Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Magnetism and Magnetic Materials 290–291 (2005) 78–81
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Structural and magnetic properties of Fe/Si and Fe/FeSi multilayers

I. Sakamoto[a,*], S. Honda[b], H. Tanoue[a], M. Koike[a], S. Purwanto[a]

[a]National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
[b]Shimane University, 1060 Nishikawatsu, Matsue, Shimane 690-8504, Japan

Available online 8 December 2004

Abstract

We investigated the formation of $Fe_{1-x}Si_x$ phases in the interfacial region of Fe/Si and Fe/FeSi multilayers (MLs). The amount of $Fe_{1-x}Si_x$ phases formed in Fe/Si MLs depends on Si layer thickness and this amount corresponds to the reduction of saturation magnetization and averaged hyperfine field (H_{hf}). On the other hand, the reduction of magnetization and averaged H_{hf} in Fe/FeSi MLs seems not to depend on the FeSi layer thickness; that is, the interface of Fe/FeSi MLs is more stable and a formation of nonmagnetic $Fe_{1-x}Si_x$ phases is not expected.

PACS: 68.35.Ct; 75.75.+a; 76.80.+y

Keywords: Structure; Magnetization; Multilayers; Mössbauer spectroscopy—conversion electron

Fe–Si system shows interesting properties like antiferromagnetic couplings (AFC) between Fe layers and Si layers of multilayer structures (MLs). The AFC are considered to be due to a formation of $Fe_{1-x}Si_x$ phases in the interfacial region by an atomic diffusion between Fe layers and Si layers at room temperature. It has been suggested that the formation of a nonmagnetic metallic metastable iron silicide phase with a CsCl structure is responsible for the exponential decay of AFC with Si spacer thickness [1]. Gareev et al. have shown that the coupling strength of Fe/$Fe_{0.56}Si_{0.44}$/Fe trilayers has two antiferromagnetic maxima at 1.2 and 2.6 nm of spacer thickness [2]. They have also shown the increase of coupling strength with increasing x of Fe/$Fe_{1-x}Si_x$-wedge/Fe trilayers and the enhanced AFC for Fe/$Fe_{0.5}Si_{0.5}$/Si-wedge/$Fe_{0.5}Si_{0.5}$/Fe structures [3,4]. The quantum interference model of exchange coupling explains an exponential decay of the coupling for only insulating spacers and an oscillatory coupling for metallic spacers [5]. However, the $Fe_{1-x}Si_x$ phases of Fe/Si MLs induced by interdiffusion are still unclear.

In this paper, we prepared Fe/Si and Fe/FeSi MLs and investigated the structural and magnetic properties in order to elucidate the $Fe_{1-x}Si_x$ phases formed in the interfacial region.

$[Fe\ (2\,nm)/Si\ (1\,nm)]_{30}$ MLs, $[Fe\ (2\,nm)/Si\ (1.5\,nm)]_{30}$ MLs, $[Fe\ (2\,nm)/FeSi\ (1.16\,nm)]_{30}$ MLs, $[Fe\ (2\,nm)/FeSi\ (1.74\,nm)]_{30}$ MLs, FeSi (60 nm) and FeSi (60 nm)/Fe (2 nm) were prepared on highly resistive n-type (1 0 0) Si substrate by the helicon plasma sputtering method in the base pressure of the chamber lower than 1×10^{-7} Torr. The deposition rates of Fe and Si layers were 0.05 and 0.068 nm/s, respectively. The FeSi layer was formed by co-sputtering of Fe and Si targets. The composition of the FeSi layer was estimated to be $Fe_{0.54}Si_{0.46}$ from each deposition rate. The structural and magnetic properties

*Corresponding author. Tel.: +81 29 861 5689; fax: +81 29 861 5673.
E-mail address: isao-sakamoto@aist.go.jp (I. Sakamoto).

0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2004.11.216

were observed by X-ray diffraction (XRD) using CuKα radiation and vibrating sample magnetometer (VSM) up to 1.5 T. Values of magnetization (emu/cm^3) were calculated from the division by sample area × total Fe layer thickness. The bilayer periods were estimated from peak positions of satellite peak and main peak at XRD patterns. The magnetoresistance (MR) was measured by DC 4 points probe. The measurement of conversion electron Mössbauer spectrum (CEM spectrum) was done using a Mössbauer Spectrometer with 740 MBq ^{57}Co γ-ray source (Rh matrix), and conversion electrons were detected with a proportional counter flowed with He + 10% methane mixture gas. CEM spectra were analyzed by least-squares fitting assuming overlapped Lorentzian curves of singlet peak or doublet peaks and sextet peaks. The distribution of hyperfine field (H_{hf}) was assumed for peak widths of sextet peaks. The ratios of peak intensities were 3:4:1 in the assumption with the direction of magnetization in the film plane.

Table 1 shows the nominal and estimated values of bilayer periods in Fe/Si MLs and Fe/FeSi MLs. Both values agree in Fe/FeSi MLs rather than Fe/Si MLs. The bilayer period of $[Fe (2 nm)/Si (1.5 nm)]_{30}$ MLs could not be estimated because of the peak broadening of main peak. These results imply the atomic diffusion in the interfacial region of Fe/Si MLs rather than Fe/FeSi MLs.

As seen in Fig. 1, in-plane magnetization curves of $[Fe (2 nm)/Si (1 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.16 nm)]_{30}$ MLs show the AFC and the values of magnetization at 1.5 T are 750 and 1250 emu/cm^3, respectively. The MR ratios ($-[\rho_{1.5}-\rho_0]/\rho_0$, where $\rho_{1.5}$ and ρ_0 are resistances at 1.5 and 0 T) of $[Fe (2 nm)/Si (1 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.16 nm)]_{30}$ MLs are 0.07% and 0.14%, respectively. On the other hand, in-plane magnetization curves of $[Fe (2 nm)/Si (1.5 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.74 nm)]_{30}$ MLs show the ferromagnetic nature and the saturated values of magnetization are 1000 and 1350 emu/cm^3, respectively. These saturated values are smaller than the value of bulk Fe (1700 emu/cm^3). The ratios of saturated values of $[Fe (2 nm)/Si (1.5 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.74 nm)]_{30}$ MLs to bulk value are 0.59 and 0.80, respectively.

Table 1
Nominal and estimated values of bilayer periods in Fe/Si MLs and Fe/FeSi MLs

Sample	Nominal period (nm)	Estimated period (nm)
Fe (2 nm)/Si (1 nm)	3	2.72
Fe (2 nm)/Si (1.5 nm)	3.5	—
Fe (2 nm)/FeSi (1.16 nm)	3.16	3.17
Fe (2 nm)/FeSi (1.74 nm)	3.74	3.86

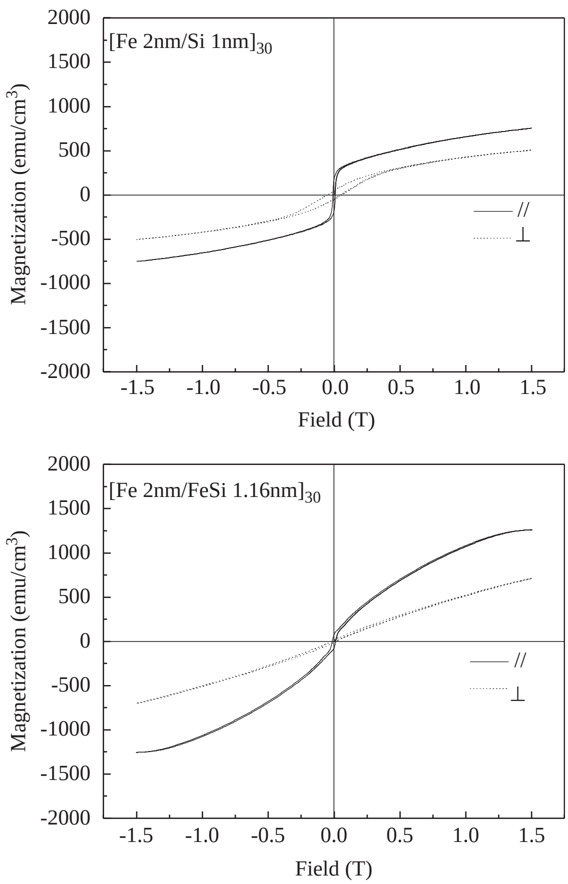

Fig. 1. Magnetization curves of $[Fe (2 nm)/Si (1 nm)]_{30}$ MLs and $[Fe (2 nm)/FeSi (1.16 nm)]_{30}$ MLs.

Fig. 2 shows the CEM spectra and the distributions of H_{hf} of $[Fe (2 nm)/Si (1 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.16 nm)]_{30}$ MLs. Both CEM spectra were fitted by singlet peak overlapped with broadened sextet peaks. The estimated peak value (0.25 mm/s) of singlet peak coincides with the isomer shift of CsCl-type FeSi phase [6]. The distribution of H_{hf} in $[Fe (2 nm)/Si (1 nm)]_{30}$ MLs in the region of 30 T is broader than that of $[Fe (2 nm)/FeSi (1.16 nm)]_{30}$ MLs. The averaged values of H_{hf} in $[Fe (2 nm)/Si (1 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.16 nm)]_{30}$ MLs are 23.0 and 26.3 T, respectively. The ratios of the averaged H_{hf} to bulk value (33 T) are 0.66 and 0.80, respectively.

Although not shown here, the nonmagnetic phases of CEM spectrum in $[Fe (2 nm)/Si (1.5 nm)]_{30}$ MLs were fitted by doublet peaks and that of $[Fe (2 nm)/FeSi (1.74 nm)]_{30}$ MLs by a singlet peak. The distributions of H_{hf} in $[Fe (2 nm)/Si (1.5 nm)]_{30}$ and $[Fe (2 nm)/FeSi (1.74 nm)]_{30}$ MLs agree with that of Fig. 2 and the

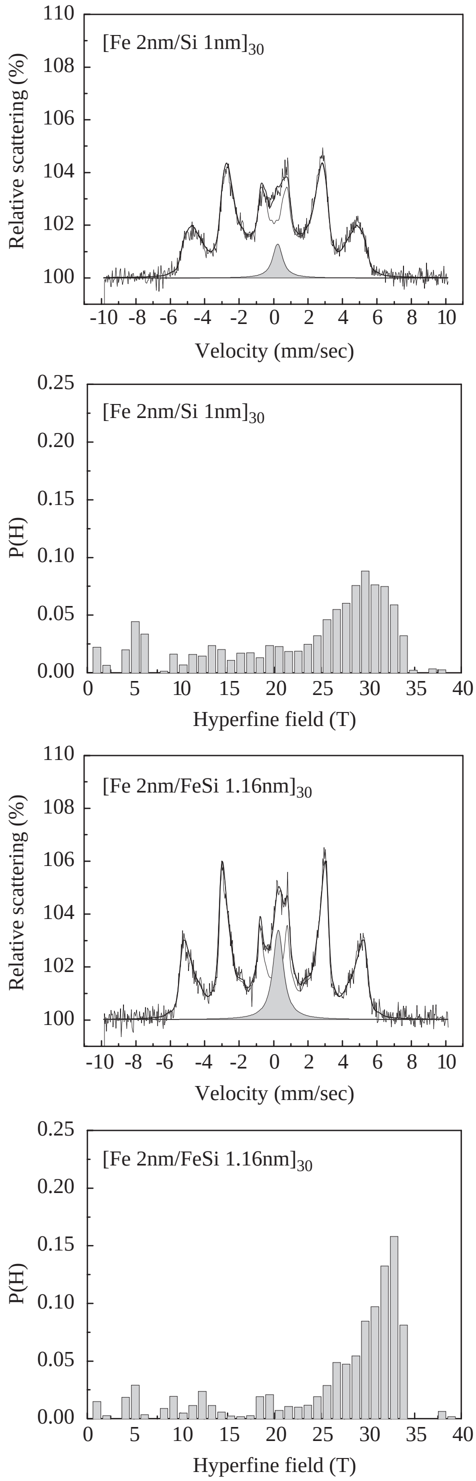

Fig. 2. CEM spectra and the distributions of H_{hf} in [Fe (2 nm)/Si (1 nm)]$_{30}$ MLs and [Fe (2 nm)/FeSi (1.16 nm)]$_{30}$ MLs.

averaged values of H_{hf} are 22.7 and 27.0 T, respectively. The ratios of magnetization in Fe/Si MLs and Fe/FeSi MLs to bulk value and that of averaged H_{hf} are listed in Table 2. These values estimated from magnetization are consistent with that of averaged H_{hf} in Table 2. Both reductions of magnetization and averaged H_{hf} indicate the degree of atomic diffusion in the interfacial region between Fe and Si layers, Fe and FeSi layers. Therefore, the large reduction of magnetization in Fe/Si MLs indicates that the degree of atomic diffusion in the Fe/Si interface is larger than Fe/FeSi interface. In addition, the degree of atomic diffusion in Fe/Si MLs depends on Si layer thickness and that of Fe/FeSi MLs not on FeSi layer thickness.

The direct deposition of FeSi (60 nm) on Si substrate induced the doublet peaks in the CEM spectrum. The CEM spectrum of FeSi (60 nm)/Fe (2 nm) on Si substrate showed the singlet peak, which corresponds to CsCl-type FeSi phase; that is, Fe layer between FeSi layer and Si substrate suppresses the atomic diffusion between FeSi layer and Si substrate. These results mean that the Fe/FeSi interface stabilizes the formation of CsCl-type FeSi phase. Nevertheless, Fe mono layers on the top and bottom sides in Fe layers of Fe/FeSi MLs face to nonmagnetic CsCl-type FeSi layers. It is expected that a part of neighboring Fe layers with FeSi layers forms magnetic $Fe_{1-x}Si_x$-like phases and induce the reductions of saturation magnetization and averaged H_{hf}.

Therefore, we conclude that the interfacial regions of Fe/Si MLs and Fe/FeSi MLs show different structures; that is, the formation of $Fe_{1-x}Si_x$ phases occurs more easily in Fe/Si interface than in the Fe/FeSi interface. The atomic diffusion in Fe/Si interface induces magnetic and nonmagnetic $Fe_{1-x}Si_x$ phases. In Fe/FeSi interface the magnetic $Fe_{1-x}Si_x$-like phases seem to be formed.

One of us (S.P.) was financially supported by the Budget for Scientist Exchange Program in Nuclear Energy Research of AIST. A part of this study was financially supported by the Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and

Table 2
Ratios of magnetization and averaged H_{hf} in Fe/Si MLs and Fe/FeSi MLs to bulk Fe value

Sample	Reduced magnetization	
	VSM	CEMS
Fe (2 nm)/Si (1 nm)	—	0.66
Fe (2 nm)/Si (1.5 nm)	0.59	0.56
Fe 2 nm/FeSi (1.16 nm)	—	0.80
Fe 2 nm/FeSi (1.74 nm)	0.80	0.82

Technology, based on the screening and counseling by the Atomic Energy Commission.

References

[1] G.J. Strijkers, J.T. Kohlhepp, H.J.M. Swagten, W.J.M. de Jonge, Phys. Rev. B 60 (1999) 9583.
[2] R.R. Gareev, D.E. Bürgler, M. Buchmeier, D. Olligs, R. Schreiber, P. Grünberg, Phys. Rev. Lett. 87 (2001) 157202-1.
[3] R.R. Gareev, D.E. Bürgler, M. Buchmeier, R. Schreiber, P. Grünberg, J. Magn. Magn. Mater. 240 (2002) 235.
[4] R.R. Gareev, D.E. Bürgler, M. Buchmeier, R. Schreiber, P. Grünberg, Appl. Phys. Lett. 81 (2002) 1264.
[5] P. Bruno, Phys. Rev. B 52 (1995) 411.
[6] M. Fanciulli, A. Zenkevich, G. Weyer, Appl. Surf. Sci. 123/124 (1998) 207.