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Interface Effect on the Magnetic Properties of Ni–Ge Bilayer Films

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Magnetic and magneto-optical properties of the Ni–Ge bilayer films are studied. The unusual temperature behavior of the magnetization curves is revealed: the hysteresis loops at room temperature have a near-rectangular shape; when the films are cooled down to 4.2 K, the coercive force increases by more than an order of magnitude and the asymmetry and displacement of the loop along the field axis are observed. These effects are stronger in thinner Ni layers. The observed features are attributed to the effect of the interlayer between the Ni and Ge layers, which has a complex magnetic structure.

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INTRODUCTION

The film structures comprised of the layers of a 3*d* ferromagnetic metal and a semiconductor attracted particular interest of the researchers and developers of technologies and devices. The Si-based structures are the focus of attention, while a few works deal with the Ge–3*d*-metal films which may manifest new unexpected properties, in particular, due to high rates of the mutual diffusion of these materials [1]. The authors of [2] demonstrated a considerable difference in the magnetic anisotropy character in the Fe/Si and Fe/Ge films. The unusual temperature behavior of magnetization was revealed in the Co/Ge/Co films [3, 4]: the resultant magnetization in the magnetic fields of about 50–200 Oe decreased to zero as the temperature decreased, while the temperature behavior of the magnetization in the fields of about 800 Oe corresponded to that in the homogeneous Co films on glass substrates. This behavior was explained in [3, 4] by the effect of Ge on the Co layer structure.

In this work, the magnetic and magneto-optical properties of the Ni–Ge bilayer films are experimentally investigated as functions of the thickness of the Ni layer.

EXPERIMENTAL PROCEDURE

The Ni–Ge films were prepared by the ion-plasma sputtering at a base pressure of 10^{-6} Torr in Ar. The glass substrate temperature during the sputtering process was 373 K. Three samples were prepared as follows: the 13-nm-thick Ge layer, and the Ni layers were 20, 14, and 10.6 nm in thickness in samples 2, 3, and 4, respectively. For comparison, the 14-nm-thick Ni film was prepared under the same conditions (sample 1). The magnetization was measured on a SQUID magnetometer at 4.2–300 K in the magnetic field H up to 1 kOe directed in the film plane. The field and spectral dependences of the Faraday and Kerr magneto-optical effects were measured in different geometries at room temperature. The Faraday effect was measured in the field up to 5 kOe normal to the film surface and parallel to the light beam in the spectral range 500–1100 nm. The longitudinal Kerr effect was measured in the field up to 200 Oe directed in the sample plane, at a wavelength of 630 nm. The light beam is directed at an angle of 30° to the sample surface.

EXPERIMENTAL RESULTS

Figure 1 presents the spectra of the Faraday effect for the samples investigated. It is seen that the Faraday effect in the bilayer samples is considerably weaker than that in the Ni film, and it is not proportional to the Ni layer thickness. The Faraday effects for samples 2 and 3 are close in magnitude, while the spectra of the Faraday effect are similar in shape to the spectrum for the Ni single-layer films. The Faraday effect for sample 4 is so weak that it is difficult to describe its spectrum.

The field dependences of the Faraday effect (Fig. 2) are typical of the in-plane anisotropic films. The saturation field H_s for the Ni single-layer film is about 3.5 kOe that corresponds to the saturation magnetization M_s ~

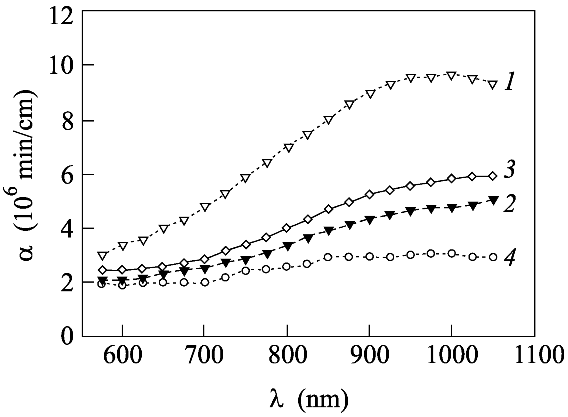

Fig. 1. Spectra of the Faraday effect in the samples (*1*) Ni (14 nm), (*2*) NiGe (20 nm/12.7 nm), (*3*) NiGe (14 nm/13.5 nm), and (*4*) NiGe (10.6 nm/12.8 nm) at H = 2.6 kOe and T = 300 K.

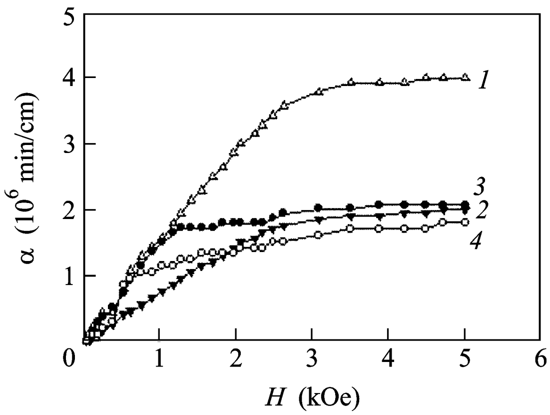

Fig. 2. Field dependences of the Faraday effect in the samples (*1*) Ni (14 nm), (*2*) NiGe (20 nm/12.7 nm), (*3*) NiGe (14 nm/13.5 nm), and (*4*) NiGe (10.6 nm/12.8 nm); the Faraday effect magnitude is given in units of the Ni layer thickness, λ = 800 nm, T = 300 K.

300 G, which is considerably lower than M_s of the Ni bulk single crystal at room temperature (~480 G) [5]. Therefore, even a Ni single-layer film prepared by the technology used has the magnetic properties differing from those of the bulk single crystal. The field H_s in the bilayer samples decreases with the thickness of the Ni layer. However, these data do not yet indicate that the magnetization of the Ni layer is low. The field dependences observed can also be determined by the features of the film anisotropy and the possible effect of the interlayer between Ni and Ge.

Figure 3 presents the magnetization curves in the plane of sample 2 at different temperatures. They are the near-rectangular hysteresis loops, as the coercive force H_C increases with a decrease in the temperature (see Figs. 3c and 3d). At room temperature, the hysteresis loop (Fig. 3a) coincides with the field dependence of the Kerr effect (Fig. 3b). This confirms the linear dependence of the magneto-optical effect on the magnetization in the case under consideration. As the Ni layer becomes thinner, the loop shape somewhat deviates from the rectangle. As the temperature is further decreased, the hysteresis loop becomes asymmetric and less rectangular and H_C reaches a magnitude of about 300 Oe at 4.2 K (Fig. 4, curve *1*); i.e., it becomes an order of magnitude higher than H_C at room temperature. Moreover, the hysteresis loop at low temperatures is shifted along the field axis that is typical of the systems with an exchange unidirectional anisotropy [6, 7]. Similar modifications of the hysteresis loop also occur for sample 3 (with a thinner Ni layer), the only difference is that the loop shape is less rectangular even at room temperature. Sample 4 at 4.2 K in the magnetic field used is not remagnetized at all: the magnetization is a linear function of the field and passes through zero at ~100 Oe; i.e., in this case, the magnetization curve is also shifted along the field axis. The ratios of the magnetizations in the sample planes agree closely with the ratios of the Faraday effect magnitudes of these samples under the magnetization normal to the plane.

DISCUSSION

Both effects—the increase in the coercive force and the appearance of the asymmetry in the hysteresis loop—are observed in the film structures comprised of the ferromagnetic (FM) and antiferromagnetic (AFM) layers or of the soft and hard FM layers and are explained by the exchange interaction of these layers or the so-called exchange anisotropy [6, 7]. However, as a rule, the former effect occurs under weak exchange anisotropy in the FM–AFM or FM–FM layers and the latter effect occurs under strong anisotropy in the FM–AFM layers. A feature of the films under consideration is the appearance of both effects in one sample. Thus, we may suggest that an interface of variable chemical composition conditioned by the mutual diffusion of Ni into Ge is formed in the bilayer films. On the Ni layer side, the Ni enrichment takes place and a compound that is similar to Ni_3Ge and has the ferromagnetic order is formed [8, 9]. Therefore, a pair of Ni and Ni_3Ge layers in the interface can be considered as a structure comprised of the soft (Ni) and hard (Ni_3Ge) magnetic layers. Actually, it is shown in [10] that the magnetization of Ni_3Ge in fields up to 400 Oe increases almost linearly with the magnetic field (see Fig. 5 in [10]). Its magnitude in a field of 400 Oe is far from saturation. Meanwhile, for example, the coercive force in sample 2 at room temperature is only 10 Oe. The authors of [11] obtained the following expression for the coercive force of the bilayer (soft FM–hard FM) film:

$$\mathbf{H}_C = \mathbf{H}_0\mathbf{t}_h/(\mathbf{t}_h + \mathbf{A}\mathbf{t}_s). \quad (1)$$

Here, H_0 is the coercive force of the hard-FM single-layer film of thickness t_h, t_s is the thickness of the soft-FM layer, and $A = M_s/M_h$, where M_s and M_h are the

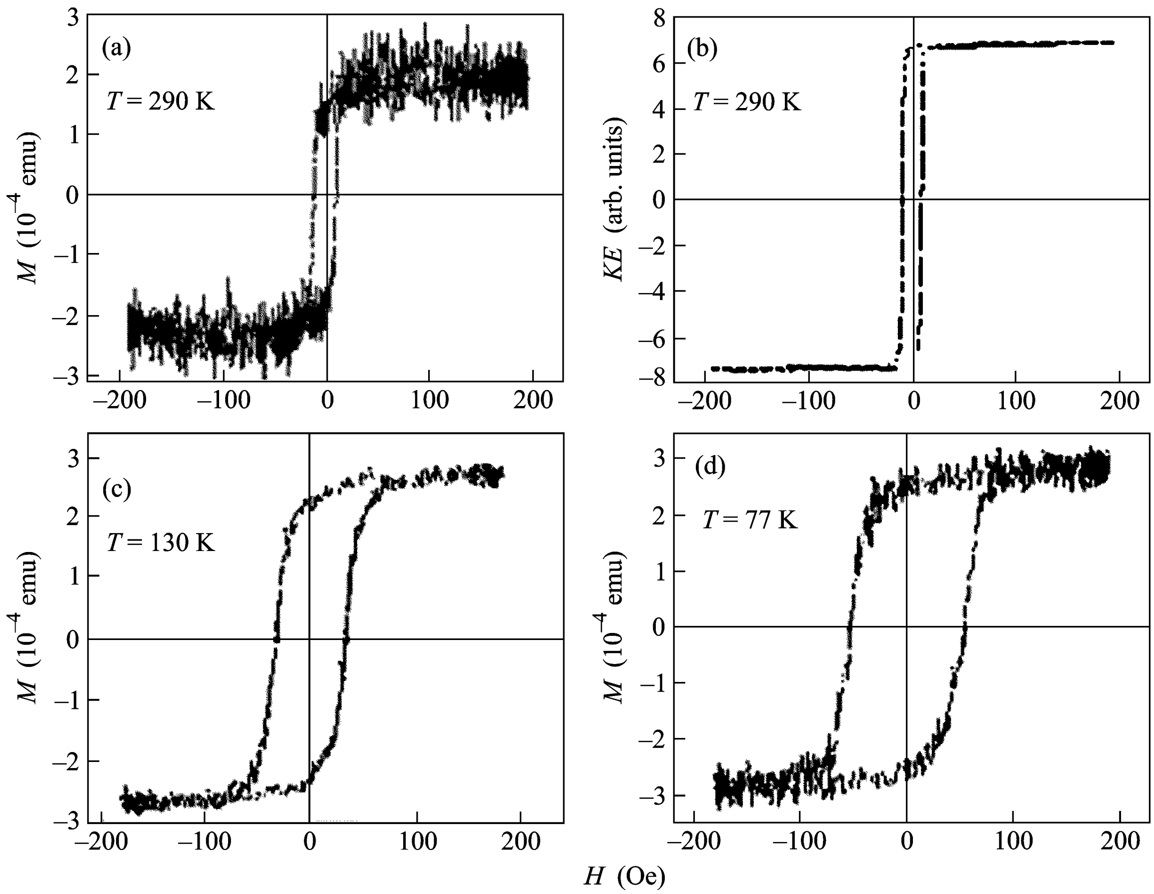

Fig. 3. (a, c, d) Magnetization hysteresis loops of the NiGe (20 nm/12.7 nm) film measured on a vibration magnetometer at different temperatures and (b) the field dependence of the Kerr effect at $T = 290$ K.

magnetizations of the soft and hard magnetic layers, respectively. In our case, where the thin interface layer serves as the hard magnetic layer, it may be assumed that $t_h \ll t_s$. Then, relation (1) implies that H_C should be proportional to M_h. Figure 5 presents (curve *2*) the magnetization of Ni_3Ge plotted by the data of [10] and (curve *1*) the coercive force of sample 2 as functions of the temperature. The correlation of curves *1* and *2* indi-

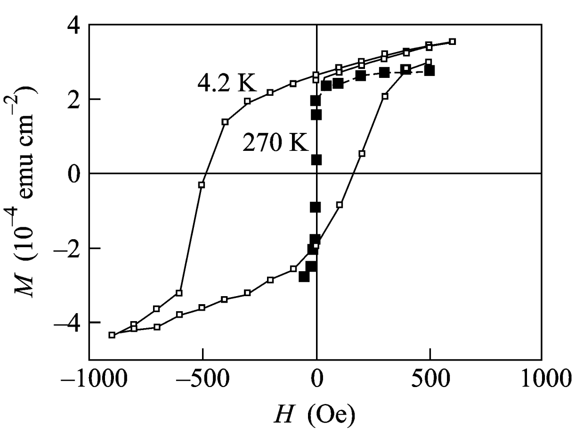

Fig. 4. Magnetization curves for the NiGe (20 nm/12.7 nm) film at $T = 4.2$ and 270 K.

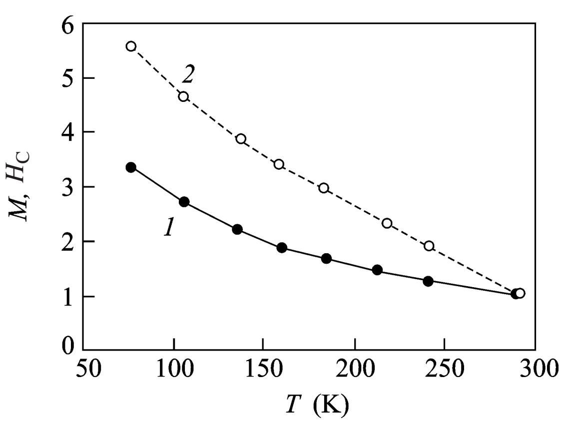

Fig. 5. Temperature dependences of the relative magnitudes of the (*1*) coercive force H_C of sample 2 (Ni 20 nm/Ge 12.7 nm) and (*2*) magnetization M of Ni_3Ge [10]. The values of H_C and M are given in units of the respective values at 290 K.

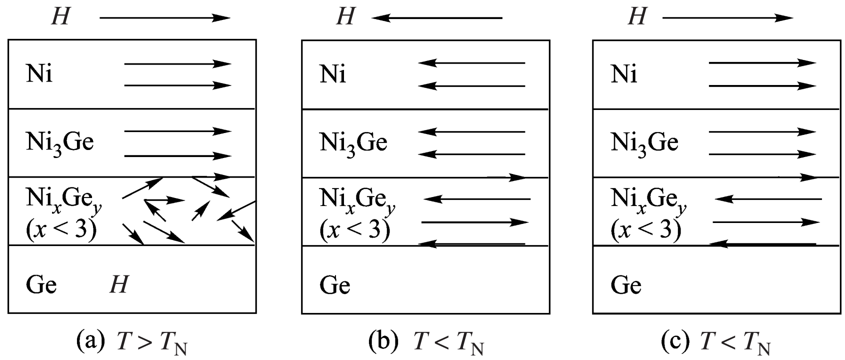

Fig. 6. Spin configurations at various temperatures.

cates that the mechanism under consideration is reasonable.

As the distance from the Ni layer increases, the compound in the interface is enriched with Ge and the antiferromagnetic compounds of the Ni_2Ge_2 or $NiGe_2$ type are formed with a rather low Néel temperature T_N by analogy with the Ge–Fe and Ge–Mn compounds [12]. This assumption explains the shift of the magnetization curve near 4.2 K. Since the magnetization curves at 77 K have no exchange shift, we can conclude that $T_N < 77$ K. Both FM layers at $T \sim 4.2$ K behave as an entity in the exchange field of the AFM layer. For sample 2, the exchange shift field is $H_E = 147$ Oe at 4.2 K, and $H_C = 318$ Oe. At temperatures above T_N of the AFM layer, this layer does not affect the film magnetization behavior. As the Ni layer becomes thinner, the effect of the FM and AFM parts of the interface on the film remagnetization becomes stronger, for example, sample 4 in the magnetic fields used is not remagnetized at low temperatures.

The spin configurations of the layers are schematically shown in Fig. 6. If the magnetic field is applied at $T > T_N$ and its magnitude exceeds the coercive force of the hard Ni_3Ge layer, then the spins in both FM layers are parallel to the field. At the same time, the directions of the spin moments in the AFM layer are randomly distributed (Fig. 6a). If $T < T_N$, the order is established in the AFM layer and the FM layer spins nearest to the AFM layer tend to arrange parallel to its spins due to the exchange interaction. Therefore, saturation is not achieved (Fig. 6b). On the contrary, the saturation of the magnetization in the opposite direction occurs at lower fields (see Fig. 6c).

CONCLUSIONS

The remagnetization processes have been investigated in the Ni–Ge bilayer films. Strong variations of the hysteresis loops at a decreasing temperature were observed: the increase in the coercive force and the appearance of asymmetry and exchange shift. All these effects are observed in the same sample. Qualitatively, this behavior is attributed to the formation of two magnetically ordered layers arranged in succession in the interface. A hard-FM layer, which is close in composition to Ni_3Ge with the Curie temperature above room temperature, is formed in the immediate vicinity of the Ni film. Then, the AFM layer is formed, which has a lower content of Ni and the Néel temperature below the liquid-nitrogen temperature.

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