Magnetic ordering of Dy in NiFe–Dy bilayer films

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The first results of measurements of the temperature and spectral dependences of the circular magnetic dichroism in NiFe–Dy bilayer films are reported. These results show that even at room temperature Dy in such systems is ordered ferromagnetically to a large depth (~600 Å).
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In the last few years much attention has been devoted to the problems of the magnetic ordering of layered systems, including layers of rare-earth metals (REMs). Many authors note that in very thin layers of REMs spin polarization or magnetic ordering exists as a result of the interaction with layers of transition metals (TMs). In Ref. 1 it is asserted that in Fe/REM multilayer films with layer thicknesses of 40 Å and 10–30 Å respectively, the REM layers are ordered at room temperature either ferromagnetically (Pr, Nd) or antiferromagnetically (Dy, Tb). Similar conjectures were made in Ref. 2 in order to explain the magnetic properties of thin Fe films coated with a 14 Å thick layer of Tb. In Ref. 3 it was observed directly that at room temperature Dy makes an appreciable contribution to the total magnetization in Fe/Dy multilayers with a 12 Å thick Dy layer.

While studying the temperature and spectral dependences of the circular magnetic dichroism (CMD) in bilayer NiFe–Dy films, we discovered that right up to Dy layer thicknesses ~600 Å the contribution of Dy to the CMD of a bilayer film at room temperature corresponds in magnitude to the CMD in a single-layer Dy film of the same thickness but measured at a temperature below the temperature of the transition of Dy into a ferromagnetic state ($T_c = 85$ K).

We report in the present letter the results of an investigation of the CMD of NiFe–Dy bilayer films as a function of the thickness of the Dy layers.

The samples were prepared by thermal deposition in an ultrahigh vacuum; vacuum-melted $Ni_{80}Fe_{20}$ and DiM1-grade Dy were deposited at a rate of 0.05 Å/s and 2 Å/s, respectively, on a glass substrate (optical quality, polished, and 0.8 mm thick) at temperature 250 °C. Three samples were obtained in a single cycle by means of special shutters: Dy, NiFe, and Dy–NiFe, or NiFe–Dy. The layer thicknesses were ~50 Å for NiFe and 50 to 900 Å for Dy.

To measure the CMD the polarization state of the light was modulated by the method described in Ref. 4 in the spectral interval from 350 to 650 nm, in the temperature

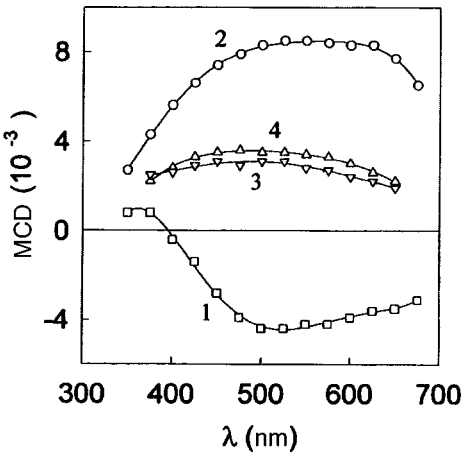

FIG. 1. Dispersion curves of CMD for the samples: *1*) Dy, $d=805$ Å, $T=80$ K; *2*) NiFe, $d=53$ Å, $T=300$ K; *3,4*) NiFe–Dy, $d_{\mathrm{NiFe}}=53$ Å, $d_{\mathrm{Dy}}=805$ Å, $t=80$ K and 300 K, respectively, in a field $H=3.5$ kOe.

interval from 300 to 80 K, and in a 3.5 kOe magnetic field applied in a direction perpendicular to the plane of the samples. Cooling was done in a flow-through cryostat in a nitrogen stream and the temperature was regulated with a PIT-3 precision isodromic temperature regulator.

Figure 1 show the spectral dependences of the CMD for single-layer Dy and NiFe films (curves *1* and *2*), obtained at $T=80$ K and $T=300$ K, respectively. We note that the CMD of these materials has never been measured before. One can see that for wavelengths $\lambda>400$ nm the CMD in Dy and NiFe has different signs and the curves pass through a maximum at ~ 525 nm for Dy and ~ 550 nm for NiFe. The CMD of Dy passes through zero at $\lambda\sim 400$ nm and then has the same sign as CMD in NiFe. As temperature increases, the CMD of Dy decreases for all wavelengths similarly to curve *1* in Fig. 2 for $\lambda=525$ nm. Curves *3* and *4* in Fig. 1 correspond to CMD in NiFe–Dy bilayer films at $T=80$ K and $T=300$ K, respectively. One can see that the dysprosium spectra at room temperature and at a temperature below T_c are virtually identical, and the magnitude of the CMD of the bilayer film is close to the sum of the CMD in unilayer Dy and NiFe films.

Figure 2 shows the temperature dependences of the CMD for NiFe, Dy, and NiFe–Dy bilayer films. The CMD of Dy (curve *1*) varies very strongly with temperature. Here one can see that the temperature variation of the CMD has a somewhat smoother form than the published temperature dependence of the magnetization of bulk Dy samples (see, for example, Ref. 5). This is apparently explained by the difference in the properties of a polycrystalline film and bulk Dy single crystals. As expected, the CMD in NiFe (curve *2*) remains approximately constant in this interval. Curve *3* shows the temperature variation of the CMD in two isolated Dy and NiFe films (~ 600 Å and ~ 50 Å thick, respectively) combined together. One can see that the CMD in this case depends on the temperature, while the CMD (curve *4*) for a bilayer film with Dy thickness ~ 600 Å and NiFe thickness ~ 50 Å remains constant as temperature varies. The 600 Å thick Dy layer (curve *4*) at room temperature makes a contribution to the CMD that is approxi-

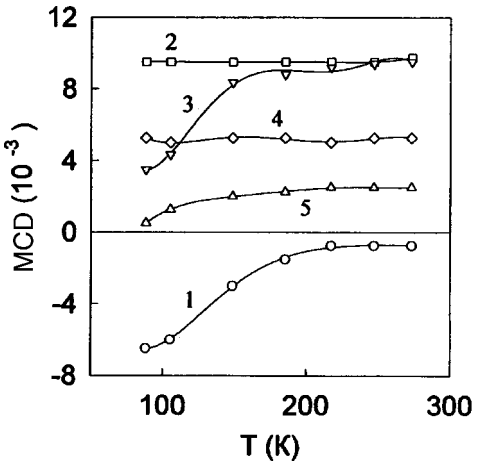

FIG. 2. Temperature dependences of CMD for the samples: *1*) Dy, $d=625$ Å; *2*) NiFe, $d=67$ Å; *3*) NiFe + Dy, $d_{\mathrm{NiFe}}=67$ Å, $d_{\mathrm{Dy}}=625$ Å; *4*) NiFe–Dy, $d_{\mathrm{NiFe}}=67$ Å, $d_{\mathrm{Dy}}=625$ Å; *5*) NiFe–Dy, $d_{\mathrm{NiFe}}=45$ Å, $d_{\mathrm{Dy}}=960$ Å; wavelength — 525 nm.

mately equal to the CMD of Dy at $T<T_c$. For the case when the Dy thickness in a bilayer film equals 900 Å, the picture is more complicated (curve *5*). The contribution of Dy to the CMD at high temperatures is higher than in the first case, and it increases with decreasing temperature. Comparing the curves *2*, *4*, and *5*, the Dy layer making a temperature-independent contribution to the CMD can be estimated to be roughly ~ 700 Å thick.

The behavior of the Dy–NiFe samples is similar to that described above.

One can offer different explanations of the observed spectral and temperature dependences of the CMD in bilayer films: formation of a new magnetically ordered compound as a result of atomic diffusion, ordering of Dy under the influence of NiFe, and an unusually strong effect of the interface. The effect of the interface can be immediately excluded on the basis of the temperature dependences presented. The formation of a new compound over the entire depth of the Dy layer is also unlikely — it is difficult to imagine a mechanism of uniform diffusion of NiFe to a depth exceeding 600 Å with a ~ 50 Å thick NiFe layer. Nevertheless, oxidation of the Dy in bilayer films to Dy_2O_3, which is not magnetooptically active, was performed to check the likelihood of this mechanism. Besides NiFe–Dy, Dy and NiFe films were also subjected to heat treatment at the same time. Heat treatment had virtually no effect on the CMD in the NiFe film, while the CMD in Dy decreased to the noise level (Dy is a chemically much more active metal than NiFe). The magnitude of the CMD of the bilayer film was restored to values characteristic for NiFe. If the small disordering at the interface is taken into account and estimated to be approximately 15 Å, then the curves for NiFe and oxidized NiFe–Dy become completely identical. From this it may be concluded that in a bilayer film substantial quantities of material are not transferred from the TM layer into the REM layer.

The ordering of the Dy layer could also be due to spin polarization of the conduction electrons,[6] which plays an important role, for example, in the formation of the magnetoresistance at magnetic metal–insulator–magnetic metal junctions.[7] However, atomic

microdiffusion cannot be rule out. It has virtually no effect on the properties of a TM layer, while in a REM layer it produces a low concentration of Fe and Ni atoms, which can influence the magnetic properties of this layer. For example, in Ref. 8 it was shown that small admixtures (0.03–0.06%) of iron change the paramagnetic Curie point of scandium by hundreds of degrees. Experiments designed to clarify the mechanism of Dy ordering are in progress.

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[1]K. Mibu, N. Hosoito, and T. Shinijo, J. Magn. Magn. Mater. **126**, 343 (1993).
[2]B. Scholz, R. A. Braud, and W. Kenne, Phys. Rev. **50**, 2537 (1994).
[3]K. Yoden, N. Hosoito, K. Kawaguchi *et al.*, Jpn. J. Appl. Phys. **27**, 1680 (1988).
[4]S. N. Jasperson and S. E. Schnatterly, Rev. Sci. Instrum. **40**, 6761 (1969).
[5]K. P. Belov, *Rare Earth Magnets and Their Applications* [in Russian], Nauka, Moscow, 1980.
[6]M. Julliere, Phys. Lett. A **54**, 225 (1975).
[7]T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **151**, 403 (1995).
[8]V. I. Chernikov, I. Pop, and O. P. Naumkin, *Problems of the Theory and Applications of the Rare Earth Metals* [in Russian], Nauka, Moscow, 1964.

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