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Effect of the Ferromagnetic Layer Thickness on the Interlayer Interaction in Fe/Si/Fe Trilayers

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Three-layer magnetic film systems Fe/Si/Fe have been studied by the method of magnetic resonance. It is established that the ferromagnetic layer thickness affects the magnitude of the interlayer exchange interaction in this system. A mechanism explaining the observed effect is proposed. © *2004 MAIK "Nauka/Interperiodica".*

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Films based on the Fe/Si layer system are of interest because they feature interesting phenomena related to the presence of a semiconductor interlayer (spacer). Depending on the conditions of synthesis, either a ferromagnetic (FM) [1] or an antiferromagnetic (AFM) [2, 3] exchange between the magnetic layers takes place. It was also established that the exchange interaction between Fe layers increases with temperature and that it may exhibit an oscillatory character depending on the Si layer thickness (t_{Si}) [4]. In addition, such films exhibit the phenomenon of photoinduced changes in the magnitude of the interlayer interaction [5, 6].

Despite extensive research, problems related to the formation of the magnetic state of a multilayer system are still unsolved. In this context, the most important task is to study the mechanisms of spin-dependent electron transfer via nonmagnetic spacers, since peculiarities of this transport determine the character of the interlayer exchange interaction. It is obvious that the efficiency of the spin-dependent electron transfer must depend both on the spacer material and on the magnetic state of the layers. For multilayer systems with nonmagnetic metallic spacers, some theoretical results [7] indicate that the magnitude of the exchange interaction between magnetic layers might depend on their thickness. This dependence was experimentally confirmed and shown to exhibit an oscillatory character [8]. In the case of a nonmetallic spacer representing a potential barrier, the existing theories [9, 10] also predicted the dependence of the interlayer interaction on the magnetic-layer thickness.

This paper presents the results of our experimental investigation of the influence of the ferromagnetic-layer thickness on the interlayer exchange interaction in a three-layer system (Fe/Si/Fe trilayer) with a semiconductor spacer.

We have studied two sets of samples, comprising (i) FM metal layers without a spacer and (ii) trilayers with a silicon spacer of thickness t_{Si} = 2 nm (corresponding to the maximum AMF interlayer exchange interaction, according to published data [1] and our previous results [6]). The thickness of the FM layer t_{Fe} in each set was varied from 2 to 10 nm at a 1-nm step. The films were obtained by the method of thermal deposition in vacuum onto glass substrates in an Angara setup with a residual pressure of $P = 10^{-7}$ Pa. The glass substrates were initially covered by a 10-nm-thick buffer layer of silicon. Then, a magnetic Fe/Si/Fe trilayer structure was deposited and covered with a protective 10-nm-thick silicon layer. For each thickness of the iron film, a control sample without a silicon spacer was prepared in the same vacuum technology cycle.

The results of electron-microscopic examination showed that the films possessed an almost completely amorphous structure. The samples were studied by method of electron magnetic resonance, which is sensitive to changes in the internal molecular fields. The microwave frequency was ω_{UHF} = 28.75 GHz and the constant magnetic field was oriented in the plane of the sample. The measurements were performed in the temperature range T = 78–300 K.

The results of the magnetic resonance measurements in Fe/Si/Fe trilayers showed that the microwave absorption lines in all samples (except for the control ones, deprived of the silicon spacer) have an asymmetric shape and exhibit no anisotropy in the film plane. The magnetic resonance line width was on the order of $\Delta H \approx 200$ Oe.

First, we measured the dependence of the resonance field on the FM-layer thickness t_{Fe} (Fig. 1). These data were used to determine the magnetization of iron layers

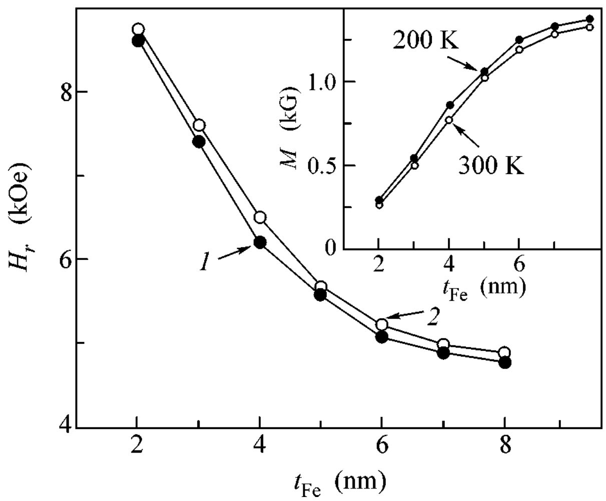

Fig. 1 Plots of the resonance field H vs. magnetic-layer thickness t_{Fe} for the control samples measured at $T = 200$ (*1*) and 300 K (*2*). The inset shows the plot of magnetization M vs. t_{Fe}.

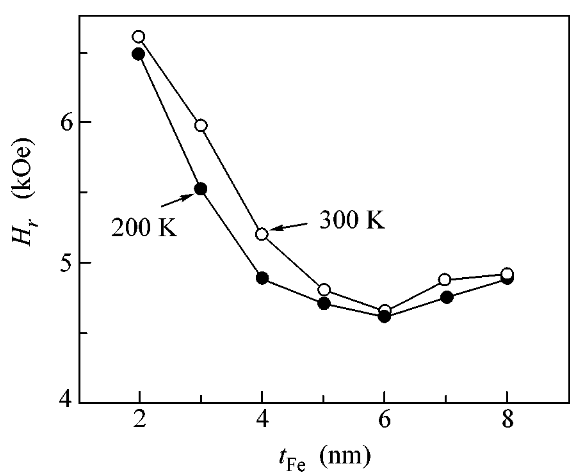

Fig. 2. Plots of the resonance field H vs. magnetic-layer thickness t_{Fe} for the Fe/Si/Fe trilayers with $t_{Si} = 2$ nm measured at $T = 200$ (*1*) and 300 K (*2*).

(inset in Fig. 1) according to the Kittel formula (see relation (2) below) [11].

Then, the measurements were performed for the samples with spacers. Figure 2 shows a plot of the resonance field versus t_{Fe} for the samples with $t_{Si} = 2$ nm measured at $T = 200$ and 300 K (where the interlayer exchange interaction constant was expected to depend strongly on the sample temperature).

The experimental data were processed using the results of calculations of the magnetic resonance spectrum for a three-layer magnetic film [12]. In application to the case under consideration, the free energy per unit area of the film is

$$E = -J\cos(\varphi_1 - \varphi_2) - t_{Fe}[\mathbf{H}(\mathbf{M}_1 + \mathbf{M}_2) + 4\pi(M_{1Z}^2 + M_{2Z}^2)], \quad (1)$$

where J is the interlayer exchange interaction constant, $\mathbf{H}$ is the applied magnetic field, $\mathbf{M}_i$ is the magnetization of the ith FM layer, φ_i is the magnetization angle in the plane (measured relative to the direction of the applied magnetic field), $i = 1, 2$ is the FM layer number, t_{Fe} is the magnetic layer thickness, and the Z axis is perpendicular to the film plane. In the calculations, we assumed that $(t_{Fe} \cdot \mathbf{H} \cdot \mathbf{M}) \gg J$ and that the FM films occur in the saturated state, so that $\varphi_i \cong \varphi_H = 0$. It was also assumed that the two FM layers are perfectly identical.

Under the above conditions, the resonance frequencies are described by the relations

$$(\omega_1/\gamma)^2 = H(H + H_M), \quad (2)$$

$$(\omega_2/\gamma)^2 = H(H + H_M) + 2(2H + H_M)H_J + 4H_J^2, \quad (3)$$

where

$$H + M = 4\pi M \text{ and } H_J = J/(t_{Fe}M). \quad (4)$$

Once the values of ω, H, and M are known, one can readily calculate H_J using Eq. (3) and then determine the interlayer exchange interaction constant J from relation (4). From such calculations, we obtained two sets of H_J values. In the first set, H_{J1} values fall within the interval from –6 to –14 kOe. These values do not satisfy the approximation adopted and do not correspond to the experimental data. For these reasons, the solution H_{J1} was rejected. The other set (H_{J2}) gives the $J(t_{Fe})$ plotted in Fig. 3. As can be seen, this dependence is nonmonotonic, and the J values in the region of the maximum agree with the published data [4]. To within the experimental error in the temperature range studied, the results exhibited virtually no temperature dependence. It should be emphasized that such dependences of the interlayer exchange interaction constant on the magnetic-layer thickness are not described by any of the existing theories.

The observed variation of the average magnetization of the magnetic layer depending on its thickness is rather typical. This behavior is explained by the fact that, for small t_{Fe} values, the interfacial (transition) regions account for a considerable proportion of the metal layer, while the role of the internal ("bulk") regions is relatively small. As the metal layer thickness is increased, the bulk fraction increases, while the width of the interfacial regions remains the same. In the presence of the silicon spacer, electrons of an FM layer, which are involved in the interaction and which bear "information" about the magnetic state of this layer, penetrate (without losing this information) into the

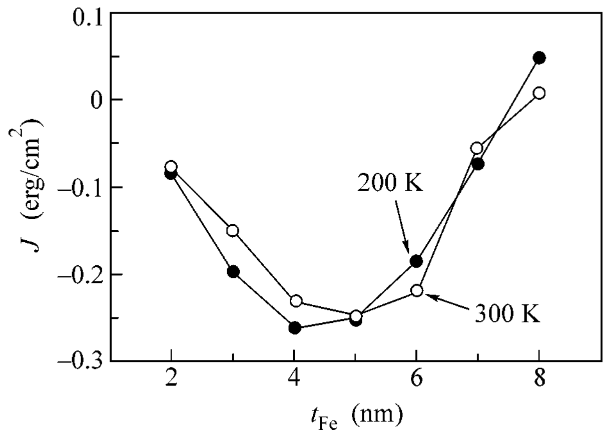

Fig. 3. Plots of the interlayer interaction energy J vs. magnetic-layer thickness t_{Fe} for the Fe/Si/Fe trilayers with t_{Si} = 2 nm measured at T = 200 (*1*) and 300 K (*2*).

other layer to a certain depth, thus determining the effective volumes of the interacting regions of both FM layers.

If the outlined scenario is valid, a value of ~5 nm is the depth to which the electrons mediating the exchange interaction penetrate into the FM layer with increasing thickness t_{Fe}. For small t_{Fe}, an increase in the magnetic-layer thickness leads to, besides an increase in the magnetization, a growth of the volume of the magnetic material involved in the interaction between FM layers and, hence, of the magnitude of the interlayer interaction. As the FM layer thickness is increased further (>5 nm), the interactions inside each such layer become prevailing and the role of the interlayer exchange becomes relatively smaller. These considerations qualitatively explain the dependences presented in Fig. 3. It should be noted that the obtained results are not related to the formation of compounds (iron silicides) in the transition regions. The results of a special investigation performed by Decoster *et al.* [13] showed that traces of ε-FeSi are detectable only in the case when the iron film is composed of coarse crystallites.

In conclusion, it should be noted that, besides a basic significance related to the investigation of the laws of formation of the magnetic structures in multilayer magnetic films, the obtained relations should be taken into consideration when studying the giant magnetoresistance in such films. Our results show that, to obtain the maximum GMR effect, it is necessary to select the optimum thicknesses not only of the nonmagnetic spacers, but of the magnetic layers as well.

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