Training and recovery behaviors of exchange bias in FeNi/Cu/Co/FeMn spin valves at high field sweep rates

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1. Introduction

The exchange bias (EB) effect in ferromagnetic/antiferromagnetic systems has been intensely studied in the last decade because of their physical complexity and important applications [1,2]. The technological importance lies in the pinning effect of the antiferromagnet (AFM) layers in which the hysteresis loop of the ferromagnet (FM) can be shifted away from the origin point by the amount of the exchange field \( H_e \), and is usually accompanied with an enhanced coercivity \( H_c \). Changes of \( H_e \) and \( H_c \) are accordingly directly related to the spin configuration of the AFM layer through the exchange coupling [3]. Among the variety of effects related to the EB phenomenon, the training effect is an important effect that reflects the AFM spin dynamic process during repeated hysteresis loops. It is ascribed to that the spin structure of the AFM layer deviates from its equilibrium configuration and approaches another equilibrium triggered by subsequent reversals of the FM magnetization. Nowadays, studies of AFM spin dynamic behaviors with training effect in both experiments and approaches another equilibrium triggered by subsecond timescale of the AFM layer deviates from its equilibrium configuration [4–13], which indicated a much shorter relaxation time of AFM spin than earlier anticipated. Therefore, it is necessary and interesting to study the AFM spin dynamic process at short timescale (technologic importance \(< 1 \) s).

In this paper, we have studied the EB training and recovery behaviors at the millisecond timescale based on the electrical transport measurements in FeNi/Cu/Co/FeMn spin valves. The experiments show that at high field sweep rates recovery time of exchange field after training procedures is three orders of magnitude shorter than the values observed by usual magnetometry techniques, and the relaxation of magnetoresistance (MR) is demonstrated in the millisecond timescale. These clearly indicate that AFM spin dynamic behaviors can be studied and resolved down to the millisecond timescale utilizing the ordinary resistance measurements.

2. Experiment and results

The spin valves of Si (001)/Cu (10 nm)/Fe20Ni80 (3 nm)/Cu (3 nm)/Co (3 nm)/FeMn (8 nm)/Ta (3 nm) were prepared by a magnetron sputtering system. The base pressure was \( 2 \times 10^{-5} \) Pa and the Ar pressure was 0.3 Pa during the deposition. The 10 nm Cu buffer layer was used to stimulate the fcc (1 1 1) preferred growth of the FeMn layer in order to enhance the EB. A magnetic field of 130 Oe was applied in the film plane during deposition to induce the uniaxial anisotropy and thus the EB.
Magnetoresistance (MR) measurements were performed to probe the switching behaviors of the pinned layer for different subsequent hysteresis loops. The magnetic field was provided by a homemade Helmholtz coils, and MR was measured in real-time system with 2 M/s sampling rate. To study training and recovery of the EB, we first performed 40 consecutive MR measurements with a fixed field sweep rate to characterize the training procedures. Then we stopped the magnetic field sweep with an waiting time and finally decreases. For the training procedure, the $H_E$ versus $n$ is fitted by a linear function of $1/\sqrt{n}$, $e^{-0.08n}$ and $\ln(n)$, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

To further study the recovery of the trained EB, we measured the recovery rate $R$ as a function of $t$ at different field sweep rates, where $R = (H_E(41) - H_E(40))/(H_E(1) - H_E(40)) \times 100\%$. Fig. 2(a) shows the dependence of $R$ on $t$ at different field sweep rates. The $R$ increases with the increasing $t$ as a linear function of $\log(t)$.
More remarkably, for a fixed waiting time $t$, $R$ correspondingly increases with the increasing field sweep rate. This logarithm behavior is in a good agreement with the previous experiments in NiFe/FeMn system, while the recovery rate is several orders of magnitude faster than the value in the low field sweep rate case [4]. The slope and the intercept as a function of the field sweep rate are shown in Fig. 2(b). The slope displays little change with different field sweep rates whereas the intercept increases greatly as the field sweep rate increases in approximate linear function of the logarithm of the field sweep rate.

To investigate the dynamic behavior of the EB with high resolution, we observed the evolution of MR after setting the magnetic field from the positive saturation field to $-210$ Oe (the point A in Fig. 1(a)) near the switch field. As shown in Fig. 3, MR initially decreases sharply and then gradually reaches a constant. The small fluctuations in the curves are caused by 50 Hz AC noise in the amplifying circuit. Remarkably, a crossover of the normalized MR from positive to negative has been observed, demonstrating the reversal of the magnetization of the Co layer. It is possible to link the time dependence of MR with the magnetic viscosity in the Co/FeMn bilayers [7], in which the magnetization of the pinned layer gradually reverses due to the thermally activated process in Co/FeMn bilayers. Because the reversal process in the EB at the first cycle consists in the single domain wall motion [6], the change of MR here is proportional to the amounts of the reversal magnetization in the pinned layer. Shown as the solid line in Fig. 3, the evolutions of MR are described well by a first order exponential decay. From fitting the data, we extracted the relaxation times $\tau$ which are 11.5, 27.6, and 61.4 ms for the field sweep rate at 4000, 2000 and 1000 Oe/s, respectively. This is again in contrast to the long relaxation time ($\sim 800$ s) in the conventional approaches [6]. One can also note that the relaxation time decreases with the increasing field sweep rate.

3. Discussion

The above results show that the recovery and relaxation of the EB at high field sweep rates are faster than that earlier observed [4–7]. Below we will interpret the experimental results in conventional models for AFM and training effects.

Firstly we consider the change and magnitude of the relaxation time constants at different field sweep rates shown in Fig. 3. The time constant for the relaxation can be described by an ordinary Arrhenius law $\tau = \nu_0^{-1} \exp(E_0/k_BT)$, where $\nu_0$ is the attempting frequency and $E_0 = KV$ represents the AFM energy barrier, $K$ is the AFM anisotropy and $V$ is the AFM grain volume. According to the AFM grain volumes distribution, we can divide the $E_0$ into three different categories [10]: (i) small $E_0$ (small grain size), which follows the FM magnetization at the timescale of the experiment. (ii) Medium energy $E_0$ (medium grain size) which will determine the EB dynamics at the timescale we investigate. (iii) Large $E_0$ (large grain size), which is a stable configuration over the timescale of the experiment. Theoretical and experimentally observed relaxation time constants at different field sweep rates shown in Fig. 3.

Fig. 3. The time dependence of the resistance after the external magnetic field is swept to $-210$ Oe (point A in Fig. 1(a)) from positive saturation field with different field sweep rates (a) 4000 Oe/s, (b) 2000 Oe/s, and (c) 1000 Oe/s. The solid lines are fits to the first-order exponential decay.
and fourth order in $\delta S$ will result in the $e^{-\alpha n}$ [22] and $1/\sqrt{n}$ [21] evolution, respectively.

However, our understanding of the system is that we have a nonvanishing odd order term. This is an effect of working at a time scale where we also have substantial coupling at the FM/AFM interface due to large grains that are too large to follow the oscillating exchange coupling of the FM. Instead that portion of the ensemble of grain will orient itself gradually according to the mean field induced by the FM in a monotonic fashion. Accordingly we also have to consider the expansion of $\delta f$ from first order of $\delta S$. We then assume $\delta S : \delta f = f(n)(\delta S)^3 + O((\delta S)^4)$, where the $f(n)$ indicates that the change in the AFM interface magnetization and $\delta S_n$ is dependent on the training procedures $n$. By replacing $\delta S$ with $[S(n+1) - S(n)]/\lambda$, with $\lambda$ being the relevant experimental time constant and the free energy expression of the first order into the LK equation, we obtain an implicit sequence equation: $\frac{\zeta}{\lambda}(S(n+1) - S(n)) = -f(n)$, where $\zeta = \zeta/\lambda$. The sum over $N$ cycles of this equation with variable $n$ yields $H_k(n+1)\propto S(n+1) = S(1) - \sum_{n=1}^{N} f(n)/\zeta$.

Since we do not know the exact energy distribution $f(V)$ of our system, we make a first-order approximation assuming a constant distribution of AFM grain volumes. An estimate of the change in thermally activated part of the interface magnetization can be found through: $f(n) = \int_{0}^{V_n} F(V) dV$, using a thermally activated grain volume $V_n$ which is found through the Arrhenius expression and a constant distribution in volume $f(V)$ we find that $f(n)$ will follow a $\ln(n+1) - \ln(n)$ dependence, a logarithmic dependence of the exchange bias. This approximation may only be valid at large $n$ when the overall reorientation due to the changed mean field dominate over other training effects. We also note that the training process $H_k$ is proportional to $\ln(n)$ has also been reported at low field sweep rates [8], where the training speed is several orders of magnitude slower than the values reported here.

In summary, for the AFM spins the relaxation time in the millisecond timescale is demonstrated when the bilayers are exposed to high field sweep rates. This behavior can be well explained in terms of a time constrained thermal activation. Our finding gives a new insight into the dynamic behavior of the AFM spins.

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