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## Impact of ultrathin garnet spacers on the magnetotransport in Tb<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub>/Pt bilayers

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**Abstract:** We studied the interfacial spin Hall magnetotransport in the Tb<sub>3</sub>Fe<sub>3</sub>O<sub>12</sub> (TbIG)/Pt system, across a non-magnetic (Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> (YAG) and Gd<sub>3</sub>Ga<sub>5</sub>O<sub>12</sub> (GGG)) spacer with the garnet structures. TbIG (30 nm)/spacer samples were grown on single-crystal (GGG) (111) substrates by pulsed laser deposition, before 5 nm of Pt was sputtered on the samples and patterned into Hall bars. The YAG spacer thickness ( $t_{YAG}$ ) dependences of anomalous Hall effect resistance ( $R_{AHE}$ ) indicated no significant change on the magnetization compensation temperature of TbIG. Hysteretic  $R_{AHE}$  loops were observed at low magnetic fields, but with reducing magnitude as  $t_{YAG}$  thickness increases. A cross-over of the  $R_{AHE}$  sign was observed at temperatures below the compensation temperature, which decreased sharply from 135 K to 34 K as  $t_{YAG}$  increased from 0 to 1 nm. We attributed this to the strong dependence of the magnetic proximity effect towards the YAG insertion in TbIG/Pt interface. Replacement of YAG spacer with GGG showed significant impact on the  $R_{AHE}$  behaviour. No obvious  $R_{AHE}$ -H loops were observed in the TbIG/Pt sample inserted with 0.5 nm GGG spacer, which could be linked to the strong magnetic

contribution of the Gd ions. This work highlights the tunability of interfacial transport behaviour in iron garnet/heavy metal systems through ultrathin spacers, providing guidance for the interfacial design of spintronic devices. Ferrimagnetic insulator (FMI)/heavy metal (HM) devices play an important role in studying spin Hall magnetotransport behavior,<sup>1-4</sup> as the strong spin-orbit-torque (SOT) of HM (like Pt) enables spin current within the layer to be reflected or absorbed by the FMI/HM interface and convert back into an charge current in the HM layer, achieving information transmission.<sup>5,6</sup> This spin transport is closely related to FMI/HM interface, because two important interface effects, spin Hall effect (SHE) and magnetic proximity effect (MPE),<sup>7</sup> would affect the direction and intensity of spin current.

The peculiar interface effects have attracted attention of researchers, focusing on spin current phenomena like spin pumping,<sup>8,9</sup>, spin Seebeck effect,<sup>10,11</sup> spin Hall effect (SHE), and inverse spin Hall effect (ISHE).<sup>7,12</sup> They also explored the complex interface by X-ray magnetic circular dichroism (XMCD) or polarized neutron reflectometry (PNR) measurements, trying to distinguish the physical origin of such effects. To achieve regulation of these interface effects, interface engineering is an effective means that helps spintronics devices to achieve controllable information storage.<sup>13</sup>

Due to the strong spin-orbit coupling, Pt has been widely used in such studies of FMI/ HM systems.<sup>14,15</sup> The most commonly-studied system is Y<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub> (YIG)/Pt, in which the anomalous Hall effect (AHE) phenomenon can be easily observed.<sup>6,16,17</sup> In a related rare earth ion garnet (REIG) structure, Tb<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub> (TbIG)/Pt has demonstrated two sign crossover in AHE resistance ( $R_{AHE}$ ) with decreasing temperatures.<sup>18,19</sup> The first sign reversal at higher temperature coincides with the magnetization compensation point ( $T_{comp}$ ) of TbIG, at which the saturation magnetization temporarily vanishes.<sup>18,20,21</sup> The effect is attributed to antiferromagnetically-coupled Tb and Fe ions in the material, which exhibit different temperature dependences of magnetization. Similar  $T_{comp}$  phenomenon was also observed in similar systems such as DyIG/Pt<sup>22</sup> and GdIG/Pt.<sup>23,24</sup>

The second sign reversal of  $R_{AHE}$  (defined as  $T_I$ ) is considered to arise from the competition between MPE-induced in the Pt layer and spin Hall magnetotransport at

REIG/Pt interface.<sup>19,21,25,26</sup> With such a linkage with MPE, this low-temperature  $R_{AHE}$  sign reversal can possibly be regulated through modifications of the FMI/HM interface, for example by dusting with a foreign material.<sup>27</sup>

For REIG/Pt heterostructures with two  $R_{AHE}$  sign cross-over behaviour, previous studies have focused on the regulation  $T_{comp}$ ;<sup>28,29</sup> relatively little attention was paid to the modulation of  $T_I$ . Some reports attempted to insert non-magnetic barriers (such as Cu and Si) at the REIG/Pt interface to modify MPE or SHE,<sup>2,30</sup> but there was no systematic exploration of  $T_I$  regulation. Moreover, the long spin diffusion length of Cu could interfere with the normal spin diffusion of Pt. Besides, metal spacers are polycrystalline in nature, and has crystal structure dramatically different from that of REIG, resulting in increased uncertainty in interface regulation. Selection of appropriate materials that ensures uniform interface quality and controlling of  $T_I$  is worth exploring.

In this work, we study the impact of lattice-matching, non-magnetic spacer on the  $R_{AHE}$  behaviour of TbIG/Pt. Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> (YAG) is a non-magnetic material with garnet structure and a lattice constant (12.003 Å)<sup>31</sup> close to that of TbIG (12.436 Å).<sup>32</sup> Their similar garnet structure implies the possibility for coherent YAG growth on TbIG (particularly for ultrathin YAG layers in which stress relaxation is mild),<sup>31,33</sup> and therefore YAG was selected here as the spacer material. Meanwhile, another lattice-matching paramagnetic spacer of Gd<sub>3</sub>Ga<sub>5</sub>O<sub>12</sub> (GGG, lattice constant = 12.383 Å)<sup>34</sup> was also used for comparison. The lattice mismatch of TbIG/YAG is 3.48 %, which is higher than that of TbIG/GGG (0.43 %). Besides, previous works have confirmed that paramagnetic GGG can achieve spin transport like other ferromagnetic insulators albeit with weaker signals.<sup>35,36</sup> The difference of magnetism between YAG and GGG could provide insights in the effect of different spacer layers on TbIG/Pt spin transport.

TbIG/YAG/Pt and TbIG/GGG/Pt samples were grown on GGG (111) substrates. The temperature (*T*) dependence of  $R_{AHE}$  in the samples for various spacer thicknesses was

measured.  $T_{comp}$  was identified by a divergence of coercivity ( $H_c$ ) in  $R_{AHE}$ -T plot, which coincides with the cross-over of the  $R_{AHE}$  sign.<sup>19</sup> Within the YAG thickness ( $t_{YAG}$ ) studied (1 nm or less), our results indicate no significant impact of the spacer on the measured  $T_{comp}$ , although the  $R_{AHE}$  amplitude decreases gradually. Below  $T_{comp}$ , a second  $R_{AHE}$  sign reversal is observed and is attributed to the competition between MPE-induced AHE and spin Hall (SH)-induced AHE. The ultrathin spacer strongly modulates the MPE behaviour, and the presence of ultrathin spacers leads to a rapid decrease of this  $R_{AHE}$  sign reversal temperature. Apart from YAG, paramagnetic spacer of GGG also strongly inhibits the spin transport at the interface at even extremely thin cases (0.5 nm or less). Possible reasons for the observed differences are discussed.

TbIG (30 nm) with ultrathin YAG overlayers (thicknesses  $t_{\text{YAG}}$  between 0 to 2 nm) were deposited on GGG (111) single crystal substrates by pulsed laser deposition, using a KrF laser (wavelength  $\lambda = 248$  nm), in an oxygen ambient of 100 mTorr and substrate temperature of 710°C. The substrates were pre-cleaned and pre-annealed in an oxygen environment of 1000°C for 6 hours, yielding a reconstructed surface that promote the smooth growth of films.<sup>18</sup> The deposited films were post-annealed for 10 mins at the same temperature *in situ* with 10 Torr oxygen pressure. Afterwards, 5 nm of Pt was deposited on the samples by d.c. magnetron sputtering (base pressure better than  $1 \times 10^{-6}$  Torr) and patterned into Hall bars (channel size 100  $\mu$ m × 50  $\mu$ m) by photolithography and Ar ion etching. Au (50 nm)/Ti (5 nm) electrodes were deposited on the Hall bar pattern by e-beam evaporation (pressure less than  $1 \times 10^{-6}$  Torr). The schematic of the completed device is shown in Fig. 1(a).

X-ray diffraction (XRD) measurements were conducted using a high-resolution X-ray diffractometer (Rigaku SmartLab) with Cu  $K_{\alpha}$  ( $\lambda = 1.541$  Å) radiation. Atomic force microscopy (AFM, Asylum 3D infinity) was used to characterize the surface morphology of the thin films. High-resolution transmission electron microscopy (HR-TEM) images

were captured by spherical aberration-corrected transmission electron microscope (AC-TEM) equipped with high-angle annular dark field (HAADF) and the energy-dispersive xray spectroscopy (EDX) to analyse the elements distribution and atomic structure.  $R_{AHE}$ -H loops were measured using a physical property measurement system (PPMS, Quantum Design). Due the out-of-plane tensile stress and positive magnetostriction coefficient of TbIG, TbIG deposited on GGG (111) exhibits perpendicular magnetic anisotropy (PMA).<sup>18,37</sup> The  $R_{AHE}$  was measured from the samples with a magnetic field applied normal to the sample surface.



Fig. 1. (a) Schematic illustration of TbIG/spacer/Pt device for AHE measurements.  $J_e$  represents the electric current and H is external field. (b) AFM image of TbIG(30 nm) (scan area: 2  $\mu$ m × 2  $\mu$ m). (c) XRD diffraction profile of TbIG (30 nm)/YAG bilayers with different YAG thickness. Inset: lattice spacing of TbIG (444) as a function of  $t_{YAG}$ . (d)

Rocking curve of TbIG (30 nm) sample.

Fig. 1 (b) presents the AFM scan of the TbIG (30 nm) sample, indicating an atomically smooth surface with a root-mean-square roughness of 0.21 nm. Fig. 1 (c) shows the  $\theta$ -2 $\theta$  scan of TbIG/YAG bilayer films for different  $t_{YAG}$  values. In addition to the sharp GGG (444) substrate peak, the TbIG film peak can be identified at smaller 2 $\theta$  values. The extracted lattice spacing of  $d_{444} = 0.182$  nm (inset of Fig. 1(c)) shows an out-of-plane expansion compared to the bulk value (0.1795 nm). With increasing  $t_{YAG}$ , the peak position of the bilayer films has shown a minute increase. Meanwhile, the ultrathin YAG layer is not expected to have a significant impact on the epitaxial growth of the underlying TbIG, as confirmed by the similar Laue oscillations and lattice spacing of the TbIG layer. The TbIG (444) peak rocking curve of GGG/TbIG (30 nm) sample (Fig. 1 (d)) shows a full-width at half-maximum (FWHM) of 0.07°, indicating a low mosaic spread. Samples with YAG overlayers essentially show the same FWHM.

A TbIG (30 nm)/YAG (2 nm)/Pt sample was prepared by focused ion beam (FIB) etching for HR-TEM. As shown in Fig. 2(a), the YAG layer can be clearly recognized through the cross-sectional TEM image. EDX mapping shows minute interdiffusion of each interface, which is a common phenomenon in garnet systems.<sup>38,39</sup> HR-TEM (Fig. 2(b) and 2(c)) shows a coherent atomic arrangement of garnet structure along the [11 $\overline{2}$ ] direction for the TbIG/YAG. Although there is a lattice mismatch of 3.48 % between TbIG and YAG, there is no significant lattice distortion observed in the YAG layer and shows good epitaxy in GGG/TbIG/YAG system. Line scan results in Fig. 2(d) indicates that the interdiffusion length is less than 0.5 nm across the TbIG/YAG interface. It provides evidence for comparing magnetotransport difference caused by direct and non-direct contact in TbIG/YAG/Pt systems.



**Fig. 2.** (a) Cross-sectional TEM image of TbIG/YAG (2 nm)/Pt sample. Elements distribution of Gd, Tb, Y and Pt are extracted from the EDX mapping. (b) HR-TEM image of the TbIG/YAG interface, with the magnetified TbIG/YAG interface extracted from the enclosed range displayed in (c). (d) Average signal intensity of Tb and Y as obtained from the line scan in (c).

The two cross-over behaviour in  $R_{AHE}$ -T plots of TbIG/Pt has been reported previously.<sup>18,38</sup>Although the interface coupling can affect the  $R_{AHE}$  signals, it remains to be explored whether changing interface coupling will affect the behaviour of  $T_{comp}$  and  $T_1$ . Here, an ultrathin layer of non-magnetic YAG (from 0-2 nm) is inserted between Pt and TbIG to regulate the interface. Fig. 3 compares the temperature-dependent  $R_{AHE}$  of TbIG/YAG/Pt samples with varying  $t_{YAG}$ . Several  $R_{AHE}$ -H loops present distortions at high field (e.g. Fig. 3(c)). Similar AHE distortion has been observed in TmIG/Pt systems, which may be attributed to the nonlinear background signal contribution at high fields.<sup>21,40</sup> Such distortions should not affect the observation of AHE signal along the field sweeping direction.



**Fig. 3.** Temperature-dependent  $R_{AHE}$ -H loops of TbIG (30 nm)/YAG/Pt, with  $t_{YAG} = 0$  nm (a), 0.5 nm (b), 1 nm (c) and 2 nm (d). Black arrows indicate the scanning directions of the external magnetic field. In all plots, measurements at different temperatures are offset in y-axis direction.

For the control sample ( $t_{YAG} = 0$ , Fig. 3 (a)), as temperature decreases from 300 K, the first  $R_{AHE}$  sign change occurs at around 230 K. A similar  $R_{AHE}$  sign reversal behaviour at around the same temperature is also observed in other samples with YAG spacer (Fig. 3 (b-c)). When the thickness of YAG increases to 2 nm (Fig. 3 (d)), the AHE characteristics of TbIG cannot be discerned across the whole temperature range, indicating that 2 nm of YAG is sufficient to block the coupling between TbIG and Pt.

Apart from the sign reversal mentioned above, the samples also demonstrate a second  $R_{AHE}$  sign reversal at lower temperatures. For the control sample ( $t_{YAG} = 0$ ), this occurs at around 135 K and is much higher than that of samples with YAG spacers (~ 65 K for  $t_{YAG} = 0.5$  nm, below 34 K for  $t_{YAG} = 1$  nm, and completely disappear for  $t_{YAG} = 2$  nm).

To observe the variations in AHE more intuitively, temperature-dependent  $H_c$  and  $R_{AHE}$  at zero magnetic field ( $R_{AHE}^0$ ) are extracted from  $R_{AHE}$ -H loops in Fig. 3 and are presented in Fig. 4, with  $H_c$  extracted from  $R_{AHE} = 0$  at various temperatures. The  $H_c$ -T plots (upper plots of Fig. 4(c)) show the temperature dependence of  $H_c$  for different spacer thickness. Due to the absence of AHE signal at YAG 2 nm, the corresponding  $H_c$  and  $R_{AHE}$  cannot be obtained for comparison.

As shown in Figs. 4(a) and (b), a similar divergence of  $H_c$  takes place around 230 K in all samples, accompanied by a sudden sign reversal of  $R_{AHE}^0$ , indicating the occurs of  $T_{comp}$  which remains stable. Within the measurement error, we conclude that the YAG spacer layer does not change the temperature where  $H_c$  divergence occurs. The  $T_{comp}$  value is slightly lower than that of bulk value (about 246 K), possibly because of the strain state

in the deposited TbIG layer.<sup>41,42</sup>



**Fig. 4.** Temperature dependence of (a)  $H_c$  and (b)  $R_{AHE}^0$  for different YAG thickness, as extracted from  $R_{AHE}$ -H loops in Fig. 3. Inset in (b) shows the enlarged  $R_{AHE}^0 - T$  curve for  $t_{YAG} = 1$  nm sample. (c) Comparison of  $T_{comp}$  and  $T_1$  for samples with different YAG thickness. Notice the difference of y-axes scales for  $T_{comp}$  (black) and  $T_1$  (red) plots.

It is known that antiferromagnetic coupling exists between Fe<sup>3+</sup> and Tb<sup>3+</sup> ions in TbIG, which is the origin of its ferrimagnetic behaviour.<sup>18</sup> The temperature-dependent magnetizations of Tb<sup>3+</sup> (at dodecahedral sites) and Fe<sup>3+</sup> (at tetrahedral and octahedral sites) cancel out at  $T_{comp}$ . Similar behaviour also occurs in other rare-earth iron garnets like GdIG<sup>43</sup> and DyIG<sup>22</sup> and were probed with  $R_{AHE}$ .

Meanwhile, the interfacial exchange coupling of REIG/Pt is dominated by Fe/Pt exchange coupling,<sup>21,22</sup> with the  $R_{AHE}$  sign orientation being determined by the Fe<sup>3+</sup> moments. At above  $T_{comp}$ , Fe<sup>3+</sup> dominates the net magnetization of TbIG. As temperature decreases to  $T_{comp}$ , the moment of Fe<sup>3+</sup> is wholly cancelled out at  $T_{comp}$  by the Tb<sup>3+</sup> moment (which has a more dramatic temperature dependence). Such magnetization can be reflected through the divergent  $H_c$ . When the temperature across  $T_{comp}$  and continues to decrease, the decreased Zeeman energy would reorient the magnetic moments of Fe<sup>3+</sup>,<sup>44</sup> resulting a sudden sign flip of  $R_{AHE}^0$ , reflected in  $R_{AHE}^0$  as a sharp sign reversal from positive to negative values (Fig. 4(b)).

Consistent divergence of  $H_c$  and sudden reversal of  $R_{AHE}^0$  sign behaviours across all TbIG/YAG/Pt samples (Fig. 4) indicate that the YAG spacer does not alter the antiferromagnetic coupling between the Fe<sup>3+</sup> and Tb<sup>3+</sup> in the TbIG layer, and confirms that the interface exchange coupling of TbIG/Pt is independent of  $T_{comp}$ .

At lower temperatures,  $R_{AHE}^0$  sign reversal occurs again at  $T_1$ . The transition temperature  $T_1$  varies drastically from ~135 K for the control sample to ~35 K for  $t_{\text{YAG}} = 1$ nm. As mentioned earlier, the occurrence of  $T_1$  is attributed to the competition between SHE and MPE.<sup>19,21,25,26</sup> For AHE induced by SHE, the spin-mixing conductance  $G_{\uparrow\downarrow} =$  $G_r + iG_i$  plays a great role in generating AHE, which is attributed to the SHE at FMI/HM interface.<sup>3</sup> According to Chen *et al.*,<sup>45</sup> the SHE-induced AHE needs to consider multiple factors, including (temperature dependent) conductivity  $\sigma$ , spin Hall angle  $\theta_{SH}$ , spin diffusion length  $\lambda$  of Pt, and the spin-mixing conductance  $G_{\uparrow\downarrow}$  at TbIG/Pt interface. This leads to the attenuated SHE-induced AHE as temperature goes down. The other contribution of AHE originates from MPE, which leads to magnetic ordering in Pt and resulting in additional AHE signal. The MPE-induced AHE is strongly related to the exchange coupling between interfacial Fe<sup>3+</sup> and Pt. The magnetic moment of Fe<sup>3+</sup> is increased as the temperature goes down, and the Fe/Pt exchange coupling strength also increases accordingly, which leads to the MPE-induced AHE becomes stronger at low temperatures.

Unlike the  $R_{AHE}$  sign change around  $T_{comp}$ , no  $H_c$  divergence is observed and the sign reversal process occurs more gradually with temperature. Reports have demonstrated a more dominant role of SHE on AHE at higher temperatures,<sup>46</sup> and MPE induced AHE dominates at low temperatures.<sup>21,22</sup> Considering the continuously increased MPE and decreased SHE as the temperature goes down, the cross-over of  $R_{AHE}^0$  occurs at  $T_1$  in TbIG/Pt.

It is worth noting that the  $R_{AHE}^0$  amplitude is reduced dramatically as the YAG thickness increases. As shown in Fig. 4 (b), the  $R_{AHE}$  amplitude decays exponentially from 1.5 m $\Omega$  (for  $t_{YAG} = 0$ ) to virtually zero (for  $t_{YAG} = 2$  nm) at 235 K. The magnetic ordering in Pt induced by MPE occurs in the region very close to the TbIG/Pt interface, and SHE also depends on the spin accumulation at the TbIG/Pt interface. After the insertion of non-magnetic YAG, the coupling of Fe/Pt will be severely weakened, and the magnetic ordering within Pt is highly dependent on direct contact with TbIG, which means that the competitive balance between MPE and SHE would be disrupted, and the induced AHE signals would be weakened, displayed as a decreased  $R_{AHE}^0$  amplitude.

The slope of  $R_{AHE}^0$  plots also provide some interesting insight on the temperature dependence of MPE and SHE. As shown in Fig. 4 (b), the  $R_{AHE}^0$  plot of control sample  $(t_{\text{YAG}} = 0 \text{ nm})$  exhibits a constant fixed value between  $T_{comp}$  and  $T_1$ , indicating the competitive balance between MPE and SHE follows a linear variation. Based on the

competitive relationship and the fact that MPE dominates at low temperatures,<sup>21,22</sup> we speculate that rising MPE impact in AHE from  $T_{comp}$  onwards with decreasing temperature.

With YAG intervention, it is noticed that such linear variation of the  $R_{AHE}^0$  at low temperatures occurs in an increasingly narrow temperature range with rising  $t_{YAG}$  values. Instead, the plots retain a fair steady amplitude for temperatures between  $T_{comp}$  and  $T_1$ . Assuming the MPE impact take effect at a transition temperature such that the  $R_{AHE}^0$  plot slope changes (see Fig. 4(b) for details), such transition occurs at ~108 K for  $t_{YAG} = 0.5$  nm and ~ 51 K for  $t_{YAG} = 1$  nm. This indicates that the YAG spacer has a greater impact on the temperature dependence of MPE, with MPE-induced AHE become more suppressed as  $t_{YAG}$ increases.

Fig. 5 shows the normalized  $R_{AHE}^0$  with an evident exponential decay with  $t_{YAG}$  increases. The fitting curve follows the formula  $\frac{R_{AHE}^0}{R_{AHE}^0} \left( \frac{1}{R_{AHE}^0} = 0 \right) = e^{-t_{YAG}/\lambda}$ , where  $\lambda$  is decay length. A decay length of  $\lambda = 0.26 nm$  across YAG spacer was obtained.



Fig. 5. Semi-log plots of normalized  $R_{AHE}^0$  as a function of the YAG thickness at 235 K. The fit indicates a decay length  $\lambda = 0.26 nm$  in TbIG/YAG/Pt system.

Considering the TbIG and Pt are separated by the insulating YAG spacer, it is speculated that the coupling between TbIG and Pt originate from the quantum tunneling

across the barrier; similar effect has been observed in YIG systems.<sup>30,47</sup> The ability of spinpolarized electrons in Pt to pass through spacer barriers can be evaluated by the spin tunneling transmission coefficient  $D_{ttc.}$  This is strongly correlated with Schottky barrier

 $\phi_{sc}$  and spacer thickness t and is described as  $D_{ttc} \propto exp \left[\frac{-2t_{YAG}\sqrt{2m\phi_{sc}}}{\hbar}\right]^{30}$ , where

*m* and  $\hbar$  represent the effective electron mass and Planck's constant. This indicates that the spin transport achieved by tunneling are negatively correlated with the thickness and work function of spacer.



Fig. 6. Temperature-dependent  $R_{AHE}$ -H loops of TbIG (30 nm)/GGG/Pt, with  $t_{GGG} = 0$  nm (a), 0.5 nm (b).

To explore the universality of the simple barrier model, we chose another paramagnetic garnet GGG as the spacer layer. The commonality between GGG and YAG is the similar garnet structure with TbIG, which can ensure the uniform crystallinity of the spacer layer and similar interface quality. However, GGG demonstrates strong paramagnetism while YAG is largely non-magnetic. The strong magnetic moment of Gd<sup>3+</sup>

in GGG under Curie temperature (292 K)<sup>48</sup> may alter the magnetotransport dominated by TbIG. This allows us to explore the difference between non-magnetic and paramagnetic garnet as spacer.

As shown in Fig. 6, samples inserted with 0.5 nm and 1 nm GGG spacer exhibit almost identical  $R_{AHE}$ -H signals, with no AHE loop to be observed. It can be considered that only the signal of the GGG spacer is displayed, indicating a strong attenuation of tunneling with just 0.5 nm of GGG spacer. Considering YAG and GGG spacers of the same thickness by the barrier model mentioned above (the Schottky barrier  $\emptyset_{sc}$  is expected to be half of the spacer band gap<sup>30</sup>), with bandgap of YAG being 6.5 eV<sup>49</sup> and is higher than that of GGG (5.66 eV).<sup>50</sup> Theoretically, the larger bandgap means lower ability of tunneling. However, comparing the results of 0.5 nm spacers in Fig. 3 (b) and Fig. 6 (a), it is evident that the decay length in YAG spacer is much larger than that in GGG spacer. This indicates that in addition to the barrier model, other factors need to be considered to judge the ability of tunneling. Although it is known that the spin transport is achieved in FMI through the propagation of magnon,<sup>51</sup> considering the strong paramagnetism of GGG, the 4*f*-shell of Gd<sup>3+</sup> contributes a large local moment,<sup>52</sup> which could significantly attenuate the spin transport from TbIG to Pt layer.

In summary, magnetotransport at the TbIG/Pt interface with non-magnetic YAG and paramagnetic GGG spacer layer was studied.  $T_{comp}$  of TbIG/Pt remained at ~230 K with varied YAG spacer thickness, indicating that the interface exchange coupling of TbIG/Pt is independent of  $T_{comp}$  and depends on the overall magnetic moment of the system. On the other hand, the presence of YAG spacer significantly affected the interfacial competition between MPE and SHE, leading to an exponential drop of  $R_{AHE}^0$  amplitude. The second cross-over of  $R_{AHE}$  sign  $T_1$  dropped significantly from ~135 K for the control sample to ~35 K for  $t_{YAG} = 1$  nm, indicating the controllability of  $T_1$ . Finally, paramagnetic GGG spacer exhibited stronger attenuation of  $R_{AHE}$  singals than non-magnetic YAG, which was attributed to strong Gd<sup>3+</sup> magnetic moment. The study illustrates the impact of spacer and interface on the AHE switching behaviour, which would be helpful for the engineering of FMI/HM heterostructures and interfaces for spintronic applications.

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## **Data Availability**

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

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