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Room Temperature Ferromagnetism of a Double-Layer $Dy_{1-x}Ni_x$/Ni Structure: in situ Magneto-Optical Measurements

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The double-layer $Dy_{1-x}Ni_x$/Ni structures have been studied in situ in an ultrahigh-vacuum chamber by the original technique using the surface meridional Kerr effect directly in the course of deposition. It has been shown that a layer of $Dy_{1-x}Ni_x$ alloy is ferromagnetically ordered at room temperature.

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1. Dysprosium has long been attracting the attention of researchers because of its exceedingly high magnetic moment and the possibility of its applied use in the nanostructures in combination with other metals, semiconductors, or dielectrics. However, because of the lack of a magnetic order in metallic dysprosium at room temperature, it has to be cooled to a temperature lower than 100 K, which restricts the possibility for its use. Recently [1], dysprosium was found to be magnetically ordered at room temperature in the double-layer $Dy_{1-x}Ni_x$/Ni films with $x \approx 0.05$. In [1], the magnetic properties of the $Dy_{1-x}Ni_x$/Ni structures were ex situ measured in air. Since Dy is highly prone to oxidation, the prepared layer was rather thick (more than 60 nm), and at least half of it was oxidized.

In bulky Dy samples, a spiral antiferromagnetic phase is observed at $T_c < T < T_N$ ($T_c = 85$ K, $T_N = 175$ K), and the ferromagnetic phase occurs at $T < T_c$. The magneto-optical Kerr signal is a characteristic of the ferromagnetic phase: it is proportional to the crystal magnetization and is absent in the antiferromagnetic phase. The ferromagnetic phase in the $Dy_{1-x}Ni_x$/Ni films was ex situ observed by measuring the magnetic hysteresis loops using the meridional Kerr effect [1] and polar Kerr effect [2] at room temperature.

In this work, we report the first results of the in situ measurements of magnetic properties by the SMOKE (surface magneto-optical Kerr effect) method. This method allows one to study thin layers without oxides and to demonstrate the presence of a magnetic order in the $Dy_{1-x}Ni_x$ layer at room temperature.

2. Films were prepared by the thermal vacuum evaporation on an updated Angara molecular-beam epitaxy apparatus [3]. The evaporation was carried out on glass substrates at a temperature of 500 K. The initial vacuum comprised 10^{-6} Pa and the working vacuum was 10^{-5} Pa. The film growth rates and the film thicknesses were in situ determined using a laser ellipsometer. The rates were found to be equal to 0.003 nm/s for nickel and 0.126 nm/s for dysprosium. The meridional Kerr effect was used as a tool for studying the film magnetic state. The beam from a helium:neon laser ($\lambda = 630$ nm) was linearly polarized by a Glan prism and fed through a special window into a chamber, where it was incident at an angle of 70° on the substrate coated with the evaporated film. The reflected beam was analyzed using a static photometric ellipsometer [4]. A magnetic field uniformly rotating in the sample plane was produced by a permanent magnet. The field strength at the magnet surface was 42 mT. The signal from the ellipsometer was recorded as a function of the angle between the direction of the magnetic field and the arbitrary direction in the sample plane.

3. We first examined the SMOKE signal from the Ni layer prior to applying the $Dy_{1-x}Ni_x$ (hereafter DyNi) alloy. A change in the rotation angle of the polarization plane (Kerr rotation) upon the magnetic rotation about the sample (8-nm Ni film) at $T = 300$ K is shown in Fig. 1. The initial magnetic field makes an angle of 45° with the plane of light incidence. The experimental data are presented as a function of the angle between the rotating magnetic field and its initial direction. Inasmuch as the turn of the polarization plane is proportional to the projection of magnetization onto the plane of light incidence, it must be maximal when the magnetization lies in the incidence plane and zero in the orthogonal orientation. The experimental points in Fig. 1 correspond to just this situation. These data can be fitted by a cosine curve (dashed curve in Fig. 1). It

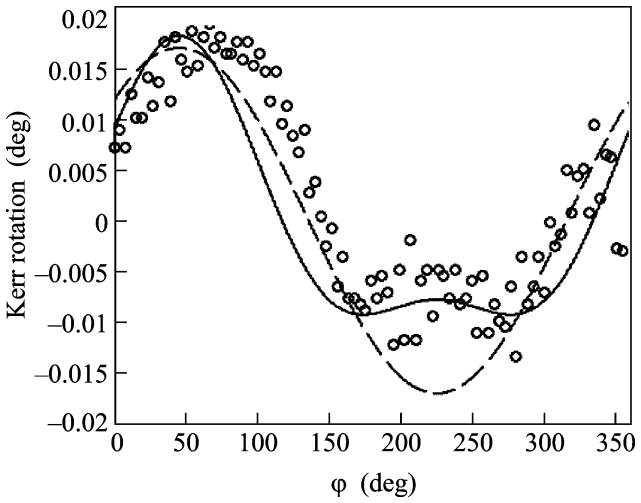

Fig. 1. Kerr signal (rotation of the polarization plane) versus the angle of the magnetic-field rotation in the 8-nm-thick Ni film.

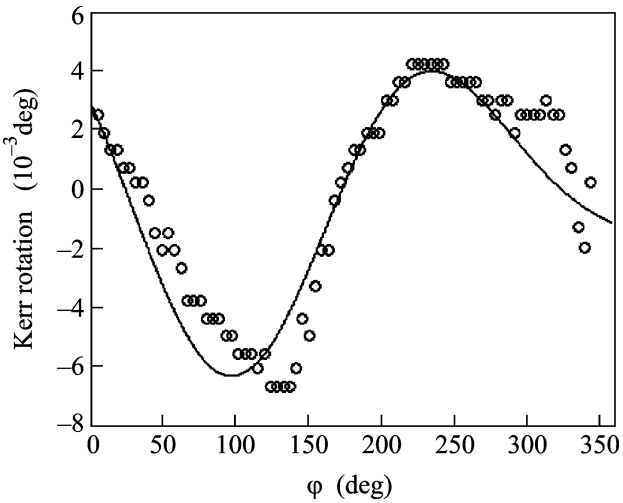

Fig. 2. Kerr effect in the double-layer Ni(8 nm)/DyNi(5 nm) structure.

turned out that the maximal value of cos(φ) corresponds approximately to a magnetic field lying in the incidence plane, which is to say that the magnetic moment follows the field and the film is magnetically isotropic. However, the sum of two cosine curves with different periods and amplitudes (solid curve in Fig. 1)

$$\alpha = A_1\cos(\varphi + \varphi_1) + A_2\cos 2(\varphi + \varphi_2) \qquad (1)$$

fits better to the experimental points. The approximation parameters of the curves are given in the table. One can see that the amplitude of cos(2φ) is approximately half as large as the amplitude of cos(φ). One can thus assume the presence of a weak biaxial anisotropy in the film.

4. In Fig. 2, the Kerr signal is obtained for the same geometry as in Fig. 1. The light is reflected from the DyNi layer of the double-layer Ni(8 nm)/DyNi(5 nm) structure. A change in the signal sign is noteworthy, because it can be due to the contribution from the DyNi film. Such a change signifies that the sign of the meridional Kerr signal in Dy is opposite to the sign in Ni. Therefore, one can assert that the major portion of the signal comes from the DyNi alloy and, hence, that this layer is magnetically ordered. One can see that the maximal signal amplitude does not correspond to the orientation of the magnetic vector in the incidence plane; i.e., the magnetic moment of the DyNi layer lags behind the magnetic field, evidencing the magnetic anisotropy of the layer. The experimental data are satisfactorily described by the relationship $\alpha = \frac{1}{2}\alpha_{Ni} + \alpha_{DyNi}$, where α_{Ni} and α_{DyNi} are obtained according to Eq. (1) and the table. The term with α_{Ni} is a contribution from the underlying Ni layer. This contribution appears because the thin DyNi layer only slightly absorbs light (term with α_{DyNi}). The term A2 in the table indicates that the biaxial anisotropy occurs both in the DyNi alloy and in the Ni layer, but its contribution in the case of a pure Ni film is considerably greater. This can likely be caused by the scatter in the angle of the molecular-beam incidence on the substrate.

Parameters of Eq. (1) approximating the experimental data for a Ni film (8-nm thick) and two DyNi alloy films (5-nm and 20-nm thick)

	φ_1	A_1	φ_2	A_2
α_{Ni}	−0.8	1	0.8	0.4
α_{DyNi5}	1.5	1	0	0
α_{DyNi20}	2.1	0.9	1	−0.4

The results of measuring the Kerr rotation in the Ni(8 nm)/DyNi(20 nm) sample are presented in Fig. 3. The signal sign is the same as in the preceding case, and the magnetic moment lags behind the field as before. The difference between the maximal and minimal values increases by a factor of 1.5. By using Eq. (1) and the data in the table, one can describe the experimental curve in Fig. 3 by the sum of two cosine curves, similar to the DyNi contribution in the preceding case. Therefore, the contribution from the Ni underlayer becomes negligible in the system with the DyNi thickness d = 20 nm, so that only the DyNi magnetization is observed at T = 300 K.

5. The data obtained in this work testify that nickel-doped Dy with the nickel concentration higher than its threshold value $x \approx 0.05$ is magnetically ordered after preparation in a vacuum in contact with a homogeneous Ni layer. The magnetic order arises if the Dy layer contacts a magnetically ordered Ni layer and includes Ni atoms. Measurements made for the DyNi samples on the glass substrate or for a double-layer Dy/Ni structure without Ni as an alloy component show that Dy is mag-

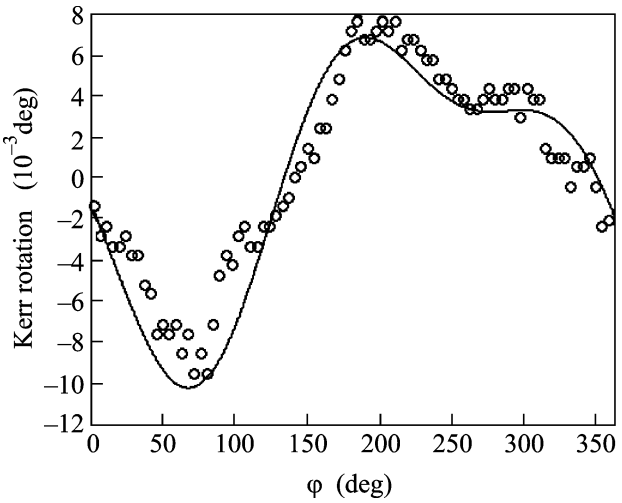

Fig. 3. Kerr effect in the double-layer Ni(8 nm)/DyNi(20 nm) structure.

netically ordered at $T \approx 100$ K [1]. Our studies on the polar Kerr effect [2] show that the $Dy_{1-x}Ni_x$/Ni structure does not attain saturation at 14 kOe. This implies that the saturation magnetization $M_s > 1100$ G. For comparison, at $T = 0$ K, $M_s = 3000$ G in a bulky Dy crystal, $M_s = 1720$ G in iron, and $M_s = 560$ G in nickel.

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