Nanoscale domain wall devices with magnetic tunnel junction read and write

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The manipulation of fast domain wall motion in magnetic nanostructures could form the basis of novel magnetic memory and logic devices. However, current approaches for reading and writing domain walls require external magnetic fields, or are based on conventional magnetic tunnel junctions (MTJ) that are not compatible with high-speed domain wall motion. Here, we report domain wall devices based on perpendicular MTJs that offer electrical read and write, and fast domain wall motion via spin-orbit torque. The devices have a hybrid free layer design that consists of platinum/cobalt (Pt/Co) or a synthetic antiferromagnet (Pt/Co/Ru/Co) into the free layer of conventional MTJs. We show that our devices can achieve good tunnelling magnetoresistance readout and efficient spin-transfer torque writing that is comparable to current magnetic random-

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access memory technology, as well as domain wall depinning efficiency that is similar to stand-alone materials. We also show that a domain wall conduit based on a synthetic antiferromagnet offers the potential for reliable DW motion and faster write speed compared to a device based on Pt/Co.

The manipulation of magnetic domain walls (DW) in nanostructures for processing information is promising for the development of next-generation logic and data storage devices [1, 2], including racetrack memory [3, 4], spin logic [5, 6, 7, 8] and neuromorphic computing [9, 10, 11]. Recently, DW motion at high velocity has been demonstrated in ultrathin magnetic layers on heavy metals based on the Dzyaloshinskii-Moriya interaction (DMI) and spin-orbit torque (SOT) [12, 13, 14, 15], in synthetic antiferromagnetic systems [16] based on the additional exchange coupling torque, and in ferrimagnets [17] based on angular momentum compensation. For practical applications, methods to electrically read and write DWs at nanoscale in these materials are required. Current approaches for writing DWs require a magnetic field, and readout requires either Hall bar devices or magnetic imaging techniques [5, 8, 9, 12, 13, 17, 14]. These schemes are useful for characterizing material properties, but they are not compatible with nanoscale DW devices. The adoption of magnetic tunnel junctions (MTJ) could potentially provide an approach to electrically write and read DWs. Current spin-transfer-torque magnetic random-access memory (STT-MRAM) technology is based on MTJs composed of a CoFeB/MgO free layer [18] that offers high tunnelling magnetoresistance (TMR) readout and low STT writing current. However, the CoFeB/MgO material stack has limitations for DW devices such as low DW speed [19] and challenges related to the etch patterning steps of the manufacturing process [20, 21]. To address these issues, we propose a hybrid free layer by introducing a second free layer for DW transport into the conventional MTJ stack. Such a design has been studied to increase the thermal stability of STT-MRAM memory cells [22, 23], but it has not yet been explored for DW devices.

In this Article, we report functional DW devices with electrical read and write using a hybrid free layer design. In such a hybrid free layer design, the second free layer is exploited to enable high-velocity DW motion: Pt/Co (Pt/Co-HFL) [12, 15], and Pt/Co/Ru/Co, where the thickness of ruthenium is varied to form a free layer based on a synthetic antiferromagnet (SAF-HFL) or a synthetic ferromagnet (SFM-HFL) [16, 24]. We first show that single MTJs with a hybrid free layer stack can offer reliable TMR readout signal and efficient STT writing and can thus be used as the outputs and the inputs of a DW device. Using time-resolved conductance measurements in single MTJs, we find that the Pt/Co/Ru/Co-based free layer with antiferromagnetic coupling provides faster STT-

driven switching dynamics than a dual-MgO reference stack while maintaining retention stability. We then build fully integrated DW devices that have MTJs for read and write. In particular, we show that an input signal can nucleate DWs locally via STT at the input-MTJ and a DW can be read out via TMR at the output-MTJ, while the DWs can propagate between input and output via SOT. We also show that external magnetic field and SOT can be used to manipulate DW dynamics at the nanoscale.

Hybrid free layer MTJ stack design

In our hybrid free layer design, the first free layer (FL1) consists of the conventional CoFeB/MgO-based free layer (Fig. 1 a). The second free layer (FL2), deposited onto a heavy metal, serves as the DW conduit, which typically consists of a ferromagnet [12] or a synthetic antiferromagnetic system [16]. FL2 offers high DW speed originating from interfacial Dzyaloshinskii-Moriya interaction, SOT [12, 13, 14, 15] and/or exchange coupling torque [16]. Note that the spacer material between FL1 and FL2 plays an important role in the stack design. First, it serves to decouple the crystallization of CoFeB (FL1) and FL2 as the fcc (111) crystal structure of cobalt is incompatible with the bcc (001) crystal structure of CoFeB. Second, it allows ferromagnetic coupling between FL1 and FL2 by interlayer exchange coupling, so they behave as a single free layer. Third, direct growth of an MgO tunnelling barrier with bcc (001) crystal structure on Co (FL2) is not trivial due to incompatible crystal structure and poor electron band matching [22]. Therefore, the addition of the CoFeB layer (FL1) in contact with the MgO barrier is indispensable for retaining high TMR [22, 23] and high STT switching efficiency. In principle, this approach could

Fig. 1 | Schematic of hybrid free layer concept. (a) Hybrid free layer (HFL) concept consisting of FL1 (top-left), based on CoFeB/MgO for efficient STT write and high TMR read, and FL2 (bottom-left), consisting of a material with inherent perpendicular magnetic anisotropy (PMA) which is optimized for high DW velocity driven by SOT. The two free layers are ferromagnetically coupled through a spacer layer (right). Schematic of DW-based devices with Pt/Co-HFL (b) and SAF-HFL (c) design, respectively. FL2 consists of a Co layer on top of Pt (Pt/Co-HFL) or of a Co/Ru/Co structure with SFM (SFM-HFL) or SAF coupling (SAF-HFL) on top of Pt.

60 potentially allow the integration of any high DW speed material in FL2, including ferrimagnets [25], for specific
61 applications such as DW or skyrmion tracks [26, 27] or spin wave computation [28].

62 Fig. 1 b-c illustrate the device concept with Pt/Co and Pt/Co/Ru/Co as DW conduits and MTJs as write and
63 read components. In this proposal, the DW device has three main components in which each one owns its specific
64 functionality: DW writing (*input*), DW transport (*conduit*) and DW reading (*output*). The operation principle is as
65 follows: STT is locally applied at the input pillar to inject DWs into the DW conduit (*i. e.*, DW writing process) via
66 the strong ferromagnetic coupling between CoFeB and FL2 (Extended Data Fig. 1 a). Subsequently, the DW travels
67 along the track driven by magnetic field or SOT (Extended Data Fig. 1 b) (*i.e.*, DW transport process). The detection
68 of the DW at the output is enabled by TMR (*i.e.*, DW reading process). As a result, this DW device concept
69 simultaneously benefits from efficient STT switching, good TMR owing to the CoFeB/MgO interface, and high DW
70 velocity, resulting from a combination of SOT, DMI and/or exchange coupling torque in the DW conduit materials
71 on heavy metals.

72 **TMR reading and fast STT writing in single MTJ pillar**

73 To verify the applicability of the hybrid free layer concept, we studied the magnetic properties of single
74 MTJs made with different types of free layer (Fig. 2 a), fabricated on 300 mm wafers using standard processes of
75 MRAM technology. Fig. 2 b-c display typical square TMR hysteresis loops of an MTJ pillar as function of field and
76 current pulse, respectively. Importantly, we obtain similar TMR values, about 80 %, and STT switching currents,
77 about 200 μA , in all types of free layer. This result suggests that the obtained TMR and STT efficiency are mainly
78 contributed by the CoFeB/MgO/CoFeB interfaces as expected in a conventional STT-MRAM device [18, 29, 30].
79 Note that the lower coercivity in the Pt/Co-based hybrid free layer device is linked to our choice of relatively low
80 anisotropy in the stack design (Supplementary Note. 3.1.2). The switching probability dependence of writing current
81 amplitude (Fig. 2 d) verifies the deterministic STT switching in all devices (Supplementary Note. 4.3). A slightly lower
82 write current ($\sim 170 \mu\text{A}$) was found in dual-MgO devices, which may be related to the lower damping constant in

Fig. 2 | Hysteresis loops showing reliable TMR and STT in HFL-MTJs. (a) Illustration of standard Dual-MgO, PtCo-HFL and SAF-HFL stack, color code similar as in Fig. 1 a, (b) typical TMR loops as function of perpendicular magnetic field in MTJs with nominal diameter of 60 nm, (c) STT induced magnetization reversal at 50 ns pulse width, (d) switching probability distribution measurement averaged over 1000 events per point.

CoFeB [31] and dual-MgO being an already optimized stack. It is worth to note that the demonstration of good TMR read and reliable STT write in synthetic antiferromagnetic-based free layer design opens the path for improving DW transport as synthetic antiferromagnetic systems are expected to be less sensitive to external perturbation and to show fast switching dynamics [24].

To evidence this statement, we compare magnetization switching dynamics of the synthetic antiferromagnetic-based free layer device to a standard dual-MgO based free layer using timed-resolved STT-driven switching measurements. The typical time-resolved single shot curves at room temperature, as displayed in Fig. 3 a, allow the extraction of three different timescales for every reversal event: the initial incubation delay t_{inc} due to thermal effects, the transition time between stable states t_{trans} , and the pinning time in a pinned state t_{pin} . For a 100 nm device size, it has been shown that the switching process is dominated by a DW-mediated reversal [32]. Note that pinning only occurs in the dual-MgO devices, as reported in Fig. 3 b. The varying nature of the pinning level and characteristic pinning timescale indicate that the origin is most likely due to the inhomogeneities of the device microstructure. More specifically, defects in the interfacial MgO/CoFeB anisotropy have been reported to induce pinning in the STT switching process [33].

The incubation delays were analyzed under the assumption of a thermally activated process [34]

$$PDF(t_{inc}) = \exp(-t_{inc}/\tau)/\tau$$

where PDF is the probability density function. In the thermal limit for small drive currents, where the incubation delay is dominant, we expect the well-known Arrhenius dependence $\tau = \tau_0 \exp(\Delta[1 - J/J_c])$. However, the absence of analytical expressions for τ_0 in the DW reversal regime will prevent further parameter extraction. As displayed in Fig. 3 c, the similar incubation delay as function of applied current indicates similar energy barriers in both stack types (Supplementary Note. 4.4). It is supposed that in all cases the switching process initiates in the top CoFeB layer (FL1) which is in contact with the STT source from the spin polarization layer. Subsequently, the switching of the whole free layer then follows due to the strong coupling with the CoFeB layer. Interestingly, we found that the transition times in the synthetic antiferromagnetic-based devices reduced by a factor of two compared to their dual-MgO counterpart as seen in Fig. 3 d. This result suggests that

Fig. 3 | Fast STT switching in SAF-HFL without degradation of retention time. (a) Typical single-shot curves of the MTJ reversal process lined up to the onset of switching (time 0), defining an incubation delay, transition time, and pinning time. (b) Extracted characteristic pinning times, only present in the dual-MgO samples. (c) The thermally activated incubation delays as function of current density, demonstrating similar behavior in the two free layer designs. (d) Transition times vary as function of current density demonstrating consistently faster reversal in the devices with the proposed SAF-HFL. Error bars in all graphs define the 68% confidence interval.

the presence of DMI and antiferromagnetic exchange coupling torque [16] in our SAF-HFL devices indeed stabilizes the DW configuration and leads to shorter transition times.

109

110 **Full operation of DW devices with MTJ write and read**

111 We now demonstrate that a nanoscale DW device with full electrical control can be achieved using the hybrid
 112 free layer design. In this study, DW devices with MTJs as electrical read and write components have been fabricated
 113 consisting of a 180 nm wide track shared by three MTJ pillars with a nominal diameter of 80 nm. The pillars are
 114 separated by 500 nm. We use the second free layer Co/Ru/Co as DW conduit with a 13 Å thick ruthenium spacer
 115 which allows the formation of a synthetic ferromagnet, SFM-HFL. In such SFM arrangement, the thicker ruthenium
 116 layer ensures PMA of the bottom Co layer even when the interfacial PMA of CFB/MgO is damaged by the etching
 117 process [35]. Importantly, the magnetic state of the DW conduit underneath and in between pillars is very similar
 118 even if the PMA of the top Co layer has collapsed by the etching process. Therefore, devices with SFM stack design
 119 can be used as demonstrators of SOT-driven DW motion where the bottom Co layer is in contact with the SOT
 120 source of Pt.

121 TMR versus field loops of three individual pillars connected by a common free layer show the coercivity (B_C)
 122 overlapping and a significant reduction of switching field (propagation field B_P) when STT was initially applied in one
 123 of the pillars (Extended Data Fig. 2). It indicates that the PMA of the DW conduit is fully preserved after device
 124 integration [21, 35, 30]. This experiment demonstrates that three basic requirements for a functional DW device
 125 are guaranteed, *i.e.*, PMA of the DW conduit is preserved, DWs can be locally written in the track by STT and read
 126 out by TMR. In addition, a large difference between B_C (~ 61 mT) and B_P (~ 33 mT) provides a wide operating
 127 window for field-driven DW transport without approaching the nucleation-dominated switching regime.

128 We now prove in Fig. 4 that the full operation of read/write using MTJs and a magnetic field and/or SOT-driven
 129 DW motion can be achieved in a single DW device. Experimentally, the measurement sequence of a DW device
 130 with the track shared by three MTJ pillars is summarized as follows. We firstly saturate the device in the parallel
 131 (P) state by a negative external field larger than the coercivity. Consecutively, STT is used to selectively write an
 132 antiparallel (AP) domain in the center pillar P2, as seen in Fig. 4 d-e-f by an abrupt change of magnetization from P
 133 to AP in P2 (blue graph). Finally, the motion of DWs through the track induced by field and/or SOT is detected by
 134 TMR in the neighboring pillars. Fig. 4 a, d show an example of field driven DW motion in which the device is
 135 operated at a constant field of 27 mT ($\ll B_C \sim 61$ mT). In this case, the nucleated domain expands from the center

136 pillar to both outer pillars driven by field and assisted by thermal activation. The result of DW motion along the
137 track is observed by TMR read as a change of magnetic state from P to AP in both P1 and P3, demonstrating the
138 isotropic nature of field driven DW motion.

139 We now demonstrate that our DW devices can be operated by applying an in-plane SOT current along the
140 track as shown in Fig. 4 b, c, e and f. In contrast to field driven DW transport, the direction of DW motion is
141 selectively manipulated by the current polarity. As seen in Fig. 4 b, e, we observe a change of TMR in P3 indicating
142 DW motion from P2 to P3 with a positive current. Similarly, Fig. 4 c, f show DW motion from P2 to P1 with
143 negative current. Note that we never observe DW motion against the direction of current flow as no switching
144 occurs at P3 (P1) with negative (positive) current (*c.f.*, Fig. 4 e, f). To verify the reproducibility of device operation,
145 we show in Extended Data Fig. 3 that the experiments are reproducible ~ 100 times.

146 The observation of DW motion along the current flow provides clear evidence that SOT originating from Pt
147 is the main driving force for DW motion in our devices as expected in stand-alone samples [12, 13, 14, 15]. In this
148 experiment, the exact shape of the nucleated domain is not obvious since TMR readout is locally sensitive to a
149 change of magnetization state underneath the pillars. However, we believe that a magnetic bubble was fully nucleated
150 under the MTJ as a full switching of MTJ resistance from P to AP is always present after STT write. Also, we do not
151 observe any change of the resistance in the neighbouring pillars during STT write meaning that a domain is locally
152 injected underneath the MTJ. In other words, two DWs are expected to form on each side of the MTJ pillar. It is
153 worth to mention that we do not observe two changes of resistance induced by a synchronous motion of two
154 DWs along the track as would be expected from SOT-driven DW motion (*i.e.*, drop of resistance in the input pillar
155 and rise in resistance in output pillar (Supplementary Note. 6.4). It might be due to the fact that the externally
156 applied field favors bidirectional expansion while the SOT-driven DW motion favors unidirectional motion (*c.f.*,
157 Supplementary Figure 6.4). We believe that fine-tuning of the device integration process will reduce the potential
158 DW pinning sites of the track at nanoscale such that the device can be fully controlled by SOT without external
159 field, as we obtained in the case of stand-alone free layer samples (Supplementary Figure 6.3).

160 Our devices also allow to control DW motion from any pillar in the track. We show in a slightly larger device
161 (track width 200 nm, pillar diameter 100 nm and interpillar spacing 500 nm) that SOT-driven DW motion can be
162 achieved from any pillar where the DW is initially written by STT (Extended Data Fig. 4). This demonstration

Fig. 4 | Full operation of a DW device with MTJs enabling STT write and TMR readout and SOT-driven DW transport. (a-c) Schematics explaining DW transport as observed in (d-f) respectively. (a, d) Field-driven domain expansion from P2 to both P1 and P3. (b, e) SOT-driven DW motion from P2 to P3 with positive current flow in the heavy metal and (c, f) SOT-driven transport from P2 to P1 with negative current. (g) Natural logarithm of the depinning time as function of external magnetic field. (h) Cumulative density functions (plotted as 1-CDF on logarithmic scale) of depinning time at a fixed field of 24.9 mT and varying current density obtained from 100 measurements at each current density and polarity. The data is fitted by an exponential law, resulting in the average depinning times as plotted in (i) as function of current.

provides an important feature for practical application of spintronic devices, for instance the operation of spin logic devices [35] which require DWs to be independently controlled from different inputs [6, 8].

In addition, we prove that such devices offer the possibility to explore DW dynamics in operation mode at nanoscale where imaging techniques become ineffective in fully integrated devices at low dimension. For this study,

we repeat a similar experiment as seen in Fig. 4 a and measure the waiting time for the DW to overcome the energy barrier to travel from P2 (i.e., where DW is written by STT) to P3 (i.e., where DW is detected by TMR read) with the assistance of external field and thermal activation. We choose four different external field values to tune the height of the energy barrier and repeat the measurement 100 times to characterize the statistics of the depinning time at each field value (Supplementary Figure 6.2.1). The cumulative distribution function (CDF) of depinning time for each field value is well described by a single exponential law, $CDF(t) = 1 - \exp(-t/\tau)$ with the characteristic depinning time τ , as theoretically predicted for DW depinning processes [36, 37]. Fig. 4 g shows the obtained τ (on ln-scale) as a function of magnetic field, fitted by an Arrhenius-law-based exponential equation $\tau = \tau_0 \exp\left(\frac{E}{k_B T} (1 - B/B_{C0})\right)$, where B_{C0} is the intrinsic critical field in the absence of thermal activation [36]. We obtain a thermal stability factor $\frac{E}{k_B T}$ of 38.8 ± 1 .

Finally, we use such devices as a tool to study the impact of SOT on the DW dynamics in full operation, where a DW is electrically read and written using MTJs. We carry out similar field induced DW depinning measurements and now add SOT on top of a fixed external field of 24.9 mT. Fig. 4 h displays the CDF of depinning times (on log scale) at varying current density and polarity. As expected, a negative current increases the DW depinning time while a positive current decreases the depinning time (Supplementary Figure 6.2.2). We find that the CDF of SOT induced DW depinning can also be fitted by a single exponential as expected for DW depinning over a single barrier. It suggests that the application of SOT does not change the nature of DW dynamics in our device. When plotting the obtained depinning time τ (on ln-scale) as function of current density (Fig. 4 i), we find that the effect of SOT on the DW depinning dynamics is equivalent with field-driven depinning. Therefore, we assume again an Arrhenius-law based exponential, including the effect of current $\tau = \tau_0 \exp\left(\frac{\Delta}{k_B T} \left[1 - \frac{B}{B_C} - \frac{J}{J_C}\right]\right)$ [37] and approach the effect of current similar to magnetic field. We then obtain $\tau = \tau_0 \exp\left(\frac{\Delta}{k_B T} \left[1 - \frac{B-\epsilon J}{B_C}\right]\right)$ which allows to estimate the DW depinning efficiency ϵ driven by SOT: $\epsilon = 1.5 \pm 0.24 \text{ mT} \times (10^{11} \text{ Am}^{-2})^{-1}$. This value is in agreement with literature for Pt/Co-based stand-alone samples [37], which indicates that the nature of DW dynamics in the conduit layer is retained in nanoscale devices under both field and SOT-driven DW depinning.

Toward high-performance DW devices with SAF-HFL design

192 The hybrid free layer proposal allows to improve device performances, for instance by integration of a
 193 synthetic antiferromagnetic system as DW conduit. For this purpose, a softer etching condition in the device
 194 integration process was used. Etching was stopped in the reference layer (RL) above the MgO barrier to avoid any
 195 magnetic damage to the synthetic antiferromagnetic-based DW conduit, *i.e.*, to the CoFeB/MgO interface of FL1.
 196 Note that this etch-stop condition potentially induces an electrical short between the pillars through the reference
 197 layer. We believe that it does not impact the demonstration of field driven DW motion in this study. We compare
 198 the dynamics of field-driven DW motion along Pt/Co-HFL and SAF-HFL conduits in a 170 nm wide track shared by
 199 three MTJs, using real-time TMR detection, Fig. 5 a (Supplementary Note 6.1). The time resolved single-shot curves

Fig. 5 | Fast DW propagation in SAF-HFL compared to Pt/Co-HFL. (a) Cross-sectional TEM image of 3 MTJs with a nominal diameter of 70 nm and interpillar spacing of 100 nm sharing the same FL. Bias tees enable individual DC and high-frequency access to each pillar. (b) Single-shot time-resolved field-driven magnetization reversal at coercivity in Pt/Co-HFL (42.5 mT) and SAF-HFL (63 mT), (c) Propagation time measured from 100 measurements as in b, showing shorter propagation time in SAF-HFL.

in Fig. 5 b show a sequential switching of pillars P1, P2 and P3 under the application of the sweeping magnetic field. It suggests that at coercivity, a domain is nucleated and sequentially expanded throughout the DW conduit. This measurement reveals that the dynamics of DW motion in high DW speed materials, more specifically in Pt/Co or in the Co-based synthetic antiferromagnetic system, can be sensed by TMR in nanoscale devices. The propagation time, defined as the delay-time between the onset of reversal in P1 and the termination of reversal in P3, is at least double in Pt/Co-HFL (28.99 ± 2.63 ns) as compared to SAF-HFL (13.09 ± 5.48 ns). It means that DW motion in synthetic antiferromagnetic-based devices with an average DW velocity of 42 m/s, is faster than in Pt/Co-based devices with an average DW velocity of 17 m/s. Faster DW motion in SAF-HFL is attributed to the combination of DMI and interlayer exchange coupling which helps to stabilize the DW structure during its motion thus extending the steady motion regime to larger fields compared to its ferromagnetic counterpart. Note that faster field driven DW motion in SAF-HFL device is due to our not fully compensated synthetic antiferromagnetic structure (Supplementary Figure 3.I.1). We believe that the effect of field on DW motion will be less sensitive if the system is more compensated urging for SOT- rather than field-driven DW motion. Thus, we finally study SOT-driven DW motion in a stand-alone Pt/Co and a Pt/Co/Ru/Co synthetic antiferromagnetic free layer by Magneto-Optic Kerr microscopy. We indeed observe more uniform and faster SOT-driven motion (DW velocity up to 460 m/s at $J = 3 \times 10^{12}$ A/m²) in the synthetic antiferromagnetic-based sample (Supplementary Figure 6.3 and Supplementary Videos 1 and 2). This suggests that a synthetic antiferromagnetic-based DW conduit could enable higher performance DW devices. Therefore, we believe that fine-tuning the MTJ stack design and improving etching conditions to ensure the PMA of the full synthetic antiferromagnetic structure will be key for fast SOT-driven DW motion devices.

219

220 Conclusions

221 We have reported the full electrical operation of a DW device with MTJs read and write using a hybrid
222 free layer design. The approach can address challenges for the practical realization of DW devices and satisfy the
223 requirements for high density and low power DW devices including STT write, TMR read and SOT-driven DW
224 motion. Our device also provides an approach to study DW dynamics at nanoscale under a magnetic field and/or
225 SOT. Furthermore, we have shown that synthetic antiferromagnet-based DW devices offer significant advantages
226 compared to their ferromagnetic counterparts, including uniform and fast DW motion. We also confirmed that in

227 single MTJs, a synthetic antiferromagnetic-based free layer achieves faster STT writing speed than a ferromagnetic
228 one. We believe that this hybrid free layer approach is promising for the development of practical DW-based
229 devices and could also be of use in the development of other spintronic devices, including skyrmion and spin-wave
230 based devices.

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236 **Acknowledgements** This work was performed as part of the IMEC IIAP core CMOS and the Beyond CMOS
237 Program of Intel Corporation. The authors gratefully acknowledge Jeroen Heijlen and the P-line for operational
238 support. The Magneto-optic Kerr effect microscopy experiments were performed at Technische Universiteit
239 Eindhoven, the authors thank Reinoud Lavrijsen. E. R. gratefully acknowledges FWO-Vlaanderen for a Strategic
240 Basic Research PhD fellowship.

241

242 **Author contributions** V.D.N. and S.C. conceived the hybrid free layer design for domain wall devices and
243 managed the project. E.R. and V.D.N were in charge of device characterizations with help of K.G., S.C., D.W., I.R.,
244 I.A, I.Y., D.N., B.S. and M.H.; E.R., O.B., V.D.N and T.D. performed the time-resolved experiments and interpreted
245 the results; D.W. was in charge of device integration process. Devices were fabricated by D.W., Y.C., L.S., A.T. and
246 D.T.; The thin films were deposited by S.C.; O. B. drafted the text to describe the results in Fig. 3. E.R., K.G. and
247 V.D.N. wrote the manuscript. All authors discussed the results and commented on the manuscript.

248

249 **Competing interests**

250 The authors declare no competing interests.

251

252 **Methods**

253 **Sample fabrication:** All devices were fabricated in imec's 300 mm pilot line. First, a buried bottom electrode
254 contact (BEC) process was used to define the bottom electrode. Here, single damascene Tungsten metallization
255 was applied two times, first to define BEC feedlines and second to define contact plugs. Next, the Tungsten contact
256 plugs were capped by an ultra-smooth TaN seed layer prior to MTJ deposition. The stack is deposited using an
257 ultrahigh vacuum (UHV) multitarget magnetron sputtering system at room temperature without breaking vacuum
258 between depositions (EC7800 Canon-Anelva). Pillars were patterned by 193 nm immersion lithography and a
259 subsequent ion-beam-etch (IBE) at normal and grazing angle for single pillar and DW devices. The DW devices
260 required additional 193 nm immersion lithography double patterning to further define the free layer shape. Finally,
261 dual damascene Cu top contacts were fabricated to provide electrical readout at the individual pillars. The dual
262 MgO free layer stack, Pt/Co-HFL stack, SAF-HFL and SFM-HFL stack consist from bottom to top, of

263 $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}(9)/\text{Mg}(6)/\text{Ta}(3)/$ $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}(11)/\text{MgO}(10)$, of $\text{Pt}(30)/\text{Co}(8)/\text{W}(3)/\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}(8)/\text{MgO}(10)$,
 264 $\text{Pt}(30)/\text{Co}(8)/\text{Ru}(8.5)/\text{Co}(6)/\text{W}(3)/\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}(8)/\text{MgO}(10)$, and of
 265 $\text{Pt}(30)/\text{Co}(8)/\text{Ru}(13)/\text{Co}(6)/\text{W}(3)/\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}(8)/\text{MgO}(10)$, respectively. Thicknesses in brackets are provided in
 266 Angstrom. The magnetic hard layer consists of a $\text{Co}_{17.5}\text{Fe}_{52.5}\text{B}_{30}$ reference layer which is ferromagnetically coupled
 267 to a synthetic antiferromagnetic that consists of $\text{Co}(12)/\text{Ru}(8.5)/\text{Co}(6)/\text{Pt}(8)/[\text{Co}(3)/\text{Pt}(8)]_6$. More information on the
 268 fabrication process can be found in [21].
 269

270 **Electrical setup:** A detailed scheme of the electrical setup of Fig. 3 is provided in Supplementary Figure 5.1, this
 271 setup allows time-resolved measurements of STT-driven magnetization reversal in single pillars. The measurements
 272 were performed on high-frequency capable 100 nm pillars. By applying voltage pulses of varying amplitude and short
 273 ramp time (~ 300 ps) we could study the magnetization dynamics down to the nanosecond regime. The magnetic
 274 offset field was compensated for by an external magnetic field during the STT-driven reversal. Prior to the recording
 275 of the single shot data, two reference traces were recorded for the P and AP state as described in Supplementary
 276 Note. 5. The single shot data travels between the two recorded reference states, which allow the normalization of
 277 the single shot data, as shown in Supplementary Figure 5.2. For each point in Fig. 3, 100 single shots were recorded.
 278 The electrical setup for the DW devices in Fig. 4, consists of a source measure unit (SMU) at each pillar, allowing
 279 individual STT-writing and TMR readout in each pillar. An additional SMU is connected to the track to allow in-
 280 plane current in the heavy metal. To avoid erroneous signals during SOT-driven DW transport, SMUs at the MTJs
 281 are kept floating while a current (100 ms) is applied through the track. Consecutively, each pillar is read out.
 282 The electrical setup in Fig. 5, consists of radiofrequency and DC paths enabled by bias tees at each pillar. A DC bias
 283 is applied at every pillar during magnetization reversal driven by field. At coercivity, the resistance of the pillar
 284 suddenly changes leading to a reflection of the applied current. The recorded rf voltages measured by the 25 GHz
 285 oscilloscope then equal the reflected rf current multiplied by the $50\ \Omega$ termination of the scope channels.
 286

287 Data availability

288 The data that support the plots within this paper and other findings of this study are available from the
 289 corresponding author upon reasonable request.

290

291 **Extended Figures**

Extended Data Fig. 1 | Representation of current flow for electrical operation of DW device. Current path for reading and writing displayed for center pillar (a) and for DW motion driven by spin orbit torque (SOT) (b).

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Extended Data Fig. 2 | Comparison of coercive field and propagation field. (a) The coercive field B_C is the switching field obtained during a conventional R(H) loop. The propagation field B_P is obtained after STT-driven nucleation in the center pillar (P2) and consecutive sweeping of the z-field from 0 mT upwards. The domain then expands to the outer pillars (P1 and P3). (b) Box plots of the coercive and propagation fields of 10 measurements. The average coercive field is 61 mT while the propagation field to both pillars is only 33 mT. (c) Demonstration of the initial state of the device before the R(H) loop is initiated. Device is fully saturated to obtain coercive field B_C (top), a domain was initially nucleated in P2 to obtain the propagation field B_P (bottom).

Extended Data Fig. 3 | Reproducibility of spin-orbit torque-driven DW motion in operation mode. STT nucleation in P2 followed by SOT-transport to P3 with positive current (top) and SOT-transport to P1 with negative current (bottom). Measurement ~ 100 x reproducible with each current polarity as described in Fig. 4 e, f. The DW never propagates to the reverse direction, *i.e.*, no switch in P1 (top) and P3 (bottom).

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Extended Data Fig. 4 | Demonstration of spin-orbit torque-driven DW motion from different inputs

(Top left) Resistance versus field loop displays the coercive field B_C , the propagation field B_P and the assist field B_A for SOT-driven motion. The schematics at the top display the applied current polarity and direction of DW motion. The domain is nucleated by STT in P1 (second row), P2 (third row), and P3 (fourth row) as shown by the schematics on the left. In the last case (fifth row), no domain is nucleated by STT. The latter confirms that all the above are SOT-driven propagation of DWs, and not SOT-driven DW nucleation.

Extended Data Fig. 5 | Fabrication process in imec’s 300 mm pilot line. (a) Bottom electrode contact (BEC), BEC feedlines and contact plugs were defined. (b) MTJ stack deposition using UHV magnetron sputtering system (c) Pillar patterning by 193 nm immersion lithography followed by ion-beam-etch (IBE) (d) FL shape is defined by 193 nm immersion lithography double patterning (e) Dual damascene Cu top contact formation (f) 3-dimensional image of DW device with individual TE for each pillar.

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