Read Optimized MRAM with Separate Read-Write Paths based on Concerted Operation of Magnetic Tunnel Junction with Correlated Material

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Introduction: With a growing interest in spin-based memories, novel design techniques are being actively explored to enhance the read/write operations and alleviate the design conflicts [1]. Amongst such techniques, separation of read-write paths with a multi-port memory device has shown an immense promise for independent optimization of the read and write operations [1-2]. In this work, we present a novel technique to boost the cell tunneling magneto resistance (CTMR) and read stability of multi-port MRAMs by connecting a correlated material (CM) in parallel with a magnetic tunnel junction (MTJ) in the read path. Our technique is based on CMs such as VO_2 which exhibit electric current driven insulator-to-metal and metal-to-insulator transitions (IMT and MIT, respectively - Fig. 1(d)). The orders of magnitude difference in the resistances of metal and insulating phases of CMs (R_{MET} and R_{INS}) is utilized for read enhancement [3]. Due to read-write path separation, the proposed technique has no effect on the write operation.

Fabrication and Simulations: We fabricated epitaxial VO_2 films on TiO_2 substrate employing reactive oxide molecular beam epitaxy and characterized them to extract material parameters (Fig. 1). These parameters were used in an in-house SPICE model for CM along with the models for the MTJ [4] and the access transistor (FinFET) [5].

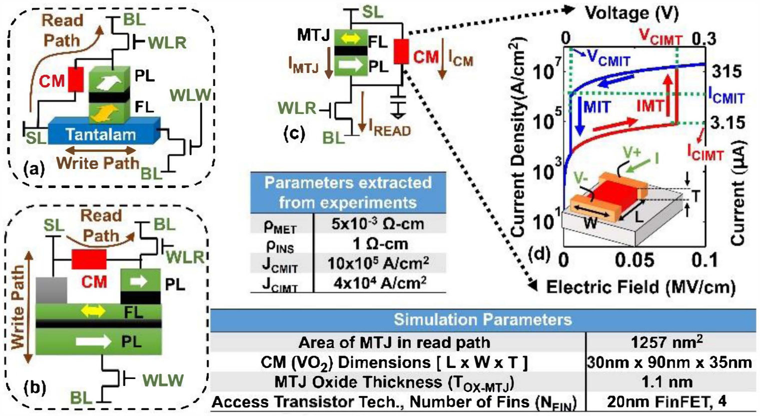
Cell Structure and Operation: Figs.1 (a)-(b) illustrate the proposed idea showing two examples of multi-port MRAMs [1-2] with CM in parallel with the MTJ in the read path. Note, the CM does not lie in the write path and therefore, has no effect on the write operation. Also, the non-volatile states of the memory are stored in the MTJ and no additional logic states are introduced by CM. A general equivalent circuit for the read path is shown in Fig. 1 (c), which will be considered for subsequent discussion. Prior to read, the voltage across the cell is zero, which keeps the CM in the insulating phase. Application of read voltage (V_{READ}) and the word-line voltage increases the voltage across the MTJ and CM (V_{CM}). With CM in the insulating phase, V_{CM} is determined by the MTJ resistance R_{MTJ} (since $R_{MTJ} << R_{INS}$). When the MTJ is in its low resistance parallel (P) state ($R_{MTJ} = R_P$), V_{CM} must be less than the critical voltage for IMT (V_{CIMT} – Fig. 1(d)) so that CM remains in the insulating phase (Fig. 2(b)). When the MTJ is in its high resistance AP state ($R_{MTJ} = R_{AP}$), V_{CM} is larger than the former case and must be sufficient to trigger IMT in the CM (Fig. 2(c)). As a result, the equivalent resistance of the cell decreases significantly leading to increase in the read current. Since $R_{MET} << R_{AP}$, the overall resistance of the cell for AP state of the MTJ is ~ ($R_{MET}+R_{MOS}$) and that for the P state is ~ (R_P+R_{MOS}). Here R_{MOS} is the resistance of the access transistor. With R_{MET} being much less than R_P, a large boost in the distinguishability is achieved. Our analysis (Fig. 3) shows that the aforementioned conditions are achieved in a range of V_{READ} which we refer to as the region of operation (RO). Any V_{READ} within the RO results in a large increase in total cell current when MTJ is in the AP state (Fig. 3 (c)). This not only leads to larger distinguishability but also enhances the read stability. Since $R_{MET} << R_{AP}$, the prime portion of the cell current flows through the CM. This results in substantial reduction of the MTJ current (Fig. 3 (b, d)) and provides better stability of data stored in the MTJ against accidental AP→P switching during read. (Note, the read current direction is such that only AP→P disturb is likely). Fig 3 shows that our technique achieves 70% boost in CTMR and 20% increase in the read disturb margin (RDM) compared to a standard read-path based on an MTJ alone (subsequently referred to as the baseline).

Tuning the region of operation (RO): As mentioned earlier, the proposed cell needs to be operated within a pre-designed RO for read enhancement. RO and hence, V_{READ} can be tuned as required by changing the dimensions of the CM (Fig. 4). We show the tuning of RO and V_{READ} by (a) changing the area and length of CM proportionally (which alters the critical currents for IMT and MIT at constant R_{MET}) and (b) reducing the length of CM to lower R_{MET}. The proposed cell shows improvement in CTMR and RDM over baseline across a range of V_{READ} (Fig. 4(c, d)).

Effect of other design parameters: Read path in multi-port MRAMs may be optimized by increasing the number of fins (N_{FIN}) of the access FinFET or MgO thickness in the MTJ ($T_{OX,MTJ}$) [1]. In Fig. 5, we show the comparison of CTMR and RDM for different N_{FIN} and $T_{OX,MTJ}$. Compared to the baseline, the effect of increasing N_{FIN} in boosting CTMR is more pronounced in the proposed cell. This is because R_{MOS} has a strong effect on CTMR due to low R_{MET}. Enhancement in CTMR with increasing $T_{OX\text{-}MTJ}$ is also significantly higher due to significant increase in R_P relative to R_{MET}. RDM of our cell is relatively less sensitive to $T_{OX\text{-}MTJ}$ since R_{MET}, which controls the MTJ current, is independent of $T_{OX,MTJ}$. The proposed technique achieves boost in RDM and CTMR across the entire range of N_{FIN} and $T_{OX,MTJ}$.

Conclusion: We propose a technique based on connecting CM like VO_2 in parallel with the MTJ in the read path of multi-port MRAMs. Utilizing insulator-metal transitions in CM, the proposed cell achieves 1.7X to 4.3X improvement in cell TMR (CTMR) along with 7% to 22% higher read disturb margin compared to a baseline cell. Due to the separation of read-write paths in multi-port MRAMs, the CM has no effect on the write operation. The proposed idea is not limited to VO_2 and its benefits may be further enhanced by exploring other suitable CMs [6] or by tuning the properties like resistivities, critical currents and thermal stability by techniques like strain [7] or Cr doping [8].

References: [1] Mojumder et al., *IEEE TED*, 5, 2011. [2] Liu et al, *Science* 336 (6081). [3] Shukla et al, *Scientific Rep.* 4:4964, 2014. [4] Fong et al, nanohub.org/resources/19048. [5] ptm.asu.edu/ [6] Chudnovskii et al, *JAP* 1998. [7] Cao et al, *Nat. Nanotech.* 2009. [8] Brown et al, *JAP*, 2013.
Acknowledgement: This research was supported by the Department of Electrical Engineering and Materials Research Institute, Penn State.



Parameters extracted from experiments	
ρ_{MET}	5×10^{-3} Ω-cm
ρ_{INS}	1 Ω-cm
J_{CMIT}	10×10^{5} A/cm^2
J_{CIMT}	4×10^{4} A/cm^2

Simulation Parameters	
Area of MTJ in read path	1257 nm^2
CM (VO_2) Dimensions [L x W x T]	30nm x 90nm x 35nm
MTJ Oxide Thickness ($T_{OX\text{-}MTJ}$)	1.1 nm
Access Transistor Tech., Number of Fins (N_{FIN})	20nm FinFET, 4

Fig. 1 (a, b) MRAM with separate read-write paths using the proposed technique of connecting a correlated material (CM) in parallel with the MTJ (c) Read equivalent circuit for the proposed MRAM cell (d) Characteristics of VO_2 (a CM) based on material parameters extracted from experiments.

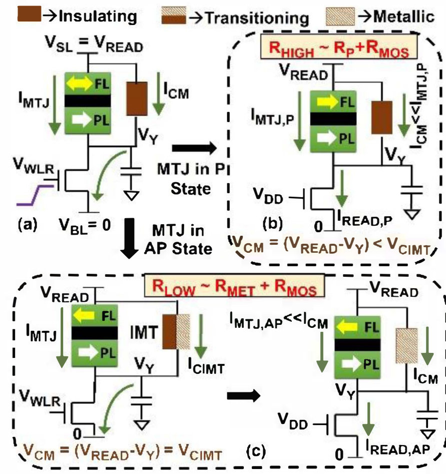


Fig. 2 Read operation of the proposed MRAM utilizing phase transition of the CM to enhance distinguishability and stability.

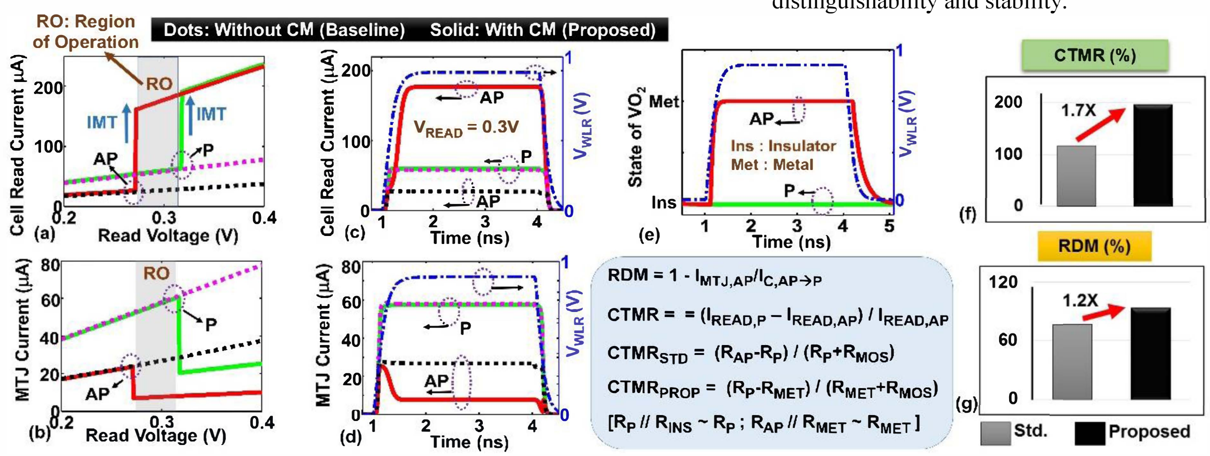


Fig. 3 (a) Read current of the cell and (b) MTJ current versus read voltage showing the region of operation (RO). Transient analysis showing (c) cell current, (d) MTJ current and (e) state of VO_2 during read. Substantial increase in the total cell current and reduction in the MTJ current for AP state leads to superior (f) cell TMR or CTMR and (g) read disturb margin (RDM) for the proposed MRAM cell compared to the baseline cell (existing multi-port MRAMs).

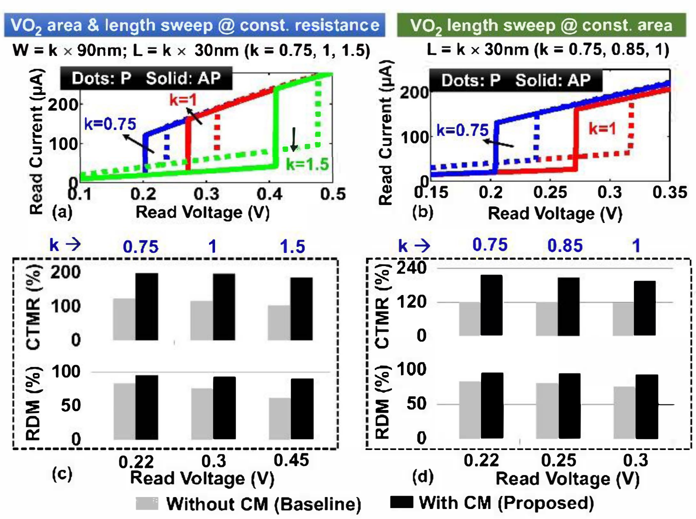


Fig. 4 Tuning of the region of operation and read voltage by changing (a) VO_2 area and length and (b) VO_2 length; (c, d) the corresponding comparison of CTMR and RDM for baseline and proposed cell.

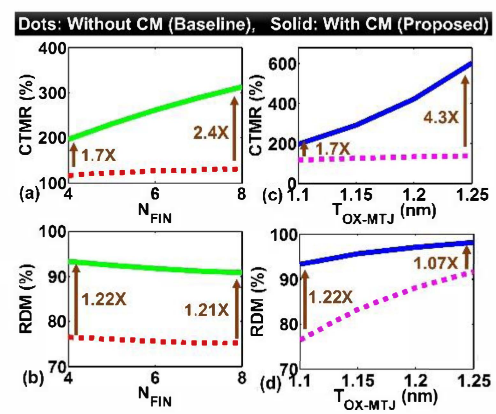


Fig. 5 CTMR and RDM for (a, b) different fin number of the read access transistor (N_{FIN}) at $T_{OX,MTJ}$=1.1nm and (c, d) for different MgO thickness in the MTJ ($T_{OX,MTJ}$) at N_{FIN}=4. The proposed technique achieves improved CTMR and RDM across different N_{FIN} and $T_{OX,MTJ}$.