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Influence of Magnetic Field on the Interlayer Interaction in $(Co/Si/Gd/Si)_n$ Films

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A singularity sensitive to the external magnetic field was observed in the temperature dependences of the magnetization of multilayer $(Co/Si/Gd/Si)_{20}$ films in the vicinity of compensation temperature. Possible mechanisms responsible for the unusual behavior of the magnetization are discussed. *© 2002 MAIK "Nauka/Interperiodica".*

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Among the class of multilayer magnetic films, the structures with a semiconducting interlayer are of considerable interest, because the magnetic state of such systems can be controlled either by changing the concentration of charge carriers in the semiconductor or by varying temperature, introducing dopants, or through optical illumination. Until recently, considerable attention in studying films of this type was focused on the systems containing magnetic iron layers and nonmagnetic layers of silicon or its alloys with other elements. The main effect distinguishing these films from the films with a metallic interlayer consists in the temperature dependence of the interlayer exchange, which can manifest itself both as the temperature-induced enhancement of the interlayer exchange interaction [1, 2] and as a change in the exchange sign with temperature, e.g., in the systems with an α-ZnSe semiconductor as an interlayer material [3]. The effect of photoinduced change in the magnetic state observed for the Fe/Si/Fe films is also noteworthy [4, 5].

One can expect that the inclusion of a layer of a rare-earth metal into the layered structure containing a 3*d*-metal layer will extend the diversity of observed effects on account of the competing interactions. For example, depending on the film preparation technology and spatial period of the structure, a compensation point (T_c) typical of the homogeneous (not layered) 4*f*–3*d* alloys [7] may appear in the magnetization versus temperature curve of a Gd/Co system [6]. However, a magnetization compensation point was also observed in the case where the Co and Gd layers were separated by a small silicon interlayer [8]. It is clear that, in the temperature range where the competing interactions almost completely compensate the contributions from different magnetic layers, the properties of the whole system can be influenced even by weak external action.

In this work, the influence of a magnetic field on the interlayer exchange interaction was observed in the $(Co/Si/Gd/Si)_n$ films.

Films were prepared by the ion rf sputtering technique [6]. Glass was used as the substrate material. Samples were sequences of twenty (Co/Si/Gd/Si) blocks protected at the bottom and the top by silicon layers with a thickness of t_{Si} = 200 Å. The thicknesses of each of the cobalt and gadolinium layers were t_{Co} = 30 Å and t_{Gd} = 75 Å, respectively, and the thickness of the silicon interlayer was varied in the range t_{Si} = 0–10 Å. All thickness parameters were specified by the sputtering time and the known deposition rate of the corresponding material. The layered character of the films and the nominal values of the spatial period of the structure were confirmed (to within ±2 Å) by the small-angle X-ray scattering technique. In addition, X-ray and electron microscopy studies of the films showed that they were close to amorphous structures. Magnetization measurements were made on a SQUID magnetometer described in [9]. When performing temperature and field measurements, the sample was placed in a demagnetizer prior to zero-field cooling. The magnetic field was parallel to the sample plane.

Earlier [6], it was shown that the compensation temperature in the Gd/Co films with the layer thickness ratio close to that in the samples studied in this work strongly depends on the period of the multilayer structure, and at temperatures $T < 200$ K the compensation is observed only if $t_{Gd} + t_{Co} \geq 130$ Å. In our case, this feature is absent for the structure with a period of 105 Å (Fig. 1a). However, the compensation point appears

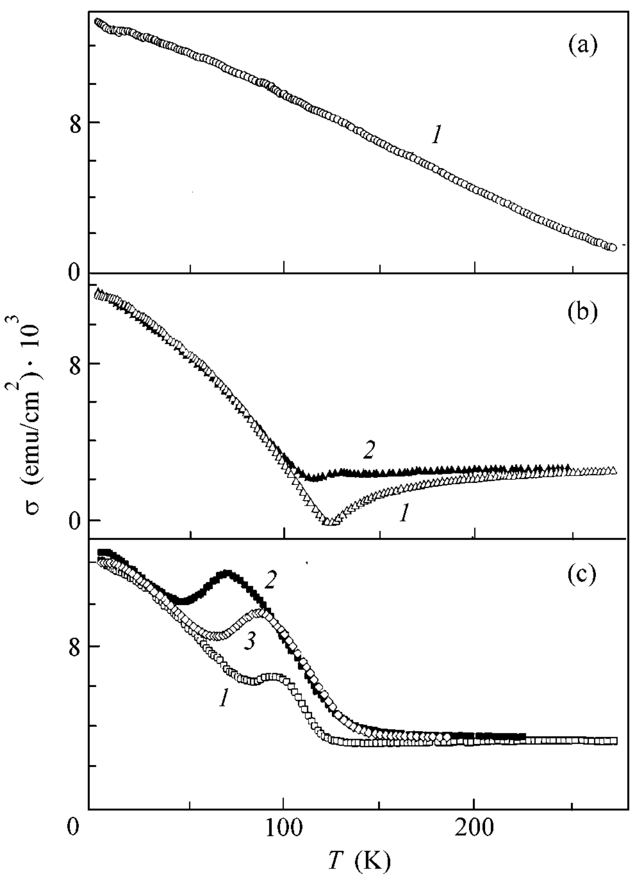

Fig. 1. Temperature-dependent magnetizations of the multilayer $(Gd/Si/Co/Si)_{20}$ films: t_{Si} = (a) 0, (b) 5, and (c) 10 Å. The curves are recorded in the fields H = (*1*) 200, (*2*) 1000, and (*3*) 500 Oe. In all films, t_{Co} = 35 Å and t_{Gd} = 70 Å.

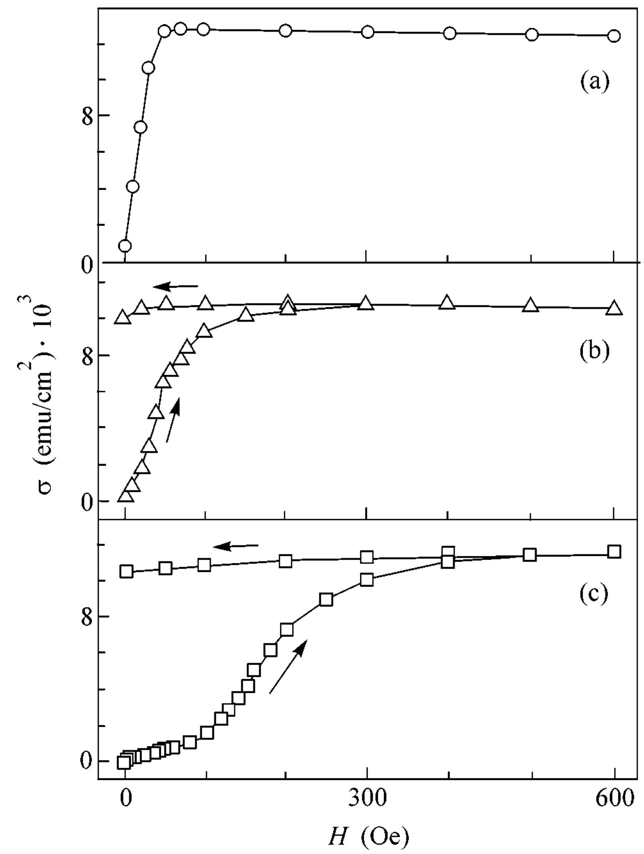

Fig. 2. Field-dependent magnetizations of the multilayer $(Gd/Si/Co/Si)_{20}$ films: t_{Si} = (a) 0, (b) 5, and (c) 10 Å; T = 4.2 K. Arrows indicate the direction of changing magnetic field.

after the inclusion of a silicon interlayer a few angstroms in thickness (Fig. 1b, curve *1*). Unexpectedly, the behavior of the magnetization in the vicinity of the compensation temperature shows a material dependence on the magnetic field even when its value is rather low. For instance, the compensation temperature, in its traditional meaning, is absent at H = 1 kOe in the film with t_{Si} = 5 Å, and the temperature dependence of magnetization takes the form shown by curve *2* in Fig. 1b. It should be noted that a small maximum appears in the temperature curve, while the magnetization minimum shifts to lower temperatures. The situation proved to be even more unusual for the film with t_{Si} = 10 Å (Fig. 1c). In this film, the magnetization minimum (not zero), which could be related to the compensation point, was observed up to the fields on the order of 100 Oe. One can see that the maximum in the magnetization versus temperature curve increases with the magnetic field and shifts to low temperatures.

We recorded field dependences of the magnetization at helium temperatures. It is seen in Fig. 2 that the magnetization curves for the films with t_{Si} = 0 Å and t_{Si} = 5 Å are similar to those in ferromagnets with saturation fields $H_s \approx 100$ Oe and $H_s \approx 300$ Oe, respectively. As for the film with t_{Si} = 10 Å, there is a knee on the magnetization curve in the vicinity of $H \cong 100$ Oe, while the saturation field is $H_s \approx 500$ Oe. The reverse run of the magnetization curve of this film only slightly deviates from the straight line. When comparing these results with the temperature behavior of magnetization, one can see that the field-induced magnetization singularity in the region of compensation temperature is most pronounced in the fields higher than the saturation field, i.e., in the region where no singularities are expected. One can see from Figs. 1 and 2 that the saturation magnetizations at low temperatures coincide with good accuracy for the films with a silicon interlayer and a Gd/Co film, indicating that the contribution from the rare-earth subsystem below the singularity temperature is the same in both cases and dominant in this region. For temperatures $T > 120$ K, where the contribution from the cobalt subsystem dominates, the magnetizations for the films with t_{Si} = 5 Å and t_{Si} = 10 Å also virtually coincide (Fig. 1).

These experimental results do not fit in the traditional scheme describing two-sublattice ferrimagnets with a compensation point. The appearance of a maximum in the vicinity of the expected compensation temperature can be explained if one assumes, for example, that the interaction of the rare-earth layers with the neighboring cobalt layers through the silicon layer contains a contribution that gives rise, not to a strictly antiferromagnetic configuration, but to a canted magnetic structure. In such a situation, the magnetic structure as a whole represents a cone of magnetic moments of the rare-earth subsystem whose overall moment is antialligned with the overall magnetic moment of the cobalt layers. As the temperature rises, this interaction is first "switched off" on the background of a decreasing overall moment of the rare-earth subsystem and, as a result, the cone of the rare-earth subsystem collapses, whereupon the process evolves following the well-known scenario. Such a behavior of multilayer films is quite realistic. As known [10], the inclusion of a biquadratic exchange interaction (J_2) can give rise, in conjunction with the bilinear exchange (J_1), to a canted magnetic structure. In multilayer films, the mechanism responsible for the biquadratic contribution to the exchange interaction can be caused by the fluctuative variations in the nonmagnetic interlayer thickness [11]. The assumed distinction in the temperature dependences of both exchange parameters [12] is then also understood. Moreover, for the multilayer magnetic films, J_1 and J_2 can be comparable in magnitude.

In our case, the experimentally observed singularities can be naturally rationalized in terms of the interlayer interaction between the magnetic layers; however, the strong dependence of this interaction on a magnetic field still remains to be understood. Clearly, this effect cannot be ascribed to the magnetic crystallographic anisotropy of the materials forming magnetic layers. First, these layers are structurally amorphous, and, second, metallic Co and Gd possess strong local magnetic anisotropy [7], so that the magnetic fields used in this work are too low to rearrange their magnetic structures. One can assume that the constant J_2 is due to the semiconducting interlayer and that J_2 is precisely the parameter which is sensitive to the magnetic field. This issue will be elucidated in a more comprehensive study.

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