Exploration of Novel Tunnel Barrier Materials for STT-RAM

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Outline

- Introduction and Motivation
- Background Theory
- Experiment Setups
- Results & Discussion
- Summary & Future Plan

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- Introduction and Motivation
  - What is Magnetic Tunnel Junction (MTJ)?
  - MRAM: Major Application of MTJ
  - New Solution: Spin Torque Transfer!
- Background Theory
- Experiment Setups
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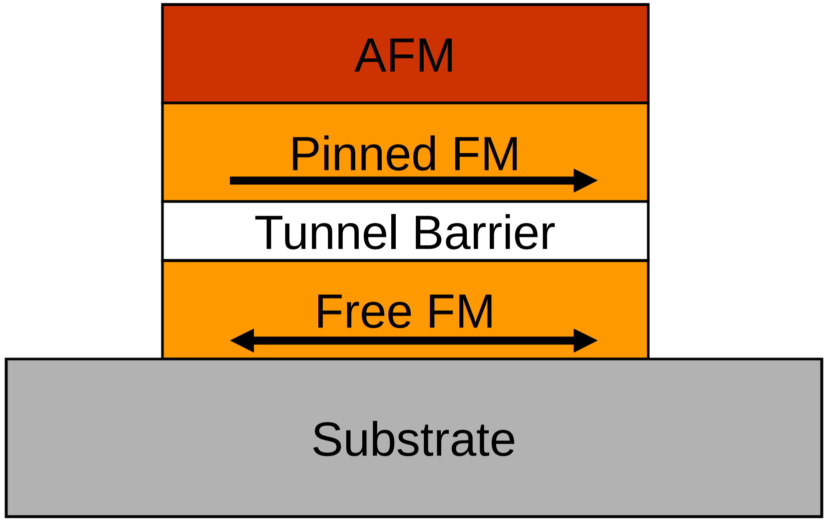
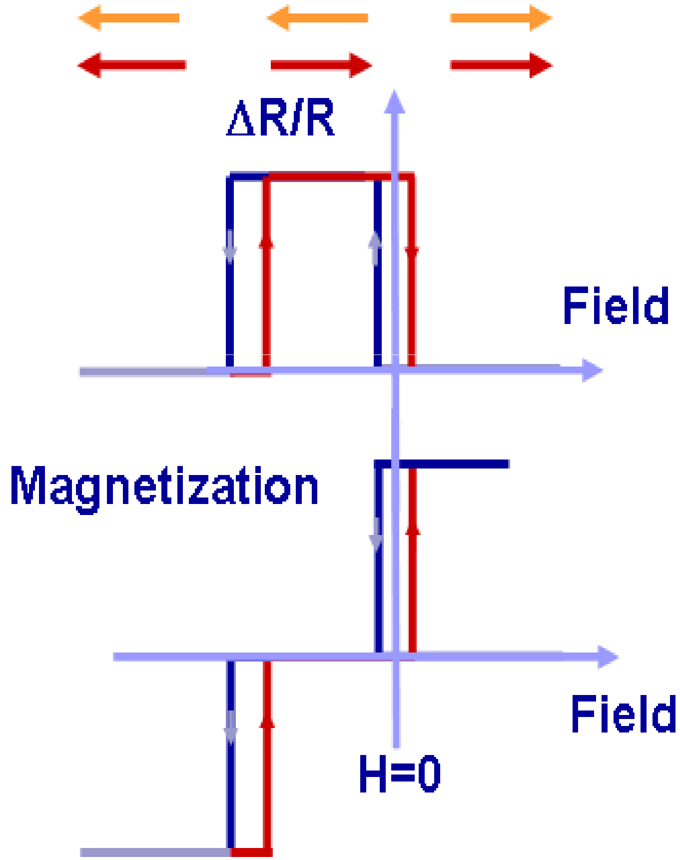
Magnetic Tunnel Junction

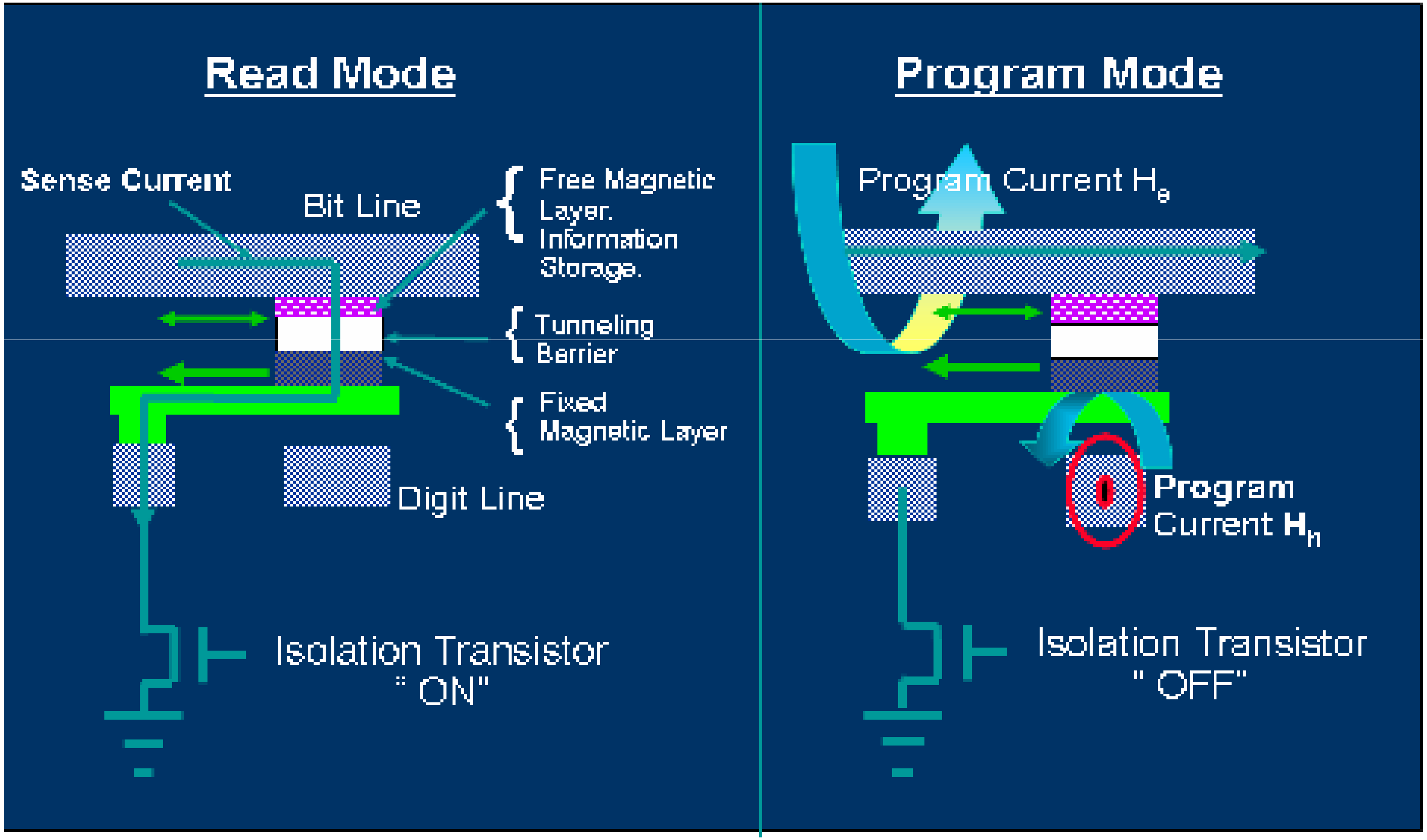


Basic Structure of Exchange Biased MTJ



[Spintronics Class Lecture Notes, Stuart Wolf, Spring 2007]

MRAM: Major Application of MTJ



[Spintronics Class Lecture Notes, Stuart Wolf, Spring 2007]

MRAM: Major Application of MTJ

Potential Advantages:

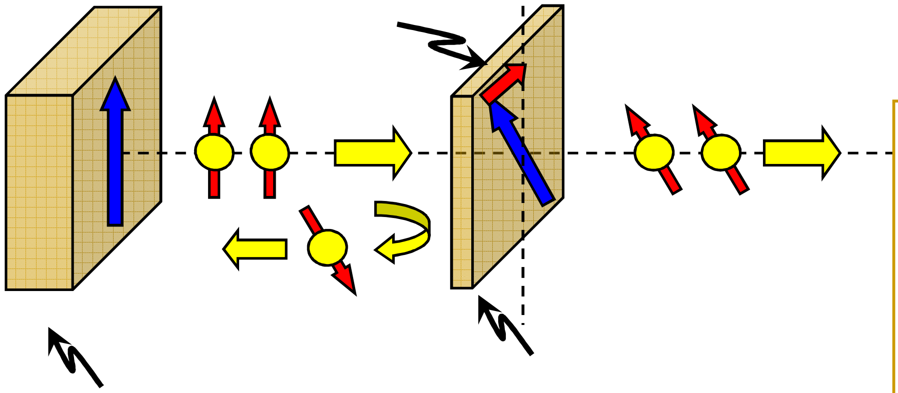
- Compatibility with CMOS
- Density and speed of DRAM
- Less power than FLASH
- Unlimited writing cycles
- Truly Non-volatile

Main Challenges:

Field Switching MRAM cannot be effectively scaled down (65nm node)!

- 1T-1MTJ cell structure limited by the size of transistor!
- Thermal Stability Factor: $\frac{K_u V}{k_B T}$

Spin Torque Transfer Switching



• A spin-polarized current injected into a ferromagnetic layer can induce a torque on its magnetization, hence rotate the magnetization.

Key Advantage compared with conventional field switching:

• Highly *Scalable* ←writing current scales down with cell size with constant **Jc**!

Key Advantages and Potentials of STTRAM

	MRAM (180 nm)	DRAM (45 nm)+	SRAM (45 nm)+	FLASH (45 nm)+	STTRAM (45 nm)*
Cell size (μm^2)	1.25	0.03	0.18	0.03	0.03
Read time	35 ns	1 ns	0.5 ns	10 - 50 ns	5 ns
Write time	5 ns	1 ns	0.5 ns	0.1-100 ms	5 ns
Write energy/bit	150 pJ	0.02 pJ Needs refresh	5 pJ	10 nJ	0.04 pJ
Endurance	$> 10^{15}$	$> 10^{15}$	$> 10^{15}$	$> 10^{15}$ read, $> 10^{6}$ write	$>10^{15}$
Non-volatile	Yes	NO	NO	YES	YES

- Excellent write selectivity ~ localized spin-injection within cell
- Highly Scalable ~ write current scales down with cell size
- Low power ~ low write current
- Simpler Architecture ~ no write lines, no bypass line and no cladding
- High Speed ~ Few nanoseconds

Spin Torque Transfer Switching

Model by Slonczewski: $$J_c = \frac{2eM_s\delta\alpha(H + 2\pi M_s)}{h\eta}$$

$J_c \sim 10^8$ A/cm^2 (Co: $\delta = 2.5nm, M_s = 1420kA/m, \alpha = 0.1$)

=> Too high to be practical! ($10^6 A/cm^2$)

What we could engineer:

- ***M$_s$*** Saturation Magnetization → Decrease
- **α** Gilbert damping parameter → Decrease
- **η** Spin Transfer Efficiency → Increase

Novel Barrier Exploration

- Only ~70% with AlOx-MTJs.
- TMR record with MgO barrier: Over 300%!

→MgO increases **η** (spin transfer efficiency) significantly!

New Barriers Exploration → Increase **η** :

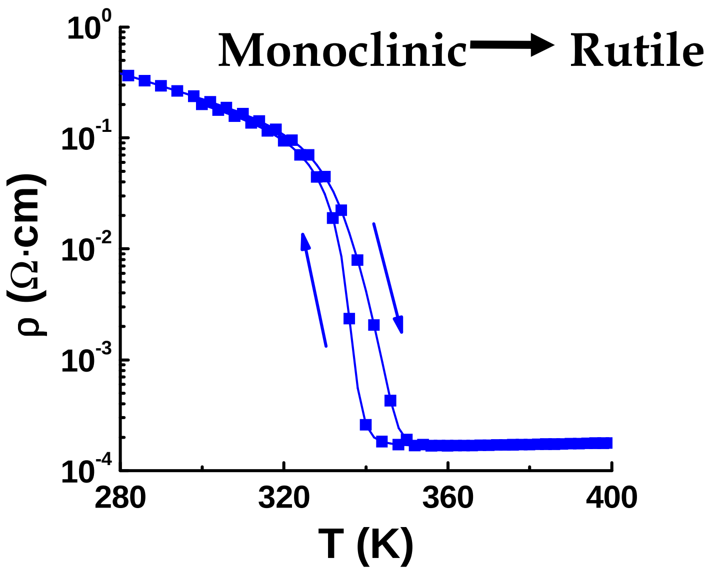
- Oxides: VOx, TiOx, TaOx
- Nitrides: BN
  - prevent the oxidation of under layer FM
  - large gap provides robust tunneling

Smart Barrier for MTJs

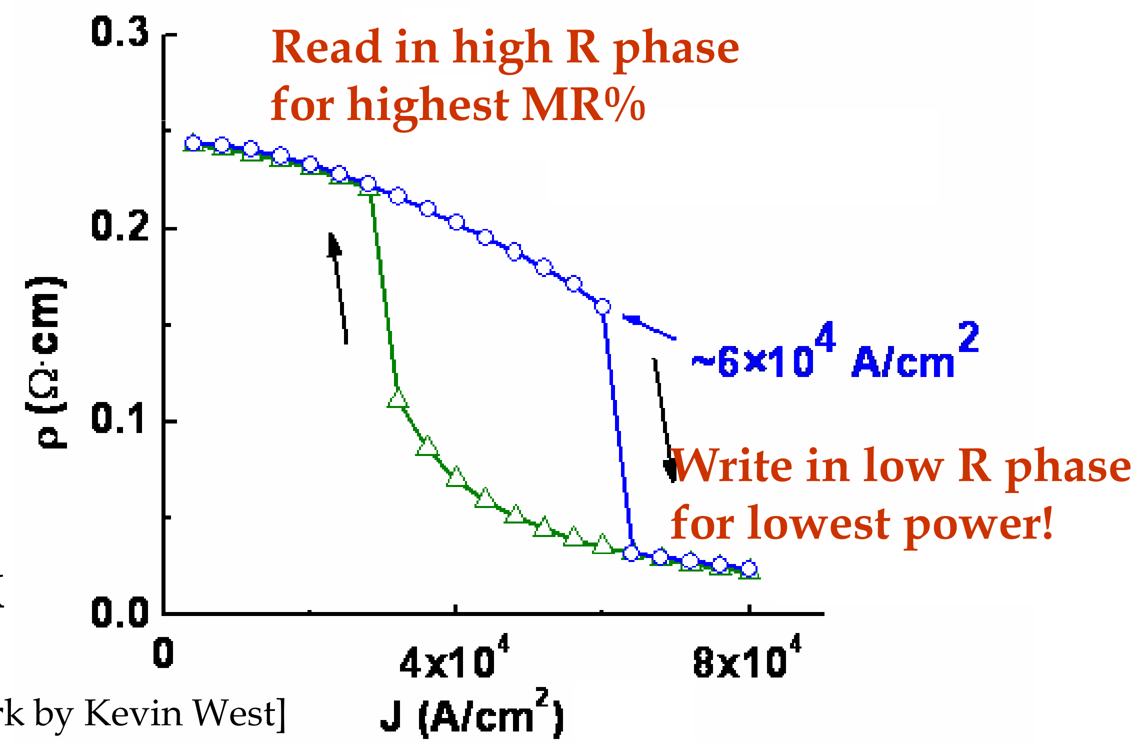
Challenge for SMT-MTJs:
High Jc→ "Writing" voltage very close to junction break down voltage

↔

VO2:
- **Structural phase transformation from *Monoclinic* to *Rutile* at ~340K**
- **Current Driven transition**



Transition temperature: ~ 340 K



[Work by Kevin West]

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- Introduction and Motivation
- Background Theory
  - Spin-dependent Transport
  - Spin Polarized Electron Tunneling: FM-I-FM
  - AFM/FM Exchange Bias
- Experiment Setups
- Results & Discussion
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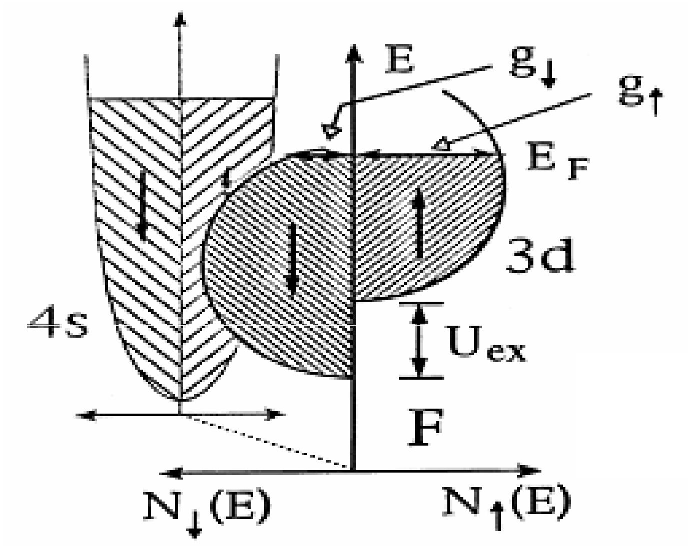
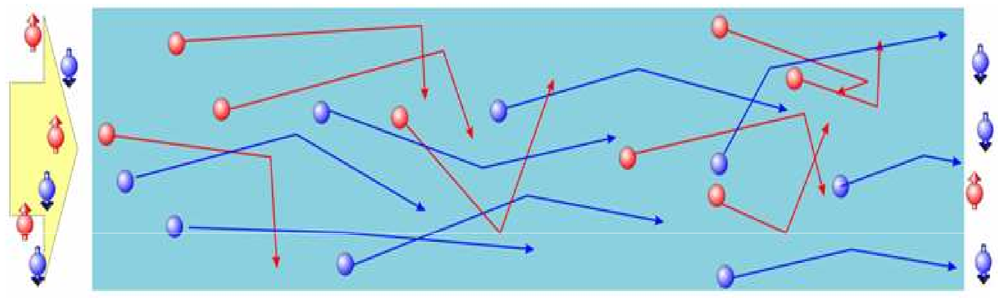
Spin-dependent Transport



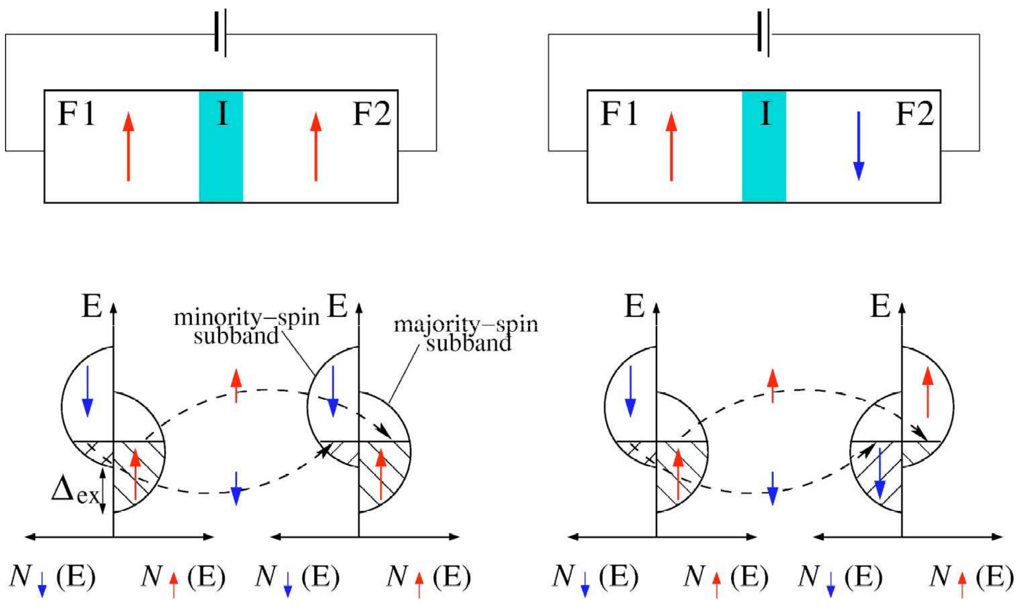
Density of State diagram for ferromagnetic metal: g↑ > g↓



current through ferromagnetic metal

[Spintronics Class Lecture Notes, Stuart Wolf, Spring 2007]
[Mark Jonson, *J. Phys. Chem. B* (2005), *109,* 14278-14291]

Spin Polarized Electron Tunneling: FM-I-FM



Julliere's model:

- spin conserved tunneling
- $G_p = N_{1\uparrow}N_{2\uparrow} + N_{1\downarrow}N_{2\downarrow}$

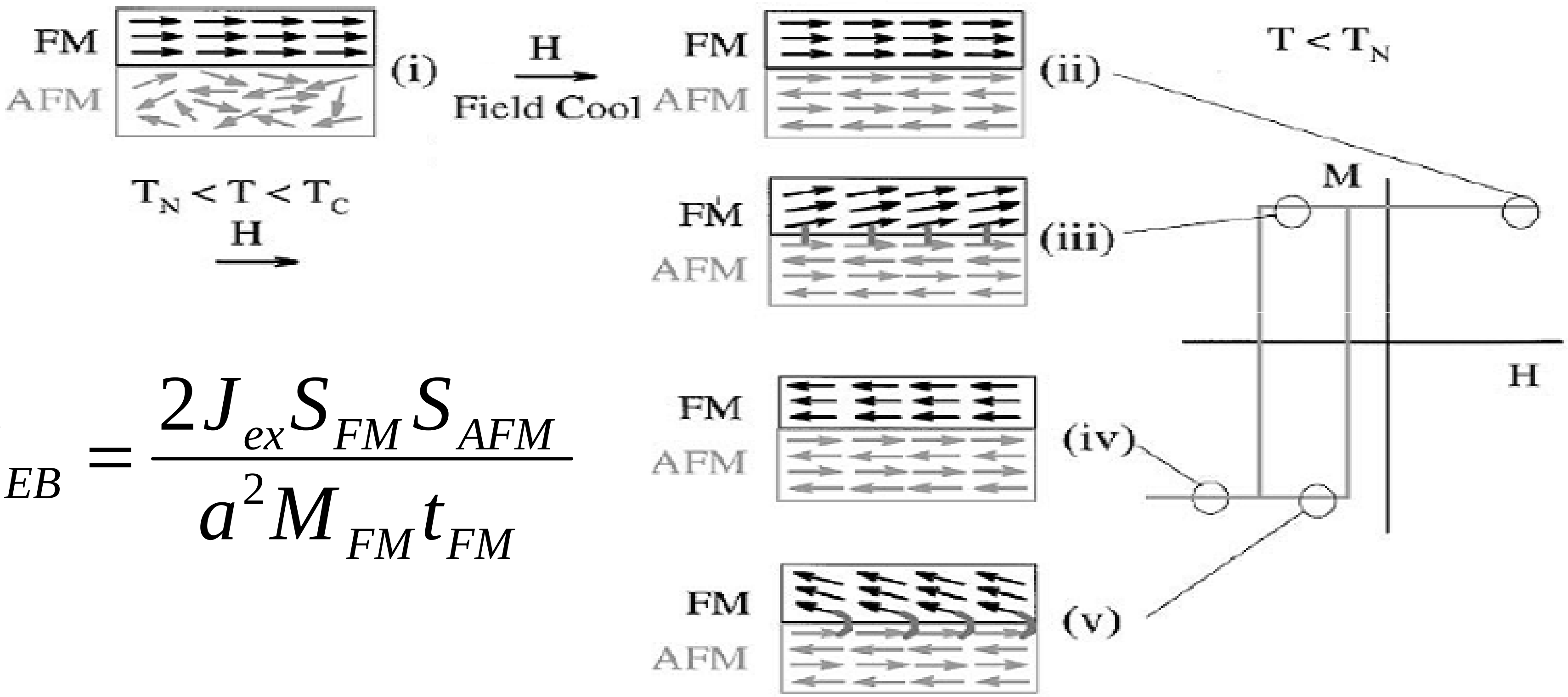
  $G_{AP} = N_{1\uparrow}N_{2\downarrow} + N_{1\downarrow}N_{2\uparrow}$

$$P_1 = \frac{N_{1\uparrow} - N_{1\downarrow}}{N_{1\uparrow} + N_{1\downarrow}}$$

$$P_2 = \frac{N_{2\uparrow} - N_{2\downarrow}}{N_{2\uparrow} + N_{2\downarrow}}$$

$$TMR = \frac{\Delta R}{R_P} = \frac{R_{AP} - R_P}{R_P} = \frac{G_p - G_{AP}}{G_{Ap}} = \frac{2P_1P_2}{1 - P_1P_2}$$

Exchange Bias



$$H_{EB} = \frac{2J_{ex}S_{FM}S_{AFM}}{a^2 M_{FM} t_{FM}}$$

[J.Nogues, Ivan Schuller, JMMM192(1999) 203-232]

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  - Reactive Biased Target Ion Beam Deposition
  - Lithographic patterning process
  - CIPTech Measurement
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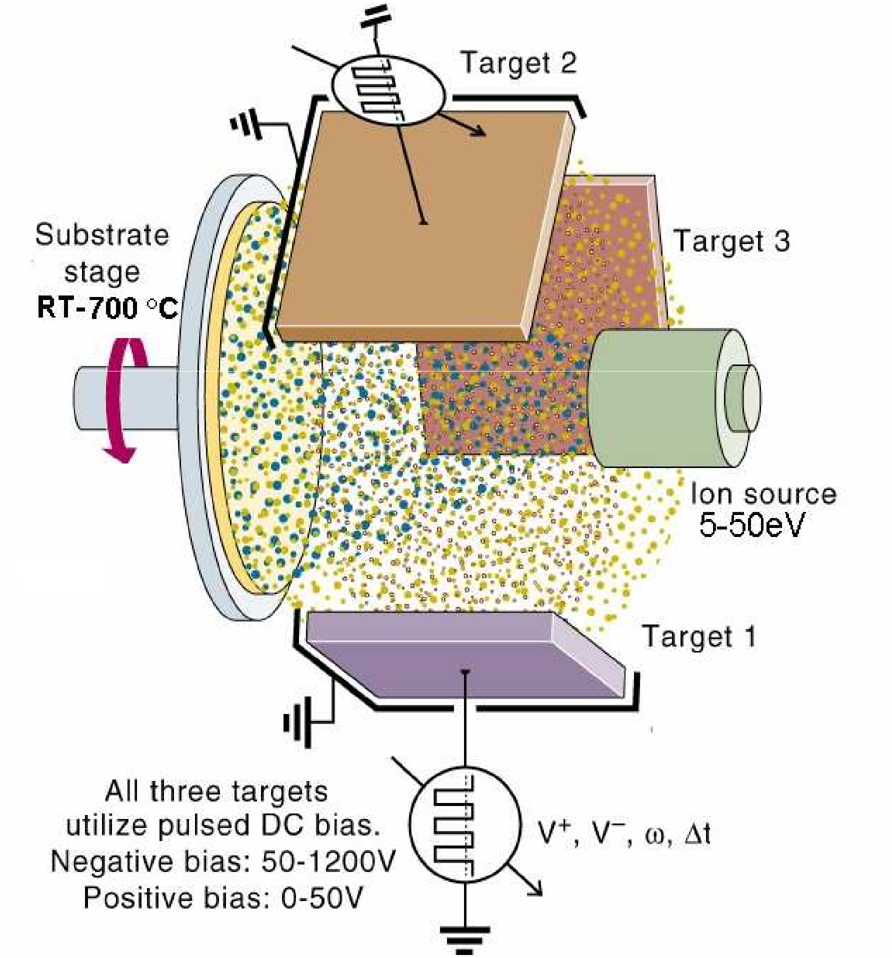
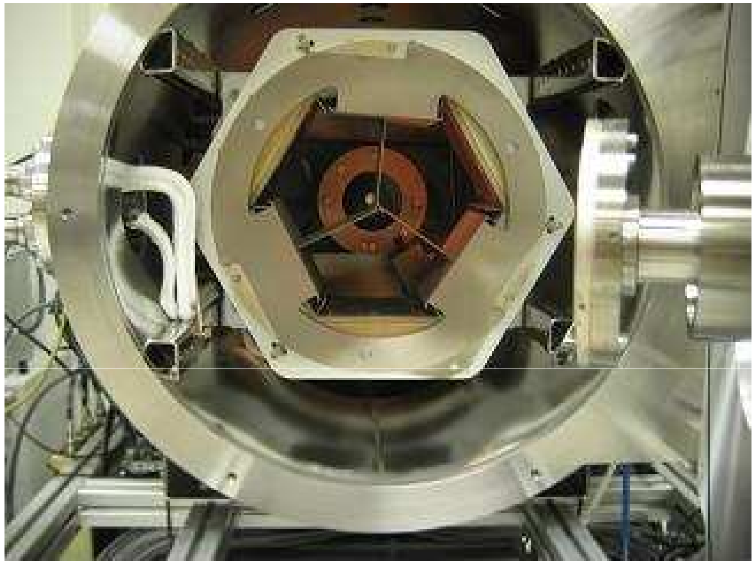
Reactive Biased Target Ion Beam Deposition

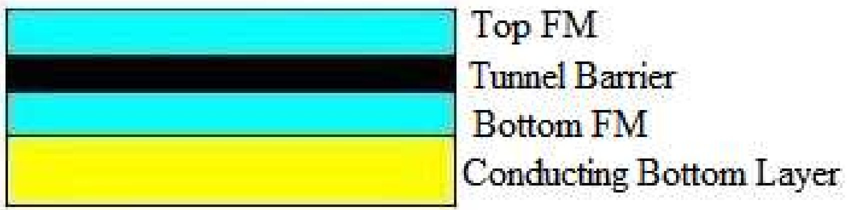




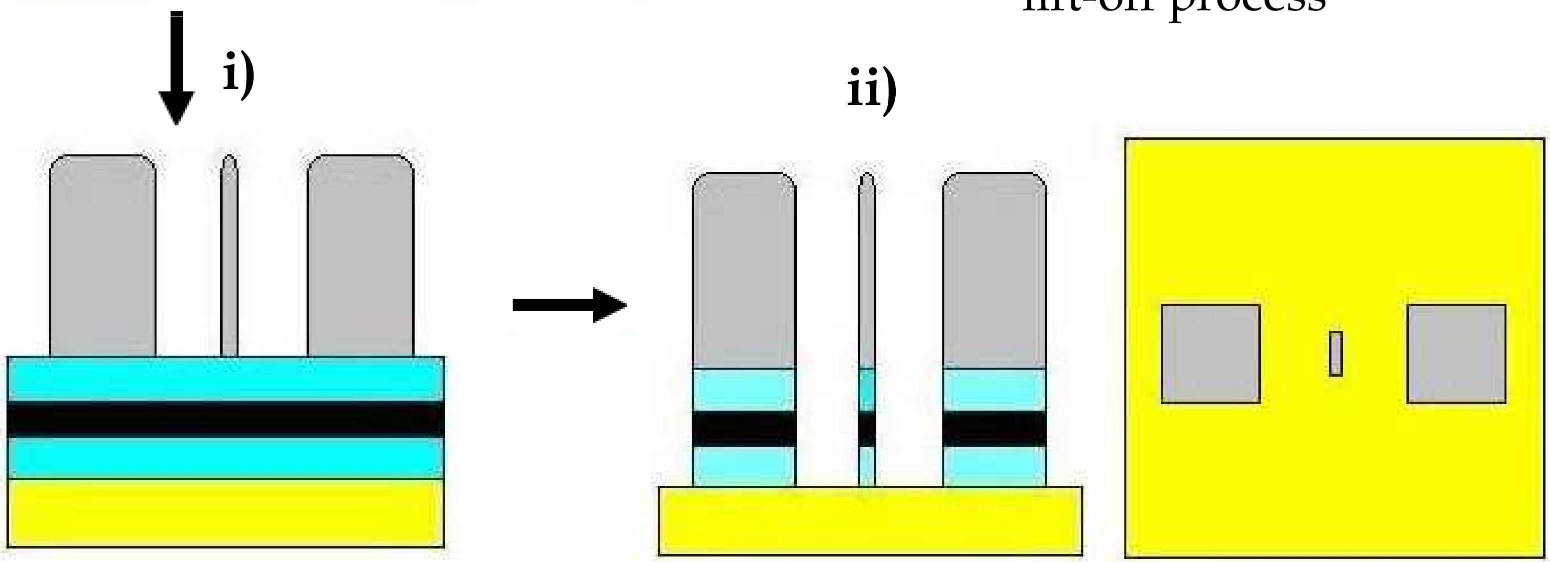
- Low Energy Ion Source (5-50eV)
- High Temperature ~ 700 °C
- Smooth Surface/Interface Layer
- Control Phase Formation
- Combinatorial Growth →Complex Oxides

Lithographic Patterning (I)

Unpatterned MTJ Film (*Cross-section View*)



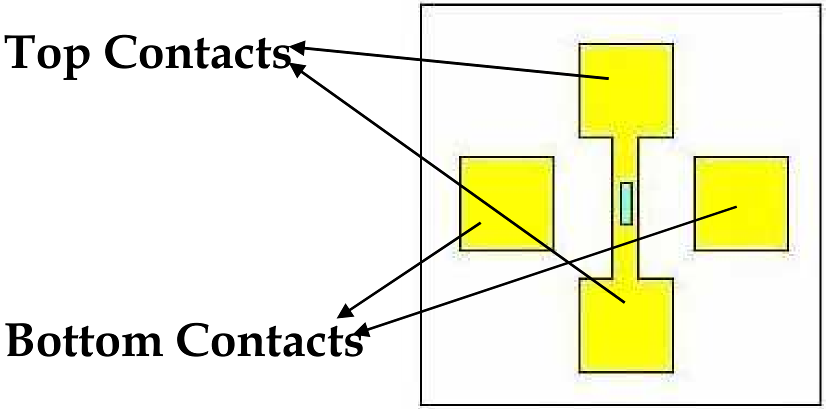
- **i)** Apply mask, develop photo resister (PR)
- **ii)** Dry etching to define junction structure; leave PR for next-step lift-off process



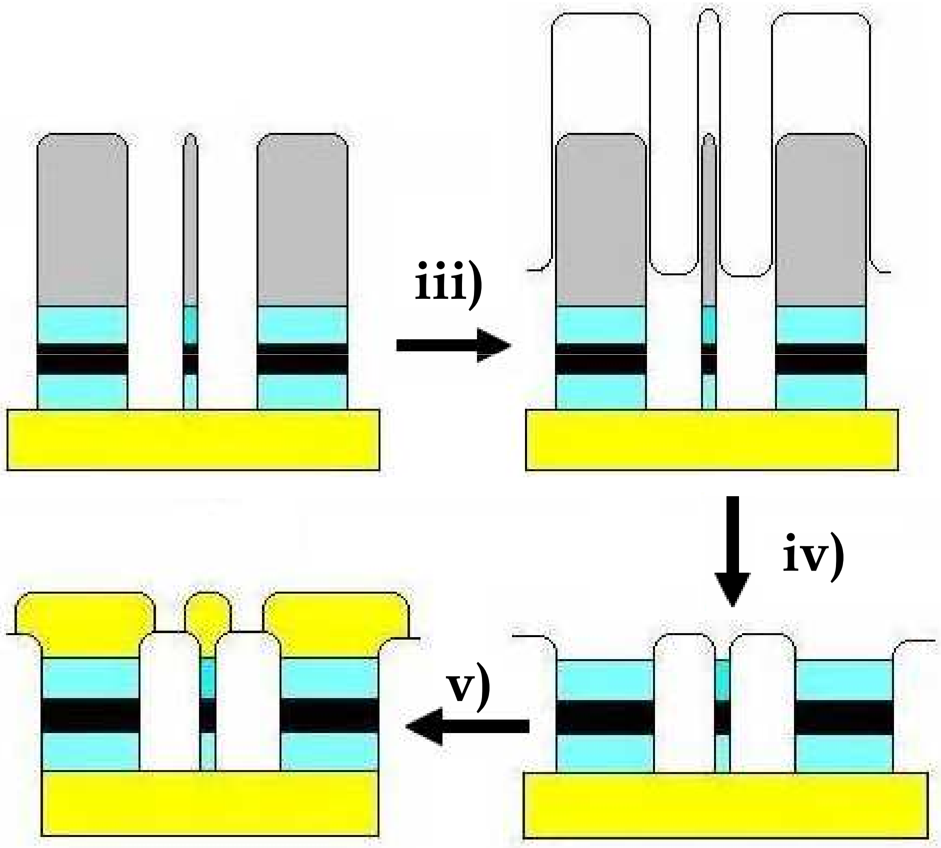
Cross-section View *Plane View*

Lithographic Patterning (II)

- **iii)** Deposition of ~ 300nm SiO2 by rf-sputtering as passivation layer
- **iv)** Dissolve PR in Acetone to finish lift-off process
- **v)** Apply and develop another layer of mask, deposit and define Ti/Au contact layer by lift-off

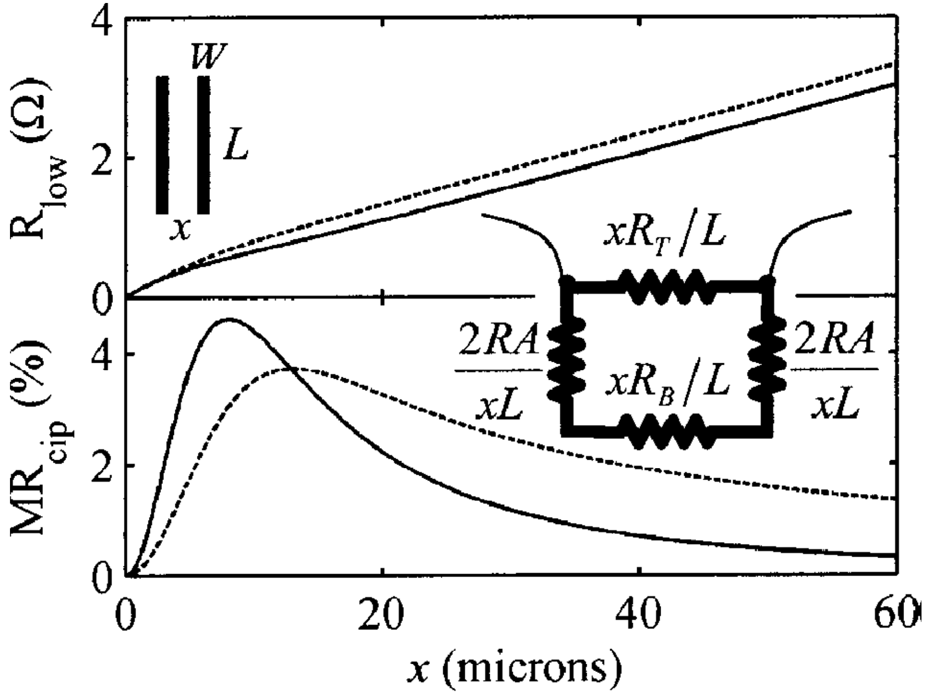


Plane View

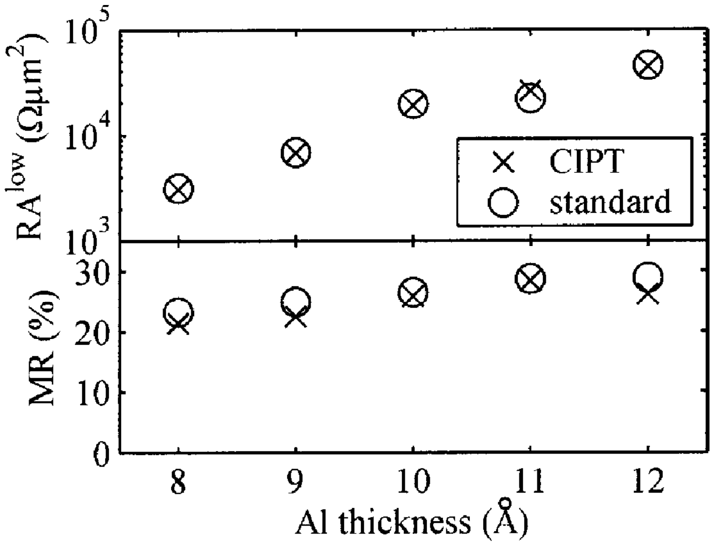


Cross-section View

CIPTech Measurement



- *Fast*, *nondestructive*, and *accurate* way to measure TMR without patterning!
- Collaboration with NIST



D. C. Worledge, etc. APL, **83**, 84 (2003)

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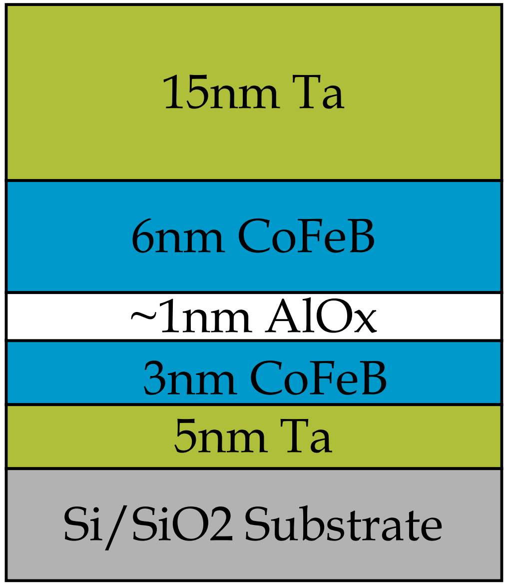
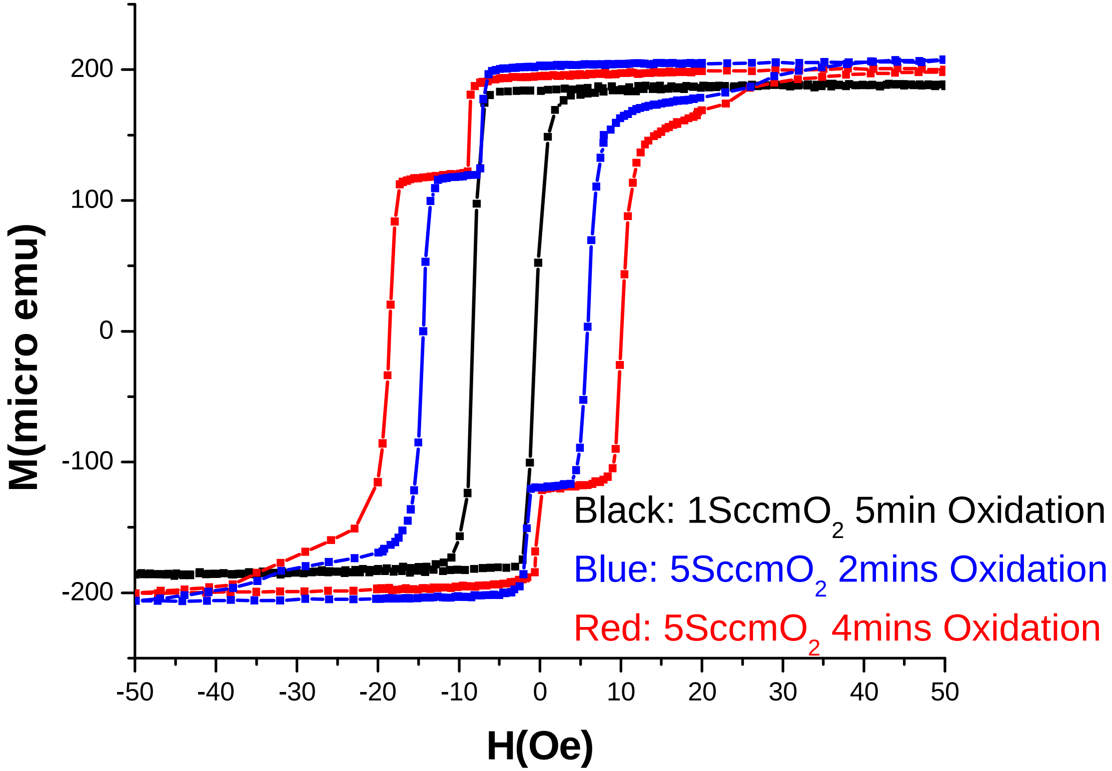
MTJ with AlOx Barrier (I)

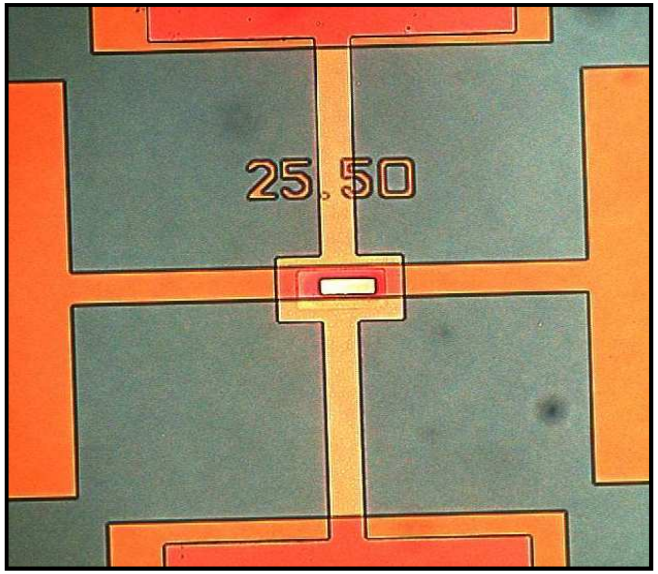


AlOx-MTJ Stack

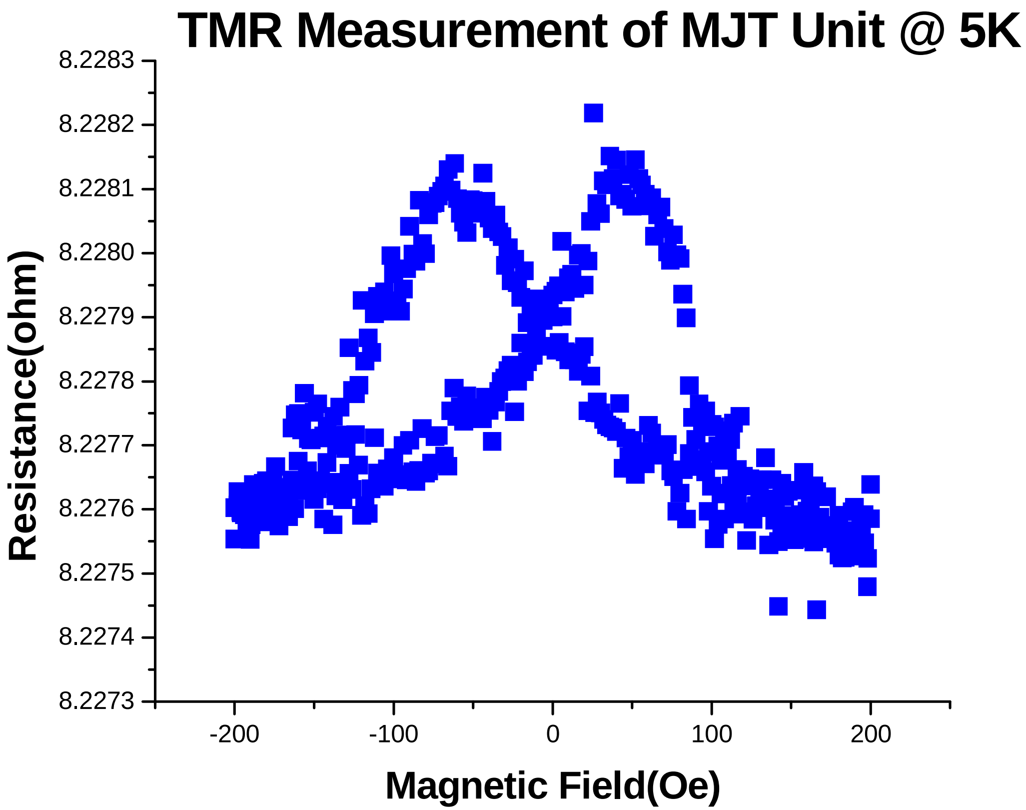


Better oxidized AlOx barrier provides better separated switching!

MTJ with AlOx Barrier (II)



Microscopic image of
patterned MTJ cell (25x50 μm)

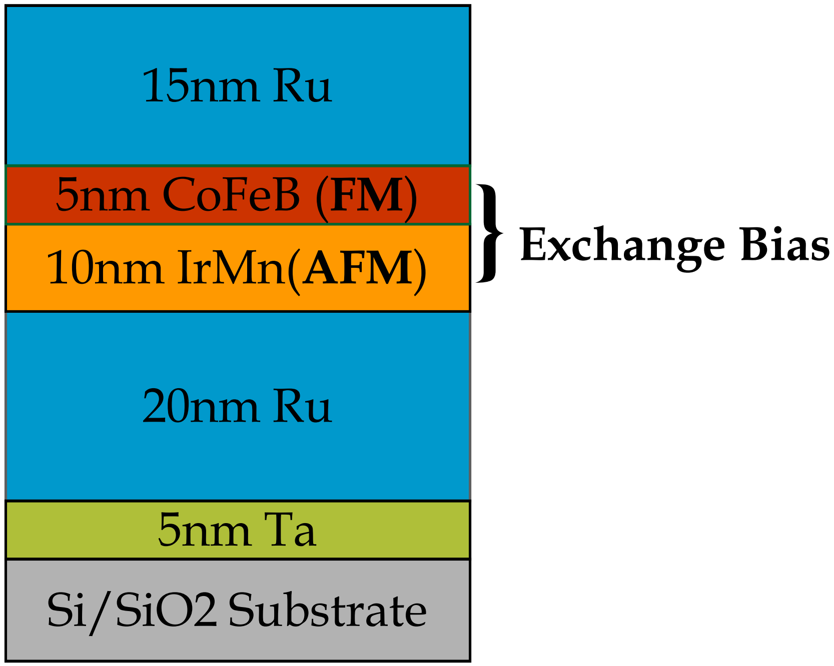


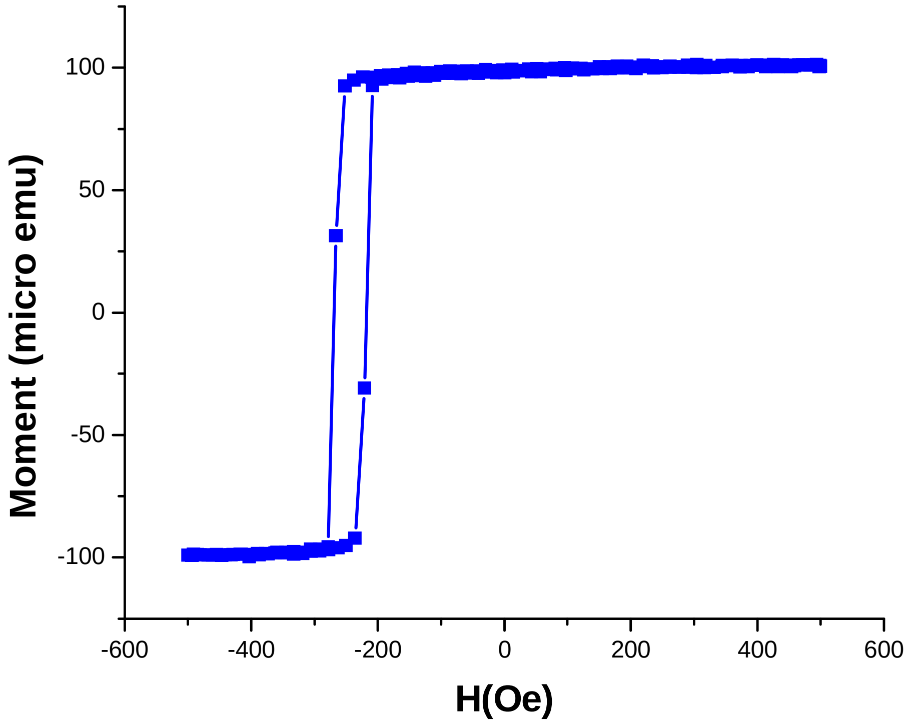
VOx Recipe Development

- Growth condition: on top of sub/CoFeB(1nm)/V(0.5nm)
- VOx thickness: ~50nm

Ar/O2 Flow Rate (Sccm)	Resistance (Ohm) Change (RT->~100C)
5.5	200K->30K
6	680K->150K
6.5	2,500K->400K
7	Too insulating
6 (with enhanced ion energy~50eV)	57K Ohm->200 Ohm (Temperature:50K->250K)

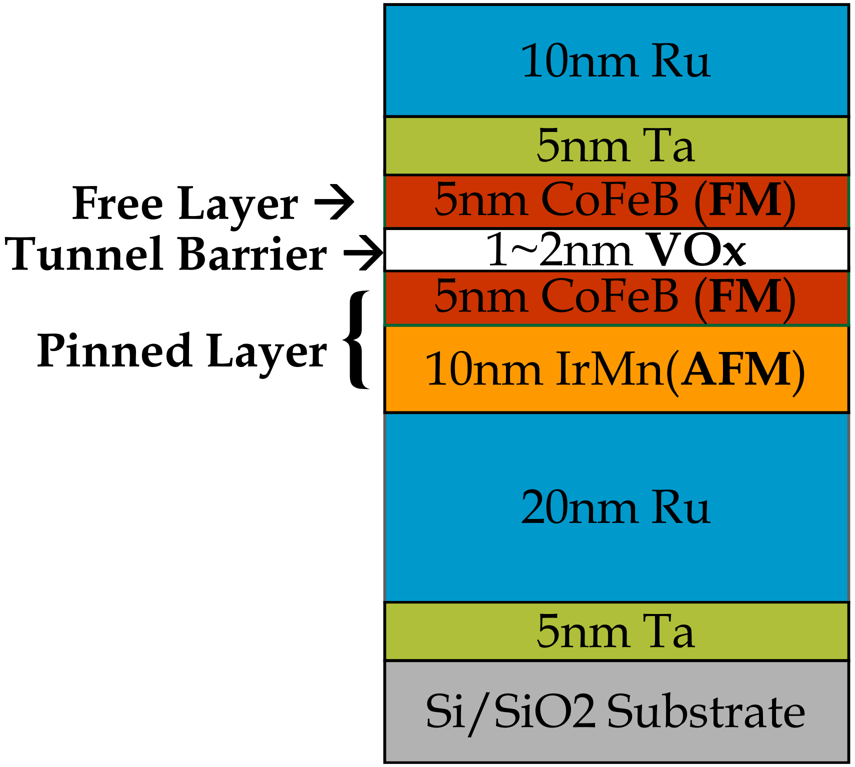
IrMn/CoFeB Exchange Bias



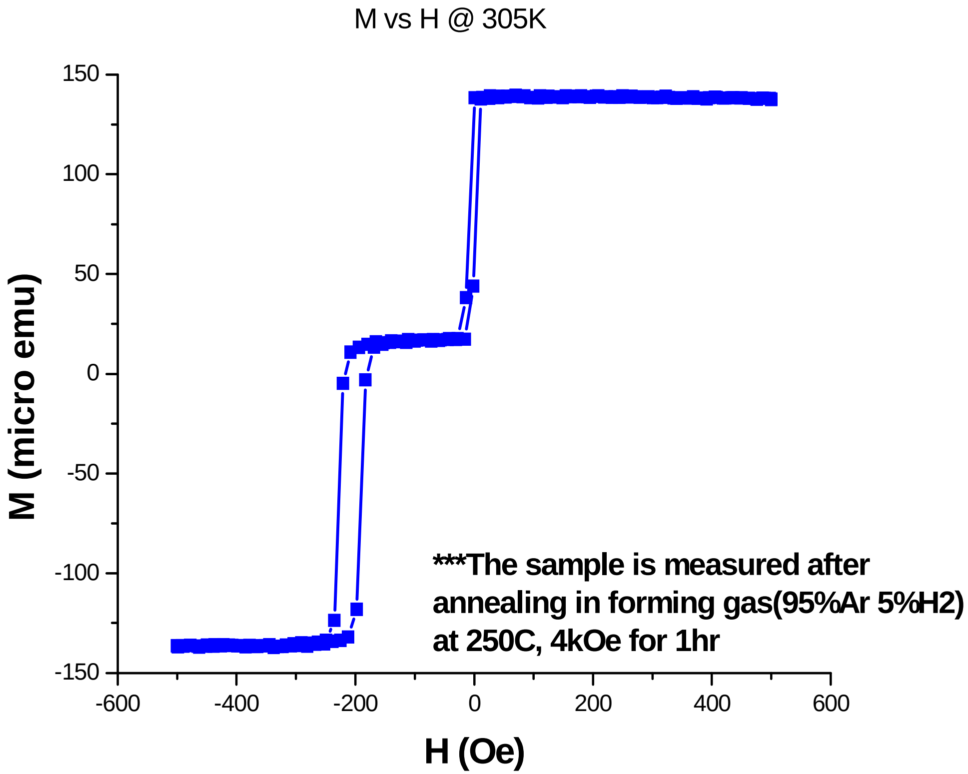


Hex ~ 250 Oe

MTJ with VOx Barrier (I)



VOx-MTJ Stack



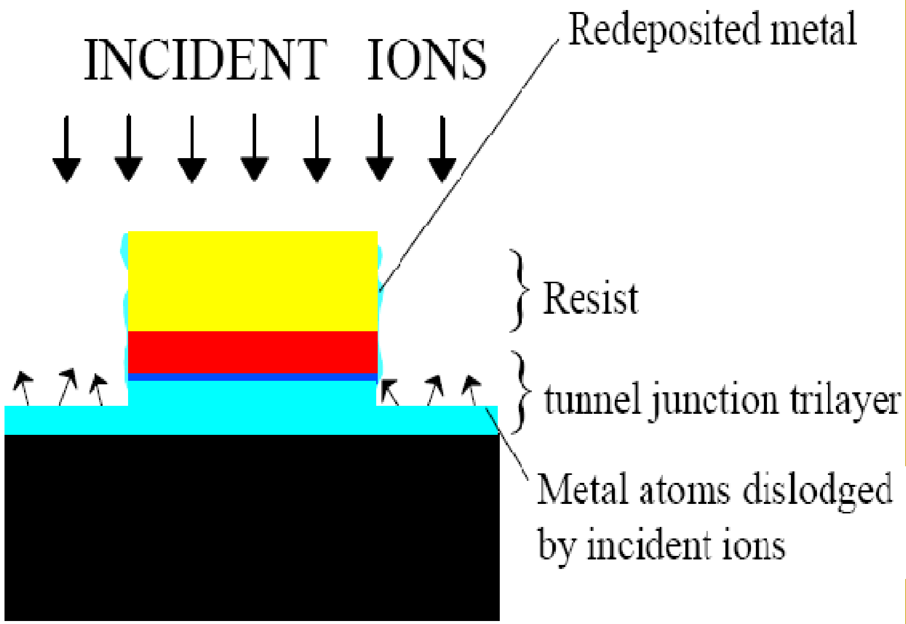
Results Analysis and Improvement (I)

- Tunneling *interfaces* are crucial!
  - Over-oxidation of bottom FM layer
  - Alloy formation between FM and barrier material: pre-oxidation to form diffusion barrier

- *Barrier* needs to be further optimized!
  - Barrier Thickness: 1~2nm; Pinholes, uniformity problem with thin barrier
  - Oxidation approaches: natural oxidation, reactive sputtering, post-deposition plasma oxidation, etc.

- *Annealing* is also very important!

Results Analysis and Improvement (II)



Dry etching is crucial in defining MTJ unit, and it could be further optimization!

→**Solutions:**

- Using tilted rotating stage
- Reactive Etching Ar+Cl2

Utilizing more tools to facilitate the lithographic processing: **AFM, SEM, EBL, etc.**

Summary

- Growth of Prototype AlOx-MTJ
- Development of Basic Patterning Process
- VOx Material Exploration
- Preliminary VOx-MTJ Experiments

Future Work

• Continuous exploration of VOx-MTJ; focusing on barrier growth and interface quality.

• Re-visit of AlOx-MTJs to better understand the dependence of interface and barrier quality on TMR

• New barrier materials exploration: Oxides like TiOx, TaOx, Nitrides like BN, etc.

• Further optimization of lithographic patterning process.