Stress-induced exchange anisotropy of epitaxial (1 1 1) NiFe/NiFeMn

Chih-Huang Lai¹,* , Shing-An Chen² , J.C.A. Huang³

¹Department of Materials Science and Engineering, National Tsing Hua University, 101, Sec. 2 Kuang-Fu Road, HsinChu 300, Taiwan, ROC
²National Cheng-Kung University, Department of Physics, 1, Ta Hsueh Road, Tainan 701, Taiwan, ROC

Abstract

Epitaxial (1 1 1)NiFe/NiFeMn films were grown on (1 1 0) Mo/Al₂O₃ (1 1 2 0) structural templates by using MBE. Since the lattices mismatch between NiFe and Mo, the exchange field of NiFe/NiFeMn was induced by the stress in NiFe. The stress-induced exchange anisotropy resulted in dual shifted hysteresis loops. Because the lattice constant of NiFeMn is close to that of FeMn, the exchange field (135 Oe) of NiFe/NiFeMn is comparable to that of NiFe/FeMn.

Keywords: Stress-induced exchange anisotropy; MBE

Exchange anisotropy of NiFe/FeMn and NiFe/NiMn have been extensively studied for the pinning structures of spin valves [1]. As-deposited γ-FeMn films are of the disordered antiferromagnetic phase, but as-deposited NiMn films are of the disordered paramagnetic phase. The annealing is needed to transfer the disordered NiMn phase into ordered antiferromagnetic phase. It would be interesting to know the magnetic properties if some amount of Fe was added into NiMn. In most reports of ferromagnetic(F)/antiferromagnetic(AF) systems, the uni-directional anisotropy was induced either by depositing ferromagnetic layers in the magnetic field or by annealing the bilayers in a magnetic field. Very little work has been reported on experiments in which the exchange anisotropy is induced by the residual stress in ferromagnetic films. In this work, epitaxial (1 1 1) NiFe and NiFeMn were prepared by a molecular beam epitaxy (MBE) system on the Mo/Al₂O₃ structural templates. During the deposition of samples, no magnetic fields were applied. For the as-deposited samples, dual shifted hysteresis loops were observed. The stress-induced exchange anisotropy, resulting from the mismatch of lattices between films, in epitaxial (1 1 1) NiFe/NiFeMn films will be discussed.

Samples with the structure Mo (20 nm)/NiFe (8 nm)/NiFeMn (12 nm)/Mo (2 nm) were prepared by MBE on the Al₂O₃ (1 1 2 0) substrates. The substrates were first heated to 900°C, and the bottom Mo layer was grown. The bottom Mo layer was used as the buffer layer for (1 1 1) epitaxial growth of NiFe and NiFeMn films. The substrate temperature for the NiFe, NiFeMn, and the top Mo layers was lowered to 300°C to prevent interdiffusion between films. The top Mo layer was used for the capping layer. The deposition rate for NiFe and Mo was 0.1 Å/s. NiFeMn was deposited by dual sources of Ni₈₀Fe₂₀ and Mn at a rate of 0.5 Å/s. During the deposition of samples, no magnetic fields were applied. During the depositions, reflective high-energy electron diffraction (RHEED) was taken in-situ to monitor the surface structure and the orientation relationship between the layers. After depositions, the crystalline structures were characterized by X-ray diffraction (XRD), and the surface roughness was measured by an atomic force microscope (AFM). The hysteresis loops were measured by using VSM and magneto-optical Kerr effect (MOKE).

The XRD 0–2θ scan of the sample with 16 nm NiFe is shown in Fig. 1. Only (1 1 1) NiFeMn, (1 1 1) NiFe and (1 1 0) Mo appear. If we assume NiFeMn is FCC, the lattice constant deduced from the 2θ value is 3.612 Å,

*Corresponding author. Tel.: +886-3-5710070; fax: +886-3-5722366.
E-mail address: chlai@mse.nthu.edu.tw (C.-H. Lai)
Fig. 1. X-ray 0°–20 scan for the sample of Al₂O₃(1 1 2 0)/Mo (20 nm)/NiFe(16 nm)/NiFeMn(12 nm)/Mo(2 nm). Only NiFe (1 1 1), NiFeMn (1 1 1) and Mo (1 1 0) peaks appear.

close to that of disordered FeMn phase, 3.625 Å. Fig. 2(a) shows the RHEED patent for the electron beam along bottom Mo [1 1 0]. Sharp diffraction lines verified the well-aligned in-plane orientations. Along the Mo [1 1 0] direction, on the NiFe and NiFeMn surfaces, NiFe [−2 1 1] and NiFeMn [−2 1 1] patterns appeared, as shown in Fig. 2(b) and 2(c), respectively. Based on RHEED and X-ray data, the epitaxial relationships are: Mo (1 1 0) // NiFe (1 1 1) // NiFeMn(1 1 1), Mo[0 0 1] // NiFe [0 − 1 1] // NiFeMn [0 − 1 1], and Mo[1 − 1 0] // NiFe[−2 1 1] // NiFeMn[−2 1 1].

The hysteresis loops taken by MOKE showed different loops in different areas of the sample. Some areas showed dual shifted loops as shown in Fig. 3, and some areas showed only a single shifted loop (either positive-field loop or negative-field loop). The exchange field for 8 nm NiFe film was 135 Oe, and the coercivity was 83 Oe.

Fig. 2. Typical RHEED patterns on the surfaces of (a) Mo [1 1 0], (b) NiFe [−2 1 1], and (c) NiFeMn [−2 1 1].

Fig. 3. MOKE results of the sample Al₂O₃(1 1 2 0)/Mo (20 nm)/NiFe(8 nm)/NiFeMn(12 nm)/Mo(2 nm). 0° is along the easy axis, and 90° is along the hard axis.

Fig. 4 shows the M–H curve taken by VSM at room temperature. It clearly shows three distinguished regions in both easy-axis (0°) and hard-axis (90°) curves. From AFM analysis, the root-mean-square roughness on the top layer is 0.38 nm, indicating a smooth layer structure for the MBE samples.

For the ferromagnetic/antiferromagnetic bilayers, the exchange field is normally introduced by the external magnetic field, either by depositing F layer in a field or by annealing the bilayers in a field. In both cases, the spins of F layers tend to align in the direction of the external field, and to form a signal domain, resulting in an unidirectional anisotropy. In our experiment, NiFe was deposited without the presence of a magnetic field, so NiFe is no longer a signal domain. From the X-ray and RHEED data (Figs. 1 and 2), FCC NiFe was epitaxially grown on the Mo buffer layer with the unit cell rotated 45° to match that of BCC Mo. This is the so-called
Nishiyama–Wassermann (NW) epitaxial relationship [2]. Since the distance of the nearest neighbor in NiFe (2.5 Å) is smaller than that in Mo (2.723 Å), when NiFe was epitaxially grown on Mo, the NiFe film was subjected to an in-plane tensile stress due to the lattice mismatch between NiFe and Mo. This in-plane stress introduced a uniaxial anisotropy in NiFe. Consequently, the spins in NiFe mainly align in this axis (either in positive or negative direction). To reduce the magneto-static energy, closure domains may form in the NiFe layer, in which the spins are mainly aligned in the easy axis but in edge domains the spins are perpendicular to the easy axis. Because of the epitaxial growth between NiFe and NiFeMn, the spins of NiFeMn at the interface are strongly coupled to those of NiFe through the interfacial exchange coupling; therefore, NiFeMn may break into multi-domains to reduce the interfacial energy between NiFe and NiFeMn. The schematic domain patterns of NiFe and NiFeMn are shown in Fig. 5, if we assume that the interfacial coupling between F and AF is parallel. Consequently, in MOKE experiment, if the laser spot shined on the area I (II) in Fig. 5, a shifted negative-field (positive-field) hysteresis loop was observed; if the laser spot covered both area I and II, the dual shifted loops were observed. These results were further verified by the VSM data. When we measured the $M-H$ curves along the easy axis ($0^\circ$), in addition to two shifted loops, one ‘hard-axis-like’ loop appeared around the zero field. This loop was contributed from the edge domains (area III), as shown in Fig. 5, with the spins aligned perpendicular to the easy axis. The hard axis curves ($90^\circ$) also showed two distinguished slopes, which corresponded to the area with spins parallel and perpendicular to the easy axis.

From the data of the as-deposited exchange field, NiFeMn behaved more like FeMn than NiMn. The spin structure of $\gamma$-FeMn can be described by the commonly accepted (1 1 1) model, with Fe and Mn randomly distributed in the FCC lattice [3]. In contrast, disordered NiMn is of FCC paramagnetic phase. After annealing, NiMn FCC lattice transforms into ordered FCT lattice and shows antiferromagnetic properties with the spins parallel to (0 0 1) planes [4]. The magnetic coupling between atoms of (Ni,Fe)Mn films seems to be strongly dependent on the crystal structure and the inter-atomic distance. Based on the X-ray data, our NiFeMn films seemed to be disordered and their lattice constant close to that of FeMn; therefore, the exchange field of NiFe/NiFeMn films was similar to those of NiFe/FeMn. The details of atomic position in NiFeMn films are currently being investigated using X-ray diffraction.

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References