The effect of underlayers on FeCo thin films

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Abstract. Microstructure, mechanical and magnetic properties of FeCo films deposited onto underlayers of Ti, V, Cr, Co, Ni, Cu, Ta, and Pd have been investigated. The microstructure, magnetic, electric properties and internal stress of the FeCo films sensitively depended on the underlayers. The grain size, magnetic softness and electrical resistivity can be tailored in a wide range by the underlayers. The coercive mechanism of the FeCo films qualitatively follows the random anisotropy model. FeCo films deposited onto underlayers with $bcc$ structure (Ti, V, Cr) show relatively low compressive stress. Large tensile stress was found for FeCo films deposited onto underlayers with $fcc$ structure (Ni, Cu, Pd). FeCo films with smaller grain size and low internal stress normally preferred to have lower coercivity. The electric resistivity of the films can be tailored in a wide range by choosing different underlayers.

1. Introduction
Fe$_{65}$Co$_{35}$ alloy has saturation magnetization as high as 23.5 kG. It has been considered as one of the prominent candidate materials for the applications in magnetic write head [1]. However, the alloy has relatively high magnetostriction, which results in higher coercivity [2]. The resistivities of the film also need to be increased for working at a higher frequency. NiFe [3], Co [4], Ru [5], and other underlayers have been reported that can dramatically reduce the coercivities of FeCo films. However, the effect of the underlayers on the magnetic, electric properties and microstructure is not fully understood.

In this experiment, we have systematically prepared FeCo thin films on underlayers from group 4 to group 11 metals. Those underlayers include Ti, V, Cr, Co, Ni, Cu, Ta, and Pd. The magnetic properties, microstructures and crystallographic properties of the films are investigated. Of particular interest is that, although the underlayers is as thin as 3 nm, the resistivity of the 100 nm thick FeCo films increase almost three times from 20 $\mu$Ω·cm for group 4 metals to about 58 $\mu$Ω·cm group 11 metals. The coercivity of the samples sensitively depended on the microstructure and stress of the samples.

2. Experimental procedure
Films were prepared by a DC magnetron sputtering system onto glass substrate. The thicknesses of all the underlayers were 3 nm and the thickness of the FeCo layer was 100 nm. Static magnetic properties of the films were measured by a vibrating sample magnetometer (VSM). The surface morphology of the samples was observed by a scanning electron microscope (SEM). The crystallographic properties of the samples were evaluated by an X-ray diffractometer (XRD). The resistivity of the films was measured by four point method. Stress and magnetostriction were measured to understanding their effects on the magnetic properties of the films. Stress was measured from the stain of the cover glass after deposition of the FeCo films.
3. Results and discussion

Fig. 1. SEM images of FeCo films prepared onto various underlayers.

Fig.1 shows the surface morphology of the FeCo films prepared onto the underlayers. For all the films the thickness of the FeCo layer is 100 nm and the underlayer thickness is 3 nm. As shown in Fig.1, the surface morphology of the films sensitively depended on the underlayers. There are typically three kinds of grain structures according to Fig.1. FeCo films deposited onto Ti and Ta underlayer show almost the same microstructure as FeCo films deposited directly onto glass substrate. Those films show needle like grain structures. The typical grain length is about 100 nm and the typical grain width is about 20 nm. Films deposited onto V underlayers show grains as large as 70 nm coexist with fine grains of 15-25 nm. FeCo films deposited onto Cr, Cu, Co, Ni, Pd underlayers show uniform grain structures with the typical grain size as small as 15 nm. It should be noted that cross sectional TEM observations show all the films have columnar structure [4]. This means the grain structure of the films almost not change with the increase of the film thickness.

Fig. 2 shows the X-ray diffraction patterns of FeCo films deposited onto the various underlayers. All the FeCo films show almost similar X-ray diffraction patterns. (110) diffraction line is strongest diffraction line for all the FeCo films. It should be noted that films deposited onto Ni, Cu, and Ta show relatively large shift of the FeCo (110) diffraction line position compared with other underlayers. The shift of the peak position may be caused by the internal stress in the films, which will be discussed later.
All the FeCo films show anisotropic in-plane magnetic properties. Fig. 3 shows the dependence of coercivities, both in the hard axis and easy axis direction, on the underlayers. $H_e$ denotes easy axis coercivity and $H_{ch}$ denotes hard axis coercivity. The structures of the underlayers, which are detected by reflection high energy electron diffraction (RHEED), also show in Fig. 3. FeCo films deposited onto Ti, Ta underlayers and glass substrate show coercivities around 100 Oe. On the other hand, the hard axis coercivities of FeCo films deposited onto Cr and Co are less than 10 Oe. Those results show that suitable underlayers can dramatically reduce the coercivities in FeCo films.

The coercive mechanism in nanocrystalline thin films has been studied in detail by the random anisotropy model proposed by Herzer [6]. When the grain size in nanocrystalline films is less than the exchange length, the effective anisotropy can be estimated from the equation of $K_{eff} \sim K_1 D^6/A^3$, where $K_1$ is the magnetocrystalline anisotropy, $D$ is the average grain size, and $A$ is the exchange stiffness. The exchange length ($l_e = (A/K)^{1/2}$) of FeCo is estimated to be about 30 nm by assuming exchange stiffness $A = 1.7 \times 10^{-11}$ J/m and $K \approx 15$ kJ/m$^3$ [1]. According to the SEM images shown in Fig. 1, FeCo films deposited onto Cr, Cu, Co, Ni, Pd all show grain size smaller than 30 nm. Hence those films are expected to have smaller coercivities following the random anisotropy model. According to the experimental results of Fig. 2, FeCo films deposited onto Cr, Cu, Co, Ni, and Pd underlayers show lower coercivities compared the films deposited onto Ti, or Ta underlayer. Those experimental results qualitatively support the random anisotropy results. However, FeCo films deposited on Cr underlayer
obviously have grain size larger than those on Ni underlayer. But films deposited onto Cr underlayer have smaller coercivity. Those results indicate that coercivities in nanocrystalline FeCo films could not be fully understood by the random anisotropy model.

Fig. 4 shows the dependence of internal stress on the underlayers. Films deposited onto Ni, Cu, and Ta show large tensile stress. Normally, magnetocrystalline anisotropy and stress are all contribute to the increase of coercivities in soft magnetic thin films. Hence it is easy to understand that FeCo films deposited onto Ni underlayer, although have relatively smaller grain size, show relatively higher coercivity due to the large tensile stress. Of particular interest is that underlayers with bcc structure show relatively low internal stresses compared with underlayers with fcc structure.

Fig. 5 shows the dependence of the electric resistivity of the films on the group number of the underlayers. The total film thickness is about 103 nm and the underlayer thickness is only about 3 nm for all the films. However, the resistivity of the films change from about 20 μΩ·cm for Ti underlayer to about 58 μΩ·cm for Ni underlayer. The resistivity of the films increased to about three times by changing the underlayers. It is clearly that the resistivity of the FeCo film increase with the increase
of the group number of the underlayer metals. It is well know that impurities and crystal imperfections such as grain boundaries can result in increase of resistivities in metals. FeCo films prepared onto Ni underlayer have small grain sizes and larger amount of grain boundaries; hence the films have higher resistivity. It should be noted that films with higher resistivity is preferred to extend the application for high frequency applications.

4. Results and discussion

In conclusion, it is found that the underlayer plays an important role on the microstructure, and magnetic softness of the FeCo films. Films deposited onto Ti, Ta underlayer and glass substrate show large coercivity. While films deposited onto Co, Cr underlayer show small coercivity. Experimental results show the coercivities of the films not only depended on the grain size of the films, but also depended on the internal stress of the films. Of particular interest is that the electric resistivity can be tailored in a wide range by suitable underlayers.

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