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Ultrafast and low-energy switching in voltage-controlled elliptical pMTJ

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Switching magnetization in a perpendicular magnetic tunnel junction (pMTJ) via voltage controlled magnetic anisotropy (VCMA) has shown the potential to markedly reduce switching energy. However, the requirement of an external magnetic field poses a critical bottleneck for its practical applications. In this work, we propose an elliptical-shaped pMTJ to eliminate the requirement of providing an external field by an additional circuit. 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 (FL) 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 pulse duration margin of 0.15 ns is obtained and low-voltage operation (~ 1 V) is favored. Finally, the MTJ scalability is considered, and it is found that scaling down may not be appealing in terms of both the energy consumption and the switching time for precession based VCMA switching.

Spin transfer torque (STT) based magnetic random access memory (MRAM)^{1,2} because of its non-volatility, high access speed and CMOS (complementary metal oxide semiconductor) compatibility³ has matured into one of a leading candidate in recent years⁴ to fill memory gaps in the extant memory hierarchy. A bit-cell of STT-RAM comprises of a magnetic tunnel junction (MTJ) which has a pinned-layer (PL) and a free-layer (FL) with their magnetization in either parallel (P) or anti-parallel (AP) state with respect to (w.r.t.) each other, which corresponds to logic “1” or “0”. In STT-RAM, a free-layer is written by passing a current with density larger than critical current density through the MTJ. If the current is flowing from FL towards PL, a spin-flux with vector parallel to the magnetization of PL ($\mathbf{M}_{\text{PL}}$) acts on the FL to align the magnetization of FL ($\mathbf{M}_{\text{FL}}$) with $\mathbf{M}_{\text{PL}}$, whereas if the current direction is reversed a reverse spin-flux with vector anti-parallel to $\mathbf{M}_{\text{PL}}$ acts on the FL to orient it in the AP state. This current based magnetization switching, however, requires a large current density which ranges from 5×10^{10} A-m⁻² for 35 ns to 1×10^{11} A-m⁻² for 2 ns write-time^{1,2} to generate enough spins to toggle all magnetic moments of the FL. Inevitably, a large current results in considerable Joule heating in the MTJ. This results in self-heating^{5–7} induced degradation of the MTJ characteristics, e.g. the spin-polarization of spin-flux degrades thereby degrading the STT efficiency at higher temperatures. In addition, electromigration^{8,9} becomes prominent because of large current densities, and the dielectric may also break¹⁰ at voltages required to sustain required current densities. Furthermore, to provide a large enough current a bulky access transistor, i.e. with a large channel width-to-length ratio for bulk-MOSFET or with a large number of fins for FinFET (Fin Field Effect Transistor), is required. This implies that STT-RAM suffers from high energy consumption, reliability issues and a huge cell area^{11,12}.

To reduce the operating current which would subsequently reduce both the energy consumption and the size of driving transistor, voltage control of magnetic anisotropy (VCMA)¹³ has been promulgated as an alternative to the STT^{14,15}. There are several possible physical origins for VCMA effect. Among them, the redox reaction and the electromigration can result in a VCMA efficiency of 1000 fJ-V⁻¹-m⁻¹¹⁶. However, the low reacting speed makes it unfeasible for memory application. Therefore, to design a memory cell, the most possible mechanism for VCMA effect is that electric field modulates the charge occupancy at the interface. First principles studies have shown that the modification of magnetic anisotropy by an electric field is contributed to the change of 3d-orbitals occupancies via spin-orbit interaction¹⁷. Since the VCMA based device relies on a voltage rather than a current to write, the current in this case can be greatly reduced by designing a MTJ with large enough resistance. Furthermore, the VCMA based precessional switching enables the FL to toggle in sub-nanosecond^{13,18}. Therefore,

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Figure 1. (a) Schematic of an elliptical pMTJ with the major axis along the x-axis. A bias layer (BL) separated by a metal is engineered to provide the exchange field for the FL. The top and bottom water-blue layers are electrodes. (b) Applied voltage pulse with $t_{\text{Rise}} = t_{\text{Fall}} = 50$ ps and t_{OFF} of 10 ns, which is long enough to ensure that the magnetization is completely relaxed. Positive voltage is defined for the electric field pointing from the PL to the FL.

the energy consumption can be substantially reduced by markedly reducing both the power-dissipation and the dissipation-time. Demonstrations^{18–20} hitherto have been on circular pMTJs. These demonstrations require an external in-plane magnetic field to enable the switching. This, however, is not a viable solution for integrated MRAM w.r.t. both the provision of an external field source and the field uniformity^{21,22}. Consequently, the requirement of an external bias field poses a critical bottleneck for realizing practical VCMA memory.

In this work, therefore, we propose an elliptical pMTJ to eliminate the requirement of an external magnetic field source. Because of the elliptical structure, via shape anisotropy, an in-plane magnetized bias-layer (BL) separated from the FL by a metallic spacer can be directly engineered within the MTJ stack²³. This in-plane BL, hence, provides a sufficient bias field for VCMA based precessional switching. We comprehensively appraise the effects of electronic, magnetic and physical design constraints on the FL switching dynamics to expound the device physics and an optimal operation window in the proposed design. Our results show that the required bias magnetic field can be contrived within the MTJ stack by an in-plane magnetized BL. For instance, a 10 nm thick BL separated by a 3 nm thick metallic spacer can provide an in-plane exchange field of 50 mT to bias the FL. Furthermore, we show that the FL can toggle in just 0.38 ns consuming only 0.3 fJ at a voltage of 1.6 V across the MTJ, which is attractive for memory applications. Our results also indicate that the pMTJ driven by precession based VCMA favors a low-voltage operation (~ 1 V) with a sufficient margin (0.15 ns) for the applied voltage pulse duration.

Methods

Figure 1(a) shows a schematic of an elliptical MTJ with perpendicular magnetic anisotropy (PMA), with major-axis (minor-axis) along x-axis (y-axis). A 1.2 nm thick $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ PL and a 1.7 nm thick $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ FL sandwich a MgO insulator of thickness t_{MgO} . In this work, t_{MgO} ranges from 1.2 nm to 2.8 nm, while the MTJ cross-section ranges from $150 \times 50 \text{ nm}^2$ to $114 \times 38 \text{ nm}^2$ with a fixed aspect-ratio (AR) of 3. Macrospin simulation, which has been shown to be valid in purview of dimensions considered in this work^{13,18,25,26}, is developed to investigate the magnetization dynamics. The dynamics is described by the Landau-Lifshitz-Gilbert (LLG) equation^{27,28} as,

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mu_0 \mathbf{H}_{\text{Eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \Gamma_{\text{MTJ-DL}} \mathbf{m} \times \mathbf{p}_{\text{PL}} \times \mathbf{m} + \Gamma_{\text{SV}} \mathbf{m} \times \mathbf{p}_{\text{BL}} \times \mathbf{m} + \Gamma_{\text{MTJ-FL}} \mathbf{m} \times \mathbf{p}_{\text{PL}}, \quad (1)$$

where γ is the gyromagnetic ratio, μ_0 is the vacuum permeability, $\alpha = 0.01$ ²⁸ is the Gilbert damping coefficient for $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$, and $\mathbf{p}_{\text{PL}}$ ($\mathbf{p}_{\text{BL}}$) is a unit-vector anti-parallel (parallel) to the magnetization of PL (BL). The magnetization unit-vector of FL $\mathbf{m}$ is $[m_x, m_y, m_z]$, which is $[0, 0, \pm 1]$ in stable states, with m_x , m_y and m_z being the projections on respective axis. $\mathbf{H}_{\text{Eff}}$ is the effective magnetic field experienced by the FL. It is the vector sum of uniaxial anisotropy field $\mathbf{H}_{\text{K}}$, demagnetizing field $\mathbf{H}_{\text{D}}$, thermal fluctuation field $\mathbf{H}_{\text{Therm}}$, and external bias field $\mathbf{H}_{\text{Bias}}$, which are expressed as,

$$\mathbf{H}_{\text{K}} = \frac{2K_{\text{U}}}{\mu_0 M_{\text{S}}} [0, 0, m_z], K_{\text{U}} = K_{\text{U-Bulk}} + \frac{K_{\text{I0}} - \xi \cdot E_z}{t_{\text{FL}}}, \quad (2)$$

$$\mathbf{H}_{\text{D}} = -M_{\text{S}} [N_x m_x, N_y m_y, N_z m_z], \quad (3)$$

$$\mathbf{H}_{\text{Therm}} = \sqrt{\frac{2\alpha K_B T}{(1 + \alpha^2)\gamma M_S V(\Delta t)}} \frac{1}{\mu_0} [G_{(0,1)}^x, G_{(0,1)}^y, G_{(0,1)}^z], \quad (4)$$

where K_U is the anisotropy energy density with contributions from bulk anisotropy, K_{U_Bulk} , and interfacial anisotropy K_I . The latter is computed as $K_{I0} - \xi \cdot E_z$. As implied from equation (2), the interfacial anisotropy is assumed to be linearly modified by the perpendicular component E_z of the electric-field $\mathbf{E}$ at the MgO-FL interface, at a rate determined by the VCMA coefficient $\xi^{24,29}$, where equation (2) assumes a positive value of E_z for the field direction shown in Fig. 1(a). For the voltage applied across the MTJ V_{MTJ} , the magnitude of E_z is assumed to be $V_{\text{MTJ}}/t_{\text{MgO}}^{18,20}$. The CoFeB and the CoFeB/MgO interface parameters like saturated magnetization $M_S = 1.257 \times 10^6 \text{ A}\cdot\text{m}^{-1}$, $K_{U_Bulk} = 2.245 \times 10^5 \text{ J}\cdot\text{m}^{-3}$, $K_{I0} = 1.286 \times 10^{-3} \text{ J}\cdot\text{m}^{-2}$ ²⁴ and $\xi = 50 \text{ fJ}\cdot\text{V}^{-1}\cdot\text{m}^{-1}$ ³⁰ are empirical parameters from experimental papers. The value of ξ at the CoFeB/MgO interface in literature is in the range of 20–100 $\text{fJ}\cdot\text{V}^{-1}\cdot\text{m}^{-1}$ ^{30–33}. More efficient VCMA effect, i.e. larger ξ , would result in even better performance of the proposed device than that predicted in this work.

In equation (3), N_x , N_y and N_z are the demagnetizing factors along x, y and z directions, which are determined by the shape and the size of magnet (shape anisotropy)^{34,35}. The dipole field from the PL has been neglected assuming that this dipole field can be cancelled out by synthetic ferrimagnetic reference layers³⁶. Thermal fluctuation is described by equation (4), where K_B , V and Δt are the Boltzmann constant, the FL volume and the calculation time step of 5 ps, respectively. The stochastic partial differential equation (SPDE) described by equation (1) is integrated via fourth order Runge-Kutta method^{37–39}. The device is assumed to operate at room temperature ($T = 300 \text{ K}$), and self-heating effects due to Joule heating have been ignored because the VCMA devices operate at much lower current densities than traditional STT devices. $G_{(1,0)}$ with superscript along respective axis are independent random numbers computed at every time-step and each has a Gaussian distribution with zero mean and unit standard deviation⁴⁰. $\mathbf{H}_{\text{Bias}}$ (c.f. Fig. 1(a)) is provided by an in-plane magnetized BL (Co/Pt multilayers) via its dipole field, which is calculated by micromagnetics simulation using MuMax3 simulator⁴¹ with the simulation cell size of 1 nm along all three dimensions. Since $\mathbf{H}_{\text{Bias}}$ is along x-axis in this study, subsequently, it is represented by H_x . The damping-like torque (DLT) with linear dependence on V_{MTJ} , and the field-like torque (FLT) with quadratic dependence on V_{MTJ} are respectively obtained as,

$$\Gamma_{\text{MTJ_DLT(SV)}} = \frac{\hbar}{2e} \frac{\gamma \eta_{\text{MTJ(SV)}}}{M_S V R_{\text{MTJ}}} V_{\text{MTJ}}, \quad \Gamma_{\text{MTJ_FLT}} = \nu \frac{\hbar}{2e} \frac{\gamma \eta_{\text{MTJ}}}{M_S V R_{\text{MTJ}}} V_{\text{MTJ}}^2, \quad (5)$$

where $\hbar$ is the reduced Planck constant, e is the electron charge, R_{MTJ} is the MTJ resistance, $\eta_{\text{MTJ(SV)}}$ is the STT efficiency, and $\nu = 2.97/7.82 \text{ V}^{-1}$ is the ratio between the two torques⁴². Analysis of R_{MTJ} includes the voltage dependence of tunneling magnetoresistance (TMR) and the dynamic angle θ between FL and PL as,

$$R_{\text{MTJ}} = R_P + \frac{R_{\text{AP0}} - R_P}{1 + \frac{V_{\text{MTJ}}^2}{V_{\text{Half}}^2}} \left(\frac{1 - \cos(\theta)}{2} \right), \quad (6)$$

where $V_{\text{Half}} = 0.4 \text{ V}^{20,43}$, is the voltage across MTJ at which TMR becomes half of its value at zero-bias i.e. $\text{TMR}_0/2$. R_P is the MTJ resistance when both magnets are exactly parallel to each other and assumed to remain invariant to $V_{\text{MTJ}}^{42,44}$, while R_{AP0} is the MTJ resistance when the MTJ is in AP state at zero bias. Since in recent years Slonczewski expression²⁷ for spin-torque efficiency has been extended to account for multiple reflections of the spin-flux in spin valves^{45–47}, the STT effect by the BL in this study is based on multi-reflection model. Hence, the STT efficiencies for the PL-MgO-FL MTJ (η_{MTJ}) and the FL-Metal-BL spin valve (η_{SV}) are computed as^{46,48},

$$\begin{aligned} \eta_{\text{MTJ}} &= \frac{P_1}{1 + P_1^2 \cos(\theta)}, \\ P_1 &= \sqrt{\frac{\text{TMR}_0/2}{1 + \text{TMR}_0/2}}, \\ \eta_{\text{SV}} &= \frac{P_2 - P_2 \zeta \cos(\theta)}{1 - \zeta^2 \cos^2(\theta)}, \\ \zeta &= 1 - 2\varepsilon + 2\varepsilon^2, \\ \varepsilon &= \frac{1 - P_2}{2}, \end{aligned} \quad (7)$$

where P_1 is obtained from Julliere's formula for equal polarization of FL and PL⁴⁹ and $P_2 = 0.35^{50}$.

Data Availability. Correspondence and requests for materials should be addressed to G.G. (gauravdce07@gmail.com) or G.L. (elalg@nus.edu.sg).

Results and Discussion

Operation Principle. Since in a VCMA based MTJ, the interfacial anisotropy energy can be tuned by an applied voltage, the competition between the uniaxial anisotropy and the demagnetizing field, which determines

Figure 2. FL switching for a voltage pulse with t_{ON} in integer multiples of the half precession periods (t_{Half}): t_{ON} is (a) 0.35 ns, (b) 0.7 ns and (c) 1.05 ns while t_{Half} is 0.35 ns. For the odd multiples the FL toggles while for the even cases it restores to the original state and remains unaltered. Insets show a full three dimensional (3D) FL dynamics for the respective cases, where the red dash arrow, green arrow and blue line is the initial $\mathbf{m}$ state, final $\mathbf{m}$ state and its trajectory, respectively. (d) Bias field acting on the FL along x-axis generated by the BL for different metal spacer thicknesses t_M and BL thicknesses t_{BL} . This large enough exchange field, e.g. 50 mT for t_{BL} of 10 nm and t_M of 3 nm, can bias the FL for precession based VCMA switching.

the easy axis direction, can be controlled by voltage. Specifically, considering the bulk and the interface PMA with the demagnetization simultaneously, the net anisotropy energy density becomes,

$$K_{U_Eff} = K_U - \frac{1}{2}\mu_0 M_S^2 N_z. \quad (8)$$

When $K_{U_Eff} > 0$, FL has a perpendicular magnetization i.e. it has easy-axis along z-axis. If $K_{U_Eff} < 0$, the magnet has easy-axis along the major-axis of the elliptical FL i.e. x-axis in this work. Among the parameters in equation (2) and equation (8), t_{FL} and N_z depend on the physical dimensions and remain fixed once the MTJ is fabricated, while E_z can be modified by controlling V_{MTJ} . For precession based VCMA switching of the pMTJ devices^{18,20}, these physical and electrical controls are designed such that in the absence of V_{MTJ} , K_U which equals $K_{U_Bulk} + K_{I0}/t_{FL}$ is large enough for K_{U_Eff} to be positive. However, V_{MTJ} is designed to have a sufficient E_z that can render K_{U_Eff} to a computationally negative value. Physically, this implies that the FL destabilizes along z-axis and its easy-axis now aligns along x-axis, thereby forcing $\mathbf{m}$ to tend towards the new stable state. Conversely, if a negative voltage pulse is applied, as evident from equation (2) and equation (8), K_{U_Eff} becomes more strongly positive because the interface anisotropy is enhanced. Categorically, this has been suggested as a scheme to read MTJ with increased reliability⁵¹. V_C and E_{zC} , respectively, symbolize the critical values, at which K_{U_Eff} is zero and thus the easy-axis orientation changes, of V_{MTJ} and E_z for given t_{FL} . Moreover, E_z should not exceed the dielectric breakdown field E_{Break} which is slightly over 2 V-nm^{-1} ¹⁰, i.e. $E_{zC} < V_0/t_{MgO} < E_{Break}$. The design is furthermore constrained by a maximum permissible voltage in the system which is not discussed in this study because it is subjective to the targeted application and the desired stability factor Δ of FL. Δ is computed in the absence of V_{MTJ} and described as⁵²,

$$\Delta = \Delta_0 \left(1 - \frac{H_x}{H_K^{Eff}} \right)^2, \quad \Delta_0 = \frac{K_{U_Eff} V}{K_B T}, \quad H_K^{Eff} = \frac{2K_{U_Eff}}{\mu_0 M_S}. \quad (9)$$

If the FL is permanently biased as in this work, the stability can be reduced quadratically, whereas if H_x is applied only during the write operation⁵³, Δ can be substantially increased to equal Δ_0 . The scheme suggested in ref.⁵³ depends on the Oersted field generated around the current carrying wire in the adjacent cells. Consequently, for a substantial H_x firstly it becomes power intensive and secondly this acts as a stray field and disturbs other bit-cells thereby limiting the memory density. Therefore, an alternative scheme of increasing Δ without compromising with V_{MTJ} or reducing H_x would be an important future direction.

For precession based VCMA switching, a V_{MTJ} as a trapezoidal pulse of duration t_{Pulse} is applied to toggle the FL, as shown in Fig. 1(b). A finite rise and fall time, t_{Rise} and t_{Fall} , respectively, of 50 ps is assumed to consider a non-ideal input. A full-scale voltage V_0 is applied for time t_{High} duration to temporarily change easy-axis from z- to x-axis. This induces the precession of $\mathbf{m}$ around the shifted $\mathbf{H}_{Eff}$. A sufficiently large H_x allows the FL m_z to swing from +1 to -1 and vice versa as illustrated in Fig. 2(a)–(c) for the FL of thickness t_{FL} 1.7 nm, cross-section $150 \times 50 \text{ nm}^2$, t_{MgO} of 2 nm, V_0 of 1.6 V and $\mu_0 H_x$ of 50 mT. As shown in Fig. 2(a)–(c), by designing t_{ON} to be odd or even multiples of the half-precession period ($t_{Half} = 0.35 \text{ ns}$ for the shown cases), m_z toggles or comes back to the original state, respectively. A large enough t_{OFF} ensures that $\mathbf{m}$ relaxes to z-axis. Consequently, the final state of $\mathbf{m}$ strongly depends on t_{ON} since it determines if $\mathbf{m}$ is above or below the x-y plane when V_{MTJ} goes to zero and easy-axis is switched back along z-axis. This implies that pulse duration should be controlled in a certain range for deterministic switching.

Pessimistically, the deterministic switching based on precise control of precession cycles requires a bias magnetic field. To simplify the design of generating H_x , an elliptical pMTJ is used, which allows an in-plane

magnetized BL separated by a metal spacer to be fabricated within the MTJ stack (c.f. Fig. 1a). The dipole field provided by the BL is shown in Fig. 2(d). It shows that, typically as expected, a thinner metal spacer results in a stronger bias field because a dipole field strengthens as the distance from the magnet decreases. Intuitively, thickening the BL, whereas ensuring that a single domain is maintained, would have more magnetic moments along the x-axis, which then would lead to a larger bias field for the same t_M . Hence, the t_M and the t_{BL} can be custom designed to obtain the required H_x . In this work, the $\mu_0 H_x$ applied on the MTJ is approximately 50 mT. As shown in Fig. 2(d), this large H_x can be provided via a 10 nm thick BL with the metal spacer of t_M 3 nm, implying that an elliptical MTJ stack can function without an additional external system to provide the bias field.

V_{MTJ} Dependence. First we investigate the electronic control of the device. To probe the effects of V_0 on the precession based VCMA switching in an elliptical pMTJ, a representative FL of size $150 \times 50 \times 1.7 \text{ nm}^3$ is chosen. The MTJ has t_{MgO} of 2 nm, resistance-area (RA) product of $1820 \Omega \cdot \mu\text{m}^2$ and TMR_0 of 144%²⁰. A 50 mT bias field along x-axis H_x is applied to assist the switching. This in-plane field reduces the FL thermal stability from 138 to 28 as calculated from equation (9). However, because of the ultra-low power sub-nanosecond writing in this design, and the stability which suffices the requirements for embedded non-volatile cache memory^{51,54,55}, the promulgated precessional VCMA based MRAM may be a promising replacement for power-intensive volatile static random-access memory (SRAM) in the cache. Furthermore, this stability also suffices for the MTJ based non-volatile logic (NVL)⁵⁶.

The phase diagrams of the switching probability for switching from P-to-AP (P10) and from AP-to-P (P01) are shown in Fig. 3(a) and (b), respectively. For sweeping t_{ON} , t_{High} is swept while t_{Rise} and t_{Fall} are held constant at 50 ps each. Each colour point is determined by simulating the device 100 times under the identical conditions while considering thermal fluctuation. Red regions (operation windows), which are directly related to the precession period, signify a deterministic toggling, i.e. 100% probability of switching, while the dark-blue regions denote an unaltered $\mathbf{m}$ state i.e. 100% probability that the original magnetic-state is retained. For given V_0 , the probability oscillates between 0 (the dark-blue regions) and 1 (the red regions) with t_{ON} because for the odd and even multiples of t_{Half} the FL toggles and gets restored to the original state, respectively. However, at small V_0 and large t_{ON} , the switching is nondeterministic and the probability is approximately 50%, as also observed experimentally in ref.¹³. This is because at low V_0 and large t_{ON} , the VCMA effect is relatively weak and t_{High} is comparable with the relaxation time, thus failing to keep the precession around x-axis for a long time and resulting in an uncertain final state in the presence of thermal fluctuation. Comparing Fig. 3(a) with 3(b) shows that there is no significant difference in the phase diagram for P10 and P01, which implies that there is symmetry in the switching from P-to-AP and AP-to-P, indicating that the STT effect, which always favours AP state in this work, is negligible. Next, the black curve with bars indicates deterministic switching without thermal fluctuation to explicitly illustrate the effect of thermal fluctuations for the fastest t_{ON} scenario. This t_{ON} equals t_{Half} . As shown in Fig. 3(a) and (b), the operation window shrinks, as expected, when thermal fluctuation is considered, implying that for precession based VCMA switching it perturbs the deterministic toggling. Moreover, the operation window expands as V_0 diminishes. This is because the reduced V_0 weakens the VCMA effect, resulting in a stronger interfacial anisotropy field along z-axis as evident from equation (2). This tends to increase m_z and reduce m_x thus subduing shape anisotropy field along x-axis, resulting in the reduction of the x-component of $\mathbf{H}_{Eff}$. The $\mathbf{m}$ still precesses around x-axis, although its trajectory is now not totally symmetrical about the x-y plane. Because the precessional period is inversely proportional to the magnetic field along the precession-axis, which is nearly along x-axis, with a reduced field along x-axis the precession period increases. As a result, the operation window, which is closely related to the precession period, increases as V_0 decreases. A larger operation window implies more tolerance in variation for t_{High} , and hence, a more reliable write-operation, indicating that the low-voltage operation is achievable for this studied device.

The V_0 dependence of current density J through the MTJ and energy consumption E is shown in Fig. 3(c) and (d), respectively, for both P-to-AP and AP-to-P switching of a unit probability with t_{ON} equal to a respective t_{Half} . As expected, J increases linearly as V_0 increases, and remains in the order of $10^8 \text{ A} \cdot \text{m}^{-2}$ because of a thick enough (2 nm) MgO layer. This low current density then ensures a relatively low switching energy as seen in Fig. 3(d). The switching energy has two components,

$$E = \int_0^{t_{ON}} \frac{(V_{MTJ}(t))^2}{R_{MTJ}(t)} dt + \frac{1}{2} \frac{\epsilon_0 \epsilon_{MgO} A}{t_{MgO}} V_0^2 \quad (10)$$

where $\epsilon_{MgO} = 9.7$ ⁵⁷ is the relative permittivity of MgO, ϵ_0 is the vacuum permittivity, and A is the MTJ cross-sectional area. The first term in equation (10) is the Joule heating E_J , and second term is the charging energy E_C consumed by the MTJ capacitance. The capacitance has been assumed to be independent of the relative magnetization of PL and FL because of the sub- μm^2 MTJ cross-section⁵⁸. E_C ranges from 0.046 fJ to 1.138 fJ for V_0 from 0.6 V to 3 V, which is 9% to 14% of E (0.5 fJ to 8.1 fJ), respectively. Because the current density stays lower than $2 \times 10^9 \text{ A} \cdot \text{m}^{-2}$, a low switching energy ($< 10 \text{ fJ/switch}$) is achieved (c.f. Table I of ref.⁵⁶, for a general comparison with other non-volatile memory technologies). Moreover, Fig. 3(e) exhibits the switching probability from P-to-AP 'AND' AP-to-P as a function of t_{ON} and V_0 . Red regions denote a deterministic switching, i.e. 100% certainty of toggling. At $V_0 = 1 \text{ V}$, the corresponding operation window of t_{ON} is from 0.31 ns to 0.46 ns i.e. 0.15 ns, a decent margin for t_{High} to vary without affecting the reliable operation. On the other hand, Fig. 3(f) presents the retention probability as a function of t_{ON} and V_0 . Red regions show with 100% probability that pre-configured data is not disturbed. As a consequence, the red regions can be used for reading, e.g. as long as the read voltage is below 0.4 V, the FL magnetic state will always remain unaltered, which implies that an absolutely disturb-free read operation can be achieved for the MRAM application.

Figure 3. Phase diagram of switching probability from (a) parallel (P) to anti-parallel (AP) state (P10) and from (b) AP-to-P (P01) as a function of t_{ON} and V_0 at t_{MgO} of 2 nm and $\mu_0 H_x$ of 50 mT (with thermal fluctuation). The black bars show the t_{ON} operation windows without considering thermal fluctuation. The increasing operation window as V_0 decreases indicates that the device favors a low-voltage operation. (c) Current density and (d) energy consumption per switch vs. V_0 . (e) Switching probability from P-to-AP ‘AND’ AP-to-P ($P10 \cdot P01$) as a function of t_{ON} and V_0 . Red regions indicate deterministic switching, i.e. 100% certainty of toggling. (f) Retention probability, i.e. $(1-P10) \cdot (1-P01)$ as a function of t_{ON} and V_0 . Red regions show with 100% probability that pre-configured data would not be altered.

MgO Thickness Dependence. As demonstrated in the previous section, the device prefers a low-voltage operation for a decent pulse duration margin unto a value at which further decreasing V_0 may fail the switching. Hence, to study the t_{MgO} dependence on the switching, V_0 is fixed to be 1.6 V in this section. This V_0 allows a sufficient t_{MgO} variation range to achieve low energy consumption as expounded later. RA-products, TMRs and V_{Half} for different MgO thicknesses are extracted from the experimental paper²⁰. For a fixed V_0 as the t_{MgO} decreases, principally, both VCMA and STT effect become stronger. The former becomes stronger because E_z at the MgO-FL interface becomes stronger (see equation (2)). Simultaneously, the RA-product decreases exponentially as t_{MgO}

Figure 4. Effects of t_{MgO} on (a) current density, (b) t_{ON} (optimal values used to switch, i.e. t_{Half}) and (c) energy consumption per switching operation at 1.6 V V_0 and 50 mT $\mu_0 H_x$. Red lines with open triangles show the process from AP-to-P. Black lines with solid circles correspond to the process from P-to-AP. The smallest switching energy achieved is 0.3 fJ. Phase diagram for switching probability from (d) P-to-AP and (e) AP-to-P vs. t_{ON} and t_{MgO} .

decreases. Since J is inversely proportional to the RA-product, J thus increases exponentially from 10^7 A·m⁻² to 10^{10} A·m⁻² for decreasing t_{MgO} , as shown in Fig. 4(a), which makes the STT increasingly stronger. Figure 4(b) shows that at large t_{MgO} , the two curves of t_{ON} , which is chosen to equal to t_{Half} , overlap, indicating that the VCMA effect dominates over the STT effect. Besides, a linear relation is observed on account of the fact that t_{ON} is inversely proportional to the precession frequency which in turn is almost proportional to H_{eff} . The H_{eff} varies linearly with H_K , and H_K is inversely proportional to t_{MgO} (see equation (2)) because of the VCMA effect. For small t_{MgO} , there is a divergence in t_{ON} between P-to-AP (black solid circles) and AP-to-P (red triangles) switching trends, implying that STT effect is substantial which can be understood as follows. Beyond the critical electric field which changes the easy axis from z- to x-axis, further strengthening of VCMA effect is inessential and has no significant additional contribution in the switching. However, STT effect has no such upper threshold in this case and starts to dictate the switching dynamics. Since the electron flow direction is from FL to PL, for P-to-AP switching, due to STT effect, the FL receives spin-flux anti-parallel to M_{PL} . As a result, STT effect assists VCMA effect to attain an AP state and accelerates the switching process. In contrast, for AP-to-P switching, STT effect still endeavors to maintain the FL in the AP state while VCMA effect strives to toggle the FL into a P-state. The two effects thus jostle to toggle the FL. This decelerates the toggling, which results in a larger t_{ON} .

As discussed in the previous section, E_c is a fraction of the Joule heating. When STT effect is substantial, the E shown in Fig. 4(c) nearly follows the declining trend of J in Fig. 4(a) since the switching time variation is relatively small. Nevertheless, when t_{MgO} becomes thicker than 2.2 nm, E_c becomes comparable to E_J because of the exponential decline in J and the corresponding Joule heating. Thus, for large t_{MgO} , VCMA effect dominates, and the E slope tapers down with E approaching 0.3 fJ, which is also the minimum energy achieved in this work. Figure 4(d) and (e), respectively, show the phase diagrams of switching probability from P-to-AP (P10) and from AP-to-P (P01) as a function of t_{ON} and t_{MgO} . An obvious oscillatory dependence on t_{ON} is observed. At large t_{MgO} and for long pulse duration, the oscillations disappear because of weak VCMA effect. Interestingly in Fig. 4(d), there is a sharp decrease in the t_{ON} operation window for the first half precession cycle for small t_{MgO} (the red region on the left-bottom around $t_{MgO} = 1.6$ nm). This happens because in the said region a strong STT effect compliments the VCMA effect for P-to-AP switching, and greatly accelerates the switching process. This sharply reduces the precession period and the scope for tolerating variations in t_{High} . For larger t_{MgO} , a wider operation window indicates that the device can tolerate more variations in t_{High} . It can be found that it is more favorable to design the device with a large MgO thickness for given V_0 , because both a larger margin in the pulse variation for deterministic switching and a lower write-energy can be achieved.

MTJ Scalability and Bias Magnetic Field. As noted earlier, the external bias field required in the switching has been a critical bottleneck in advancing it for memory applications and therefore in this work, the elliptical pMTJs have been presented so that H_x can be engineered within the stack and provided by a BL. Besides the thickness of BL discussed earlier, it is the MTJ cross-section that determines the number of magnetic moments in

Figure 5. Phase diagram for switching probability of (a) P-to-AP and (b) AP-to-P as a function of t_{ON} and bias magnetic field $\mu_0 H_x$. H_x is the magnitude of $\mathbf{H}_{Bias}$ projecting along x-axis. Optimal t_{ON} used to switch (t_{Half}) in (c) and energy consumption in (d) 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 $40 \times 120 \text{ nm}^2$. The black and red bars indicate the t_{ON} operation regions during which switching probability is 100%. The inset shows the critical voltage V_C vs. the MTJ width.

the BL to provide a bias field through the FL. Furthermore, the demagnetizing field scales with the cross-section thereby modifying the switching time, required bias field and energy landscape. Therefore, the MTJ cross-section is an important physical constraint to investigate and comprehend the device physics in our proposed VCMA device.

The effect of H_x on the switching probability is shown in Fig. 5(a) and (b). For a pMTJ with FL of $150 \times 50 \times 1.7 \text{ nm}^3$ dimensions, t_{MgO} of 2 nm and V_0 of 1.6 V, there is a limited functional region in the range of 38–58 mT for $\mu_0 H_x$. This range can be shifted for different conditions. As seen from Fig. 5(a) and (b), increasing the bias field H_x shrinks the red region, i.e. the operation window, which is similar to the case exhibited in Fig. 3(a) and (b). When $\mu_0 H_x$ increases to more than 58 mT, an excessively strong $\mathbf{H}_{Eff}$ results in overly fastened precession, thus sharply reducing the relaxation time, which is too fast to allow deterministic switching. Conversely, if $\mu_0 H_x$ is insufficient, i.e. less than 38 mT, deterministic switching around x-axis would not be supported. Hence, a probabilistic final state is attained by virtue of thermal fluctuation. To reduce the required H_x for switching, one possible way is to design t_{FL} even closer to the critical thickness but this would further sacrifice Δ . This adjustment has three effects: it would weaken both the interfacial anisotropy and the demagnetizing field along z-axis, and enhance the demagnetizing field along x-axis. All of these would enable the operation at smaller V_C . In consequence, a stronger VCMA effect is obtained at the same V_0 , which then relieves the requirement for larger $\mu_0 H_x$.

Scalability of the pMTJ is next investigated in Fig. 5(c) and (d). The AR is held at 3, t_{FL} at 1.7 nm, t_{MgO} at 1.5 nm and V_0 at 1.6 V, while the MTJ length and width are swept. The bars in Fig. 5(c) represent the operation windows, within which switching happens with 100% certainty. Figure 5(c) also shows that when the MTJ cross-section (represented as MTJ width) is scaled down, the optimal t_{ON} (the data-markers on the curve), which equals respective t_{Half} , increases. This happens because on scaling down the MTJ, N_z decreases which thus increases $K_{U, Eff}$. As a result, V_C (c.f. the inset), where $K_{U, Eff} = 0$, as seen from equation (2) and equation (8), becomes larger. In consequence, it is more difficult to switch. Hence, it takes larger t_{ON} or the switching may even fail altogether. It

is found that a considerable operation window is achieved for the MTJ cross-section between $39 \times 117 \text{ nm}^2$ and $45 \times 135 \text{ nm}^2$.

For the designs in Fig. 5(c), the respective energy consumption is shown in Fig. 5(d). At first a descending and then an ascending trend is observed when scaling down on account of the competition between t_{ON} and the MTJ resistance as evinced in equation (10). The former increases as observed in Fig. 5(c), while the latter also increases because for given RA-product, the MTJ resistance increases as the MTJ cross-section reduces. These two have opposite contributions to the Joule heating; therefore, the trends exhibit a local minima. These trends also imply that unduly scaling down the MTJ cross-section may not be attractive in terms of energy consumption.

Conclusion

We propose and appraise the elliptical pMTJs for voltage controlled precessional switching. The V_{MTJ} , t_{MgO} , STT, bias magnetic field and MTJ scalability effects on the pMTJ properties are investigated. We show that an in-plane magnetized BL designed within the MTJ stack can bias the FL to eliminate the need of providing a uniform in-plane magnetic field for the FL by an additional circuit. The pMTJ can be switched for as low as 0.3 fJ in just 0.38 ns at 1.6 V. Furthermore, it is shown that Joule heating can be adequately suppressed by increasing t_{MgO} . We also find that the design favors to operate at low voltage ($\sim 1 \text{ V}$) and large MgO thickness. There is also a sufficient margin for the variation in t_{High} without affecting the reliable operation. This should be encouraging for a practical disposition of the VCMA based MRAM. The advantages like fast switching, ultra-low energy consumption and non-volatility are very attractive for VCMA based MRAM application in cache memories.

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Author Contributions

G.G. conceived and designed this project. G.G. and G.L. supervised the study. J.D. performed the computations and wrote the manuscript. All authors critically analyzed the data and modified the manuscript.

Additional Information

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