

Nanoscale Based ThermalMagnetic Energy Harvesting

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July 30th, 2012

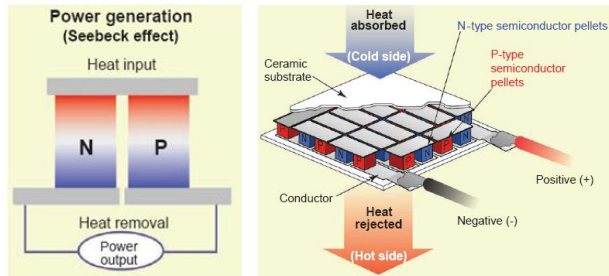
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Background

Project goal:

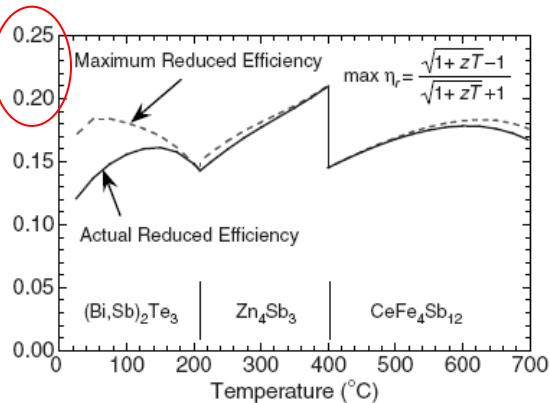
**Thermomagnetic Efficiency of
30~50% of Carnot**

Thermoelectrics



Bell, 2008

Seebeck device: Efficiency is limited at **~20%**



Rowe, 2006

Thermomagnetics

1949 Brillouin
55% of Carnot

1959 Elliot

Materials affect performance

1984 Kirol

Regeneration 75 % of Carnot

1988 Solomon

Magnetic field
increases efficiency

2007 UCLA

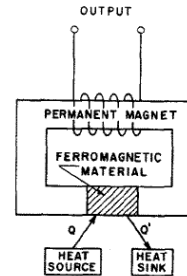
Multi-ferroic and small scale

2011 James

Multi-ferroic alloy

2012 UCLA

Single domain



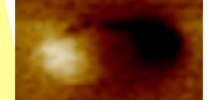
■ AML's previous works

- Exploit nano-scale phenomena

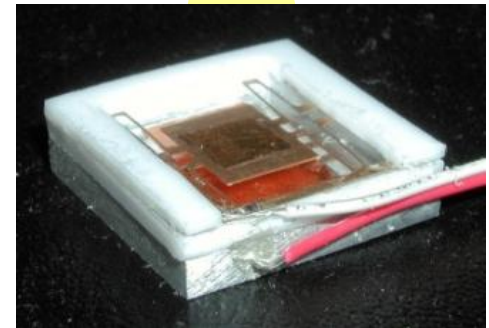
Multi-domain



Single domain



- Thermal-magnetic philosophy



Miniaturized thermomagnetic generator

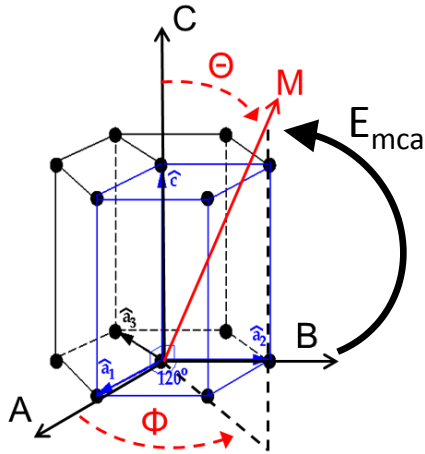
■ Application

- Thermal energy harvesting



To power wireless network
of sensors

Summary UCLA ThermoMagnetic



Curie Point Gd Harvesting:

Multi-Domain

- $\eta_{rel} \approx 12\%$
- Energy Density = 50 kJ/m^3

Single Domain

- $\eta_{rel} \approx 30\%$
- Energy Density = 105 kJ/m^3

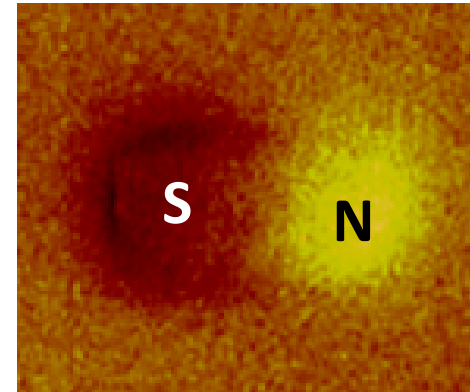
Spin Reorientation:

Gd Single Domain

- trivial

NdCo₅ Single Domain

- $\eta_{rel} \approx 44\%$
- Energy Density = 2 MJ/m^3



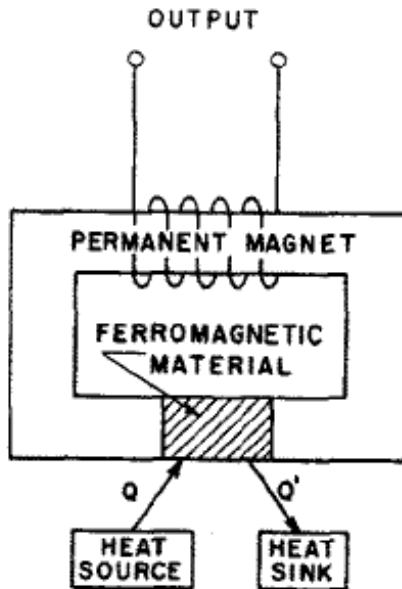
Energy > NdFeB or larger than conventional EM designs

Three Journal articles Three being Written

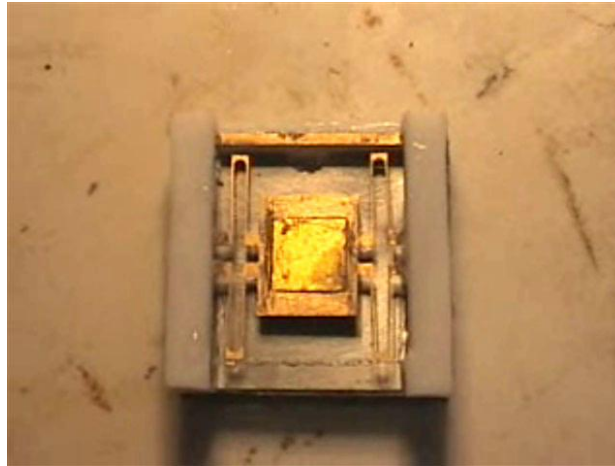
Two Device concepts

1) Coil (Hoover Dam Approach)

- a) Thermal
- b) Magnetic
- c) Electrical

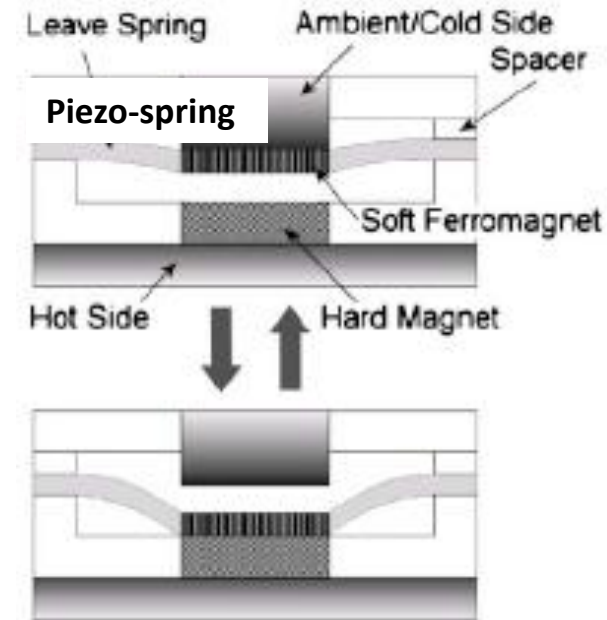


Kirol and Mills, 1984



2) Multi-ferroics (Smart Materials)

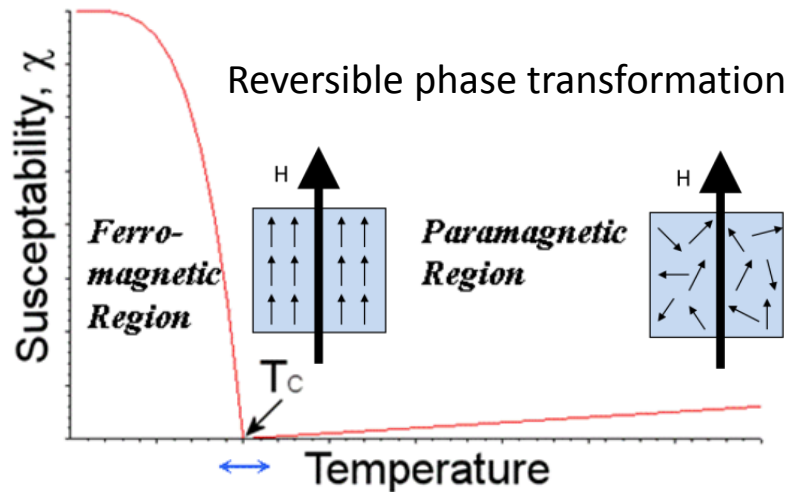
- a) Thermal
- b) Magnetic
- c) Mechanic
- d) Electrical



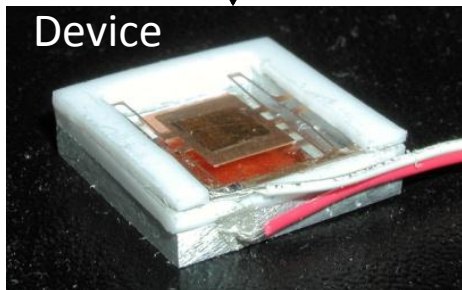
Ujihara et al, 2007

Focus on **efficiency** and **energy** production from thermal to magnetic

Thermomagnetic cycle

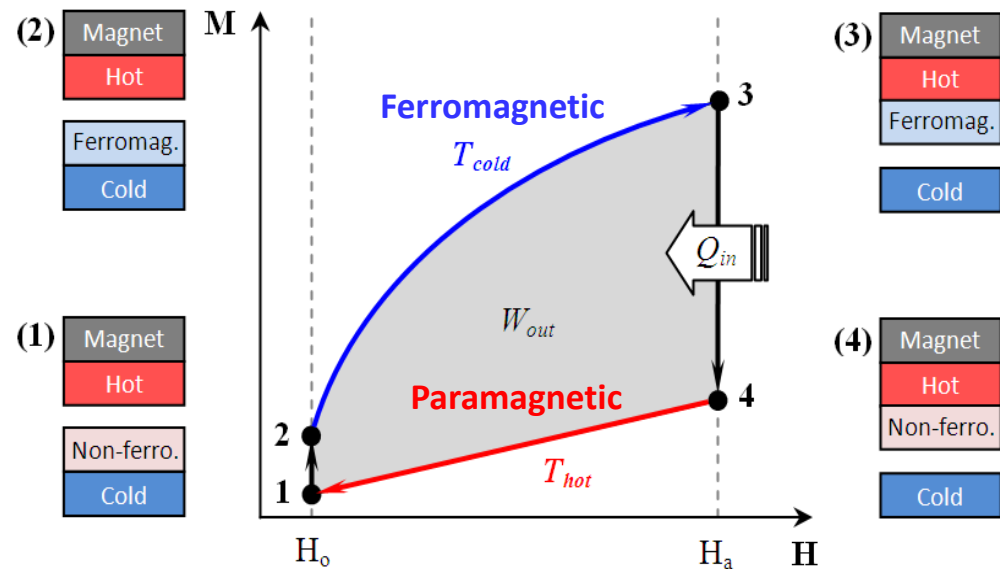


$$Q_{in} = \rho \cdot C_p \cdot (T_{hot} - T_{cold})$$



Q_{out}

$$W_{out} = \oint_{\text{cycle}} H dM(T, H)$$



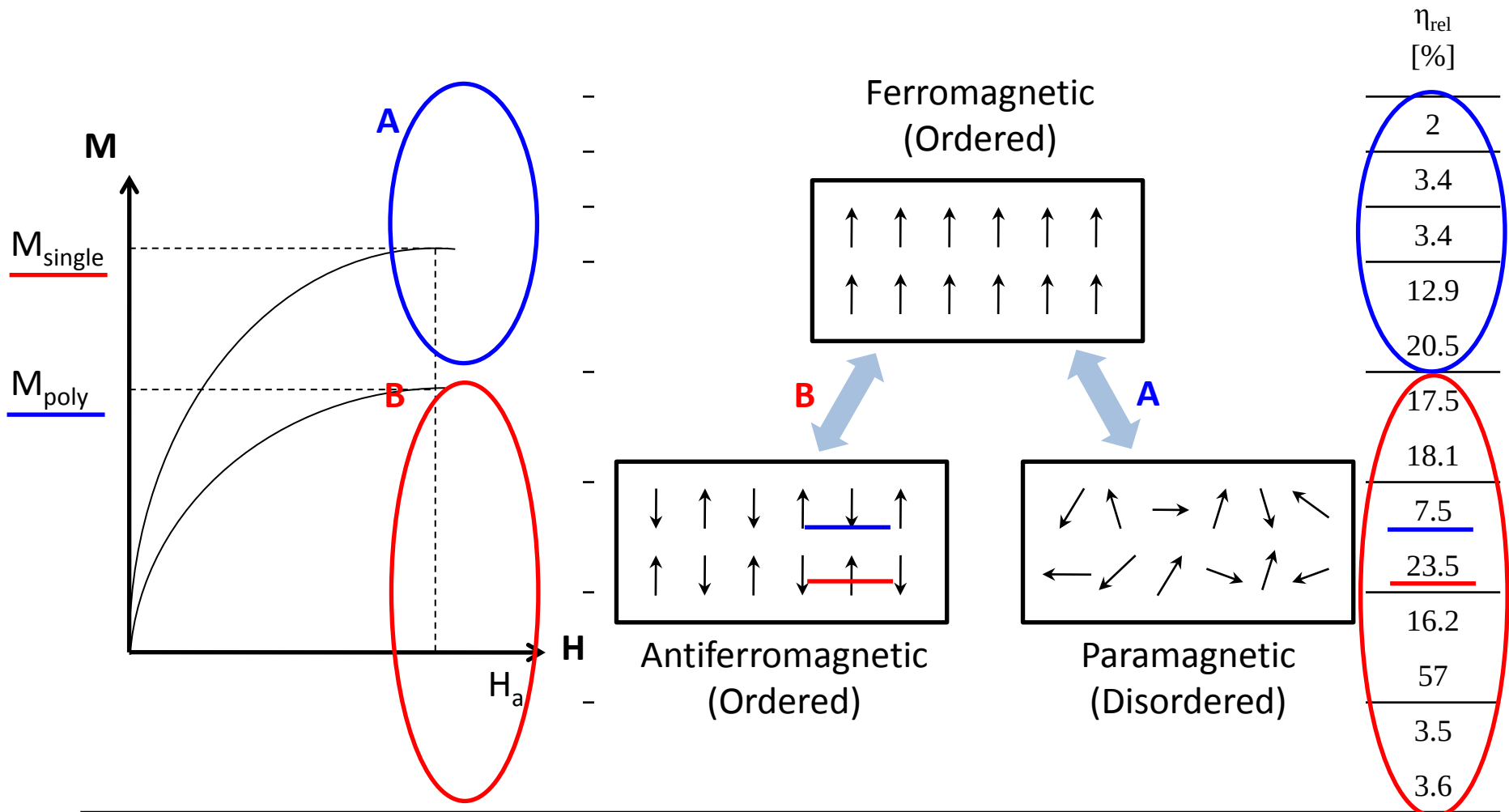
$$\eta_{abs} = \frac{W_{out}}{Q_{in}} = \frac{\text{Bounded } M-H \text{ area}}{\rho C_p \Delta T}$$

$$\eta_{rel} = \frac{\eta_{abs}}{\eta_{Carnot}} = \frac{\text{Bounded } M-H \text{ area}}{\frac{\rho C_p \Delta T}{\Delta T}} \cdot \frac{\Delta T}{T_{hot}}$$

(% of Carnot)

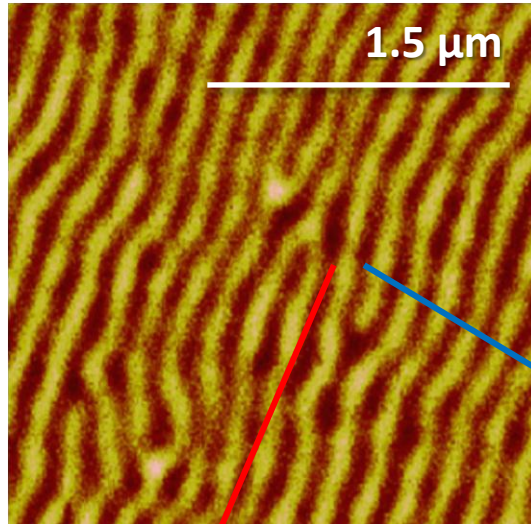
Magneto-thermal Properties of Ferromagnetic Elements

For a thermomagnetic cycle of $H = 3000\text{Oe}$ and $\Delta T = 5\text{K}$



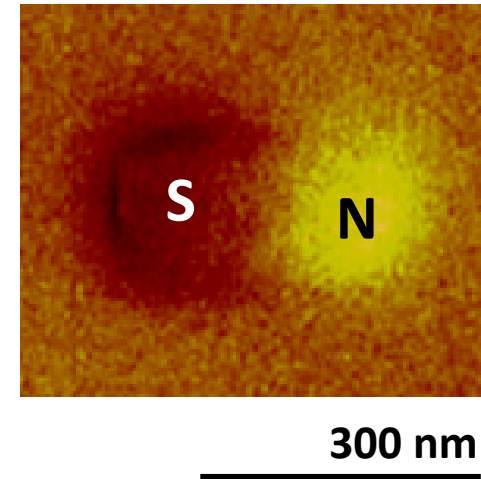
Single domain – better ordered magnetic state

Ni thin film

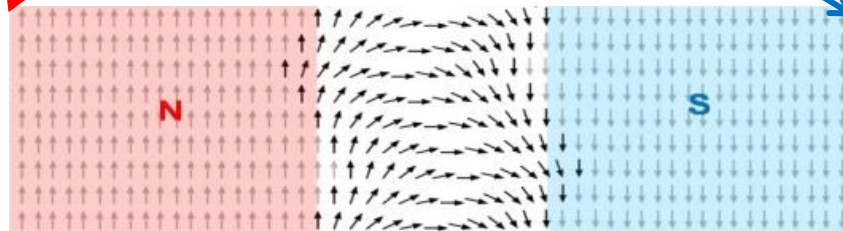


Size ↓
Shape anisotropy ↑

Ni nanobar

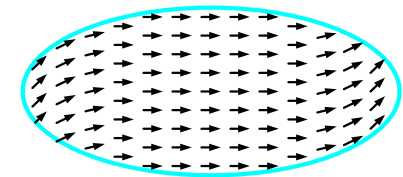


Spin structure



Domain wall

Spin structure

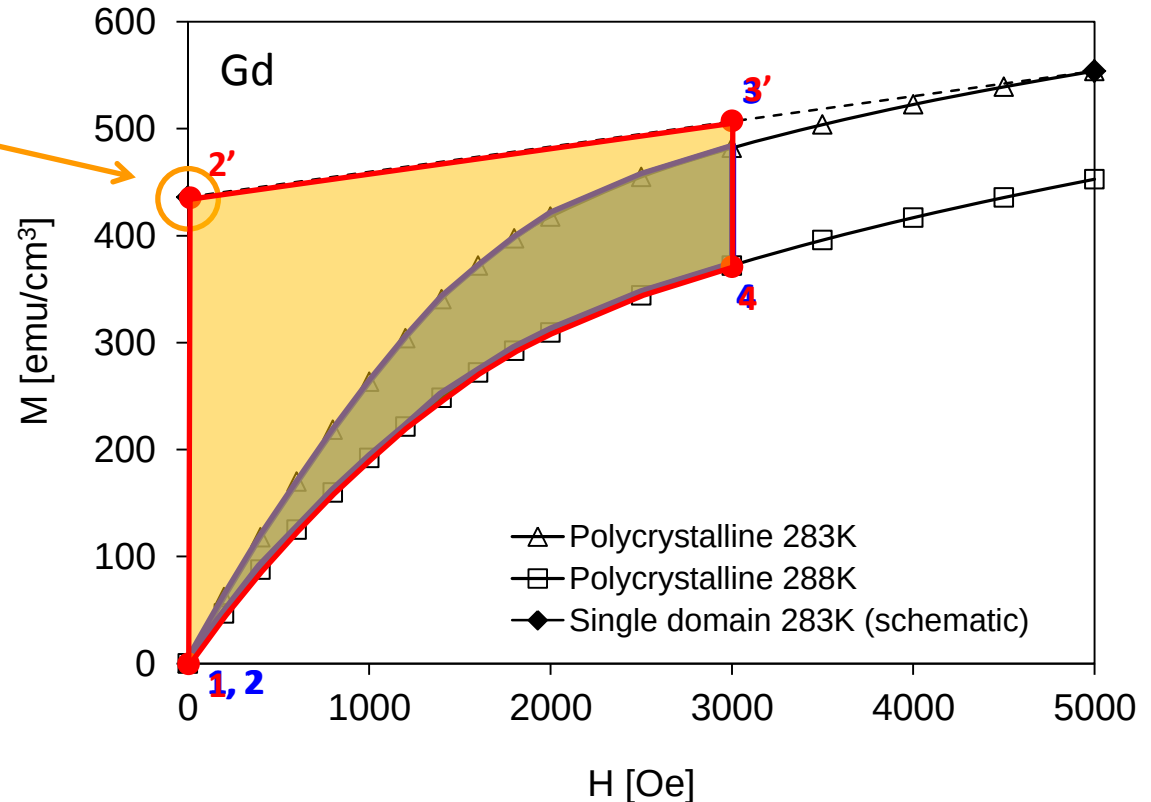
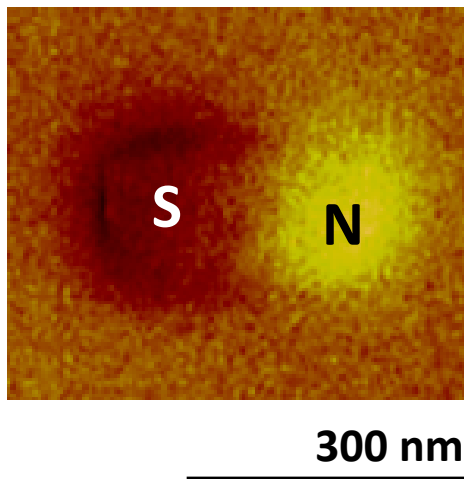


No domain wall

Single domain has high remanence giving higher conversion efficiency!

Single domain improves efficiency

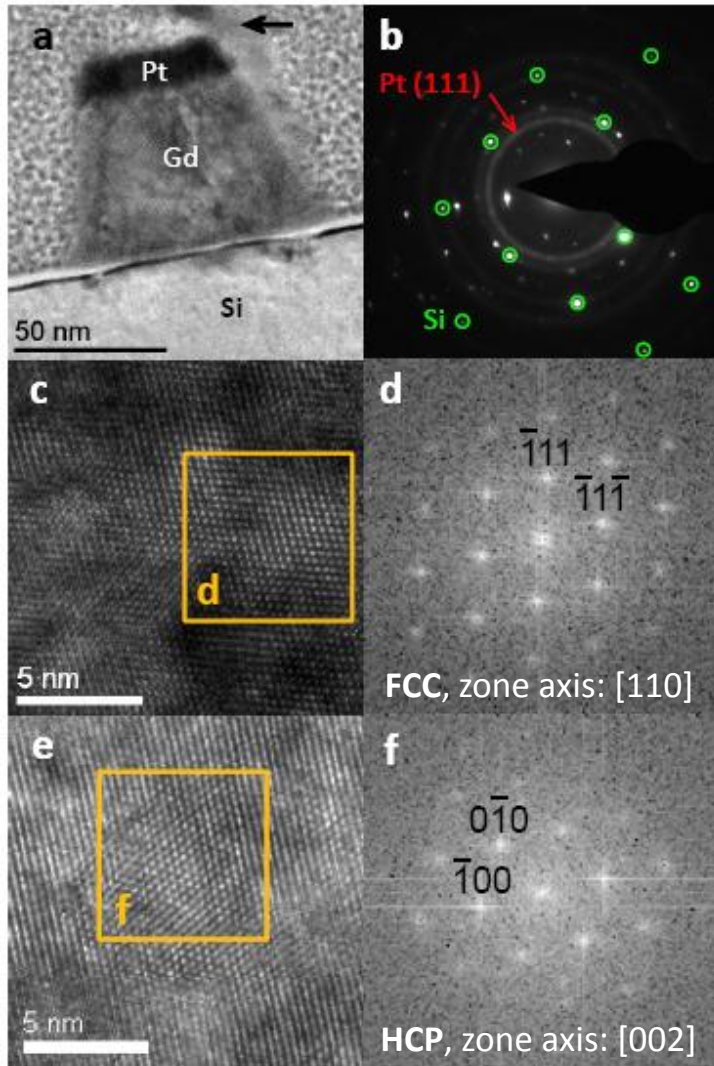
Single domain nanostructure has high remanence



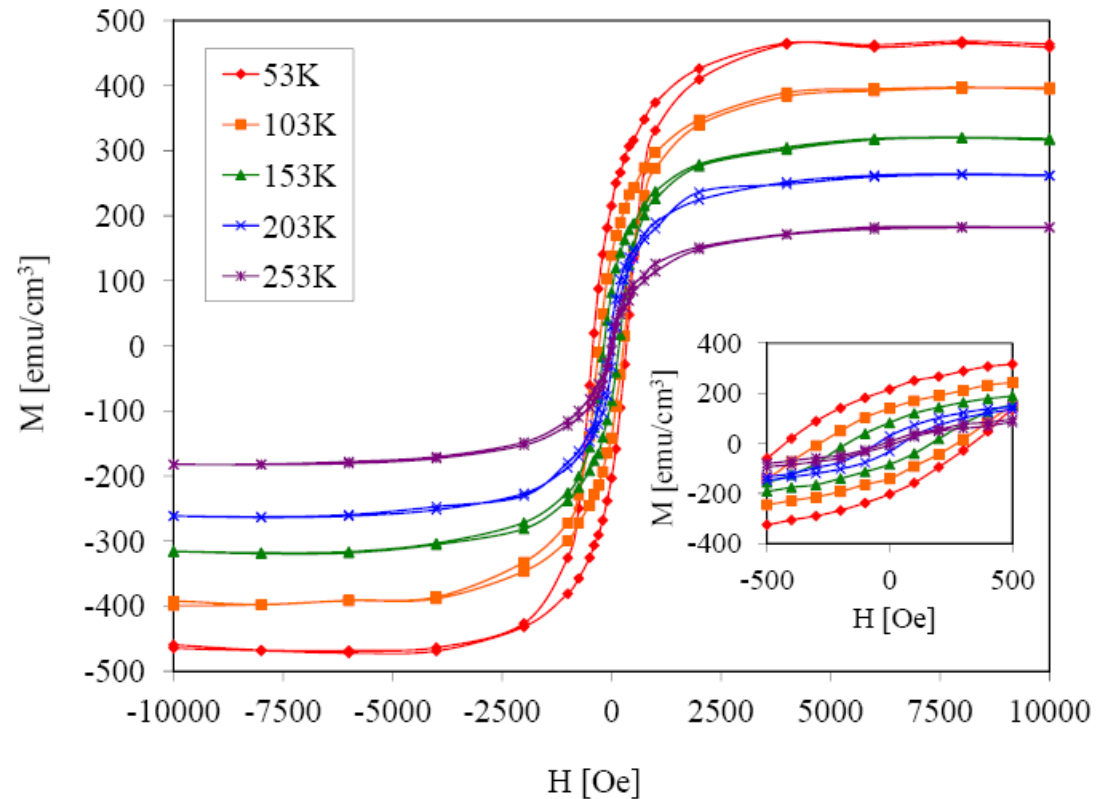
$$\eta_{\text{rel}} = \frac{\eta}{\eta_{\text{Carnot}}} = \frac{\text{Bounded } M\text{-}H \text{ area}}{\frac{\rho C_p \Delta T}{T_{\text{hot}}}} \approx 10\% (\text{bulk}) \rightarrow \sim 30\% (\text{Single domain})$$

Nanobar structure: Issues

HR-TEM analysis:



M-H curves of Gd nanobar array



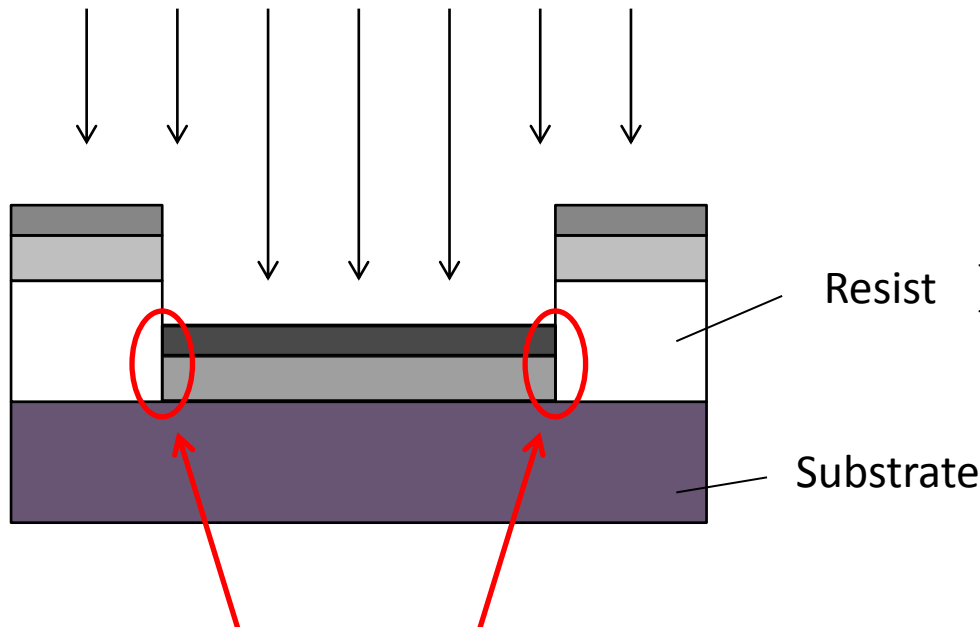
ISSUES

- ✓ Significant M_s reduction
- ✓ HCP to FCC transformation at the nanoscale
- ✓ Surface oxidation – How to prevent?

Nanobar structure: New process

Problem

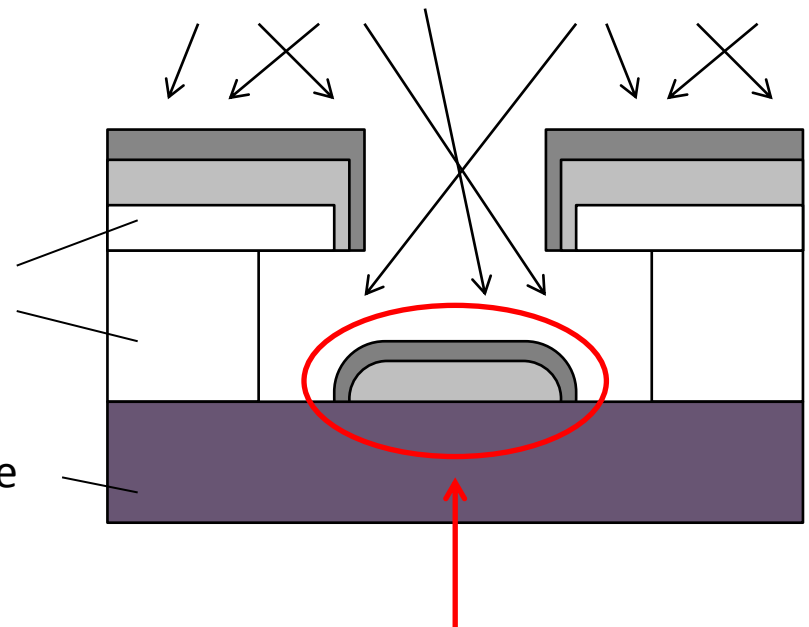
Ebeam evaporation



Inevitable sidewall exposure

Solution

Sputtering



Full coverage

Gd Nanostructures to be tested this month

Basic Science Questions

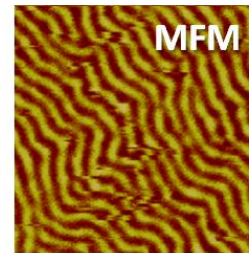
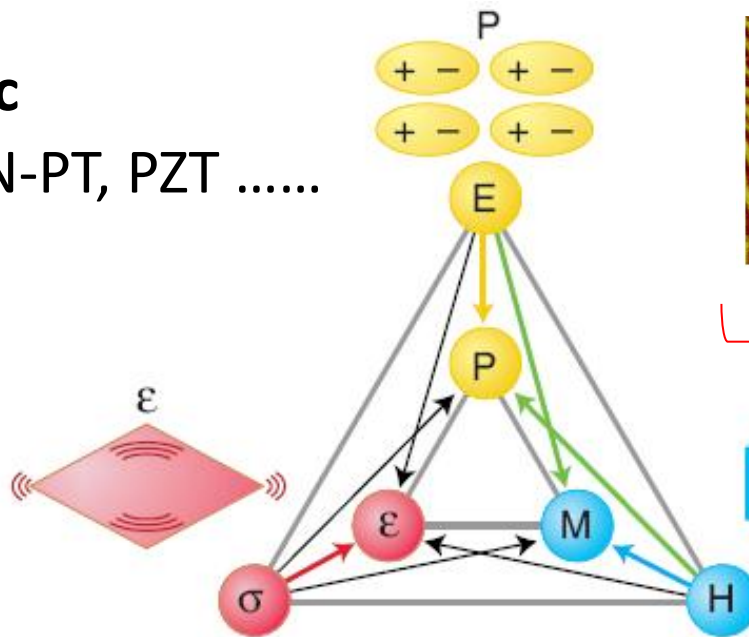
	Ni	Gd
Electron configurations	[Ar] 4s ² 3d ⁸	[Xe] 4f ⁷ 5d ¹ 6s ²
Source of magnetic moment	3d shell	4f shell
Relative shell position	Outmost shell	Inner shell
Exchange coupling	Direct exchange	<i>Indirect</i> exchange
Exchange length	~10 nm	?
Single domain	Exist	?
Superparamagnetic size	~20 nm	?

Multiferroic Energy Transfer

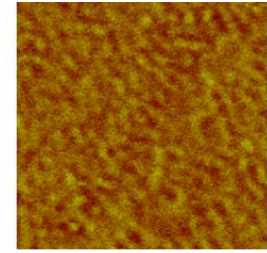
Can we Induce Single Domain from Multi-Domain
Magnetic Structures

Ferroelectric

PMN-PT, PZN-PT, PZT



0 kV/cm



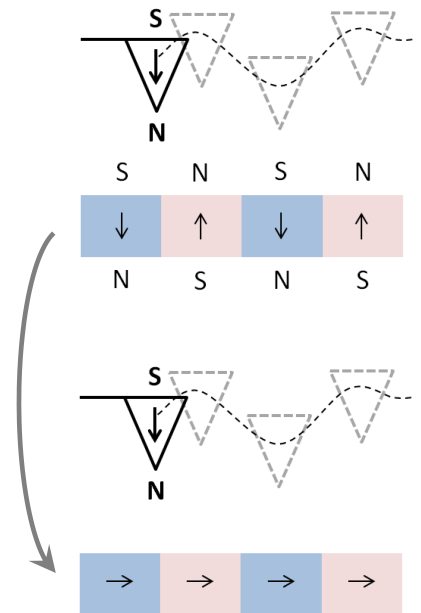
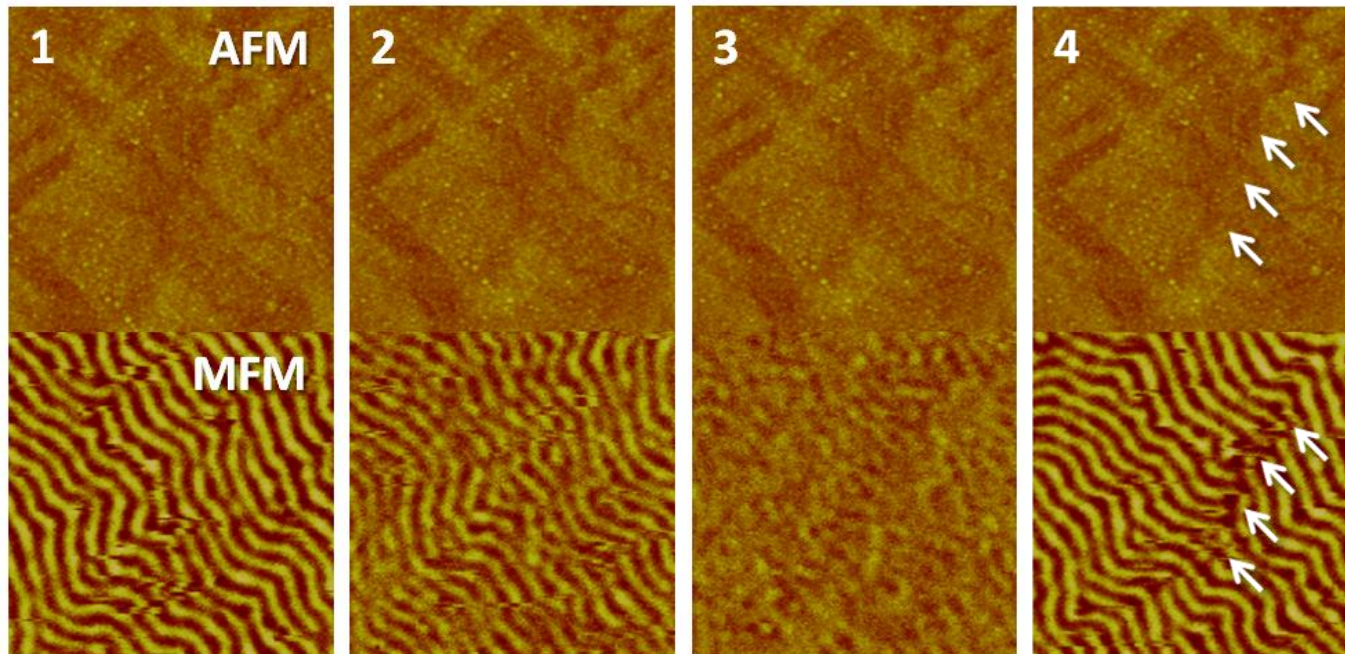
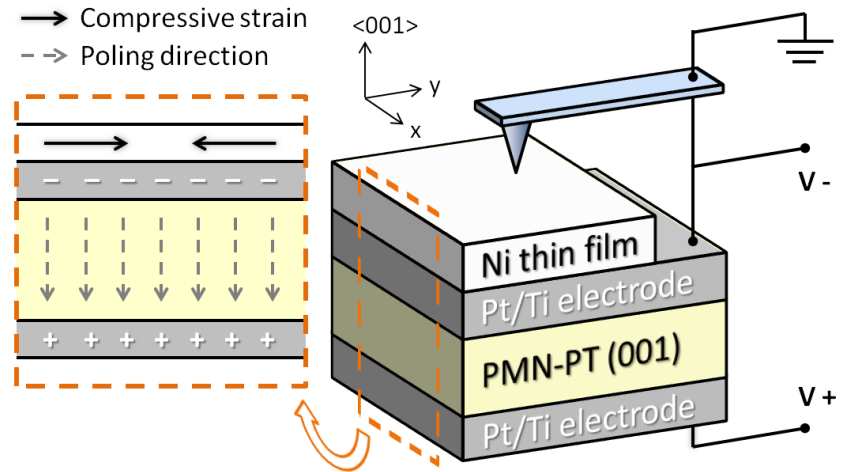
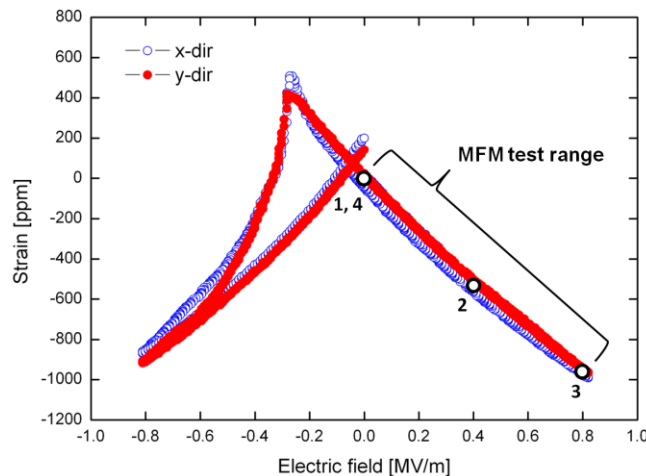
**E-field control
single domain?**

Spaldin and Fiebig, Science, 2005

Ferromagnetic

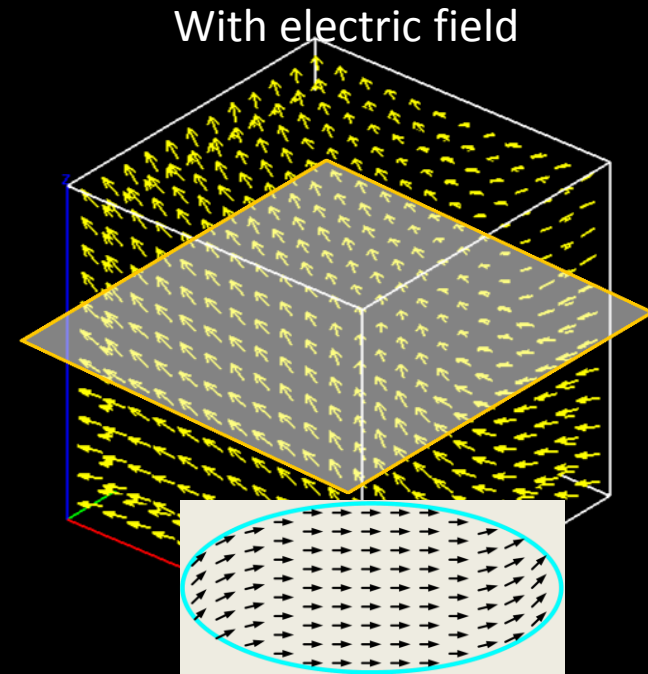
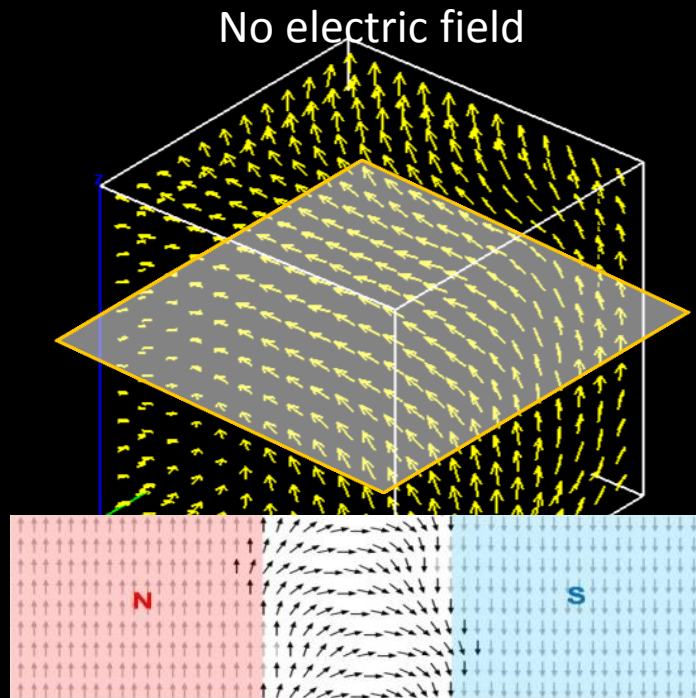
Ni, Gd, Terfenol-D

Experimental Demonstration



2.5 μm

Analytical Model Development



Modeling

1. LLG micromagnetics
2. Mechanical Equilibrium
3. Control magnetic instability



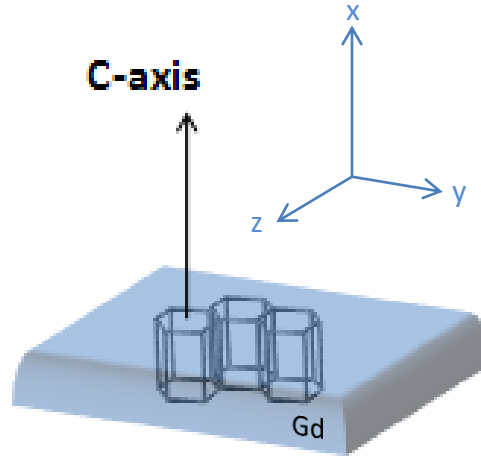
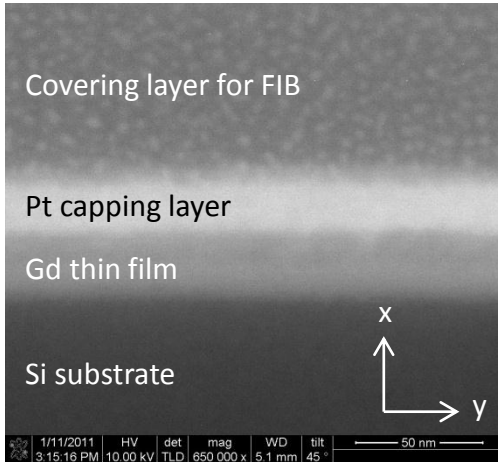
Higher efficiency possible?

Spin-reorientation

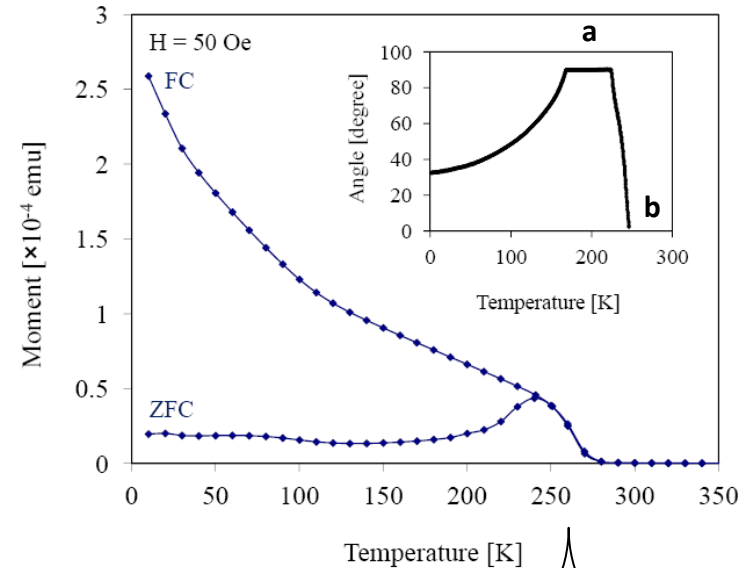
- Gd
- NdCo₅

Spin-reorientation: Gd thin film

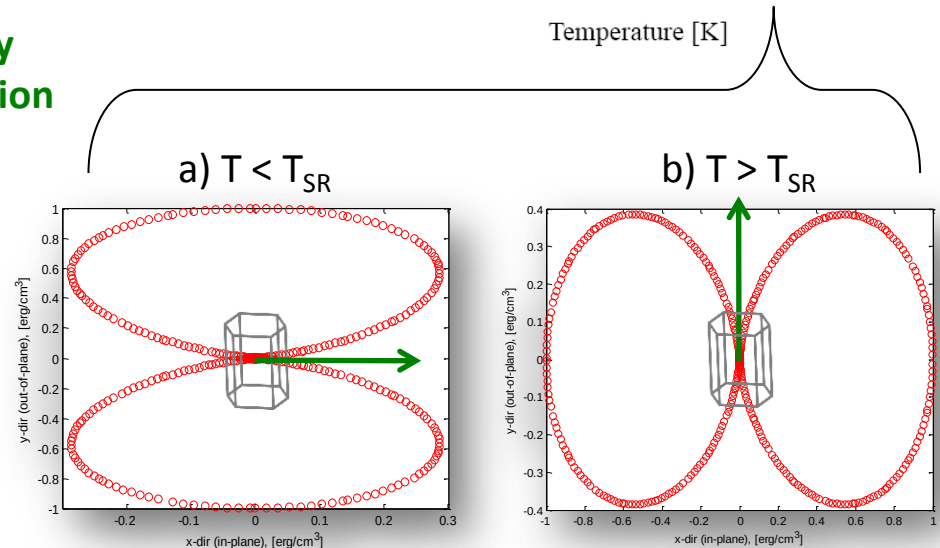
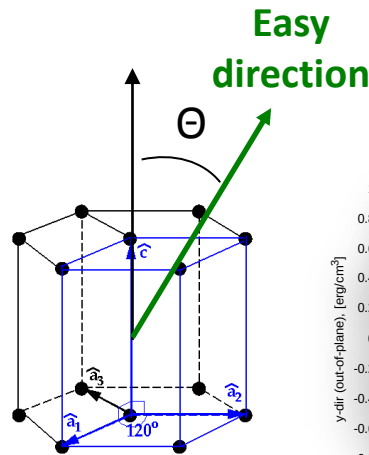
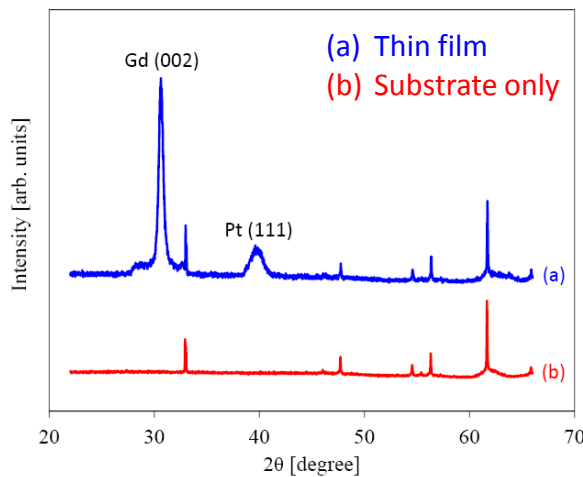
FIB/SEM image



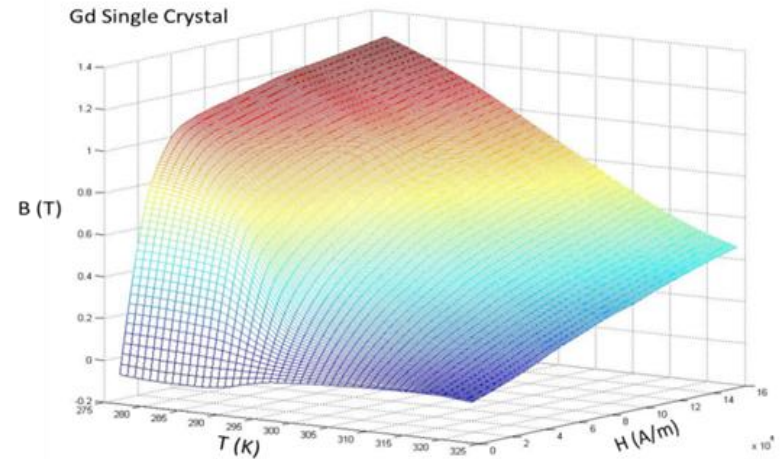
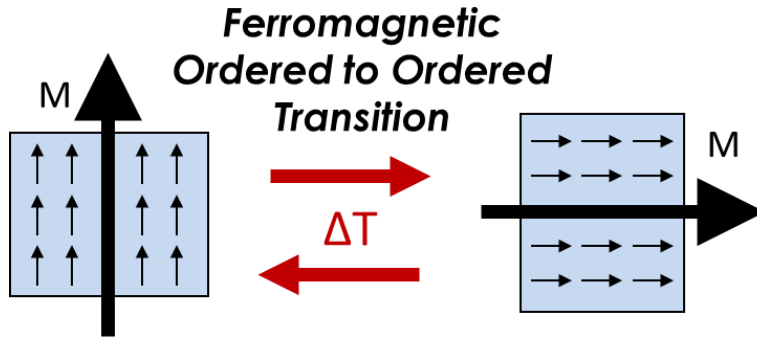
Magnetocrystalline , function of temp.



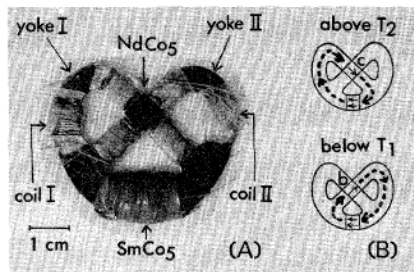
XRD: Textured crystal structure



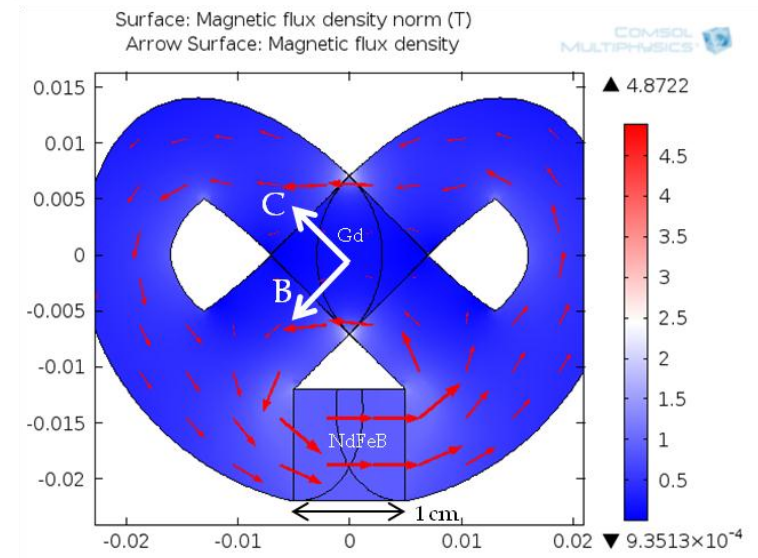
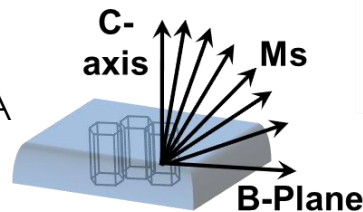
Moving to spin-reorientation harvesting



- 1968 Spin Reorientation: Horner and Varma
- 1968 1st SR Application: Ohkoshi: 8.6% of Carnot



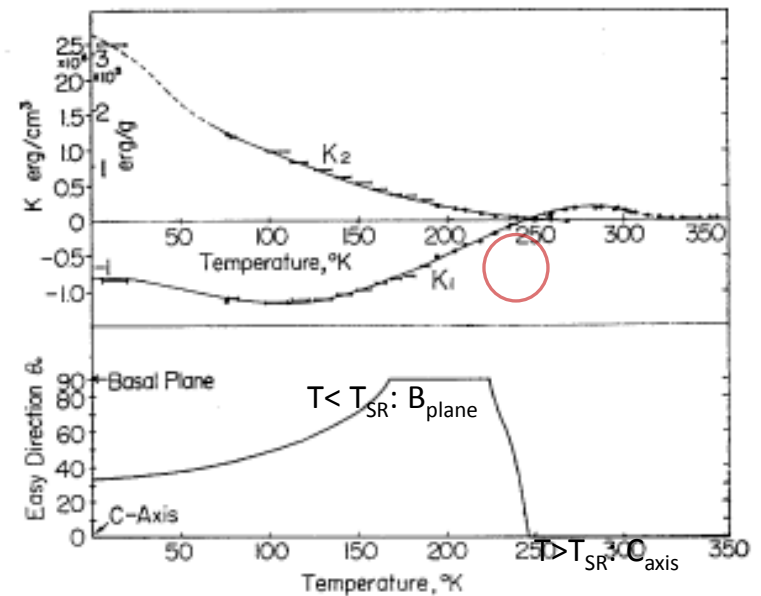
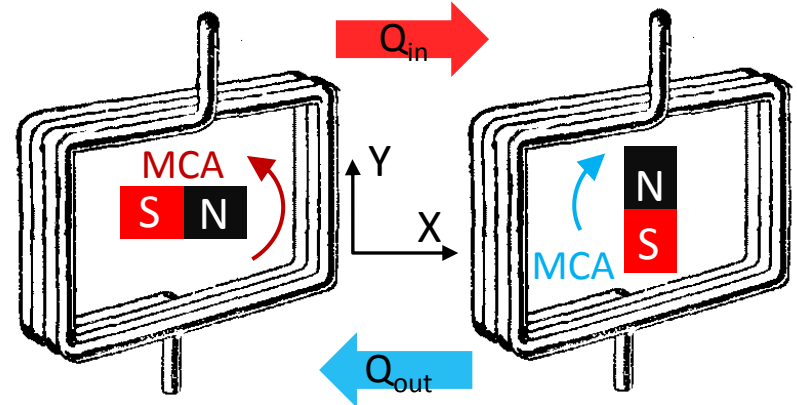
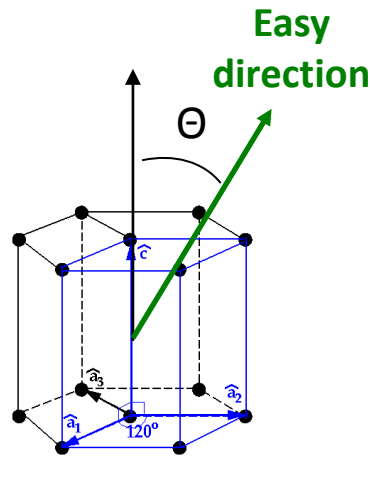
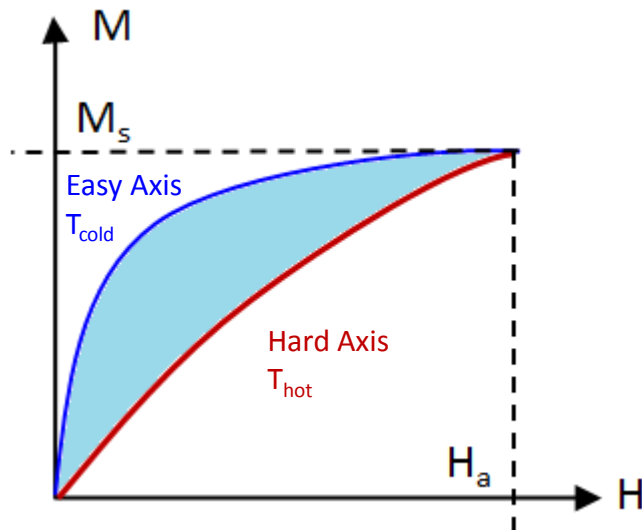
- 2010 NdCo5 Thin Films: M. Seifert
- 2012 Textured Gd Thin Films: UCLA



Change of MCA energy in Gd

- The easy axis of magnetization is dependent on the minimum MCA energy state
- MCA energy can be thought of as “doing work” on the magnetic direction

$$\text{Solving } \frac{dE_{mag}}{d\theta} = 0 \Rightarrow \theta = \pm \arccos \left(\sqrt{\frac{K_1(T) + 2K_2(T)}{2K_2(T)}} \right)$$



Problem very little energy available Gd 5kJ/m(3)

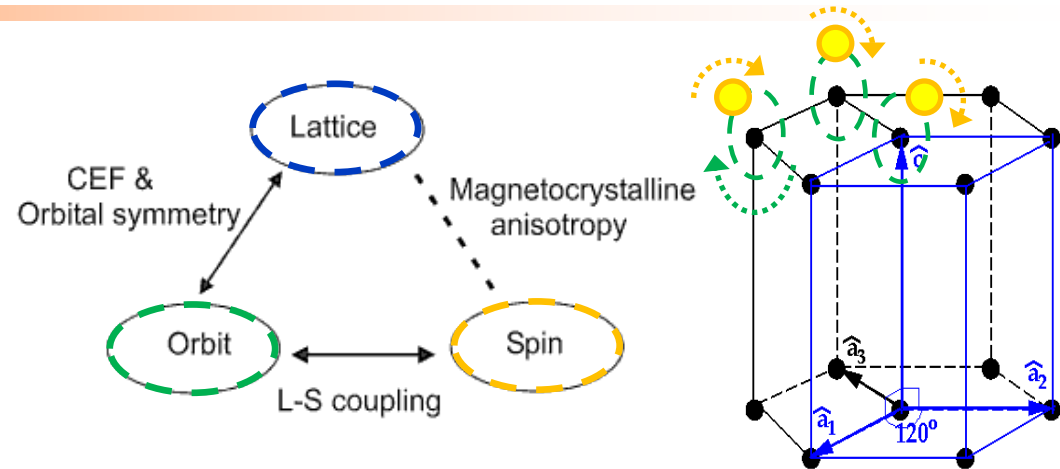
Gd vs. NdCo₅

Rare earth magnets

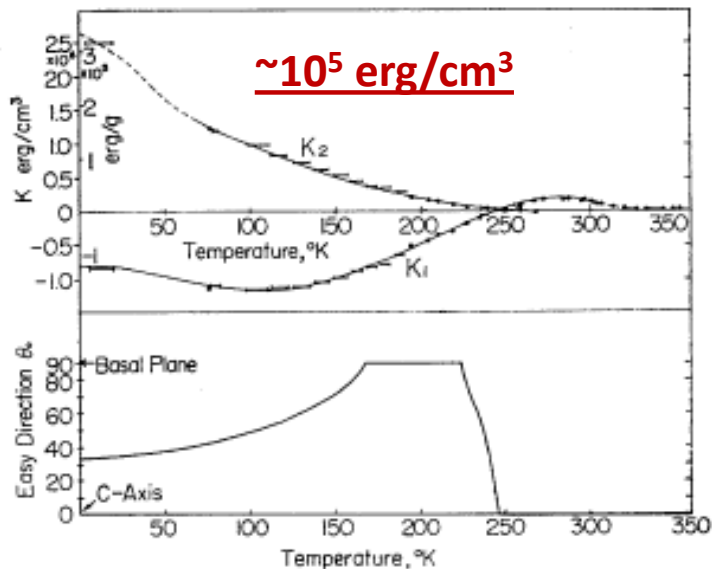
- Magnetization controlled by anisotropic 4f shell

Gadolinium

- Has a half-filled 4f shell -> Very low orbit moment resulting low MCA energy than other RE magnets

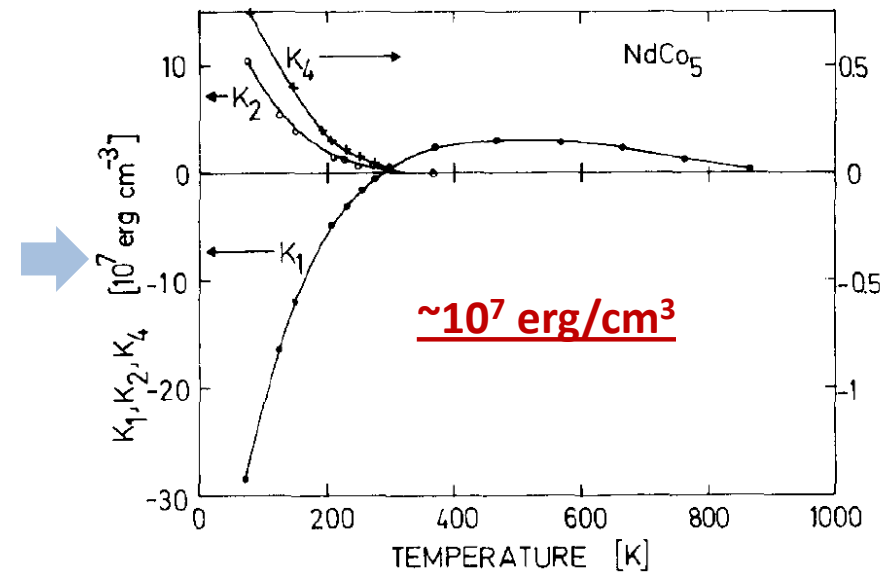


Gadolinium



C.D. Graham, Magnetocrystalline Anisotropy of Gadolinium

NdCo₅

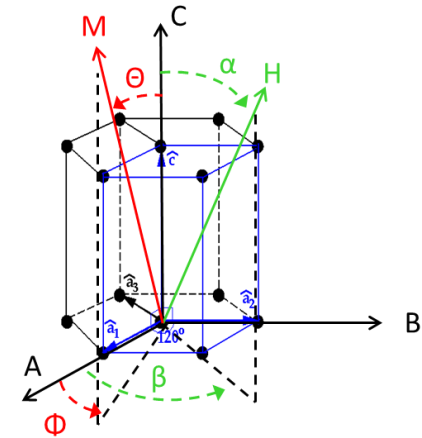
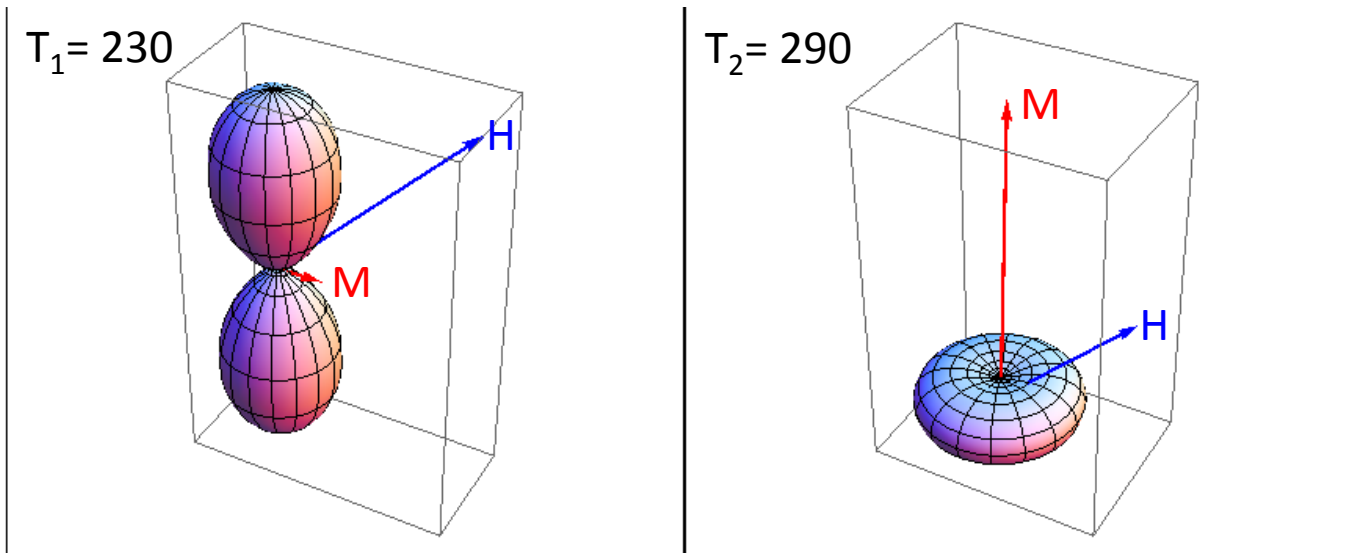


H.P Klein, Magnetocrystalline Anisotropy of Light RE Cobalt Compounds

Analytical Model Single Domain NdCo₅

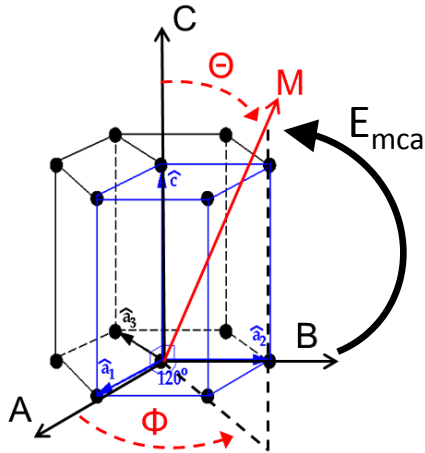
Magnetic Energy Model

- $E_{mag}(\theta, \phi, \alpha, \beta, T, H, N) = E_{ms}(\theta, \phi, \alpha, \beta, H) + E_{mca}(\theta, \phi, T) + E_{sh}(\theta, \phi, N)$
- Solving $\frac{dE_{mag}}{d\theta} = 0$ gives $\theta_{easy}(T)$ or the direction of $M(T)$



- Energy output potential $E_{out} \approx 2 \text{ MJ/m}^3$ yielding $\eta_{rel} \approx 44\%$
- **Currently fabricating film to test**

Summary UCLA ThermoMagnetic



Curie Point Harvesting:

Multi-Domain

- $\eta_{rel} \approx 12\%$
- Energy Density = 50 kJ/m³

Single Domain

- $\eta_{rel} \approx 30\%$
- Energy Density = 105 kJ/m³

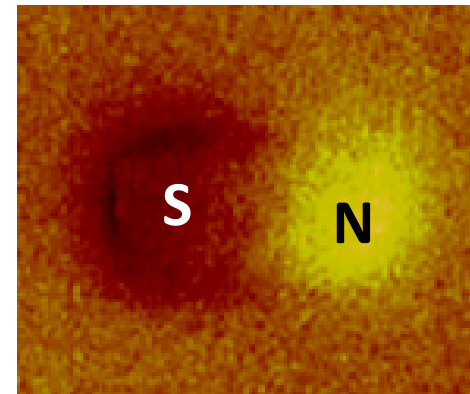
Spin Reorientation:

Gd Single Domain

- $\eta_{rel} < 1\%$
- Energy Density = 12 kJ/m³

NdCo₅ Single Domain

- $\eta_{rel} \approx 44\%$
- Energy Density = 2 MJ/m³



Energy Larger Than NdFeB or large than conventional EM designs

Summary

- **ThermalMagnetics represents a very promising energy harvesting methodology**
- **Efficiency increases by 3X using single domain**
 - More energy output nanobar structure
 - Multiferroic structure
- **Spin-reorientation**
 - MCA dominates work output
 - NdCo_5 superior than Gd in terms of MCA change
 - Very large energy density present in NdCo_5



The Nation that Controls
Magnetism will Control the
Universe.