Hybrid Spintronics and Straintronics: A New Technology for Ultra-Low Energy Computing and Signal Processing Beyond the Year 2020 (NEB: 1124714)

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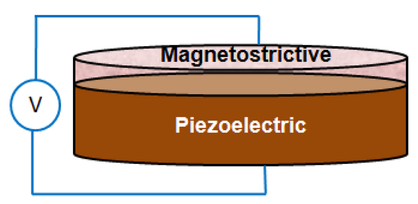
STRAINTRONICS WITH MUTIFERROICS

- Multiferroic two-phase composites – a ferroelectric layer and a ferromagnetic layer with intimate contact to each other.
- Enhanced magnetoelectric coupling in a two-phase multiferroic by strain.
  - Ferroelectric: piezoelectric.
  - Ferromagnetic: magnetostrictive.



- A voltage is applied on the piezoelectric layer, generating a strain in it.
  - strain = (volt/t_{piezo}) × d_{31}.
  - Constrained along the in-plane hard-axis.
  - Uniaxial stress along the easy axis.

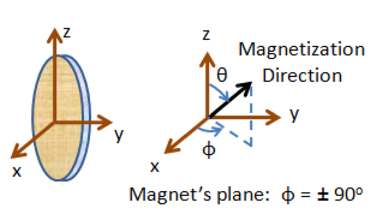
✓ Electric writing
✓ Magnetic reading

- Generated strain is transferred to the magnetostrictive layer.
  - Piezoelectric layer is much thicker than the magnetostrictive layer. stress = strain × Young's modulus.
  - Stress anisotropy rotates the magnetization axis of the magnetostrictive nanomagnet.
- Few millivolts of voltage required, which can be powered by harvesting energy from the environment (e.g., implantable medical devices).

✓ **K. Roy, S. Bandyopadhyay, and J. Atulasimha. Appl. Phys. Lett., 99, 063108, 2011.**
✓ **K. Roy, S. Bandyopadhyay, and J. Atulasimha. Phys. Rev. B, 83, 224412, 2011.**
✓ **Nature news: Switching up spin, Aug 25, 2011, AIP news, PhysicsWorld …**

STOCHASTIC MAGNTIZATION DYNAMICS

Magnetization dynamics of a magnetostrictive nanomagnet



Stochastic Landau - Lifshitz - Gilbert (LLG) Equation

$$\frac{dn_m(t)}{dt} - \alpha\left(n_m(t)\times\frac{dn_m(t)}{dt}\right) = -\frac{|\gamma|}{M_V}\left[T_E(t)+T_{TH}(t)\right]$$

α : damping constant, $M_V=\mu_0 M_s\Omega$, M_s : saturation magnetization, Ω : volume

Torque due to shape and stress anisotropy

$$T_E(t) = -2B(t)\sin\theta(t)\cos\theta(t)\hat{e}_\phi - B_{0e}(t)\sin\theta(t)\hat{e}_\theta$$

$$B(t) = B_{shape}(t) + B_{stress}(t)$$

$$B_{shape}(t) = \frac{\mu_0}{2}M_s^2\Omega\left[N_{d-xx}\cos^2\phi(t) + N_{d-yy}\sin^2\phi(t) - N_{d-zz}\right]$$

N_{d-ii} : demagnetization factor in the i^{th} direction

$$B_{stress}(t) = (3/2)\lambda_s\sigma(t)\Omega$$

$(3/2)\lambda_s$: saturartion magnetostriction coefficient, σ : stress

$$B_{0e}(t) = \frac{\mu_0}{2}M_s^2\Omega\left(N_{d-xx} - N_{d-yy}\right)\sin 2\phi(t)$$

Torque due to random thermal field

$$T_{TH}(t) = P_\theta(t)\hat{e}_\phi - P_\phi(t)\hat{e}_\theta$$

$$P_\theta(t) = M_V\left[h_x(t)\cos\theta(t)\cos\phi(t) + h_y(t)\cos\theta(t)\sin\phi(t) - h_z(t)\sin\theta(t)\right]$$

$$P_\phi(t) = M_V\left[h_y(t)\cos\theta(t) - h_x(t)\sin\theta(t)\right]$$

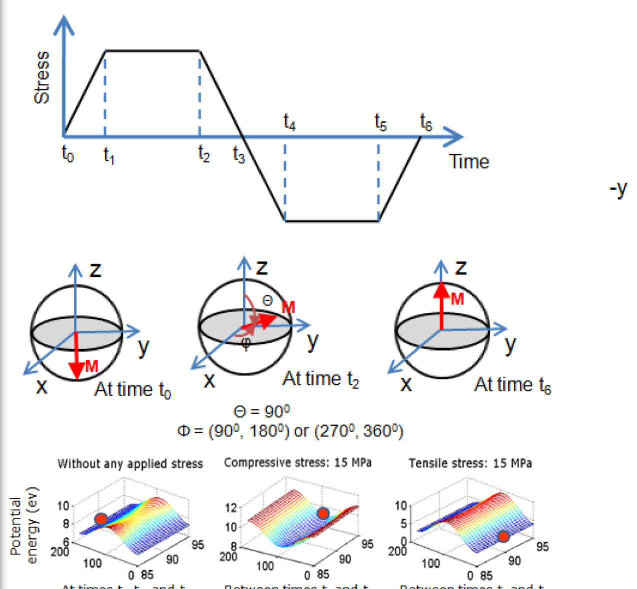
h_i : random thermal field in the i^{th} direction

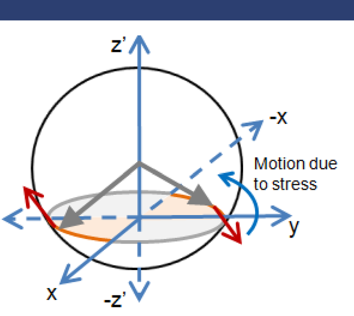
Equations of motion

$$\left(1+\alpha^2\right)\frac{d\theta(t)}{dt} = \frac{|\gamma|}{M_V}\left[B_{0e}(t)\sin\theta(t) - 2\alpha B(t)\sin\theta(t)\cos\theta(t) + \left(\alpha P_\theta(t) + P_\phi(t)\right)\right]$$

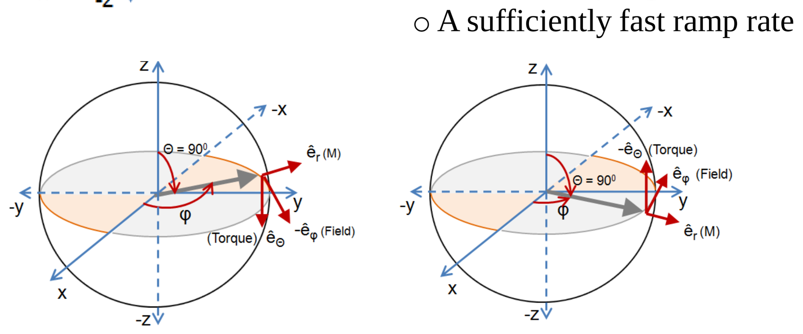
$$\left(1+\alpha^2\right)\frac{d\phi(t)}{dt} = \frac{|\gamma|}{M_V}\left[\alpha B_{0e}(t) + 2B(t)\cos\theta(t) - \sin^{-1}\theta(t)\left(P_\theta(t) - \alpha P_\phi(t)\right)\right] \quad (\sin\theta \neq 0)$$

ILLUSTRATION OF MAGNETIZATION DYNAMICS





- Interaction between motion due to stress and out-of-plane demagnetization field keeps magnetization in the quadrants ϕ = (90°, 180°) or (270°, 360°) when θ reaches 90°.
  - A sufficiently high stress
  - A sufficiently fast ramp rate

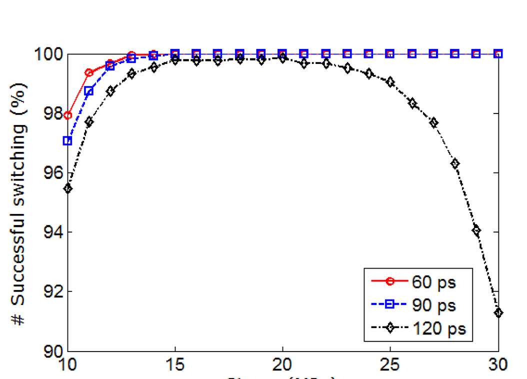


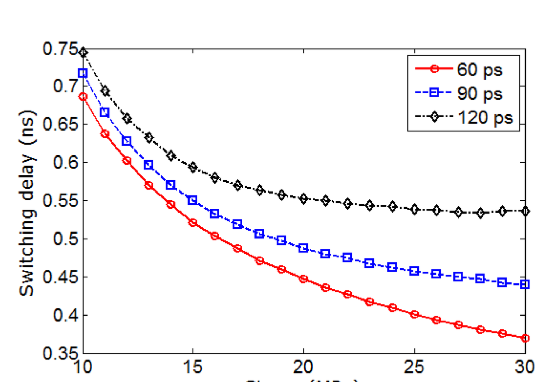
Magnetization can traverse in the correct direction

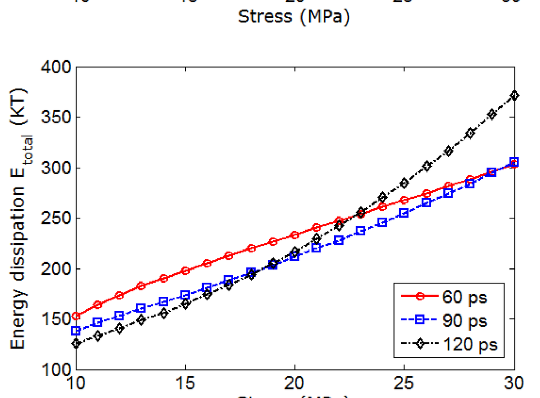
Magnetization backtracks in the opposite direction

✓ **K. Roy, S. Bandyopadhyay, and J. Atulasimha under preparation, Phys. Rev. Lett.**

SIMULATION RESULTS: MEMORY APPLICATION





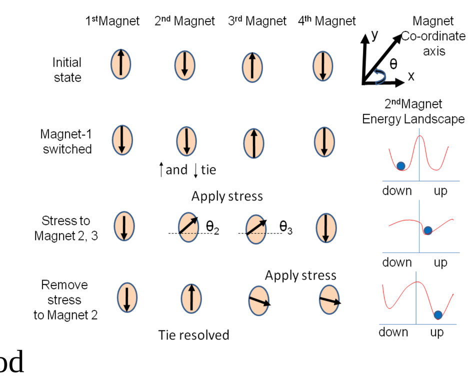


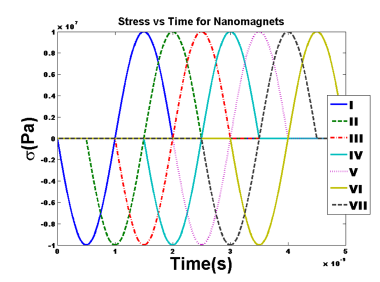
- Fast ramp rates and higher stress levels are conducive to successful switching.
- Sub-nanosecond switching delay is achievable.
  - Switching delay decreases with higher stresses and faster ramp rates.
- Energy dissipation of only 200 kT at room temperature with thermal mean switching delay 0.5 ns for 15 MPa stress and 60 ps ramp duration.
- Application in energy-efficient non-volatile memory.

2-STATE STRAINTRONICS FOR LOGIC

- Multiferroic nanomagnetic "wires": Bennett-clocking ~ 1 GHz with electrostatic potential of ~ few mV applied to the piezoelectric layer.
- All multiferroic nanomagnetic NAND gate with fan-in/fan-out: simulated using the Landau-Lifshitz-Gilbert (LLG)
- Clocking in multiferroics

→3-5 orders of magnitude more energy efficient than other current method for rotating the magnetization direction through large angles





✓ **J. Atulasimha and S. Bandyopadhyay, Appl. Phys. Lett. 97, 173105, 2010**
✓ **M.Salehi Fashami, K.Roy, J.Atulasimha, S.Bandyopadhyay Nanotechnology 22 ,155201, 2011.**
✓ **M Salehi Fashami, J.Atulasimha, S.Bandyopadhyay, Nanotechnology (under review), arXiv:1108.5758, 2011.**

MAGNETIZATION DYNAMICS: "WIRES" & GATES

Magnetization dynamics in multiferroic nanomagnetic logic

The Landau-Lifshitz-Gilbert (LLG) Equation

$$\frac{d\vec{M}(t)}{dt} = -\gamma\vec{M}(t)\times\vec{H}_{eff}(t) - \frac{\alpha\gamma}{M_s}\left[\vec{M}(t)\times\left(\vec{M}(t)\times\vec{H}_{eff}(t)\right)\right]$$

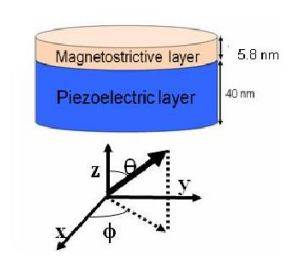
$\vec{H}_{eff}$: The Effective Magnetic Field on i^{th} Nanomagnet

γ: The gyromagnetic ratio, M_s: The saturation magnetization of the magnetostrictive layer

α: The Gilbert damping factor

Effective Magnetic Field Due to energy of U_i(t)

$$H_{eff}^i(t) = -\frac{1}{\mu_0\Omega}\frac{\partial U_i(t)}{\partial\vec{M}_i(t)} = -\frac{1}{\mu_0 M_s\Omega}\nabla_{\vec{m}}U_i(t)$$



The total potential energy of any Nanomagnet in this chain

$$U_i(t) = \underbrace{\sum_{j\neq i}E_{dipole-dipole}^{i-j}(t)}_{E_{dipole}} + \underbrace{\left(\frac{\mu_0}{2}\right)\left[M_s^2\Omega\right]\left(N_{d\_xx}\left[\sin\theta_i(t)\cos\phi_i(t)\right]^2 + N_{d\_yy}\left[\sin\theta_i(t)\sin\phi(t)_i\right]^2 + N_{d\_zz}\left[\cos\theta_i(t)\right]^2\right)}_{E_{shape-anisotropy}}$$

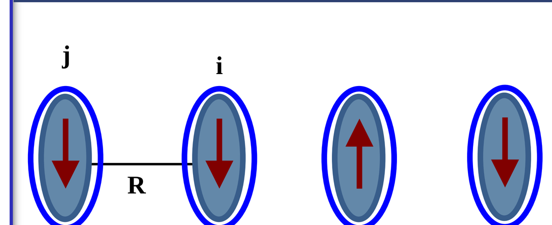
$$\underbrace{-\left(\frac{3}{2}\lambda_s\sigma_i\Omega\right)\sin^2\theta_i(t)\sin^2\phi_i(t)}_{E_{stress-anisotropy}} + \text{other terms}$$

N_d : Demagnetization factor , σ : *Mechanical Stress*, $\frac{3}{2}\lambda_s$: Saturation Magnetostriction Coefficient , Ω: Volume of Nanomagnet

$$E_{dipole-dipole}^{i-j}(t) = \frac{\mu_0 M_s^2\Omega^2}{4\pi|\vec{r}_{i-j}|^3}\left[\left(\vec{m}_i(t).\vec{m}_j(t)\right) - \frac{3}{|\vec{r}_{i-j}|^2}\left(\vec{m}_i(t).\vec{r}_{i-j}\right)\left(\vec{m}_j(t).\vec{r}_{i-j}\right)\right]$$

μ_0 : *Permeability of Vacumm* , $\vec{r}_{i-j}$: Nanomagnet center-center spacing

ALL-MULTIFERROIC LOGIC WIRES AND GATES

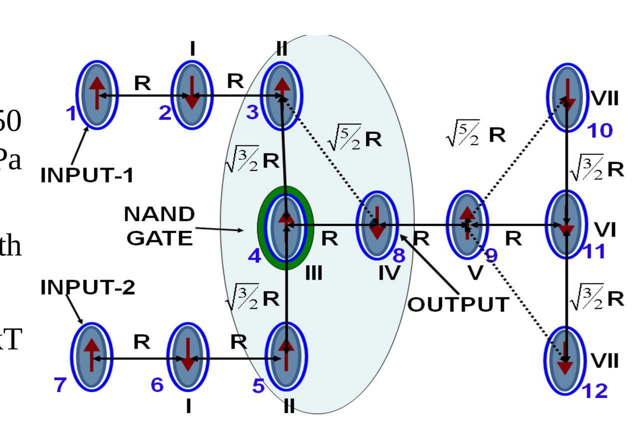


LOGIC WIRE

1. Bennett clocking: 5.2 MPa compressive Stress on magnet 2 & 3.
2. Total energy dissipation → 430 KT/bit @ 1GHz in the wire.

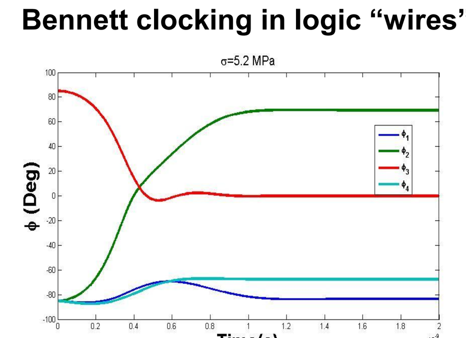
UNIVERSAL GATE: NAND LOGIC WITH FAN-OUT

1. Nanomagnets are clocked with electrostatic potential of ~50 mV applied to the piezoelectric layer generating 10 MPa stress in the magnetostrictive layers.
2. Pipelined bit throughput rate of ~ 0.5 GHz is achievable with sinusoidal four-phase clocking.
3. Total Energy dissipation → ~ 500kT in the gate and ~1300 kT in the 12-magnet array.

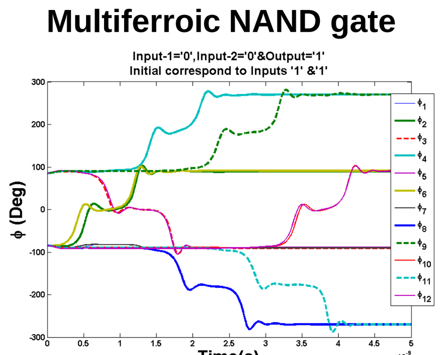


SIMULATION RESULTS: 2-STATE LOGIC

Bennett clocking in logic "wires"



Multiferroic NAND gate

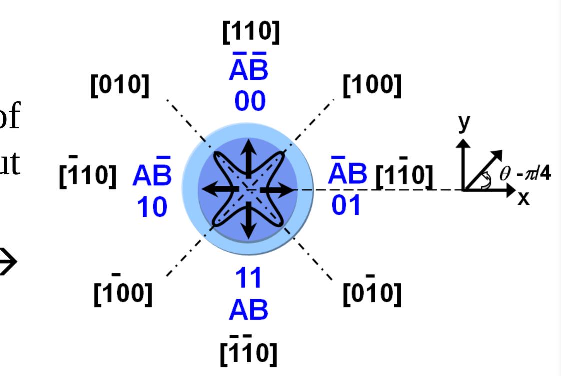


M Salehi Fashami, J.Atulasimha, S.Bandyopadhyay, Nanotechnology (under review), arXiv:1108.5758, 2011.

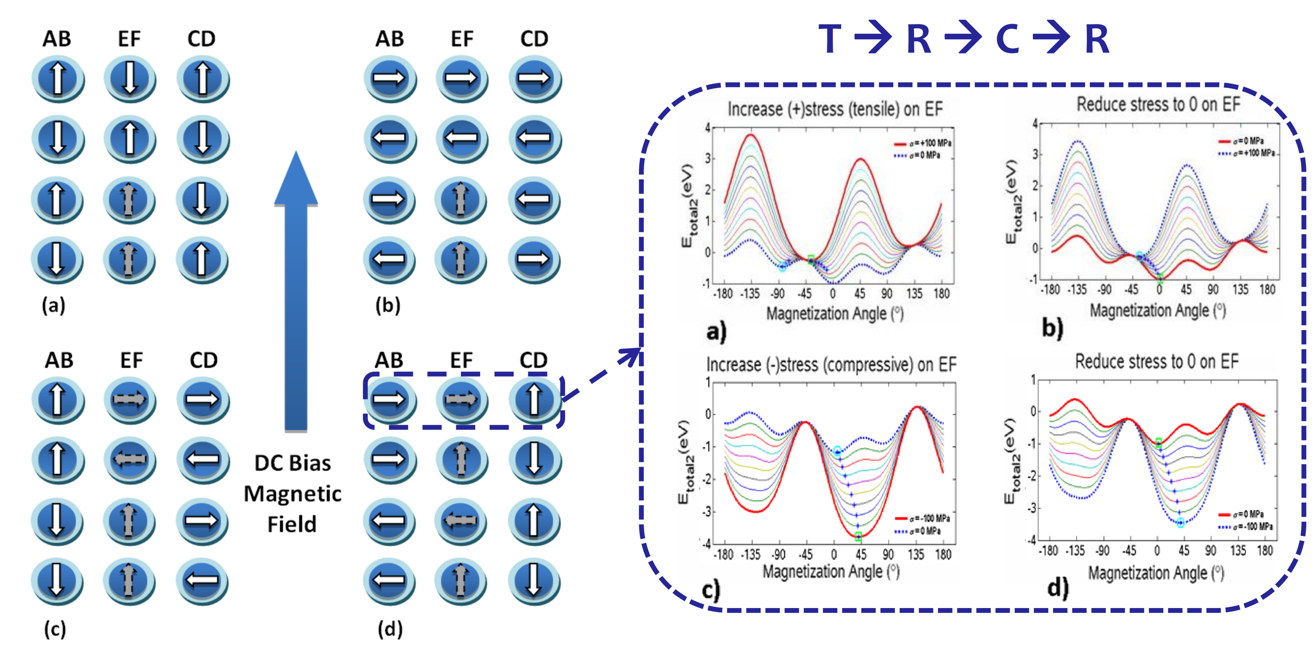
- The initial condition in all of cases are $\phi_0 = \pm 85^0$, $\theta_0 = 89.9^0$
- The NAND gate operation is completed in 2 ns with a latency of 4 ns.
- The total energy dissipation in the gate is respectively 3 and 5 orders of magnitude more energy-efficient than complementary-metal-oxide-semiconductor-transistor (CMOS) based and spin-transfer-torque-driven nanomagnet based NAND gates.

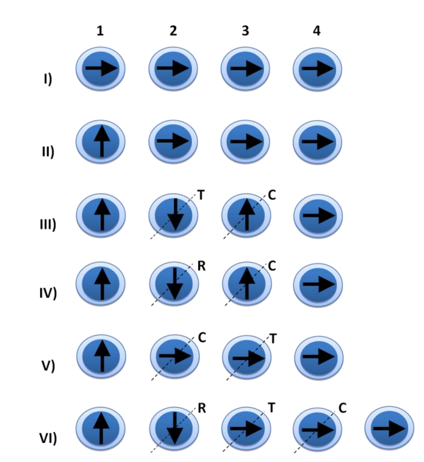
4-STATE STRAINTRONICS

- Biaxial magnetocrystalline anisotropy in the magnetostrictive layer: four stable magnetization directions.
- "up" (00), "down" (11), "left" (10), "right" (01)
- NOR logic: apply clock cycle, involving a sequence of stresses to the output nanomagnet, with an input nanomagnet on each side of it.
- Stress Sequence: Tension (T) → Relaxation (R) → Compression (C) → Relaxation (R)



✓**N.D'Souza, J.Atulasimha & S.Bandyopadhyay, 2011, J Phys D: Appl Phys, 44, pp. 265001**
✓**N.D'Souza, J.Atulasimha & S.Bandyopadhyay, 2011, IEEE Trans. Nanotech., accepted**
✓**N.D'Souza, J.Atulasimha & S.Bandyopadhyay, 2011, Appl. Phys. Lett., under review,** http://arxiv.org/abs/1109.6932

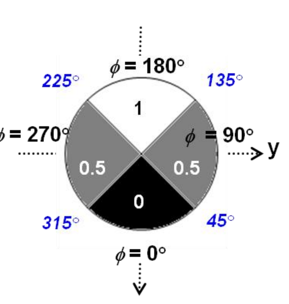


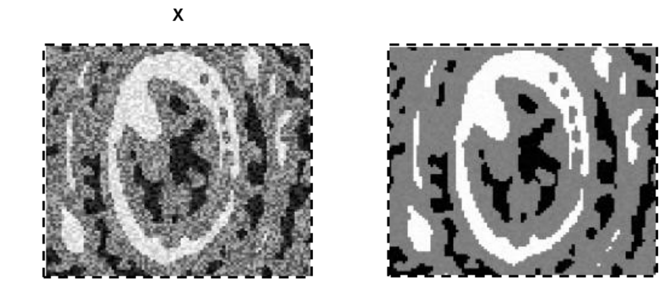


- 4-state logic propagation along nanomagnet "wire"
- Synchronous "straintronic clocking" on nanomagnet pairs along the array
- Magnet 2: T→R→C→R
- Magnet 3: C→C→T→T

SIMULATION: 4-STATE IMAGE RECONSTRUCTION

- The 4 stable magnetization states of the magnet encode black, gray, white and gray.
- Noise can corrupt the image by perturbing the magnetization vector and deflecting it away from the initial stable state.
- Magnetization dynamics studied by solving the LLG equation to determine the final state of every pixel of the image.
- 512 × 512 black-white-gray image, when perturbed, is recovered in ~2 ns

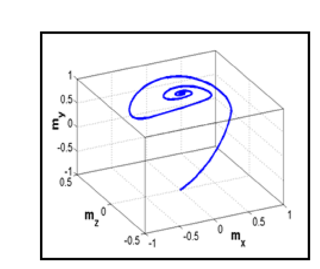




t = 0 ns

t = 1 ns

t = 2 ns



$$E_{total}(t) = E_{magnetocrystalline-anisotropy}(t) + E_{shape-anisotropy}(t)$$

$$\frac{d\mathbf{n_m}(t)}{dt} - \alpha\left(\mathbf{n_m}(t)\times\frac{d\mathbf{n_m}(t)}{dt}\right) = \frac{-\gamma}{M_s\Omega}\mathbf{T_E}(t)$$

$$\mathbf{T_E}(t) = -\mathbf{n_m}\times\nabla E_{total}\left(\theta(t), f(t)\right)$$

N.D'Souza, J.Atulasimha & S.Bandyopadhyay, 2011, Appl. Phys. Lett. (Under Review)

ACKNOWLEDGEMENTS

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