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THE EFFECTS OF Sm ON THE MICROSTRUCTURE AND MAGNETOSTRICTION OF Fe-Co ALLOYS

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Abstract-We investigated the effects of Sm on the microstructure and magnetic properties of Fe-Co alloy films prepared by a DC triode sputtering. The magnetostriction was found to be changed with the Sm content from positive to negative values, taking a zero magnetostriction was at about 3 at% Sm. The Sm content dependence of magnetostriction was explained by the formation of Sm enriched amorphous phase surrounding the main bcc (Fe,Co) crystalline phase, which was observed by a high resolution transmission electron microscopy.

I. INTRODUCTION

The magnetostriction and magnetocrystalline anisotropy are main factors for determining magnetic properties of a material and it is therefore important to control them properly in order to obtain a magnetic material with desired properties. As confirmed in the nanocrystalline soft magnetic materials, the magnetocrystalline anisotropy can effectively be reduced by decreasing the grain size at a level smaller than the ferromagnetic exchange length [1, 2]. This suggests there is a possibility to use Fe-Co alloys as a soft magnet with strong magnetization. The remaining task is, however, to control the magnetostriction.

It is well known that Fe-Co alloys have higher saturation magnetization values than the constituent elements, the maximum being 2.4 T [3,4]. However, since the magnetostriction of the alloys is very large (about $+40 \times 10^{-6}$ [5]), the wide spread use of the alloys, except for some particular applications, has been hindered. It is therefore desirable to design new Fe-Co alloys with low magnetostriction but still having high saturation magnetization. Some studies have been made on the addition of metalloid elements to Fe-Co alloys and it has been found that a large amount of these elements should be added to obtain the zero magnetostriction, which leads to a drastic decrease of magnetization.

Recently, we have reported that the addition of rare earth elements can reduce the magnetostriction (without a drastic decrease) at no cast of high saturation magnetization. One of the most suitable rare earth elements is Sm. This is because Fe-Co alloys exhibit positive magnetostriction and Sm possesses positive values of the Stevens factor [6], based on one ion models [7], which tends to make the magnetostriction of Sm-added alloys negative. In this study, we investigate the effects of Sm addition on the magnetic properties and the morphology of Fe-Co alloys.

II. EXPERIMENTAL PROCEDURES

The samples were prepared by a high rate DC triode sputtering [8] using Fe-Co-Sm alloy targets of 40 mm diameter. The alloy targets were prepared by arc-melting 99.9% Fe, 99.9% Co and 99.9% Sm under an Ar atmosphere. The alloy samples were deposited on Cu substrates. The base pressure was under 3.0×10^{-7} Torr and the Ar gas pressure during sputtering was 4.0×10^{-2} Torr. The distance between the target and the substrate was 20 mm. The deposition rate was about 100 nm/min. The thickness of the samples ranged from 0.1 mm to 0.2 mm. The composition of the Fe-Co-Sm samples was determined by a inductivity coupled plasma (ICP) spectroscopy. In order to accurately measure the magnetostriction and other magnetic properties of the deposited thick films only, the measurements

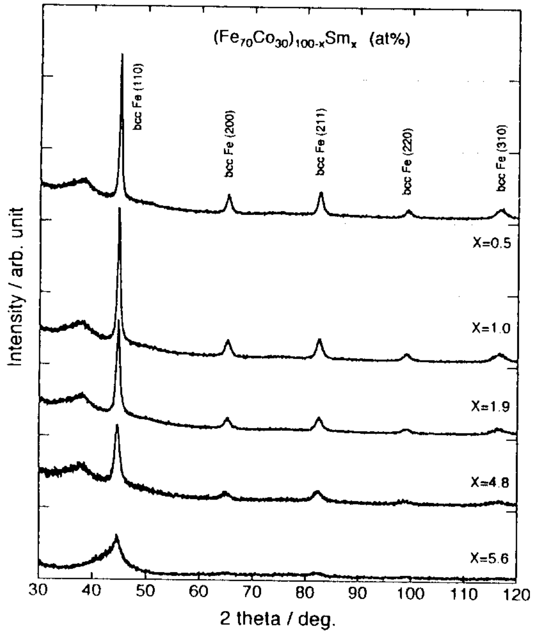

Fig.1. X-ray diffraction patterns of as-deposited Fe-Co-Sm alloy thick films.

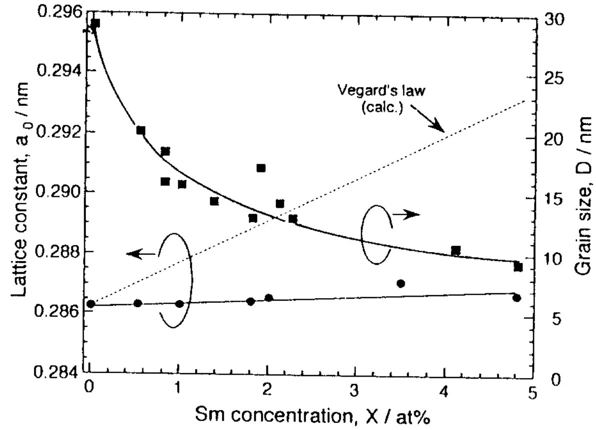

Fig.2. Sm concentration dependence of the lattice constant and the grain size of Fe-Co-Sm films. The solid circles and the solid squares denote the lattice constant and the grain size, respectively. The dotted line indicates the results for lattice constant calculated by using the Vegard's law.

were carried out after the Cu substrate was removed by dissolving it in a chromic acid solution. Magnetostriction was measured by the strain gauge method under the applied fields up to 5 kOe. The microstructure was observed by a X-ray diffractmetry using Cu K α radiation, a differential scanning calorimetry (DSC) and a transition electron microscopy (TEM). Coercivity and saturation magnetization were measured using a vibrating sample magnetometer (VSM) in the magnetic fields range up to 15 kOe.

III. RESULTS AND DISCUSSION

Figure 1 shows the X-ray diffraction patterns of as-deposited Fe-Co-Sm alloy deposites. The measurements were done in the powdered state. The maximum amount of Sm addition is 5.6 at%, in order to minimize the decrease in the saturation magnetization of $Fe_{70}Co_{30}$ alloy. It is seen from the diffraction patterns that the intensity of (110) plane of bcc Fe is very high indicating a strong preferred orientation of the plane. With increasing the Sm content, the intensity of the bcc peaks decreases. The alloy with 5.6 at% Sm was confirmed to be in the amorphous state. Neither an oxide nor an intermetallic compound phase was observed from the diffraction patterns.

Figure 2 shows the Sm concentration dependence of the lattice constant and the grain size of $(Fe_{0.7}Co_{0.3})_{100-X}Sm_X$ deposites calculated from X-ray results. The solid circles and the solid squares denote the lattice constant and the grain size, respectively. The dotted line indicates the results for lattice constant calculated by using the Vegard's law [9]. Suppose that the Sm element is soluble with Fe and Co, and exists interstitially or substitutionally in the FeCo alloys, the lattice constant must increase rapidly with the Sm content, being close to that estimated by the Vegard's law, since the radius of the RE atom is larger than Fe or Co atom. Contrary, the lattice constant observed increases only slightly with the addition of Sm up to 5at%. On the other hand, the grain size decreases drastically at about 1 at% Sm content. With the further increase in Sm concentration, the grain size decreases gradually and finally the structure becomes amorphous at 5.6 at% Sm. The present

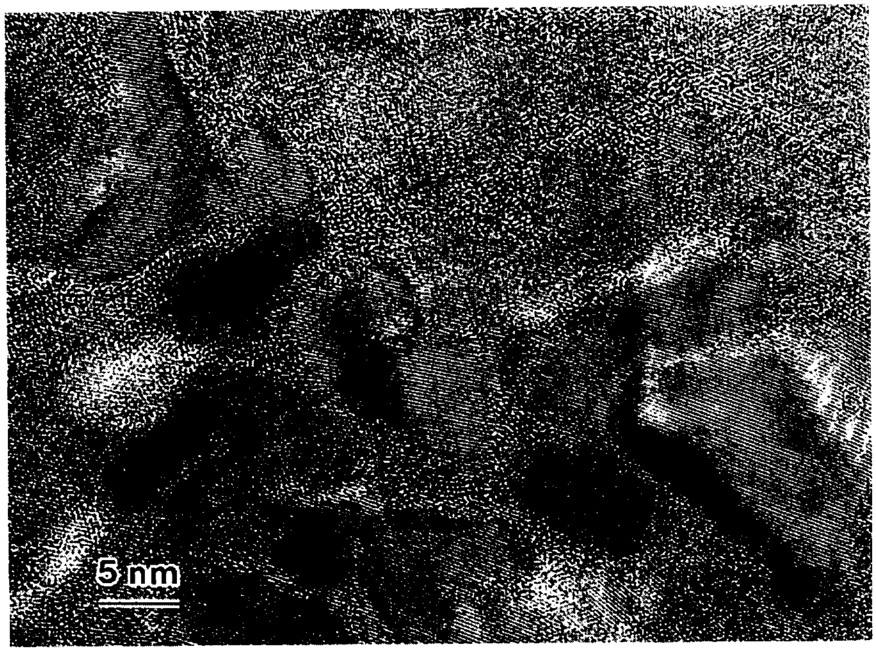

Fig.3. HRTEM images of a $Fe_{71.9}Co_{22.5}Sm_{5.6}$ (at%) film.

results clearly show that Sm addition brings about the grain refinement and, at large addition of Sm, amophization. The crystallization behavior was investigated by DSC. Alloys with less than 4.8at.% Sm does not exhibit exothermic peaks, indicating the formation of no amorphous phase.

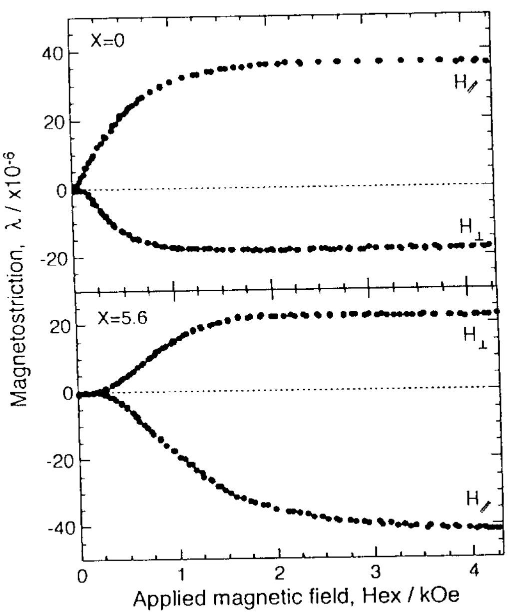

Fig.4. Field dependence of magnetostriction at room temperature for $Fe_{70}Co_{30}$ and $Fe_{71.9}Co_{22.3}Sm_{5.6}$ films.

Furthermore, high resolution (HR) TEM observation was performed in order to examine the microstructure in more detail. Figure 3 shows the HRTEM images of the Fe-Co alloy with 5.6 at.% Sm. For this alloy, only the amorphous phase was identified from XRD and it was considered to be due to the forced solid solution during sputtering. However, the HRTEM results clearly show that the alloy consists of two phases; one is crystalline phase and the other is amorphous phase. From an EDS analysis, the crystalline region is surrounded by the Sm-enriched amorphous region. It is also found that most of Sm atoms resides in the amorphous region; the Sm compositions of crystalline and amorphous regions are 3.9at% and 54at%, respectively. The actual Sm content in the crystalline phase is considered to be even smaller, since the Sm content of crystalline region is thought to be overlapped by the Sm enriched amorphousregion overestimating the Sm content of

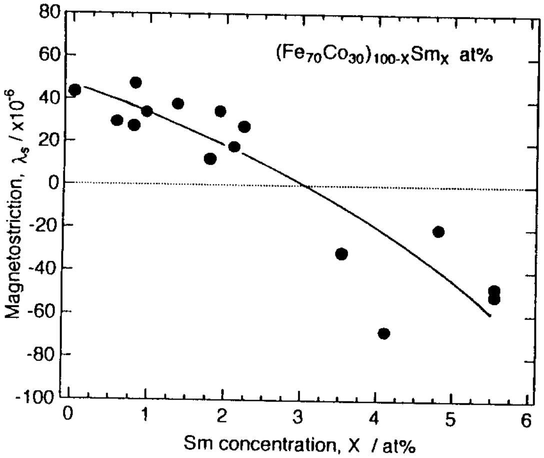

Fig.5. Sm concentration dependence of saturation magnetostriction for $(Fe_{0.7}Co_{0.3})_{100-X}Sm_X$ ($0 \leq X \leq 5.6$ at%) films.

amorphous region overestimating the Sm content of crystalline phase.

Figure 4 shows the field dependence of magnetostriction at room temperature for $Fe_{70}Co_{30}$ and 5.6at%Sm-Fe-Co deposites. The $Fe_{70}Co_{30}$ deposites show a large positive magnetostriction of about $+40 \times 10^{-6}$ and the saturation field of about 2 kOe. The addition of 5.6at%Sm to the alloy changes the sign of magnetostriction to negative and increases the saturation field to about 4.0 kOe indicating increased magnetocrystalline anisotropy of 5.6at%Sm-Fe-Co films.

The magnetostrictions of several samples were also measured. Figure 5 shows the Sm concentration dependence of saturation magnetostriction for $(Fe_{0.7}Co_{0.3})_{100-X}Sm_X$ ($0 \leq X \leq 5.6$at%) deposites. A slightly negative magnetostriction is obtained at 3.5at% Sm, indicating that a zero magnetostriction can be achieved at about 3at% Sm. The decrease in the magnetostriction of $Fe_{70}Co_{30}$ alloy with the addition of Sm may be explained by the Sm enriched amorphous phase which is known to have negative magnetostriction. Since the amount of Sm enriched phase increases with the Sm content, the magnetostriction of the combined phases is expected to decrease.

IV. CONCLUSION

The magnetostriction and microstructure of Fe-Co-Sm alloy thick films have been investigated. We have shown how the large magnetostriction value is reduced by the addition of Sm whilst keeping the high saturation magnetization. It is found from the HRTEM images and the EDS analysis that the crystalline region is surrounded by the Sm-enriched amorphous region and most of Sm atoms exist in the amorphous region. The mechanism of the magnetostriction behavior of Fe-Co-Sm alloy is thought to be the balance of the volume of positive magnetostriction of crystalline Fe-Co region and negative magnetostriction of Sm-rich amorphous region.

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