The Interplay between NiMn/NiFe Epitaxial Growth and NiMn Atomic Ordering in NiMn/NiFe Exchange Biased Layers: A Structural Perspective

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Abstract—**The atomic structure across the annealed NiMn/NiFe exchange coupled interface has been studied. NiMn grows epitaxially on NiFe (111) according to a cube on cube orientation relationship. This yields a semi-coherent interface which is made up of atomic ledges. Due to the stabilizing effect of fcc NiFe, it was found that the NiMn crystal cannot attain the ordered $L1_0$ structure thus holding down the strength of the exchange bias field. However, twinning at the interface seemingly helps to assist NiMn ordering.**

I. INTRODUCTION

The exchange anisotropy induced by spin coupling across an antiferromagnet/ferromagnet interface[1,2] has attracted enormous interest recently as it plays an essential role in the proper function of both anisotropic magnetoresistive (AMR) and giant-magnetoresistive (GMR) flux sensors[3,4]. In such devices, the magnetization within a flux sensing NiFe layer is stabilized/pinned through interfacial exchange coupling with an antiferromagnetic film which results in the shifting of the hysteresis loop of the amount of a bias field. The nature of this exchange bias field (H_e) can subsequently be utilized in various means in device design. To be suitable for any biasing applications, H_e must be sufficiently high at room temperature to achieve the desired performance of the device. The strength of H_e has been shown to be determined predominantly by the coupling strength across the interface. $Ni_{50}Mn_{50}$ has been shown to be a promising candidate as an exchange layer material because it possesses a high crystalline anisotropy field, a high blocking temperature and satisfies the chemical stability requirements[5-7]. At room temperature, bulk NiMn is antiferromagnetic with a CuAu-I ($L1_0$) ordered tetragonal crystal structure which consists of alternating planes of Ni and Mn atoms (Figure. 1). The Néel temperature of ordered NiMn is around 800°C[8]. H_e in the NiMn/NiFe system is obtained through post-deposition annealing which promotes atomic ordering in the NiMn layer. In this work, we examine the atomic structure of the NiMn/NiFe interface to determine its microstructural characteristics and its the effect on NiMn ordering. This can provide a better understanding on the mechanisms which controls H_e in this system.

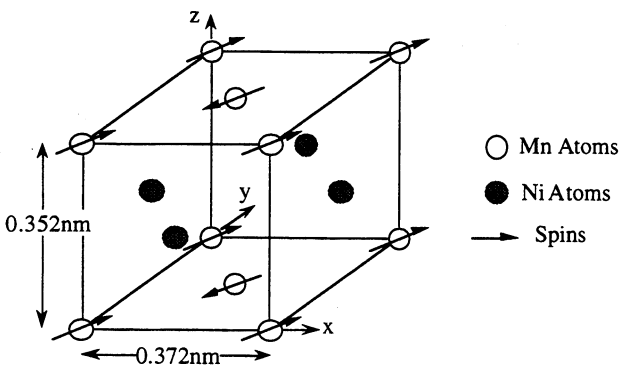

Figure. 1 A schematic of the ordered NiMn unit cell[8].

II. EXPERIMENTAL PROCEDURES

10nmMo/40nmNiMn/25nmNiFe/10nmTa layers were deposited onto an Al_2O_3 underlayer that was sputtered on Si substrates. An external field of 60 Oe was applied during deposition to induce an easy axis in the NiFe film. All specimens were sputtered with Ar gas pressures between 5-20mTorr and with forward powers between 400-1000W. The NiFe layer was deposited in two steps. After the deposition of the first half of NiFe, the chamber vacuum was disrupted. A light sputter etching was administered to remove any surface oxide before depositing the second half of NiFe, NiMn and Mo layers. The sample was annealed at 300°C for 6 hr and was then examined in cross section by conventional and high resolution transmission electron microscopy (HRTEM) in a JEOL 4000EX microscope.

III. RESULTS AND DISCUSSIONS

The H_e of the specimens studied was between 40 and 50 Oe. The x-ray diffraction spectrum of the specimen with a H_e of 50 Oe is shown in Figure 2. The co-existence of strong

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(111) NiFe and (111) NiMn peaks indicates a possible growth relationship between them. However, it is not feasible to deduce form the spectrum the degree of ordering in NiMn as the {111} planes are unique in a tetragonal structure since they all have identical interplanar spacing.

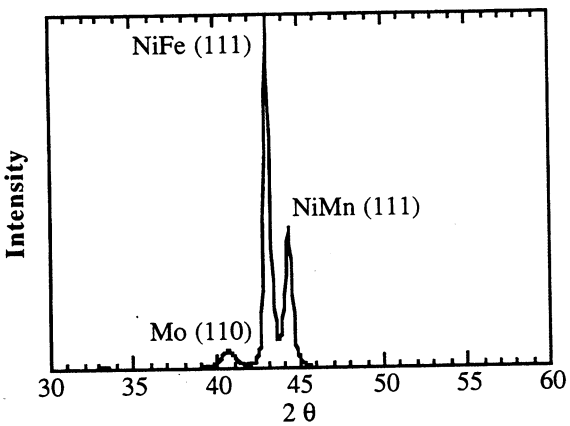

Figure 2. X-ray diffraction spectrum of an exchange biased NiMn/NiFe film.

A cross sectional TEM image of the film is shown in Figure 3. Strong columnar growth is present in both the NiFe and NiMn layers and the interphase boundary is not very well defined. A number of twins (arrows) can be observed within the NiMn film. Other planar defects can be found to extend across the interface indicating good epitaxy between grain columns.

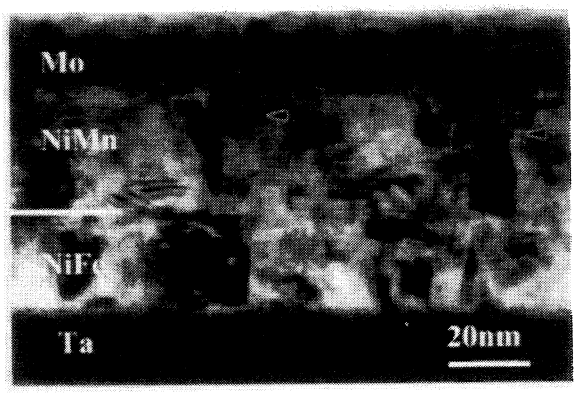

Figure 3. A cross-sectional TEM image of an exchange biased NiMn/NiFe specimen.

The atomic structure across a NiMn/NiFe interface is shown in Figure 4a and the average atomic interface is marked by the white line. Good atomic matching is evident and it came about due to the epitaxial growth on the (111) plane between the two crystals. In addition to (111), the (111) planes from both layers are also parallel to each other resulting in a cube on cube orientation relationship of $(111)_{NiMn}/(111)_{NiFe}$, $(110)_{NiMn}/(110)_{NiFe}$ (Figure 4b). Upon closer observation, one can depict the misfit dislocations (arrows) which accommodate the lattice misfit between the two crystals and allow the interface to reach an equilibrium state. Such strain relaxation gives rise to a semi-coherent interface. The location of the these dislocations also marks the contour ~~of~~ the interphase boundary. By tracing their position, atomic steps/ledges between one to four (111) planes high can be observed in the different interfaces studied. This interfacial roughness is vital to obtaining H_e on an antiferromagnetically compensated atomic plane such as (111) NiMn[9].

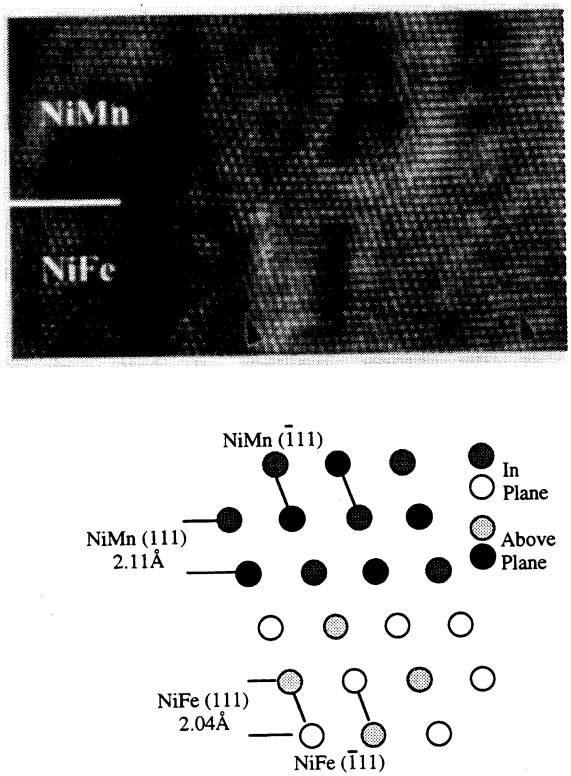

Figure 4. (a) Atomic structure across a NiMn/NiFe interface and (b) a schematic of the atomic arrangement.

The degree of atomic ordering in the NiMn crystal can be estimated by measuring the interplanar angle ($\angle$111) between (111) and (111) planes. This is because the tetragonal distortion initiated by NiMn ordering will shift $\angle$ 111 to either 73.39° or 69.98° in the fully ordered $L1_0$ structure as opposed to 70.52° in the disordered cubic phase. At the interface in Figure 4a, $\angle$111 was measured to be 70.5 in NiMn indicating the cubic dimensions it possesses. This is a consequence of the stabilizing effect of fcc NiFe by means of epitaxial growth. It tires to maintain the NiMn

across the interface in a cubic lattice thus arresting the ordering reaction. This incomplete ordering has strong implications on the strength of H_e as it, in all probability, reduces the anisotropy field and the Néel temperature in anti-ferromagnetic NiMn and leads to a lower H_e in such exchange coupled system.

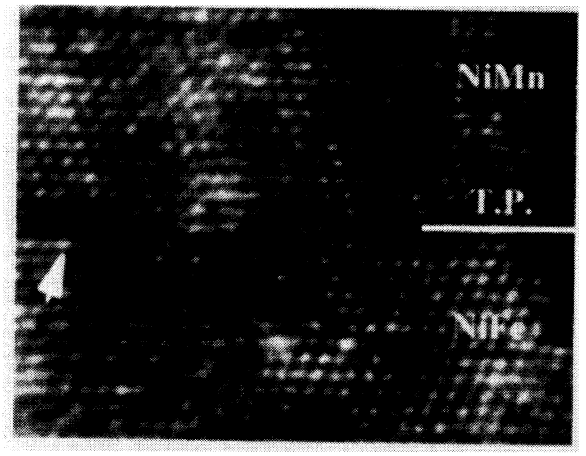

Figure 5. Atomic structure of a NiMn/NiFe interface in a twinned orientation. (T.P.: twin plane)

Figure 5 shows another NiMn/NiFe interface. In stead of the direct cube on cube orientation observed above, NiMn grows on NiFe (111) in a twinned orientation i.e. the twin plane is also the interface. Misfit accommodating dislocation (white arrow) and atomic steps can again be found at the interface. ∠111 in NiMn is measured to be 71.2° which indicates that a twinned interface is beneficial to NiMn ordering.

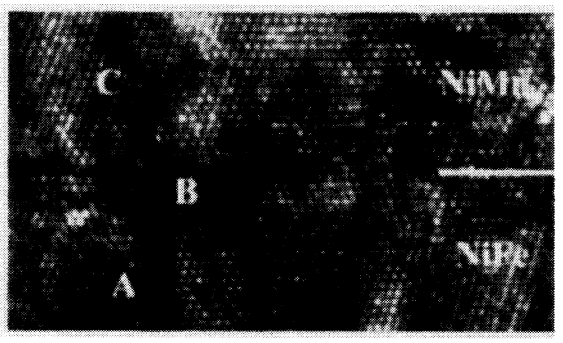

Figure 6. Atomic structure of a twinned NiMn/NiFe interface

A twin band which crosses over the interface is shown in Figure 6. ∠111 from regions A, B and C were measured to be 70.5°, 70° and 69° respectively which reflects crystal twinning facilities ordering. The reason for this can be two fold. First, a twinned interface can help accommodate the misfit strain and reduces the stabilizing effect of fcc NiFe. Second, twinning helps relieve the lattice distortion due to atomic ordering as observed in bulk NiMn alloys[10].

IV. Conclusions

The NiMn/NiFe interface has been studied by HRTEM and epitaxy between the two layers was readily observed. As a result of the epitaxial growth, NiMn ordering was found to be impeded by fcc NiFe. The existence of twins at the interface were found to help NiMn become more ordered.

Acknowledgement

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