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Extreme Exchange Bias Effect of Nanostructured Magnetic Phase Mixture Films with Increased Internal Interface

Min-Seung Jung[1], Jung-Il Hong[1*]

[1] Daegu Gyeongbuk Institute of Science & Technology (DGIST)
333 Techno Jungang-daero, Hyeonpung myeon, Dalsung-gun, Daegu 42988, South Korea
Phone : +82-53-785-6511, E-mail: jihong@dgist.ac.kr

Abstract

With the formation of 3-dimensional phase mixture films consisting of ferro- and antiferro-magnetic phases with nanometer scale grain sizes, extremely high density of interfaces was shown to be introduced compared with conventionally studied bilayer magnetic films. It was shown that the exchange bias property can be significantly enhanced compared with conventionally studied 2-dimensional bilayers of ferromagnetic and antiferromagnetic materials.

1. Introduction

Exchange bias effect has been recognized to be an important issue from both academic and technological point of view, and has been utilized as an essential component in the spin valve structures. It is basically understood as an interface phenomenon related to the exchange couplings between atoms belonging to ferromagnetic (FM) and antiferromagnetic (AFM) materials, and much studies have focused on the bilayers thin films although original discovery of this phenomenon by Meiklejohn and Bean was with the particles of Co [1]. With the advent of nanotechnologies for extremely fine manipulation of material structures, control of interfaces between materials can be considered as an emerging tool to generate new materials with novel physical properties. This interface engineering can also be applied to the magnetic materials with the expectation to enhance or modify the previously known interface-related magnetic properties including exchange bias field, its FM thickness dependence, and thin film induced shape anisotropies.

With the ubiquitous usage of nanotechnologies and nanomaterials, the present work demonstrates that the interface properties can be considered as a representative properties of the materials and this opportunity expands the chance for development of customized engineering materials.

2. Fabrication of Nanophase Mixtures

Metallic Co discs were used as a sputtering target and films were deposited in the Ar and O_2 mixture atmosphere. Total pressure within the chamber was maintained at 3 mTorr during the deposition procedure, while Ar and O_2 ratio in the atmosphere was varied with the control of individual gas flow rates. Depending on the relative contents of gas in the chamber, deposited Co films are expected to have various degree of oxidations. X-ray diffraction patterns of the films prepared at various O_2 partial pressures are shown in Fig. 1. Crystallographic phases of pure metallic Co and fully oxidized CoO phases can be recognized and their relative amounts in the films varied depending on the partial fraction of oxygen available in the atmosphere during the deposition process. CoO is a well known antiferromagnetic materials with T_N of approximately 293 K. Considering the broad xrd peak widths, both Co and CoO phases are expected to exist as nanograins of a few nanometers in widths.

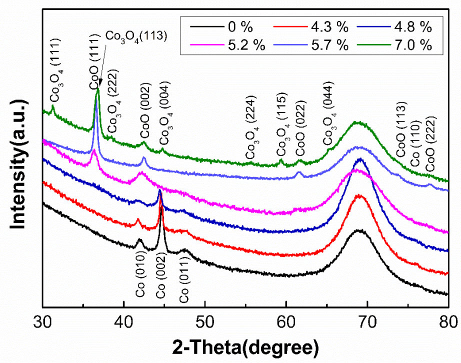

Figure 1. XRD patterns of films prepared at various oxygen partial fractions varying from 1 to 7 % of the total pressure in the deposition chamber.

3. Magnetic Characterizations

Magnetic properties of the films were measured using Quantum Design MPMS systems. After field cooling in 5 T, hystereses loops were measured at temperatures from 10 K to 300 K which is above the T_N of bulk CoO. As shown in Fig. 2(a), significantly shifted hysteresis loops were measured for Co-CoO mixture films. We emphasize that the magnitude of the exchange bias field, H_{eb}, is more than 10 times greater than the typically measured H_{eb} obtained from Co/CoO bilayer films with equivalent thicknesses [2]. This represent significantly increased interface area between FM and AFM phases in the film. As oxygen concentration increases over 5.2%, further increase in H_{eb} is not observed (see Fig. 2(b)). Increase in individual grain sizes of CoO is expected to occur rather than further increase in the interface area.

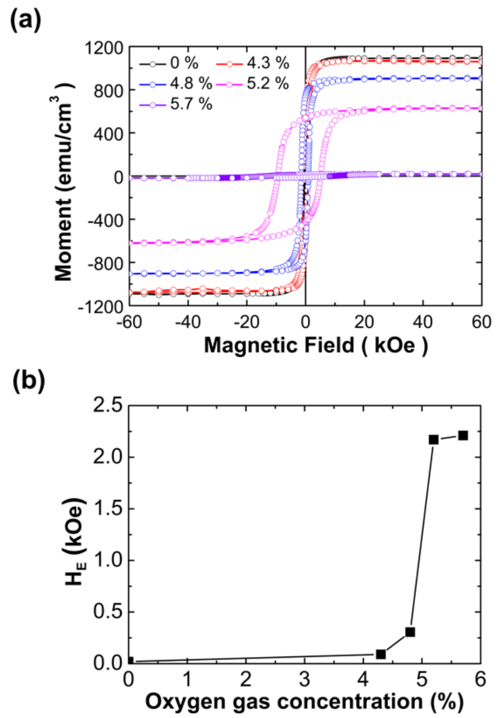

Figure 2. (a) Hysteresis loop and (b) Exchange bias field of films fabricated with different oxygen gas concentration at 10 K.

As the oxidation and metallic deposition progress simultaneously, their spatial distribution is random, which suppresses spatial anisotropy in the film. Therefore, shape anisotropy, which is typical for the magnetic thin films, is significantly reduced for the case of mixture films in the present study. This was confirmed for the exchange biasing of the film in both parallel and perpendicular directions of the film plane. In both cases, the film exhibited high exchange bias field strengths. Slight change in anisotropy is noticed in Fig. 3, but the exchange biasing can be effectively carried out in any direction relative to the film geometry. This is expected to allow increased functionality to be implemented in the design of thin film based devices. Another advantage of the 3-dimensional random mixture structure is the absence of FM thickness dependence of exchange biased bilayers. Fig. 4 shows the hysteresis loops of the films prepared under an identical deposition conditions except for the deposition time resulting in two different thicknesses of 98 and 48 nm's as measured by x-ray reflectivity. Unlike for the bilayer films, in which increased FM thickness is accompanied with reduced H_{eb}, exchange bias effect retains high magnitud regardless of the saturation magnetization of the film.

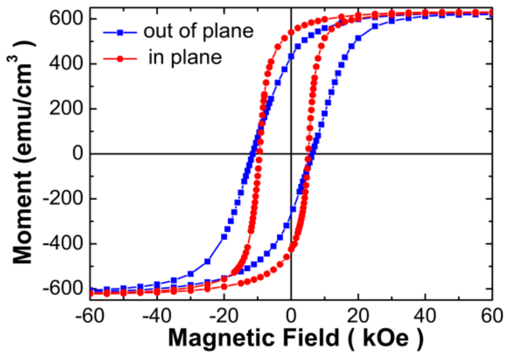

Figure 3. Hysteresis loops of Co-CoO mixture film measrured at 10 K after field cooled in two different directions as indicated in the inset.

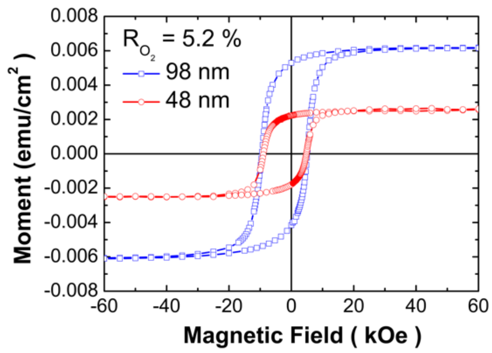

Figure 4. Thickness dependence of the exchange bias effect of the phase mixture film.

4. Conclusions

With the introduction of nanoscale AFM-FM phase mixture, new functional materials with controlled exchange biasing was achieved. It is demonstrated to exhibit extremely high exchange bias field, and no reduction in the exchange bias effect with the increased FM, known as $1/t_F$ dependence in the bilayer films, was observed. Furthermore, formation of internal nanostructure also allows the suppression of the magnetic shape anisotropy enabling the exchange biasing the film in any directions relative to the film plane. These characteristics are expected to remove restrictions in applying the exchange bias effect of thin films in the device designs.

Acknowledgements

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