Special MRAM poster session

IEDM (Dec 6, 2022, Hilton Union Square, San-Francisco)

Tuesday afternoon Dec 6, 2:20pm-5:30 pm

Yosemite room

For the 6th year, a special poster session entirely dedicated to MRAM is organized during IEDM. This session is technically organized by the IEEE Magnetics Society and embedded in the IEDM 2022 conference. This event will be a great opportunity to foster closer interactions between the microelectronics and magnetism communities. The posters will cover a number of topics including MRAM materials, phenomena, technology (STT, SOT, E-field control), testing, hybrid CMOS/MTJ technology and circuits, and MRAM applications.

The list of accepted posters is shown below.

Presented posters :

1. Endurance characteristics of MgO based 120 nm size MTJ for various write/erase switching pulse width

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It has been reported that by suppressing leakage current at the edge, the clear MR curve and highly reliable MgO films can be observed, and the MR ratio can be improved in MTJ cells with SiN sidewall shown in Fig. 1 [1-2]. However, the endurance characteristics have been examined at long write/erase switching pulse of 50 µs, and it is necessary to evaluate the endurance characteristics at a pulse width closer to actual memory operation. Therefore, we investigated the pulse width dependence of endurance characteristics in a 120 nm size MTJ cell with SiN sidewall. The current-voltage characteristics were measured. The voltage was varied from -0.6 V to 0.6 V and from 0.6 V to -0.6 V with the step voltage of 0.01 V and the pulse widths were applied beetween 50 µs and 400 ns. The current at resistance-change-voltage (write/erase voltage) and the resistance at 0.02 V (R@0.02V) just after the resistance change were compared for each pulse width as shown in Figs. 2 and 3. The current required to change resistance increases, and the variation of the current increases as the pulse width decreases although R@0.02V shows almost constant. These results indicate that the current required for write/erase decreases as write/erase period increases, however the charge which is integral of the current in the write/erase cycle is not constant. It is considered that the write/erase depend on not only the charge during the write/erase cycle but also the other factors, such as heat generated by the write/erase.

[1] H. Nakanishi, et al., Special MRAM poster session at IEDM 2021, 13.
[2] Y. Amemiya, et al., Ext. Abst. of SSDM 2022, 383.

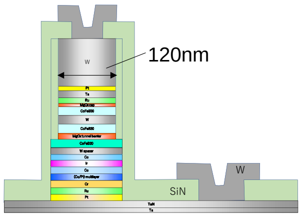

Fig. 1 Schematic cross section of MTJ structure

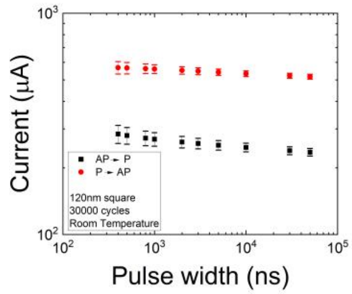

Fig. 2 Pulse width dependence of current at write/erase voltage

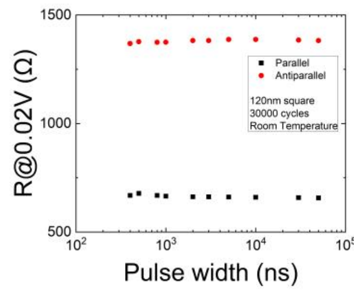

Fig. 3 Pulse width dependence of R@0.02V just after write/erase

2. Reducing structural disorder in W-CoFeB-MgO materials using He ion irradiation

Johannes W. van der Jagt[1], Song Chen[1], Dominique Mailly[2], Liza Herrera Diez[2], Elmer Monteblanco[1], Benjamin Borie[1], Roméo Juge[1] and Dafiné Ravelosona[1,2]

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We have developed a new manufacturing process based on He ion irradiation to tailor the structural properties of ultra-thin magnetic films and spintronic devices at atomic level and improve their performance. The key feature of the technology is the post-growth control at the atomic scale of structural properties, which enables a precise control of magnetic properties. When realized through a mask this technology allows lateral modulation of magnetic properties without any physical etching. Here, we show that by using He ion irradiation in W-CoFeB-MgO based-materials and devices magnetic properties can be strongly improved through reduction of structural disorder.

3. Field Free Switching in Spin-Orbit Torque Memories with spin current gradient

Vaishnavi Kateel[1,2], Viola Krizakova[3], Maxwel Gama Monteiro[1,2], Farrukh Yasin[1], Bart Soree[1], Johan De Boeck[1,2], Kaiming Cai[1], Siddharth Rao[1], Pietro Gambardella[3], Sebastien Couet[1], Gouri S. Kar[1], Kevin Garello[1,4]

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Current-induced spin-orbit torques (SOTs) enable fast and energy-efficient writing of magnetic tunnel junctions (MTJs) [1,2]. For deterministic switching of perpendicularly magnetized MTJs, the inherent SOT symmetry needs to be broken; this is traditionally achieved by applying an external magnetic field along the current direction. Because the use of external fields limits the application readiness of this technology, various solutions were suggested in the literature to achieve field-free switching (FFS). This is either achieved by creating a structural asymmetry, local in-plane field sources, spin current geometry or other hybrid approaches [3].

In this work, we propose and experimentally demonstrate a FFS solution in SOT-MTJs by geometrically modifying the SOT layer to create a structural asymmetry. This modification causes spatial variation of SOT charge current in the field-free structure, which creates a spin current gradient below the MTJs (fig1.a). In contrast, the standard structure shows a uniform spin current (fig1b).

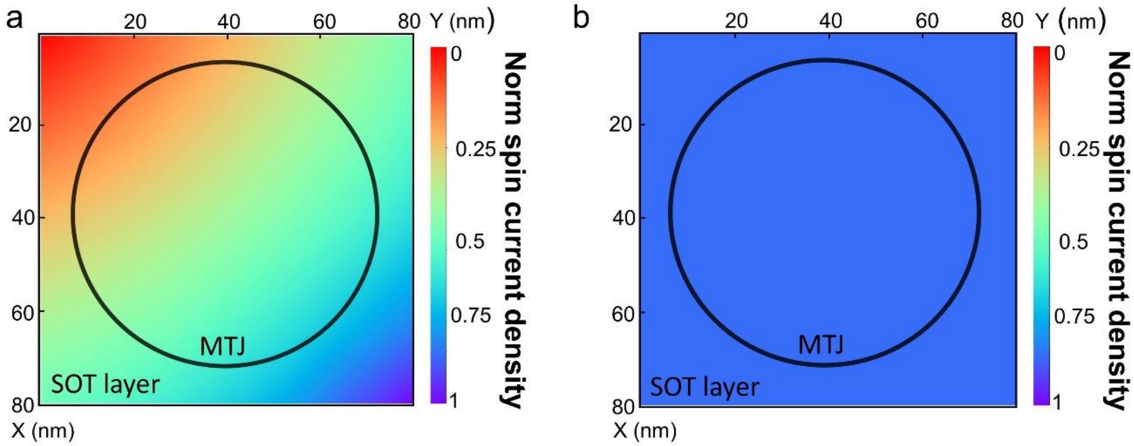

Figure 1: Color map of normalised spin current density. a) Field free structure b) standard structure.

We demonstrate our FFS scheme on 60 to 100 nm diameter MTJ consisting of CoFeB/MgO/CoFeB structure and tungsten (β-W) as SOT track [2]. The MTJ properties of field-free structures and standard SOT structures are similar, with a tunnel magnetoresistance ratio of 85% and coercivity of 66 mT. Deterministic bipolar switching is possible in the absence of a field with a current of 530 µA for field-free structures (fig. 2a), whereas the standard structure needs a minimum of ±10 mT of in-plane field (fig.2b). We elucidate the field-free switching mechanism using field-dependent measurements, finite elements, and micromagnetic simulations. Such FFS scheme is scalable, material-agnostic, and readily compatible with wafer-scale manufacturing, thus creating a pathway for developing purely current-driven SOT systems.

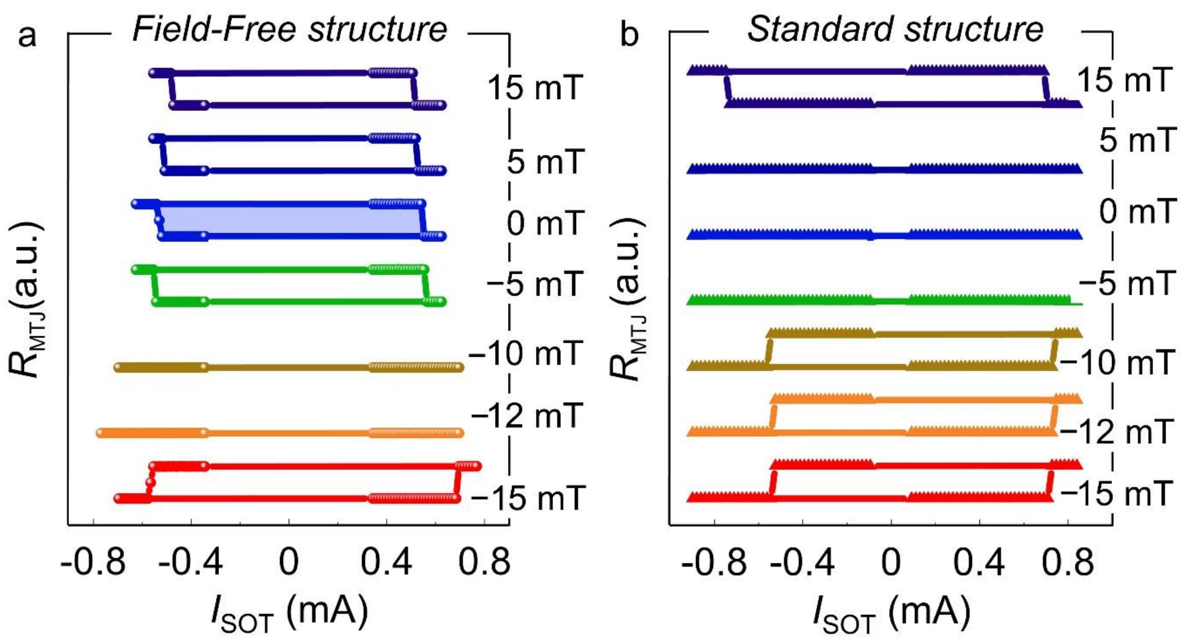

Figure 2: In-plane field dependence DC switching for 60 nm device: a) Field-free structure b) Standard structure.

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4. Efficient spin-orbit torque in magnetic trilayers using all three polarizations of a spin current

Jeongchun Ryu[1], Ryan Thompson[2], Jae Yeol Park[1], Seok-Jong Kim[1,3], Gaeun Choi[1], Jaimin Kang[1], Han Beom Jeong[1], Makoto Kohda[2,4,5], Jong Min Yuk[1], Junsaku Nitta[2,4,5] Kyung-Jin Lee[3,*] and Byong-Guk Park[1,*]
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SOT-MRAM device is one of the promising memory devices for fast operation [1-2]. However, its high switching current density and requirement of the symmetry-breaking field are challenging for commercializing SOT-MRAM. In this work, we show that these challenges can be overcome by exploiting additional spin currents in magnetic trilayers. In hetero-structures including ferromagnets, the polarization of spin current consists of three vectors in general; $(\hat{\mathbf{z}} \times \hat{\mathbf{E}})$, $\hat{\mathbf{m}}$, and $\hat{\mathbf{m}} \times (\hat{\mathbf{z}} \times \hat{\mathbf{E}})$, where $\hat{\mathbf{z}}$ is the film normal, $\hat{\mathbf{E}}$ is the electric-field direction, and $\hat{\mathbf{m}}$ is the magnetization direction [3-12]. We experimentally and numerically show that using all three polarizations reduces the field-free SOT switching current of a perpendicular magnetization by employing a bottom ferromagnet with a tilted easy-axis in ferromagnet/non-magnet/ferromagnet trilayer systems. Moreover, this approach even works for a sputtered polycrystalline trilayer, merited to mass production [13].

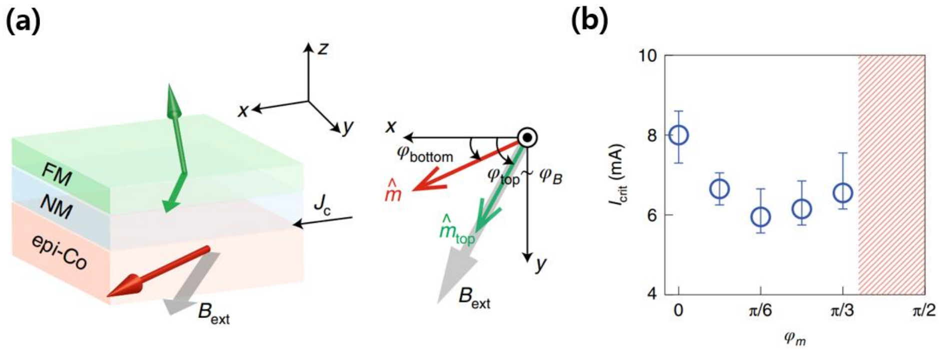

Fig. 1. (a) Illustration of a ferromagnet (FM)/non-magnet (NM)/epi-Co (FM) trilayer, where the red and green arrows represent the magnetization directions of epi-Co ($\hat{\mathbf{m}}$) and top ferromagnet ($\hat{\mathbf{m}}_{top}$). The azimuthal angles of the $\hat{\mathbf{m}}$ and $\hat{\mathbf{m}}_{top}$ are ϕ_{bottom} and $\phi_{top}(\sim\phi_B)$ respectively, when ϕ_B is the azimuthal angle of in-plane magnetic field $\boldsymbol{B_{ext}}$. (b) Critical switching current I_{crit} as a function of ϕ_m, where ϕ_m is angle difference between current density and ϕ_{bottom}. In shaded area, field-free switching is not observed.

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5. Experimental Demonstration of BEOL-Compatible, Field-Free STT-Assisted SOT-MRAM (SAS-MRAM) with One or Multiple Bits per SOT Programming Line

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Spin Orbit Torque (SOT) Magnetoresistive Random Access Memory (MRAM) and its variants have emerged as a promising candidate for use in SRAM-replacement applications (e.g., last layer cache, buffer memories, etc.) owing to its sub-nanosecond switching performance and favorable write-endurance properties. In this poster, we investigate STT-Assisted SOT-MRAM (SAS-MRAM) with multiple magnetic tunnel junctions (MTJs) sharing the same SOT line as one such technology that promises a significantly higher bit-cell density compared to conventional 3-terminal SOT-MRAM. In conventional SOT-MRAM devices, the areal-density is constrained by the area footprint of the SOT drive transistor due to the switching current requirements resulting from limited charge-to-spin conversion efficiencies of today's SOT materials. We seek to overcome these challenges by sharing the SOT line and drive transistor between multiple MTJs in order to amortize the area cost of the SOT drive transistor (typically the largest transistor) and leverage spin transfer torque (STT) to break the symmetry between the parallel (P) and antiparallel (AP) states. We introduce a novel writing scheme which overcomes the unique disturb mode inherent to the shared SOT line structure and enables simultaneous switching of multiple MTJs sharing the same SOT line in the absence of an external magnetic field. We fabricate SAS-MRAM devices with in-plane magnetic anisotropy and MTJ critical dimensions as low as 30 nm using doped tungsten as a BEOL-compatible SOT material and experimentally demonstrate our writing scheme.

6. Enhanced spin-orbit torque in amorphous light element silicide

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Spin-orbit torque (SOT) has been an active field of research for the past decade owing to its potential to replace the conventional spin-transfer torque due to separate read-write current path, faster switching speed and larger material design space for magnetic memory applications [1]. However, several roadblocks exist for further adoption of spin-orbit torque in memory applications including material compatibility with current silicon manufacturing platform, trade-off between conductivity and spin-torque efficiency resulting in the challenge of reducing the switching current, and the requirement of field-free switching [2]. To reduce the switching current, not only high spin-torque efficiency is important ($\xi_{SOT} > 1$) but also high conductivity is required [2]. However, the conventional scaling trend of increasing spin-torque efficiency with decreasing conductivity across different material systems [3] (or within the same alloying system [4]) prevents the further reduction of switching current via SOT. Here, we report three interesting findings in a new family of material systems - amorphous iron silicide (a-Fe_xSi_{100-x}) - for efficient generation of SOT. This work aims to address the first two roadblocks by demonstrating: 1. a large spin-torque efficiency ($\sim$ 2) in a fully amorphous non-ferromagnetic iron silicide 2. a novel scaling trend between conductivity and spin-torque efficiency which lifts the conventional trade-off and 3. a concentration dependent SOT that can be tuned by the relative energy position of the Fermi level and the reduced density of states through concentration engineering of iron and silicon. These results not only show the technological advantage of a new family of material for next-generation magnetic memory but also serve as a new vehicle to study spin-dependent physical phenomena.

References:

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7. Picosecond Spin-Orbit Torque Induced Coherent Magnetization Switching in a Ferromagnet

Debanjan Polley [1,2], Akshay Pattabi [2,3], Ashwin Rastogi[2], Kaushalya Jhuria [1,4], Eva Diaz[4], Hanuman Singh[2], Aristide Lemaitre[5], Michel Hehn[4], Jon Gorchon[4] and Jeffrey Bokor [1,2]

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Magnetic memories show great promise for the replacement of conventional semiconductor-based memory technologies due to their non-volatility and speed. Current controlled spin-orbit torque (SOT)-induced magnetization reversal draws significant attention due to the devices' increased lifetime and speed of operation when compared to other alternatives. However, the SOT switching mechanism, so far limited to ~ns current pulse excitation, is governed by domain-wall driven dynamics. Recent studies revealed an incubation delay due to stochasticity in the magnetic domain nucleation which degrades the switching speed. Here, we experimentally demonstrate ultrafast SOT-induced magnetization switching dynamics of a ferromagnetic sample with no incubation delay by avoiding the nucleation process and driving the magnetization coherently. We employ an ultrafast photo-conducting (Auston) switch and a co-planar strip line to generate and guide a ~9 ps current pulse into the heavy metal/ferromagnetic layer stack and thereby induce ultrafast spin and thermal torque. Depending on the relative current pulse and in-plane magnetic field polarities, we observe a zero-crossing of magnetization in ~70 ps, which is approximately an order of magnitude faster compared to previous studies. Complete switching occurs in ~250 ps and is limited by cooling back to room temperature via thermal diffusion to the substrate. We use a macro-magnetic LLB simulation coupled with an ultrafast heating model to analyze the effects of ultrafast thermal anisotropy torque and current-induced torque in the observed dynamics and estimate a switching current density of 7.6 $\times 10^{12}$ $A/m2$ for the ~9 ps current pulse. Our simulations suggest that the current density can be reduced by a factor of 3 by stretching the current pulse-width to ~75 ps while maintaining the coherent sub-200 ps time for full switching. Our work suggests a potential pathway towards dramatically increasing the writing speed of SOT magnetic random-access memory devices at a moderate current density via a coherent switching mechanism.

8. Ultra-low current switching via voltage-controlled exchange coupling assisted with spin-orbit torque

Brandon Zink, Delin Zhang, Yang Lv, Deyuan Lyu, Onri Benally, Hongshi Li and Jian-Ping Wang
Electrical and Computer Engineering, University of Minnesota

Magnetic random access memory (MRAM) is a promising candidate for beyond-CMOS memory and logic technologies and has been developed for commercial purposes in recent years [1]. The key building block of commercial MRAM is magnetic tunnel junction (MTJ), which is operated through either spin transfer torque (STT) or spin-orbit torque (SOT). STT-based MRAM benefits from higher cell density but suffers from reliability and energy-efficiency due to the current flow through the MTJ whereas SOT-based MRAM has superior reliability, endurance, and faster switching times [2]. For realizing the ultralow switching current density and ultrafast switching MRAM cell, two or more driving forces are normally employed to switch MTJs. One acts as the principal switching mechanism and the other serves to assist in switching. For example, ultrafast switching speed of ~ 0.27 ns has been reported in SOT switching of perpendicular MTJs (p-MTJs) assisted with STT and voltage-controlled magnetic anisotropy (VCMA), however, the key challenge is still large switching current densities (J_c) ~ 2.0×10^8 A/cm^2 for SOT and ~ 2.3×10^6 A/cm^2 for STT [3].

Voltage controlled exchange coupling (VCEC) occurs in perpendicular MTJs (p-MTJs) with synthetic antiferromagnetic (SAF) free layers and can realize bidirectional switching at switching current densities as low as 1×10^5 A/cm^2 [4]. In this work, we designed and fabricated the p-MTJ stacks with SAF free layers on bi-layered spin Hall channels (Ta/Pd). The p-MTJ stacks were patterned into 150-nm pillars, and MTJ devices are switched through combination of SOT and VCEC effects, as illustrated in Fig. 1(a). Bidirectional switching of p-MTJs were obtained with current densities as low as 3×10^3 A/cm^2 for VCEC and 6.8×10^7 A/cm^2 for SOT, as shown in Fig. 1(b), where the VCEC switching current density is two orders of magnitude lower than the reported value for VCEC-only switching [4]. Furthermore, by studying the contribution of SOT and VCEC for MTJ switching, it is found that SOT plays a crucial role for ultralow energy VCEC bidirectional magnetization switching.

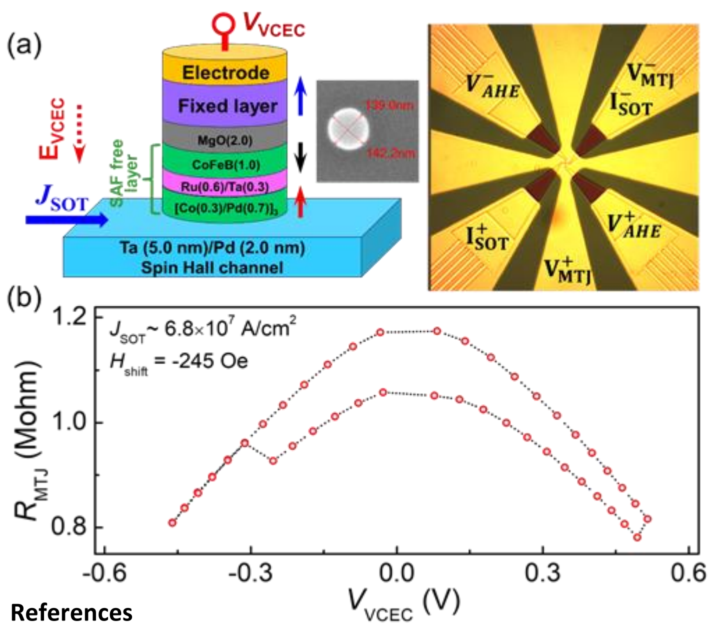

Fig. 1. (a) *Schematic of p-MTJ devices with SAF free layers switched through SOT + VCEC and the 150-nm MTJ pillar. The SAF free layer has a stack of [Co (0.3 nm)/Pd (0.7 nm)]$_3$/Co (0.3 nm)/Ru (0.6 nm)/Ta (0.3 nm)/CoFeB (1.0 nm) and the bi-layered spin Hall channel has a stack of Ta (5.0 nm)/Pd (2.0 nm) and a width of 250-nm.* ***(b)*** *R_{MTJ} vs. V_{VCEC} loop of the 150-nm p-MTJ pillar, where H_{shift} = -245 Oe and $J_{SOT} = 6.8\times10^7$ A/cm^2 (I_{SOT} = 1.2 mA) are utilized to assist VCEC switching. Switching voltages correspond to switching current densities of -1.1 x 10^3 A/cm^2 and +3.0 x 10^3 A/cm^2. Note that H_{shift} is used to center the R_{MTJ} vs V_{VCEC} curve around V_{VCEC} ~ 0.*

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9. Design and evaluation of efficient random bit-streams using spin orbit torque and voltage-controlled magnetic anisotropy in magnetic tunnel junctions

Samuel Liu[1], Jaesuk Kwon[1], Paul W. Bessler[1], Suma Cardwell[2], Catherine Schuman*[3], Darby Smith[2], Shashank Misra[2], James B. Aimone[2], and Jean Anne C. Incorvia*[1]

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Magnetic tunnel junction (MTJ) deterministic resistive switching is widely used in the application of nonvolatile magnetic random access memory (MRAM) due to its advantages of energy efficient subnanosecond operation speed, scalability, thermal stability, high endurance, and compatibility with CMOS [1-4]. Spin transfer torque (STT) and spin orbit torque (SOT) MTJ devices have been successfully developed to create the deterministic resistive bits with resistance switching between parallel and anti-parallel magnetic states [5]. Voltage-controlled magnetic anisotropy (VCMA) [6] is also deeply investigated as a way to modulate the MTJ magnetization using applied biased voltage, as shown in Fig. 1. Recently, the MTJ is considered as a candidate for unconventional stochastic hardware with applications in probabilistic computing (p-bits) [7,8]. The MTJ is suitable for optimization in high-dimensional algorithms of machine learning or sampling problems due to its low-power operation at room temperature and the high density of random noise bits that can be generated in fast nano-second time scales [9,10]. However, created random bits from MTJs requires better evaluation of the quantity, uniformity, and type of bits generated, as well as requires better co-design for implementing the MTJ as a random number generator for specified machine learning algorithms. Here, we present our results building a perpendicular MTJ model using the Landau-Lifshitz-Gillbert (LLG) equation [11,12] that allows us to compare the generation of random bit steams using the various control knobs we have on the MTJ, including STT, SOT, and VCMA. We use the generated code to analyze the resulting bit streams, including their time, energy, randomness, and the ability to control the weight of the coinflip (Fig. 2). The MTJ-generated random bit streams are used to implement simulated annealing in Boltzmann machined applied to the MAX-SAT problem. This work quantifies the design space of MTJs as p-bits and random number generators.

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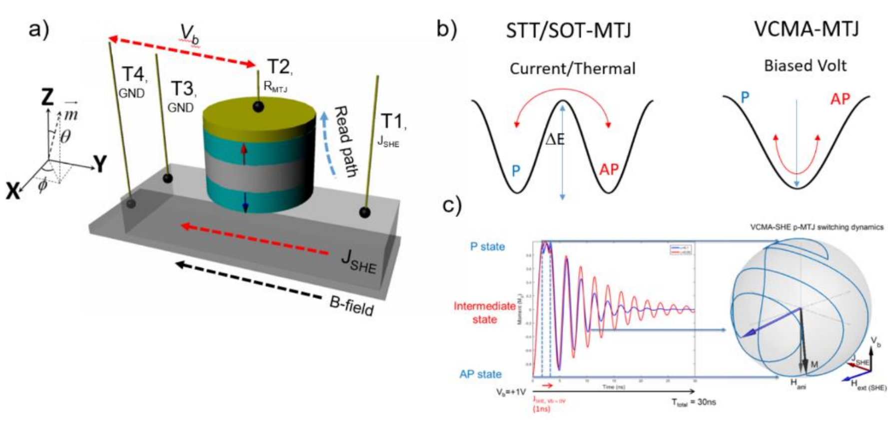

Fig. 1: a) Schematic illustration of the MTJ device structure with various knobs to control the switching probability. b) Parallel (P) and antiparallel (AP) are stable magnetic energy states. E.g. using VCMA eliminates the stable states into intermediate states with c) a precessional switching as shown in spin dynamics. When voltage is removed, the magnetization recovers randomly to the P or AP state.

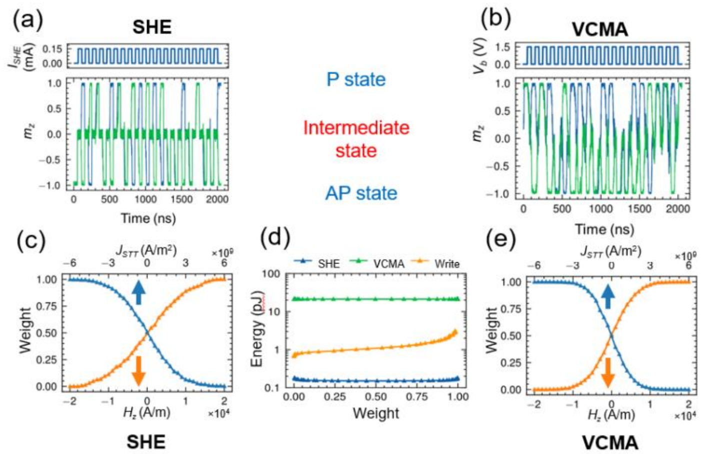

Fig. 2: Examples of random bit-streams are produced with a) two sets of SHE and b) VCMA, comparably. The switching causes from intermediate to P or AP energy states, randomly. c, e) The produced bitstreams'probabilisti c distribution follows a sigmoidal function (time-averaged), using biased-STT and perpendicular field. d) The SHE operation is energetically beneficial to create bits with ~ 0.18 pJ.

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10. Sub-Volt Switching of Nanoscale Voltage-Controlled Perpendicular Magnetic Tunnel Junctions

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Magnetic random-access memory (MRAM) based on voltage-controlled magnetic anisotropy (VCMA) in magnetic tunnel junctions (MTJs) is a promising candidate for high-performance computing applications, due to its lower power consumption, higher bit density, and the ability to reduce the access transistor size when compared to conventional current-controlled spin-transfer torque MRAM. The key to realizing these advantages is to have a low MTJ switching voltage. Here, we report a new perpendicular MTJ structure with high VCMA coefficient (~130 fJ/Vm) and high tunnel magnetoresistance exceeding 150%. Owing to the high VCMA coefficient, we demonstrate sub-nanosecond precessional switching of nanoscale MTJs with diameters of 50 and 70 nm, using a voltage lower than 1 V. We also show scaling of this switching mechanism down to 30 nm MTJs, with voltages close to 2V. The results pave the path for the future development and application of voltage-controlled MRAM and other voltage-controlled spintronic devices in emerging computing systems.

11. VCMA and STT-pMTJ Switching for Low Temperature Applications

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Spin transfer torque and voltage controlled magnetic anisotropy perpendicular magnetic tunnel junctions (STT-pMTJ and VCMA-pMTJ) are of particular interest for low temperature application due to their scalability, non-volatility and the possibility to adjust the retention of the cell to a given operating temperature[1,2]. In the context of cryocomputing, possibly involving superconductors[3], it can be envisioned that this technology is capable of cryogenic operation at 77K as well as 4K[4,5,6,7] would provide a non-volatile memory solution adapted for more energy efficient computing in these cryogenic environments. For these applications including possible interfaces with quantum computation, current developments must achieve higher electrical efficiency of the write process to become compatible with typical refrigeration cooling powers below 100mW[8].

Our approach consists in adjusting the storage layer anisotropy K_{eff}Vol (where K_{eff} is the effective surface anisotropy and Vol is the layer volume) so that the thermal stability factor Δ (given by the ratio Keff Vol/k_BT, where k_BT is the thermal energy) is maintained in the range 60-100 to provide the required retention at the low operating temperature (i.e. 10K). Compared to conventional MRAM operating at 300K, this allows reducing the storage layer anisotropy by at least one order of magnitude, which will consequentially lower the critical switching current and voltage (I_C and V_C).

For STT devices, this is done by modifying the MTJ stack structure with insertion layers such as Ru or permalloy, reducing the K_{eff} and its blocking temperature. This type of device can show high thermal stability at cryogenic temperatures while having no retention at 300K. This change in magnetization saturation and surface anisotropy will modulate the operating temperature of these devices that can be exploited for either shallow (~77K) or deep cryogenic operation (<4K).

For VCMA, by suppressing the STT effect by increasing the resistance of the junction, the capacitive energy loss will become the major contributor to power consumption, and with a lower V_C <0.1V, the expected writing energy per bit is of the order of 10aJ. Additionally, using macrospin models, its shortcomings due to its precessional regime are expected to be overcome at temperatures below 10K due to the ability to reach a deterministic switching regime.

Through numerical simulations and experiments, we report on these two types of MTJs for MRAM cells: VCMA-MRAM and STT-MRAM, exhibiting increase in VCMA efficiency and higher figure of merit (f.o.m. = Δ/I_C) through STT effect at low temperatures.

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12. Reliable all-optical switching in Tb/Co based magnetic tunnel junctions

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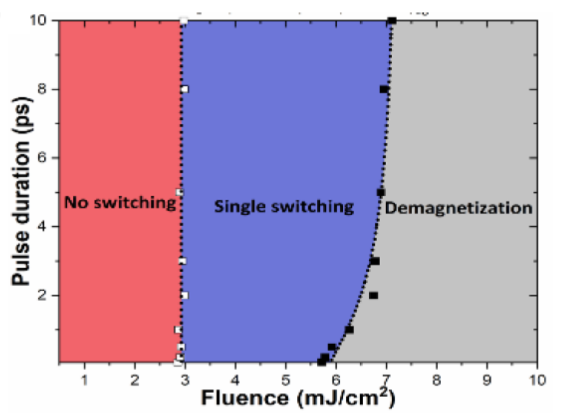
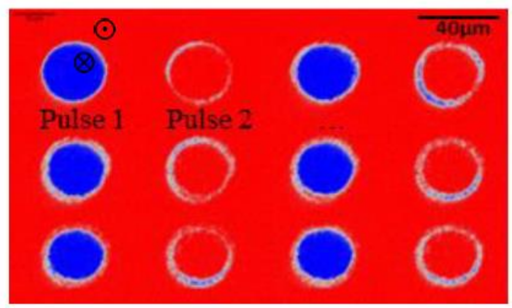
The integration of an all-optical switchable storage layer into perpendicular magnetic tunnel junctions (MTJs) is a technological challenge for the development of magnetic memories operating in the THz regime. Our solution to this problem combines the use of indium tin oxide (ITO) as a transparent conducting electrode on top of [Tb/Co] multilayers coupled to a FeCoB layer through an ultrathin Ta layer and a high quality MgO barrier.

This full sheet stack exhibits reliable magnetization switching after laser pulse excitation with duration ranging from 50fs to 10 ps and fluences from 3.0 mJ/cm2 to 6.5 mJ/cm2. Pilars with nominal diameters down to 80 nm have been successfully nanopatterned, exhibiting large TMR ratios up to 74% for a resistance area product (RxA) around 112 Ωμm².

State diagram of CoFeB/[Tb(0.64 nm)/Co(1.27 nm)]$_5$





Background corrected magneto-optical images showing robust and reliable single shot AOS of CoFeB/[Tb(0.64 nm)/Co(1.27 nm)]$_5$ (half-MTJ).

13. A magnetic memory based on tunable RUDERMAN-KITTEL-KASUYA-YOSIDA (RKKY) interaction

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A memory cell is proposed comprising a first layer of magnetic metal; a Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction spacer coupled to the first layer of magnetic metal; and a second layer of magnetic layer coupled to the RKKY spacer. The effective thickness of the RKKY spacer is changed by applied terahertz radiation resulting in changing the sign of RKKY interaction from a first sign of RKKY interaction to a second sign of RKKY interaction; thus, enabling an RKKY-tunable magnetic memory cell; wherein the first state of the memory corresponds to the first sign of RKKY interaction, and wherein the second state of the memory corresponds to the second sign of RKKY interaction.

14. Ferroelectric spin-orbit devices for ultralow power computing

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We present a new kind of spintronic/ferroelectric device, the FerroElectric Spin-Orbit (FESO) device. We demonstrate that the spin-to-charge conversion due to the spin-orbit coupling can be directly controlled in sign, in a remanent way, through the ferroelectric polarization. This constitute the birth of a ferroelectric spintronics, which could result in a drastic reduction of the power consumption of non-volatile spintronic devices, down to the attojoule range, and at low operating voltages.

While spintronics has traditionally relied on ferromagnetic metals as spin generators and detectors, the efficient spin-charge interconversion enabled by spin-orbit coupling in non-magnetic systems has drawn a considerable interest in recent years. It allows extending the field of spintronics beyond CoFeB and MgO-based devices, towards classes of materials exhibiting other types of magnetoelectric coupling, such as ferroelectricity. This provides new opportunities for creating spin-based devices, such as the MESO device proposed recently by Intel [1], which relies on the writing of a magnetic information through magnetoelectric coupling, and of its reading by spin-charge interconversion.

Here, by controlling directly the sign of the interconversion through a ferroelectric state, it is possible to merge the writing and reading blocks, and thus to avoid the need for switching a magnetic state using multiferroicity. Moreover, by merging spintronics and ferroelectricity, the FESO device circumvents several drawbacks of competing technologies, such as the destructive reading of Fe-RAMs, or the sensitivity to external magnetic fields of Magnetic Tunnel Junctions (MTJs) and MESO devices.

The spin orbit coupling allows interconverting spin and charge currents both in the bulk of materials by spin Hall effect, or at interfaces by Rashba-Edelstein effect. We demonstrate its ferroelectric control in two classes of materials: two-Dimensional Electron Gases (2DEGS) appearing at oxides surfaces or interfaces [2, 3], and ferroelectric Rashba semiconductors [4]. The demonstration of a non-volatile ferroelectric control of the conversion in two classes of materials constitute an important argument for the feasibility of the FESO device. Both these classes of materials present specific challenges and assets for their industrial integration, and could constitute the future platform of ultralow power computing.

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15. Scalability of the Perpendicular Shape Anisotropy MTJ

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The Perpendicular Shape Anisotropy (PSA) shows promise as a candidate concept to extend spin transfer torque (STT) MRAM technology below sub-20 nm lateral dimensions, where the more conventional perpendicular magnetic tunnel junctions (pMTJ) based on interfacial anisotropy (iPMA) exhibit a small thermal stability Δ, which is below the industry requirements for sufficient memory retention. In pMTJ, at those small dimensions, the reversal of the magnetic volume is almost coherent, leading Δ to scale down with the device area [1-3]. A promising answer to this challenge relies on taking advantage of the shape anisotropy of the storage layer by increasing its thickness. The perpendicular shape anisotropy becomes then the major source for stability, contributing on top of the surface anisotropy already used in pMTJs. The combination of these anisotropy sources allows to extend the downsize scalability of STT-MRAM towards sub-20 nm technological nodes [4, 5].

As the storage layer thickness is affecting its thermal stability and the writing operation of the cell, a deeper knowledge of the physical phenomena at play during magnetization reversal is important for the engineering of optimized devices. For this purpose, we provide guidelines for the development of spin-torque driven reversal PSA-MTJ based on micromagnetic simulations. It is shown that, by increasing the thickness of the storage layer to aspect-ratios higher than 1 a non-uniform reversal takes place. A coherent reversal can be observed for smaller aspect-ratios (smaller than 1), which translate to a faster reversal and less switching voltage [6].

It is also known that the interfacial anisotropy decays significantly with an increase in temperature. This results in a drawback for applications that have to operate in a wide temperature range. In this work, making use of coercivity and electron holography results we show that using the perpendicular shape anisotropy it is possible to mitigate the impact of temperature in the operation of the device. Proving a much more robust source of anisotropy with temperature variations than the interfacial pMTJ, the PSA-MTJ proves useful for applications that operate in a wide range of temperatures [7, 8].

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16. Design of Domain Wall-Magnetic Tunnel Junction Analog Content Addressable Memory using Current and Projected Prototype Data

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Resource intensive computational tasks are hindered by latency issues due to the memory wall bottleneck in traditional von Neumann architectures [1]. In-memory computation (IMC) and associative memory offera promising alternative. Among these emergent technologies is content-addressable memory (CAM). CAM allows for highly parallel comparison of an input search word to an array of storage elements in one or few clock cycles. CAM can be implemented in ternary, multi-bit, and analog operation, making it favorable in a wide range of applications, such as its use in classification tasks and search applications for memory augmented neural networks for few-shot learning and hyperdimensional computing [2]. Here, we design an analog content-addressable memory (ACAM) cell circuit using domain wall magnetic tunnel junctions (DW-MTJ). Data is stored within the ACAM cell by using DW-MTJs with distinct programmable resistance states through SOT-induced domain wall movement between multiple notches along a track under the MTJ shown in Fig. 1. The resistance states were recorded experimentally through device cycling, demonstrating 3 distinct resistance states with variability not exceeding ±1.1Ω per state over 10-15 cycles [3]. These prototype results were used to characterize the ACAM cell using simulations in CADENCE, showing that we can achieve a programmable range of 80 mV for the ACAM. We then analyze the cell circuit and show that if we can achieve reasonable parameters of 5-10 resistance states at 200% TMR and 25-70 $\Omega \cdot \mu m^2$ RA, then we can achieve a larger search range and higher resolution analog/multi-bit CAM functionality, shown in Fig. 2. In addition, our ACAM circuit maintains picosecond level search latency and maintains an area consumption notably smaller than that of similar ACAM designs implementing SRAM technology and conventional TCAM architectures [4]. Given the results of both our experimentally informed and ideal simulation scenarios, we conclude that our proposed DW-MTJ ACAM is capable of reducing power consumption and search latency while also maintaining low area consumption.

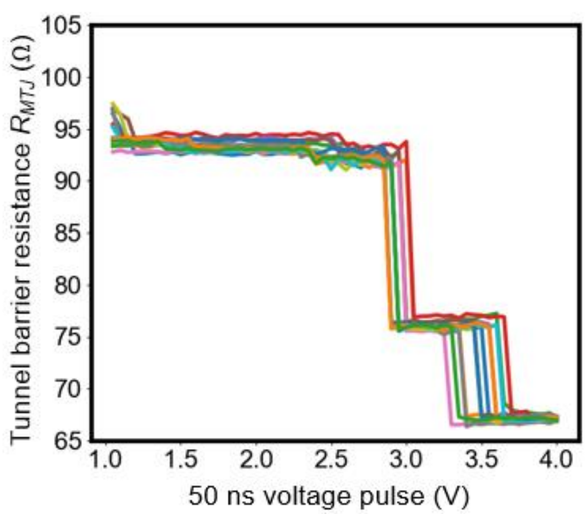

Fig. 1: Measured resistance levels for 10 cycles of trapezoidal DW-MTJ (Ref. 3)

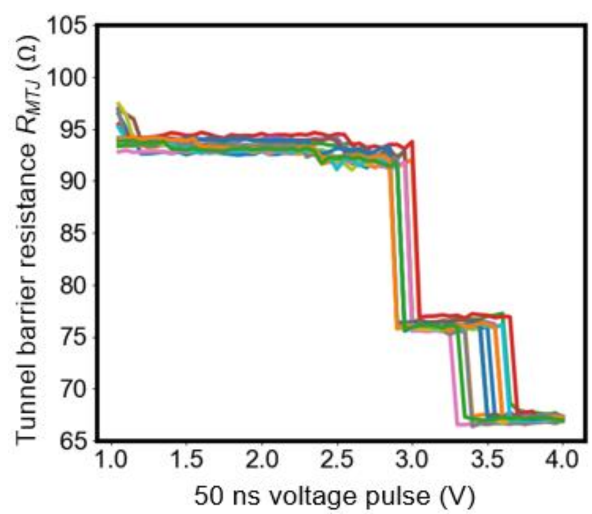

Fig. 2: Maximum ACAM bounds range vs. RA sweep

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17. Probabilistic Autonomous Sensing Using p-Bits

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This paper proposes a probabilistic sensing approach (Fig. 1) that employs p-bits (probabilistic bits) [1-2] – conventionally implemented using stochastic magnetic tunnel junctions (sMTJs) [3-4], in order to autonomously acquire event-based data from energy-constrained sensors with a degree of probabilistic confidence. This is achieved by real-time extraction of analog event features that feed the input of a p-bit, which controls the probabilistic activation of data-acquisition (Fig. 2). In conventional event-based systems, which employ binary event-detection (BED) [5], when no event features are detected all system blocks remain in sleep-mode (including the Analog-to-Digital Converter (ADC)). When event features become prominent enough to declare an event, binary deterministic activation of data-acquisition takes place. On the other hand, in the proposed probabilistic autonomous sensing approach, all system blocks remain in sleep-mode until a p-bit activates probabilistic random sampling at the onset of an event. In such a sampling scheme, the prominence of the detected event-features control the average percentage of time random sampling takes place. Once event features become prominent enough to declare a definitive event, 100 % (continuous) regular uniform sampling is triggered. This is illustrated through Fig. 1(b). Moreover, the p-bit's response can be tuned so that the probabilistic sensing system can sample randomly at an average rate (named as X in Figs. 1 and 2) when no event features are detected; to compensate for any undetected information of interest. This feature of tunable sensitivity - when no event features are detected - gives the probabilistic sensing system the ability to shift between regular sampling and probabilistic event-based sampling, and can be achieved by controlling the bias voltage ($VGate$ shown in Fig. 2). In order to demonstrate the feasibility and impact of this approach, a proof-of-concept probabilistic data acquisition system, shown in Fig. 2(a), is designed and tested on real data obtained from an active seismic survey employing geophone sensors. The results demonstrate the feasibility of lossless probabilistic autonomous data acquisition during an active seismic event, as shown in Fig. 2(b) and Fig. 2(c), with a normalized mean squared error in the frequency spectrum of the acquired signal as low as 0.007 %, while being able to achieve close to 50 % saving in the overall operation time of the sensing system and the number of generated samples.

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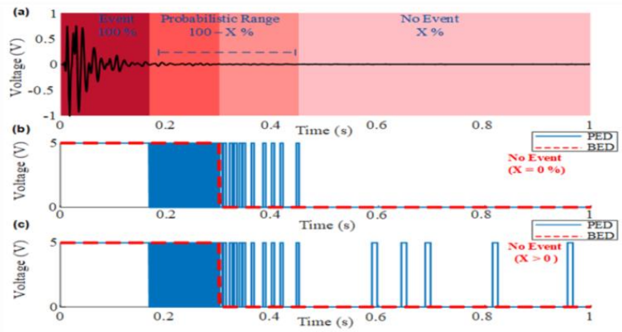

Figure 1: The concept of probabilistic autonomous sensing. (a) A sensor signal – an active seismic geophone signal in this case – illustrating regions that are definitive events (event 100 %), definite 'no events' (no event 100 %), and the probabilistic range in-between where the identification of the occurrence of an event of interest is probabilistic. (b) Activation of sampling based on binary event detection (BED) – dashed red curve – and probabilistic event detection (PED) – solid blue curve. (c) Activation of sampling based on BED and PED with an average no-event random sampling rate (X) above zero during periods of definitive no events.

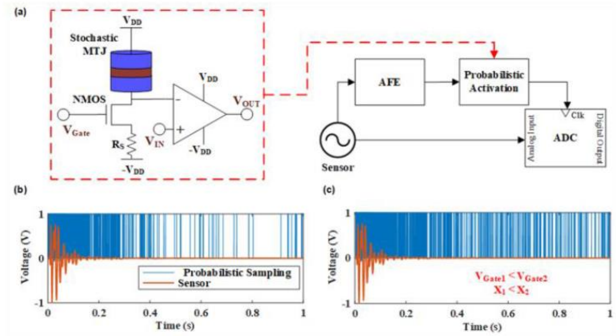

Figure 2: Probabilistic autonomous sensing using stochastic magnetic tunnel junction (sMTJ) based p-bits. (a) Block diagram of the probabilistic autonomous sensing system with the output from the analog feature extraction (AFE) circuit driving the input of the p-bit, which in turn activates probabilistic event-based data acquisition. Simulation results showing the activation of probabilistic sampling (blue curves) due to a geophone sensor signal (orange curve) for the same active seismic event at (b) $V_{Gate} = -0.5\ V$ and (c) $V_{Gate} = -0.3\ V$.

18. Hardware-accelerating variational inference with probabilistic nanomagnetic arrays

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Scalar/conventional neural networks cannot provide meaningful estimates of how they are wrong, which is a major issue for hardware safety in deployed edge system. Specifically, native uncertainty Quantification (UQ) capabilities could perform error checking locally (this may be important when said systems cannot check against known adversarial/noise cases). Bayesian neural networks (BNNs) are a promising way to achieve UQ capability; however, they are power intensive for edge AI due to the need to generate abundant pseudo-random or true random numbers. We focus on effective co-design for training a class of BNNs trained by Bayes by Backprop [1] , one variant of variational inference training methods in order to approximate Bayes' rule in neural networks. We build on a novel crossbar mapping that, unlike other schemes, allows us to combine spintronic scalar weight values (analog domain-wall magnetic tunnel junctions (MTJs) encoding the mean values[2]) and spintronic random number generators (in-plane MTJs encoding sigma /uncertainty in our system[3]), within the same fabric. Our system, which is validated by micromagnetic, macro-spin and device-model informed neural network simulations (using the CrossSim modeling tool), was validated relative to our key metrics of interest . These include: a) matching UQ quality metrics derived from similar software system to our system, which by entropy and other measures demonstrates the effectiveness of spintronic sampling; b) reducing energy cost per probabilistic multiply-and-accumulate (MAC) operation to at least 20x better than digital, and perhaps even more, in larger analog fabrics using resistive MTJs.

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19. Automated Acquisition of Switching Dynamics in Reflexion Mode of MRAM Magnetic Tunnel Junctions

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Switch timings of MRAM technologies, such as Spin Transfer Torque (STT) and Spin Orbit Torque (SOT), are critical in the context of SRAM replacement for last level cache applications [1]. Magnetic tunnel junction (MTJ) operating conditions result from the compromise between writing current level, retention and stability during read operation, to target the requirements of the final application. To optimize the operating conditions and tune the physical parameters of the MTJs, we propose a new system able to extract the incubation and switching times under writing pulses application.
The proposed system operates by acquiring and analyzing the reflected signal of the writing pulse applied on the MTJ, which could be a 2 or 3 terminal (STT[3] or SOT[2]) MRAM. The test system includes a pulse generator, a set of RF circuits and a high resolution scope. The test sequence operates in a fully automated manner, in a 2 steps process. Firstly, an average signal in both P (red line) and AP (blue line) states are acquired as reference measurements. Secondly, single shots or averaged measurements of the switching events are acquired and the reference data is subtracted, as shown in Fig.1 on STT-MRAM devices. The probability of switching and average switching time versus pulse amplitude and width can be extracted. The validity of fast macrospin switching, without any domain wall formation can be verified. With single shot measurements, switching time of single events can be acquired, as well as the incubation time before the switching occurs [3]. The full test flow is executed in a few seconds, enabling the possibility to test population of devices using automated probing stations. Using the system and our 3D magnetic generator, the test protocol can also be executed under application of an external magnetic field to study the field immunity of the device and the corresponding influence on the switching dynamics.

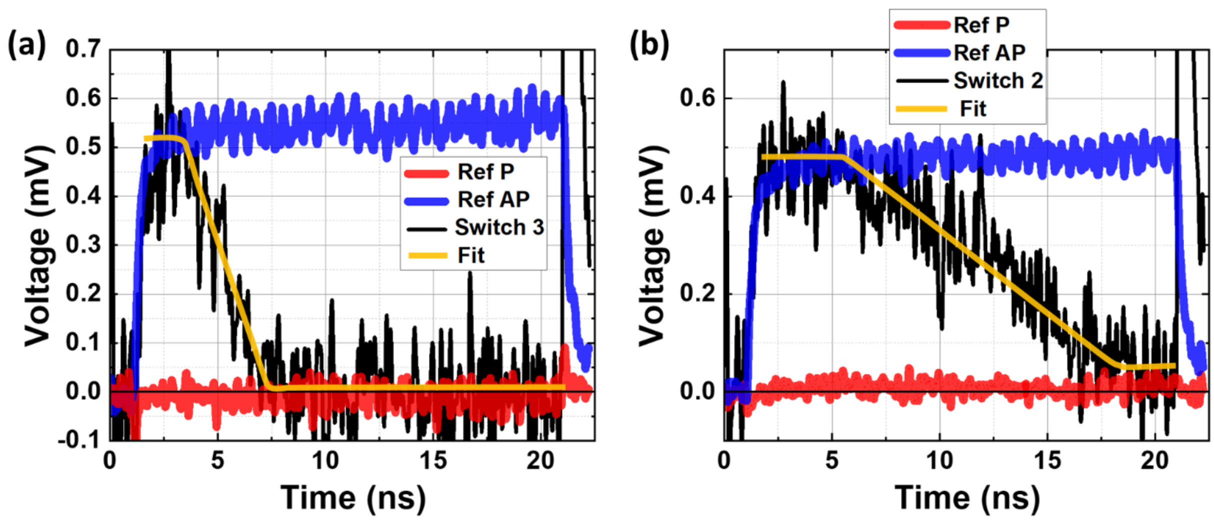

Figure 1: Switching events measured in real-time with Hmap 2 software, pulse of 0.4V and 25 ns duration. The P and AP signals (red and blue lines) are both substracted to the P one. The signal of the switching event (black line) is averaged over 10 measurements. The orange line shows a linear fit of the switching.

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20. Free layer magnetic stability in double MgO magnetic tunnel junctions: An integrated workflow from ab initio calculations to atomistic spin dynamics

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In this work we study the magnetic stability of the free layer in a double MgO perpendicular magnetic tunnel junction (pMTJ) forming the storage layer in a spin transfer torque (STT) MRAM. We present an integrated workflow with a direct coupling between density functional theory (DFT) calculated parameters and atomistic spin dynamics simulations. Parameters entering a classical spin Hamiltonian are calculated from first principles in QuantumATK[1] and subsequently directly transferred as input parameters to atomistic spin dynamics simulations using the Vampire package[2]. Specifically, we first setup the MgO-$Fe_{1-x}Co_x(t_{FL})$ -MgO structures using a dedicated MTJ builder tool, where we vary the Co concentration from 0 to 30 % as well as the free layer thickness, t_{FL}. The atomic structure is relaxed using a computationally very efficient machine-learned moment tensor potential (MTP). After the relaxation, the Heisenberg exchange coupling constants are calculated from DFT using the Liechtenstein formula. The bulk magneto-crystalline anisotropy energy as well as the interface anisotropy energy are efficiently calculated using the magnetic force theorem. We validate the use of MTP by showing a close agreement between magnetic properties calculated from structures relaxed with MTP and structures relaxed with DFT. The full workflow is demonstrated by calculating the Curie temperature and temperature dependent magnetic anisotropy energy of the free layer in double MgO layer p-MTJs. We find that close to zero temperature, the anisotropy energy is showing pronounced oscillations with the number of FeCo layers, with a maximum anisotropy obtained at the smallest t_{FL}. However, in the spin dynamics simulations at elevated temperatures, the oscillations are washed out and the maximum value is shifted to larger t_{FL} values. As an example, for a cylindrical shaped structure with a diameter of 10 nm and pure Fe free layer, the thermal stability factor, ⍰ at 300 K decreases from $\Delta=27$ for t_{FL}=1.9 nm to $\Delta=19$ for t_{FL}=0.9 nm. While we find that the area specific anisotropy energy is rather insensitive to the diameter, we do observe a significant variation in the calculated Curie temperatures depending on both diameter and t_{FL}. The presented work demonstrates an easy to use workflow directly coupling DFT calculated parameters with atomistic spin dynamics simulations, enabling a detailed study of design relevant parameters such as Curie temperature and stability factor for STT-MRAM design.

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21. Modeling Ultra-Scaled Multi-Layer STT-MRAM Cells: A Unified Spin and Charge Drift-Diffusion Approach

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Miniaturizing spin-transfer torque (STT) magnetoresistive random access memory (MRAM) devices, in particular the bit cell size, is paramount to increased storage densities. The main path towards this goal is to consider structures with interface-induced perpendicular magnetic anisotropy (PMA) [1]. In order to increase the PMA provided by the interface between an MgO tunnel barrier and a CoFeB free layer (FL), the latter is often interfaced by a second MgO layer [2]. To boost the PMA, quad-interface composite FLs were proposed [3]. Introducing more MgO layers in the FL and benefiting from the shape anisotropy of elongated FLs allows to increase the PMA even further [4], while also improving scalability thanks to the reduced FL diameters. At the same time, adding a second reference layer (RL) on top of the FL reduces the switching current while maintaining the speed [5]. To not compromise the TMR and data read, the second RL is separated from the FL by a metal spacer [5].

To accurately model ultra-scaled multi-layered MRAM cells it is paramount (i) to generalize the traditional Slonczewski approach for the torque computation [6], applicable to thin FLs, to incorporate normal metal buffers and MgO barriers between multiple parts of CoFeB FLs and RLs. (ii) The model must include non-linear bias voltage dependences of both the torques and the TMR. As the Slonczewski torque and the torques acting on a non-uniform magnetization may interfere with each other, (iii) both the interfacial and the bulk torques must be treated within the same formalism. To satisfy the requirements (i)-(iii), we generalized the coupled spin and charge drift-diffusion approach to accurately evaluate the torques in a FL composed of several elongated pieces separated by MgO barriers or metal spacers [7]. The model is implemented in a finite element micromagnetic solver based on open-source software.

To demonstrate the versatility of our approach, we elaborate on the improved switching behavior in double reference layer STT-MRAM cell. The results of the simulations agree well with the experimental behavior [5]. We also model the switching in single-digit shape-anisotropy MRAM cells with elongated FLs. We demonstrate that the switching behavior is improved with a multi-layered FL due to its composite nature. Finally, our approach is generalized to treat simultaneously the spin-transfer and spin-orbit torques.

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22. Spin Swapping Effect of Band-Structure Origin in Centrosymmetric Ferromagnets

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We theoretically demonstrate the spin swapping effect of band-structure origin in centrosymmetric ferromagnets. The proposed mechanism does not require inversion asymmetry or impurity spin-orbit scattering, but only mediated by an orbital degree of freedom. Analytic and tight-binding models reveal that its main contributions originate from **k** points in which bands with different spins and different orbitals are nearly degenerate and thus it has no counterpart in normal metals. The spin swapping conductivities calculated from first-principles calculations for 3*d* transition-metal ferromagnets are comparable in magnitude to the intrinsic spin Hall conductivity of Pt. Our theory generalizes transverse spin currents generated by ferromagnets and highlights the significance of orbital degree of freedom in spin-orbit-coupled transport. Furthermore, a widened understanding about the spin swapping effect provides an additional knob for realizing field-free spin-orbit torque switching in MRAM.