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Exchange bias effects of NiFe/NiO bilayers through ion-beam bombardment on the NiO surface

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ABSTRACT

The influence of ion-beam bombardment of the NiO surface on the exchange bias behavior of NiFe/NiO bilayers was systemically investigated with different bombardment energies and durations. The results show that by varying the bombardment energies, different crystallographic orientations are created which modifies the NiO spin structures. This results in the changes in the coupling type in NiO when it is in contact with the NiFe layer. The NiFe/NiO bilayers exhibited either enhanced or decreased exchange bias filed, depending on the uncompensated moments or misaligned NiO spin created by ion-beam bombardment. The variations in coercivities of NiFe/NiO bilayers imply that the NiO anisotropy could be tuned by ion-beam bombardment.

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1. Introduction

Exchange bias is a phenomenon, which provides the pinning field for ferromagnetic layer [1–3] and also increases the ferromagnetic layer coercivity [4–7]. A ferromagnetic (FM)/antiferromagnetic (AF) bilayer structure is the most common configuration. After cooling through the Neel temperature of AF layer, the exchange bias effect can be set into the system [8–10]. With a field-cooling process, the final exchange bias field can be either positive or negative, and it can be tuned by bombardment of moderate-energy Ar ions on the AF layer surface [11–13].

Ion beam bombardment during the thin film growth process can influence the film properties including adhesion, nucleation, internal stress, morphology, and composition [14–16]. Pranevicius previously studied the influence of ion-beam bombardment on the nucleation of thin film during deposition [14]. It was found that with no bombardment process during the Al film growth at a rate of 10^{16} atoms/cm^2-s, a considerable incubation time (40 s) was required before the superimposed growth of Al islands. On the other hand, the presence of ion-beam bombardment (5 keV Ar) would decrease the overlap time duration to 15 s, due to the increased nucleation sites produced for island formation and growth. The grain size of thin films shows complicated dependence on the ion beam energy [15]. Most metals show significant decreases in grain sizes with increasing ion beam energy. It was argued that the ions becomes incorporated at the grain boundaries during the film growth process, and an ion beam of sufficiently high energy may inhibit the grain growth; also high beam energies can lead to irradiation-induced lattice disorders that would limit the grain growth [15]. The influence of ion-beam bombardment on the surface roughness was modeled using molecular dynamics simulations, and it was found that the thin film deposition with ion-beam bombardment could remove coated atoms via sputtering [16].

NiO as an AF material has been widely investigated as the pinning layer in magnetoresistive spin valve structures [17–20]. Sputtered NiFe/NiO bilayers possess a blocking temperature as high as 230 °C and an exchange bias field of 20 Oe [21]. The NiO film morphology would influence the properties of the ferromagnetic underlayer. Smaller grain sizes of NiO layer with diameter of 12 nm exhibited an exchange bias field of 20 Oe, which is two-times larger than that of similar structure but with larger grains of 37 nm [22]. Larger surface roughness of NiO layer is found to introduce larger coercivity (10 Oe) than smooth NiFe/NiO bilayer (5 Oe) [23]. In addition, Yu et al. [24] reported that the formation of magnetic defects due to interface reaction strongly affects both coercivities as well as exchange bias field. Also, Lee et al. [25] reported that nonmagnetic second phase (Ni_2O_3) formed during fabrication of the NiO layer may destroy the NiO antiferromagnetism and thus weaken the exchange coupling in a NiFe/NiO bilayer.

We previously investigated a series of different exchange bias bilayers. For example, the exchange bias fields of NiFe/NiO bilayers are strongly influenced by the ratio of oxygen and Ar, due to the expanded NiO structures formed during fabrication processes [26].

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Using different oxygen/argon flow rate ratios ranging from 8% to 26% during the Cr-oxide sputtering process, the exchange bias field of NiFe/Cr-oxide bilayer changed from −25 to −75 Oe [27]. Using different ion bombardment voltages from 70 to 150 V during sputtering, the exchange bias field of NiFe/Mn bilayer changed from −250 to −400 Oe [28]. Thus we found that the exchange bias could be modified by energetic Ar ion-beam bombardment. However, a widely studied exchange bias system of NiFe/NiO bilayer has not been investigated by ion-beam bombardment so far.

In this study, we investigated the exchange bias behavior in NiFe/NiO bilayers with different ion-bean bombardment voltages (from 0 to 150 V) and different bombardment durations (from 1 min to 20 min) on the surface of the bottom NiO layer. It was found that by using higher ion-beam bombardment energy or longer bombardment duration, the changes in NiO crystallographic orientations may affect the corresponding spin structures and give rise to the polarity switch in exchange bias fields.

2. Experiments

A dual ion-beam deposition technique [29] was used to sputter NiFe (8 nm)/NiO (15 nm) bilayers on the SiO_2 substrates. A Kaufman ion source was used to bombard the Ni target with 3 sccm Ar and the End–Hall ion source was used to bombard the SiO_2 substrate with 2.6 sccm Ar and 0.5 sccm O_2 to oxidize Ni into NiO in-situ [30]. Then the NiO surface was either bombarded with different ion-beam bombardment energies (V_{EH}) from 0 to 150 V for 5 min, or bombarded for different durations (1–20 min) with $V_{EH} = 150$ V to induce changes on the NiO surface conditions. After that the Kaufman ion source was used to focus the argon ion-beam onto a commercial $Ni_{80}Fe_{20}$ (at%) target surface for depositing the NiFe layer on top of the NiO layer. The crystalline structures of the NiFe/NiO bilayers were characterized by a Bruker x-ray diffractometer (XRD). Magnetic measurements were performed in a commercial SQUID magnetometer (Quantum Design MPMS), where the thin films were field-cooled (FC) with a 20 kOe in-plane magnetic field from 300 K down to 5 K. The surface morphology of the bottom NiO layer was characterized by a NT-MDT Solver Pro-M atomic force microscope (AFM).

3. Results and discussion

To characterize the crystalline structure and composition of the sputtered NiFe (8 nm)/NiO (15 nm) bilayers, the samples bombarded with different ion-beam energies and durations were investigated with XRD. The XRD spectra of NiFe/NiO bilayers with different ion-beam bombardment energies ($V_{EH} = 0$–150 V) are shown in Fig. 1. The structures of the NiFe/NiO bilayers were determined to be fcc NiFe (lattice constant $a \sim 3.55$ Å) and rock-salt NiO ($a \sim 4.21$ Å), as revealed by the diffraction peaks of (111) and (200) of NiFe and (111), (200), (220) of NiO, respectively. This is consistent with those reported in our previous work [30]. However, as the ion-beam bombardment energy was increased from 0 to 150 V, the peak ratio of (111)/(200) in NiO was found to decrease with increasing ion-beam bombardment energies, as shown in the inset of Fig. 1. The reason for the change in the peak ratio is likely attributed to the changes in preferred orientations due to ion-beam bombardment, as observed in our previous work [31]. This in turn changes the spin/magnetic structures and affects the corresponding exchange bias effects when the NiO layer is capped with a top NiFe layer. In addition, the peak positions in XRD spectra in Fig. 1 did not change indicating no new phases were formed after the ion-beam bombardment. Instead, the role of varying the ion-beam bombardment energies seems to change the preferred orientations of NiO layers. This in turn changes the magnetic anisotropy in NiO and affects the corresponding magnetic properties in NiFe/NiO bilayers.

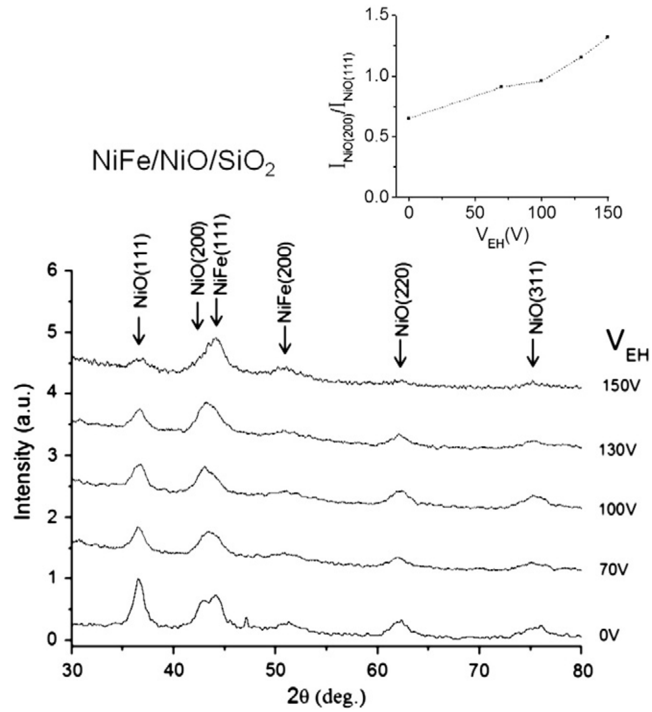

Fig. 1. X-ray diffraction spectra of the NiFe/NiO bilayers with different ion-beam bombardment energies ($V_{EH} = 0$–150 V).

To further probe the ion-beam bombardment effects on the antiferromagnetic NiO layers in NiFe/NiO bilayers, the ion-beam bombardment energy was fixed at $V_{EH} = 150$ V and the NiO layers were bombarded with different durations (1–20 min). The results are shown in Fig. 2. It is seen that at low ion-beam bombardment durations (1, 2, and 5 min), two peaks of NiO (200) and NiFe (111) are still resolved. In contrast, increasing the ion-beam bombardment durations (10 and 20 min) resulted in the peak broadening (2-theta~42°) of NiO (200) that is attributed to the grain size refinement due to ion-beam bombardment. In addition, no diffraction peak shift in NiO was observed at all ion-beam bombardment durations. This indicates that varying the ion-beam bombardment durations (and thus irradiation dosages) changes the NiO grain sizes while the rock-salt NiO structures remain unchanged, as evidenced by the same NiO lattice constants (a~4.21 Å). The above

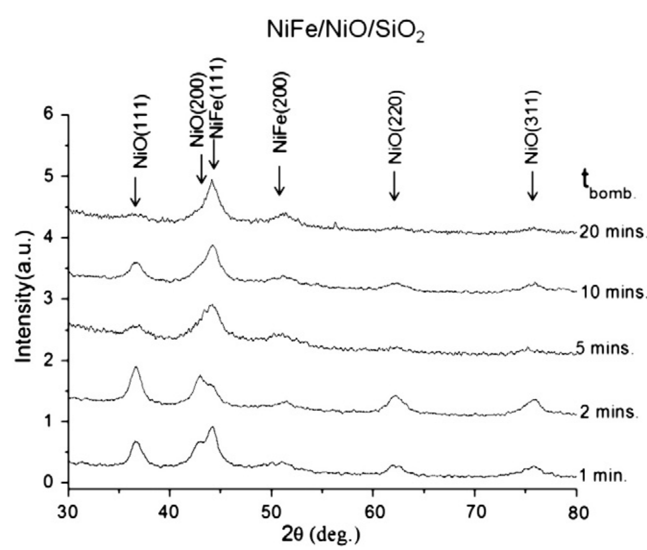

Fig. 2. X-ray diffraction spectra of the NiFe/NiO bilayers with different ion-beam bombardment durations ($t_{bomb.} = 1$–20 min).

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