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The Features of TKE and FMR in Nanocomposite-Semiconductor Multilayers

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Abstract. Magnetic and magneto-optical properties of multilayers based on the $(Co_{45}Fe_{45}Zr_{10})_Z(Al_2O_3)_{100-Z}$ composite and amorphous hydrogenated silicon with various thicknesses both of magnetic and semiconductor layers have been investigated. The nonlinear dependence of magnetic and MO characteristics of the nanostructures on the thickness of layers was found. The interface formed on the boundary of two phases (the ferromagnetic granules and the semiconductor ones) strongly influences the magnetic and MO properties of the structures with thin Si layers.

Introduction

The artificial multilayer structures – the multilayer magnetic films of metal-semiconductor (or metal-dielectric) type with layers of nanometer thickness are of great interest both for various technological applications and for fundamental physics. The physical properties of such systems are to a great extent determined by their structure and interface effects, in particular, by the direct contacts between metallic layers as well as diffusion processes on the interfaces of heterogeneous phases that result in formation of the metal-semiconductor compounds. In order to minimize the influence of contacts of adjacent layers on the macroscopic properties of the system and to slow down the formation of compounds on the metal-semiconductor interface it was suggested to use a metal-dielectric composite as a magnetic layer [1].

Here we present the results of investigation of magnetic and magneto-optical (MO) properties of $[(Co_{45}Fe_{45}Zr_{10})_Z(Al_2O_3)_{100-Z}(X)/\alpha\text{-Si}(Y)]_n$ multilayers (ML) in which the composite with granules of $Co_{45}Fe_{45}Zr_{10}$ embedded into the Al_2O_3 matrix was used as a magnetic layer. Samples of four series that differed in thickness of magnetic (X) and non-magnetic (Y) layers as well as X to Y ratio were investigated, which made it possible to vary the relative contributions of the interfaces to the properties of the nanostructures.

Experimental details and results

The samples were manufactured by ion-beam sputtering. The parameters of the studied multilayer nanostructures are shown in the table. The concentration of metal in the composite layers was less than that at which a percolation occurs in the bulk samples of the composite with the same composition. The characteristic granule size at the shown concentrations was 2-3 nm [2].

The series 1 and 2 differed from the series 3 and 4 in smaller thickness of the layers and lesser *X/Y* ratio; in the series 1 and 2 the magnitudes of effective thickness of the composite layers was below the size of the granules or comparable with it.

Series	X [nm]	Y [nm]	X/Y	n
1	1.29–3.96	0.44–2.83	2.9–1.4	36
2	1.30–2.70	0.15–0.98	8.7–2.8	69
3	3.60–7.56	0.27–1.77	13.3–4.3	40
4	3.67–7.56	0.12–0.78	30.6–9.7	35

The multilayer films were investigated by ferromagnetic resonance (FMR) and magneto-optic methods, recording the magnetization curves and the measurement of specific resistance ρ.

The FMR spectra were measured at the frequency f=9.13 GHz for perpendicular ($\alpha = 90^o$), and in-plane ($\alpha = 0^o$) orientation of dc magnetic field. Magnetization curves were obtained with magnetometer for $\alpha = 90^o$. The magnetization magnitude was calculated from magnetic moment on the assumption that thicknesses of the layers are equal to ones preset at fabrication.

The MO properties were measured in the transversal Kerr effect (TKE) geometry in the 0.5-4.3 eV energy range and magnetic field up to 3 кOe.

Figure 1 demonstrates the FMR resonance field H_{rez} for an in-plane magnetization, TKE and specific resistance ρ versus the thickness of Si layer for all the series. It is obvious that introduction of Si considerably affects the magnetic and MO properties of the multilayer nanostructures and this effect is different in the series with thin (1, 2) and thick (3, 4) composite layers. For all series anomalous behavior of the magnetic and magneto-optical properties in the region of small *Y* was observed. Supplement of Si led to an increase in the magnetization and TKE magnitudes and a decrease in H_{rez} (for series 1 $Y < 1.1$ nm; 2 – $Y < 0.5$ nm; 3 – $Y < 0.8$ nm; 4 – $Y < 0.4$ nm).

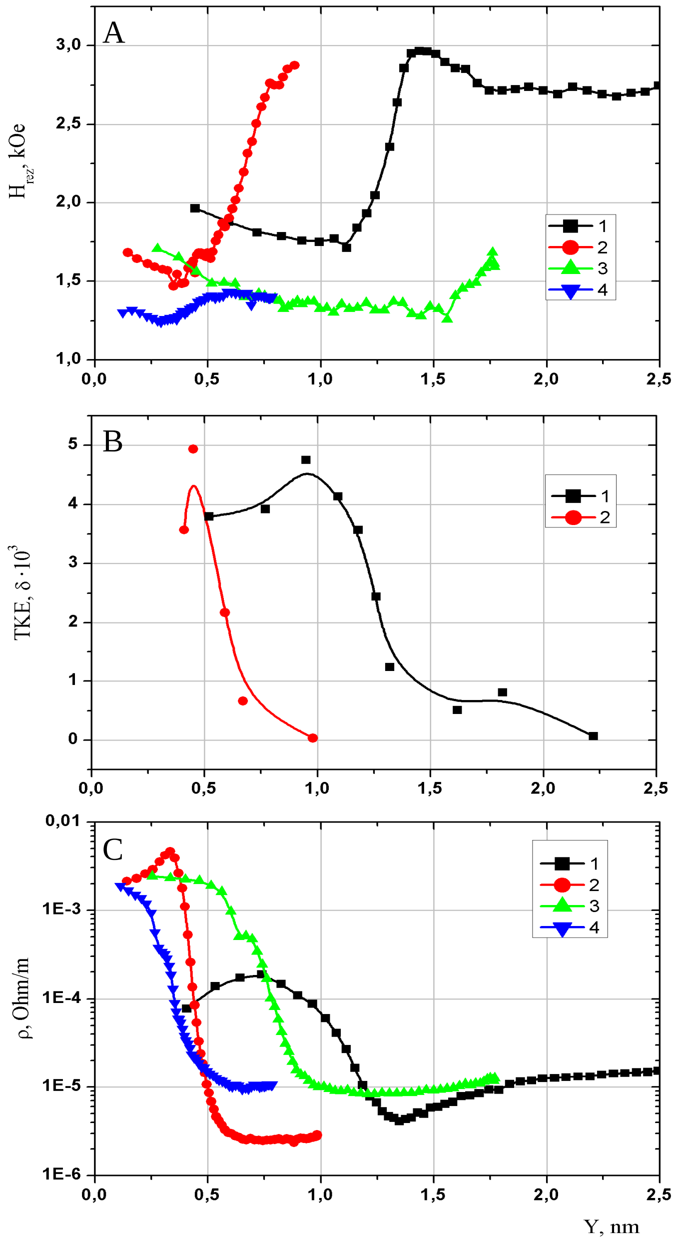

Fig. 1. Dependences of H_{rez} (A), TKE (B) and resistance ρ (C) on the thickness of Si layers.

With further increase of the interlayer thickness the magnetization and TKE drop to zero and H_{rez} increases steeply up to ~3000 Oe in the series 1 and 2, but in the series 3 and 4 both magnetization and H_{rez} virtually do not change with an increase of *Y*. For the samples of the series 3 and 4 that are characterized by the largest thickness of magnetic layer *X*>4 nm and the largest *X/Y* ratio, changing from 5 to 30, the resonance fields (H_{rez} = 1.25 kOe for an in-plane and 9-10 kOe for normal magnetization) are close to that obtained in the composites $[(Co_{45}Fe_{45}Zr_{10})_Z(Al_2O_3)_{100-Z}]$ of micron-range thickness with $Z \approx 40$ at% concentration. The magnetization curves of these samples and the magnetic field dependence of TKE have a shape typical of superferromagnetic interaction, the mean magnetization being close to 500 G.

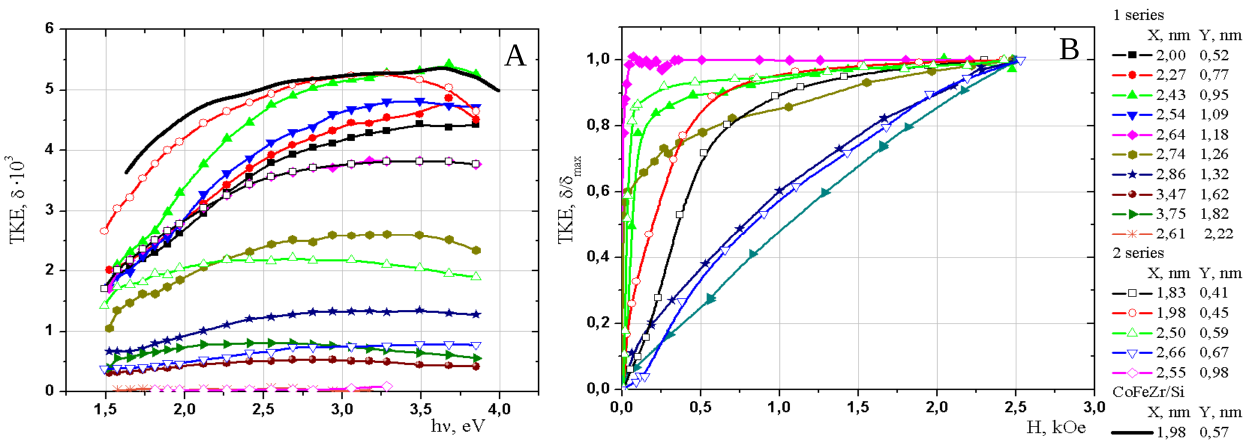

Fig. 2. Spectral (A) and magnetic field dependences of TKE (B) for 1st and 2nd series ML

For the samples with *X* in the range 2.5-3.5 nm (series 1 and 2) the resonance fields are roughly equal to 3 kOe and the mean magnetization was very small (15-35 G). For these samples the shape of magnetization curves and the magnetic field dependence of TKE were typical of superparamagnetic state (Fig. 2b). But for the samples with $X < 2$ nm (series 1 and 2) the magnetization was of the order of 200 G. The shapes of magnetization curves are similar to that obtained on the samples with $X > 4$, and the resonance fields are ≈ 1.5 kOe for an in-plane and 6-8 kOe – for perpendicular magnetization.

The TKE spectra values for the samples of series 1 and 2 are strongly dependent on the semiconductor and composites layer thickness (fig.2a). The shape of TKE spectra of all the series is similar to the spectra of $Co_{45}Fe_{45}Zr_{10}$/Si ML but drastically differ (both in sign and shape) from the spectra of the composite with concentration of metal below the percolation threshold [2-4].

The experimental results obtained show that semiconductor has a considerable influence on the properties of multilayer systems. The influence of Si on magnetic, MO, and resistive properties depends on the thickness of the composite layers. The thicknesses *X* and *Y* where the anomalous changes in the magnetic and magneto-optical properties take place are well correlated with sharp changes in electric properties for all the series.

For the samples of all series the concentration dependences $\rho(Y)$ were found to be similar (Fig. 1c). This similarity suggests that the abrupt decrease of resistance by two orders of magnitude is caused by a common mechanism connected with particularities of the silicon interlayer growth on the nanocomposite surface [1, 4]. Because of the difference in the magnitude of the surface energy γ for the alloy CoFeZr (2.8 J/m^2), and Al_2O_3 (1.4 J/m^2) and Si (1.2 J/m^2) embryos semiconductor film will concentrate on the metal grains. The first atomic layers of semiconductor are likely to form a connection with the metal in the form of a silicide, and then grow on the surface in the form of island structure. The resulting island structure layer of Si will have a negligible impact on the value of resistivity to the thickness that yields a grid of infinite channels of conduction granule-semiconductor-granule but leads to the abrupt decrease in the resistance at the percolation transition. The ρ(Y) dependencies show that the percolation in the ML composite-semiconductor system occurs in the thickness ranges of $Y \approx 0.8$-1.3 nm (1), $Y \approx 0.4$ -0.6 (2), $Y \approx 0.6$-1 (3) and $Y \approx 0.2$ -0.6 (4).

So at the FM granule – semiconductor interface there is a formation of new composite (CoFeZr)-silicides+Si, where a concentration of magnetic phase depends on either shapes and sizes of granules in the magnetic layer or *X/Y* thickness ratio and the rate of silicide formation. Increasing of *Y* in the $Y<Y_{per}$ range will lead to merging the neighboring granules through the Si island within the layer as well as between the adjacent layers, and hence to increasing of magnetic phase in the shapes and magnitudes of ML nanocomposite-silicon and CoFeZr/Si in the range of small Si thicknesses. The maximum of magnetization values and TKE have been observed in the vicinity of a percolation (CoFeZr)- silicides+Si composite. This can be an explanation of magnetization and

TKE growth with Si institution. The similar conclusions can be made from the coincidence of TKE spectra shapes and magnitudes of ML nanocomposite-silicon and CoFeZr/Si in the range of small Si thicknesses. The maximum of magnetization values and TKE have been observed in the vicinity of a percolation threshold for the (CoFeZr) - silicides + Si composite. Such a percolation transition is responsible for increasing of the effective magnetic interaction between FM granules through the semiconductor layer (or silicide) which explains the observed features in the magnetic and magneto-optical properties of samples with the small thickness of Si.

Further growth of *Y* (Si thickness above percolation threshold range) expands the amount of non-magnetic phase from silicides at the layer interfaces and at the same time the connection between of FM granules through Si and silicides becomes extinct. Formed interface blocks subsequent diffusion of FM in Si and a silicon streak appears, that isolates silicides and breaks the magnetic interaction between adjacent layers. Different behavior of magnetization and FMR spectra in the $Y>Y_{per}$ range for the systems with thick and thin magnetic layers can be related to the difference of characteristic granule sizes in the composite layers: for the 1st and 2nd series of samples the size of granules is smaller then in the 3rd and 4th series. This leads to the greater number of contacts FM granule – silicon in the samples with smaller thicknesses *X*. So, the major part of magnetic phase passes into non-magnetic state (silicides) through the interaction with Si. For the samples with thick layers *X* and larger *X/Y* ratio the relative contribution of silicides is smaller and its influence on the total magnetization is small. Therefore, the magnetic properties of samples are determined mainly by the properties of composites.

The magnitudes of *Y* at which the anomalous behavior of magnetic, MO, and electrical properties is observed show the good correlation with each other within each series but are different in each series. This may be caused both by low accuracy in estimation of the thicknesses of thin layers and a strong dependence of the interface properties on the technology-dependent parameters.

Conclusions

Evolution of the granular ferromagnet-semiconductor system reaction on varying the thickness of constituent layers is traced and a nonlinear dependence of magnetic and MO characteristics of the nanostructures on the thickness of composite and semiconductor layers was found. The experimental data demonstrate that the semiconductor exerts a significant influence on the properties of multilayer systems. The effect of Si on magnetic, MO, and resistive properties depends on the composite layer thickness. The thicknesses *X* and *Y* at which the anomalous changes in magnetic and MO properties take place are well correlated with sharp changes in the electric properties for all series, and this is related to the intrinsic features of the process by which the composite ($Co_{45}Fe_{45}Zr_{10}$) is formed on the interface in the (Si+silicides) matrix.

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