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Magnetic coupling governed pinning directions in magnetic tunnel junctions under magnetic field annealing with zero magnetic field cooling

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With the rapid development of emerging concepts, such as the Internet of things and big data, the use of various magnetoresistance (MR) sensors, especially tunneling MR (TMR) in magnetic tunnel junctions (MTJs), for information perception is considered the critical first step. A typical topic in this field is the construction of a Wheatstone bridge structure to restrain the temperature drift and amplify the magnetic response signal. Recently, a new full-Wheatstone bridge design scheme is proposed under magnetic field annealing with zero magnetic field cooling (hereinafter referred to as "zero magnetic field cooling") treatment [1,2]. However, this method is incompatible with the commonly used magnetic field cooling process. And MTJs present a complex film structure and abundant magnetic coupling effects among different materials. Under zero magnetic field cooling treatment, the Zeeman energy disappears. The pinning direction is determined by multiple coupling effects, such as the exchange bias coupling between the ferromagnetic (FM) and antiferromagnetic (AFM) layers, AFM coupling of the synthetic AFM (SAF) layer, and interlayer (i.e., orange peel) coupling between the free layer (FL) and fixed layer. In brief, the study on the pinning direction under the zero magnetic field cooling process can not only clarify the impacting factors of MTJs' magnetic characteristics, but also bridge the gap between MTJ components and MR sensors.

A thin film stack, as illustrated in Figure 1(a), is deposited on an 8-inch Si/SiO_2 substrate using a magnetron sputtering. The wedgy IrMn layer is fabricated, with its thickness varying from 2.2 to 17.5 nm along the notch direction (X axis). The films are annealed in a high-vacuum chamber at 270°C under a magnetic field of 10 kOe ($H_{\rm Anneal}$) along the $+Y$ direction for 1 h. Then, the magnetic field is removed during the cooling process. The details of the experiments and the quality of film stacks are presented in Appendix A.

To demonstrate the quality of a series of MTJ membrane stacks, the TMR ratio as a function of the IrMn thickness ($t_{\rm IrMn}$) is measured using a current in-plane tunneling equipment, as shown in Figure A1(c) of Appendix A. On the one hand, the high TMR ratio clearly reveals the high quality of the fabricated multilayer films with various IrMn thicknesses. On the other hand, the observed sign change and the peak of the TMR ratio with the magnetic field sweeping along the X/Y directions indicate that the pinning direction of the MTJ changes with the increasing IrMn thickness.

Figure 1(b) presents the magnetic hysteresis (M-H) of the MTJ stack with various $t_{\rm IrMn}$ with the magnetic field sweeping along the Y axis. For the sample with $t_{\rm IrMn}$ = 3.5 nm, the remarkable minor hysteresis loop under the magnetic field from 2.5 to 5 kOe clearly represents that the magnetization of P1 reverses (black arrow). A minor hysteresis loop is also observed under magnetic fields from −1.8 to −2.5 kOe, which is induced by the magnetization switching of P2. These results reveal that the pinning direction of the sample with $t_{\rm IrMn}$ = 3.5 nm aligns along the $-Y$ direction (antiparallel to the direction of $H_{\rm Anneal}$) after the treatment of zero magnetic field cooling. Meanwhile, the inverted M-H curve for the sample with $t_{\rm IrMn}$ = 16.5 nm indicates that the pinning direction is flipped by 180°. Similarly, the magnetic field dependent sheet resistance ($R_{\rm s}$-H) loops are consistent with the M-H curves, as shown in Appendix B.

To clearly present the $t_{\rm IrMn}$-related phenomenon, energy-related terms, including the exchange bias field of IrMn ($H_{\rm ex}$), interlayer coupling field ($H_{\rm in}$), and AFM coupling field of SAF ($H_{\rm SAF}$), are extracted from the M-H curves, as shown in Figure 1(b). Particularly, the magnetization

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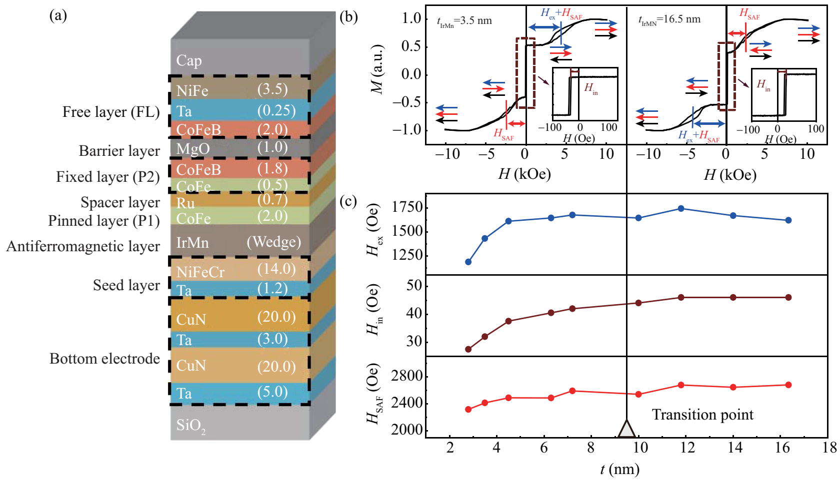

Figure 1 (Color online) (a) Schematic of the synthetic MTJ membrane stack (the number is in unit of nm). (b) M-H loop of the membrane stack with different IrMn thicknesses under magnetic field sweeping along the Y axis. The blue, red, and black arrows denote the magnetization direction of the FL layer, P2 layer, and P1 layer, respectively. (c) $H_{\rm ex}$, $H_{\rm in}$, and $H_{\rm SAF}$ are the functions of the IrMn thickness. Note: $H_{\rm ex}$, $H_{\rm in}$, and $H_{\rm SAF}$ are absolute values.

switching of P1 is induced by the broken exchange bias coupling from the IrMn layer and AFM coupling from P2, from which we can obtain the value of '$H_{\rm ex} + H_{\rm SAF}$'. The value of $H_{\rm SAF}$ can be obtained according to the minor switching loop of P2, which only breaks the AFM coupling between P1 and P2. As a result, the values of $H_{\rm ex}$ and $H_{\rm SAF}$ are obtained. Obviously, the direction of the three fields ($H_{\rm ex}$, $H_{\rm in}$, and $H_{\rm SAF}$) changes with the $t_{\rm IrMn}$ across a transition point of 9.5 nm. Figure 1(c) summarizes the dependence of $H_{\rm ex}$, $H_{\rm in}$, and $H_{\rm SAF}$ on $t_{\rm IrMn}$, from which we can find that the three fields slightly increase. Here, a thick IrMn naturally leads to a strong exchange coupling, i.e., large $H_{\rm ex}$ and then large $H_{\rm SAF}$. Meanwhile, $H_{\rm in}$ originates from the dipole field, which is closely related to the surface roughness. As the surface roughness increases with $t_{\rm IrMn}$, the value of $H_{\rm in}$ presents an increasing trend.

Based on the above results, we can confirm that the pinning direction of MTJs is antiparallel or parallel to the direction of $H_{\rm Anneal}$ ($+Y$) when the $t_{\rm IrMn}$ is smaller or larger than 9.5 nm, respectively. In brief, the underlying mechanism of the tunable pinning direction can be described below. During the treatment of magnetic field annealing, P1, P2, and the FL are all oriented in the direction of $H_{\rm Anneal}$ (10 kOe). For the zero magnetic field cooling treatment, the magnetization directions of P1, P2, and FL are determined by the competition between exchange coupling at the IrMn/P1 interface and interlayer coupling between the FL and P2. The following points should be stated. (1) The blocking temperature of IrMn depends on its thickness. That is, the thicker the IrMn layer is, the higher its blocking temperature becomes. (2) The AFM coupling of the SAF layer plays a bonding role between the exchange bias coupling and interlayer coupling [3]. (3) The Curie temperature (t_c) of the FM layer, such as the free and fixed layers, is much higher than 270°C. For the sample with $t_{\rm IrMn} = 3.5$ nm, the exchange coupling field $H_{\rm ex}$ vanishes at 270°C because of the low blocking temperature. Therefore, the $H_{\rm in}$, aligned by the applied $H_{\rm Anneal}$, dominates the coupling process during the zero magnetic field cooling treatment. In other words, the interlayer coupling field $H_{\rm in}$ would configure the direction of the exchange bias field $H_{\rm ex}$ opposite to $H_{\rm Anneal}$ because of the AFM coupling of the SAF layer. As a result, the pinning direction of the fixed layer is along the direction of $H_{\rm Anneal}$. For the sample with $t_{\rm IrMn} = 16.5$ nm, the exchange bias field $H_{\rm ex}$, aligned by the applied $H_{\rm Anneal}$, dominates the coupling process, resulting in the opposite pinning direction.

We present a simple theoretical model and a control experiment, as shown in Appendixes C and D, to verify this competing mechanism and to provide a deep insight into the $t_{\rm IrMn}$-manipulated pinning direction. These results further verify that the competition between the exchange bias coupling energy and interlayer coupling energy is responsible for aligning the pinning direction in MTJs under the zero magnetic field cooling process.

Conclusion. This study demonstrates the manipulation of the pinning direction in MTJs with varying $t_{\rm IrMn}$ under the zero magnetic field cooling process, which results from the competition between the exchange bias coupling and interlayer coupling through the SAF layer. Our results clarify the coupling mechanism for determining the pinning direction of MTJs under the zero magnetic field cooling treatment, which can guide the design scheme of full Wheatstone bridge-based TMR sensors.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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