}^m T_2$$

$$N_{33}^E = 0$$

$$N_{12}^E = 0$$

Then from (21) we find

$$\delta H_E = \frac{3\lambda_s d_{31} {}^p_t E}{M_0 [{}^p_t ({}^m s_{11} + {}^m s_{12}) + {}^m_t ({}^p s_{11} + {}^p s_{12})]} \tag{33}$$

The dependence of the FMR resonance line shift of the on the electric field is a direct proportion

$$\delta H_E = kE \tag{34}$$

where δH_E is in Oe, and E is in kV/cm.

The theoretical results of our calculations presented on the next Figures. Results for Ni deposited on PZT, PMN-PN and PZN-PT are shown on Fig. 1.

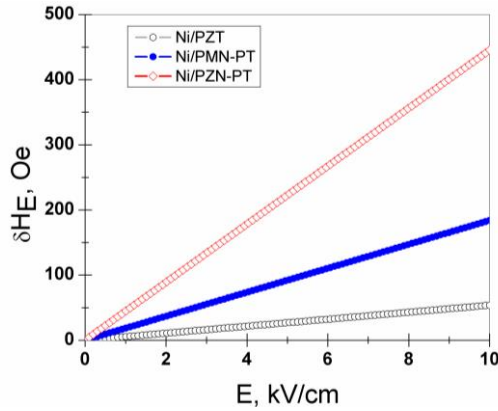


Fig. 1. Result of the FMR line shift calculation for composite structures of Ni/PZT, Ni/PMN-PT and Ni/PZN-PT.

Results for Fe deposited on PZT, PMN-PN and PZN-PT are shown on Fig. 2.

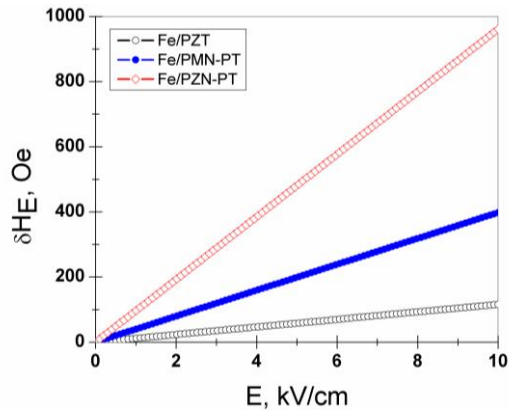


Fig. 2. Result of the FMR line shift calculation for composite structures of Fe/PZT, Fe/PMN-PT and Fe/PZN-PT.

Results for Co deposited on PZT, PMN-PN and PZN-PT are shown on Fig. 3.

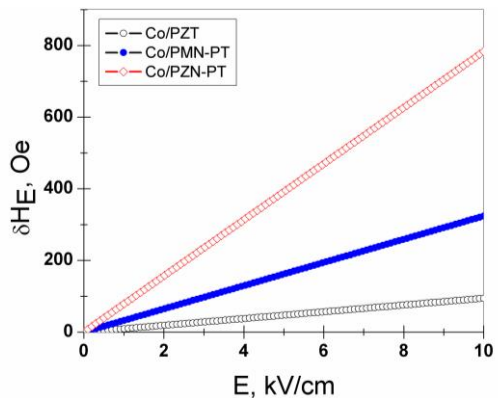


Fig. 3. Result of the FMR line shift calculation for composite structures of Co/PZT, Co/PMN-PT and Co/PZN-PT.

Due to the specific symmetry of the problem, k does not depend on the directivity of the magnetizing field and the magnitude of the resonant frequency f .

4 Conclusion

A calculation method for determining the FMR line shift in two-layer ME composites based on thin ferromagnetic metals films under the influence of an electric field is proposed.

Analytical dependences of the FMR line shift in such composites on the electric field strength are obtained.

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