Control of Magnetism
with
Oxide Hybrid Structures

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Magnetism

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

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Oxide

AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

FA9550-12-1-0381

Acknowledgement

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Principal Investigator

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Thin Film, Magnetism

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Diffraction, Magnetism

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Thin Film, Simulation,
Fabrication

Outline

- ***Introduction***
  - Review Control of Magnetism
  - Phase Transition in Vanadium Oxide (VO_x)

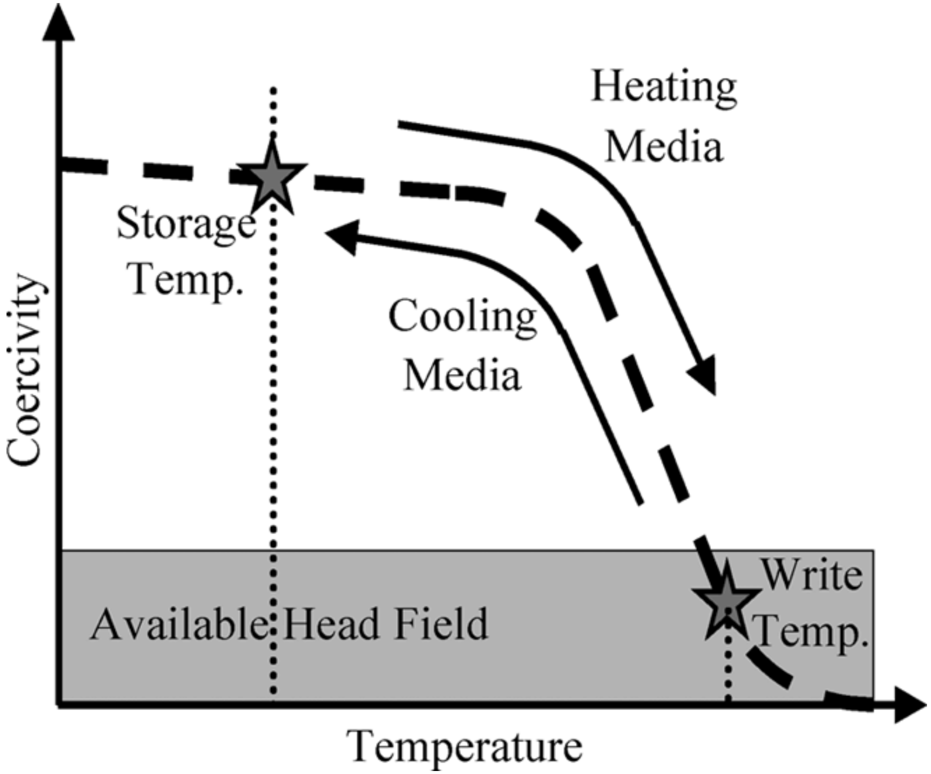
- ***Control of Magnetism with VO_x/FM***
  - Tuning with Magnetostrictive Effect

- ***Coercivity Enhancement in V_2O_3/Ni***
  - Competing Length Scales on Nanoscale

- ***Summary and Outlook***

Control of Magnetism

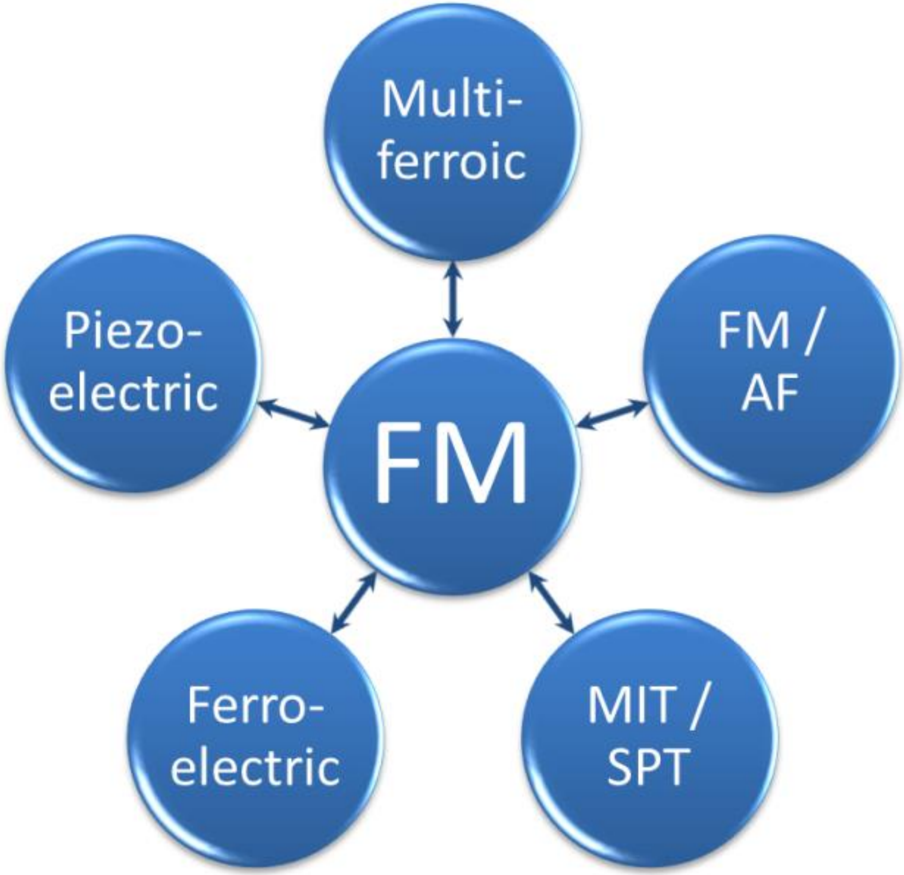
Heat Assisted Magnetic Recording (HAMR)



- Microwave Assisted
- Acoustic Phonon Assisted
- Ultrafast Laser Induced

M. H. Kryder, E. C. Gage, T. W. McDaniel, W. A. Challener, R. E. Rottmayer, G. Ju, Y.-T. Hsia, and M. Fatih Erden, Proc. IEEE **96**, 1810 (2008)

“Sun-Wheel” of Oxide Hybrid Structures



Multi-ferroic

Piezo-electric

FM / AF

FM

Ferro-electric

MIT / SPT

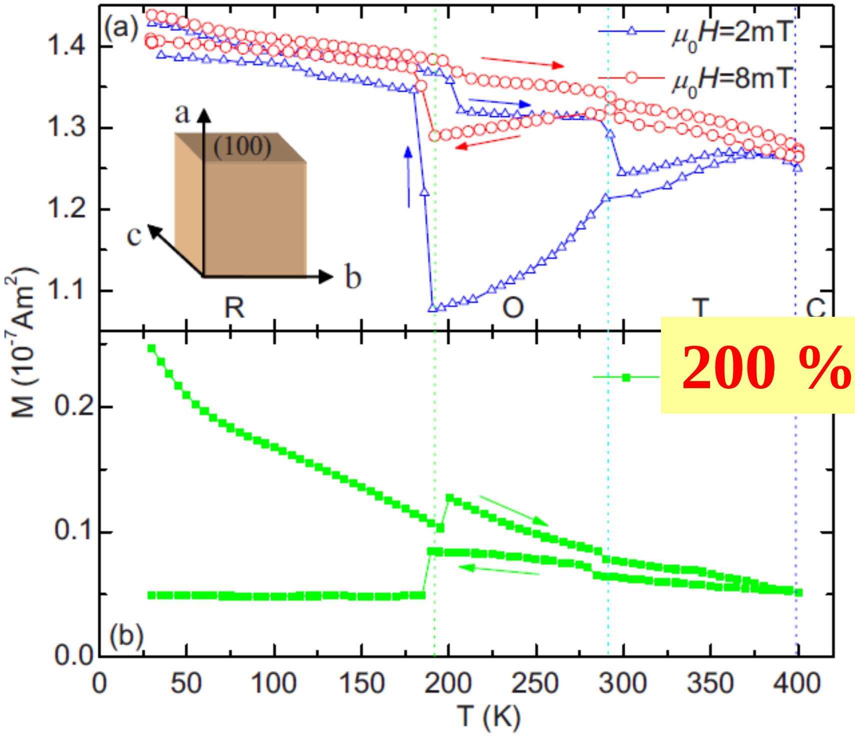
FM: Ferromagnetic
AF: Antiferromagnetic

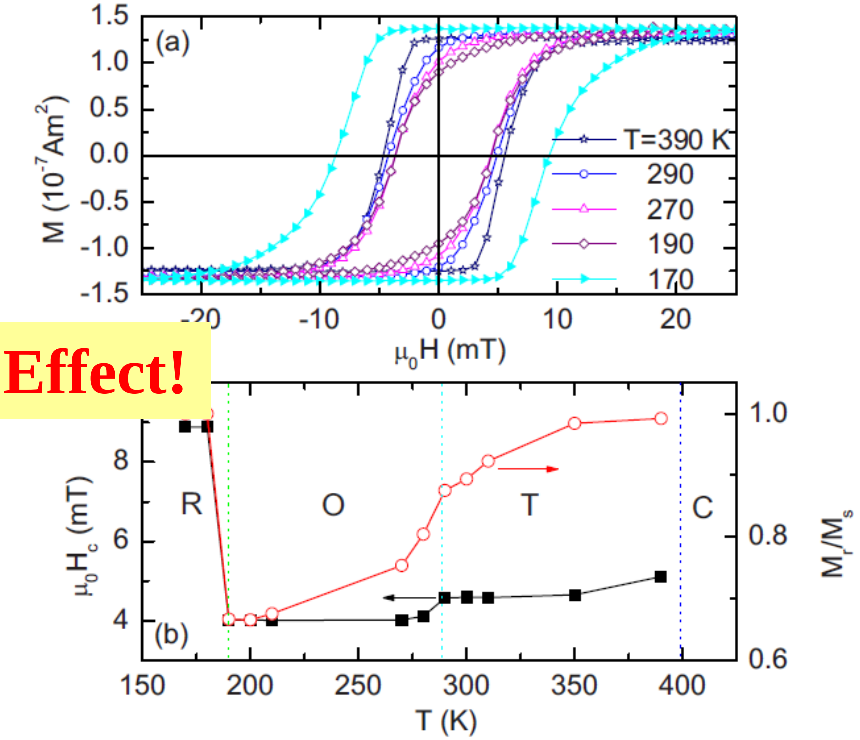
MIT: Metal Insulator Transition
SPT: Structural Phase Transition

T. Saerbeck, J. de la Venta, S. Wang, J. G. Ramirez, M. Erekhinsky, I. Valmianski, I. K. Schuller, J. Mater. Res., Invited Review (2014)

Control of Magnetism with SPT

BaTiO$_3$ /Fe Bilayer: Control through Interface Strain Coupling



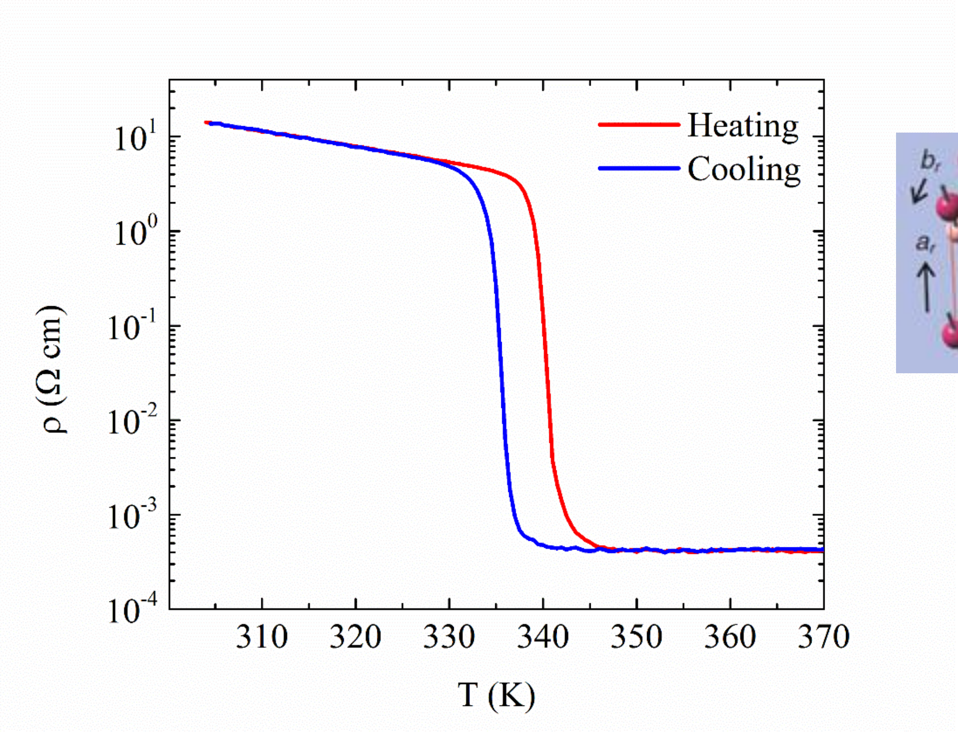


200 % Effect!

S. Sahoo *et al*., Phys. Rev. B **76**, 092108 (2007)

Phase Transition in VO_2

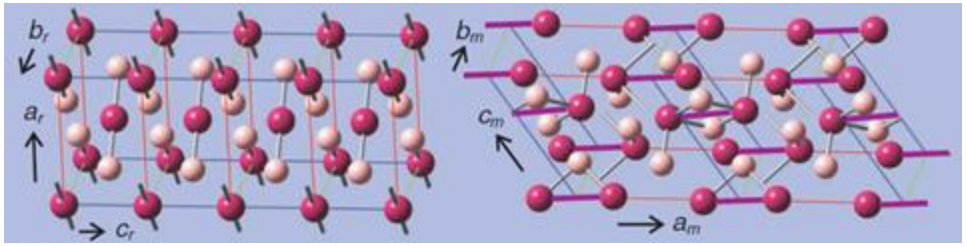
MIT



$T_C = 340$ K

SPT

High-T Rutile **Low-T Monoclinic**



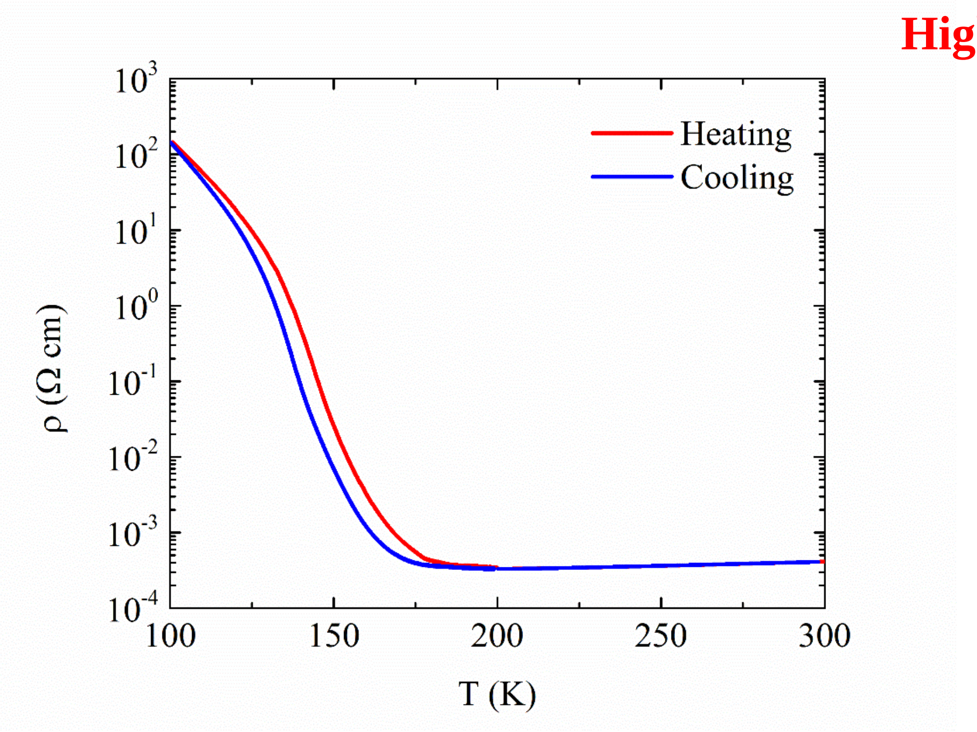
P. Baum *et al.*, Science **318**, 788 (2007)

~ 1 % Lattice Distortion

~ 1 % Volume Change

Phase Transition in V_2O_3

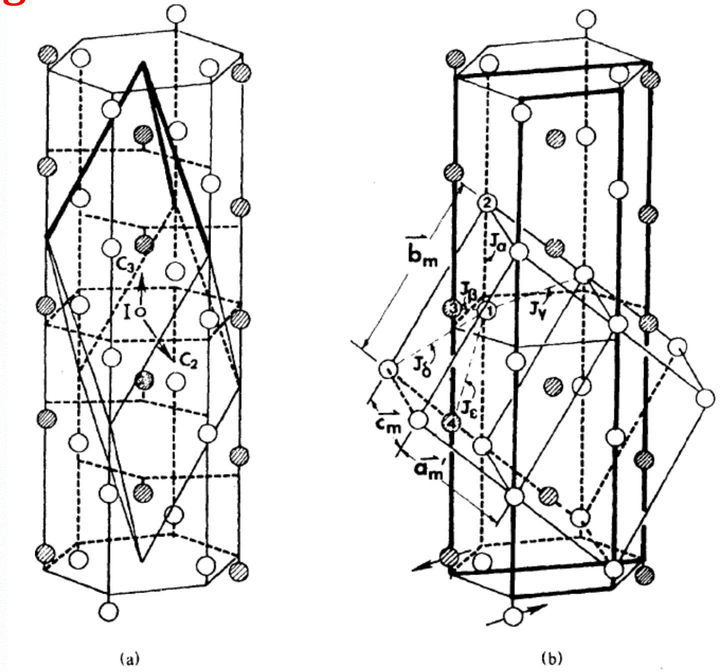
MIT



T_C = 150 – 165 K

SPT

High-T Rhombohedral **Low-T Monoclinic**



R. E. Word *et al.*, Phys. Rev. B **23**, 3533 (1981)

~ 1 % Lattice Distortion

~ 1 % Volume Change

Why VO_x?

- First Order Phase Transition

Abrupt Structural Change in **Narrow** Temperature Range

- Choice of Transition Temperatures

$T_C(VO_2)$ = 340 K, $T_C(V_2O_3)$ = 150 – 165 K

- Multiple Driving Forces to Induce SPT

Temperature, Voltage/Current, Light, Gating, Pressure, etc.

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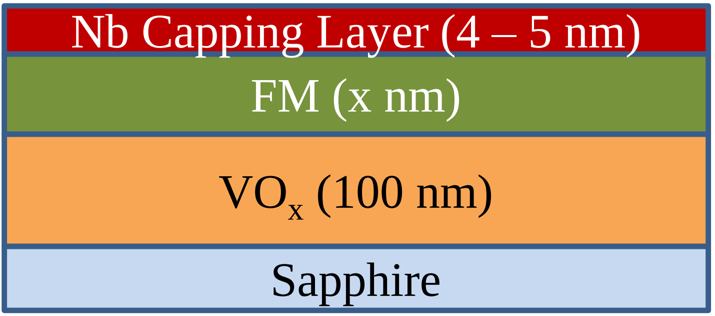
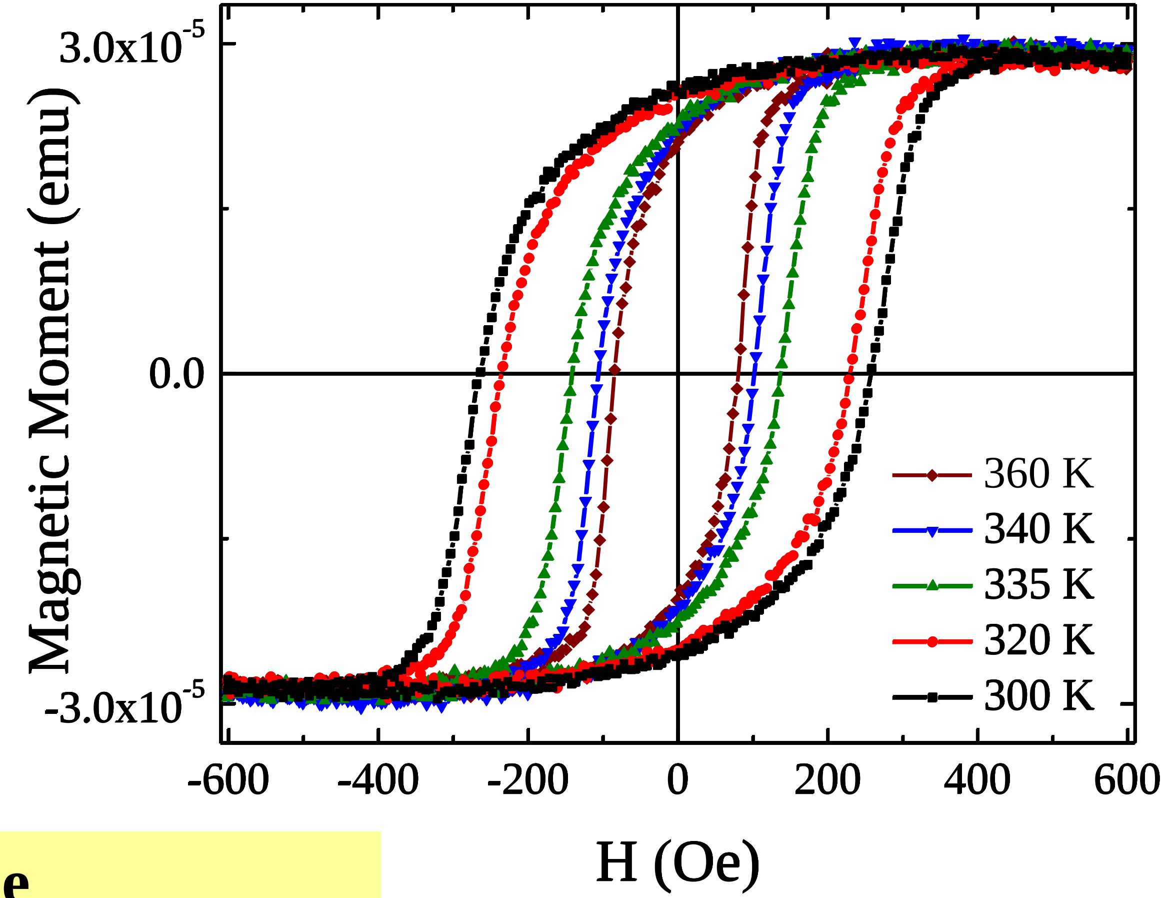
  - Competing Length Scale on Nanoscale

- ***Conclusions***

VO_2 / Ni

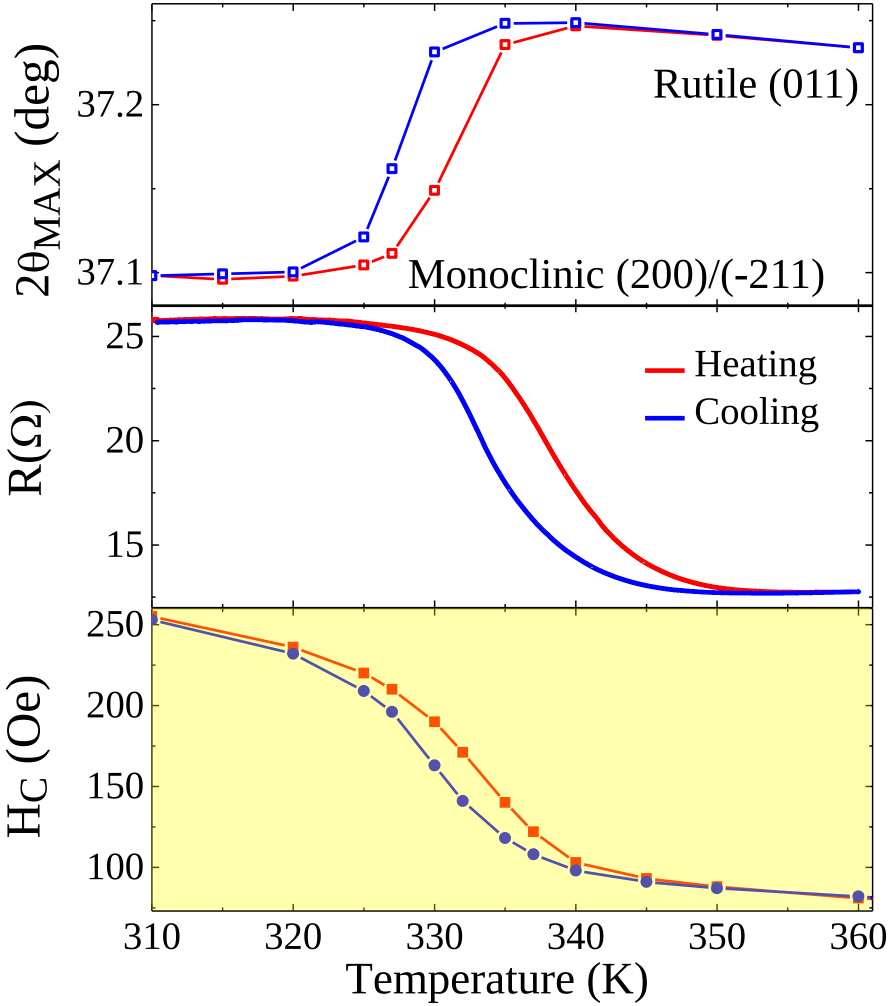


100 nm VO_2 / 10 nm Ni



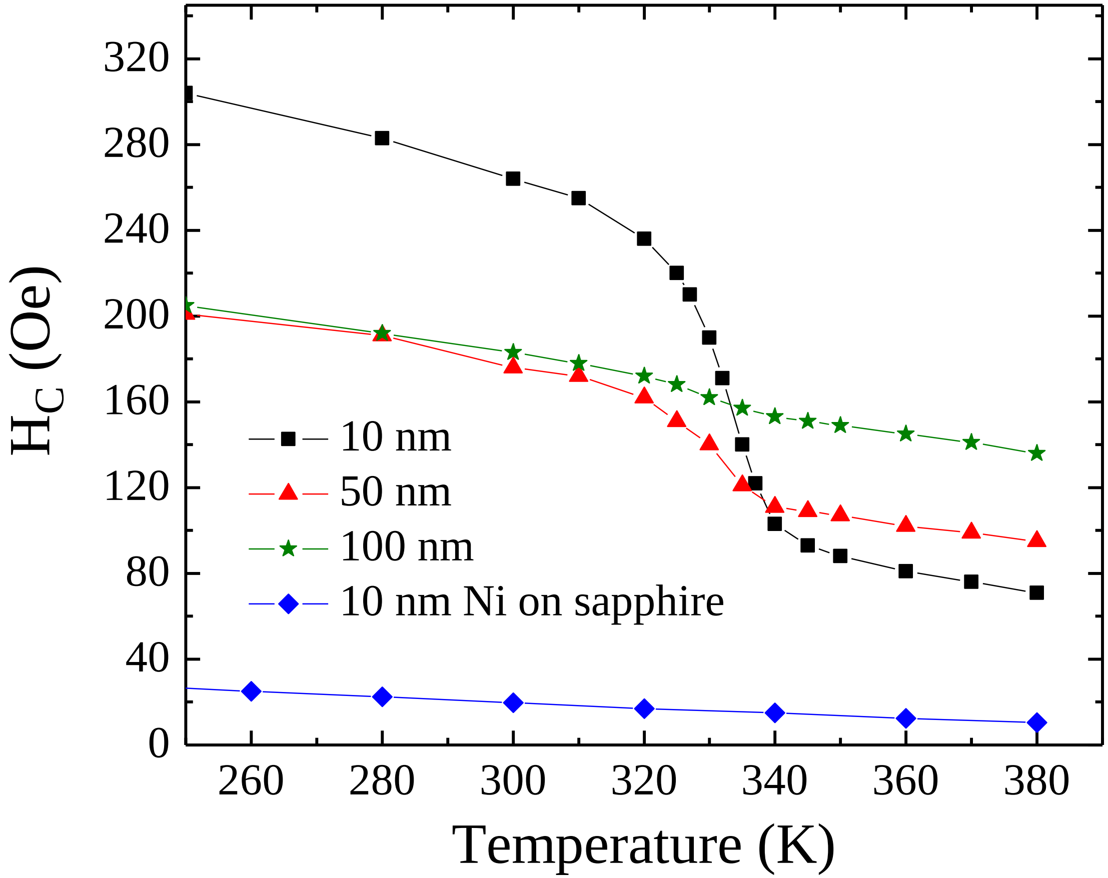
200 % Coercivity Change across VO_2 Phase Transition at 340 K

Correlation: Phase Transition & Magnetism



Temperature Dependence & Thermal Hysteresis of H_C Coincide with MIT & SPT of VO_2

Ni Thickness Dependence



Effect Reduces as Ni Thickness Increases ➡ **Interface Effect**

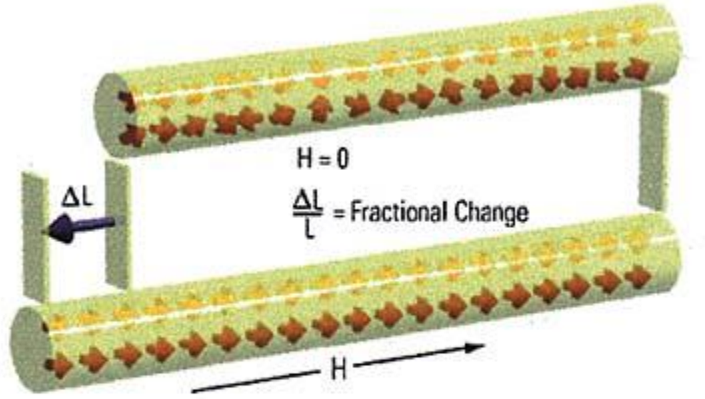
Magnetostriction

Change of Dimensions in the Applied Field Direction

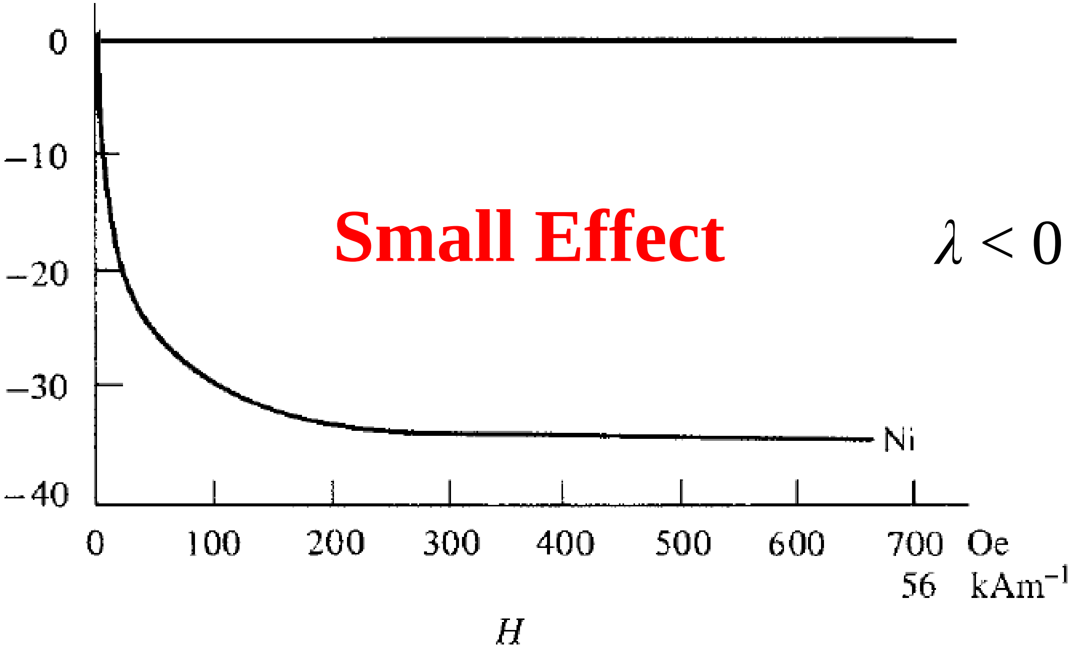
Magnetostriction Coefficient $\lambda = \dfrac{\Delta L}{L}$

$\lambda < 0$ Contracts when Magnetized

$\lambda > 0$ Elongates when Magnetized



Polycrystalline Ni λ (10^{-6})



Small Effect

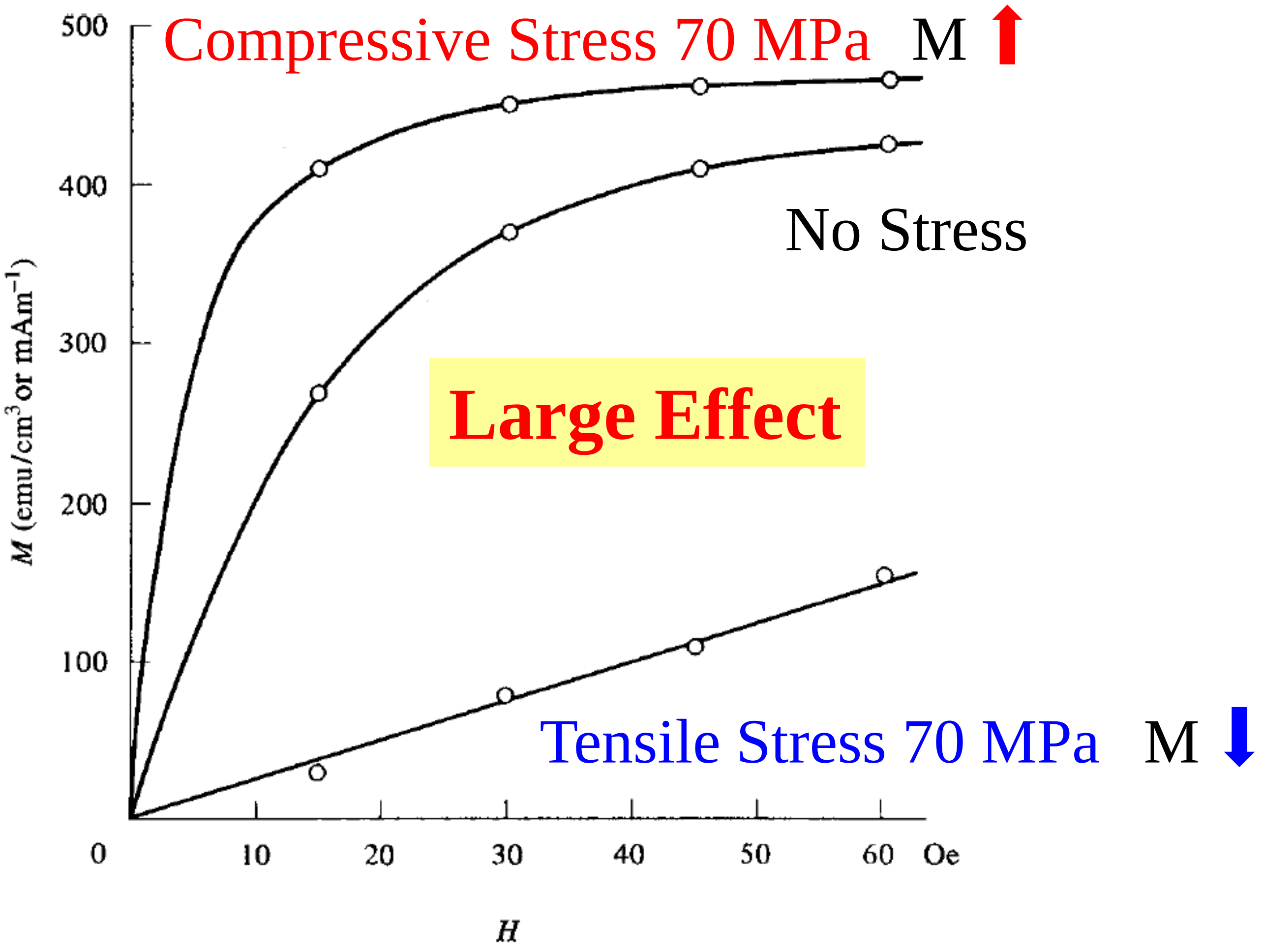
$\lambda < 0$

B. D. Cullity and C. D. Graham. Introduction to Magnetic Materials

Inverse Magnetostriction

Change of Magnetization due to Applied Stress

Polycrystalline Ni



Compressive Stress 70 MPa M ⬆

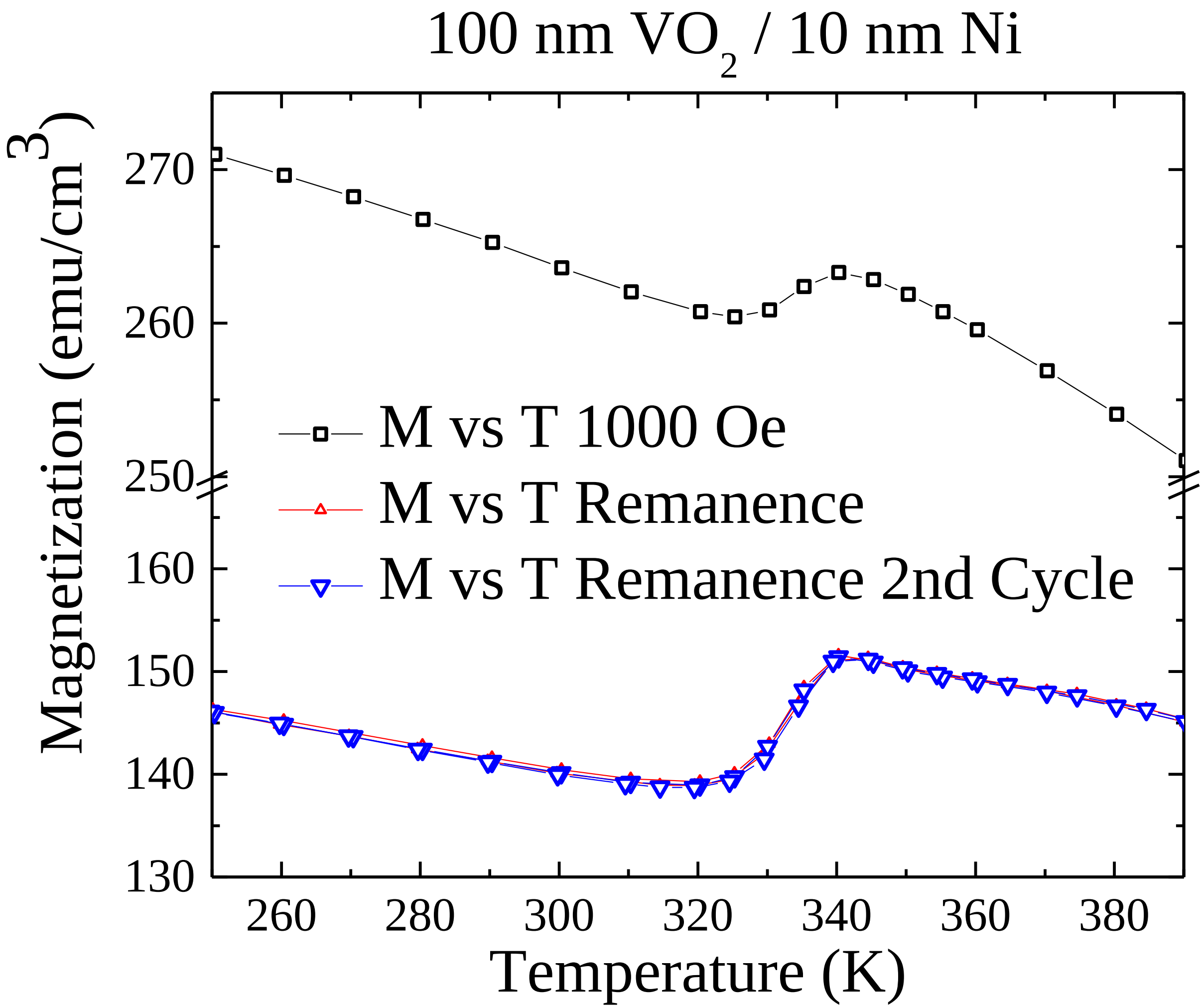
No Stress

Large Effect

Tensile Stress 70 MPa M ⬇

B. D. Cullity and C. D. Graham. Introduction to Magnetic Materials

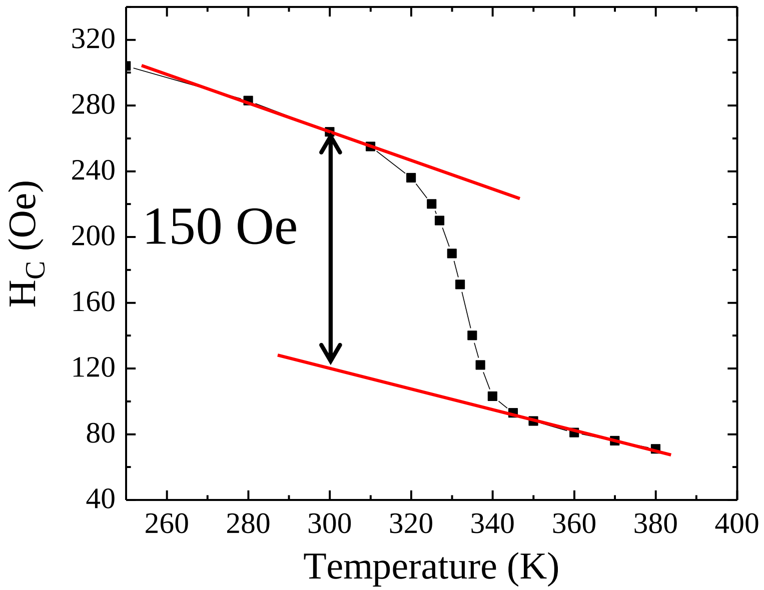
Magnetization vs. Temperature



Magnetic Domain Dynamics

Stress Anisotropy

100 nm VO_2 / 10 nm Ni



Stress Anisotropy Field

$$H_{K\sigma} = \frac{3\lambda\sigma}{M_S}$$

M_S = 470 emu/cm^3

λ = - 34 × 10^{-6} Polycrystalline Ni

→ **σ ~ 59 MPa**

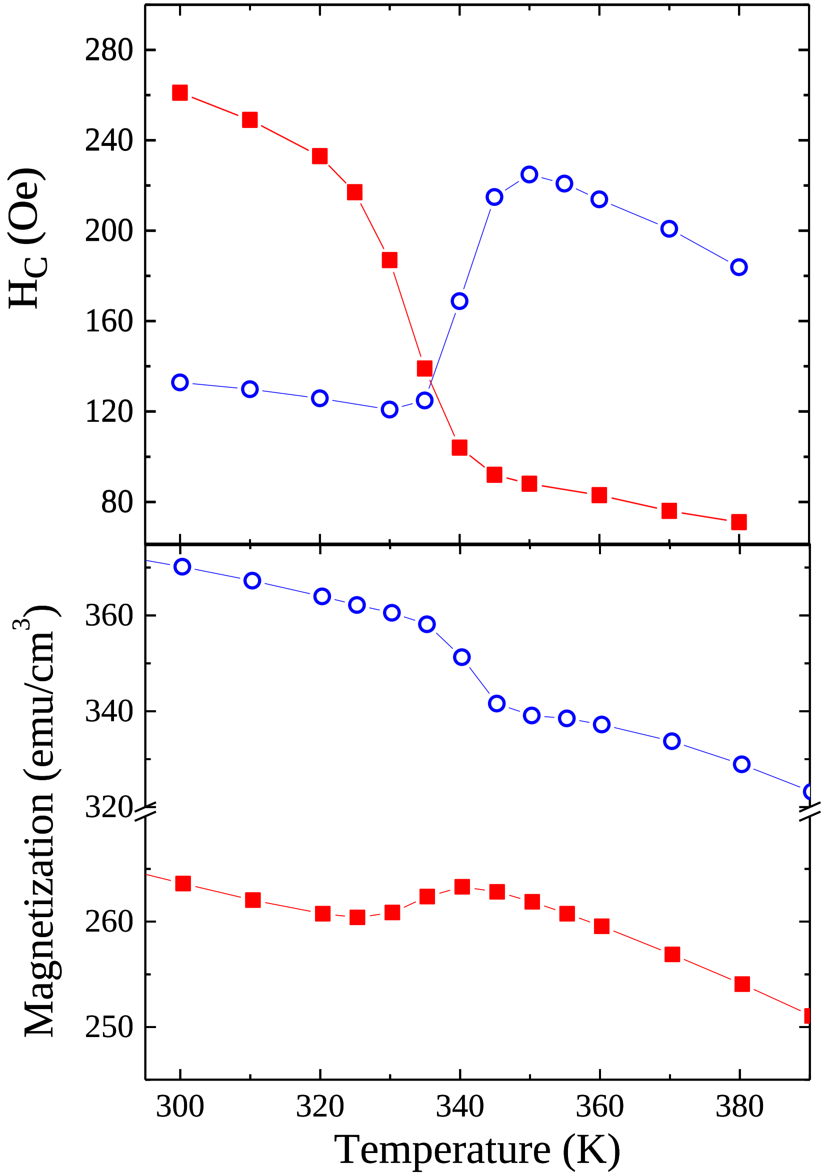
Stress Measured in VO_2 Films **σ ~ 400 MPa**

B. Viswanath *et al*., Scr. Mater. **64**, 490 (2011)

Tailoring the Effect

- Ni Deposited at 420 K
→ VO_2 Rutile

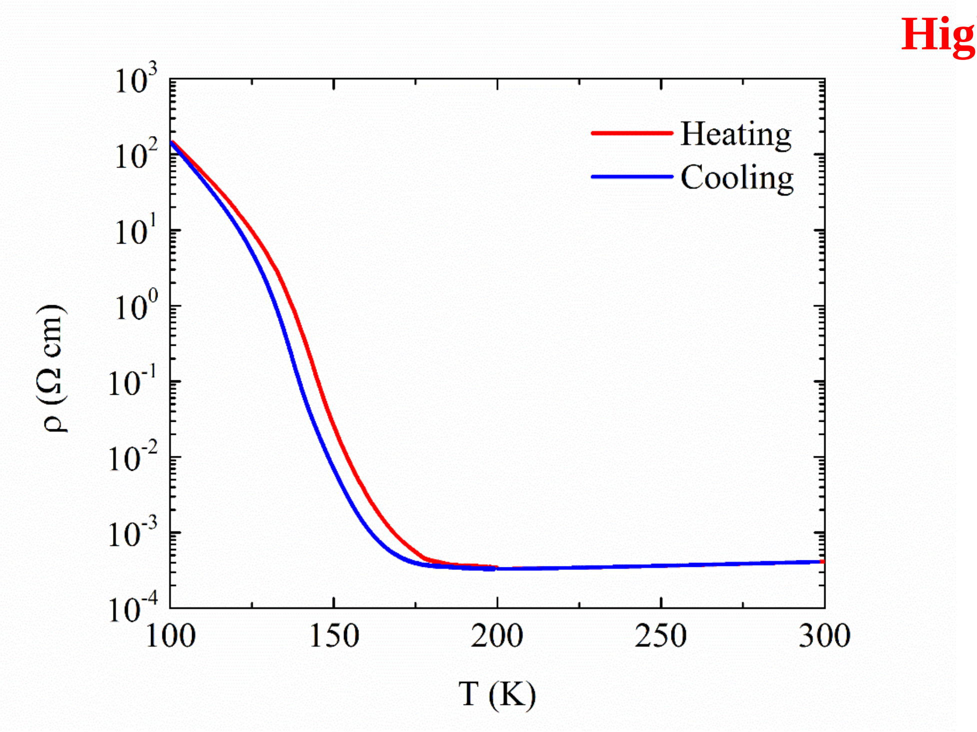
- Ni Deposited at RT
→ VO_2 Monoclinic



Reverse the Effect by Selecting the Deposition Temperatures, i.e. VO_2 Structures

Phase Transition in V_2O_3

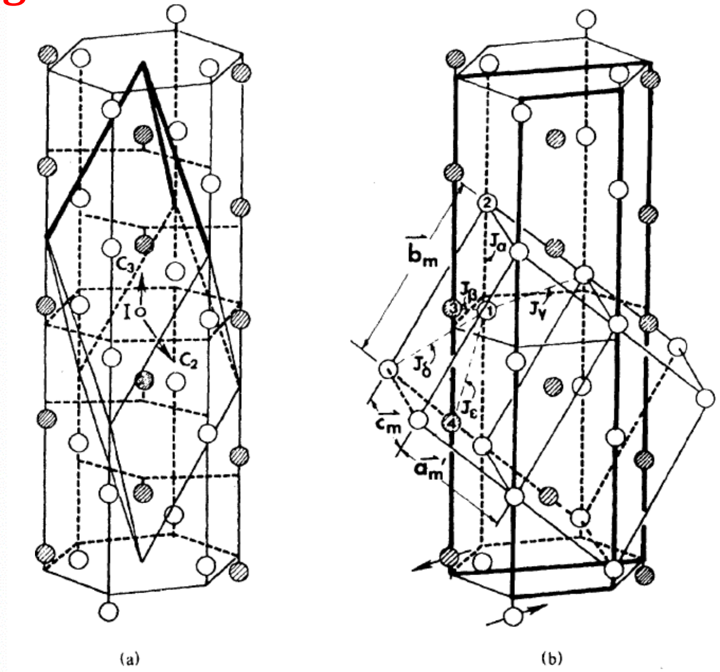
MIT



$T_C = 150 – 165$ K

SPT

High-T Rhombohedral Low-T Monoclinic



R. E. Word *et al.*, Phys. Rev. B **23**, 3533 (1981)

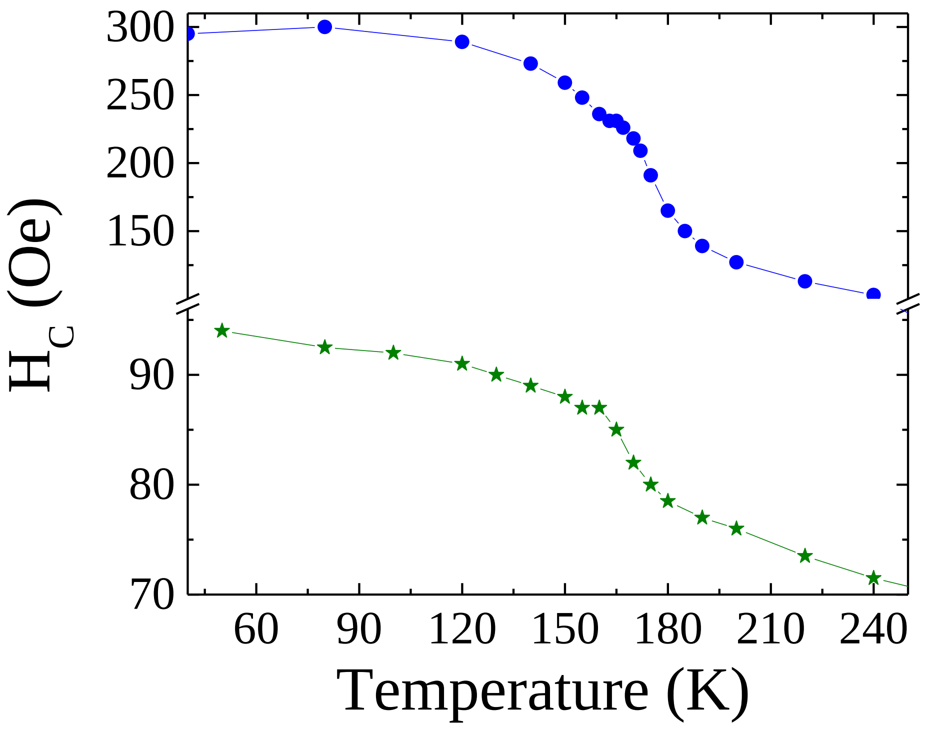
~ 1 % Lattice Distortion

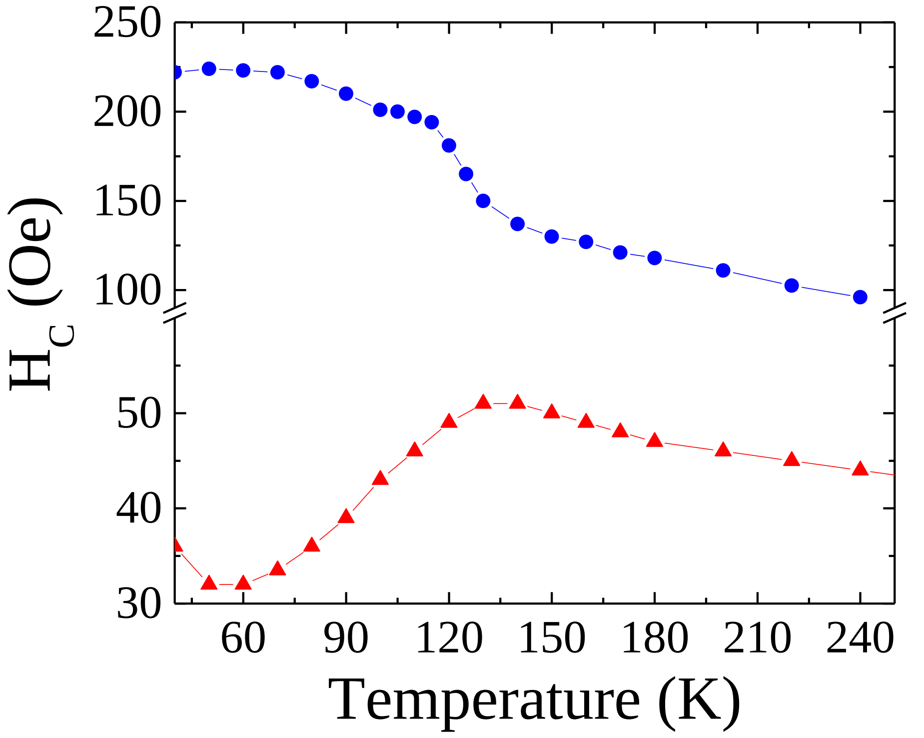
~ 1 % Volume Change

V_2O_3 / FM: Generalization

100 nm V_2O_3 | 10 nm Ni
10 nm Co

100 nm V_2O_3 | 10 nm Ni
10 nm Fe





- Fe & Co Smaller Effect ⬅ Smaller $\frac{\lambda}{M_S}$
- Fe Inverse Effect ⬅ $\lambda_{Fe} > 0$

$$H_{K\sigma} = \frac{3\lambda\sigma}{M_S}$$

Control of Magnetism with VO_x/FM

- Control **Coercivity** & **Magnetization** with **SPT** of VO_x
- Interface Effect – **Reduces with Increasing FM Thickness**
- Tuning with Stress – **Choose Deposition Temperatures**
- Tuning with FM – **Choose λ & M_s**

J. de la Venta, S. Wang, J. G. Ram ŕez, and Ivan K. Schuller, Appl. Phys. Lett. **102**, 122404 (2013)

T. Saerbeck, J. de la Venta, S. Wang, J. G. Ramirez, M. Erekhinsky, I. Valmianski, I. K. Schuller, J. Mater. Res., Invited Review (2014)

I. K. Schuller, J. de la Venta, S. Wang, J. G. Ramirez, M. Erekhinsky, and A. Sharoni. Magnetic and Electrical Control of Engineered Materials. United States Patent 61/915,715, Issued December 13, 2013

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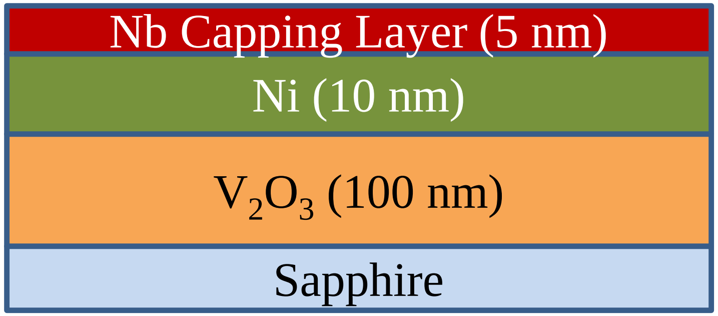
- ***Conclusions***

V_2O_3/Ni



Nb Capping Layer (5 nm)

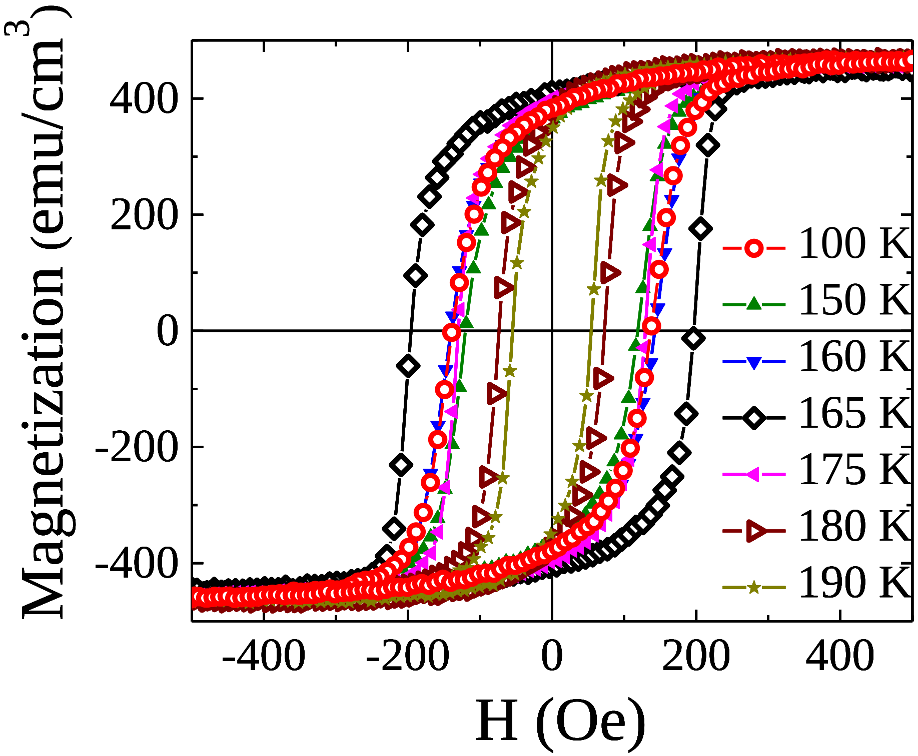
Ni (10 nm)

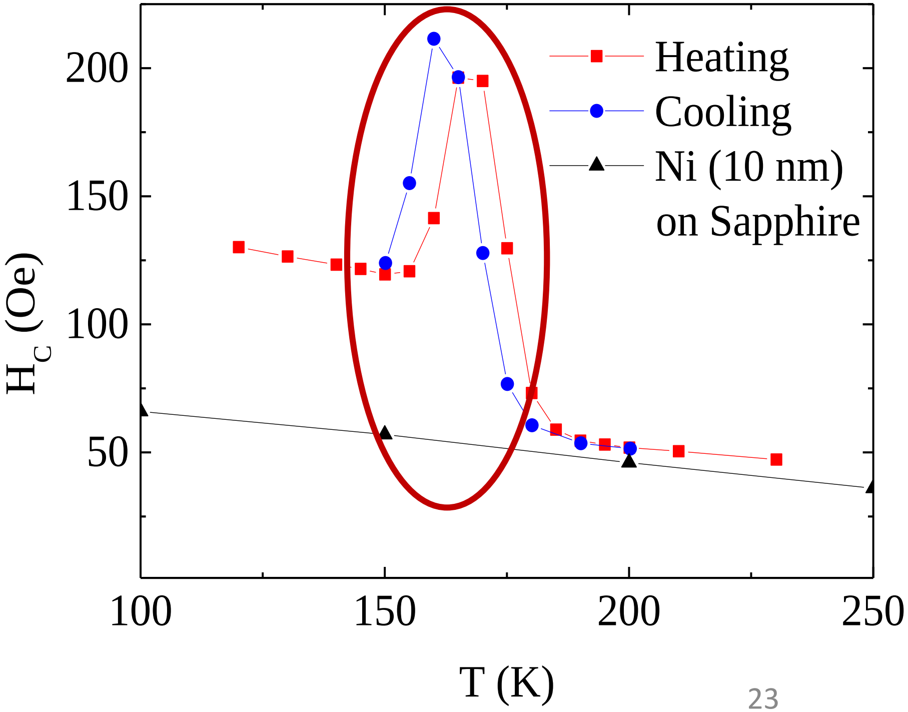
V_2O_3 (100 nm)

Sapphire

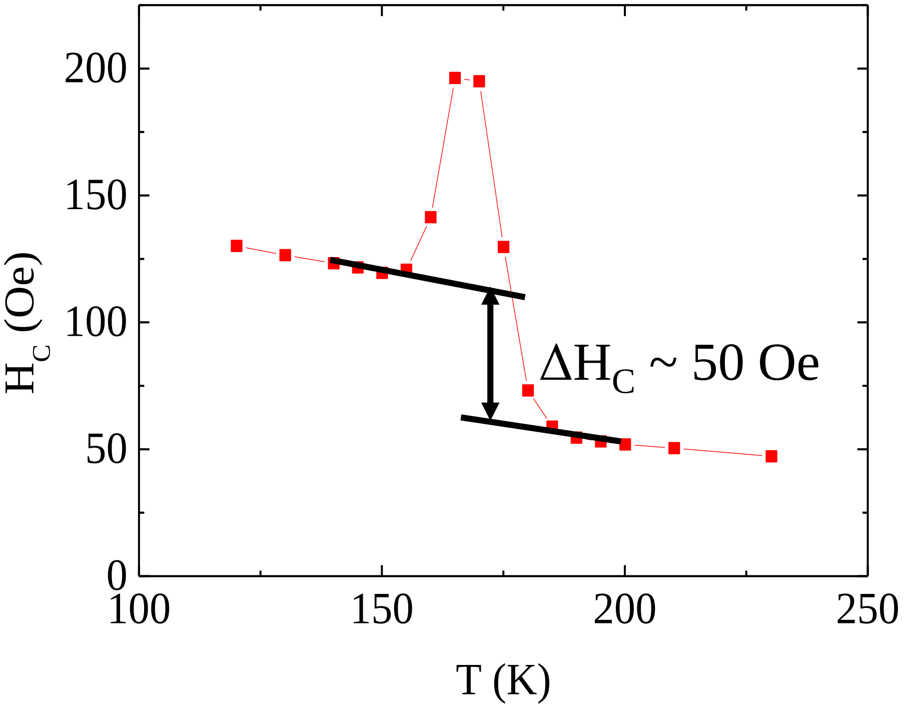
Peak at T_C = 150 – 165 K!

Coercivity Enhancement





Coercivity Enhancement



Structural Phase Transition in V_2O_3

↓

Stress in Ni ~ 10’s of MPa

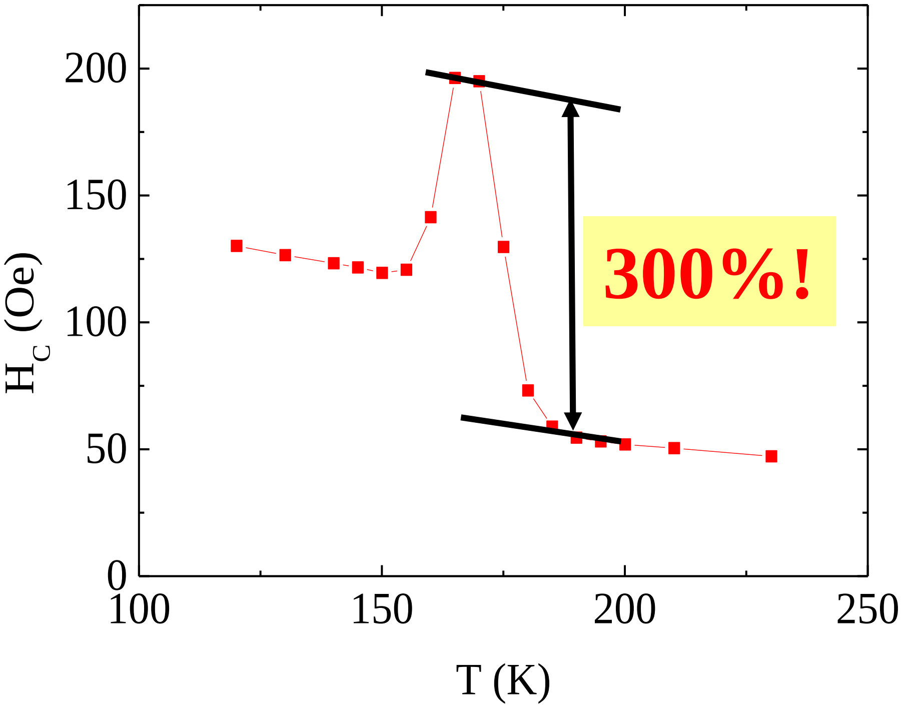
↓

Stress Anisotropy Field ~ 50 Oe

J. de la Venta, S. Wang, J. G. Ramirez, and I. K. Schuller, Appl. Phys. Lett. **102**, 122404 (2013)

Coercivity Enhancement

What Reaches Maximum at T = 165 K in V_2O_3?



H_C Reaches Maximum at T = 165 K

Phase Coexistence in V_2O_3

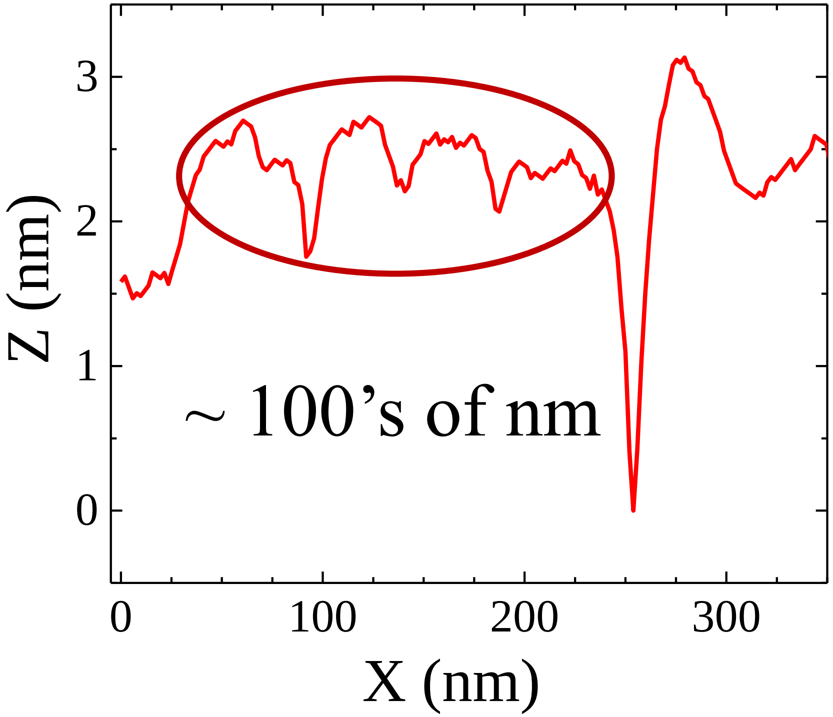
Single Phase Domain $\lambda_{V_2O_3} \leq 100$ nm

A. S. McLeod *et al.*, J49.00011, Cryogenic Infrared Nano-Imaging of the Metal-Insulator Transition in V_2O_3, APS March Meeting, 2014

Competing Length Scales

Surface Morphology

Terraces



Magnetic Domain $d_{Ni} > 100$ nm

Single Phase Domain $\lambda_{V_2O_3} \leq 100$ nm

$d_{Ni} > \lambda_{V_2O_3}$

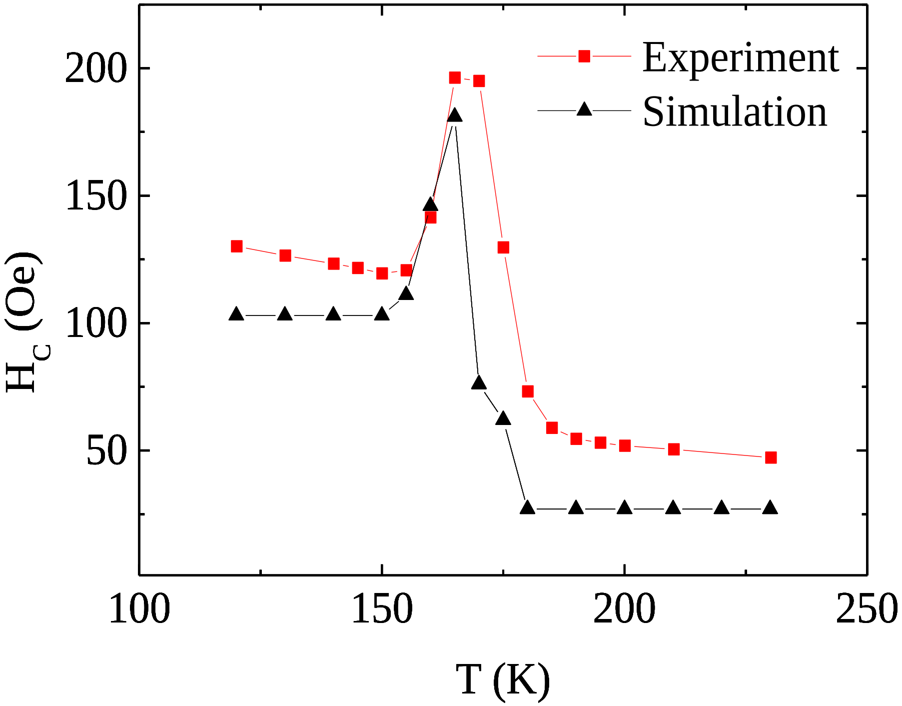
Phase Coexistence of V_2O_3

T-dependent Disorder

Enhanced Coercivity

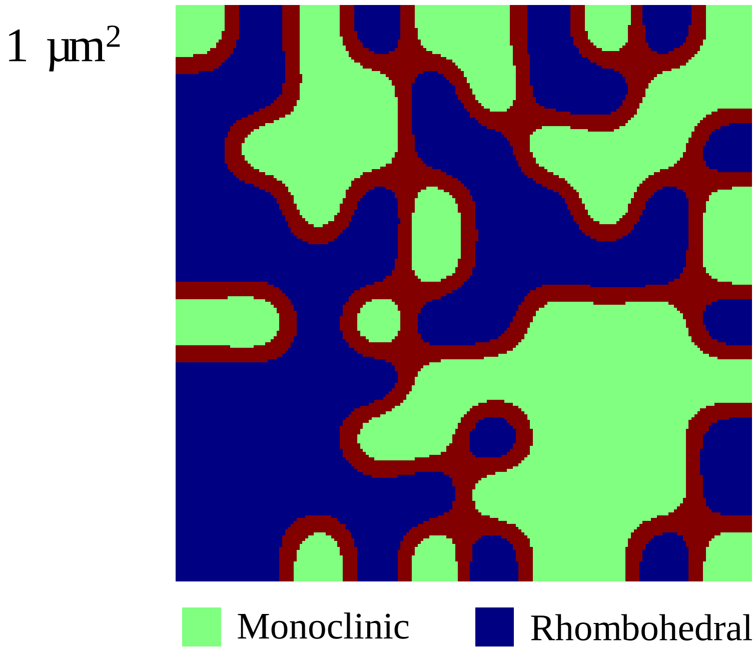
Micromagnetic Simulation

Ni



V_2O_3: $\lambda_{V_2O_3} = 100$ nm

T = 165 K



$K_{Stress} = 1 \times 10^4$ J/m^3 $K_{Pin} = 4 \times 10^4$ J/m^3

25 – 30 nm Boundary

Gaussian Distribution of T_C

T_C(Mean) = 165 K

OOMMF, NIST

Magnetization Reversal

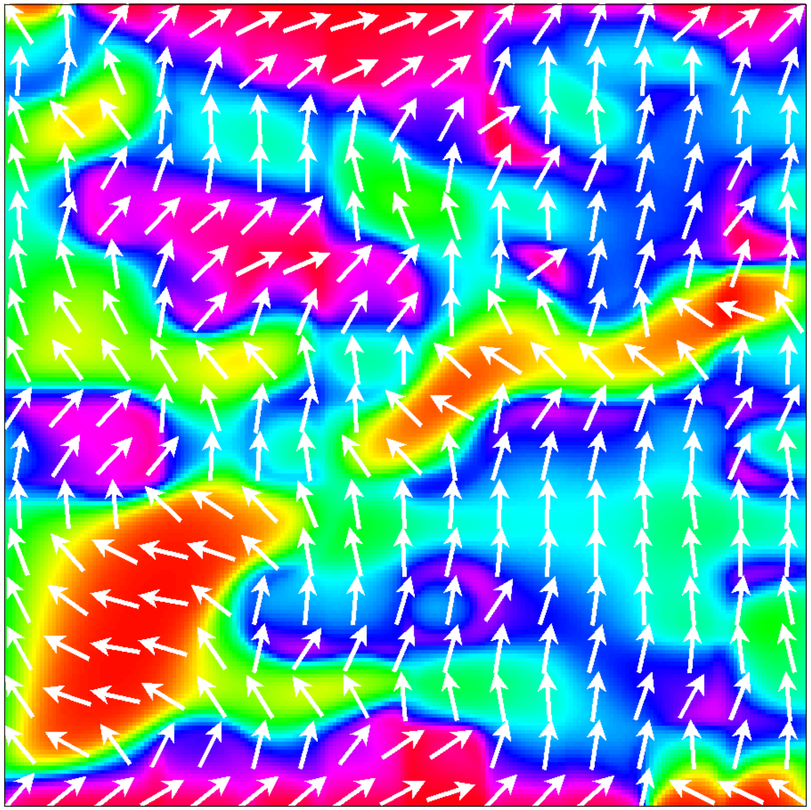
1 μm^2

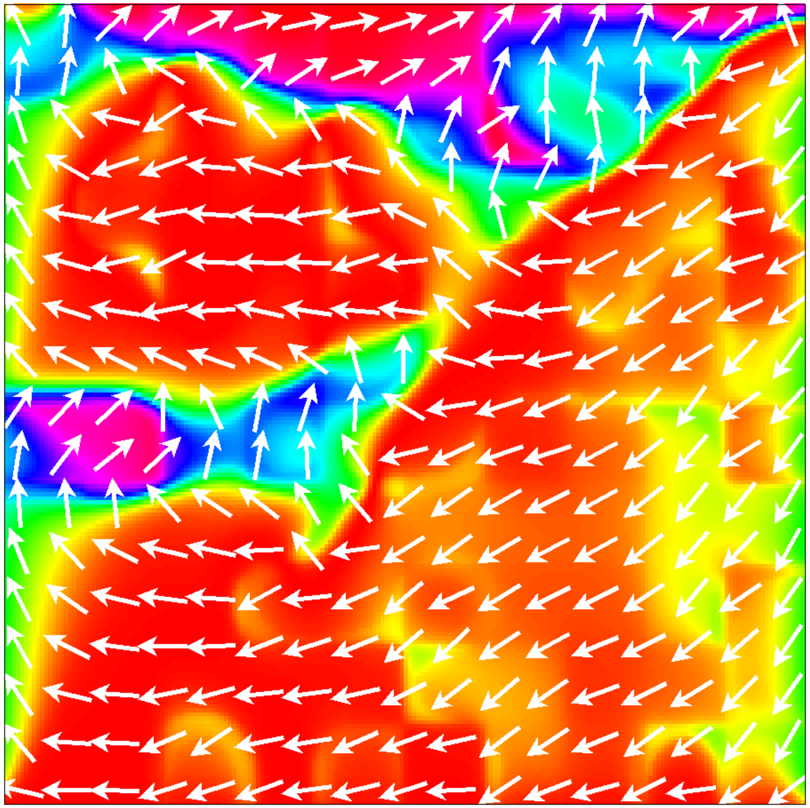
165 K

Before H_C

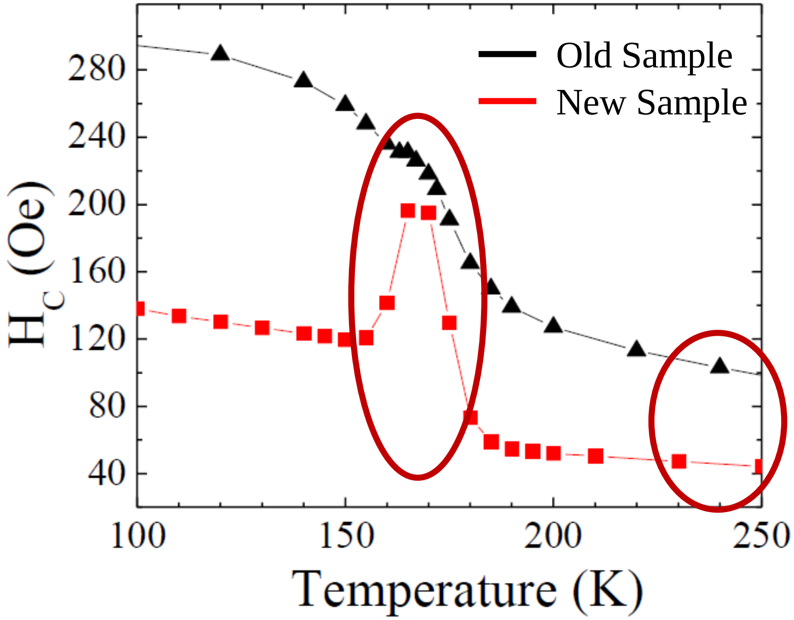
H ↔

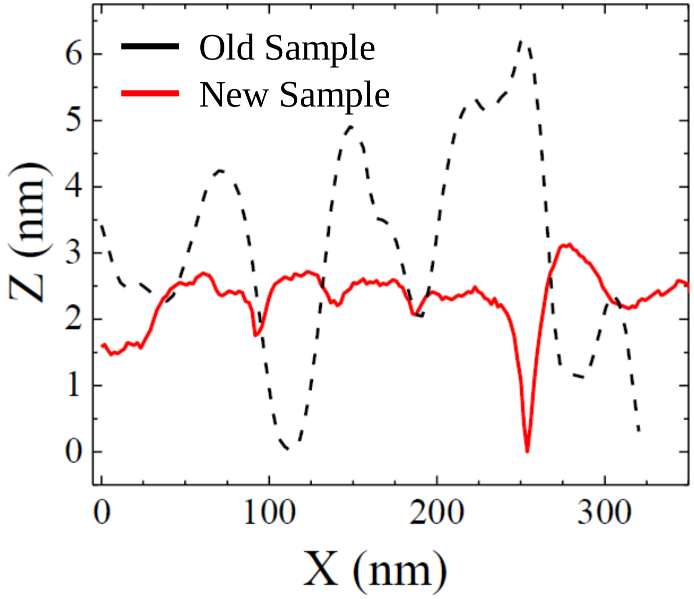
After H_C





Microstructure Comparison





New Sample: 100's of nm Terraces (< 1 nm)

⬇

$d_{Ni} > 100$ nm

⬇

$d_{Ni} > \lambda_{V_2O_3}$, Enhancement

Old Sample: Higher Roughness (> 3 nm)

⬇

$d_{Ni} \sim 50 – 100$ nm

⬇

$d_{Ni} \approx \lambda_{V_2O_3}$, No Enhancement

Coercivity Enhancement in V_2O_3/Ni

- Magnetic Measurement – **Enhanced Coercivity** in V_2O_3/Ni
- Microstructure – **Competing Length Scales (d_{Ni} vs. $\lambda_{V_2O_3}$)**
- Model – **Phase Coexistence** Induced Pinning
- Simulation – **Quantitatively Reproduce** Enhanced Coercivity

J. de la Venta, S. Wang, T. Saerbeck, J. G. Ram ŕez, I. Valmianski, and Ivan K. Schuller, Appl. Phys. Lett. **104**, 062410 (2014)
T. Saerbeck, J. de la Venta, S. Wang, J. G. Ramirez, M. Erekhinsky, I. Valmianski, I. K. Schuller, J. Mater. Res., Invited Review (2014)

Summary

- First Order SPT – **Large Stress within a Narrow Temperature Range**

- Multiple Driving Forces to Induce SPT – **Temperature, Voltage/Current, Light, Gating, Pressure and etc.**

- Multiple Tuning Parameters – **Different FMs & Deposition Conditions**

- Competing Length Scales – **Disorder due to Nanoscale Inhomogeneity**

Outlook

- Probe V_2O_3 Domain – **Scanning Near-Field Optical Microscopy (SNOM)**

- Probe Magnetic Domain in Ni – **Neutron Scattering**

- Coercivity Enhancement with VO_2 – **Smooth Surface** (TiO_2 or MgF_2 Substrate)

- Dynamics (FMR) – **Damping Divergence due to Nanoscale Disorder**

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