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Exchange Coupling in NiFe/Ni Bilayer Fabricated By Electrodeposition

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Bilayers of soft NiFe (150 nm-420 nm) on hard Ni (150 nm) were prepared by electrodeposition. The process of magnetization reversal in the NiFe/Ni bilayers was then investigated. The hysteresis loop generated by a magnetization reversal of soft NiFe under a positive saturation state of a hard Ni layer shows a shift along the negative field axis, which is clear evidence for the exchange spring effect in the NiFe/Ni bilayers. The dependence of the coercive field H_c and exchange bias field H_{ex} on the thickness of the NiFe layer was also investigated. As the NiFe thickness increases from 150 nm to 420 nm, both H_c and H_{ex} decrease rapidly from $H_c = 51.7$ Oe and $H_{ex} = 12.2$ Oe, and saturate to $H_c = 5.8$ Oe and $H_{ex} = 3.5$ Oe.

Keywords : exchange spring effect, hard/soft bilayers, magnetization reversal, exchange bias field

1. Introduction

Magnetic multilayers are used most recently in applications such as magnetic recording media, magnetic reading heads and sensors, and the exchange coupling effect in magnetic multilayers has attracted great interest. There are two basic kinds of exchange coupling effect: the exchange spring (XS) effect in soft/hard bilayers and exchange bias (XB) effect in ferromagnetic/antiferromagnetic bilayers [1-3].

The XS effect was first studied in magnet design because the composite of embedded hard magnetic materials in soft ferromagnetic matrix has both the benefits of high coercivity and high saturation magnetization [4].

The XS effect has recently received much attention in the development of perpendicular recording media with ultra high density, because it can be a means of simultaneously achieving enhanced writability and thermal stability, which are the current conflicting media design constraints [5, 6]. Similar to the XB effect, the XS effect has hysteresis characteristic of a two-phase hysteresis loop at full magnetization of the hard and soft layers (major loop), and a shifted hysteresis loop at minor magnetization of only the soft layer (minor loop) [3].

In this paper we investigate the XS effect in soft NiFe/hard Ni bilayers fabricated by electrodeposition. There are currently no reports on the XS effect in in-plane NiFe/Ni bilayers. The major and minor hysteresis loops were measured for the NiFe/Ni bilayers with various thicknesses. The dependence of the XS effect on the soft NiFe layer thickness was investigated.

2. Experiments

NiFe/Ni bilayers were prepared on Au coated Si-wafer substrates by electrodeposion. The electrodeposition was performed in potentiostatic mode with a three electrodes configuration: a thin platinum sheet as a counter electrode (CE), Ag/AgCl as a reference electrode (RE), an Au coated Si-wafer as a working electrode (WE). The thickness of Au on WE was 100 nm. The room temperature bath for Ni deposition contained 52.6 g/L $NiSO_4$ and 24.6 g/L H_3BO_3 dissolved in deionized water, and the bath for NiFe contained 52.6 g/L $NiSO_4$, 2.8 g/L $FeSO_4$ and 24.6 g/L H_3BO_3. The electrodeposition of Ni and NiFe was conducted potentiostatically at WE-potential of –1.0 V with respect to the RE. Firstly, Ni was deposited, followed by NiFe, which was subsequently deposited by changing the bath. The deposition thicknesses of Ni and NiFe films were controlled by the total electrodeposited charges of Ni and NiFe (Q_{Ni} and Q_{NiFe}), respectively. The structure and composition of electrodeposited layers were measured by the field-emission scanning electron microscope (FE-SEM, Jeol JSM-6700F) with an energy dispersive X-ray (EDX) spectrometer. The hysteresis loop was measured by a

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vibrating sample magnetometer (VSM).

3. Results and Discussion

Fig. 1(a) shows the FE-SEM image for the fractured cross-sectional surface of the NiFe/Ni bilayer with total electrodeposited charges of Q_{Ni} = 3 C and Q_{NiFe} = 3 C. The total thickness of the deposited NiFe/Ni/Au films on the Si wafer is about 460 nm as shown in Fig. 1(a). Since the thickness of Au was 100 nm, the total thickness of the NiFe/Ni bilayers is about 360 nm. Fig. 1(b) shows the variation the amounts of Ni and Fe with the height from Si substrate measured by scanning the EDX spectrometer along the vertical line. From this result, the thicknesses of the bottom Ni layer and upper NiFe layer can be estimated at about 150 nm and 210 nm, respectively, and the composition of the NiFe layer was found to be $Ni_{88}Fe_{12}$ in atomic weight percentage.

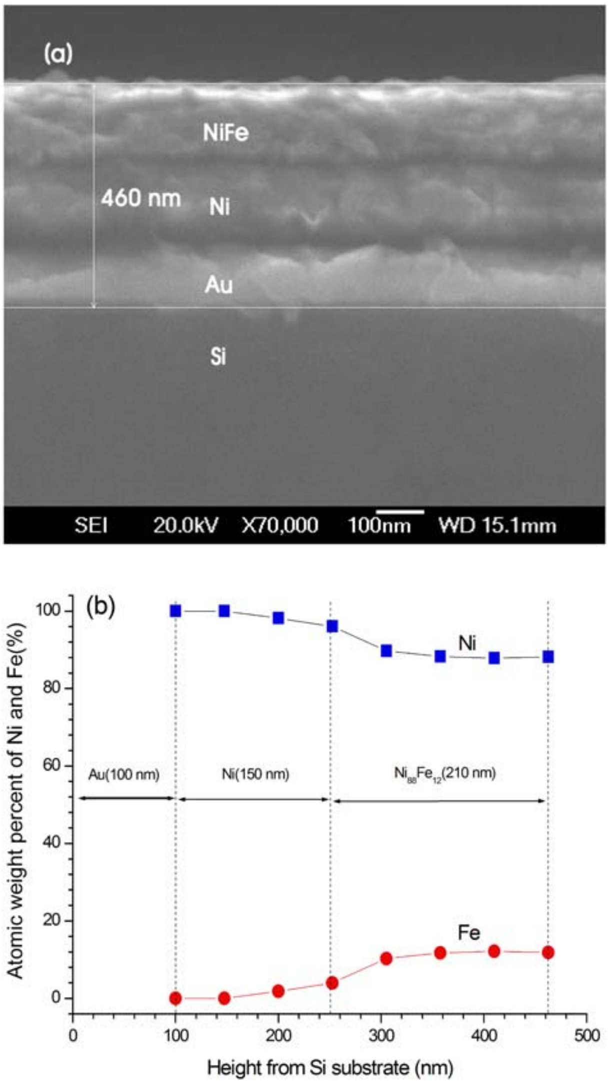

Fig. 1. (a) FE-SEM image (b) variation of Ni and Fe compositions for the cross-sectional surface of NiFe/Ni bilayers electrodeposited on Si-wafer with total electrodeposited charges of Q_{Ni} = 3 C and Q_{NiFe} = 3 C.

Fig. 2(a) and (b) show the major and minor hysteresis loops for the $Ni_{88}Fe_{12}$(210 nm)/Ni(150 nm) bilayer, respectively. The major loop shows a two phase hysteresis characteristic resulting from a magnetization switching of the softer NiFe layer first, followed magnetization switching of the harder Ni layer. The minor loop of Fig. 2(b), which was generated by a cyclic field H with an amplitude less than the switching field of the harder Ni layer in the positive saturation state by prior exposure to 1000 Oe, shows a shift along the negative H axis. This shift reflects that the softer NiFe layer is switching under XS coupling with the harder Ni layer as shown by the illustrations inserted in Fig. 2(b). The exchange bias field H_{ex} and coercive field H_c have been determined from the horizontal offset

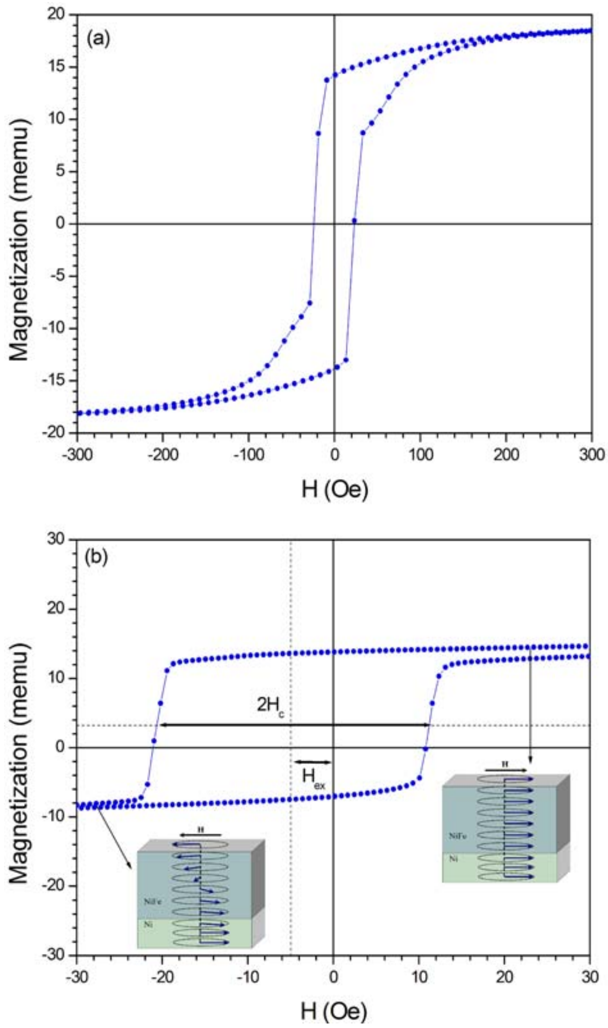

Fig. 2. (a) Major and (b) minor hysteresis loops of the $Ni_{88}Fe_{12}$ (210 nm)/Ni (150 nm) bilayer.

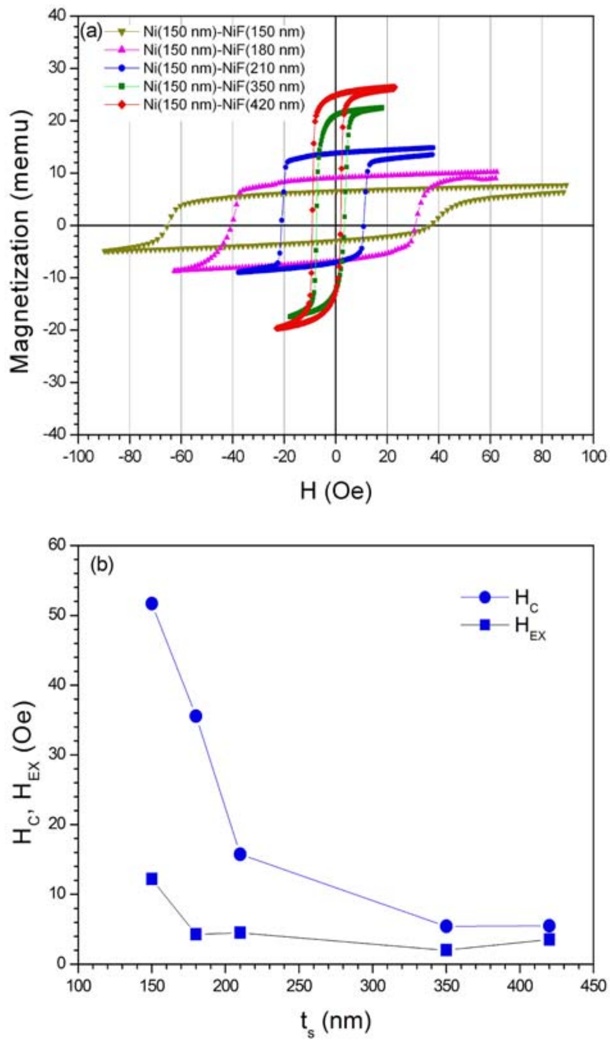

Fig. 3. Dependence of (a) minor hysteresis loops and (b) H_c and H_{ex} of $Ni_{88}Fe_{12}$ (150 nm-420 nm)/Ni (150 nm) bilayers on the NiFe layer thickness.

from the origin and the half-width of minor loop, respectively, as indicated in Fig. 2(b). The determined values of the coercive field and the exchange bias field for the $Ni_{88}Fe_{12}$(210 nm)/Ni(150 nm) bilayer are about H_c = 15.7 Oe and H_{ex} = 4.5 Oe, respectively.

Various thicknesses of the $Ni_{88}Fe_{12}$ layer on the Ni layer of a fixed thickness of 150 nm were prepared. Fig. 3(a) shows the dependence of the minor loop on the soft NiFe layer thickness t_s. All minor loops show a shift along the negative H axis with the coercive field H_c and exchange bias field H_{ex} depending on t_s. Fig. 3(b) shows the dependence of H_c and H_{ex} on the t_s determined from Fig. 3(a). As t_s increases, both H_c and H_{ex} decrease quickly and then saturate to H_c = 5.8 Oe and H_{ex} = 3.5 Oe, respectively. The rapid decrease arises because the soft layer is strongly pinned by the exchange spring coupling at the NiFe and Ni interface. The saturation of H_c is reasonable because H_c will approach the coercive field of the NiFe single layer for higher t_s. The saturation of H_{ex} is an unexpected result because theoretical models predict that H_{ex} approaches zero for higher t_s [7].

If we can fabricate a bilayer with similar H_c and H_{ex} values, then the magnetization reversal in the soft layer will occur near zero field as shown in the loop of NiFe (210 nm)/Ni(150 nm). This is useful for developing sensitive magnetic sensors without the necessity of an external bias field [8].

4. Conclusion

NiFe(150 nm-420 nm)/Ni(150 nm) bilayers were prepared by electrodeposition to investigate the exchange spring effect between hard Ni and soft NiFe layers. The exchange spring effect is clearly detected in the process of magnetization reversal of soft NiFe under a positive saturation state of hard Ni. Both H_c and H_{ex} decrease rapidly and saturate for an increasing NiFe layer thickness.

In order to achieve a full understanding of the exchange spring effect in NiFe/Ni bilayers, we are considering further studies on the magnetization reversals in the bilayers with various anisotropic orientations prepared by electrodeposition and field-annealing. This investigation could be adapted for developing a magnetic field sensor element with a self bias field.

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