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Study of electronic and magnetic structure of Fe/Cr superlattices with various Fe layer thicknesses

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Abstract

The giant magnetoresistance, magnetic, optical, and magnetooptical properties of the MBE-grown Fe/Cr superlattice series on single-crystal MgO(1 0 0) substrate with various Fe layer thicknesses (t_{Fe} = 3–48 Å) are studied. The angles θ_0 characterizing the noncollinear magnetic ordering in superlattices are defined. The nonmonotonic dependence on Fe layer thickness of properties investigated is discussed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic superlattice; Magnetoresistance; Noncollinear ordering; Magnetooptics

In Fe/Cr superlattices (SLs), the giant magnetoresistance (GMR) dependence on Cr layer thickness (t_{Cr}) is known to be of nonmontonic, oscillatory-like character due to the exchange coupling effect. The dependence on the Fe layer thickness (t_{Fe}) remains less studied and the concerned results are contradictory [1,2]. In this work the measurements of the GMR, magnetic, optical, and magnetooptical (MO) properties are performed to study their dependence on t_{Fe}.

The [Fe(t)/Cr(10 Å)]$_n$/Cr 90 Å/MgO(1 0 0) SLs with t_{Fe} = 3–48 Å were grown by the MBE method. The 90 Å Cr buffer was deposited on the substrate at a temperature of 600°C to establish the epitaxial orientation with the substrate. The substrate was then cooled down to 180°C, and the SL was grown by sequential deposition of Fe and Cr layers. The number of bilayers n was adjusted in such a way that the total SL thickness was constant ~ 1000 Å. The formation and periodicity of a single-crystal structure were confirmed by low and high-angle X-ray diffraction with Co K_α radiation. Magnetoresistance (MR) was measured by a standard four-probe technique in applied magnetic fields H up to 32 kOe. The MR is defined as $r = [\rho(H) - \rho(0)]/\rho(0)$, with $\rho(0) = \rho(H = 0)$, $\rho(H)$ being the resistivity in the field H. The magnetization M was obtained using the VSM method in the field up to 17 kOe lying in the film plane. Measurements of the equatorial Kerr effect (δ_p-effect) were performed in the spectral range λ = 0.3–2.5 μm and in applied fields up to 10 kOe. The effective refractive index n_{eff} and absorption coefficient k_{eff} were measured using ellipsometric Beattie method in the spectral range λ = 0.25–7 μm and their values were used to calculate the optical conductivity $\sigma_{eff} = nk\omega/4\pi$($\omega$ is the circular frequency of light in vacuum). All measurements were performed at room temperature.

Recently it has been established [3–5] that the Fe/Cr SLs may have noncollinear (NC) magnetic structures characterized by misalignment angle θ_0 ($0 < \theta_0 < 180°$) in remanence between the magnetization vectors $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$($|\boldsymbol{M}_1| = |\boldsymbol{M}_2|$) of neighbouring Fe layers. The NC structure can be described in terms of biquadratic exchange J_2 which is introduced through the following

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expression for exchange coupling energy: $E_{ex} = J_1(\boldsymbol{M}_1\boldsymbol{M}_2) + J_2(\boldsymbol{M}_1\boldsymbol{M}_2)^2$. If the in-plane anisotropy is weak compared to exchange, the NC phase exists in the range $|J_1| < 2J_2$ [5], and

$$\cos(\theta_0/2) = \sqrt{\tfrac{1}{2} - (J_1/4J_2)}. \quad (1)$$

In order to define the magnetic structure of a Fe/Cr SL, we have measured the magnetization curves, hysteresis loops, and field dependence of δ_p-effect. Fig. 1 shows the magnetic field dependence of r. The change of the t_{Fe} is seen to lead to the substantial change of the shape of r–H curve and of the MR value. Fig. 2 shows how the saturation values of MR and magnetization (r_S and M_S) change with t_{Fe}. It is convenient to divide all the samples into three groups. The first one consists of the samples with ultrathin Fe layers ($t_{Fe} = 3$; 4 Å); these samples exhibit rather small values of M_S and anomalous minor magnitude of δ_p-effect. We believe that in these samples, iron is the superparamagnetic clusters. This is confirmed, in particular, by zero value of coercivity and by satisfactory description of $M(H)$ dependence by the Langevin function. The second group with 6.5 Å $\leqslant t_{Fe} \leqslant$ 26 Å is characterized by the presence of NC ordering which is close to being AFM. Such SLs have large values of saturation fields ($H_S > 10$ kOe), MR values (Fig. 1), and angles θ_0 (Fig. 3). Finally, the third group consists of the samples with $t_{Fe} > 30$ Å. M_S and r_S of these SLs (Fig. 2) weakly depend on t_{Fe} and in addition the angle θ_0 is less than in the second group, indicating that the AFM coupling becomes reduced with increasing t_{Fe}.

To determine θ_0, we used the model of magnetizing the SL with NC ordering [5]. According to this model, there exists the critical magnetic field H_1 ($H_1 < H_S$) at which the vector $\boldsymbol{M} = \frac{1}{2}(\boldsymbol{M}_1 + \boldsymbol{M}_2)$ becomes parallel to $\boldsymbol{H}$ and the angle between $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$ has a certain value θ_1. In the fields $H > H_1$, there is the increase of SL magnetization due to a decrease of misalignment angle down to zero at $H = H_S$. The field H_1 may be considered as equal to the field of confluence of branches of the maximal hysteresis loop. Generally, $\theta_1 \leqslant \theta_0$ but if $H_1 \ll H_S$ (in our case this condition is fulfilled), we may take $\theta_0 \cong \theta_1$. Then θ_0 can be obtained from the relation:

$$\delta_p(H_1) = \delta_p(H_S)\cos(\theta_0/2). \quad (2)$$

Notice that finding θ_0 from Eq. (2), one does not need to know the θ–H curve. Fig. 3 shows θ_1 versus t_{Fe} for $t_{Fe} \geqslant 6.5$ Å. One can see that over the interval $6.5 < t_{Fe} < 26$ Å, the angle θ_0 experiences insignificant oscillations in the vicinity of 160° and it has a tendency of lowering with further rise of t_{Fe}. The θ_0 versus t_{Fe} dependence differs sufficiently from the dependence of θ_0 on t_{Cr} [6], which has the striking oscillatory-like character with a period of ~ 18 Å (Fig. 3). The ratio J_1/J_2, calculated in accordance with Eq. (1) is also shown in Fig. 3.

We investigated the spectral dependence of diagonal σ_{xx} over the range $0.25 < \lambda < 7$ μm and off-diagonal σ_{xy} ($\lambda = 0.3$–2.4 μm) components of effective optical conductivity tensor $\hat{\sigma} = i\omega/4\pi(\hat{\varepsilon} - 1)$ of the SLs ($\hat{\varepsilon}$ is the effective dielectric tensor). The thickness dependence of Re $\sigma_{xx}(t_{Fe})$ and ω Im $\sigma_{xy}(t_{Fe})$ of Fe(t)/Cr(10 Å) system is shown in Fig. 4a and b. The curves calculated within the frames of the phenomenological theory of a multilayered

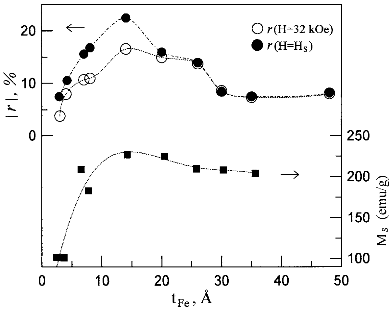

Fig. 2. Dependence of $|r|$ and M_S on the Fe layer thickness.

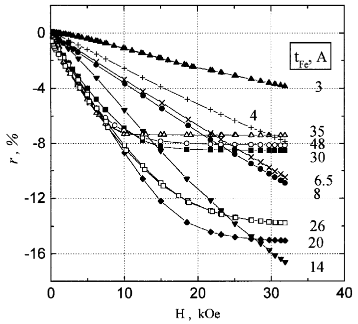

Fig. 1. Dependence of magnetoresistance r on the magnetic field.

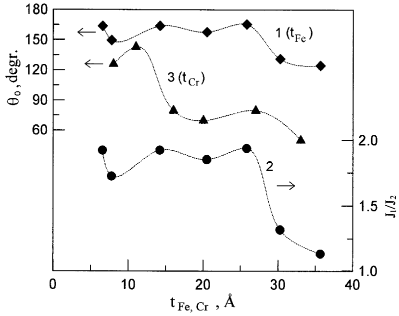

Fig. 3. Thickness dependence (1) $\theta_0(t_{Fe})$, (2) $J_1/J_2(t_{Fe})$, (3) $\theta_0(t_{Cr})$ at $t_{Fe} \sim 20$ Å [6].

structure and also shown (broken lines). In the calculations we have used σ_{xx}^{Cr}, σ_{xx}^{Fe}, and σ_{xy}^{Fe} measured for thick (~ 1000 Å) films. The nonmonotonic behaviour of the experimental Re $\sigma_{xx}(t_{Fe})$ and ω Im $\sigma_{xy}(t_{Fe})$ curves and their essential deviation from model curves is clearly seen. One can also see that in the infrared spectrum range the thickness dependence of Re $\sigma_{xx}(t_{Fe})$ is oscillatory-like with the period $\Lambda \cong 10$ Å. In contrast, in the short-wave range of the spectrum ($\lambda = 0.4$–0.8 μm), where the main interband absorption bands of Fe and Cr are formed, the oscillations of Re $\sigma_{xx}(t_{Fe})$ are smoothing away. In the latter range there is the essential enhancement of MO absorption at $t_{Fe} = 14$, 20 and 26 Å, see Fig. 4b. We may conclude that both the diagonal σ_{xx} and the off-diagonal σ_{xy} components of the effective optical conductivity tensor $\hat{\sigma}$ change if $t_{Fe} < 30$ Å, which points to the modification of the electronic structure of multilayers. This modification may be considered as the manifestation of the quantum size effect, i.e. formation of quantum well states.

Thus we have shown that the angle θ_0 characterizing the noncollinear magnetic structure weakly depends on t_{Fe}, in contrast to the θ_0 dependence on t_{Cr}, which perhaps is due to strong t_{Cr} dependence of J_1. Both static (magnetoresistance and spontaneous magnetization) and high frequency (Re σ_{xx} and ω Im σ_{xy}) properties of the superlattices studied show nonmonotonic dependence on Fe layer thickness. The shape of the thickness dependence can be due to the quantum size effects in multilayers.

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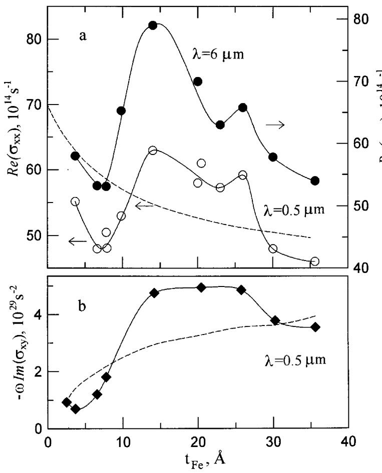

Fig. 4. Thickness dependence on t_{Fe}: (a) Re σ_{xx}; (b) ω Im σ_{xy}; broken curves are the results of calculation of these functions at $\lambda = 0.5$ μm, solid lines are guide to the eye.

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