Effect of optical radiation on magnetic resonance in Fe/Si/Fe trilayer films

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A photoinduced change in the magnetic resonance parameters is observed in trilayer films of the system Fe/Si/Fe. The shifts of the resonance field and the character of the interlayer interaction are investigated as functions of the temperature, illumination of the films, and thickness of the silicon interlayer. It is found that at low temperatures the photoinduced contribution to the exchange interaction constant between the iron layers is antiferromagnetic. © *1998 American Institute of Physics.* [S0021-3640(98)00716-6]

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The production of multilayer magnetic films has opened up wide prospects for developing magnetic materials with prescribed properties. Varying the chemical components and thicknesses and the manner of stacking of the components sometimes leads to unexpected effects. In multilayer metal films with a nonmagnetic interlayer the main features are giant magnetoresistance and an exchange parameter which oscillates as a function of the thickness of the nonmagnetic interlayer.[1] The characteristic period of the spatial variations for these films is 10–20 Å, and the magnitude of the oscillations depends on the interlayer material, i.e., essentially, on the characteristic features of the conduction-electron density-of-states function. The diversity of observed effects is enriched even more by using combined methods of acting on the material. In this respect, it is very tempting to study systems with a semiconductor interlayer, since here the charge-carrier density can be controlled by varying the temperature or by implanting dopants or by optical irradiation.

In the present letter we report the results of investigations of the change produced in the magnetic state in the Fe/Si/Fe film system by optical irradiation, as detected by electron magnetic resonance.

Fe/Si/Fe trilayer films were obtained by molecular-beam epitaxy on the Angara apparatus, modified for depositing magnetic materials.[2] Four samples with different silicon interlayer thicknesses t_{Si} were prepared in one deposition cycle. In all the experimental samples the iron layer was 50 Å thick. The thicknesses were monitored with a quartz meter for measuring thickness and rate of film growth. In each deposition cycle

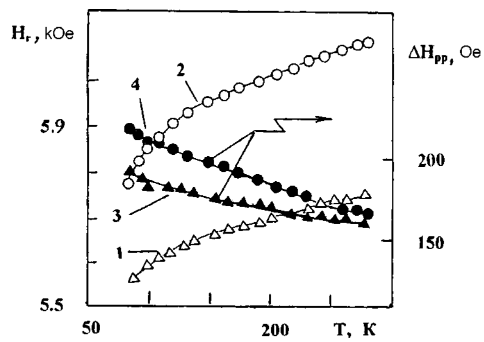

FIG. 1. Temperature dependences of the magnetic-resonance parameters: *1,3* — Reference film, *2,4* — with a silicon interlayer $t_{\mathrm{Si}}=20$ Å, ΔH_{pp} — the magnetic resonance linewidth.

one reference film with iron thickness $t_{\mathrm{Fe}}=100$ Å was prepared. All these films were also compared with one another in respect to the microwave absorption intensity for the purpose of determining the difference in the mass of the magnetically active material. According to the magnetic resonance parameters, the best films were obtained on a mica substrate. The measurements of the magnetic-resonance parameters were performed on the apparatus described in Ref. 3. The microwave frequency was $f=35$ GHz. The magnetic field lay in the film plane. An Ar laser operating in the range $\lambda=0.49-0.514\ \mu$m served as the source of optical radiation.

It has been established[4] from data on direct measurements of the magnetization on a SQUID magnetometer and on the magnetooptic Kerr effect that ferromagnetic iron layers interact antiferromagnetically at room temperature, and on cooling to $T\geqslant 80$ K they become virtually uncoupled and the entire system shows ferromagnetic behavior. Under laser irradiation ($\lambda=0.5145\ \mu$m) the system once again shows indications of antiferromagnetic coupling between iron layers.

Since the conditions of magnetoresonance absorption are determined by the effective internal fields, the magnitude and sign of the exchange coupling constant,[5] both with and without optical irradiation, can be judged according to the shift of the resonance field of a film with a semiconductor interlayer relative to a film without such an interlayer.

Figure 1 illustrates the temperature behavior of the magnetic resonance parameters of the reference film (curves *1,3*) and a film with silicon interlayer thickness $t_{\mathrm{Si}}=20$ Å (curves *2,4*). One can see that the silicon layer induces an appreciable change in the resonance conditions. As the temperature increases, the difference of the resonance fields of these two films increases, which can be interpreted as an increase in the interaction between the iron layers. Conversely, the difference of the linewidths of the magnetoresonance peaks decreases, apparently because of the decrease in the stresses in the films at the iron–silicon interfaces.

The change in the shift of the resonance field (δH_r) as a function of the silicon layer thickness is shown in Fig. 2. The intensification of the ferromagnetic interaction (negative shift δH_r) for small silicon thicknesses ($t^{*}_{\mathrm{Sr}}\leqslant 15$ Å) is interesting. For silicon interlayers $t^{0}_{\mathrm{Si}}>70-80$ Å the sign of the exchange interaction depends on the temperature. In the

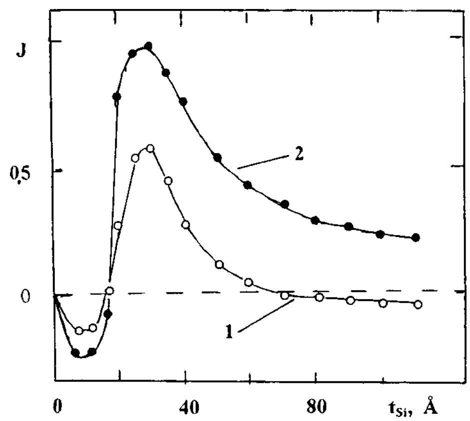

FIG. 2. Normalized shift of the resonance field as a function of the silicon interlayer thickness: $J=\delta H_r/\delta H_r^{\max}$; curve *1* — $T=80$ K, *2* — $T=300$ K.

region $t_{Si}^{*}\leqslant t_{Si}\leqslant t_{Si}^{0}$ the interaction of the layers is of an antiferromagnetic character at all temperatures investigated.

In the case of an intermediate layer prepared from a semiconductor material, it is obvious that the shifts of the resonance field under optical irradiation, as a result of the appearance of photoelectrons in the conduction band, and under trivial heating should be of the same sign. When light is absorbed in the substrate and iron layers, a portion of the energy of the optical radiation is dissipated in the form of heat. For this reason, we measured the heating-induced shift (δH_r^h) of the resonance field in the reference sample as function of temperature (Fig. 3a). It was then subtracted from the total shift of the resonance field in the sample under irradiation. The remainder $\delta H_r^{\text{ind}}=\delta H_r-\delta H_r^h$ was

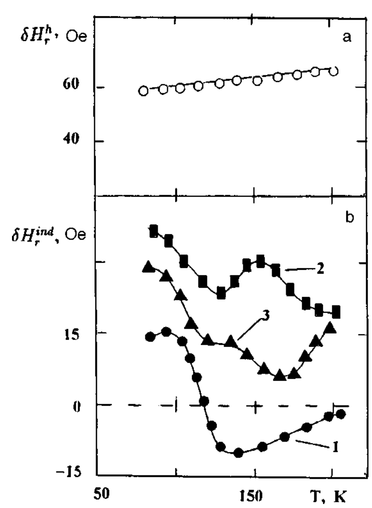

FIG. 3. Temperature dependences of the photoinduced shift of the resonance field: a — Reference film, b — Fe/Si/Fe film, curve *1* — $t_{Si}=5$ Å, *2* — $t_{Si}=10$ Å, *3* — $t_{Si}=20$ Å; $S_{opt}=2.8$ W/cm^2.

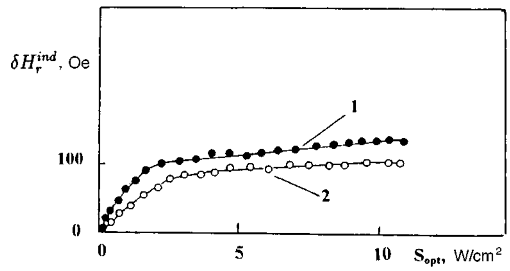

FIG. 4. Shift of the resonance field of Fe/Si/Fe films as a function of the irradiance: *1* — $t_{Si}=10$ Å, *2* — $t_{Si}=20$ Å; $T=80$ K.

attributed to the action of light on the semiconductor material. The temperature dependences of the photoinduced shifts $\delta H_r^{\mathrm{ind}}$ of the resonance field for samples with different silicon thicknesses are presented in Fig. 3b. Here a nonmonotonic variation of $\delta H_r^{\mathrm{ind}}$ is present. In the temperature range $T\cong 80-100$ K, for small silicon thicknesses, specifically, $t_{Si}<t_{Si}^*$, the photoinduced shift of the resonance field increases as t_{Si} increases, while for $t_{Si}>t_{Si}^*$ it decreases somewhat. For larger semiconductor interlayer thicknesses ($t_{Si}>t_{Si}^0$) the effect can be attributed almost entirely to the thermal action of the radiation.

For $T\leqslant 120$ K the photoinduced changes in the exchange interaction are exclusively of an antiferromagnetic character, and a change in sign of the exchange parameter in the region $T\approx 120$ K is observed only for very thin silicon interlayers (Fig. 3b, curve *1*). In the latter case, as the temperature increases further, the photoinduced changes in the magnetic system tend to zero. As a function of the irradiance (S_{opt}), the photoinduced shift of the resonance field saturates, for example, at $S_{opt}=2$ W/cm^2 for $t_{Si}=10$ Å and at $S_{opt}=3.5$ W/cm^2 for $t_{Si}=20$ Å (see Fig. 4).

We do not attribute the observed properties in Fe/Si/Fe layered structures to the formation of Fe–Si compounds, since it is well known[6] that silicon doping of iron always decreases the magnetic moment and weakens the exchange interaction. Here, however, we have an increase in the effective internal field, which can be explained by assuming that the exchange coupling between the iron layers intensifies.

At present the ''quantum well'' model is most widely used to describe the magnetic properties of multilayer magnetic structures.[7,8] In this model the oscillations of the exchange interaction parameter in the case of a metal interlayer are determined by the oscillations of the spectral density of the electronic states, which depends on the number of planes of the intermediate layer. In application to our case, the situation must be corrected, since, most likely, for the present technological regime the silicon interlayer has an amorphous structure, and this means that short-range order is only approximately preserved in the interlayer, and the spectral density of electronic states is not necessarily periodic.[9] Here the characteristic thickness of the silicon interlayer at which the maximum interaction of the iron layers is observed should be related with the electron mean free path in amorphous silicon. This fact can explain the absence of clearly expressed oscillations of the exchange parameter and consequently of a shift of the resonance field as a function of the thickness of the semiconductor. The sign of the exchange parameter (phase of the oscillations) at the start of the dependence on the interlayer thickness is determined both by the type of extremum on the Fermi surface and by the character of the line-up of the bands at the interfaces.[8]

The change in the magnetic state under irradiation is primarily due to the change in the density of the charge carriers in the semiconductor, which are carriers of the interaction between the magnetically active layers, and to the restructuring of the electron density of states. We note once again that at low temperatures the photoinduced contribution is always antiferromagnetic. The temperature-induced changes in the magnetic properties in the system Fe/Si/Fe can be understood by assuming that the chemical potential is temperature-dependent.

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