A Concatenable Magnetoelectric Magnetic Tunneling Junction (MEMTJ) Computational Device

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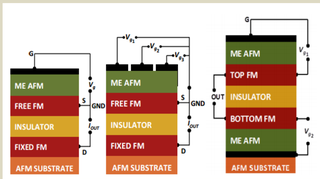
Introduction

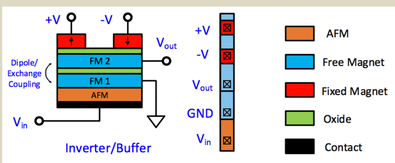


Basic Cell | Majority Gate | XOR Gate

[1] N. Sharma, et. al., *Energy Efficient Electronic Systems (E3S), 2015 Fourth Berkeley Symposium on*, 2015, pp. 1-3.
[2] N. Sharma, et. al., *Circuits and Systems Conference (DCAS), 2015 IEEE Dallas*, 2015, pp. 1-4.

- **Original proposal**: Device/circuit concepts from N. Sharma, A. Marshall, J. Bird, and P. Dowben [1,2]
- Basic Operation
  - Voltage induced change in boundary magnetization, generates exchange bias field to switch the free magnet
  - Free magnet magnetization determines the output MTJ resistance
  - MTJ resistance value converted to voltage by passing a current with a MOSFET.

Proposed device structure



Modified structure

- Using two MTJ stacks (opposite magnetization of fixed magnets) on top to provide complementary output
- Avoid the need for extra transistors with a complicated clocking scheme
- Output voltage can directly drive next stage (concatenability)

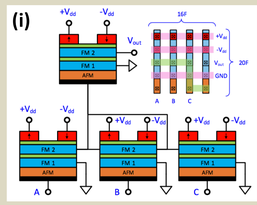
Proposed majority gate using MEMTJ

Previous proposal

- Connects 3 inputs directly to the AFM
- Assumption of single-domain magnet switching may not be valid

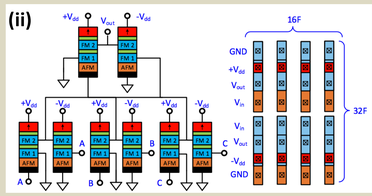
Modified proposal (fig.i)

- Two-stage majority gate with four basic MEMTJ devices
- Stable error-free switching behavior



Alternative design (fig. ii)

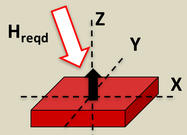
- Separate pull-up and pull-down networks
- Same magnetization of fixed magnets on top – avoid fabrication challenges.



Modeling approach

Switching Time of Free FM layer

- Dimension = 210 x 30 x 10 nm^3
- Saturation magnetization M_s = 650 kA/m*
- Perpendicular anisotropy K_{PMA} = 0.19 MJ/m^3*
- Magnetoelectric switching field [1] E_{me} = 2.6 MV/m
- Magnetoelectric exchange bias [1] B_{me} = 9 mT
- Dielectric constant ε_{me} = 13
- Required ME field B_{reqd} = 35 mT (from simulation)
- Required electric field $E_{reqd} = \left(\frac{E_{me}}{B_{me}}\right) B_{reqd}$



simulation set up [2]
(need a better approach to model exchange bias)

[1] He, Xi, et al., Nature materials 9.7 (2010): 579-585.
[2] Nikonov, D E. et. al., Journal of Materials Research 29.18 (2014): 2109-2115.
* assumed for simulation

Further investigation of exchange bias field required to obtain more accurate results

Delay calculation

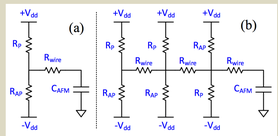
$$t_{\text{int}} = (R_p \| R_{ap} + R_{wire}) C_{in} + t_{switch}$$

Energy Calculation

$$E_{\text{int}} = E_e + E_{Leak}$$

where $E_e = \frac{1}{2}(C_{AFM} + 2C_{MTJ})\ V^2$,

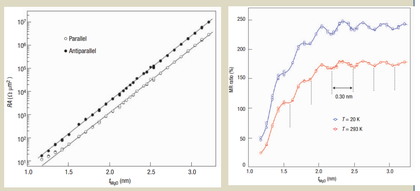
$$E_{Leak} = \frac{V_{dd}^2}{R_p + R_{ap}} t_{\text{int}}, \quad V = V_{dd} \frac{R_{ap}\ R_p}{R_{ap} + R_p}$$



- High resistance high TMR MJTs are desired
- Magnet switching time t_{switch} obtained through numerical simulation

Device Optimization

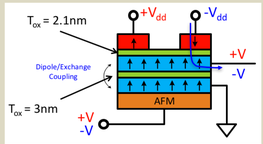
- RA product and TMR vs. tunneling oxide thickness
- The RA product increases exponentially as the tunneling oxide thickness increases.

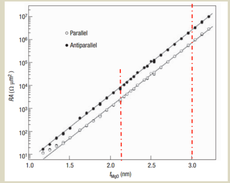


Yuasa, Shinji, et al., *Nature materials* 3.12 (2004): 868-871.

Oxide Thickness Selection

- MTJ oxide thickness 2.1nm , insulation layer thickness 3nm
- RA would be ~500X larger between the two free magnets compared to the RA of the MTJs
- 3nm separation between magnets allows good dipolar coupling.

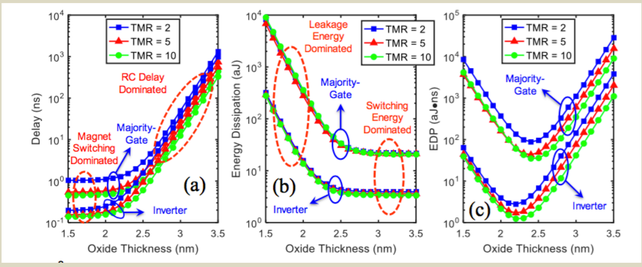




- Alternatively, insulating magnet can be used
- For benchmarking, conservative TMR 200% and optimistic TMR 500% used

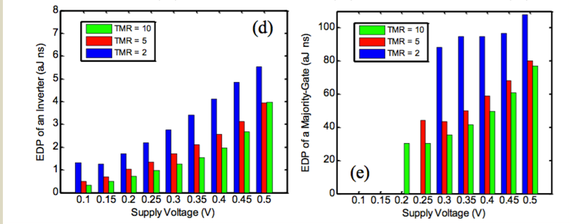
Performance analysis

- Delay is dominated by magnet switching time when t_{ox} is small.
- Energy is dominated by the leakage energy when t_{ox} is small.

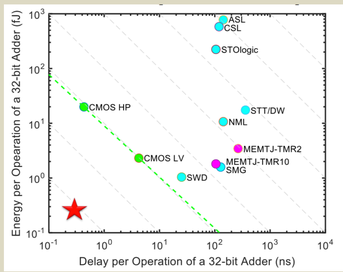


- Optimal oxide thickness exists to minimizing the overall EDP.

Intrinsic device and majority gate



Circuit level analysis



Conclusion

- **Enhanced MEMTJ device** is proposed that satisfies five essential properties that allow it to be used as a **stand-alone logic device**
- Two schemes with different fixed magnet magnetization and layout are proposed to address the fabrication challenge.
- **Optimal tunneling oxide thickness** and **supply voltage** are found to minimize the overall EDP under different TMR assumptions.
- At the circuit-level analysis, MEMTJ devices are **more energy efficient compared to their CMOS counterpart** but operate **slower due to the larger magnet switching time as well as the RC delay**