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EPR STUDY OF INTERLAYER INTERACTION IN Gd_2O_3/Fe NANOSTRUCTURE

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In this work, a nanoscale structure consisting of contacting layers of a metal of the iron subgroup and a rare earth metal oxide (REM) is considered. Such nanostructures have an interesting feature, which is that as a result of the contact of these layers, an increase in the galvanomagnetic, magneto-optical and kinetic properties of ferromagnetic metals are observed. Presumably, the enhancement is due to an increase in the magnetization of these metals, caused by the exchange f - d interaction between the unfilled f- and d-electron shells of the atoms that make up the contacting layers. The aim of this work is to find the possibility of such f - d exchange interaction by the EPR method.

To compose the studied nanostructure, Fe used as it has the strongest magnetic properties in its subgroup. Gd_2O_3 was used as an REM oxide as one of the few oxides giving a significant signal in the EPR region. The Gd_2O_3/Fe nanostructure created by sequential electron-beam deposition of Gd_2O_3 and Fe layers on a sitall substrate. The thickness of the oxide and metal layers was 68 and 112 nm, respectively. EPR spectra were recorded at room temperature on a computerized spectrometer Radiopan 2547 SE / X at the frequency of 9.3 GHz. The set of the obtained spectra was processed using the OriginPro and MatLab programs, which confirmed their compliance with the Lorentz model.

From the experimentally obtained EPR linewidth, the parameter of the exchange f - d interaction is determined under the condition of a number of assumptions. The value of the g-factor is also found. Comparison of the EPR parameters of the spectra of individual layers of Gd_2O_3 and Fe with the spectra of the Gd_2O_3/Fe nanostructure composed of them, including the value of the g factor and the exchange interaction parameter, suggests that the presence of an iron layer affects the EPR spectrum of the REM oxide layer Gd_2O_3. The exchange interaction parameter increases from 985 to 4685 (rel. units), the g-factor decreases from 3.5 to 2.4. The most probable reason for the change in the spectrum is the exchange f - d interaction between atoms with unfilled f- and d-electron shells that are parts of the contacting layers.

Keywords: *nanostructure, layer, iron, gadolinium oxide, EPR spectra, f - d interaction*

INTRODUCTION

Nanosized film structures consisting of contacting layers of oxides of rare-earth metals (REM) and metals of the Fe, Co, Ni subgroup of iron have an interesting feature. As a result of such contacts in film structures, there is an increase in the galvanomagnetic [1], magneto-optical [2], and kinetic [3] properties of the layers of the above metals. The authors of these reports attributed this enhancement to an increase in the magnetization of ferromagnetic films of Fe, Co, Ni, caused by the exchange *f-d* interaction between the unfilled *f*- and *d*- shells of atoms that make up the contacting layers. However, practical verification of the magnitude of magnetization in nanoscale films encounters significant difficulties.

For the first time, an attempt to measure the effect of REM oxides on the magnetization of metals of the iron subgroup was undertaken in [4–6]. Here, even the use of highly sensitive SQUID sensors and Mössbauer spectroscopy did not allow obtaining an unambiguous answer about the possibility of such an influence. Apparently, the reason for this was the too small thickness of the studied layers (2–3 nm). In works [1–3], a significant role of the layer thickness was also noted. The effects of enhancement of magnetization became noticeable when their thickness exceeded 30 nm.

The aim of this work is to study the magnetic interaction of layers in the film structure of Gd_2O_3 /Fe by EPR, as well as to find the possibility of exchange *f-d* interaction between atoms with unfilled *f*- and *d*-electron shells that are part of the contacting layers of Gd_2O_3 and Fe. Of the three metals Fe, Co, Ni, iron was chosen as having the strongest magnetic properties. And Gd_2O_3 is one of the few rare-

earth oxides that give a significant signal for EPR.

EXPERIMENTAL CONDITIONS

The film structure of Gd_2O_3/Fe was formed by successive electron-beam deposition of layers on a sitall substrate under the following conditions: Gd_2O_3 – the partial pressure of oxygen in the working chamber is $p_{O2} = 5 \cdot 10^{-2}$ Pa, the substrate temperature is $T_{sub} = 230$ °C, the layer growth rate is ν = 45 nm/min, Fe – the pressure in the working chamber is $p = 5 \cdot 10^{-3}$ Pa, the substrate temperature is $T_{sub} = 25$ °C, the layer growth rate is ν = 22 nm/min. The thickness of the Gd_2O_3 layer is 68 nm, and the thickness of Fe is 112 nm, that of Gd_2O_3/Fe is 180 nm.

The EPR spectra of the Gd_2O_3 and Fe layers, as well as the Gd_2O_3/Fe structure composed of them, were recorded at room temperature on a computerized Radiopan 2547 SE/X spectrometer equipped with an RCX660A resonator, an ER 2505 electromagnet, and an MS212 high-frequency irradiation of ν = 9.3 GHz.

RESULTS AND DISCUSSION

The EPR spectrum is a graph of the dependence of the derivative of the signal intensity J on the magnetic field H - dJ/dH (H). Fig. 1 shows an example of recording EPR spectra as a function of the power of the high-frequency signal **I** for the Gd_2O_3/Fe structure.

The set of high-resolution spectra obtained was processed using the OriginPro and MatLab software package, integrated and approximated by the Lorentz model in Fig. 2.

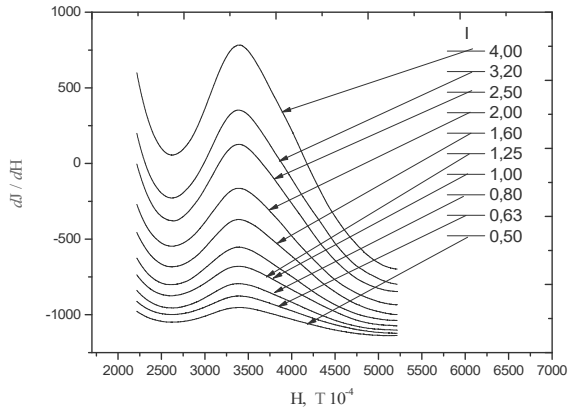

Fig. 1. EPR spectra for the Gd_2O_3/Fe structure dependent on the power **I** of the high-frequency signal

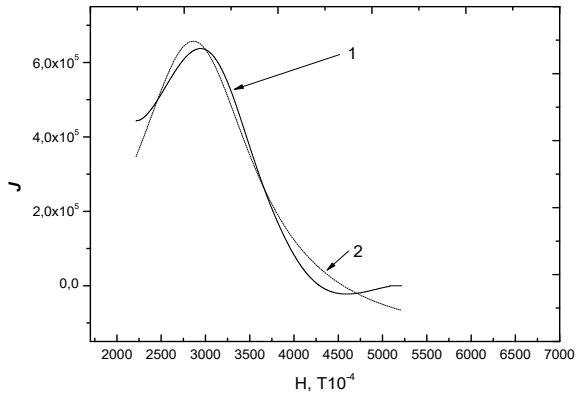

Fig. 2. An example of integration – *J* and approximation – *2* of the EPR spectra of the Gd_2O_3/Fe structure presented in Fig. 1 for **I** = 4.0 rel. units

The quality of measurements, processing procedures and approximation by the theoretical model are confirmed by the values of the corrected R-Square (R^2) or the coefficient of determination [7]. This indicator is used to explain the degree of influence of input variables on changes in output variables (predicted variables). It ranges from 0 to 1. If the R^2 is 0.9, this means that 90 % of the variation in the output variables is due to the input variables. A higher R-Square value indicates a better fit to the model. The value of the R^2 for all samples on average was 0.98 (see Fig. 3 *a* and Table), which indicates good agreement between the theoretical Lorentz model and experiment. The parameters were processed for each spectrum of the studied samples. The deviations of the line width W at half-height did not exceed 4 % (Fig. 3 *b*). The change in the magnetic field of the resonance H_R (I) for all samples did not exceed 4 %.

From the EPR spectra of the films (Fig. 4), the parameter of the exchange f - d interaction P (1) [8] can be estimated and the g-factor (2) can be calculated.

$$P \sim \mu W H_R \,, \tag{1}$$

$$h\nu = g\mu H_R \tag{2}$$

where μ is Bohr's magneton, H_R is the resonance magnetic field, W is the width of the EPR spectrum, ν is the frequency of irradiation, h is Planck's constant.

Estimation of P does not take into account the distance between the interacting magnetic moments, as well as other mechanisms of spin-spin interaction and spin-lattice relaxation. A

more rigorous analysis should also take into account the specific distribution of spins over the lattice sites. However, formulas (1) and (2) make it possible to compare, in order of magnitude, the parameters of the exchange interaction and the g-factor (Table).

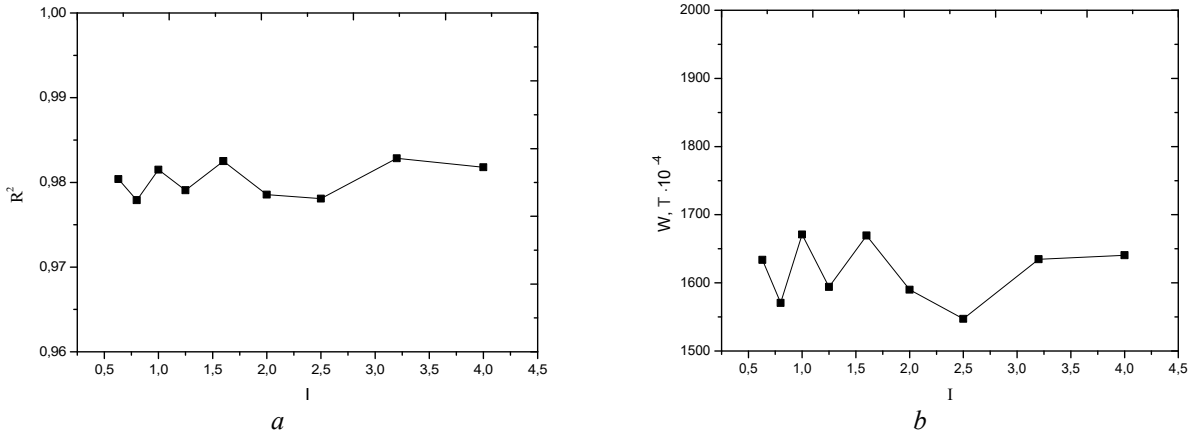

Fig. 3. Dependence of the EPR line parameters on the power of the high-frequency signal I for the Gd_2O_3/Fe structure. *a* –R^2 or coefficient of determination; *b* – W – line width at half height

Table. Parameters of the investigated objects determined from the EPR spectra

Parameter	Gd_2O_3	Fe	structure Gd_2O_3/Fe
Resonance magnetic field H_R, T 10^{-4}	1604	1986	2862
EPR line width W, T 10^{-4}	296	496	1637
R^2 or coefficient of determination	0.97	0.98	0.98
Parameter of exchange interaction P, rel. units	474	985	4685
g-factor	4.4	3.5	2.4

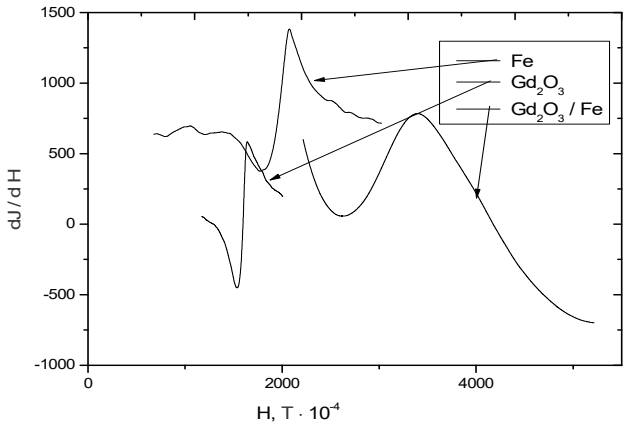

Fig. 4. EPR spectra of Fe, Gd_2O_3 and Gd_2O_3/Fe films

The Lande factor or g-factor determines the relative magnitude of the magnetomechanical ratio, as well as the scale of the splitting of energy levels in a magnetic field. In many-electron atoms, the interaction of spin and mechanical moments becomes important, which is considered as a perturbation. The Lande factor reflects the totality of many properties of the material under study. Thus, in $Pb_{1-x}Sn_xTe$ solid solutions, a change in the composition x leads to variations in the band gap, effective mass of current carriers, the exchange interaction

integral, *etc.* [9, 10]. However, the most impressive are the changes in the value of the g-factor, which reaches values of the order of 40 in the region of the composition close to the inversion of the zones. Significant changes in the g-factor and the exchange interaction parameter P for the Gd_2O_3/Fe structure (see Table 1) indicate the probability of a strong exchange *f* - *d* interaction.

CONCLUSIONS

It has been found that the presence of an iron layer in the Gd_2O_3/Fe film structure has a significant effect on the EPR spectrum of the Gd_2O_3 REM oxide layer. The most probable reason for the change in the spectrum is the exchange *f* - *d* interaction between atoms with unfilled *f* - and *d*-shells that are parts of the contacting layers.

Дослідження методом ЕПР міжшарової взаємодії в наноструктурі Gd_2O_3/Fe

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У цій роботі розглянуто нанорозмірні структури, що складаються з контактуючих шарів металу підгрупи заліза і оксиду рідкісноземельного металу (РЗМ). Такі наноструктури мають цікаву особливість, яка полягає в тому, що в результаті контакту даних шарів, спостерігається посилення гальваномагнітних, магнітооптичних і кінетичних властивостей феромагнітних металів. Імовірно, посилення обумовлено підвищенням намагніченості цих металів, що викликається обмінною f - d взаємодією між незаповненими f - і d-електронними оболонками атомів, що входять до складу контактуючих шарів. Метою цієї роботи є встановлення методом ЕПР можливості такої f - d обмінної взаємодії.

Для складання досліджуваної наноструктури був використаний Fe, який має в своїй підгрупі найбільш сильні магнітні властивості. Як оксид РЗМ був використаний Gd_2O_3 як один з небагатьох оксидів, що дають значний сигнал в області ЕПР. Наноструктура Gd_2O_3/Fe створювалася послідовним електронно-променевим осадженням на ситалову підкладку шарів Gd_2O_3 і Fe. Товщина шару Gd_2O_3 дорівнювала 68 нм, Fe – 112 нм, Gd_2O_3/Fe – 180 нм.

Спектри ЕПР знімалися при кімнатній температурі на комп'ютеризованому спектрометрі Radiopan 2547 SE/X на частоті 9.3 Ггц. Набір отриманих спектрів оброблявся за допомогою програм OriginPro і MatLab, що підтвердило їхню відповідність моделі Лоренца.

З експериментально отриманої ширини лінії ЕПР визначено параметр обмінної f - d взаємодії за умови ряду припущень. Знайдена також величина g-фактора. Порівняння параметрів спектрів ЕПР окремих шарів Gd_2O_3 і Fe з спектрами складеної з них наноструктури Gd_2O_3/Fe, в тому числі величини g-фактора і параметра обмінної взаємодії, дозволяє зробити висновок про те, що присутність шару заліза значно впливає на спектр ЕПР шару оксиду РЗМ Gd_2O_3. Параметр обмінної взаємодії зростає з 985 до 4685 (відн. од.), g-фактор зменшується від 3.5 до 2.4. Найбільш імовірною причиною зміни спектра є обмінна f - d взаємодія між атомами з незаповненими f- і d-електронними оболонками, що входять до складу контактуючих шарів.

Ключові слова: *наноструктура, шар, залізо, оксид гадолінію, ЕПР-спектри, f - d взаємодія*

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