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1 **Current-induced magnetization switching across a nearly room-temperature**
2 **compensation point in an insulating compensated ferrimagnet**

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11

12 ABSTRACT

13 Insulating compensated ferrimagnets, especially hosting room-temperature compensation points,
14 are considered promising candidates for developing ultrahigh-density and ultrafast magnonic
15 devices owing to combining the characteristics of both ferromagnets and antiferromagnets. These
16 intriguing features become outstanding close to their compensation points. However, their spin-
17 orbit torque (SOT)-induced magnetization switching, particularly in the vicinity of the
18 compensation points, remains unclear. Herein, we systematically investigated the SOT in
19 insulating compensated ferrimagnetic $\text{Gd}_3\text{Fe}_5\text{O}_{12}/\text{Pt}$ heterostructures with perpendicular magnetic
20 anisotropy. A nearly room-temperature compensation point ($T_{\text{comp}} \sim 297$ K) was consistently
21 identified by the magnetization curves, spin Hall-induced anomalous Hall effect, and spin Hall
22 magnetoresistance measurements, respectively. Moreover, using 100 ns duration pulsed current,
23 deterministic current-induced magnetization switching below and above T_{comp} , even at 294 K and
24 301 K, was achieved with opposite switching polarity. It is found that a large current is required
25 to switch the magnetization in the vicinity of T_{comp} although the effective SOT field increases close
26 to T_{comp} . Our finding provides alternative opportunities for exploring ultrafast room-temperature
27 magnon-based devices.

28 **Keywords:** Insulating compensated ferrimagnet, spin-orbit torque, perpendicular magnetic
29 anisotropy, spin current

30

31 INTRODUCTION

32 Electrical manipulation of the magnetic state through the spin orbit torque (SOT) is of particular
33 significance for both fundamental physics and technological applications. Beyond ferromagnets,
34 the control of the Néel vector *via* the SOT in antiferromagnetic materials offers potential prospects
35 in exploiting ultrafast and high-density spintronic devices, benefitting from the absence of
36 magnetization and the antiferromagnetic exchange coupling-dominated dynamics.^{1,2} Nonetheless,
37 achieving efficient readouts and writing the antiferromagnetic state remains challenging because
38 of the vanishing net magnetization. In some metallic ferrimagnets, such as the rare earth-transition
39 metal alloys CoTb, GdCo, and GdFeCo, the net magnetization can be adjusted to approximately
40 zero by varying the chemical composition or temperature.^{3,4} These compensated ferrimagnets
41 possess antiferromagnetic exchange coupling and finite net magnetization, and thus exhibit the
42 combined advantages of both ferro- and antiferromagnets, such as reliable electrical reading and
43 writing, high SOT switching efficiency close to the magnetization compensation point, and
44 ultrafast domain wall velocity at the angular momentum compensation point.⁵⁻⁹ Note that the
45 intriguing features of these compensated ferrimagnets strongly benefit from their compensation
46 points. To exploit the possible high-performance ferrimagnetic devices, compensated
47 ferrimagnetic materials with room-temperature compensation points are thus highly desired.⁹

48 Electrically insulating compensated ferrimagnets, allowing long-range spin information
49 communication and storage, possess great potential for integrated magnon-based devices beyond
50 conventional metallic ferrimagnetic systems.¹⁰⁻¹² However, their SOT switching has been much
51 less addressed so far, particularly in the vicinity of the compensation points. Gd₃Fe₅O₁₂ (GdIG) is
52 a compensated ferrimagnetic insulator with a high Curie temperature (~550 K).¹³ Long spin
53 transmission length and excellent magnon propagation in GdIG, even though not observed
54 previously, are naturally expected in view of its low magnetic damping and absence of Ohmic
55 loss.¹⁴ More strikingly, magnetization compensation temperature of bulk GdIG is close to the
56 room-temperature ($T_{\text{comp}} \sim 295$ K).^{15,16} The characteristics of GdIG make it a prominent platform
57 for room-temperature, ultrafast, and low-dissipation magnonic applications. In this work, we report
58 the unambiguous observation of a nearly room-temperature compensation point ($T_{\text{comp}} \sim 297$ K) in
59 an insulating compensated ferrimagnetic GdIG film with perpendicular magnetic anisotropy
60 (PMA). In addition, we achieve deterministic current-induced magnetization switching with

61 opposite switching polarity in GdIG/Pt heterostructures at temperatures below 294 K and above
62 301 K. It is found that a large critical switching current is required in the vicinity of T_{comp} although
63 the effective SOT field significantly increases as approaching to T_{comp} .

64 RESULTS AND DISCUSSION

65 6.5 nm-thick $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ (GdIG) films were grown on (111)-oriented $\text{Gd}_3\text{Sc}_2\text{Ga}_3\text{O}_{12}$ (GSGG)
66 substrate by pulsed laser deposition, and then transferred to a magnetron sputter system, in which
67 a 5 nm-thick Pt layer was deposited on the GdIG films. For the electrical transport measurements,
68 the samples were fabricated into Hall bar device, as schematically shown in the bottom panel of
69 Figure 1a. The cross-sectional scanning transmission electron microscopy (STEM) image in the
70 up-right panel of Figure 1a shows the good epitaxial relationship between the GdIG film and the
71 GSGG substrate with sharp interface viewed along the $[11\bar{2}]$ direction. GdIG consists of three
72 magnetic sublattices: an octahedral Fe sublattice (a -sites), a tetrahedral Fe sublattice (d -sites) and
73 a dodecahedral Gd sublattice (c -sites), as shown in the up-left panel of Figure 1a. The magnetic
74 configurations depend on both magnetic field and temperature, as schematically drawn in Figure
75 1b; the data originate from references ^{17, 18}. The effective Fe sublattices, which are composed of
76 octahedral Fe sublattice (a -sites) and tetrahedral Fe sublattice (d -sites), are antiferromagnetically
77 coupled to the Gd sublattice with collinear ferrimagnetic configurations at low magnetic fields.
78 The net moment vanishes at the magnetic compensation temperature T_{comp} . Moreover, the
79 magnetic moments of the Fe sublattices do not vary significantly whereas those of the Gd sublattice
80 decrease significantly with increasing temperature. Therefore, the net magnetization is dominated
81 by the Fe sublattices above T_{comp} and by the Gd sublattice below T_{comp} . In addition, the exchange
82 coupling between the Gd sublattice and effective Fe sublattices is much weaker than the dominant
83 antiferromagnetic coupling between the two Fe sublattices. Thus, a canted magnetic phase is
84 accessible at a large magnetic field [~ 3 T at 300 K and ~ 14 T at 280 K (see Figure 1b)], particularly
85 in the vicinity of T_{comp} . In this case, the moments of a -Fe and d -Fe are generally antiparallel owing
86 to the strong antiferromagnetic exchange coupling between them.¹⁸

87 The measured hysteresis loops *via* sweeping the out-of-plane magnetic field confirm the PMA
88 in the GSGG/GdIG sample at different temperatures, as shown in Figure 2a. Such a PMA is
89 induced by the tensile strain between the GdIG film (lattice constant: 12.480 Å) and GSGG(111)
90 substrate (lattice constant: 12.554 Å). The values of the saturation magnetization M_s at various

91 temperatures are extracted from the $M-H$ loops and plotted against temperature in Figure 2d. The
 92 net saturation magnetization M_s almost vanishes close to 297 K, which corresponds to the magnetic
 93 compensation temperature T_{comp} of GdIG. Moreover, a charge current was applied to the Pt layer
 94 along the x axis, as shown in Figure 1a; it generated a spin current owing to the spin Hall effect
 95 (SHE). The transmission and reflection of the spin current at the GdIG/Pt interface give rise to
 96 different effects on the GdIG and Pt sides:¹⁹ the SOT in GdIG layer and the spin Hall-induced
 97 anomalous Hall effect (SH-AHE) and spin Hall magnetoresistance (SMR) in Pt layer owing to the
 98 simultaneous action of the SHE and inverse SHE.^{20, 21} According to the SH-AHE theory and
 99 previous experiments in magnetic insulator/heavy metal, the SH-AHE signal is proportional to the
 100 out-of-plane magnetic moment,²⁰ which provides a chance to characterize magnetic switching of
 101 magnetic insulator. Figure 2b shows the SH-AHE resistance R_H after subtracting the linear
 102 background from the ordinary Hall effect by sweeping the out-of-plane magnetic field at various
 103 temperatures. Evidently, the sign of the R_H-H loop is opposite at temperatures above and below
 104 T_{comp} . Practically, the magnetic moment of Gd ion originates from the inner $4f$ shell, which is more
 105 localized than that of the $3d$ shell of Fe ions. The transfer of spin angular momentum between Pt
 106 and GdIG is therefore dominated by the Fe sublattices *via* $s-d$ exchange. Furthermore, given that
 107 the net magnetization is dominated by the Fe sublattices above T_{comp} and the Gd sublattice below
 108 T_{comp} , the R_H-H loops thus change sign across T_{comp} .

109 The angle-dependent magnetoresistance $\rho(\varphi_{yz})$ was measured by rotating the sample in the yz
 110 plane under the applied magnetic field \mathbf{H} (5 T) at various temperatures, as shown in Figure 2c.
 111 $\Delta\rho_{SMR}/\rho_z$ is defined by $[\rho_z - \rho(\varphi_{yz})]/\rho_z$, where ρ_z and φ_{yz} are the magnetoresistance with
 112 respect to the applied magnetic field along the $-z$ axis and the rotation angle in the yz plane with
 113 respect to the $+z$ axis, respectively. Far away from T_{comp} , the orientation of the net magnetization
 114 is approximately along \mathbf{H} in a large magnetic field (5 T). Moreover, the measured resistivity at 340
 115 K and 260 K is maximized (minimized) when \mathbf{H} is oriented along the z (y) axis, manifesting a
 116 standard characteristic of the SMR effect like those in ferromagnetic systems²². However, the
 117 measured resistivity at 300K is almost minimized (maximized) when \mathbf{H} is along z (y) axis, which
 118 is similar to the SMR effect in antiferromagnetic films, as observed in $\alpha\text{-Fe}_2\text{O}_3$ with weak
 119 ferromagnetism.²³ As shown in Figure 1b, the vector sum of the $a\text{-Fe}$ and $d\text{-Fe}$ moments under a
 120 large magnetic field is nearly perpendicular to \mathbf{H} in the vicinity of T_{comp} and parallel to \mathbf{H} far away
 121 from T_{comp} . Given that SMR is dominated by the Fe sublattices owing to the weak efficiency of

122 spin current transport between the Gd sublattice and Pt layer, the angular dependence of SMR at
 123 300 K is opposite to these at temperatures far away from T_{comp} . In this respect, the effective moment
 124 vector of the two Fe sublattices in the vicinity of T_{comp} can be treated as the Néel vector for GdIG.
 125 Furthermore, the SMR ratio is defined by $(\rho_z - \rho_y)/\rho_z$, where ρ_y is the magnetoresistance with
 126 respect to the applied magnetic field along the +y axis. The SMR ratio at different temperatures is
 127 also presented in Figure 2d. Far away from T_{comp} , the SMR ratio can reach up to $\sim 6 \times 10^{-4}$, which
 128 is larger than that ($\sim 2.5 \times 10^{-4}$) in YIG/Pt.²⁴ Experimental results of SMR and SH-AHE yield the
 129 real ($G_r^{\uparrow\downarrow}$) and imaginary ($G_i^{\uparrow\downarrow}$) parts of the spin mixing conductance ($G^{\uparrow\downarrow}$), $G_r^{\uparrow\downarrow} \approx$
 130 $2.3 \times 10^{14} \Omega^{-1}\text{m}^{-2}$ and $G_i^{\uparrow\downarrow} \approx 6.4 \times 10^{12} \Omega^{-1}\text{m}^{-2}$, indicating substantial spin transparency at
 131 the GdIG/Pt interface even though GdIG is an insulator. Pronounced variation in the SMR ratio
 132 occur from ~ 280 K to ~ 320 K. This suggests that magnetic fluctuations emerge at ~ 280 K and
 133 ~ 320 K, and the nonlinear magnetic configurations between the Gd and Fe sublattices exist at \sim
 134 300 K at a large external magnetic field. Noteworthy, the net saturation magnetization of GdIG
 135 nearly vanishes at ~ 297 K, at which both R_H and SMR ratio showed sign-reversal. These
 136 experimental observations unambiguously verify that the magnetic compensation temperature is
 137 approximately 297 K.

138 Although charge currents cannot flow in the insulating GdIG films, spin currents generated by
 139 the SHE in the Pt layer can exert a torque on the magnetization of GdIG. To determine the current-
 140 induced effective fields and SOT switching efficiency, we performed the angular dependent
 141 harmonic Hall measurements. The first (R_H^ω) and second harmonic resistance ($R_H^{2\omega}$) upon injecting
 142 sinusoidal alternating current \tilde{I}_ω into devices are simultaneously detected when rotating in-plane
 143 magnetic field. The rotation angle φ_{xy} in the xy plane is defined with respect to the +y axis. In
 144 addition, the actual temperature is estimated by calibrating the temperature-dependent resistance
 145 R_{xx} . In an in-plane magnetic field urging single domain approximation,²⁵⁻²⁸ the current-induced
 146 field-like effective field H_{FL} and damping-like effective field H_{DL} can be extracted from the angular
 147 dependent $R_H^{2\omega}$ with the following expression:

$$148 \quad R_H^{2\omega} = R_{\text{PHE}} \frac{H_{\text{FL}}}{|H_{\text{ext}}|} \cos 2\varphi_{xy} \sin \varphi_{xy} + \left(\frac{R_H}{2} \frac{H_{\text{DL}}}{|H_{\text{ext}}| - H_K} + R_{\text{SSE}} \right) \sin \varphi_{xy}. \quad (1)$$

149 Here, H_{ext} , H_K , R_{PHE} and R_{SSE} are the in-plane external magnetic field, effective perpendicular
 150 magnetic anisotropy field, planar Hall resistance, and spin Seebeck effect-induced resistance,

151 respectively. The amplitudes of the terms $\cos 2\varphi_{xy} \sin \varphi_{xy}$ and $\sin \varphi_{xy}$ are marked as $R_{FL}^{2\omega}$ and $R_{DL}^{2\omega}$,
152 respectively. Figures 3a and c show the angle-dependent first harmonic Hall signals R_H^ω , from
153 which R_{PHE} can be extracted. The observation of R_{PHE} further supports the fact that an SHE-driven
154 spin current can be injected and scattered across the Pt/GdIG interface. Figures 3b and d show the
155 in-plane angular dependent $R_H^{2\omega}$, which are separated into the $\cos 2\varphi \sin \varphi$ and $\sin \varphi$ components.
156 The observed small field-like torque contribution is presented in Supporting Information (SI) [see
157 Figure S5]. The damping-like torque contribution can be distinguished *via* fitting $R_{DL}^{2\omega}$ versus
158 $1/(|H_{ext}| - H_K)$, as indicated in Figure 3e. The inset in Figure 3f presents the effective damping-
159 like field per unit current density H_{DL}/J_e as a function of temperature. Here, J_e is the applied
160 charge current density. Evidently, H_{DL}/J_e increases with increasing temperature below T_{comp} , and
161 decrease with temperature above T_{comp} . The value of H_{DL}/J_e at 335 K, which is approximately ~ 1.2
162 $\text{mT}/(10^{10} \text{Am}^{-2})$, is comparable to the reported results ($0.06\sim 25 \text{mT}/(10^{10} \text{Am}^{-2})$) for TmIG/Pt
163 and ($0.1\sim 0.7$) for GdFeCo/(BiSb)₂Te₃.^{19, 29, 30} Noticeably, H_{DL}/J_e is significantly enhanced nearby
164 T_{comp} , which reaches up to $2.1 \text{mT}/(10^{10} \text{Am}^{-2})$ at 272 K and $4.3 \text{mT}/(10^{10} \text{Am}^{-2})$ at 325 K. In
165 theory, the damping-like torque generated by the injected charge current in the Pt layer can be
166 expressed by¹¹

$$167 \quad \tau_{DL} = -\frac{\gamma_{eff} \xi_{DL} J_e \hbar}{\mu_0 M_s t} \frac{1}{2e} (\hat{\mathbf{m}} \times (\hat{\boldsymbol{\sigma}} \times \hat{\mathbf{m}})). \quad (2)$$

168 Here, e , \hbar , μ_0 , γ_{eff} , $\hat{\boldsymbol{\sigma}}$, $\hat{\mathbf{m}}$, J_e , ξ_{DL} , and t are the elementary electric charge, reduced Plank
169 constant, vacuum permeability, effective gyromagnetic ratio, polarization of spin, unit vector of
170 net magnetization, charge current density, effective spin Hall angle, and thickness of the magnetic
171 layer, respectively. Therefore, the effective damping-like field should scale linearly with $1/M_s$,
172 and thereby diverge from the linear increase when the temperature approaches to T_{comp} because the
173 net magnetization at T_{comp} is vanishingly small. This $1/M_s$ dependence has been verified in most
174 metallic ferrimagnetic systems, such as CoTb/Pt, GdFeCo/Pt and GdFeCo/(BiSb)₂Te₃.^{3, 30, 31} In
175 our experiment, H_{DL}/J_e is proportional to $1/M_s$ far away from T_{comp} whereas it remarkably
176 deviates from the linear dependence in the vicinity of T_{comp} , as shown in Figure 3f. Far away from
177 T_{comp} , the increase in H_{DL}/J_e with respect to $1/M_s$ can be explained by the reduction in the net
178 magnetization. When approaching to T_{comp} , magnetic fluctuations emerge, which is probably
179 related to the giant enhancement of H_{DL}/J_e close to T_{comp} . Besides, it was reported that the effective

180 damping-like field was significantly enhanced in CoGd/Pt owing to the negative exchange
 181 interaction and tilt angle between Co and Gd, thereby following $\sim 1/M_s^2$.⁵ In our harmonic
 182 measurements, the nonlinear magnetic configurations between Gd and Fe sublattices close to T_{comp}
 183 are accessible under a large magnetic field, which have also been verified in our SMR
 184 measurements. Therefore, the other possible contribution to the enhanced H_{DL}/J_e could be the
 185 negative exchange interaction.

186 Furthermore, the SOT efficiency can be estimated with the effective spin Hall angle $\xi_{DL} =$
 187 $\frac{2e}{\hbar}\mu_0 M_s t H_{DL}/J_e$ when $H_{DL}/J_e \propto 1/M_s$.³² As shown in the inset in Figure 3f, ξ_{DL} is nearly
 188 independent of the temperature in the range $H_{DL}/J_e \propto 1/M_s$. Upon increasing temperature, ξ_{DL}
 189 increases slightly from 0.026 at 221 K to 0.037 at 262 K below T_{comp} . Further increasing the
 190 temperature above T_{comp} , ξ_{DL} slightly decreases from 0.036 at 335 K to 0.027 at 366 K. The
 191 measured ξ_{DL} is comparable to the reported value of the spin Hall angle in Pt.³²⁻³⁴ In addition, we
 192 also calculated ξ_{DL} approaching to T_{comp} using the aforementioned equation. When H_{DL}/J_e versus
 193 $1/M_s$ deviates from the linear dependence in the vicinity of T_{comp} , ξ_{DL} increases to 0.09 at 273 K
 194 and to 0.12 at 325 K, which are even comparable to ~ 0.13 in topological insulator Bi_2Se_3 and ~ 0.14
 195 in two-dimensional material MoS_2 .^{28, 30} Such a dramatic increase in ξ_{DL} may originate from the
 196 negative exchange interaction and the existence of magnetic fluctuations close to T_{comp} , as
 197 mentioned above.

198 The above-mentioned damping-like SOT field can be utilized to switch the magnetization in
 199 GdIG/Pt films. In our SOT switching experiments, a sequence of current pulses with $\tau = 100$ ns
 200 pulse width were injected during the application of an in-plane magnetic field H_x along the x axis.
 201 After the application of the current pulses at periods of 1 s, R_H was recorded with a small probe
 202 current. Figure 4a presents the reversible current-induced switching with different in-plane
 203 magnetic fields H_x at $T = 280$ K. The R_H - j loops are clockwise at $H_x > 0$ while anticlockwise at
 204 $H_x < 0$. Such a reversed chirality under opposite magnetic field unambiguously demonstrates the
 205 deterministic current-induced magnetization switching in GdIG/Pt. Moreover, the SOT-driven R_H
 206 with the amplitude of ~ 1.3 m Ω corresponds to nearly 100% of magnetization switching. The
 207 critical switching current density is about $\sim 2 \times 10^{11}$ A/m², which is comparable to those in
 208 TmIG/Pt and metallic ferrimagnet/Pt systems.^{3, 29} In addition, current-induced SOT switching with
 209 different H_x values was also realized at $T = 310$ K, as shown in Figure 4b. Remarkably, at a

210 constant H_x , the R_{H-j} loops at 310 K have opposite polarity to those at 280 K. The reverse of the
 211 SOT switching polarity below and above T_{comp} is because the transfer of the spin angular
 212 momentum between GdIG and Pt is dominated by the $s-d$ exchange coupling between the Fe
 213 sublattices and Pt layers. This is consistent with the observations for metallic ferrimagnetic
 214 systems, such as CoTb/Pt, CoGd/Pt and GdFeCo/Pt.^{3, 5, 31} The extracted critical switching current
 215 density J_c is presented as a function of H_x in Figures 4c and d. J_c is $\sim 2 \times 10^{11}$ A/m² and decreases
 216 with increasing magnetic field. Besides, the asymmetry of the positive and negative critical
 217 switching current can be ascribed to the surface tension of domain wall.^{35, 36}

218 When a current is injected into the devices, Joule heating can result in a large increase of the
 219 actual temperature in the magnetic layers. This raises hurdles in detecting the current-induced SOT
 220 switching for ferrimagnetic systems, particularly in the vicinity of T_{comp} . For instance, the current-
 221 switching polarity was not reported to change across T_{comp} in TbIG/W and always happens in the
 222 Fe-dominated scenario because the actual measured temperature is always above T_{comp} owing to
 223 the excessive Joule heating.³⁷ Co-rich and Tb-rich samples host the same current-switching
 224 polarity in ferrimagnetic CoTb owing to the Joule heating effect.³⁸ Essentially, the large spin
 225 transparency at the GdIG/Pt interface can reduce the required injected charge current and decrease
 226 the excessive Joule heating in some extent. To evaluate the role of Joule heating in the SOT
 227 switching in our experiment, we performed SOT switching measurements with different pulse
 228 widths. As shown in Figures 5a and b, the current-switching loops become gradually narrower
 229 with increasing pulse width. Figures 5c and d summarize the average critical switching current
 230 density $J_c = (J_c^+ - J_c^-)/2$ as a function of pulse width. Here, J_c^+ and J_c^- are positive and negative
 231 switching currents, respectively. It can be seen that J_c decreases with increasing pulse width and
 232 becomes gradually saturated. According to the thermal activation model,^{39, 40} the critical switching
 233 current density J_c can be expressed by

$$234 \quad J_c = J_{c0} \left[1 - \frac{1}{\Delta} \ln \left(\frac{\tau}{\tau_0} \right) \right] \quad (3)$$

235 where J_{c0} is the intrinsic critical switching current density at 0 K; $\Delta \equiv U/k_B T$ is the thermal
 236 stability factor with respect to the energy barrier U ; τ_0 , which is assumed to be 1 ns, is the attempt
 237 timescale for thermally activated switching. By fitting the experimental results, we obtained $J_{c0} =$
 238 2.98×10^{11} Am⁻² and $\Delta = 13$ for $\tau < 2.5 \mu\text{s}$ while $J_{c0} = 1.33 \times 10^{11}$ Am⁻² and $\Delta = 75$ for $\tau >$

239 2.5 μs at 280 K. At 310 K, the fitting results yield $J_{c0} = 2.58 \times 10^{11} \text{ Am}^{-2}$ and $\Delta = 12$ for $\tau <$
240 2.5 μs . For the long time rang ($\tau > 2.5 \mu\text{s}$) at 310 K, J_c remain almost unchanged. Furthermore,
241 $J_{c0} = 1.17 \times 10^{11} \text{ Am}^{-2}$ is obtained at a fixed value $\Delta = 75$ for $\tau > 2.5 \mu\text{s}$. The values of Δ at 280
242 K and 310 K are nearly identical for $\tau < 2.5 \mu\text{s}$. However, the Δ values are different in the long-
243 and short-time ranges. In reality, the actual measured temperature is affected by the long pulse
244 width owing to the excessive Joule heating, further resulting in the variation of the local magnetic
245 properties. This also reduces the switching current threshold. By comparison, the pulsed current
246 with $\tau < 2.5 \mu\text{s}$ can effectively suppress the large increase of the preset temperature.

247 We next performed current-induced SOT magnetization switching experiments at various
248 temperatures across T_{comp} . To reduce the impact of Joule heating, 100 ns duration current pulses
249 was employed here. Figures 6a and b show the deterministic current-induced SOT switching
250 approaching to T_{comp} at $\mu_0 H_x = \pm 50 \text{ mT}$. As expected, the sign reversal of the R_H - H loop across
251 T_{comp} in Figure 2b is also observed in the current-induced SOT switching loops, as shown in
252 Figures 6a and b, further verifying that R_H is mainly sensitive to the Fe sublattices. In particular,
253 the SOT switching at 294 K and 301 K, which are very close to T_{comp} , is realized with reversed
254 switching polarity. Evidently, the critical switching current density at 301 K is larger than those at
255 temperatures far away from T_{comp} . Figures 6c and d show the 50 cycles of SOT switching at 294
256 K and 301 K with $\mu_0 H_x = -50 \text{ mT}$ and a successive positive/negative pulsed current sequence.
257 Switching in the other direction is clearly observed on reversing the pulsed current polarity. The
258 high and low resistance states at 294 K and 301 K have opposite signs at a pulsed current with the
259 identical polarity. The repeatable SOT switching also verify the stability of our experimental
260 method that involves the application of a short pulsed current (pulse width: 100 ns) to minimize
261 the effect of Joule heating. The critical switching current J_c with respect to the temperature is
262 presented in Figure 6e. Overall, J_c decreases almost linearly with increasing temperature.
263 Noticeably, J_c becomes considerably larger with temperature approaching to T_{comp} . Given that the
264 effective damping-like SOT field H_{DL}/J_e is greatly enhanced near the T_{comp} [see Figure 3f], such
265 an increase of J_c appears counterintuitive. As discussed in SI, magnetic reversal in GdIG/Pt is
266 generally *via* domain nucleation and domain-wall propagation. Besides, the coherent rotation of
267 the magnetization also happens in the pinned domain. In the macrospin approximation (i.e.
268 coherent rotation and switching), the intrinsic critical switching current J_{c0} can be expressed by⁴¹

$$J_{c0} = \frac{2e\mu_0 M_s t}{\hbar \xi_{DL}} \left(\frac{H_K}{2} - \frac{H_x}{\sqrt{2}} \right). \quad (4)$$

For the GdIG/Pt films, the effective perpendicular magnetic anisotropy field H_K substantially increases whereas the net magnetization M_s decrease as approaching T_{comp} [see Figure S3c in SI]. As shown in Figure 6e, the product of H_K and M_s gradually increases as the temperature approaches T_{comp} from both sides, which is a possible reason for the enhanced J_c around T_{comp} . Moreover, thermal fluctuations in the SOT switching experiments can create random domains that are very hard to align together, particularly in the vicinity of T_{comp} . Such a variation can increase the domain pinning field given that the magnetic reversal in GdIG/Pt is predominantly mediated by the domain nucleation and domain-wall propagation. In this case, an enhanced J_c is also expected. Besides, the increased pinning field near the compensation also decreases the the velocity of domain wall to some extent⁷. To summarize, the enhancement of J_c near T_{comp} is ascribed to two possible reasons: the increased $H_K * M_s$ product and random domains close to T_{comp} . According to the above harmonic Hall measurements, the large damping-like SOT field H_{DL}/J_e is the direct consequence of the small net magnetization M_s close to T_{comp} . As a result, the larger effective SOT field close to T_{comp} does not directly cause a more efficient current-induced SOT switching in ferrimagnetic GdIG-based devices.

CONCLUSION

In summary, the SOT in insulating compensated ferrimagnetic GdIG/Pt heterostructures with PMA was thoroughly studied. We explicitly observed a nearly room-temperature compensation point (~ 297 K). Considerable spin transparency at the GdIG/Pt interface are consistently confirmed by the SH-AHE, SMR and harmonic measurements, respectively. The SMR experiments in GdIG/Pt exhibit a quasi-antiferromagnetic behavior close to the compensation temperature. More importantly, effectively deterministic current-induced magnetization switching below and above T_{comp} , even at 294 K and 301 K, was realized with thermal stability and opposite switching polarity using 100 ns duration pulsed current. Moreover, the critical switching current increases in the vicinity of T_{comp} although the measured effective SOT field from harmonic experiments increases close to T_{comp} . Our work deepens the understanding to electrically manipulate the net magnetization of insulating compensated ferrimagnets and offers great prospects for room-temperature magnon-based magnonics with ultrafast operation.

298 **METHODS**

299 **Sample Fabrication.** $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ (GdIG, 6.5 nm) films were grown on (111)-oriented
300 $\text{Gd}_3\text{Sc}_2\text{Ga}_3\text{O}_{12}$ (GSGG) substrates by pulsed laser deposition at the laser repetition frequency of 5
301 Hz. During deposition, the substrate temperature was set to 720 K, and the oxygen pressure was
302 85 mTorr. After deposition, the samples were cooled down to room temperature at a rate of 10
303 K/min. Subsequently, the samples were transferred to the magnetron sputter system, in which 5
304 nm-thick Pt layer was deposited on them at room temperature.

305 **Structural and Magnetic Characterization.** Magnetization measurements were measured using
306 a magnetic property measurement system (MPMS3, Quantum Design). The structure
307 characterization was performed using STEM (Titan 80-300, FEI) after the sample was prepared
308 using a focused ion beam (Helios 450, FEI).

309 **Electric Transport Measurements.** The films were fabricated into 5 μm wide Hall bar devices
310 by standard photolithography technique and Ar ion milling. Ti(10 nm)/Au(100 nm) layers were
311 deposited as electrical contacts. All electrical transport measurements were performed in a
312 Quantum Design DynaCool. In the SOT switching experiments, switching pulses with different
313 pulse widths were provided by AV-1011B1-B pulse generator (Avtech Electrosystems), and then
314 the Hall resistance is detected by Keithley 2182 voltage source and Keithley 6221 current source
315 upon a small probe current. In the ac harmonic Hall measurements, a Keithley 6221 current source
316 was used to supply an ac current with a frequency of 13.7 Hz. Meanwhile, the in-phase first and
317 out-of-phase second-harmonic voltage signals were probed using two Stanford Research SR830
318 lock-in amplifiers.

319 **Supporting Information**

320 The Supporting Information is available free of charge on the ACS Publications website.

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324 2019-CRG8-4081, respectively.

325 **Conflict of Interest**

326 The authors declare no competing interests.

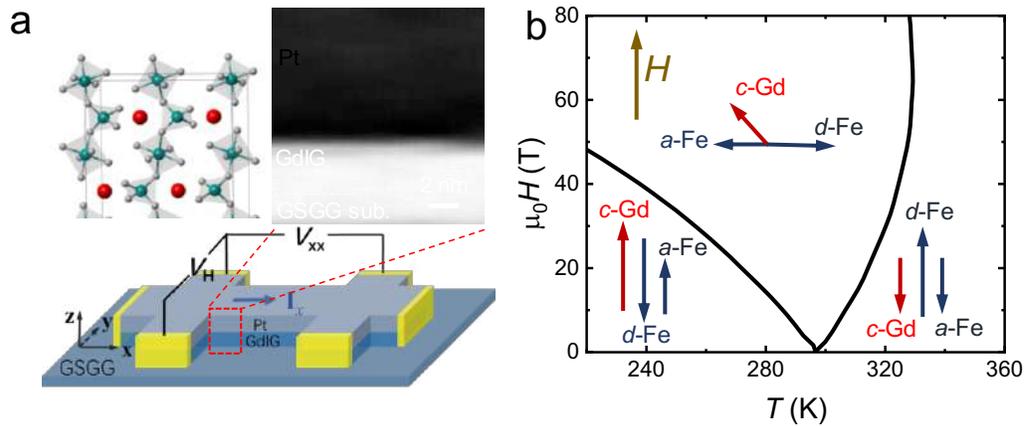
327 REFERENCES

- 328 (1) Baltz, V.; Manchon, A.; Tsoi, M.; Moriyama, T.; Ono, T.; Tserkovnyak, Y. *Rev. Mod. Phys.*
329 **2018**, 90, 015005.
- 330 (2) Jungwirth, T.; Marti, X.; Wadley, P.; Wunderlich, J. *Nat. Nanotech.* **2016**, 11, 231-41.
- 331 (3) Finley, J.; Liu, L. *Phys. Rev. Applied* **2016**, 6, 054001.
- 332 (4) Ueda, K.; Mann, M.; de Brouwer, P. W. P.; Bono, D.; Beach, G. S. D. *Phys. Rev. B* **2017**, 96,
333 064410.
- 334 (5) Mishra, R.; Yu, J.; Qiu, X.; Motapothula, M.; Venkatesan, T.; Yang, H. *Phys. Rev. Lett.*
335 **2017**, 118, 167201.
- 336 (6) Kim, K. J.; Kim, S. K.; Hirata, Y.; Oh, S. H.; Tono, T.; Kim, D. H.; Okuno, T.; Ham, W. S.;
337 Kim, S.; Go, G.; Tserkovnyak, Y.; Tsukamoto, A.; Moriyama, T.; Lee, K. J.; Ono, T. *Nat. Mater.*
338 **2017**, 16, 1187-1192.
- 339 (7) Caretta, L.; Mann, M.; Buttner, F.; Ueda, K.; Pfau, B.; Gunther, C. M.; Hessian, P.;
340 Churikova, A.; Klose, C.; Schneider, M.; Engel, D.; Marcus, C.; Bono, D.; Bagnschik, K.;
341 Eisebitt, S.; Beach, G. S. D. *Nat. Nanotech.* **2018**, 13, 1154-1160.
- 342 (8) Siddiqui, S. A.; Han, J.; Finley, J. T.; Ross, C. A.; Liu, L. *Phys. Rev. Lett.* **2018**, 121, 057701.
- 343 (9) Kim, S. K.; Beach, G. S. D.; Lee, K. J.; Ono, T.; Rasing, T.; Yang, H. *Nat. Mater.* **2022**, 21,
344 24-34.
- 345 (10) Geprägs, S.; Kehlberger, A.; Della Coletta, F.; Qiu, Z.; Guo, E. J.; Schulz, T.; Mix, C.;
346 Meyer, S.; Kamra, A.; Althammer, M.; Huebl, H.; Jakob, G.; Ohnuma, Y.; Adachi, H.; Barker,
347 J.; Maekawa, S.; Bauer, G. E.; Saitoh, E.; Gross, R.; Goennenwein, S. T.; Klau, M. *Nat.*
348 *Commun.* **2016**, 7, 10452.
- 349 (11) Finley, J.; Liu, L. *Appl. Phys. Lett.* **2020**, 116, 110501.
- 350 (12) Liensberger, L.; Kamra, A.; Maier-Flaig, H.; Geprags, S.; Erb, A.; Goennenwein, S. T. B.;
351 Gross, R.; Belzig, W.; Huebl, H.; Weiler, M. *Phys. Rev. Lett.* **2019**, 123, 117204.
- 352 (13) Pauthenet, R. *J. Appl. Phys.* **1958**, 29, 253-255.
- 353 (14) Ng, I.; Liu, R. Z.; Ren, Z. Y.; Kim, S. K.; Shao, Q. M. *IEEE Trans. Magn.* **2022**, 58, 1-6.
- 354 (15) Nakamoto, R.; Xu, B.; Xu, C.; Xu, H.; Bellaiche, L. *Phys. Rev. B* **2017**, 95, 024434.
- 355 (16) Bayaraa, T.; Xu, C.; Campbell, D.; Bellaiche, L. *Phys. Rev. B* **2019**, 100, 214412.
- 356 (17) Bernasconi, J.; Kuse, D. *Phys. Rev. B* **1971**, 3, 811.
- 357 (18) Ganzhorn, K.; Barker, J.; Schlitz, R.; Piot, B. A.; Ollefs, K.; Guillou, F.; Wilhelm, F.;
358 Rogalev, A.; Opel, M.; Althammer, M.; Geprägs, S.; Huebl, H.; Gross, R.; Bauer, G. E. W.;
359 Goennenwein, S. T. B. *Phys. Rev. B* **2016**, 94, 094401.
- 360 (19) Li, J.; Yu, G.; Tang, C.; Liu, Y.; Shi, Z.; Liu, Y.; Navabi, A.; Aldosary, M.; Shao, Q.;
361 Wang, K. L.; Lake, R.; Shi, J. *Phys. Rev. B* **2017**, 95, 241305.
- 362 (20) Chen, Y.-T.; Takahashi, S.; Nakayama, H.; Althammer, M.; Goennenwein, S. T. B.; Saitoh,
363 E.; Bauer, G. E. W. *Phys. Rev. B* **2013**, 87, 14441.
- 364 (21) Nakayama, H.; Althammer, M.; Chen, Y. T.; Uchida, K.; Kajiwara, Y.; Kikuchi, D.; Ohtani,
365 T.; Geprags, S.; Opel, M.; Takahashi, S.; Gross, R.; Bauer, G. E.; Goennenwein, S. T.; Saitoh, E.
366 *Phys. Rev. Lett.* **2013**, 110, 206601.
- 367 (22) Jie, W.; Yang, Z.; Zhang, F.; Bai, G.; Leung, C. W.; Hao, J. *ACS nano* **2017**, 11, 6950-6958.
- 368 (23) Lebrun, R.; Ross, A.; Bender, S. A.; Qaiumzadeh, A.; Baldrati, L.; Cramer, J.; Brataas, A.;
369 Duine, R. A.; Klau, M. *Nature* **2018**, 561, 222-225.
- 370 (24) Lin, W.; Chien, C. L. *Phys. Rev. Lett.* **2017**, 118, 067202.

371 (25) Garello, K.; Miron, I. M.; Avci, C. O.; Freimuth, F.; Mokrousov, Y.; Blugel, S.; Auffret, S.;
372 Boulle, O.; Gaudin, G.; Gambardella, P. *Nat. Nanotech.* **2013**, 8, 587-93.
373 (26) Avci, C. O.; Garello, K.; Gabureac, M.; Ghosh, A.; Fuhrer, A.; Alvarado, S. F.;
374 Gambardella, P. *Phys. Rev. B* **2014**, 90, 224427.
375 (27) Alghamdi, M.; Lohmann, M.; Li, J.; Jothi, P. R.; Shao, Q.; Aldosary, M.; Su, T.; Fokwa, B.
376 P. T.; Shi, J. *Nano Lett.* **2019**, 19, 4400-4405.
377 (28) Shao, Q.; Yu, G.; Lan, Y. W.; Shi, Y.; Li, M. Y.; Zheng, C.; Zhu, X.; Li, L. J.; Amiri, P. K.;
378 Wang, K. L. *Nano Lett.* **2016**, 16, 7514-7520.
379 (29) Avci, C. O.; Quindeau, A.; Pai, C. F.; Mann, M.; Caretta, L.; Tang, A. S.; Onbasli, M. C.;
380 Ross, C. A.; Beach, G. S. *Nat. Mater.* **2017**, 16, 309-314.
381 (30) Wu, H.; Xu, Y.; Deng, P.; Pan, Q.; Razavi, S. A.; Wong, K.; Huang, L.; Dai, B.; Shao, Q.;
382 Yu, G.; Han, X.; Rojas-Sanchez, J. C.; Mangin, S.; Wang, K. L. *Adv. Mater.* **2019**, 31, 1901681.
383 (31) Seung Ham, W.; Kim, S.; Kim, D.-H.; Kim, K.-J.; Okuno, T.; Yoshikawa, H.; Tsukamoto,
384 A.; Moriyama, T.; Ono, T. *Appl. Phys. Lett.* **2017**, 110, 242405.
385 (32) Nguyen, M. H.; Ralph, D. C.; Buhrman, R. A. *Phys. Rev. Lett.* **2016**, 116, 126601.
386 (33) Liu, L.; Lee, O. J.; Gudmundsen, T. J.; Ralph, D. C.; Buhrman, R. A. *Phys. Rev. Lett.* **2012**,
387 109, 096602.
388 (34) Shao, Q.; Tang, C.; Yu, G.; Navabi, A.; Wu, H.; He, C.; Li, J.; Upadhyaya, P.; Zhang, P.;
389 Razavi, S. A.; He, Q. L.; Liu, Y.; Yang, P.; Kim, S. K.; Zheng, C.; Liu, Y.; Pan, L.; Lake, R. K.;
390 Han, X.; Tserkovnyak, Y.; Shi, J.; Wang, K. L. *Nat. Commun.* **2018**, 9, 3612.
391 (35) Zhang, X.; Vernier, N.; Zhao, W.; Yu, H.; Vila, L.; Zhang, Y.; Ravelosona, D. *Phys. Rev.*
392 *Applied* **2018**, 9, 024032.
393 (36) Velez, S.; Schaab, J.; Wornle, M. S.; Muller, M.; Gradauskaite, E.; Welter, P.; Gutgsell, C.;
394 Nistor, C.; Degen, C. L.; Trassin, M.; Fiebig, M.; Gambardella, P. *Nat. Commun.* **2019**, 10, 4750.
395 (37) Ren, Z.; Qian, K.; Aldosary, M.; Liu, Y.; Cheung, S. K.; Ng, I.; Shi, J.; Shao, Q. *APL*
396 *Mater.* **2021**, 9, 051117.
397 (38) Pham, T. H.; Je, S. G.; Vallobra, P.; Fache, T.; Lacour, D.; Malinowski, G.; Cyrille, M. C.;
398 Gaudin, G.; Boulle, O.; Hehn, M.; Rojas-Sánchez, J. C.; Mangin, S. *Phys. Rev. Applied* **2018**, 9,
399 064032.
400 (39) Koch, R. H.; Katine, J. A.; Sun, J. Z. *Phys. Rev. Lett.* **2004**, 92, 088302.
401 (40) Khang, N. H. D.; Nakano, S.; Shirokura, T.; Miyamoto, Y.; Hai, P. N. *Sci. Rep.* **2020**, 10,
402 12185.
403 (41) Lee, K.-S.; Lee, S.-W.; Min, B.-C.; Lee, K.-J. *Appl. Phys. Lett.* **2013**, 102, 112410.

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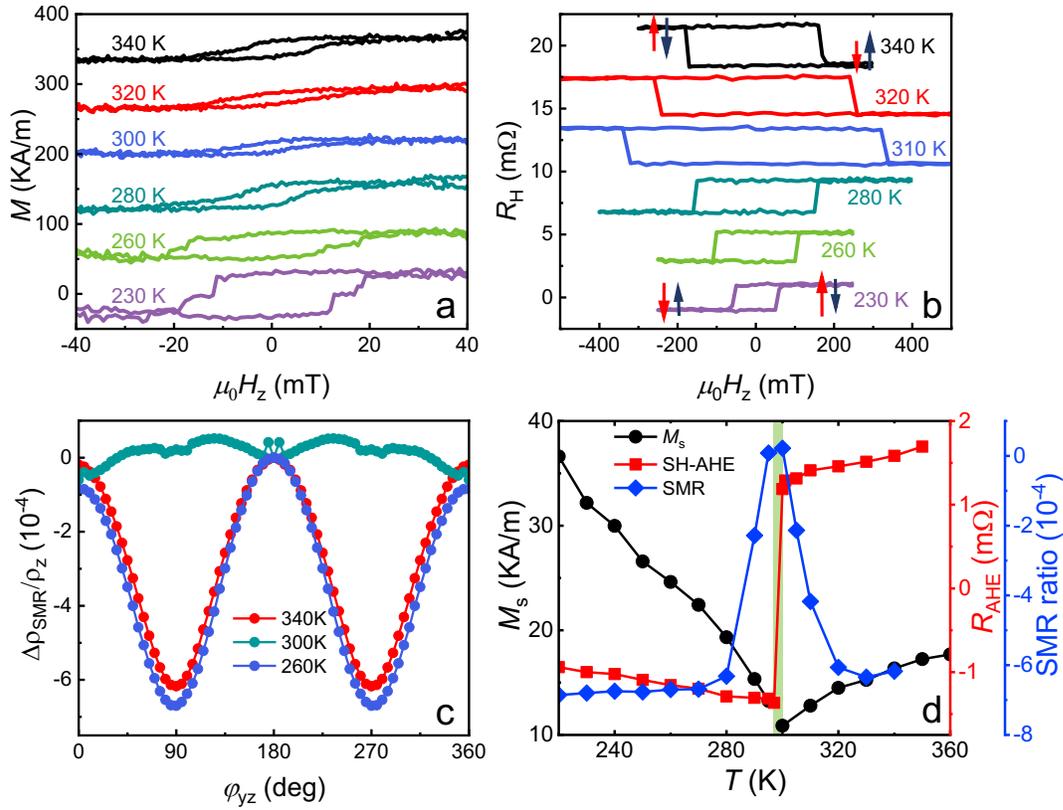
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407 **Figure 1.** (a) Bottom panel: schematic illustration of the transport measurement set-up for GdIG/Pt
 408 film grown on GSGG (111). Up-left panel is the schematic of the crystal structure of GdIG with
 409 Fe (green), Gd (red), and O (gray) atoms. Octahedral Fe sublattice, tetrahedral Fe sublattice, and
 410 dodecahedral Gd sublattice occupy a -site, d -site and c -site in the Wyckoff positions, respectively.
 411 Up-right panel is atomic-resolution STEM image. (b) Magnetic phase diagram of GdIG at different
 412 magnetic fields and temperatures^{17, 18}. The arrows indicate the directions of the moments of the
 413 different sublattices.

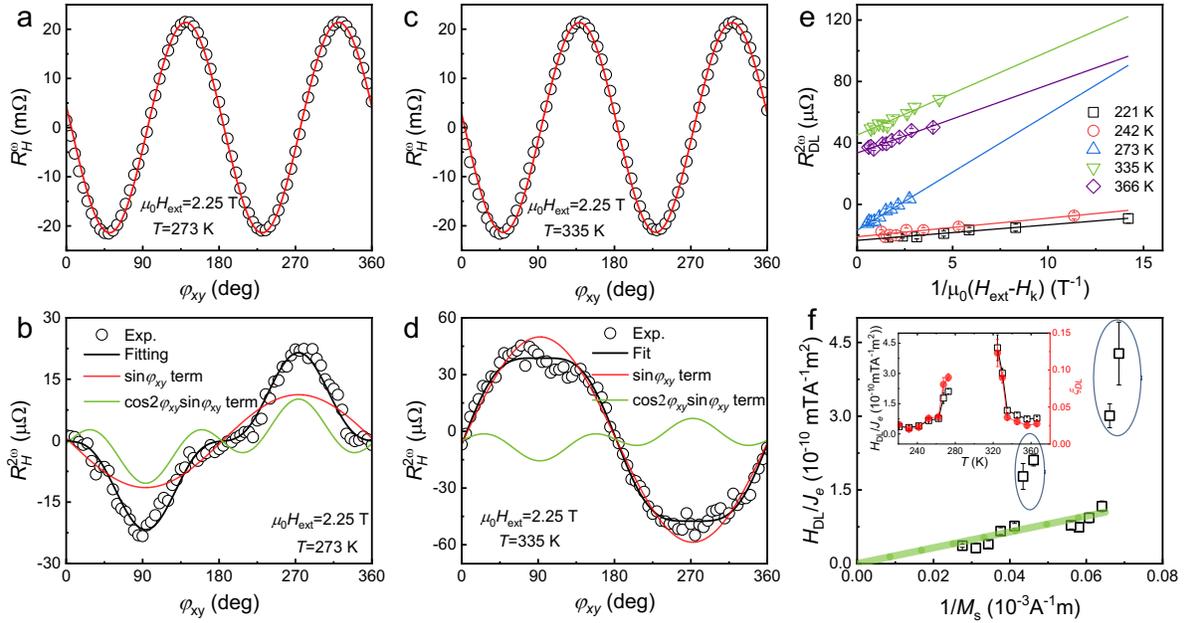
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416 **Figure 2.** (a) Magnetic hysteresis loops *via* sweeping out-of-plane magnetic field at various
 417 temperatures. For clarity, the curves are vertically shifted. (b) Spin Hall-induced anomalous Hall
 418 resistance R_H as a function of the out-of-plane magnetic field H_z at different temperatures. The red
 419 (navy) arrow represents the moment of the Gd sublattice (effective Fe sublattices). (c) Angular-
 420 dependent SMR at a fixed magnetic field (5 T) at various temperatures. (d) Extracted saturation
 421 magnetization, SH-AHE resistance, and SMR ratio as function of temperature (from Figures. 2 a–
 422 c).

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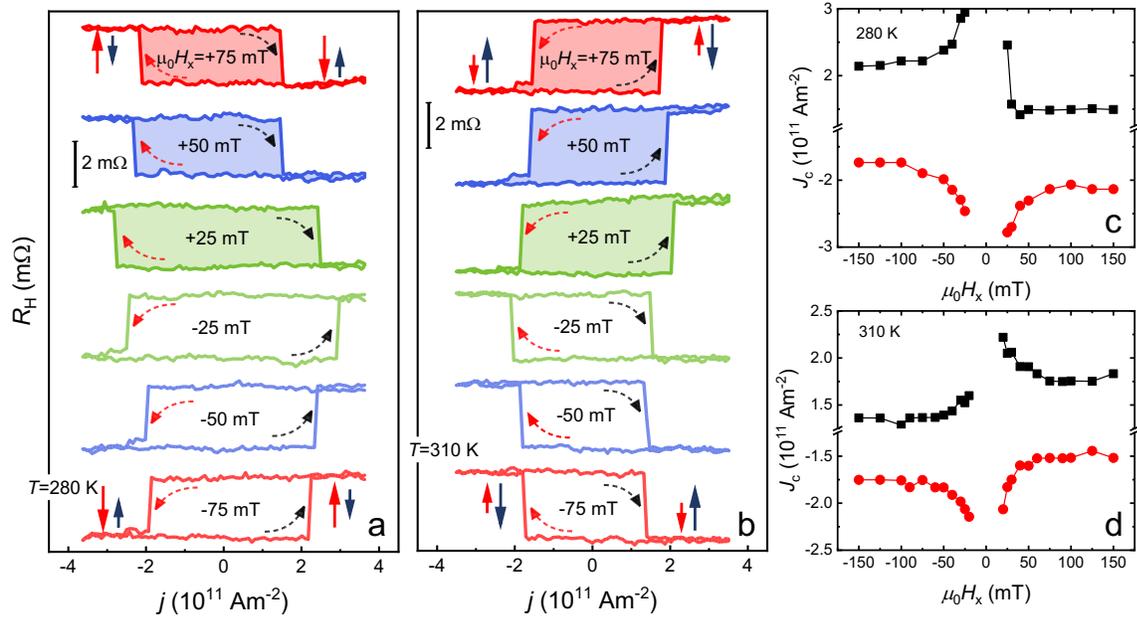


424

425 **Figure 3.** In-plane angle-dependent planar Hall resistance (a) and second-order harmonic
 426 resistance (b) at $T=273$ K and $\mu_0 H_{\text{ext}} = 2.25$ T. In-plane angular dependent planar Hall resistance
 427 (c) and second-order harmonic resistance (d) at $T=335$ K and $\mu_0 H_{\text{ext}} = 2.25$ T. (e) Extracted
 428 amplitudes of damping-like torque term as a function of $1/(H_{\text{ext}} - H_k)$. (f) H_{DL}/J as a function of
 429 $1/M_s$. Inset in (f) shows temperature dependent H_{DL}/J (black) and ξ_{DL} (red). The bold green curve
 430 is the $1/M_s$ fitting curve without the points marked in the ellipses.

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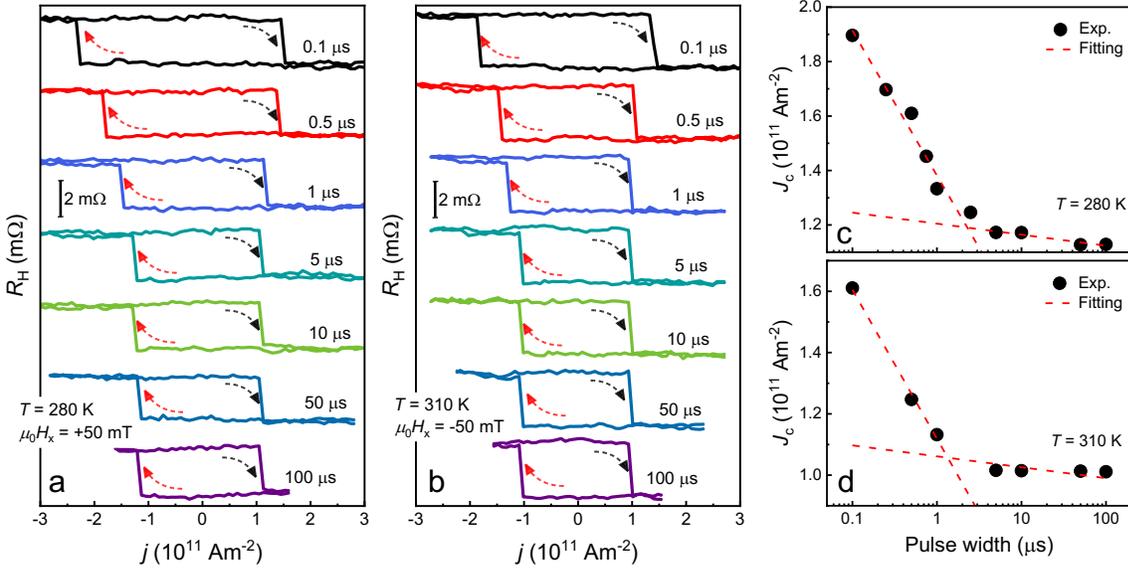
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434 **Figure 4.** Current-induced SOT switching at different in-plane magnetic fields H_x at 280 K (a) and
 435 310 K (b). The red (navy) arrow represents the moment of the Gd sublattice (effective Fe
 436 sublattices). Extracted critical switching current density J_c at different H_x at 280 K
 437 (d).

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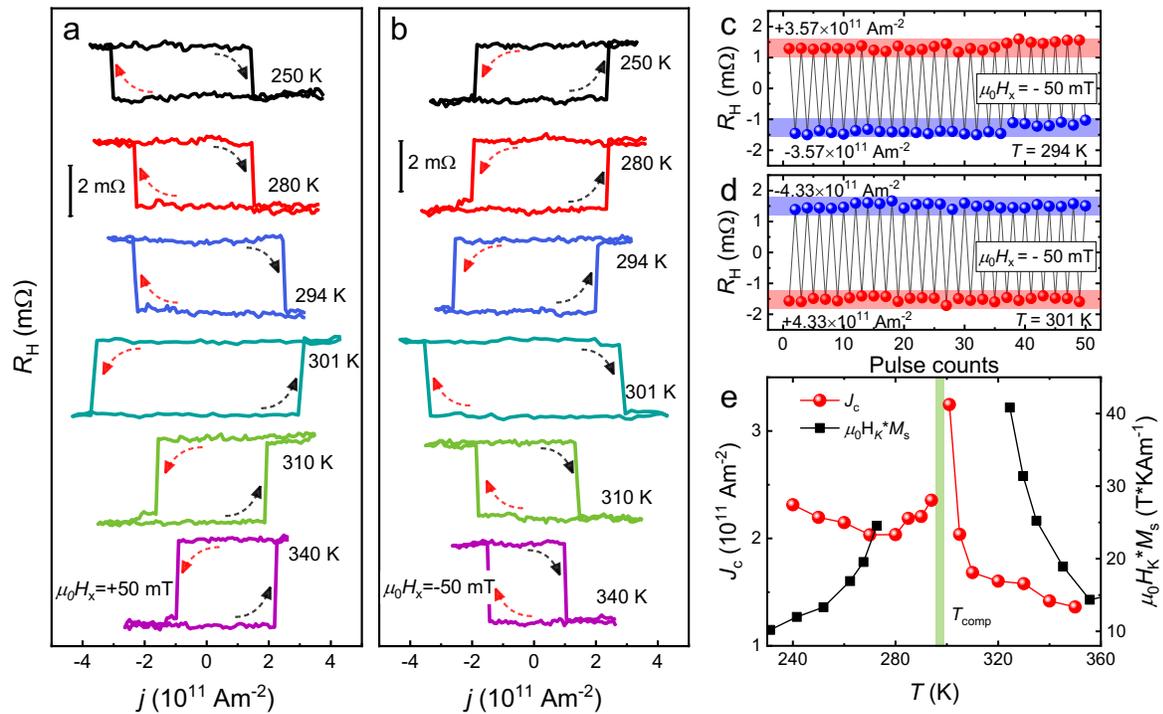
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440 **Figure 5.** Current-induced SOT switching for different pulse widths at 280 K (a) and 310 K (b).

441 Extracted critical switching current density J_c as a function of pulse width at 280 K (c) and 310 K

442 (d). Red dashed lines are fitting curves of the thermal activation model.

443



444

445 **Figure 6.** Current-induced SOT switching at different temperatures with in-plane magnetic field

446 $\mu_0 H_x = +50$ mT (a) and $\mu_0 H_x = -50$ mT. (b) Repeatable SOT switching at 294 K (c) and 301

447 K (d) with in-plane magnetic field $\mu_0 H_x = -50$ mT with successive positive/negative current

448 pulses with 100 ns duration at periods of 1 s. (e) Critical switching currents density J_c and $\mu_0 H_K * M_s$

449 at various temperatures. The blue dashed line is an eye guide to show the nearly dependence

450 of J_c versus T .

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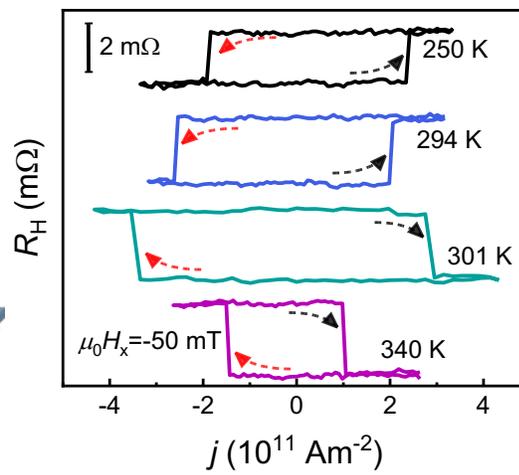
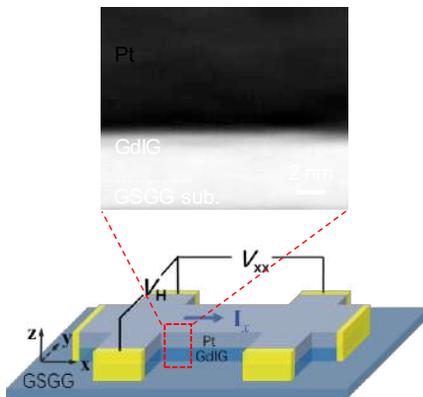
453 **Table of Contents**

454

455 **Current-induced magnetization switching across a nearly room-temperature compensation**
456 **point in an insulating compensated ferrimagnet**

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458 *Aurélien Manchon,[‡] and Xixiang Zhang^{†*}*

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