Special MRAM poster session

IEDM (Dec 13-15, 2021, Hilton Union Square, San-Francisco)

Wednesday morning Dec 15th, 9:00am-12:00 noon

Yosemite room

For the 5th 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 2021 conference. This event will be a great opportunity to foster closer interactions between the microelectronics and magnetism communities. The poster session 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. This year, 14 posters were accepted for presentation.

The list is shown below.

Bernard Dieny, Kevin Garello, Luc Thomas
IEEE Magnetics Society

Presented posters :

1. Perspectives on Perpendicular Shape Anisotropy magnetic tunnel junctions

N. Caçoilo[1], B. M. S. Teixeira[1], A. Palomino Lopez[1], T. Almeida[2], I.L. Prejbeanu[1], B. Dieny[1], L. Vila[1], L. Buda Prejbeanu[1], D. Cooper[1], O. Fruchart[1], R. C. Sousa[1]

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Perpendicular Shape Anisotropy (PSA) is a candidate concept to extend spin transfer torque (STT) MRAM technology below sub-20 nm lateral dimensions, where conventional perpendicular magnetic tunnel junctions (pMTJ) based on interfacial perpendicular magnetic anisotropy (iPMA) exhibit an inherently small thermal stability Δ [1, 2]. At small dimensions, reversal of the pMTJ magnetic volume is almost coherent, leading Δ to scale down with the device area, below minimum requirements for 10 year memory retention [3-5]. In PSA-MTJ the thickness of the storage layer is made similar to the cell diameter, such that perpendicular shape anisotropy becomes the major source for stability. The perpendicular surface anisotropy at the interface between the ferromagnet and the MgO tunnel barrier becomes only minor contribution to the total anisotropy.

In PSA-MTJ the aspect-ratio of the storage layer governs the main device properties impacting thermal stability ratio Δ and STT critical switching current. Further device optimization requires the investigation of the magnetization reversal process itself. For that purpose PSA-MTJ cells were investigated with micromagnetic simulation for both STT-driven and magnetic field-driven reversals. It was observed that, for both cases, a variation in aspect-ratio leads to transitions between different reversal mechanisms. For STT-driven reversal, it is shown that, for a constant diameter and increasing the storage layer thickness it is possible to observe coherent reversal for aspect-ratios close to 1, or non-uniform reversal for aspect-ratios larger than 1 [6]. The field-driven reversal is fundamentally different from the STT reversal. While with STT the reversal initiates near the interface with the MgO tunnel barrier, for the field-driven reversal, micromagnetic simulations show a transition from coherent reversal to vortex creation and annihilation, for larger diameters under perpendicular applied field. Experimental results confirm the vortex-based reversal in PSA-MTJs and the possibility to control its characteristic fields by modifying the magnetic saturation of the free layer.

It is also known that the interface PMA decays significantly as the temperature increases. This creates a drawback for pMTJ operation in a wide temperature range. By means of electrical measurements and electron holography studies, we show that PSA is capable of mitigating the impact of temperature on the device operation. It proves to be a more robust source of anisotropy against temperature variations showing improvements for operation in a wide range of temperatures [7, 8].

Based on these simulation and experimental results we provide a perspective view on the merits of PSA for a variety of applications depending on the fabricated pillar diameter, ranging from cells for high temperature applications at D≥20 nm, to high-density DRAM-like applications in the sub-20 nm diameter range.

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[6] N. Caçoilo et al, Phys. Rev. Applied 16, 024020 (2021).
[7] S. Lequeux et al., Nanoscale 12, 6378 (2020)
[8] S. Lequeux et al., 2021 IEEE International Memory Workshop (IMW), (2021)

2. Double magnetic tunnel junction with switchable assistance layer for high efficiency STT-MRAM

D.S. Hazen[1], B.M.S Teixeira[1], D. Salomoni[1],S. Auffret[1], L. Vila[1], R.C. Sousa[1], I.L. Prejbeanu[1], L. D. Buda-Prejbeanu[1], B. Dieny[1]
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Perpendicular Spin Transfer Torque Magnetic Random Access Memory (p-STT-MRAM) still requires improvements to be usable for fast cache applications [1]. To be able to replace Static Random Access Memory (SRAM), p-STT-MRAM needs to combine high speed and low critical switching current at technological nodes below 30 nm. Higher STT write efficiency is therefore needed [2]. Double magnetic tunnel junctions (DMTJ) have recently been proposed to achieve this goal [3-5]. A typical DMTJ stack is shown in Fig. 1(a). It consists of a storage layer (SL) sandwiched between two tunnel barriers with antiparallel top and bottom hard reference polarizers. The SL retention is improved thanks to the two FeCoB/MgO interfaces contributing to the effective SL perpendicular anisotropy. The critical switching current (I) is decreased by the combined effect of the STT exerted from the two antiparallel polarizers on the SL. Despite the efficiency advantage, these p-DMTJ have several flaws [6]. A first difficulty arises in creating a top polarizer with high perpendicular anisotropy. The main source of perpendicular anisotropy is commonly a (Co/Pt) multilayer-based synthetic antiferromagnetic structure (SAF) coupled to the FeCoB electrode. The SAF perpendicular anisotropy is highly dependent on the (Co/Pt) multilayer crystallographic texture [7]. While high anisotropy can be easily obtained in the bottom polarizer by the use of a proper seed layer, this approach is not possible with the top polarizer, which must be grown seedless on top of the tunnel barrier. Another complexity to the design and optimization of this structure is the requirement to compensate stray fields generated by both top and bottom references which comprise overall four magnetic layers. Besides, the etching of these DMTJ stacks is even more difficult than that of conventional STT-MRAM stacks due to the additional thickness of the top polarizer. In this work, we present the first experimental proof of concept of a novel type of double magnetic tunnel junction structure [8] illustrated in Fig.1.(b). This ASL-DMTJ is simpler and thinner than conventional DMTJ. It is based on the use of a switchable top polarizer acting as an assistance layer (ASL). The ASL is designed to switch its magnetic orientation during the write operation in such a way to maximize STT efficiency during both the parallel (P) to antiparallel (AP) and AP to P transitions while always ending parallel to the SL magnetization in standby. To achieve these properties, the SL/ASL interlayer coupling and ASL thermal stability must be finely adjusted. Real-time observations of the devices resistance variations confirm the expected operation mechanism in the fabricated cells. The performances were evaluated by using the ratio between retention energy barrier and critical switching current as Figure of Merit (FOM).

They are compared to those of conventional single magnetic tunnel junction structures without ASL. The comparison highlights the benefits of the proposed stack design for high performance STT-MRAM applications.

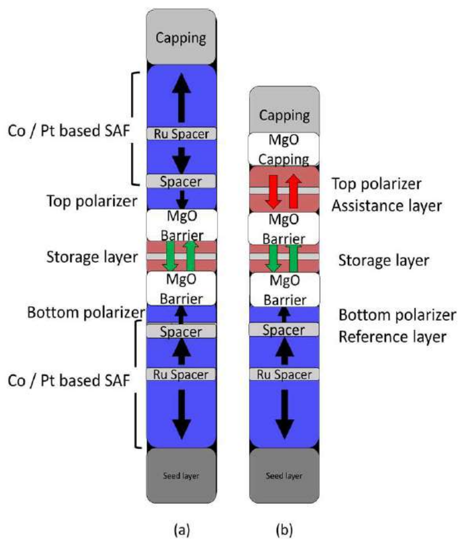

Fig. 1. (a) Stacks comparison between a conventional p-DMTJ with static top and bottom polarizer and (b) an ASL-DMTJ

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[4] B.Rodmacq et al. Patent US8513944B2. (2008)
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3. Dependence of interfacial magnetic anisotropy on insertion layer Mo thickness in CoFeB-MgO structure for MRAM with high thermal stability

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Perpendicularly magnetized magnetic tunnel junctions (pMTJs) based on HM (heavy metal)/CoFeB/MgO structure is a promising candidate for the next-generation ultra-low energy memory and logic device owing to its fast speed, high endurance, high tunneling magnetoresistance and low damping factor. To integrated pMTJs into practical applications, a high thermal stability over 400C is required for compatibility with back end of line (BEOL) process of CMOS technology. However, a degradation of perpendicular magnetic anisotropy (PMA) occurs for conventional HM seed layer like Ta under annealing temperature higher than 300C. Here, we studied the thickness dependence of PMA on inserted Mo layer in the structure of Ta/Mo(t)/CoFeB/MgO/Ta where Mo is a good thermal barrier and Ta acts as a boron getter. The experimental results show that the tolerance of annealing over 400C can be achieved by suppressing the diffusion of HM atoms from underlayer. Two different physical mechanisms which dominate the PMA deterioration during annealing in Ta/Mo/CoFeB/MgO structure with different Mo thickness are illustrated: when the thickness of Mo insertion layer is below 2 nm, the Ta atoms diffusion into CoFeB/MgO interface and the formation of Ta-O lead to the degradation of PMA; When the thickness of Mo insertion layer is above 2 nm, thicker Mo layer hinders the absorption of boron atoms by Ta layer underneath and consequently degrades the PMA due to a lower crystallization degree of CoFeB.

4. Toggle Spin-Orbit Torque MRAM with Perpendicular Magnetic Anisotropy

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Writing magnetic random-access memory (MRAM) by ultrafast and energy-efficient spin-orbit torque (SOT) has been impeded by the orthogonality between spin polarization and thermally stable perpendicular magnetic anisotropy (PMA). Previously proposed approaches to break this symmetry increase the fabrication complexity, are highly sensitive to the SOT current duration and magnitude, or increase the switching energy. To overcome these challenges, we exploit the precessional nature of the field-like SOT to propose a toggle PMA SOT-MRAM with simple structure that is controlled by a unidirectional SOT current. The proposed MRAM achieves field-free and energy-efficient switching that is robust to variations in the SOT current magnitude and duration with greater than 50% tolerance demonstrated through micromagnetic simulation. The deformation-free structure provides efficient data read-out and can be leveraged for directional writing through a simple XOR between the stored and incoming bits.

5. Asymmetric SOT switching induced by in-plane magnetic fields in MTJ-compatible Ta/CoFeB/MgO structures

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SOT-MRAM may address the possible limitationsof STT-MRAM with fast switching processes and separated writing and reading paths. However, the possible asymmetric switching behaviors between up-down and down-up switching that can cause serious problems in the circuit-level designs in SOT-MRAM products has not been investigated. Here we demonstrate the potential asymmetric SOT switching induced by the applied in-plane magnetic field (H). We directly measured the SOT efficiency as the functions of the strength of H and its tilt angle away from the writing currents and found that the SOT efficiencies are intrinsically different for up-down and down-up switching. Furthermore, the resultant critical switching currents are also quite different. Our results provide additional guidelines for designing SOT-MRAM to achieve symmetric SOT switching processes.

6. Direct detection of spin Hall effect in an antiferromagnetic material

Saima Siddiqui[1], Sandra Ruiz-Gómez[2], Kisung Kang[1], Jordan Katine[3], Muhammad W. Khaliq[2], John E. Pearson[3], André Schleife[1], Michael Foerster[2], Manuel Valvidares[2], and Axel Hoffmann[1,4]

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The spin Hall effect (SHE) is an efficient way of converting a charge current into a spin current that can modulate the magnetization in an adjacent magnetic layer. Antiferromagnetic metals can have high spin Hall angles (θSH, ratio of spin to charge currents) as measured using indirect electrical measurement, such as spin torque ferromagnetic resonance in adjacent ferromagnetic layers [1,2]. These indirect electrical measurements of SHE depend on the transparency of the spins at the interface between the antiferromagnet and the adjacent ferromagnetic layer and may be affected by the spin losses and transport in the ferromagnetic layers and many other non-idealities [3,4]. There are often discrepancies in the measured values of θSH in a single material based on its interfaces even at the same temperature [1,2]. Therefore, an interface-free, direct measurement of intrinsic SHE is highly desirable for an improved fundamental understanding and optimizing technological applications.

Here, we report the direct measurement of the interfacial spin accumulation induced by the spin Hall effect in antiferromagnetic PtMn thin films using magnetic circular dichroism (XMCD)- photoemission electron microscopy (PEEM). We show that the XMCD has opposite sign at the L3 edge of Mn for opposite charge current directions and scales linearly with current density. We quantitatively determine the current-induced spin accumulation at the PtMn interface as 8.8×10−12 μBA−1cm2 per atom averaged over the probing depth which translates into a positive spin Hall angle of 0.25 (±0.1). Our results show the direct, spatially resolved, interface free and element-selective measurement of the SHE in a CuAu-I-type antiferromagnetic material by means of X-ray microscopy.

Supported by the NSF through the Illinois MRSEC (DMR-1720633) and the U.S. DOE, Office of Science, Materials Science and Engineering Division.

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7. Efficient voltage-controlled magnetic anisotropy in wafer-scale magnetic tunneling junction

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Voltage Control Magnetic Anisotropy (VCMA) MRAM is a promising candidate for next-generation MRAM due to its low energy consumption and high endurance. Even though high VCMA coefficient has been demonstrated in laboratory experiments, the number in wafer-scale MTJ is relatively low, which is the major bottleneck for VCMA MRAM manufacturing. In this work, we realize the ns-pulse switching in top-pinned perpendicular-MTJ on 8 inch wafers annealed at 400℃, compatible with CMOS backend processing. The effective anisotropy field is determined 0.27 T by voltage-induced ferromagnetic resonance. With the critical switching voltage (3 V), the VCMA coefficient is estimated at around 68.9 fJ/Vm, which is around twice of standard MTJ. Our results show a higher VCMA coefficient solution and can be helpful for further enhancement.

8. Voltage Controlled Static Skyrmion Device for Neuromorphic Computing Applications

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The topological protection of the swirling magnetic structures, known as Skyrmions, has gained a lot of attention in the Spintronics community [1]. These novel spin textures are promising an increased density and energy efficient data storage due to small nanometric size and topological protection [2]. For different logic and memory applications skyrmions have been created, annihilated and driven by the application of external magnetic fields and or current [3]. On the other hand, voltage control of the surface anisotropy in magnetic tunnel junctions has gained a lot of interest, owing to the energy efficient switching as low as a few femtojoules [4]. In this presentation we propose a voltage controlled skyrmion based MTJ device for neuromorphic computing applications. The skyrmion is confined in a region bound by increased anisotropies as shown in Fig. 1(a). The MTJ device consists of a thin ferromagnetic free layer/Tunnel Barrier/Reference layer. The free layer has the confined skyrmion in it whose size is controlled by voltage pulses. Thick 3nm tunnel barrier is considered to ensure STT current doesn’t have an effect on the skyrmion. As skyrmion stability depends particularly upon Dzyaloshinskii Moriya Interaction (DMI) and anisotropy. The writing voltage pulses applied across the MTJ change the surface anisotropy at heavy metal/free layer interface, thus changing the skyrmion diameter. The control of confined skyrmion size will allow increased memory density and power efficiency. In addition, the interaction between neighbouring skyrmions is also minimized. To demonstrate the neuromorphic computing capabilities of the proposed device, we present the MTJ with positive voltage pulses of 1 ns, each followed by a 0.5 ns break. As shown in Fig. 1(b) we observe the integrating behaviour of MTJ when a voltage is applied and the skyrmion size reduces which also reflects in the neuron output voltage. In absence of voltage, the skyrmion tries to increase its diameter and neuron voltage drops, thus the MTJ mimics the leaky neuron behaviour i.e., neuron leaks some part of the membrane potential. We continue the application of pulses till the voltage crosses the threshold and a spike is generated by the sensing unit. The neuron is reset by a negative voltage pulse which decreases the anisotropy and the skyrmion regains its full size abruptly. The neuron activation function with respect to gate voltage is shown in Fig. 2(a). In Fig. 2(b), we test the proposed neuron model on MNIST data set for a fully connected dense neural network to observe the pattern classification efficiency.

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9. Ultrafast all-optical switching of FeCoB/Ta/[Tb/Co] magnetic tunnel junctions for spintronic-photonic memory

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In this work we describe the stack development of all-optical switching perpendicular magnetic tunnel junctions (MTJ) and their nano-fabrication using Indium Tin Oxide (ITO) as hard mask and transparent conductive electrode. The fabricated cells have optical access for laser pulse switching.

The design and fabrication of the MTJ is based on a [Tb/Co] multilayer stack with optically switchable magnetization. We explore the magneto-optical properties of [Tb/Co] multilayer and their stability under annealing temperatures up to 300°C [4]. In order to fabricate optically switchable magnetic tunnel junction electrodes, [Tb/Co] multilayers were coupled to a FeCoB layer through a Ta ultra-thin layer. Toggling of the magnetization in the Tb/Co multilayered stack was observed using both 60 femtosecond- and 5 picosecond-long laser pulses with fluences down to 4.7 mJ/cm² [3]. The all-optical switching (AOS) of the Tb/Co multilayers was achieved for Co-rich composition of the multilayers, either alone or embedded in a tunnel junction stack coupled to a FeCoB electrode on an MgO barrier. Electrical evaluation of nanopatterned AOS-MTJ showed TMR ratios up to 40 % for a resistance area product (RxA) around 150 Ωµm²[1][3].

To provide for optical access to the MTJ free layer, while also allowing for an electrical read-out of the

MTJ state, a process flow using indium tin oxide as a top transparent electrode was successfully developed. Patterning of ITO was done using a reactive ion etch based on a CH_4/H_2 chemistry, to achieve almost vertical sidewalls for diameters down to 50 nm [2]. The ITO based process flow was compared to a standard magnetic tunnel junction fabrication flow based on Ta hard mask, both achieving the same TMR signal levels. A device matrix with magnetic tunnel junctions was fabricated with the mentioned stacks and process flow to demonstrate a path of spintronic-photonic integration. The fabricated devices confirmed all optical switching after fabrication, using picosecond pulses to switch the AOS electrode and electrical read-out of the magnetic tunnel junction resistance.

Our results contribute to advances in ultrafast magnetic random access memories, showing how Tb/Co-based optically switchable magnetic tunnel junctions are good candidates for photonic-spintronic integration in electronic circuits.

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10. Multifunctional Design of Quantized Domain Wall-Magnetic Tunnel Junction Artificial Synapses for Flexible Training of Neural Networks

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The processing of artificial neural networks (ANNs) is limited by the memory wall in von Neumann architectures, driving the need for hardware ANNs realized by neuromorphic devices [1]. Previously proposed multi-weight synaptic devices often suffer from a nonlinear and asymmetric update response, limiting their viability for supervised learning [2]. Domain wall-magnetic tunnel junction (DW-MTJ) devices driven by spin transfer torque (STT) and spin orbit torque (SOT) have shown promise in neuromorphic applications, realizing neuron behavior in simulation [3-8]. Simulations also show that DW-MTJs can implement synaptic spike-timing dependent plasticity [9]. A type of DW-MTJ with multiple MTJs was demonstrated experimentally [10], but there has not yet been a demonstration of multi-weight switching in a DW-MTJ with a single MTJ. Most prior work on DW-MTJ synapses in ANNs does not consider thermal effects and process variation. We evaluate notched DW-MTJ designs shown in Fig. 1a and account for these effects using MuMax3 for device simulation and CrossSim for network simulation [11-13]. Figure 1b shows that excellent linearity, high symmetry, and low thermal noise are maintained at 300 K, leading to high training accuracy on the Fashion-MNIST task, shown in Fig. 2 [14]. Notably, the greater stochasticity of SOT-driven synapses counters the discretizing effect of notches, boosting accuracy to near ideal. We also show that the ferromagnetic track can have lithographically defined metaplasticity, enhancing network performance on online learning tasks. These results propose a magnetic synapse with tunable plasticity, superior backpropagation performance, and fast updates, a foundational step toward ANNs with fully spintronic matrix operations.

11. Experimental Demonstration of Neuromorphic Network with STT MTJ Synapses

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One of the primary hardware costs incurred by artificially-intelligent neural networks is due to vectormatrix multiplication (VMM). Non-volatile analog resistive memory devices appear to naturally mimic the behavior of neurobiological synapses, and can be used to perform VMM by taking advantage of Ohm's and Kirchhoff's laws to efficiently perform these calculations in terms of voltage and current. Most research in this area has focused on crossbars composed of memristors and phase change memory (PCM). However, these devices suffer from several major challenges which limit their utility for VMM crossbars, including imprecise setting to desired resistance state, weights drifting over time, limited endurance, and compatibility challenges with CMOS processes. Magnetic tunnel junctions (MTJs) provide solutions to the limitations of memristors and PCM, and their binary resistance states can provide analog neuromorphic behavior through the stochastic nature of STT-MRAM switching. Here we present the first experimental demonstration of a neuromorphic network using MTJ synapses for VMM. While

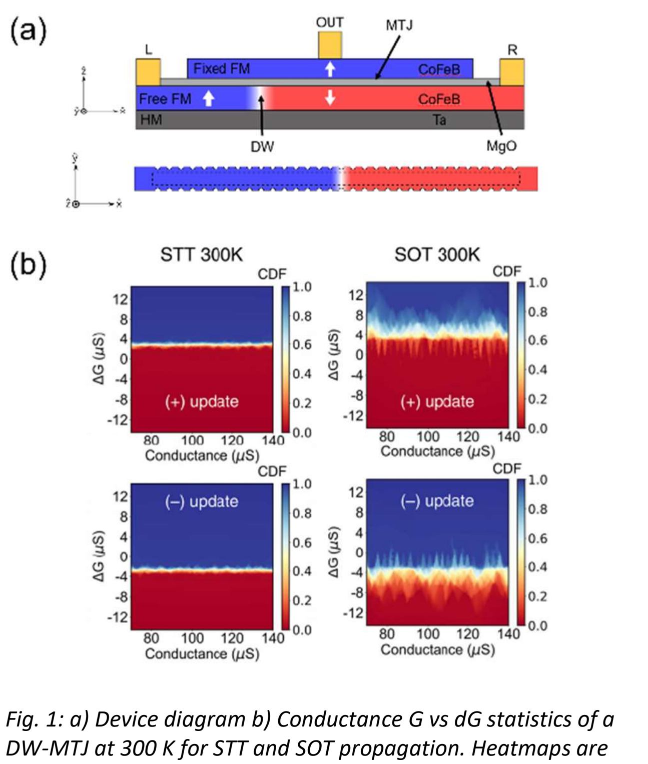

Fig. 1: a) Device diagram b) Conductance G vs dG statistics of a DW-MTJ at 300 K for STT and SOT propagation. Heatmaps are generated from micromagnetic simulations. The CDF represents the probability that a given conductance update is less than the average.

spintronic devices have been demonstrated for other neuromorphic functions --*e.g.,* spin-torque nano oscillators, domain wall MTJs, and stochastic p-bits -- they have not previously been demonstrated as adjustable synapses in a neuromorphic network. This poster reports the experimental demonstration of a small binarized neuromorphic network with MTJ synapses, greatly advancing the development of highly-efficient, robust hardware amenable to neural applications.

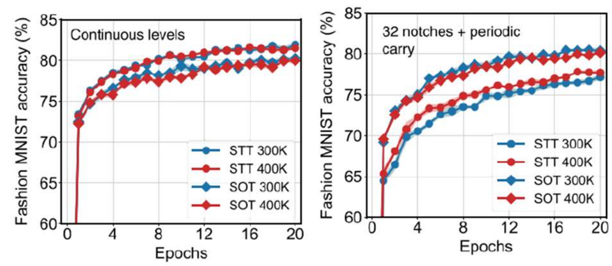

Fig. 2: Validation accuracy of a two-layer perceptron of STT and SOT DW-MTJ synapses at 300 K assuming (a) continuous levels and (b) 32 notches and periodic carry.

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12. Enhancing the performances of MRAM materials and devices using light ion irradiation

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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 MRAM devices at atomic level and improve their performances. The utilization of light ions provides the precise control of inter-atomic displacements through low energy transfer. The key feature of the technology is the post-growth control at the atomic scale of structural properties and the related magnetic properties. When realized through a mask this technology allows lateral modulation of magnetic properties without any physical etching. To perform ion irradiation, we have used a compact ion irradiation facility (Helium-S® from Spin-Ion Technologies), capable of ultra-fast He+ ion irradiation on 1 inch wafers with energies ranging between 1-30 keV.

In this poster, we will show a few important results that suggest a pathway to optimize the performances of future generation of MRAM devices using He ion irradiation : (1) crystallization of CoFeB-MgO layers can be obtained with lower distribution of magnetic properties than pure annealing, (2) Spin Orbit Torques MRAM devices can switch at lower current densities, (3) skyrmions can be nucleated and channeled in racetrack and (4) chiral domain walls can propagate at higher domain wall velocities in narrow wires.

13. New Isolation Method for MTJ Fabrication Using SiN-Sidewall

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The metal adsorption on MgO sidewall at the bottom etching process causes a very large leakage current and degrade the reliability [1], and the sidewall protection of MgO during the bottom electrode etching is essentially required. We have already reported the leakage current could be suppressed, and reliability could be maintained in the simple stuck structure of CoFeB/MgO/CoFeB, because the bottom electrode etching is very simple [1]. However, the adsorption of the metal contamination during bottom electrode etching in full stuck structure case has to be suppressed, because the bottom electrode is thicker and more complicated than the above simple structure. To eliminate the leakage current in full-stack MTJs, we have investigated a new isolation method MTJ cells by using SiN-sidewall. The cross-sectional view of process steps is shown in Fig.1. At the first ion beam etching (IBE), the etching stopped at the surface of CoFeB layer under the MTJ, and then the SiN was formed on the sidewall of the cell, following IBE was done for all bottom electrode metals. The sidewall SiN film can protect the metal adsorption during bottom electrode etching. The etch stop was determined by using the signal of SIMS during the etching. By eliminating the leakage current at the edge, the clear MR curve and the high reliable MgO films can be observed as shown in Fig. 2 and 3.

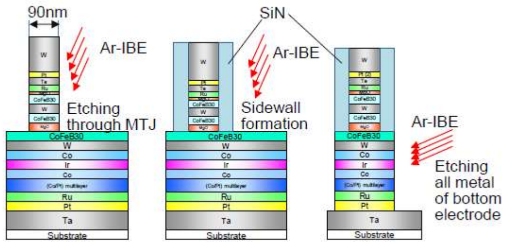

Fig. 1 Formation steps of isolation of MTJ by using SiN-sidewall.

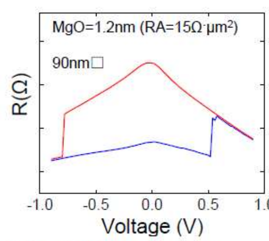

Fig. 2 House curve of MTJ

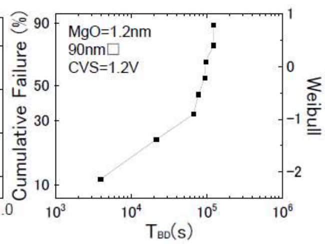

Fig .3 Weibull plot of T_{BD} for MgO.

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14. Design Support for Ultra-Scaled MRAM Cells

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The design of advanced, single-digit shape-anisotropy MRAM cells [1] requires accurate evaluations of spin currents and torques in magnetic tunnel junctions (MTJs) with composite elongated free layers (FLs). For this purpose, we generalized the coupled spin and charge drift-diffusion approach previously successfully applied to nanoscale metallic multilayer structures [2][3] to accurately evaluate the spin and charge transport and the torques acting in an MTJ on a FL composed of several pieces separated by MgO tunnel barriers (TBs) [1].

To evaluate the charge current density, we model the TB as a poor conductor with a local resistance being dependent on the relative orientation of the magnetization across the TB. We demonstrated that the expected dependence of the current density flow on the magnetization state is reproduced [4].

To model correctly the spin current density, the coupled spin and charge drift-diffusion approach must be supplemented by *appropriate boundary conditions for the spin current at the TB interfaces*. With the addition of such conditions, the expected dependence of the torques on the relative angle between the magnetization vectors [5][6] is reproduced. Our approach can be generalized to model non-linear bias dependences of the torques as an on-demand feature by making the interface polarization parameters depend on the voltage. The observed voltage dependencies of both the damping-like and field-like torques are thereby properly reproduced.

The magnetization in elongated FLs of ultra-scaled MRAM cells during switching is highly nonuniform along the FL as the formation and propagation of a domain wall is expected. The additional torques acting in the presence of a domain wall are usually modeled by the Zhang and Li [7] expression. We demonstrate that, in the presence of a TB, the Slonczewski and Zhang and Li torques are *not additive* and must be treated on equal footing to correctly describe the torques acting on nonuniform magnetization in elongated FLs with several MgO TBs. Our simulations of the magnetization dynamics in composite elongated FLs agree well with recent experimental demonstrations of switching of ultra-scaled MRAM cells.

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