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Role of an ultrathin platinum seed layer in antiferromagnet-based perpendicular exchange coupling and its electrical manipulation

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ABSTRACT

The requirement for low-power consumption advances the development of antiferromagnetic (AFM) spintronics manipulated by electric fields. Here we report an electrical manipulation of metallic AFM moments within IrMn/[Co/Pt] by interface engineering, where ultrathin non-magnetic metals are highlighted between IrMn and ferroelectric substrates. Ultrathin Pt seed layers are proved to be vital in elevating the blocking temperature and enhancing the perpendicular exchange coupling through modulating the domain structures of as-prepared IrMn AFM. Further electrical manipulations of perpendicular magnetic anisotropy crucially verify the indispensable role of pre-deposited ultrathin Pt layers in modulating IrMn antiferromagnetic moments, which is confirmed by the intimate correlation between the electrically manipulating AFM and improving its blocking temperature. Instead of immediate contact between IrMn AFM and ferroelectric substrates in a conventional way, interface engineering by adopting ultrathin seed layers here adds a new twist to the electrical modulation of AFM metals. This would provide scientific basis on how to manipulate AFM moments and optimize the design of practical AFM spintronics.

1. Introduction

Perpendicular exchange coupling has stimulated intense interest due to their potential for realizing low-power and ultrahigh-density spintronic devices [1–9]. Recently, the understanding of exchange coupling [10], a long-standing issue, has been renewed by the emerging antiferromagnet (AFM) spintronics [11–16], which promote the transition of AFM from static supporting materials in exchange bias to functional materials in spintronic devices. In addition to the memory resistors based on FeRh and current-induced spin orbit torque in CuMnAs [16,17], room-temperature tunneling anisotropic magnetoresistance has been successfully achieved in the IrMn-based tunnel junctions [18,19], ascribed to the superior thermal tolerance of perpendicular exchange coupling. In terms of the increasingly crucial role of AFM in current memory devices, one key issue in their practical applications is maintaining a high blocking temperature (T_B), which is generally dependent on the interface features and crystal structures of AFM [10]. How to optimize the as-deposited AFM metals and efficiently manipulate AFM moments is an intriguing but challenging topic.

Electrical control of exchange coupling manifests great superiority for the future development of low-power spintronics [20–24], and favorable progress has been made in ferromagnet (FM)/AFM coupling systems by adopting ferroelectric substrates [20,23,25,26]. So far, direct electrical manipulation of AFM mainly involves multiferroic $BiFeO_3$ or Cr_2O_3 [21,22], through coupling between ferroelectricity and antiferromagnetism in the insulated AFM itself. In general, the electrical manipulation of metallic AFM is greatly overshadowed by their FM counterparts, where FM films are directly deposited on ferroelectric substrates. Then the crystalline structure of post-deposited AFM are intimately related to pre-deposited FM, and the antiferromagnetism is imprinted by the domain pattern of FM [18,27,28]. Especially for AFM metals such as IrMn and FeMn, which play an irreplaceable role in traditional spintronic devices [11,29], realizing an accessible modulation of as-deposited AFM spin structure and direct electrical control are crucial issues.

In this work, beyond the conventional idea of immediate contact between IrMn and ferroelectric substrates, interfacial modification of IrMn is proposed, which would undoubtedly plays a significant role in their electrical control, because the whole exchange spring in AFM is closely related to the interfacial spin structures. Here interface engineering is highlighted by employing different kinds of nonmagnetic metals with different thicknesses between IrMn and ferroelectric substrates, verifying the crucial role of an ultrathin Pt seed layer in

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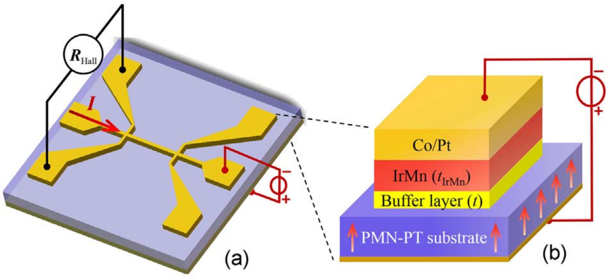

Fig. 1. (a) Measurement configuration with an applied voltage. (b) The stack structure of the Hall devices.

modulating AFM as well as enhancing perpendicular exchange coupling. And their electrical manipulation provides new approaches to manipulating AFM moments.

2. Experimental methods

A series of Pt(t_{Pt})/IrMn(t_{IrMn})/Pt(0.5)/[Co(0.5)/Pt(1)]$_5$ multilayers (units in nanometers) with different thicknesses of Pt seed layers (t_{Pt}) and IrMn AFM (t_{IrMn}) were deposited on $Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$ (PMN-PT) substrates by magnetron sputtering at room temperature. Here, 0.2 mm-thick PMN-PT ferroelectric single crystal with (001) orientation was used as the piezoelectric substrate to produce electrically-reversible lattice strain [9,23,30]. The PMN-PT substrates were purchased commercially after surface polishing, with the roughness of less than 0.3 nm. Note that the AFM material we choose is $Ir_{20}Mn_{80}$ (short in IrMn), which was deposited using an alloy target with precise stoichiometric ratio. Magnetization measurements were carried out using a superconducting quantum interference device (SQUID-VSM). The multilayered films were then patterned into Hall devices with channel width of 30 μm (Fig. 1), using photolithography and ion milling techniques. A direct observation of the perpendicular magnetic anisotropy (PMA) and exchange bias is revealed by anomalous Hall effect (AHE) of Hall devices, where an out-of-plane magnetic field is applied. To investigate the electrical manipulation of deposited coupling layers, an electric field is exerted on the PMN-PT substrate with Ag electrode on its back side, as shown in the right part of Fig. 1.

3. Results and discussions

3.1. *Effect of seedlayers on IrMn and perpendicular exchange coupling*

In order to verify the effect of seed layers on modifying IrMn as well as exchange bias, IrMn (t_{IrMn}=3 nm, 5 nm, 8 nm)/Pt/[Co/Pt]$_5$ multilayers with and without 0.5 nm-thick Pt buffer layer were firstly prepared. The AHE loops of each Hall device were collected at 10 K after a field-cooled procedure from room temperature with a cooling field of +5 kOe. For the samples without Pt seed layers (solid lines in Fig. 2(a)), the sharp reversal of resistance and clear exchange bias towards negative fields reveal a strong exchange coupling between IrMn and Co/Pt, together with a good PMA of the coupling layers. As expected, the bias field H_E at 10 K enlarges as the thicknesses of IrMn increases from 3 nm to 8 nm. From the temperature-dependent H_E tendencies depicted in Fig. 2(b), it is estimated that the T_B of the three samples are all below 100 K, at which the exchange bias vanishes. Note that although the Néel Temperature (T_N) of 8 nm-thick IrMn is above room temperature [10,31], the relatively lower T_B here is immediately related to the interface features of IrMn/[Co/Pt] and crystal structures of the coupling layers [10,31]. To be specific, the pre-deposition of IrMn always damages the fcc texture of the top Co/Pt [19], resulting in a weaker exchange coupling as well as a lower T_B of IrMn. In the practical use of AFM spintronics, AFM layers inevitably have to be placed under FM layers or directly on substrates without post-annealing. In this case, how to modulate the AFM layer and enhance its T_B stands out as a key concern.

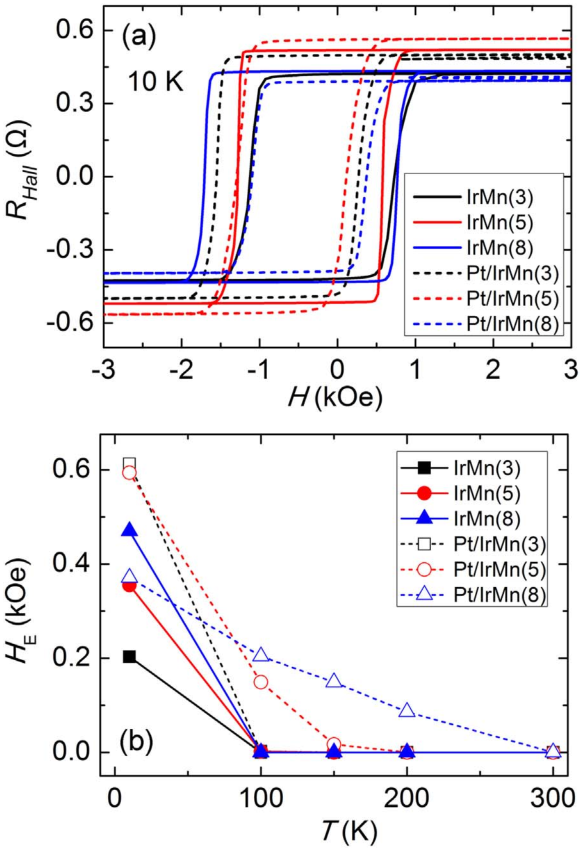

Fig. 2. (a) R_{Hall} acquired at 10 K by sweeping vertical H (AHE loops) of samples IrMn (3 nm, 5 nm, 8 nm)/[Co/Pt] without (solid lines) and with (dashed lines) 0.5 nm-thick Pt buffer layers. (b) Temperature-dependent H_E for the samples in (a).

Remarkably, the pre-deposition of an ultrathin Pt (0.5 nm) layer on the substrate greatly enhances the perpendicular exchange coupling in IrMn/[Co/Pt]. For the sample with 8 nm-thick IrMn, the T_B is elevated by up to 200 K (from below 100 K to nearly 300 K), as indicated in Fig. 2(b). These transport results are convinced by corresponding magnetization loops (Fig. S1 in the Supplementary material), where the bias fields are consistent with that of AHE curves. As the thickness of IrMn is 5 nm, the exchange bias for Pt(0.5)/IrMn(5)/[Co/Pt] also enhances to above 150 K, compared to that of below 100 K for the sample without Pt seed layer. When the IrMn thickness decreases to 3 nm, although the T_B is always below 100 K, the H_E at 10 K clearly increases from 200 Oe to 610 Oe by inserting the Pt layer. On the whole, for samples with different thicknesses of IrMn, both of the elevated T_B and modulated H_E prove the modulation of IrMn and enhancement of perpendicular exchange coupling by inserting an ultrathin Pt (0.5 nm) layer.

We further change the thicknesses of Pt seed layer to clarify the key role of Pt in modifying IrMn AFM. A series of AHE loops are carried out for samples of Pt(t_{Pt})/IrMn(8)/[Co/Pt], where t_{Pt} varies from 0.3 nm, 0.5 nm, 2 nm to 10 nm. As shown in Fig. 3(a), the reduced value of Hall resistance with the increase of Pt thickness is related to the diversion of current in Pt. Remarkably, T_B of the multilayers increases at first and then decreases when increasing t_{Pt} from 0 to 10 nm, as depicted in Fig. 3(b). The maximum value of T_B as t_{Pt}=0.5 nm indicates that insert of relatively thin Pt is crucial for the enhanced exchange coupling in IrMn/[Co/Pt]. Note that the highest H_E of the sample without Pt at 10 K (indicated in Fig. 3(b)) probably benefits from the field-cooling procedure, since the moments as well as