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 years1 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 \(\mathbf{M}_P\) acts on the FL to align the magnetization of FL \(\mathbf{M}_F\) with \(\mathbf{M}_P\), whereas if the current direction is reversed a reverse spin-flux with vector anti-parallel to \(\mathbf{M}_P\) 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 \(5 \times 10^{10} \text{ A-m}^{-2}\) for 35 ns to \(1 \times 10^{11} \text{ A-m}^{-2}\) for 2 ns write-time12 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-heating5-7 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, electromigration8,9 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 area11,12.

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 STT14,15. 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^{-1}16. 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-nanosecond13,18. Therefore,
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 stack 23. 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 Co$_{20}$Fe$_{60}$B$_{20}$ PL and a 1.7 nm thick Co$_{20}$Fe$_{60}$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 $150 \times 50$ nm$^2$ to $114 \times 38$ 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,

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mu_0 \mathbf{H}_{eff} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \Gamma_{MTJ,DL} \mathbf{m} \times \mathbf{p}_{PL} \times \mathbf{m} + \Gamma_{5V} \mathbf{m} \times \mathbf{p}_{BL} \times \mathbf{m} + \mathbf{H}_{MTJ,FL} \mathbf{m} \times \mathbf{p}_{FL},$$  

(1)

where $\gamma$ is the gyromagnetic ratio, $\mu_0$ is the vacuum permeability, $\alpha = 0.01$ is the Gilbert damping coefficient for Co$_{20}$Fe$_{60}$B$_{20}$, and $\mathbf{p}_{PL}$ ($\mathbf{p}_{BL}$) 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. $\mathbf{H}_{MTJ,FL}$ is the effective magnetic field experienced by the FL. It is the vector sum of uniaxial anisotropy field $\mathbf{H}_K$, demagnetizing field $\mathbf{H}_D$, thermal fluctuation field $\mathbf{H}_{Therm}$, and external bias field $\mathbf{H}_{bias}$, which are expressed as,

$$\mathbf{H}_K = \frac{2K_U}{\mu_0 M_S} [0, 0, m_z] \text{, } \mathbf{H}_D = -M_S [N_x m_x, N_y m_y, N_z m_z],$$

(2)

$$\mathbf{H}_{MTJ,FL} = K_{U Bulk} + \frac{K_{10} - \xi \mathbf{E}_z}{t_{FL}} \mathbf{m},$$

(3)

For the simulations, we start with an initial condition $\mathbf{m}(0) = [m_x(0), m_y(0), m_z(0)]$, where $m_x(0)$, $m_y(0)$, and $m_z(0)$ are chosen randomly from $[0,1]$.
\[ H_{\text{Therm}} = \frac{2\alpha K_u T}{(1 + \alpha^2)\gamma M_s V(\Delta \theta)} \left( G_{(0,1)}^x - G_{(0,1)}^y \right) \]

where \( K_u \) is the anisotropy energy density with contributions from bulk anisotropy, \( K_{U,\text{Bulk}} \) and interfacial anisotropy \( K_I \). The latter is computed as \( K_I = \xi E_r \). As implied from equation (2), the interfacial anisotropy is assumed to be linearly modified by the perpendicular component \( E_r \) of the electric-field \( E \) at the MgO-FL interface, at a rate determined by the VCMA coefficient \( \xi \), where equation (2) assumes a positive value of \( E_r \) for the field direction shown in Fig. 1(a). For the voltage applied across the MTJ \( V_{\text{MTJ}} \), the magnitude of \( E_z \) is assumed to be \( V_{\text{MTJ}}/d \) at the CoFeB/MgO interface in literature is in the range of 20–100 \( fJ/V^{-1}m^{-1} \) to \( 50 fJ/V^{-1}m^{-1} \) are empirical parameters from experimental papers. The value of \( \xi \) at the CoFeB/MgO interface in literature is in the range of 20–100 \( fJ/V^{-1}m^{-1} \). More efficient VCMA effect, i.e. larger \( \xi \), 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 layers\(^{36}\). Thermal fluctuation is described by equation (4), where \( K_B, V \) and \( \Delta \theta \) 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 (\( T = 300 K \)), 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. \( \gamma_{(0,1)} \) 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 deviation\(^{40}\). \( H_{\text{bias}} \) (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 simulator\(^{41}\) with the simulation cell size of 1 nm along all three dimensions. Since \( H_{\text{bias}} \) is along \( x \)-axis in this study, subsequently, it is represented by \( H_x \). The damping-like torque (DLT) with linear dependence on \( V_{\text{MTJ}} \) are respectively obtained as,

\[ \Gamma_{\text{MTJ-LDT}} = \frac{h \gamma_{\text{MTJ}}(SV)}{2 e M_s V R_{\text{MTJ}}} V_{\text{MTJ}}^2 \]

where \( h \) is the reduced Planck constant, \( e \) is the electron charge, \( R_{\text{MTJ}} \) is the MTJ resistance, \( \gamma_{\text{MTJ}}(SV) \) is the STT efficiency, and \( \nu = 2.97/7.82 V^{-1} \) is the ratio between the two torques\(^{42}\). Analysis of \( R_{\text{MTJ}} \) includes the voltage dependence of tunneling magnetoresistance (TMR) and the dynamic angle \( \theta \) between FL and PL as,

\[ R_{MTJ} = R_p + \frac{R_{A0}}{1 + V_{\text{bias}}^2} \left( \frac{1 - \cos(\theta)}{2} \right) \]

where \( V_{\text{bias}} = 0.4 V \) to \( 0.4 V \) is the voltage across MTJ at which TMR becomes half of its value at zero-bias i.e. TMR/2. \( R_p \) is the MTJ resistance when both magnets are exactly parallel to each other and assumed to remain invariant to \( V_{MTJ} \) \(^{42,44}\), while \( R_{A0} \) is the MTJ resistance when the MTJ is in AP state at zero bias. Since in recent years Slonczewski expression\(^{23}\) 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 (\( \eta_{\text{MTJ}} \)) and the FL-Metal-BL spin valve (\( \eta_{SV} \)) are computed as\(^{46,48}\),

\[ \eta_{MTJ} = \frac{P_1}{1 + P_1 \cos(\theta)} \]

\[ P_1 = \sqrt{\frac{\text{TMR}_0/2}{1 + \text{TMR}_0/2}} \]

\[ \eta_{SV} = \frac{P_2 - P_2 \xi \cos(\theta)}{1 - \xi^2 \cos^2(\theta)} \]

\[ \xi = 1 - 2e + 2e^2, \]

\[ \varepsilon = \frac{1 - P_2}{2} \]

where \( P_1 \) is obtained from Julliere’s formula for equal polarization of FL and PL\(^ {49}\) and \( P_2 = 0.3550\).

Data Availability. Correspondence and requests for materials should be addressed to G.G. (gauravdce07@gmail.com) or G.L. (elelg@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
and vice versa as illustrated in Fig. 2(a)–(c) for the FL of thickness $t_{	ext{FL}} = 1.7$ nm, cross-section swing from $-1$ to $1$ for MTJ with increased reliability. $V_C$ and $E_zC$, respectively, symbolize the critical values, at which $K_{U_{\text{Eff}}}$ is zero and positive because the interface anisotropy is enhanced. Categorically, this has been suggested as a scheme to read applied only during the write operation, as evident from equation (2) and equation (8), $t_{\text{FL}}$ 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, these physical and electrical controls are designed such that in the absence of $V_{MTJ}$, $K_C$ which equals $K_{U_{\text{bulk}}} + K_{U_{\text{interface}}}$ is large enough for $K_{U_{\text{Eff}}}$ to be positive. 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), $K_{U_{\text{Eff}}}$ becomes more strongly positive because the interface anisotropy is enhanced. Categorically, this has been suggested as a scheme to read MTJ with increased reliability. $V_C$ and $E_zC$, respectively, symbolize the critical values, at which $K_{U_{\text{Eff}}}$ is zero and thus the easy-axis orientation changes, of $V_{MTJ}$ and $E_z$ for given $t_{\text{FL}}$. Moreover, $E_z$ should not exceed the dielectric breakdown field $E_{\text{break}}$, which is slightly over 2 V-nm$^{-1}$, i.e. $E_z < V_0/t_{\text{MgO}} < E_{\text{break}}$. 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 $\Delta$ of FL. $\Delta$ is computed in the absence of $V_{MTJ}$ and described as:

$$\Delta = \Delta_0 \left(1 - \frac{H_x}{H_K}\right)^2, \quad \Delta_0 = \frac{K_{U_{\text{Eff}}}}{K_B} V_0, \quad H_K = \frac{2K_{U_{\text{Eff}}}}{\mu_0 M_S}$$

If the FL is permanently biased as in this work, the stability can be reduced quadratically, whereas if $H_z$ is applied only during the write operation, $\Delta$ can be substantially increased to equal $\Delta_0$. The scheme suggested in ref. 33 depends on the Oersted field generated around the current carrying wire in the adjacent cells. Consequently, for a substantial $H_z$ 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 $\Delta$ without compromising with $V_{MTJ}$ or reducing $H_z$ would be an important future direction.

For precession based VCMA switching, a $V_{MTJ}$ as a trapezoidal pulse of duration $t_{\text{Pulse}}$ is applied to toggle the FL, as shown in Fig. 1(b). A finite rise and fall time, $t_{\text{rise}}$ and $t_{\text{fall}}$, respectively, of 50 ps is assumed to consider a non-ideal input. A full-scale voltage $V_0$ is applied for time $t_{\text{High}}$ duration to temporarily change easy-axis from $z$- to $x$-axis. This induces the precession of $\mathbf{m}$ around the shifted $H_{\text{Eff}}$. A sufficiently large $H_z$ 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 $t_{\text{FL}} = 1.7$ nm, cross-section $150 \times 50$ nm$^2$, $t_{\text{MgO}}$ of 2 nm, $V_0$ of 1.6 V and $\mu_0 H_z$ of 50 mT. As shown in Fig. 2(c)–(d), by designing $t_{\text{ON}}$ to be odd or even multiples of the half-precession period ($t_{\text{Half}} = 0.35$ ns for the shown cases), $m_z$ toggles or comes back to the original state, respectively. A large enough $t_{\text{OFF}}$ ensures that $\mathbf{m}$ relaxes to $z$-axis. Consequently, the final state of $\mathbf{m}$ strongly depends on $t_{\text{OFF}}$ 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 $H_z$, 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 \( t_{BL} \). Hence, the \( t_{BL} \) and the \( t_{M} \) can be customized designed to obtain the required \( H_x \). In this work, the \( \mu_B H_x \) 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 \( 150 \times 50 \times 1.7 \) nm\(^2\) is chosen. The MTJ has \( t_{MGO} \) of 2 nm, resistance-area (RA) product of 1820 \( \Omega \cdot \mu \text{m}^2 \) and TMR 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 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 \( t_{half} \), 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 \( t_{half} \), 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 \( H_{eff} \). The magnetic field on the 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 \( 10^9 \) A-m\(^{-2} \) because of a thick enough (2 nm) MgO layer. This low current density current then ensures a relatively low switching energy as seen in Fig. 3(d). The switching energy has two components, \[
E = \int_{0}^{t_{ON}} \left( \frac{V_{MTJ}(t)}{R_{MTJ}} \right)^2 dt + \frac{1}{2} \frac{\varepsilon_0 \varepsilon_{MGO} A \mu_0 A}{t_{MGO}} V_0^2
\]
where \( \varepsilon_{MGO} = 9.7 \) is the relative permittivity of MgO, \( \varepsilon_0 \) 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 FL and PL because of the sub-\( \mu \text{m}^2 \) MTJ cross-section\(^{20} \). \( E_J \) 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 \( 2 \times 10^{8} \text{ A-} \mu \text{m}^{-2} \), a low switching energy (<10 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.
**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 $t_{\text{MgO}}$ dependence on the switching, $V_0$ is fixed to be 1.6 V in this section. This $V_0$ allows a sufficient $t_{\text{MgO}}$ variation range to achieve low energy consumption as expounded later. RA-products, TMRs and $V_{\text{Half}}$ for different MgO thicknesses are extracted from the experimental paper. For a fixed $V_0$ as the $t_{\text{MgO}}$ 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 $t_{\text{MgO}}$ decreases.

**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 $t_{\text{ON}}$ and $V_0$ at $t_{\text{MgO}}$ of 2 nm and $\mu_0H_0$ of 50 mT (with thermal fluctuation). The black bars show the $t_{\text{ON}}$ 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 · P01) as a function of $t_{\text{ON}}$ and $V_0$. Red regions indicate deterministic switching, i.e. 100% certainty of toggling. (f) Retention probability, i.e. $(1-P_{10}) \cdot (1-P_{01})$ as a function of $t_{\text{ON}}$ and $V_0$. Red regions show with 100% probability that pre-configured data would not be altered.
decreases. Since $J$ is inversely proportional to the RA-product, $J$ thus increases exponentially from $10^7 \text{ A} \cdot \text{m}^{-2}$ to $10^{10} \text{ A} \cdot \text{m}^{-2}$ for decreasing $t_{\text{MgO}}$, as shown in Fig. 4(a), which makes the STT increasingly stronger. Figure 4(b) shows that at large $t_{\text{MgO}}$, the two curves of $t_{\text{ON}}$, which is chosen to equal to $t_{\text{Half}}$, overlap, indicating that the VCMA effect dominates over the STT effect. Besides, a linear relation is observed on account of the fact that $t_{\text{ON}}$ is inversely proportional to the precession frequency which in turn is almost proportional to $H_{\text{Eff}}$. The $H_{\text{Eff}}$ varies linearly with $H_{\text{K}}$, and $H_{\text{K}}$ is inversely proportional to $t_{\text{MgO}}$ (see equation (2)) because of the VCMA effect. For small $t_{\text{MgO}}$, there is a divergence in $t_{\text{ON}}$ 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 $M_{\text{PL}}$. 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 $t_{\text{ON}}$.

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 $t_{\text{MgO}}$ 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 $t_{\text{MgO}}$, 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 $t_{\text{ON}}$ and $t_{\text{MgO}}$. An obvious oscillatory dependence on $t_{\text{ON}}$ is observed. At large $t_{\text{MgO}}$ 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 $t_{\text{ON}}$ operation window for the first half precession cycle for small $t_{\text{MgO}}$ (the red region on the left-bottom around $t_{\text{MgO}} = 1.6 \text{ nm}$). 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 $t_{\text{High}}$. For larger $t_{\text{MgO}}$, a wider operation window indicates that the device can tolerate more variations in $t_{\text{High}}$. 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 $H_z$ 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
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 $\mu_0H_x$. 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 $\mu_0H_x$ increases to more than 58 mT, an excessively strong $H_{\text{Eff}}$ results in overly fastened precession, thus sharply reducing the relaxation time, which is too fast to allow deterministic switching. Conversely, if $\mu_0H_x$ 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 $\Delta$. 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 $\mu_0H_x$. 

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 relieves the requirement for larger $\mu_0H_x$. $V_C$ decreases which thus increases $K_{U_{\text{Eff}}}$. As a result, $V_C$ (c.f. the inset), where $K_{U_{\text{Eff}}}=0$, 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

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 $\mu_0H_x$. $H_x$ is the magnitude of $H_{\text{Bias}}$ projecting along x-axis. Optimal $t_{ON}$ used to switch ($t_{\text{Half}}$) 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.
is found that a considerable operation window is achieved for the MTJ cross-section between 39 × 117 nm² and 45 × 135 nm².

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 tON 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 ellipsical pMTJ for voltage controlled precessional switching. The V_{MTJ,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 (~1 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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