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Irradiation Effects in Fe/Si and Fe/FeSi Multilayers

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Fe/Si and Fe/FeSi multilayers (MLs) have been irradiated by 400 keV Ar ions in order to investigate interfacial structures of Fe/Si MLs inducing antiferromagnetic coupling (AFC) nature. The Ar ion irradiation up to 1×10^{14} ions/cm^2 leads to a change from AFC nature to ferromagnetic nature and a decrease of magnetoresistance (MR) ratio in both MLs. The measurements of conversion electron Mössbauer spectroscopy (CEMS) shows a decreasing relative intensity of FeSi alloy assumed with a CsCl structure and a decreasing averaged hyperfine field with increasing ion fluence. These decreasing values with increasing ion fluence indicate a interdiffusion of Fe/Si and Fe/FeSi interface region by the irradiation. This interdiffusion causes a formation of magnetic Fe-rich $Fe_{1-x}Si_x$ phases from nonmagnetic $Fe_{1-x}Si_x$ phases in the interface region, by which suppresses the AFC nature.

Key words: GMR, irradiation, interface, multilayers, CEMS

1. INTRODUCTION

Fe/Si multilayers (MLs) show an antiferromagnetic couplings (AFC) between Fe layers depending on layer thickness of Si spacers [1]. In addition, atomic mixing in Fe/Si interface regions occurs easily even at room temperature. It has been suggested that this interdiffusion induces a nonmagnetic metallic metastable iron silicide phase with a CsCl structure which 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 have two antiferromagnetic maxima at 1.2 nm and 2.6 nm of spacer thickness [2]. Therefore, they concluded the AFC nature in Fe/FeSi MLs like Fe/Cr MLs or Co/Cu MLs. 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 [3]. Gareev et al. also have reported the AFC nature of $Fe/Fe_{1-x}Si_x$-wedge/Fe trilayers and $Fe/Fe_{0.5}Si_{0.5}$/Si-wedge/$Fe_{0.5}Si_{0.5}$/Fe structures [4, 5]. They have shown that 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. However, the $Fe_{1-x}Si_x$ phases of Fe/Si MLs induced by interdiffusion is still unclear.

In this paper, we have performed 400 keV Ar ion irradiation for Fe/Si MLs and Fe/FeSi MLs in order to investigate interfacial structures of Fe/Si MLs which induce the AFC nature.

2. EXPERIMENS

[Fe (2nm)/Si (1nm)]$_{30}$ MLs and [Fe (2nm)/FeSi (1.1nm)]$_{30}$ MLs were prepared on high resistive n-type (100) Si substrate by 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 are 0.05 and 0.068 nm/sec, respectively. The FeSi layer was formed by co-sputtering of Fe and Si targets. The structural and magnetic properties were observed by X-ray diffraction (XRD) using CuKα radiation and vibrating sample magnetometer (VSM) up to 1.5 T. 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 square fitting assuming overlapped Lorentzian curves of singlet peak and sextet peaks. The distribution of hyperfine field is assumed for peak widths of sextet peaks. 400 keV Ar ion irradiation was performed by AIST 400 keV ion implanter with the beam current less than 0.25 μA. The ion range of 400 keV Ar ion in [Fe (2nm)/Si (1nm)]$_{30}$ MLs and [Fe (2nm)/FeSi (1.1nm)]$_{30}$ MLs were estimated to be 364 nm and 338 nm by TRIM code, respectively. Therefore, all Ar atoms stop at the Si substrate.

3. RESULTS and DISCUSSION

Fig.1 shows XRD patterns of Fe/FeSi MLs before and after irradiation. The layered structure was confirmed by the observation of satellite peaks in the XRD patterns. The periods in the layered structure before and after irradiation were estimated to be 3.069 nm and 3.072 nm, respectively. These values are almost same irrespective of irradiation. However, the values of peak position in the XRD patterns were shifted the lower angle side after irradiation. This behavior implies the change of interfacial structure by the irradiation although the period of layered structure does not change. We have reported previously that 400 keV Ar ion irradiation does not change the XRD patterns of Fe/Si MLs [6]. This difference seems to be due to different interfacial structures between Fe/Si MLs and Fe/FeSi MLs. Fig.2 is the magnetization curves of Fe/Si MLs and Fe/FeSi MLs before and after irradiation. As seen in Fig.2, both MLs before irradiation have shown the AFC nature. The remanent component of the magnetization

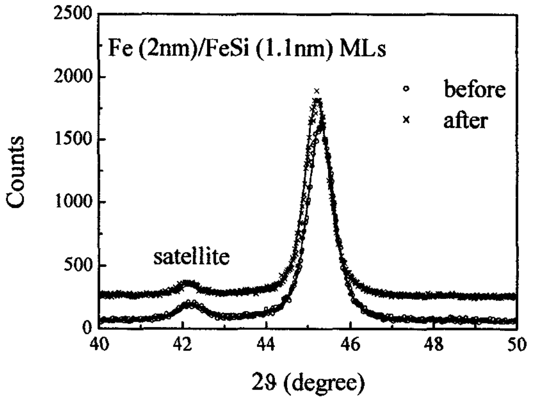

Fig.1 X-ray diffraction patterns of Fe (2nm)/FeSi (1.1nm) MLs before and after 400 keV Ar ion irradiation.

curve in Fe/Si MLs is larger than that of Fe/FeSi MLs, but the saturation field seems to be higher than that of Fe/FeSi MLs. As reported by Graeev et al. [4], Si spacers correspond to stronger AFC nature of Fe/Si MLs compared with Fe/FeSi MLs. The magnetization curves of Fe/Si MLs and Fe/FeSi MLs after irradiation changed from AFC nature to ferromagnetic nature depending on the ion fluence. In Fig.2, the magnetization of Fe/Si MLs after 1×10^{14} Ar ions/cm^2 saturated near 0 T whereas the magnetization of Fe/FeSi MLs saturated near 0.25 T.

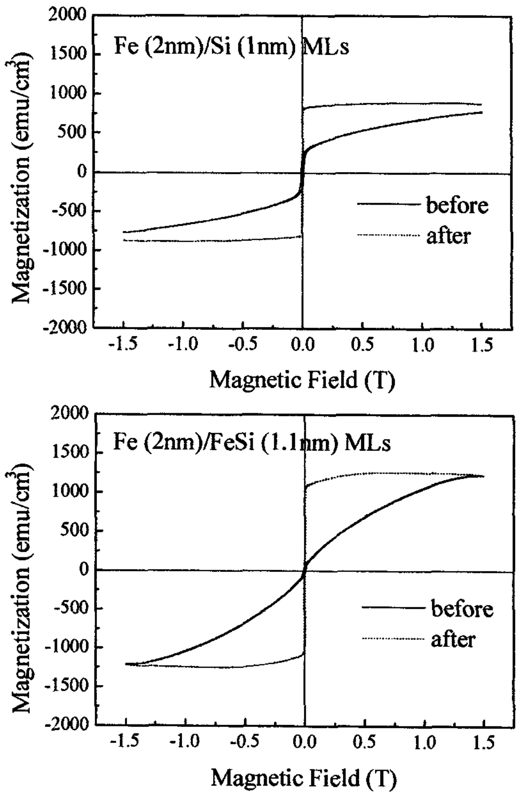

Fig.2 Magnetization curves of Fe (2nm)/Si (1nm) MLs and Fe (2nm)/FeSi (1.1nm) MLs before and after 400 keV Ar ion irradiation.

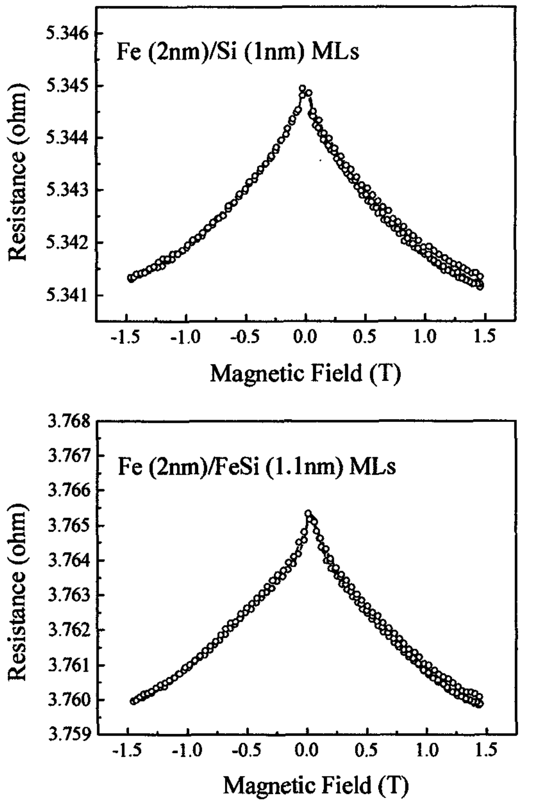

Fig.3 Magnetoresistance curves of Fe (2nm)/Si (1nm) MLs and Fe (2nm)/FeSi (1.1nm) MLs before 400 keV Ar ion irradiation.

This result also indicates the different interfacial structures between Fe/Si MLs and Fe/FeSi MLs. The values of saturated magnetization of Fe/Si MLs and Fe/FeSi MLs after irradiation are roughly 900 emu/cm^3 and 1300 emu/cm^3, respectively. The smaller values than the bulk α-Fe (1700 emu/cm^3) means rough or interdiffused interfacial structures of Fe/Si MLs and Fe/FeSi MLs. The smaller saturated magnetization of Fe/Si MLs than Fe/FeSi MLs indicates that the interfacial structures in Fe/Si MLs are more rough or interdiffused than Fe/FeSi MLs. Fig.3 shows the MR curves of Fe/Si MLs and Fe/FeSi MLs before irradiation. The MR ratios ($-(\rho_{1.5} - \rho_0)/\rho_0$, which $\rho_{1.5}$ and ρ_0 are resistance at 1.5 T and 0 T.) of Fe/Si MLs and Fe/FeSi MLs decrease with ion fluence; from 0.07 % to 0.05 %, 0.04 % and from 0.14 % to 0.09 %, 0.04 %, for the ion fluence of 0, 3×10^{13}, 1×10^{14} ions/cm^2, respectively. The decrease of MR ratio in Fe/Si MLs and Fe/FeSi MLs after irradiation corresponds to the change from AFC nature to ferromagnetic nature. Fig.4 is CEM spectra of Fe/Si MLs and Fe/FeSi MLs before irradiation, which indicate the existence of a nonmagnetic peak with ferromagnetic sextet peaks. The estimated hyperfine parameters of Fe/Si MLs and Fe/FeSi MLs before and after irradiation are listed in Table I. As shown in Fig.4, the CEM spectrum of Fe/FeSi MLs before irradiation shows a good fitting by singlet peak overlapped with sextet peaks, while the fitting of CEM spectrum in Fe/Si MLs seems to be not enough near 0 mm/sec. As listed in Table I, the averaged hyperfine field (B_{hf}) of Fe/FeSi

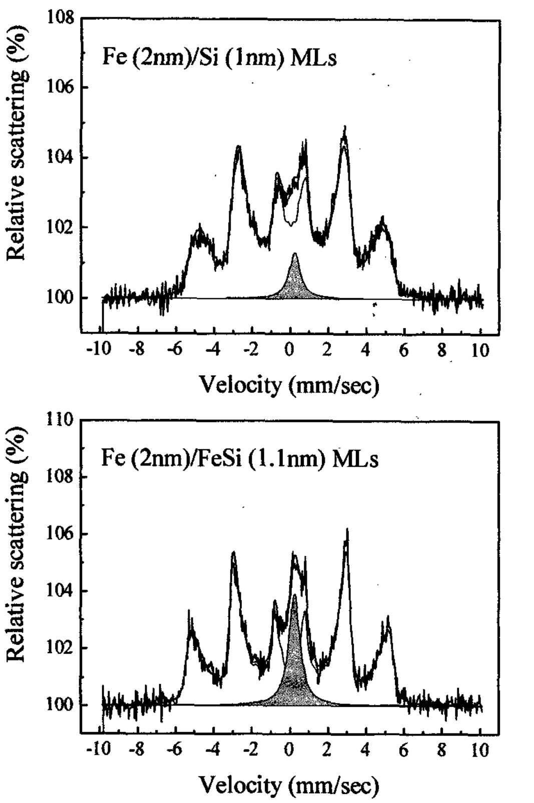

Fig.4 CEM spectra of Fe (2nm)/Si (1nm) MLs and Fe (2nm)/FeSi (1.1nm) MLs before 400 keV Ar ion irradiation.

Table I The hyperfine parameters of Fe (2nm)/Si (1nm) MLs and Fe (2nm)/FeSi (1.1nm) MLs before and after irradiation of 400 keV Ar 3×10^{13}, 1×10^{14} ions/cm^2, which are isomer shift (δ), averaged hyperfine field (B_{hf}) and relative intensities (I_{sin} and I_{sex}) of singlet and sextets. Isomer shifts are given relative to α–Fe. The isomer shift of singlet is fixed, which are estimated from fits to FeSi (60nm)/Fe (2nm) bilayers.

	singlet		sextets		
	δ (mm/s)	I_{sin} (%)	δ (mm/s)	B_{hf} (T)	I_{sex} (%)
Fe/Si					
before	0.25	5.5	0.05	23.0	94.5
3E13	0.25	4.4	0.05	22.4	95.6
1E14			0.06	21.5	100
Fe/FeSi					
before	0.25	15.3	0.01	25.9	84.7
3E13	0.25	8.4	0.02	24.2	91.6
1E14	0.25	4.9	0.03	22.8	95.1

MLs before irradiation is larger than that of Fe/Si MLs before irradiation and the isomer shift (δ) of sextets in Fe/Si MLs is larger than that of Fe/FeSi MLs. The values of B_{hf} and δ in α–Fe is 33 T and 0 mm/sec, respectively. Therefore we can guess that the interface region in Fe/Si MLs has more rough or interdiffused structures than Fe/FeSi MLs. Both values of B_{hf} and relative intensities of singlet peak in Fe/Si MLs and Fe/FeSi MLs decrease with increasing ion fluence. In addition, the values of δ increase with increasing ion fluence. These results show that the nonmagnetic phases change to the ferromagnetic phases due to the interdiffusion in the interface region by the irradiation, by which the values of B_{hf} decrease and the values of δ increase depending on the ion fluence. Therefore, we conclude that the interfacial structures of Fe/Si MLs before irradiation are more complex than Fe/FeSi MLs and the irradiation induces magnetic $Fe_{1-x}Si_x$ phases from nonmagnetic $Fe_{1-x}Si_x$ phases in the interface region.

4. CONCLUSION

Fe (2nm)/Si (1nm) MLs and Fe (2nm)/FeSi(1.1nm) MLs were irradiated by 400 keV Ar ions in order to investigate the interfacial structures of Fe/Si MLs inducing the AFC nature. The interfacial structures of Fe/Si MLs before irradiation are different with that of Fe/FeSi MLs. The Ar ion irradiation induces the formation of magnetic $Fe_{1-x}Si_x$ phases from the nonmagnetic $Fe_{1-x}Si_x$ phases in the interface region of Fe/Si MLs and Fe/FeSi MLs, which causes to suppress the AFC nature.

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