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# Electrical Manipulation of Exchange Spring in Antiferromagnetic Metals

Cheng Song[1], Yuyan Wang[1], Shiming Zhou[2] and Feng Pan[1]

[1] Tsinghua Univ.
School of Mater. Sci. Eng., Beijing 100084, China
Phone: +86-10-6278-1275 E-mail: songcheng@mail.tsinghua.edu.cn
[2] Tongji Univ.
School of Phys. Sci. Eng., Shanghai 200092, China.

**Abstract**

**We primarily report a reversible electrical control of exchange spring in antiferromagnetic (AFM) metals, using an ionic liquid to exert a substantial electric-field effect. The exchange spring could transfer the "force" to the ferromagnet/antiferromagnet interface, enabling a deep modulation depth in AFM metals. The manipulation of AFM moments by gate voltage is demonstrated in [Co/Pt]/AFM model system with the IrMn and FeMn thickness up to 5 nm and 15 nm, respectively. Besides the fundamental significance of modulating the spin structures in metallic AFM via all-electrical fashion, the present finding would advance the development of low-power-consumption AFM spintronics.**

## 1. Introduction

Manipulation of antiferromagnetic (AFM) spins by electrical means is on great demand to develop the AFM spintronics with low power consumption. Much beyond the passive role of AFM as pinning layer, great efforts have been made in manipulating the AFM spins to realize the AFM-based memory resistors[1] and tunneling anisotropic magnetoresistance.[2,3] Controlling magnetism by means of electric fields manifests great superiority for the future development of low power spintronics, and favorable progress has been made in ferromagnetic (FM) systems. In contrast to FM, the spin structures in AFM are hard to probe since they exhibit no net magnetic moment. Recently, electrical control of interfacial coupling has been demonstrated in FM/AFM heterostructures containing multiferroic $Cr_2O_3$[4] or $BiFeO_3$[5] as the dielectric layer, However, for metallic AFM such as IrMn and FeMn, which plays an irreplaceable role in traditional spintronic devices, direct electrical control remains challenging because of the screening effect by the surface charge. Generally, the manipulation is confined to a limited depth of atomic dimensions, which is insufficient to form a stable AFM exchange spring. Thus it is significant to investigate the electrical control of comparatively thick AFM with stable moments.

## 2. General Instructions

In this talk, we specially adopt an ionic liquid as the dielectric gate to modulate the exchange spring in IrMn and FeMn AFM with different thicknesses. Compared with conventional solid gate insulator, the electric double layer (EDL) transistor has been developed as a powerful device structure allowing an extremely high electric field effect and penetrating a deeper thickness.[6] The stack structures of Ta(4)/Pt(8)/[Co(0.5)/Pt(1)]$_4$/Co(0.5)/Pt(0.6)/AFM($t$) (nm) with different AFM (AFM = IrMn or FeMn) thicknesses ($t$), 3 nm, 5 nm and 8 nm for IrMn, and 6, 15, 30 nm for FeMn, respectively, capped by a 2 nm-thick $HfO_2$ to prevent the direct chemical reaction between metallic IrMn and ionic liquid. Then the multilayers were patterned into Hall devices, with a drop of ionic liquid utilized on top of $HfO_2$ as the electrolyte. The exchange spring formed in IrMn could be manipulated by the electric field and transfer the modulation to the [Co/Pt]/IrMn interface, in analogy to a real mechanical spring which transfers the force (Fig. 1).

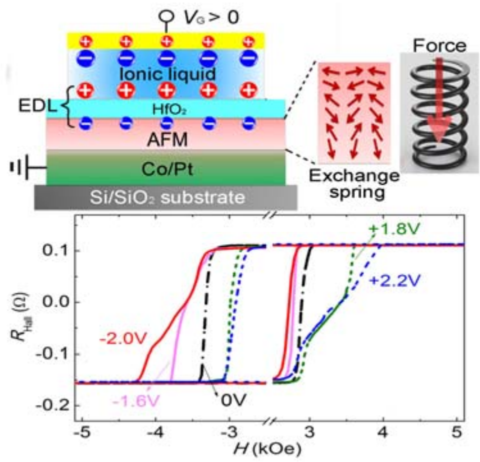


Fig. 1 The schematic cross-section view along the channel to the gate electrode with positive $V_G$, and the charge distribution under the effect of electric double layer. Also shown is the schematic of spins in AFM exchange spring, and a illustration of mechanical spring which enables the transfer of the force from top to the bottom. The $V_G$-dependent Hall resistance acquired by sweeping vertical $H$ when IrMn thickness is 3 nm[6].

To verify the effect of gate voltage ($V_G$) on AFM IrMn or FeMn, we investigate the anomalous Hall effect (AHE, $R_{Hall}$-$H$) of the Hall devices, which reflects the magnetization properties of [Co/Pt]/AFM at vertical fields ($H$). When $V_G$ is negative, the whole $R_{Hall}$-$H$ loop moves towards the negative $H$, which indicates an increasing magnitude of bias field ($H_E$) compared with that at 0 V. Differently, positive $V_G$ does the opposite. That is, the hysteresis loop moves backwards to positive $H$, weakening the initial exchange bias and even generating a positive $H_E$. This tendency would decrease with increasing the AFM thickness. It remains when the IrMn and FeMn thickness are 5 nm and 15 nm, respectively. This difference can be ascribed to the different anisotropy of these two AFM and the corresponding different exchange spring. These thickness-dependent experiments clearly illustrate the electrical control of the exchange spring in AFM in turn.

We then attempt to make a deep insight into the intrinsic physics of the electrical manipulaton of metallic AFM. Inspired by the configuration of field-effect transistor which enables the direct detection of carrier densities, we have investigated the longitudinal resistance as a function of $H$ of the Hall device substrate/IrMn/$HfO_2$ without Co/Pt FM, where IrMn is the only conductive medium. On the other hand, to directly detect the induced change of interfacial uncompensated spins in IrMn, a FM/AFM system consists of insulating $Y_3Fe_5O_{12}$ (YIG) FM and IrMn AFM is adopted to investigate the $V_G$ control of exchange bias, where the electrical transport is purely originated from metallic IrMn.

It is generally accepted that the electric field could not penetrate into the bulk of traditional metals and is confined to a depth on the order of atomic dimensions, due to the screening effect. However, it is not surprising that the exchange bias could still be changed by different $V_G$ when $t$ is up to 5 nm and 15 nm for IrMn and FeMn, respectively, considering the following two aspects: (i) substantial electric-induced effects can be realized by using the EDL though injecting or extracting electrons from the film, and act on a deeper thickness; (2) the tunable exchange bias in 5 nm-thick IrMn or 15 nm FeMn further confirms the electrical modulation of exchange spring, since the electric-field effect is hard to reach the interface between Co/Pt and IrMn directly. The critical vale is exactly within the exchange spring of AFM, which are 7.8 nm and 28 nm for IrMn and FeMn, respectively.[7]

## 3. Conclusions

We demonstrate the electric-field manipulation of metallic antiferromagnet IrMn and FeMn using an ionic liquid as the gate electrode. From the anomalous Hall effect of the substrate/[Co/Pt]/AFM devices, a reversible modulation of the exchange bias is observed at different $V_G$. Distinct controlling effects varying with AFM thicknesses and operating temperatures are presented, proposing the manipulation of exchange spring in AFM by electric field. In addition, electrical control of anisotropic magnetoresistance in single layered AFM devices further reveals that the modulation of AFM exchange spring is correlated to the change of magnetic anisotropy as well as carrier density by injecting or extracting electrons.


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