# Ultrafast switching in elliptical pMTJ via Voltage Control of Magnetic Anisotropy 

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#### Abstract

We propose an elliptical-shaped pMTJ to eliminate the requirement of an external field source for precession based VCMA switching. We demonstrate that a 10 nm thick in-plane magnetized bias layer (BL) separated by a metallic spacer of 3 nm from the free layer ( $\mathbf{F L}$ ) can be engineered within the MTJ stack to provide the 50 mT bias magnetic field for switching. By conducting macrospin simulation, we find that a fast switching in 0.38 ns with energy consumption as low as 0.3 fJ at a voltage of 1.6 V can be achieved. Furthermore, we study the phase diagram of switching probability, showing that a low-voltage operation $(\sim 1 \mathrm{~V})$ is favored.


## 1. Introduction

Perpendicular magnetic tunnel junction ( pMTJ ) based on the spin transfer torque (STT) is a promising candidate for magnetic random access memory (MRAM) [1]. However, a large switching current limits its applicability as it leads to large energy consumption and a huge cell area [2]. Voltage control of the magnetic anisotropy (VCMA) [3] has recently emerged as a low-energy alternative to STT. The demonstrations [4-6] hitherto have been on individual circular MTJs that behest an external in-plane (IP) bias field $H_{x}$, which is not a viable solution for the integrated MRAMs w.r.t both the provision of an external field source and the field uniformity [7]. Therefore, it poses a critical bottleneck for realizing a practical VCMA memory. Since in an elliptical structure, via shape anisotropy, an IP magnetized bias-layer (BL) separated by a metallic spacer of thickness $\mathrm{t}_{\mathrm{M}}$ from the free-layer (FL) can be engineered [8], we appraise the elliptical pMTJs (FL magnetization unit-vector $\mathbf{m}=\left[\mathrm{m}_{\mathrm{x}} \mathrm{m}_{\mathrm{y}} \mathrm{m}_{\mathrm{z}}\right]$ $=[00 \pm 1]$ in stable states) for the VCMA based switching. We show that the required bias field can be contrived within the MTJ stack, yet the FL can toggle in just 0.38 ns consuming only 0.3 fJ at 1.6 V across MTJ.

## 2. Simulation Methods and Results

Fig. 1(a) shows a conceptual illustration of an elliptical pMTJ of cross-section $150 \times 50 \mathrm{~nm}^{2}$ with major-axis along xaxis. A 1.2 nm thick $\mathrm{Co}_{20} \mathrm{Fe}_{60} \mathrm{~B}_{20}$ pinned-layer (PL) and a 1.7 nm thick $\mathrm{Co}_{20} \mathrm{Fe}_{60} \mathrm{~B}_{20}$ FL sandwiches MgO insulator of thickness $\mathrm{t}_{\mathrm{MgO}}$ ranging from 1.2 nm to 2.8 nm . A trapezoidal voltage pulse $\mathrm{V}_{\mathrm{MTJ}}$ of rise and fall time of 50 ps each, a high time (all 3 collectively termed $t_{\mathrm{ON}}$ ) of amplitude $\mathrm{V}_{0}$ and a sufficient off-time of 10 ns for the FL to relax is applied.

Macrospin simulation described by the Landau-LifshitzGilbert equation is performed considering the effects of demagnetization, room temperature thermal fluctuation, ex-
change bias field, uniaxial anisotropy field $\mathbf{H}_{\mathrm{K}}$, STT damp-ing-like torque (DLT) from the PL and the BL, and fieldlike torque (FLT) from the PL. The $\mathbf{H}_{\mathbf{K}}$ is linearly modified by the perpendicular z-component of the electric-field $\mathrm{E}_{\mathrm{z}}=$ $\mathrm{V}_{\mathrm{MTJ}} / \mathrm{t}_{\mathrm{MgO}}$ at the $\mathrm{MgO}-\mathrm{FL}$ interface, at a rate of the magnetoelectric coefficient $\xi$. Saturated magnetization $\mathrm{M}_{\mathrm{S}}=$ $1.257 \times 10^{6}{\mathrm{~A}-\mathrm{m}^{-1}}$, bulk anisotropy $\mathrm{K}_{\mathrm{U} \_ \text {Bulk }}=2.245 \times 10^{5} \mathrm{~J}-\mathrm{m}^{-3}$, interfacial anisotropy constant $\mathrm{K}_{\mathrm{I} 0}=1.286 \times 10^{-3} \mathrm{~J}-\mathrm{m}^{-2}$ and $\xi$ $=50 \mathrm{fJ}-\mathrm{V}^{-1}-\mathrm{m}^{-1}$ are extracted from the experimental papers $[9,10]$. For $\mathrm{V}_{\mathrm{MTJ}}=0$, the FL has a perpendicular easy-axis while at $V_{0}, E_{z}$ is larger than the critical VCMA field which renders the easy-axis along x -axis and destabilizes the FL , resulting in its precession. For a sufficiently large $H_{x}$ the $m_{z}$ swings from +1 to -1 or vice versa in time $t_{\text {Half }}$. This $H_{x}$ can be contrived from an IP BL ( $\mathrm{Co} / \mathrm{Pt}$ multilayers) as shown in Fig. 1(b), e.g. a 10 nm BL spaced by a 3 nm metal can provide a dipole field along x -axis of 50 mT . Fig. 1(c, d) show that in a MTJ with $2 \mathrm{~nm} \mathrm{t}_{\mathrm{MgO}}$, a $1.6 \mathrm{~V} \mathrm{~V}_{0}$ and a 50 mT bias field are applied for the FL to toggle and restore with $\mathrm{t}_{\mathrm{ON}}$ of 0.35 ns and 0.7 ns respectively.


Fig. 1. (a) An elliptical pMTJ with major axis along x -axis. (b) $\mu_{0} H_{x}$ versus $t_{B L}$ for different spacer metal thicknesses. The field generated within the MTJ is large enough to bias the FL for VCMA switching. FL switching with $\mathrm{t}_{\mathrm{ON}}$ in integer multiples of $t_{\text {Half, }}$, where odd multiples toggle the FL while even multiples restore it into the original state: $t_{\text {Half }}$ is 0.35 ns while $\mathrm{t}_{\mathrm{ON}}$ is (c) 0.35 ns and (d) 0.7 ns . This drives (retains) the MTJ into P (AP) state in (c) ((d)).

Fig. 2(a-c) show the effect of $\mathrm{t}_{\text {Mgo }}$ on VCMA switching. The $t_{\text {ON }}$ in Fig. 2(a) is set to be $t_{\text {Half }}$, at which switching is
most probable to happen. The divergence in $\mathrm{t}_{\mathrm{ON}}$ for parallel (P) to anti-parallel (AP) and AP-to-P switching for small $\mathrm{t}_{\mathrm{MgO}}$ is due to a significant STT contribution, while an overlapping trend for larger $\mathrm{t}_{\mathrm{MgO}}$ shows dominating VCMA effect. The suppressed STT effect is because of the exponentially reduced current density with an increasing $\mathrm{t}_{\mathrm{MgO}}$ as shown in Fig. 2(b). Accordingly, Fig. 2(c) shows that at a sharply reduced current density of $10^{7} \mathrm{~A}-\mathrm{m}^{-2}$ for a 2.8 nm $\mathrm{t}_{\mathrm{MgO}}$, VCMA enables the device to switch in 0.38 ns with just 0.3 fJ of energy. Then, to probe the switching probability when considering thermal fluctuation from P -to-AP in Fig. 2(d) and AP-to-P in Fig. 2(e) at small enough switching energy, $\mathrm{t}_{\mathrm{MgO}}$ is fixed to 2 nm and $\mathrm{V}_{0}$ and $\mathrm{t}_{\mathrm{ON}}$ are varied. For any given $\mathrm{V}_{0}$ the probability oscillates between 0 (blue regions) and 1 (red regions) with $t_{\text {ON }}$ because for odd and even multiples of $\mathrm{t}_{\text {Half }}$, the FL toggles and get restored into the original state, respectively. Furthermore, the blue regions indicate that $\mathrm{V}_{\text {MTJ }}$ pulse can be designed with a set of $\mathrm{t}_{\mathrm{ON}}$ and $\mathrm{V}_{0}$ to have an absolutely disturb-free read operation. The red regions signify the operation windows, where deterministic switching is obtained. Without thermal fluctuation, the deterministic switching windows, denoted as the black bars, are enlarged, indicating that thermal fluctuation perturbs the deterministic toggling. Furthermore, the operation window augments as the $\mathrm{V}_{0}$ diminishes, implying that the device favors a low voltage operation in respect of the pulse margins.


Fig. 2. Effect of $t_{\mathrm{MgO}}$ on (a) $\mathrm{t}_{\mathrm{ON}}$ (optimal values used to switch), (b) current density and (c) energy per switching operation at $1.6 \mathrm{~V} \mathrm{~V}_{0} .0 .3 \mathrm{fJ}$ switching energy is achieved. Phase diagram for switching probability from (d) P-to-AP (P10) and (e) AP-to-P (P01) versus $t_{O N}$ and $V_{0}$ for $2 \mathrm{~nm} t_{\text {Mgo }}$. The black bars show the $t_{\text {ON }}$ operation windows without thermal fluctuation. An increasing operation window as $\mathrm{V}_{0}$ decreases, especially for small $t_{\mathrm{ON}}$ implies that the device supports an ultrafast low-voltage operation.

Scalability of the pMTJ is next investigated in Fig. 3(a) and $3(\mathrm{~b})$. The AR is held at 3 , FL thickness at $1.7 \mathrm{~nm}, \mathrm{t}_{\mathrm{MgO}}$ at 1.5 nm and $\mathrm{V}_{0}$ at 1.6 V , while the MTJ cross-section is swept. The bars in Fig. 3(a) represent the operation windows, which are extracted by simulating the devices 100 times
under identical conditions (thermal fluctuations enabled). Within the operation window, switching happens with $100 \%$ certainty. A considerable operation window ( $0.15-0.2 \mathrm{~ns}$ ) is achieved for the MTJ cross-section between $39 \times 117 \mathrm{~nm}^{2}$ and $45 \times 135 \mathrm{~nm}^{2}$. The respective energy consumption is shown in Fig. 3(b). At first a descending and then an ascending trend is observed because of the competition between the $\mathrm{t}_{\mathrm{ON}}$ and the MTJ resistance, implying that unduly scaling down the MTJ cross-section beyond a certain limit may not be attractive in terms of the energy consumption.


Fig. 3. Optimal $\mathrm{t}_{\mathrm{ON}}$ used to switch ( $\mathrm{t}_{\mathrm{Half}}$ ) in (a) and energy consumption in (b) as a function of the MTJ width. The AR and FL thickness are held constant at 3 and 1.7 nm , respectively, e.g. for width of 40 nm , the MTJ cross-section is $40 \times 120 \mathrm{~nm}^{2}$. The inset shows the critical voltage $\mathrm{V}_{\mathrm{C}}$ vs. the MTJ width.

## 3. Conclusions

We propose and appraise the elliptical pMTJs for VCMA switching. We show that an IP magnetized BL designed within the MTJ stack can bias the FL and switch it for as low as 0.3 fJ in just 0.38 ns at 1.6 V . This should eliminate the need of an external structure to provide the bias field for realizing practical VCMA memories.

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