

Changes in the Structure and Magnetic Characteristic of Nanofilms and Control of Spin Current by Short Laser Pulses

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Abstract The article focuses on photon drag effect under laser radiation in solid state materials. This effect causes a high concentration of nonequilibrium electrons in the area of the laser beam the exit out of material. Coulomb interaction of spatial charge of these electrons with the charged impurity atoms can cause their drift in the direction of laser radiation. The photon drag effect can be used in laser doping technology of thin films. In multilayer magnetic nanofilms the photon drag effect of polarized electrons can lead to magnetic reversal of magnetic layers, which can be used to control a high speed spin current in the elements of spintronics.

Keywords: laser radiation, photon drag effect, semiconductors, multilayer magnetic nanofilms, spin current

1. Introduction

Spintronics is a field microelectronics, which is based on the transport processes of spin-polarized current between the elements of electronic devices. Manipulation of the spin current assumes using efficient spin current sources (injectors), control unit device by a spin filtering. Therefore, the main efforts of researchers and technologists working in the field of spintronics are aimed at searching for magnetic materials with a high degree of spin polarization, the development of techniques of active control of degrees of freedom of electron spin in solid state systems and creation of new functional devices of spintronics.

Search of materials with a high degree of spin polarization remains one of the main directions of researches in spintronics. At room temperatures there is a predominant orientation of electron spins in ferromagnetic metals, magnetic semimetals and magnetic semiconductors. For the latter the spin polarization degree at the Fermi surface can reach 100% [1,2,3]. Obviously, in the production of spintronic elements the problem concerning the adaptation of using materials to existing microelectronic technology arises. The majority of the known half-metallic magnetic alloys are complex compounds, and technologies of their production are complicated enough. Widely used in microelectronics semiconductors such as silicon, gallium arsenide and germanium are non-magnetic, meanwhile under magnetic impurity doping clusters appear in their structure. At the same time, the researches [4] of a structure modification and changes of the physical characteristics of thin films irradiated by short laser pulses show that the use of laser

technology makes it possible to obtain doping in thin-film magnetic semiconductors with a high homogeneity.

For a spin current control in spintronics devices it is necessary to change the state of magnetization of spin filter elements. Usually, it is realized with the help of the magnetic field created with the electric current flowing through special electrodes. At such simple approach there are difficulties of realization of strong local magnetic fields in macro ranges and high-speed controlling of the spin currents. Magnetized in opposite directions, magnetic nanostructures can be obtained by passing strong electron polarized electric current through them. Such electric current creates not only a well-known magnetic field but also a magnetic field related to magnetic moments of the polarized electrons [5]. The value of this field is proportional to the density of the electron spins. Under such current magnetic reversal of a low coercive layer in nonhomogeneous magnetic nanostructures and the transition from a state with oppositely magnetized layers to the state with the magnetic layers magnetized in one direction can be obtained. However, to achieve the reverse transition from the state with magnetic layers magnetized in one direction to the state with oppositely magnetized layers by passing electric current through such an inhomogeneous magnetic nanostructures is virtually impossible.

One of the possible ways to control spin current appears when using short laser pulses. Such short laser pulses in magnetic materials can not only create a significant magnetic field in local micro-regions due to the inverse Faraday effect [6,7], but also get the directional motion of electrons in the direction of the laser beam due to momentum transfer of photons to electrons [8,9]. The latter effect is called the photon pressure of laser radiation. Under the action of the photon pressure the reversal of the magnetic low coercive nanolayer can be obtained in

nanofilm heterostructure with two magnetic nanolayers [10]. Such magnetic reversal occurs at the strong enough intensity of laser radiation in a very short time of about several picoseconds [11]. It is clear that because of the large light absorption in magnetic materials a laser beam should be used only with thin nanofilm magnetic heterostructures as they are basic materials used to create elements for spintronic devices.

In the present article we would like to consider some features of the photon drag effect in multilayer nanofilms and to show that by using ultrashort laser pulses it is possible not only to study the dynamics of the spin current in multilayer magnetic nanofilms but also to control the spin transport in spintronic elements. We hope that these results will be useful in studying spin-dependent processes in magnetic materials as well as for the development of new high-speed spintronic elements.

2. Photon Drag Effect, Spin Current and Drift of Impurities in Multilayer Films

Photon drag effect was registered for the first time in semiconductors [12,13]. This effect is connected with the transfer of the moment of photon to an electron at absorption of light. As a result, electrons move in the direction of the laser beam. The density of the laser-induced current j is proportional to the intensity I of laser radiation [12,14],

$$j = -(1-R)e\alpha I \frac{n_0 \tau_p \gamma}{m_e c} \quad (1)$$

where e and m_e are the charge and effective mass of an electron; c is the velocity of light; n_0 is the refractive index; R and α are reflection and absorption coefficients of laser radiation; τ_p is electron momentum relaxation time; γ is numerical factor less than unity, which defines the momentum transfer of photons by electrons. Under the action of this current a nonequilibrium electron concentration N_e in the output area of the laser beam occurs in semiconductors.

$$N_e \approx (1-R)\alpha I \frac{2\pi n_0 \tau_p \gamma}{h\omega} \quad (2)$$

Besides, the spatial charge of nonequilibrium electrons on the output semiconductor surface causes an electrical potential. The potential energy of electrostatic interaction of the charged impurity atom with the field of the nonequilibrium spatial charge W_p can be written as

$$W_e \approx N_e S_0 l_0 \frac{\varepsilon e^2}{4\pi\varepsilon_0 l} \approx (1-R)\alpha I e^2 \frac{n_0 r_0^2 l_0 \tau_p \gamma}{2\varepsilon_0 \varepsilon h\omega l} \quad (3)$$

Here $S_0 = \pi r_0^2$ is an area of a section of the laser beam; $l > l_0$, l_0 is thickness of the area of localization of a space charge of nonequilibrium electrons. For $I=100\text{W}/\text{cm}^2$, $\omega=2 \times 10^{14} \text{c}^{-1}$, $\alpha=0,05 \text{cm}^{-1}$, $\varepsilon=4$, $R=0,5$, $r_0=0,5 \text{cm}$, $\tau_p=10^{-10}-10^{-11} \text{s}$, $l=1 \text{cm}$, $l_0=0,01 \text{cm}$ and $\gamma=0,8$ we obtain

for the energy of electrostatic interaction high enough values $W_e \approx 0,3-3 \text{eV}$.

This potential can cause a laser-induced drift of charged impurity atoms and defects. In semiconductors the activation energy of motion of single impurity atoms is small $W_a=0,1-0,4 \text{eV}$, and their mobility μ_i increases with the temperature.

The laser-induced drift of impurity atoms is most easily observed in semiconductor crystals with a very low absorption coefficient [15]. We have observed the impurity drift in crystals CdS and ZnSe in the field of the powerful CO₂ laser [16]. The CO₂ laser irradiation causes various changes in the spectra of low-temperature impurity luminescence on the input and the output surface of the crystals ("Figure 1"). Besides, for some group of ZnSe single crystals with absorption coefficient of the CO₂ laser $\alpha=0,05-0,01 \text{cm}^{-1}$ it causes the appearance of a spot on the output surface. This spot consists of separate dark spots.

Mass spectrometer measurements of distribution of impurity in such crystals after irradiation with the CO₂ laser have shown a noticeable increase of the concentration of carbon in the area of the exit of laser radiation. Research of a chemical compound of the substance in the spot also has shown the presence of the big concentration of carbon. The obtained results give us reason to believe that photon drag of electrons under CO₂ laser radiation causes the drift of impurity carbon atoms ionized with laser radiation.

Our researches [17] showed that after irradiation of the films dye-bismuth-dye and SiC-Bi-SiC by the laser pulses bismuth atoms move along the laser beam. In these films the layers of the semiconductor and the dye are virtually transparent to the laser light and the layer of bismuth absorbs the light strongly. After irradiation of even a single laser pulse in the film, there appears an asymmetry in the distribution of bismuth atoms caused by the increase of the concentration of bismuth atoms in the output layer of dye or semiconductor ("Figure 1"). At the same time, the distribution of bismuth atoms in the input layer is changed very little. The temperature difference between the input and output surface of the crystal with laser irradiation is not greater than 1 degree.

These results testify that powerful laser pulses cause the drift of the bismuth atoms in the semiconductor layer or the dye. The reason for this drift is electrostatic interaction of ionized atoms of bismuth with the field of nonequilibrium electrons. The possibility of electrostatic interaction of bismuth ions with the area of space charge of electrons generated by laser radiation is confirmed by photoelectric measurements.

The above mentioned results of experimental studies show that the photon drag effect plays an important role in the doping of semiconductor materials and it can and even must be taken into account for doping of semiconductor thin films. High speed doping process, small temperature heating and rapid cooling of thin films by using short laser pulses make it possible to use laser technology for doping of thin-film materials. This must prove useful for solving the problem of producing magnetic semiconductors with high uniformity of impurity distribution.

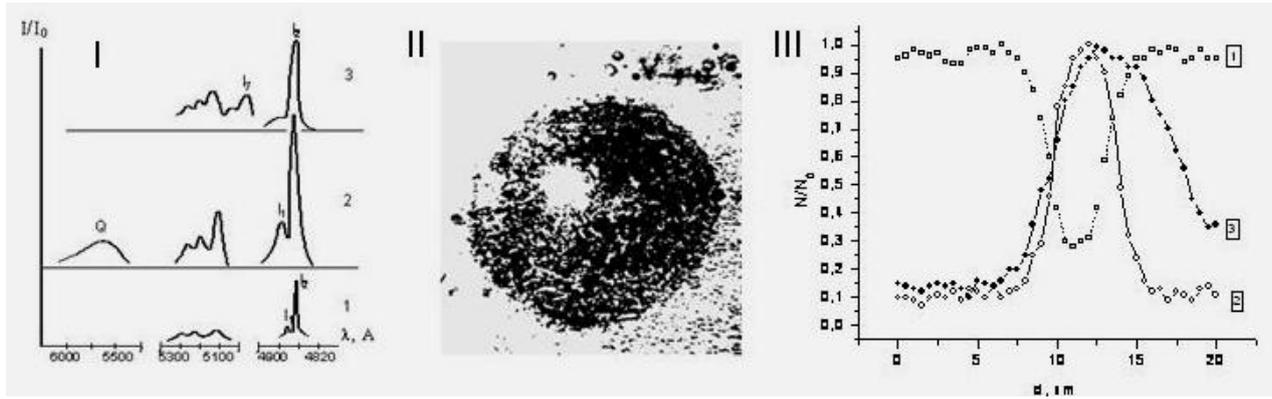


Figure 1. Luminescent spectra of the CdS crystal (I) at the temperature of 4,2 K and the photo (II) of the dark spot on the output surface of ZnSe crystal after irradiation with continuous CO₂ laser with an intensity of 200 MW/cm² and the changes in the distribution of the concentration of bismuth (III) in a three-layer film of dye-bismuth-dye after the pulse irradiation ($\tau_i=20$ ns) with the ruby laser: I-1 initial spectrum, I-2 and I-3-luminescence spectra after 10 min irradiation of CO₂ laser: I-2-spectrum of input and I-3 - spectrum with the output of a crystal surface; III-1 – dye concentration, III-2 – concentration of bismuth prior to irradiation, III-3 –bismuth concentration after irradiation.

The irradiation-induced drift of the charged impurity must take place occur in metals as well. The photon drag effect in metals is studied in several research papers [14] but experimental researches in this direction are practically absent. To observe it in metal materials is much more difficult. It is connected with big absorption coefficient of light, with big concentration equilibrium electrons of conductivity and larger activation energy of motion of the impurity in such materials.

On the other hand, it should be noted that the photon drag effect can be observed in magnetic multilayer nanofilms. In such films there is spin current in the laser irradiation. It takes place because in magnetic films the electrons have the specified polarization direction. Let's consider a bilayer nanostructure consisted of magnetic and nonmagnetic layers. When the irradiation with laser pulses of the magnetic layer spin polarized electrons are injected into the nonmagnetic layer. Consequently, these electrons are accumulated on the spin free path and complementary magnetization arises in the nonmagnetic layer [18]. The spin free path is $l_s = v_p \tau_s$, where τ_s is the character relaxation time of the spin polarization, $v_p = \hbar k / 2\pi m_e^*$ is the velocity of the injected electrons, $\hbar k / 2\pi$ is the photon momentum, m_e^* is the electron effective mass. The spin relaxation time of polarized electrons in nonmagnetic material is more than the momentum relaxation time $\tau_s > \tau_p$. On the basis of equation (1), we obtain the following formula to estimate the magnitude of the nonequilibrium magnetization created by laser-induced spin current

$$M_s \approx \mu_B N_{es} V_{es} \approx (1-R) \alpha \mu_B I \frac{\pi n_0 r_0^2 \tau_s \tau_p \gamma \xi}{cm_e} \quad (4)$$

Here V_{es} is the volume of localization of polarized electrons, $\xi < 1$ is a transmission coefficient of electrons through the interface. At laser intensity $I = 10^5$ W/cm², $h\nu = 1$ eV, $\alpha = 10^4 - 10^5$ cm⁻¹, $R = 0,5$, $\tau_s = 10^{-9}$ s, $\xi = 0,8$, and $\gamma = 0,8$ we will receive larger values for $v_p \sim 10^5$ cm/s, $l_s \sim 10^3$ nm, and $N_{es} = 10^{19} - 10^{18}$ cm⁻³.

Experimental studies of nonequilibrium polarized electrons in the nonmagnetic layers are complicated enough problem. It is caused by small lifetimes of nonequilibrium electrons and a small total magnetic moment because of the small volume V_{es} . One of the best methods of solving this problem is to use magneto-optical

measurement techniques. It is possible to measure magneto-optical Kerr and Faraday angles in local points with a big accuracy and high speed of measurements. We can conclude [19] that the magnitude of the additional nonequilibrium Kerr angle φ_e in the nonmagnetic layer is proportional to the ratio of the concentration N_{es} of polarized nonequilibrium electrons to the concentration of equilibrium electrons N_0 . The magnitude of the additional nonequilibrium Faraday angle θ_e is proportionality to the nonequilibrium magnetization M_s and thickness l_s of a nonmagnetic medium

$$\varphi_e \approx A \chi(\omega) \frac{N_{es}}{N_0}$$

$$\theta_e = AKM_s l_s = (1-R) \alpha \mu_B A I K l_s \frac{\pi n_0 r_0^2 \tau_s \tau_p \gamma \xi}{cm_e} \quad (5)$$

Here $\chi(\omega)$ is magneto-optic coefficient, K is the Hund constant, A is a proportionality coefficient.

We have studied change of magneto-optical characteristics of films Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃/Bi and SiC/Tb/Au/Fe/SiC at their irradiation nanosecond ($\tau_i = 15$ ns) and picosecond ($\tau_i \approx 80$ ps) pulses of the Nd-YAG laser ($\lambda = 1,06 \mu\text{m}$). The films are sprayed by a magnetron deposition technique on plates with sizes 10×14 mm from optical fused quartz with the thickness $1,2$ mm. The thicknesses of the layer TbCoFe constituted 20 nm and the thicknesses of the layer Tb and Fe constituted approximately 4 nm and 8 nm respectively. The thicknesses of the nonmagnetic layer Bi constituted $10-20$ nm. The thicknesses of the barrier layer Al₂O₃ and Au constituted $2-4$ nm. The thicknesses of the cover layer Al₂O₃ and SiC constituted 40 nm. Amorphous ferromagnetic films Tb₂₂Co₅Fe₇₃ have a high perpendicular anisotropy and a big coercive force [20] that provides a long lifetime for a state of the saturation magnetization in such materials and the high degree of an electron polarization.

The change of magneto-optical characteristics in the films Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃/Bi and SiC/Tb/Au/Fe/SiC is studied with the research technique, the scheme of which is shown ("Figure 2"). The beam of the Nd-YAG laser ($\lambda = 1,06 \mu\text{m}$) with Gaussian energy distribution in its cross-section (TEM₀₀) passed through the polarizer 2 and

through the 50 % mirror 3, and then it was directed by 100 % mirror 4 on the special microscope objective 5 with the numerical aperture 0.45. This microscope objective focused laser radiation on a researched film through the substrate 6. Polarized radiation ($\lambda=630nm$) of the He-Ne laser 8 with Gaussian energy distribution in its cross-section (TEM_{00}) was focused by the microscope objective 7 with the numerical aperture 0.5 into that range of the film from its opposite side.

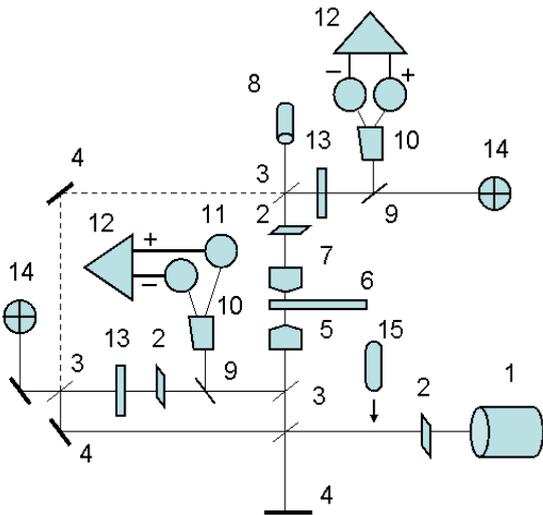


Figure 2. Experimental scheme of the optical investigation: Nd-YAG laser –1, polarizer –2, interference mirror –3, total reflection mirror –4, standard microscope objective –5, substrate with a film –6, special microscope objective –7, He-Ne laser, –8, half-mirror –9, Senarmon prism –10, photodiode of reading –11, differential amplifier –12, light filter –13, photodiode with four active area –14, Babinet compensator –15.

The film reflected radiation of the Nd-YAG and He-Ne lasers with the help of interference mirrors 9 were directed to the polarization Senarmon prism 10, where they were separated into two beams and registered by reading photodiode 11. The electric signals from the reading photodiode are amplified by the differential amplifiers 12. Then these signals are registered by the double-beam oscilloscope. Reflected or transmitted through the film the laser beam can be directed to the polarization Senarmon prism by light filters 13. This light filter is used for registration of radiation of He-Ne or Nd-YAG lasers. The rotation of the laser radiation polarization plane upon reflection or transmission was measured with the help of the differential signal from photodiodes 11. The time resolution of the registration system constitutes 3 ns.

Electrical signals were directed from photodiodes 14 to the microdrivers that provided a constant autofocusing of the microscope objectives 5 and 7 on the surface of the films. By reposition of the substrate with film we could direct the beam of the Nd-YAG laser on the film from the opposite side. For the research of the magnetic switching by circularly polarized laser pulses we introduced the Babinet compensator 15 into the system.

For the time resolution enhancement of the system working with picosecond laser pulses the probing polarized beam of the Nd-YAG laser was formed by the system of 50% mirrors 3 and 100% mirrors 4. That beam

with the controlled delay with respect to an excitation picosecond pulse could be focused into the researched area of the film structure both on the side of the excitation picosecond pulse and on the opposite film side. The rotation of the laser radiation polarization plane upon reflection or transmission through the film of such a probe beam was determined as changing of the signal amplitude registered by the reading photodiodes and oscilloscope. Such approach allows studying magnetic switching dynamics of magnetic layers with temporary resolution up to 5×10^{-11} s.

The described scheme allows to study by means of changing photoelectric Kerr and Faraday signals dynamics in the nonmagnetic layer Bi of the concentration of the laser-injected nonequilibrium polarized electrons, as well as to study dynamics of magnetic switching of magnetic layers in the films with perpendicular anisotropy. We could also write and read information in the magnetic film $Al_2O_3/Tb_{22}Co_5Fe_{73}/Al_2O_3$ deposited on the substrate in the form of a rotating disk. The recording of the information was carried out using the Nd-YAG laser to generate nanosecond pulses with a frequency of 20Hz, and to read the recorded information (points to the opposite direction of magnetization) carried out by the continuous He-Ne laser.

Our researches [21] showed that magneto-optical characteristics of films $Al_2O_3/Tb_{22}Co_5Fe_{73}/Al_2O_3/Bi$ and $SiC/Tb/Au/Fe/SiC$ depend on the direction of falling of the Nd-YAG laser pulses on films (“Figure 3”). The value of the photoelectric Kerr signal for the He-Ne laser from layer Bi increases, when the pulse of the Nd-YAG laser falls on the film $Al_2O_3/Tb_{22}Co_5Fe_{73}/Al_2O_3/Bi$ from the protective coating Al_2O_3 . At irradiation of this film with high intensities laser pulse in an external magnetic field antiparallel to the initial magnetization of the $Tb_{22}Co_5Fe_{73}$ layer this signal increases after falls, passes through zero and becomes negative. If the pulse of the Nd-YAG laser falls on this film from the layer Bi the photoelectric Kerr signal for the He-Ne laser from layer Bi practically does not change.

When the Nd-YAG laser pulse falls on the films $SiC/Tb/Au/Fe/SiC$ from the side SiC/Tb we observe the increase in the photoelectric Kerr signal with the intensity of the laser pulse. The dependence of the maximum value of the Faraday angle Φ on the intensity of the incident laser radiation, calculated from the change of the amplitude of the transmitted laser pulse, is presented in (“Figure 3”).

The results of our experimental studies agree with the statement that at the moment of the laser pulse time the spin-polarized electron current is excited in the multilayer nanostructures. According to the equation (5) this results in the nonequilibrium magnetization and Kerr effect in the nonmagnetic layers of Bi. In the films $SiC/Fe/Au/Tb/SiC$, where the layer Tb is paramagnetic and the layer Fe is ferromagnetic, the laser-induced polarized electron current under the laser irradiation from the side of from the Fe layers exerts magnetization the layers Au and Tb. Such non-equilibrium magnetization of these layers provides increased the value of the Faraday angle in this film by increasing the laser intensity.

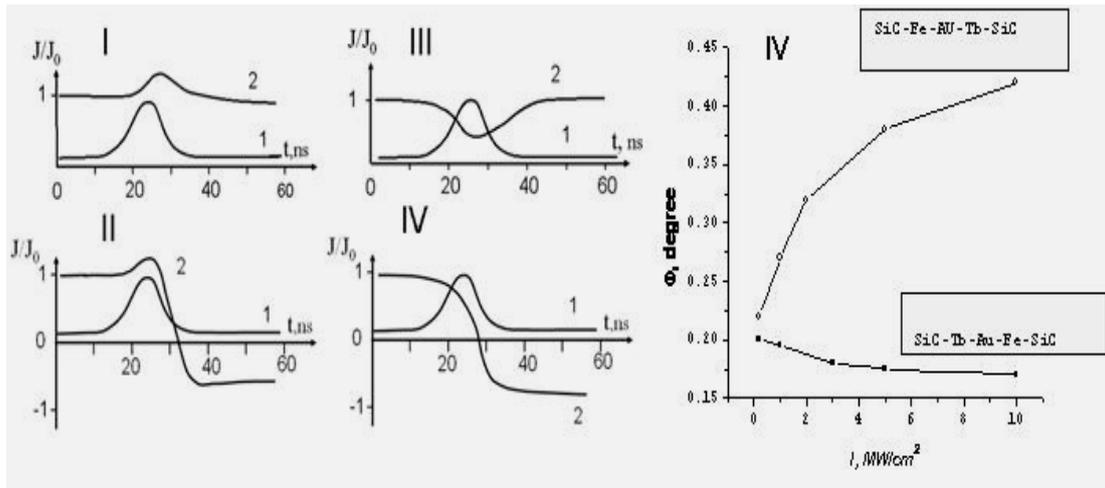


Figure 3. Change of the photoelectric signals J (I-IV, curve 2) for the helium-neon laser reflected from the film $\text{Al}_2\text{O}_3/\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}/\text{Bi}$ at the radiation by nanosecond pulse of Nd-YAG laser (curve 1) from the side of the layer Al_2O_3 (I and II) and from the side of the layer Bi (III and IV) and the change of the value of the Faraday angle Φ (IV) in the film $\text{SiC}/\text{Fe}/\text{Au}/\text{Tb}/\text{SiC}$ at the irradiation its of the nanosecond laser pulse: I- intensity in the laser pulse $I=2 \text{ MW/cm}^2$, external magnetic field $H=0$; II –intensity in the laser pulse $I=8 \text{ MW/cm}^2$, $H=100 \text{ kA/m}$; III –intensity in the laser pulse $I=3 \text{ MW/cm}^2$, $H=0$; IV –intensity in the laser pulse $I=10 \text{ MW/cm}^2$, $H=100 \text{ kA/m}$; IV –the laser pulse falls from the side of the layers SiC/Fe (top) and from the side of the layers SiC/Tb (bottom). The magnetic field $H=200 \text{ kA/m}$

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Thus our researches show that the laser radiation can strongly enough influence on the magneto-optic properties of

the multilayer magnetic nanostructures. One can be used to control the spin current in the elements of spintronics.

3. Magnetic Reversal of Magnetic Films and Management of Spin Current with Picosecond Laser Pulses

Let’s consider the basic mechanisms of the magnetic switching of magnetic films under the influence of laser pulses. The magnetic switching in magnetic layers can be caused by both the laser-induced thermal and nonthermal effects. In the case of the thermal action, laser heating of the layers considerably reduces their coercive force. When the coercive force of a magnetic layer becomes smaller than the oppositely directed external magnetic field H_0 , reversal magnetization takes place in this layer. Such a mechanism of magnetic reversal is well-known and is widely used for a magneto-optical recording [22] in which strong dependence coercive forces on the temperature is observed. The time of thermal laser action is determined by the spin-electron and spin-phonon relaxation times and lies on the nanosecond time scale.

In magnetic films with perpendicular anisotropy (ferrimagnetic films TbCoFe) a magnetization reversal may also occur in zero magnetic field under the action of demagnetizing fields H_{dm} emerging in the region of action of laser radiation. Demagnetizing field in the area of diameter d_0 and thickness h of the magnetic layer heated to the Curie temperature (in TbCoFe the Curie point $T_c < 500 \text{ K}$) can be estimated using by the expression.

$$H_{dm} \approx \frac{h}{d_0} H_a \quad (6)$$

where H_a is the coercive force of the magnetic layer.

The major mechanism of nonthermal magnetic reversal of films is the inverse Faraday effect [6,7]. This mechanism is realized only at the circular polarization of laser radiation and the created magnetic field proportional to the intensity of light. Nonequilibrium magnetization \vec{M}_F is directed along the propagation of the laser beam

$$\vec{M}_F = \frac{\chi}{16\pi} \left[\vec{E} \times \vec{E}^* \right] \quad (7)$$

In the thin conducting magnetic films, where the value of the magnetization is induced by circularly polarized light wave can be found on the basis of a circular current

induced by laser radiation [7]. For the magnetic field HF in the conductive magnetic film we obtain the following formula

$$H_F = \frac{|\overline{M}_F| \mu}{4\pi\mu_0} = \frac{e^3 \mu N E^2}{16\pi\mu_0 n (m_e^*)^2 \omega^3} = \frac{e^3 \mu N I}{8\pi\mu_0 c \varepsilon_0 n (m_e^*)^2 \omega^3} \quad (8)$$

where ω is a laser frequency; c is the light speed; m_e^* and N are effective masse and concentration of conductive electrons; ε and μ are dielectric and magnetic constant.

The direction of the magnetization vector varies with the direction of rotation of the field vector of circularly polarized electromagnetic radiation on the opposite. Therefore, by using laser radiation with the right circular polarization or the left circular polarization we can obtain the magnetic field directed towards the laser beam or against it. The calculated value of laser-induced internal magnetic field can reach large values $H_F > 10^5 - 10^6$ A/m for magnetic films with the magnetic permeability $\mu = 10^3 - 10^4$ under relatively low radiation intensity of picosecond pulses $I = 10^9$ W/cm² at the average concentration of conductive electrons $N \approx 10^{22}$ cm⁻³. The characteristic relaxation time for the inverse nonlinear magneto-optical Faraday effect ranges from 10^{-13} to 10^{-14} s.

In multilayer magnetic structures, a significant contribution to the variation in magneto-optical characteristics of the second and next magnetic layers is made by a new physical mechanism of magnetic switching. That mechanism is related to the laser-induced spin current because of the photon drag effect. The laser-induced injection of spin-polarized electron from the first magnetic layer produces a nonequilibrium magnetic field H_i in the next layer. This field consists of the self-field H_e of the electric current and magnetic field H_s related to the total magnetic moment of the injection spins $H_i = H_e + H_s$. These magnetic fields have different directions: the field produced by electric current H_e lies in the plane of the film, while the field of the total spin moment of the electrons injected from the first magnetic layer H_s is directed to the magnetization M_I of the first magnetic layer. In case of perpendicular anisotropy, the first magnetic layer H_s is directed normally to the second magnetic layer. The results of the article [9] showed that the relation $H_e/H_s \sim d_0$ (d_0 is the diameter of the current conductor).

Since the laser pulse duration τ_i is larger or comparable with the pulse τ_p and the spin relaxation time τ_s in the magnetic layer the magnetic field H_s and H_e , can be described by the estimating expression [10]

$$H_s = l_s \alpha (1-R) I \mu_B \mu \frac{n_0 \tau_p \tau_s \gamma \eta \xi}{2\mu_0 h_1 m_e c}, \quad (9)$$

$$H_e = l_e \alpha (1-R) I e r \frac{n_0 \tau_p \gamma \xi}{4\pi m_e c}$$

where α , R and n_0 are absorption and reflection coefficients and refractive index respectively; h_1 and m_e are the thickness of the first magnetic layer and effective electron mass; $\gamma < 1$, $\eta < 1$ and $\xi < 1$ are coefficients characterizing a momentum transfer from photons to electrons and the degree of electron polarization and the passage from the first into the second layer; μ_B is the Bohr magneton; μ and μ_0 are the a magnetic and absolute

magnetic permeability; l_s and l_e are proportionality constant.

At $I = 100$ MW/cm², $\alpha = 10^5$ cm⁻¹, $R = 0,5$, $r = 10^{-6}$ m, $\tau_s = 10^{-10} - 10^{-11}$ s, $\tau_p = 10^{-11} - 10^{-12}$ s, $\mu = 10^3$, $\gamma = 0,8$, $\eta = 0,8$, $\xi = 0,5$ we can obtain the value $H_s > 10^6$ A/m and $H_e = 10^4 - 10^5$ A/m.

Generally, because of absorption of laser radiation and heating of the magnetic layer the value of magnetic moment \overline{M} in the area of irradiation will change, the dynamics of variation of magnetization in the magnetic layer can be described with the help of the Landau-Gilbert-Bloch equation of the form

$$\frac{d\overline{M}}{dt} = \gamma \left[\frac{\overline{M}}{M_0} \times \overline{H} \right] + \frac{\gamma \alpha_{\parallel}}{n^2} \left[\frac{\overline{M}}{M_0} \times \overline{H}_{\text{eff}} \right] - \frac{\gamma \alpha_{\perp}}{n^2} \left[\frac{\overline{M}}{M_0} \times \left[\frac{\overline{M}}{M_0} \times \overline{H}_{\text{eff}} \right] \right] \quad (10)$$

Here $M = f(T)$ and $M_0 = M(T=0)$; α_{\parallel} and α_{\perp} are coefficients of a longitudinal and cross-section relaxation, γ -is a coupling factor.

The effective magnetic field can be represented as the sum $\overline{H}_{\text{eff}} = \overline{H}_{\text{ext}} + \overline{H}_{\text{an}} + \overline{H}_F + \overline{H}_i + \overline{H}_{\text{dm}}$, where H_{ext} is the external magnetic field, H_{an} is the coercive forcer, H_F is the magnetic field of inverse Faraday effect, $H_i = H_e + H_s$ is the magnetic field of the laser-injected current and H_{dm} is the demagnetizing field. Through variation of the experimental conditions it is possible to make any of these mechanisms predominant and use it for information recording as well as for developing of high-speed optoelectronic switches and other spintronics devices.

We have studied the magnetic switching dynamics in the films $\text{Al}_2\text{O}_3/\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}/\text{Al}_2\text{O}_3$, $\text{Al}_2\text{O}_3/\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}/\text{Pr}_6\text{O}_{11}/\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}/\text{Al}_2\text{O}_3$, at their irradiation with nanosecond ($\tau_i = 15$ ns) and picosecond ($\tau_i \approx 80$ ps) pulses of the Nd-YAG laser ($\lambda = 1,06$ μm). Besides, we studied the influence of a laser pulse on the conductivity of the contacts $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}/\text{Pr}_6\text{O}_{11}/\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ and $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$. The films are sprayed by a magnetron deposition technique on plates with sizes 10×14 mm and discs with the diameter 110 mm from optical fused quartz with the thickness 1,2 mm. the thicknesses of the magnetic layers TbCoFe and CoFe constituted 20 nm. For the barrier layer Pr_6O_{11} that thickness constitutes 2-4 nm. For the cover layer Al_2O_3 that thickness constitutes 40 nm. The tunnel contacts with a conductive surface $S = 20 \mu^2$ are produced by photolithography technique. The contact zone and conductive magnetic strips are also protected by the Al_2O_3 cover with the thickness near 40 nm.

The high energy of the perpendicular anisotropy and considerable coercive force ensure a long lifetime for the magnetization state in the films TbCoFe, which is close to saturation magnetization. It should result in the high degree of electron polarization. Strong temperature dependence of the coercive force and low Curie temperature (near 400 K) make it possible not only to use such films for optical information recording, but also to develop optoelectronic microelements of spintronics on the basis of these films. The ferrimagnetic amorphous films $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ and $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ have a composition which is close to the composition in compensation point $\text{Tb}_{22}\text{Fe}_{78}$ that provides high energy of the perpendicular anisotropy. A small distinction in composition to a significant difference in the coercive force. At $T = 300$ K the coercive forces of the layers $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ and

Tb₁₉Co₅Fe₇₆ constitute $H_1 \approx 3 \times 10^5 A/m$ and $H_2 \approx 1,2 \times 10^5 A/m$ respectively.

The ferromagnetic films CoFe in the magnetized state also have a high degree of electron polarization. In our samples the substrate at film deposition of the layers Co₃₀Fe₇₀ and Co₈₀Fe₂₀ was under the external magnetic field. That provides production of a magnetic layers and the tunnel contact Co₈₀Fe₂₀/Pr₆O₁₁/Co₃₀Fe₇₀ with a small angular dispersion ($\Delta\alpha < 3^\circ$) of planar single-axis magnetic anisotropy. Different composition of these layers provided a difference in the coercive force: Co₃₀Fe₇₀ ($H_1 \approx 300 A/m$) and Co₈₀Fe₂₀ ($H_2 \approx 800 A/m$).

The described features of magnetic characteristics show that our magnetic films present a good model for the research of mechanisms of magnetic reversal by laser radiation in a magnetic films with perpendicular anisotropy and films with planar single-axis magnetic anisotropy.

Due to differences in the magnitude of the coercive force of the layers in the investigated contacts we could remagnetize the layer with low coercivity without the reversal layer with high coercivity. The magnetic field direction coincided with the easy magnetization axis and its value varied from 0 to $8 \times 10^5 A/m$. As a result we have obtain contacts Co₈₀Fe₂₀↑/Pr₆O₁₁/↑Co₃₀Fe₇₀, and Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/↑Tb₁₉Co₅Fe₇₆ to the magnetised layers in parallel or antiparallel (Co₈₀Fe₂₀↑/Pr₆O₁₁/↑Co₃₀Fe₇₀, and Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/↑Tb₁₉Co₅Fe₇₆). Besides, we investigated the change of conductivity of these contacts

under the influence of nanosecond and picosecond laser pulses.

The technique of research of the dynamics of magnetic reversal of magnetic layers is described above ("Figure 2"). The described scheme allows studying dynamics of magnetic switching of magnetic layers in the films with perpendicular anisotropy. The dynamic of magnetic switching of magnetic layers in the films Al₂O₃/Co₈₀Fe₂₀/Pr₆O₁₁/Co₃₀Fe₇₀/Al₂O₃ under the laser pulses was studied on the variation of current transmitted through the tunnel contact Co₈₀Fe₂₀/Pr₆O₁₁/Co₃₀Fe₇₀.

The results of our research have shown that characteristics of magnetic reversal of magnetic layers in a film depend on structure of the film and also on polarization and duration of laser pulse. The magnetic switching of Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃ films under the influence of nanosecond laser pulses takes place even in zero magnetic fields or in the external magnetic field antiparallel to the initial magnetization of this layer. As a result of such magnetic switching the value of photoelectric signal IR(He-Ne) for radiation of the He-Ne laser reflected from the Tb₂₂Co₅Fe₇₃ changes during radiation of the Nd-YAG laser pulses. For very high radiation intensity, the value of this photoelectric signal passes through zero and becomes negative indicating magnetization reversal in the Tb₂₂Co₅Fe₇₃ layer in the region exposed to the nanosecond laser pulse ("Figure 4"). The magnetic switching occurs faster than $\tau \leq 3 \times 10^{-9} s$.

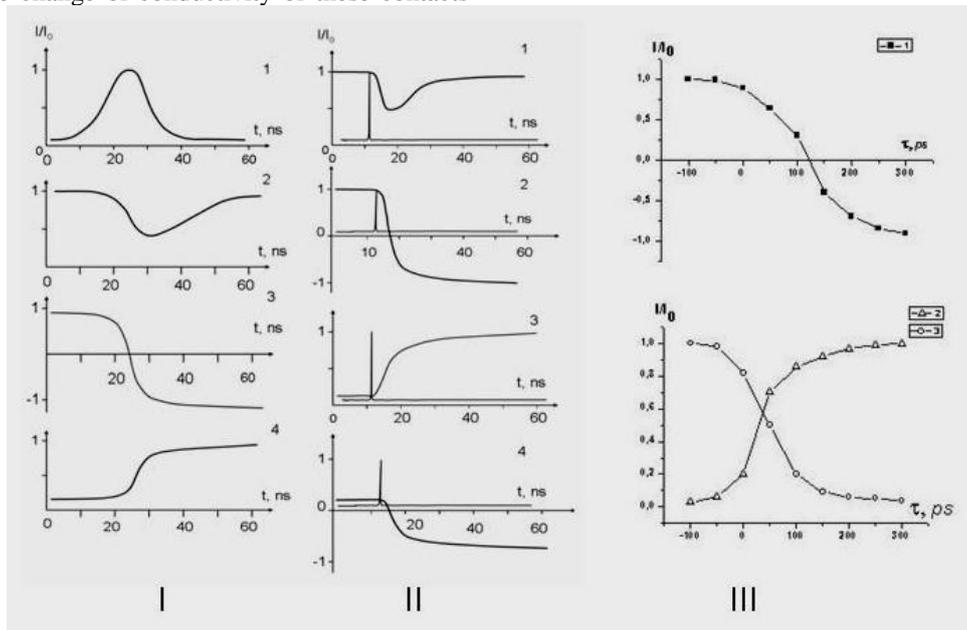


Figure 4. The change of photoelectric signal for He-Ne laser radiation reflected from the layer Tb₁₉Co₅Fe₇₆ (I-2, I-3, II-1, II-2) and transmitted through film Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/↓Tb₁₉Co₅Fe₇₆/Al₂O₃ (I-4, II-3, II-4) at an irradiation nanosecond (I) and picosecond (II) Nd-YAG laser pulses and change of the amplitude of the linearly polarized probe picosecond pulse of Nd-YAG laser (III) depending on the time delay of this pulse with respect to the circularly polarized picosecond laser pulse causes the magnetization reversal of layer Tb₂₂Co₅Fe₇₃ (III-1) and layer Tb₁₉Co₅Fe₇₆ (III-2, III-3): I-2 and II-1 –linearly polarized laser pulse incident from the side of layer Tb₁₉Co₅Fe₇₆; I-3, I-4 and II-2 –linearly polarized pulse incident from the side of layer Tb₂₂Co₅Fe₇₃; II-3 and II-4 –right-hand circularly polarized pulse incident from the side of layer Tb₂₂Co₅Fe₇₃, I=300 MW/cm²; II-4 –left-hand circularly polarized pulse incident from the side of layer Tb₂₂Co₅Fe₇₃, I=800 MW/cm²; III-1 –probe laser pulse is reflected from the film Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃; III-2–probe laser pulse passes through the film Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↓/Al₂O₃, III-3 –probe laser pulse passes through the film Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/ Tb₁₉Co₅Fe₇₆↑/Al₂O₃.

The described results agree well with thermomagnetic switching. Estimation the demagnetizing field in the layer Tb₂₂Co₅Fe₇₃ heated above the Curie temperature T_c gives the value $H_{dm} \approx 10^3 - 10^4 A/m$. After cooling of the layer Tb₂₂Co₅Fe₇₃ (for which $T_c < 450K$) the heated area is

magnetized in the opposite direction of its initial magnetization.

The magnetic switching of this layer under picosecond laser pulses with circular polarization of radiation can be produced not only of the thermomagnetic mechanism, but

also under the effective internal magnetic field of the inverse Faraday effect. As be shown the magnetic field for this effect at the intensity of laser radiation of $I=10^9$ W/cm² can the large values of $H_F > 10^5 - 10^6$ A/m, that considerably exceeds the value of the coercive force in these films.

The magnetic switching of layer Tb₂₂Co₅Fe₇₃ by the linear polarized picosecond pulse of the Nd-YAG is not reached even at very big intensity of laser radiation. All these facts lead to the conclusion that irradiation of Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃ films by picosecond laser pulses with circular polarization of radiation lead to the magnetic switching under the action of the magnetic field of the laser pulse owing to the inverse Faraday effect. We have carry out research of the dependence of amplitude of the probe linearly polarized picosecond pulse from time of its delay concerning the to the excitation circularly polarized picosecond pulse ("Figure 4). The analysis of the results shows that time of the magnetic switching of layer Tb₂₂Co₅Fe₇₃ at irradiation a circularly polarized picosecond laser pulse is smaller than $\tau_c \leq 5 \times 10^{-11}$ s.

In the Al₂O₃/Tb₂₂Co₅Fe₇₃/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆/Al₂O₃ film with two magnetic layers Tb₂₂Co₅Fe₇₃ and Tb₁₉Co₅Fe₇₆, magnetization reversal at the thermomagnetic mechanism occurs in the same way as in the Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃ film. At the set value of external magnetic field and intensity of radiation in a nanosecond or picosecond pulse of Nd-YAG laser we can get magnetization reversal of one layer Tb₁₉Co₅Fe₇₆ with a minor coercive force or for a higher intensity of laser radiation of two magnetic layers Tb₂₂Co₅Fe₇₃ and Tb₁₉Co₅Fe₇₆ simultaneously. Without the external magnetic field, magnetization reversal of the first magnetic layer (relative to the laser pulse) occurs in the Al₂O₃/Tb₂₂Co₅Fe₇₃/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆/Al₂O₃ film in the same way as in the Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃ film.

Magnetization reversal of the second magnetic layer depends not only on the pulse duration and the polarization of laser radiation, but also on the state of magnetization in both magnetic layers.

In the film Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↑/Al₂O₃ with parallel magnetized magnetic layers the laser-induced switching by circularly polarized picosecond pulses occurs without external magnetic field. Depending on the laser radiation intensity magnetic switching can be realized only for one Tb₁₉Co₅Fe₇₆ layer with a less coercive force, or simultaneous magnetic switching of two Tb₁₉Co₅Fe₇₆ and Tb₂₂Co₅Fe₇₃ layers. At magnetic switching of the layer Tb₁₉Co₅Fe₇₆, the film passes from the state Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↑/Al₂O₃ with parallel magnetized magnetic layers to the state Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↓/Al₂O₃ with antiparallel magnetized layers. At magnetic switching of two Tb₁₉Co₅Fe₇₆ and Tb₂₂Co₅Fe₇₃ layers the film passes from state Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↑/Al₂O₃ with parallel magnetized magnetic layers to the state Al₂O₃/Tb₂₂Co₅Fe₇₃↓/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↓/Al₂O₃ with parallel magnetized magnetic layers, but their magnetization is directed to the opposite side.

Such switching is registered by the photoelectric signal I_T(He-Ne) for the radiation of the He-Ne laser passed through the film ("Figure 4). At magnetic switching of one layer the signal I_T(He-Ne) is decreased nearly twice, and at magnetic switching of two layers it becomes

negative. Temporal characteristics of such magnetic switching are close to dynamic behavior of the magnetic switching in the film Al₂O₃/Tb₂₂Co₅Fe₇₃/Al₂O₃ differing only in a power-level of the laser radiation.

The laser-induced magnetic switching without external magnetic field in the film with antiparallel magnetized layers Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↓/Al₂O₃ depends not only on the pulse duration and polarization but also on the incidence direction of laser pulses in respect of the film. At the laser radiation of this film from the side of the layer Tb₂₂Co₅Fe₇₃ the magnetic switching of the layer Tb₁₉Co₅Fe₇₆ can occur, even for linearly polarized picosecond and nanosecond pulses. Such magnetic switching is accompanied by the increase of the photoelectric signal I_T(He-Ne) of the He-Ne laser radiation transmitted through the film ("Figure 4"). At the irradiation of this film from the side of the layer Tb₁₉Co₅Fe₇₆ by the linearly polarized laser radiation we did not succeed in getting magnetic switching without external magnetic field.

The results of the investigations of the films Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↓/Al₂O₃ with antiparallel magnetized layers show that a new physical mechanism of magnetic switching occurs in them. That mechanism is related to laser-induced spin current caused by a photon pressure. The laser-induced injection of the spin-polarized electron from the layer Tb₂₂Co₅Fe₇₃ through the tunnel barrier results in the nonequilibrium magnetic field H_i . As it was shown above this field consists of the self field H_e of the electric current and magnetic field H_s related to the total magnetic moment of the injection spins. The self-field of the electric current H_e is directed to the film plane and the field of the total spin moment of injecting electrons is perpendicular to the film plane H_s .

Our films are characterized by a large perpendicular anisotropy. Therefore, the effect of the magnetic field H_e on magnetic switching of layers is minimal. Conducted estimation of the field size shows that a spin current can result in magnetic switching of the layer Tb₁₉Co₅Fe₇₆. The results of experimental researches of magnetic switching of the film Al₂O₃/Tb₂₂Co₅Fe₇₃↑/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆↓/Al₂O₃ at its radiation by nanosecond and picosecond laser pulses certify this conclusion well.

The investigation of the tunnel contacts Co₈₀Fe₂₀/Pr₆O₁₁/Co₃₀Fe₇₀ has shown that the laser-induced switching can be realized not only for the case of perpendicular but also uniaxial planar magnetic anisotropy of the magnetic layers. However, in the latter case the magnetic switching technique is very limited. As our research showed, the magnetic reversal of one of the electrodes changes the value of tunnel resistance in Co₈₀Fe₂₀/Pr₆O₁₁/Co₃₀Fe₇₀ contacts almost in two times at the temperature $T=80K$ and in one and a half times at the temperature $T=300K$ ("Figure 5"). In contacts Tb₂₂Co₅Fe₇₃/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆ the similar changes of resistance reach large values. If to determine the value of tunnel magnetoresistance (TMR) [238] as $TMR = (R_{max} - R_{min}) / R_{min}$, where R_{max} and R_{min} are the maximal and minimum values of resistance, we will get for contacts Tb₂₂Co₅Fe₇₃/Pr₆O₁₁/Tb₁₉Co₅Fe₇₆ at $T=300K$ value of TMR > 70% and TMR > 240% at $T=80K$. For contacts Co₈₀Fe₂₀/Pr₆O₁₁/Co₃₀Fe₇₀ values of TMR will be smaller and reach the values of TMR ≈ 25% at $T=300K$ and TMR ≈ 100% at $T=80K$.

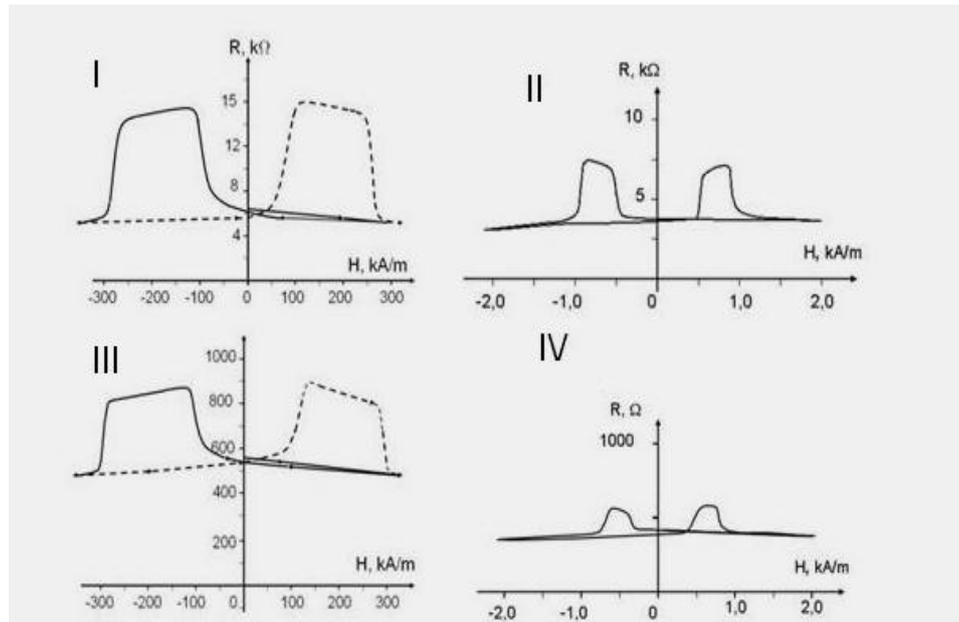


Figure 5. The change of resistance of tunnel contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}/\text{Pr}_6\text{O}_{11}/\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ (1) and $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ (2) at their magnetic switching of an external magnetic field at $T=300\text{K}$ (down) and $T=80\text{K}$ (up).

The research of the influence of laser radiation on resistance of contacts $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ at the absence of magnetic field showed that at small intensity of laser radiation the resistance of contacts falls at the moment of action of laser pulse, but after finishing of the pulse it returns back to the practically initial value. At a large intensity of laser radiation the resistance of the contact $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ changes after the end of the laser pulse and this change depends on the state of magnetization of magnetic layers, on the intensity, and even on the incidence direction of laser pulses on the contact. In the external magnetic field directed towards the magnetization of the low-coercive layer $\text{Co}_{30}\text{Fe}_{70}$, the resistance of the contacts $\text{Co}_{80}\text{Fe}_{20}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Co}_{30}\text{Fe}_{70}$ after radiation with a powerful laser pulse increases on the value ΔR_0 ("Figure 6").

The resistance of the contacts $\text{Co}_{80}\text{Fe}_{20}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Co}_{30}\text{Fe}_{70}$ with antiparallel magnetizations of the layers decreases after irradiation in the same magnetic field on the value $\Delta R \approx \Delta R_0$. Such a change of resistance of the contacts is conditioned by the magnetic switching of the layer $\text{Co}_{30}\text{Fe}_{70}$. The obtained change of resistance of the contacts $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ ΔR_0 is close to the similar change of resistance that we observed during the magnetic switching of the same contacts only in external magnetic field.

In the contacts $\text{Co}_{80}\text{Fe}_{20}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Co}_{30}\text{Fe}_{70}$ with parallel magnetizations of the layers in the absence of the magnetic field it is impossible to get the change of resistance after the radiation with a laser pulse. For such magnetic switching in the contact $\text{Co}_{80}\text{Fe}_{20}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Co}_{30}\text{Fe}_{70}$ it is necessary to select the laser radiation intensity and external magnetic field carefully. In the contacts $\text{Co}_{80}\text{Fe}_{20}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Co}_{30}\text{Fe}_{70}$ with antiparallel magnetizations of the layers it is possible to get the change of resistance even without external magnetic field at radiation of the nanosecond and picosecond pulses of lasers.

The change of resistance in such contacts occurs only for the laser pulses directed from the side of the layer $\text{Co}_{80}\text{Fe}_{20}$. For the laser pulses directed from the side of the

layer $\text{Co}_{30}\text{Fe}_{70}$ the change of resistance does not take place. The obtained results show that the magnetic switching of the low-coercive layer $\text{Co}_{30}\text{Fe}_{70}$ without external magnetic field takes place under the action of the effective magnetic field H_i of laser-induced spin injection through the tunnel barrier Pr_6O_{11} . The magnetic layers in the contacts $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ have a planar single-axis magnetic anisotropy therefore the self-field H_e of the electric current and the magnetic field H_s related to the total magnetic moment of the injection spins have the direction in the plane of layer $\text{Co}_{30}\text{Fe}_{70}$. In this case the value of the internal effective magnetic field is the sum of these two fields $H_i = k_s H_s + k_e H_e$, where k_s and k_e are constants.

Theoretical estimate (11) shows that amplitudes of this field for the contact $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ have one order of size.

Total internal effective magnetic field H_i is larger than the coercive force of the layer $\text{Co}_{30}\text{Fe}_{70}$ that results in its magnetic switching at the irradiation contacts $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ by laser pulses from the side of the layer $\text{Co}_{80}\text{Fe}_{20}$.

The large variety of physical mechanisms of magnetic switching of magnetic layers in the tunnel contacts $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}/\text{Pr}_6\text{O}_{11}/\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ results in wider capabilities for their control by short laser pulses. The known dependences of the tunnel resistance of such contacts on external magnetic field and thickness of the barrier layer [53] show that tunnel structures have a good perspective for spintronics. The laser-induced magnetic switching in the contacts $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ with parallel magnetizations of the layers is related to thermomagnetic and magneto-optic mechanism of the inverse Faraday effect at circularly polarized laser pulses ("Figure 6").

Total internal effective magnetic field H_i is larger than the coercive force of the layer $\text{Co}_{30}\text{Fe}_{70}$ that results in its magnetic switching at the irradiation contacts $\text{Co}_{80}\text{Fe}_{20}/\text{Pr}_6\text{O}_{11}/\text{Co}_{30}\text{Fe}_{70}$ by laser pulses from the side of the layer $\text{Co}_{80}\text{Fe}_{20}$.

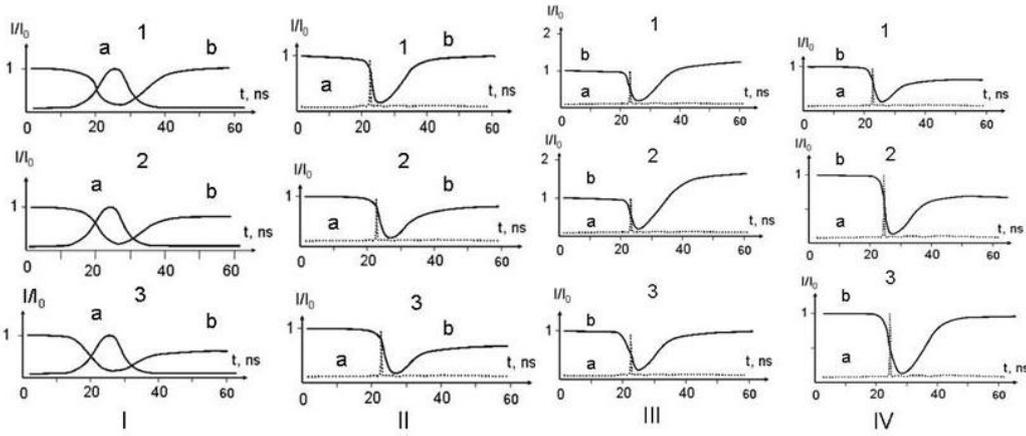


Figure 6. Change of resistance (b) of contacts $\text{Co}_{80}\text{Fe}_{20}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Co}_{30}\text{Fe}_{70}$ (I-1, I-2, II-2), $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ (I-3, II-1, II-3, IV-1, IV-2, IV-3) and $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ (III-1, III-2, III-3) at an irradiation by linearly polarized pulse of Nd-YAG laser (a) from the side of low-coercive layers $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ or $\text{Co}_{30}\text{Fe}_{70}$ (I-1, II-1) and high-coercive layers $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ or $\text{Co}_{80}\text{Fe}_{20}$ (I-2, I-3, II-2, II-3); and at an irradiation from the side of layer of $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ by circular polarized picosecond pulse of Nd-YAG laser with different direction of rotation of plane of polarization (III-1, III-2, IV-3 –right-hand; III-3, IV-1, IV-2 –left-hand): I-1 –intensity of laser radiation $I_1=10\text{ MW/cm}^2$, $T=80\text{ K}$; I-2 – $I_1=10\text{ MW/cm}^2$, $T=80\text{ K}$; I-3 – $I_1=5\text{ MW/cm}^2$, $T=80\text{ K}$; II-1 – $I_1=300\text{ MW/cm}^2$, $T=80\text{ K}$; II-2 – $I_1=1\text{ GW/cm}^2$, $T=80\text{ K}$; II-3 – $I_1=300\text{ MW/cm}^2$, $T=80\text{ K}$; III-1 – $I_1=1\text{ GW/cm}^2$, $T=300\text{ K}$; III-2 – $I_1=3\text{ GW/cm}^2$, $T=80\text{ K}$; III-3 – $I_1=1\text{ GW/cm}^2$, $T=300\text{ K}$; IV-1 – $I_1=1\text{ GW/cm}^2$, $T=300\text{ K}$; IV-2 – $I_1=3\text{ GW/cm}^2$, $T=80\text{ K}$; IV-3 – $I_1=8\text{ GW/cm}^2$, $T=80\text{ K}$

The large variety of physical mechanisms of magnetic switching of magnetic layers in the tunnel contacts $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}/\text{Pr}_6\text{O}_{11}/\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ results in wider capabilities for their control by short laser pulses. The known dependences of the tunnel resistance of such contacts on external magnetic field and thickness of the barrier layer [53] show that tunnel structures have a good perspective for spintronics. The laser-induced magnetic switching in the contacts $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ with parallel magnetizations of the layers is related to thermomagnetic and magneto-optic mechanism of the inverse Faraday effect at circularly polarized laser pulses (Figure 6). At a larger laser radiation intensity the resistance of the contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ decreases during the laser pulse action, but after the end of the laser pulse the contact resistance is increased on the value ΔR . At a yet greater laser radiation the intensity $I_2 > I_1$ when the external magnetic field is directed antiparallely to the layers magnetization of the contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$, the resistance is decreased but after the end of the laser pulse it returns to its initial value R . The reason for such change of conductivity of the contact is the transition from the state $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}\uparrow$ with parallel magnetized layers to the state $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\downarrow/\text{Pr}_6\text{O}_{11}/\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}\downarrow$ also with parallel magnetized magnetic nanolayers in the direction of initial magnetized of the layer $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$. Under the influence of picosecond circularly polarized laser pulses the resistance of the contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ occurs without external magnetic field. The resistance of the contact increases on the value ΔR at the right-handed laser polarization, when the laser-induced magnetic field of the inverse Faraday effect is directed antiparallely to the magnetization of this layer. The magnitude ΔR_3 is a little smaller than the appropriate resistance change under external magnetic field ($\Delta R_3 < \Delta R_2$). The change of resistance did not occur in the contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ under picosecond laser pulses with the left-handed circular polarization of radiation when the external magnetic field was absent. For the linearly polarized laser radiation directed from the

side of the low-coercive layer $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ the change of resistance without external magnetic field does not occur. For the same pulses directed from the side of the highly-coercive layer $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ the resistance of reduction of the contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ on the value ΔR without external magnetic field was observed.

Such changes of resistance of these contacts after irradiation of the lasers pulses are caused by magnetic switching of the layer $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ and it passes from the state $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ with antiparallel magnetized layers to the state with parallel magnetized magnetic layers $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$. The magnetic switching of the low-coercive layer $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ without external magnetic field takes place under the action of the internal effective magnetic field H_s related to the total magnetic moment of the injection through the tunnel barrier Pr_6O_{11} of polarized electrons.

For the circular polarization of picosecond laser pulses which induce the magnetic field antiparallely to the initial magnetization of the layer $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ the resistance of the contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ R_4 decreases on the value ΔR without external magnetic field at the irradiation of this contact from any direction. At the irradiation of this contact from the side of the highly-coercive layer $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}$ its resistance reduction on the value ΔR takes place at the laser radiation intensity I_3 . At the irradiation of this contact from the side of the low-coercive layer $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ its resistance reduction on the value ΔR_5 takes place at a smaller laser intensity $I_4 > I_3$. Such changes of resistance of the contacts $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ after irradiation with the circular polarization laser pulses are caused by magnetic switching of the layer $\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ of the laser-induced magnetic field (the inverse Faraday effect) and passes from the state $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ with antiparallel magnetized layers to the state $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\uparrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ with parallel magnetized magnetic layers.

At the opposite rotation of polarization plane of circular polarized picosecond laser pulses a change of resistance of contact $\text{Tb}_{22}\text{Co}_5\text{Fe}_{73}\uparrow/\text{Pr}_6\text{O}_{11}/\downarrow\text{Tb}_{19}\text{Co}_5\text{Fe}_{76}$ takes place at a

higher intensity of laser radiation. At the irradiation of this contact from the side of the layer $Tb_{22}Co_5Fe_{73}$ this resistance increases on the value ΔR at the radiation intensity $I_5 > I_4$. At the irradiation of this contact from the side of the layer $Tb_{19}Co_5Fe_{76}$ this resistance increases on the value ΔR at the radiation intensity $I_6 > I_5$. Such changes of resistance are connected with the transition of contacts from the state $Tb_{22}Co_5Fe_{73}\uparrow/Pr_6O_{11}/\downarrow Tb_{19}Co_5Fe_{76}$ with antiparallel magnetized layers to the state $Tb_{22}Co_5Fe_{73}\downarrow/Pr_6O_{11}/\downarrow Tb_{19}Co_5Fe_{76}$ with parallel magnetized layers in the direction of initial magnetized of layer $Tb_{19}Co_5Fe_{76}$. The difference in intensities of radiation of the circular polarization picosecond laser pulses is explained by the fact that magnetic switching of the input magnetic layer takes place only under the influence of the magnetic field of inverse Faraday effect H_F , while the magnetic switching of the output magnetic layer is caused by the sum of this field H_F and field H_s related to the total magnetic moment of the injection spins.

4. Conclusions

The analysis of the features of laser interaction with thin films outlines perfect prospects for using laser radiation for doping technology of thin films as well as for high-speed spin current control in spintronic elements. In both cases, the laser-induced photon drag effect plays an important role. Under this effect, in the output area of the laser beam a nonequilibrium spatial electron charge arises. The electrostatic interaction of the nonequilibrium spatial electron charge with ionized impurity atoms causes the drift of these atoms in the direction of the laser beam. Such laser-induced drift of impurities can be used in doping technology of thin films.

In multilayer magnetic films the photon drag effect leads to the spin current in the direction of laser radiation. The laser-induced injection of the spin-polarized electrons can cause non-equilibrium magnetization in the nonmagnetic semiconductor and metal layers and may also lead to a reversal of the magnetic nanolayers. The results of our experimental studies show that using ultrashort laser pulses can manage with a high speed ($\tau \sim 10^{-11}$ s) the spin current in spintronics devices due to excitation of the magnetic field of the inverse Faraday effect or the magnetic field of the spin current.

For the effective work of such optical controlled spin elements it is necessary not only to look for proper materials but also to set duration, intensity and polarization of controlling laser radiation.

High values obtained in the tunnelling magnetoresistance of the junctions $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$ and $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$ irradiated with picosecond laser pulses outline prospects of application of these contacts to create new elements for spintronics.

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