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ABSTRACT

We report the observation of two temperature-driven polarity reversals of the anomalous Hall effect (AHE) in an ultrathin thulium iron garnet $\text{Tm}_3\text{Fe}_5\text{O}_{12}$, TmIG and platinum (Pt) heterostructure, grown by scalable *on-axis* sputtering. Hall-bar devices fabricated from a 6-nm-thick, epitaxially strained TmIG film grown on (111) gadolinium gallium garnet exhibit polarity reversals of the anomalous Hall resistance at ~81 and 124 K. A pronounced divergence of the coercive field is observed only at the lower temperature, indicating a compensation-like transition. True magnetic compensation has not previously been reported in TmIG owing to the weak exchange coupling between the Tm and Fe sublattices. We attribute the two polarity reversals to distinct physical mechanisms: a crossover in the dominant contribution to the AHE within the Pt layer, and a strain-induced modification of the magnetic structure of the TmIG layer, detected via the magnetic proximity effect. These results demonstrate strain as an effective control parameter for engineering proximity-induced magnetotransport in heavy-metal/rare-earth iron garnet heterostructures.

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I. INTRODUCTION

Rare-earth iron garnets (REIGs) are attracting considerable interest in spintronics due to their insulating ferrimagnetism and highly tunable magnetic properties through the choice of the rare-earth element.^{1,2} Low magnetic damping, perpendicular magnetic anisotropy (PMA), and interfacial Dzyaloshinskii–Moriya interaction make REIGs highly attractive candidates for future skyrmionic,³ spintronic,⁴ and magnonic devices.^{5,6} A distinguishing feature of some of these materials is the possibility of achieving a magnetization compensation temperature (T_{comp}), at which the opposing

magnetic sublattices produce zero net magnetization.⁷ At or near such a compensation point, the system exhibits antiferromagnet-like dynamics (net magnetic moment ≈ 0), enabling ultrafast dynamics, high-speed domain wall motion,⁵ energy-efficient switching of magnetization,^{8,9} and ultrastrong magnon–magnon coupling.¹⁰ Among REIGs, thulium iron garnet ($\text{Tm}_3\text{Fe}_5\text{O}_{12}$, TmIG) stands out for its negatively large magnetostriction constant ($\lambda_{111} \approx -5.2 \times 10^{-6}$), resulting in strong strain-induced effects such as PMA and a compensation-like temperature in thin films.¹¹ TmIG consists of three coupled magnetic sublattices: Fe^{3+} ions occupy two octahedral and three tetrahedral sites, and Tm^{3+} ions reside on

dodecahedral sites.¹² The rare-earth Tm^{3+} sublattice antiferromagnetically couples with the net Fe-sublattice magnetization.¹¹ The weak exchange interaction between the Tm moments and the Fe moments is described by an exchange-enhanced paramagnetic magnetization: the RE ions are affected by an external field with superimposed Curie–Weiss law behavior with a strong temperature dependence.^{13–16} This results in a strain-sensitive orientation of the spin and orbital moments.

The magnetization compensation temperature in TmIG is a low-dimensional effect that appears only in thin-film structures with strain present.¹⁷ In bulk form, TmIG does not exhibit a magnetic compensation point owing to the small magnetic moment of the Tm sublattice. Classical pendulum magnetometry measurements on ultrapure single crystals did not reveal a clear zero crossing of the spontaneous magnetization within the experimentally accessible temperature range ($T > 1.4$ K).^{7,18} Instead, to date, such effects in TmIG are understood to be phenomena that emerge only in single-crystalline epitaxial thin films. In these systems, substrate-induced strain and finite-size effects modify the inter-sublattice exchange coupling, thereby profoundly altering the magnetic anisotropy and the balance of the sublattice magnetizations. While perpendicular magnetic anisotropy in strained TmIG thin films has been well established,^{19,20} the microscopic origin of a compensation(-like) temperature in these low-dimensional, strain-engineered systems remains poorly understood. Recent studies report compensation-like behavior in REIG thin films. Soares *et al.*¹¹ observed a compensation-like temperature ~ 50 K in a 30-nm-thick tensile-strained TmIG film, while Shao *et al.*²¹ systematically investigated the thickness dependence of TmIG and TbIG films grown on Nd:GGG substrates and capped with different heavy metals (lattice mismatch $\sim 1.4\%$), observing transitions at 75 and 45 K. Whether similar phenomena occur on GGG substrates, which provide a lower lattice strain but are more commonly used as commercial substrates, has remained unexplored. Previous TmIG/GGG studies using off-axis sputtering, pulsed-laser deposition, or liquid-phase epitaxy growth methods reported only single compensation-like temperatures or no compensation at all, raising questions about the role of the growth method and resulting film quality.^{12,22–26} The ability to access compensation phenomena in ferrimagnetic thin films, such as ultrathin Pt/TmIG heterostructures, has important implications for spintronic device applications. Near a true magnetization compensation temperature T_{comp} , the net magnetic moment vanishes, while the angular momentum compensation temperature T_A , which does not necessarily coincide with T_{comp} , corresponds to a minimum in the net angular momentum of the system. Operation close to T_A enables faster magnetization dynamics and reduced switching energy thresholds.^{8,9}

Here, we advance the field by demonstrating two distinct anomalous Hall effect (AHE) resistance $\Delta R_{\text{AHE}}(T)$ polarity reversals in uniform ultrathin, *on-axis* sputtered 6-nm TmIG films grown on (111)-oriented GGG and capped with Pt cross-shaped Hall-bar devices,^{6,27,28} measured in a physical property measurement system (PPMS). The lower-temperature reversal is accompanied by a maximum in coercive field, while the transition at higher temperature exhibits a smooth transition. Our results reveal previously unobserved magnetic phase behavior in thin Pt/TmIG/GGG, elucidate the conditions required to observe TmIG magnetic compensation-like points (such as composition and film thickness),

and highlight the intricate multisublattice dynamics in ultrathin garnets.

II. RESULTS

We perform AHE measurements as a function of temperature to probe the magnetic response of Pt/TmIG/GGG heterostructures. We deposited a 6-nm-thick TmIG layer on a (111)-oriented GGG substrate (supplied by K&R Creation, Osaka, Japan) by industry-compatible *on-axis* RF sputtering at room temperature followed by post-annealing. With a base pressure below 5×10^{-6} Pa, depositions were carried out at a working pressure of 3.0×10^{-3} Pa. The 50.8-mm-diameter TmIG target was prepared in-house by sintering mixed Tm_2O_3 and Fe_2O_3 powders (99.9% purity) supplied by Kojundo Chemical Lab. Co.

To check the uniformity of the sputtered film, we examine the deposition rate and the structure by X-ray reflectivity (XRR), an X-ray diffraction (XRD) $2\theta - \omega$ scan, and the rocking curve (XRC) as shown in Fig. 1. A detailed structural and magnetic characterization of this fabrication process and further characterization are reported elsewhere.^{6,27,28} To ensure homogeneity, we mount five square substrates ($5 \times 5 \text{ mm}^2$) on a sample holder at 10-mm intervals, corresponding to radial distances (R) ranging from 0 to 40 mm from the center of the holder [Fig. 1(a)]. The thin films are deposited while rotating the sample holder. This setup allows for the systematic evaluation of the uniformity of the deposition rate, lattice constant, and full width at half maximum (FWHM) of the XRC relative to the distance from the center. The results confirm highly uniform film

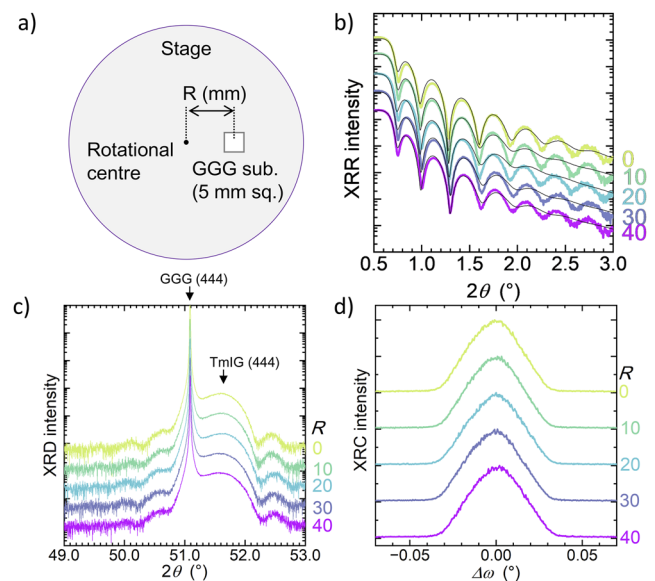


FIG. 1. Structural uniformity of TmIG. (a) Schematic image of the substrate holder and the position of chips of GGG substrate. In total, five samples were fabricated to establish TmIG homogeneity at radial distances from the center point $R = 0, 10, \dots, \rightarrow 40$ mm. (b) XRR patterns of TmIG/Si samples at multiple positions with best-fitting models. (c) XRD patterns of the TmIG/GGG sputtered at multiple positions. (d) X-ray rocking curves (XRC) of the TmIG (444) peaks of the samples deposited at multiple positions.

growth within the 40-mm radius. The deposition rate is determined to be 0.396 ± 0.005 nm/min, calculated from the periodicity of the XRR patterns shown in Fig. 1(b). In Fig. 1(c), XRD (2θ - ω) scans reveal consistent peak positions near 51.6° . From this, the d -spacing of the TmIG(444) planes is determined to be 0.17718 ± 0.00005 nm, which corresponds to a lattice strain of $0.42\% \pm 0.03\%$. This strain is in good agreement with previous reports on similarly grown films^{6,27,28} and is relatively low for such a small film thickness.¹⁹ The XRC FWHM is measured at 0.037° and remains consistent within a range of $\pm 0.001^\circ$ across all samples [Fig. 1(d)]. Furthermore, as reported in our previous work,⁶ the composition along the thickness direction is uniform. These structural characterizations demonstrate that the 6-nm ultra-thin films used in this study possess a highly homogeneous structure and composition.

Following TmIG growth, we grow a 3-nm Pt layer *ex situ* by magnetron sputtering. We pattern the resulting heterostructure into Hall cross devices with arm widths and lengths of $8\ \mu\text{m}$ using ion milling, as shown in Figs. 2(a) and 2(b). We carry out electrical transport measurements in the PPMS using the built-in current and voltage sources. At each temperature, we sweep the out-of-plane magnetic field between positive and negative values exceeding the saturation magnetization M_s , which yields AHE hysteresis loops for both sweep directions under a bias current of $500\ \mu\text{A}$, well below the switching current of similar samples.⁶ Figure 2(c) shows representative raw and processed Hall resistance data at $T = 100$ K. Because the Pt layer is metallic, in addition to the AHE, the Hall signal contains a (linear) background arising from the ordinary Hall effect (OHE). To isolate the anomalous Hall contribution, we remove the OHE signal by fitting a linear function to the low-field region around zero field where anomalous Hall contributions are negligible to first order. We then extract the coercive fields $H_{C,+}$ and $H_{C,-}$ from the extrema of the numerical derivative of the Hall resistance with respect to field, and we define the mean coercive field $|H_C|$ as the half-width

of the major hysteresis loop. Finally, the AHE resistance, $\Delta R_{\text{AHE}} = \frac{1}{2}(R_{+H \rightarrow -H} - R_{-H \rightarrow +H})$, is defined as the half-difference between the two resistance plateaus. We repeat this analysis for the entire series of temperatures. In this manuscript, the results are representative of a typical device. In [supplementary material A](#), we show similar results obtained in another device on the same chip to showcase this. Furthermore, data are shown for a device fabricated on a 23.7 nm-thick TmIG film that exhibits no compensation-physics-related behavior.

A key result of this study is the observation of two distinct polarity reversals in the temperature dependence of ΔR_{AHE} . In Fig. 2(d), we plot the transversal resistance R_{xy} as a function of the applied magnetic field $\mu_0 H$ for three representative temperatures, highlighting the observed polarity reversals after subtraction of the linear OHE background. The corresponding temperature-dependent $|H_C|$ is plotted in Fig. 3(a). The error bars represent the uncertainty in determining $|H_C|$ due to the finite magnetic field step size used in the hysteresis measurements and are defined as twice the field increment step.

Three distinct temperature regimes are identified in the evolution of the coercivity [see fits in Fig. 3(a)]. At room temperature, the coercive field is small ($|H_C| \approx 5$ mT) and increases exponentially upon cooling. Fitting this regime with the exponential phenomenological form of Eq. (1) yields a characteristic temperature scale of $T_0 = 70.8 \pm 26.5$ K. Such behavior is commonly associated with thermally activated magnetization reversal processes governed by the interplay between domain-wall motion and pinning at material imperfections:^{29,30}

$$|H_C| = A \exp(-T/T_0) + C. \quad (1)$$

As the temperature approaches the first polarity-reversal temperature $T_{\text{PR},1} \approx 124$ K, the coercive field increases smoothly to ~ 58 mT. At this temperature, the ΔR_{AHE} -signal changes polarity for the first

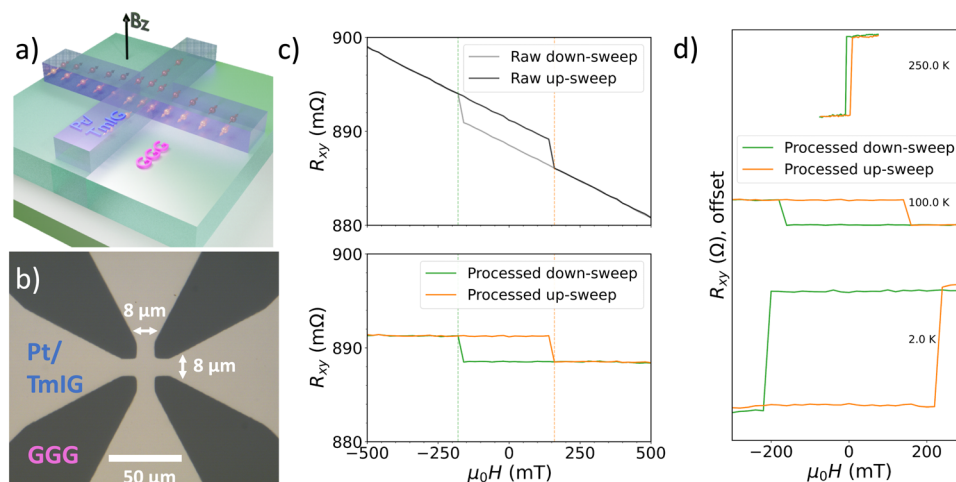


FIG. 2. (a) Schematic stack of the sample structure. The 3-nm thin-film Pt is sputtered on 6 nm of TmIG, grown using on-axis sputtering on GGG. (b) Microscope image of the Hall bar used for the measurements, with channels of width $8\ \mu\text{m}$. Light gray is Pt on top of TmIG; dark gray is the underlying GGG layer. (c) Representative anomalous Hall effect (AHE) measurement at 100 K. Both the raw data (gray) and the processed data after subtraction of the ordinary Hall effect contribution, as described in the text, are shown. The data are split into down-sweep (from maximum field to minimum field) and up-sweep. (d) AHE measurements at three different temperatures $T = 2.0, 100, 250$ K, offset from each other. The linear OHE component has been removed. The sweep direction from positive (negative) field to negative (positive) field is indicated as down (up)-sweep.

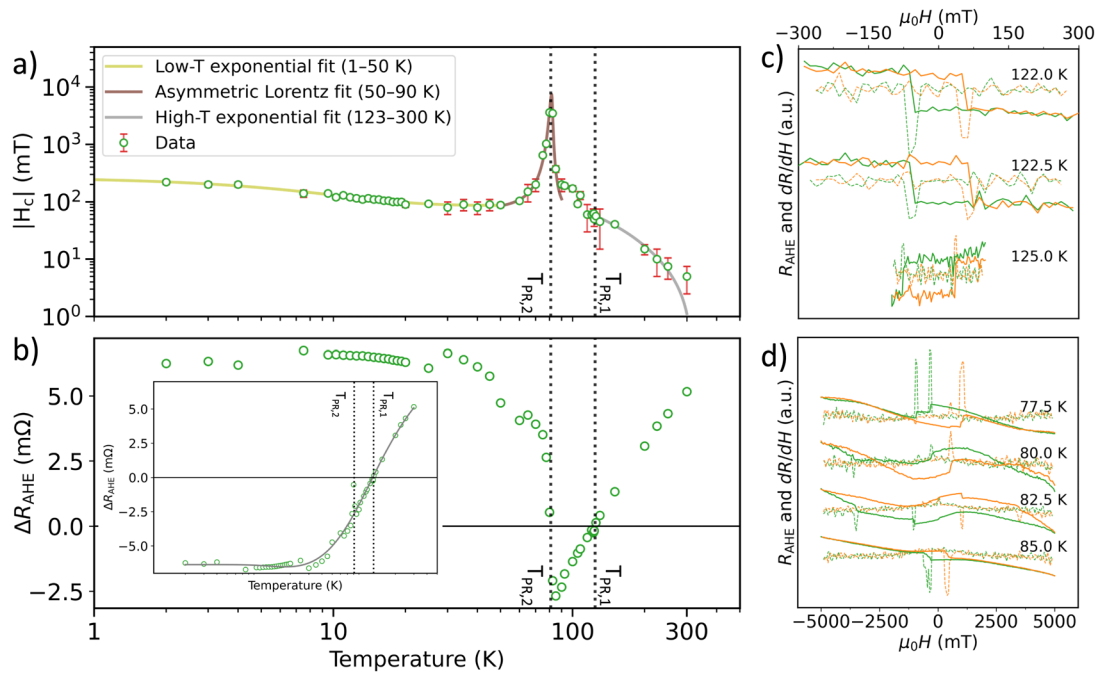


FIG. 3. (a) Mean coercive field $|H_C|$ as a function of temperature extracted from the anomalous Hall hysteresis loops. Error bars reflect the uncertainty arising from the finite magnetic field step size. A pronounced divergence of $|H_C|$ is observed in the vicinity of $T_{PR,2}$, whereas no such divergence occurs near $T_{PR,1}$. The data are fitted in three temperature intervals (see text) using exponential or asymmetric Lorentzian functions to guide the eye. (b) Half-difference of the anomalous Hall resistance plateaus, ΔR_{AHE} , as a function of temperature for a Pt/TmG/GGG heterostructure. This quantity serves as a broad proxy for the net magnetization sensed by the proximitized Pt layer; its sign can change through a reversal of the magnetic state or through a change in the dominant Hall-conversion mechanism. Two zero crossings are observed at $T_{PR,2} \approx 81$ K and $T_{PR,1} \approx 124$ K (vertical dotted lines), where ΔR_{AHE} changes polarity, indicating two distinct polarity reversals of the anomalous Hall signal. *Inset:* ΔR_{AHE} data for $T < T_{PR,2}$ plotted with inverted sign, together with a guide-to-the-eye fit using a double Brillouin function [cf. Eq. (B1) in [supplementary material B](#)] with fixed $J_1 = \frac{5}{2}$ and $J_2 = 6$, corresponding to the total angular momenta of the Fe and Tm sublattices, respectively. Vertical axis: ΔR_{AHE} ; horizontal axis: temperature, with the same scale as plots [(a) and (b)]. [(c) and (d)] Anomalous Hall effect data of a field sweep going down (green) and going up (orange), with corresponding numerical derivative data (slightly transparent), shifted with respect to each other and scaled for visibility: (c) around $T_{PR,1}$ and (d) around $T_{PR,2}$, showcasing multiple transitions.

time, as indicated by the zero crossing in [Fig. 3\(b\)](#), with no pronounced anomaly (in a ± 1 K range) observed in $|H_C|$. Upon further cooling, the coercivity increases sharply and reaches a maximum value of ~ 3.5 T in the temperature interval between $T_{PR,1}$ and the second polarity-reversal temperature $T_{PR,2} \approx 81$ K. This pronounced enhancement reflects the large magnetic field required to reverse the magnetization when the net ferrimagnetic moment becomes small. To quantitatively capture the asymmetric shape of this coercivity peak, we fit the data in this temperature interval using a phenomenological asymmetric Lorentzian function of [Eq. \(2\)](#),

$$|H_C(T)| = \frac{A}{1 + \left(\frac{T - T_c}{w_{L,R}}\right)^2} + C, \quad (2)$$

where A denotes the peak amplitude, T_c the temperature at which $|H_C|$ is maximal, and w_L and w_R describe the widths of the low- and high-temperature flanks, respectively. The extracted widths differ significantly ($w_L = 3.0 \pm 0.7$ K and $w_R = 0.84 \pm 0.08$ K), indicating a much sharper decrease of $|H_C|$ above $T_{PR,2}$ than below. This asymmetry reflects the distinct thermal evolution of the rare-earth and iron sublattice magnetizations,¹¹ and it has been demonstrated

in several ferrimagnetic systems, although the relative asymmetry can be inverted depending on the material system and heterostructure design.^{1,21,23,31} We show the full fit results and uncertainties in [supplementary material C](#). The fit furthermore yields $T_c = 82.3 \pm 0.4$ K in excellent agreement with $T_{PR,2}$. Moreover, as illustrated in the inset of [Fig. 3\(b\)](#), numerically inverting the ΔR_{AHE} data for $T < T_{PR,2}$ renders the transition smooth rather than abrupt. This behavior is consistent with a reversal of the magnetization of one of the sublattices.^{17,23,32} Given the strong antiferromagnetic exchange coupling between the Tm and Fe sublattices across the full temperature range, a reversal of either sublattice's magnetization naturally leads to the observed polarity change in ΔR_{AHE} , and the smooth transition upon sign change. A two-component Brillouin-function fit [Eq. (B1), as a guide to the eye] further illustrates the smooth character of the response. Furthermore, we compare the behavior of the AHE curves around $T_{PR,1}$ and $T_{PR,2}$, respectively, in [Figs. 3\(c\) and 3\(d\)](#). While there is clear, uniquely defined switching around $T_{PR,1}$, multiple transitions are present at $T_{PR,2}$. This indicates the presence of multiple sublattice configurations and thus multiple switching events, either due to lattice reorientation or the presence of a canted phase.^{33,34}

For temperatures below $T_{PR,2}$ (the lowest-temperature range), the coercive field initially decreases and reaches a nearly constant baseline value of ~ 87 mT between 20 and 50 K. Upon further cooling below ~ 20 K, the coercive field increases exponentially with decreasing temperature, following Eq. (1), with a characteristic temperature scale of $T_0 = 7.2 \pm 1.1$ K, and reaches a maximum value of ~ 220 mT at 2 K.

III. DISCUSSION

The observation of two distinct polarity-reversal temperatures in a uniform ultra-thin Pt/TmIG/(111)GGG heterostructure has not been previously reported or explained in the literature, particularly in heterostructures with relatively small epitaxial strain. Table I summarizes TmIG-based heterostructures, indicating the temperatures of polarity reversal and the presence or absence of a divergence of $|H_C|$. The magnetic properties of TmIG are highly strain-sensitive. Films grown on Nd:GGG and SGGG substrates have exhibited true magnetic compensation points, as demonstrated in Refs. 21 and 35. In contrast, no such compensation point has been observed for TmIG on GGG substrates to date. Although high-temperature annealing can induce a compensation-like polarity reversal without a reversal of the Fe sublattice magnetization, a true magnetic compensation temperature remains elusive for this specific material.¹¹ A divergence in $|H_C|$ is often used as a proxy for identifying a magnetic compensation point.^{1,20,35} However, this criterion is not definitive: Soares *et al.* and Wang *et al.*'s data showed that $|H_C|$ can diverge even when a residual net magnetization remains, indicating only a compensation-like transition, even when $\Delta R_{AHE} = 0$.^{11,12} Similarly, Ding *et al.*²⁵ reported that in the absence of a divergence of $|H_C|$, no true magnetic compensation occurs. The temperature evolution of $|H_C|$ and ΔR_{AHE} observed in our devices more closely resembles that reported for W(5 nm)/TbIG(6 nm)/Nd:GGG heterostructures²¹ than that of Pt(5 nm)/TmIG(20 nm)/GGG studied by Ding *et al.*²⁵ This highlights that the magnetic properties of TmIG depend sensitively on film thickness, and the ultra-thin films investigated experience significantly lower epitaxial strain than those studied previously.^{11,25,36}

Two physically distinct mechanisms are responsible for the polarity reversals. The higher-temperature transition at $T_{PR,1}$, in the absence of a divergence of $|H_C|$, can be understood in terms of a crossover in the dominant interfacial contribution to the AHE.^{12,21,25} In ferrimagnet/heavy-metal heterostructures, the AHE can arise from multiple mechanisms whose relative strengths are temperature dependent, including the combination of the spin Hall effect (SHE) and the inverse spin Hall effect (ISHE), and the magnetic proximity effect (MPE), whose presence in Pt-capped REIGs has been independently confirmed by polarized neutron reflectometry²¹ and by an intermediate Cu layer.²⁵ The former effect allows conversion from spin current to corresponding charge current, while the MPE arises from the induction of magnetic moments in Pt atoms through exchange coupling with the Fe^{3+} (3d) or Tm^{3+} (4f) orbitals at the interface.

Phenomenologically, this means that the measured Hall amplitude can be written as

$$\Delta R_{xy}(T) = m_z(T)[C_{SH}(T) + C_{MPE}(T)], \quad (3)$$

where $m_z(T)$ describes the out-of-plane magnetic state of the TmIG layer, while C_{SH} and C_{MPE} denote the spin-Hall-related and magnetic-proximity-induced Hall coefficients of the transport, respectively. Here, C_{SH} originates from SHE-generated spin accumulation in Pt, spin-current reflection or absorption at the Pt/TmIG interface, and inverse-SHE conversion into a transverse voltage. Its magnitude is, therefore, governed by the Pt spin Hall angle, spin-diffusion length, resistivity, and spin-mixing conductance.³⁹

The magnetic-proximity term C_{MPE} , by contrast, scales with the induced Pt magnetic moment and the anomalous Hall coefficient of the proximitized Pt layer. Importantly, while the proximity-induced Pt moment can scale linearly with the net magnetization of the adjoining magnetic layer, it does not necessarily do so. Inyang *et al.* directly compared the temperature-dependent interfacial magnetization of a ferromagnet with the induced Pt moment and found that the latter vanished while a finite interfacial magnetization remained.⁴⁰ This behavior indicates that a threshold interfacial magnetization, or equivalently a threshold exchange field, may be required to induce a measurable Pt moment. Therefore, C_{MPE} may exhibit a threshold-like and strongly non-linear temperature dependence, rather than following the net ferrimagnetic magnetization continuously.

Consequently, in a multisublattice ferrimagnet like TmIG, the relevant interfacial exchange field does not need to follow the net magnetization, since the latter can become small through cancellation of individually finite sublattice moments. Our Hall measurements do not directly determine the local Fe moment at the Pt/TmIG interface, the induced Pt moment, or the magnitude of the effective interfacial exchange coupling. Thus, these measurements do not establish by themselves whether the interfacial exchange field remains above the threshold for inducing a detectable Pt moment. However, such threshold-like behavior provides a physical basis for $C_{MPE}(T)$ having a substantially different temperature dependence from $C_{SH}(T)$.²¹ The spin-Hall-related contribution is governed by the temperature dependences of the Pt resistivity, spin Hall angle, spin-diffusion length, and interfacial spin-mixing conductance,³⁹ whereas the MPE-related contribution depends on whether the local exchange field is sufficient to induce a magnetic moment in Pt. Because the spin-Hall-related and MPE-related Hall contributions can have opposite signs, their distinct temperature dependences may lead to a zero crossing when

$$C_{SH}(T) + C_{MPE}(T) = 0. \quad (4)$$

In particular, C_{SH} (from both SHE and ISHE) can be modified as magnetic proximity develops in Pt.⁴¹ Whereas the MPE-induced AHE becomes more pronounced upon cooling as the interfacial exchange-induced Pt moment increases^{21,42} (C_{MPE} typically increases at low temperatures as thermal fluctuations are suppressed, enhancing the exchange field perceived by the Pt electrons), C_{SH} typically decreases in strength at lower temperatures due to the increased presence of MPE.⁴¹

This interpretation is supported further by the results of Ding *et al.*,²⁵ who investigated closely related TmIG/Pt heterostructures. They observed a Hall-sign reversal near 80 K in TmIG/Pt that was absent after inserting a Cu spacer. Their analysis attributed the

TABLE I. Reported or extracted (visually estimated) compensation and compensation-like temperatures in TmIG thin films capped with heavy metals (HM) on differing substrates. Measurement methods include anomalous Hall effect (AHE) and magnetization M (SQUID magnetometry¹¹ and vibrating sample magnetometry²⁵). Only the present work reports two polarity reversals within a single uniform Pt/TmIG film. † Estimated from unstrained lattice constant values.

Material stack (HM/REIG/sub.) thickness (nm)	Temperature of the polarity reversal (K)		Strain (%)	Measurement method	References
	With H_C div.	W/o H_C div.			
Pt (3)/TmIG (6)/GGG	81	121	0.42	AHE	This study
.../TmIG/GGG	46	...	1.31	M	11 and 37
W (5)/TmIG (6)/Nd:GGG	75	45	1.44 [†]	AHE	21 and 38
Pt (5)/TmIG (6)/Nd:GGG	82	...	1.44 [†]	AHE	
Pt (5)/TmIG (20)/GGG	...	80	0.48 [†]	AHE, M	25
Pt (5)/Cu (2)/TmIG (20)/GGG	...	...	0.48 [†]	AHE	
Pt(10)/BiGa:TmIG (1410)/GGG	135	60	1.31	AHE	36
Pt (6)/TmIG (6)/2-graphene/SGGG	150	15	−2	AHE	35
Pt (6)/TmIG (6)/SGGG	...	50	−1.25	AHE	

reversal to these two oppositely signed contributions: C_{SH} dominates at higher temperature and decreases upon cooling, while C_{MPE} becomes more important at lower temperature.

Importantly, this crossover changes the sign of the Hall readout but does not require a reversal or vanishing of m_z . This explains why the polarity reversal at $T_{PR,1}$ is not accompanied by a divergence of H_C . The coercive field remains governed by the magnetic anisotropy, pinning, and domain-wall reversal of the TmIG layer, which evolve smoothly through this temperature.

Summarizing, depending on temperature, either the SHE or MPE contribution dominates the measured interfacially driven Hall response. This scenario is consistent with our observations and supported by the vanishing or zero-crossing of ΔR_{AHE} , with a remaining net magnetization, observed at $T_{PR,1}$. The higher-temperature polarity reversal at $T_{PR,1}$ should, therefore, not be interpreted as a reversal of the net ferrimagnetic moment. Instead, it reflects a change in the sign of the interfacial Hall readout in Pt.

In contrast, the polarity reversal at $T_{PR,2}$ likely reflects a change in the dominant magnetic sublattice that contributes to the total magnetization of TmIG, rather than a change in the transport mechanism within the Pt layer. The Fe and Tm sublattice magnetizations exhibit distinct temperature dependences and intersect at $T_{PR,2}$, where their combined contributions to the total magnetization are minimized, resulting in a negligible or lowest net magnetization. Strain and finite-size effects in the present ultra-thin films are expected to enhance these differences in sublattice magnetization and thereby sharpen the compensation(-like) behavior. As shown in the inset of Fig. 3(b), the apparent discontinuity in ΔR_{AHE} becomes nearly continuous when the signal is numerically inverted for $T < T_{PR,2}$. This symmetry operation does not alter the physical content of the data but highlights the continuity of the underlying magnetization evolution. This behavior indicates that at $T_{PR,2}$, there is a full magnetization reversal of the entire sublattice over a range of ± 3 K,

which is our data resolution. Due to the antiferromagnetic exchange between the Fe and Tm sublattices, a reversal in the magnetization of one sublattice enforces an opposite change in the other. As the magnetization of the Tm sublattice grows with decreasing temperature, we expect that the resulting R_{AHE} signal follows the magnetization of the Tm-ions for $T \ll T_{PR,2}$.

Near $T_{PR,2}$, an intermediate regime can emerge in which multiple configurations are favored since the total magnetization is, to first order, the linear sum of the antiferromagnetically coupled sublattice magnetizations.³⁴ The transition at $T_{PR,2}$ is accompanied by signatures of multiple transitions, as illustrated in Fig. 3(b). In the Pt/TmIG heterostructure, there can be regions with slightly differing compensation(-like) temperatures because of spatial inhomogeneities in strain (from film roughness or substrate defects) or composition (from O-vacancies) that produce local variations in the sublattice exchange coupling. The effect is a (small) spatial redistribution of the compensation temperature. Thus, while a region could have compensatory behavior at $T_{PR,2}$, the interaction with neighboring magnetic regions with a displaced compensation temperature can lead to a net remaining magnetization.¹⁵ However, in other rare-earth iron garnet systems such as GdIG and HoIG, studies have shown that these features originate instead from the interaction between domains associated with different sublattices and their distinct switching dynamics.^{34,46} The multi-switching behavior then arises from the coexistence of multiple sublattice configurations that stabilize near the compensation-like temperature. Furthermore, multi-domain signatures and corresponding multiple switching events can be induced by the fabrication of the Pt/TmIG heterostructure. Constrictions due to the edge of the Hall cross can induce the formation of domains.⁴⁷ In our samples, the TmIG is uniform, as shown in Fig. 1, and thus the second multi-domain explanation is more consistent. These multiple switching events are absent for the transition at $T_{PR,1}$, where there is a unique transition.

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At present, a comprehensive description of the magnetic configuration for temperatures below and around $T_{\text{PR},2}$ remains elusive. Two competing scenarios may account for the observed behavior: the occurrence of a true magnetic compensation point or the presence of a compensation-like temperature. At a true magnetic compensation point, the Fe sublattice magnetization is expected to reverse and become antiparallel to the applied magnetic field, whereas at a compensation-like temperature, the Fe magnetization remains parallel to the field. Given that the present TmIG/GGG heterostructure employs the same GGG substrate as used by Soares *et al.*,¹¹ a compensation-like scenario—where the Fe magnetization remains parallel to the field—appears plausible at first glance. However, this interpretation fails to account for the observed polarity reversal of the anomalous Hall effect in the Pt layer. Since the Pt-AHE is widely attributed to magnetic proximity coupling between Fe 3d and Pt 5d orbitals,²⁵ a compensation scenario would require an additional proximity-induced contribution from the Tm 4f electrons to explain the polarity reversal.⁴⁸ Consequently, for $T < T_{\text{PR},2}$, the signal would follow the Pt–Tm coupling compared to the Pt–Fe coupling, leading to non-monotonous behavior in the inset of Fig. 3(b). Conversely, if one assumes that the Pt magnetic proximity effect is dominated by interaction with Fe 3d electrons, the observed AHE polarity change implies a reversal of the Fe sublattice magnetization, consistent with the realization of a true magnetic compensation point in the Pt/TmIG/GGG system. The lattice strain in our films is approximately a third of that reported in earlier studies on Nd:GGG substrates²¹ and the TmIG thickness investigated here is nearly five times smaller than that in Ref. 11. The ultrathin film structure may facilitate the emergence of a true compensation point, in line with recent observations by Yu *et al.*, who demonstrated thickness-dependent shifts of the compensation temperature in TmIG films grown on SGGG substrates.³⁵ We, therefore, suggest that a similar thickness-driven effect may occur even on GGG substrates with modest strain. While the transition at $T_{\text{PR},2}$ corresponds to a divergence in $|H_C|$, it is not certain this is a true compensation temperature. Due to the similarities in materials, we determine from the magnetometry results of Soares *et al.*¹¹ via an order-of-magnitude estimate what the remaining magnetization of our Pt/TmIG sample at $T_{\text{PR},2}$ is. This is a simplified picture, and while there is no causal relationship between the AHE and magnetization, the existence of $T_{\text{PR},2}$ indicates a correlation nonetheless. Here, we use the inverse scaling of the coercive field with magnetization near a compensation point: $H_C \sim \frac{1}{M}$. Furthermore, we assume that ΔR_{AHE} relates linearly to the magnetization M .⁴⁹ Relating their results to ours ($M_{300\text{K}} = 2 \mu_B/\text{f.u.}$, $M_{T_{\text{comp}}} \approx 0.5 \mu_B/\text{f.u.}$), we obtain a remaining magnetization at $T_{\text{PR},2}$ of $M_{T_{\text{comp},2}} \approx 6 \times 10^{-6} \mu_B/\text{f.u.}$, which is negligibly low and indicates that $T_{\text{PR},2}$ is a true compensation temperature. This estimate relies on the assumption that $H_C \sim 1/M$ scales identically between our 6 nm strained films and the 30 nm films of Ref. 11. Deviations from this scaling due to inhomogeneous strain could alter this estimate by an order of magnitude, yet do not change the general conclusion.

Based on the pronounced $|H_C|$ divergence (reaching 3.5 T), the sign inversion of ΔR_{AHE} producing smooth behavior after numerical flipping, the small remnant magnetization when comparing to literature values, and the multi-domain switching behavior [Figs. 3(c) and 3(d)], we interpret $T_{\text{PR},2}$ as a temperature where the Fe and

Tm sublattice magnetizations cancel. In other words, $T_{\text{PR},2}$ exhibits all the hallmarks of a magnetization compensation point. However, because true compensation in TmIG has not been observed before and confirming the sublattice magnetizations requires element-specific probes, the exact nature of the transition remains indefinite, and we conservatively refer to this point as “compensation-like” to acknowledge the ambiguity in its precise magnetic nature. Ultimately, a definitive distinction requires element-specific measurements of the sublattice magnetizations, for instance, by X-ray magnetic circular dichroism (XMCD). Until such measurements are performed, the exact magnetic configuration below $T_{\text{PR},2}$ remains unresolved.

IV. CONCLUSION

In conclusion, we report the temperature-dependent anomalous Hall response of Pt (3 nm)/TmIG (6 nm)/GGG(111) heterostructures and demonstrate the presence of two distinct polarity reversals. The higher-temperature polarity reversal at $T_{\text{PR},1} \approx 124$ K is not accompanied by a divergence of the coercive field $|H_C|$ or other signatures of vanishing net magnetization. This behavior suggests that $T_{\text{PR},1}$ arises from interfacial transport effects, such as the temperature-dependent competition between spin Hall magnetoresistance and the magnetic proximity effect, rather than from a competition between the magnetization of the ferrimagnetic sublattices. In contrast, the lower-temperature transition at $T_{\text{PR},2} \approx 81$ K is accompanied by a pronounced divergence of the coercive field and signatures of multi-domain switching. This is consistent with established ferrimagnetic compensation physics and highlights the strong influence of strain and finite-size effects on the balance of sublattice magnetizations in ultrathin TmIG films. However, because of the lack of element-specific magnetic measurements, we cannot definitively confirm whether this represents a true compensation temperature or a near-cancellation of sublattice magnetizations. Our results thus demonstrate that multiple polarity reversals observed in Hall-based measurements do not necessarily correspond to multiple true magnetization compensation points. Instead, they underscore the importance of carefully disentangling bulk ferrimagnetic compensation from interface- and band-structure-driven effects, particularly in ultrathin ferrimagnetic insulator/heavy-metal heterostructures. They highlight the rich interplay between sublattice magnetism, finite-size effects, epitaxial strain, and interfacial coupling in rare-earth iron garnets. By clarifying the distinct physical origins of these two polarity-reversal temperatures, this work provides a framework for interpreting Hall-based measurements in Pt/TmIG heterostructures as a versatile platform for exploring compensation-driven phenomena and advances the understanding of compensation physics in nanoscale systems. These insights open avenues for spintronic and magnonic applications leveraging antiferromagnetic coupling, temperature-tunable magnetization and sharp coercive transitions, and temperature-dependent transport signatures.

SUPPLEMENTARY MATERIAL

The results on related samples, the details of the non-linear behavior of the OHE at fields larger than 1.5 T (at 130 K), and

the temperature dependence of the OHE on a Pt/TmIG/GGG sample compared to a Pt/GGG sample are shown in the [supplementary material](#). Furthermore, the results of the fitting of different regions of $|H_c|$ and of the Brillouin fits performed in the main body are shown. Finally, SQUID magnetometry data as a function of temperature is presented.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Ivo P. C. Cools: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Project administration (supporting); Resources (supporting); Software (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Jinyu Xu:** Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Resources (supporting); Validation (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Lei Yan:** Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Resources (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Divya P. Dubey:** Investigation (supporting); Validation (supporting); Visualization (supporting). **Saroj P. Dash:** Conceptualization (supporting); Funding acquisition (supporting); Project administration (supporting); Resources (supporting); Supervision (lead); Writing – original draft (supporting); Writing – review & editing (supporting). **Naoto Yamashita:** Conceptualization (supporting); Formal analysis (supporting); Funding acquisition (lead); Methodology (supporting); Project administration (lead); Resources (lead); Supervision (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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