All-electrical control of scaled spin logic devices based on domain wall motion

E. Raymenants1,2, D. Wan1, S. Couet1, L. Souriau1, A. Thiam1, D. Tsvetanova1, Y. Canvel1, I. Asselberghs1, M. Heyns1,2, D.E. Nikonov3, I.A. Young3, S. Pizzini4, V.D. Nguyen1 and I.P. Radu1
1imec, Leuven, Belgium, email: eline.raymenants@imec.be, van.dai.nguyen@imec.be
2KU Leuven, 3001 Leuven, Belgium, 3Intel Corporation, Hillsboro, OR USA
4Univ. Grenoble Alpes, CNRS, Institut Neel, F-38000 Grenoble, France

Abstract— Spin logic devices based on domain wall (DW) motion offer flexible architectures to store and carry logic information in a circuit. In this device concept, information is encoded in the magnetic state of a magnetic track shared by multiple magnetic tunnel junctions (MTJs) and is processed by DW motion. Here, we demonstrate that all-electrical control of such nanoscale DW-based logic devices can be realized using a novel MTJ stack. In addition to field-driven motion, which is isotropic, we show directional motion of DWs driven by current, a key requirement for logic operation. Full electrical control of an AND logic gate using DW motion is demonstrated. Our devices are fabricated in imec’s 300 mm CMOS fab on full wafers which clears the path for large scale integration. This proof-of-concept thus offers potential solutions for high-performance and low-power DW-based devices for logic and neuromorphic applications.

I. INTRODUCTION

Spin logic devices based on DW motion combine unique properties such as non-volatility, fast operation, and ultra-low energy consumption [1,2,5,7]. These devices are currently explored to enable functional rather than dimensional scaling [8,9]. Many DW-based device concepts have been demonstrated for logic operation, Fig. 1. However, the lack of all-electrical control impedes practical applications. Thanks to their fast reading and low writing current, MTJs can be used to electrically control the input and output. Nevertheless, DW-based devices require an additional scheme to electrically move the DW from input to output. As reported previously [4,10], a major challenge of the current MTJ design is reliance on interfacial perpendicular magnetic anisotropy (PMA) of the CoFeB/MgO free layer (FL) in the DW conduit. Specifically, to enable DW transport, device integration requires a pillar patterning step with controlled etch-stop on the MgO tunnel barrier to electrically isolate the MTJs while keeping them magnetically connected through the FL [10]. This typically results in loss of PMA in the extended FL as seen in Fig. 2(a). Here, we overcome these challenges and demonstrate that all-electrical control of a DW is achieved. Additionally, we prove directional control of DW motion and thus information transfer which satisfies one of the key requirements for logic device functionality [11].

II. RESULTS AND DISCUSSION

A. Development of novel MTJ stack for spin logic devices

We developed a novel MTJ device concept that incorporates a second FL into a conventional MTJ stack for DW transport, Fig. 2(b). Carefully selected high PMA materials for the DW conduit are exploited for reliable DW transport and robustness against process induced damage. High tunneling magnetoresistance (TMR) and efficient spin transfer torque (STT) are maintained by the CoFeB FL in contact with MgO. The role of the spacer is two-fold: 1) it decouples the crystallization between CoFeB and the DW conduit, 2) it enables strong ferromagnetic coupling between CoFeB and the DW conduit to behave as a single ferromagnet. At run time, a DW is electrically written into the DW conduit by STT at the input pillar. Subsequently, the DW moves along the track by magnetic field and/or by electrical control. Arrival of the DW at the output is detected by TMR. This DW device concept benefits from the energy-efficient write and read processes of current MRAM technology and from fast DW motion in the separate DW conduit layer. Remarkably, this device concept also allows to independently optimize the DW conduit material for transport and to reduce sensitivity to process-induced damage.

Reliable DW motion is key for device operation. Therefore, we optimized the DW conduit layer by varying its thickness. Fig. 3(a-c) illustrates the magnetic state evolves from in-plane to out-of-plane with increasing DW conduit thickness. Importantly, magneto-optic Kerr effect (μMOKE) microscopy images in Fig. 3(e-f) indicate that a controllable switching process, dominated by a single DW nucleation and propagation, is obtained in the t, thickness region defining the process window.

Demonstration of STT write and TMR read in the DW conduit layer is another key requirement. We integrate the DW conduit material into the FL of an MTJ aiming for electrical manipulation (schematic Fig. 4). Fig. 4(a-b) displays typical TMR loops of MTJ pillars driven by field and current pulses (50 ns). As expected, measured TMR values, Fig. 4(c), are mostly insensitive to the DW conduit thickness indicating that TMR is primarily attributed to the CoFeB/MgO interface. The enhancement of magnetic coercivity Hc (left axis of Fig. 4(d)) and STT switching voltage VsW (right axis) with increasing conduit thickness is consistent with higher PMA observed in the thicker conduit layers (c.f. Fig. 3). It importantly reveals that the magnetic state in the DW conduit layer can be electrically set and probed using an MTJ. The switching efficiency (VsW/Hc) is preserved even with the addition of the DW conduit in the MTJ. This experimental finding demonstrates that the pristine properties of a standard MTJ device are not compromised by the integration of DW conduit materials. Note that STT switching is not achieved if the PMA of the DW conduit is too strong (t > t,).
B. Largescale device integration on 300 mm wafer

Functional DW devices require that the DW conduit layer preserves PMA during device integration. We compare the magnetic properties of a dual-MgO stack with the novel stack in MTJ pillars with FL extension (FLE). The pillars were fabricated under two different etching conditions, Fig. 5(a-d). To maintain the PMA of the FL, the dual-MgO stack requires etching to stop far above the MgO tunnel barrier. This results in remaining reference layer (RL) material [4] which causes electrical shorting between pillars. On the contrary, the novel stacks permit etching to stop directly on MgO, eliminating electrical shorting pathways. Similar TMR values were obtained in both conditions (not shown). However, the coercivity $H_c$ decreases with FLE in dual-MgO devices indicating partial damage to the FLE, Fig. 5(e), while they are almost constant in the novel stack, Fig. 5(f). Therefore, the novel stack is more robust against process induced damage to the DW conduit which is a necessity for manufacturability and reliability of spin-logic devices.

To further optimize device integration with the novel stack, we show that the spacer significantly protects the PMA of the DW conduit against etching damage, Fig. 5(g-j). The TMR values remain constant for all pillar diameters with 50 nm FLE (not shown). However, a large dispersion of $H_c$ in thin spacer devices, Fig. 5(i), indicates damage to the PMA of the DW conduit, in contrast to the narrow distribution with thick spacer, Fig. 5(j). Note that the $H_c$ in the thick spacer layer devices is generally lower as the coupling is weaker. We carried out µMOKE experiments on blanket samples on which the same process in the thin spacer samples, Fig. 5(a, b), confirm damage to the DW conduit layer. In contrast, the thick spacer samples, Fig. 6(a, c), show higher $H_c$ and controlled DW nucleation and propagation. These results evidence that challenges of device integration can be solved by precisely tuning the novel stack.

C. Operation of DW based spin logic devices

With all parameters optimized, Fig. 7, DW devices with the novel stack were integrated on 300 mm wafers. We first simultaneously measure TMR versus magnetic field loops of three pillars (CD 100 nm, spacing 500 nm) sharing the nanotrack (width 200 nm). We then observe overlapping switching fields in all pillars, confirming a single domain nucleated and expanded along the track, Fig. 8(a) [4]. Note that a small variation of $H_c$ on the antiparallel (AP) to parallel (P) transition might be due to stray fields [12]. In the following experiment, Fig. 8(b-c), STT is selectively applied at input pillar P1, seen as an increase in resistance (TMR). Subsequently, under a constant external field ($H<0$, the domain expands along the track, sequentially passing the next pillars (P2, then P3). The measurement proves that a DW was locally and electrically nucleated and detected in a nanotrack using MTJs. High TMR values provide reliable device operation. Note that a small variation of TMR in each individual pillar might be due to process variations.

The field-driven experiment in Fig. 9(a-b) starts from a uniformly magnetized FL $\oplus$, a domain is nucleated by STT in the center pillar (P2) $\oplus$, and we finally monitor TMR of all pillars while sweeping the field from 0 to 100 mT $\oplus$, Fig. 9(b). The domain initiated at P2 expands isotropically through the track to both sides of P2 at the propagation field $H_p$. This was observed as an increase in resistance from P to AP in both P1 and P3.

We now demonstrate all-electrical control of DW motion, a critical requirement in practical applications. As in the previous experiment, we perform steps $\oplus$ and $\oplus$. Now, a current (and small assist field $<H_p/2$) is applied in the track, Fig. 9(c), from time $\oplus$ onwards. In contrast to the field-driven case, the DW propagates instantly to P1 as its resistance state changes from P to AP, while it does not arrive at P3 (resistance remains in P state) in the measured time frame ($\approx$ 20 s). The same experiment was performed with the reversed current polarity (not shown), where instant switching in P3 and no switching in P1 was observed, confirming directional DW motion. Finally, to verify that the switching is not due to random current-driven DW nucleation, the same measurement procedure was carried out while no domain was initially nucleated by STT. Indeed, no magnetization reversal in any pillar was observed. This experiment proves directional DW transport was achieved by electrical control.

Finally, we present the operation of a logic AND gate using DW motion in a device with 2 pillars, Fig. 10(a). Input IN1 is the resistance state at the input pillar, set by STT. Input IN2 is the driving force to propagate the DW from input to output (field or current). Output OUT is defined by the resistance state of the output pillar, read by TMR, Fig. 10(b). OUT is only logic 1 if a DW was injected (IN1 = 1) and transported to the output (IN2 = 1). Fig. 10(c) displays the truth table of the AND gate where field is used to propagate the DW to the output (IN2 = 0 or 1 corresponds to no field or $H_p$, respectively). Importantly, we also obtained the logic AND gate fully electrically, by choosing IN2 = 0 for negative current and IN2 = 1 for positive current (not shown). Note that the OR function was also obtained when IN2 was chosen as 0 at $H = H_p$ and 1 at $H = H_c$.

III. CONCLUSION

We have experimentally demonstrated all-electrical control of a nanoscale logic device based on DW motion using MTJs as inputs and outputs. We employed a novel MTJ stack that not only offers efficient STT write and high TMR read but also provides the possibility for fast device operation through the introduction of high DW speed materials in the DW conduit layer. The demonstration of current-induced directional DW motion and robust largescale device integration on 300 mm wafers paves the path towards ultra-fast, energy-efficient spintronic devices for implementation in beyond CMOS logic, racetrack memory, and artificial neural networks.

ACKNOWLEDGMENT

This work was performed as part of the imec IIAP core CMOS and the Beyond CMOS program of Intel Corporation. The authors gratefully acknowledge Jeroen Heijlen and the P-line for operational support, and the MCA team for TEM images. E. Raymenants gratefully acknowledges FWO Flanders for a Strategic Basic Research PhD fellowship.
Fig. 1. Achievements and challenges for spin logic devices where information is stored in magnetic domains and transferred by DW motion.

Fig. 2. (a) Conventional dual MgO stack with etching damage in CoFeB FL track. (b) Novel stack where a second FL, DW conduit, is coupled to the standard CoFeB FL by a non-magnetic spacer layer. DW conduit is undamaged from etching.

Fig. 3. Optimization of DW conduit thickness. (a)-(c) Hysteresis loops vs field for increasing thickness. (d) DW conduit layer to be optimized. (e)-(f) µMOKE images corresponding to (b)-(c), respectively. Thickness $t_*$ is selected as target thickness with uniform PMA: high $H_C$ and DW propagation dominated reversal.

Fig. 4. (a)-(b) MTJs with novel stack can be switched by magnetic field or by STT (50 ns pulses) (c) TMR is constant with conduit thickness. (d) Coercivity and switching voltage increase with increasing thickness. Green shaded area is region of interest.

Fig. 5. Largescale device integration comparison. (a,b) TEM of FL track between pillars, (c,d),(g,h) cartoons of devices under test with etching damage to CoFeB layer, (e) coercivity drops in dual MgO and (f) remains constant in novel stack with increasing FLE. (i) Large dispersion of coercivity in novel stack with thin spacer; (j) narrow dispersion with thick spacer. Each experimental data point is collected from few tens of devices across 300 mm wafer.
Fig. 6. Impact of spacer thickness on magnetic properties of DW conduit layer. (a-c) µMOKE images on etched samples. (b) Thin spacer shows nucleation dominated reversal (small coercivity) while (c) thick spacer displays proper DW propagation (large coercivity).

| DW conduit | Spacer | TMR read | STT write | Etch-robust | DW transport properties in integrated DW device |
|------------|--------|----------|-----------|-------------|-------------------------------------------------|
| Optimized thickness | Thin | YES | YES | NO | DW nucleation |
| Target | | YES | YES | YES | DW propagation |
| Thick | | YES | NO | YES | DW propagation |

Fig. 7 Requirements of DW conduit layer and spacer material (first and second column) in novel MTJ stack for DW based devices and results of their largescale integration for DW based devices. DW conduit thickness was optimized in Fig. 3 – Fig. 5 while spacer thickness was optimized in Fig. 5 – Fig. 6.

Fig. 8. (a) Hysteresis loops of 3 pillars on a track (b) Field-driven DW motion measurement scheme. (c) A domain is locally written at P1 by STT, sequential DW motion driven by external field from P1 to P2 and P3. The DW position is electrically read-out at each pillar by TMR.

Fig. 9. (a) DW transport experiments starting from saturated low-resistance state (①), then STT-driven AP-nucleation in center pillar (②), and finally DW is driven (③) by field (b) or current (d). TEM image in (c) presents how the current is applied in the track from via-to-via. Directional DW transport was achieved when driven by current (d).

Fig. 10. Logic AND gate. (a) The device consists of a track shared by two MTJs. (b) AND truth table defining IN1, IN2 and OUT (c) experimental data of AND operation with IN1 = (no) STT, IN2 = 0/Hₜ and OUT = TMR.

REFERENCES

[1] Allwood, D. A., et al. Science 309 (2005) 1688
[2] Curriervan-Incorvia, J. A., et al., Nat. Commun. 7.1 (2016): 1-7.
[3] Lequeux, S., et al., Sci. Rep. 6.1 (2016): 1-7.
[4] Raymenants, E., et al. 2018 IEEE International Electron Devices Meeting (IEDM)
[5] Zhaochi, L., et al. Nature 579.7798 (2020): 214-218.
[6] Siddiqui, S., et al. Nano Letters 20.2 (2019): 1033-1040.
[7] Zhang, B., et al Appl. Phys. Let. 116.25 (2020): 252403.
[8] Vedmedenko E., et al., J. Phys. D: Appl. Phys. 53 (2020) 453001
[9] Manipatruni S., et al., Nat. Phys. 14.4 (2018): 338-343.
[10] Wan D., et al., Jpn. J. Appl. Phys. 57.4S (2018): 04FN01.
[11] Nikonov, D., et al., Proceedings of the IEEE 101.12 (2013): 2498-2533.
[12] Devolder, T., et al., J. Phys. D: Appl. Phys. 52.27 (2019): 274001