CEMS AND COUPLING EFFECT OF INTERLAYERS IN MULTILAYERED FeSi/Si AMORPHOUS FILMS*

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ABSTRACT

Multilayered FeSi/Si amorphous films with fixed FeSi layer thickness and different Si layer thicknesses have been studied by conversion electron Mössbauer spectroscopy at room temperature. The results showed that with decreasing the Si layer thickness, the hyperfine field of samples increased and the thickness of interface dead layers arisen from the atomic interdiffusion effect decreased. These are due to the coupling effect between the magnetic layers. When the Si layers are thinner than 0.88 nm, the direction of the magnetization is out of the film plane.

Keywords: Multilayered films Dead layers Coupling between the magnetic layers Conversion electron Mössbauer spectroscopy

1 INTRODUCTION

Coupling of interlayers in the multilayered films (MLFs) is an important and attractive problem, which directly influences the properties of MLFs. Researching the origin and variation of the coupling of interlayers is useful for controlling the properties of MLFs. In this report, the exchange coupling between the magnetic layers in the multilayered FeSi/Si amorphous films have been studied by the conversion electron Mössbauer spectroscopy (CEMS). In the FeSi/Si MLFs, the atomic interdiffusion between the magnetic and nonmagnetic layers inevitably exist because of the ion implantation effect during the sputtering process and the solubility of Fe and Si. This results in the formation of paramagnetic dead layers at the interfaces. This dead layers also affects the magnetic properties of MLFs[1,2]. When the nonmagnetic layers are thin enough, the magnetic coupling between magnetic layers is induced and strengthened with decreasing the nonmagnetic layer thickness. This influences the dead layers and the internal fields of samples. The magnetic properties of MLFs must be changed accordingly.

2 EXPERIMENTAL

Amorphous FeSi/Si MLFs were prepared by rf sputtering system with two targets.

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During the process of sample preparation, the base pressure was about 1×10^{-4} Pa, and then 99.999 % pure Ar gas was introduced. The Ar gas pressure was kept at 0.5 Pa. The rf input power was about 180 W. The substrates were glass slides of 0.2 mm thickness and were cooled by water. The deposition rates of FeSi and Si were 0.085 nm/s and 0.088 nm/s, respectively. By alternatively controlling the sputtering time of FeSi and Si, a series of samples were obtained. The thickness of the FeSi layers was fixed at 1.7 nm, while the Si layers varied from 0.88 nm to 10.1 nm. The total number of bilayers was 40 for all samples. Single FeSi films were also prepared for comparison. The composition of FeSi films determined by the electron microprobe analysis was $Fe_{80.5}Si_{19.5}$. This is the inferior limit of the composition where the amorphous feature is observed[3]. No crystalline peak was observed for single FeSi films from X-ray diffraction measurement. High angles X-ray diffraction showed that all samples were amorphous. The Bragg peaks due to the modulated structure were observed in the low angle region for all samples. Four orders of diffraction peaks can be seen mostly. It indicated that all samples have good modulated structures. The modulated wavelengths of samples calculated by using Bragg diffraction law were in good agreement with the design values according to the deposition rates and the deposition time of FeSi and Si. The error was within 5%. Conversion electron Mössbauer spectra of samples were recorded at room temperature by using a gasflow (CH_3COCH_3) proportional counter, a 1.85×10^8 Bq ^{57}Co/Rh source (in the constant acceleration mode), and an 1024 channel multichannel analyzer. The spectrometer was calibrated with a standard α - Fe foil.

3 RESULTS AND DISCUSSION

Fig.1 shows the Mössbauer spectra of FeSi/Si MLFs samples with different thickness of the Si layers and a single FeSi film. For FeSi/Si MLFs, the spectra can be roughly divided into two subspectra: One is a ferromagnetic sextet spectrum which originated from the ferromagnetic part in FeSi layers. Since the samples were amorphous, the lines are broadened. Another one is a paramagnetic spectrum originated from the nonmagnetic part at the interfaces, i.e., the dead layers. The spectra were fitted with above two subspectra by using the Meisel's method[4] on a PDP11/34 computer system. The fitting curves are shown as the solid curves in Fig.1. The data of the Mössbauer spectra are listed in Table 1. As shown in Table 1, with decreasing the thickness of the Si layers (d_s), the hyperfine field of samples (H_f) increases, while the percentage of the paramagnetic component (α_p) decreases and so does same effect on the thickness of the dead layers (d_p) which is defined as ($d_m \cdot \alpha_p$). Here d_m is the thickness of the FeSi layers, in our case, $d_m = 1.7$ nm. The parameters of the paramagnetic subspectrum (the isomer shift (IS) of about 0.22mm/s (vs α - Fe), the

quadrupole splitting (QS) of about 0.65 mm/s and the line width (LW) of about

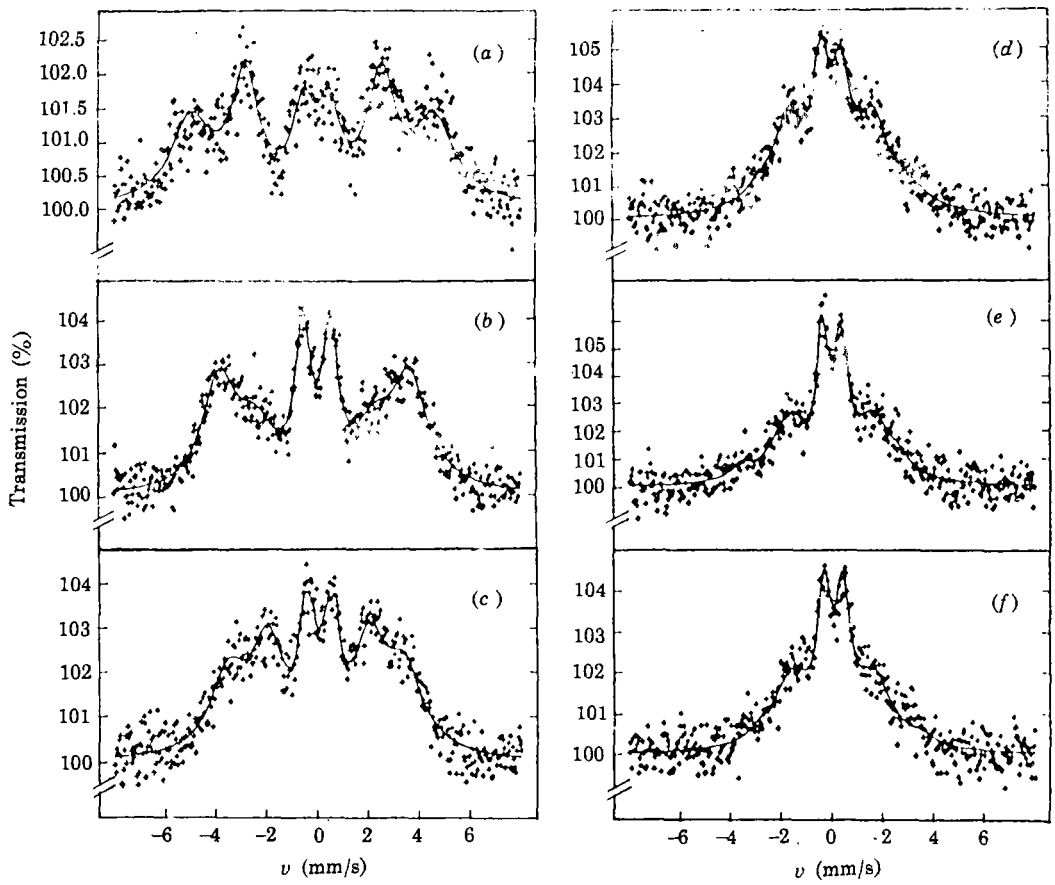

Fig.1 Conversion electron Mössbauer spectra at room temperature for a single FeSi film (*a*) and FeSi/Si MLFs in which the Si layer thickness d_s=0.88 (*b*), 1.32 (*c*), 2.64 (*d*), 5.3 (*e*), 10.1 (*f*)nm, respectively

Table 1

CEMS data of the amorphous FeSi/Si MLFs*

		Ferromagnetic component			Paramagnetic component				
	d_s	H_f	Γ_{16}	δ	IS	QS	LW	α_p	d_p
Spectrum	(nm)	($10^6/4\pi$ ·A/m)	(mm/s)	(mm/s)	(mm/s)	(mm/s)	(mm/s)	(%)	(nm)
Fig.1 (*a*)* *	–	289.69	0.98	0.07	–	–	–	–	–
Fig.1 (*b*)	0.88	225.87	0.80	0.17	0.22	0.65	0.35	4.06	0.069
Fig.1 (*c*)	1.32	208.22	0.82	0.19	0.24	0.63	0.32	12.39	0.211
Fig.1 (*d*)	2.64	195.26	0.84	0.22	0.21	0.72	0.36	16.80	0.286
Fig.1 (*e*)	5.30	192.30	0.87	0.23	0.21	0.68	0.31	18.01	0.306
Fig.1 (*f*)	10.1	190.82	0.85	0.23	0.22	0.62	0.34	18.50	0.314

* Γ_{16} is the line width of the first or sixth line and δ is the IS of the ferromagnetic subspectrum, δ and IS vs α – Fe * * Single FeSi film with a thickness of 137 nm

0.35 mm/s) are independent of the Si layer thickness. They are the same as those of the

FeSi/Si MLFs with different FeSi layer thickness[1], and close to those obtained from $Fe_{50}Si_{50}$ amorphous films reported by Oswald *et al.*[5] This indicates that for the FeSi/Si MLFs with different FeSi or Si layer thicknesses, the Fe atoms in the dead layers are in the same chemical circumstances and geometric structures which are similar to those in the amorphous $Fe_{50}Si_{50}$ films.

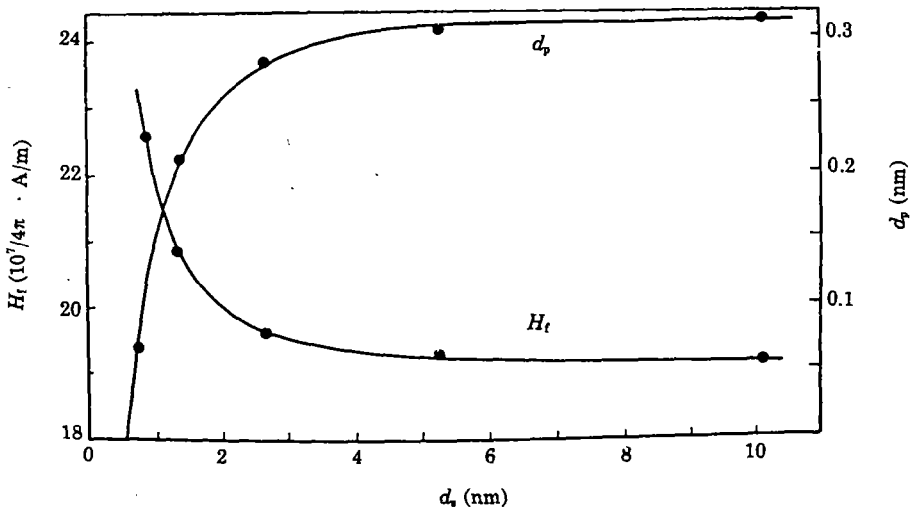

Fig.2 Hyperfine field H_f and the thickness d_p of the dead layers as a function of the thickness d_s of the Si layers

Fig.2 shows the hyperfine fields of samples (H_f) and the thickness of the dead layers (d_p) as a function of the thickness of Si layers (d_s). When the Si layers are thicker than 3 nm, the values of H_f and d_p change slightly with varying of d_s. When d_s becomes smaller than 3 nm, the thickness of dead layers decreases rapidly and the hyperfine field of samples increases rapidly. When d_s reduces to a certain value, the thickness of dead layers decreases to zero. It indicates that there is a coupling between the magnetic layers when the Si layers are thin enough. This coupling includes the dipolar and exchange interactions of magnetization in the magnetic layers through the barrier of Si layers, and the exchange interaction of magnetic moments of the Fe atoms in the interfaces through the Fe atoms which are inevitably introduced into the Si layers by sputtering process. Due to the atomic interdiffusion of interlayers which mainly came from the ion implantation effect during the sputtering process, a dead layer, which consists of the paramagnetic clusters of iron atoms, and a weak magnetic transitional layer with lower concentration of iron atoms, would be formed at the interfaces. When the Si layers are thick enough, the coupling between FeSi layers is very weak and even isolated, the magnetic properties of samples are mainly determined by the individual FeSi layers. When the Si layers are thin enough,

the coupling between the magnetic layers strengthens rapidly. This results in decreasing the number of paramagnetic iron atoms in the dead layers, and the enhancement of the magnetic moments of iron atoms in the weak magnetic transitional layers. Therefore, the thickness of the dead layers decreases and the hyperfine field of samples increases. The magnetic measurements have been shown that the saturation magnetization M_s of FeSi/Si MLFs has the same variation tendency as H_f, i.e., M_s increases with decreasing d_s rapidly when $d_s < 3$ nm[6]. This is the influence of the coupling of interlayers on the magnetic properties of MLFs.

In the Mössbauer spectra with six lines, the relative peak intensity of the second or fifth line to others reflects the angle between the directions of the hyperfine field and γ -rays. We can see from Fig.1 (*b*) that, for the sample with Si layers as thin as 0.88 nm, the peak intensity of the second or fifth line in the Mössbauer spectrum is much lower than others but, for other samples with thicker Si layers, the peak intensity of the second or fifth line is higher than that of the first or sixth line as shown in Fig.1. In order to identify this difference, we inspected the magnetic properties of various samples with different Si layer thicknesses and found that the sample with Si layers as thin as 0.88 nm has a perpendicular anisotropy as large as 3×10^4A/m (measured by the hysteresis loop and the magnetic torque), but the others do not have this anisotropy or only have a very small anisotropy. This proved that the difference between the relative peak intensities of Mössbauer spectra is caused by the difference between the magnetization directions of the samples with respect to the γ -ray direction. For the sample with Si layers as thin as 0.88 nm, the direction of magnetization is out of the film plane, but for the others it is in the film plane. The origin of this perpendicular anisotropy is not clear yet. It seems that this anisotropy is different from the surface (or interface) anisotropy proposed by Néel[7] and Gradmann[8] and is probably related to the coupling of interlayers.

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