Radiation Effect on Materials for Spintronics and Nanomagnetism Application

Nattawut Anuniwat

Department of Physics

University of Virginia

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Prof.Joe Poon, Manli Ding, Yishen Cui, Lin Kittiwatanakul

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Dr.Brad Weaver

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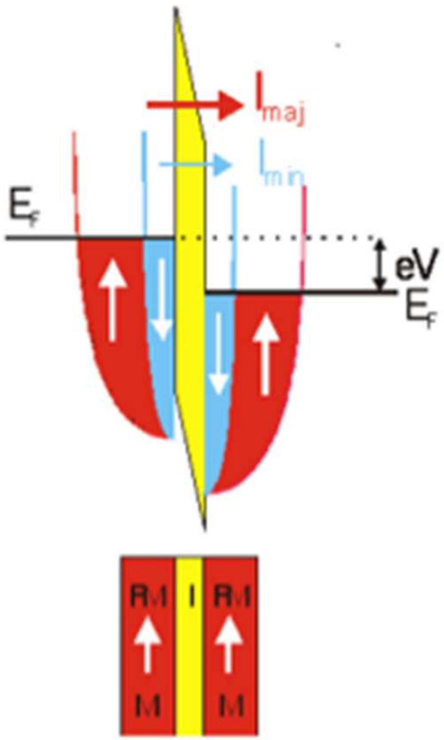
Dr. Eugene Chen

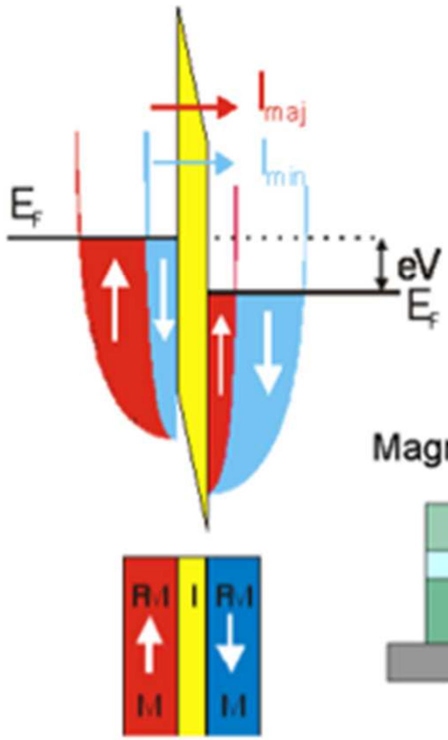
Outline

- Background and Motivation
  - Spintronics
  - Basics radiation
- Experiment and Results
  - Crystalline MnAl and Amorphous TbFeCo
- Summary and Future work

Spin Dependent Transport



$$I_P \approx N_\uparrow^1 N_\uparrow^2 + N_\downarrow^1 N_\downarrow^2$$



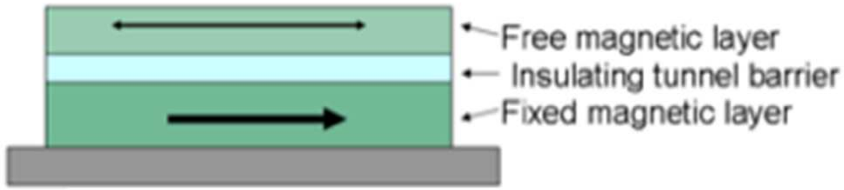
$$I_{AP} \approx N_\uparrow^1 N_\downarrow^2 + N_\downarrow^1 N_\uparrow^2$$

Juliere (1975)

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$$

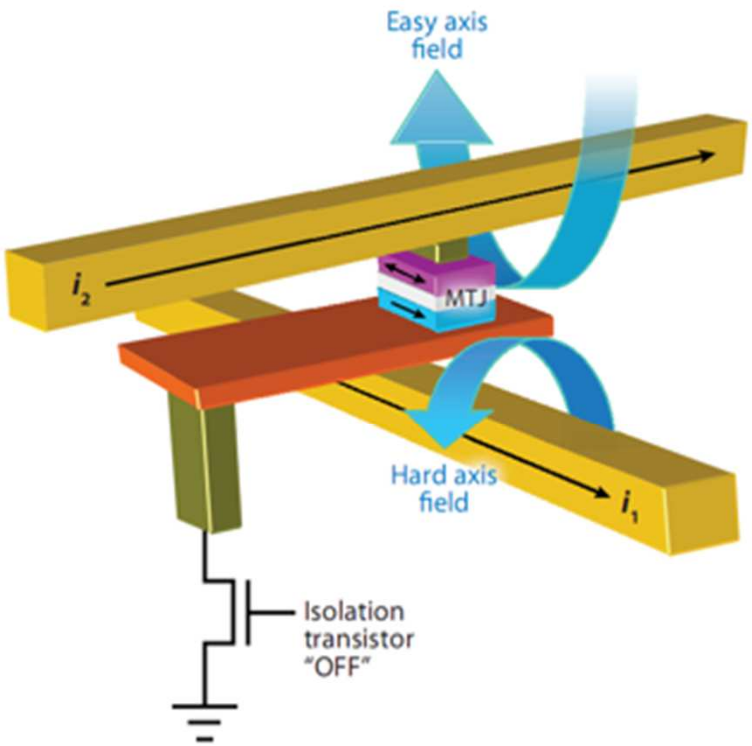
$$\text{with } P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Magnetic Tunnel Junction (MTJ)



AlO_x → TMR~ 70%
MgO → TMR ~800%

MRAM: The challenge



Advantages:

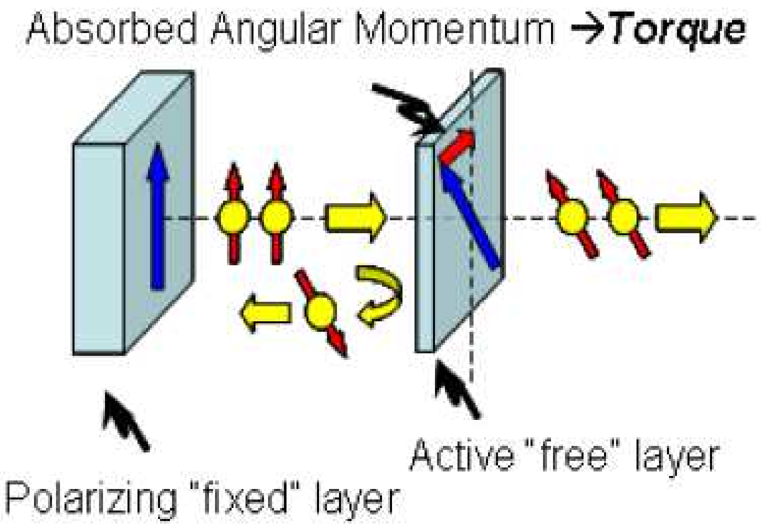
- Truly Non-volatile
- Compatibility with CMOS
- Fast (~20 ns read and write time)
- Endurance (>10^{15})

Main Challenge: cannot scale down!

- Thermal stability factor $K_u V/k_B T$ ~ 60 *(10-yr retention time)*

[J. M. Slaughter, Annu. Rev. Mater. Res. **39**, 277 (2009)]

STT: Spin Torque Transfer



$$J_c = \frac{2e\alpha M_s t_F \left(H + H_K + 2\pi M_s\right)}{\hbar\eta}$$

[J.C. Slonczewski J. Magn. Magn Mater. **159** L1 (1996)]

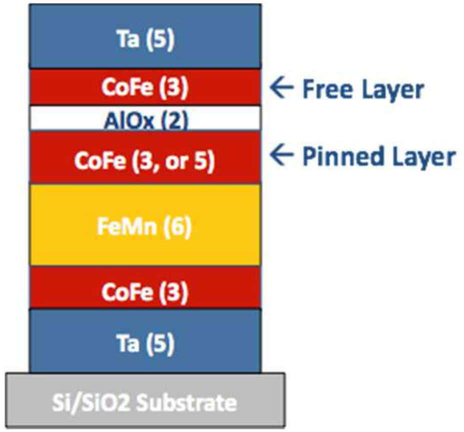
Current density (*not current*!) determine the threshold for switching!
→ *Switching current scales down correctly with cell size!*

PMA materials

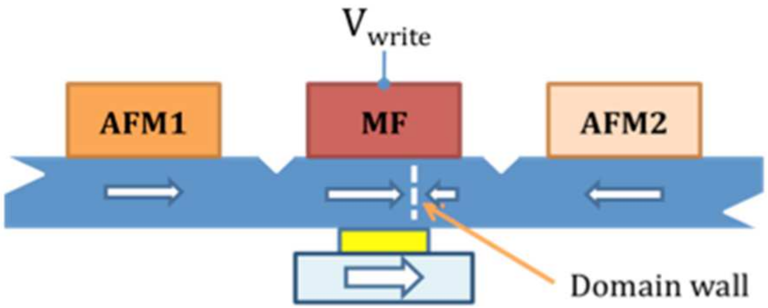
	Interfacial effect	Crystalline magnetic anisotropy	Amorphous RE-Co-Fe
Materials	CoFeGe Co2FeAl	$L_1{}^0$ MnAl	GdCoFe TbCoFe
Compatible with MgO barrier	**Yes**	**??**	**CoFeB interlayer**
Thermal stablity Δ	**low**	**high**	**high**
Damping parameters	**0.002~0.005**	**0.008**	**typically >0.1**
Ms (emu/cc)	**> 1000**	**400**	**50~ 200**
Processing temperature	**250~350 °C**	**400 ~ 700 °C**	**< 250 °C**

STT device structures

STT-MTJ

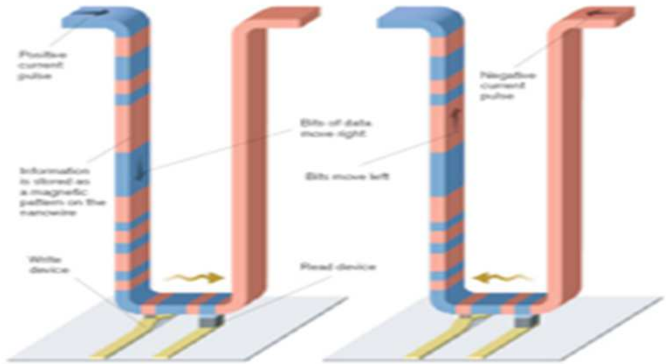


Magnetic memristor



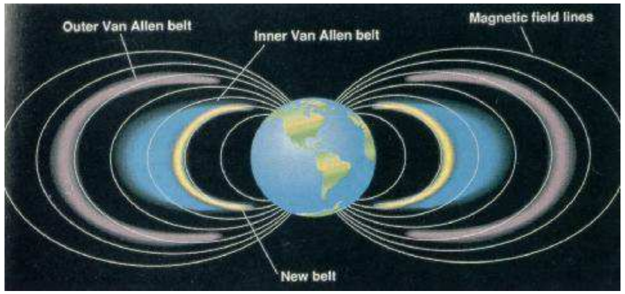
Wolf,Lu and Stan, UVA

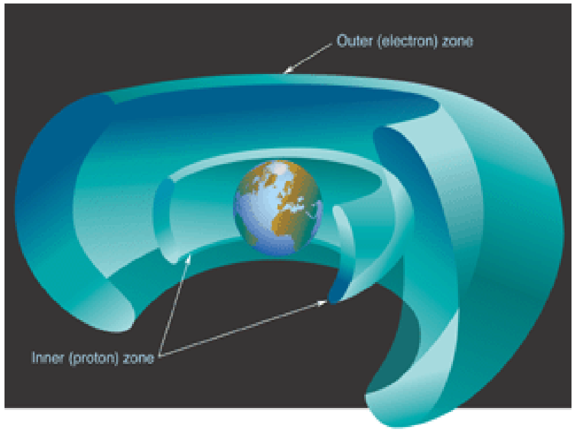
Racetrack Memory



S. P. Parkin, IBM

Why study radiation?





Particles
(e^-, p^+, n^o, ions)

High energy photons

Ionization damage

Displacement damage

Aerospace Electronics require “RAD HARD” properties!!

Spin Disorder in Magnetism: Building the foundation

Third, we may recognize that certain solids, such as the ferromagnetic and ferroelectric solids, have highly individual properties, not widely shared, with which characteristic imperfections may be associated. Consider, for example, an ideal ferromagnetic solid in which all potentially alignable spins (electronic or nuclear) are aligned. An imperfection may be introduced in this structure by reversing one of the spins. If the interaction between spins is sufficient, this imperfection may have the property that, under proper conditions, it can move through the medium in the manner[10] of a spin wave and hence be ascribed dynamic characteristics. It follows that the preceding lists of imperfections can be increased by the addition of other somewhat more specialized types such as spin waves and perhaps the analogous type of imperfection for a ferroelectric[11] material. In the interest of simplicity, we shall

[10] F. Bloch, *Z. Physik*, **61**, 206 (1931); J. C. Slater, *Phys. Rev.*, **52**, 198 (1937).

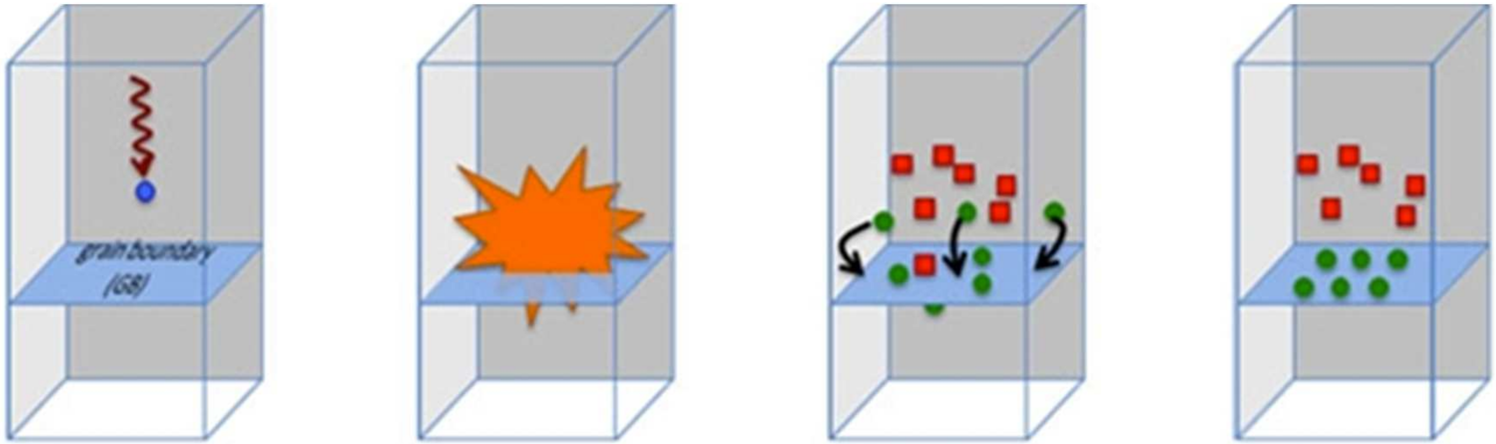
[11] See the review article by A. von Hippel, *Rev. Mod. Phys.*, **22**, 221 (1950).

omit such topics from detailed consideration, recognizing, however, that there is the possibility of expansion in this direction as the properties of somewhat atypical systems are included.

•*Imperfections in Nearly Perfect Crystals: A Synthesis (Frederick Seitz, 1952)*

"Ferromagnetic and ferroelectric solids can contain **imperfections in the form of spin disorder but in the interest of simplicity, we shall omit such topics** from detailed consideration…."

Basic Radiation Damage Mechanism



Energy Frontier Research Centers (EFRCs), DOE

Long-lived effects
Charge trapped in nonconductive regions, charge build-up, oxidation reduction reactions, stable free radicals, bond scission, internal fields, coloration

Transient effects
excess current, voltage spikes, latching, flip-flop, breakdown/ Burnout due to excess current, short-lived color centers…

Long-lived effects
↑defect concentration,
↓decreased lifetime
↓ mobility, ↓ n_s
- Local disorder leading to dilation and stress

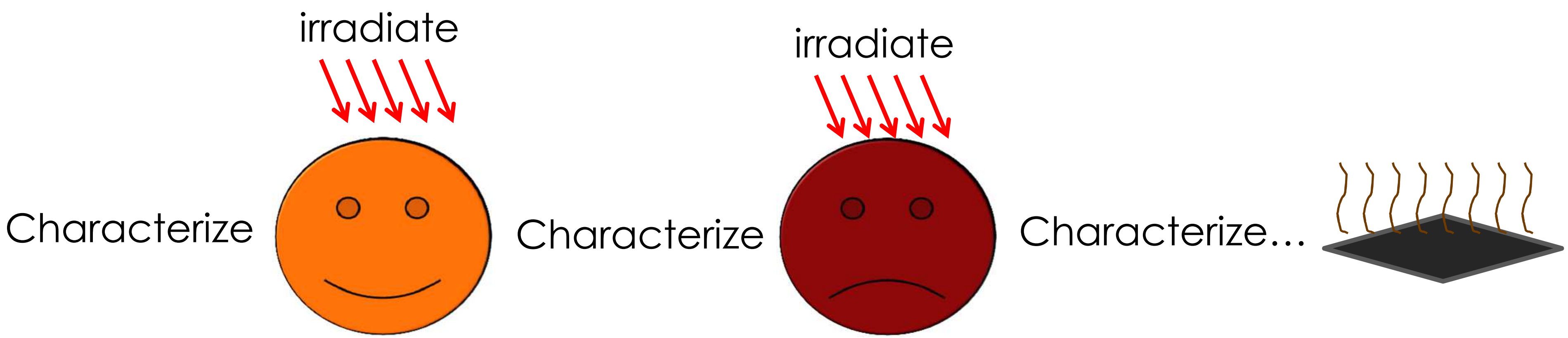
ionization

Displacement

Irradiation process

3 basic types of displacement and ionization damage experiment

In-situ **Single exposure** **Incremental**



Samples:
MnAl and TbCoFe thin films
Multilayer samples

Irradiation condition:

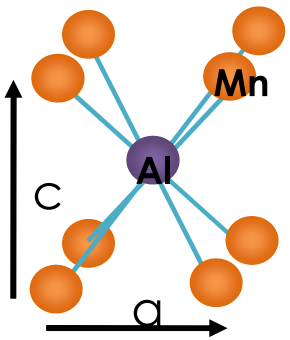
- ☑ Source: 2 MeV Proton (Displacement damage)
- ☑ Fluence: 1×10^{14} cm^{-2} and 1×10^{15} cm^{-2}

Characterization:

- ☑ XRD (crystallinity, chemical ordering)
- ☑ TEM (defects)
- ☑ AFM and MFM (morphology and magnetic domain structure)
- ☑ VSM (magnetism and magnetic anisotropy)
- ☑ Hall measurement (spin dependent transport).

Crystalline systems: MnAl

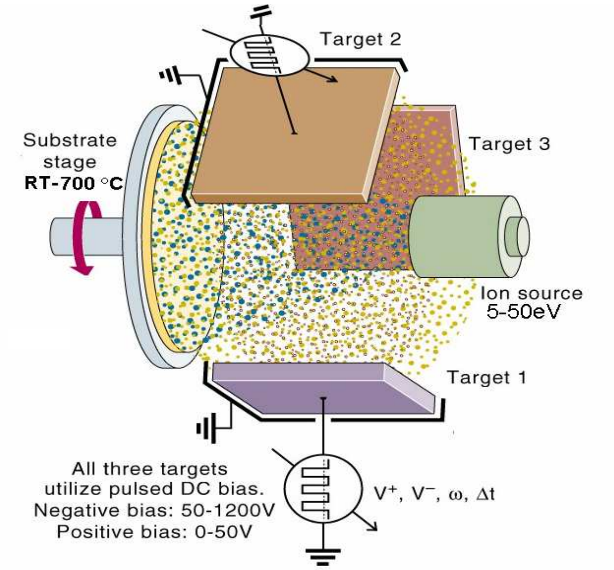
- **Bulk Structual and Magnetic Properties**
  - **$L1_0$ tetragonal structure**
  - **High saturation moment (490emu/cc);**
  - **Large uniaxial anisotropy ($1x10^7$erg/cc);**
- **Metastable and Formed only with Mn atomic percentage between 50% -60%.**



Film Growth and Characterization

Deposition & Post annealing

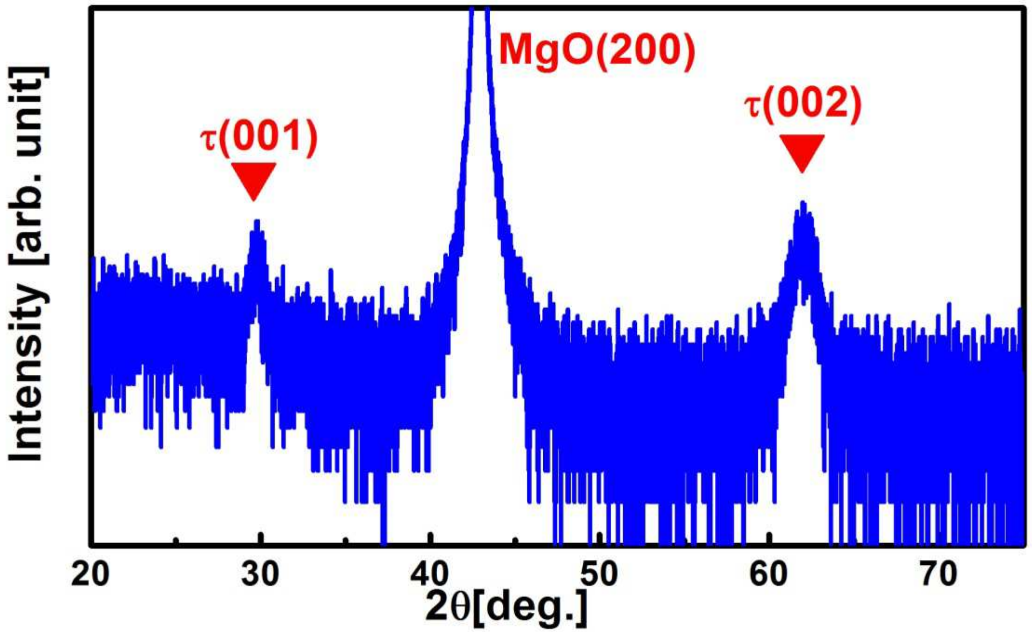
- Alternating Al/Mn quasi-monolayer deposition on MgO(100) substrates.
- Bias Target Ion Beam Deposition system (BTIBD) (Base pressure at 6×10^{-8} torr)
- Rapid Thermal Annealing(in vacuum at 400°C fo 12s)



Characterization:

- XRD (crystallinity, chemical ordering)
- VSM and MOKE (magnetism and magnetic anisotropy)
- Hall measurement (spin dependent transport)

XRD characterization of MnAl thin films

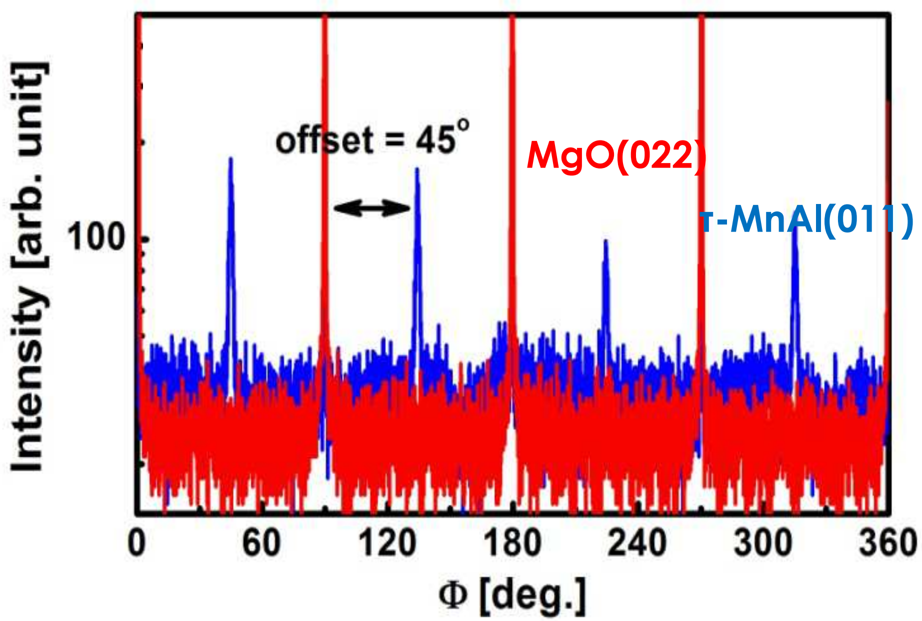


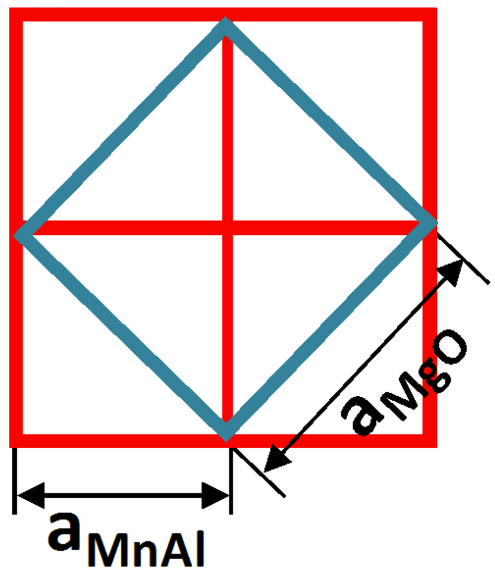
•Fundamental Peak τ(002)→tetragonal cubic structure;
•Superlattice Peak τ(001)→constructive diffraction between highly ordered Mn and Al atomic planes.

Y. Cui et al, JAP, 110, 103909 (2011)

τ- Phase MnAl Grows Epitaxially on MgO Lattice

[Al/Mn(5.7Å)]$_{18}$ (10.2nm)



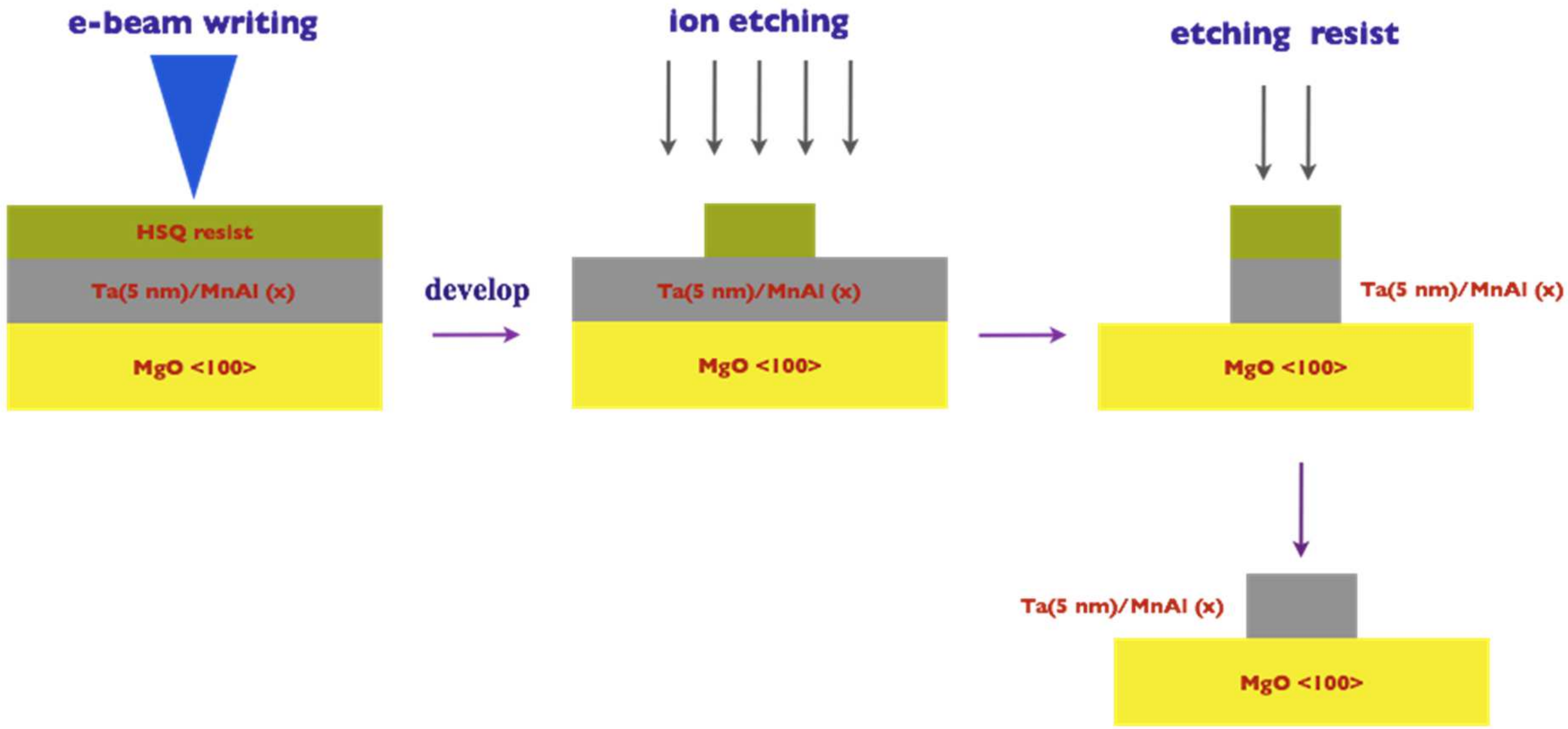


$2\theta_{MgO(022)}$ = 62.50° → $a_{MgO}/\sqrt{2}$=2.97 Å

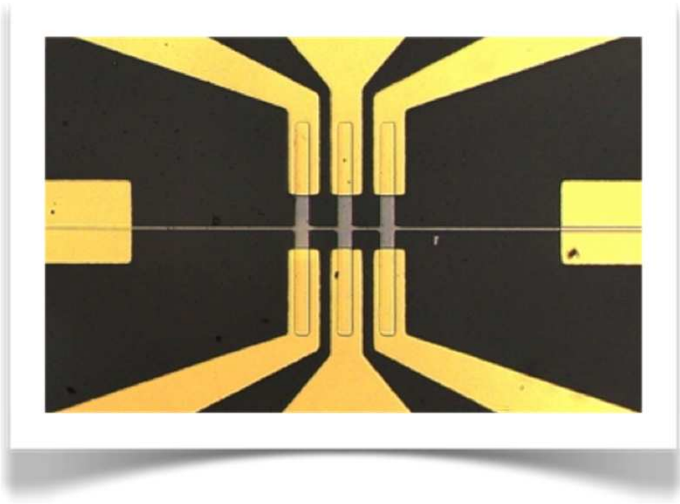
$2\theta_{\tau\text{-}MnAl(011)}$ = 42.37° → a_{MnAl}=3.02Å

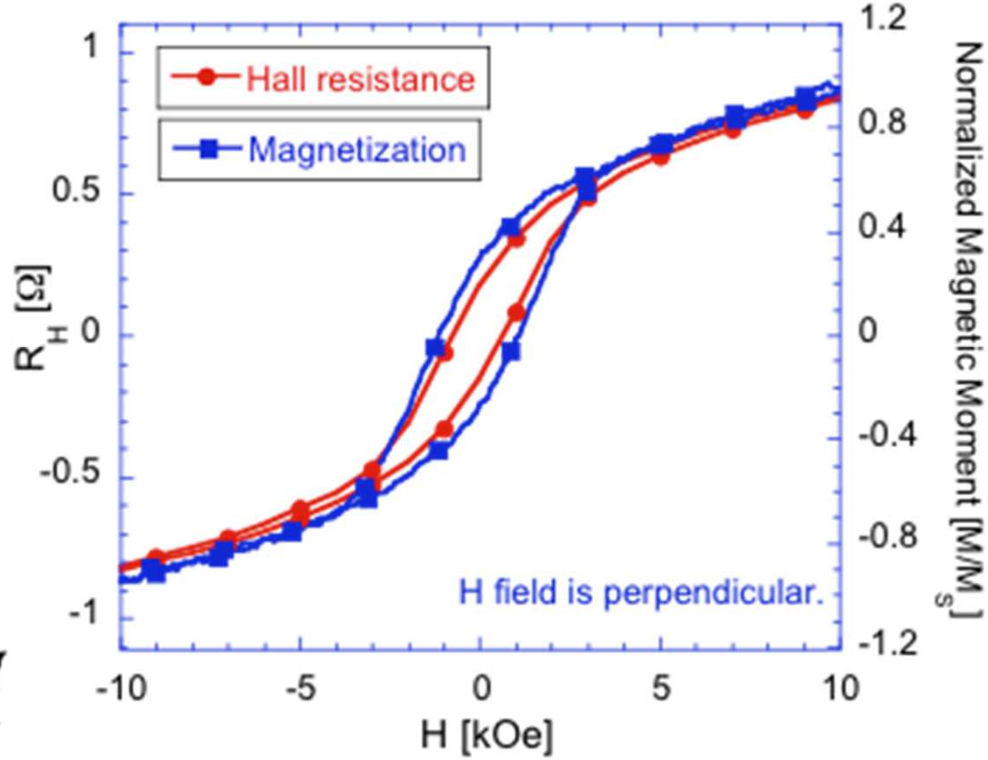
Y. Cui et al, JAP, 110, 103909 (2011)

Hallbar Fabrication



Magneto-transport of MnAl

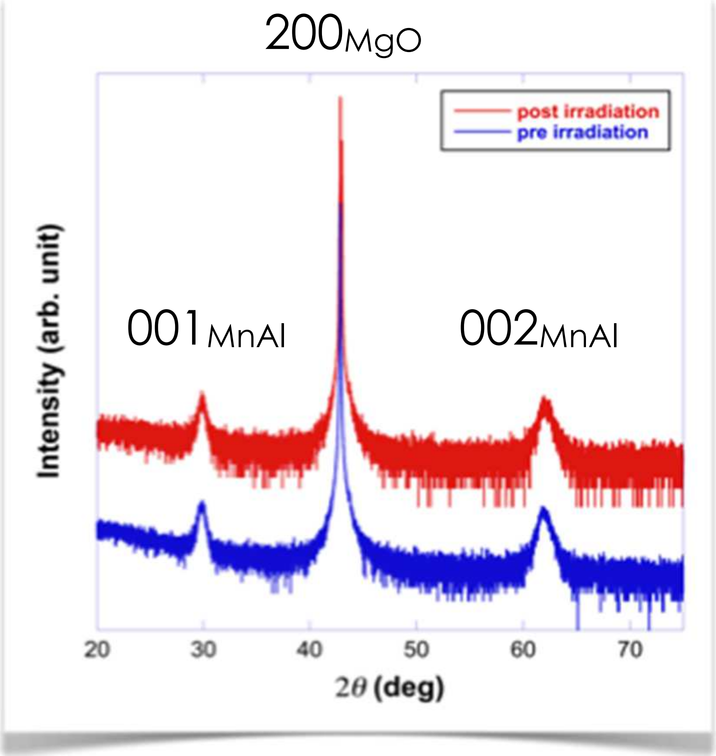


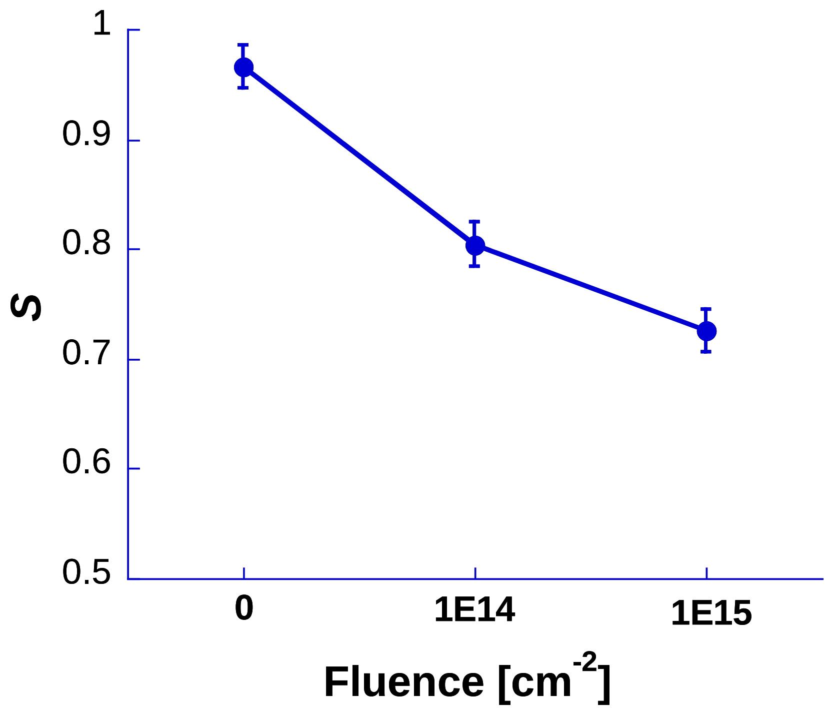


$$R_{Hall} = \underbrace{R_0(H)\mu_0 H}_{\text{Ordinary Hall effect}} + \underbrace{R_s(H)\mu_0 M}_{\text{Anomalous Hall effect}}$$

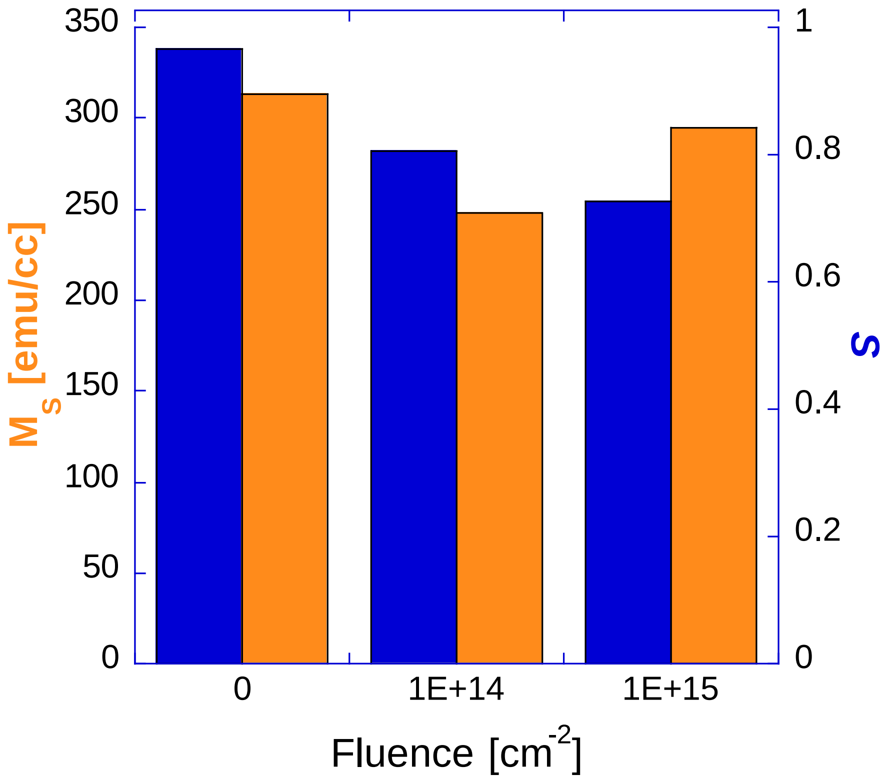
Ordinary Hall effect **Anomalous Hall effect**

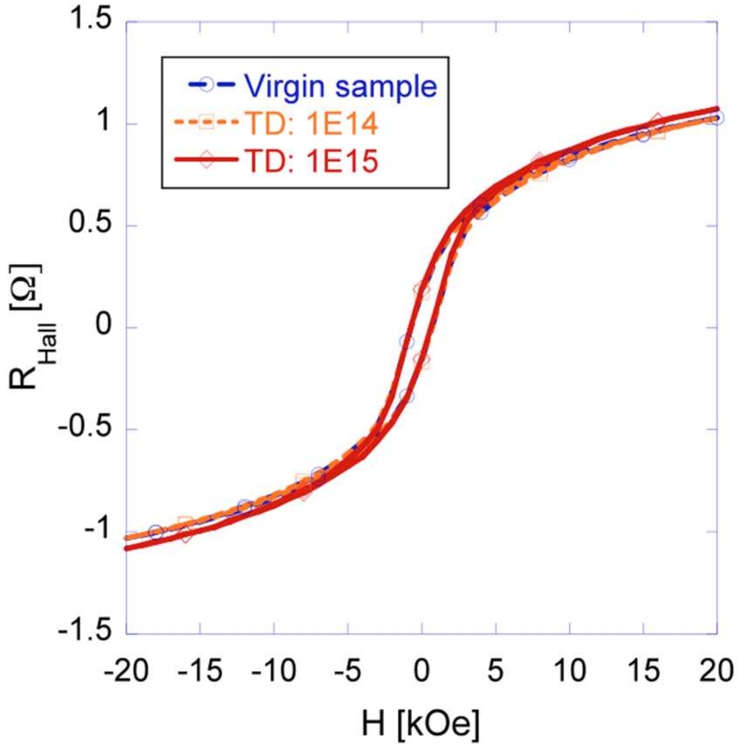
Chemical ordering (*S*) vs. Fluence





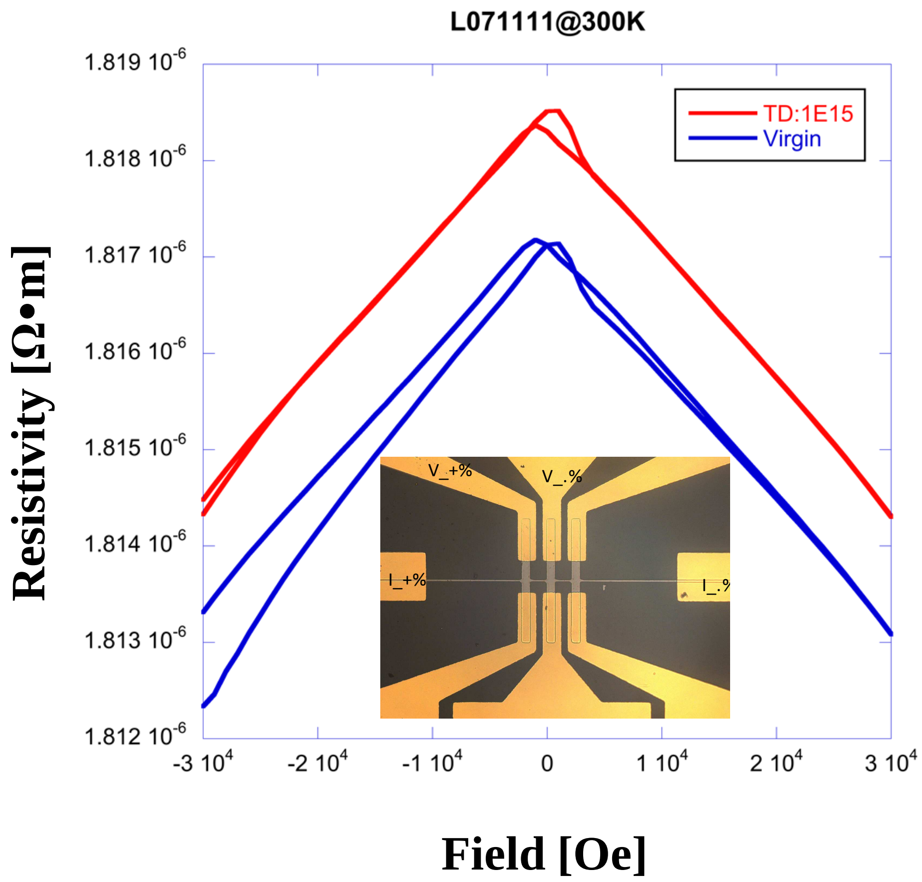
M_S and Hall effect vs. Fluence

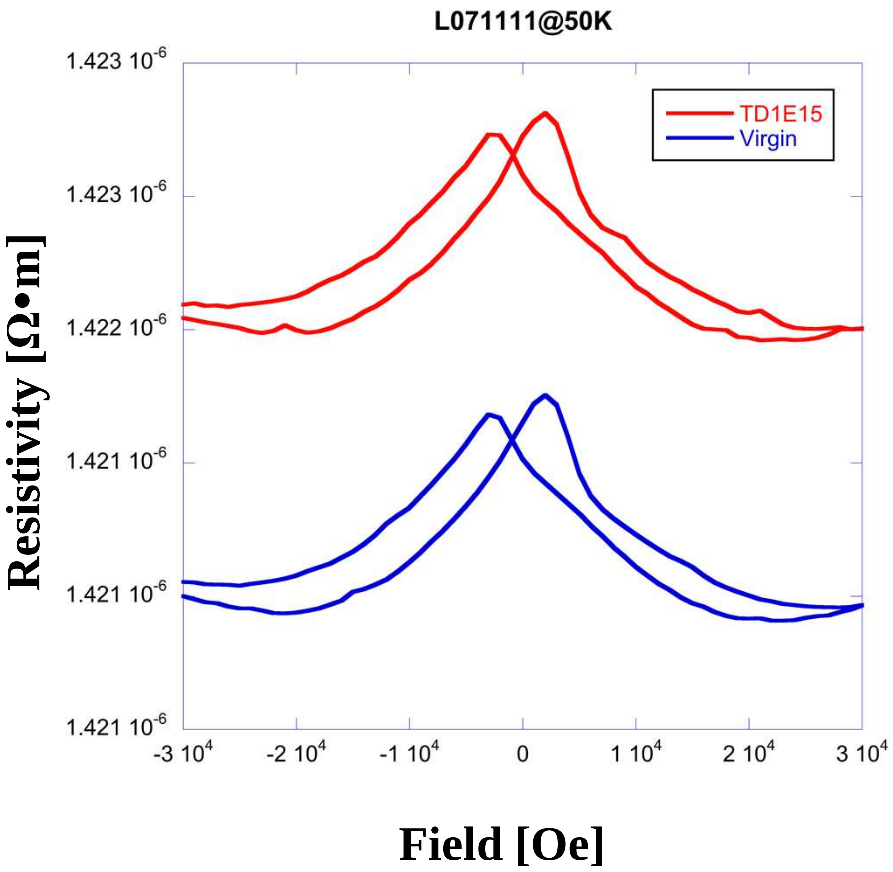




- The Chemical ordering decreases monotonically indicate the structural disorder after irradiation .
- There appear to be fluctuation in saturation moment.
  It was not clear whether the magnetic defects were introduced during irradiation.

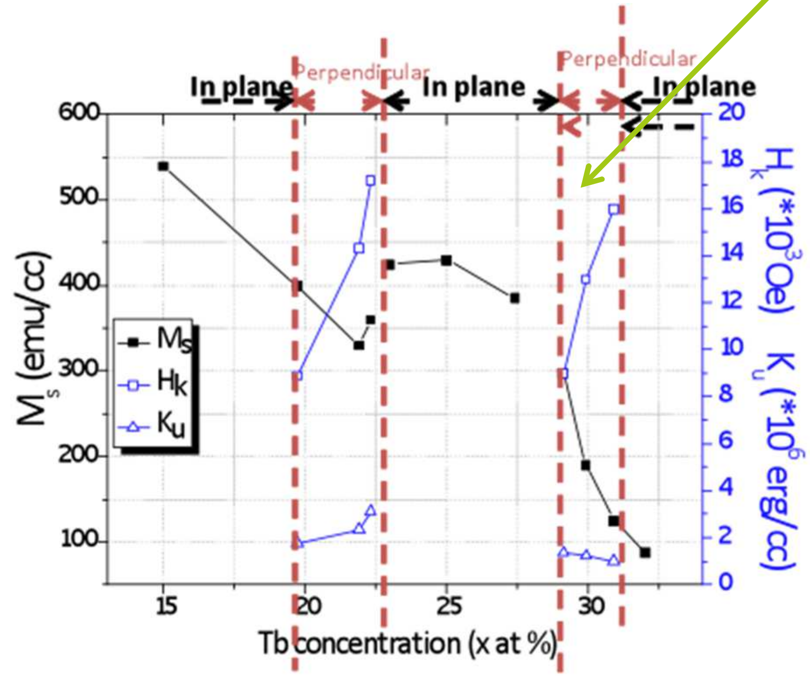
Resistivity measurement

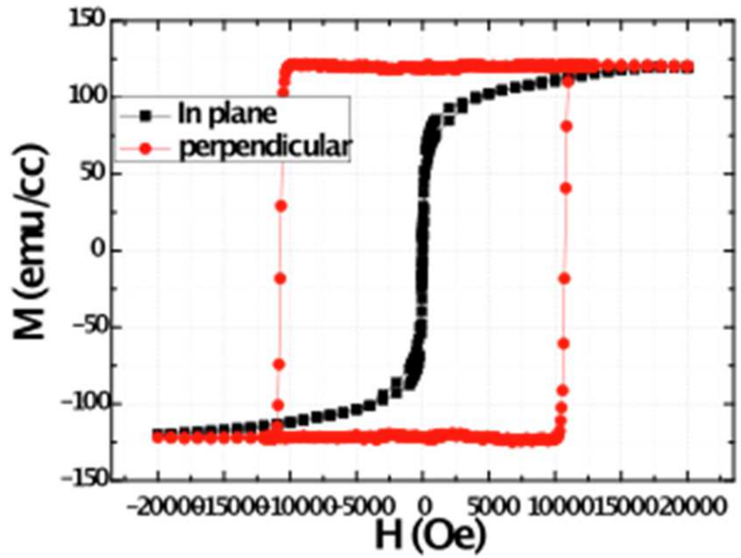




Amorphous System: TbFeCo

All samples were from this region which has never been reported before



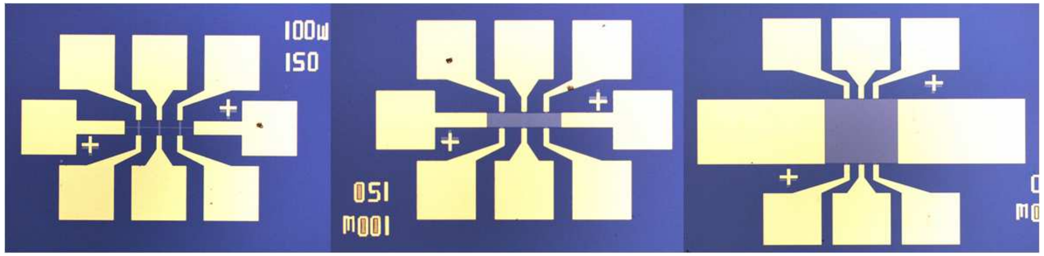


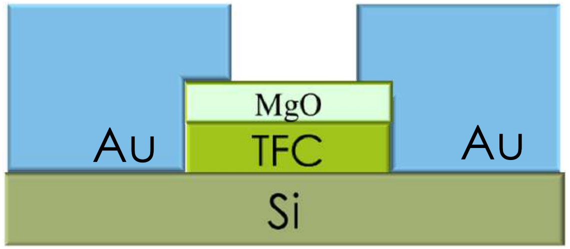
M. Ding and J. Poon, unpublished

Growth and Characterization

- RF Magnetron sputtering system: co-deposition of Tb, Co, Fe
- Based pressure at 8 x 10^{-7} Torr
- Growth at room temperature
- (100)-oriented crystal Si/SiO2 substrate
- As-deposited films were characterized magnetic properties by VSM and MOKE
- Magneto transport – AHE

Fabrication:

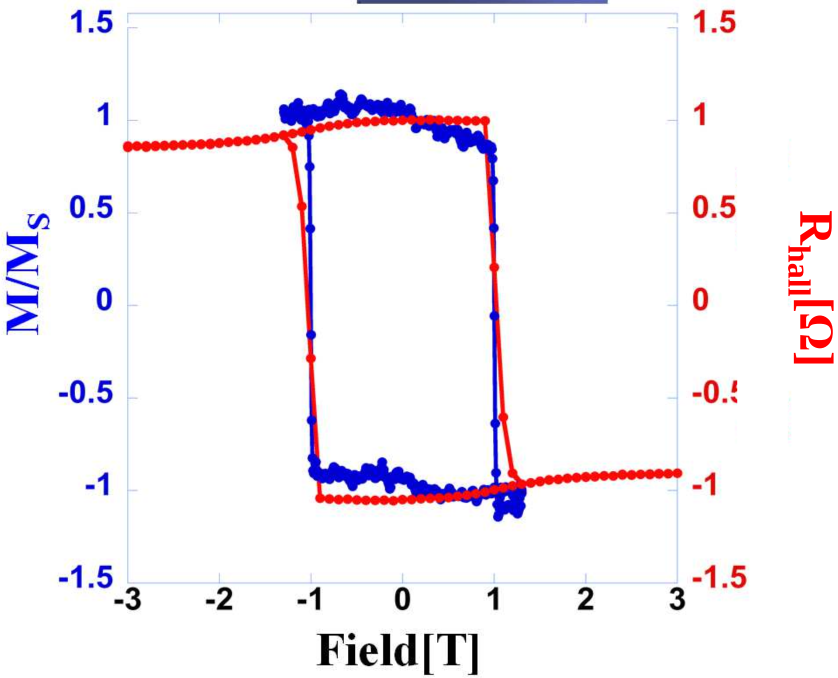




- Hall Bar were fabricated using Photolithography technique
- Diluted HCl was use to etch away TbFeCo film
- Au/Ti electrical contacts were deposited by e-beam evaporator via lift-off process.

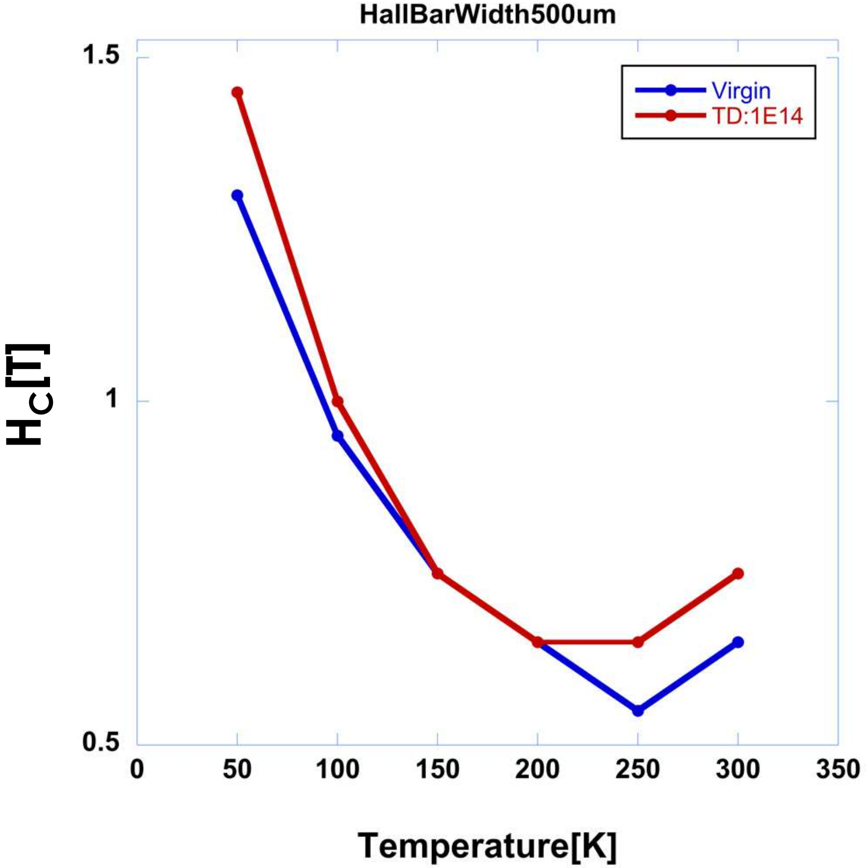
Magneto-Transport

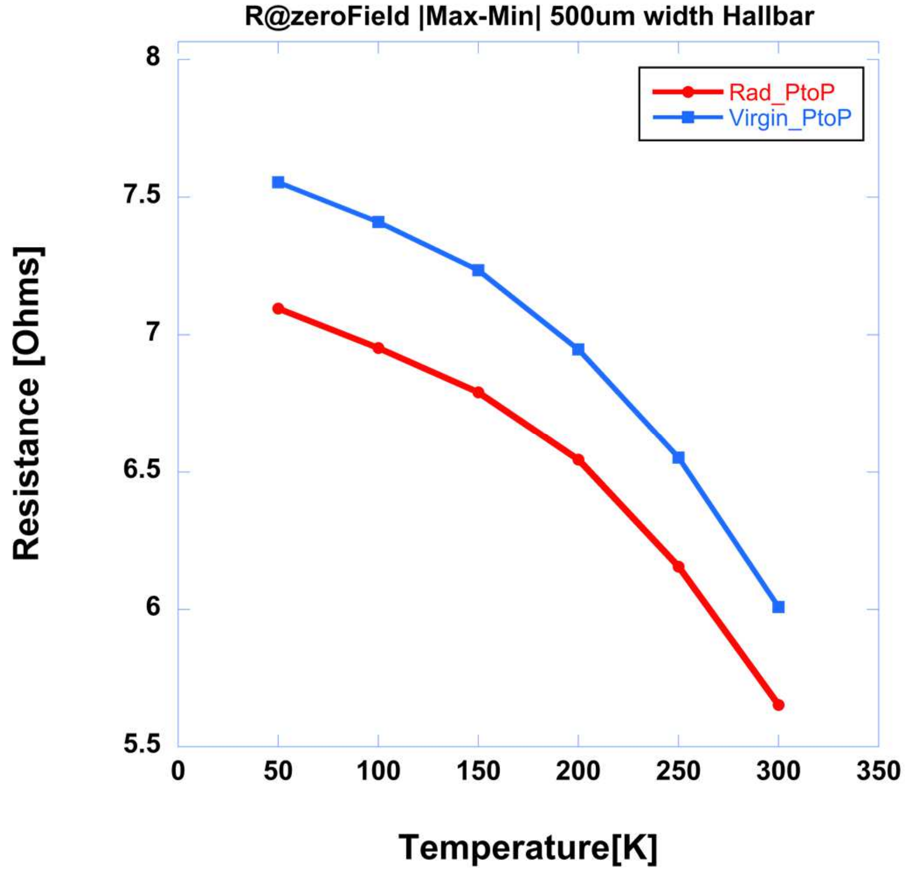
500 µm



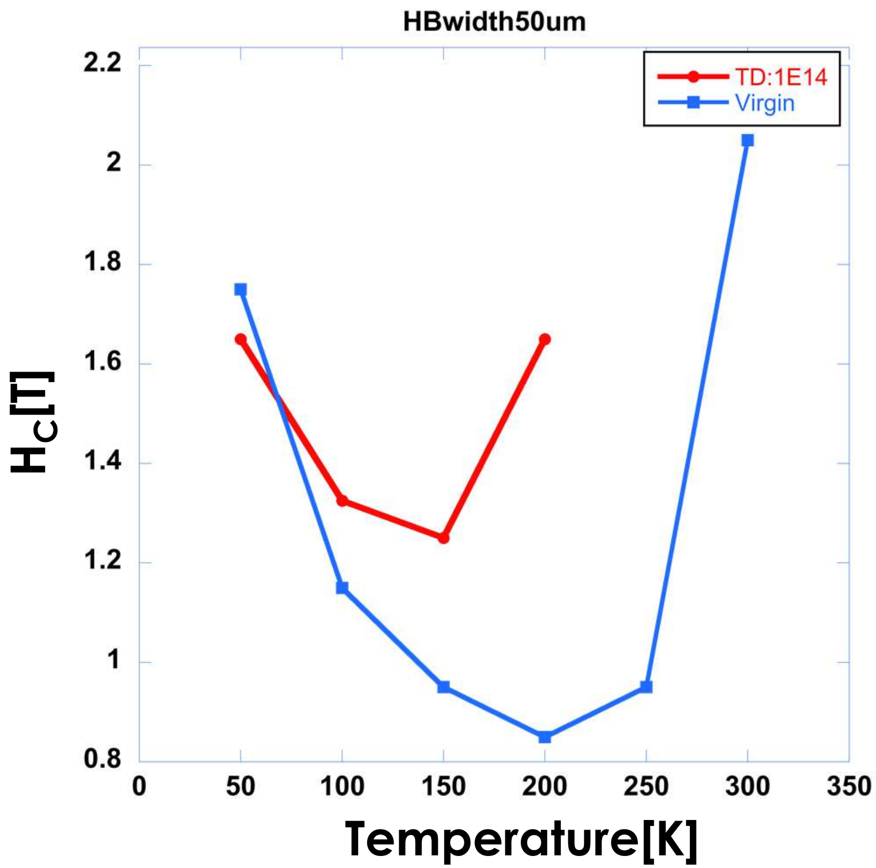
- AHE resistance mimics magnetization loop nicely
- Extract H_C from AHE data

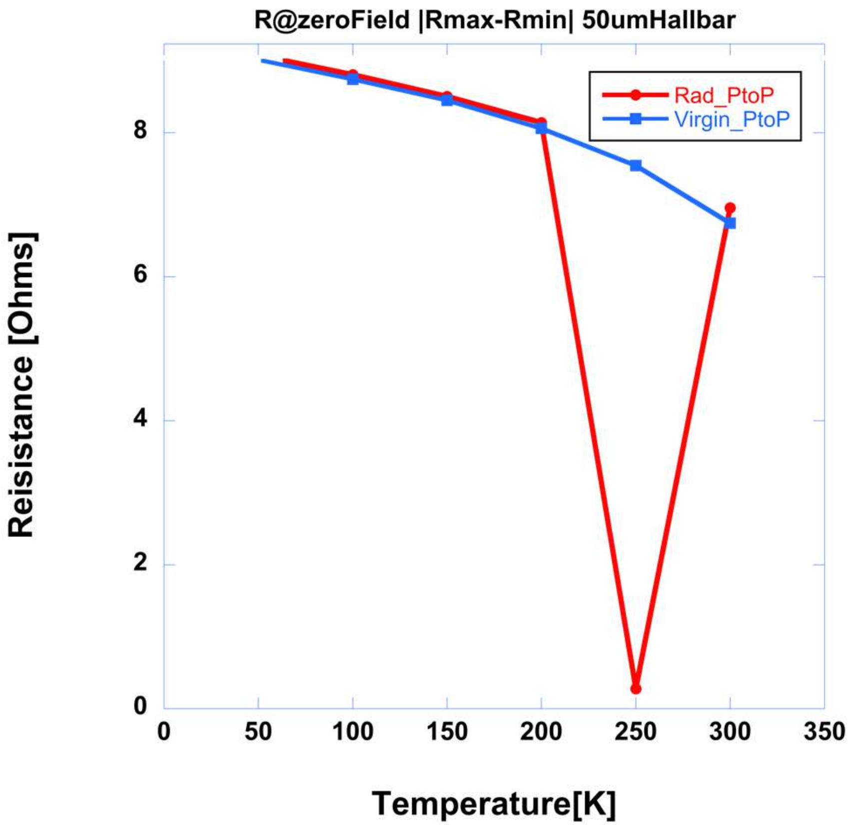
500umwidth Hallbar

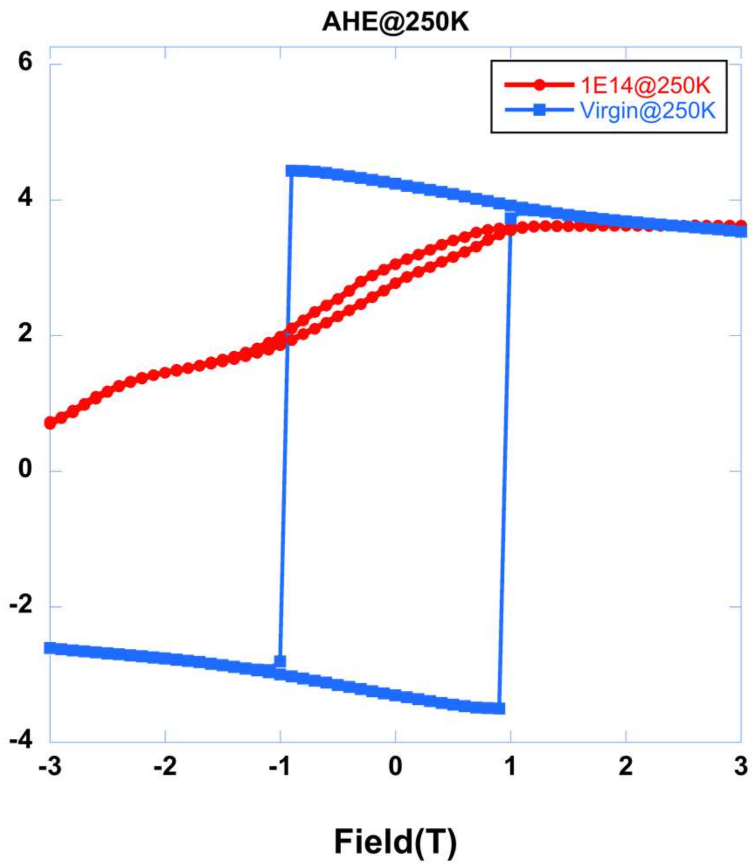


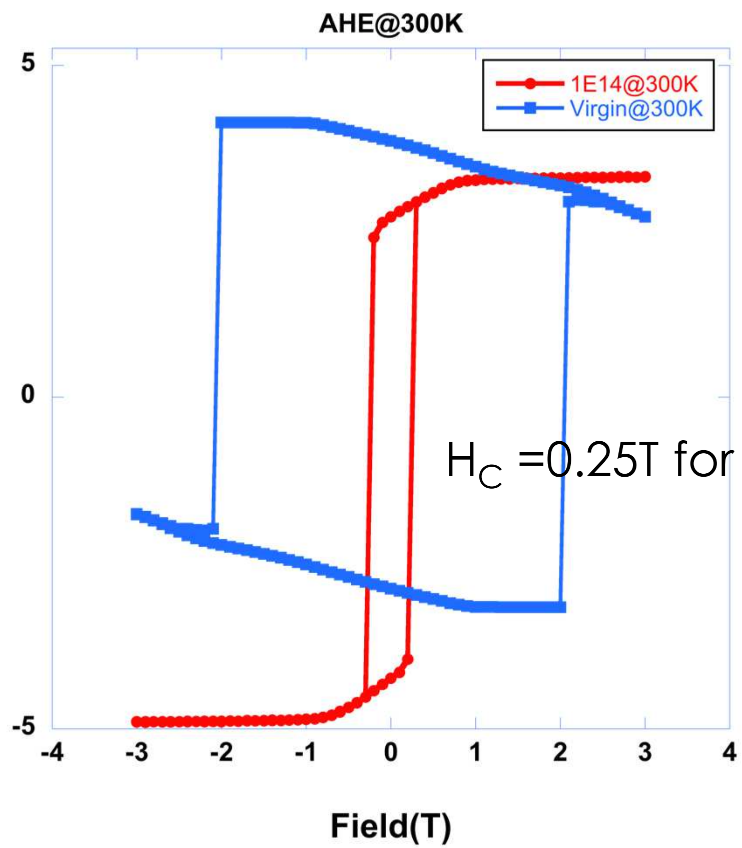


50umwidth Hallbar



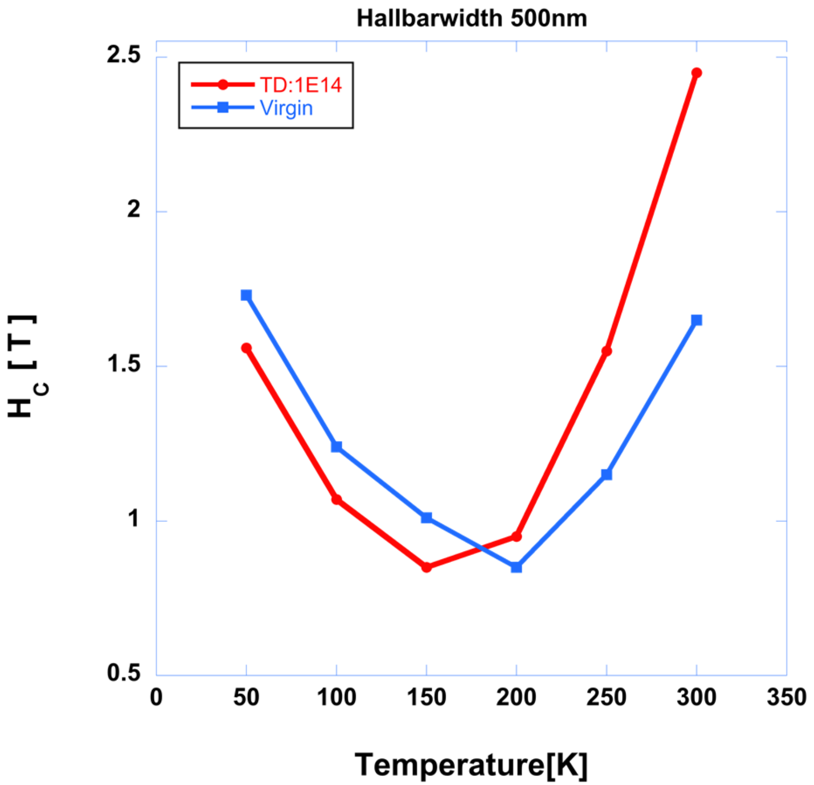


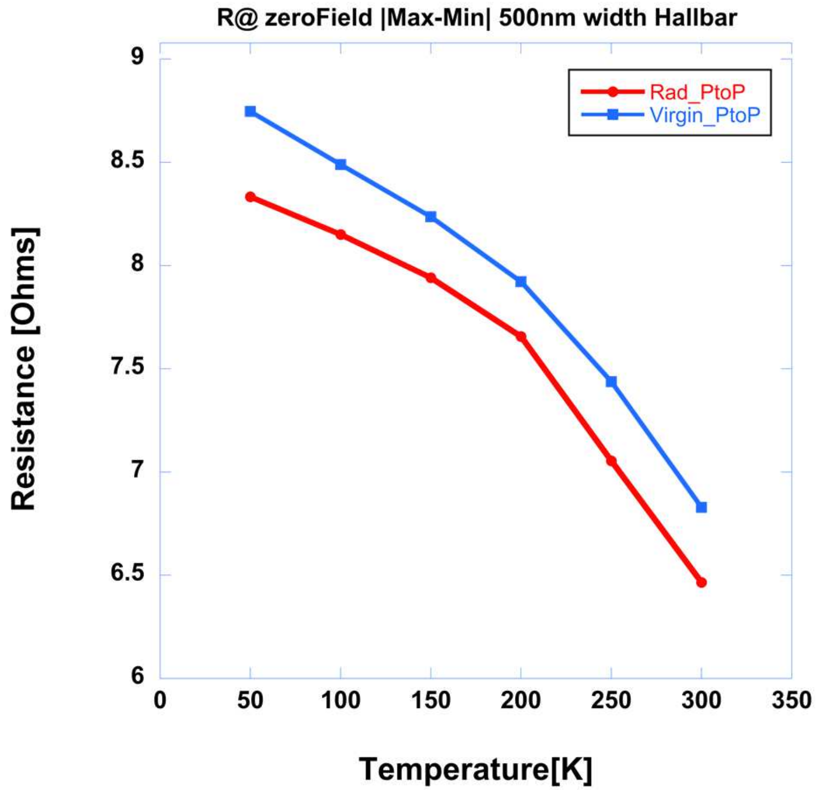




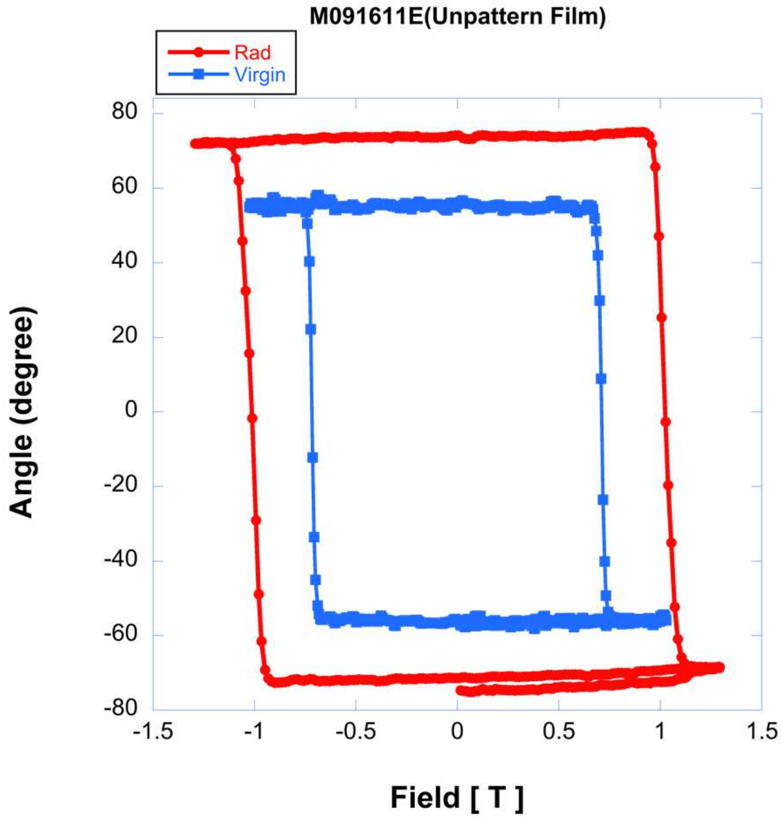
H_C =0.25T for Radiatior

500nm width HallBar



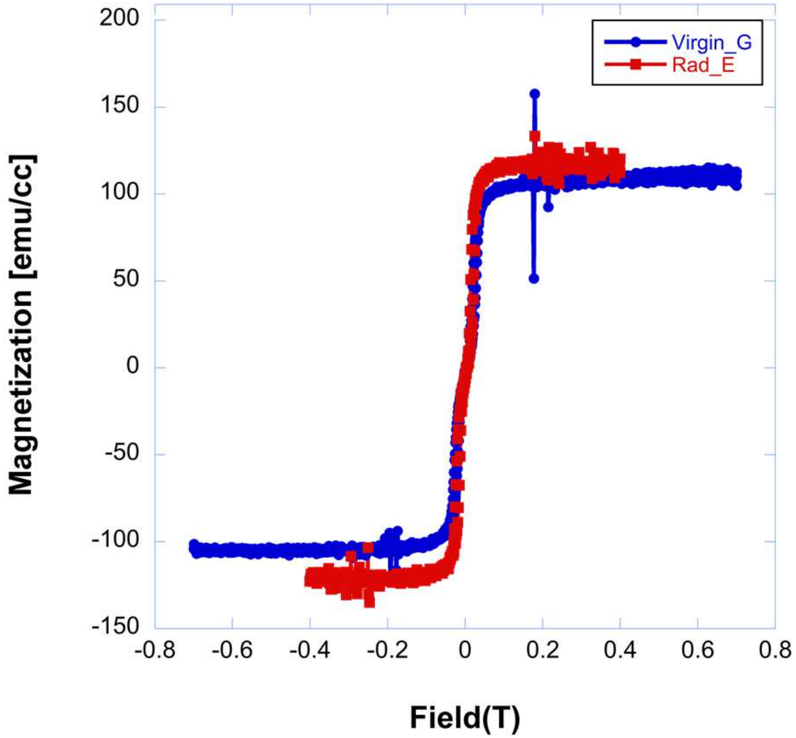


Magnetization: Unpatterned film



Sample G, M_S =107.81 emu/cc

Sample E_rad M_S = 119.15 emu/cc



Virgin H_C= 7150 Oe

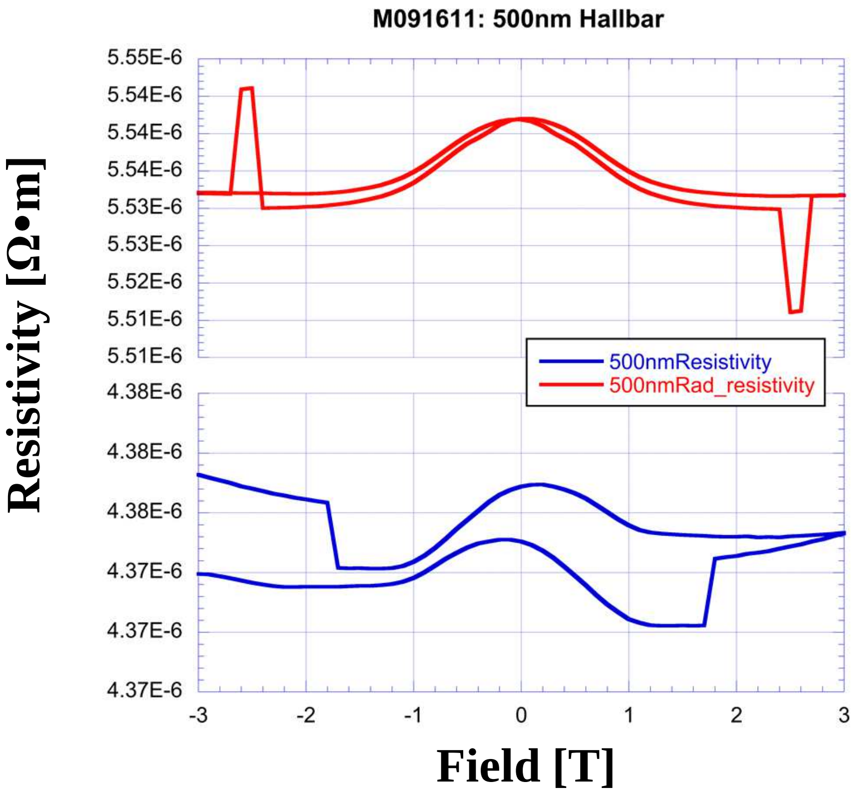
Rad H_C =10000 Oe

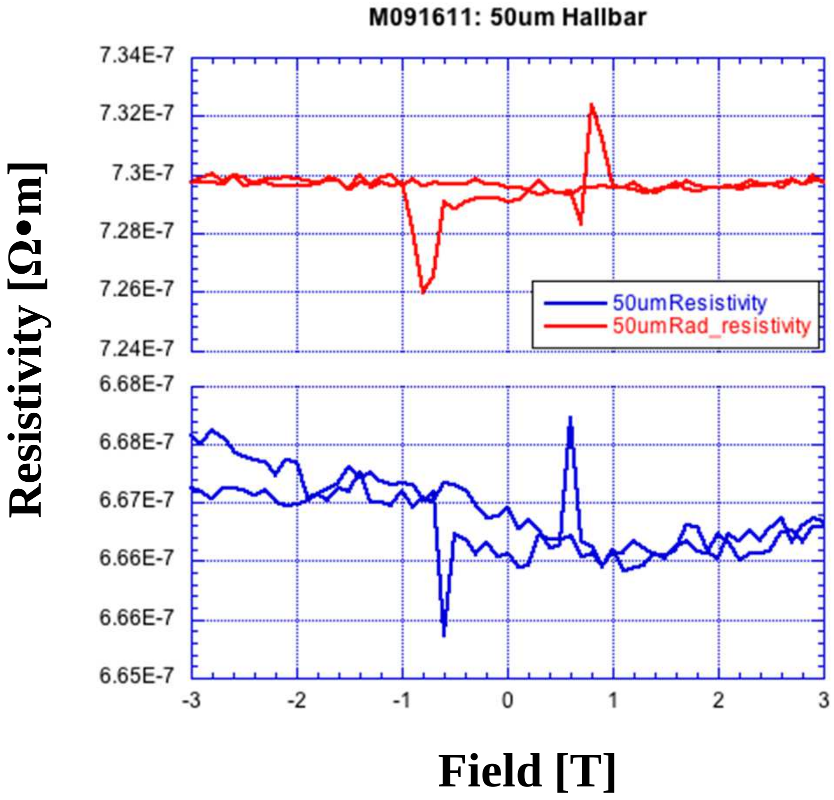
MOKE

In-plane VSM

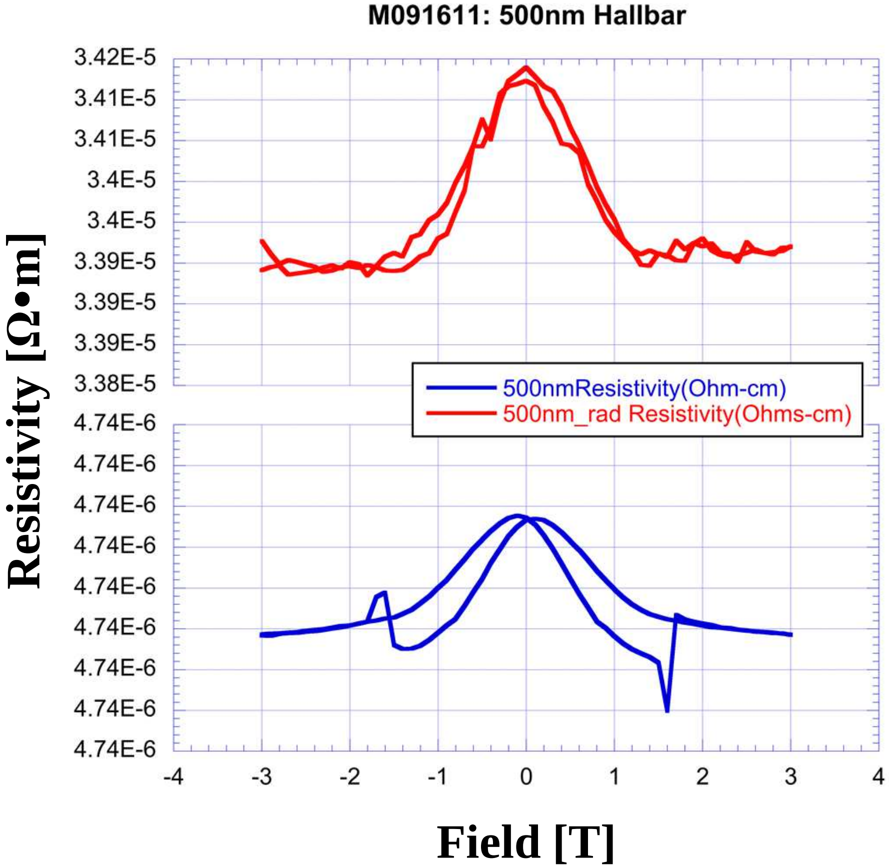
Resistivity Measurement

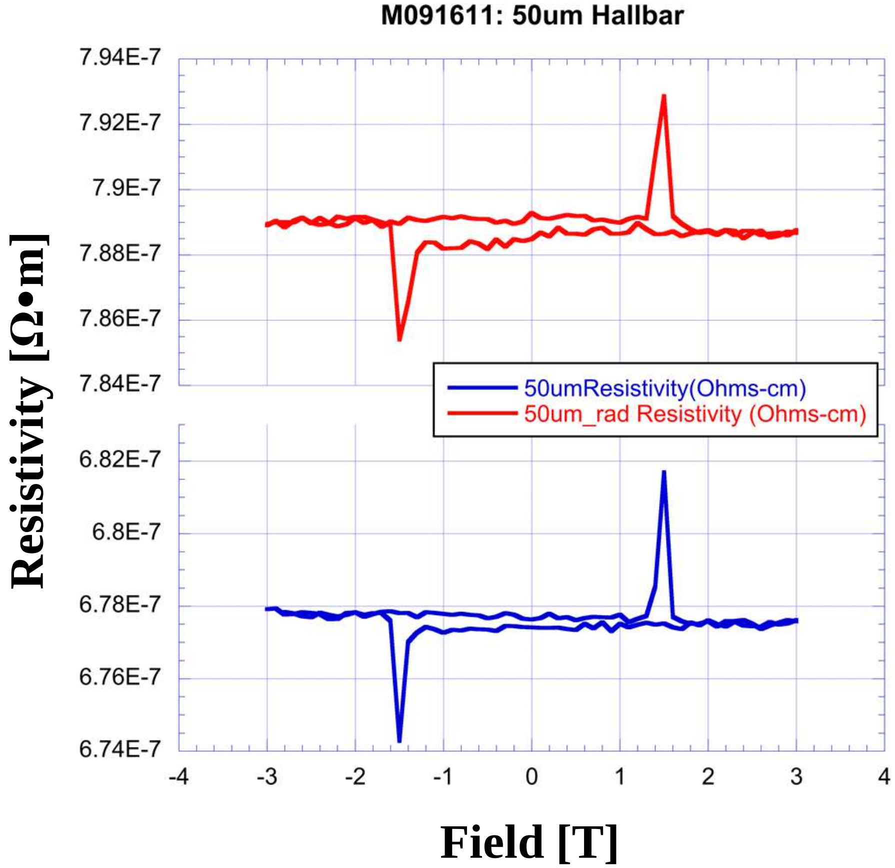
Temp@300K





Temp@50K


M091611: 500nm Hallbar
3.42E-5
3.41E-5
3.41E-5
3.4E-5
3.4E-5
3.39E-5
3.39E-5
3.39E-5
3.38E-5
4.74E-6
4.74E-6
4.74E-6
4.74E-6
4.74E-6
4.74E-6
4.74E-6
4.74E-6
4.74E-6
-4
-3
-2
-1
0
1
2
3
4
Resistivity [Ω•m]
Field [T]
500nmResistivity(Ohm-cm)
500nm_rad Resistivity(Ohms-cm)

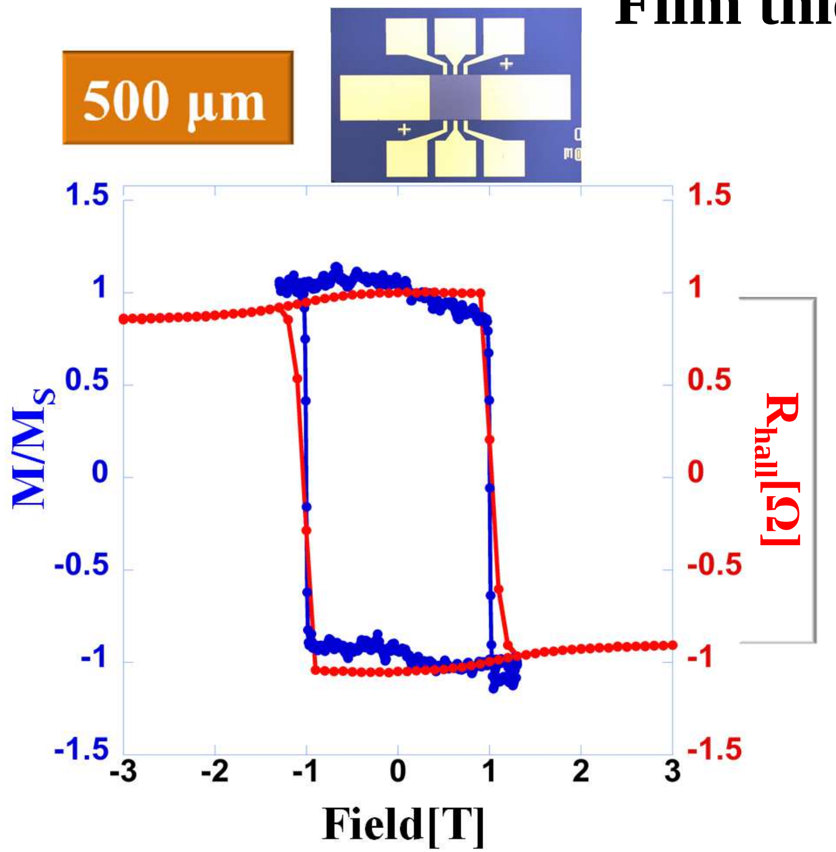

M091611: 50um Hallbar
7.94E-7
7.92E-7
7.9E-7
7.88E-7
7.86E-7
7.84E-7
6.82E-7
6.8E-7
6.78E-7
6.76E-7
6.74E-7
-4
-3
-2
-1
0
1
2
3
4
Resistivity [Ω•m]
Field [T]
50umResistivity(Ohms-cm)
50um_rad Resistivity (Ohms-cm)

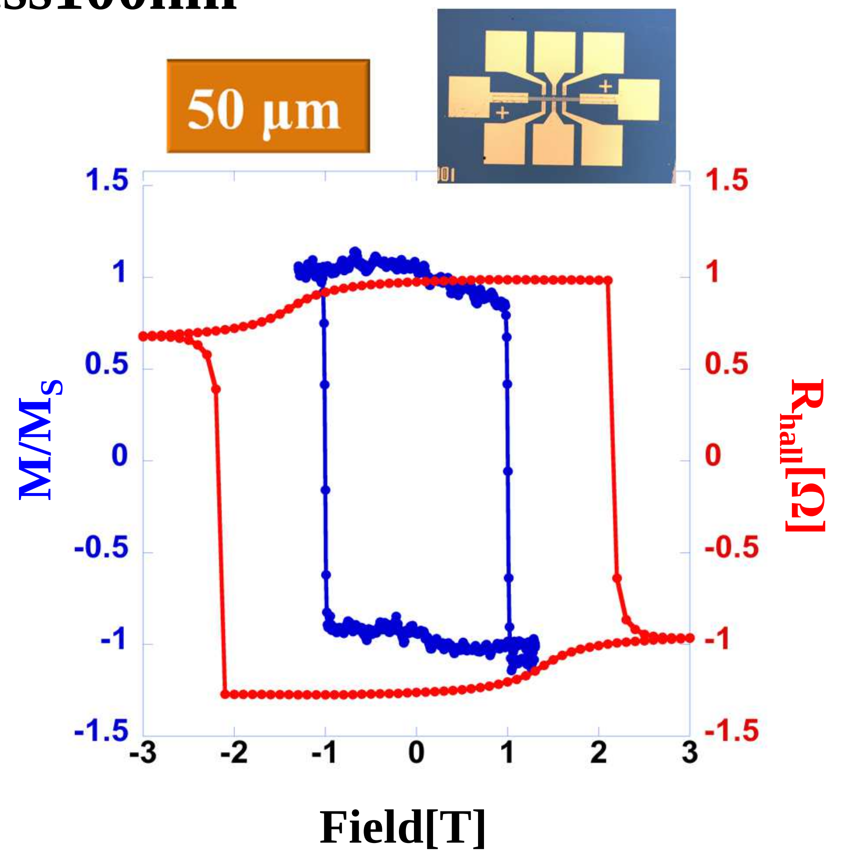
Summary and Future Work

- With the advent of spintronics and nanomagnetics, a fundamental understanding is required to understand the spin related disorder effects, particularly in nanoscale system.
- 2MeV proton have been used to investigate the displacement damage on crystalline MnAl and Amorphous TbFeCo system.
- The chemical order in MnAl decrease monotonically as the radiation fluence increase indicating microstructure change. However, there was a fluctuation in saturated moment after the second irradiation.
- Resistivity change dramatically in TbFeCo after irradiation compared to the change in MnAl system. MnAl is more robust in term of electrical transport.
- comprehensive characterization on microstructure, magnetic structure and magneto-transport will be required to understand the spin related disordering effect.
- The effect of displacement damages and ionization damage will be studied on the multilayer structures including spin valves or magnetic tunnel junctions.

Hall bar width vs. Coercive field

Film thickness100nm





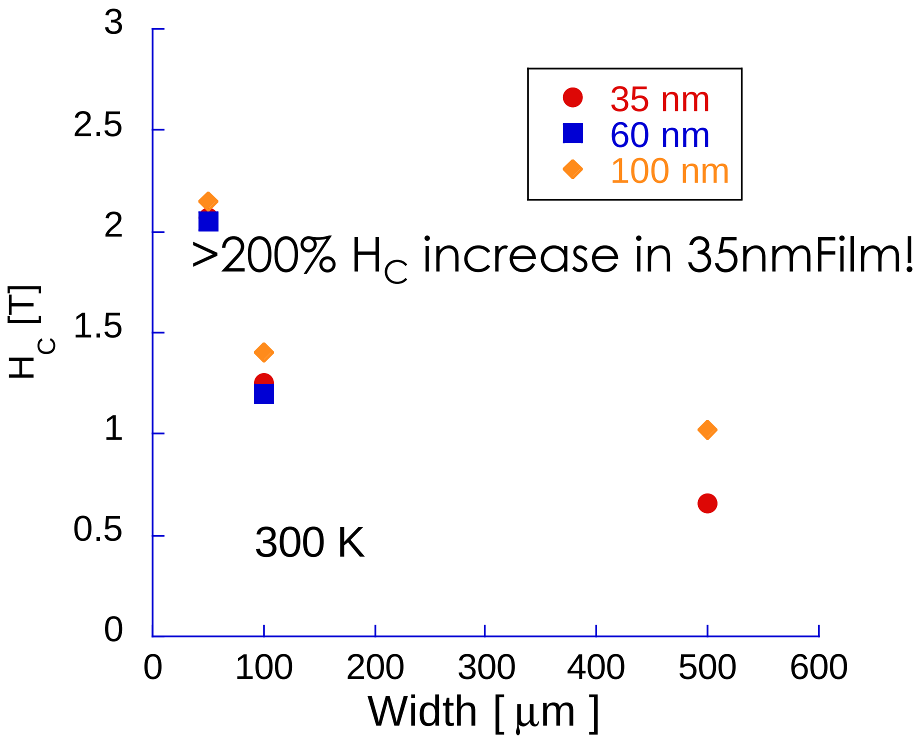
$$R_{Hall} = R_0(H)\mu_0 H + R_s(H)\mu_0 M$$

Ordinary Hall effect

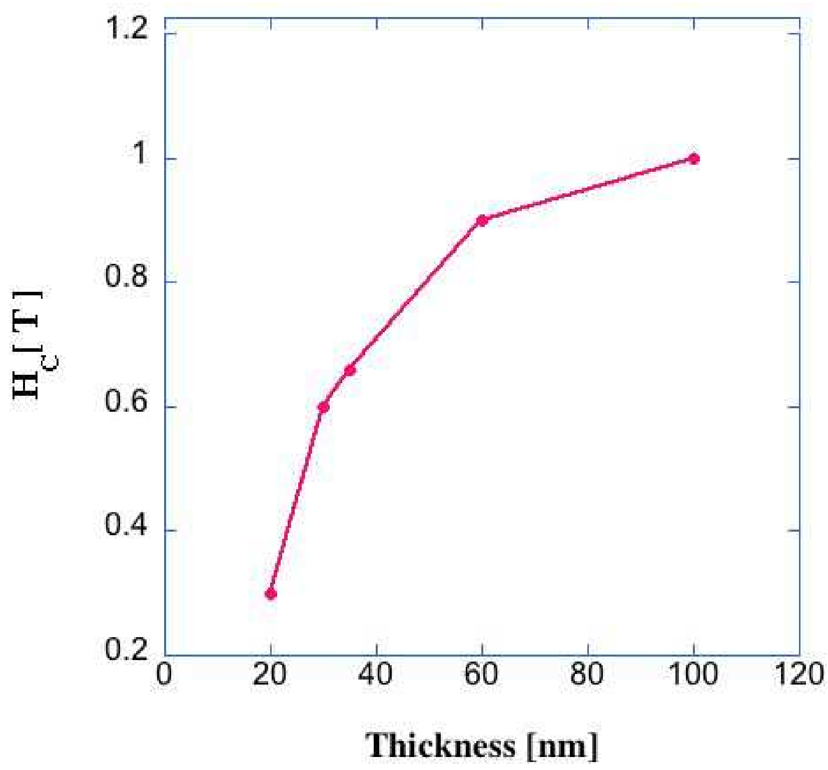
Anomalous Hall effect

Coercivity Field Enhancement

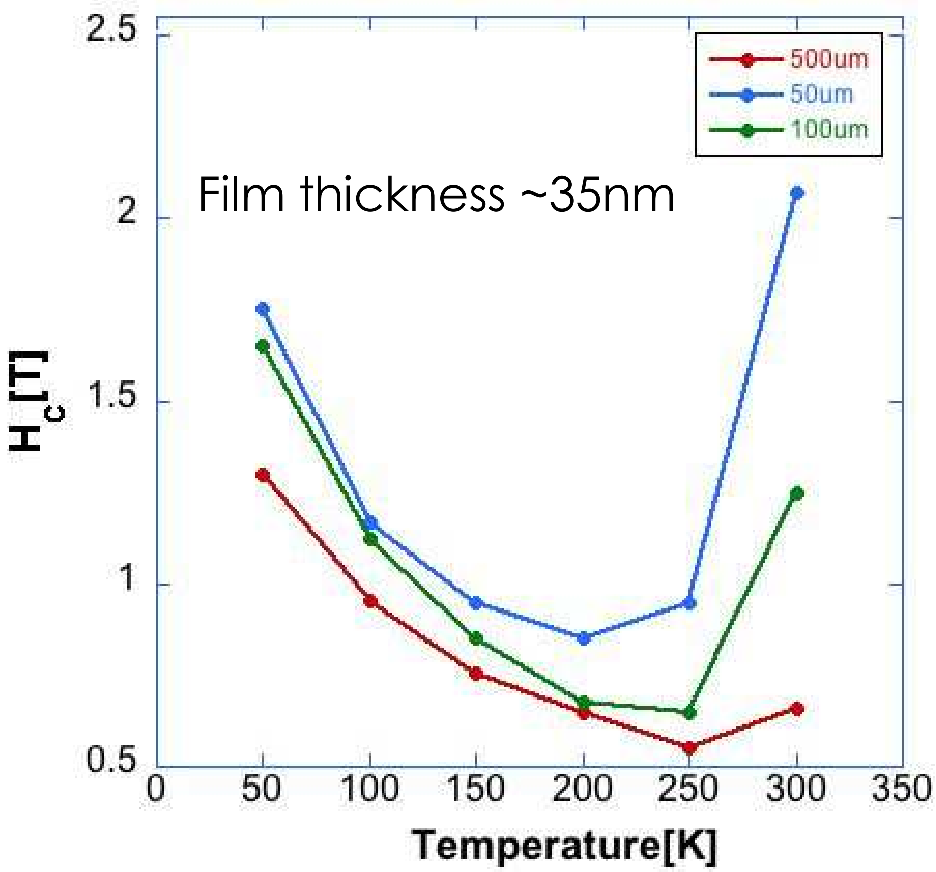
Hall Bar Coercivity at RT



Unpattern film Coercivity at RT



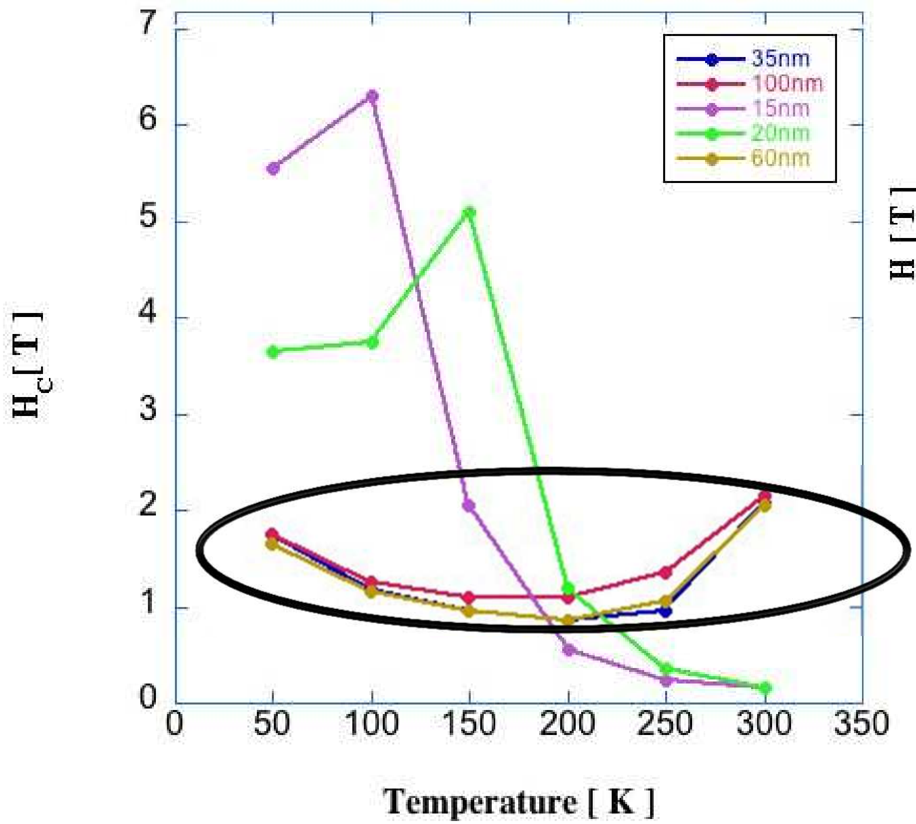
Temperature dependence

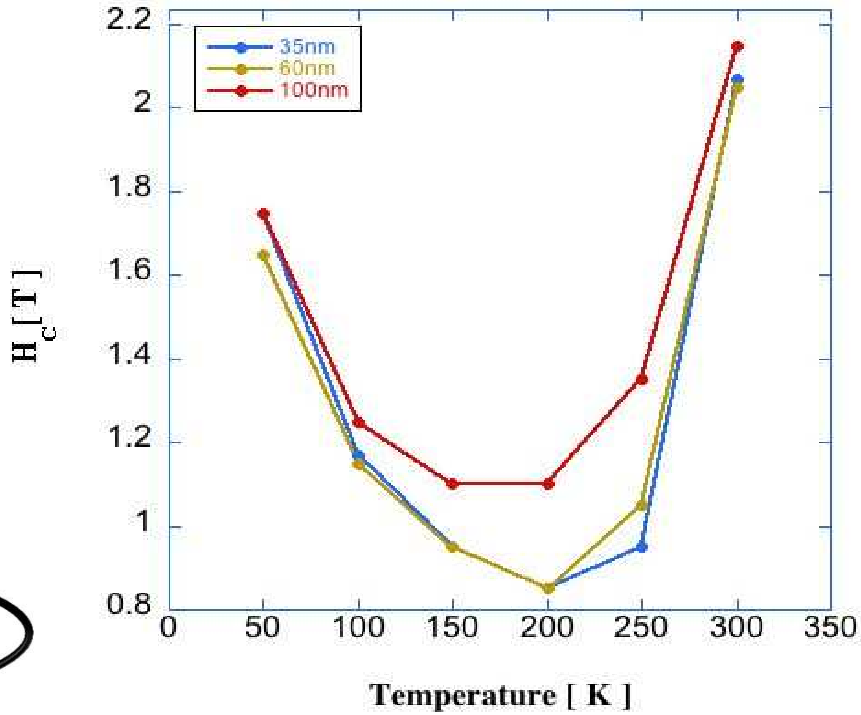


- Minimum coercivity (H_{Cmin})exists as we did Temperature scan!
- The position H_{Cmin} vary for different Hall Bar width.
- The temperature dependence of H_C is reversible

Thickness comparison

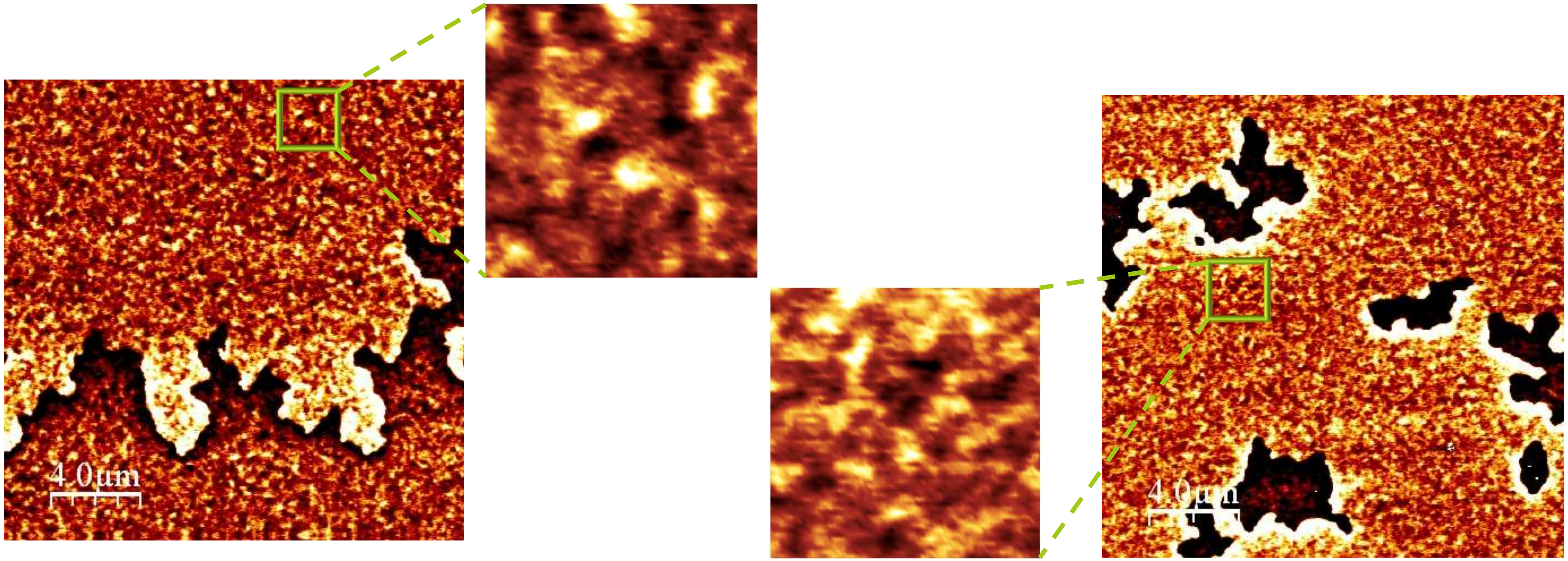
Hall Bar width = 50 µm





Thinner film→H_{Cmin} shift toward 300K

Blocking of Domain Wall Motion?

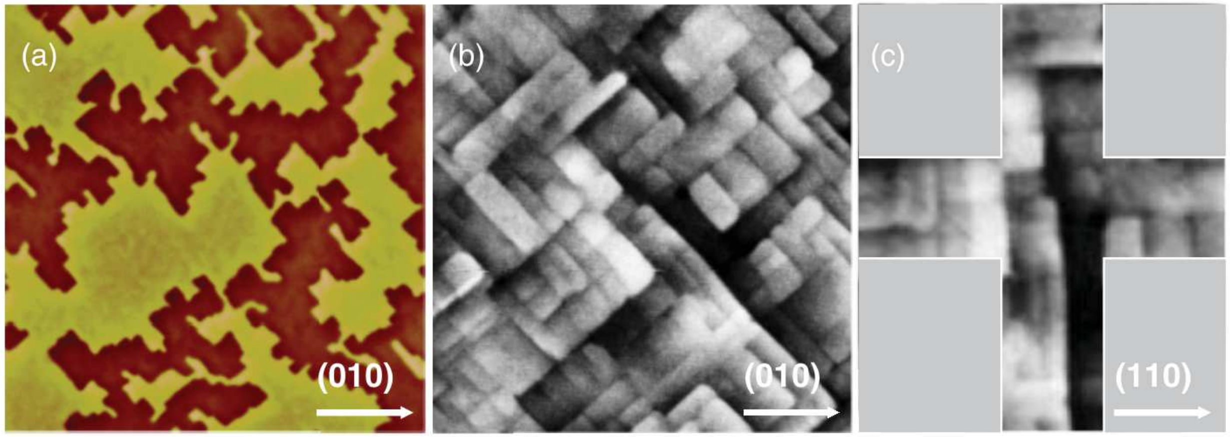


500 micron Hall Bar

50 micron Hall Bar

20nmTbFeCo: Demagnatized State

H_C enhancement in FePt

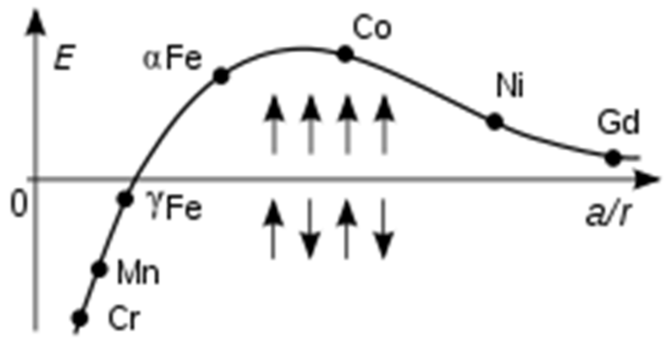


The decrease of branch widths reduces the number of available paths and thus forces the DW to cross microtwins with larger pinning strengths, increasing the coercivity.

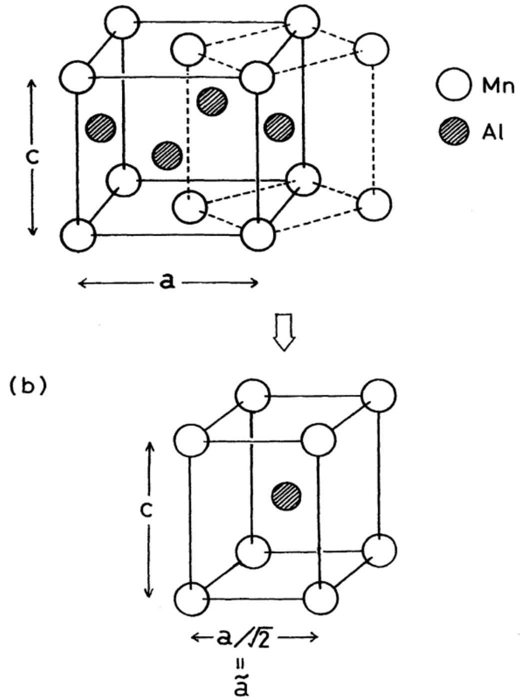
J.P.Attane et al.,PRB 84, 144418(2011)

Supplementary

- **Origin of the magnetism: exchange coupling vs. the ratio of the interatomic distance a to the radius of 3d electron shell r.**

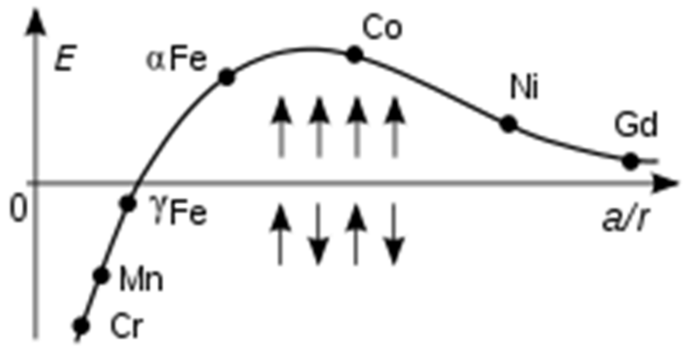


$L1_0$ reduced to distorted B2



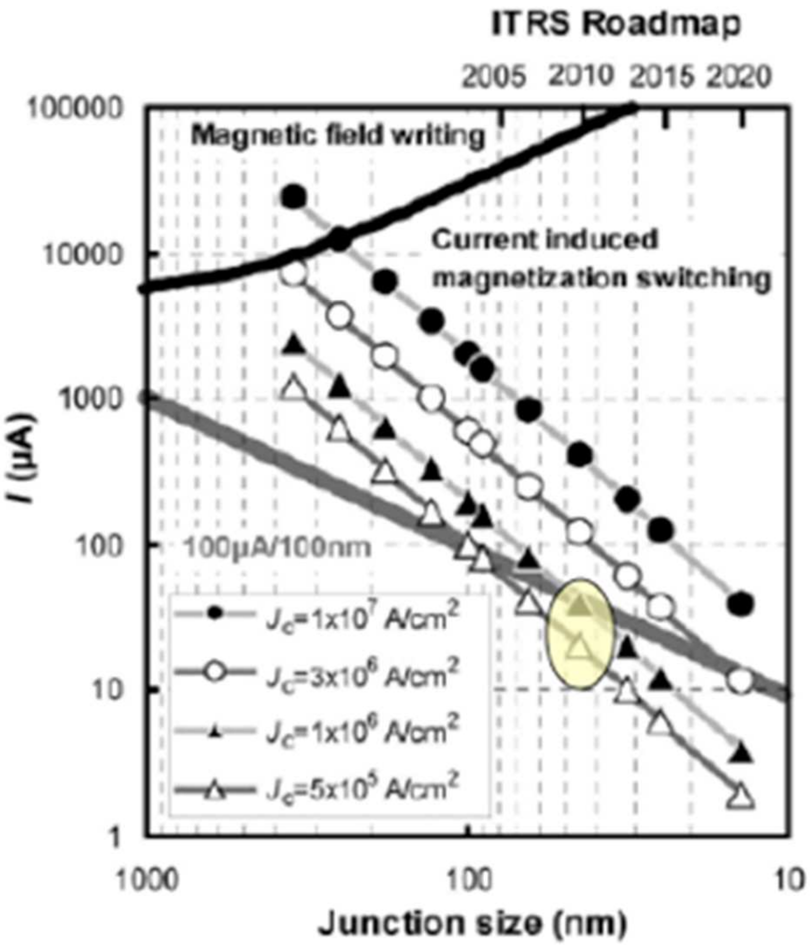
Bethe-Slater Curve

exchange coupling vs radius of 3d electron shell



From link: http://en.wikipedia.org/wiki/Bethe_Slater_curve

Promise of STT-RAM



STT-RAM architecture → 1MTJ-1T for maximum device density

Switching current supplied by CMOS transistor

Switching current density needs to be lowered to 5×10^5 A/cm^2

Switching energy needs to be reduced