Magnetic and resonance properties of multilayer $(Gd/Si/Co/Si)_n$ films

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Presented are the experimental investigation results of magnetic static and resonance properties of multilayer magnetic films in the system of 4*f*-3*d* elements separated by a semiconductor interlayer. Effects of temperature and magnetic field on interlayer coupling are detected. The role of the biquadratic exchange in formation of magnetic state in the whole system is established.

Представлены результаты экспериментального исследования статических и резонансных магнитных свойств многослойных магнитных пленок в системе элементов 4*f*-3*d*, разделенных полупроводниковым промежуточным слоем. Обнаружено влияние температуры и магнитного поля на межслоевое взаимодействие. Установлена роль биквадратного обмена в формировании магнитного состояния системы как целого.

Among the multilayer films, structures with a semiconductor interlayer are of considerable interest, because the magnetic state of such a system can be controlled either by changing the concentration of charge carriers or by varying temperature, introducing dopants, or through optical illumination. In this case, the main effect distinguishing these films from the films with metal interlayer [1] consists in the temperature dependence of the interlayer exchange interaction, which can manifest itself both as the temperature-induced enhancement of the interlayer exchange interaction [2] and as the sign change with temperature [3].

The inclusion of a rare-earth metal layer into the layered structure containing a 3*d*-metal will expand the variety of observed effects due to competing interactions. So, in the $(Gd/Co)_n$ system films, the compensation point of magnetization (T_k) is observed in temperature curve of magnetization at some preparation process parameters and structure periods of multilayer films [4]. But when the Gd and Co layers are separated by thin silicon interlayer, the compensation point of magnetization is present, too [5].

The films investigated were prepared by the ion rf sputtering technique [4]. Glass was used as the substrate material. The samples were formed as sequences of twenty (Gd/Si/Co/Si) blocks protected at the bottom and the top by silicon layers of t_{Si} = 200 Å thickness. The thicknesses of each of the cobalt and gadolinium layers were t_{Co} = 30 Å and t_{Gd} = 75 Å, respectively, while the silicon interlayer thickness was varied in the range t_{Si} = 0 to 10 Å. All thickness parameters were set by the sputtering time and the known deposition rate of the respective materials. The layered character of the films and the nominal values of the structure spatial period 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 those were close to amorphous structure. Magnetization measurements were done using a SQUID magnetometer. When performing temperature and field measurements, the sample was placed in a demagnetizer prior to zero-field cooling. The magnetic resonance measurements were performed using a spectrometer with tunable magnetic field and microwave frequency $f_{MWF} = 9.4$ GHz in temperature range from liquid nitrogen temperature up to room one. At all measurements, the magnetic field was parallel to the film plane.

Unexpectedly, the magnetization behavior in the vicinity of the compensation temperature depends appreciably 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, although it is seen very well at $H = 200$ Oe. At this point, 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 more unusual for the film with $t_{Si} = 10$ Å [6]. 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. It is seen that the maximum in the magnetization vs. temperature curves increases with the magnetic field and shifts to lower temperatures.

We recorded the field dependences of magnetization at helium temperatures. It is established that the magnetization curves for the films with $t_{Si} = 0$ Å and $t_{Si} = 5$ Å are similar to those in ferromagnetics with saturation fields $H_S = 100$ Oe and $H_S = 300$ Oe, respectively. As for the film with $t_{Si} = 10$ Å, there is a knee on the magnetization curve of this film in the vicinity of $H = 100$ Oe while the saturation field is $H_S = 500$ Oe. The reverse run of the magnetization curve of this film only slightly deviates from the straight line. It should be noted that the field-induced magnetization singularity in the region of compensation temperature is most pronounced in the fields exceeding the saturation one, i.e., in the region where no peculiarities are expected. The situation is still more attractive by transiting to the range of magnetic fields of some tens of Oersteds (Fig. 1) [7]. At temperature measurements of magnetization in the film with silicon interlayer $t_{Si} = 10$ Å, it was found that in low magnetic fields ($H < 100$ Oe),

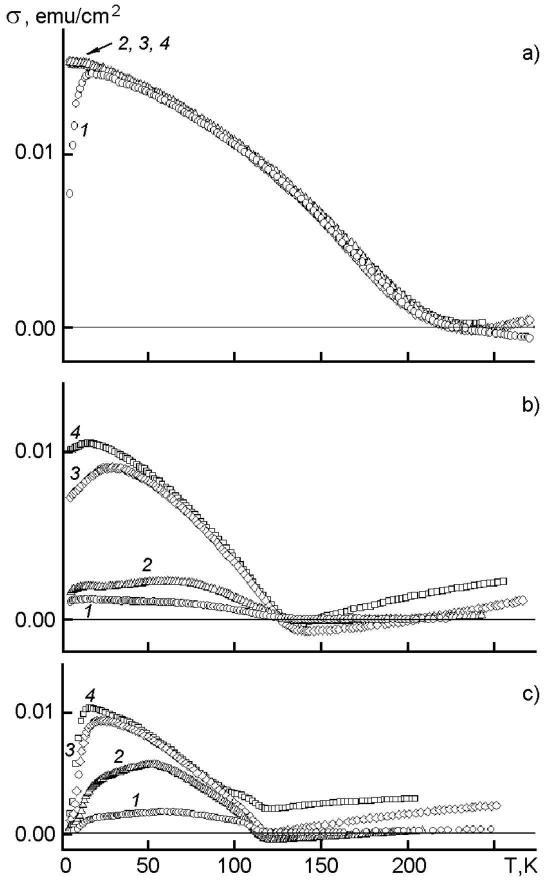

Fig. 1. Temperature dependences of magnetization for the films under heating. Cooling conditions, ZFC. t_{Si} (Å): *2* (a), *5* (b), 10 (c). Curves *1*, *2*, *3*, *4* are obtained in fields $H = 10$, 20, 50, 100 Oe, respectively.

the curves have different shapes independent of thermo-magnetic prehistory (the film was cooled in magnetic field (FC) or without it (ZFC)). In the case FC at $T <$ 100 K, the curve is the same both at the film heating and cooling. Such a behavior is similar to that observed in spin glasses [8].

Since the dynamics of magnetic system is sensitive to a distribution of effective intrinsic magnetic fields [9], we investigated these films by electron magnetic resonance method. For the reference film without silicon interlayer, the resonance shape of microwave absorption is typical to ferromagnetics. A solitary line of Lorentz shape has been observed. The temperature behavior patterns of resonance field (H_r) and intensity (I), determined as the area under the curve, are represented in Fig. 2 (a, b). The inclusion of a silicon interlayer changes essentially the magnetic system dynamics. In all cases with $t_{Si} \neq 0$, the microwave absorption curve has either pronounced fine struc-

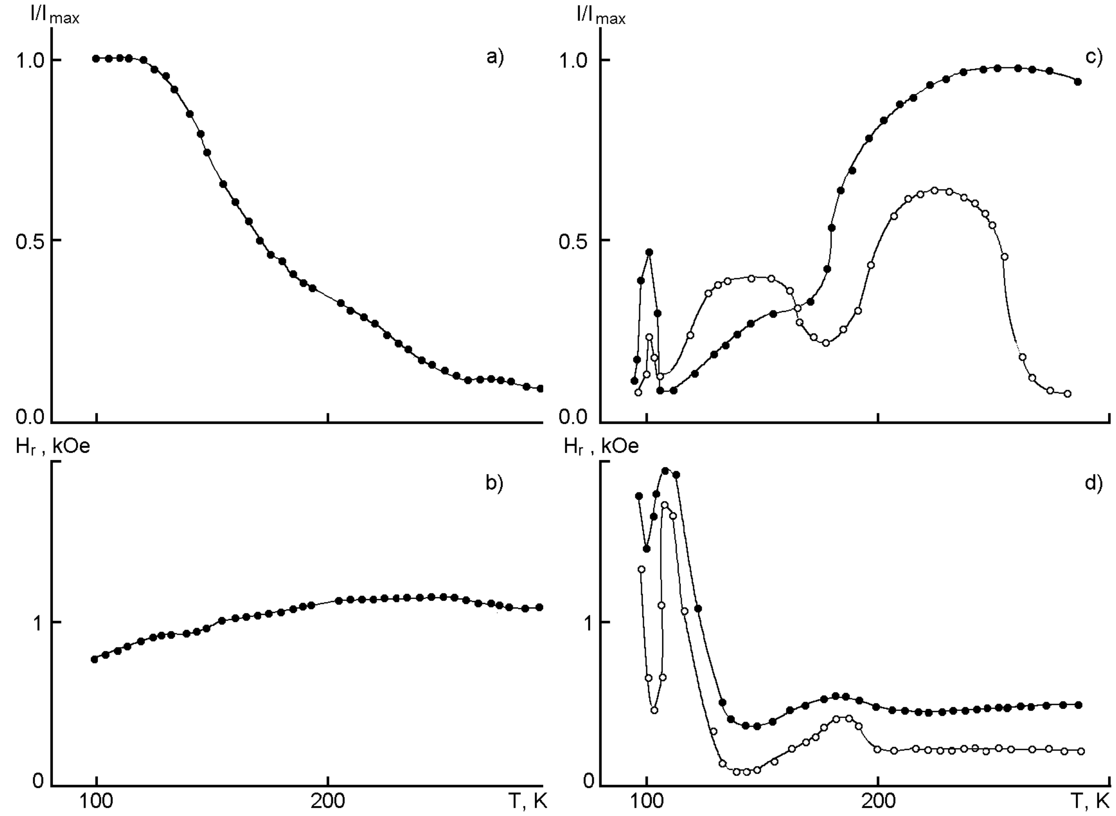

Fig. 2. The temperature dependences of the magnetic resonance parameters. a, c – intensity of microwave absorption, b, d, resonance field. t_{Si} (Å): 0 (a, b), 5 (c, d).

ture, as it is in Fig. 3 for film with t_{Si} = 2 Å, or noticeably distorted waveform for other silicon thickness values. The fitting to Lorentz type curves shows that the experimental plot can be represented as a superposition of two lines. In Fig. 2, the temperature dependences of H_r and I are given for film with t_{Si} = 5 Å. If these lines are attributed to "ferromagnetic" and "exchange" modes, then it is seen as the temperature elevates, the intensity of ferromagnetic mode is decreased but that of the exchange one is raised, and the anomalies of magnetic resonance parameters are observed in the vicinity of the compensation temperature (cf. to Fig. 1,b).

Both magnetic static and resonance experimental results do not fit in the traditional scheme describing two-sublattice ferrimagnetics 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

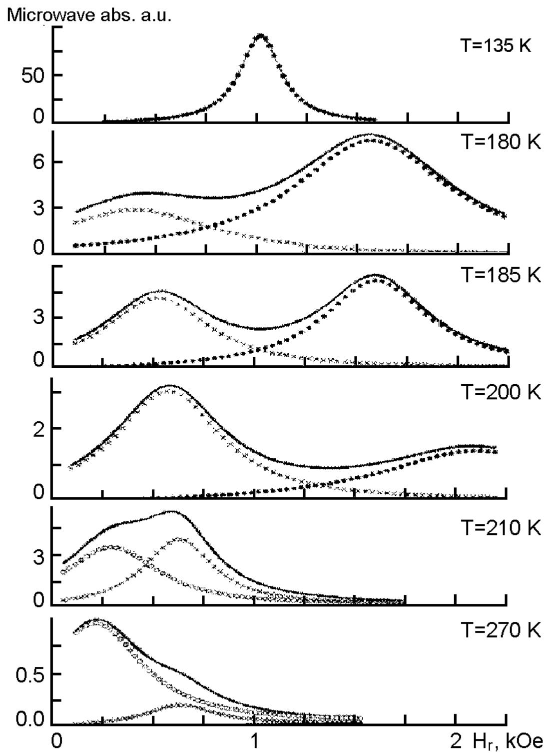

Fig. 3. The magnetic resonance spectrum in the film with t_{Si} = 2 Å at different temperatures.

magnetic structure. In such a situation, at temperatures $T > T_k$, where the coupling between rare-earth and cobalt is weaker than cobalt-cobalt one (because gadolinium magnetization $M_{Gd} \approx 0$), the magnetic structure as a whole represents a cone of magnetic moments of the cobalt subsystem with the overall moment anti-a ligned with the overall magnetic moment of gadolinium layers. At low temperatures, gadolinium magnetization is a lot more than cobalt one, and this interaction is determinative. In this case, we have a cone of the rare-earth subsystem with total moment antiparallel to the resulting cobalt moment.

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 both by the fluctuative variations in the nonmagnetic interlayer thickness [11] and by a spin-dependent tunneling through potential barrier [12]. For the multilayer magnetic films with a nonmetallic interlayer, the parameters J_1 and J_2 can depend on the temperature and have comparable magnitudes. At the same time, one can assume that the constant J_2 is due to the semiconducting interlayer.

Thus, the principal conclusion of present paper is that the presence of a semiconducting layer determines the interlayer exchange interaction between magnetic layers and influences the dynamics of magnetic system in cardinal manner.

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Магнітні та резонансні властивості багатошарових плівок $(Gd/Si/Co/Si)_n$

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Представлено результати експериментального дослідження статичних та резонансних магнітних властивостей багатошарових магнітних плівок в системі елементів 4*f*-3*d*, розділених напівпровідниковим проміжним шаром. Виявлено вплив температури та магнітного поля на міжшарову взаємодію. Встановлено роль біквадратного обміну у формуванні магнітного стану системи як цілого.