Supplementary Information

Extraordinary Hall Balance

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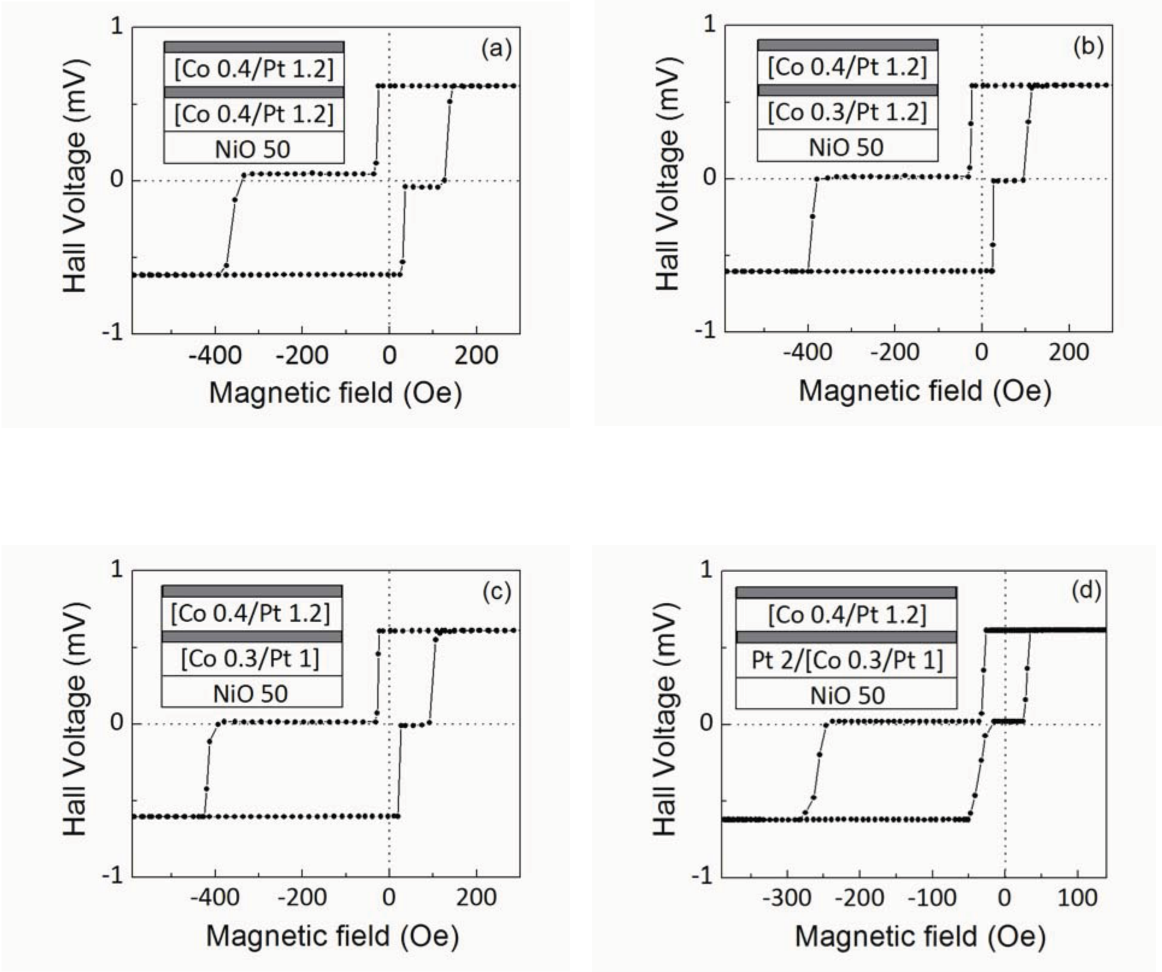
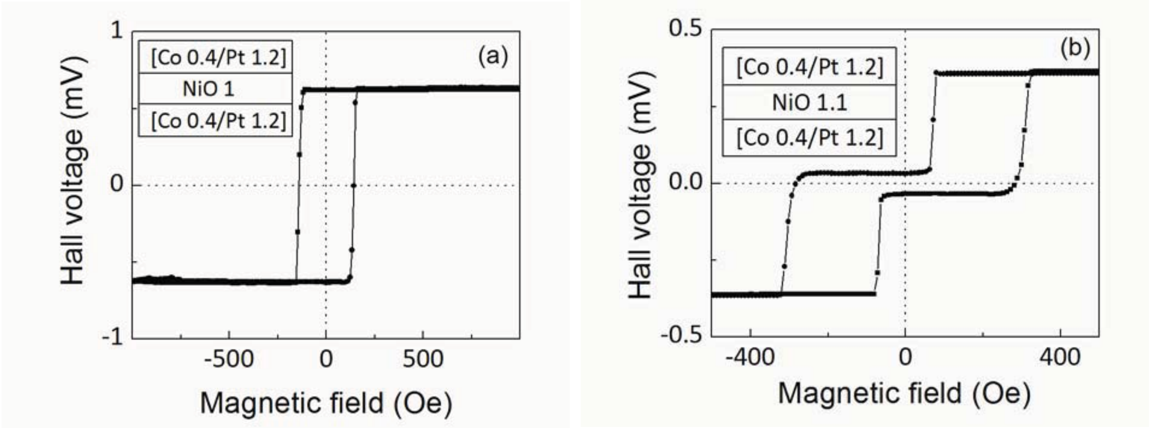
Supplementary Figures



Supplementary Figure S1: Structure engineering of ferromagnetically coupled EHBs. **a-d** show room-temperature Hall loops for (a) NiO(50)/[Co(0.4)/Pt(1.2)]$_3$/MgO(8)/[Co(0.4)/Pt(1.2)]$_3$/NiO(1), (b) NiO(50)/[Co(0.3)/Pt(1.2)]$_3$/MgO(8)/[Co(0.4)/Pt(1.2)]$_3$/NiO(1), (c) NiO(50)/[Co(0.3)/Pt(1)]$_3$/MgO(8)/[Co(0.4)/Pt(1.2)]$_3$/NiO(1), and (d) NiO(50)/Pt(2)/[Co(0.3)/Pt(1)]$_3$/MgO(8)/[Co(0.4)/Pt(1.2)]$_3$/NiO(1) device structures (thickness in nm).



Supplementary Figure S2: **EHB using AFM-coupled layers**. Hall loops for (a) Pt(0.6)/[Co(0.4)/Pt(1.2)]$_3$/NiO(1)/Pt(0.6)/[Co(0.4)/Pt(1.2)]$_3$ and (b) Pt(0.6)/[Co(0.4)/Pt(1.2)]$_3$/NiO(1.1)/Pt(0.6)/[Co(0.4)/Pt(1.2)]$_3$.

Supplementary Methods

a. Optimisation of the extraordinary Hall balance in an exchange biased system

Antiferromagnetic (AFM) layers are commonly used to pin the magnetisation of ferromagnetic (FM) layers in a spin-valve structure via the interfacial exchange coupling[1]. NiO was used for the extraordinary Hall balance (EHB) as it produces a non-zero exchange-bias field (H_{EB}) even in its polycrystalline state[2]. The resulting coupling energy J is given by $J = M_{\mathrm{S}} \cdot t_{\mathrm{FM}} \cdot H_{\mathrm{C}}$, where M_{S} is the spontaneous magnetisation of the FM layer, t_{FM} the thickness, and H_{C} is the coercive field[3]. The coercive field is found to be influenced by the interface roughness, i.e., H_{C} increases as the interface becomes rougher. Therefore, the coercivity can be tuned by changing the morphology of the NiO/FM interface, which is achieved by varying the thickness of the NiO (t_{NiO}) and the FM layer. Above a critical thickness of ~ 30-35 nm of the NiO layer, a non-zero biasing field of ~ 130 Oe is observed which remains roughly constant independent of the NiO thickness[4,5].

On the other hand, the extraordinary Hall effect (EHE) is found to be sensitive to interfaces, in particular the interfaces between a FM layer and an oxide[6], i.e., the [Co/Pt]/NiO and the [Co/Pt]/MgO interface in case of the EHB. Therefore, the magnetic (H_{EB} and H_{C}) and transport (Hall resistance, R_{H}) properties of the EHB can be adjusted by carefully engineering the thicknesses of the layers.

Supplementary Figure S1 shows the systematic variation of film parameters in an EHB structure achieving a symmetric four-state behaviour in one extreme, and a horizontally biased three-state behaviour in the other extreme. In Fig. 1f, H_{EB} is zero because the NiO layer thickness (20 nm) is below the critical thickness. A symmetric hysteresis loop with a larger coercive field (163 Oe) is observed. In order to transform the EHB shown in Fig. 1f into a memory cell, the Hall loop of the pinned [Co/Pt] bottom layer has to be shifted leaving only the 'free' [Co/Pt] top layer switchable under small magnetic field. Consequently, a thicker NiO (50 nm) layer has to be employed to produce the necessary exchange bias field. The Hall loop is shown in Supplementary Figure S1(a). The pinned stack is shifted to the left and H_{EB} reaches 115 Oe. Simultaneously, the coercivity increases due to the enhanced exchange coupling energy to 235 Oe, which requires further adjustment. The compensated Hall state shows a Hall voltage below zero, which indicates that the EHE generated by the top [Co/Pt] layer is smaller than that generated by the bottom [Co/Pt] layer. To improve the Hall resistance ratio (HRR), the Co thickness in the pinned [Co/Pt] stack is reduced to 0.3 nm to decrease its EHE contribution. As shown in Supplementary Figure S1(b), the low Hall resistance value is vanishing. Moreover, due to the reduced thickness of the ferromagnetic layer, H_{EB} increases to

139 Oe, while H_C is 240 Oe. Further optimisation of the EHB structure includes a further increase of the H_{EB}, while simultaneously maintaining the value of H_C, by introducing a Pt spacer between the NiO layer and the bottom [Co/Pt] stack. The effect is demonstrated in Supplementary Figure S1(c & d) and Fig. 2a.

b. EHB optimisation in an antiferromagnetically coupled system

Ferromagnetic layers separated by a nonmagnetic spacer display oscillatory interlayer exchange coupling between the FM layers[7]. The coupling type switches between FM and AFM as a function of spacer thickness (as shown in Supplementary Figure S2). Based on this effect, the EHB can be optimised to show symmetric three-state behaviour, which is suitable for complex logic operations. By carefully tuning the structure, the net EHE in the antiparallelly aligned state can be lowered down to zero while maintaining a well-defined AFM coupling (Fig. 3b).

Supplementary References

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