Center for Spintronic Materials, Interfaces, and Novel Architectures

Emerging spintronics-based logic technologies

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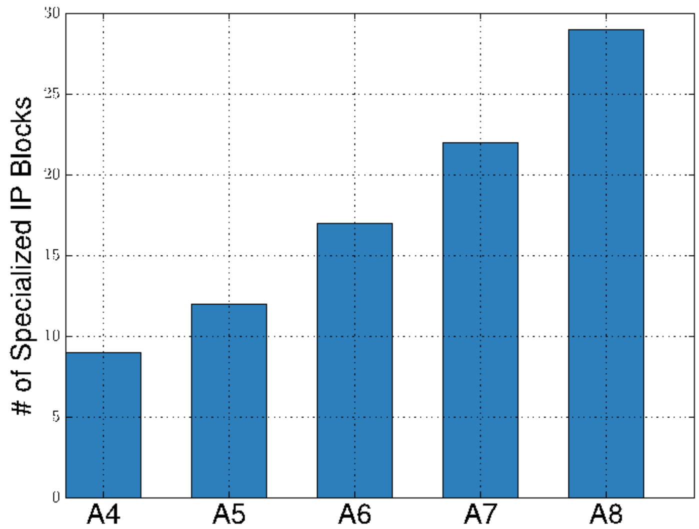
C-SPIN

Workshop on the Future of Spintronics (June 5, 2016)

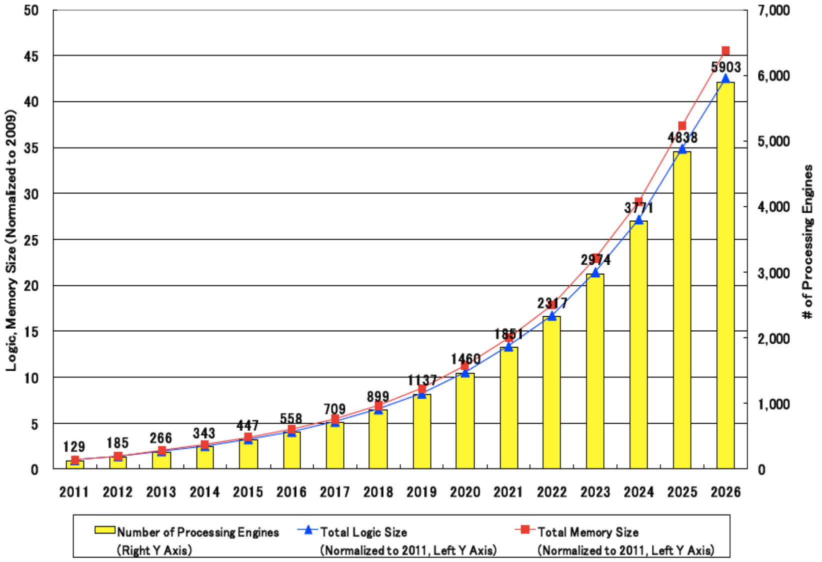
STARnet

On-chip heterogeneity

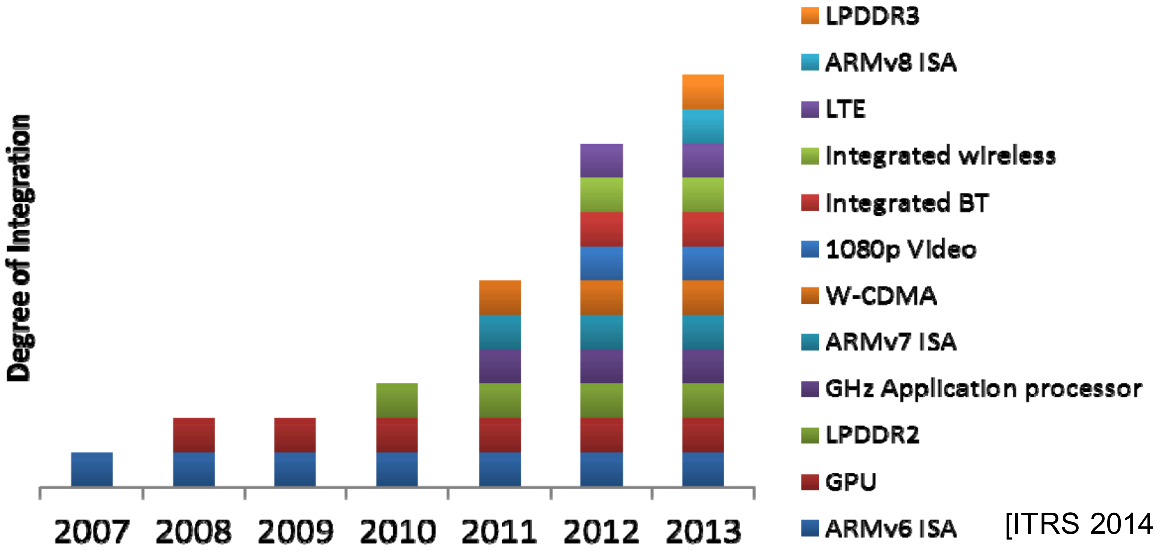
Apple



[http://vlsiarch.eecs.harvard.edu/accelerators/die-photo-analysis]



Snapdragon

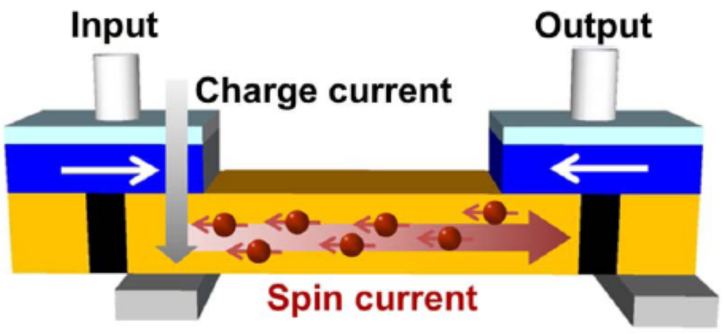


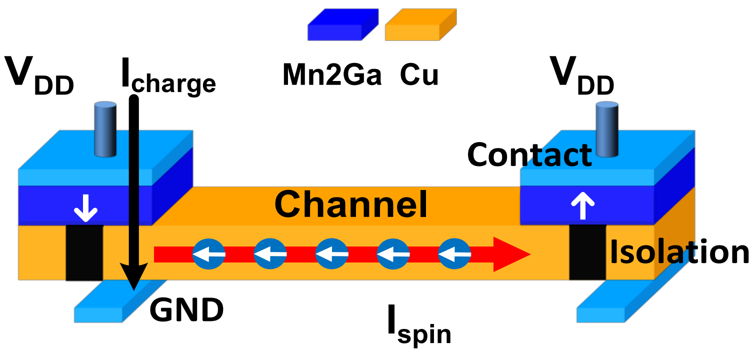
[ITRS 2014 whitepaper]

Outline

- Contenders: spintronic logic
- Requirements for spin-based logic
- A new device concept

Background: ASL and HEAL



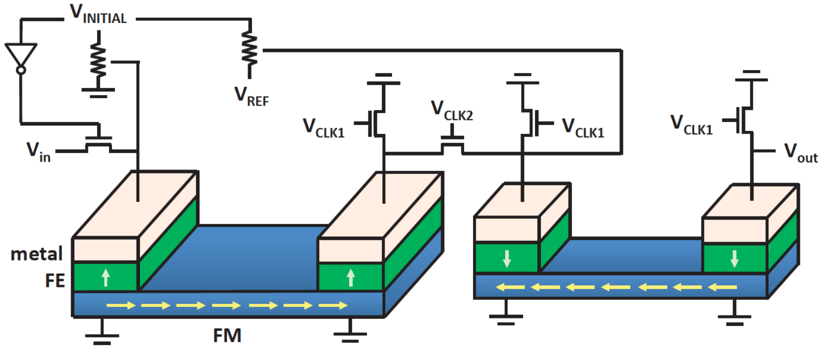


- Input magnet injects spin into channel
- Channel transfers spin to output end
- Output magnet receives spin and stores state

- Heusler-based ASL (HEAL)
  - Heusler alloys: high spin polarization (0.7~1.0), high perpendicular magnetic anisotropy (H_k>10000 Oe), high spin injection efficiency, no tunnel barrier
- Other variations based on Spin-Hall effect

Background: Magnetoelectric (ME) devices

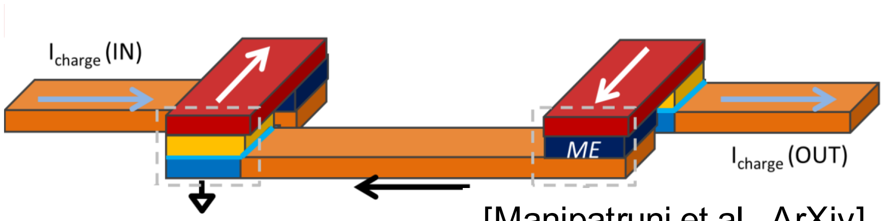
- ME-based device



[Chang et al., JxCDC16]

  - ME effect used to switch input
  - Signal propagation and majority evaluation using domain wall automotion
  - Inverse ME effect used to switch output

- MESO
  - Charge-mediated device



[Manipatruni et al., ArXiv]

  - Charge used to switch input magnet using the ME effect
  - Spin-orbit coupling (Spin-Hall effect, inverse Rashba-Edelstein effect) creates output charge current

Goals for spin-based logic devices

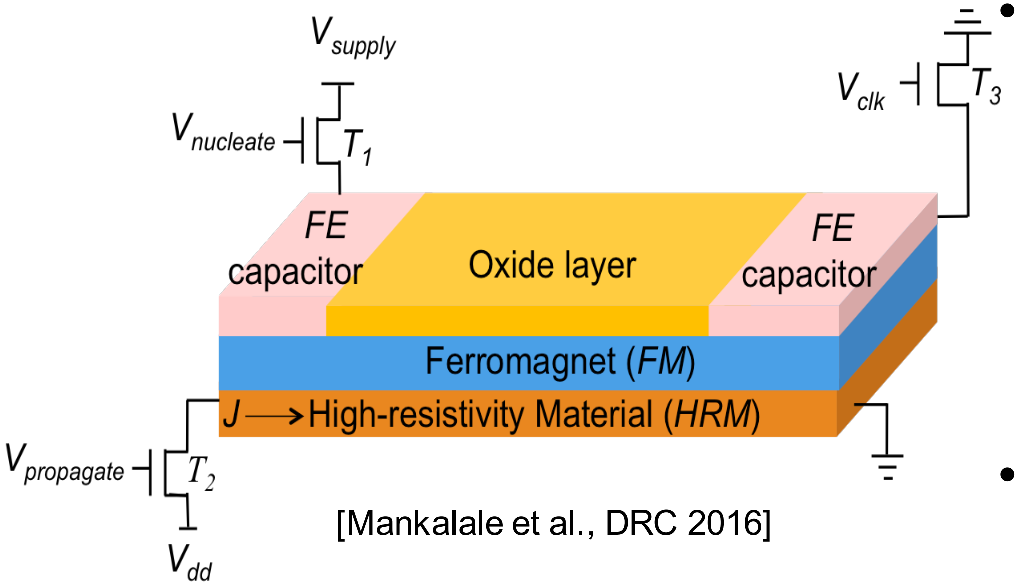
- High speed

  ~100ps switching time

- Low energy

  ~100aJ energy

ME + current-driven domain walls



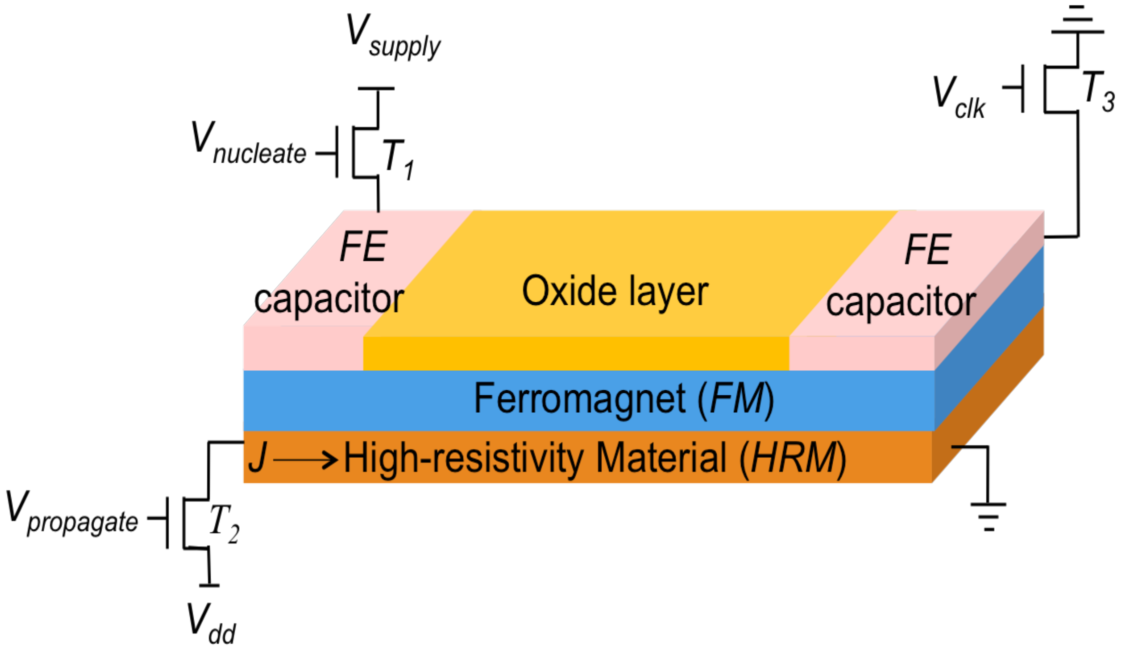
[Mankalale et al., DRC 2016]

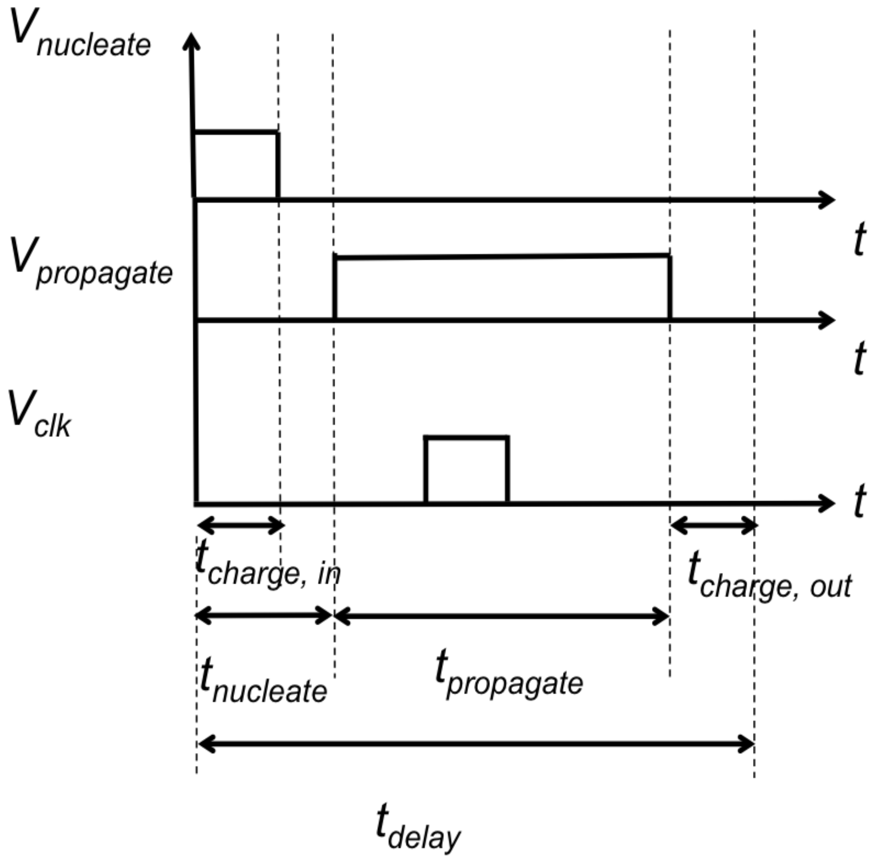
Goal: ~100ps delay, < 100aJ energy

- Domain wall speed bottleneck
  - ME-based device using automotion proposed in [1]
  - Experimentally, automotion ~70m/s [2]
  - Expend energy, fast propagation
- Design-space exploration of material parameters
  - Existing/exploratory material
  - We propose **CoMET**: **Co**mposite-input **M**agneto-**E**lectric **T**echnology with domain wall propagation using spin orbit torque

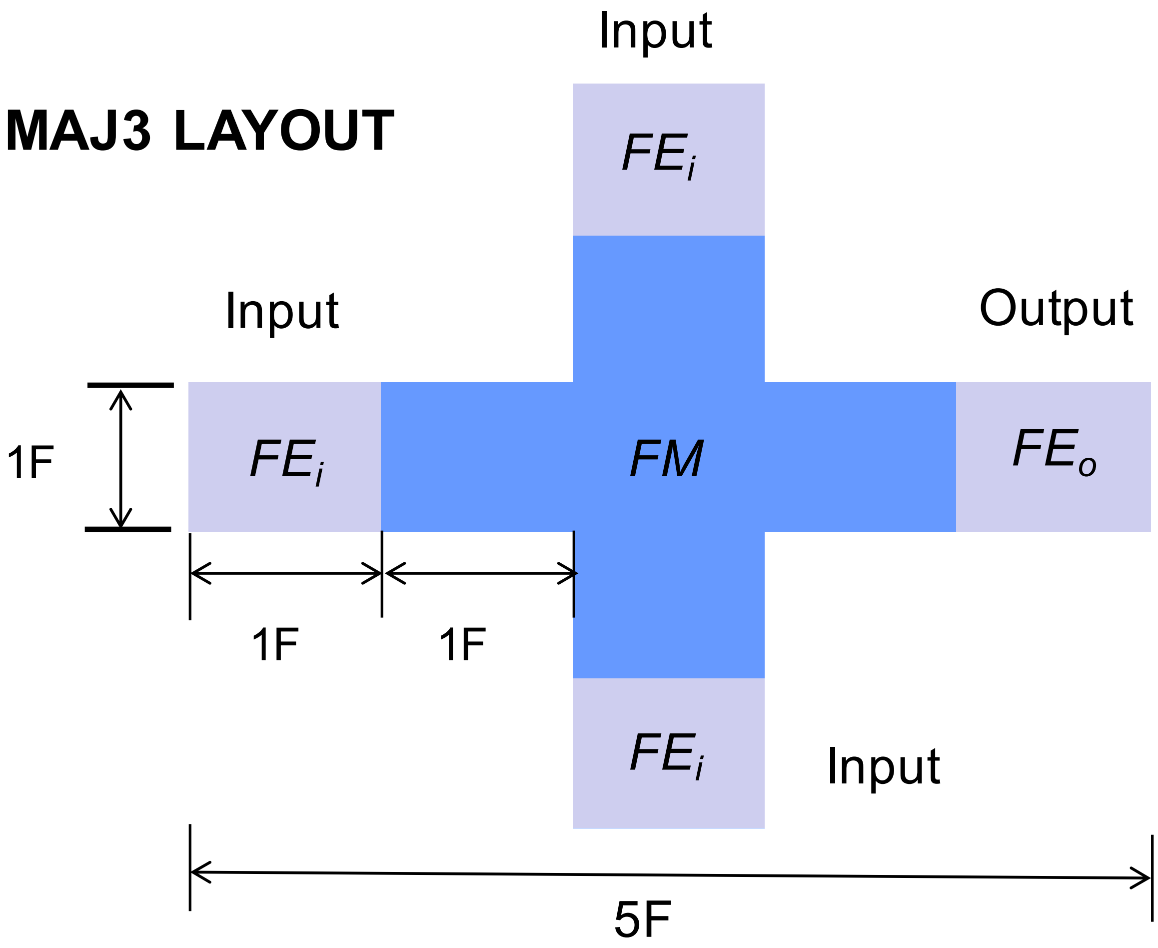
[1] S-. C. Chang et al., IEEE JxCDC, 2016 [2] J. Chauleau et al., PRB, 2010.

ME Logic with Current–driven DW Motion





Device Dimensions



Dimension	(l x w x h)
FE	1F x 1F x 1 nm
FM/HRM	5F x 1F x 1 nm
Oxide	3F x 1F x 1 nm

Technology nodes considered: 1F = 5nm, 7nm,10nm

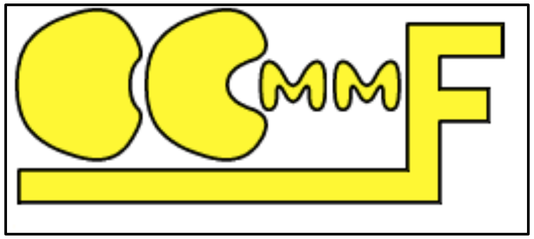
Domain Wall Nucleation

V_{supply}

↓

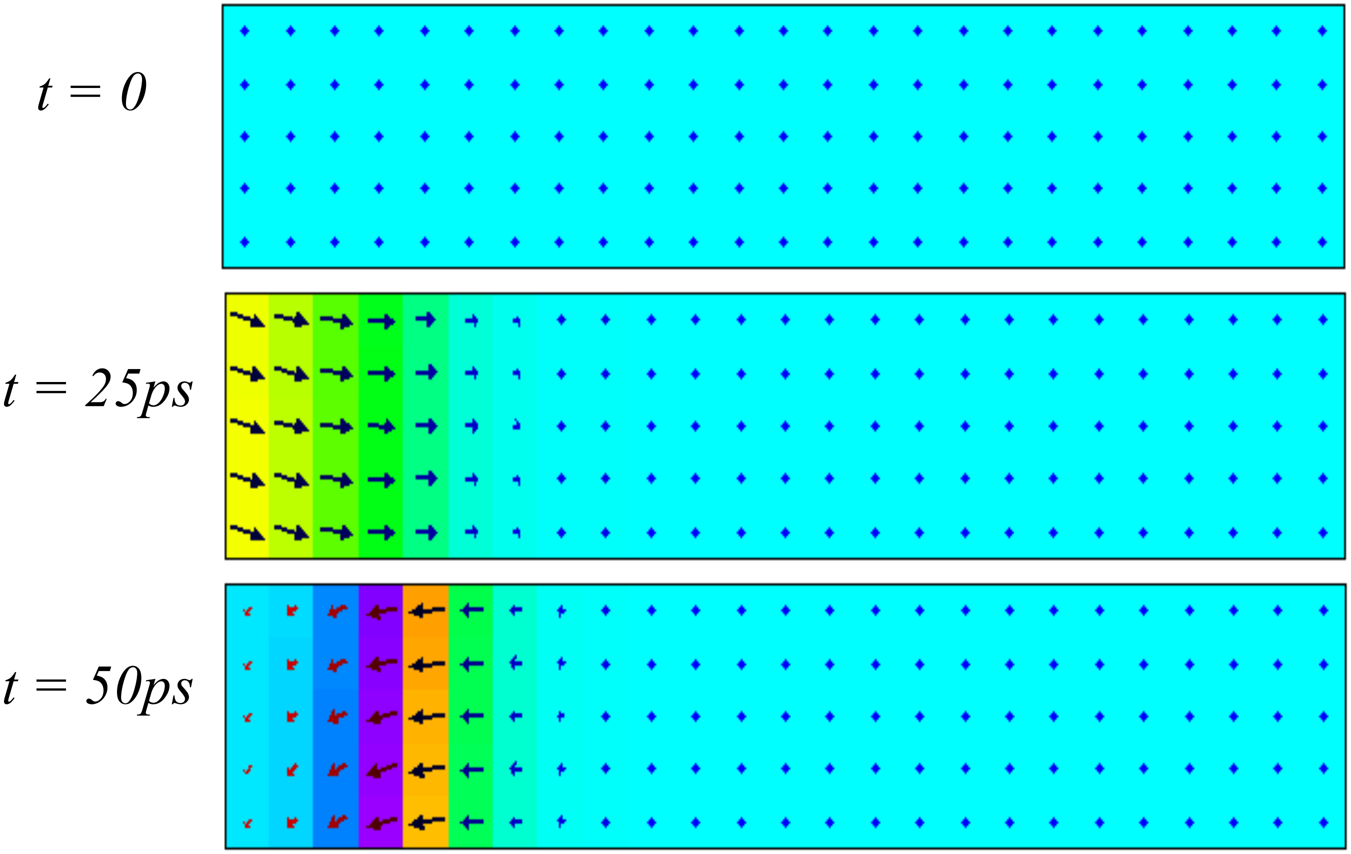
Effective magnetic field from ME coupling, H_{ME}

↓ Zeeman field



↓

Obtain $t_{nucleate}$



DW nucleation in *FM*

Current-driven Domain Wall Propagation

$$1+\alpha^2\,\frac{dV}{dt} = -\gamma\Delta\,\frac{H_K}{2}\sin(2\phi) + (1+\alpha^2\beta)\,B_{STT} + \gamma\Delta\frac{\pi}{2}\,[\alpha H_{SHE} + H_{DMI}\sin(\phi)]$$

$$1+\alpha^2\,\frac{d\phi}{dt} = -\gamma\alpha\frac{H_K}{2}\sin(2\phi) + \frac{(\beta-\alpha)}{\Delta}B_{STT} + \gamma\frac{\pi}{2}[\,H_{SHE}\cos(\phi) + \alpha H_{DMI}\sin(\phi)]$$

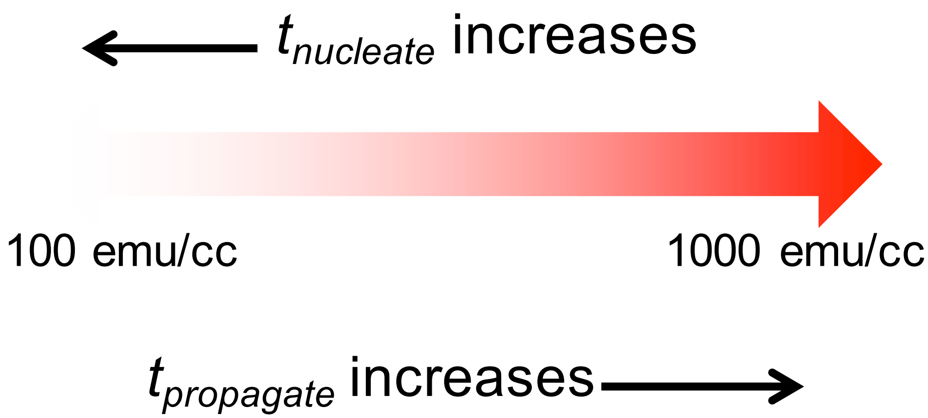
where $H_{SHE} = \frac{\hbar\,\theta_{SHE}J}{2\mu_0 e M_s\,h_{FM}}$, $H_{DMI} = \frac{D}{\mu_0 M_s\Delta}$, $B_{STT} = \frac{\mu_B P_{FM} J}{e M_s}$, $\Delta = \frac{\sqrt{A/K_u}}{\sqrt{1+\frac{\mu_0 M_s^2}{K_u}\left[\frac{h_{FM}}{h_{FM}+\Delta} - \frac{h_{FM}}{h_{FM}+w_{FM}}\right] sin^2(\phi)}}$

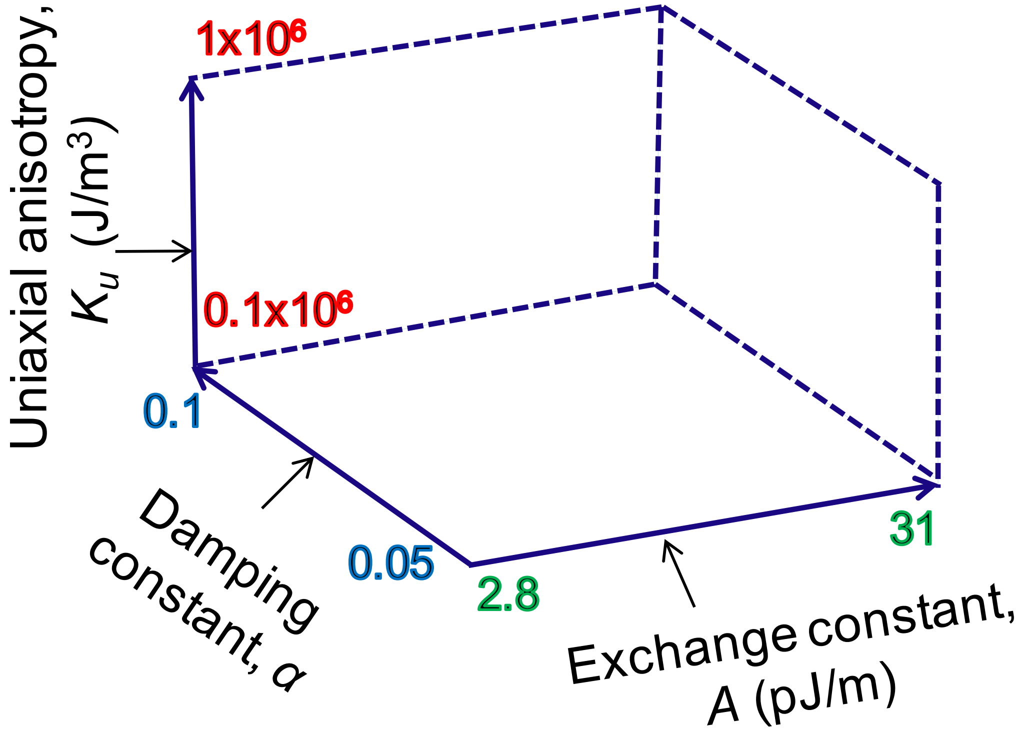
- Impact of scaled geometries considered for calculation of *V*, velocity of DW and *Φ*, phase of the DW.
- Current density, $J = 9 \times 10^{10}$ A/m^2 (below electromigration limit).
- Walker breakdown field also accounted for.

Design Space Exploration

- Design space large – Focus only on *FM* material parameters
- Range of parameters chosen to cover both existing and exploratory materials

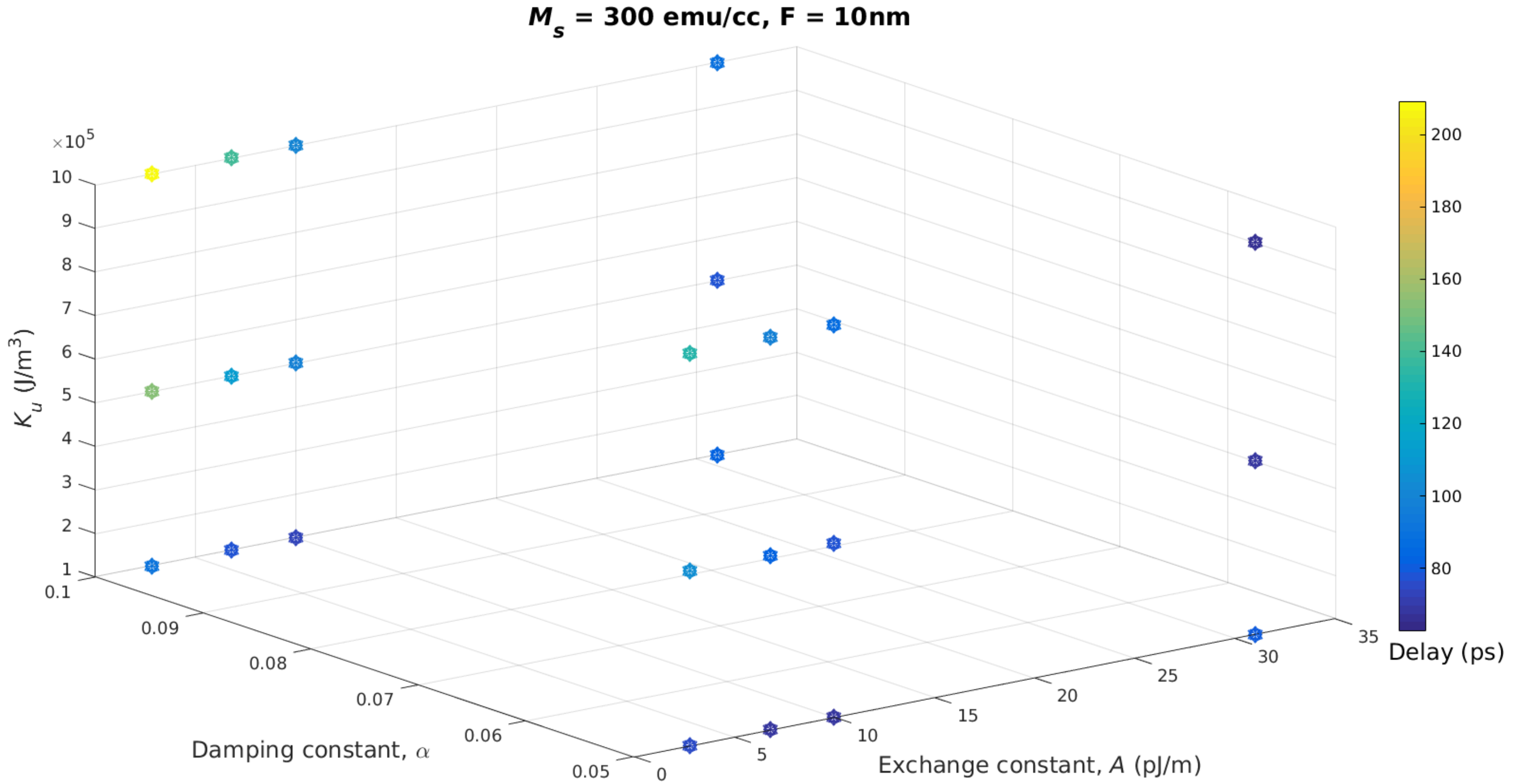
Saturation Magnetization,
M_s (emu/cc)



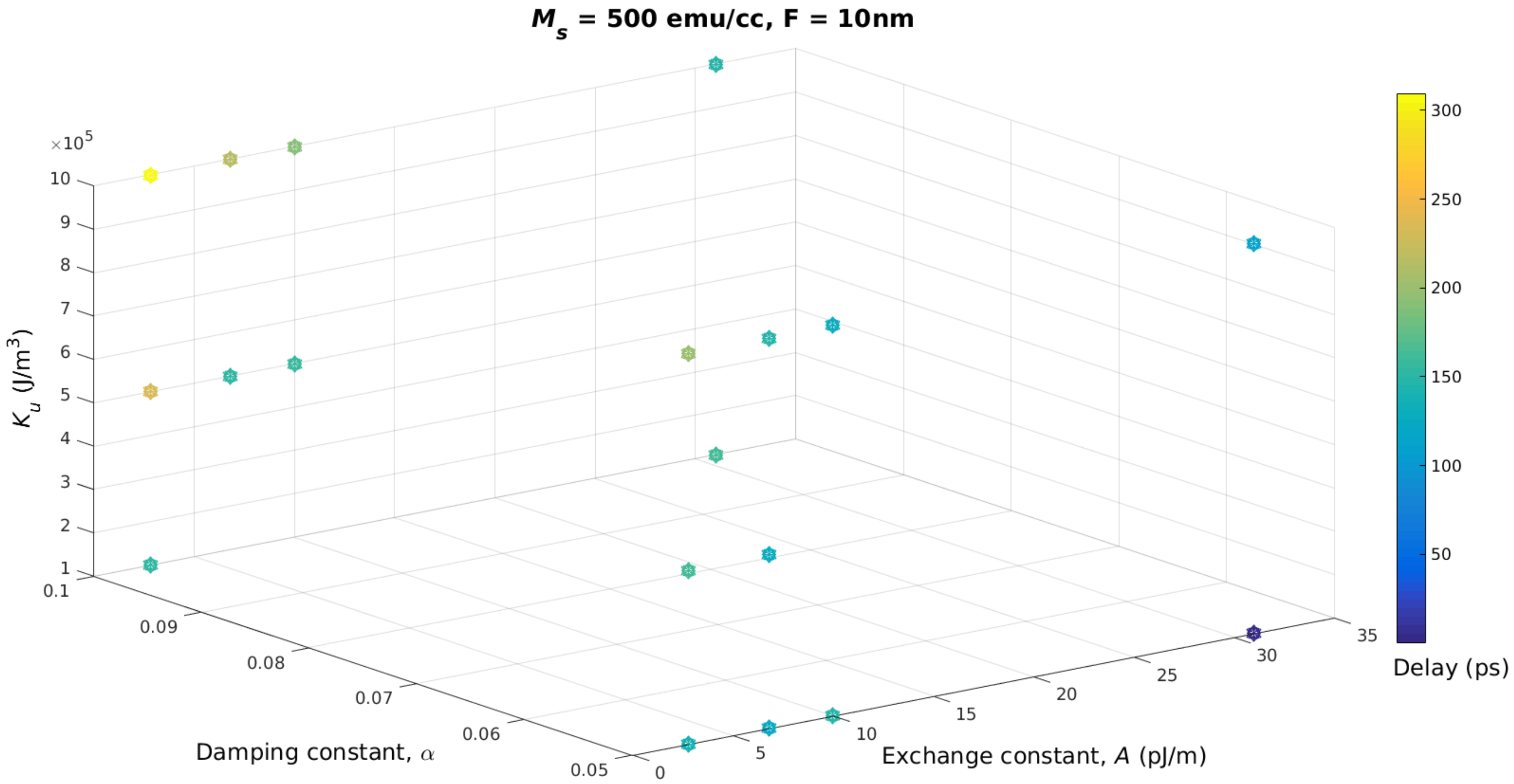


Balance $t_{nucleate}$ vs. $t_{propagate}$

Design Space Exploration - DW Propagation



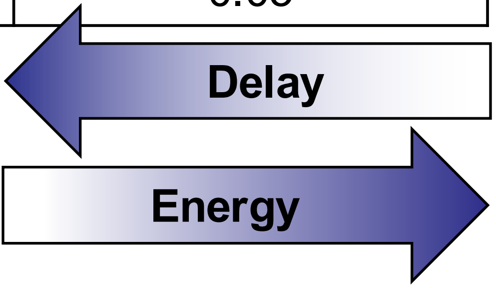
Design Space Exploration - DW Propagation



Results

Set / Parameters	**Set 1**	**Set 2**	**Set 3**
Exchange constant , A (pJ/m)	**10**	**2.8**	**6.8**
Saturation Magnetization, M_s (emu/cc)	**500**	**300**	**300**
Supply voltage, V_{supply} (V)	**0.93**	**1.50**	**2.12**
Spin Polarization	**0.5**		
Spin Hall Angle	**0.5**		
Uniaxial anisotropy, K_u (J/m^3)	**10^6**		
Damping constant, α	0.05		

Energy-delay tradeoff between parameter sets.



t_{delay}

Technology node (1F)	Set 1 (ps)	Set 2 (ps)	Set 3 (ps)
5nm	128	125	117
7nm	156	149	124
10nm	198	184	155

DW Velocity (m/s)	362	420	540

Energy

Technology node (1F)	Set 1 (aJ)	Set 2 (aJ)	Set 3 (aJ)
5nm	67.4	130.6	212.0
7nm	108.6	209.0	417.6
10nm	173.4	375.6	701.0

Mapping to Materials

Set / Parameters	Set 1	Set 2	Set 3
Exchange constant , *A* (pJ/m)	10	2.8	6.8
Saturation Magnetization, M_s (emu/cc)	500	300	300
Spin Polarization	0.5		
Uniaxial anisotropy, K_u (J/m^3)	10^6		
Damping constant, α	0.05		

FM

Mn-Ga based Heusler alloy

FE Capacitor BFO

HRM β-Ta, Pt, β-W

Sneak Peek of CoMET

(currently being validated)

- Based on the use of a composite input structure
  - Similar speeds
  - Much lower Vdd
    - 0.93 – 2.12V → < 0.3V
    - Energy ~60aJ

Supply voltage (V)	Set 1	Set 2	Set 3
5nm	0.75	0.27	0.58
7nm	0.58	0.14	0.27
10nm	0.27	0.14	0.14

t_{delay}

Technology node (1F)	Set 1 (ps)	Set 2 (ps)	Set 3 (ps)
5nm	137	123	105
7nm	175	156	131
10nm	233	206	170

DW Velocity (m/s)	362	420	540

Energy

Technology node (1F)	Set 1 (aJ)	Set 2 (aJ)	Set 3 (aJ)
5nm	106.2	56.4	83.2
7nm	110.6	52.6	62.4
10nm	78.6	57.0	57.0

Summary

- New device for logic applications: ~100ps, ~100aJ per device
- Currently being extended to build larger circuits
- Possible applications
  - Logic circuits
  - In-/Near-memory processing structures
  - IoT elements

- Acknowledgments
  - Angeline Smith, Mahendra DC, Mahdi Jamali