TANMS

Magnetics + Mechanics + Nanoscale = Electromagnetic Future

11-537

Greg P. Carman & OTHERS!!!

Funding : AFOSR, DARPA, NSF ERC Award EEC-1160504

- **IEEE Magnetics Society Home Page:** ***www.ieeemagnetics.org***
  - 3000 full members
  - 300 student members

- **The Society**
  - Conference organization (INTERMAG, MMM, TMRC, etc.)
  - Student support for conferences
  - Large conference discounts for members
  - Graduate Student Summer Schools
  - Local chapter activities
  - Distinguished lectures

- **Journals (Free Electronic Access for Mambers)**
  - *IEEE Transactions on Magnetics*
  - *IEEE Magnetics Letters*

- **Online applications for IEEE membership:** ***www.ieee.org/join***
  - 360,000 members
  - IEEE student membership IEEE full membership

GOAL

- Convince you to work in Nanoscale Multiferroics

Why

- Future for small scale magnetic devices (1mm > device > 1nm)

Philosophy

- Innovators (W. Isaacson) – Computers – Critical Mass

Presentation

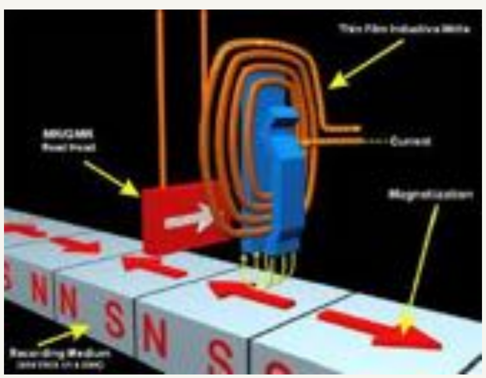
- Motivate NOT impress

Outline

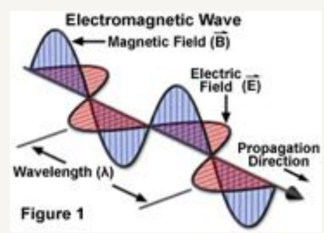
- Motivation – Multiferroic
- Nano-Ellipses (Efficiency/memory)
- Nano-Rings (substrate clamping/motor)
- Superparamagentic Control (cool stuff)
- Summary

<u>EM devices are ubiquitous throughout our society</u>

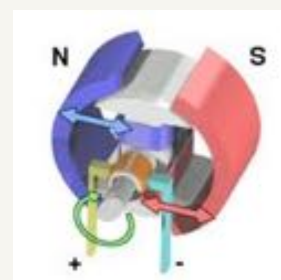
Memory



Antenna



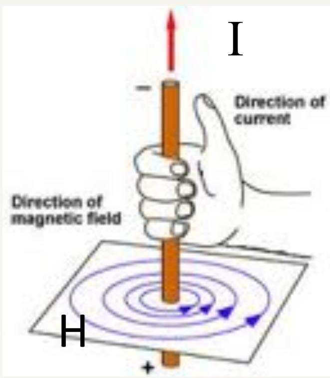
EM Motor



Why Electrical Control of Magnetism

- 1820 Oersted, H Field generated by current
  - ***Problem*** - Current/Magnetic field magnitude in the small scale

EM Devices

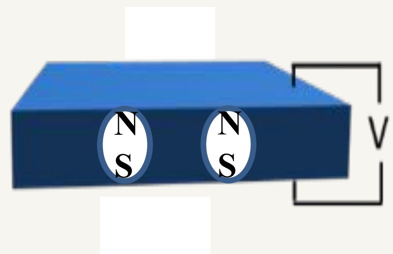


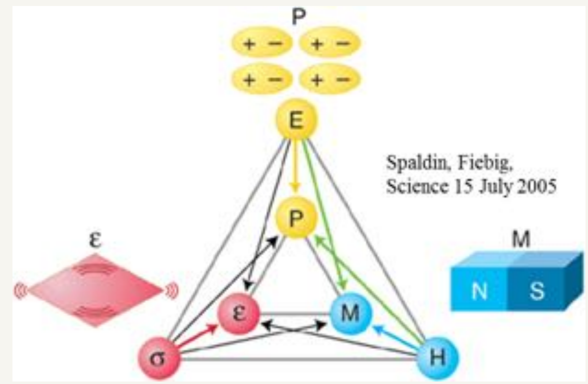
Magnetic field H limited by current I

H → 1 kOe today

Multiferroic Illustration

Intrinsic Effect





Electric field E Scales with size

TANMS

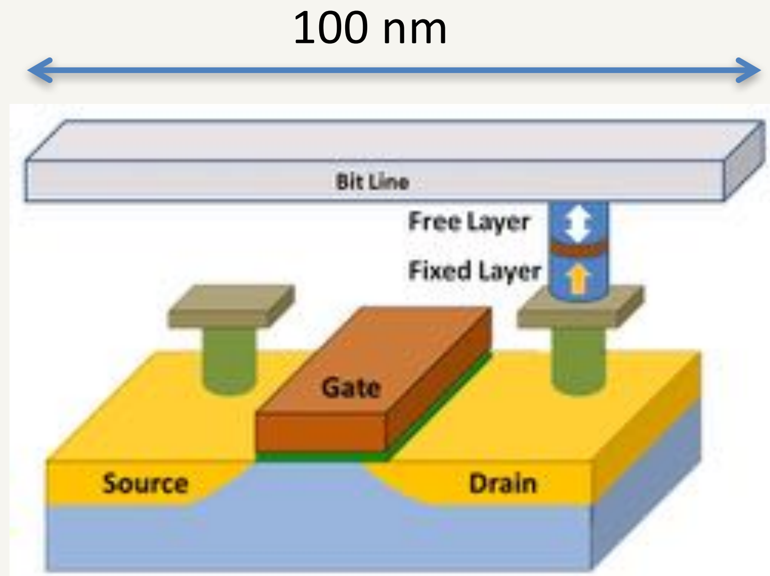
Efficiencies

Internal Combustion Engine

Chemical- Mechanical

η = 20 % Efficient

STT – MRAM State of the Art



Electrical – Magnetic

100 fJ to write

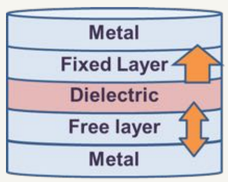
~0.3 aJ barrier

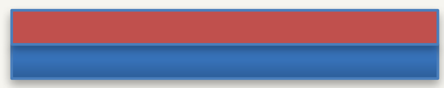
η = 0.0003 % Efficient

Types of Multiferroics

- Single phase – Homogeneous material with only one phase most popular is BiFeO(3) –(note antiferromagnetic and ferroelectric)
- Composite – Heterogeneous material system

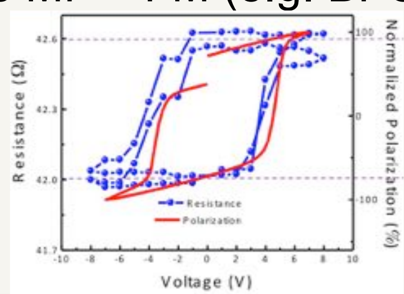
  – Charge mediated systems- VCMA – test data- ***5 fJ***





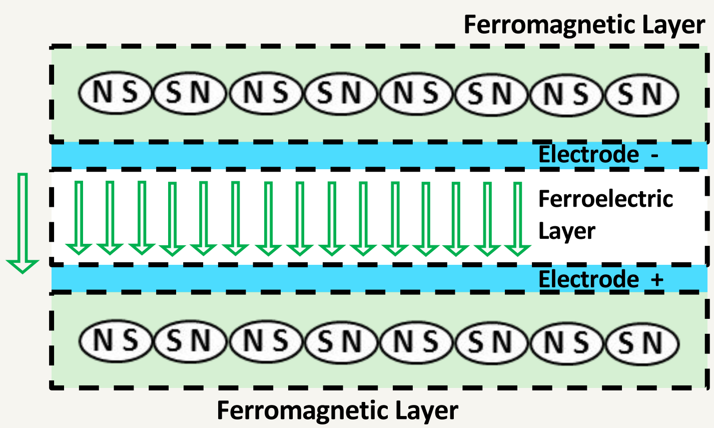
~10nm

  – Exchange coupled– single phase MF + FM (e.g. BFO + CoFe) ~***1fJ***



  – Strain Mediated systems – Piezoelectric layer (i.e. ferroelectric) + magnetoelastic/magnetostrictive (i.e. ferromagnetic).

Solution Strain Mediated Multiferroics



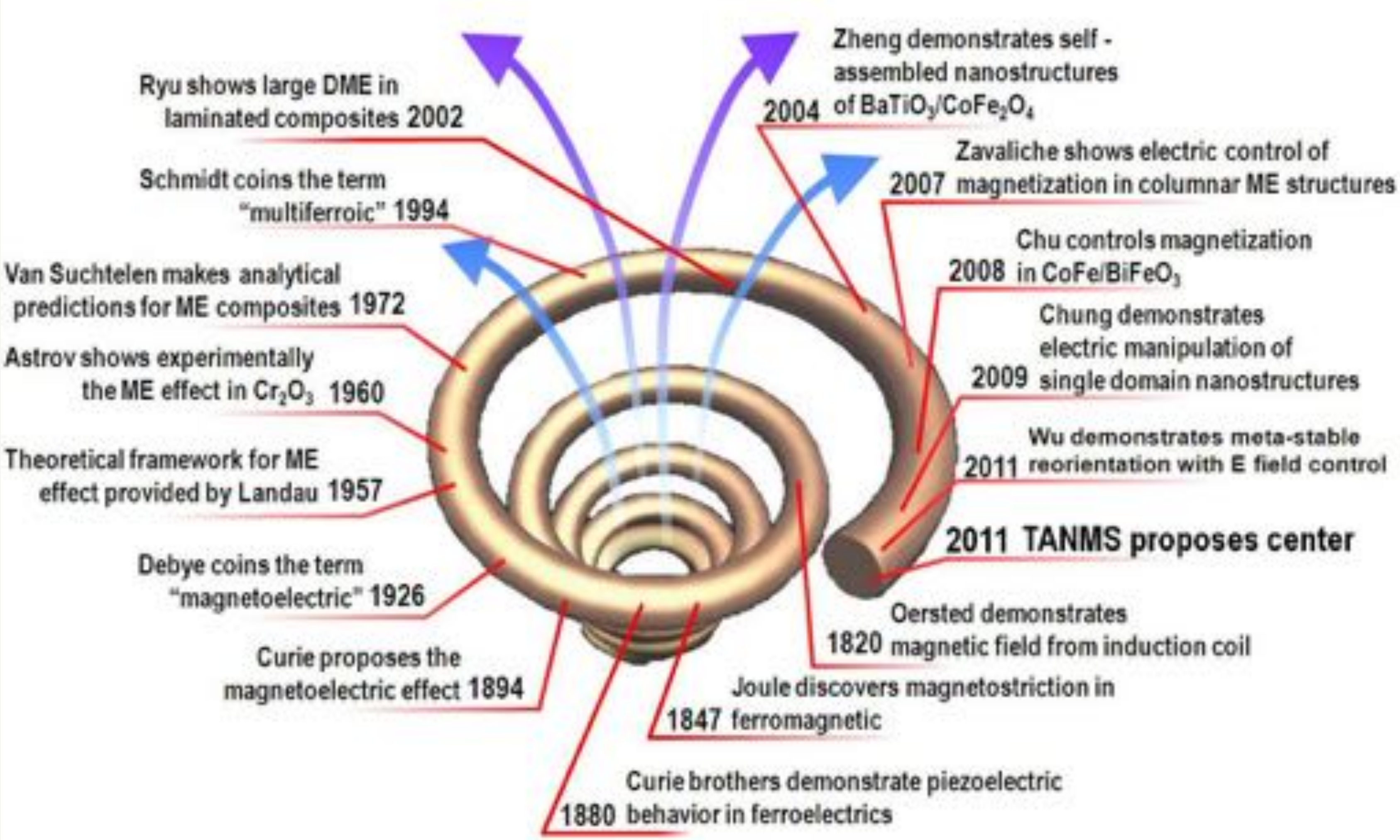
Magnetostrictive/Magnetoelastic/Ferromagnetic

Piezoelectric/Ferroelectric

Existing Piezo (0.8) + Magnetoelastic (0.8)
= 0.3aJ/(.8*.8) ~1 aJ
or **η=60% efficient**

- **Problems Nanoscale**
  1. Models ~unavailable
  2. Experimental demonstration challenging
  3. Substrate clamping problem
  4. Why do this? Applications?

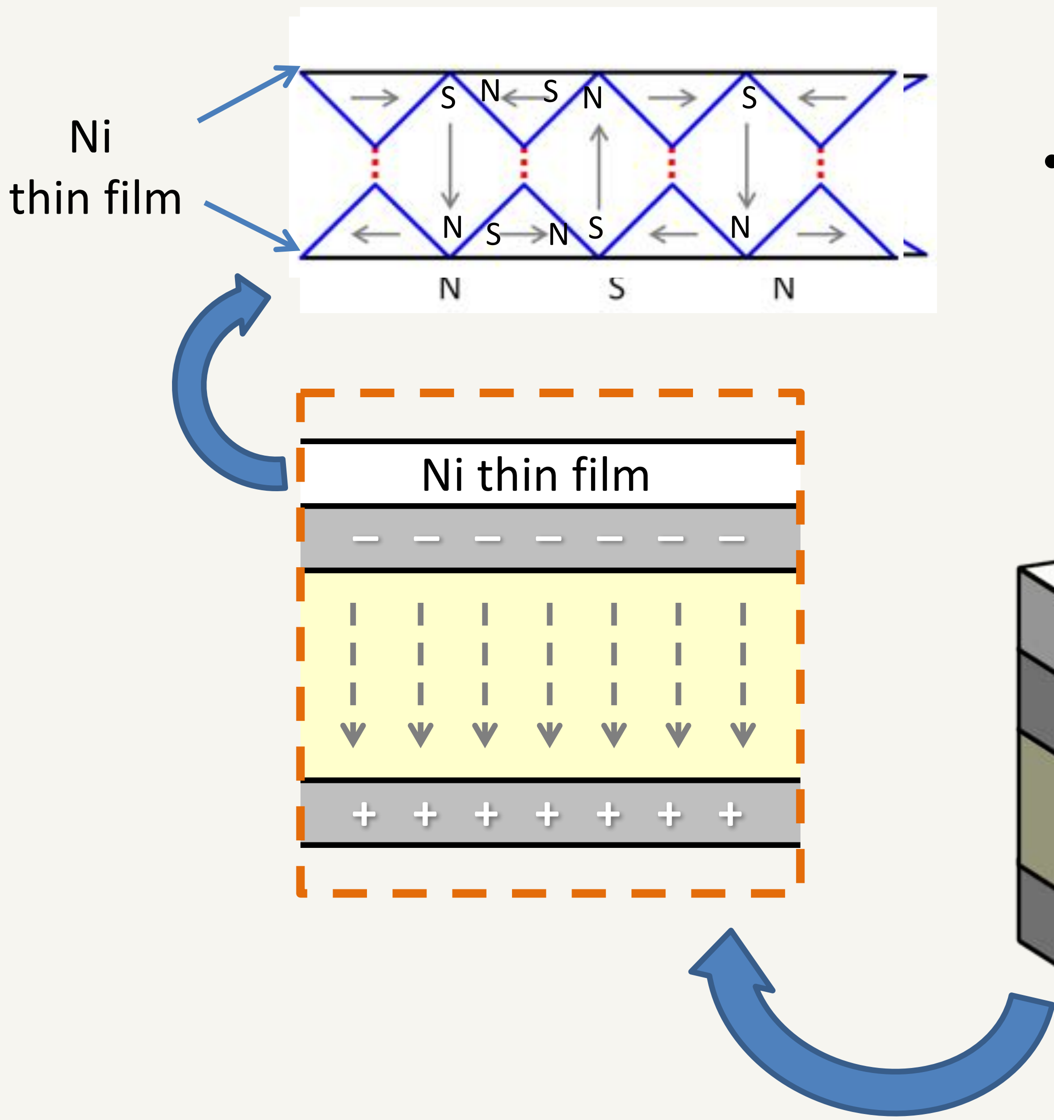
What has been done?

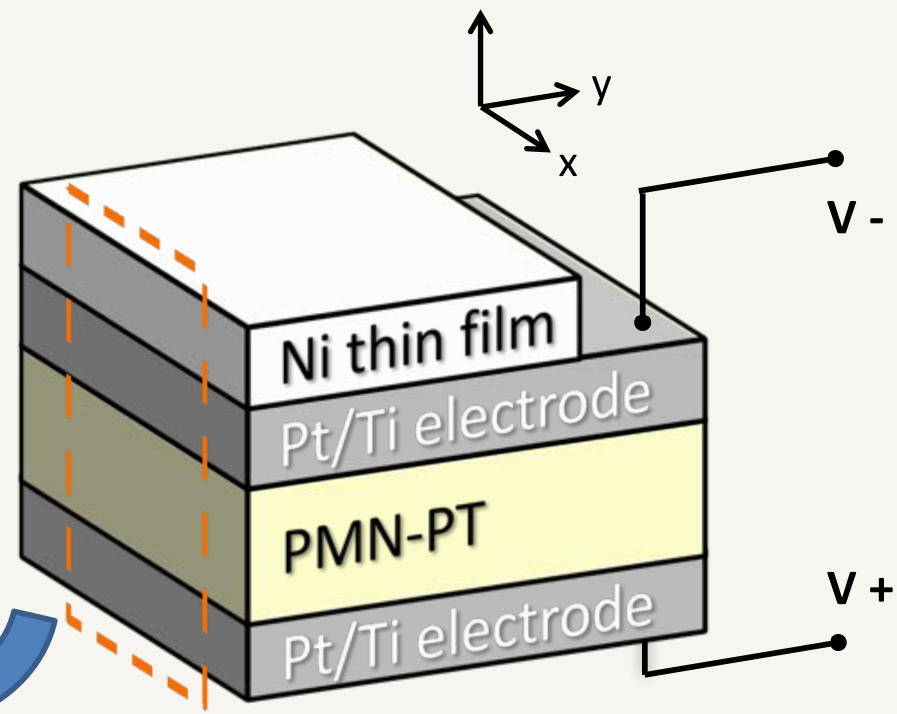


• Bulk multiferroic (DME)	>1000 papers
• Thin Film (CME)	~ 100 papers
• Single domain & smaller	~ 10 papers

Thin Film Multiferroics

- Single crystal piezoelectric PMN-PT
  - Smooth surface
  - Good strain properties/anisotropic
- Ni 30-100nm thin film
  - Magnetoelastic properties good
  - Easy to deposit



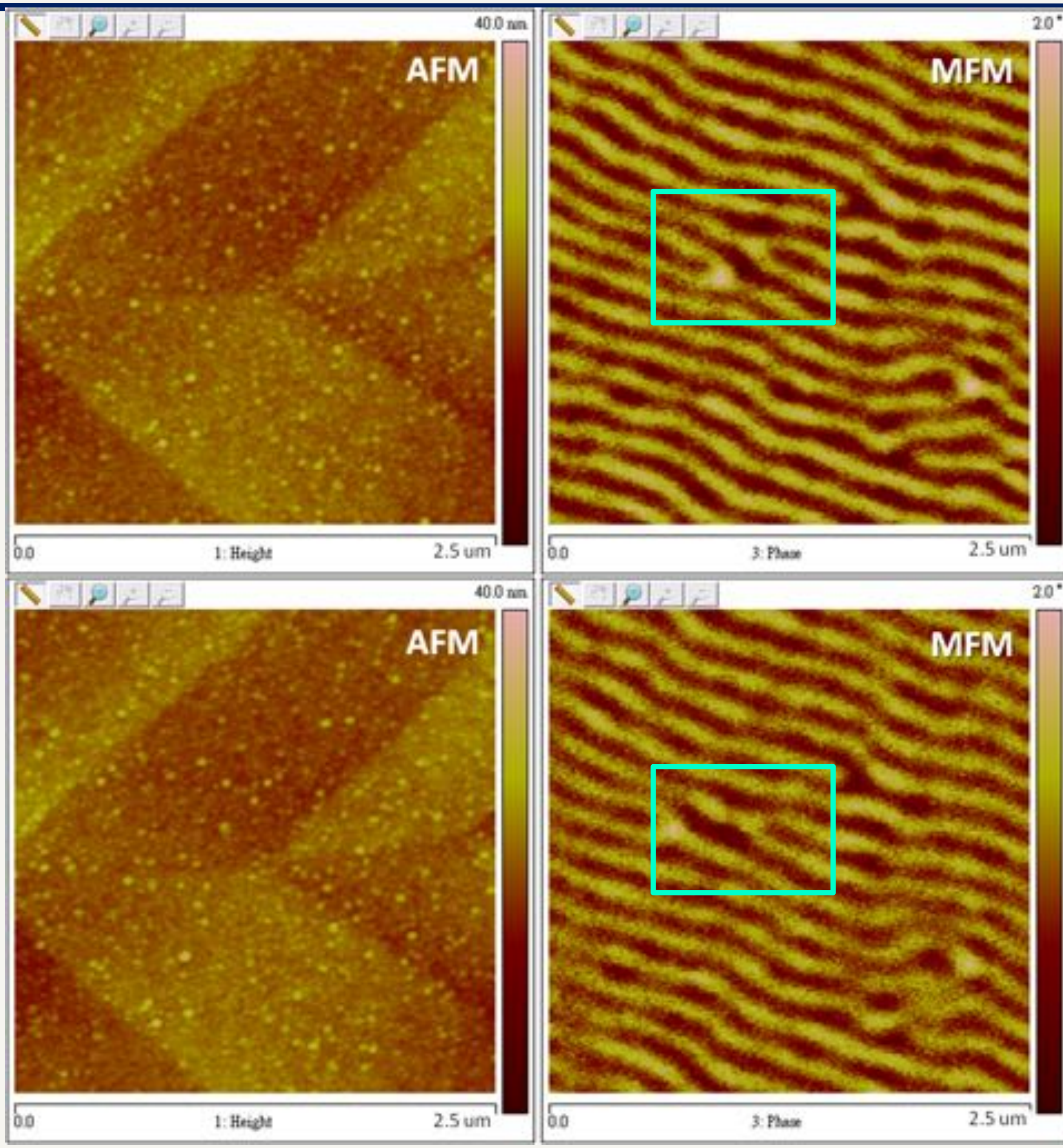


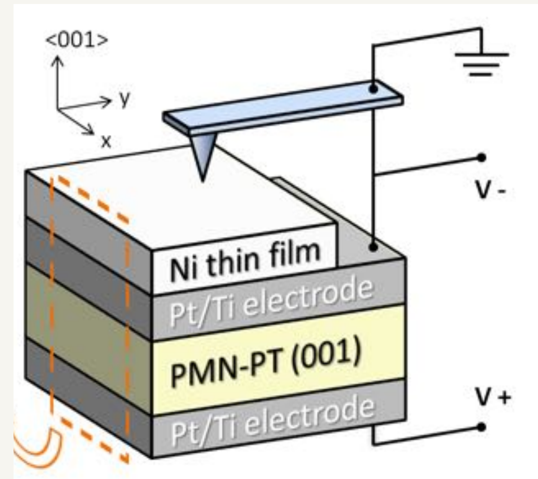
Hsu, Hockel, Carman, Appl. Phys. Lett. V **100**, Issue 9 (2012)

MFM Imaging100 nm Ni Film

(0 MV/m)

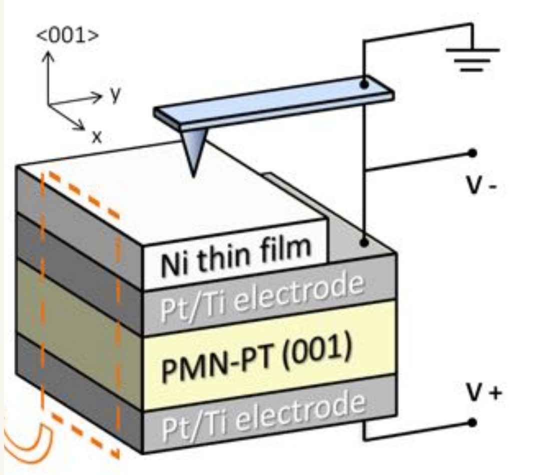
0.8 MV/m

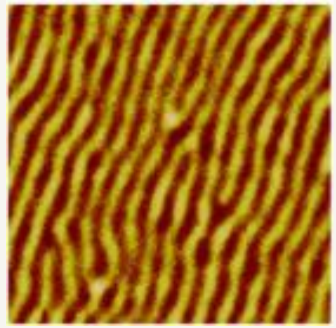




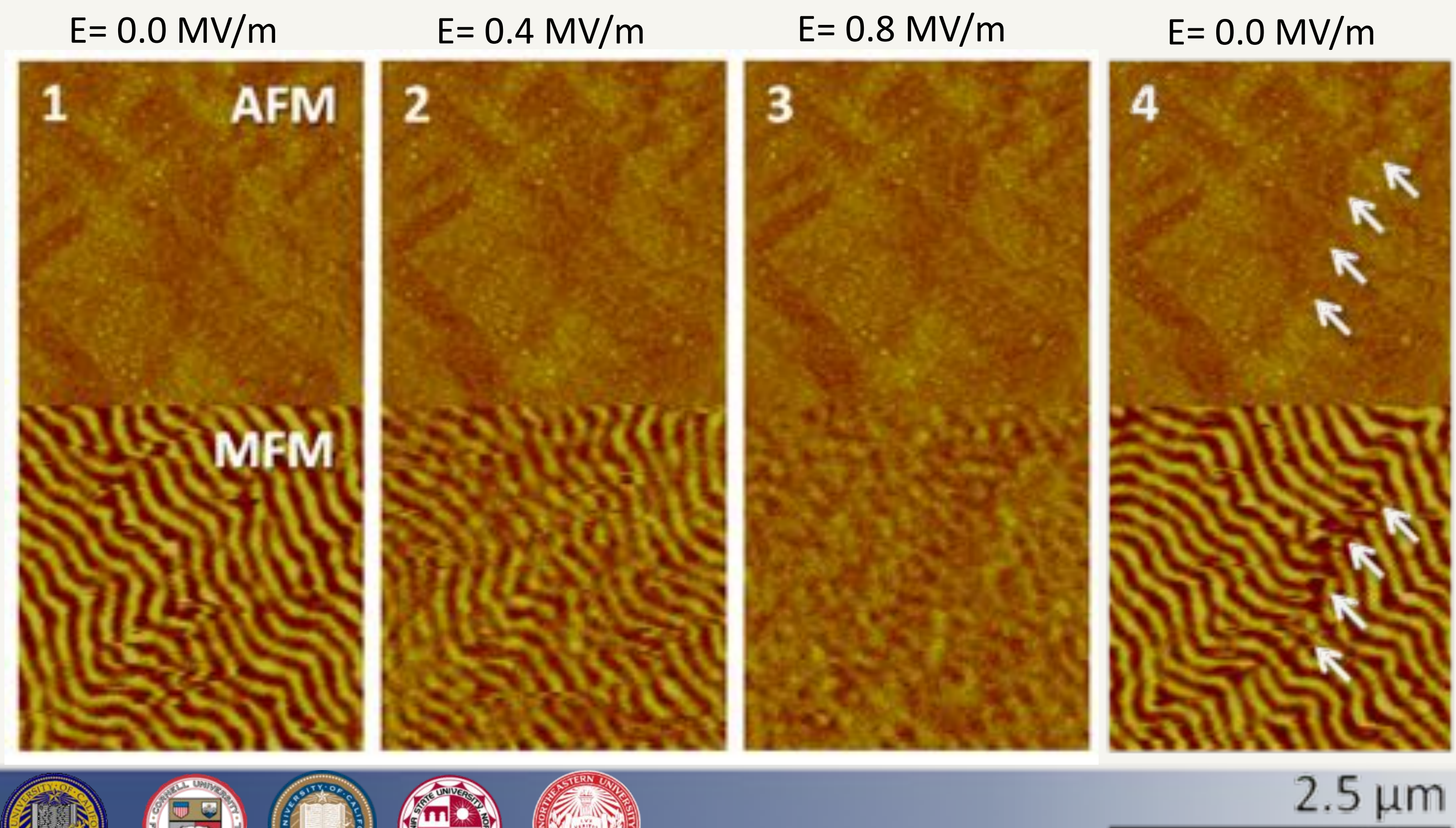
- MFM revealed little change
- Bulk response does change but dependent upon local phenomenon

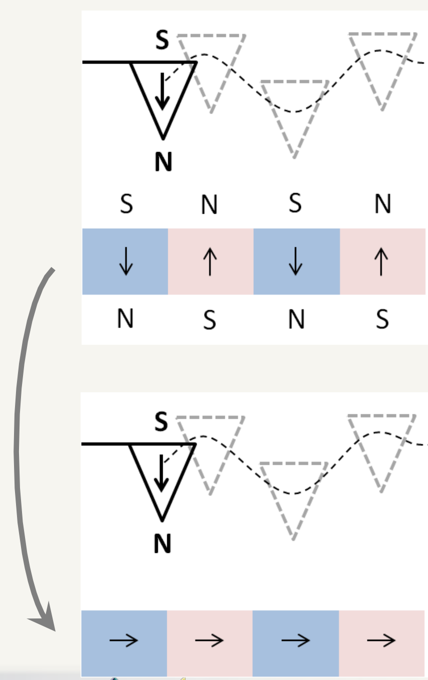
MFM Imaging 60 nm Ni Film





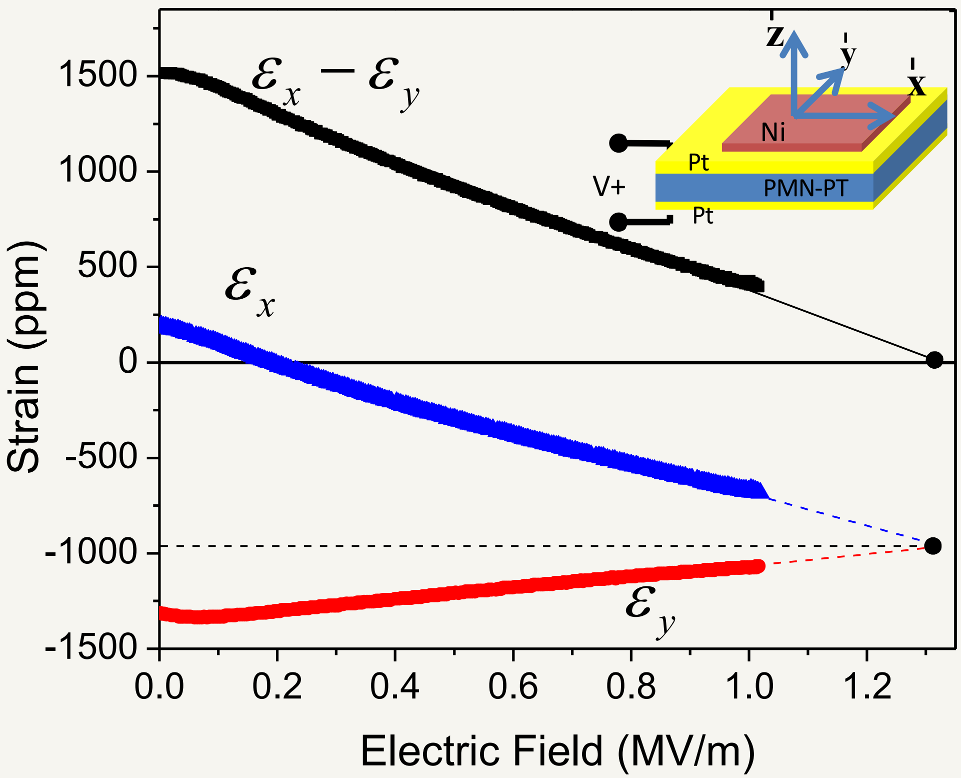
- Thin film (60nm) stripe domains
- Electrical induced transition from Block Wall to Neel wall
- Process is reversible or nonvolatile depending upon PMN-PT and E





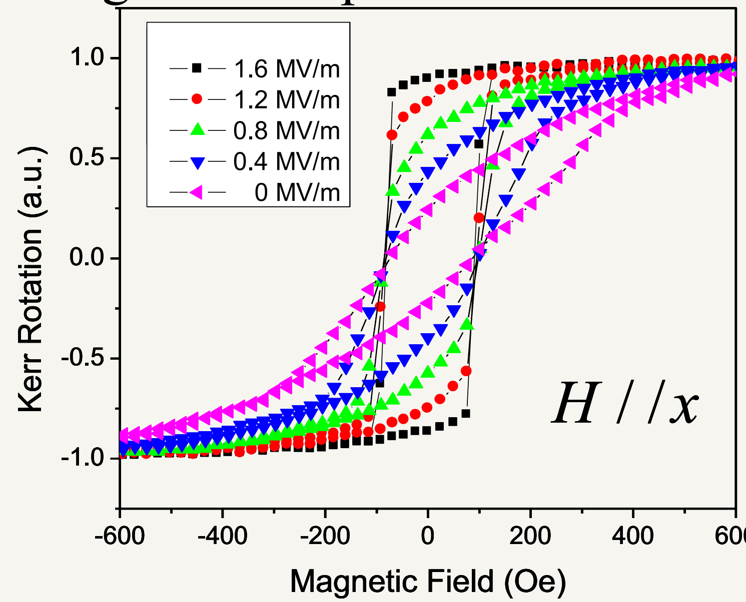
Voltage Control 35nm Ni Film

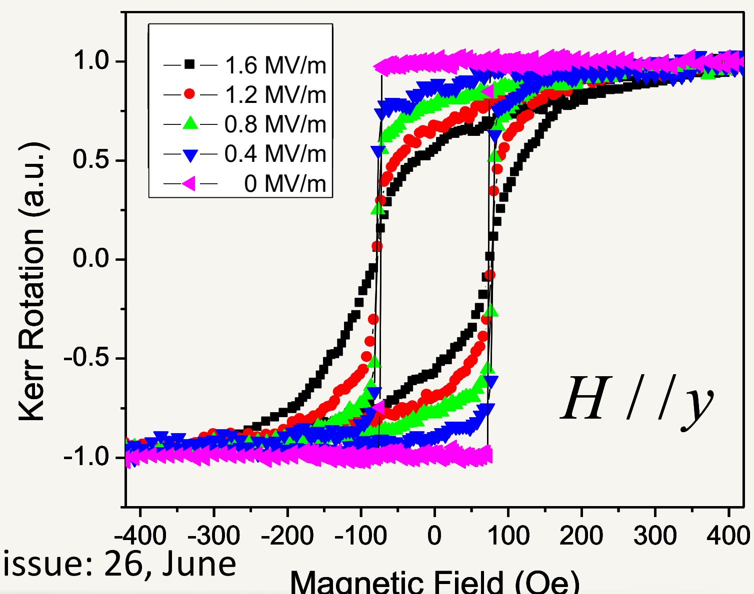
Strain Voltage Response (011) PMN-PT



- Piezoelectric anisotropic
- Voltage induces magnetic reorientation of sample

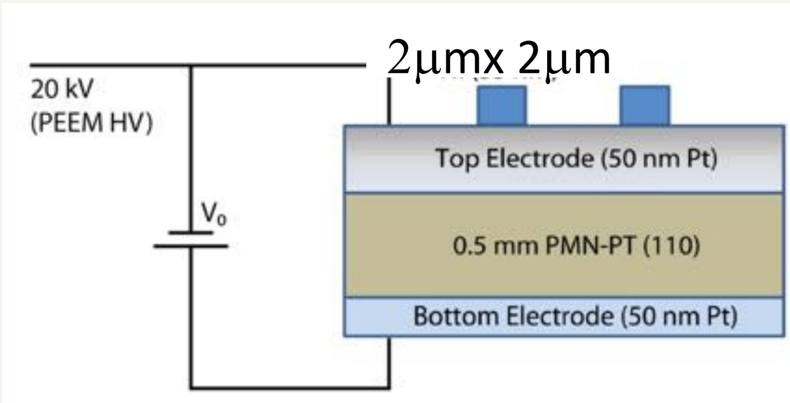
Magnetic Response of Ni Thin Film





Wu, Bur, Wong… Carman, Applied physics letters (2011) volume: 98 issue: 26, June

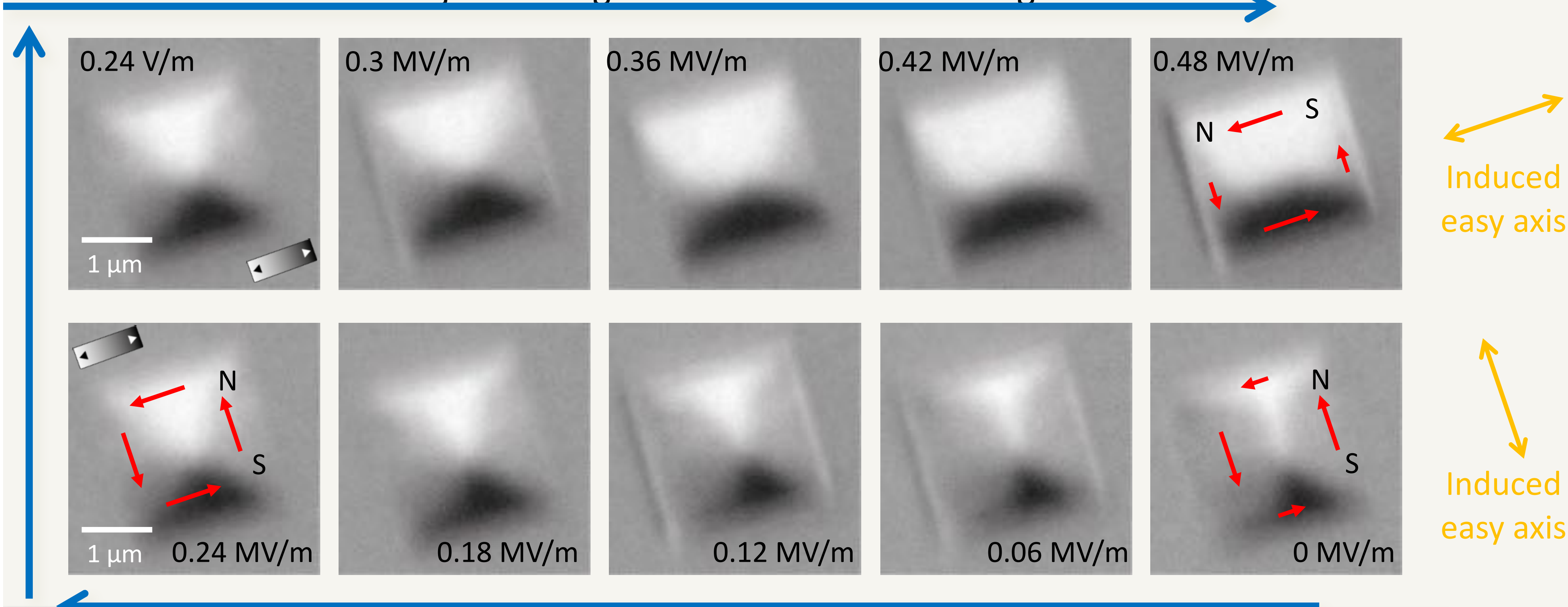
Control of Micro-Structures



- Ni dots 35 nm thick
- Data shows Neel wall can be manipulated
- Easy axis can be rotated 90 degree, similar to thin film work

Finzio, …Carman.., Phys. Rev. Applied V1, Issue 2 Mar 2014

PEEM --M. Klaui & Frithjof Nolting et al Johannes Gutenberg & Paul Scherrer



Phys. Rev. Applied 1, 021001

Modeling Background

- 1687 Newton (elastodynamics)
- 1948 Stoner Wohlfarth
- 1955 Landau-Liftshitz-Gilbert (micromagnetics)
- 2000's LLG + uniform strain (uncoupled) > 50 papers
  - 2001 Zhu, 2006 Hu, 2010 Roy, 2011 Atulasimha, 2011 Bur
- 2000's LLG + elastodynamics (coupled) ~10 paper
  - 2004 Shu Analytical 2D solution
  - 2005 Banas Analytical solution
  - 2005 Chen Numerical solutions
  - 2012 Miehe variational principles
  - 2012 **Liang nanoscale single domain –UCLA ~4 papers**

Elastodynamics

$$\nabla \cdot \tilde{\underline{\underline{\sigma}}} + \underline{f} = \rho \ddot{\underline{u}}$$

$$\tilde{\underline{\underline{\sigma}}} = \underline{\underline{\underline{\underline{C}}}}\,\underline{\underline{\varepsilon}}$$

$$\underline{f} = -\nabla \cdot \left[\underline{\underline{\underline{\underline{C}}}}\,\underline{\underline{\varepsilon}}^{m} - \underline{\underline{\underline{C}}}\,d E \right]$$

Landau-Lifshitz-Gilbert Equation

$$\frac{\partial \underline{M}}{\partial t} = -\mu_0 \gamma \underline{M} \times \underline{H}_{eff} + \frac{\alpha}{M} \underline{M} \times \frac{\partial \underline{M}}{\partial t}$$

$$\underline{H}_{eff} = -\frac{1}{\mu_0 M_S} \frac{\partial E_{tot}}{\partial \underline{m}} = \underline{H}_{ext} + \underline{H}_{ex} + \underline{H}_{anis} + \underline{H}_{d} + \underline{H}_{me}\left(\underline{m}, \underline{u}(E)\right)$$

Modeling Coupled System of Equations

Landau-Lifshitz-Gilbert Equation

$$\frac{\partial \underline{M}}{\partial t} = -\mu_0 \gamma \underline{M} \times \underline{H}_{eff} + \frac{\alpha}{M} \underline{M} \times \frac{\partial \underline{M}}{\partial t}$$

$$\underline{H}_{eff} = -\frac{1}{\mu_0 M_S} \frac{\partial E_{tot}}{\partial \underline{m}} = \underline{H}_{ext} + \underline{H}_{ex} + \underline{H}_{anis} + \underline{H}_{d} + \underline{H}_{me}(\underline{m}, \underline{u}(\underline{E}))$$

Elastodynamics

$$\nabla \bullet \tilde{\underline{\underline{\sigma}}} + \underline{f} = \rho \ddot{\underline{u}}$$

$$\tilde{\underline{\underline{\sigma}}} = \underline{\underline{\underline{\underline{C}}}}\, \underline{\underline{\varepsilon}}$$

$$\underline{f} = -\nabla \bullet \left[\underline{\underline{\underline{\underline{C}}}}\, \underline{\underline{\varepsilon}}^{m} - \underline{\underline{\underline{\underline{C}}}}\, \underline{\underline{\underline{d}}}\, \underline{E} \right]$$

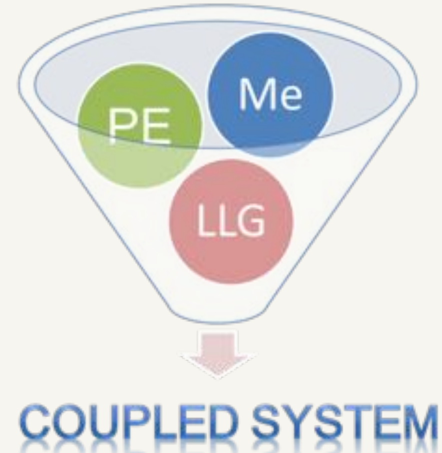
Piezoelectric effect (electrostatic)

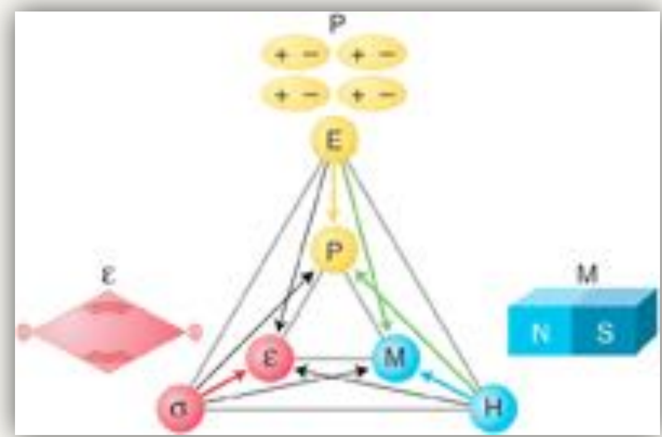
$$\nabla \bullet \underline{D} = 0$$

$$\underline{E} = -\nabla V$$

$$S_{ij} = s^{E}_{ijkl} T_{kl} + d_{ijk} E_k$$

$$D_{ij} = d_{ijk} T_{kl} + s^{T}_{ik} E_k$$

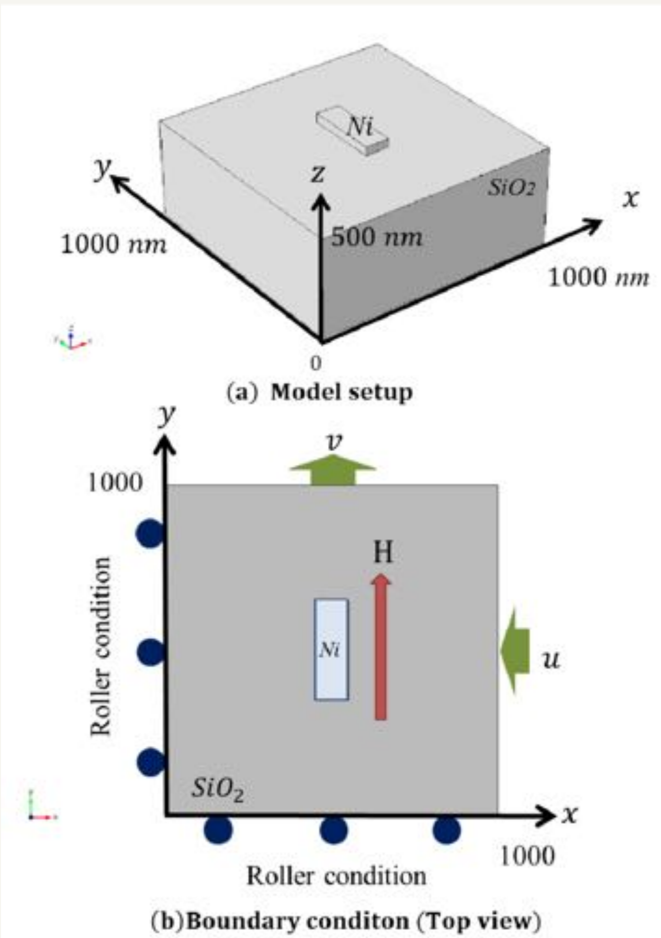




- Equations of LLG, piezoelectric effect and elastodynamics are a system of coupled partial differential equations
- Total equal 7 coupled PDE + 4 coupled PDE.

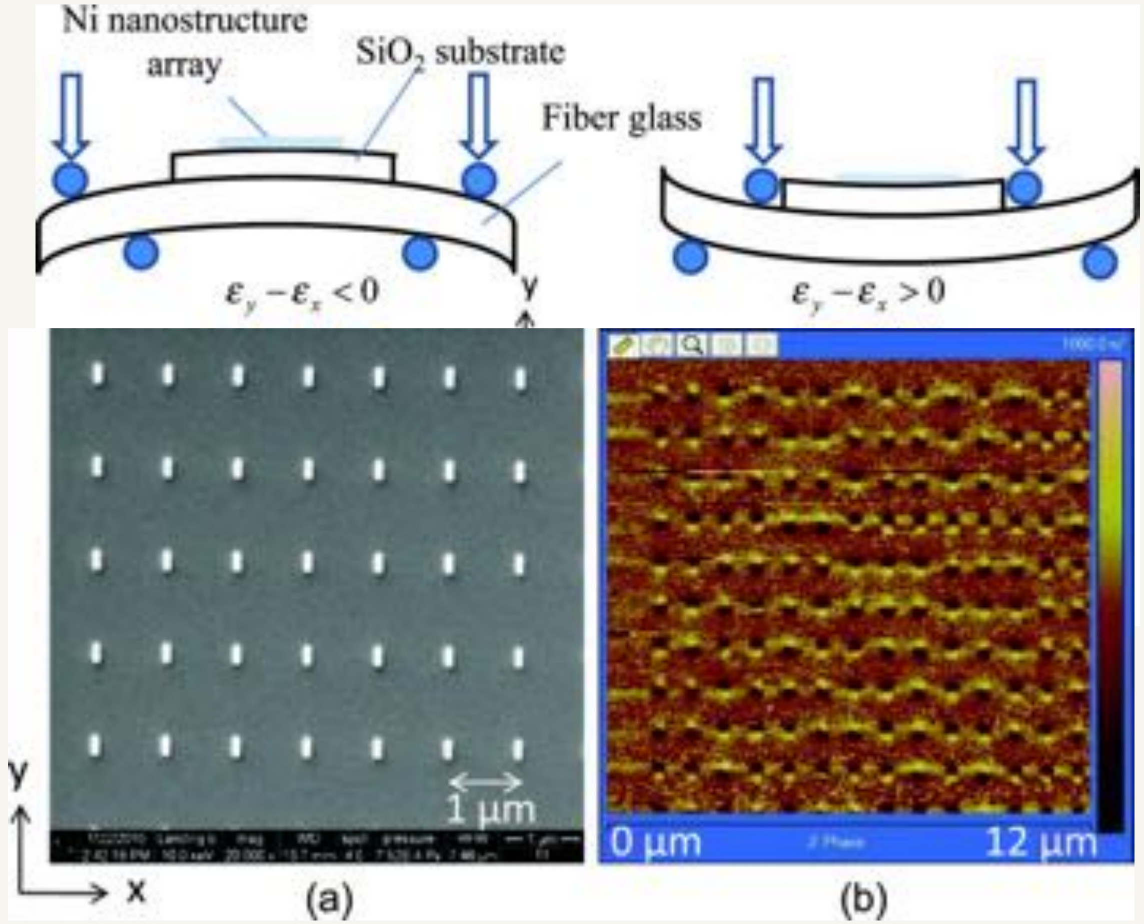
Analytical & Experimental Setup

(a) Element size ~ exchange length 7 nm
(b) Coupled model
(c) M, H, ε, σ spatially vary



(a) Model setup
(b)Boundary conditon (Top view)

(a) Ni magnetoelastic material 300 x 100 nm
(b) Array of nanostructures
(c) MOKE measurements



(a) (b)

Bur, … Carman,, JOURNAL OF APPLIED PHYSICS, Vol 109 Iss: 12, JUN 2011

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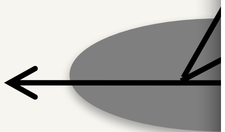
Quantitative Agreement Exp & Models

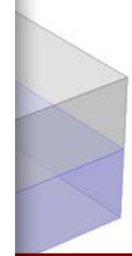
Stoner–Wohlfarth model (Un

LLG model

LLG/EQ model n Strain)

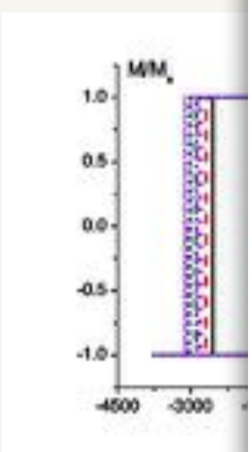


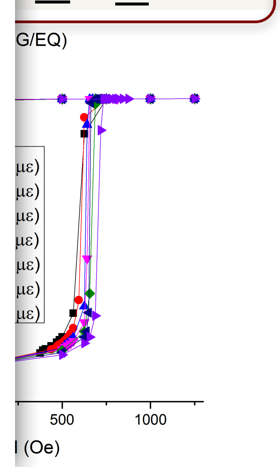
$E = K_u V \sin^2(\varphi$

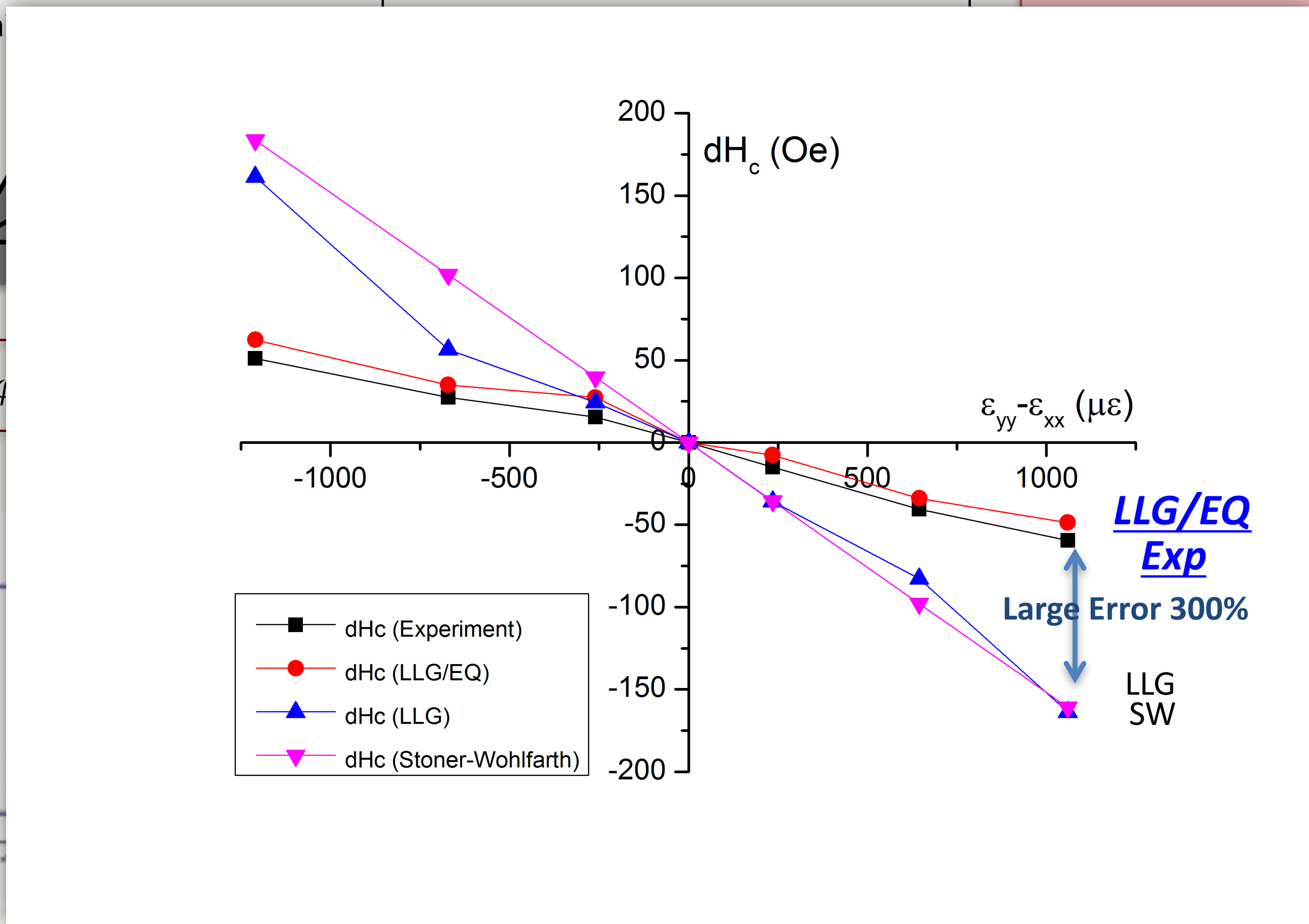


$- \frac{\alpha}{M} \underline{M} \times \frac{\partial \underline{M}}{\partial t}$

$\cdot \underline{\tilde{\sigma}} + \underline{f} = \rho \underline{\ddot{u}}$



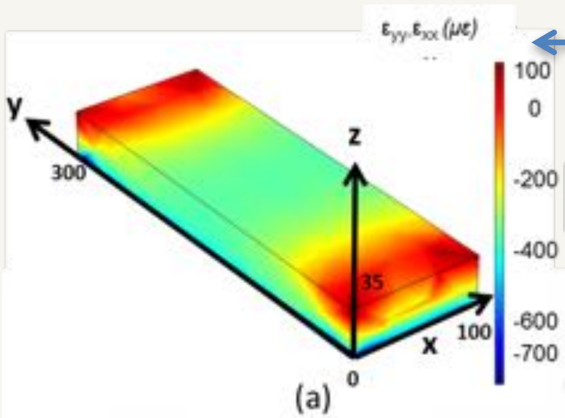




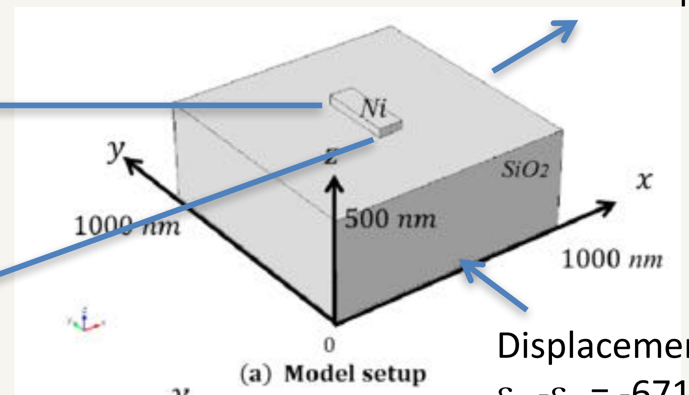
The LLG/EQ model good agreement less than 2% error
Stoner-Wolhfarth model and the LLG model as much as 300% error.

JAP + App Phy Rev

Shear Lag Dependence

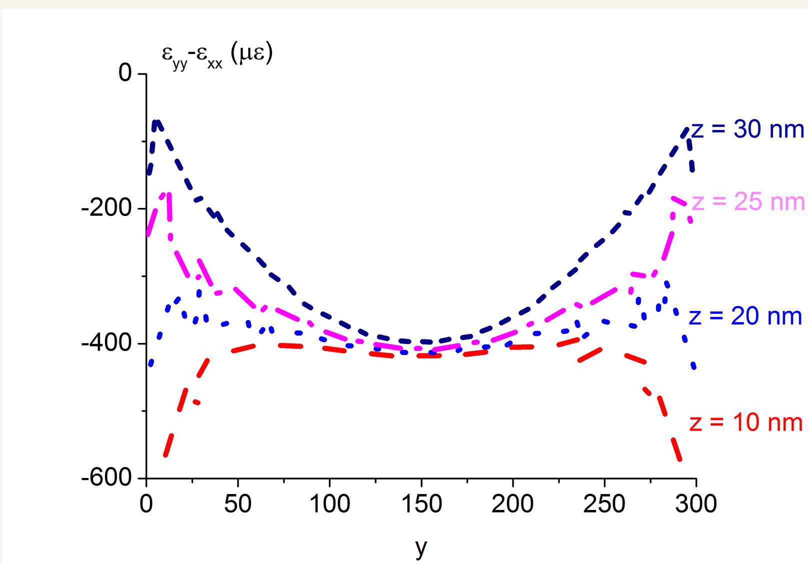


displacement



Displacement

ε_{yy}-ε_{xx}= -671 $\mu\varepsilon$



- Stress/strain distribution is non-uniform
- M/H distribution is non-uniform.
- Constant strain present is inappropriate for this structure..

Liang , … Carman, NANOTECHNOLOGY, Vol 25 Iss 43, OCT 31 2014

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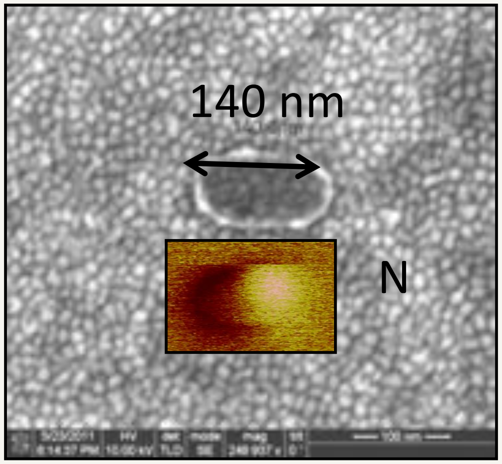
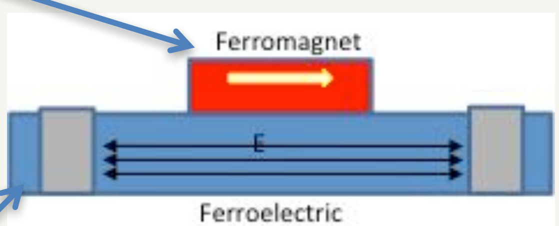
Single Domain PEEM

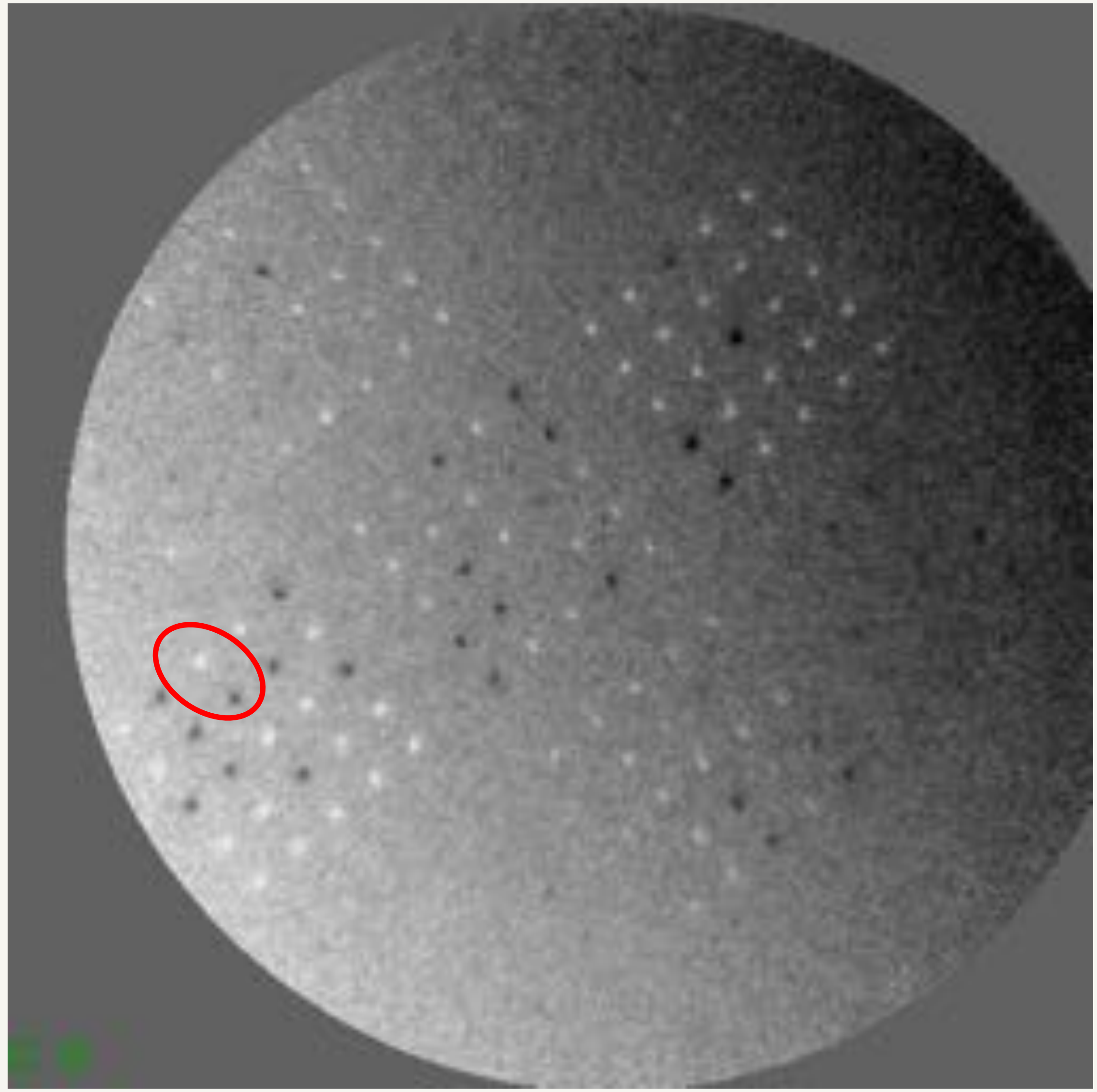
Experimentally confirmed Nolting Paul Scherrer Inst



15nm
ME material



0.5mm
Piezo

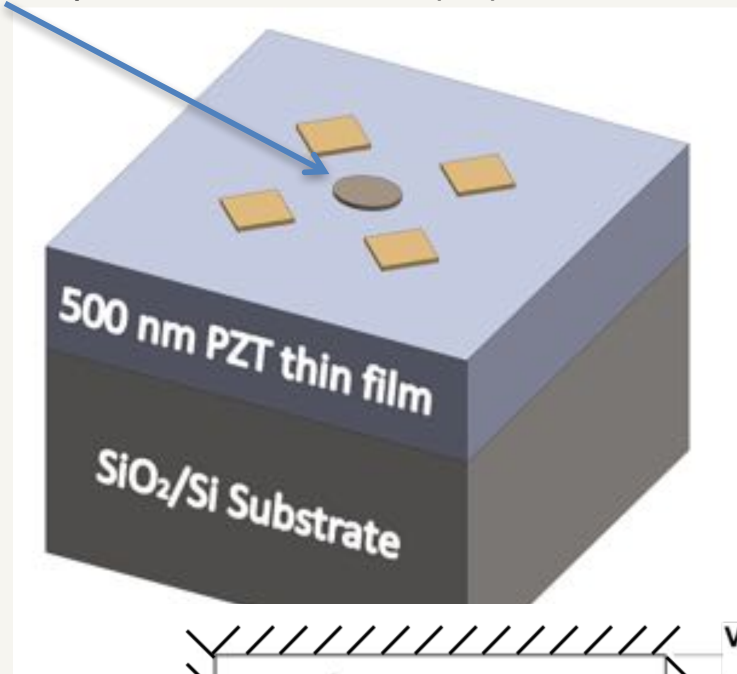


Buzzi ,… Carman, PHYSICAL REVIEW LETTERS Vol 111 Iss: 2, JUL 9 2013

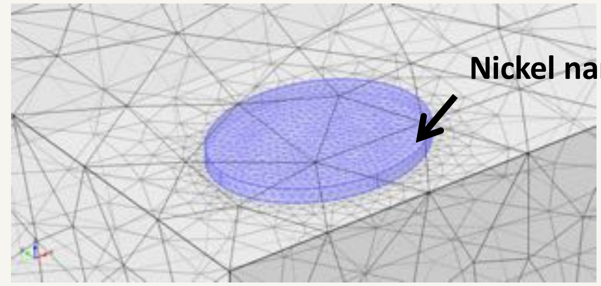
Energy = 10fJ *NOT better*

Substrate Clamping Problem

Ni Ellipse disk size: 150-120-10 (nm)

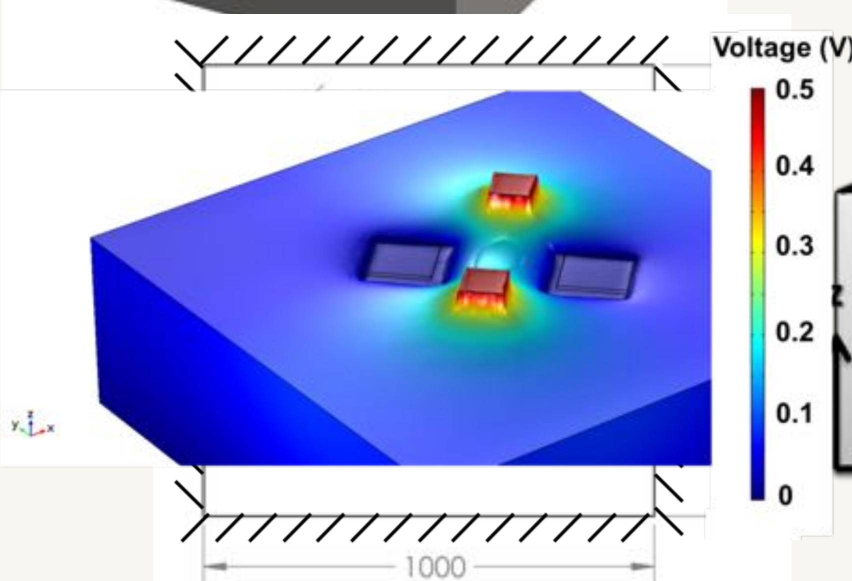


Simulation Setup:

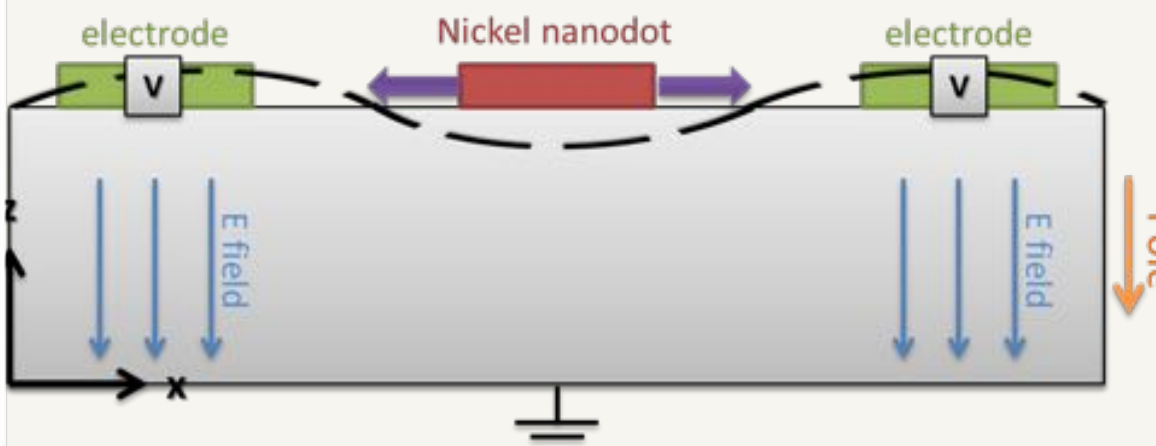


Mesh size is on the order of exchange length

Cui, Lynch, .. Carman, APL, V 103, Is 23, 2013



All four boundaries are clamped



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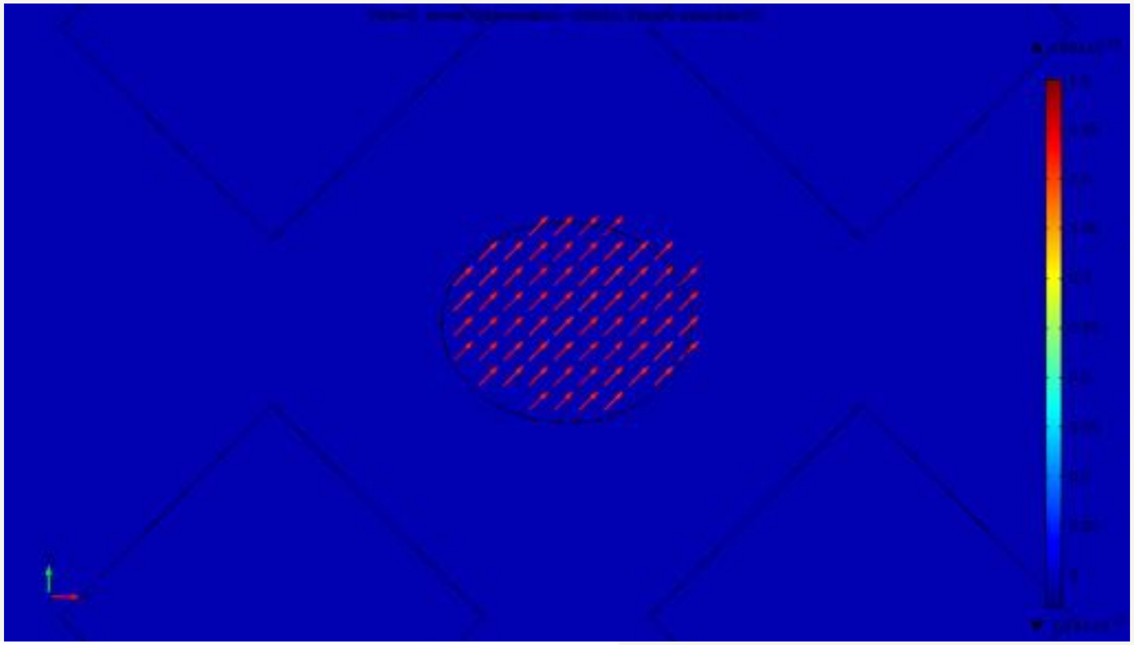
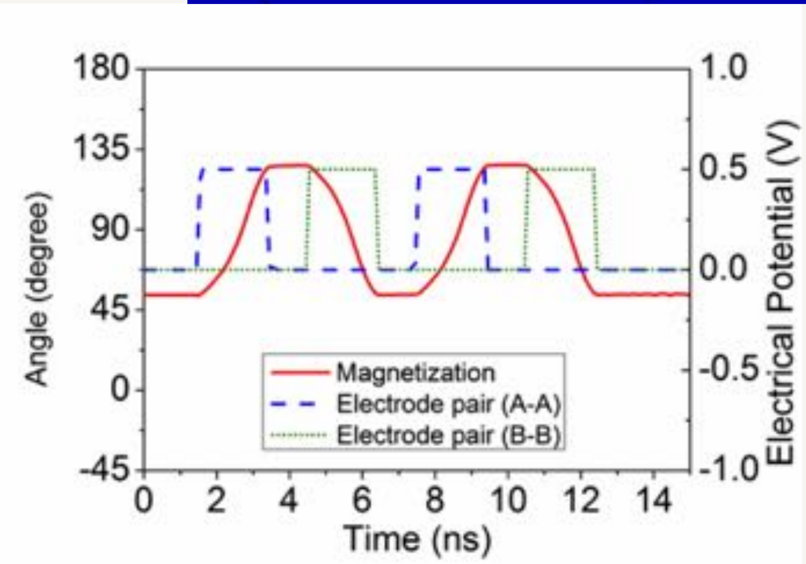
Simulation Results





Write Energy =0.3 fJ

TD= 0.08fJ or 80 aJ

Optimized = 10 aJ

Liang… Carman, JOURNAL OF APPLIED PHYSICS, Vol: 116 Issue: 12, SEP 2014

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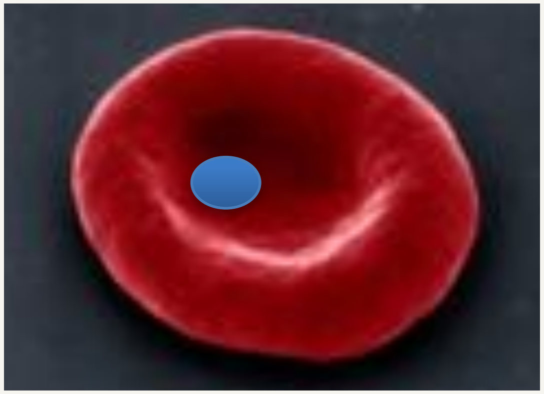
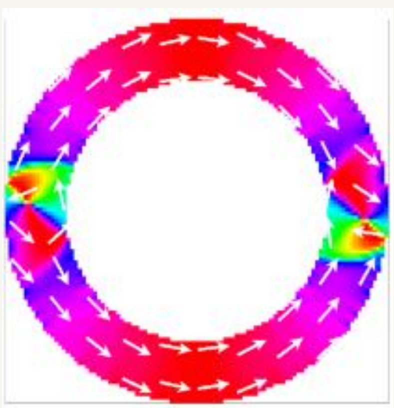
Magnetic states in micron-scale rings (stator)

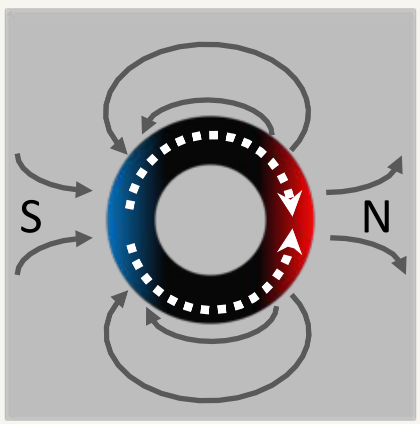
Red Blood Cell



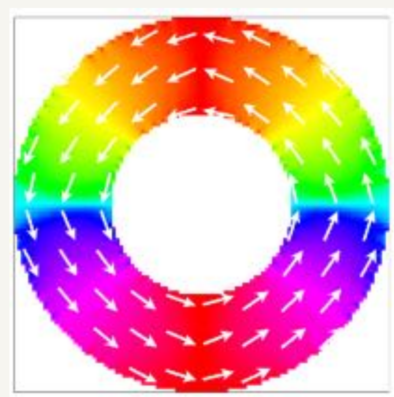
Magnetic state
- Onion state
- Vortex state

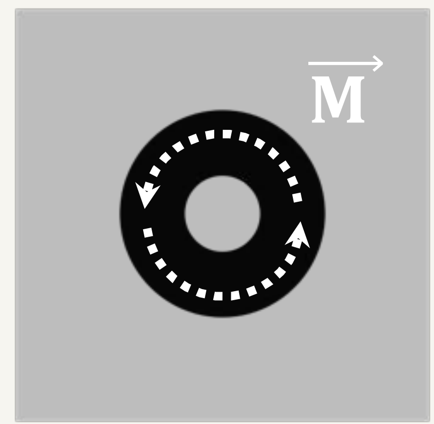
Onion state





Vortex state

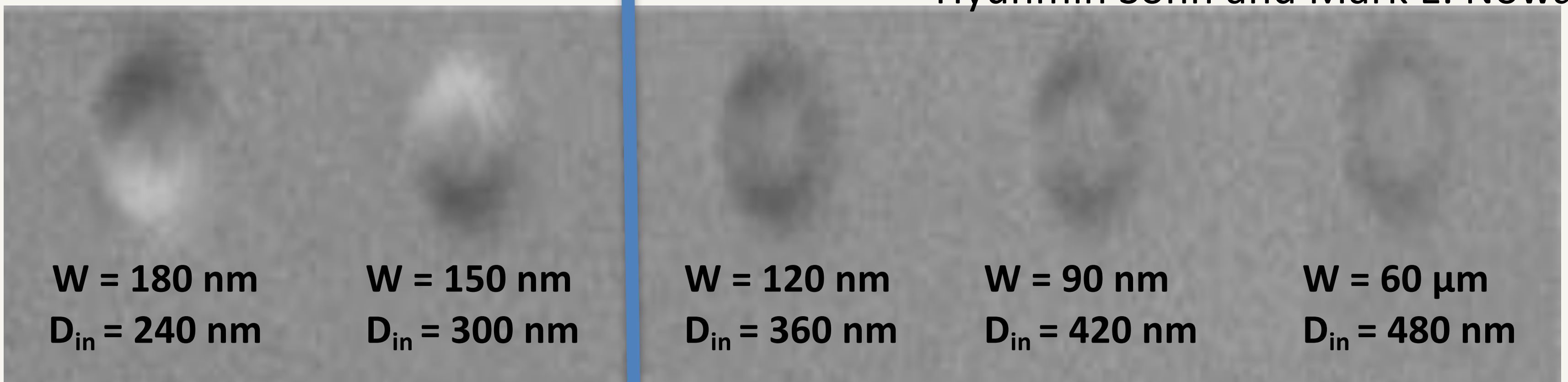


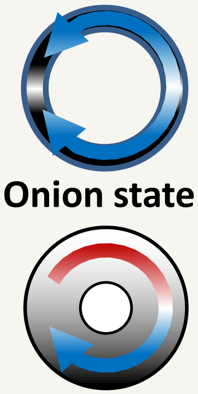


Simulation vs. Experiment (cont'd)

Experimental (PEEM) Results

Hyunmin Sohn and Mark E. Nowakowski, 2014





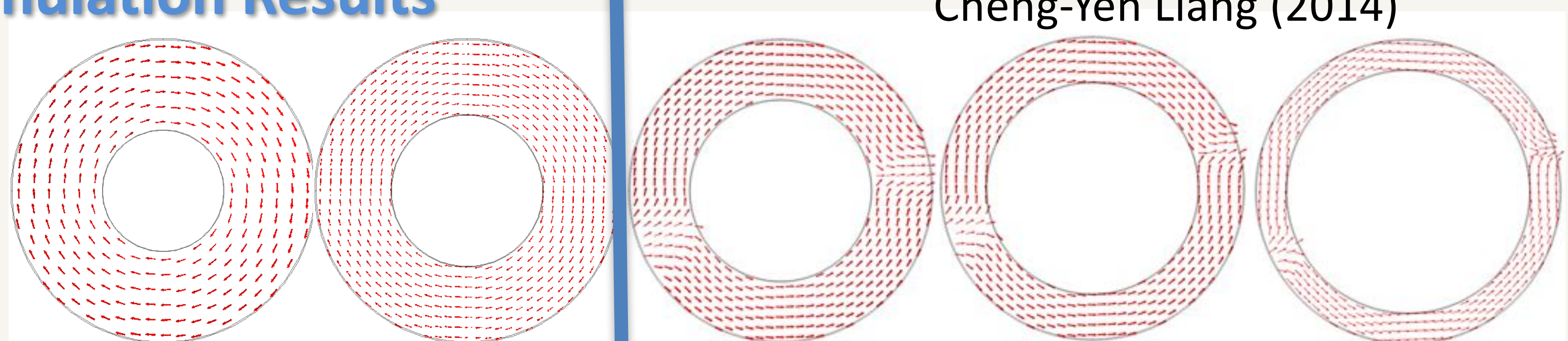
Onion state

Vortex state

Outer diameter 600 nm

Simulation Results

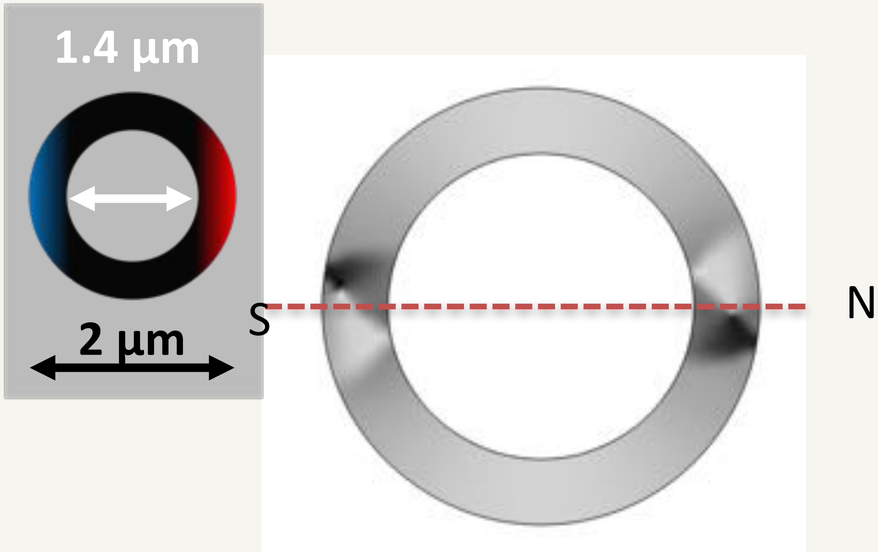
Cheng-Yen Liang (2014)



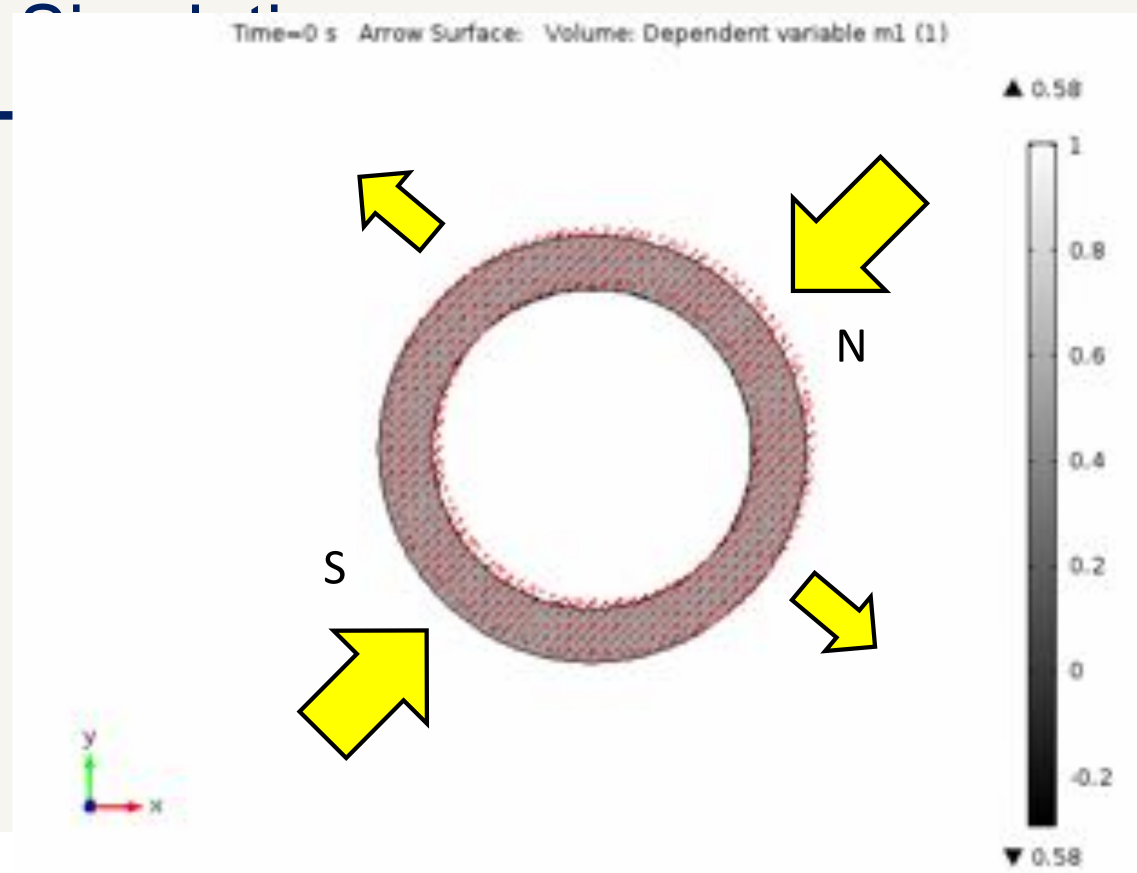
W = 180 nm	W = 150 nm	W = 120 nm	W = 90 nm	W = 60 µm
D_{in} = 240 nm	D_{in} = 300 nm	D_{in} = 360 nm	D_{in} = 420 nm	D_{in} = 480 nm

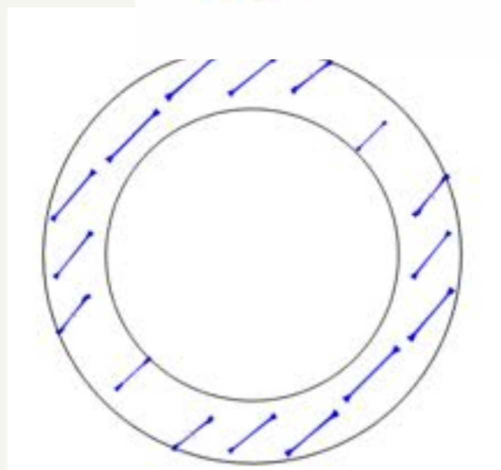
Sohn, Nowakowski, ... Carman, ACS NANO, Vol: 9 Issue: 5 MAY 2015

Modeling



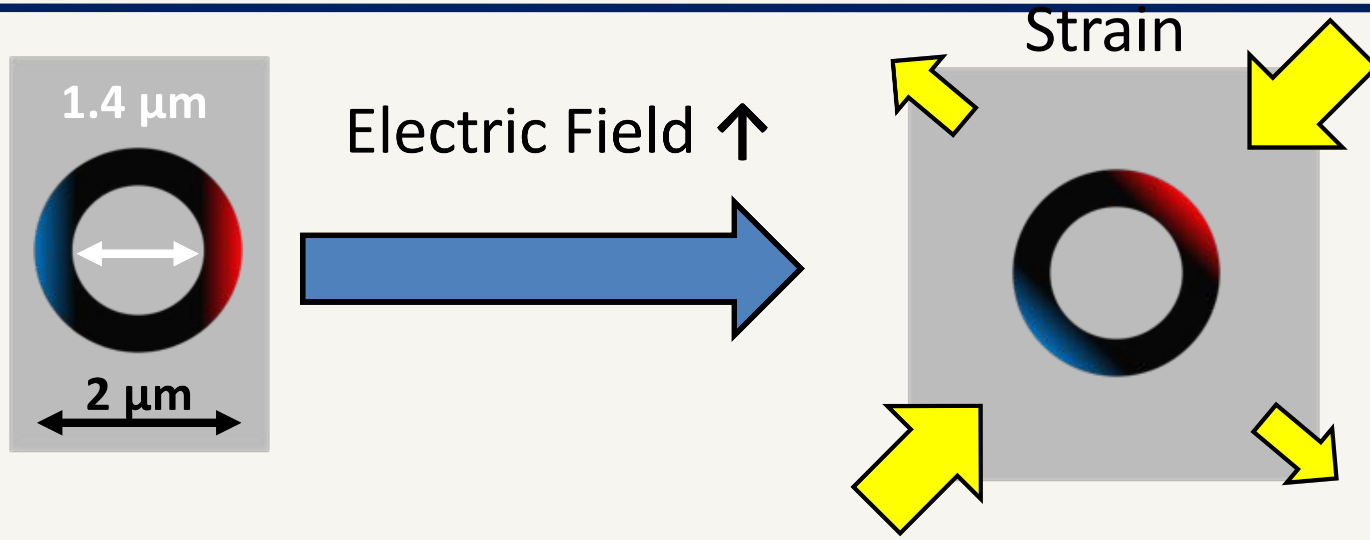
Before Strain



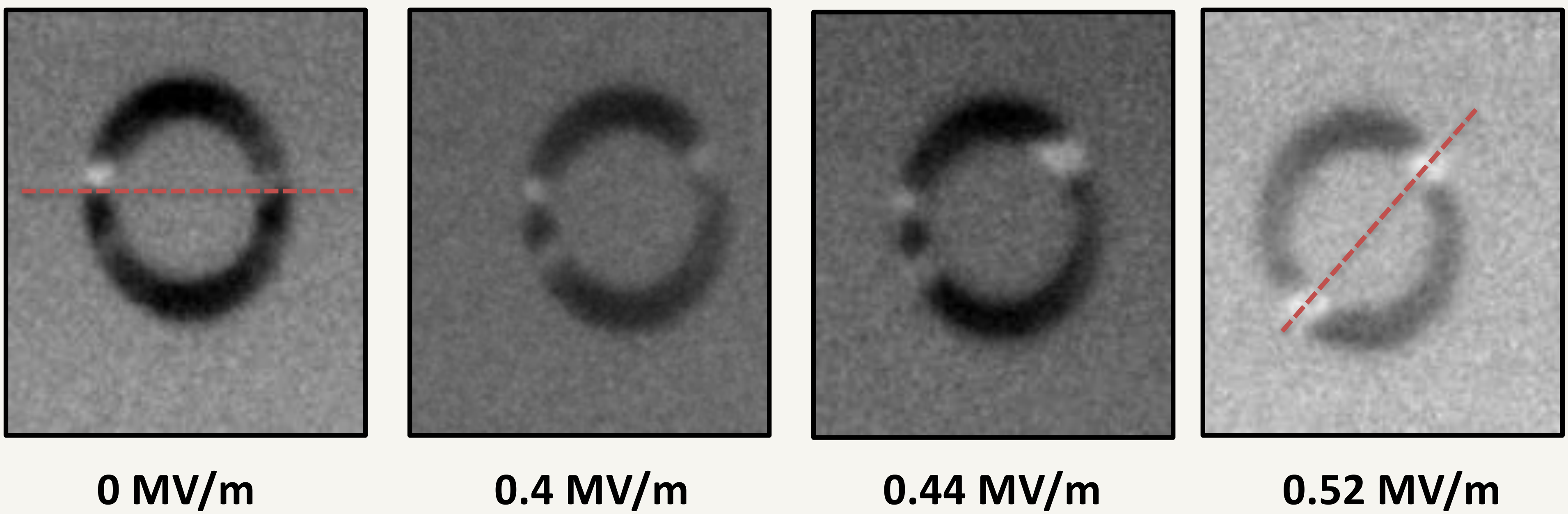


Principal stress direction

45˚ Rotation PEEM Data

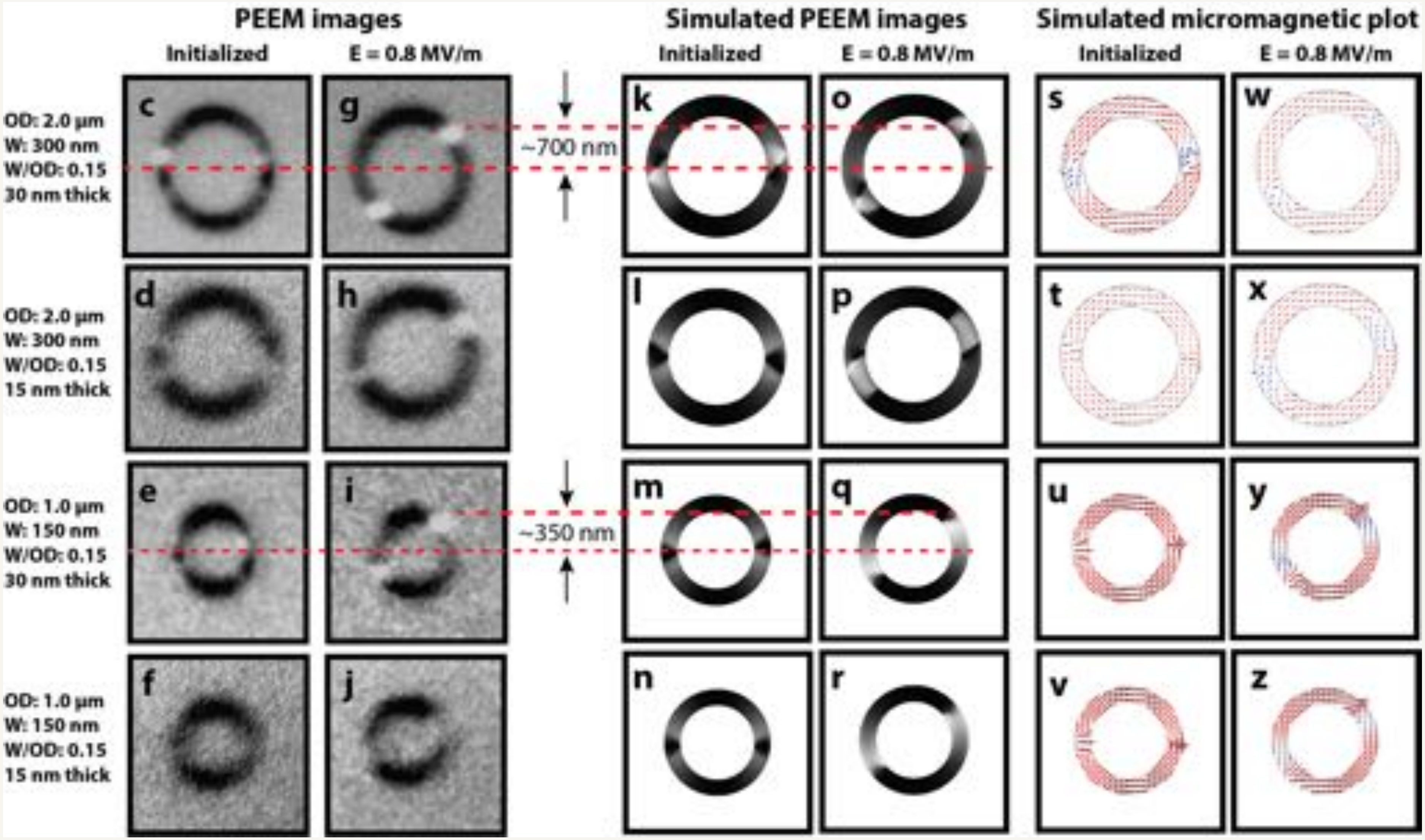


PEEM with increasing Electric Field



*First Demonstration of **Deterministic** Onion State Rotation in Nanoscale Multiferroic Rings!*

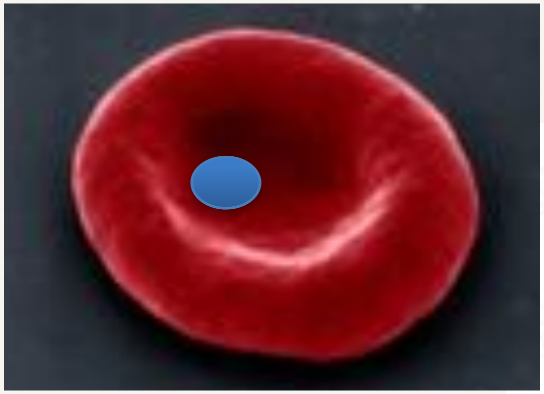
Analytical vs Experimental **AGREEMENT**



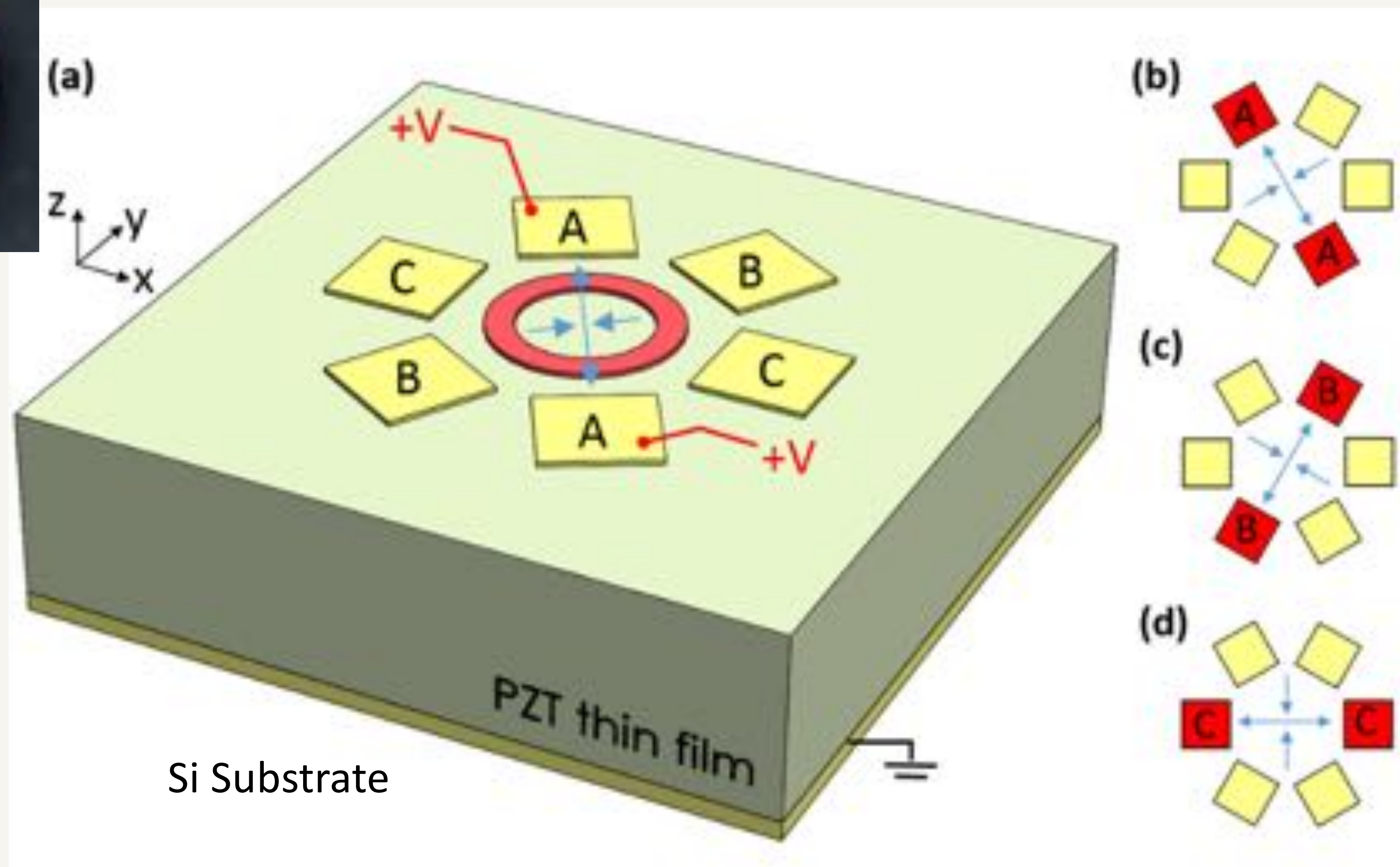
Sohn, Nowakowski, ... Carman, ACS NANO, Vol: 9 Issue: 5 MAY 2015

Surface Electrodes on Thin Film Ferroelectrics

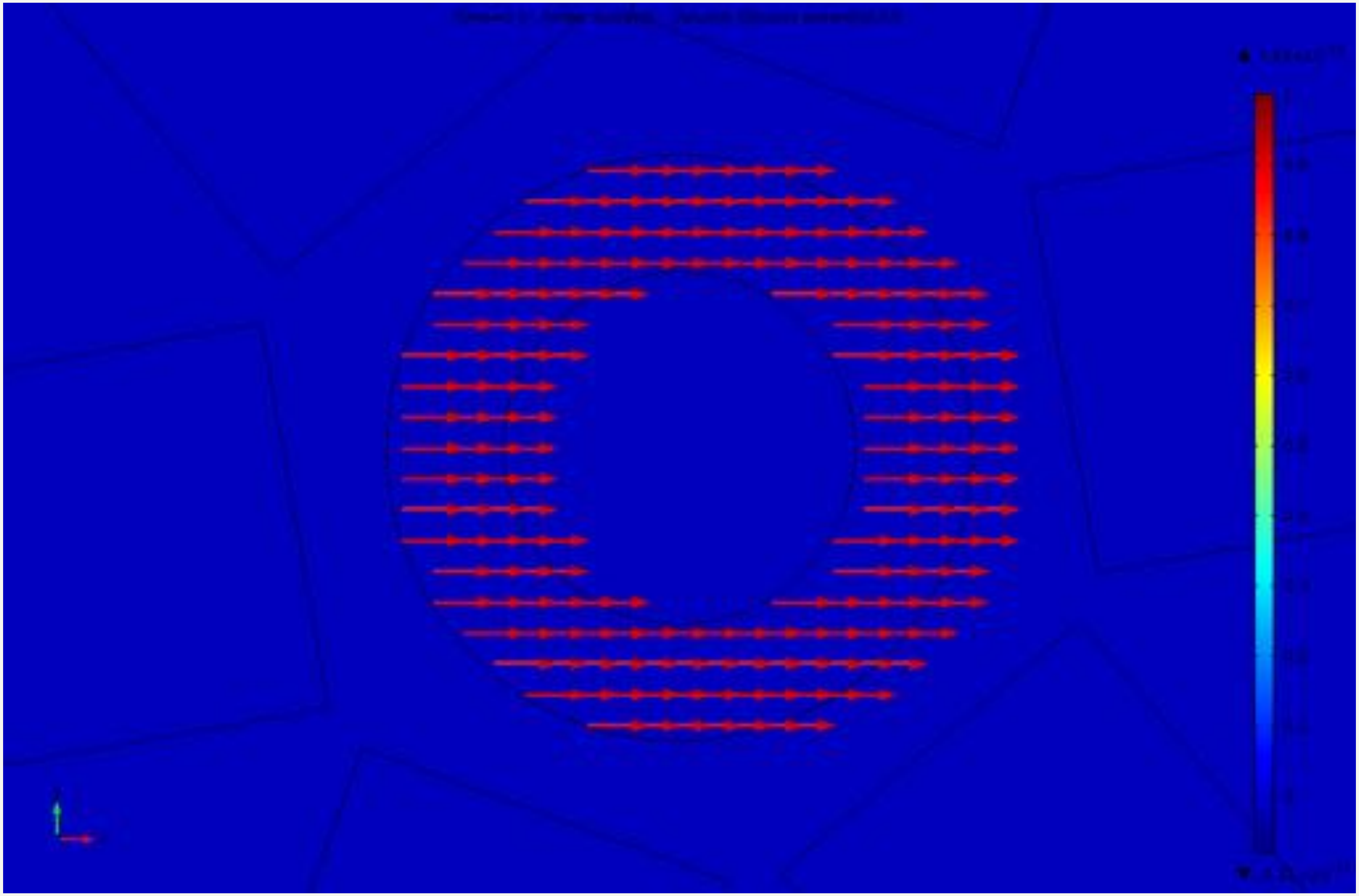
Red Blood Cell



500 nm



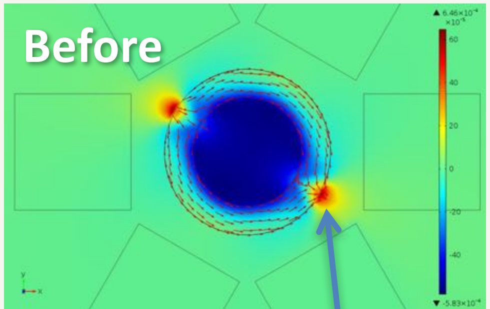
Model of 360 Rotation

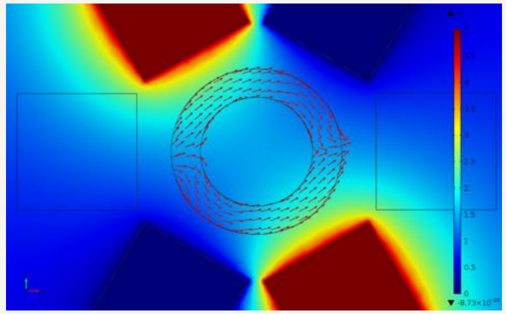


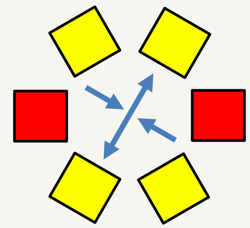
Liang .. Carman, Journal of Applied Physics, Vol. 118, Iss 17, Nov 2015

Surface Electrodes – First results

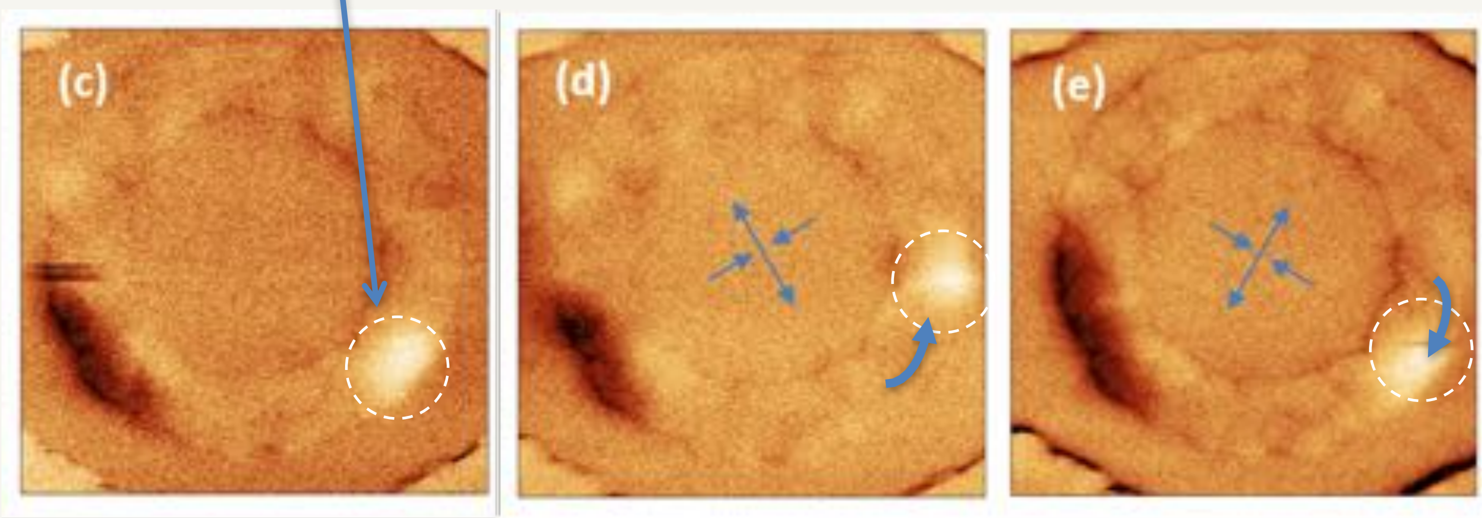
Domain wall motion from surface electrodes







Cui, Lynch, Carman et al
Submitted JAP 2015



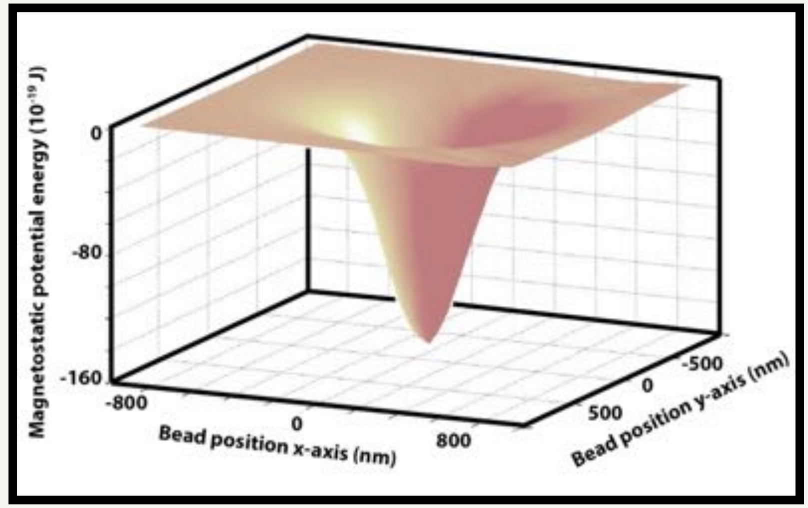
- Bidirectional rotation
- Path toward full 360° rotation

Magnetic Force Microscopy Images

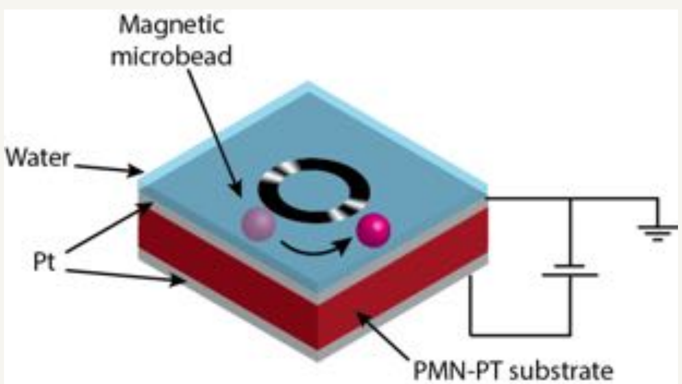
Initial state   V at A-A   V at B-B

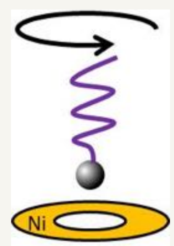
Cui, Lynch.. Carman, APPLIED PHYSICS LETTERS Vol: 107 Iss: 9, AUG 2015

New Motor Concept: Moving Magnetic Micro-beads



Can we deterministic manipulate a magnetic object coupled to the ring DWs?



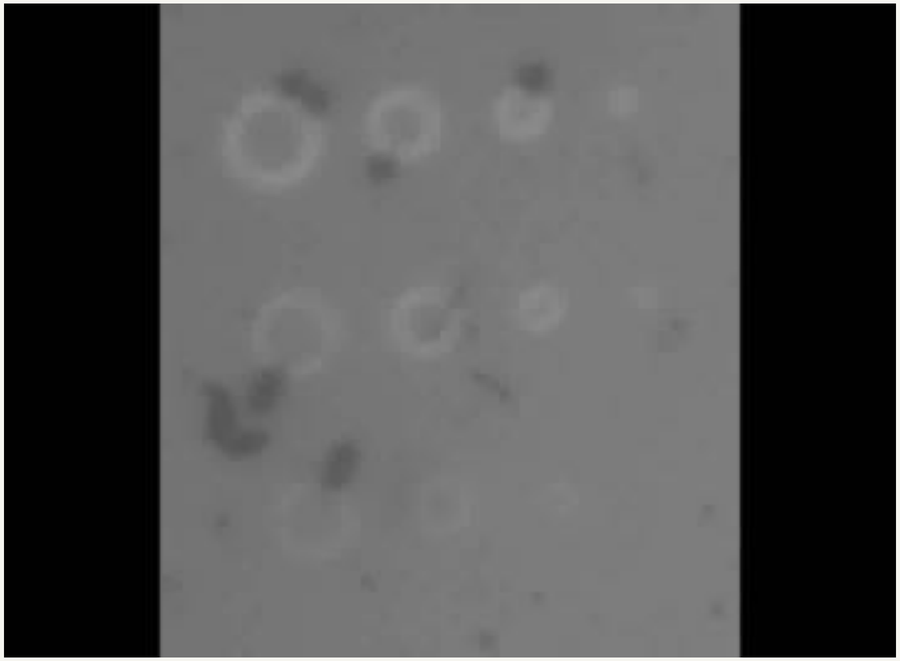


Axial rotation
- Rotor
- Rotating tail

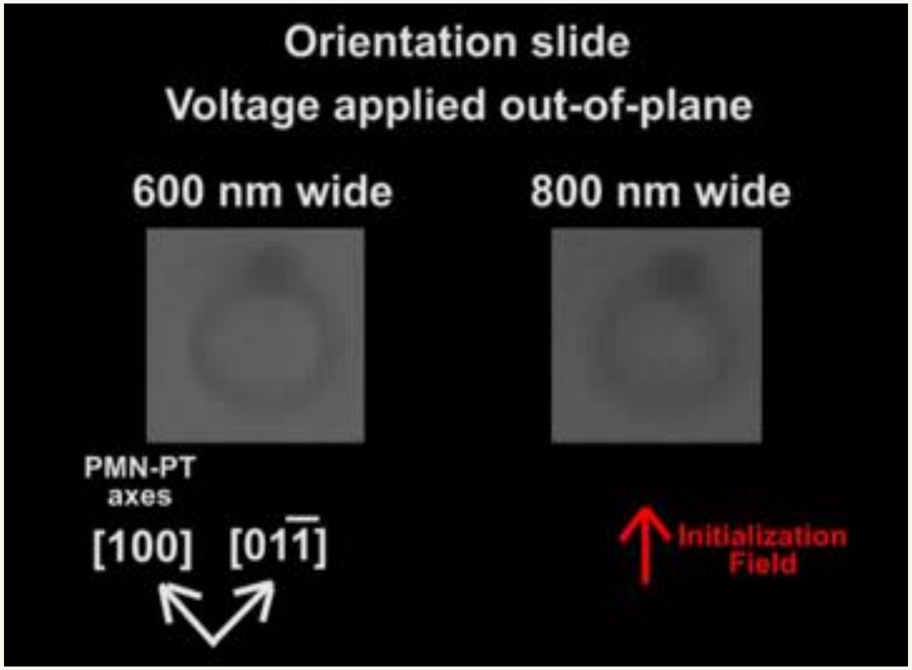
Magnetic bead and tail synthesis: Collaboration with Sarah Tolbert (UCLA)

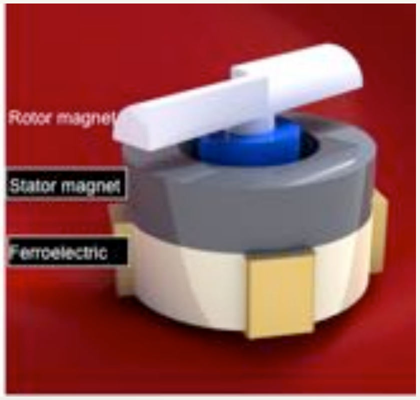
This can be a Motor

Magnetic Field Rotation
Rapoport/Beach APL 2012



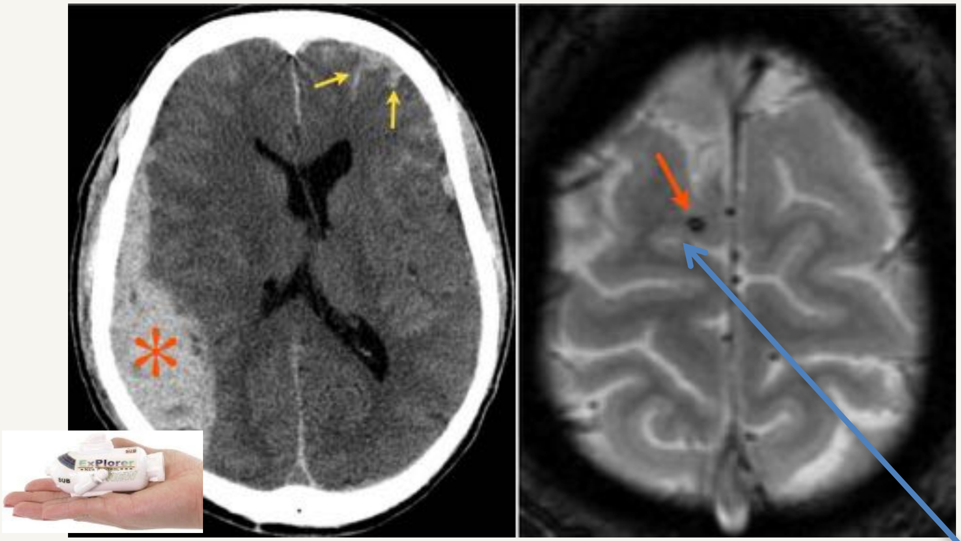
Electric Field Rotation





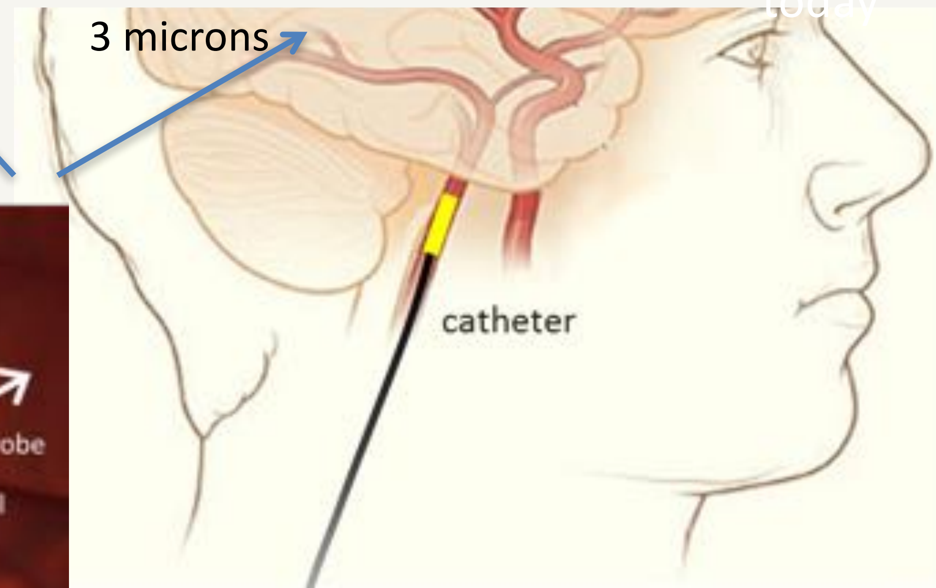
Sohn, Nowakowski, ... Carman, ACS NANO, Vol: 9 Issue: 5 MAY 2015

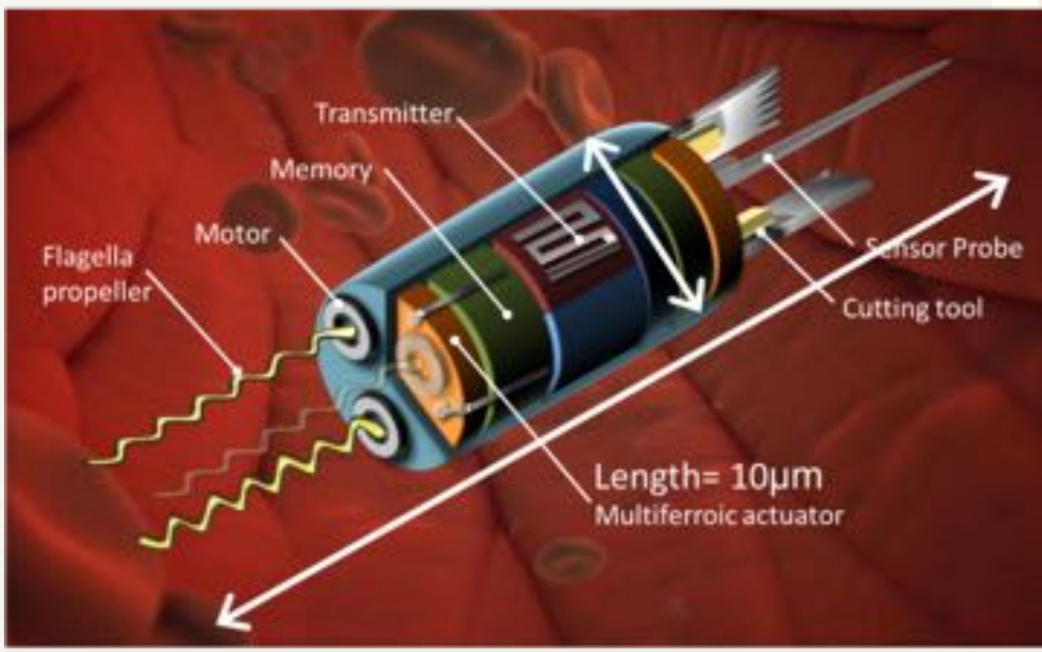
Enable Other Technologies



Stanford today

3 microns





Traumatic Brain Injury (TBI) caused by sudden impact resulting in loss of body function, cognitive abilities, coma, or death (not understood).

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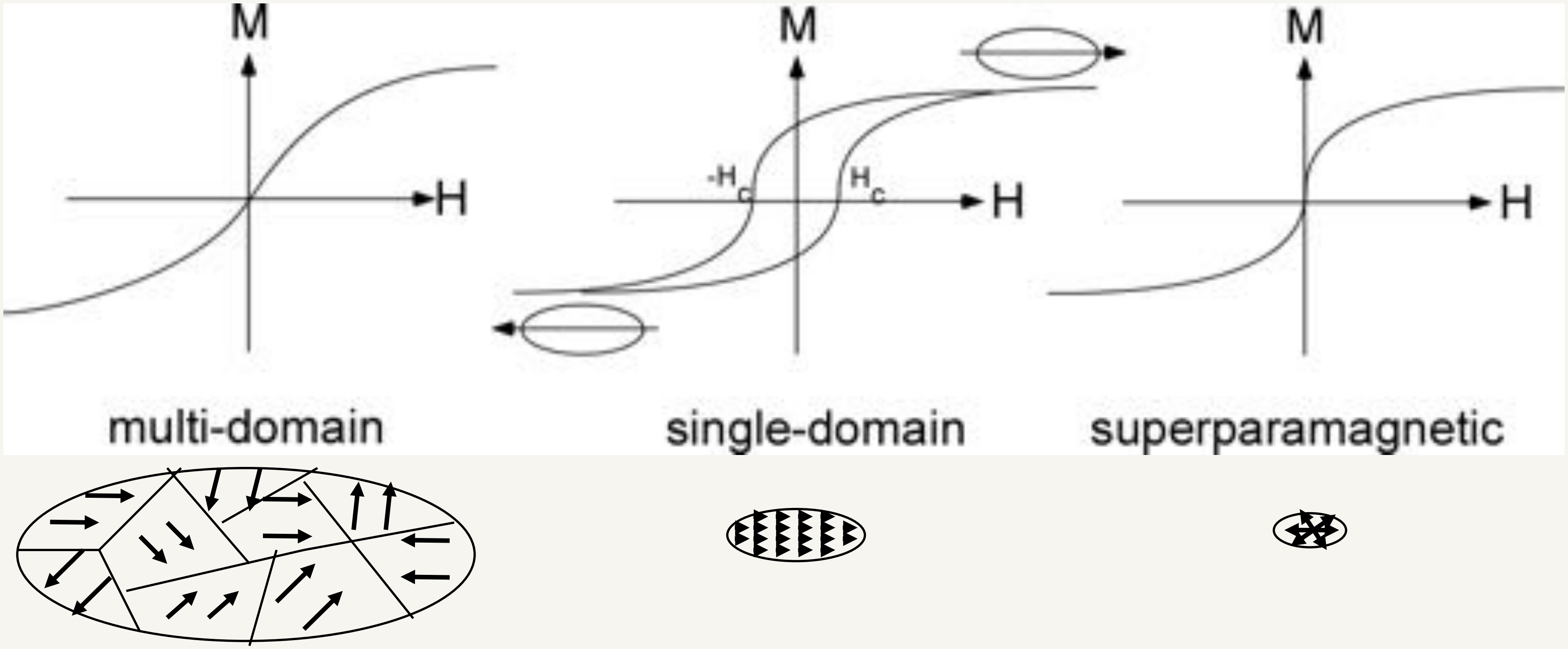
Other Cool New Stuff f(size)

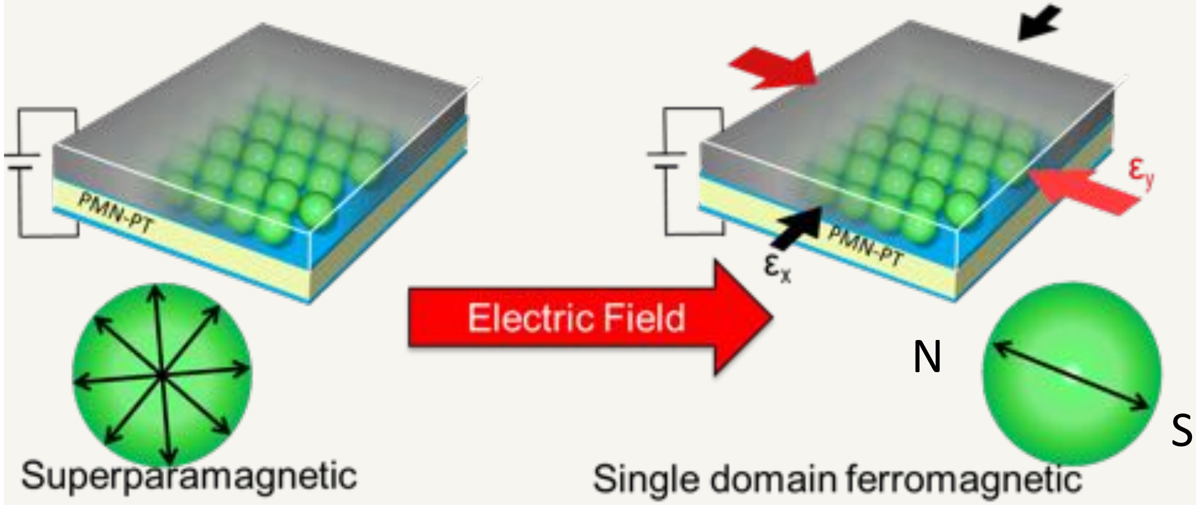


- Low remanence
- Low hysteresis

- High remanence
- High hysteresis

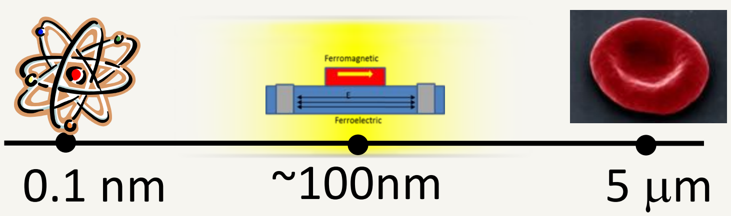
- No remanence
- No hysteresis
- High susceptibility

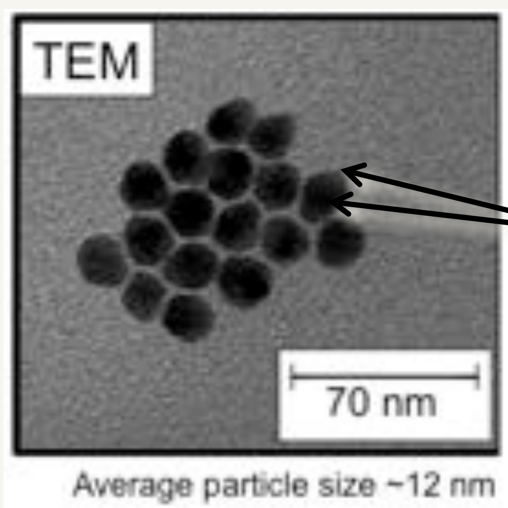
Superparamagnetic Control

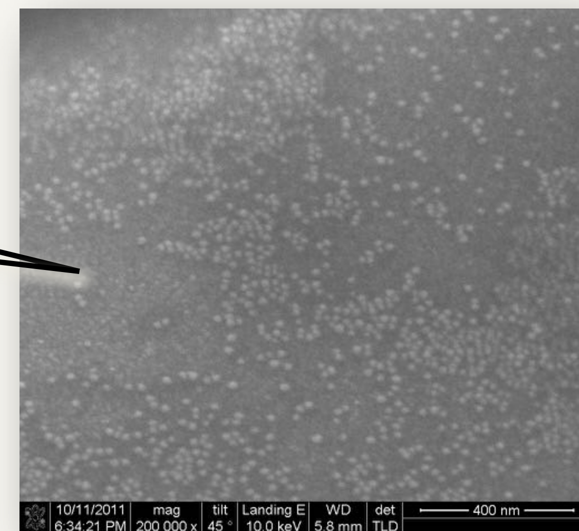


Collaboration with Sarah Tolbert UCLA

- Ni Nanocrystals thermal decomposition (Tolbert)
- Deposition on 011 PMN-PT
- Single layer of nanocrystals



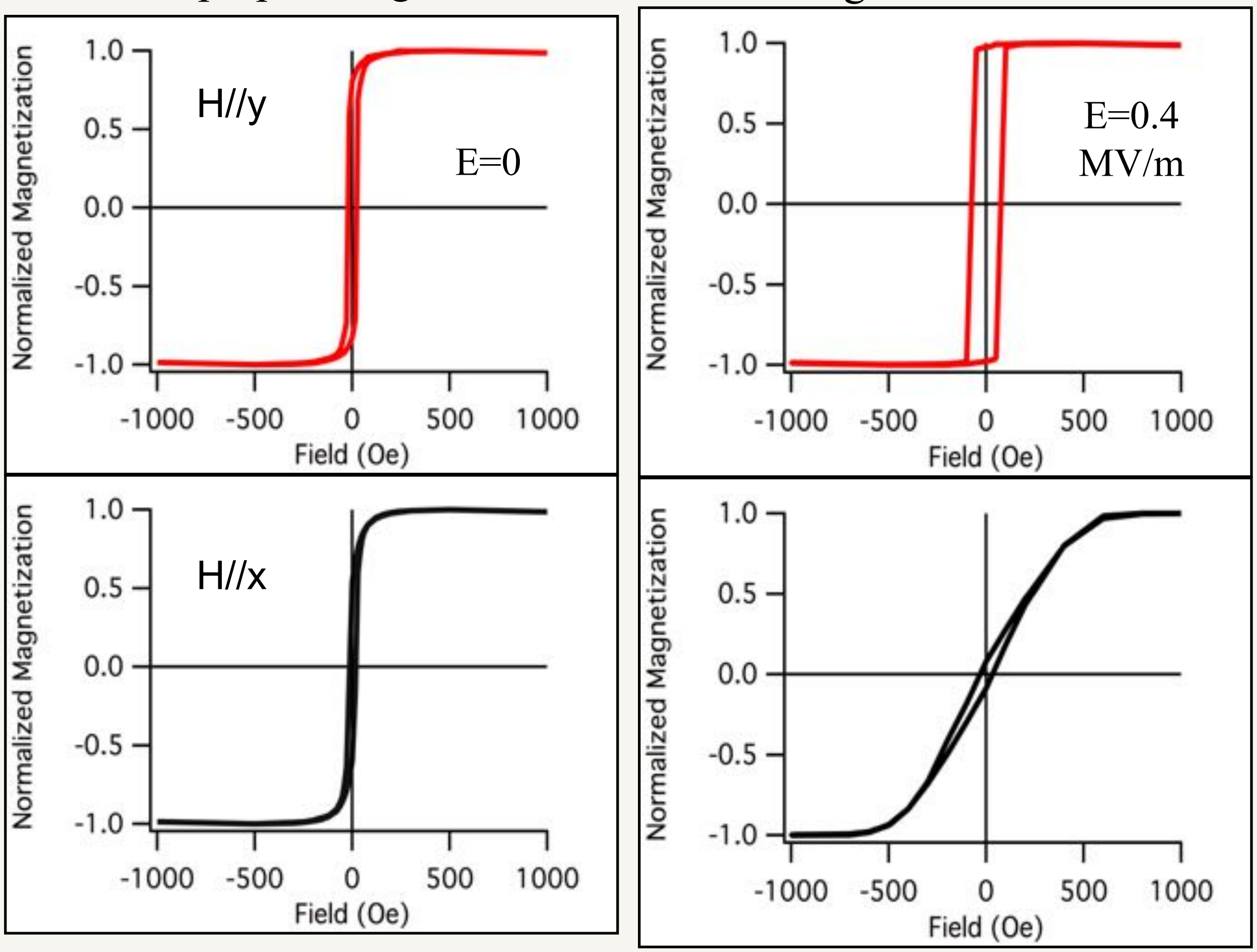


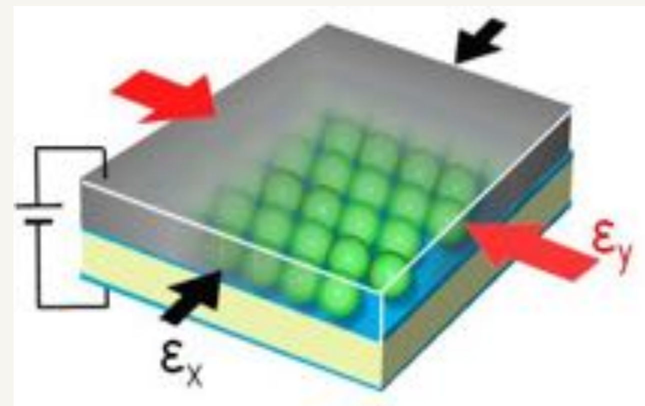


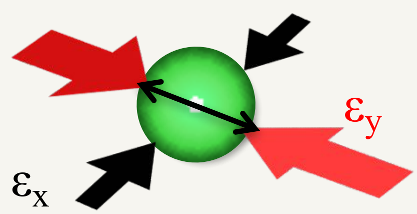
Kim, Schelhas... Carman,"NANO LETTERS, Vol: 13 Iss: 3, MAR 2013

Electric Control M vs H (RT)

Superparamagnetic | Single Domain

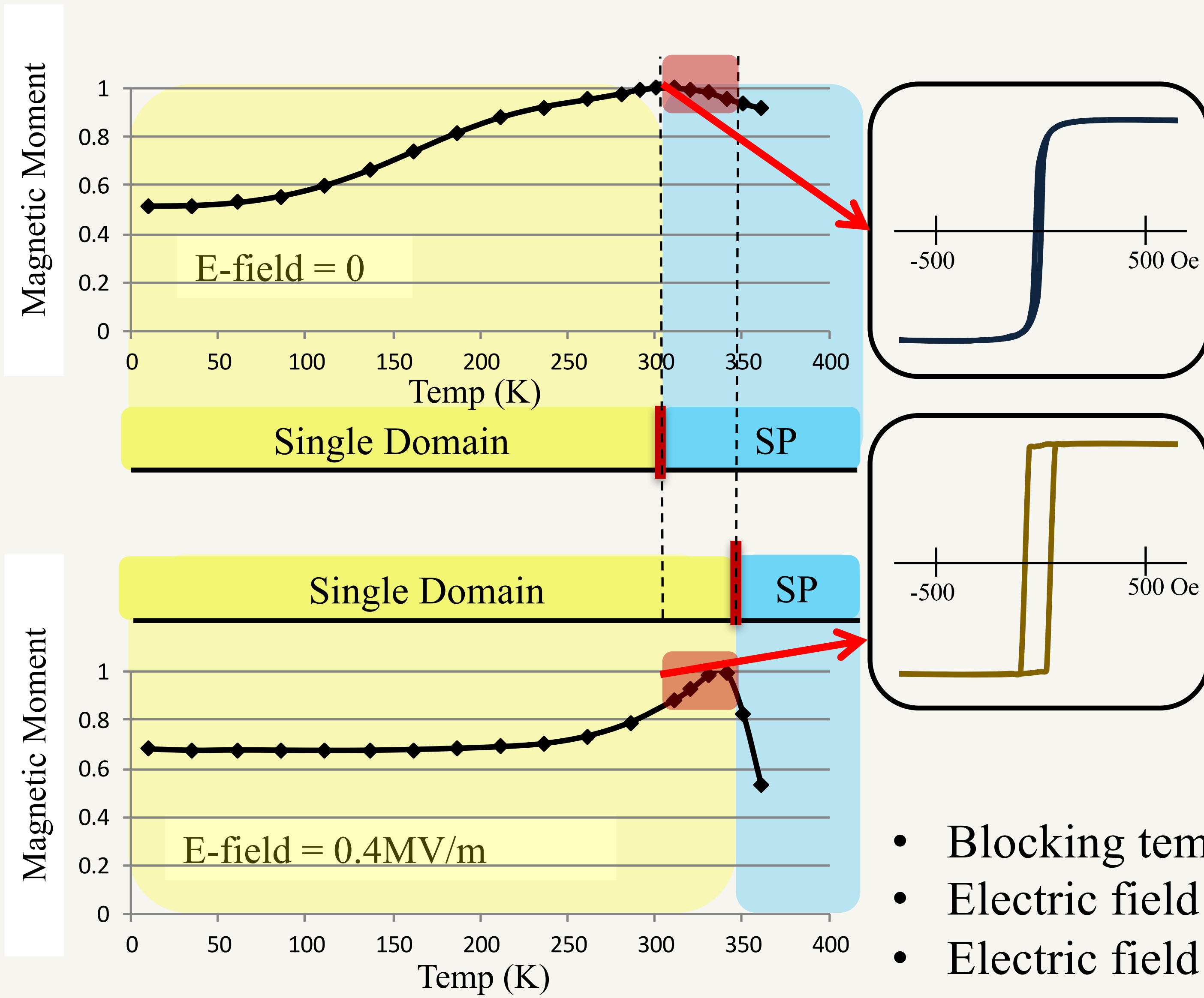


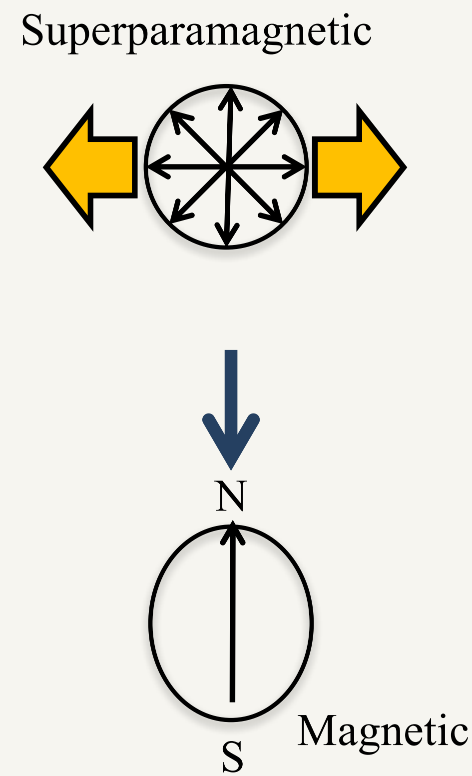




- E field turns on stable single domain
- Hc increased by ~100 Oe
- Ha increased to ~600 Oe

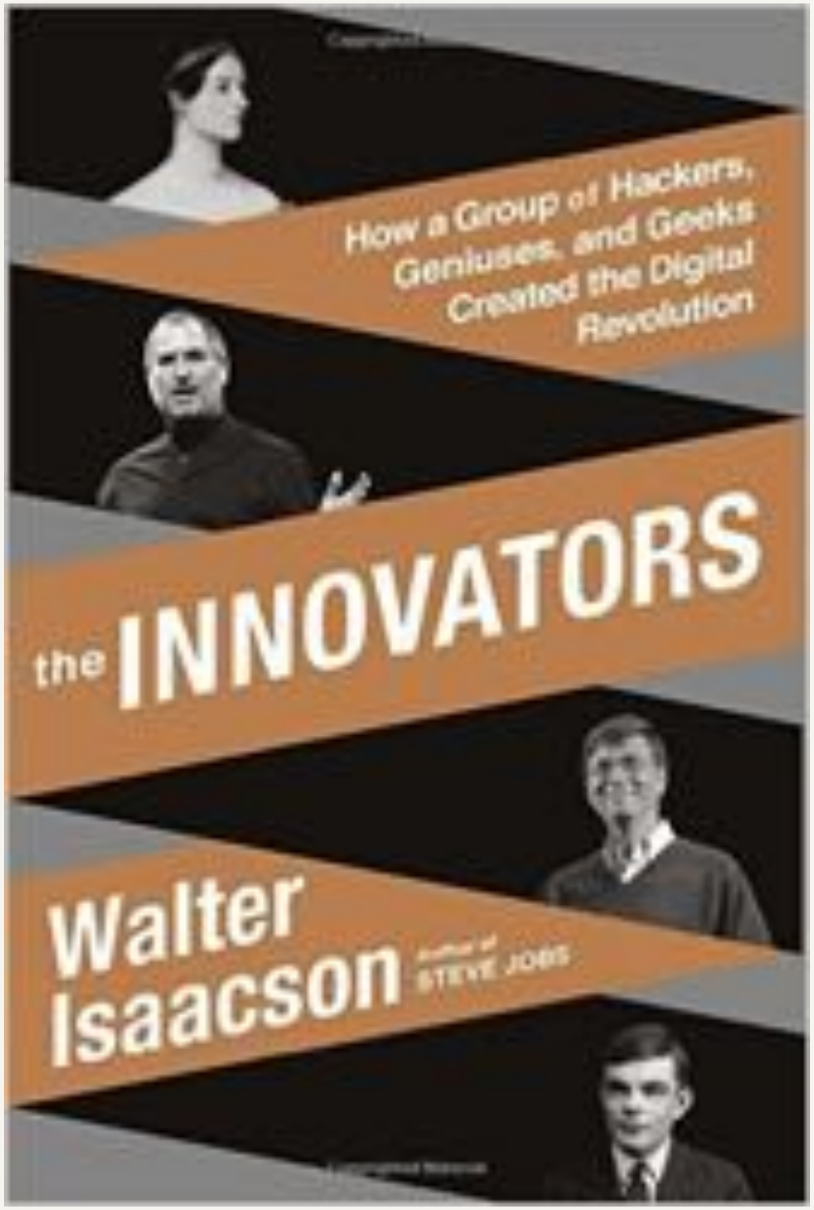
ZFC Electric Control T_B





- Blocking temperature shifted by ~40K
- Electric field off, superparamagnetic
- Electric field on, single domain

Critical Mass



Computers developed because multiple people solved different hard problems – critical mass

Problems being solved were by groups of individuals - collaboration

Now is the time for a breakthrough in control of magnetism in the small scale – ***Future is now***

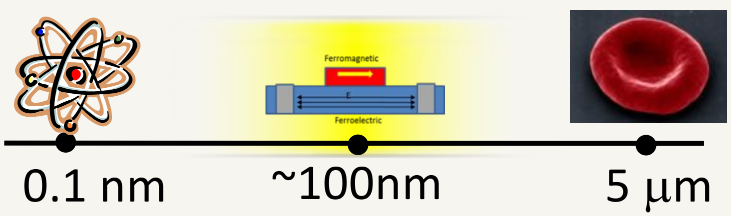
Summary

- Nanoscale multiferroics control magnetization small scale
  - **<u>Efficiency/ Order of magnitude better</u>**

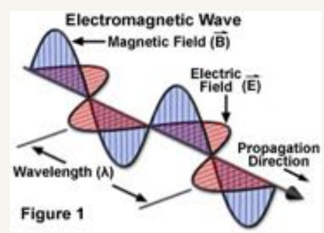
- Modeling needed to guide concepts, **must have**

- Testing of concepts challenging**<u>, small scale</u>**

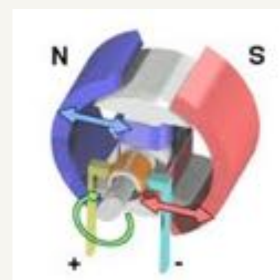
- Application memory, motors and **much more**
  - ***<u>Other just cool stuff – Future of miniature electromagnetics</u>***



Antenna



EM Motor



Thanks to Students & Research Scientists

- Josh Hockel
- Scott Keller
- Paul Nordeen

- Hyungsuk Kim
- Cheng-Yen Liang
- Chin-Jui Ray Hsu

- Tao Wu

PEEM --M. Klaui & Frithjof Nolting et al Johannes Guenberg & Paul Scherrer
PEEM – R. Candler & J. Bokor UCLA & UCB
Superparamagnetic – S. Tolbert UCLA

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TANMS ERC is seeking new Industry Partners

"We have a new way to control magnetism, in the small scale, that we think will CHANGE the world."

TANMS is currently seeking new Industry Partners to collaborate with and to join its industrial advisory board!

(Companies with an interest in Nanoscale Multiferroic applications in Memory, Antennas, Motors, Materials, and Modeling)

Please contact us if interested in learning more at:
https://sites.google.com/a/tanms-erc.org/tanms-industry/home

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Director of Industrial Relations
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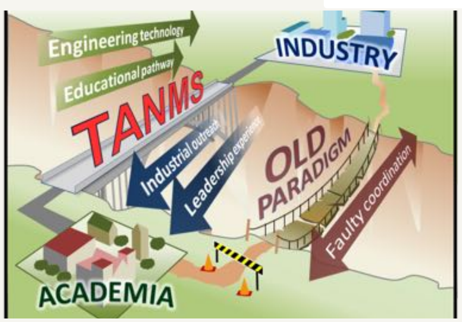
310-825-7855



Thank You and Please Join Us!