Study of the barrier height in exchange coupled Fe/Fe1-xSix (x>0.70) multilayers

著者	遠藤　恭
journal or publication title	Journal of Applied Physics
volume	87
number	9
page range	6836-6838
year	2000
URL	http://hdl.handle.net/10097/46572

doi: 10.1063/1.372858

JOURNAL OF APPLIED PHYSICS VOLUME 87, NUMBER 9 1 MAY 2000

Study of the barrier height in exchange coupled Fe/Fe$_{1-x}$Si$_x$ ($x>0.70$) multilayers

Yasushi Endo,[a] Osamu Kitakami, and Yutaka Shimada
Research Institute for Scientific Measurements, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

Fe/Fe$_{1-x}$Si$_x$ multilayers show distinct antiferromagnetic (AF) coupling for a wide spacer composition range $0.50<x\leqslant 1.00$. As the Si content x increases, the spacer changes from metallic to insulating and the AF coupling strength (J) is significantly enhanced from 0.05 to 1.20 erg/cm^2. We have explained the temperature dependence of the coupling constants J_1 and J_2 in terms of the quantum interference model by taking an unknown energy difference $\Delta(=U-\epsilon_F)$ as a fitting parameter, where ϵ_F is the Fermi level of Fe and U is the potential of the Fe$_{1-x}$Si$_x$. The aim of the present work is to determine the quantity Δ experimentally for the insulating composition range of $x>0.70$. The quantity Δ was evaluated both from $I-V$ characteristics and the temperature dependence of the resistivity with the current perpendicular to the sample plane using a crossed electrode geometry junction. It is found that the barrier height increases from 0.15 to 0.70 eV with increasing the Si content x. These values almost agree with the parameter Δ deduced from the temperature dependence of J_1 and J_2. This agreement supports the validity of our previous calculations based on the quantum interference model. © *2000 American Institute of Physics.* [S0021-8979(00)88708-3]

I. INTRODUCTION

Interlayer magnetic coupling of metallic multilayers has been investigated intensively since the discovery of the giant magnetoresistance effect in Fe/Cr multilayers.[1] Recently, there has been a renewal of interest in the interlayer coupling between adjacent magnetic layers across a nonmetallic spacer, such as Si, Ge, and so on. A typical example is the Fe/Si multilayer system.[2–8] Very strong antiferromagnetic (AF) coupling has been found when the Si layer is very thin (~10 Å). However, the origin of the coupling still remains unclear. In the previous work,[9] we found distinct AF coupling in Fe/Fe$_{1-x}$Si$_x$ for a wide Si composition range of $0.50<x\leqslant 1.00$. With the increase of the x, Fe$_{1-x}$Si$_x$ changed from metallic to insulating around $x\sim 0.70$ and both bilinear and biquadratic coupling constants J_1, J_2 were considerably enhanced. As shown in Fig. 1,[9] the J_1 monotonically increases from 0.05 (at $x\sim 0.05$) to 1.20 erg/cm^2 (at $x=1.00$). The interlayer coupling in the insulating spacer region is extremely strong compared with those of usual metallic multilayer systems. We explained this strong coupling and its temperature dependence in terms of the quantum interference model formalized by Bruno[10] by taking the energy difference $\Delta(=U-\epsilon_F)$ as a fitting parameter, where ϵ_F is the Fermi level of Fe and U is the potential of Fe$_{1-x}$Si$_x$.

The aim of the present work is to determine the barrier height Δ experimentally in order to check the validity of our previous calculations based on the quantum interference model.

II. EXPERIMENT

A series of Fe/Fe$_{1-x}$Si$_x$/Fe trilayers was grown by sputtering with the Fe layer thickness fixed at 100 Å and the nominal Fe$_{1-x}$Si$_x$ layer thickness t_s varied from 5 to 25 Å. The Si content x of the spacer was varied in the range of $0.70<x\leqslant 1.00$, where the spacer exhibits insulating properties, such as high electric resistivity and its negative temperature dependence. During the deposition process interdiffusion occurs at Fe/Fe$_{1-x}$Si$_x$ interfaces to some extent, reducing the effective spacer thickness.[2–9] According to our precise structural characterization using low-angle x-ray diffractometry and magnetization measurements,[8] diffusion is most serious for pure Si($x=1.00$) and consequently decreases the effective spacer thickness. By decreasing the Si content of Fe$_{1-x}$Si$_x$, the effective spacer thickness approaches the nominal value t_s due to suppression of interdiffusion. The barrier height Δ was evaluated from $I-V$ characteristics[11] with the current perpendicular to the sample plane using a crossed electrode geometry junction.[12] The barrier thickness is assumed to be equal to the effective

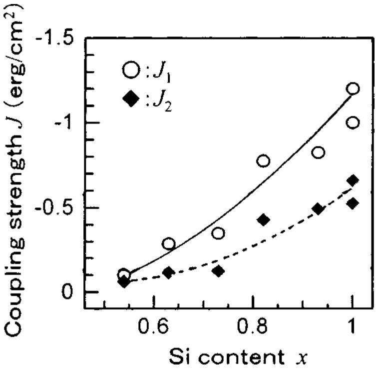

FIG. 1. Interlayer coupling J_1 and J_2 of Fe/Fe$_{1-x}$Si$_x$ multilayers as a function of Si content x (see Ref. 9). Empty circles (○) and solid diamonds (◆) indicate J_1 and J_2, respectively. The solid and dotted lines are guides to the eyes.

---

[a] Electronic mail: endo@rism.tohoku.ac.jp

0021-8979/2000/87(9)/6836/3/$17.00

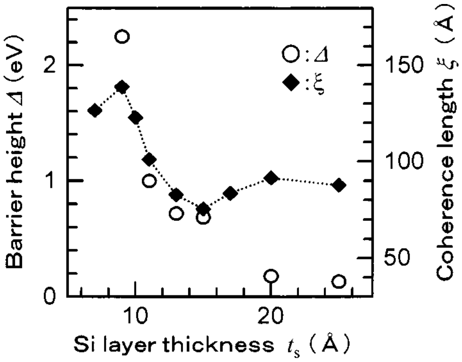

FIG. 2. Barrier height Δ and crystalline coherence length ξ of Fe(100 Å)/Si(t_s Å)/Fe(100 Å) as a function of spacer thickness t_s. Empty circles (○) and solid diamonds (◆) indicate Δ and ξ, respectively.

spacer thickness determined by the structural analyses described elsewhere.[8] In this work, the junction area was set to 100 μm^2 to keep uniform current flow over the junction.[12]

III. RESULTS AND DISCUSSION

Figure 2 shows the crystalline coherence length ξ along the film normal and the barrier height Δ of Fe(100 Å)/Si(t_s Å)/Fe(100 Å) as a function of Si spacer thickness. The coherence length ξ is larger than each Fe layer thickness $t_F = 100$ Å for $t_s \leqslant 15$ Å and becomes equal to t_F for $t_s > 15$ Å. This result indicates that the spacer is crystalline for $t_s \leqslant 15$ Å due to severe interdiffusion and an amorphous or heavily disordered phase appears for $t_s > 15$ Å, as already confirmed by low-angle x-ray diffractometry and cross-sectional transmission electron microscope (TEM) observations.[8,9] This structural change affects the barrier height significantly. For $t_s > 15$ Å, where the amorphous phase exists, the barrier height Δ is as small as 20 meV, which is equal to the value of amorphous Si reported by Meservey *et al.*[13] In a previous paper, we have already discussed the interlayer coupling behavior caused by amorphous Si.[14] With decreasing t_s below 15 Å, the spacer changes into a diffused crystalline phase and the barrier height abruptly increases above $\Delta \sim 0.70$ eV. In general, very strong AF coupling has been found in this thickness range ($t_s \sim 13$ Å).[2–9] From the present result, strong AF coupling in Fe/Si is mediated by the diffused insulating spacer with the energy gap of $2\Delta \sim 1.40$ eV. This value coincides with the barrier height deduced from the temperature dependence of J_1 and J_2,[9] as described later. In the present work, however, we assumed that the barrier thickness is equal to the effective spacer thickness evaluated from the structural analyses. Therefore, to some extent, there might be some uncertainty in the evaluated barrier height.

In the same manner, we evaluated the barrier height Δ and the effective spacer thickness t_{eff} for a series of Fe/Fe$_{1-x}$Si$_x$/Fe($0.70 < x \leqslant 1.00$). Figures 3(a) and 3(b) show the barrier height Δ and the effective thickness t_{eff} as a function of the Si content x. In Fig. 3(a), open circles indicate the measured barrier height using the experimentally determined t_{eff} and crosses show the values deduced from the temperature dependence of J_1 and J_2.[9] We note that both data agree very well and give a monotonic increase of the barrier height and a decrease of the effective thickness with increasing the Si content x of Fe$_{1-x}$Si$_x$.

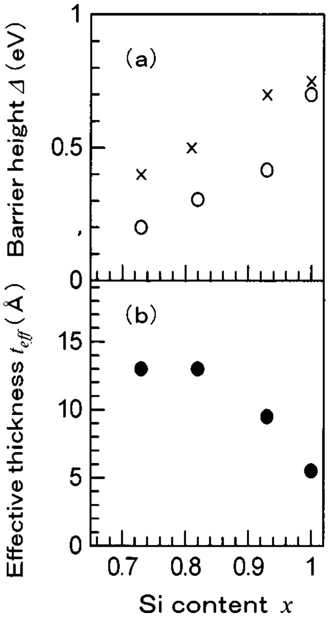

FIG. 3. (a) Barrier height Δ and (b) effective spacer thickness t_{eff} of Fe/Fe$_{1-x}$Si$_x$/Fe as a function of Si content x of Fe$_{1-x}$Si$_x$. In (a), empty circles (○) show the barrier height determined from $I-V$ properties, and crosses (×) indicate the values deduced from the temperature dependence of J_1 and J_2 based on the quantum interference model (see Ref. 9).

As mentioned above, it is concluded that the very strong AF coupling found in Fe/Fe$_{1-x}$Si$_x$ multilayers is caused by the diffused insulating spacer with a somewhat large barrier height and a small effective spacer thickness. The barrier height depends on the Si content x, and this value coincides with the barrier height deduced from the temperature dependence of J_1 and J_2.[9]

IV. CONCLUSION

In summary, we have determined the barrier height of Fe/Fe$_{1-x}$Si$_x$/Fe for the insulating spacer composition range ($x > 0.70$) from the $I-V$ characteristics with the current perpendicular to the sample plane using a crossed electrode geometry junction. It is found that the barrier height Δ increases from 0.15 to 0.70 eV with increasing the Si content x. These values agreed very well with those deduced from the temperature dependence of J_1 and J_2 based on the quantum interference model. All these present results indicate that the very strong AF coupling found in Fe/Fe$_{1-x}$Si$_x$ multilayers is caused by the diffused insulating spacer with a somewhat large barrier height and a small effective spacer thickness.

ACKNOWLEDGMENTS

One of the authors (Y.E.) was Research Fellow of the Japan Society for the Promotion of Science and acknowledges financial support by the Storage Research Consortium in Japan. The low-angle XRD measurements were performed at the Laboratory for Developmental Research of Advanced

Materials, the Institute for Material Research, Tohoku University. This work was supported by Research for the Future Program of Japan Society for the Promotion of Science under Grant No. 97R14701.

[1] P. Grunberg, R. Schreiber, Y. Pang, U. Walz, M. B. Brodsky, and H. Sowers, J. Appl. Phys. **61**, 3750 (1987).

[2] S. Toscano, B. Briner, H. Hopster, and M. Landolt, J. Magn. Magn. Mater. **114**, L6 (1992).

[3] E. E. Fullerton, J. E. Mattson, S. R. Lee, C. H. Sowers, Y. Y. Huang, G. Felcher, S. D. Bader, and F. T. Parker, J. Magn. Magn. Mater. **17**, L301 (1992).

[4] A. Chaiken, P. R. Michel, and M. A. Wall, Phys. Rev. B **53**, 5518 (1996).

[5] E. E. Fullerton and S. D. Bader, Phys. Rev. B **53**, 5112 (1996).

[6] J. J. de Vries, J. Kohlhepp, F. J. A. den Broeder, R. Coehoorn, R. Jungblut, A. Reinders, and J. M. de Jonge, Phys. Rev. Lett. **78**, 3023 (1997).

[7] K. Inomata, K. Yusu, and Y. Saito, Phys. Rev. Lett. **74**, 1863 (1995).

[8] Y. Endo, O. Kitakami, and Y. Shimada, J. Magn. Soc. Jpn. **21**, 541 (1997).

[9] Y. Endo, O. Kitakami, and Y. Shimada, Phys. Rev. B **59**, 4279 (1999).

[10] P. Bruno, J. Appl. Phys. **76**, 6972 (1994).

[11] J. Simmons, J. Appl. Phys. **34**, 1793 (1963).

[12] Y. Endo, O. Kitakami, and Y. Shimada, Appl. Phys. Lett. **72**, 495 (1998).

[13] R. Meservey, P. M. Tedrow, and J. S. Brooks, J. Appl. Phys. **53**, 1563 (1982).

[14] Y. Endo, O. Kitakami, and Y. Shimada, J. Appl. Phys. **85**, 5741 (1999).