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Influence of the Inverse Faraday Effect on Switching and Oscillations of Magnetization in Single-Domain Nanoparticles

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We have performed a numerical simulation of magnetization switching and oscillations in a ferromagnetic single-domain particle in the disk form under the influence of nanosecond laser pulses with linear and circular polarization. The analysis has shown that the interaction of laser pulses with a ferromagnetic nanodisk leads to change in the direction of its magnetization. This process is accompanied by magnetization oscillations with duration from units to tens of nanoseconds. As it follows from the obtained results, the main cause of magnetization switching is the reduction of magnetic anisotropy energy at heating of the structure by laser. The field of the inverse Faraday effect can lead to an increase in frequency and amplitude of this oscillations.

Keywords: Magnetic properties of nanoparticles, Magnetic oscillations, Magnetooptics.

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1. INTRODUCTION

An important practical application of single-domain ferromagnetic nanoparticles is the development of non-volatile magnetic memory. The speed of such memory depends on the duration of magnetization reversal. It is necessary to use single-domain nanoparticles with a large value of the coercive force H_c in order to increase the storage density. However, modern writing/reading systems using an external magnetic field are not capable of switching of the magnetization of nanoparticles with a large H_c value. One perspective way of the local decrease of the H_c value is heating by a laser. Moreover, if the radiation has a circularly polarization then the laser interaction with a ferromagnetic particle produces the additional magnetic field due to the so-called magnetooptical inverse Faraday effect. If a magnetic nanoparticle is included in a structure ferromagnetic / nonmagnetic metal / ferromagnetic, then in this structure the spin-polarized current is induced by photon pressure [1]. This current influences magnetization of the particle by the Slonczewski-Berger mechanism of the spin transfer torque [2]. In this case the stable magnetization oscillations in this structure may be excited. This effect can be used for development of microwave nanogenerators. However, the main problem here is the request of large current density.

Recent experimental investigations have shown that it is possible to switch locally magnetization in magnetic thin films by nano- and picoseconds laser pulses. Depending on conditions the reason of such a magnetization reversal includes various factors. It is the decrease of the coercive force due to heating of the sample, the influence of the magnetooptical inverse Faraday effect and the influence of the spin-polarized current. However, the transient process and magnetization oscillations during the moment of switching are not completely investigated.

The purpose of this work is to clarify the role of the inverse Faraday effect on the switching process and magnetization oscillations in a ferromagnetic single-domain particle of hexagonal cobalt under the influence of nanosecond laser pulses at zero magnetic field.

2. MODEL

We consider a single-domain ferromagnetic nanoparticle in the form of a disk with diameter D and thickness L. Let the coordinate z axis be perpendicular to the plane of the disk. We choose the size of the disk in order to have its magnetic state as a single-domain. For that it should has the thickness less than the exchange length l_{ex} and any diameter, or the diameter less than $2l_{ex}$ and any thickness [3]. Cobalt and permalloy have l_{ex} ~ 5 nm. Also at room temperature the minimal size of the disk should be larger than 5 nm that thermal fluctuations could not change the disk magnetization.

The surface of the disk is irradiated by laser pulses. The laser pulses heat up electronic gas which during the some picoseconds transfers thermal energy to the crystal lattice of ferromagnetic [4]. According to the solution of the heat conduction equation we obtain that the crystal cools down during 10^{-4} seconds.

Due to absorption of radiation the average temperature of a ferromagnetic disk changes under the law

$$T(t) = Q / c_T \rho L = b\int_0^t I(t')dt' ,$$

where $b = [1 - \exp(-L)]/(c\rho L)$, Q is the amount of transmitted heat per unit surface, c_T is the specific thermal capacity and ρ is the density of a disk material, I is the intensity of radiation at the disk surface, β is the absorption coefficient. We suppose that the intensity I is changed under the time law [5]

$$I(t) = I_m \exp[-(t - t_m)^2 / (2\sigma^2)] ,$$

where t_m is the time moment of the maximum intensity I_m, $\sigma = \Delta t / (2\sqrt{\ln 2})$, Δt is the duration of laser pulse at its half-height. Then the average disk temperature can be presented as

$$T(t) = T_0 + bI_m \sqrt{2}\sigma\{1 + \text{erf}[(t - t_m)/\sqrt{2}\sigma]\} ,$$

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where T_0 is the initial temperature (at the moment $t = 0$), "erf" is the error function.

The dependence of saturation magnetization from temperature T is approximated by expression $M(T) = M_0\sqrt{1-(T/T_C)^2}$, where M_0 is the saturation magnetization at zero temperature, T_C is the Curie temperature. We use the Landau-Lifshitz-Gilbert equation for description of magnetization dynamics:

$$\frac{d\mathbf{m}}{d\tau} = -[\mathbf{m}\times\mathbf{h}] - a[\mathbf{m}\times[\mathbf{m}\times\mathbf{h}]] \tag{1}$$

where $\mathbf{m} = \mathbf{M}/M(T)$, $|\mathbf{m}|=1$ is the unit vector of the magnetization $\mathbf{M}$, $\mathbf{h} = \mathbf{H}/M_0$ is the dimensionless effective field, $\tau = \gamma M_0 t/(1+a^2)^2$, t is the time, a is the damping parameter, γ is the gyromagnetic ratio. The effective field $\mathbf{h}$ includes the field of magnetic crystallographic anisotropy $\mathbf{h}_a$, the demagnetization field $\mathbf{h}_d$, the field of the inverse Faraday effect $\mathbf{h}_{mo}$ and the field of thermal fluctuation $\mathbf{h}_T$.

The demagnetization field can be written as

$$\mathbf{h}_d = -N_x m_x\mathbf{i} - N_y m_y\mathbf{j} - N_z m_z\mathbf{k},$$

where $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ are unit vectors of the x, y, z axes; m_x, m_y, m_z is coordinates of the vector $\mathbf{m}$; $N = \mathrm{diag}(N_x, N_y, N_z)$ is the tensor of demagnetizing factors, which depends only on the form of ferromagnetic. For a symmetric disk they are functions of aspect ratio $\varepsilon = L/D$ and $N_x = N_y$, $N_z = 1 - 2N_x$ [3].

The field generated by circularly polarized radiation with intensity I due to the inverse magneto-optical Faraday effect [6] is

$$\mathbf{h}_{mo} = \frac{q^3\mu N_e I}{8\pi\mu_0\varepsilon_0 cnm_e\omega^3 M_0},$$

where q, N_e, m_e is the charge, the concentration and the effective mass of conduction electrons, μ is the magnetic permeability of disk material, μ_0 and ε_0 is the magnetic and electric constants, c is the speed of light, n is the index of refraction, ω is the frequency of electromagnetic radiation.

The magnetic field of crystallographic anisotropy depends on the crystal lattice of a ferromagnetic material. For a crystal with the hexagonal lattice the free energy density of magnetic anisotropy is equal to $E_a = K_1\sin^2\zeta + K_2\sin^4\zeta$, where K_1, K_2 is the constants of magnetic anisotropy, ζ is the angle between the magnetization vector $\mathbf{m}$ and the [0001] crystallographic direction. Then the dimensionless field of crystallographic anisotropy is equal to

$$\mathbf{h}_a = -\frac{1}{\mu_0 M}\frac{\partial E_a}{\partial\mathbf{M}} = \frac{1}{\mu_0 M}[2K_1 + 4K_2(1-(\mathbf{n}\cdot\mathbf{m})^2)](\mathbf{n}\cdot\mathbf{m})\mathbf{n},$$

where $\mathbf{n}$ is the unit vector along the [0001] direction.

As the length of the vector $\mathbf{m}$ in eq. (1) is constant and it is equal to unity, so we can set the direction of this vector by two angle θ and φ in the spherical coordinate system:

$$m_x = \sin\theta\cos\varphi,\quad m_y = \sin\theta\sin\varphi,\quad m_z = \cos\theta.$$

From eq.(1) we can easily obtain the following system

$$\begin{cases}(1+a^2)^2\sin\theta\dfrac{d\varphi}{d\tau} = ah_\varphi - h_\theta,\\ (1+a^2)^2\dfrac{d\theta}{d\tau} = h_\varphi + ah_\theta,\end{cases} \tag{2}$$

where

$$h_\theta = h_x\cos\theta\cos\varphi + h_y\cos\theta\sin\varphi - h_z\sin\theta$$
$$h_\varphi = -h_x\sin\varphi + h_y\cos\varphi.$$

We have solved the system (2) numerically. In the model we use cobalt with the hexagonal lattice as a material of the ferromagnetic disk. This material has the following parameters: $M_0 = 1.432\cdot10^6$ A/m, T_C = 1394 K, a = 0.02, $\beta = 10^5$ cm^{-1}, n = 3, $\mu/\mu_0=10^3$, $N_e = 6.4\cdot10^{22}$ cm^{-1}, m_e = $9.1\cdot10^{31}$, c_T = 420 J/(kg·K), ρ = 8900 kg/m^3, $\omega = 10^{14}$ s^{-1}. In this work we consider a thin disk with the aspect ratio L/D = 0.28 (the height L = 5 nm and the diameter D = 18 nm), a thick disk with L/D = 2 (L = 20 nm, D = 10 nm) and a very thick disk with L/D = 14 (L = 140 nm, D = 10 nm). The surface of the disk is irradiated by a laser beam with power of 5-100 MW/cm^2 and duration of 0.1-2 ns. In all cases we assume the initial temperature of a disk to be equal to room temperature (i.e. 300 K). We use such power of a laser that the disk heats up to 700 K (this temperature at which the hexagonal structure of cobalt transforms into the cubic one).

The temperature dependences of magnetic anisotropy constants in the interval from 0 K to 700 K are approximated by reference data [7]: $K_1(T) = K_1^0 + \eta_1 T$ и $K_2(T) = K_2^0 + \eta_2 T$, where $K_1^0 = 9.84\cdot10^5$ J/m^3, K_2^0 = $1.06\cdot10^5$ J/m^3 is values of K_1 and K_2 at zero temperature; η_1 = – 1833 J/(K·m^3) and η_2 = – 83 J/(K·m^3) are coefficients, which describe the changes in $K_1(T)$ and $K_2(T)$ with temperature.

The initial position of the magnetization vector $\mathbf{m}$ has been chosen to be near its steady equilibrium state with a small deviation, which in a real physical system always happens because of the thermal fluctuations field $\mathbf{h}_T$. We set values of intensity and duration of laser pulses in order to switch of magnetization.

3. RESULTS AND DISCUSSION

Thin disk. Let the aspect ratio be L/D=0.28 and $\mathbf{n}||x$ (the vector $\mathbf{n}$ is parallel to x axis, i.e. the [0001] direction lies in the plane of the disk). If this disk is heated from 300 to 610 K by a linearly polarized laser pulse with peak intensity I_m = 95 MW/cm^2 and duration of 0.1 ns, its magnetization is switched from the x direction to the y direction (Fig. 1, a). This switching is accompanied by magnetization oscillation with average frequency of 8.5 GHz. If laser beam has left circularly polarization, the magnetization vector $\mathbf{m}$ deviates towards the negative direction of z axis and rotates around this axis during the moment of action of a laser pulse. Then it moves to the position parallel to the y axis (Fig. 1, b).

In case of a thin disk with the same size and $\mathbf{n}||z$ (i.e. the [0001] direction is perpendicular to the plane of this disk), the influence of the inverse Faraday effect leads to an increase in frequency of magnetization oscillation during the moment of the laser pulse action. It occurs because of the increase in the total effective field.

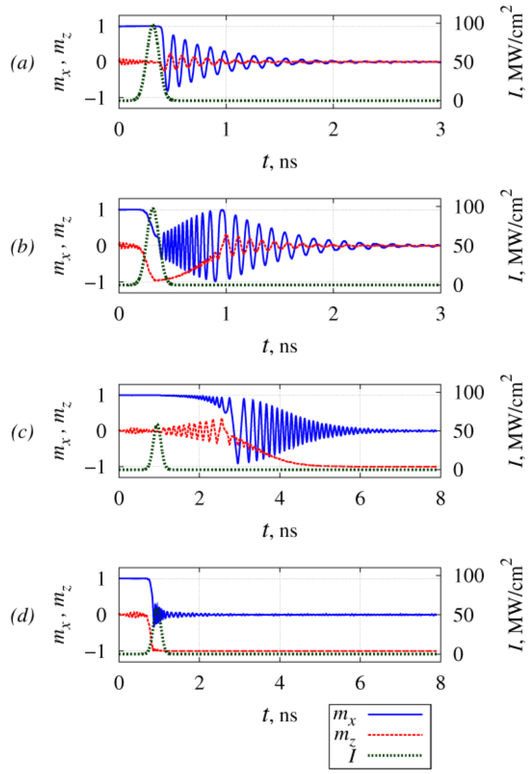

Fig. 1 – The oscillation of magnetization **m** in a single-domain cobalt disk: the thin disk with $L/D = 0.28$ and **n**||x under the influence of a laser pulse with linear (*a*) and left circular (*b*) polarization and intensity I; the thick disk with $L/D = 2$ and **n**||x under the influence of a laser pulse with the linear (*c*) and left circular (*d*) polarization

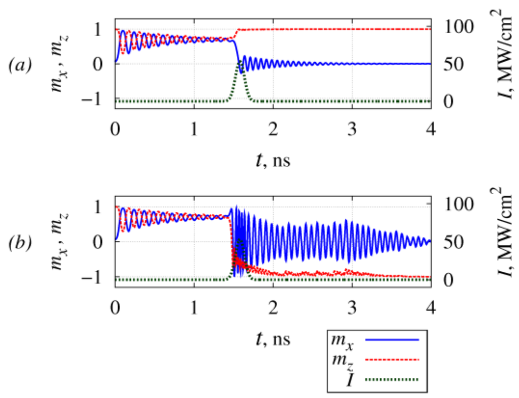

Fig. 2 – The switching of magnetization **m** in a thick single-domain cobalt disk with aspect ratio $L/D = 14$ and **n**||x under the influence of a laser pulse with linear (*a*) and left circular (*b*) polarization and intensity I

Thick disk. The steady magnetic state in the thick disk with the aspect ratio L/D = 2 and **n**||x at temperature T_0 is parallel to the x axis, while at temperature T_1 it is parallel to the z axis. A laser pulse with peak intensity I_m = 60 MW/cm^2 and duration of 0.15 ns heats up this disk from T_0 = 300 K to T_1 = 590 K. If the laser has the linearly polarization, the inverse Faraday effect is absent. In the case of heating the disk by laser the magnetization is switched from the x direction to the positive or negative direction of the z axis with equal probability due to thermal fluctuations (fig. 1, c). The frequency of accompanied magnetization oscillation is ranging from 3 to 10 GHz.

If the laser has the right circularly polarization, the magnetization is switched only to the positive direction of the z axis. In the case of the left circularly polarization, the magnetization is switched only to the negative direction of the z axis (Fig. 1, d). Thus, in this thick disk for any polarization of the laser beam the magnetization is switched from the planar state to the one of perpendicular states, but the specific direction depends on the laser polarization.

When we take a thick disk of same size and **n**||z, then the state **m**||z is the equilibrium state at any temperature (below the Curie temperature). At influence of laser with the linear polarization, the transient processes is not observed. The presence of the inverse Faraday effect in the case of circularly polarized radiation also does not change the magnetization direction of the disk.

When we take a very thick disk with aspect ratio $L/D = 14$, **n**||x and heat it up by a laser pulse with the linear polarization up to 460 K, then the final steady state of magnetization is the state along the positive direction of the z axis (Fig. 2, *a*). If polarization of a laser is circular, then the field of the inverse Faraday effect leads to switching of magnetization along the negative direction of the z axis. It is accompanied by damped magnetization (Fig. 2, *b*).

4. CONCLUSION

It is shown the process of magnetization switching of cobalt single-domain nanoparticles in the disk form under the influence of laser nanosecond pulses is accompanied by magnetization oscillations. The frequencies and duration of these oscillations depend on thickness of the disk and crystallographic orientation.

The influence of the magnetooptical inverse Faraday effect on the switching and oscillation of magnetization has been investigated. Two cases have been considered when the inverse Faraday effect has essential influence: thin and thick disks with the [0001] crystallographic direction in the plane of the disk. For the thin disk the influence of the inverse Faraday effect leads to the deviation of the magnetization vector along the axis of the disk only during the moment of action of a laser pulse. For the thick disk the direction of laser polarization (right circularly or left circularly) determines the direction of magnetization switching: along the positive or negative direction of the z axis. Also in the case of a very thick disk ($L/D \geq 14$) we can switch magnetization by a laser with the circular polarization.

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