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# Anomalous Nernst effect in $Ir_{22}Mn_{78}/Co_{20}Fe_{60}B_{20}$/MgO layers with perpendicular magnetic anisotropy

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The anomalous Nernst effect in a perpendicularly magnetized $Ir_{22}Mn_{78}/Co_{20}Fe_{60}B_{20}$/MgO thin film is measured using well-defined in-plane temperature gradients. The anomalous Nernst coefficient reaches 1.8 $\mu$V/K at room temperature, which is almost 50 times larger than that of a Ta/$Co_{20}Fe_{60}B_{20}$/MgO thin film with perpendicular magnetic anisotropy. The anomalous Nernst and anomalous Hall results in different sample structures revealing that the large Nernst coefficient of the $Ir_{22}Mn_{78}/Co_{20}Fe_{60}B_{20}$/MgO thin film is related to the interface between CoFeB and IrMn. *Published by AIP Publishing.* https://doi.org/10.1063/1.4996399

A branch of spintronics called spin caloritronics[1–13] focuses on the interplay of spin and heat currents. The effects discovered in this emerging research field have revived interest in the anomalous Nernst effect (ANE), which is defined as the voltage observed perpendicular to both the heat current and the spontaneous magnetization. So far, the ANE has been investigated in many different materials, such as ferromagnetic (FM) metals like Py,[14–16] $L1_0$-type Mn-Ga Heusler alloy, and FePt thin film,[17] $Fe_3O_4$ single crystals,[18] rare-earth metal $Tb_{30}Fe_{35}Co_{35}$,[19] $[Pt/Co]_n$ multilayers,[20] and others.[21] A typical setup, utilizing an out-of-plane temperature gradient and an in-plane magnetic field, has been used to investigate the ANE in previous works.[22–26] The trouble with this configuration is that, in addition to generating an ANE voltage, the out-of-plane temperature gradient can also generate a spin current through the so-called longitudinal spin Seebeck effect (LSSE),[22,27–33] which flows directly from the ferromagnetic (FM) into the adjacent non-magnetic metal (NM) and generates a voltage because of the inverse spin Hall effect (ISHE). In order to distinguish the spin Seebeck effect (SSE) and ANE, extensive efforts[34–37] have been made to compare the voltage in different temperature gradient configurations. However, it is quite challenging to define precisely the out-of-plane temperature gradient which is established over a few nm thickness. Usually, the temperature gradient is calculated by simulation, rather than directly measured.[24,38] Alternatively, the converse geometry is used, i.e., in-plane temperature gradient and out-of-plane magnetic fields.[39] The geometry with an out-of-plane magnetic field and an in-plane temperature gradient is the natural configuration when studying perpendicularly magnetized ordered-alloy thin films. Then, this measurement avoids SSE[19,40–42] and allows a precise determination of the temperature gradient since it is in-plane, e.g., by using a thermal camera.[43,44]

Previous experiments observed an enhancement of the ANE in stacks containing heavy elements, indicating the relevance of strong spin orbit coupling (SOC) to obtain large Nernst coefficients $N_{ANE}$,[20,45] e.g., Uchida *et al.* showed that the anomalous Nernst coefficients change from about 0.1 $\mu$V/K to 1 $\mu$V/K by introducing strong SOC. In this work, we observed an ANE in Ta/IrMn/CoFeB/MgO/Ta structures that is almost 50 times larger than that of a thin film of Ta/CoFeB/MgO/Ta, i.e., without the IrMn layer.

We study the Nernst effect in a thin film of the following structure: Ta (5)/IrMn (2.5)/CoFeB (0.9)/MgO (1)/Ta (2), where thicknesses are in nm, and the layers are listed from bottom to top [Fig. 1(a)]. The film is grown by magnetron sputtering at room temperature on the silicon substrate capped with 100 nm of a thermal oxide.[46] The base pressure of the sputtering chamber was lower than $2 \times 10^{-8}$ Torr. The films were annealed at 250 °C in vacuum under an out-of-plane magnetic field. Their magnetization was measured using a vibrating sample magnetometer (VSM) at 300 K in an out-of-plane magnetic field geometry [Fig. 1(c)]. We found that the coercive field was about 4 Oe. Owing to the antiferromagnetic (AFM)-ferromagnetic (FM) interface between IrMn and CoFeB, we also observed an exchange-bias field ($H_{EB}$) of approximately 2 Oe. Such exchange biasing is one of the phenomena associated with the exchange anisotropy created at the interface between an AFM and a FM material.[47] In order to investigate the ANE, the films were patterned into a Hall bar structure using standard photolithography and ion beam etching (IBE). The Hall bar was 3 mm in width, 10 mm in length, and connected to 100 nm thick gold pads [Fig. 1(b)].

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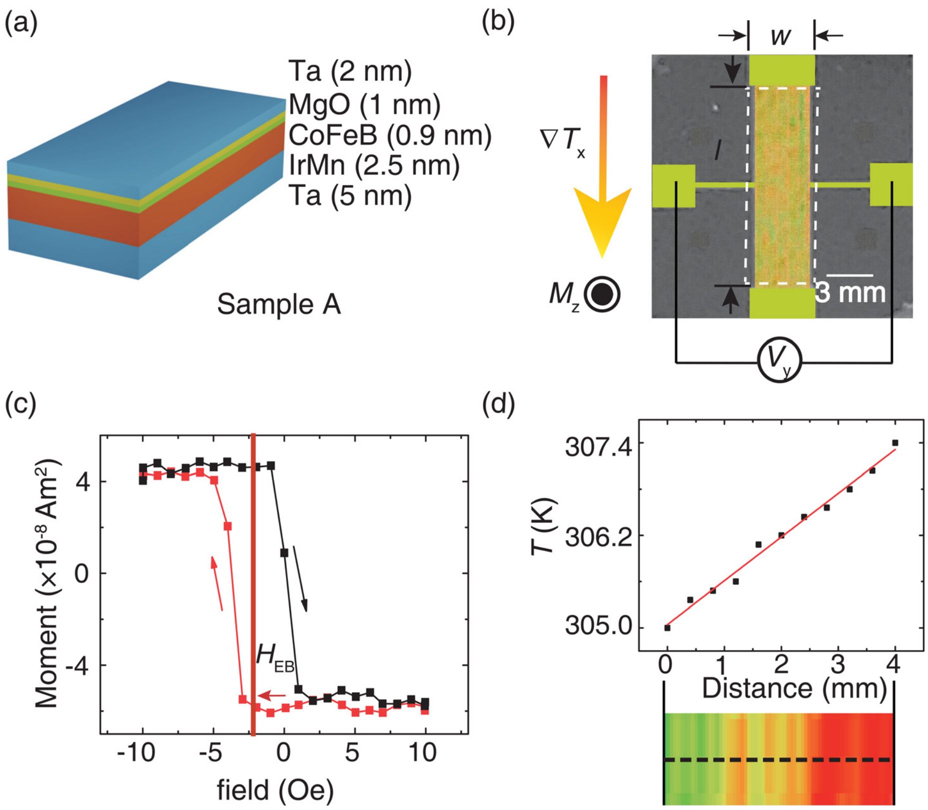


FIG. 1. (a) Schematics of the AFM/FM layer thin film (layer thicknesses indicated in parentheses). (b) Optical micrograph of the Hall bar structure. (c) Vibrating sample magnetometer (VSM) measurement of the sample in an out-of-plane magnetic field. (d) Top: temperature distribution across central part of the sample surface. Bottom: image of the sample surface taken using an infrared thermal camera.

Two Peltier elements along the $x$-axis were put on the backside of the sample to induce an in-plane temperature gradient and enable ANE measurements with an out-of-plane magnetic field. An infrared thermal camera was used to determine the temperature gradient of the sample surface [Fig. 1(d)]. The anomalous Hall effect (AHE) and ANE measurements reported here were performed on the same sample at room temperature, using a current source and a Keithley 2182A nanovoltmeter.

The anomalous Hall voltage as a function of out-of-plane magnetic field is shown in Fig. 2(a). The square loop is consistent with the magnetic hysteresis loop shown in Fig. 1(c). The anomalous Hall resistance $R_{AHE}$ is about 1.4 Ω. In anomalous Nernst measurements, instead of a charge current, a temperature gradient is applied along the sample length direction, which also generates a transverse voltage. By sweeping the out-of-plane magnetic field, the voltage changes its sign, as shown in Fig. 2(b). The ANE can be described by the Nernst coefficient $N_{ANE}$, according to[38]

$$E_{ANE} = -N_{ANE} m \times \nabla T = \frac{-N_{ANE}(\hat{m} \times \hat{x})\Delta T}{l}, \qquad (1)$$

where $l$(10 mm) is the length of the IrMn/CoFeB/MgO stripe [Fig. 1(b)], $\hat{m}$ and $\hat{x}$ are the normal vectors along the magnetization M and the $x$-axis, $E_{ANE}$ is the effective electric field, and $N_{ANE}$ is the Nernst coefficient. Thus, when M is aligned in the $z$-direction and the temperature gradient $\nabla T$ is aligned in the $x$-direction, the voltage $V_y$ is generated along the $y$-direction. A reversal of the temperature gradient leads to a change of the voltage sign (Fig. 3). This confirms that the observed voltage is indeed caused by the thermomagnetic

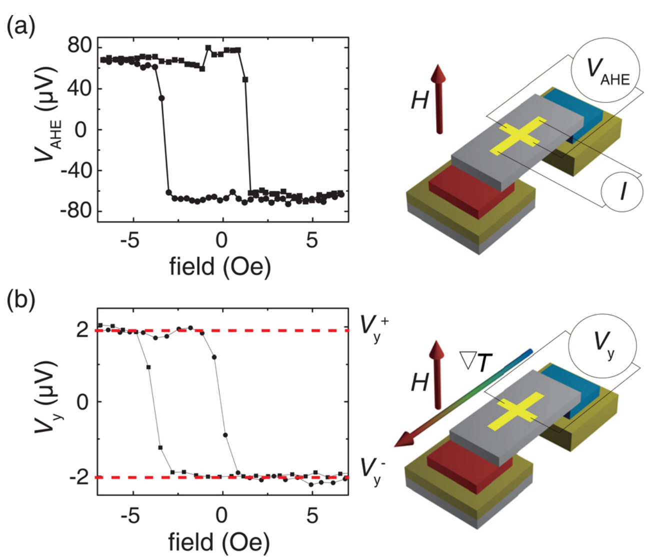


FIG. 2. Perpendicularly magnetized IrMn/CoFeB/MgO layers' magnetic field $H_x$ dependence of (a) the AHE voltage $V_{AHE}$ with −50 μA DC. (b) The Nernst voltage $V_y$ under an applied temperature gradient $\nabla T_x$ of −2.4 K/cm.

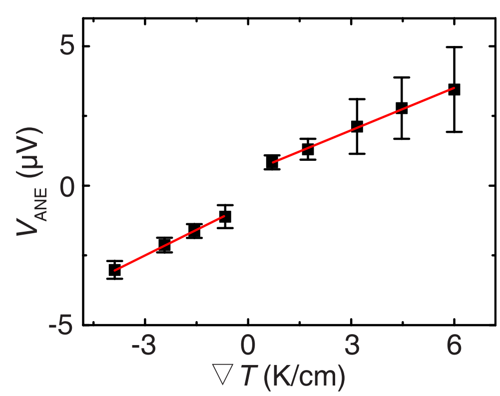


FIG. 3. Temperature gradient $\nabla T$ dependence of $V_{ANE}$ in IrMn/CoFeB/MgO layers. The red line shows the separate line fitting for the positive and negative temperature gradients.

effect [Fig. 2(b)]. We define the Nernst voltage as $\overline{V}_{\rm ANE} = (V_y^+ - V_y^-)/2$ in Fig. 2(b).

In order to further investigate the relationship between the ANE voltage and the temperature gradient, the same magnetic field sweeps as shown in Fig. 2(b) have been performed at different temperature gradients from $-4$ K/cm to $+6$ K/cm. We observed a linear dependence between the ANE voltage and the temperature gradient (Fig. 3). By obtaining the slopes for the positive and negative temperature gradients, we get the separate values of 1.66 $\mu$V/K and 1.98 $\mu$V/K for $N_{\rm ANE}$ with Eq. (1), respectively. Based on this, we estimate the average value of 1.82 $\mu$V/K for $N_{\rm ANE}$ with an error bar of about 0.16 $\mu$V/K. Here, we must point out that the error bars above 3 K/cm start increasing to rather high values. This is most likely due to the fact that when the in-plane temperature gradient is increased, the surface temperature of the Peltier elements fluctuates somewhat, owing to the large temperature difference between the Peltier faces and ambient air.

The ANE value we thus found is surprisingly large compared to typical values in the previously reported experiments. We presume that this large Nernst coefficient is due to the interface between CoFeB and IrMn. In order to test this assumption, we characterized the sample of IrMn(1.5 nm)/CoFeB/MgO and Ta/CoFeB/MgO corresponding to sample B and sample C, respectively. All measurements were performed under the same experimental conditions as above, i.e., the same geometry, substrate, and environmental temperature. The magnitude of the anomalous Nernst coefficient in Ta/CoFeB/MgO was found to be 0.04 $\mu$V/K [Fig. 4(d)]. This is almost 50 times smaller than that of the IrMn(2.5 nm)/CoFeB/MgO structure which was defined as sample A in Fig. 4(f). We also measured the anomalous Hall voltage [Figs. 4(a) and 4(b)]. We compare the Hall resistivity of the three samples and see that the Hall resistivity is enhanced by the presence of the IrMn layer [Fig. 4(c)]. Of course, the pronounced increase in both the Hall resistivity and the Nernst coefficient is influenced by the film resistivity, total thickness, interface roughness, the crystalline structure of the CoFeB, and the interfacial exchange interaction. However, here, the film resistivities of CoFeB and IrMn are 160 and 278 $\mu\Omega$ cm, respectively.[46] Furthermore, the total film thickness difference was 2.5 nm, which was the thickness of IrMn, and the resistivity of the whole films was of the same order of magnitude. Therefore, a change in film resistivity may only play a slight role in AHE and ANE enhancement. Our results on $N_{\rm ANE}$ and Hall resistivity are consistent with the idea that what the observed large Nernst effect is due to the interface between IrMn and CoFeB, e.g., a proximity effect[48,49] or an interfacial exchange interaction.[50–52] Moreover, the polarity of the AHE and ANE signal changed after the IrMn layer was inserted, as shown in Figs. 2 and 4. Among perpendicular magnetic

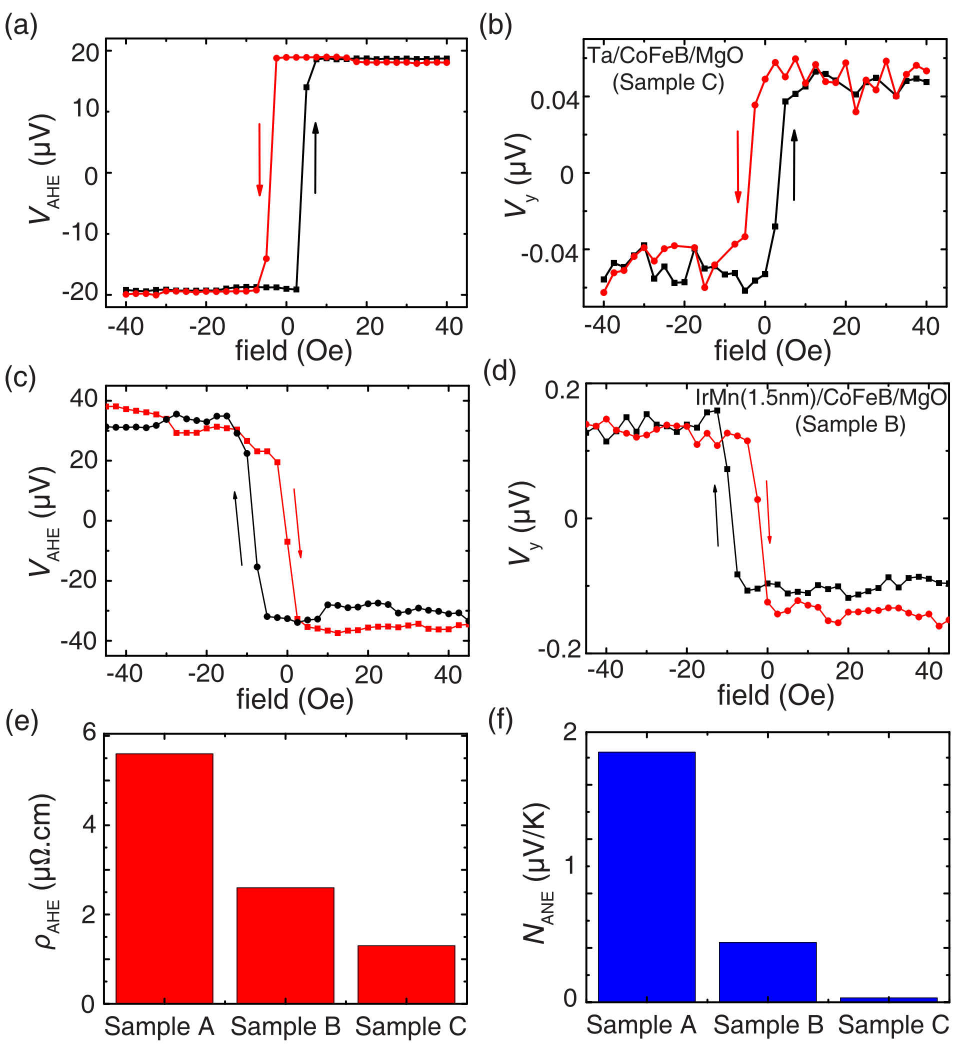


FIG. 4. Magnetic field $H_x$ dependence of the AHE voltage $V_{\rm AHE}$ with $-50\,\mu$A DC in (a) and the Nernst voltage $V_y$ under an applied temperature gradient $\nabla T_x$ of $-4.7$ K/cm in (b) for the perpendicularly magnetized Ta/CoFeB/MgO layers. (c) and (d) The AHE voltage $V_{\rm AHE}$ with $-50\,\mu$A DC and the Nernst voltage $V_y$ under an applied temperature gradient $\nabla T_x$ of $-1$ K/cm in perpendicularly magnetized Ta/IrMn(1.5 nm)/CoFeB/MgO layers, respectively. (e) AHE resistivity and (f) Anomalous Nernst coefficients in different samples. Here, sample A, sample B, and sample C represent Ta/$Ir_{22}Mn_{78}$(2.5 nm)/$Co_{20}Fe_{60}B_{20}$/MgO, Ta/$Ir_{22}Mn_{78}$(1.5 nm)/$Co_{20}Fe_{60}B_{20}$/MgO, and Ta/$Co_{20}Fe_{60}B_{20}$/MgO thin films with all being Ta capped.

anisotropy (PMA) studies, there are several AHE studies on thin Co-Pd alloys and Co/Pd multilayers. Kim *et al.*,[53] for example, explored the Pd thickness dependence of the AHE of Co/Pd multilayers. The polarity of the AHE signal of the Pd/Co multilayer changed between 4 and 5 monolayers (ML) of Pd. They suggested that the reason for this phenomenon was the change in the Fermi level position when the Pd thickness was changed. Jen *et al.*[54] studied the AHE coefficient of $Co_{1-x}Pd_x$ alloys. Depending on the Pd concentration, different types of scattering mechanisms lead to a change of the AHE sign. The reverse polarity of AHE and ANE signals is likely to be connected to a shift of the Fermi level due to the insertion of an IrMn layer. Further insight into the mechanism of this sign reversal could be gained by increasing the number of atomic layers of IrMn.

Other groups have also measured the Nernst coefficients by using either out-of-plane[39] or in-plane[24] magnetized CoFeB films capped with non-magnetic metal. The values obtained by them are much larger than that of our Ta/CoFeB/MgO film. For example, Wells *et al.* observed $N_{\mathrm{ANE}}$ of $2.5\,\mu$V/K in perpendicularly magnetized CoFeB/Pt nanowires.[39] It is not clear why there is such a large difference between our results and theirs. It could be due to the difference in the properties of the CoFeB layer (composition and thickness) and the measurement techniques.

As a last check experiment, we tried to detect the Nernst voltage of a film with the structure: Ta/IrMn/MgO. The observed voltage was within the noise level, i.e., far less than the Nernst voltage detected in the samples that contained a PMA ferromagnetic layer.

From the above results, it can be argued that the IrMn/CoFeB/MgO layers would be promising materials for thermoelectric applications. Even though the Nernst coefficient is small compared to the Seebeck coefficient of a high performance thermoelectric, we point out that PMA structures offer a unique possibility for obtaining a large voltage, as illustrated in Fig. 5. Sakuraba *et al.*[41] have proposed a method, namely, the thermopiles, to get a large voltage in both PMA and no PMA samples. Yin *et al.* in Ref. 16 have compared the voltage between $V_x$ and $V_y$ in samples without PMA by applying an out-of-plane temperature gradient and an in-plane magnetic field. The larger the separation between the voltage contacts is the greater is the ANE voltage that we get. Indeed, if the temperature difference $\Delta T$ is applied across the width $w$ of the strip, then we have[38]

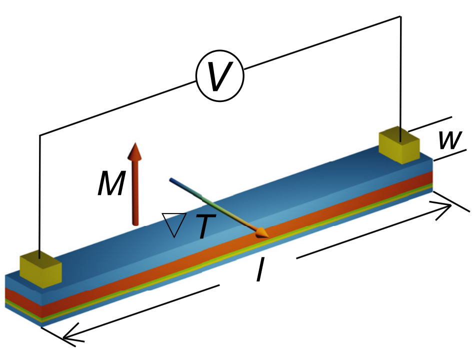


FIG. 5. The schematic of the thermoelectric device based on ANE in IrMn/CoFeB/MgO layers.

$$V_{\mathrm{ANE}} = \frac{-l}{w} N_{\mathrm{ANE}} \Delta T. \tag{2}$$

The Nernst voltage is therefore proportional to the ratio $l/w$, which can be made quite large.

In conclusion, we have found that the anomalous Nernst coefficient of the IrMn/CoFeB/MgO thin film with PMA is almost 50 times larger than that of Ta/CoFeB/MgO, which is also with good PMA. The results with and without IrMn indicate that this enhanced Nernst coefficient is related to the interface between CoFeB and IrMn. The underlying mechanism responsible for the strength of the ANE effect, when both SOC and exchange biasing play a role, is yet to be understood. We point out a possible application of ANE that takes advantage of the perpendicular magnetization to obtain large Nernst voltage, owing to the in-plane geometry of the device.

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