Electric-field-tunable linear unipolar magnetic switch based on a spin-valve multiferroic heterostructure

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Abstract. This work reports an energy-efficient strategy for realizing linear unipolar giant magnetoresistance (GMR) switch by using electric fields (E-fields). Herein, a modified spin-valve (SV) structure of double antiferromagnetic (AFM) pinning layers was adopted. Since the magnetization direction of ferromagnetic (FM) layer can be controlled via the strain-mediated magnetoelectric (ME) effect, a multiferroic heterostructure of SV/PMN-PT was fabricated. By applying an E-field on the PMN-PT substrate, an effective magnetic field $H_{\text{eff}}$ was produced along the $[1\bar{1}0]$ direction of PMN-PT. It can turn the magnetic moments of FM layer toward $[1\bar{1}0]$ direction. Accordingly, a linear GMR curve with a wide sensing field range was achieved. This E-field-induced linear magnetic switch can satisfy the demand for different switching field ranges in the same application system.

1. Introduction
The giant magnetoresistance (GMR) effect was discovered in 1988\cite{1}. Subsequently, abundant researches have sprung up like mushrooms, which is due to GMR’s attractive advantages such as high sensitivity, large MR effect, and large saturation field. The spin valve (SV) structures which can obtain GMR effect have been widely applied in several magnetic devices\cite{1-3}. Typically, an SV has two ferromagnetic (FM) layers, which are inserted by a thin nonmagnetic metal layer. The pinned FM layer is fixed by an antiferromagnetic (AFM) material through an exchange coupling field $H_{\text{EB}}$, while the magnetic moments of the free layer can be manipulated via a magnetic field H. Accordingly, the magnetic field dependence of MR curve is obtained, resulting from the varied magnetization angles between the two FM layers. For an SV, the MR effect, exchange bias field, and saturation field are the important factors which directly determine the operation performance of GMR sensors. For example, switching fields of a magnetic switch are determined by magnetic properties of FM materials. Therefore, the operating range of a sensor has been fixed during the fabrication process. This hinders the further development of flexible magnetic sensors with tunable sensing ranges. A tunable linear GMR switch can fulfill the requirements of different operation fields in a same system, exhibiting a future prosperous application prospect.
Recently, a strain-mediated magnetoelectric (ME) coupling effect, which combines the FM and ferroelectric (FE) properties, has attracted much attention due to its expected performance of manipulating the magnetic anisotropy of FM layer with ultra-low power consumption [4-5]. In the operation process, an E-field is applied on the FE substrate to produce a strain. Such strain can be homogeneously transferred to the FM layer. Thus, an effective magnetic field is generated by the magnetostrictive effect, which can control the magnetic properties of the FM layer. It provides an energy-efficient strategy to further develop magnetoresistive and spintronic devices. In previous researches, a 90 degree magnetization rotation of the FM layer has been investigated in several multiferroic heterostructures. Subsequently, the voltage-tunable devices were introduced. These works offer a convincing and feasible approach to realize tunable linear unipolar magnetic switches.

Generally, the exchange bias field and saturation field determine the operation range and switching fields of a GMR magnetic switch, which can be affected by the SV’s structure, fabrication condition, film material and thickness. Thus, we fabricated three different SV structures in this work. To realize a unipolar GMR switch, a modified SV structure of double AFM pinning layers was adopted. The SV was patterned into a strip shape and fabricated on a FE single crystal (110)-cut Pb(Mg\textsubscript{1/3}Nb\textsubscript{2/3})\textsubscript{0.7}Ti\textsubscript{0.3}O\textsubscript{3} (PMN-PT) substrate. For the GMR curve, a large and a small exchange bias fields respectively produced by the synthetic antiferromagnetic (SAF) structure and the IrMn layer are obtained along the [001] direction of PMN-PT. By applying an E-field on the PMN-PT substrate, a large effective H is produced along the [1-10] direction via the ME effect. It can turn magnetic moment orientation of free layer toward [1-10] direction. Accordingly, the magnetic moment directions between the free and pinned layers arise a certain angle. A tunable linear GMR curve was achieved. The linear unipolar magnetic switch reveals a flexible and broad application range.

2. Experiment
In this study, three samples of different SV structures were fabricated by using magnetic sputtering. The sputtering powers for all SVs are 50 W. During the film fabrication process, a constant H of 300 Oe was applied to produce the exchange bias in CoFe/IrMn layers. To realize a unipolar GMR switch, a modified structure of Ta (5)/CoFe (2)/IrMn (15)/CoFe (3)/Ru (0.8)/CoFe (3)/Cu (3)/CoFe (8)/IrMn (15)/Ta (5) (nm) was chosen. The SV films were patterned into a micrometre-sized strip shape, which were fabricated on PMN-PT. The photolithography process was repeated to fabricate electrode pads for the GMR tests, as shown in the inset of Fig. 2. The pinning fields in the double AFM layers were aligned along the [001] direction.

3. Results & Discussion
In a unipolar GMR switch, the switching field range is on the side of the measured magnetic field. Thus, this study emphasizes on the exchange bias that determines the operation range of a magnetic switch. To realize the unipolar magnetic switch, three samples of different SV structures were prepared, named S-I, S-II, and S-III, respectively. The corresponding GMR curves are shown in Fig. 1. For the S-I in Fig. 1a, magnetic moment direction of free layer is switched by an external H, while the pinned layer is pinned at initial direction. Accordingly, the parallel and antiparallel configurations between free and pinned layers are observed, resulting in low and high MR states. This is the working principle of a magnetic switch to achieve the on and off switching states. The operation point (Bop) and release point (Brp) are defined by the switching fields of free layer. Subsequently, when H is increased to saturate the AFM layer (larger than the $H_{EB}$), a parallel configuration of free and pinned layers is observed again. High MR platform is disappeared. Here, the magnetic switch is insensitive to the external H. Normally, the exchange bias field in the FM/AFM layers is controlled to be much larger than operating range of a magnetic switch. So, the SAF structure, which can realize the AFM couple between two FM layers, was carried out to enhance the exchange bias field in an SV. As shown in Fig. 1b, the $H_{EB}$ is increased larger than 1000 Oe (not shown here). In contrast, the loop of the free layer is consistent with the result in Fig. 1a, which switching fields are near zero magnetic field. Thus, the S-I and S-II are not suitable for using in unipolar magnetic switch. Based on the above investigations, the SV structure of double pinning
layers IrMn (15)/CoFe (3)/Ru (0.8)/CoFe (3)/Cu (3)/CoFe (8)/IrMn (15) (nm) was adopted. A large $H_{EB}$ produced by the bottom SAF structure, and a 200 Oe $H_{EB}$ in the top CoFe/IrMn layers, are observed. As shown in Fig. 1c, the Bop and Brp of the GMR curve are deviated from zero magnetic field. The operation range is on the side of measured magnetic field. Therefore, this modified SV structure S-III is suitable for fabricating the unipolar GMR switch.

Figure 1. The GMR curves of the SV samples.

Figure 2 shows the tunable GMR curves of the S-III by using an E-field. Herein, the SV structure of double AFM pinning layers was adopted to realize the unipolar magnetic switch. It was grown on a FE single crystal PMN-PT. As shown in the inset of Fig. 2, the long dimension was parallel to [001] direction. The measured current and H were applied along the [001] direction. At initial state (0 kV/cm), a typical square shape of the GMR curve is observed on the side of the negative magnetic field, which is consistent with the result in Fig. 1c. In contrast, a slanted and slim loop is observed under an E-field of 8 kV/cm. When an E-field is applied, an $H_{eff}$ is produced by the ME effect, which can be shown as [4]:

$$H_{eff} = \frac{3\lambda(\sigma_{001} - \sigma_{1-10})}{M_S}$$ (1)
where $\sigma_{001}$ and $\sigma_{1-10}$ denote the in-plane piezo stress values of the [001] and [1-10] directions, $\lambda$ is the magnetostriction constant of FM material. Accordingly, due to the positive magnetostriction constant of CoFe and the negative $(\sigma_{001} - \sigma_{1-10})$ of PMN-PT, an $H_{eff}$ along the [1-10] direction is introduced. Such $H_{eff}$ can overcome the small $H_{EB}$ in the top CoFe/IrMn layers, and rotate the magnetic moments orientation of CoFe free layer toward [1-10] direction. Meanwhile, the magnetization of the bottom pinned CoFe layer cannot be affected by the $H_{eff}$, which is due to the large $H_{EB}$ produced by the bottom SAF structure. The magnetic moment orientation angle between free and pinned layers is modulated toward 90 degree. Accordingly, the MR values change slowly with measured $H$, as shown in Fig. 2, exhibiting a linear GMR curve. This linear rather than a rapid switching of the high-low MR states is actually preferred for magnetic switch applications, which yields an enhanced operation range in the same magnetic switch. This work offers an energy-efficient and convenient strategy to achieve the GMR switch with controllable linear switching range.

![GMR curve](image)

Figure 2. The GMR curves measured under the E-field of 0 kV/cm and 8 kV/cm, the schematic structure is shown in the inset.

4. Conclusions

In summary, we have achieved a unipolar magnetic switch with a controllable linear switching range. It was realized by fabricating a SV/PMN-PT heterostructure. Via the strain-mediated ME effect, magnetization direction of the free layer can be manipulated toward [1-10] direction under an E-field of 8 kV/cm. The magnetization angle between the free and pinned layers was approximately modulated to 90 degree. Thus, a linear GMR curve was achieved. This linear GMR switch has a considerable potential for the utilization in special configurations with stringent requirements or in the Internet of Things.

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References

[1] Baibich, M. N., Broto, J. M., Fert, A., Van Dau, F. N., Petroff, F., Eitenne, P., Creuzet, G.
Friederich, A., Chazelas, J. (1988) Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices. Phys. Rev. Lett., 61: 2472-5.

[2] Dieny, B., Speriosu, V. S., Parkin, V. S., Gurney, B. A., Wilhoit, D. R., Mauri, D. (1991) Giant magnetoresistance in soft ferromagnetic multilayers. Phys. Rev. B, 43: 1297-1300.

[3] Wang, Z. G., Nakamura, Y. (1996) A new type of GMR memory. Jour. Magnet. Mag. Mater., 155: 161-163.

[4] Liu, M., Howe, B. M., Grazulis, L., Mahalingam, K., Nan, T., Sun, N. X., Brown, G. J. (2013) Voltage-Impulse-Induced Non-Volatile Ferroelastic Switching of Ferromagnetic Resonance for Reconfigurable Magnetolectric Microwave Devices. Adv. Mater., 25: 4886-4892.

[5] Liu, M. L. et al. (2021) A voltage-pulse-modulated giant magnetoresistance switch with four flexible sensing ranges. Nanotechnology, 31: 505504.