The magnetic-resonance properties study of nanostructures for spintronics by FMR

G Kupriyanova, A Zhubin, A Astashonok, A Orlova and E Prokhorenko

Immanuel Kant Baltic Federal University, 236041, A.Nevskogo 14, Kaliningrad, Russia

e-mail: galkupr@yandex.ru

Abstract. In this work we report the study of the magnetic-resonance properties such as magnetic anisotropy, magnetic damping, and interlayer exchange coupling between ferromagnetic layers separated by a nonmagnetic spacer by FMR to assess their applicability in a functional magnetic tunnel junction.

1. Introduction

One of the important tasks today is to create new materials and combinations for the applications of spintronics. The magnetic tunnel junctions (MTJ) are of a very special interest. The basic element of MTJ consists of the ferromagnetic – insulator – ferromagnetic structures, which are the main element of the random access memory of novel generation. The magnitude of the tunnel magnetoresistance (TMR), which determines the functional properties of the memory cell based on MTJ, is defined as the relative current resistance for parallel and antiparallel orientations of magnetizations in FM electrodes, and according to the Julliere model [1] critically depends on the spin polarization of both electrodes. The magnetic property of MTJ ferromagnetic layers differs considerably, as it involves the possibility of an independent magnetization switching in two ferromagnetic electrodes. It was found that the materials combination for the MTJ must satisfy a number of requirements, which are the following: a) high conductivity electrons polarization in a ferromagnetic electrode, b) the absence of paramagnetic phase on the interface; c) the thickness of the tunnel insulator layer should be within 2-3 nm; d) homogeneity of insulator; e) the roughness of the insulator within the ranges of monolayer thicknesses; f) defectlessness [2]. Many of these properties, including magnetic anisotropy and interlayer exchange coupling parameters which play the most important role in MTJ effect may be studied by ferromagnetic resonance.

The perspective class of materials for the application as a magnetic stiff layer for magnetic tunneling junctions is the ferromagnetic oxides. The common ferromagnet Fe₃O₄ (magnetite) has been predicted by band structure calculations to be half metal with the minority spin polarization at the Fermi level [3]. According to the latest experimental investigations, thin film Fe₃O₄ shows spin polarization P≈-80% [4]. Furthermore, Fe₃O₄ meets important prerequisites for the compatibility with a memory cells industry, like a Curie temperature (T_C) = 860 K and relatively high (~100-400 Oe) coercivity [5]. However, to use ferrite as a magnetic stiff layer we should master several anomalous properties which make it impossible to reach the saturation magnetization by fields up to 10 kOe and flat hysteresis curve. With the aim of choosing of an optimum structure for the magnetic stiff layer, we have analyzed structures with different consequences of layers Fe₃O₄/Fe and Fe/Fe₃O₄. The other applicable magnetic material, which might be used as the second ferromagnetic layer is Fe₂Si. It is a...
ferromagnetic binary Heusler alloy and was found to have a spin polarization of 43% and a high Curie temperature of 820 K [6] and coercive force 500e. It was obtained that for thin film structures Fe$_3$Si with the Fe upper layer a 100 % spin polarization is inherent. As samples to be analyzed some structures were grown on Si/SiO$_2$, which differ by the position of layers and the nature of the isolating layer and a growth temperature such as Fe/Fe$_3$O$_4$/MgO/Fe$_3$Si, Fe$_3$/SiO$_2$/Fe$_3$O$_4$/Fe, Fe$_3$Si/SiO$_2$/Fe/Fe$_3$O$_4$.

2. Experimental details and results
At first we analyzed the magnetic properties of polycrystalline sample Si/SiO$_2$/Fe$_3$Si and the magnetic film properties of magnetite during the introduction of a Fe sublayer which were investigated with regard to the position of a Fe sublayer and the annealing temperature by the FMR method and by using vibrating sample magnetometer (VSM). Polycrystalline sample Si/SiO$_2$/Fe$_3$Si was grown by the method of pulse laser deposit method by evaporation (PLD) of alloyed target Fe$_3$Si. After depositing the sample was annealed at in situ in the growth camera at T=600 °C for 30 minutes. The samples Fe$_3$O$_4$/Fe and Fe/Fe$_3$O$_4$ structure on Si/SiO$_2$ substrate were grown at room temperature by means of PLD technique, and then Fe/Fe$_3$O$_4$ structure divided in four parts, three of which were vacuum-annealed at T=200 °C, 350 °C and 500 °C respectively. The structure Fe/Fe$_3$O$_4$/MgO/Fe$_3$Si was grown on the amorphous surface Si/SiO$_2$ substrate by pulsed laser deposition technique. A Fe sublayer of 10 nm thick was deposited on the amorphous surface of SiO$_2$, then a Fe$_3$O$_4$ layer 20 nm thick was deposited from the stechiometrical alloyed target Fe$_3$O$_4$ at room temperature in ultrahigh vacuum (P = $10^{-6}$ Pa) in one vacuum cycle. The formation of the upper polycrystalline FM layer Fe$_3$Si was performed by means of deposition from the stechiometrical alloyed target Fe$_3$Si with the following vacuum annealing up at temperature 400 °C.

The obtained thicknesses results are inherent to all layers except MgO (3nm).The POP data analysis and ion profiling analysis by electronic spectroscopy evidence the formation of MgO layer of 3-5 nm.

The ferromagnetic resonance spectra of the thin film samples were analyzed by the Radiopan electron spin resonance spectrometer operating at the X-band frequency 9.5 GHz and the modulation frequency 100 kHz. The first field derivative of the microwave power absorption was registered as a function of applied magnetic field at room temperature. The samples were mounted on the side of a special holder passing through the center of the TE$_{102}$ microwave cavity. The orientation of the film was controlled by a two axial goniometer with the accuracy by 0.5°. The out-of-plane dependencies of FMR spectra and line widths have been measured for the thin magnetic films made at the different annealing temperatures. The magnetic parameters such as the effective magnetization, magnetic anisotropy and line widths were extracted for the samples with different positions of layers.

| № | Fe/Fe$_3$O$_4$ | Annealing T, °C | $H_c$, Oe | $M_s$, emu/cm$^3$ | The results of modelling $M_1$/M$_2$ emu/ cm$^3$ | Interrelation constants (of the first and the second order) J(erg/cm$^3$) | Anisotropy constants, erg/cm$^3$ |
|---|----------------|----------------|-------------|----------------|---------------------------------|---------------------------------|-----------------|
| 1 | Fe/Fe$_3$O$_4$ | 20 | 10 | 490 | $M_1$=500, $M_2$=500 | $J_1$=+0.2 | $K_2$ = -2*10$^5$ |
|   |                |                |             |                |                                 |                                 | $K_4$ = -2.3*10$^5$ |
For the sample with structure Si/SiO$_2$/Fe$_3$O$_4$/Fe two signals were observed: the narrow intense signal in area $H_{oa}$ = 336 mT with the line width $\Delta H$=18 mT, which doesn’t depend on the sample orientation, and the wide weak signal which is lower by one order of magnitude, its resonance field and line width depend on the $\theta$ angle. For each of the three samples [7] with the reverse sequence of layers Si/SiO$_2$/Fe/Fe$_3$O$_4$ one integrated signal is observed. Its position and the line widths depend on the sample orientation. Moreover, for the unannealing sample, along direction of external magnetic field, a very narrow line $H$=4,1 mT is observed, if compared in width to the line width of the pure Fe $H$ =1,8 mT. Magnetic anisotropy of Fe/GaAs(001) ultrathin films was investigated by in situ ferromagnetic resonance [8]. It was obtained that the absolute values of magnetization in systems Si/SiO$_2$/Fe/Fe$_3$O$_4$ is considerably at higher annealing temperature 500 °C, $M_s$ ~ 760 emu/cm$^3$, than in Fe$_3$O$_4$ ($M_s$ = 480 emu/cm$^3$ for the volume sample and comparable to the values obtained in epitaxial films Fe/Fe$_3$O$_4$ on the MgO substrate. In work [9] it is given that the maximum magnetization of saturation $M_s$ = 970 emu/cm$^3$ is found at the sample with Fe layer width, equal to 8 nm in the field with 10 kOe. In the quoted work it was obtained that the difference of the sample Fe$_3$O$_4$, the absolute value of magnetization saturation in samples of Fe/Fe$_3$O$_4$ depends on the annealing temperature. The magnetization rises together with the rise of annealing temperature. This fact was derived from the analysis of the hysteresis curve and from the FMR experiments analysis. With increasing of annealing temperature the FMR line width is broadening. It is important, that the value of coercive force of the analyzed samples (Table 1) is increased several times if compared to the coercive force of the thin film of the magnetite and the coercive force of film Fe (10÷15 Oe), and reaches the values relevant for the realization of MTJ (100÷200 Oe). When this happens the hysteresis loop form becomes rectangular in comparison to the initial flat hysteresis curve of the thin film Fe$_3$O$_4$.

Table 2. Different samples and its properties.

| Sample # | The sample structure (in brackets the layers' thicknesses are given in A) on Si/SiO$_2$ substrate | Magnetization (M), emu/cm$^3$ | Sample thickness L, A | Coercive force ($H_C$), Oe | The value of resonance fields (line width) mT |
|----------|---------------------------------------------------------------------------------|-----------------------------|----------------------|--------------------------|-----------------------------------|
| 2669     | Fe$_3$Si(190)/SiO$_2$/Fe$_3$O$_4$(200)/Fe (80) /Pt(1000) RT                      | 1029                        | 350                  | 15                       | Br$_1$=58 (7,5) Br$_{r1}$=111 (9,3) |
| 2671     | Fe$_3$Si(190)/SiO$_2$/Fe$_3$O$_4$(200)/Fe (80) /Pt(1000) the larger growth temperature T of Fe$_3$O$_4$ and Fe, | 1014                        | 400                  | 135                      | Br$_1$=73(11) Br$_{r1}$=97 (6,5) (low angular dependence) |
Annealing temperature ~ 450 °C.

| Sample | Structure | Thickness (Å) | Hc1 | Hc2 | Br1 | Br2 |
|--------|-----------|---------------|-----|-----|-----|-----|
| 2673   | Fe₃Si(190A)/SiO₂/Fe₅₇(60)/Fe₅₇(160) | 683 | 400 | 60  | Br₁=93.9(20.3) | Br₂=120 (6.0) |
| 2642   | Fe₅₇(40)Fe₅₇(100)/MgO(30)/Fe₃Si(130) | 1399.2 | 270 | 5   | Hc₁=115 | Hc₂=850 |
|        |           |               |     |     | Br₁=98 (29) | Br₂=131(11) |

The preliminary study of samples 2669 and 2671, which have the similar structure but different growth temperature was carried out by using vibrating sample magnetometer (VSM), showed that, unlike one-layer structures, increased annealing temperature result in the formation of structures with smaller magnetization value but higher coercive force (Table 2).

With the aim of anisotropic properties analysis, the in-plane and out-of-plane dependencies of FMR spectra and line widths have been measured for thin magnetic films. Two distinct resonance peaks were observed in out-of-plane FMR spectra for all the samples. For in-plane spectra the positions of the two resonance fields don’t change with the azimuthal angle of the applied field. However, only minor changes of resonance peak intensities were observed. Picture 1 shows angular dependencies of the resonance fields of the both modes for samples 2671 and 2669. The strong angular dependence is attributed mainly shape anisotropy. The comparison of pictures shows, that the position of resonance peaks of the sample 2671 undergoing the larger growth temperature T of Fe₃O₄ and Fe grow closer if compared to sample 2669. This effect is the same for decreasing of spacer thickness effect, which is equivalent to increase of magnetic coupling between ferromagnetic layers. Figure 2 shows the angular dependencies of the line widths. It is seen that the two narrow signals symmetrical to the direction when the field is applied to the film normal.

Figure 1. Dependence of the experimental and simulated resonance field value as a function of θₜ₁ for sample 2671.
**Figure 2.** Dependence of the experimental and simulated linewidth as a function of $\theta_H$ for sample a) 2671 and b) 2669

**Figure 3.** The behaviour of the resonance signals for a) sample 2669 and b) sample 2671 close to the position where the magnetic field is perpendicular to the film

The particular interest is represented by the sample Fe/FeOx/MgO/Fe$_3$Si. The analysis a hysteresis curve shows that in the structure (2642) Fe/FeOx/MgO/Fe$_3$Si there is an independent switching of magnetization ferromagnetic layers, switching soft layer Fe$_3$Si is distinctly observed at fields $H \sim (-100 \pm 100 \text{ Oe})$, while the hard layer Fe/Fe$_3$O$_4$ keeps the magnetization in a range of magnetic fields $H \sim (-500 \pm 500) \text{ [10].}$
3. Theoretical aspects

The experimental data for a system consisting two magnetic layers with saturation magnetization $M_{1,2}$ and layer thickness $d_{1,2}$ in external field $H$ can be described by following theoretical model. Magnetic energy surface density of such system is

$$E = d_1 F_1 + d_2 F_2 - J_1 (\sin \theta_1 \sin \theta_2 \cos (\varphi_1 - \varphi_2) + \cos \theta_1 \cos \theta_2) -$$

$$- J_q (\sin \theta_1 \sin \theta_2 \cos (\varphi_1 - \varphi_2) + \cos \theta_1 \cos \theta_2)^2$$

(1)

Here $F_1$ and $F_2$ are free energy density for first and second layer. In general case free energy $F$ consist of Zeeman energy $F_z$ of structure, magnetostatic $F_{ms}$ and magnetocrystalline anisotropy energy $F_c$:

$$F = F_c + F_{ms} + F_x,$$

$$F_x = -M \cdot H (\sin \theta \sin \theta_H \cos (\varphi - \varphi_H) + \cos \theta \cos \theta_H), F_{ms} = -2 \pi M^2 \sin^2 \theta,$$

$$F_c = -K_2 \cos^2 \theta - K_4 \cos^4 \theta - \frac{K_4}{8} (3 + 4 \cos 4 \varphi) \sin^4 \theta,$$

(2)

where $K_2$ is the uniaxial out-of-plane anisotropy constant, and $K_4$ is fourfold anisotropy constant. The angles $(\theta_1, \theta_H)$ and $(\varphi_1, \varphi_H)$ are, respectively, the polar and azimuthal angles for magnetization vector $M$ and external field vector $H$ with respect to the film normal. $J_1$ and $J_q$ are, respectively, the bilinear and biquadratic coupling parameters. The value of $J_1$ can be either positive or negative (ferromagnetic or antiferromagnetic coupling respectively). The large negative value of $J_q$ corresponds $90^\circ$-type coupling. The biquadratic term is smaller compared to the bilinear term and can be neglected.

Strictly speaking the Equations (1), (2) are valid in a case of monocrystalline film. For polycrystal the accounting of domain structure is necessary. If distribution of easy axis magnetization is isotropic in film plane the effective magnetocrystalline energy is

$$F_c = -K_2 \cos^2 \theta - \frac{K_4}{2} \cos^4 \theta - \frac{3K_4}{8} \sin^4 \theta = -\tilde{K}_2 \cos^2 \theta - \frac{\tilde{K}_4}{2} \cos^4 \theta + \text{const},$$

(3)

where $\tilde{K}_2 = K_2 - 3K_4 / 4, \tilde{K}_4 = 7K_4 / 4$. Further constants are omitted. Equation (3) is obtained from (2) by averaging on azimuthal angle. The expressions for Zeeman and interaction energy do not change if $(\varphi_1, \varphi_2)$ are understood as the azimuthal angles of resulting vector $M_{1,2}$ of layers as a whole.

The equilibrium conditions for azimuthal angles $(\varphi_1, \varphi_2)$ give

$$\frac{\partial E}{\partial \varphi_{1,2}} = 0 \Rightarrow$$

$$d_1 M_1 H \sin \theta_1 \sin \theta_H \sin (\varphi_1 - \varphi_H) + J_1 \sin \theta_1 \sin \theta_2 \sin (\varphi_1 - \varphi_2) +$$

$$2J_q \sin \theta_1 \sin \theta_2 \sin (\varphi_1 - \varphi_2) \sin \theta_1 \sin \theta_2 \cos (\varphi_1 - \varphi_2) + \cos \theta_1 \cos \theta_2 = 0;$$

$$d_2 M_2 H \sin \theta_2 \sin \theta_H \sin (\varphi_2 - \varphi_H) + J_1 \sin \theta_1 \sin \theta_2 \sin (\varphi_2 - \varphi_1) +$$

$$2J_q \sin \theta_1 \sin \theta_2 \sin (\varphi_2 - \varphi_1) \sin \theta_1 \sin \theta_2 \cos (\varphi_2 - \varphi_1) + \cos \theta_1 \cos \theta_2 = 0.$$

(4)

For sustainable equilbrium condition $\partial^2 E / \partial \varphi^2 > 0$ must be hold also. From this and Eqs.(4) follows that $\varphi_1 = \varphi_2 = \varphi_H$ for positive $J_1$. If $J_1 < 0$ and $J_q > 0$ there are three possible variants:

(i) $\varphi_1 = \varphi_2 = \varphi_H$ (for $H > H_{\text{crit}}^{(1)}, H > H_{\text{crit}}^{(2)}$)

(ii) $\varphi_1 = \varphi_H, \varphi_2 = \varphi_H + \pi$ (for $H < H_{\text{crit}}^{(2)}$)
Critical fields are \( H_{\text{crit}}^{(1)} = \frac{|J_f|}{d_1 M_1 \sin \theta_1} \) and \( H_{\text{crit}}^{(2)} = \frac{|J_f|}{d_2 M_2 \sin \theta_2} \). For large resonance fields \( H > H_{\text{crit}} \) therefore \( \varphi_1 = \varphi_2 = \varphi_H \).

The resonance frequency \( \omega \) is given by the following fourth-order equation:

\[
\omega^4 - \left( \frac{\gamma_1}{M_1 \sin \theta_1} \right)^2 \det(F_{11}^\sigma) + \left( \frac{\gamma_2}{M_2 \sin \theta_2} \right)^2 \det(F_{22}^\sigma) + \frac{2\gamma_1 \gamma_2}{M_1 M_2 \sin \theta_1 \sin \theta_2} \det(F_{12}^\sigma) \omega^2 + \left( \frac{\gamma_2}{M_1 M_2 \sin \theta_1 \sin \theta_2} \right)^2 \det(F^\sigma) = 0,
\]

where \( \gamma_i \) is a gyromagnetic ratio for each layer. In Equation (5) matrices \( F_{ij}^\sigma, F_{ij} \) \( (i, j=1,2) \), are introduced. Each of them consists of second derivatives of free energy on angles in equilibrium:

\[
F_{ij}^\sigma = \begin{bmatrix}
F_{\theta \theta_i} & F_{\theta \phi_i} & F_{\theta \phi_j} & F_{\theta \phi_j} \\
F_{\theta \phi_i} & F_{\theta \phi_i} & F_{\theta \phi_j} & F_{\theta \phi_j} \\
F_{\phi \phi_i} & F_{\phi \phi_i} & F_{\phi \phi_j} & F_{\phi \phi_j} \\
F_{\phi \phi_i} & F_{\phi \phi_i} & F_{\phi \phi_j} & F_{\phi \phi_j}
\end{bmatrix}
\]

\[
F_{ij} = \begin{bmatrix}
F_{\theta \theta_i} & F_{\theta \phi_i} & F_{\theta \phi_j} & F_{\theta \phi_j} \\
F_{\theta \phi_i} & F_{\theta \phi_i} & F_{\theta \phi_j} & F_{\theta \phi_j} \\
F_{\phi \phi_i} & F_{\phi \phi_i} & F_{\phi \phi_j} & F_{\phi \phi_j} \\
F_{\phi \phi_i} & F_{\phi \phi_i} & F_{\phi \phi_j} & F_{\phi \phi_j}
\end{bmatrix}
\]

The equilibrium polar angles \( (\theta_1, \theta_2) \) can be derived from equations:

\[
M_1 H \sin(\theta_1 - \theta_H) - (2\pi M_1^2 - K_1^{(1)}) \sin 2\theta_1 + 2K_4^{(1)} \sin \theta_1 \cos^3 \theta_1 - d_1 J_f \sin(\theta_1 - \theta_2) = 0,
\]

\[
M_2 H \sin(\theta_2 - \theta_H) - (2\pi M_2^2 - K_2^{(2)}) \sin 2\theta_2 + 2K_4^{(2)} \sin \theta_2 \cos^3 \theta_2 + d_2 J_f \sin(\theta_1 - \theta_2) = 0.
\]

We obtain from Equations. (5), (8) the following equation for the dependence of resonance field \( H(\theta_0) \):

\[
\omega^4 - \left( \gamma_1^2 f_1 g_1 + \gamma_2^2 f_2 g_2 + 2\gamma_1 \gamma_2 f_1 f_2 + f^2 (g_1 g_2 - g^2) \right) \omega^2 + \gamma_1^2 \gamma_2^2 (f_1 f_2 - f^2) (g_1 g_2 - g^2) = 0,
\]

\[
f_i = \sigma_i \left( H \cos(\theta_i - \theta_H) + 4\pi M_i + \frac{2K_4^{(i)}}{M_i} \cos 2\theta_i + \frac{K_1^{(i)}}{M_i} \cos 4\theta_i \right) + \frac{J_f}{M_i} (d_1 + d_2)^{-1} \cos(\theta_i - \theta_2),
\]

\[
g_i = \sigma_i \left( H \cos(\theta_i - \theta_H) + 4\pi M_i + \frac{2K_4^{(i)}}{M_i} \cos 2\theta_i + \frac{K_1^{(i)}}{M_i} \cos 4\theta_i \right) + \frac{J_f}{M_i} (d_1 + d_2)^{-1} \cos(\theta_i - \theta_2),
\]

\[
f = -\frac{J_f}{(M_1 M_2)^{1/2} (d_1 + d_2)} g = -\frac{J_f}{(M_1 M_2)^{1/2} (d_1 + d_2)} \sigma_i = d_i (d_1 + d_2)^{-1}.
\]

If interlayer coupling is absent Equation (9) reduces to two independent equations:

\[
(\omega^2 - \gamma_1^2 f_1 g_1) (\omega^2 - \gamma_2^2 f_2 g_2) = 0
\]
Solutions of Eq. (10) simply describe resonant modes for first and second layer. For example if external field is applied in film plane (i.e. $\theta_1 = \theta_2 = \theta_H = 90^\circ$) we have from (10) the well-known relation for a polycrystalline film:

$$\alpha^2 = \gamma^2 H_{\text{re}}(H_{\text{re}} - 4\pi M_{\text{eff}}), \quad 4\pi M_{\text{eff}} = -4\pi M + 2K_2 / M.$$  

In general case for fixed frequency Equation (9) with Equation (8) gives two solutions for resonance field. This corresponds to two mode FMR-signals. Polar dependence of resonance field provides information on magnetization density, magnetic anisotropy and interlayer coupling.

The line width for frequency may be evaluated by the follow expression:

$$\Gamma = \alpha_0^2 \left( p_1 b_1 \Delta_{\phi_1} F + p_2 b_2 \Delta_{\phi_2} F \right) - G$$

$$\alpha_0^2 = \frac{p_1^2 p_2^2}{\sin^2(\theta_0)} \sin^2(\theta_{20}) \det(F^*)$$  

Then the peak – to – peak line width is given as follows:

$$D_H = \frac{dH g^b D_{q,0} F}{dw M},$$

where $b$ is the dimensionless intrinsic damping factor in the Landau-Lifshitz-Gilbert equation, $D_{q,0}$ is the angle part of Laplace operator.

The the peak – to – peak line width along magnetic field is $D_0 = \frac{2bw}{g}$.

We can see modeling data for # 2671 and 2669 samples in the table 3.

|       | $M_1$, emu/cc | $M_2$, emu/cc | $K_2^{(1)}$ | $K_2^{(2)}$ | $K_4^{(1)}$ | $K_4^{(2)}$ | $J_f$, erg/cm² |
|-------|---------------|---------------|-------------|-------------|-------------|-------------|----------------|
| 2669  | ~700          | ~1270         | -1.6        | -5.6        | -1.2        | -1.4        | +0.20          |
| 2671  | ~960          | ~1040         | 3.3         | 2.05        | 2.1         | -0.18       | +0.05          |

4. Summary

The modeling experimental data for 2470 showed that the rise in annealing temperature, the layers magnetization increases and tends to equalize. As supplementary to this, the constant which describes the interaction between the layers, has a ferromagnetic character and decreases. The possible underlying factor is that during the annealing process the consistent ferromagnetic phase Fe₃O₄ with increased concentration of ferrum is formed, which causes the merger of the border between the ferrum and the magnetite layers. In addition the linewidth broadening is observed, caused by diminishing of the antiphase boundarys' density and growing of grain size. It was derived that the optimum annealing temperature is 400°C – 450°C. This data was used at obtaining multilayer structures.

An additional point is that the anisotropy constants depend on the annealing temperature. It should be noted that the preliminary investigations of magnetite structures which contain ferrous substrates showed that the rising annealing temperature change the magnetization level and the coercive force and anisotropy constants. The modelling allowed follow the magnetization changes in each of the layer. The analysis showed that there is the optimum temperature at which the structure has
the relevant properties. At 350°C the magnetization of the second layer rises, as well as the interrelation constant, which determines the nonferromagnetic character of the ferrous substrate and magnetite interrelation. At a higher temperature the magnetization rises, however, the interrelation constant does not change. The comparison of spectral data of FMR samples 2669 and 2740 shows the similarity of one of the signals of sample 2669 to the signal of annealing sample 2740, which allows us to draw a conclusion of the weak interchanges between the layers.

From (12) Gilbert constant was evaluated. For sample 2669 \( b_1 = 0.012, b_2 = 0.010 \), its gives the possibility to find the Gilbert constants \( G_1 = 1.4 \times 10^8 \text{ s}^{-1} \), \( G_2 = 2.2 \times 10^8 \text{ s}^{-1} \) for each layer. Gilbert constant for the first layer some decreases, but increasing for second layer of annealing sample 277. \( G_1 = 1.3 \times 10^8 \text{ s}^{-1} \), \( G_2 = 4.0 \times 10^8 \text{ s}^{-1} \)

It is necessary to notice that the magnetic properties differences for samples made with the same structure but with different annealing temperature. The process of №2671 sample annealing initiate cooptation of resonance lines and intensity. Annealing process also leads to coercive force values grow. It equivalent to exchange coupling value rising process between film layers through interface. Inversing layers order (for samples №2669 and №2673) leads to intensity change and initiate cooptation of resonance lines. The change of coercive force parameter had been registered caused by Fe sublayer bringing in film structure before magnetite deposition process. The same picture had been observed for 2740 series.

For sample with independence switching we observed resonance field shift into higher fields and leveling of resonance modes signals intensity with its cooptation.

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