Exchange Coupling in NiFe/NiMn Bilayer And Properties of NiMn-pinned Spin Valve

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Abstract- The effects of annealing on the exchange coupling in NiFe/NiMn bilayers and the properties of NiMn-pinned spin valve are studied. With increasing annealing time and annealing temperature, the exchange coupling field $H_{ex}$ first increases, followed by a decrease. The evolution of $H_{ex}$ with annealing is the competing result between nonmagnetic fcc-antiferromagnetic fct phase transition and interfacial diffusion. The exchange coupling between NiFe and NiMn layers is very stable at temperatures from room temperature to about 210 °C. The distribution of blocking temperature $T_{B}$ is responsible for the thermal stability. For the NiMn-pinned spin valve, a lower annealing temperature is favorable, at the expense of a longer time to obtain a desired exchange coupling field.

Key words: exchange coupling, spin valve, giant magneto-resistance

1. Introduction

The exchange coupling phenomenon between a ferromagnetic(FM) layer and an antiferromagnetic (AFM) layer is very useful in both the anisotropy magnetoresistance(AMR)\(^1\)\(^2\) magnetic sensor and the spin valve(SV) giant magnetoresistance(GMR) sensor\(^3\). The AFM layer provides a pinning field in an AMR sensor to saturate the magnetic layer and suppress the Barkhausen noise, while in a SV structure the pinning field plays a key role in the relative rotation of magnetisations between two FM layers separated by a nonmagnetic(NM) layer. Many materials of AFM have been studied for pinning layer\(^4\)\(^5\). Among them, NiMn is a potential candidate because of its high coupling strength and thermal stability\(^6\). The chemical stability is also better than most of other candidate materials\(^7\)\(^8\)\(^9\). However, the as-deposited NiMn is nonmagnetic fcc phase and thus the annealing is indispensable to obtain AFM fct phase\(^5\)\(^6\)\(^8\). It was also reported that the exchange coupling increased with annealing time and then eventually levelled off\(^5\)\(^6\)\(^9\).

A systematic study on the effects of annealing time and temperature on the exchange coupling properties of NiFe/NiMn bilayers has been carried out. The exchange coupling field $H_{ex}$ and the exchange coupling energy $J_{ex}$ under various annealing conditions were examined. The $H_{ex}$ at elevated temperatures was also measured to evaluate the thermal stability. For the spin valve with a NiMn pinning layer, the effects of annealing on its properties were studied.

2. Experimental Procedure

The NiFe/NiMn bilayers were deposited using a 4-source DC magnetron sputtering system and the spin valve multilayers were deposited with a 6-source DC magnetron sputtering system. For both the bilayer and the spin valve multilayers, 9 nm and 6 nm Ta layers were employed as the underlayer and overlayer respectively. Glass and silicon were used as substrate and the substrate was water-cooled during depositing. Vacuum melted alloy targets of Ni$_{50}$Mn$_{30}$ and Ni$_{50}$Fe$_{50}$ were used, and the resultant compositions in the film were Ni$_{53}$Mn$_{55}$ and Ni$_{53}$Fe$_{50}$. Films were deposited at a rate of 1–1.5 Å/s in a magnetic field of about 200 Oe. Background pressure was below 3×10$^{-5}$ Pa and Ar pressure during sputtering was 0.55 Pa. After deposition, annealing was carried out in a vacuum better than 4×10$^{-5}$ Pa and a magnetic field of about 500 Oe at temperatures up to 320 °C.

The crystal structure was characterized by a X-ray diffractometer (XRD) with Cu-Kα radiation and the composition was analysed by Energy Dispersive Spectrum(EDS). Thermal stability was examined by measuring $H_{ex}$ at various elevated temperatures. The $M_S$ and $H_{ex}$ were obtained from the M-H loops measured with Alternating Gradient Magnetometer(AGM).

Measurement of MR properties were conducted using a conventional 4-probe method.

3. Results and discussion

Figure 1 shows the effects of annealing time $t_{an}$ on exchange coupling in NiFe(39nm)/NiMn(50nm) bilayers. NiMn layer is on the top of NiFe Layer. The annealing temperature was kept at 260 °C. With increasing annealing time, it can be observed that the $H_{ex}$ increases firstly. However, after about 10 hours, it starts to decrease with further annealing, which is different from some other report\(^1\)\(^9\)\(^10\). The corresponding exchange coupling energy $J_{ex}$, obtained from $J_{ex} = H_{ex}M_Sd_{NiFe}$ shows a similar evolution with annealing time, as depicted in the same figure.

For the initial increase of the exchange coupling field with annealing time, it should be attributed to the NM fcc - AFM fct phase transition, which increases the exchange coupling. The phase transition also leads to the change of
annealing, the phase transition in the NiMn layer and the interfacial diffusion are the main two factors contributing to the evolution of $H_{ex}$ and $J_{ex}$. The formation of the AFM phase, which arises the exchange coupling, is the dominant factor at the early stage of annealing, and accordingly $H_{ex}$ and $J_{ex}$ increases with increasing annealing time. With further annealing, the interfacial mixing dominates, leading to the lowering of $H_{ex}$ and $J_{ex}$. It has been reported that interdiffusion across the NiFe/FeMn interface formed a weak AFM Ni-Fe-Mn ternary alloy. The variation of $d_{111}$ plotted in Fig.2 also shows that after about 10 hours, the annealing did not cause further significant change of $d_{111}$, i.e. further annealing has little effect on the phase transition, but causes further interdiffusion at interfaces.

The effects of annealing temperature on the exchange temperature were also studied. A similar evolution of exchange coupling was observed.

In many cases, the operating temperature of the MR and the spin valve devices is higher than 100 °C. Therefore, it is important for the AFM layer to sustain an exchange coupling strength high enough even at high temperatures. The $H_{ex}$ at various temperatures from room temperature (RT) to 250 °C was examined. The resulted $H_{ex}$-T curve is shown in Fig.3. Similar to some previous studies, a slight increase of $H_{ex}$ can be observed when the temperature increases from room temperature to about 140°C, and then starts to decrease as the temperature increases further. However, when raising the temperature to 210°C, $H_{ex}$ still has a value almost equal to that at room temperature. By extrapolating the $H_{ex}$-T curve to $H_{ex}$=0, the blocking temperature can be roughly estimated to be about 300 °C. The results show that NiMn has good thermal stability on exchange coupling with NiFe layer. As for the abnormal increase of $H_{ex}$ before reaching 140 °C, it should be partly related to the change of $M_s$ with temperature. $M_s$ usually decreases with increasing

- **Fig.1** Effects of annealing time on exchange coupling

- **Fig.2** Effects of annealing time on saturation magnetization and (111) spacing.

- **Fig.3** Exchange coupling field at elevated temperatures and the distribution of blocking temperature.

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temperature. According to $H_{ex} = J_{ex}/M_{S}M_{NiFe}$, the decrease of $M_{S}$ would induce the increase of $H_{ex}$.

There have been several models to account for the observed result of $H_{ex}$ vs measuring temperature. Among them, the exchange paths model assumes that there are many exchange paths in the interface of a FM/AFM bilayer, and each one has its own blocking temperature. The $H_{ex}$-T curve was claimed to be mainly determined by the distribution of the blocking temperatures for all the exchange paths.\textsuperscript{12,14,15} Given a temperature $T$, for some of the exchange paths, their blocking temperatures are lower than $T$. $H_{int}(T < T_{c})$, which represents the exchange coupling field provided by these exchange paths, can be determined by cooling down procedure in a field applied opposite to the total exchange coupling field $H_{ex0}$. If the contribution of these exchange paths to $H_{ex}$ is denoted as the percentage $P(T_{c} < T)$ in all the exchange paths, then one can obtain $P(T_{c} < T) = H_{int}(T < T)/H_{ex0}$, as also shown in Fig. 3. To ensure the fully reversing of the pinned layer during cooling as described by Y.B. Zhang et al.\textsuperscript{12}, the field during cooling was 650 Oe, which was opposite to the exchange coupling field in the bilayer and much larger than it. It is apparent that there are few exchange paths with $T_{c}$ lower than 150 °C, and almost 50% of the exchange paths have $T_{c}$ higher than 250 °C. Such a distribution of $T_{c}$ is in agreement with the good thermal stability.

Using NiMn as the pinning layer, a spin valve multilayer NiFe(9nm)/Co(1.1nm)/Cu(3nm)/Co(1.3nm)/NiFe(3nm)/NiMn(25nm) was fabricated. It was observed that while the exchange coupling field was obtained through annealing, the GMR ratio decreased with annealing. In Fig.4 is shown the relationship between GMR ratio and the corresponding exchange coupling field $H_{ex}$ at annealing temperatures 280 °C and 300 °C, respectively. It can be seen that the increasing of exchange coupling field is at the cost of GMR ratio, and vice versa. As above-mentioned, the exchange coupling field was enhanced by annealing. And the interdiffusion across the Co/Cu interfaces caused by annealing results in spin-independent electronic scattering and accordingly decreases the GMR ratio. That is the negative effect of the annealing. According to the figure, one may note that provided the same exchange coupling field is obtained, a lower annealing temperature brings about a higher GMR ratio. Although a lower annealing temperature may need longer time to obtain the desired exchange coupling field, it brings less negative effects on the GMR properties of the spin valve.

Other two important parameters in a spin valve multilayer are the coercivity of the free layer $H_{Cf}$ and the interlayer coupling field $H_{int}$ between the free and pinned layers. The annealing time dependences of $H_{Cf}$ and $H_{int}$ are given in Fig.5. A rapid increase of interlayer coupling and a rapid decrease of free layer coercivity could be observed after annealing for about 15 hours. This may be related to grain boundary diffusion across the Cu spacer, which could form coupling channels in the Cu layer.

4. Summary

With both increasing annealing time and elevating annealing temperature, both the exchange coupling field $H_{ex}$ and the exchange coupling energy $J_{ex}$ in NiFe/NiMn bilayers increase initially and then fall down after reaching a maximum. The evolution of the exchange coupling is believed to be due to the competition between the phase transition from NM to AFM and the interdiffusion across the interfaces, both of which are caused by annealing.

The exchange coupling between NiFe and NiMn layers is thermally very stable. The $H_{ex}$ even shows an increase with raising measuring temperature from RT to about 140 °C, which is partly attributed to the decrease of magnetization with elevating measuring temperature. The
exchange path model was examined and the distribution of the blocking temperature is found to be consistent with the thermal stability result.

For NiMn-pinned spin valve, a lower annealing needs more annealing time to obtain the desired exchange coupling strength but brings less negative effects.

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References
