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Local exchange anisotropy of microstructured CoFe / MnIr (001) bilayers

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Abstract. Molecular beam epitaxy (MBE) grown CoFe/MnIr (001) epitaxial bilayers were microfabricated by electron beam (EB) lithography and Ar^+ ion etching, and their local exchange biasing was studied by using a magnetic force microscopy. The circular patterned CoFe/MnIr annealed applying a magnetic field H_a parallel to [100] direction was found to show significant distribution of the direction of exchange bias from [100] direction: the mean direction of the exchange bias. On the other hand, when the CoFe/MnIr was annealed applying a field H_a // [110], the distribution of the exchange bias direction was found to be quite narrow, and almost all the circular patterns exhibit the exchange bias parallel to [110] direction. These results suggest that the local exchange anisotropy is controlled by the applied field direction during the annealing relative to the crystallographic axis of antiferromagnetic MnIr.

1. Introduction

Exchange biasing at ferromagnet (F) / antiferromagnet (AF) interface plays an important role in spin valve magnetic heads and magnetic random access memories (MRAMs). The exchange biased bilayers are usually patterned in deep submicrometer range for the application to the high density of hard disk drive and MRAMs, and in future, the fabrication size is expected to be comparable to the grain size of the AF layer. However, the local exchange anisotropy in nano-structured bilayers is still unclear even though both experimental and theoretical researches on the exchange bias have been carried out [1-7]. The most direct way to study the local exchange anisotropy in submicrometer or nanometer range is to observe the magnetic structure of the microfabricated exchange biased bilayers [4, 5].

In this paper we present the microscopic observation of the microfabricated exchange bilayer. In order to discuss the effect of the grain size and the magnetocrystalline anisotropy of AF on the local exchange bias, epitaxial bilayers prepared by MBE method and polycrystalline bilayers prepared by sputtering were studied. The MBE method is considered to be useful to control the crystal orientation of the film, and enlarge the grain size compared to the sputtering.

2. Experiment

(001) oriented epitaxial CoFe/MnIr bilayers were prepared by MBE method. The film stack is Ir (5 nm) / $Co_{90}Fe_{10}$ (10 nm) / $Mn_{80}Ir_{20}$ (30 nm) / Au (30 nm) / Cr (10 nm) / MgO(001) substrate. Before the deposition of the bilayer, the Au layer was annealed at 400˚C for 3 hours to flatten the Au (001) surface. The $Mn_{80}Ir_{20}$ layer was grown by the co-evaporation from independently controlled Mn and Ir

e-beam sources, and the $Co_{90}Fe_{10}$ layer was grown from an alloy source. During the growth of the CoFe and MnIr layers, a static magnetic field of 200 Oe was applied along MgO[100] or [110] direction. For comparison, polycrystalline CoFe/MnIr bilayers were prepared by rf magnetron sputtering. The film stack is Ta (5 nm) / $Co_{90}Fe_{10}$ (10 nm) / $Mn_{80}Ir_{20}$ (30 nm) / CuAl (30 nm) / Ta (5 nm) / thermally oxidized Si substrate. After the growth, the bilayers were annealed at 300°C in a vacuum below 2 x 10^{-5} Pa under a magnetic field of H_a = 850 Oe. The direction of the H_a is parallel to the field direction during the deposition. The bilayers were patterned into circular shape with diameters of 170 nm - 1 μm by using EB lithography followed by Ar^+ ion etching.

The patterned shape was checked by atomic force microscope (AFM), and the magnetic domain structure was measured by magnetic force microscope (MFM). Magnetic properties of the sheet films were measured by alternating gradient field magnetometer (AGM) and torque magnetometer. The crystal structure was characterized by *in-situ* reflection high energy electron diffraction (RHEED) and *ex-situ* X-ray diffraction (XRD). The surface morphology of polycrystalline and epitaxial MnIr films was observed by AFM and scanning electron microscope (SEM). For these observations, polycrystalline $Mn_{80}Ir_{20}$ (30 nm) / CuAl (30 nm) / Ta (5 nm) / oxidized Si and epitaxial $Mn_{80}Ir_{20}$ (30 nm) / Au (30 nm) / Cr (10 nm) / MgO(001) were prepared by sputtering and MBE, respectively.

3. Results and Discussion

Figure 1 shows XRD profiles of polycrystalline and epitaxial CoFe/MnIr bilayers. For the polycrystalline bilayer, the peaks from MnIr (111), CuAl(111), and CoFe(111) are seen in 2θ = 41 - 45 deg, and the film was confirmed to have (111) orientation. While in the profile of the epitaxial bilayer, the peaks from MnIr(002), CoFe(002), and Au(002) are seen in 2θ = 44 - 50 deg, indicating the film has (001) oriented structure. From RHEED observation during the deposition of the epitaxial bilayer, the Au(001) was confirmed to have 5 x 1 re-constructed surface, and MnIr and CoFe layers grew epitaxially onto the Au(001). The epitaxial growth of MnIr layer was also confirmed by in-plane ϕ-$2\theta\chi$ XRD profiles (not shown in the figure).

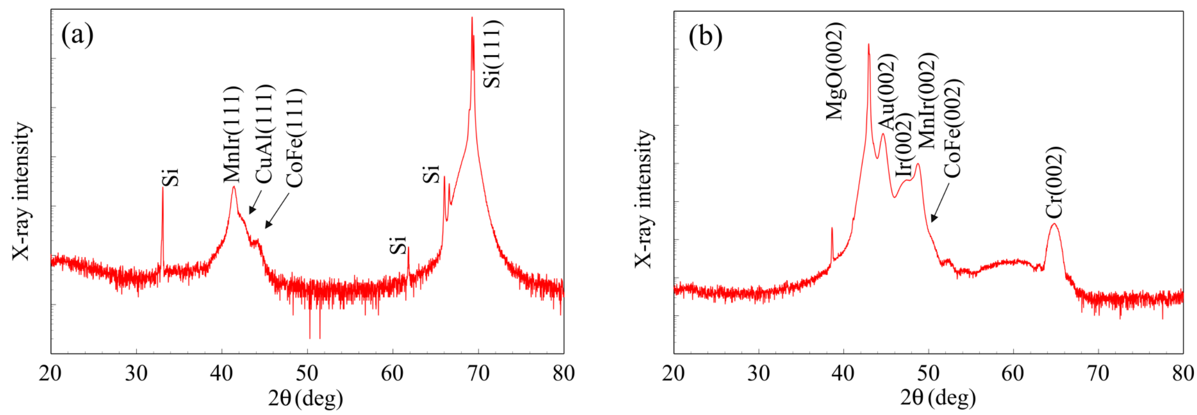


Fig. 1 X-ray diffraction profiles of (a) polycrystalline and (b) epitaxial CoFe/MnIr bilayers.

Figure 2 shows torque curves measured for (a) the polycrystalline bilayer annealed at 300˚C and epitaxial bilayer annealed at 300˚C applying a magnetic field H_a along (b) [100] and (c) [110] directions. As shown in Fig. 2 (a), the polycrystalline bilayer exhibits an unidirectional anisotropy of 0.1 erg/cm^2, and its easy direction was parallel to the direction of the applied field during the annealing. The epitaxial bilayers exhibited larger unidirectional anisotropy around 0.4 erg/cm^2 than that of the polycrystalline sample. The easy directions of the epitaxial bilayers were parallel to the applied field directions: [100] direction when H_a // [100], while [110] direction when H_a // [110]. The possible origin of the large anisotropy in epitaxial bilayers compared to the polycrystalline one is the difference of the in-plane grain size [6, 7]. The epitaxial bilayers prepared by MBE method are considered to have larger in-plane grain size than the polycrystalline sample prepared by sputtering. This is supported by SEM and AFM observations for the polycrystalline and epitaxial samples. The surface grains of 10-30 nm diameter and 100-300 nm diameter were visible in SEM images of sputtered and MBE grown MnIr films, respectively, and we consider these are closely related with the crystallographic grain size in MnIr.

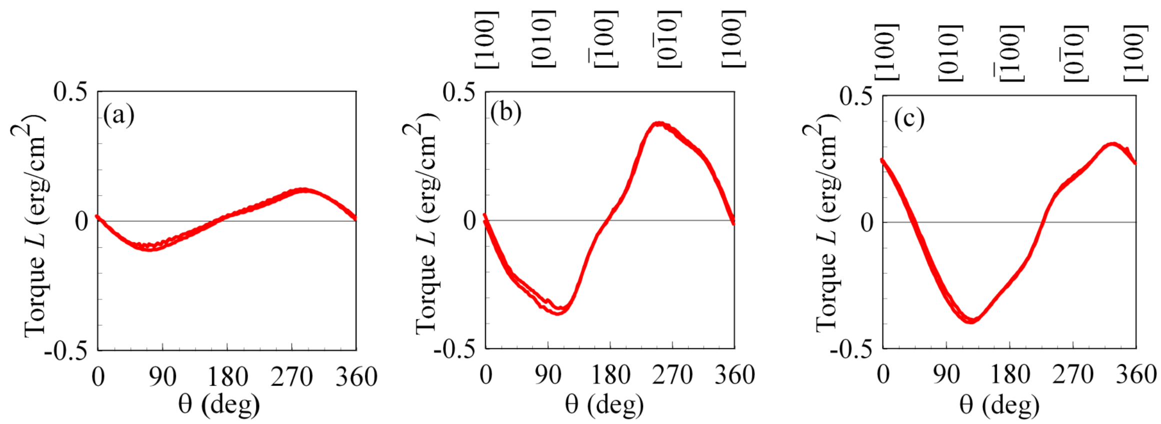
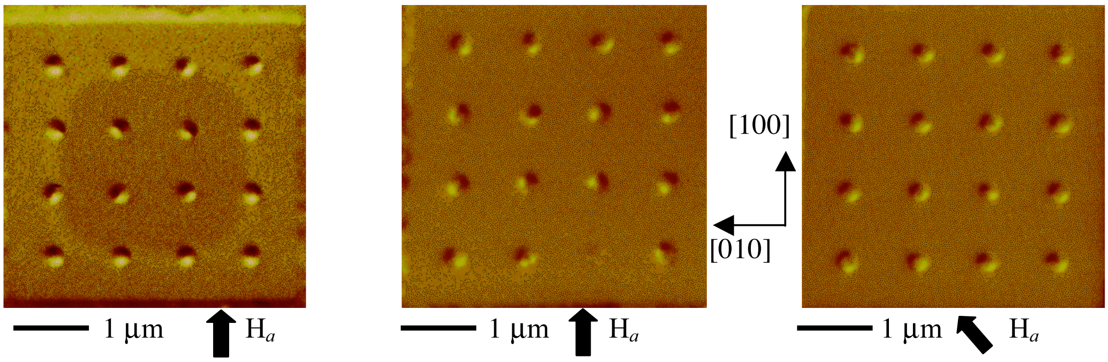


Fig. 2 Torque curves measured for (a) polycrystalline bilayer annealed in the field H_a and epitaxial bilayers annealed in the field H_a along (b) [100] and (c) [110] directions.
For the polycrystalline bilayer, the angle $\theta = 0$ corresponds to the direction of H_a.
For the epitaxial bilayers, the [100] direction was set at $\theta = 0$

Figure 3 shows the MFM images taken for circular patterned (a) polycrystalline CoFe/MnIr and (b), (c) epitaxial CoFe/MnIr with 250 nm diameter. The applied field direction during the annealing at 300˚C was shown as arrows in the figure. In the epitaxial bilayers, the field H_a was along (b) [100] and (c) [110] directions. The bright and dark contrasts indicate negative and positive magnetic poles appeared at the edge of the patterns, respectively, and the direction from negative to positive pole represents the direction of the magnetization in the pattern. The MFM observation was carried out at the remanent state after the field annealing, which means the direction of the magnetization of the pattern reflects the easy direction of local exchange anisotropy. As shown in Fig. 3 (a), the direction of the remanent magnetization of the polycrystalline bilayer was roughly along the field direction during the annealing even though some directional distribution was observed. The standard deviation of the easy direction estimated from 50 patterns for this bilayer was 20 deg. The epitaxial bilayer annealed applying H_a // [100] showed significant directional distribution of the remanent magnetization. As shown in Fig. 2 (b), the mean direction of the exchange bias was confirmed to be [100], however the direction of the remanent magnetization of the each pattern distributes significantly from the mean [100] direction. Differently from the case of H_a // [100], when the epitaxial bilayer was annealed applying H_a // [110], the distribution of the exchange bias direction was found to be quite narrow, and almost all the circular elements exhibit the exchange bias parallel to [110] direction as shown in Fig. 3 (c). The mean easy direction of the patterns is consistent with the easy direction estimated from the torque measurement (Fig. 2 (c)). The standard deviations of the easy direction from the H_a direction estimated in the same manner as the polycrystalline bilayer were about 60 deg and 10 deg for H_a // [100] and H_a // [110], respectively. These results suggest that the distribution of the local exchange anisotropy is closely related to the cubic magnetocrystalline anisotropy of the antiferromagnetic MnIr. The distribution of the easy direction was also influenced by the diameter of the circular pattern. With decreasing the diameter down to 180 nm, the distribution of the easy direction increased, however, the distribution for the bilayer annealed under H_a // [110] is much narrower than that prepared under H_a // [100]. This implies that the distribution of the local exchange anisotropy is affected by not only the magnetocrystalline anisotropy of the antiferromagnetic MnIr but also the number of the antiferromagnetic grains within the circular pattern.



(a) (b) (c)

Fig. 3 MFM images taken for circular patterned (a) polycrystalline CoFe/MnIr, epitaxial CoFe/MnIr annealed in the field (b) H_a // [100] and (c) H_a // [110]. The direction of H_a for each sample was indicated as arrows in the figure.

4. Summary

MBE grown CoFe/MnIr (001) epitaxial bilayers and sputter deposited CoFe/MnIr polycrystalline bilayers were microfabricated by EB lithography and Ar^+ ion etching, and their local exchange biasing was studied. The epitaxial bilayer exhibited large exchange bias of 0.4 erg/cm^2 compared with the polycrystalline sample (around 0.1 erg/cm^2), which is possibly due to the large in-plane grain size in the epitaxial bilayers. The circular patterned eptaxial bilayers annealed applying H_a parallel to [100] direction was found to show significant distribution of the direction of exchange bias from [100] direction: the mean direction of the exchange bias. On the other hand, the polycrystalline CoFe/MnIr showed the narrow distribution of the easy axis. When the epitaxial bilayer was prepared applying H_a // [110], the distribution of the exchange bias direction was found to be quite narrow. From these results, the distribution of the local exchange anisotropy is closely related to the cubic magnetocrystalline anisotropy of the antiferromagnetic MnIr and to the number of the antiferromagnetic grains within the pattern. Thus, we consider that the local exchange anisotropy is controlled by the applied field direction during the annealing relative to the crystallographic axis of antiferromagnetic MnIr even in the nano-structured exchange bilayer.

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