Dependence of exchange coupling in Cu/FeMn/permalloy on the Cu buffer layer thickness

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Abstract

A wedged-Cu(0–30 nm)/Fe50Mn50(10.0 nm)/permalloy (25.0 nm) sample was prepared by a magnetron sputtering system. The exchange field $H_E$ at room temperature increases approximately linearly with the Cu layer thickness $d_{Cu}$ up to 30.0 nm. The blocking temperature and the room temperature coercivity increase at small $d_{Cu}$ and saturate with further increasing $d_{Cu}$. Additionally, $H_E$ changes linearly with temperature at low temperatures. These phenomena are related to the changes in the microstructure of the FeMn layer, due to the variation of Cu layer thickness. This work will be helpful to technological application of spin valve magneto-resistance devices.

Keywords: Exchange coupling; Ferromagnetic; Antiferromagnetic

1. Introduction

The characteristics of the exchange biasing have been studied extensively because of its importance in both basic research and applications for read heads used in magnetic recording technique and magnetic field sensor [1,2]. If ferromagnetic (FM)/antiferromagnetic (AFM) bilayer is cooled in an external magnetic field, from a temperature above $T_N$, the Néel temperature of the AFM layer, to a temperature below $T_N$, the hysteresis loop will shift from the origin, characterized by an exchange field $H_E$ and enhanced coercive force $H_C$ [3]. $H_E$ and $H_C$ strongly depend on the constituent materials and their thickness as well as temperature [4]. Previous studies have shown that $H_E$ is inversely proportional to $t_{FM}$ (= the FM layer thickness) [5]. $H_C$ was found to scale as $t_{FM}^{-z}$ in exchange coupled bilayers, such as permalloy (Py)/CoO [6]. When the AFM layer thickness increases from an onset value, the exchange field begins to increase [7]. With further increasing AFM layer thickness, the $H_E$ reaches a maximum and then finally decreases. In addition to the FM and AFM layer thickness, the exchange coupling was also found to depend on the buffer layer materials [8–11]. However, up to now, the effect of the buffer layer thickness on the characteristic of exchange coupling remains unclear. With suitable $T_N$, large $H_E$ and small $H_C$, γ-FeMn was once one of the most promising AFM materials in spin valve GMR devices [1,2]. Despite its imperfect thermal stability, the AFM FeMn is still widely used in...
basic research because of its other prominent advantages, such as $T_N$. In this work, we report the effect of the buffer layer thickness on the exchange coupling using wedged-$Cu(d)/Fe_{50}Mn_{50}$ (10 nm)/Py(25 nm)/Cu(30 nm) sample, in which the Cu buffer layer is a unique variable.

2. Experiments

A layered structure of $Cu/Fe_{50}Mn_{50}/Py$ was fabricated in a DC magnetron sputtering system, which can accommodate layers with a uniform thickness and wedge shape layers. All layers have uniform thickness except the Cu buffer layer, which has a wedge shape. In this way, we can alleviate the run-to-run variation commonly encountered in individually fabricated samples. The background pressure was in the order of $10^{-8}\text{ mbar}$ and the Ar pressure during deposition was 7 mbar. The deposition rate ranged from 0.2 to 0.3 nm/s. The 10.0 nm thick FeMn layer was deposited from a FeMn alloyed target. The 25.0 nm thick Py layer was deposited in a magnetic field of 200 Oe, which was applied perpendicular to the wedge direction and parallel to the film plane during deposition, to induce in-plane uniaxial anisotropy. In order to avoid oxidation, a 30 nm thick Cu capping layer was deposited. Before, magnetic measurements, the sample was cut into many small pieces along the wedge direction, thus providing many small samples which have been prepared at the same time but vary in Cu buffer layer thickness $d_{Cu}$. Each sample was first cooled from 460 K, above $T_N \approx 440 \text{ K}$ of FeMn, to room temperature with a magnetic field of 10 kOe, which is perpendicular to the wedge direction and parallel to deposition field. The direction of the unidirectional anisotropy was established by the cooling field. Magnetization loops were measured using a vibrating sample magnetometer.

3. Results and discussion

Typical hysteresis loops of $Cu/Fe_{50}Mn_{50}/Py$ samples with different $d_{Cu}$ (= Cu layer thickness) are shown in Fig. 1. The loops shift from the origin $H = 0$, accompanied with an enhanced coercive force. Obviously, the values of $H_E$ and $H_C$ are strongly related to $d_{Cu}$.

Fig. 2 shows the dependence of the room temperature exchange field and coercivity in substrate (Si)/Cu ($d$)/FeMn(10.0 nm)/Py(25.0 nm)/Cu(30.0 nm). The inset shows the variation of the exchange field at 80 K with the Cu buffer layer thickness.
transition metal buffer layers. Unlike at room temperature, $H_E$ at 80 K, increases at small $d_{Cu}$ and saturates at 15.0 nm, as shown in the inset. With increasing $d_{Cu}$, however, $H_C$ at room temperature increases initially but saturates at 15.0 nm. One can see that $H_C$ will reach the value of the free single Py layer as $d_{Cu} \to 0$. The exchange field and coercivity have different dependencies on Cu buffer layer thickness, demonstrating further different mechanism of $H_E$ and $H_C$. Previously, they were shown to have different dependencies on both FM and AFM layer thickness. Therefore, understanding the results of the coercivity will provide insight into the mechanism of exchange coupling. Because $H_{C1} = -H_E + H_C$ and $H_{C2} = -H_E - H_C$ change monotonically with $d_{Cu}$ in Fig. 3, the magnetization reversal process is predicted to reoccur by the movement of one single domain wall \[10\], which actually needs a direct observation of the domain structure. For the switching from $\pm M$ to $\mp M$, the switching width $\Delta H_i = (\partial H_C / \partial d_{Cu}) (\partial d_{Cu} / \partial x) \Delta x (i = 1, 2)$, where $x$ and $\Delta x$ are, respectively, the location and sample dimension in the wedge direction, and $\partial d_{Cu} / \partial x = 6 \text{ nm/cm}$. Because the slopes of $H_{C1}$ and $H_{C2}$ do not change much with variation of $d_{Cu}$, $\Delta H_i$ is almost the same for various $d_{Cu}$, as shown in Fig. 1, unlike in wedged-FM/uniform-FeMn bilayers \[12,13\].

Fig. 4 shows the temperature dependence of $H_E$ in the Cu($d$)/Fe$_{50}$Mn$_{50}$(10.0 nm)/Py(25.0 nm) bilayer. Obviously, $H_E$ changes as an approximately linear function of the temperature within the range of $8$–$250$ K. The slope of the curve increases slightly with increasing Cu buffer layer thickness. The linear dependence of the exchange field on the temperature has been observed before \[5\]. Fujiwara et al. proposed a model to explain the linear dependence \[14\], in which a ripple structure of domain is formed in the FM layer during magnetization reversal if the AFM grains have a distribution of crystalline orientation. However, as seen above, the magnetization reversal process in Cu/Fe$_{50}$Mn$_{50}$/Py can be realized by a movement of single domain wall. So the temperature dependence of in $H_E$ in FM/AFM bilayers is not determined by the domain structure during the magnetization reversal. In polycrystalline system, the linear dependence can be explained by the simple model without symmetry restrictions \[15\]. In the temperature region far below the Néel temperature, the exchange field is a linear function of temperature and the slope depends on the ratio of the interface interaction energy to the zero temperature domain wall energy of the AFM layer. The present results in Fig. 4, confirm the above theoretical prediction.

The exchange bias vanishes above the blocking temperature, which is obtained from the intercepts of these curves with the temperature axis. Fig. 5 shows the $d_{Cu}$ dependence of the blocking temperature $T_B$. With increasing $d_{Cu}$, $T_B$ increases and saturates at 15.0 nm. Apparently, the so-called
finite size effect is excluded in the explanation of the present results [7], because the AFM layer thickness does not change at all. Actually, the variation or the blocking temperature results from the change in the AFM layer microstructure, which was induced by the different buffer layer materials of thickness [4]. The multiple phase in the FeMn layer was found to change the content of each phase for various buffer layer materials or thickness, which will induce a change in the blocking temperature [4,16]. The variation of the buffer layer thickness was found to induce a change in the grain size of the top layer, and thus the blocking temperature. This is because the blocking temperature is proposed to be dependent on the AFM grain size [17]. So the change in the microstructures in the AFM layer results in the variation of the blocking temperature with the variation of $d_{Cu}$.

The Cu buffer layer thickness dependence of the exchange field, as shown in Fig.2, can be attributed to the change in the microstructure of the FeMn layer with Cu buffer layer thickness. Previous experiments show that the exchange field strongly depends on the microstructure of the AFM layer. For example, the exchange field has been found to increase with increasing (1 1 1) diffraction peak intensity of the AFM layer before [8]. The coercivity of a FM layer, coupled to an AFM layer, was found to be related to the domain size and grain size in the FM layer [18]. When the interface interaction energy $\Delta \sigma (= H_{EFM}M_{FM})$ increases with increasing buffer layer thickness, as shown above, the domain size in the FM layer decreases and coercivity increases. When the FM domain size becomes comparable to the grain size, the coercivity ceases to increase, as shown in Fig.2. While the characteristics of the exchange coupling in FM/AFM bilayers and the function of GMR devices are improved as the buffer layer thickness increases [19], the shunting effect of the buffer layers in spin valve GMR devices will increase and reduce the magnitude of the GMR ratio. So there will be a compromise between the two effects. In practical applications, other buffer materials, such as Ta, NiO and NiFeCr are being used because of their large resistivity and small shunting effect.

4. Conclusion

In summary, we have prepared a sample of Si/wedged-Cu/Fe$_{50}$Mn$_{50}$(10.0 nm)/Py(25.0 nm)/Cu (30.0 nm) and studied the dependence of the exchange coupling on $d_{Cu}$. Room temperature $H_E$ increases linearly with increasing $d_{Cu}$. At the same time both $H_C$ at room temperature and $T_B$ increase at small thickness and saturate at about 15.0 nm. Additionally, $H_E$ changes linearly with the temperature in the range of 80–250 K. The changes of the exchange biasing are suggested to result from the modification of the microstructures of the AFM layer, by the variation of the Cu buffer layer thickness. This will be helpful to the application of spin valve GMR devices.

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References