Origins of transverse voltages generated by applied thermal gradients and applied electric fields in ferrimagnetic-insulator/heavy-metal bilayers

Arnab Bose¹, Rakshit Jain², Jackson J. Bauer³, Robert A. Buhrman¹, Caroline A. Ross³, Daniel C. Ralph²

ABSTRACT

We compare thermal-gradient-driven transverse voltages in ferrimagnetic-insulator/heavy-metal bilayers (Tm₃Fe₅O₁₂/W and Tm₃Fe₅O₁₂/Pt) to corresponding electrically-driven transverse resistances at and above room temperature. We find for Tm₃Fe₅O₁₂/W that the thermal and electrical effects can be explained by a common spin-current detection mechanism, the physics underlying spin Hall magnetoresistance (SMR). However, for Tm₃Fe₅O₁₂/Pt the ratio of the electrically-driven transverse voltages (planar Hall signal/anomalous Hall signal) is much larger than the ratio of corresponding thermal-gradient signals, a result which is very different from expectations for a SMR-based mechanism alone. We ascribe this difference to a proximity-induced magnetic layer at the Tm₃Fe₅O₁₂/Pt interface.

* Equal contributions
INTRODUCTION

In solid state materials that have a magnetic moment or are subject to an external magnetic field, an applied electric field or thermal gradient can generate transverse charge currents and voltages, resulting in Hall effects, anomalous Hall effects [1], or Nernst effects [2]. In systems with strong spin-orbit coupling, an electric field or thermal gradient can also drive analogous transverse-flowing spin currents, yielding spin Hall effects (SHE) [3] or spin Nernst effects (SNE) [4]. When heterostructures are made containing both layers with strong spin-orbit coupling and magnetic layers, spin currents can themselves generate transverse voltages and novel forms of magnetoresistance. The precise mechanisms by which these spin-current-driven electrical signals arise has been a matter of controversy, with arguments made for combinations of spin Hall magnetoresistance (SMR) [5,6] magnetic proximity effects (MPE) [7,8], and magnetic scattering [9]. Here we investigate these issues using a simple model system – combining a thin film of heavy metal with an insulating ferrimagnet (TmFeO$_3$ = TmIG), so that the transport characteristics are not affected by charge flow within the magnetic layer. We compare thermally-driven transverse voltages to their electrically-driven counterparts. We find that different mechanisms are active between TmIG/W and TmIG/Pt. In TmIG/W, both electrically-driven and thermally-driven transverse voltages can be understood from a single spin-current detection mechanism, the physics that gives rise to SMR. In TmIG/Pt, this is not the case, and we conclude that a MPE in the Pt as well as SMR affect the results.

BACKGROUND: SPIN HALL AND ANISOTROPIC MAGNETORESISTANCE

When an electric field ($E$) is applied to generate a charge current density $J_C$ within the plane of a ferrimagnetic insulator (FMI)/ heavy metal (HM) bilayer, a spin current density $J_S = \theta_{SH} (J_C \times \sigma)$ is created due to the spin Hall effect (SHE) in the HM (Fig. 1(a)), with $\theta_{SH}$ the spin Hall ratio of the HM and $\sigma$ the orientation of the current-generated spins being in-plane and perpendicular to $J_C$. A fraction of this spin current can be reflected at the interface depending upon the angle between $\sigma$ and the magnetization, $M$. The reflected spin current is then transduced back into an electric voltage within the HM by the inverse SHE. The result is spin Hall magnetoresistance (SMR) [5,6,10], a contribution to the sample resistance that depends on the magnetization orientation. For the definition of coordinate axes shown in Fig. 1(b), SMR produces changes in the longitudinal ($\rho_{xx}$) and transverse ($\rho_{xy}$) resistivity of the form:

$$\rho_{xx} = \rho_0 + \Delta\rho_{xy} m_y^2$$

$$\rho_{xy} = \Delta\rho_{xy}^z m_z + \Delta\rho_{xy}^\phi m_x m_y$$

where $m_x = \sin\theta\cos\phi$, $m_y = \sin\theta\cos\phi$, and $m_z = \cos\theta$ represent the orientation of the magnetization saturated parallel to the applied magnetic field and $\Delta\rho_{xy}^\phi$ and $\Delta\rho_{xy}^z$ are the SMR coefficients. The values of $\Delta\rho_{xy}^\phi$ and $\Delta\rho_{xy}^z$ are predicted to depend on the real and imaginary parts of the effective spin mixing conductance of the interface ($G_{\text{eff}}^{\text{t}}$) [6,10]:

$$\frac{\Delta\rho_{xy}^\phi}{\rho_0} = \theta_{SH}^2 \frac{\lambda}{t_{HM}} 2\lambda \rho_0 \text{Re}(G_{\text{eff}}^{\text{t}})$$

$$\frac{\Delta\rho_{xy}^z}{\rho_0} = -\theta_{SH}^2 \frac{\lambda}{t_{HM}} 2\lambda \rho_0 \text{Im}(G_{\text{eff}}^{\text{t}})$$

2
where for the heavy metal \( \lambda \) is the spin diffusion length, and \( t_{HM} \) is the thickness, and \( G^\uparrow_{\text{eff}} = G^\uparrow \tanh^2 \frac{t_{HM}}{2\lambda} / (1 + 2\lambda \rho_0 G^\uparrow \coth \frac{t_{HM}}{\lambda}) \) where \( G^\uparrow \) is the bare interfacial spin mixing conductance.

The existence of a spin Nernst effect (SNE) in ferromagnet/HM bilayers, a thermal analogue to the SHE, has been reported in Ref. [11–16]. In this case, an in-plane thermal gradient (\( \nabla T_{ip} \)) in a sample with no net charge current flow (i.e., open-circuit condition) generates a spin current density

\[
J_S = -\theta_{SN} \frac{S_{HM}}{\rho_{HM}} (\nabla T_{ip} \times \sigma),
\]

where \( \theta_{SN} \) is the spin Nernst angle and \( S_{HM} \) is the Seebeck coefficient of the HM. One can alternatively define a different quantity (we will call this \( \theta_{SN}^0 \)) to characterize the spin current generated by a thermal gradient in a sample with no longitudinal electric field, so that in the presence of an electric field the total transverse spin current has the form

\[
J_S = \theta_{SH} \frac{1}{\rho_{HM}} (E \times \sigma) - \theta_{SN}^0 \frac{S_{HM}}{\rho_{HM}} (\nabla T_{ip} \times \sigma).
\]

In the open-circuit condition corresponding to our measurements, there is a longitudinal electric field due to the Seebeck effect, \( E = S_{HM} \nabla T_{ip} \), so that

\[
\theta_{SN} = -\theta_{SH} + \theta_{SN}^0.
\]

A thermally-generated spin current reflected at the interface can again be transduced into a voltage by the inverse-SHE in the heavy metal, resulting in thermally-induced voltages in both the longitudinal and transverse directions: [11–13]:

\[
\frac{V_{Txy}^{\text{SMR}}}{L_y} = - \left( S_{HM} + \Delta S_0^{\text{SMR}} + \Delta S_{xy}^{\phi,\text{SMR}} m_y^2 \right) \nabla T_{ip}
\]

\[
\frac{V_{Txz}^{\text{SMR}}}{L_x} = - \left( \Delta S_{xz}^{\phi,\text{SMR}} m_z + \Delta S_{xy}^{\phi,\text{SMR}} m_x m_y \right) \nabla T_{ip}
\]

where \( L_x \) and \( L_y \) are the length and width of the device (Fig. 1(c)). Within the framework of the SMR spin-current detection mechanism, one would expect [10]

\[
\frac{\Delta S_{xy}^{\phi,\text{SMR}}}{S_{HM}} = \theta_{SH} \theta_{SN} \frac{\lambda}{t_{HM}} 2\lambda \rho_0 \text{Re} \left( G_{\text{eff}}^\uparrow \right)
\]

\[
\frac{\Delta S_{xz}^{\phi,\text{SMR}}}{S_{HM}} = -\theta_{SH} \theta_{SN} \frac{\lambda}{t_{HM}} 2\lambda \rho_0 \text{Im} \left( G_{\text{eff}}^\uparrow \right).
\]

If SMR is the only mechanism contributing to both the electrically-driven and thermally-driven voltage signals, then one should have

\[
\frac{\Delta \rho_{xy}^{\text{SMR}}}{\Delta \rho_{xy}^{\text{SMR}}} = \frac{\Delta S_{xy}^{\phi,\text{SMR}}}{\Delta S_{xy}^{\phi,\text{SMR}}}
\]

when all coefficients are measured at the same temperature. In this case, it should also be possible to determine \( \theta_{SN} / \theta_{SH} \) by taking the ratio of either Eqs. (10) & (3) or Eqs. (11) & (4):

\[
\theta_{SN} / \theta_{SH} = \frac{\Delta S_{xy}^{\phi,\text{SMR}}}{S_{HM}} \frac{\rho_0}{\Delta \rho_{xy}^{\text{SMR}}} = \frac{\Delta S_{xz}^{\phi,\text{SMR}}}{S_{HM}} \frac{\rho_0}{\Delta \rho_{xy}^{\text{SMR}}}.
\]
In the case of an electrically-conducting magnetic film, such as Pt magnetized by the MPE, magnetization-dependent deflection of electrons can also produce both electrically and thermally-driven transverse voltage signals. In this case the longitudinal and transverse resistivities take the form [1]

\[ \rho_{xx} = \rho_0 + \Delta \rho_{xy}^{AMR} m_x^2 \]
\[ \rho_{xy} = \Delta \rho_{xy}^{AHE} m_z - \Delta \rho_{xy}^{AMR} m_x m_y \]

where \( \Delta \rho_{xy}^{AMR} \) is the coefficient of anisotropic magnetoresistance (AMR) and \( \Delta \rho_{xy}^{AHE} \) is the coefficient of the anomalous Hall effect (AHE). The thermal analogue for the transverse voltage contains terms corresponding to the anomalous Nernst effect (ANE) and planar Nernst effect (PNE)

\[ \frac{\nu_{xy}^{T-AMR}}{L_y} = -\left( \Delta \rho_{xy}^{ANE} m_z - \Delta \rho_{xy}^{PNE} m_x m_y \right) \nabla T_{ip} \]  \hspace{1cm} (16)

Within an electrically-conducting magnet in general the equality analogous to Eq. (12) does not hold. For example, we show data for 1-nm-thick CoFeB samples in the Supplementary Materials [17] for which \( \Delta \rho_{xy}^{AMR} \) is very weak, below our detection limit, so \( \Delta \rho_{xy}^{AMR} / \Delta \rho_{xy}^{AHE} \) is at least a factor of 20 greater than \( \Delta \rho_{xy}^{PNE} / \Delta \rho_{xy}^{ANE} \). This difference can be understood based on Mott’s relation [2] assuming the scaling relationships \( \Delta \rho_{xy}^{AHE} = Y_{AHE} \rho_{xx}^n \) and \( \Delta \rho_{xy}^{PHE} = Y_{PHE} \rho_{xx}^m \). The electrically and thermally-driven coefficients for an electrically-conducting magnet should then be related as (see Supplementary Material):

\[ \frac{\Delta \rho_{xy}^{PHE}}{\Delta \rho_{xy}^{PNE}} = \frac{\gamma_{PHE}^n}{\gamma_{PHE}^m} \frac{1}{T \frac{\Delta \rho_{xy}^{AHE}}{\Delta \rho_{xy}^{ANE}}} \]

(17)

where \( T \) is temperature, \( k_B \) is the Boltzmann constant, \( e \) is electronic charge, and \( \gamma_{PHE} \) and \( \gamma_{AHE} \) are the energy derivatives of \( \gamma_{PHE} \) and \( \gamma_{AHE} \). Since the mechanisms giving rise to the AHE and PHE are unrelated, in general \( \gamma_{AHE} / \gamma_{PHE} \neq \gamma_{PHE} / \gamma_{PHE} \) and \( n \neq m \). It follows that the ratio in Eq. (17) has no reason to be equal to 1 for an electrically-conducting magnetic layer.
Fig. 1. (a) Origin of spin current generation by the spin Nernst effect. (b) Orientation of magnetic field rotation for z-y scans and z-x scans. (c) Schematic diagram of the experimental set-up for measurement of transverse voltages generated by a thermal gradient. (d) Magnetoresistance ($\Delta R_{xx}/R_0$) signals for TmIG/W (d) and TmIG/Pt (e). $R_0 = 13.3 \text{ kΩ}$ for the TmIG/W sample and $R_0 = 1.5 \text{ kΩ}$ for the TmIG/Pt sample.

EXPERIMENTAL METHODS

Experiments were performed on bilayers of TmIG with both W and Pt. The TmIG films (6 nm) were grown on single-crystal (111) gadolinium gallium garnet (GGG) substrates via pulsed laser deposition (PLD) in 150 mTorr O$_2$ at a substrate temperature of 650 °C from a bulk TmIG target [18]. The TmIG has perpendicular magnetic anisotropy (PMA) with an anisotropy field of 1.3 kOe, based on the applied field required to reorient the magnetization in-plane (see Supplemental Material). The PMA is a result of the tensile strain of the TmIG combined with its negative magnetostriction $\lambda_{111}$, which leads to a magnetoelastic anisotropy that overcomes the shape anisotropy.

After TmIG growth, the samples were transferred through air to a separate vacuum system where W (4 nm) or Pt (4 nm) was deposited by sputtering without further surface treatment. The average resistivities of the W and Pt films are 205 $\mu\Omega$-cm and 46 $\mu\Omega$-cm. The high resistivity in the W films implies that they are primarily $\beta$-phase [19]. Device structures were patterned by optical lithography and then Ar-ion milling fully through the TmIG to the GGG substrate. Electrical contacts were made by sputtering and lift-off of Ti (5 nm) and Pt (75 nm). More details about film growth, characterization, and sample fabrication are provided in the Supplemental Material.

We measure the longitudinal resistance ($R_{xx}$) for both TmIG/W (Fig. 1(d)) and TmIG/Pt (Fig. 1(e)) while rotating the magnetic field in z-x and z-y planes (field orientations shown in Fig. 1(b)). Already we observe an important difference between the W and Pt samples. The TmIG/W devices show a large oscillation of magnetoresistance for a magnetic field rotated in the y-z plane with an angular dependence that fits well $\propto m_y^2$, with negligible magnetoresistance for field rotation in the x-z plane. This is consistent with a signal due entirely due to SMR (Eq. (1)) with negligible AMR (Eq. (14)). In contrast, the TmIG/Pt
sample has significant magnetoresistance for field rotations in both the x-z and y-z planes, suggesting contributions from both SMR and AMR. Since TmIG is insulating, the presence of significant AMR in TmIG/Pt suggests the influence of a magnetic proximity effect in the Pt layer, as has been reported previously [20,21].

To measure the transverse voltages produced by a thermal gradient, we made TmIG/HM wires 650 μm long \(L_x\) and 20 μm wide \(L_y\) placed between two heater lines made of 15 nm thick and 200 μm wide Pt as shown in Fig. 1(c). The separation \(d\) between the TmIG/HM wires and each heater line was varied in different devices between 15 μm and 200 μm. The advantage of this device geometry is that a \(\nabla T_{ip}\) of either sign can be applied along the x-axis, and the large value of \(L_y\) increases the magnitude of the measured thermally-induced voltage. We calibrated the temperature in the sample wires as a function of \(d\) by measuring the resistances of both the heater wire and the sample wires when current is flowing in the heater, and comparing to independent measurements of resistance as a function of temperature using external heating of the entire sample chip. Based on these measurements we can map \(\nabla T_{ip}\) as a function of heater spacing (Fig. 2(f)) (see Supplementary Information). We explored heater temperatures up to 400 K, which is significantly less than the 550 K Curie temperature of the TmIG.

MEASUREMENTS OF TRANSVERSE MAGNETORESISTANCE AND NERNST EFFECT FOR TmIG/W

Our measurements of the electric-field-driven Hall resistance for TmIG/W (Fig. 2(a,b)) as a function of magnetic field angle fit well to the dependence

\[
R_{xy} = \Delta R_{xy}^Z m_z + \Delta R_{xy}^\phi m_x m_y. \tag{18}
\]

We determine \(\Delta R_{xy}^Z\) based on sweeps of field perpendicular to the sample plane (e.g., Fig. 2(a)), and \(\Delta R_{xy}^\phi\) based on measurements as a function of rotating the field angle in the x-y plane (Fig. 2(b)). We have measured \(\Delta R_{xy}^Z\) and \(\Delta R_{xy}^\phi\) from room temperature to 390 K as shown with the blue and red curves in Fig. 2(e). \(\Delta R_{xy}^Z\) is approximately independent of temperature while \(\Delta R_{xy}^\phi\) decreases by almost a factor of two over this temperature range.

To measure the thermally-driven transverse voltage (Fig. 2(c,d)), we apply current through one of the Pt heaters adjacent to the TmIG/W wire, which generates thermal gradients both in the sample plane, \(\nabla T_{ip}\), and out of the plane, \(\nabla T_{op}\) at the position of the TmIG/W wire (Fig. 1(a)). We then measure the transverse voltage in the TmIG/W wires generated as a function of changing the direction of the applied magnetic field (Fig. 2(c-d)). For a fixed heater power, we find that the transverse voltage as a function of magnetic-field angle is well described by

\[
V_{xy}^T = \Delta V_{xy}^Z m_z + \Delta V_{xy}^\phi m_x m_y + \Delta V_{SSE} m_x. \tag{19}
\]

We measure \(\Delta V_{xy}^Z\) by sweeping the magnetic field perpendicular to the sample plane (Fig. 2(e)). \(\Delta V_{xy}^\phi\) and \(\Delta V_{SSE}\) are determined using measurements as a function of rotating the magnetic field in the sample plane with a fit to the function \(\Delta V_{xy}^\phi \sin \phi \cos \phi + \Delta V_{SSE} \cos \phi\) (Fig. 2(d)). We ascribe the term proportional to \(\cos \phi\) to the longitudinal spin Seebeck effect (SSE) [22] produced by \(\nabla T_{op}\), that generates a transverse voltage by the inverse spin Hall effect (ISHE). As a function of heater power, \(\Delta V_{xy}^Z\) scales linearly (blue curve in Fig. 2(e)).
2(g)), while $\Delta V_{xy}^\phi$ scales slightly sub-linearly (red curve in Fig. 2(g)). This suggests that $\Delta S_{xy}^\phi \equiv \Delta V_{xy}^\phi / (L_x \nabla T_{ip})$ decreases with increasing temperature, similarly to $\Delta R_{xy}^\phi$. All three contributions, $\Delta V_{xy}^x$, $\Delta V_{xy}^\phi$, and $\Delta V_{SSE}$, decrease with increasing spacing between the heater and the TmIG/W wire (inset of Fig. 2(g), Fig. 2(h)) as expected on account of the decreasing thermal gradients, with the $\Delta V_{SSE}$ term (corresponding to $\nabla T_{op}$) decreasing fastest (Fig. 2(h)), such that the contribution from $\nabla T_{op}$ becomes negligibly small for spacings greater than 100 $\mu$m in the range of heater power we explored.

To test whether the mechanism behind SMR is sufficient to explain both the electrically-driven and thermally-driven transverse voltages, we consider the ratio

$$\eta = \left| \frac{\Delta R_{xy}^\phi / \Delta R_{xy}^x}{\Delta V_{xy}^\phi / \Delta V_{xy}^x} \right| = \left| \frac{\Delta \rho_{xy}^\phi / \Delta \rho_{xy}^x}{\Delta S_{xy}^\phi / \Delta S_{xy}^x} \right|$$

(20)

As noted above (Eq. (12)), if SMR is the dominant spin-current detection mechanism contributing to both electrically-driven and thermally-driven signals, then $\eta$ is predicted to be equal to 1. In making this comparison, it is important to take into account that during the thermally-driven measurements the TmIG/W wires are heated substantially above room temperature (Fig. 2(g)), so we make the comparisons using values of $\Delta R_{xy}^\phi$ and $\Delta R_{xy}^x$ at the same elevated temperatures present for the thermally-driven measurements. The results are shown in Fig. 2(i). Over a range of heater spacing from 15 $\mu$m to 200 $\mu$m we find that the ratio $\eta$ is equal to one within 20%, which is on the scale of the experimental uncertainty in the measured values. We conclude that SMR is the dominant spin-current detection mechanism in determining both the electrically-driven and thermally-driven signals in TmIG/W.

![Figure 2](image-url)

FIG. 2. Results for TmIG/W. Hall resistance of TmIG/W for (a) out-of-plane magnetic-field sweep and (b) in-plane field rotation for a field magnitude of 2.7 kOe. Thermally-induced transverse voltages, (c) $V_{xy}^x$ and (d) $V_{xy}^\phi$, for a heater power of 630 mW and for two different heater spacings, $d = 15 \mu$m (closed squares) and 50 $\mu$m (open circles). (e) Temperature dependence of $\Delta R_{xy}^\phi$ (red) and $\Delta R_{xy}^x$ (blue). (f) Temperature
profile as function of $d$ for heater power, $P_{\text{heater}} = 630$ mW (black) and 490 mW (red). (g) Heater power dependence of $\Delta V_{xy}^\phi$ (red) and $\Delta V_{xy}^Z$ (blue) for $d=15$ μm. Inset of (g): Dependence on $d$ for $\Delta V_{xy}^\phi$ (red) and $\Delta V_{xy}^Z$ (blue) for $P_{\text{heater}} = 630$ mW. (h) Spin-Seebeck component $\Delta V_{\text{SSE}}$ as function of $d$ for $P_{\text{heater}} = 630$ mW. (i) Variation of $\eta$ as a function of $d$ for $P_{\text{heater}} = 630$ mW (black) and 560 mW (red).

MEASUREMENTS OF TRANSVERSE MAGNETORESISTANCE AND NERNST EFFECT FOR TmIG/Pt

Figure 3 shows results for the electrically-driven and thermally-driven transverse voltages for the TmIG/Pt samples analogous to those shown in Fig. 2 for TmIG/W. We observe both qualitative and quantitative differences. The signs of the electrically-driven coefficients $\Delta R_{xy}^\phi$ and $\Delta R_{xy}^Z$ are the same for both heavy metals (compare Fig. 2(a,b) with Fig. 3(a,b)), but the signs of the thermally-driven signals $\Delta V_{xy}^\phi$ and $\Delta V_{xy}^Z$ differ between TmIG/W and TmIG/Pt (compare Fig. 2(c,d) with Fig. 3(c,d)). There is also a striking difference in the scale of $\Delta R_{xy}^\phi$ and $\Delta R_{xy}^Z$ for TmIG/Pt (compare Fig. 2(e) and Fig. 3(e)). The ratio $\Delta R_{xy}^\phi/\Delta R_{xy}^Z$ varies from about 40 to 15 over the temperature range from room temperature to 400 K.

FIG. 3. Results for TmIG/Pt. Hall resistance of TmIG/Pt for (a) out-of-plane magnetic-field sweep and (b) in-plane field rotation for a field magnitude of 2.7 kOe. Thermally-induced transverse voltages, (c) $V_{xy}^Z$ and and (d) $V_{xy}^\phi$, for a heater power of 590 mW and for two different heater spacings, $d = 15$ μm (closed squares) and 50 μm (open circles). (e) Temperature dependence of $\Delta R_{xy}^\phi$ (red) and $\Delta R_{xy}^Z$ (blue). (f) Temperature profile as function of $d$ for heater power, $P_{\text{heater}} = 590$ mW (black) and 410 mW (red). (g) Heater power dependence of $\Delta V_{xy}^\phi$ (red) and $\Delta V_{xy}^Z$ (blue) for $d = 15$ μm. Inset of (g): Dependence on $d$ for $\Delta V_{xy}^\phi$ (red) and $\Delta V_{xy}^Z$ (blue) for $P_{\text{heater}} = 590$ mW. (h) Spin-Seebeck component $\Delta V_{\text{SSE}}$ as function of $d$ for $P_{\text{heater}} = 590$ mW. (i) Variation of $\eta$ as a function of $d$ for $P_{\text{heater}} = 590$ mW (black) and 515 mW (red).
whereas for TmIG/W this ratio varies only from about 4.6 to 2.5. Compared to the TmIG/W samples, $\Delta R_{xy}^\phi$ for TmIG/Pt is less dependent on the temperature (red curve in Fig. 3(e)) while $\Delta R_{xy}^z$ increases by factor of 2.7 (blue curve in Fig. 3(e)) from room temperature to 400 K rather than being approximately constant. As a function of heater power, both $\Delta V_{xy}^\phi$ and $\Delta V_{xy}^z$ for TmIG/Pt (red and blue curves in Fig. 3(g)) scale approximately linearly. Similar to TmIG/W, $\Delta V_{xy}^\phi$, $\Delta V_{xy}^z$ and $\Delta V_{SSE}$ all decrease as a function of heater spacing $d$ with $\Delta V_{SSE}$ decaying much faster (inset of Fig. 3(g), Fig. 3(h)).

Using the same technique we employed for TmIG/W, we can test for TmIG/Pt whether the spin-current detection mechanism associated with SMR is sufficient to explain both the electrically-driven and thermally-driven transverse voltages by calculating the ratio $\eta$ (Eq. 20). For TmIG/Pt we find $\eta = 30$-50 depending on the heater spacing $d$ (Fig. 3(i)), which is substantially different from our result $\eta \approx 1$ for TmIG/W (Fig. 2(i)). We therefore conclude for TmIG/Pt that the SMR spin-current detection mechanism cannot be dominant in determining both the electrically-driven and thermally-driven transverse voltages in this system. Based on previous measurements of a magnetic proximity effect in TmIG/Pt bilayers at room temperature [20], and our observation of an anisotropic magnetoresistance signal in our TmIG/Pt samples (Fig. 1(d)) consistent with a MPE in the Pt, we suggest that the difference between the TmIG/Pt and TmIG/W samples is the existence of an electrically-conducting magnetic layer in the Pt due to the proximity effect at the measurement temperature. The influence of a MPE in TmIG/Pt but not TmIG/W in our measurements is consistent with previous measurements that the onset temperature of the MPE upon cooling in TmIG(6 nm)/Pt is well above room temperature while in TmIG(6 nm)/W it is well below room temperature [20].

Previously, Avci et al. studied similar TmIG/Pt samples and also found values for $\eta \approx 8$-10 [23], qualitatively similar to our result in that the value was much greater than 1. Instead of a MPE, they suggested that the mechanism for this result was a thermal spin-drag effect, in which the SSE of TmIG due to $\nabla T_{op}$ induces spin accumulation in the heavy metal, and $\nabla T_{ip}$ then induces an in-plane spin current that generates a transverse voltage due to the inverse-SHE. We can rule out this possibility for our samples because the dependence of our signals ($\Delta V_{xy}^\phi$) on heater power (Figs. 2(g), 3(g)) is to a good approximation linear, while $\nabla T_{op} \nabla T_{ip} \propto (\text{heater power})^2$. Furthermore, the out-of-plane thermal gradient $\nabla T_{op}$ should scale proportional to the spin Seebeck voltage $[\Delta V_{SS}]$ as the heater spacing $d$ is varied (Fig. 3(h)). We find $\eta$ decreases much more slowly with increasing $d$ compared to $[\Delta V_{SS}]$ (Figs. 3(h) & 3(i)), which again indicates that a thermal spin drag effect cannot explain our data.

**DISCUSSION**

Thus far we have focused on mechanisms by which the spin currents are detected, arguing that in TmIG/W both the electrically-driven and thermally-driven signals are consistent with a read-out mechanism dominated by spin Hall magnetoresistance (SMR), while this is not the case for TmIG/Pt. If we take as established that the thermally-generated transverse voltages for TmIG/W are due to SMR read-out, then our data also allow us to consider the mechanism by which the thermally-induced spin currents are generated in TmIG/W, by analyzing the value of the spin Nernst angle, $\theta_{SN}$ (Eqs. (5) & (7)).

If the transverse spin current generation in $W$ were due entirely to the intrinsic SHE [3,24], theory predicts that one should be able to compute the transverse spin current as an appropriate integral over occupied electronic states of a transverse anomalous velocity
\[ \vec{v}(\vec{k}, \sigma) = e\vec{E} \times \vec{\Omega}(\vec{k}, \sigma), \]  

(21)

where \( \vec{k} \) is the electron wavevector, \( \sigma \) is a spin index, \( e \) is the electron charge, \( \vec{\Omega}(\vec{k}, \sigma) \) is the spin Berry curvature (see Ref. [25] for an elementary discussion) and \( \vec{E} \) is the electric field. Since only the electric field and not a thermal gradient appears in Eq. (21), a thermal gradient should not directly generate a spin current by an intrinsic spin Hall effect. However, even in the absence of any net charge current a thermal gradient that gives rise to an electric field due to the Seebeck effect should generate the same spin current as if that value of electric field were applied externally. In other words, under the assumptions associated with Eq. (21), \( \theta_{SN}^0 \) in Eq. (6) should be zero and hence one should have \( \theta_{SN} = -\theta_{SH} \) by Eq. (7).

Making a precise measurement of the absolute Seebeck coefficient of materials at room temperature is non-trivial because it is not possible to use a superconductor as a reference electrode. We have performed measurements on our TmIG(6 nm)/W(4 nm) films using lithographically-defined Au wires as reference electrodes and have corrected for the literature value of the absolute Seebeck coefficient of Au, \( \sim +1.5 \mu V/K \) [26] (see Supplemental Materials). The resulting estimate for the Seebeck coefficient for our 4 nm W films is \( S_{HM}(W) = -4.5 \pm 0.5 \mu V/K \). With this value, Eq. (13) yields \( \frac{\theta_{SN}}{\theta_{SH}} = -1.9 \pm 0.6 \) based on \( \frac{\Delta S_{xy}^{SMR}}{S_{HM}} \frac{\rho_n}{\Delta \rho_{xy}^{SMR}} \) and \( \frac{\Delta S_{xy}^{SMR}}{S_{HM}} \frac{\rho_n}{\Delta \rho_{xy}^{SMR}} \) based on \( \frac{\Delta S_{xy}^{SMR}}{S_{HM}} \frac{\rho_n}{\Delta \rho_{xy}^{SMR}} \). These values are consistent with previous reports for bilayers consisting of W with a conducting magnet [12,13]. The fact that \( \theta_{SN}/\theta_{SH} \) is of order \(-1\) suggests to us that the intrinsic SHE largely sets the scale of the thermally-generated spin current in W. This is interesting in that even in the absence of any net charge current flow spin current is still driven by an electric field. However, we suggest that this is not the whole story, since \( \theta_{SN}/\theta_{SH} \) differs from \(-1\) by more than our estimated experimental uncertainty. Deviations might result from extrinsic contributions to the SHE or strong energy dependence of the spin Hall ratio.

**SUMMARY**

In conclusion, we find that the mechanisms that lead to the generation of transverse voltages are different between TmIG/W and TmIG/Pt samples. In TmIG/W, both the electrically-generated and thermally-generated transverse voltages are consistent with the spin-current detection mechanism associated with spin Hall magnetoresistance (SMR). For TmIG/Pt, in contrast, the ratio of the thermally-generated anomalous Nernst signal \( \Delta S_{xy} \) to the corresponding anomalous Hall signal \( \Delta \rho_{xy} \) is much larger than would be expected for a purely SMR-based spin-current detection mechanism. We suggest the reason for this difference is that proximity-induced magnetism exists near the TmIG/Pt interface in an electrically-conducting interface layer at room temperature, allowing for an anomalous Hall signal in addition to signals due to SMR.
REFERENCES

[1] N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, Anomalous Hall Effect, Rev. Mod. Phys. 82, 1539 (2010).

[2] Y. Pu, D. Chiba, F. Matsukura, H. Ohno, and J. Shi, Mott Relation for Anomalous Hall and Nernst Effects in Ga1−xMnx As Ferromagnetic Semiconductors, Phys. Rev. Lett. 101, 117208 (2008).

[3] J. Sinova, S. O. Valenzuela, J. Wunderlich, C. H. Back, and T. Jungwirth, Spin Hall Effects, Rev. Mod. Phys. 87, 1213 (2015).

[4] A. Bose and A. A. Tulapurkar, Recent Advances in the Spin Nernst Effect, J. Magn. Magn. Mater. 491, 165526 (2019).

[5] H. Nakayama, M. Althammer, Y.-T. Chen, K. Uchida, Y. Kajiwara, D. Kikuchi, T. Ohtani, S. Geprägs, M. Opel, S. Takahashi, R. Gross, G. E. W. Bauer, S. T. B. Goennenwein, and E. Saitoh, Spin Hall Magnetoresistance Induced by a Nonequilibrium Proximity Effect, Phys. Rev. Lett. 110, 206601 (2013).

[6] M. Althammer, S. Meyer, H. Nakayama, M. Schreier, S. Altmannshofer, M. Weiler, H. Huebl, S. Geprägs, M. Opel, R. Gross, D. Meier, C. Klewe, T. Kuschel, J.-M. Schmalhorst, G. Reiss, L. Shen, A. Gupta, Y.-T. Chen, G. E. W. Bauer, E. Saitoh, and S. T. B. Goennenwein, Quantitative Study of the Spin Hall Magnetoresistance in Ferromagnetic Insulator/Normal Metal Hybrids, Phys. Rev. B 87, 224401 (2013).

[7] S. Y. Huang, X. Fan, D. Qu, Y. P. Chen, W. G. Wang, J. Wu, T. Y. Chen, J. Q. Xiao, and C. L. Chien, Transport Magnetic Proximity Effects in Platinum, Phys. Rev. Lett. 109, 107204 (2012).

[8] B. F. Miao, S. Y. Huang, D. Qu, and C. L. Chien, Physical Origins of the New Magnetoresistance in Pt/YIG, Phys. Rev. Lett. 112, 236601 (2014).

[9] B. F. Miao, L. Sun, D. Wu, C. L. Chien, and H. F. Ding, Tuning the magnetoresistance symmetry of Pt on magnetic insulators with temperature and magnetic doping, Appl. Phys. Lett. 110, 222402 (2017).

[10] Y.-T. Chen, S. Takahashi, H. Nakayama, M. Althammer, S. T. B. Goennenwein, E. Saitoh, and G. E. W. Bauer, Theory of Spin Hall Magnetoresistance, Phys. Rev. B 87, 144411 (2013).

[11] S. Meyer, Y.-T. Chen, S. Wimmer, M. Althammer, T. Wimmer, R. Schlitz, S. Geprägs, H. Huebl, D. Ködderitzsch, H. Ebert, G. E. W. Bauer, R. Gross, and S. T. B. Goennenwein, Observation of the Spin Nernst Effect, Nat. Mater. 16, 977 (2017).

[12] P. Sheng, Y. Sakuraba, Y.-C. Lau, S. Takahashi, S. Mitani, and M. Hayashi, The Spin Nernst Effect in Tungsten, Sci. Adv. 3, e1701503 (2017).

[13] D. J. Kim, C. Y. Jeon, J. G. Choi, J. W. Lee, S. Surabhi, J. R. Jeong, K. J. Lee, and B. G. Park, Observation of Transverse Spin Nernst Magnetoresistance Induced by Thermal Spin Current in Ferromagnet/Non-Magnet Bilayers, Nat. Commun. 8, 1400 (2017).

[14] A. Bose, S. Bhuktare, H. Singh, S. Dutta, V. G. Achanta, and A. A. Tulapurkar, Direct Detection of Spin Nernst Effect in Platinum, Appl. Phys. Lett. 112, 162401 (2018).

[15] A. Bose, A. S. Shukla, S. Dutta, S. Bhuktare, H. Singh, and A. A. Tulapurkar, Control of Magnetization Dynamics by Spin-Nernst Torque, Phys. Rev. B 98, 184412 (2018).

[16] J.-M. Kim, D.-J. Kim, C.-Y. Cheon, K.-W. Moon, C. Kim, P. Cao Van, J.-R. Jeong, C. Hwang, K.-J. Lee, and B.-G. Park, Observation of Thermal Spin–Orbit Torque in W/CoFeB/MgO
Structures, Nano Lett. 20, 7803 (2020).

[17] Supporting Information.

[18] A. Quindeau, C. O. Avci, W. Liu, C. Sun, M. Mann, A. S. Tang, M. C. Onbasli, D. Bono, P. M. Voyles, Y. Xu, J. Robinson, G. S. D. Beach, and C. A. Ross, $\text{Tm}_3\text{Fe}_5\text{O}_{12}/\text{Pt}$ Heterostructures with Perpendicular Magnetic Anisotropy for Spintronic Applications, Adv. Electron. Mater. 3, 1600376 (2017).

[19] C.-F. Pai, L. Liu, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, Spin Transfer Torque Devices Utilizing the Giant Spin Hall Effect of Tungsten, Appl. Phys. Lett. 101, 122404 (2012).

[20] Q. Shao, A. Grutter, Y. Liu, G. Yu, C.-Y. Yang, D. A. Gilbert, E. Arenholz, P. Shafer, X. Che, C. Tang, M. Aldosary, A. Navabi, Q. L. He, B. J. Kirby, J. Shi, and K. L. Wang, Exploring Interfacial Exchange Coupling and Sublattice Effect in Heavy Metal/Ferrimagnetic Insulator Heterostructures Using Hall Measurements, x-Ray Magnetic Circular Dichroism, and Neutron Reflectometry, Phys. Rev. B 99, 104401 (2019).

[21] J. J. Bauer, P. Quarterman, A. J. Grutter, B. Khurana, S. Kundu, K. A. Mkhoyan, J. A. Borchers, and C. A. Ross, Magnetic Proximity Effect in Magnetic-Insulator/Heavy-Metal Heterostructures across the Compensation Temperature, Phys. Rev. B 104, 094403 (2021).

[22] K. I. Uchida, H. Adachi, T. Ota, H. Nakayama, S. Maekawa, and E. Saitoh, Observation of Longitudinal Spin-Seebeck Effect in Magnetic Insulators, Appl. Phys. Lett. 97, (2010).

[23] C. O. Avci, E. Rosenberg, M. Huang, J. Bauer, C. A. Ross, and G. S. D. Beach, Nonlocal Detection of Out-of-Plane Magnetization in a Magnetic Insulator by Thermal Spin Drag, Phys. Rev. Lett. 124, 027701 (2020).

[24] G. Vignale, Ten Years of Spin Hall Effect, J. Supercond. Nov. Magn. 23, 3 (2010).

[25] D. C. Ralph, Berry Curvature, Semiclassical Electron Dynamics, and Topological Materials: Lecture Notes for Introduction to Solid State Physics, arXiv: 2001.04797 (2020).

[26] N. Cusack and P. Kendall, The Absolute Scale of Thermoelectric Power at High Temperature, Proc. Phys. Soc. 72, 898 (1958).