Modifying interlayer coupling in CoFe/Bi/Co trilayer junction by post-annealing treatments

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Abstract

The interlayer coupling has been observed in CoFe/Bi/Co trilayer junctions. Magnetization studies show that the coupling strength oscillates with the thickness of Bi at room temperature as seen in most metallic spacers but with an unusually long period. Furthermore, it has been found that the interlayer coupling can be easily modified with low-temperature post-annealing treatments.

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1. Introduction

The discovery of interlayer coupling between two ferromagnetic layers separated by a nonmagnetic spacer has aroused strong interest among international scientific community [1], because such coupling has great potential to be used in various applications such as magnetic recording head as well as magnetic random access memory [2]. The variation in the coupling strength with the thickness of the spacer layer and the oscillatory behavior of interlayer coupling make this field even more interesting and useful. Up to now, the studies on interlayer interactions have been limited to use metal, insulator [3], or semiconductor [4] as the spacer materials. There is no report yet regarding interlayer coupling across semimetallic Bi spacer. In our previous study, interlayer coupling with a very long range has been found in a trilayer system with Bi as the spacer [5]. Additionally, the interlayer coupling exhibits a unique dependence on temperature. No exact theory that explains satisfactorily the special characteristics

of interlayer coupling in the system described herein is available.

To investigate the dependence of interlayer coupling on the interface structure could increase our understanding of this issue. Changing the interlayer coupling strength following sample preparation is normally non-trivial. However, the low melting point of Bi enables thermal annealing to be easily used to modify the layer structures, to enable the variation in the interlayer coupling with interface structure to be observed.

2. Experimental

Trilayer structures CoFe/Bi/Co having thickness of magnetic layer as 15 nm and bismuth ranging from 1 nm to 60 nm were prepared by DC sputtering through different masks at room temperature. The as-deposited samples were annealed with Ar flow at various temperatures from 50 to 250 °C for 30 min in each run. The crystalline structures of as-deposited and annealed samples were checked by X-ray diffraction (XRD). Cross-section TEM images have been investigated in order to characterize the microstructure of the as-deposited and annealed samples. Composition of the films was determined by energy dispersive X-ray diffractometer (EDS). Room-temperature magnetization loops

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were obtained using a vibrating sample magnetometer (VSM) with a magnetic field applied in the film plane. And it is either parallel to Co or CoFe layer during measurements.

3. Results and discussion

The XRD patterns measured in θ - 2θ configuration for as-deposited samples indicate that the major diffraction peaks are from Bi due to its larger scattering factor. No additional phase other than Bi, Co or CoFe has been detected indicating no formation of any alloy or compound at the interface. After the samples with Bi layer thickness less than 20 nm were annealed at 100 °C, a decrease in the peak intensity with an increase of peak width has been seen. This is an indication that the annealing process promotes the mobility of Bi atoms. This intensity gradually rises again as the annealing temperature is further increased. Above 200 °C, a larger number of diffraction peaks appear with reduced intensity; these peaks are broader than those of as-deposited samples. The broadening of the peaks and the loss of high-order peaks are characteristic of increased layer roughness. Therefore, the roughness increases with the annealing temperature above 200 °C, leading to less intense and broader reflections. These changes can be interpreted as associated with an initial sharpening of the interface or a decrease in its roughness, followed by the onset of de-stratification [6]. However for a thick Bi spacer, the intensity of the peaks remains approximately constant and the X-ray diffraction pattern does not change much.

Fig. 1 reveals a complicated variation of saturation field H_s with the thickness of Bi spacer layer. The as-deposited

samples possess interlayer coupling of oscillating type with a long period of about 18 nm, which oscillates between antiferromagnetic (AFM) coupling and ferromagnetic (FM) coupling. Furthermore, the interaction range extends up to 50 nm, much longer than using metal as the spacer. In order to exclude demagnetization effect, we have repeated experiments with the samples of sandwich structure, and they exhibited similar behavior. Annealed samples at 50 °C shows a similar behavior, but those annealed at higher temperatures present completely different behavior. The effect of annealing can be essentially divided into two regions. For $t_{\text{Bi}} \leq 2$ nm, samples annealed at 100 °C have a large reduction of saturation field. The reduction of saturation field falls with higher annealing temperatures. In addition, the original AFM coupling even becomes FM coupling and vice versa. On the other hand, the values of H_s are close to each other for thicker samples. Moreover, when the annealing temperature reaches 250 °C—close to the melting temperature of Bi, which is approximately 271 °C—the variation in H_s with the nominal thickness of Bi is similar to that of as-deposited samples but values of H_s are above those of as-deposited samples in all cases. The trend of H_s variation with annealing temperatures is in agreement with that in XRD patterns.

In order to account for the change of interlayer coupling with post-annealing treatments, we proposed two possible mechanisms. It is well known that Bi film behaves like a semiconductor when the film thickness is below 20 nm [7]. In such a way, the interlayer coupling through a semiconducting spacer can be easily tuned through thermal

Fig. 1. Variation of H_s with thickness of Bi spacer layer for as-deposited samples and annealed at various temperatures.

Fig. 2. Cross-section TEM pictures for $t_{\text{Bi}} = 2$ nm (a) as-deposited, (b) annealed sample ($T_a = 250$ °C) and for $t_{\text{Bi}} = 30$ nm, (c) as-deposited, and (d) annealed sample ($T_a = 250$ °C).

excitation of charge carriers [8]. Another possibility is due to the change of interface roughness from annealing. The roughness of interface has been found to play an important role in interlayer coupling [9,10]. Cross-section TEM images in Fig. 2(a) and (c) indicate that the as-deposited samples have clear three-layer structure with thickness of bismuth spacer layer close to the nominal value. The roughness is about 0.5 nm for $t_{\text{Bi}} = 2$ nm. However, annealing below 100 °C yielded rougher interfaces than those of as-deposited samples. As the annealing temperature was increased, the interface became smoother because the atoms diffused in the plane of the interface, smoothing it out. Furthermore, as the annealing temperature reached 250 °C, interdiffusion of Bi and Co layers also occurs, causing the spacer layer to behave like a ferromagnet with thin spacers. No clear boundary was easily identified for thin Bi spacer. The detailed quantitative analysis to find the correlation of interface roughness determined from TEM images with interlayer coupling strength is underway.

4. Conclusion

In summary, the interlayer coupling of CoFe/Bi/Co trilayer junction exhibits an oscillating behavior with a very long range. The interaction could be even switched from AFM coupling into FM coupling and vice versa with low-temperature annealing treatments. The variation of

interlayer coupling is associated with the change of interface structure.

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