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Exchange bias and training effect in Ni/Ag-doped NiO bilayers

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ABSTRACT

A series of polycrystalline Ag-doped $Ni_{1-x}Ag_xO$/Ni bilayers with x up to 0.2 were prepared by magnetron sputtering. X-ray diffraction, atomic force microscopy and transmission electron microscopy analyses reveal that Ag doping significantly reduces the mean NiO grain size and leads to the appearance of Ag nanoparticles on the surface of the Ag-doped NiO films. As x increases, the exchange bias field and coercivity at room temperature decrease as a consequence of the reduced thermal stability of smaller NiO grains and the screening effect resulting from the interfacial Ag nanoparticles. At lower temperatures, a slight enhancement of the exchange bias field is observed in the Ag-doped sample, indicating that the Ag doping increases the uncompensated NiO spin density. In addition, our studies find that the training effect of the Ag-doped sample can be well described by a spin configurational relaxation model, regardless of the presence of Ag nanopartiles at the interface.

1. Introduction

The exchange coupling at the interface in ferromagnetic (F)/antiferromagnetic (AF) systems can give rise to the shift of hysteresis loop along the magnetic field axis after the latter one has ordered in the presence of a magnetized F component. This effect, known as exchange bias (EB), continues to receive great interest due to its intriguing physics as well as its wide applications in spintronic devices [1,2].

Although the mechanism of EB is not fully understood, it is believed that EB originates from the stable uncompensated AF spins at the F/AF interface, which exert a unidirectional exchange force on the F material [3–6]. The density of uncompensated AF interfacial moments has been proposed to determine the magnitude of the EB field, suggesting that EB can be tuned by changing this moment density. Recently, nonmagnetic substitutional elements have been used to tune the density of the uncompensated AF interfacial moments. For metallic polycrystalline AF materials, a maximum of EB field as a function of doped Cu concentration has been observed in CoFe/IrMn and NiFe/FeMn bilayers [7,8]. In expitaxial CoO/Co bilayers, EB field can be enhanced by two times when the AF CoO is diluted by Mg substitution [9]. Enhancements of EB field in polycrystalline CoO/Co bilayers by Mg dilution have also been observed [10]. However, in Mg-diluted polycrystalline NiO/Ni granular systems, decreases of EB field and coercivity have been reported, which probably come from the rougher interface and increased grain defects [11]. In Co/untwined single crystalline $Fe_{1-x}Zn_xF_2$ bilayers no significant enhancement of EB field was also observed due to a lack of percolation of nonmagnetic impurities at higher Fe concentrations [12].

Compared with the atomic substitution, effects of incorporating nonmagnetic clusters into AF layers are less studied and have received more attention recently. In NiFe/granular $(FeMn)_{1-x}(MgO)_x$ bilayers prepared by co-sputtering of FeMn and MgO, the EB field is significantly enhanced at $x \sim 0.025$, where the FeMn grain size exhibits maxima [13]. Urazhdin et al. [14] found a significant difference between the effects of doping in epitaxial and polycrystalline films, i.e. in CoO/Co systems, the EB field increased with Pt doping in epitaxial films but did not significantly change in polycrystalline films at 5 K and decreased at higher temperatures. So far, detailed understanding of the effects of introducing nonmagnetic clusters or nanoparticles on EB is still missing. Therefore, further investigations are required to clarify this problem.

In this paper, EB and training effect in polycrystalline Ni/Ag-doped NiO bilayers were studied. NiO is isostructural to CoO and the NiO/Ni system is to a large extent similar to the extensively studied CoO/Co system. The electronic structure and atom radius of Ag are different from Ni so that its introduction into the NiO matrix must efficiently affect the microstructure, the AF anisotropy, the thermal stability and thus the EB of the NiO/Ni system. We found that Ag doping can effectively reduce the NiO grain size and introduces inhomogeneous distributions of a large amount of Ag nanoparticles at the Ni/NiO interface, resulting in the reduction of EB field and coercivity at room temperature. At lower temperatures, a slight enhancement of the exchange bias field was observed in the Ag-doped sample.

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2. Experimental details

A series of Ni (18 nm)/$Ni_{1-x}Ag_xO$ (60 nm) films with x ranging from 0 to 0.2 were deposited by dc magnetron sputtering on Si (1 0 0) substrates. The $Ni_{1-x}Ag_xO$ was deposited from a metallic Ni target with chips of Ag attached to its surface in Ar/O mixture at O_2 partial pressure of 0.05 Pa and Ar pressure of 0.25 Pa, and the substrate temperature was 210 °C. The partial oxygen pressure was adjusted until the resulting $Ni_{1-x}Ag_xO$ films exhibited negligible ferromagnetic response at room temperature. The technique proposed by Urazhdin et al. [14] minimizes over-oxidation, which can lower the Néel temperature. A Ni layer was grown subsequently when the substrates were cooled down to approximately 90 °C. Finally, a 30-nm-thick Ag layer was deposited at room temperature to avoid corrosion in ambient atmosphere. The as-deposited Ni/$Ni_{1-x}Ag_xO$ bilayers usually exhibit double-shifted hysteresis loops due to the stray magnetic field from the magnetron gun [15]. Therefore, the as-deposited films were vacuum annealed in an applied field of 4 kOe along the easy axis of the Ni layer to redefine the bias direction at 430, 480 and 520 K for 60, 40 and 20 min, respectively.

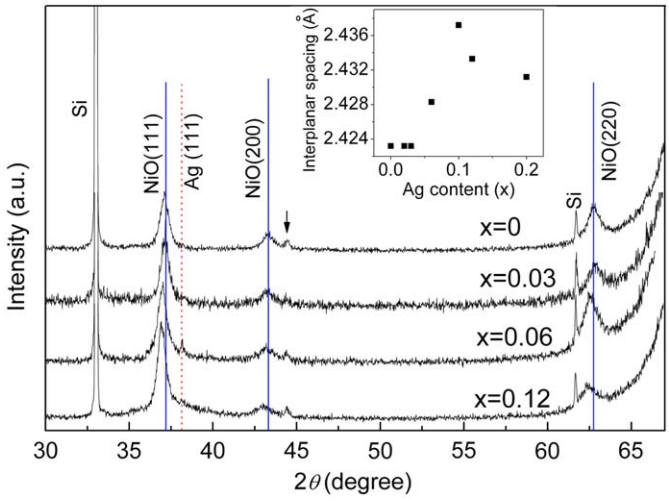

Fig. 1. Representative θ–2θ XRD patterns of the 60 nm $Ni_{1-x}Ag_xO$ films grown on Si (1 0 0) substrates. The vertical lines indicate the positions of the NiO and Ag reflections. The weak peaks at 2θ=44.44° indicated by an arrow may come from the underoxidized Ni. In the inset, interplanar spacing is shown as a function of the Ag doping x.

The $Ni_{1-x}Ag_xO$ composition was determined by fluorescent X-ray spectrometry. The structure and crystalline quality of the $Ni_{1-x}Ag_xO$ films were characterized by X-ray diffraction (XRD) using a Rigaku diffractometer with Cu K_α radiation. Selected $Ni_{1-x}Ag_xO$ films were deposited onto NaCl single-crystal chips and then dissolved in distilled water before observation with a JEOL 2011 transmission electron microscope (TEM) with energy-dispersive X-ray spectrometer (EDS). The surface morphologies of the films were observed by atomic force microscopy (AFM) and scanning electronic microscopy (SEM, Hitachi S5500). Magnetization studies were carried out using a vibrating sample magnetometer (VSM, LakeShore) at room temperature. Low-temperature

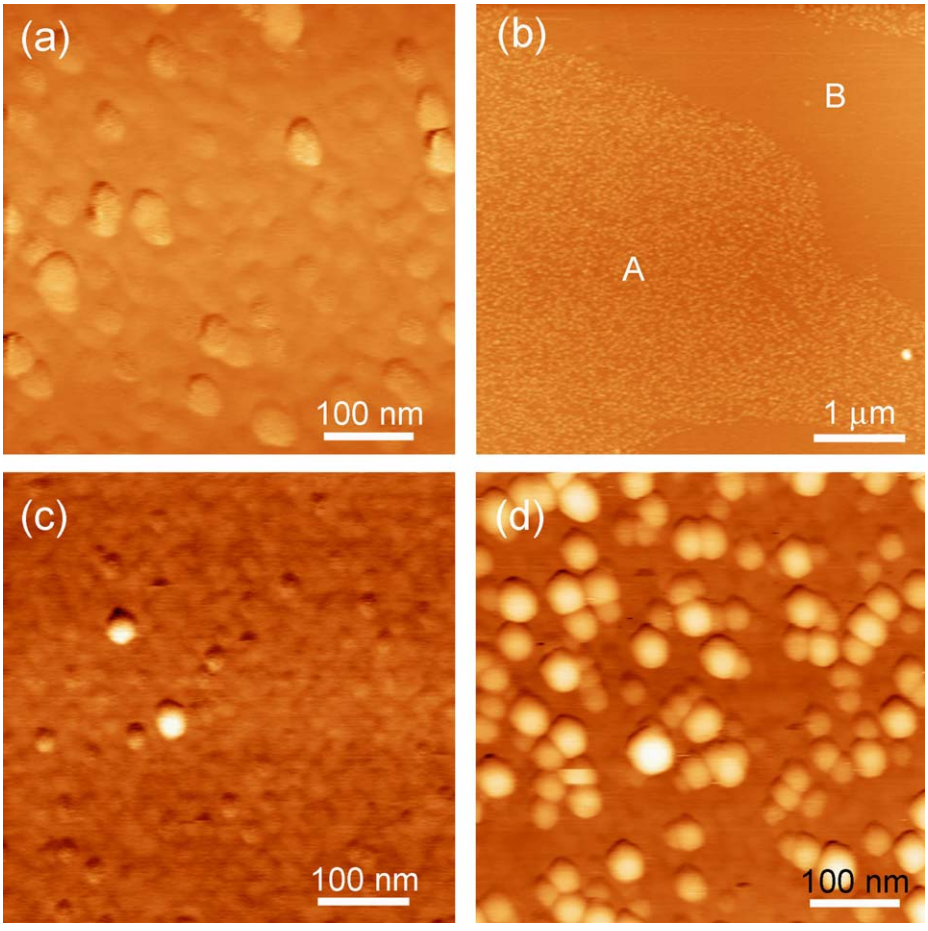

Fig. 2. AFM morphologies of the as-deposited $Ni_{1-x}Ag_xO$ surface with (a) x=0 and (b) x=0.12. In (b) the "rough" region and the smooth region are labeled as A and B, respectively. (c) and (d) are the large magnification images of the B and A regions in (b).