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Observation of Magnetic Depth Profiles for C Cluster Ion Irradiated FeRh Thin Films with Depth-resolved X-ray Magnetic Circular Dichroism

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1 Introduction

Equi-atomic FeRh is known to exhibit a first order phase transition from anti-ferromagnetic to ferromagnetic around room temperature. It was revealed that ion beam irradiation induced the ferromagnetic state below room temperature, which was mainly determined by elastic deposition energy by ion irradiation.[1-3] According to our previous studies on Au cluster ion beam irradiation for FeRh thin films, however, we revealed that the magnetic moment of the sample irradiated with the Au3 cluster ion was larger than that of the sample irradiated with the Au single ion especially in the surface region of the samples, even when the same number of Au ions were irradiated.[4] Considering these results, the cluster ion irradiation is possibly considered to be a method to effectively deposit the ion irradiation energy at the surface region, which may accelerate the magnetic phase transition from AFM to FM. In the present studies, we examined the effect of carbon cluster ion beam irradiation on the depth profile of magnetization in the surface of FeRh thin films by depth-resolved technique in the x-ray magnetic circular dichroism (XMCD).

2 Experiment

Iron-Rhodium thin films about 50 nm thick were fabricated by using ion beam sputtering of Fe50Rh50 target on MgO(100) substrates. Then the samples were irradiated with 1 MeV C2 cluster ion and 0.5 MeV C1 ion beam at room temperature by using the ion beam facilities at Quantum and Radiological Science and Technology (QST)-Takasaki. The ion fluence was determined to be 1.5×10^{14} C/cm^2 and 4.5×10^{14} C/cm^2. When the ion fluence C is 4.5×10^{14} C/cm^2, the maximum irradiation induced magnetization for FeRh is produced for the 0.5 MeV irradiation sample. The magnetic properties were characterized by a superconducting quantum interference device (SQUID) magnetometer as well as x-ray magnetic circular dichroism (XMCD) measurements in total electron yield mode (TEY). In spite that the SQUID measurement evaluates whole magnetization of the thin film samples, the XMCD measurement sensitively evaluates the surface region (~3 nm) of the thin film samples. Furthermore, a depth-resolved XMCD measurement was also performed to evaluate the depth profile of ion beam irradiation induced ferromagnetism for the samples. Depth-resolved XMCD technique provides depth-resolved magnetic moments through the XMCD signals with different probing depths by collecting the emitted electron at various detection angles. Both TEY and depth-resolved XMCD measurements were carried out at Beam Line #16A at Photon Factory in High Energy Accelerator Research Organization (KEK-PF).

3 Results and Discussion

The observed magnetic moment per Fe atom, which can be calculated from the result of the SQUID and XMCD measurements in TEY mode, is shown in Fig. 1. The magnetic moment data from the XMCD measurements were estimated by using sum rule analysis. As can be seen in the figure, the SQUID measurement data for the C1 and C2 samples irradiated with 1.5×10^{14} C/cm^2, were almost the same, which suggests that the entire magnetic moment (from surface to 50 nm) of the samples are almost identical. On the other hand, from the viewpoint of the evaluation of the surface region of the samples (to about 3 nm), the corresponding magnetic moment values from the XMCD measurements (TEY) are totally different. That is, the magnetic moment of the C2 irradiation sample is larger than that for the C1 irradiation sample, which means that the C2 cluster ion irradiation induced larger surface magnetic moments (~3 nm) rather than the C1 ion irradiation. With increasing in the

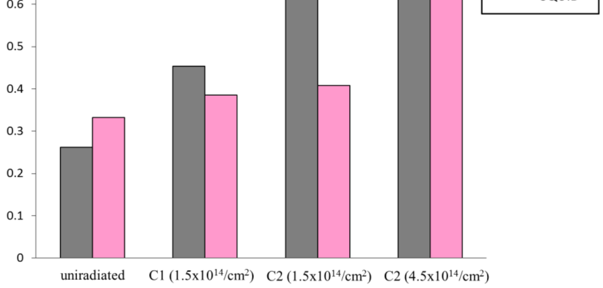

Fig. 1: Magnetic moment for the unirradiated and irradiated samples with the C1 ion under the ion fluence of 1.5×10^{14} C/cm^2, C2 cluster ion of 1.5×10^{14} C/cm^2, 4.5×10^{14} C/cm^2.

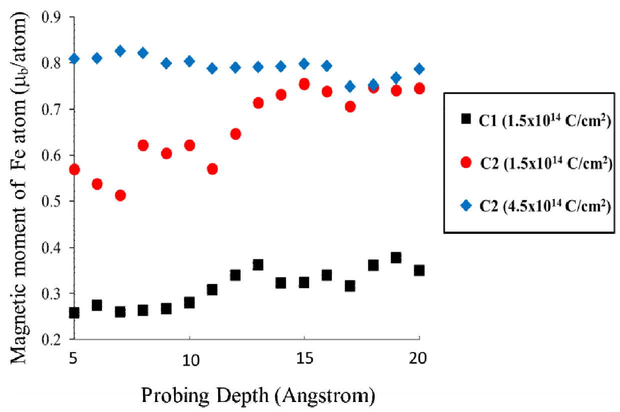

Fig. 2: Probing depth dependence of magnetic moment of Fe atom for irradiated samples under the fluence of $1.5x10^{14}$ C/cm^2 and $4.5x10^{14}$ C/cm^2.

irradiation fluence of C2 cluster ion, the magnetic moment measured by SQUID is found to increase, whereas that by XMCD is unchanged. These results show that the cluster ion irradiation can effectively modify the magnetization at the surface region, which is significantly consistent with the past experimental results on the Au cluster ion beam irradiation for FeRh thin films.[5]

In order to analyze the surface region of the samples irradiated with C1 ion and C2 cluster ion in detail, we performed the depth-resolved XMCD measurements. Figure 2 shows the probing depth dependence of the magnetic moment for the irradiated samples with C1 and C2 cluster ions. The plotted values of the magnetic moment at each depth can be attributable to the average magnetic moment from surface to each depth. As clearly seen in the figure, the different profiles of the magnetic moments can be observed for each irradiated sample. Even from the results of the depth-resolved XMCD measurements, the absolute values of the average magnetic moment of each sample up to 20 nm in depth, exhibit quite well consistence with the results of the TEY mode measurements. However of this, it should be noted that depth profile of each sample significantly depends on the cluster ion number as well as the ion fluence. In the case of the sample irradiated with C1 ions, the magnetic moment increases with increasing the depth. Hereby the magnetic moment of the C2 irradiated sample shows a steep increase with increasing the depth, then gradually saturates from 15 nm region in the depth. In contrast to this, the magnetic moment decreases as the probing depth increases for the C2 cluster ion irradiated sample with larger ion fluence ($4.5x10^{14}$ C/cm^2).

In order to evaluate this behavior quantitatively, the model in which the 8 layers (n=8, in the following formula) having some amplitude of the magnetization in the surface region of the samples was considered. Each layer is assumed to be 0.2 nm thick. In this model, the detected XMCD signal at probing depth x, $y(x)$, is represented by the following formula:

$$y(x) = \frac{M(top) + \sum_{j=2}^{n} M(j) \cdot exp\left(-\frac{(j-1)a}{x}\right)}{\sum_{j=1}^{n} exp\left(-\frac{(j-1)a}{x}\right)}$$

where 'x' and 'a' denote the probing depth and interlayer distance, respectively. $M(top)$ is a most surface layer of the film that is always considered to be 0 μ_b /atom, since it is impossible to accurately measure the XMCD signal at the ultra-surface layer (~0.2 nm), due to the effects of oxidation, adsorption atoms at surface and so on.

By using this model, we have tried to fit the depth dependence curves of the magnetization determined by the XMCD measurements. Here, it is worthwhile reminding that the irradiation induced magnetization of FeRh is significantly correlated with the deposition energy through the elastic collisions between the sample and ion species.[3] According to the knowledge from the previous experiments, the irradiation induced

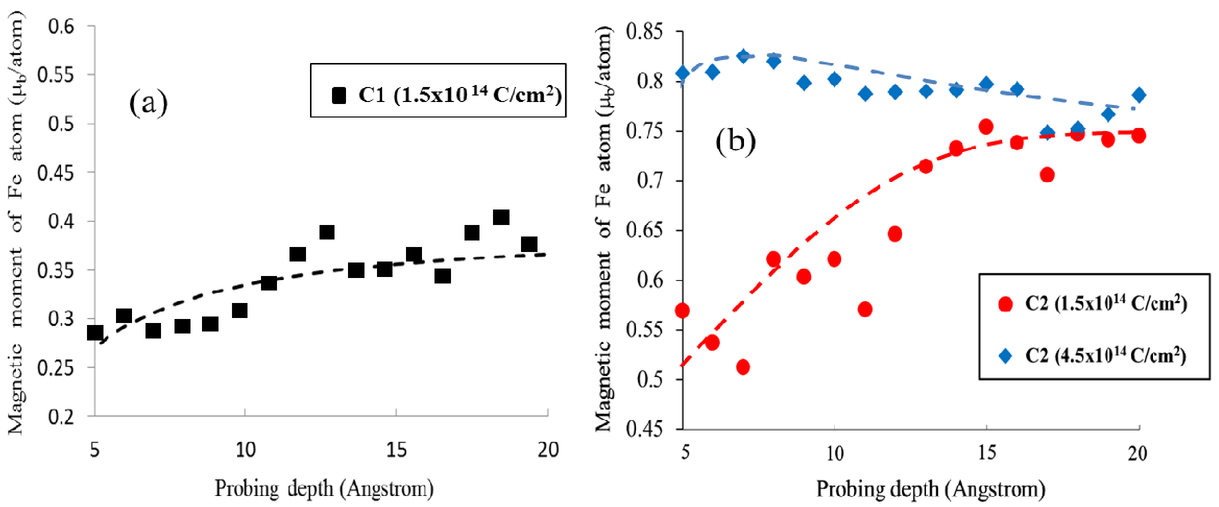

Fig. 3: Probing depth dependence of the magnetic moment of Fe atom for irradiated samples with (a) C1 ion and (b) C2 cluster ion. The dotted lines represent the simulation result, which details are written in text.

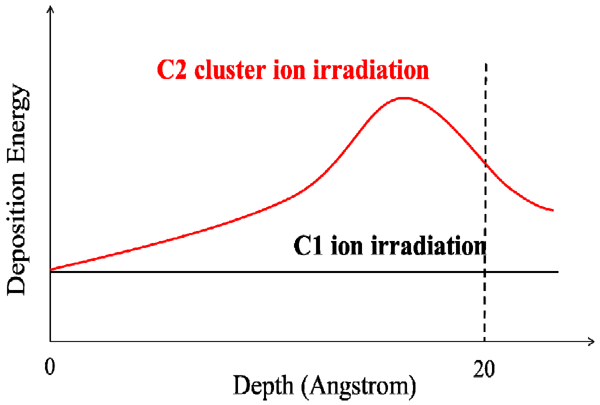

Fig. 4: Estimated depth profile of the apparent deposition energy by elastic collisions.

ferromagnetism is well known to be almost linearly increase with increasing the deposition energy, at the initial stage of the irradiation. Then further increase in the deposition energy causes the saturation of the irradiation induced ferromagnetism, followed by the decrease of it.[3] It should be mentioned here, that the deposition energy by ion beam irradiation was calculated by the TRIM simulation using the Monte Carlo method.[6]

In case of the C1 ion irradiation, the deposition energy can be plausibly estimated by using the TRIM simulation. Since almost uniform energy is calculated to be deposited regardless of the depth from surface (~ 50 nm), the irradiation induced ferromagnetism at this region (M(j)) can be regarded to be constant values. By using these parameters, the simulation result shows the upward-sloping probing depth dependence of the magnetic moment. That is, the depth dependence profile of the C1 irradiated sample can be suitably fitted as a broken line that is shown in Fig. 3(a).

Next, we consider the C2 cluster ion irradiation case. In order to account for the behavior of the depth profile indicated in Fig. 2, it is indispensable to assume that the magnetic moment of each layer ($M(j)$) should have a peak somewhere. When we consider the previous relation between the magnetization and the deposition energy, it can be concluded that the depth dependence of the apparent deposition energy must be the curve as is indicated in Fig. 4. By assuming such curve, the behavior of the C2 irradiated samples both with small and large influence, which are indicated in Fig. 3(b), can be fairly well explained by broken fitting curves in the figure.

Accordingly, it can be concluded that the cluster ion irradiation effectively causes the ion irradiation induced ferromagnetism. By using this technique suitably, the surface magnetic ordering state can designedly modified. Although it is still unknown that the cluster ion irradiation can deposit the relatively larger elastic collision energy at the surface region rather than single ion beam or not, it can conclude that the cluster ion beam is possible to deposit apparent elastic collision energy effectively. The detailed mechanism of such behavior as well as the experimental results on the irradiation effect for C cluster ion with increased cluster number, will be discussed

Acknowledgement

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