SWITCHING TIME OF SPIN-TORQUE-DRIVEN MAGNETIZATION IN BIAXIAL FERROMAGNETS

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SIGNIFICANCE OF SPIN-TORQUE MAGNETIC DEVICES

FEATURES

- Compatible with Silicon Technology
- No moving parts as in conventional hard disks
- SOT reduces chances of dielectric breakdown
- Fast Read and Write
- Volatile Memory (Cache)
  - High endurance
- Non-volatile memory
  - High thermal stability
  - Negligible standby power

NEED FOR SPIN DEVICE INNOVATION

- NV memory in magnetic-silicon hardware
  - Lower power dissipation even for ML tasks
- Neuromorphic Computing
  - Cache memory in processors
  - Storing weights for ML tasks
- Low Energy Oscillators (GHz)
- Probabilistic Computing
  - Energy Efficient
  - Image processing, ML, Spin-Logic

RECENT PROGRESS

- Ultrafast bipolar SOT-MRAM [4]
  - 275 nm p-MTJ deposited on top of Ta
  - 0.4 ns writing speed with in-plane magnetic field along current direction
  - TMR of 55%
- Field-Free writing in canted SOT-MRAM [5]
  - i-MTJ with 55 nm CMOS
  - 0.35 ns writing speed
  - High thermal stability
  - High TMR
- 1 Gb standalone STT-MRAM [6]
  - p-MTJ with 28 nm CMOS
  - High endurance and stability
  - Reliable switching for wide range of voltages

[1] A. Kent, Nat. Nanotech. 10.3 (2015), [2] T. Hanyu et al., 2019. 237-281, [3] A. Shukla et al., Phys. Rev. Appl. 13.054020 (2020), [4]M. Cubukcu et al., IEEE Trans. on Magn. 54.4 (2018), [5] H. Honjo et al., IEEE IEDM (2019), [6] S. Aggarwal et al., IEEE IEDM (2019)

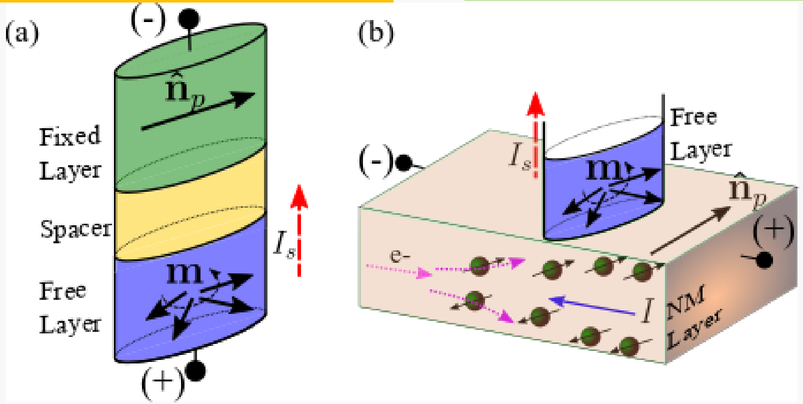
DIFFERENT CONFIGURATION

STT vs. SOT

- STT
  - Both spin and electric current flow perpendicular to the plane of spin-valve
  - Vulnerable to dielectric breakdown
  - Smaller area but problem of read disturb
- SOT
  - In-plane electric current in a NM layer
  - Spin-polarized current due to SHE
  - No dielectric breakdown
  - Larger area due to separate read and write path but high endurance

i-MTJ vs. p-MTJ

- Perpendicular Anisotropy FL
  - Low writing current
  - Faster switching time
  - High density memory
  - Symmetry breaking field required
  - Fabrication complexity
- In-plane Anisotropy FL
  - Thin film FL
  - Simpler fabrication and field-free switching
  - Lower switching current but inferior switching time

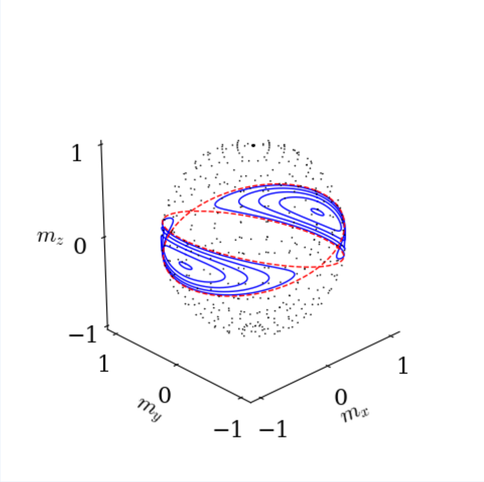


[1] A. Shukla et al., Phys. Rev. Appl. 13.054020 (2020),

THEORY

- Numerical Solution
  - Solve stochastic Landau-Lifshitz-Gilbert Equation under Macrospin approximation
  - Energy Density
    - Biaxial Anisotropy
    - No external magnetic field
  - Gaussian Random Thermal Noise with zero mean
  - Computationally Expensive

- Analytical Solution- Deterministic Limit
  - Constant-Energy Orbit Approximation
  - 3D LLG to a more tractable 1D equation
  - No Thermal Noise considered
  - Control parameter $R = \frac{M_S}{H_k}$



[1] D. Pinna et al., Phys. Rev. B 88, 104405 (2013)
[2] A. Shukla et al., Phys. Rev. Appl. 13, 054020 (2020)

MAGNETIZATION DYNAMICS

$I_s = 1.01 I_s^{\mathrm{thm}}$

$I_s = 1.5 I_s^{\mathrm{thm}}$

$I_s = 2 I_s^{\mathrm{thM}}$

I_s^{thm} - lower threshold (separates deterministic vs. thermal switching regime)
I_s^{thM} - upper threshold (validity of CEOA)

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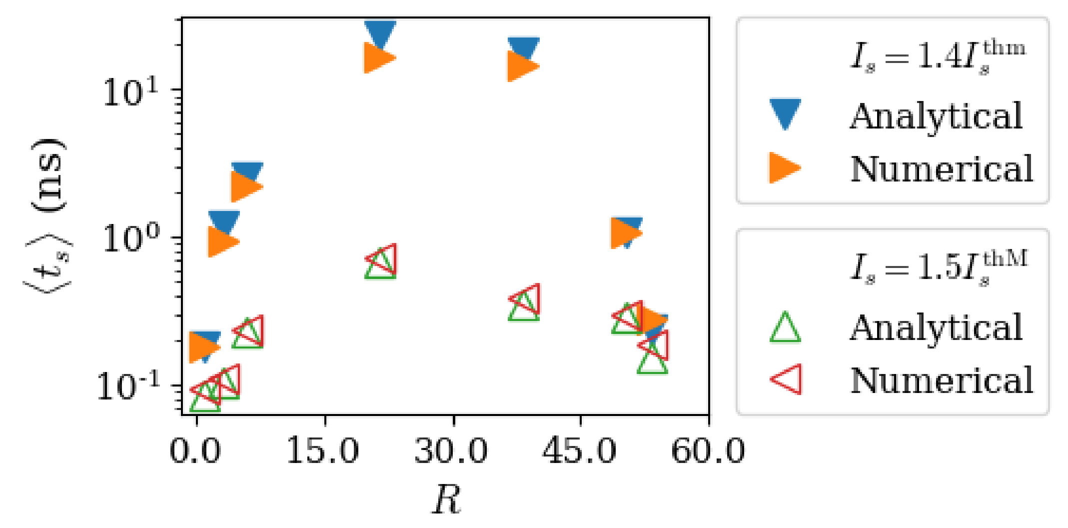
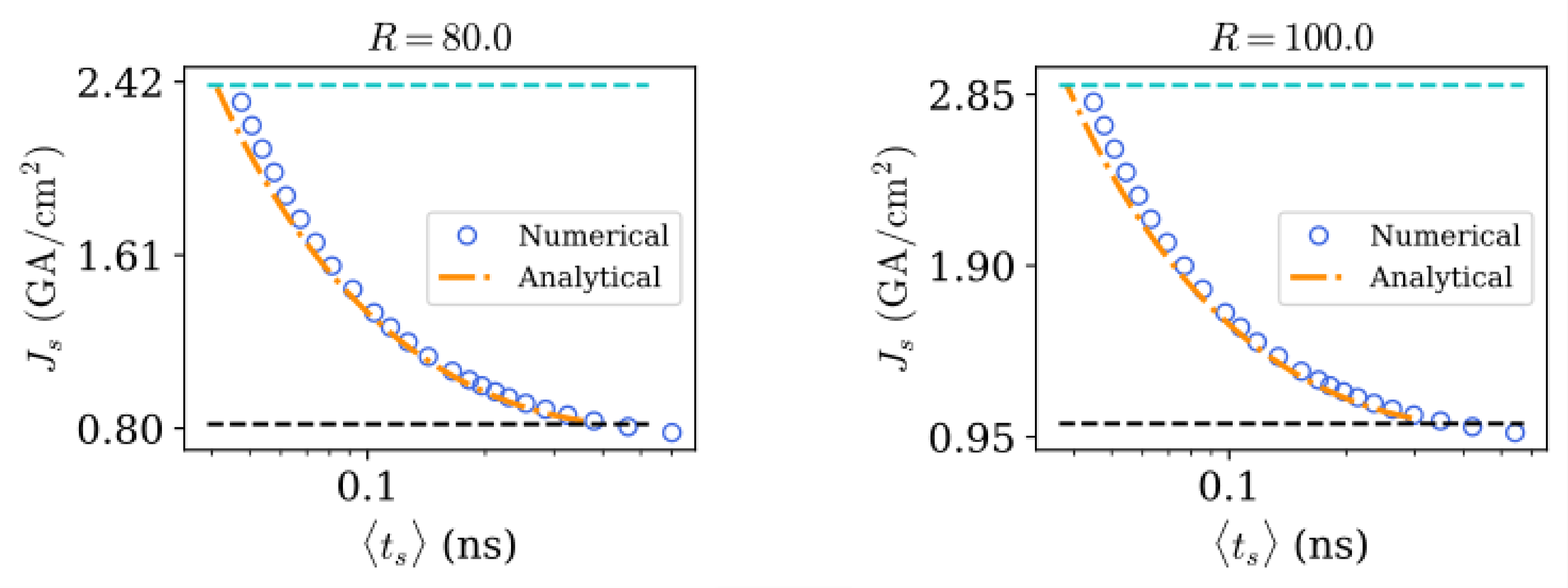
BENCHMARKING OUR ANALYTICAL SOLUTIONS AGAINST NUMERICAL DATA- SWITCHING TIME



- 5-10 % error between analytical results and numerical solution of sLLG for switching time.
- Model validity extends beyond that of CEOA
- Robust model

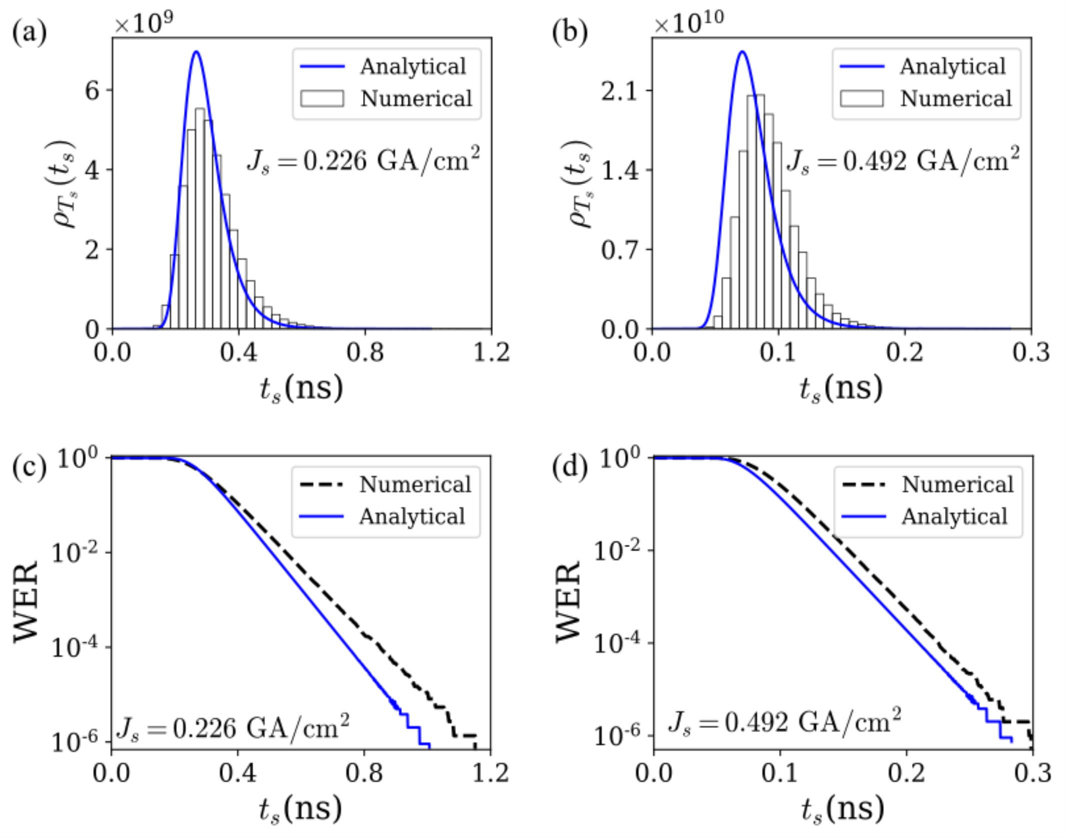
Data and References



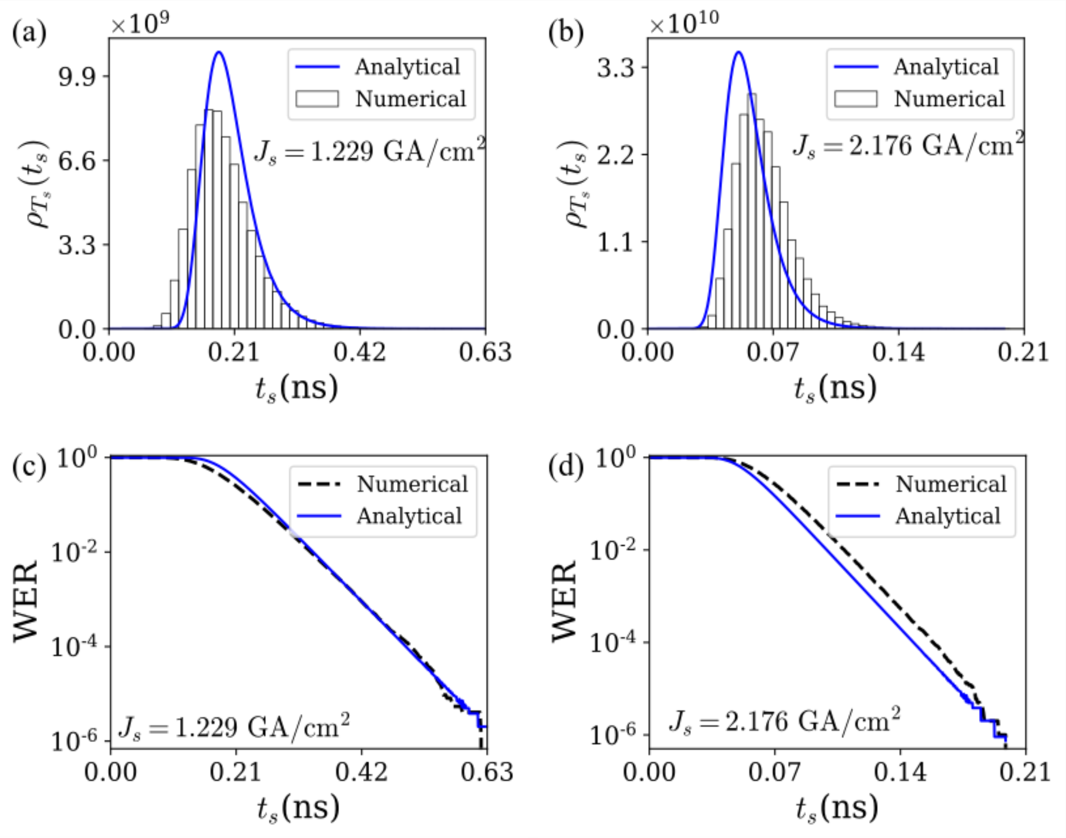
- Maximum error between analytical results and numerical solution is ~12% for $I_s = 2I_s^{\text{th}\,M}$
- $\alpha = 0.03$

BENCHMARKING OUR ANALYTICAL SOLUTIONS AGAINST NUMERICAL DATA- DISTRIBUTION FUNCTIONS

$R = 15$



$R = 100$



CONCLUSIONS

- Spin-MRAMs have high endurance, could be used for both volatile Cache memories and long-term non-volatile storage.
- They have possible applications in the field of Neuromorphic computing, ML, Image processing, spin-logic, energy efficient computing.
- Both STT and SOT are used for writing with their respective advantages and disadvantages.
- i-MTJ is easy to fabricate, does not require a symmetry breaking field and requires lower current to switch when compared to p-MTJ but has smaller switching time.
- Our analytical results show good agreement against numerical solution of LLG for small to medium spin current density.
- Models developed should complement experiments aid design, analysis and development of non-volatile memory.

FERROMAGNETIC MATERIALS AND THEIR MAGNETIC PROPERTIES

MATERIALS	M_s(T)	K_u(MJ/m^3)	R	α	Ref.
Terfenol-D	1.00	0.390	1.04	0.100	[1]
Co	1.81	0.410	3.20	0.020	[2]
$Co_{0.6}Fe_{0.2}B_{0.2}$	1.20	0.095	6.00	0.015	[3, 4]
NiMnSb	0.84	0.013	21.6	0.002	[2, 5]
Fe	2.15	0.048	38.3	0.001	[2, 6]
EuO	2.36	0.044	50.4	0.015	[2]
Fe-Ga-B	1.63	0.020	53.4	0.100	[1]

[1] N. Kani, Ph.D. thesis, Georgia Institute of Technology, (2017)

[2] J. M. Coey, Magnetism and Magnetic Materials (Cambridge University Press, 2010)

[3] G. Rowlands et al., Deep subnanosecond spin torque switching in magnetic tunnel junctions with combined in-plane and perpendicular polarizers, Appl. Phys. Lett. 98, 102509 (2011)

[4] S. Yakata et al., Influence of perpendicular magnetic anisotropy on spin-transfer switching current in CoFeB/MgO/CoFeB magnetic tunnel junctions, J. Appl. Phys. 105, 07D131 (2009)

[5] P. Durrenfeld et al., Spin Hall effect-controlled magnetization dynamics in NiMnSb, J. Appl. Phys. 117, 17E103 (2015)

[6] H. Yoda et al., High efficient spin transfer torque writing on perpendicular magnetic tunnel junctions for high density MRAMs, Curr. Appl. Phys. 10, e87 (2010).

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