Magnetic Properties of Thin Chromium Layers in Gd/Cr and Y/Cr Multilayers Studied Using ^{119}Sn Mössbauer Spectroscopy

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Magnetism of Cr layers in Cr/Sn/Cr/Gd and Cr/Sn/Cr/Y multilayers with monatomic Sn layers grown on polyimide substrates has been studied using ^{119}Sn Mössbauer spectroscopy. The results are quite different from those for Cr/Sn multilayers without the rare-earth metals. It is suggested that the Gd and Y layers have a strong effect that makes neighboring Cr nonmagnetic.

Index Terms—**Antiferromagnetic materials, Mössbauer spectroscopy, nonhomogeneous media, rare-earth metals, transition metals.**

I. Introduction

MAGNETIC properties of thin Cr layers have been attracting scientific interest since the discovery of the giant magnetoresistance effect in Fe/Cr multilayers, where the Cr layers intermediate the magnetic coupling between the Fe layers. However, it is difficult to obtain experimentally clear information on magnetism from antiferromagnetic thin layers.

We have been studying magnetic properties of thin Cr layers using ^{119}Sn Mössbauer spectroscopy with Sn layers of about one monolayer thickness (0.2 nm) inserted in the Cr layers. Since Sn is a nonmagnetic element, we can interpret the hyperfine field (HF) induced at the Sn nucleus as reflecting the magnetic moments of Cr atoms adjacent to the Sn atom. Our previous results showed that magnetic moments of Cr in epitaxial Fe/Cr/Sn/Cr multilayers at room temperature are reduced due to magnetic frustration effects at Fe/Cr interfaces in both Fe/Cr(001)/Sn/Cr [1] and Fe/Cr(011)/Sn/Cr multilayers [2] (Fig. 1). In this paper, we present magnetic properties of Cr layers in nonepitaxial Gd/Cr and Y/Cr multilayers with ^{119}Sn probe layers, and compare the obtained results with those of the Fe/Cr multilayers.

II. Experiments

Samples were prepared on polyimide substrates at the substrate temperature of 120 to 150 K using an ultrahigh vacuum deposition system. The configurations of the samples were the following: polyimide/[Cr(2.0 nm)/^{119}Sn(0.2 nm)/Cr(2.0 nm)/Gd or Y(4.0 nm)] $\times$ 30 or 40/Cr(4.0 nm) as samples with rare-earth metals, and polyimide/[Cr(2.0 nm)/^{119}Sn(0.2 nm)] $\times$ 30/Cr(4.0 nm) as a reference sample. X-ray diffraction measurements with the scattering vector normal to the surface were performed to know the crystallographic orientation and the grain size of Cr. ^{119}Sn Mössbauer spectra were measured with the transmission geometry. The HF distributions were obtained from the least-square fitting for the spectra. Magnetization as a function of magnetic field applied in the sample plane was measured by a superconducting quantum interference device (SQUID).

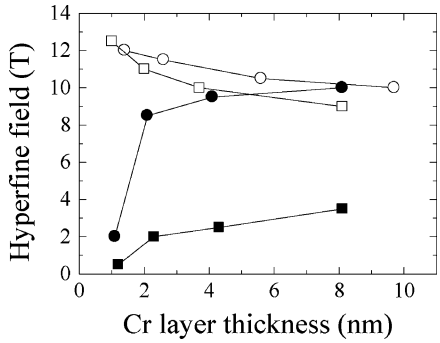

Fig. 1. Hyperfine field (HF) at Sn nuclear sites for [Sn(0.2 nm)/Cr($t_{\rm Cr}$)] $\times$ N and [Fe(1.0 nm)/Cr($t_{\rm Cr}$)/Sn(0.2 nm)/Cr($t_{\rm Cr}$)] $\times$ N multilayers, where $t_{\rm Cr}$ is the thickness of each Cr layer [2]. There are a few sites with different HFs, and the HF with the maximum distribution is plotted here. The symbols denote the data as follows: ○, Cr(001)/Sn; ●, Fe(001)/Cr/Sn/Cr; □, Cr(011)/Sn; ■, Fe(011)/Cr/Sn/Cr. The HF in the Fe/Cr/Sn/Cr multilayer is smaller than that in the Cr/Sn multilayer with the same orientation. This means that the Fe/Cr interface reduces the magnetic moment of Cr.

III. Results

Fig. 2 displays X-ray diffraction patterns for the Cr/Sn, Cr/Sn/Cr/Gd, and Cr/Sn/Cr/Y multilayers. The broad peak at around 20° and small peaks at around 18° and 25° are from the polyimide substrates. These patterns show that Cr in each multilayer was grown mainly with the (110)-orientation directed perpendicularly to the surface. It is found from Scherrer's equation applied to the Cr(110) peaks that the grain size is about 13 nm in the Cr/Sn multilayer and 5 nm in the Cr/Sn/Cr/Gd and Cr/Sn/Cr/Y multilayers. Broad peaks around 30° are from the Gd and Y layers. The Gd and Y are polycrystalline with small grain size without a strong preferred orientation.

The ^{119}Sn Mössbauer spectra with the corresponding HF distributions for the reference Cr/Sn multilayer are shown in Fig. 3. It is difficult to know the angle between the direction normal to

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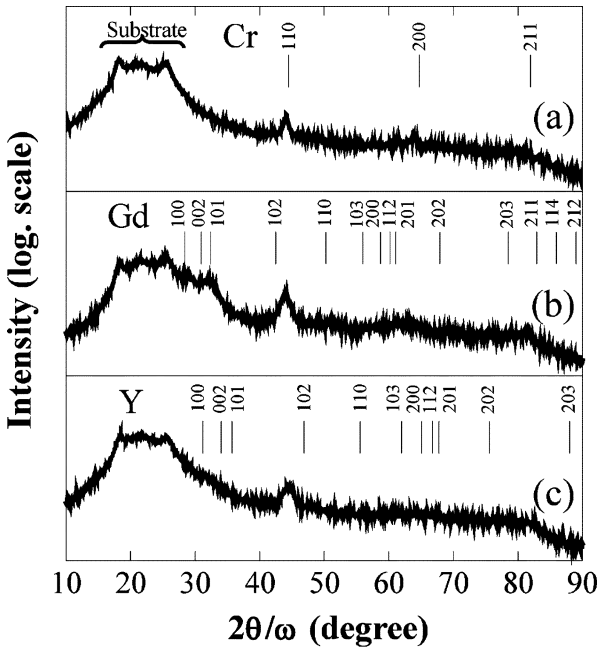

Fig. 2. X-ray diffraction patterns for (a) Cr/Sn, (b) Cr/Sn/Cr/Gd, and (c) Cr/Sn/Cr/Y multilayers. The positions of the peaks deduced from the lattice parameters of bulk Cr, Gd, and Y are indicated by vertical bars.

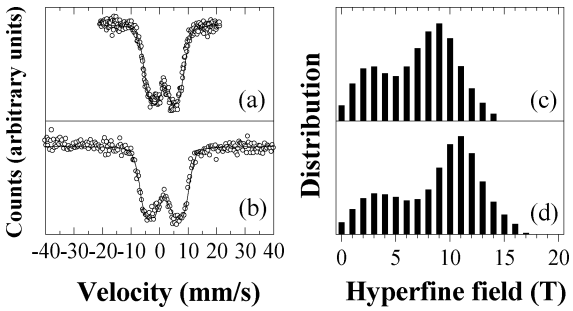

Fig. 3. ^{119}Sn Mössbauer spectra for the Cr/Sn multilayer at (a) room temperature and (b) 4.2 K with their hyperfine field distributions (c) and (d), respectively.

the surface and the direction of the HF from such spectra of a nonepitaxial multilayer. At the fitting, the initial value of the angle was set to be 54.7°, which corresponds to the random orientation of the HF. As a result of the fitting, this angle remained around 54.7°. The isomer shift for this multilayer at each temperature is found to be from 1.6 to 1.7 mm/s. These values are similar to those of Sn in Cr–Sn alloys [3]. There are two peaks in the HF distribution in Fig. 3(c) and (d). This means that there are two kinds of atomic sites of Sn at the Cr/Sn interfaces. The concrete atomic positions are not clear. The HF at maximum in distribution is 9 T at room temperature and 11 T at 4.2 K. These results indicate that Cr in this multilayer has an ordered magnetic moment at room temperature. This HF at room temperature is similar in magnitude to that of the epitaxial [Cr(2.0 nm)/Sn(0.2 nm)] multilayers with the bcc (001) and (011) orientation, where Cr has antiferromagnetic ordering [2], [4].

The ^{119}Sn Mössbauer spectra and the HF distributions for the Cr/Sn/Cr/Gd and Cr/Sn/Cr/Y multilayers are shown in Figs. 4 and 5, respectively. The isomer shift at each temperature is from 1.6 to 1.9 mm/s for the Cr/Sn/Cr/Gd multilayer and 1.7

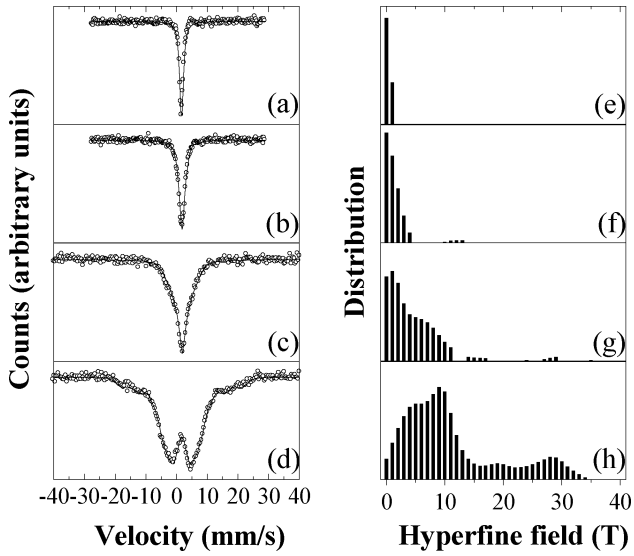

Fig. 4. ^{119}Sn Mössbauer spectra for the Cr/Sn/Cr/Gd multilayer at (a) room temperature, (b) 150 K, (c) 80 K, and (d) 4.2 K with their hyperfine field distributions (e), (f), (g), and (h), respectively.

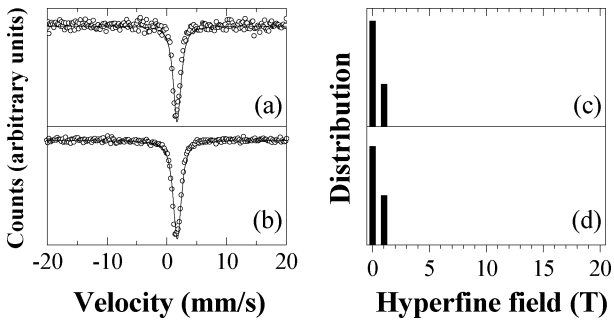

Fig. 5. ^{119}Sn Mössbauer spectra for the Cr/Sn/Cr/Y multilayer at (a) room temperature and (b) 4.2 K with their hyperfine field distributions (c) and (d), respectively.

to 1.8 mm/s for the Cr/Sn/Cr/Y multilayer. The HF is zero at room temperature in the Cr/Sn/Cr/Gd multilayer, and at both room temperature and 4.2 K in the Cr/Sn/Cr/Y multilayer. These results are in contrast to the Cr/Sn multilayer, where HF of 9 T is found at room temperature. In the Cr/Sn/Cr/Gd multilayer at 4.2 K, a large HF up to 30 T is observed, which is much larger than that in the Cr/Sn multilayer. One of the possible origins of this large HF is the spin polarization of Cr induced by the ferromagnetic Gd layers. The magnitude of the magnetic moment per Gd atom determined by means of Arrott plot of magnetization curves and the averaged HF are plotted versus temperature in Fig. 6.

IV. Discussion

In epitaxial Fe/Cr/Sn/Cr multilayers, the HFs at room temperature are smaller than those in epitaxial Cr/Sn multilayers due to the magnetic frustration between the ferromagnetic Fe layers and antiferromagnetic Cr layers [1], [2]. Simple pictures of magnetic configuration at the Fe/Cr interfaces are drawn in the [2]. On the other hand, the Y layers in the Cr/Sn/Cr/Y multilayer are expected to be nonmagnetic at all temperatures, and the Gd layers in the Cr/Sn/Cr/Gd multilayer are nonmagnetic above

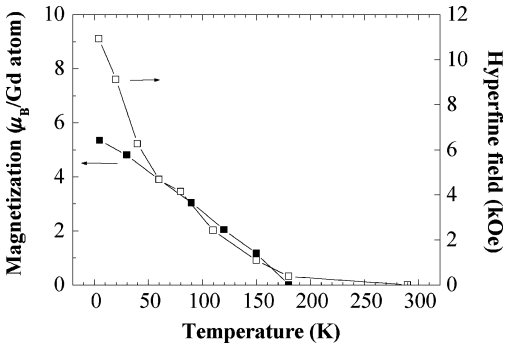

Fig. 6. Magnetic moment per Gd atom and averaged hyperfine field at Sn nucleus as functions of temperature.

180 K as shown in Fig. 6. The zero HFs in the Cr/Sn/Cr/Gd at the temperatures above 180 K and in the Cr/Sn/Cr/Y multilayers in the temperature range from room temperature to 4.2 K suggest that there is another effect to suppress the magnetic moments of Cr.

The crystal structure of Cr in the bulk state is quite similar to that of Fe [5]. The structure of Cr is bcc and the lattice parameter is 0.2884 nm at 20 °C. The structure of Fe is also bcc and the lattice parameter is 0.28664 nm at the same temperature. Hence, the magnetic behavior of the thin Fe layers embedded between the Gd and Y layers is a good reference for our Cr/Sn/Cr/Gd and Cr/Sn/Cr/Y multilayers. Thin Fe layers between Gd or Y layers have amorphous structure up to a certain critical thickness and it was attributed to the large misfit of crystalline parameters between Fe and the rare-earth metals [6], [7]. In Fe/Gd multilayers, the ^{57}Fe Mössbauer spectrum at room temperature shows broad peaks when the Fe thickness is below 2.3 nm due to an amorphous structure. The Fe structure changes to nanocrystalline one when the thickness is above 2.3 nm and a typical sextet pattern of bcc Fe appears in the Mössbauer spectra at room temperature. Also, for the Fe layer sandwiched by the Y layers, the critical thickness is 2.3 nm. When the Fe layer is thinner than 2.3 nm, it is nonmagnetic at room temperature. When it is thicker than 2.3 nm, magnetic components appear in the Mössbauer spectra.

The X-ray patterns in Fig. 2 show that Cr has a smaller grain size in the Cr/Sn/Cr/Gd and Cr/Sn/Cr/Y multilayers than that in the Cr/Sn multilayers. The effect that makes Cr nonmagnetic can be possibly related to the reduction of its grain size. However, the magnetic behavior of Cr is quite different from that of Fe. The 4-nm-thick Cr layer sandwiched by the Gd layers is nonmagnetic at least above 180 K and that sandwiched by the Y layers is nonmagnetic down to 4.2 K, although the Cr thickness of 4.0 nm between the Gd or Y layers is much larger than the critical thickness for the Fe/Gd and Fe/Y multilayers. The effect of the neighboring rare-earth metals on magnetism of Cr appears to be much stronger than in the case of Fe.

In the Cr/Sn/Cr/Gd multilayer, the magnetic moment per Gd atom and the HF are in proportion above 50 K. This can be attributed to the spin polarization in nonmagnetic Cr induced by the ferromagnetic Gd layers, which causes the increase of the HF at the Sn nuclei. Below 50 K, the HF increases more sharply than the magnetic moment per Gd atom. We speculate that the Néel temperature of the Cr layers is around 50 K and the sharp increase of HF below 50 K comes from the antiferromagnetic ordering of Cr.

V. Conclusion

We have studied the magnetic properties of the Cr layers in the Cr/Sn/Cr/Gd and Cr/Sn/Cr/Y multilayers. It was found that Cr is nonmagnetic at least above 180 K in the Cr/Sn/Cr/Gd multilayer and in the temperature range from 4.2 K to room temperature in the Cr/Sn/Cr/Y multilayer. These results come from reduction of the grain size of Cr due to the existence of the neighboring Gd and Y layers.

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