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Enhancement of the Faraday Effect in Thin Film Structure Tb_2O_3/Fe Due to *f–d* Layer Interaction

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Separation of two factors influencing the Faraday effect in the thin film structure Tb_2O_3/Fe, namely, interference and *f–d* interaction of the Tb_2O_3 and Fe layers, is performed. As shown, the interaction of the layers enhances the Faraday effect with a maximum at a Tb_2O_3 layer thickness of 40 nm. The highest enhancement is by two times, and the largest specific Faraday angle is $1.8 \cdot 10^6$ deg/cm. The enhancement increases with thickening of Fe film from 40 nm to 120 nm and disappears at a thickness of 30 nm and below. It is provided with the action of both single spontaneous and combined spontaneous and induced magnetizations of Fe film.

У тонкоплівковій структурі Tb_2O_3/Fe було проведено відокремлення впливу інтерференції і *f–d*-взаємодії шарів на Фарадеїв ефект. Показано, що *f–d*-взаємодія шарів Tb_2O_3 і Fe приводить до посилення Фарадейового ефекту, що сягає свого максимуму при товщині шару Tb_2O_3 у 40 нм. Найбільше посилення, одержане для структури Tb_2O_3/Fe, досягає значення вдвічі, а найбільший питомий Фарадеїв кут при цьому становить $\varphi_F = 1{,}8 \cdot 10^6$ град/см. Посилення зростає зі збільшенням товщини плівки Fe в діяпазоні від 40 до 120 нм і зникає при товщині у 30 нм і менше. Посилення Фарадейового ефекту забезпечується як впливом лише спонтанної, так і спільним впливом спонтанної та наведеної намагнетованостей плівки Fe.

В тонкоплёночной структуре Tb_2O_3/Fe проведено разделение влияния интерференции и *f–d*-взаимодействия слоёв на эффект Фарадея. Показано, что *f–d*-взаимодействие слоёв Tb_2O_3 и Fe приводит к усилению эффекта Фарадея, достигающего максимума при толщине слоя Tb_2O_3 40 нм. Наибольшее усиление, полученное для структуры Tb_2O_3/Fe, составляет 2 раза, а наибольший удельный угол Фарадея $\varphi_F = 1{,}8 \cdot 10^6$ град/см. Усиление возрастает с увеличением толщины плёнки Fe от 40 до 120 нм и исчезает при толщине 30 нм и менее. Усиление эффекта Фарадея обеспечивается как действием только спонтанной, так и совместным влиянием спонтанной и наведённой намагниченностей плёнки Fe.

Key words: Faraday effect, *f*–*d* interaction, thin film, terbium oxide, magnetization.

Ключові слова: Фарадеїв ефект, *f*–*d*-взаємодія, тонка плівка, оксид тербію, магнетування.

Ключевые слова: эффект Фарадея, *f*–*d*-взаимодействие, тонкая плёнка, оксид тербия, намагничивание.

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1. INTRODUCTION

Thin film structures composed of contacting layers of *f* (rare earth) and *d* (Fe group) transition metals have been attracting much attention of researchers over 40 years thanks to the opportunity to use them in spintronics, magnetooptics, and magnetic record of information [1]. Both the layers themselves and their f–d interaction determine magnetic properties of such structures. Upon replacing one of the layers, for instance, *f*-metal with its oxide, a new film formation takes place with a complex magnetic structure (ferromagnetic/paramagnetic) and a possibility of the *f*–*d* interaction at the layer boundary through intermediate oxygen ions, similar to that in rare earth orthoferrites $RFeO_3$ and ferrites-garnets $R_3Fe_5O_{12}$ (*R* is rare earth metal) [2]. The electric structure of such formations corresponds to the metal/dielectric transition. Taking into account the sensibility of these film structures to electric and magnetic fields as well as high transparency of *R*-oxides and their chemical stability capable to protect thin *d*-metal films against oxidation, it is reasonable to hope for their successful application in galvanomagnetism, magnetooptics, and spintronics. However, despite the attractive promise, investigation of film structures *R*-oxide/*d*-metal is still at the starting stage.

Earlier, the authors have studied the thin film Dy_2O_3/Ni structure [3] and established that deposition of Dy_2O_3 layer onto Ni film results in changing magnetic resistance $\Delta\rho/\rho_0$ and thus magnetization I of nickel according to the relation $\Delta\rho/\rho_0 = \alpha I^2$ [4]. As magnetization could only change due to the magnetic interaction of layers, then the change in it indicated the presence of *f*–*d* interaction between Dy_2O_3 and Ni. There was observed both an increase and a decrease in magnetic resistance and magnetization depending on the directions of current passing through the Ni film and external magnetic field with respect to the sample surface.

The growth of *d*-metal magnetization due to the contact with *R*-oxide gave hope for the achievement of enhancement of not only galvanic but also magnetooptical effects dependent on magnetization. Therefore, the aim of the present work was to study the peculiarities of the Faraday effect related to the *f*–*d* layer interaction in the thin film structure *R*-oxide (Tb_2O_3)/*d*-metal (Fe). The metals Tb and Fe were chosen, as they possess the highest magnetic moments in their groups, which provide, according to [2], intense interaction between *f* and *d* electron shells.

2. EXPERIMENTAL SECTION

The thin film Tb_2O_3/Fe structure was formed through successive deposition of metal and *R*-oxide layers on a glass substrate using an electron beam evaporation of chemically pure Fe and Tb, the latter during the input of oxygen inside the working chamber. The deposition conditions were as follows: pressure $5\cdot10^{-3}$ Pa, deposition rate 8–24 nm/min, and temperature 25°C for Fe and partial oxygen pressure $2\cdot10^{-2}$ Pa, deposition rate 30–60 nm/min, and temperature 25°C for Tb. Under them, the structure of Fe layers was polycrystalline and that of Tb_2O_3 was amorphous. It was examined using electron diffraction. The thickness of layers was determined with an interference microscope and varied within 30–120 nm for Fe and within 0–140 nm for Tb. It was controlled during deposition using a spectrophotometer combined with the working chamber.

The thin film Tb_2O_3/Fe structure deposited on a glass substrate, together with the surrounding medium, can be described as a complex optical system air/Tb_2O_3/Fe/glass/air, in which magnetooptical effects are sure to be markedly affected by light interference due to multiple reflections from the interlayer boundaries.

In order to reveal the peculiarities of the Faraday effect related to the *f*–*d* layer interaction under the above conditions, first of all, it is necessary to separate them from those involved by interference. A detailed analysis of the Faraday and Kerr effects in multilayer structures with arbitrary magnetization has been performed in [5]. There was considered passing of light through the optical system air/transparent film/magnetic film /substrate/air, which is analogous to the Tb_2O_3/Fe structure on glass (Fig. 1).

For a normal incidence of light onto the surface of sample, the Faraday angle, φ_F, is described by the following expression [5]:

$$\phi_F = \mathrm{Re}\left(\frac{[4\pi\lambda^{-1}n_3d_3(1+F_3^2r_{321}r_{345}) - i(1-F_3^2)(r_{321}+r_{345})]Q}{4(1-F_3^2r_{321}r_{345})}\right), \quad (1)$$

where r_{jkl} is the reflectivity at the boundary of *j*, *k*, *l* media;

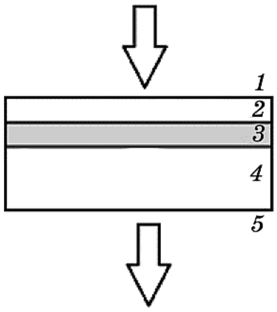

Fig. 1. Scheme of the Tb_2O_3/Fe film structure for the Faraday effect observation: (*1*) and (*5*) air, (*2*) transparent film (Tb_2O_3), (*3*) magnetic film (Fe), and (*4*) glass substrate.

$F_3 = \exp(-2\pi i\lambda^{-1}n_3d_3)$ is the phase factor related to the wave attenuation in the magnetic film; n_3 is the complex index of refraction; d_3 is the thickness of magnetic film; λ is the light wavelength, and Q is a magnetooptical parameter proportional to the film magnetization.

Expression (1) makes it possible to draw an important conclusion. For an intensely absorbing magnetic film with a high complex index of refraction (Fe film is the case) and large d_3, the phase factor $F_3 \to 0$, and expression (1) becomes markedly simpler. Herein, the Faraday angle becomes independent of reflectivity, indexes of refraction and the thicknesses of the transparent film, n_2, d_2, and the substrate n_4, d_4. That is, the influence of interference diminishes. Thus, the Faraday angle only depends on the parameters n_3, d_3, Q, and λ. It follows that, in order to weaken the influence of interference on the Faraday effect, it is necessary to increase d_3 significantly at fixed n_3, Q, and λ.

In addition, it follows from [3] that, with growing thickness of a magnetic layer, the *f*–*d* interaction between the layers in the *R*-oxide/*d*-metal structure increases, which results in changing in the metal magnetization. Comparison of this result with the above made conclusion from expression (1) makes it possible to develop a method for separation of the influences of interference and *f*–*d* layer interaction on the Faraday effect. The method consists in determining the peculiarities in the dependences of the Faraday angle on different parameters, for instance, on oxide layer thickness d_2 and magnetic field strength H, arising in the Tb_2O_3/Fe structure with thickening of magnetic film, when the influence of interference diminishes whereas the *f*–*d* layer interaction, on the contrary, grows.

In the course of implementation of this method, a grating monochromator was used as a light source. The Faraday angle was determined using a polariscope with an accuracy of 0.1 deg. Transmission spectra were recorded in the visible region of light with the aid of a spectrophotometer.

3. RESULTS AND DISCUSSION

The conclusion made on the basis of expression (1) about diminishing influence of interference in the case of thick Fe film was confirmed in the spectrum of optical transmission, which is usually used for observation of the Faraday effect. Figure 2 represents the dependence of the optical transmission of the Tb_2O_3 /Fe structure on the thickness of Tb_2O_3 layer at various Fe film thicknesses. The light wavelength was 620 nm.

As seen, with the growing Tb_2O_3 layer thickness, the transmission of structure passes through a number of extremes related to interference of light in the structure layers. With growing Fe film thickness, intensity of the extremes decreases down to their disappearance at a Fe film thickness of 120 nm, which evidences to decrease in the influence of interference on the light transmission through the structure, that is, on the Faraday effect observed under transmitted light as well.

Using this opportunity to avoid the influence of interference, one can determine the peculiarities related to the influence of *f–d* interaction between the Tb_2O_3 and Fe layers on the dependence of the Faraday angle on the parameters d_2, d_3, and H.

Figure 3 demonstrates the dependence of the Faraday angle on the Tb_2O_3 layer thickness both in the absence of magnetic field and under its action (600 Oe) for different Fe film thicknesses. The vector of the external magnetic field and the direction of light beam were perpendicular to the structure surface. The wavelength was 620 nm.

As shown in Figure 3, the Faraday effect occurs even without magnetic field (curves *1–4*) that indicates the presence in the Fe film of significant spontaneous magnetization leading to rotation of the polarization plane at $H = 0$ Oe.

With thickening of the Fe film from 30 to 120 nm, curves *1–4* change. In the beginning (curve *1*), the Faraday angle gradually decreases, but at $d_2 = 40$ nm and maximum begins to form and then markedly increases (*2–4*). The origin of the maximum cannot be related to interference, whose influence diminishes with growing film thickness. It is more probable that the appearance and growth of the maximum are caused by the *f–d* interaction between Fe and Tb_2O_3 accompanied by increase in metal magnetization. In such a case, the physical role of the film thickness 40 nm for the Tb_2O_3 layer can be considered as a maximal depth of penetration of the *f–d* interaction into Tb_2O_3.

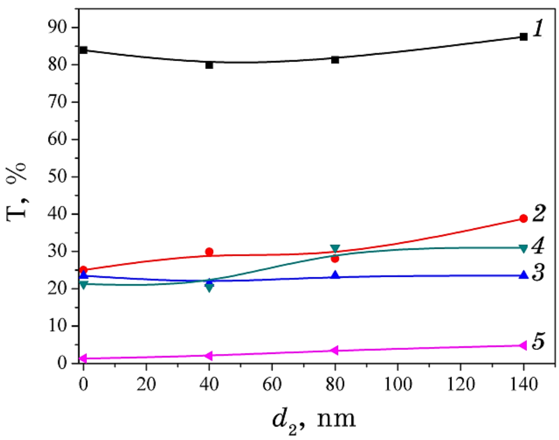

Fig. 2. Dependence of the Tb_2O_3/Fe structure optical transmission T on the Tb_2O_3 layer thickness d_2 at different thicknesses d_3 of Fe film: (*1*) 30 nm, (*2*) 40 nm, (*3*) 50 nm, (*4*) 65 nm, and (*5*) 120 nm. The light wavelength is 620 nm.

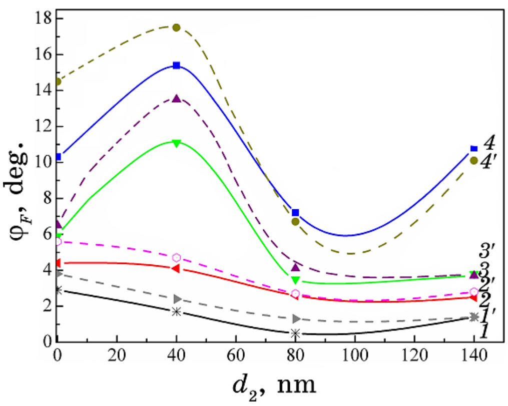

Fig. 3. Dependence of the Faraday angle φ_F on the Tb_2O_3 layer thickness d_2 in the Tb_2O_3/Fe structure in the absence (*1*–*4*) and under the action (*1′*–*4′*) of external magnetic field 600 Oe for different thicknesses of Fe film: (*1*, *1′*) 30 nm, (*2*, *2′*) 40 nm, (*3*, *3′*) 65 nm, and (*4*, *4′*) 120 nm.

Application of external magnetic field of 600 Oe leads to rise of curves *2*–*4* to *2′*–*4′* with preservation of maxima, which implies that, in this case, the influences of induced and spontaneous magnetization of Fe film are summarized.

The maximum at the oxide layer thickness 40 nm permits the achievement of higher Faraday angles than those without it. Thus, at $H = 600$ Oe, with thickening of Tb_2O_3 layer from 0 to 40 nm the

Faraday angle increases on curve *3′* by 2 times, and on curve *4′* by 1.2 times. Therefore, near the maximum, which is related to the *f*–*d* interaction between the Tb_2O_3 and Fe layers and accompanied with increase in the Fe film magnetization, enhancement of the Faraday effect occurs. At the expense of the enhancement, a large value of the specific Faraday angle is achieved. For instance, near maximum on curve *4′*, it equals $1.5 \cdot 10^6$ deg/cm, which is close to the known value $2 \cdot 10^6$ deg/cm for EuS.

Furthermore, Figure 3 shows that there is no maximum at a Fe film thickness of below 40 nm (*1* and *1′*), which may be associated with the known decrease in the atomic magnetic moment in Fe films with their thinning [1]. This decrease, according to [2], weakens the *f*–*d* interaction in the Tb_2O_3/Fe structure and thus makes the appearance of maximum impossible.

By reconstructing the dependences in Figure 3 into the dependence of the Faraday angle on the Fe film thickness, one can reveal other peculiarities of the Faraday effect in the Tb_2O_3/Fe structure (Fig. 4).

It follows from Figure 4 that, in the studied Fe film thickness range, 30–120 nm, the Faraday angle increases with thickening of Fe film, which agrees with expression (1). The influence of interference is revealed in the absence of direct proportionality between these parameters.

A peculiarity of Figure 3 is the fact that none of the curves (both

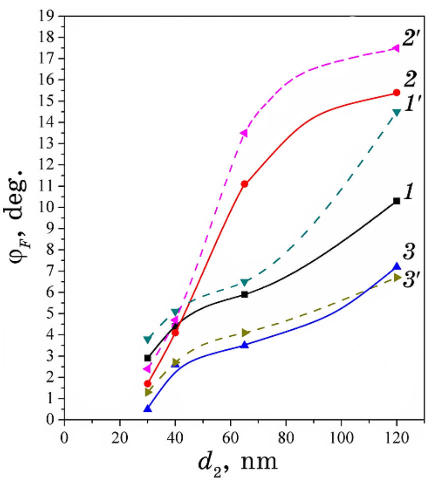

Fig. 4. Dependence of the Faraday angle φ_F on the Fe film thickness d_3 in the Tb_2O_3/Fe structure in the absence (*1*–*3*) and under the action (*1′*–*3′*) of external magnetic field 600 Oe for different thicknesses of Tb_2O_3 layer: (*1*, *1′*) 0 nm, (*2*, *2′*) 40 nm, and (*3*, *3′*) 80 nm.

1–3 and *1′–3′*) originates from zero (as expression (1) requires). This indicates the presence of spontaneous magnetization of the Fe film, which causes the Faraday effect beginning from the Fe film thickness 10–30 nm.

Figure 5 represents experimental (*1–3*) and averaged (*1′–3′*) dependences of the Faraday angle on the strength of external magnetic field for the Tb_2O_3/Fe structure. The thickness of the Tb_2O_3 layer was 0, 40, and 80 nm and that of the Fe film was 120 nm. As mentioned above, at such a Fe film thickness, the influence of interference on the optical transmission of light through the Tb_2O_3/Fe structure is minimal. The directions of magnetic field and light beam as well as wavelength were the same as before.

As seen in Figure 5, the experimental curves (*1–3*) are characterized by some maxima, which are not related to light interference. Their origin has not clarified yet. Despite their wave-like behaviour, the averaged values (*1′–3′*) correspond to the theoretical expression (1), according to which $\phi_F \approx Q = \mathrm{const}I = \mathrm{const}\chi H$, where χ is the magnetic susceptibility. This suggests that the Faraday angle is to be almost proportional to H, which is observed in the averaged dependences *1′* and *2′*. Line *3′* practically does not depend on H, since, as shown in Figure 3, the influence of magnetic field on the Faraday angle becomes weak for thick Tb_2O_3 layers. This may be due to the strong paramagnetic properties of Tb_2O_3.

Enhancement of the Faraday effect at a thickness of Tb_2O_3 layer of 40 nm can also be seen in Figure 5: curves *2* and *2′* are located

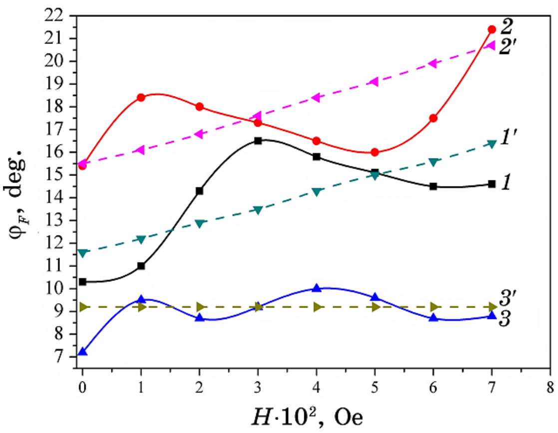

Fig. 5. Experimental (*1–3*) and averaged (*1′–3′*) dependences of the Faraday angle φ_F on the external magnetic field strength H in the Tb_2O_3/Fe structure for different thicknesses of Tb_2O_3 layer: (*1*, *1′*) 0 nm, (*2*, *2′*) 40 nm, and (*3*, *3′*) 80 nm. The Fe film thickness is 120 nm. The light wavelength is 620 nm.

much higher than *1* and *1′*. At $H = 700$ Oe, the enhancement is by 1.5 times, and the specific Faraday angle is $1.8\cdot10^6$ deg/cm.

4. CONCLUSIONS

It has been established that, in the Tb_2O_3/Fe structure, enhancement of the Faraday effect is observed owing to the *f*–*d* layer interaction, which increases the magnetization of the Fe film. The largest enhancement, by a factor of two, was achieved at a Tb_2O_3 layer thickness of 40 nm; herein, the specific Faraday angle was equal to $1.8\cdot10^6$ deg/cm.

Enhancement of the Faraday effect increases with thickening of Fe film in the range of 40–120 nm. At a Fe film thickness of 30 nm and less, no enhancement is observed. A possible reason for this is weakening of *f*–*d* layer interaction due to decreasing atomic magnetic moment with thinning of Fe film.

Enhancement of the Faraday effect takes place under the action of both single spontaneous and combined spontaneous and induced magnetization of Fe film. In the latter case, the two actions are summarized.

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