Straintronic magneto-tunneling-junction based ternary content addressable memory

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Straintronic magneto-tunneling junction (s-MTJ) switches, whose resistances are controlled with voltage-generated strain in the magnetostrictive free layer of the MTJ, are extremely energy-efficient switches that would dissipate a few aJ of energy during switching. Unfortunately, they are also relatively error-prone and have low resistance on/off ratio. This suggests that as computing elements, they are best suited for non-Boolean architectures. Here, we propose and analyze a ternary content addressable memory implemented with s-MTJs and some transistors. It overcomes challenges encountered by traditional all-transistor implementations, resulting in exceptionally high cell density and an energy-delay product that is orders of magnitude lower.

Keywords: Ternary content addressable memory, non-Boolean computing, straintronics, nanomagnets

I. INTRODUCTION

The primary threat to continued downscaling of electronic devices envisaged in Moore’s law is the excessive energy dissipation that takes place in the device during switching. Straintronic magneto-tunneling junctions (s-MTJ) are among the most energy-efficient three-terminal resistance switches extant. Unfortunately, they are also relatively error-prone and have low resistance on/off ratios. The switching error probability is typically larger than $10^{-9}$ at room temperature which makes it problematic to utilize them in Boolean logic. This has turned attention to non-Boolean computing paradigms which may be more forgiving of errors and do not always demand high resistance on/off ratios. Here, we explore one such application, namely Ternary Content-Addressable Memory (TCAM) and show that replacing transistors with s-MTJ results in significant energy saving and increased cell density. The low on/off ratio does not inhibit circuit operation, although a higher on/off ratio would be desirable.

TCAM is useful for high-speed parallel data processing. It finds application in platforms such as packet forwarding in network routers, image encoding, parametric curve extraction, and Hough transformation. It compares input search data against a table of stored data to return the memory address of fully or partially matching data. Each TCAM cell has three states in its search and storage bit: ‘0’, ‘1’ and ‘X’ (don’t care). The “don’t care” state allows masking, i.e., a match regardless of the storage and/or search data bit. Key challenges in a large scale TCAM are to achieve a high cell density and low standby power dissipation. Conventional CMOS-based TCAM cells consume large areas on a chip. Although CMOS scaling improves the cell density, the standby power dissipation deteriorates. On the other hand, an s-MTJ based TCAM can overcome these challenges and achieve a very high cell density along with little or no standby power dissipation.

II. SKewed STRAINTRONIC MAGNETO-TUNNELING JUNCTION (S-MTJ)

An s-MTJ is a standard MTJ (fixed layer-spacer-free layer) with one difference. The free layer is a magnetostrictive nanomagnet in elastic contact with an underlying poled piezoelectric thin film of thickness $a$ as shown in Fig. 1(a). Square electrodes of edge $L$ ($\approx a$), separated by a distance $d$ ($L \leq d \leq 2L$), are delineated on the piezoelectric surrounding the MTJ stack. The bottom of the conducting substrate is grounded. The electrode ‘1’ is used to read the s-MTJ resistance by passing a current to ground. Application of a voltage across the piezoelectric film using the electrode pair ‘2’ shown in Fig. 1(a) generates biaxial strain in the film (compression along the line joining the electrode pair and tension perpendicular to it, or vice versa, depending on the polarity of the voltage), which is partially or fully transferred to the soft layer of the s-MTJ in elastic contact with the film. This rotates its magnetization via the Villari effect and changes the s-MTJ resistance, realizing the action of a switch. A tiny amount of voltage $V$ (few mV) is required to rotate the magnetization through a large an-
gle and change the s-MTJ resistance substantially if thepiezoelectric film is ~100 nm thick, resulting in a switchingenergy dissipation $CV^2$ ($C =$ capacitance associatedwith charging the piezoelectric, which is 1-2 fF) of a fewtens of a $\mu$J. The internal energy dissipation withinthemagnetostrictive free layer due to Gilbert damping isnegligible.\(^{23}\)

The s-MTJ operation has been experimentally demonstrated.\(^{23,25}\) Here, we first show that an s-MTJ canbe engineered to produce very unusual device characteristicsand then show that such device characteristics elicit TCAM behavior.

Consider a “skewed” s-MTJ where the major axes ofthe fixed and free layers sublend an angle of 45° between them as shown in Fig. 1(b). The fixed layer is implemented with a synthetic anti-ferromagnet (SAF) to reducethe dipole interaction with the free layer, but not completely eliminate it. Because of shape anisotropy, the magnetization orientations of both layers will lie along the respective major axes of the ellipses, but owing to the remanent dipole interaction, the angle between them will be obtuse rather than acute (see Fig. 1(b)). When the free layer is strained by the voltage applied at the electrode pairs ‘2’, its magnetization begins to rotate. The remanent dipole interaction, will make it rotate clockwise and $\theta$ gradually increases from 135° to 225°.

The MTJ resistance depends on $\theta$ according to\(^{23}\)

$$\frac{R(\theta) - R_P}{R_{AP} - R_P} = \frac{1 - \cos \theta}{\chi (1 + \cos \theta) + 2}, \quad (1)$$

where $R_{P(AP)}$ is the MTJ resistance when the magnetizations of the fixed and free layers are parallel (anti-parallel), $R(\theta)$ is the resistance when the angular separation between the magnetizations is $\theta$, and $\chi = (R_{AP} - R_P) / R_P$. Since $\theta$ varies between 135° and 225°, the conductance of the MTJ (or current flowing through terminal ‘1’ at a fixed bias) plotted as a function of the voltage applied at terminal ‘2’ (which generates the rotation) will exhibit a “valley”. The bottom of the valley corresponds to $\theta = 180°$ when the MTJ resistance becomes maximum.

We can alter the stress distribution in the free layer ofthe s-MTJ by applying an additional voltage across thepiezoelectric with a third pair of electrodes ‘3’ shown in Fig. 1(a). This will allow us to shift the position of the valley bottom in the transconductance characteristic $I_1$ versus $V_2$ ($I_n$ is the current through the n-th terminal at a fixed bias and $V_n$ is the voltage applied at the n-th terminal). Thus, we have a 4-terminal switch with terminals ‘1’, ‘2’, ‘3’ and ground, where the current between ‘1’ and ground is changed with a voltage applied to ‘2’ and the transfer characteristic associated with this change can be modulated with a voltage applied at terminal ‘3’.

When both electrode pairs ‘2’ and ‘3’ are activated, thestrain distribution in the piezoelectric (and hence in thefree layer of the s-MTJ) becomes complex. Exact strainprofiles can be calculated with three dimensional finiteelement analysis (e.g. with COMSOL Multiphysics package)as in\(^{19,25}\) but in order to keep the analysis tractable,we will assume that activating an electrode pair generatesonly uniaxial stress along the line joining that pair. Note that if anything, this over-estimates the stress required to produce a given rotation $\theta$, and is hence conservative. The sign of the uniaxial stress (tensile or compressive) depends on the polarity of the voltage. If we activate electrode pair ‘2’, then we will generate uniaxial stress along the major axis of the elliptical free layer of the s-MTJ (compressive or tensile depending on the voltage polarity at ‘2’), whereas if we activate electrode pair ‘3’ we will generate uniaxial stress along the minor axis of the free layer. We have assumed that the free layer is made of Terfenol-D which has a positive and large magnetostriction coefficient (900 ppm). Compressive stress along any direction in the free layer will rotate its magnetization away from that direction (maximum rotation is 90°) while tensile stress will keep it aligned along that direction. This allows us to control the angle $\theta$ with voltages at ‘2’ and ‘3’.

We have computed $\theta$ versus the voltage $V_2$ (assuming $V_3 = 0$) at 0 K temperature (no thermal noise) using the Landau-Lifshitz-Gilbert equation which yields the magnetization orientation of the free layer as a function of

\[\text{FIG. 1. (a) A 4-terminal s-MTJ switch showing the MTJ stack, the piezoelectric layer and the electrodes. (b) The top view of the free and fixed layers of the MTJ. The major axes of the two ellipses subtend an angle of 45° between themselves.}\]
TABLE I. Parameters for the free layer

| Parameter                  | Value          |
|----------------------------|----------------|
| Saturation magnetization ($M_s$) | $8 \times 10^5$ A/m |
| Major axis dimension       | 80 nm          |
| Minor axis dimension       | 60 nm          |
| Thickness                  | 15 nm          |
| Magnetostriction coefficient| 900 ppm        |
| Gilbert damping constant   | 0.1            |

The MTJ resistance at 300 K increases to 8000 Ω-µm when the thickness increases to 2 nm, the resistance-area product of the MTJ is about 10 Ω-µm.

The resistance-area product of the MTJ is given in Table I. For the MTJ, we assumed the spacer layer to be made of MgO layer (material Terfenol-D) are given in Table I. For the MTJ, we assumed the spacer layer to be made of MgO.

The dispersion in the 300 K curve is due to thermal noise. (b) The transfer characteristic $I_1$ versus $V_2$ for different temperatures 0 K and 300 K. The results are plotted for $V_3 = 0$ and $H_{dipole} = 7.05$ mT directed along the major axis of the fixed layer. The results are plotted for two different temperatures. The dispersion in the 300 K curve is due to thermal noise. (b) The transfer characteristic $I_1$ versus $V_2$ for two different temperatures 0 K and 300 K. The results are plotted for $V_3 = 0$ and $H_{dipole} = 7.05$ mT directed along the major axis of the fixed layer.

In Fig. 3, we show how the transfer characteristics depend on the dipole field strength, assuming that the temperature is 0 K.

In Fig. 4, we plot the transfer characteristic $I_1$ versus $V_2$ at 0 K temperature for three different values of $V_3$. Note that this characteristic has a notch or valley. Note also that there is no significant difference between the 0 K and (average of) 300 K results. Therefore, in the rest of this paper, we will present the 0 K results, noting that the 300 K results will not be significantly different. In Fig. 3, we show how the transfer characteristics depend on the dipole field strength, assuming that the temperature is 0 K.

FIG. 2. (a) The angle $\theta$ between the magnetizations of the free and fixed layers plotted as a function of the applied electrode pair ‘2’. The voltage $V_3 = 0$ V and the dipole field $H_{dipole}$ experienced by the free layer is assumed to be 7.05 mT directed along the major axis of the fixed layer. The results are plotted for two different temperatures. The dispersion in the 300 K curve is due to thermal noise. (b) The transfer characteristic $I_1$ versus $V_2$ for two different temperatures 0 K and 300 K. The results are plotted for $V_3 = 0$ and $H_{dipole} = 7.05$ mT directed along the major axis of the fixed layer.

FIG. 3. The transfer characteristic plotted at 0 K temperature for three different values of the dipole field $H_{dipole}$ directed along the major axis of the fixed layer, assuming $V_3 = 0$ V.

We then use Equation (1) to extract the s-MTJ resistance $R_0$ versus $V_2$ from the $\theta$ versus $V_2$ relation in Fig. 2(a) and plot the transfer characteristic $I_1 (= V_1 / R_0)$ versus $V_2$ (at 0 K and 300 K temperatures) in Fig. 2(b) for two different values of $V_1$. Note that this characteristic has a notch or valley. Note also that there is no significant difference between the 0 K and (average of) 300 K results. Therefore, in the rest of this paper, we will present the 0 K results, noting that the 300 K results will not be significantly different. In Fig. 3, we show how the transfer characteristics depend on the dipole field strength, assuming that the temperature is 0 K.

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FIG. 4. The current $I_1$ through the cell s-MTJ at varying search bit potentials $V_2$. The dipole field $\mathbf{H}_{\text{dipole}}$ is assumed to be 7.05 mT directed along the major axis of the fixed layer.

Clearly, the position of the notch can be shifted around with the voltage $V_3$ which generates an additional uniaxial stress (negative voltage tensile and positive voltage compressive) along the line joining the electrode pads ‘3’. This makes it a 4-terminal switch.

III. S-MTJ-BASED DYNAMIC TERNARY CONTENT ADDRESSABLE MEMORY (TCAM)

In a skewed s-MTJ, the current $I_1$ between the free and fixed layers can be controlled by the gate voltages at $V_2$ and $V_3$ [Fig. 4]. At any given value of $V_1$, $I_1$ is lowest when $V_2$ and $V_3$ ‘match’, meaning that they obey the relation $V_3 = V_2 + V_F$, where $V_F$ is a fixed voltage that we call the ‘offset voltage’. The current $I_1$ increases steeply when $V_2$ and $V_3$ deviate from the ‘match’ condition. Therefore, the current through skewed s-MTJ characterizes similarity between the gate voltages $V_2$ and $V_3$. Moreover, a current-based similarity index in skewed s-MTJ is suitable for an easier inter-cell aggregation and for evaluating similarity between large scale vectors/patterns. When multiple skewed s-MTJs are arranged in parallel, the column current aggregates the similarity index (i.e., the s-MTJ current $I_1$) from each cell. Therefore, the skewed s-MTJ significantly reduces the complexity of match operation in a TCAM.

The cell schematics for an s-MTJ-based dynamic TCAM is shown in Fig. 5(a). The cells exploit high parasitic capacitance at $V_3$ node for a dynamic storage of the storage bit. Note that the capacitance at $V_3$ is high due to an underlying high dielectric constant ($\epsilon > 1000$) piezoelectric layer. The parasitic capacitance can be further enhanced by thinning down the piezoelectric layer, and/or by increasing the contact area of $V_3$ electrode atop the piezoelectric layer. The parasitic capacitance is charged through the access NMOS transistor M1.

respectively. The store bits ‘1’, ‘0’, and ‘X’ center the valley peak to 0.2 V, 0.4 V, and 0.6 V, respectively. In the encoding scheme, a high s-MTJ current (i.e., a lower resistance in the s-MTJ) indicates a match between the stored and search bit. If the stored bit in a cell is ‘X’, current through the s-MTJ is high at all search bits ‘0’, ‘1’ & ‘X’, thereby ignoring (masking) the search bit. Similarly, when the search bit is ‘X’, a high current is induced in the s-MTJ indicating a match irrespective of the stored bit. Therefore, the skewed s-MTJ significantly reduces the complexity of match operation in a TCAM.

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FIG. 7. (a) s-MTJ-based TCAM array. (b) Column Sense Amplifier.

The cell in Fig. 5(b) supports local refresh of the storage bit, i.e., the storage potential is generated within the cell using MTJ-1, MTJ-2, and M2. MTJ-1 and MTJ-2 are standard MTJs (not skewed) and can be switched by spin polarized current generating spin transfer torque or domain wall motion. MTJs locally store the storage bit and refresh the storage potential at $V_3$ node when read and access transistors (M1 & M2) are activated. Both MTJs are programmed at high resistance ($R_H$) to store ‘1’ and both at low resistance ($R_L$) to store ‘X’. One of the MTJs is programmed at $R_H$ and the other at $R_L$ to store ‘0’. The MTJs are designed such that MTJ-2 has a slightly higher critical switching current ($I_C$) than MTJ-1. To program both MTJs at low resistance, a positive programming voltage magnitude is applied at the $V_{DD}$ node [Fig. 5(b)]. To program both MTJs at high resistance, programming voltage polarity is reversed from the previous case (i.e., a negative $V_{DD}$). To write MTJ-1 at $R_H$ and MTJ-2 at $R_L$, first both MTJs are programmed at $R_L$. Then a programming pulse of negative polarity whose width is greater than the switching time of MTJ-1 but less than the switching time of MTJ-2 is applied at $V_{DD}$ node. Since the critical switching current of MTJ-1 is lower than that of MTJ-2, MTJ-1 switches to $R_H$ while MTJ-2 remains at $R_L$. The cell in Fig. 5(a) is designed for a global refresh, i.e., refresh potentials are supplied externally to the array (as in a DRAM). Note that a local refresh in Fig. 5(b) does not interfere with the regular search operation, and therefore is useful for improving performance and mitigating the complexity of refresh operation. Meanwhile, the global refresh-based cell in Fig. 5(a) also reduces cell area.

FIG. 8. Differential resistance between ‘worst case match’ and ‘worst case one-bit mismatch’ with increasing word length.

FIG. 9. (a) Decoder Circuitry for the search bit. (b) Combination of multiple s-MTJ column blocks to process a 144 bit word.

Standard CMOS-based static and dynamic TCAM cells are shown in Fig. 6(a-b) for comparison against the s-MTJ-based TCAM cells. The unconventional characteristic of the s-MTJ greatly reduces the footprint. Note that a standard CMOS-based static TCAM cell requires 16 transistors and a dynamic TCAM cell requires six transistors and two trench capacitors. In contrast, the skewed s-MTJ based design requires a single s-MTJ. Non-volatile storage in the standard MTJs eliminates standby power dissipation in the TCAM array. A narrow valley in the transfer characteristic of an s-MTJ (see Fig. 4) scales down the required minimum voltage difference between
FIG. 10. Transient waveforms for a 144-bit word search operation: (a, left) Match and mismatch. (b, middle) Local masking. (c, right) Global masking.

the stored logic ‘0’ and ‘1’, leading to a lower bias current through M1 and lower dynamic power in charging search lines ($V_2$ capacitance). Moreover, only a single ended search word mapping (unlike CMOS designs) is needed, resulting in lower dynamic power dissipation and lower wiring overheads.

TCAM cells in a column are connected in parallel to form the n-bit search/stored word. A TCAM array constitutes multiple such search columns each storing a word from the database [Fig. 7(a)]. Fig. 7(b) shows the column sense-amplifier schematic comparing the resistance of a s-MTJ-based TCAM column against a reference resistance. Nodes OUT and OUTB in the sense-amplifier are charged to high in the precharge mode (CLK = 0). Transistors M7-M10 equalize the node potential at their source and drain ends when CLK = 0. In the evaluate mode (CLK = 1), if the column resistance due to TCAM cells is lower than the reference resistance ($R_{ref}$), the current through branch M5-M8 is higher leading to OUT = 1 (Match). Otherwise, OUT = 0 (Mismatch), if the column resistance is higher.

The reference resistance is configured such that it has a resistance in between the ‘worst case match’ and the ‘worst case one-bit mismatch’. For an n-bit search word, the ‘worst case match’ column resistance $R_{match,n,w}$ obeys the relation

$$\frac{1}{R_{match,n,w}} = \frac{n}{R_{match,w}}$$

(4)

where $R_{match,w}$ is the worst case match resistance in an s-MTJ-based TCAM cell. Note that for a match in the TCAM cell, the match resistance ($R_{match}$) in s-MTJ follows $R_{match} \leq R_{match,w}$ for any combination of ternary bits: 0, 1, and X. Meanwhile, the ‘worst case one-bit mismatch’ column resistance $R_{mismatch,n,w}$ obeys the relation

$$\frac{1}{R_{mismatch,n,w}} = \frac{n-1}{R_{match,b}} + \frac{1}{R_{mismatch}}$$

(5)

where $R_{match,b}$ is the best case match resistance in an s-MTJ-based TCAM cell, and $R_{mismatch}$ is the mismatch resistance. Note that in case of a mismatch, the mismatch resistance $R_{mismatch}$ is always $\geq R_{mismatch,w}$ for any combination of ternary bits: 0, 1, and X. Figure 8 plots differential resistance between the ‘worst case match’ and the ‘worst case one-bit mismatch’, i.e., $\Delta R = R_{mismatch,n,w} - R_{match,n,w}$ at varying search word size ($n$). Note that $\Delta R < 0$ for $n > 20$. Thus, the s-MTJ characteristics limit the maximum number of TCAM cells in a column. The maximum number of parallel cells in a column can be increased by enhancing peak to valley resistance in s-MTJ (i.e., $R_{mismatch}/R_{match}$) and/or enhancing sharpness of the valley (i.e., by minimizing $R_{match,w} - R_{match,b}$). Nonetheless, large size search words can still be processed using s-MTJ-based TCAM cells by combining multiple block through an AND-tree as shown in Fig. 9(b), albeit at the cost of increasing peripheral area and power.

Operational waveforms for the TCAM array are shown in Fig. 10. At CLK = 0, the search bits $B_0$ and $B_1$ are decoded to search bit potential (0, 0.2, or 0.4 V depending on the search bit being ‘X’, ‘0’, or ‘1’, respectively) using circuitry shown in Fig. 9(a). At CLK = 1, column peripherals in each block determine a match or mismatch and the following AND-tree combines their outputs to determine an n-bit (full length) match. Fig. 10 shows simulated transient of the TCAM array for a 144-bit search operation. As indicated in Fig. 10(a), the output (ML) is high in the case of a match between the search word and stored word, and ML becomes low with mismatch. Fig. 10(b) shows the case of a don’t care (‘X’) in the least significant bit (LSB) of the stored word. Therefore, in the search operation ML is high regardless of the LSB in search word (local masking). Similarly, when the search bit is ‘X’, Fig. 10(c) shows a match irrespective of the corresponding stored bit (global masking).

In Fig. 11, at varying operational frequencies, the energy-delay-product (EDP) of the proposed s-MTJ-based dynamic TCAM is compared against that of CMOS-based dynamic TCAM. The energy-efficiency of s-MTJ-based TCAM is remarkably higher than that of
CMOS-TCAM. Owing to a much more simplified cell and search operation, the minimum energy-delay product (EDP) is \(~\sim\times12\times\) smaller than the minimum EDP in CMOS-TCAM. Furthermore, while the operational frequency of CMOS-based TCAM is limited, the s-MTJ-based TCAM delivers a significantly improved performance. Note that the minimum EDP in s-MTJ-based TCAM occurs at \(~\sim7\times\) higher frequency than the minimum EDP frequency in CMOS-TCAM. At an operational frequency of \(~\sim1\) GHz, the EDP in sMTJ-based TCAM is \(~\sim100\times\) smaller than that in CMOS-TCAM. As interest in data-intensive and search-driven platforms (such as BigData) grows, the unique characteristics of an s-MTJ-based cell will become increasingly important to reduce energy-delay product in such systems.

IV. CONCLUSIONS

This work has shown that the unique characteristics of a skewed s-MTJ can significantly simplify TCAM design and operation. In a skewed s-MTJ, the MTJ resistance can be controlled by the gate voltages \(V_2\) and \(V_3\). The resistance of an s-MTJ becomes maximum when \(V_2\) and \(V_3\) ‘match’, i.e., they differ only by a fixed amount which we have called the ‘offset’. This associative property of the skewed s-MTJ enabled us to design a single s-MTJ-based match operation in a TCAM cell. The s-MTJ-based cell is minimized to one access transistor and one s-MTJ for a dynamic TCAM with global refresh. The cell is minimized to two transistors, two MTJs and one s-MTJ for dynamic TCAM with local refresh. The dynamic TCAM with local refresh has higher performance at the cost of slightly higher cell area. In the explored TCAM cell, the operation is non-Boolean and single ended which also minimizes dynamic power and routing. The s-MTJ-based cell shows \(~\sim12\times\) lower minimum energy-delay product (EDP) than CMOS-based cell. Moreover, the frequency at minimum EDP in the discussed cell is \(~\sim7\times\) higher than the frequency of minimum EDP in CMOS-based TCAM.

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