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Competition between chiral energy and chiral damping in the asymmetric expansion of magnetic bubbles

Arnab Ganguly^{1,2§}, Senfu Zhang¹, Ioan Mihai Miron³, Jürgen Kosel¹, Xixiang Zhang¹, Aurelien Manchon^{1,4*}, Nirpendra Singh² Dalver H. Anjum² and Gobind Das^{2*}

¹ Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia.

²Department of Physics, Khalifa University, Abu Dhabi 12788, United Arab Emirates.

³CNRS, SPINTEC, 38000 Grenoble, France.

⁴CINaM, Aix-Marseille University, CNRS, Marseille, France.

*Corresponding email: manchon@cinam.univ-mrs.fr, gobind.das@ku.ac.ae

§ Present address: Department of Physics, Khalifa University, Abu Dhabi 12788, United Arab Emirates.

Abstract

Magnetic chirality is an important knob in spintronics and can be engineered through structural symmetry breaking of magnetic thin film multilayers. The dynamics of chiral domain walls is determined by the cooperation of chiral contributions in the magnetic energy functional as well as in the dissipation tensor which need to be better controlled for the sake of the device applications. In this work, we performed a systematic study of magnetic field-induced magnetic bubble expansion in structural inversion asymmetric multilayers with different Pt thicknesses using polar magneto-optical Kerr microscopy. Asymmetric expansion of magnetic bubble is investigated in the creep regime as a function of in-plane and out-of-plane magnetic fields. The results reveal the competition between two key mechanisms governing the asymmetry in the field-driven domain wall expansion, namely the Dzyaloshinskii-Moriya interaction and the chiral magnetic damping. The interplay between these two effects leads to seemingly counterintuitive experimental signature, depending on the strength of the external magnetic field. The effective control on the

29 bubble asymmetry expansion can be of great importance for the future memory and multiplexer
30 based applications.

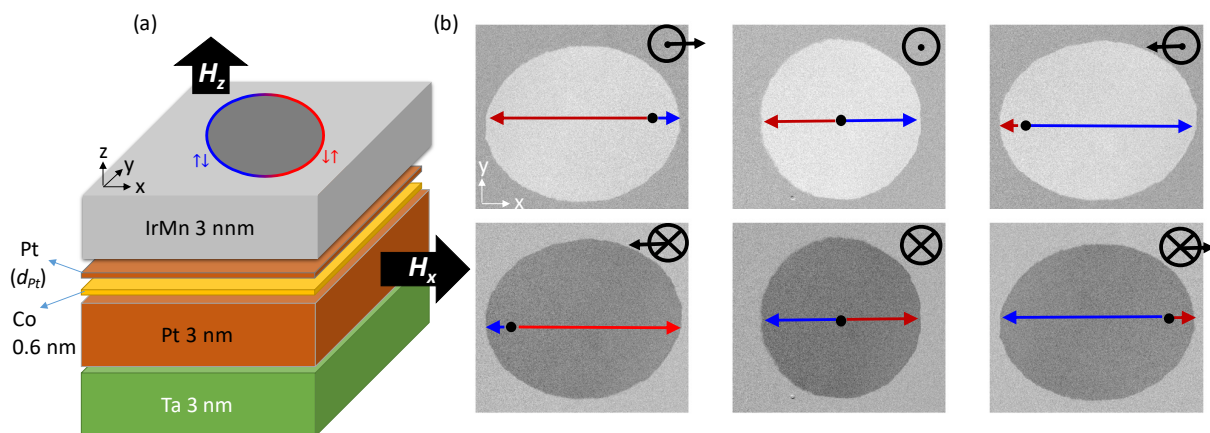
31 **Keywords:** chiral damping, Dzyaloshinskii-Moriya interaction, magnetic bubble expansion

32 Magnetic domains are candidate building blocks for modern long-term magnetic data storage[1-
33 3]. The out-of-plane magnetic domains with switchable magnetization direction are commonly
34 used as binary memory bits for non-volatile devices[4-6]. The ultrahigh mobility of current-driven
35 magnetic domain walls recently observed in non-centrosymmetric heterostructures[7-9] opening
36 attractive opportunities for alternative storage and data transfer technologies such as the magnetic
37 racetrack[1,10]. Hence, a precise understanding of the physical characteristic of the dynamics of
38 magnetic domain walls in such heterostructures can substantially enhance the magnetic devices
39 performance [11-15]. The typical system (e.g., Pt/Co/AlO_x) consists of a perpendicularly
40 magnetized thin film embedded between dissimilar heavy metals shows current-driven high
41 domain wall velocity up to 400 m/s [7,8]. The high velocity is attributed to the cooperation between
42 damping-like torque arising from the adjacent heavy metals and Dzyaloshinskii-Moriya interaction
43 (DMI) present at the interfaces[16,17]. The magnitude of the damping-like torque is normally
44 assessed through spin-torque or spin-pumping measurements[18-20], while magnitude of the DMI
45 is determined by the following ways. Various imaging techniques such as Nitrogen vacancy
46 centers magnetometry[21-23], scanning transmission X-ray microscopy[24], electron or X-ray
47 holography[25-28], and Lorentz microscopy[29-32] allow for direct observation of the chirality of
48 the domain wall, confirming that interfacial DMI favors Néel configuration over Bloch
49 configuration[33]. Brillouin light scattering[34-36] determines the momentum shift of counter-
50 propagative spin waves through inelastic scattering. Finally, several methods have been proposed
51 based on the dynamical characteristics of the domain wall motion. In the simplest model, DMI
52 translates into an effective in-plane magnetic field, which can be determined by recording the
53 velocity shift obtained when applying an external field or probing the asymmetric expansion of
54 magnetic bubbles[37-41]. The asymmetric expansion in the magnetic bubble is driven by a small
55 external magnetic field in the creep regime, *i.e.*, a regime of motion dominated by thermal
56 activation in the presence of a considerable disorder. However, the creep motion is a subtle regime
57 of motion where energy dissipation plays a crucial role. Herein, we propose the symmetry breaking
58 of the system translate into the emergence of a chiral contribution to the magnetic damping. To
59 date, it remains unclear how DMI (chiral energy) and chiral damping compete with each other in
60 the context of creep motion. In this article, we perform a systematic study of field and current-
61 induced domain wall motion in multilayers with inversion symmetry breaking. We also suggest
62 that both effects (DMI and chiral damping) display quite different domain-velocity dependency on

63 materials. As such, we propose that the asymmetric expansion of the magnetic bubble is dominated
 64 by either DMI or chiral damping in opposite limits.

65 Results

66 Thin film multilayer of Ta(3 nm)/Pt(3 nm)/Co (0.6 nm)/Pt (d_{Pt})/IrMn(3 nm) is deposited using
 67 dc/rf magnetron sputtering. Here, d_{Pt} varies from 0 to 1 nm for field induced and 0 to 5 nm for
 68 current induced domain wall motion studies. The thin film stack, along with the experimental
 69 configuration, is illustrated in fig. 1(a). The sputtering conditions are carefully chosen to obtain
 70 perpendicular magnetic anisotropy in these films. The experiment is performed using magneto-
 71 optical Kerr effect microscopy in polar geometry[42-45]. A differential Kerr imaging is performed
 72 to observe the magnetic domains and to eliminate the contribution of any nonmagnetic intensities.
 73 Square pulses of the magnetic field are applied both in-plane and out-of-plane of the sample using
 74 two independent electromagnets. To nucleate a bubble, the thin film magnetization is saturated in
 75 one perpendicular direction followed by an out-of-plane field pulse in the opposite direction. The
 76 bubbles nucleate from defects or pinning centers present in the sample. The in-plane magnetic
 77 field (H_x) alone cannot nucleate or drive bubbles because of strong perpendicular magnetic
 78 anisotropy (PMA) of the sample but it induces asymmetric motion when combined with the out-
 79 of-plane field (H_z). For proper synchronization and temporal overlap between the fields, the in-
 80 plane pulse is chosen longer than the out-of-plane pulse.



81
 82 **Figure 1:** (a) Schematic illustration of sample along with the field configuration of bubble expansion
 83 experiment. (b) Kerr microscopy images of magnetic bubbles at different field orientations. The

84 orientation for the H_x and H_z are denoted in the top right corner of each figure. Red and blue arrows
85 indicate the propagation of opposite domain walls from the nucleation center.

86 **Asymmetric bubble expansion.**

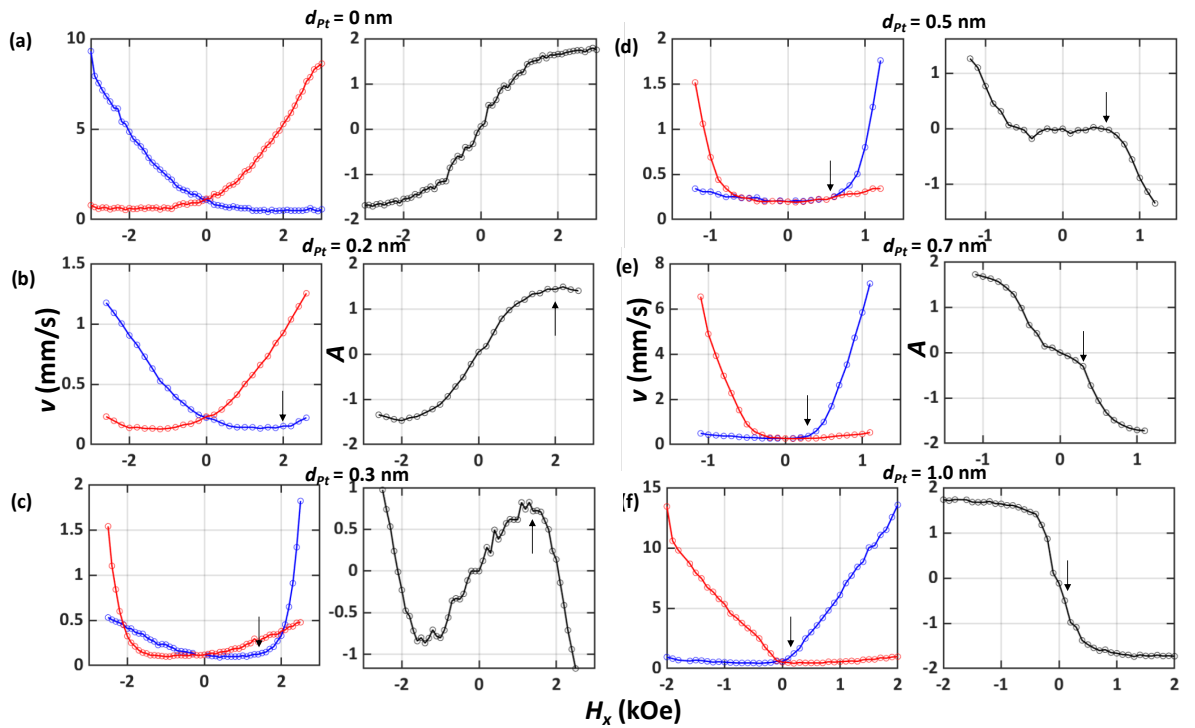
87 Figure 1(b) shows differential Kerr images of magnetic bubbles in Ta(3 nm)/Pt(3 nm)/Co(0.6
88 nm)/IrMn(3 nm) under six different field configurations. The dark and bright contrasts in this
89 image indicate \downarrow and \uparrow out-of-plane configuration of the magnetization vector. Red and blue arrows
90 indicate the expansion of $\downarrow\uparrow$ and $\uparrow\downarrow$ domain walls while the black dot between the arrows indicates
91 the nucleation center of the bubbles. Here, a 15 ms long out-of-plane field pulse ($H_z = 120$ Oe) is
92 applied for the expansion of the bubbles. The direction of H_z is shown at the top right corner of
93 each image. An additional in-plane field ($H_x = 2$ kOe) is applied in some cases as indicated in the
94 top right corner of the figures.

95 We observe that without an in-plane field the bubbles are circular or symmetric with respect to
96 origin. In the presence of an in-plane field, the velocities of $\downarrow\uparrow$ and $\uparrow\downarrow$ domain walls are very
97 asymmetric along x -direction. The asymmetry changes sign with the reversal of H_x . This
98 asymmetry can be originated in two ways. In the widely accepted scenario, the presence of DMI
99 creates an effective in-plane magnetic field, normal to the domain wall, and favors the Néel
100 configuration[46]. An external magnetic field lowers the energy of one side of the bubble with
101 respect to the other (in one case, Néel wall is enforced, while it is weakened in the other), resulting
102 in an asymmetric creep expansion. Another scenario is possible, though, and does not necessitate
103 the presence of a DM field. If no such field is present, magnetostatics dictates that the magnetic
104 moments at the bubble boundary adopt a Bloch configuration. Applying an in-plane magnetic field
105 therefore promote Neel configuration. Thus, the two opposite sides of the bubble adopt the
106 opposite chirality. If the magnetic damping is sensitive to this chirality[47], then the opposite sides
107 of the bubble are expected to dissipate energy differently, resulting in a different creep velocity
108 and, thereby, an asymmetric expansion. As a general rule, one expects that both effects should
109 coexist, and till now, it remains unclear how to distinguish them. To do so, we analyze the
110 dependence of the velocity of the bubble boundary as a function of the in-plane and out of plane
111 field.

112 **In-plane field dependence of domain wall velocity**

113 The variation of domain wall velocities with in-plane field is studied in this section. Figure 2(a-f)
114 shows velocities for $\downarrow\uparrow$ and $\uparrow\downarrow$ domain walls by red and blue curves plotted on the left side and
115 velocity asymmetry ($A = 2(v_{\downarrow\uparrow} - v_{\uparrow\downarrow})/(v_{\downarrow\uparrow} + v_{\uparrow\downarrow})$) on the right side of each figure. The thickness
116 of top Pt, d_{Pt} is indicated on each figure. Figure 2(a)-left shows that for $d_{Pt}=0$, the velocity of $\downarrow\uparrow$
117 domain walls (red curve) is larger than that of $\uparrow\downarrow$ domain walls (blue curve) at positive in-plane
118 field. Moreover, the former increases with the field value whereas the latter decreases with it. At
119 negative field, we have the opposite scenario. All the curves in Fig. 2 are symmetrically opposite
120 with respect to zero field as the sample does not have any preferential direction. On the right side
121 of Fig. 2(a), the velocity asymmetry A changes sign from positive to negative as the field is
122 reversed from positive to the negative direction. The magnitude of A increases faster at lower field
123 and slows down at higher field, although saturation is not observed until 3 kOe. In Fig. 2(b) for d_{Pt}
124 $=0.2$ nm the velocity of the $\uparrow\downarrow$ wall (blue curve) starts to increase after a critical field $H_C = +2$ kOe
125 thus causing a slope reversal in the blue curve as well as in the A curve around the same region
126 (indicated by arrows). At $d_{Pt}=0.3$ nm the feature is observed at a lower field of $H_C \sim 1.5$ kOe [Fig.
127 2(c)]. The velocity of the $\uparrow\downarrow$ wall (blue curve) starts increasing dramatically after H_C , and overtakes
128 the $\downarrow\uparrow$ wall velocity (red curve) at 2 kOe. In this case, A changes sign for the same sign of H_x across
129 2 kOe. For $d_{Pt}=0.5$ and 0.7 nm, H_C is around 0.5 and 0.2 kOe and finally at $d_{Pt}=1$ nm the value is
130 close to zero [Fig. 2(d-f)]. In Fig. 2(f) ($d_{Pt}=1$ nm) the velocity of $\uparrow\downarrow$ wall (blue curve) is much
131 higher than that of the $\downarrow\uparrow$ wall (red curve) at positive field. The asymmetry is opposite as compared
132 to Fig. 2(a) ($d_{Pt}=0$ nm). Apart from that, another contrast between Figs. 2(a) and 2(f) is the
133 saturation field of asymmetry curves. In the first case no saturation is observed until 3 kOe while
134 in the second case it occurs ~ 1.2 kOe. The shape of the velocity curves for $d_{Pt}=0$ and 1 nm are
135 completely different. In the former case it is exponential and in the latter case it is linear. From
136 these observations it appears that there is a competition between two effects responsible for the
137 velocity asymmetry, one dominating at lower values of d_{Pt} and the other at higher values of d_{Pt} .
138 The chiral contribution to the magnetic energy, i.e., the DMI contribution, can be viewed as an
139 internal in-plane field acting on the domain wall, a change of which causes an opposite lateral shift
140 of in-plane velocity curves for the two opposite walls. Any feature in the velocity curve thus gets
141 laterally shifted and manifested at different field but at same velocity. The chiral contribution to
142 energy dissipation, i.e. the chiral damping, does not impact the magnetic energy itself, rather the

143 attempt frequency controlling the thermal activation[12,40]. This gets the velocity curves shifted
 144 vertically in opposite directions, thus the feature manifested at same field but at different
 145 velocities[40]. In Fig. 2(a), H_C is out of the measurement range and from Figs. 2(b) to (f) H_C
 146 monotonically decreases close to zero value. This suggests that for $d_{Pt}=0$, we have the highest
 147 internal DMI field which progressively vanishes upon increasing the top Pt layer thickness. The
 148 observation is consistent with previous literature showing that DMI arising from opposite
 149 interfaces tend to cancel each other[38,48]. The exponential variation of the velocity curve in Fig.
 150 2(a) also supports that the asymmetry is coming from energy. In Fig. 2(c) opposite asymmetry is
 151 observed across 2 kOe for the same applied field direction as the asymmetry curve crosses the zero
 152 line. A mere decrease internal DMI field cannot explain this phenomenon. Indeed, in such case the
 153 sign of A would remain the same for a particular direction of H_x . This unconventional sign reversal
 154 process suggests that a completely different mechanism takes over the DMI field upon increasing
 155 d_{Pt} . This mechanism is attributed to chiral damping, eventually dominating over the internal DMI
 156 field which will be discussed in the later part of the paper. This argument is also supported by the
 157 non-exponential velocity curve in Fig. 2(f) that strongly differ from the more exponential
 158 dependence observed in Fig. 2(a).

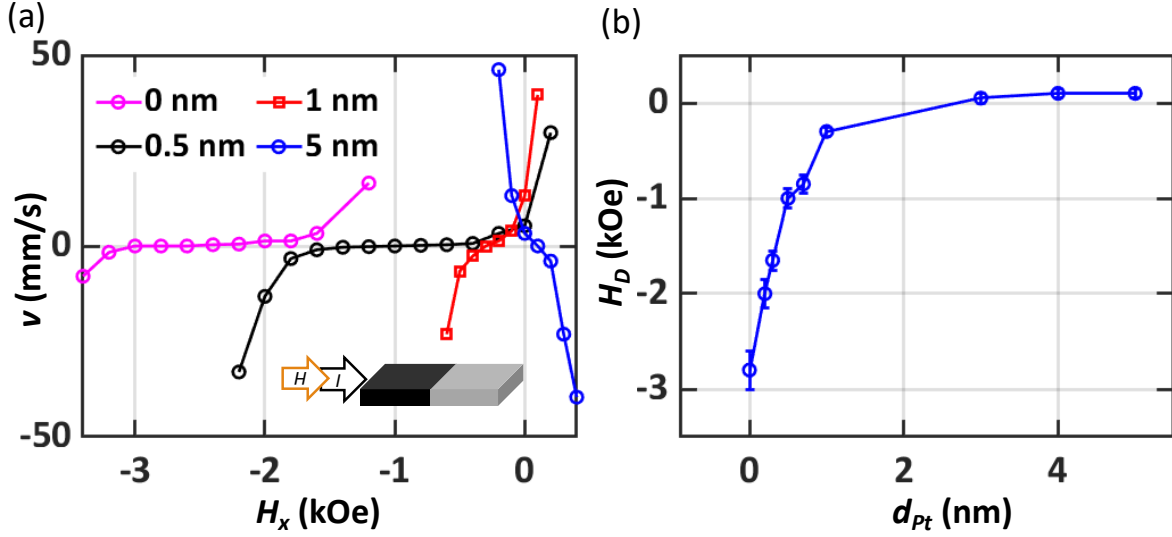


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160 **Figure 2:** (a-f: left) In-plane field dependent velocity curves of $\downarrow\uparrow$ (red) and $\uparrow\downarrow$ (blue) domain walls and
161 (a-f: right) corresponding velocity asymmetry for top Pt thicknesses of $d_{Pt}=0, 0.2, 0.3, 0.5, 0.7$ and 1 nm.

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163 To estimate the values of DMI field and its dependence upon increasing top Pt thickness, current-
164 induced domain wall motion has been studied in presence of in-plane magnetic field. Thin film
165 micro strips are fabricated using photo-lithography. A transverse domain wall is created on the
166 strip. Simultaneous current and in-plane magnetic field pulse are applied along the length of the
167 film. The current drives the domain wall while the in-plane field either helps or opposes the
168 propagation by favoring one Néel chirality over the other, depending on the direction of the field.
169 Thus, there exists a compensating field H_x for which the current-induced domain wall velocity
170 vanishes. In that case, the applied field completely opposes the internal DMI field. Thus by
171 measuring the compensation field we extract the DMI field value of the film. Figure 3(a) shows
172 velocity curve as a function of in-plane field for a constant current density. In our experiment a $\downarrow\uparrow$
173 domain wall is driven by current pulses from the left. A field parallel (antiparallel) to the current
174 direction is considered positive (negative). For all different values of d_{Pt} , the domain wall velocity
175 changes exponentially with field. In each of the cases, there is a field range for which the velocity
176 of the domain wall is zero and there exists two avalanche fields (H_{av}) in either side of which domain
177 wall starts to move either along or opposite to the current direction, respectively. It is found that
178 with increasing current density both the H_{av} 's converge to their mean value. That means that the
179 mean value of H_{av} does not change with current density which is nothing but the DMI field (H_D)
180 of the sample. At lower current density the error associated with H_D is larger because of the flatness
181 of the curve. On the other hand, at higher current density the probability of nucleation of other
182 domains masking the domain wall of interest increases. Hence, practically the experiment is
183 limited to a certain current density and the corresponding error on H_D . The estimated H_D is plotted
184 in Fig. 3(b) as a function of the Pt thickness. The experiment confirms the DMI changes sign at
185 $d_{Pt}=3$ nm. From $d_{Pt}=0$ to 1 nm the DMI field decreases but does not change sign to cause opposite
186 asymmetry as observed in Fig. 2. This observation confirms the scenario of the two distinct
187 competing mechanisms.



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Figure 3: (a) In-plane field dependent $\downarrow\uparrow$ domain wall velocity. Inset shows the positive current and field convention. (b) The DMI field estimated as a function of top Pt thicknesses.

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Out-of-plane field dependence of domain wall velocity

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In the previous part, we have discussed asymmetric domain wall motion on qualitative grounds, avoiding entering into the details of the motion regime. General arguments based on the global behavior of the velocity asymmetry led us to postulate the competition between two chiral mechanisms. Let us now provide a more quantitative analysis of these two effects, based on the specific motion regime experienced by the domain wall. In our experiments, the domain wall moves in the thermally activated creep regime. Recent literature by Jué *et al.*[40] show that the velocity of domain wall in the creep regime can be modeled by creep scaling law as

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$$v = (d_0 f_0) \cdot e^{\left[\frac{-U_c(H_p)}{K_B T} \left(H_z^{-\frac{1}{4}} - H_o^{-\frac{1}{4}} \right) \right]} \quad (1)$$

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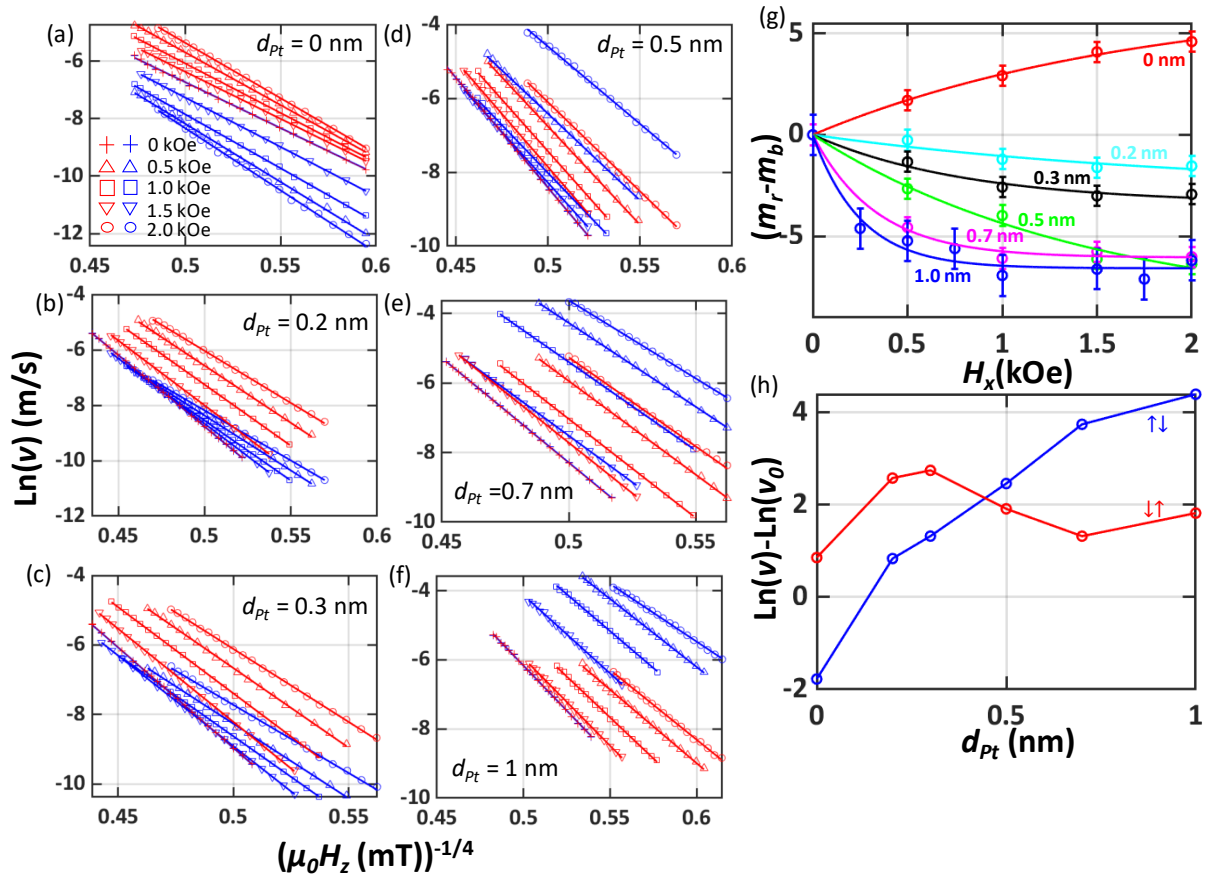
Where, $H_o = H_p / C^4$ ($C \sim 1$ is an empirical constant) and d_0 , f_0 , H_p , and U_c are the disorder correlation length, de-pinning attempt frequency, pinning field and pinning barrier respectively. In the exponent, the energy barrier $U_c(H_p)$ accounts for non-dissipative processes described by the magnetic energy functional. In particular, DMI is one such energy process that is discussed in previous literatures as a factor for controlling the asymmetry of the domain wall velocity[41,48-51]. On the other hand, f_0 is inversely proportional to the energy dissipation[52] In other words, a

206 change in the exponential coefficient reflects a change in the energy functional while a change in
 207 the pre-factor indicates a change in the energy dissipation of the system. When the logarithmic
 208 velocity is considered with respect to $H_z^{-1/4}$, the curve is linear in the creep regime with a change
 209 in slope indicating change in the energy and vertical shift representing change in the dissipation.

210 In Fig. 4(a-f), logarithmic velocities are plotted with varying out-of-plane field for different top Pt
 211 layer thicknesses as mentioned in each figure. The variation is well fitted by straight lines with
 212 negative slope (m) confirming that our measurement is in the creep regime. Each velocity curve is
 213 measured in presence of a constant H_x indicated next to the curve in Fig. 4a. For each in-plane
 214 field, the velocity is measured for $\downarrow\uparrow$ and $\uparrow\downarrow$ domain walls, reported in red and blue color,
 215 respectively. In general, the velocity curves in Fig. 4 are approximately parallel or make a small
 216 angle with each other. For $d_{Pt}=0$ [Fig. 4(a)], when an in-plane field is applied along x, the $\downarrow\uparrow$
 217 domain wall velocity slope (red curves) is shifted up to higher velocity while the $\uparrow\downarrow$ domain wall
 218 velocity slope (blue curves) moves down to lower velocity side with respect to zero field curve. In
 219 the other cases [Fig. 4(b-f)], when top Pt layer is introduced, H_x causes a positive shift for *both* $\downarrow\uparrow$
 220 and $\uparrow\downarrow$ curves. With increasing Pt thickness the $\uparrow\downarrow$ (blue) curves experience a dramatic vertical
 221 shift achieving higher velocity while the shift for the $\downarrow\uparrow$ (red) curves remains very small. This
 222 suggests that the chiral damping mechanism, present in the prefactor of Eq. (1), gets activated with
 223 the insertion of Pt assisting the $\uparrow\downarrow$ (blue) domain wall to move faster than $\downarrow\uparrow$ (red) walls and thus
 224 altering the asymmetry.

225 In order to provide a synthetic picture of the overall behavior of the velocity asymmetry, Fig. 4(g)
 226 displays $\delta m = (m_r - m_b)$, the difference between the slope of the velocity of $\downarrow\uparrow$ (red) and $\uparrow\downarrow$
 227 (blue) walls as a function of H_x . The colors indicate different values of d_{Pt} , as indicated next to each
 228 curve. The curves are fitted by the phenomenological formula $a(e^{-bH_x} - 1)$ where a and b are
 229 constants denoting the amplitude and saturation of the curve. From Fig. 4(g), it is found that the
 230 saturation field decreases with Pt thickness very similar to Fig. 3(b). Here the saturation essentially
 231 means that the energy difference between the opposite domain walls saturates at a field equal to
 232 the DMI field of the sample. As the DMI field decreases with Pt thickness the saturation field
 233 decreases. Figure 4(h) shows the vertical shift of the velocity curves in Fig. 4(a-f) with respect to
 234 $H_x=0$ curve at constant fields [$H_x=1.5$ kOe and $\mu_0 H_z=0.55$ (mT) $^{-1/4}$]. As mentioned above, the
 235 asymmetry in the vertical shift is attributed to the chiral contribution in the prefactor of Eq. (1),

236 i.e., to chiral damping. It is found that the $\uparrow\downarrow$ (blue) curves get monotonically shifted to higher
 237 velocity with Pt thickness while for $\downarrow\uparrow$ (red) curves the shift is significantly smaller and weakly
 238 depends on the Pt thickness. This suggests that the chiral damping mechanism gets activated with
 239 the insertion of Pt assisting the $\uparrow\downarrow$ (blue) domain wall to move faster than the $\downarrow\uparrow$ (red) one and thus
 240 altering the asymmetry. It is intriguing to observe that $\uparrow\downarrow$ and $\downarrow\uparrow$ domain walls are affected
 241 differently by the chiral damping.

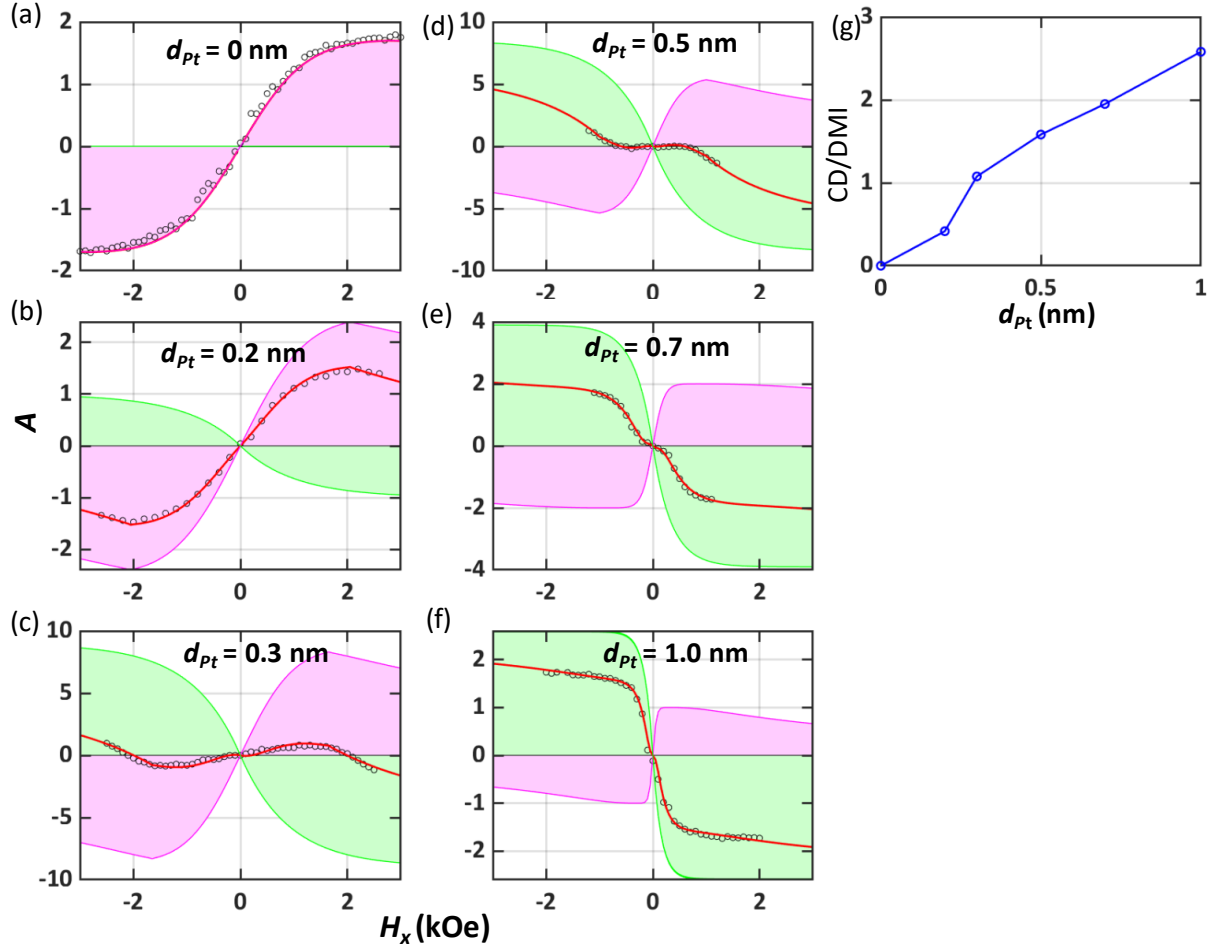


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 243 **Figure 4:** (a-f) out-of-plane field dependence of the logarithmic velocity of bubble domain. The scattered
 244 points are experimentally observed data while the straight lines are the fitted data. The red and blue lines
 245 correspond to $\downarrow\uparrow$ and $\uparrow\downarrow$ domain wall velocities (g) The slope difference for the opposite domain walls
 246 obtained from fig. 4(a-f) as a function of in-plane field and (h) velocity shift for the red and blue domain
 247 walls with respect to $H_x=0$ for different Pt thicknesses.

248

249 The analysis of current-driven motion (Fig. 3) and field-driven motion (Fig. 4) confirm the
 250 competition of two chiral mechanisms that we interpret as DMI field and chiral damping, which
 251 dominate at different Pt thicknesses. In Fig. 5, the asymmetry curves reported in Fig. 2 are fitted
 252 using the DMI and chiral damping models. From the very definition two distinct asymmetry curves
 253 can be identified as at a large field asymmetry reduces close to zero in case of DMI while it
 254 saturates in case of chiral damping. The domain wall velocity asymmetry due to DMI is
 255 represented by $v = v_0 e^{c|H_x + H_D|}$ and the asymmetry by $A_{DMI} = 2 \frac{v_{\uparrow\uparrow} - v_{\uparrow\downarrow}}{v_{\uparrow\uparrow} + v_{\uparrow\downarrow}}$. The chiral damping
 256 asymmetry is characterized by a phenomenological saturation function $A_{CD} = 2 \left(1 - e^{-\frac{H_x}{s}}\right)$, s
 257 being a parameter related to the saturation. Both the asymmetries are multiplied by a weight factor
 258 to consider their relative contribution to the overall asymmetry. All the asymmetry curves are well
 259 fitted by a combination of these two effects with H_D as a fixed parameter extracted from the
 260 current-induced experiment in Fig. 3. The purple shade of each figure denotes the DMI
 261 contribution while the green shade indicates the chiral damping contribution. From Fig. 5 we see
 262 that both curves are symmetrically opposite which means that chiral damping and DMI compete
 263 with each other. From Fig. 5(a) to (f) we see that the DMI contribution decreases progressively
 264 when increasing Pt thickness, while the chiral damping contribution increases. Figure 5(g) displays
 265 the ratio between the chiral damping and DMI contributions to the asymmetry, as obtained from
 266 Fig. 5(a-f). It clearly indicates that chiral damping steadily increases over DMI upon increasing
 267 the Pt thickness, indicating a transition from a velocity asymmetry dominated by chiral energy to
 268 an asymmetry governed by the chiral dissipation.

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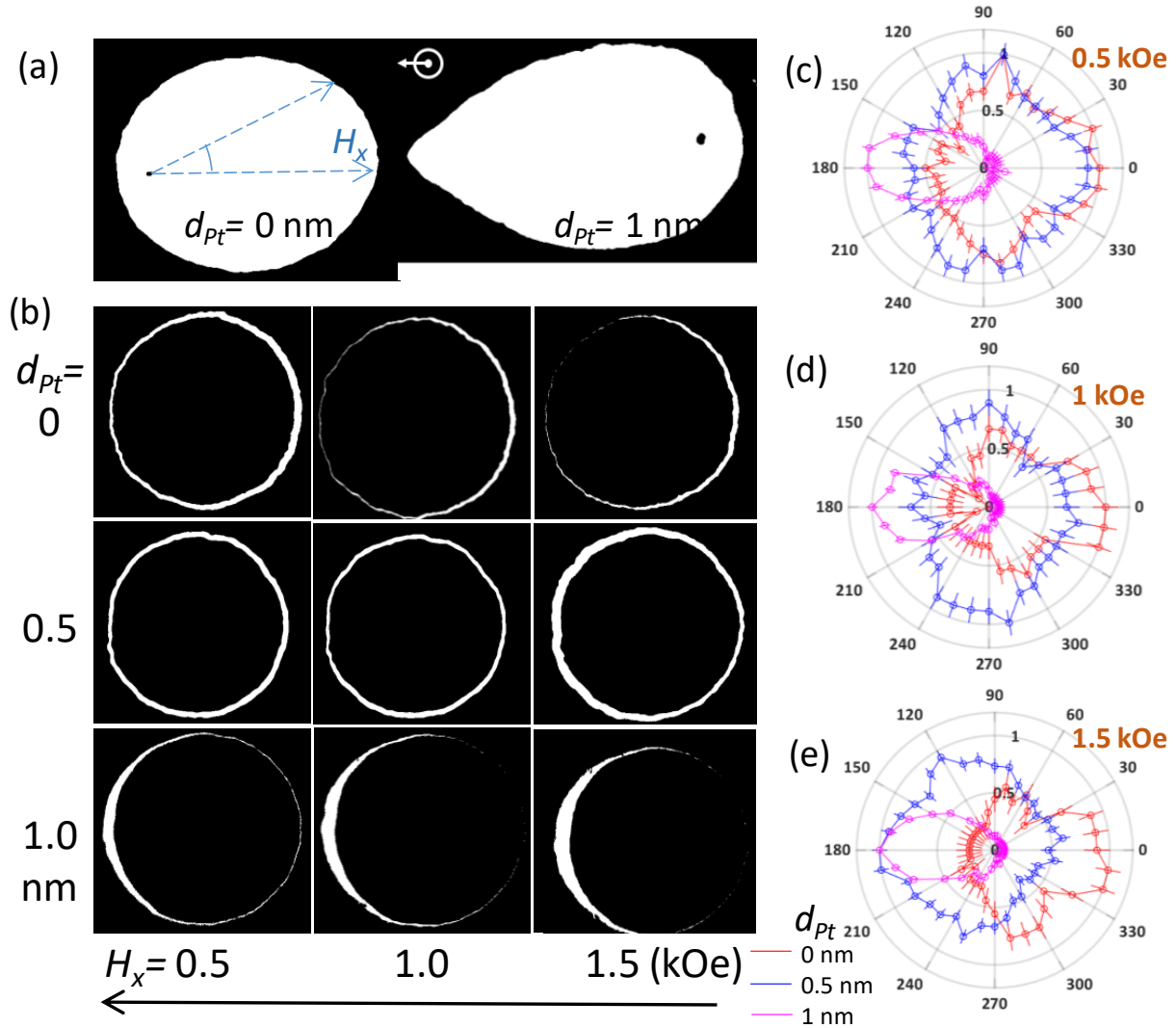
271 **Figure 5:** (a-f) In-plane field dependent asymmetry curves fitted as a combination of DMI (purple) and
 272 chiral damping (green) contribution and (g) The ratio of chiral damping and DMI (*i.e.* weight factor ratio)
 273 contributing to the asymmetry for different Pt thicknesses.

274 **Angle dependence of velocity**

275 To complete this study, we analyze the shape of the magnetic bubbles for various Pt thicknesses.
 276 Figure 6(a) shows bubble expansion in a sample with $d_{Pt}=0$ nm (left) and 1 nm (right) under the
 277 same field configuration. Based on the analysis provided above, these two samples correspond to
 278 different asymmetry mechanism: the former is dominated by DMI, while the latter is dominated
 279 by chiral damping. We immediately observe that the asymmetric bubble expansion in these two
 280 regimes is not only opposite but also present quite a different shape. To further analyze this
 281 behavior, we study the domain wall velocity as a function of angle θ , with respect to the in-plane

282 field. First, a circular bubble is created by an out-of-plane field and then it is expanded
283 infinitesimally with a short out-of-plane field pulse in presence of an in-plane field. From the
284 differential image shown in Fig. 6(b), displacements at different θ are obtained and summarized in
285 Fig. 6(c-e). For an infinitesimal expansion, the magnetization vector at a certain θ does not change
286 significantly. Thus, the distance measured at an angle θ corresponds to the displacement of a
287 particular magnetization vector at boundary during expansion. Images in Fig. 6(b) correspond to
288 the Pt thickness $d_{Pt}=0, 0.5$ and 1 nm (top, middle and bottom panels) at three different fields
289 $H_x=0.5, 1$ and 1.5 kOe (left, central and right panels). For $d_{Pt}=0$ nm the expansion is favored on
290 the right side, for $d_{Pt}=0.5$ nm it is more or less symmetric and for $d_{Pt}=1$ nm it expands mostly on
291 the left side. Figure 6(c-e) shows normalized polar plot of domain wall velocity as a function of θ
292 at three different $H_x, 0.5$ kOe, 1 kOe and 1.5 kOe (top, middle and bottom panels). Here we clearly
293 see two distinct natures of θ dependence curve for $d_{Pt}=0$ nm (red) and $d_{Pt}=1$ nm (magenta). For d_{Pt}
294 $=1$ nm (magenta), the displacement is more sensitive to θ , resulting a sharp structure at 180°
295 whereas for $d_{Pt}=0$ nm (red) the change in displacement is more gradual giving rise to a flatter curve
296 having maxima at 0° . For $d_{Pt}=0.5$ (blue), we see a superposition of these two patterns. At lower
297 field, $H_x=0.5$ kOe the curve is more similar to $d_{Pt}=0$ nm, while with increasing field the curve starts
298 having more similarities with $d_{Pt}=1$ nm. From this observation, we can speculate, in line with the
299 above discussion, that the two distinct angular dependence patterns at $d_{Pt}=0$ and 1 nm establish the
300 fact that the asymmetry stems from two fundamentally different phenomena. Now we can identify
301 that the flatter variation is a consequence of the energy related asymmetry and the sharp variation
302 corresponds to the chiral damping. At 0.5 nm both the phenomena are contributing to the opposite
303 asymmetry and thus the superposition effect is observed in angular dependence curve.

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305

306 **Figure 6:** (a) The shape of bubbles for $d_{Pt}=0$ and 1 nm for the same field configuration, (b) Differential
 307 Kerr image of small expansion of a circular bubble for different d_{Pt} at different values of H_x and (c-e)
 308 show the angular displacements of bubbles corresponding to the in-plane fields 0.5, 1 and 1.5kOe. Red,
 309 blue and magenta curves correspond to top Pt thickness of 0, 0.5 and 1nm respectively.

310 **Conclusions**

311 In summary, we systematically study field-driven bubble expansion in structure lacking inversion
 312 symmetry. In such samples magnetic bubbles expand asymmetrically in presence of in-plane and
 313 out-of-plane field. The velocity of the domain wall in the creep regime can be well fitted by the
 314 creep scaling law. The velocity asymmetry can occur along or opposite to the field direction
 315 depending on the domain wall chirality and DMI of the sample. Damping and energy are the most
 316 important factors which control the asymmetry. Energy related asymmetry corresponds to a change

317 in slope while chiral damping asymmetry can be identified through a vertical shift in the out-of-
318 plane velocity curve. In this study the velocity asymmetry is investigated in Ta(5 nm)/Pt(3 nm)/Co
319 (0.6 nm)/IrMn(3 nm) by systematically inserting thin layer of Pt between Co and IrMn interface.
320 The thickness of Pt varies from 0 to 1 nm. With no Pt, the asymmetry is dominated by energy
321 having a strong effective internal field. As Pt thickness increases the internal field starts to
322 disappear while at the same time chiral damping appears taking a leading role on asymmetry. The
323 chiral damping asymmetry acts opposite to the energy asymmetry. As a result of these two
324 competing effects, the asymmetry reversal occurs with increasing Pt thickness. The study is helpful
325 for the effective control of magnetic bubbles which can be used for future memory and logic based
326 applications.

327

328 **Methods**

329 **Sample preparation:** Thin film multilayer of Ta(5 nm)/Pt(3 nm)/Co (0.6 nm)/Pt(d_{Pt})/IrMn(3 nm)
330 with d_{Pt} ranging from 0 to 5 nm were deposited on thermally oxidized Si substrates using Singulus
331 dc/rf magnetron sputtering. The sputtering conditions were carefully chosen to obtain
332 perpendicular magnetic anisotropy in these films. The patterned strip tracks and the electrodes are
333 prepared using lithography and Ar-ion milling.

334 **MOKE measurements:** The experiment was performed using magneto-optical Kerr effect
335 (MOKE) microscopy in polar geometry[42-45]. To observe the domains differential Kerr imaging
336 was performed which helped us to eliminate nonmagnetic intensities from the image. Square
337 pulses of the magnetic field were applied both in the plane and out-of-plane of the sample using
338 two independent electromagnets. To nucleate a bubble, the thin film magnetization was saturated
339 in one perpendicular direction followed by an out-of-plane field pulse in the opposite direction.
340 The bubbles nucleate from defects or pinning centers present in the sample. An in-plane field alone
341 cannot nucleate or drive bubbles because of strong PMA but combined with out-of-plane field it
342 induces asymmetric motion. To ensure a proper synchronization and temporal overlap between the
343 fields, in-plane pulse is chosen longer than the out-of-plane pulse.

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