Leveraging Voltage-Controlled Magnetic Anisotropy to Solve Sneak Path Issues in Crossbar Arrays

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Abstract—In crossbar array structures, which serves as an “in-memory” compute engine for artificial intelligence (AI) hardware, write sneak path problem causes undesired switching of devices that degrades network accuracy. While custom crossbar programming schemes have been proposed, device-level innovations leveraging nonlinear switching characteristics of the cross-point devices are still under exploration to improve the energy efficiency of the write process. In this work, a spintronic device design based on magnetic tunnel junction (MTJ) exploiting the use of voltage-controlled magnetic anisotropy (VCMA) effect is proposed as a solution to the write sneak path problem. In addition, insights are provided regarding appropriate operating voltage conditions to preserve the robustness of the magnetization trajectory during switching, which is critical for proper switching probability manipulation.

Index Terms—Crossbar array, magnetic tunnel junction (MTJ), sneak path current, spintronic devices, voltage-controlled magnetic anisotropy (VCMA).

I. INTRODUCTION

A RTIFICIAL intelligence (AI) has undergone significant development in the past decade and has been applied in various areas, such as speech processing [1], [2], video object recognition [3], and financial fraud detection [4], among others. Abstraction of functionality of biological neural networks (NNs) as computing models, a singular module consists of synapses (which serve as the memory component) and neurons (which perform the compute role). The fundamental mismatch between such memory-embedded compute-based architectural models and current von-Neumann-based computers results in significant area and energy consumption overhead and limits the performance of AI systems on applications with large problem space complexity. For this reason, research interest on hardware systems based on “in-memory” compute that is compatible with NN models at a fundamental architectural level has been growing recently. For a network-level design, a crossbar array structure provides a promising pathway toward a resource-efficient AI hardware platform [5], [6].

In a crossbar array, devices (i.e., synapses) are present at the junction points of the array, as is shown in Fig. 1(a). The crossbar in the figure receives input voltage signals, \( U_i \), along the horizontal lines and produces output current signals, \( I_j \), along the vertical lines. Following Kirchhoff’s law, output current along the column is given by the equation:

\[
I_j = \sum U_i G_{ij}, \text{ where } G_{ij} \text{ is the conductance of device at the cross point. Though the crossbar array structure is intrinsically efficient in dot-product calculation (key computational primitive required in NN hardware acceleration), errors may occur due to undesired “sneak path” problems [7], [8], [9]. Sneak path issue refers to the situation where an applied voltage causes undesired current flowing through devices that are not supposed to be read/written, which results in an error in the reading/writing process. For example, in Fig. 1(b), the blue current indicates the desired current, which passes through device \( D_5 \), while there may also be the undesired red current along the other row, because there can be a voltage drop across devices \( D_{E,1} \), \( D_{E,2} \), and \( D_{E,3} \), since the other input and output terminals of the array are floating. While sneak path issue occurs both in the reading and writing process, write sneak path issue is a more challenging problem in “in-memory” dot-product calculation. To solve the sneak path issue, usually, a custom programming scheme is adopted for the write process [10]. As is shown in Fig. 1(c), instead of just applying a voltage signal to terminals linked to the device to switch, all terminals receive a voltage input, such that the voltage difference is controlled, and sneak path current is mitigated. The device to switch is noted as the “selected cell” (\( D_S \)) and applied a full set voltage, \( U_{Sel} \), and the devices noted as “half-selected cells” (\( D_{HS} \)) are under a half-set voltage, which is not sufficient enough for switching to occur. The remaining cells are “unselected cells” (\( D_{US} \)), which experience zero voltage drop. Though the sneak path issue can be reduced under this programming scheme, current flowing through...
In this article, a single-device bit-cell solution leveraging spintronic devices has not been leveraged before to mitigate the sneak path current issue in crossbar array-based systems. However, the intrinsic nonlinear physics of emergent novel switching mechanisms of spintronic devices has not been explored before for spintronic cross-point devices has not been explored before for spintronic cross-point designs with multiple devices are not area-efficient and have been succeeded by single-device cell design proposals that leverage intrinsic nonlinear $I–V$ characteristics of the cross-point device itself. The cell design exhibiting similar $I–V$ characteristics as a 1S-1M cell is called a self-selective memristor [21], [22], [23], while that behaving similar to a 1D-1M cell is called a self-rectifying memristor [24], [25]. The nonlinear $I–V$ characteristics of the single-device cell design enable the reduction of undesired current in a similar manner as the multiple-device cell structure along with a higher area efficiency. However, such a bit-cell proposal exploiting nonlinear $I–V$ characteristics of cross-point devices has not been explored before for spintronic cross-point arrays.

Compared with other nonvolatile memory technologies, spintronic devices possess the advantage of lower operating voltage, which reduces energy consumption, faster read and write processes, unlimited endurance, and compatibility to conventional CMOS-based systems, which makes it a promising choice to build the next generation hardware platform for neuromorphic computing systems [26]. However, the intrinsic nonlinear physics of emergent novel switching mechanisms of spintronic devices has not been leveraged before to mitigate the sneak path current issue in crossbar array-based systems. In this article, a single-device bit-cell solution leveraging voltage-controlled magnetic anisotropy (VCMA) effect is proposed. During the writing process, the full set voltage applied to selected cell switches the device via VCMA effect, while the switching of half-selected cells is still dominated by spin transfer torque (STT). Since the pulselength to achieve high switching probability by VCMA effect is much shorter, the pulselength of set voltage signal can be chosen properly, so that a high switching probability is achieved for selected cell, while the half-selected cells still have a low switching probability tending to zero. The sharp switching probability difference among half-selected cells and selected cells under the applied voltage signal enables a high write accuracy, since undesired switching of half-selected cells is restrained. More importantly, the sharp increase in switching probability is due to change in the switching mechanism and is independent of the pulselength and can be achieved even with a short pulse in this proposed framework. Compared with the STT dominated mechanism, where the sharpness of switching probability increase with pulse amplitude is related to the pulselength [27], the proposed framework provides more design-time flexibility. Simultaneously, the proposed solution reduces the system-level energy consumption due to short pulse widths required by the VCMA effect for magnetic state switching.

**II. Preliminaries**

### A. Device Physics

Magnetic tunnel junctions (MTJs) are the basic building block of spintronic devices. A typical MTJ consists of two nanomagnets sandwiching an oxide spacing layer, as is shown in Fig. 2(a). One of the magnetic layers is called “pinned layer”,
layer (PL),” since its magnetization is pinned to one direction. The other magnetic layer is called “free layer (FL),” because its magnetization is free to be switched by external stimuli, such as magnetic field or spin current. The state of an MTJ can be defined by the relative configuration of FL and PL magnetization directions. Parallel state (P state) refers to the case where the two layers have the same magnetization direction. P state is associated with a lower electrical resistance, while the antiparallel state with opposite FL and PL magnetic orientation exhibits a higher resistance. The difference in resistance enables information encoding.

For information encoding purposes, STT induced by spin current can be used to switch the device state. But, to achieve a high switching probability, a long current pulse is required, since the switching probability increases with pulselength. To reduce the energy consumption, it is necessary to reduce the pulselength of applied pulses. A recent work has shown that short switching pulses can be achieved through VCMA effect [28]. VCMA effect enables manipulation of device magnetocrystalline anisotropy energy (MAE, which is the magnetic energy difference between perpendicular and in-plane direction) by an applied voltage via spin–orbit interactions (which consists of two contributions, namely, angular momentum and magnetic dipole momentum [29], [30]). The orbital angular momentum dominates in strong ferromagnetic materials [31] and can be modulated by doping of charges with selective spin direction. On the other hand, magnetic dipole moment modification (which results from intraatomic electron redistribution) is the dominating mechanism in materials where spin–orbit interaction is not strong enough [32]. Such VCMA effect enables the change of magnetic anisotropy from perpendicular to in-plane direction.

During the transition of magnetic anisotropy from perpendicular direction to in-plane direction, the FL magnetization performs precession along the in-plane easy axis, as is shown in Fig. 2(b). Considering that the initial magnetization is at the south pole, the switching probability is high when the magnetization stops in the upper half of the unit sphere [region near point A in Fig. 2(b)] and low in the lower half [region near point B in Fig. 2(b)], such that the switching probability can be controlled by the pulselength. Prior work has reported that the VCMA-induced switching requires a shorter pulselength that STT-induced switching [28].

The difference in required pulselength between VCMA-induced switching and STT-induced switching leads to a possible solution to the sneak path problem based on the programming scheme illustrated in Fig. 1(b). If the set voltage is chosen appropriately, such that the selected cell operates via the VCMA-induced switching mechanism (although STT is present in this case, the switching process is dominated by the VCMA effect), while half-selected cells operate via the STT-induced switching mechanism, the pulselength applied to switch the selected cell will only result in near-zero switching probability to half-selected cells. In this way, a sharp difference in switching probability of selected and half-selected cells can be achieved.

### B. Landau–Lifshitz–Gilbert Equation

The behavior of magnetization under an applied external voltage signal that causes STT and VCMA effect can be simulated by the Landau–Lifshitz–Gilbert equation [33], [34]

\[
\frac{d\hat{m}}{dt} = -\gamma (\hat{m} \times H_{\text{eff}}) + \alpha \left(\hat{m} \times \frac{d\hat{m}}{dt}\right) + \frac{1}{q N_s} (\hat{m} \times \mathbf{I}) \times \hat{m}.
\]

In (1), \(\hat{m}\) is the unit vector in the direction of FL magnetization, \(\gamma = (2\mu_B\mu_0/\hbar)\) is the gyromagnetic ratio, \(\alpha\) is Gilbert’s damping ratio, \(N_s = (M_s V/\mu_B)\) is the number of spins in FL of volume \(V\), where \(\mu_B\) is Bohr magneton and \(M_s\) is saturation magnetization, \(q\) is the charge of an electron, and \(\mathbf{I}\) is the spin current. \(H_{\text{eff}}\) is the effective magnetic field, including thermal field, demagnetization field, and effective magnetic field caused by the VCMA effect. \(H_{\text{thermal}} = ((\alpha/1 + \alpha^2)(2K_B T K / \gamma \mu_0 M_s V \delta_t))^{1/2}\) is used to characterize the thermal noise, where \(G_{0.1}\) is a Gaussian distribution with zero mean and unit standard deviation [35]. \(H_{\text{VCMA}} = (2K_{\text{eff}}(U) / \mu_0 M_s t_{\text{FL}}) m_z \hat{z}\) is the effective magnetic field caused by the VCMA effect [36], where \(t_{\text{FL}}\) is the FL thickness, and \(m_z\) is the \(z\) component of \(\hat{m}\). \(K_{\text{eff}}(U) = K_f - \xi (U/t_{\text{OX}})\) is the expression of effective energy density for interface perpendicular anisotropy, where \(K_f\) is the energy density of perpendicular anisotropy without applied voltage \(U\), \(\xi\) is the VCMA coefficient, and \(t_{\text{OX}}\) is the oxide layer thickness. If not mentioned specifically, simulations are based on parameters mentioned in Table I. The electrical resistance of the MTJ in the P and AP states is obtained from the modeling framework [37] benchmarked to experimental data reported previously in [28].

### III. PROPOSAL

#### A. Simulation Results

Fig. 3(a) shows the relation between MTJ switching probability and pulselength for 0.7-V voltage pulses. The fluctuation in switching probability results from the precession along the in-plane axis. The peaks (valleys) are according to the cases where the voltage pulse terminates when the magnetization rotates to the top (bottom) positions of the trajectory. The peaks and valleys tend to 50% switching probability, as the magnetization gradually rotates to the in-plane direction with increasing pulselength, which is the new easy axis under

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**TABLE I**

| Parameters | Value |
|------------|-------|
| Free-layer width, \(W_{\text{MTJ}}\) | 40 nm |
| Free-layer length, \(L_{\text{MTJ}}\) | 70 nm |
| Free-layer thickness, \(t_{\text{MTJ}}\) | 0.9 nm |
| Oxide layer thickness, \(t_{\text{OX}}\) | 1.3 nm |
| Saturation magnetization, \(M_s\) | 1257.3 kA/m [37] |
| Gilbert-damping factor, \(\alpha\) | 0.075 |
| Temperature, \(T\) | 300 K |
| VCMA co-efficient, \(\xi\) | 200 D/V m |
| Interfacial perpendicular anisotropy, \(K_i\) | 0.9267 mJ/m² [37] |
VCMA effect. The switching probability is stable at 50% when the FL magnetization remains at the in-plane direction. The 92.1% switching probability at the first peak implies the viability to switch the device with a set voltage pulse as short as 1.8 ns. Fig. 3(b) shows the relation between switching probability and pulse amplitude for 1.8-ns wide switching pulses. The switching probability remains low for pulses with small amplitude (region A). The reason is that the VCMA effect induced by such low amplitude pulses is not strong enough. In this region, the STT dominates the switching event, which requires a longer pulse for high switching probability. The sharp increase of switching probability at 0.65 V indicates that the VCMA effect induced by 0.65-V pulse is strong enough to change the magnetic anisotropy from perpendicular direction to in-plane direction. The 1.8-ns pulse enables the magnetization to reach the top half of the trajectory [see Fig. 2(b)], resulting in a switching probability of 92.1% (region B). The switching probability again drops when the pulse amplitude is larger than 0.8 V (region C). This can be explained by the magnetization trajectory robustness, which will be discussed in the next section.

To further increase the switching probability, another STT pulse can be applied after the VCMA pulse, as is proposed in prior literature [28]. In our work, the VCMA-STT combined pulse consists of a short VCMA pulse (0.7 V, 1.8 ns) and a following STT pulse (0.6 V). The pulselength of the STT pulse can be fixed in accordance with the desired switching probability of the selected cell. In order to justify the contribution of VCMA switching to the proposal, we also compare against a pure STT pulsing scheme consisting of a first STT pulse (0.6 V, 1.8 ns) and a following STT pulse (0.6 V). Fig. 3(c) shows that the switching probability of the selected cell under VCMA-STT combined switching increases with the pulselength of the following STT pulse. The switching probability reaches 97% when the following STT pulse is longer than 9 ns. On the other hand, the switching probability for the pure STT pulse scenario is much lower than that of VCMA-STT combined pulse, which indicates that the VCMA-STT combined pulse can be much shorter (and, therefore, much more energy-efficient) than pure STT pulse to reach a high switching probability for the selected cell.

On the other hand, in the programming scheme shown in Fig. 1(b), there are also half-selected cells that experience half-set voltage during the switching process. To avoid undesired switching, such half-selected devices should exhibit near-zero switching probability. As is shown in Fig. 3(d), the switching probability remains near zero for the half-selected cell even when the selected cell experiences a switching probability over 97%. The sharp difference in switching probability resulting from the VCMA effect makes it possible to ensure a high switching probability for selected cells and a near-zero switching probability for half-selected cells and, therefore, provides a solution to the sneak path problem for MTJ-based spintronic cross-point arrays.

Unlike logic applications, neuromorphic computing applications are resilient to minor imprecision in hardware operation. While the maximum switching probability shown for AP to P switching was ≈97% (note that P to AP switching will have a slightly reduced switching probability, since VCMA pulse is always of the same polarity, and STT pulse varies in polarity in the two cases), this did not have any significant impact at the system level. On-chip learning simulations were performed for a 784 × 10 network on the MNIST dataset. The ideal software accuracy was evaluated to be 91.13% (five epochs). The weight values in the network were implemented using 10-bit resolution. The weight discretized network (considering 100% switching probability in the devices) had an accuracy of 90.35% (five epochs), while the hardware-realistic simulation with slightly reduced switching probabilities had an accuracy of 89.34% (five epochs, averaged for five independent runs of the training process), which is only ≈1.01% lower than the network with no switching error. The training convergence time is not affected due to the hardware nonidealities and constraints (see Fig. 4).
B. Robustness

It is observed that even when the magnetization motion is dominated by VCMA effect, switching probability may still be low, as is shown in Fig. 3(b) (region C). This is due to the loss of magnetization trajectory robustness. The robustness refers to the uniqueness of the route of magnetization precession. The high switching probability results from the fact that every time when the voltage pulse ends, the magnetization is right at the top of the trajectory, which only happens when the magnetization follows the same trajectory. If the magnetization precession trajectory is random, there is no determined relation between pulsewidth and final position of magnetization. In other words, a high switching probability can be ensured only when there is a certain magnetization trajectory (i.e., the robustness is preserved).

In order to figure out how the robustness is preserved, it is necessary to study the motion of FL magnetization, \( \vec{m} \). The FL magnetization motion can be characterized by the motion “velocity” on the unit sphere, \( d\vec{m}/dt \), which is given by the LLG equation in (1). The precession is mainly related to the first term, \( -\vec{m} \times \vec{H}_{\text{eff}} \), where VCMA effect contributes by adding an effective field \( \vec{H}_{\text{VCMA}} \) in the \( \hat{z} \)-direction. Denoting the total magnetic field along \( \hat{x} \) (short axis), \( \hat{y} \) (long axis), and \( \hat{z} \) (perpendicular axis) directions as \( \vec{H}_{x}, \vec{H}_{y}, \) and \( \vec{H}_{z} \) respectively, Fig. 5 shows the direction of the vector field \( -\vec{m} \times \vec{H}_{x}, -\vec{m} \times \vec{H}_{y}, \) and \( -\vec{m} \times \vec{H}_{z} \) under \( U = 0.7 \) V. Any component of \( \vec{H}_{i}(i \in \{x, y, z\}) \) forms a precession along axis \( i \) solely. Note that since \( \vec{m} \cdot \vec{H}_{i} < 0 \), there is also a component repelling \( \vec{m} \) from axis \( i \). Direction of the total field depends on the relative magnitude of \( \vec{H}_{x}, \vec{H}_{y}, \) and \( \vec{H}_{z} \).

![Fig. 4. Accuracy of network with and without switching error has been obtained for different training epochs. Switching error only causes a reduction of 1.01% in accuracy after five epochs of training.](image)

![Fig. 5. Field vectors \(-\vec{m} \times \vec{H}_{x}, -\vec{m} \times \vec{H}_{y}, \) and \(-\vec{m} \times \vec{H}_{z}\) under \( U = 0.7 \) V are plotted on the unit sphere. Each of the fields leads to a precession of the magnetization along the corresponding axis, with a repelling component. Since the field vectors have components along opposite directions in the adjacent region between any two pairs of the three fields, the direction of the total field depends on the relative magnitude of \( \vec{H}_{x}, \vec{H}_{y}, \) and \( \vec{H}_{z} \).](image)

![Fig. 6. (a) Total \( d\vec{m}/dt \) field under applied voltage \( U = 0.7 \) V in the region around the south pole of the unit sphere. The relative magnitude of \( \vec{H}_{x}, \vec{H}_{y}, \) and \( \vec{H}_{z} \) results in two symmetric exit windows along diagonal directions in the \( XY \) plane. (b) Trajectories of ten LLG simulations leave the pole area from the exit windows, which enables stable magnetization motion. (c) Total \( d\vec{m}/dt \) field under applied voltage \( U = 0.8 \) V in the region around the south pole. In this situation, \( \vec{H}_{z} \) dominates, and the total field does not form definite exit windows unlike the \( U = 0.7 \)-V case. (d) Trajectories of ten LLG simulations for applied voltage \( U = 0.8 \) V are almost random.](image)
On the other hand, although the magnetization trajectories are random in this case, the switching probability is still increasing with pulse amplitude, as is shown in Fig. 3(b). The reason is that the magnetic energy in the $z$-direction increases with applied pulse amplitude due to increasing $|H_z|$ caused by the VCMA effect. Due to larger magnetic energy, for larger pulse amplitude, the magnetization is more likely to leave the pole and switch to the other side when the pulse ends, leading to a higher switching probability.

As a result, to enable a high switching probability, the applied voltage $U$ has to be in a range determined by device parameters

$$t_{ox} \left( \frac{(N_{xx} - N_{zz})M^2_{\text{ox} FL}}{2} + K_i \right) < U < t_{ox} \left( \frac{(N_{yy} - N_{zz})M^2_{\text{ox} FL}}{2} + K_i \right)$$

where $N_{xx}$, $N_{yy}$, and $N_{zz}$ are demagnetization factors determined by the device shape. Other parameters are the same as the ones introduced in Section II-B. Since VCMA is a surface effect occurring at the interface between the FL and the oxide layer, variations in FL thickness play a critical role in ensuring that a given operating voltage range is robust enough to device variations. The robustness of the operating voltage range to device parameter variations implies that there should be an overlapping region in the operating voltage ranges of all devices in the system, such that they can be programmed at the same voltage. To verify the operating voltage range robustness, the operating window of 1000 devices was calculated according to (2) and $6\sigma = 1.5\%$ [36] variation in the FL thickness was considered. It was found that over 99% of all 1000 devices can work at the same applied voltage in the operating voltage range between 0.68 and 0.73 V. It is worth mentioning here that other device, circuit, and system-level parameters, such as Gilbert’s damping ratio, input pulse shape waveform variations can also influence the magnetization reversal in the time domain [38].

IV. CONCLUSION

In this article, a spintronic device utilizing VCMA effect-induced switching scheme is proposed as a solution to the sneak path problem in neuromorphic nonvolatile cross-point arrays. The required pulselwidth difference between VCMA-induced switching and STT switching leads to a sharp difference in switching probability (over 97% for VCMA-induced switching and $\approx 0\%$ for STT switching) and, thereby, enables a potentially energy efficient solution to the write sneak path problem. In addition, it is also observed that ensuring a specific operating voltage range is critical for the VCMA effect to ensure high switching probability of selected cells, such that the effective magnetic field $H_z$ does not exceed $H_c$, which leads to the loss of FL magnetization trajectory robustness.

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