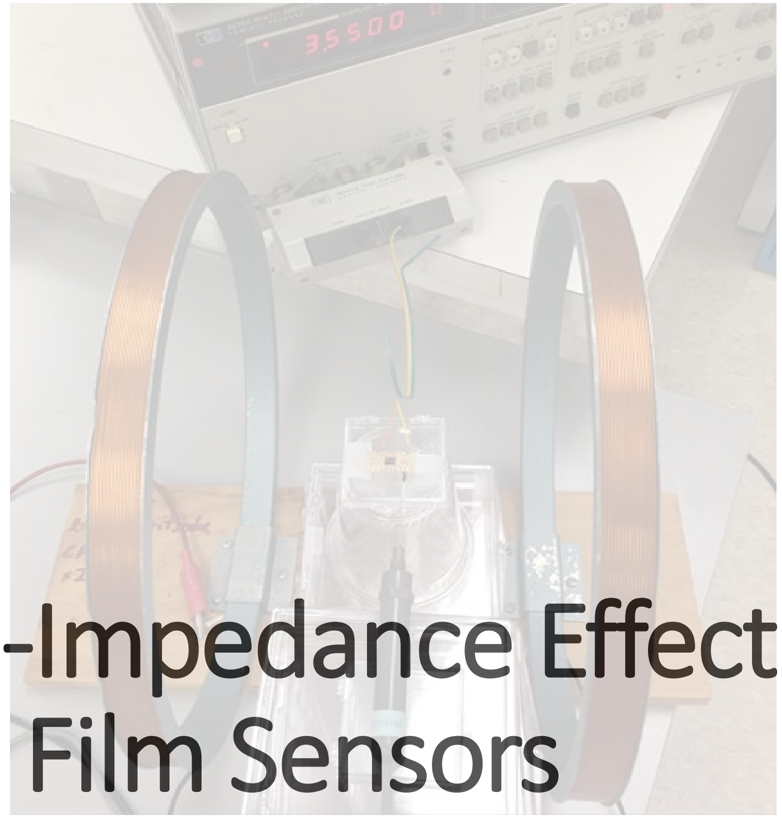

Giant Magneto-Impedance Effect in Multilayer Thin Film Sensors

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Overview

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Introduction

Magnetic sensors output a voltage or resistance due to an external magnetic field

Magnetic sensors currently in industry:

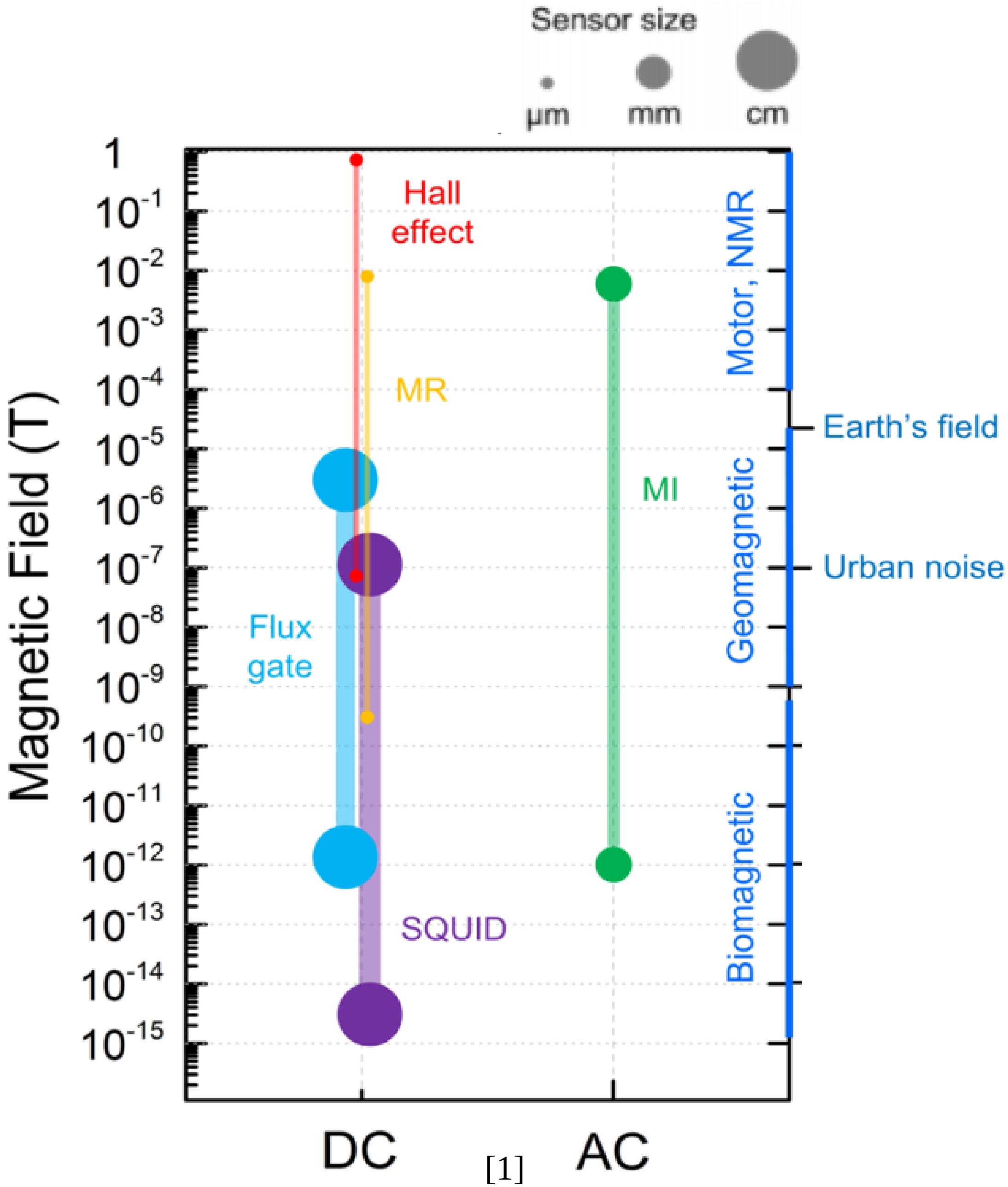
- Flux-gate
- Hall-effect
- Giant-Magneto Resistance (GMR),
- superconducting quantum interference device (SQUID)

GMI sensor:

- Offers high sensitivity, small size, large operating range, low production costs

Fabricated multilayer thin film GMI sensors

- Conductive layer, Cu, sandwiched between two soft ferromagnetic films, Permalloy (Ni 80%, Fe 20%)
- Measures change in magnetic field and outputs impedance

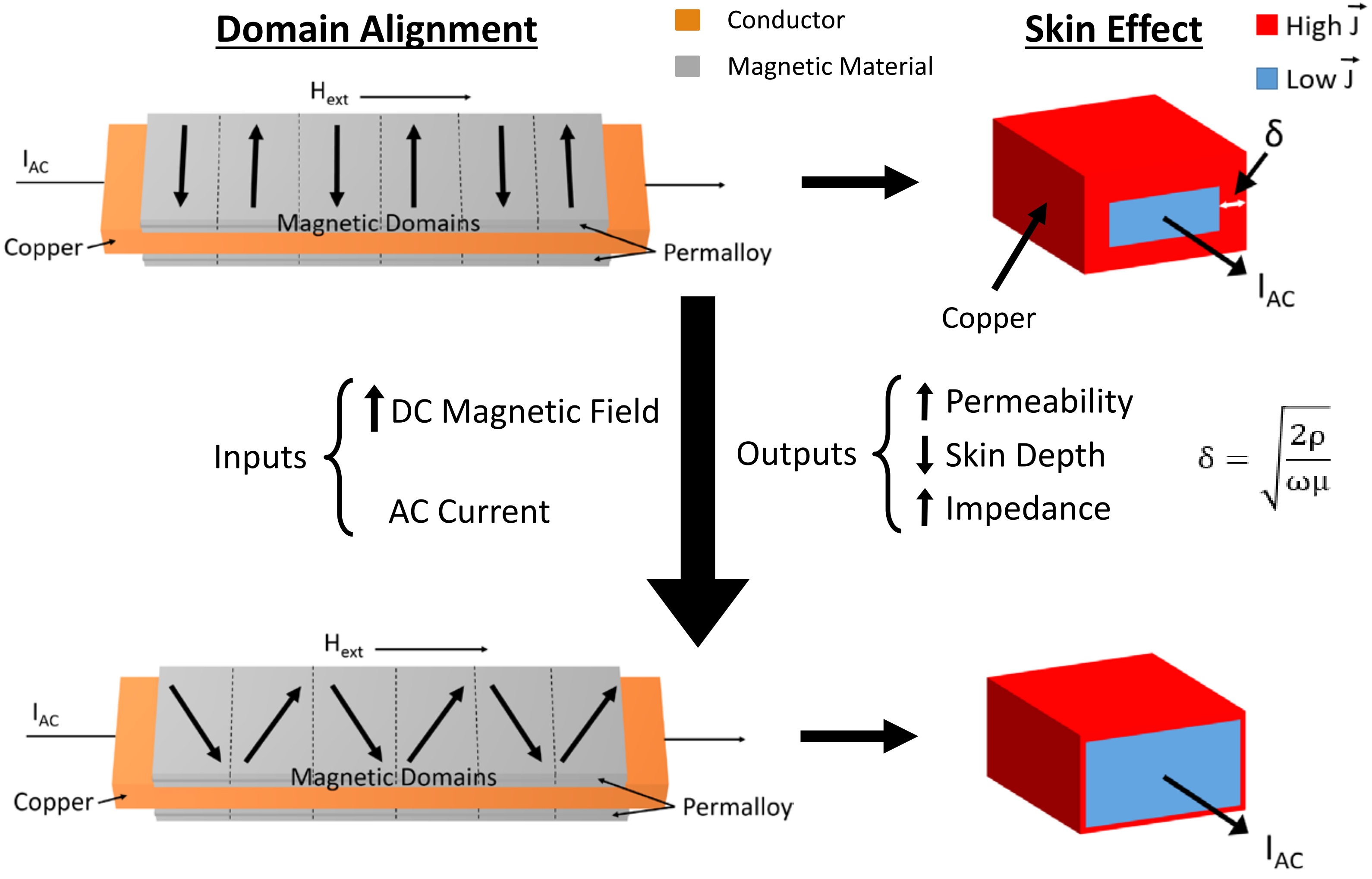


[1]

Theory of Operation

How does it work?

- **GMI Effect**: Change in complex impedance of the magnetic material while under bias by an external DC magnetic field, H_{ext}
  - H_{ext} causes magnetic domain wall rotation in the magnetic material of the sensor
  - Shifting of the domains changes magnetic permeability, μ
  - Increase in permeability results in decrease in skin depth, δ
  - Decreasing skin depth results in increasing impedance, Z



Inputs { ↑ DC Magnetic Field, AC Current

Outputs { ↑ Permeability, ↓ Skin Depth, ↑ Impedance

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

Theory of Operation

Impedance and Skin Depth Equations:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \qquad k = \frac{i+1}{\delta} \qquad \mathrm{Z} = \mathrm{R_{DC}} * \frac{\mathrm{kt}}{2}\coth\left(\frac{\mathrm{kt}}{2}\right)$$

Performance Criteria:

$$\text{GMI Ratio} = \frac{\Delta \mathrm{Z}}{|\mathrm{Z_0}|} = \frac{(\mathrm{Z_{H_{ext}=H}} - \mathrm{Z_{H_{ext}=0}})}{\mathrm{Z_{H_{ext}=0}}} \qquad \%\ \text{Sensitivity} = \frac{\mathrm{d}\left(\frac{\Delta \mathrm{Z}}{\mathrm{Z_0}}\right)}{\mathrm{dH_{ext}}} * 100$$

Design

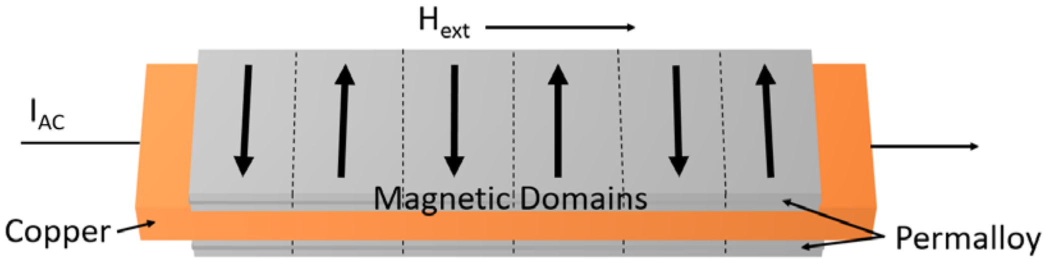
Materials:

- Permalloy – soft ferromagnetic material with high remnant magnetization and low coercivity
- Copper – low resistivity

Geometric Design Goals:

- To Induce **transverse anisotropy** (perpendicular magnetic domain alignment to the easy axis, direction of current)
  - More perpendicular alignment → performance increases
- Domains tend to randomly align in lowest energy state
  - Can be overcome through design and processing
- **Experimentation**: Varying width, length, and Permalloy thickness
- Target dimensions for max transverse domain alignment
  - Best performance seen at higher frequencies (300 – 500 MHz)
- Multilayer stack can be integrated into standard CMOS processes
- Multiple magnetic films increase overall inductive reactance

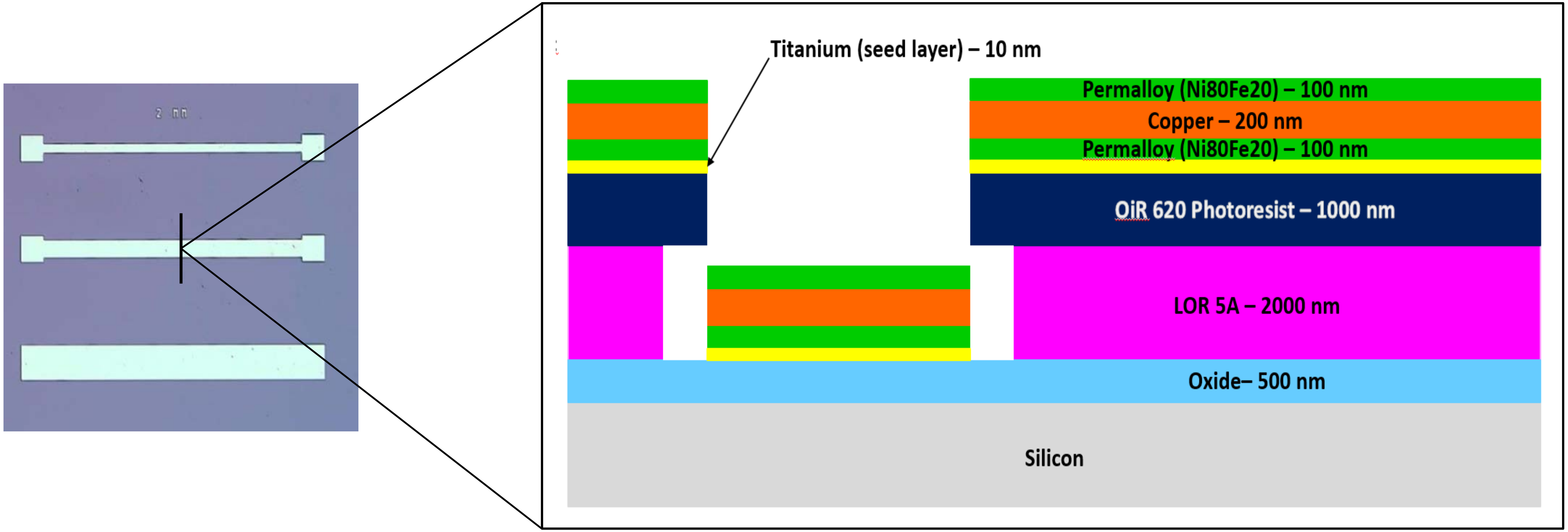
Transverse Domain Alignment



Film Thickness (Py / Cu/ Py) [nm]	**Width [um]**	**Length [mm]**
50 / 200 / 50	50	1
100 / 200 / 100	100	2
200 / 200 / 200	200	4

Design Theory – Film Stack

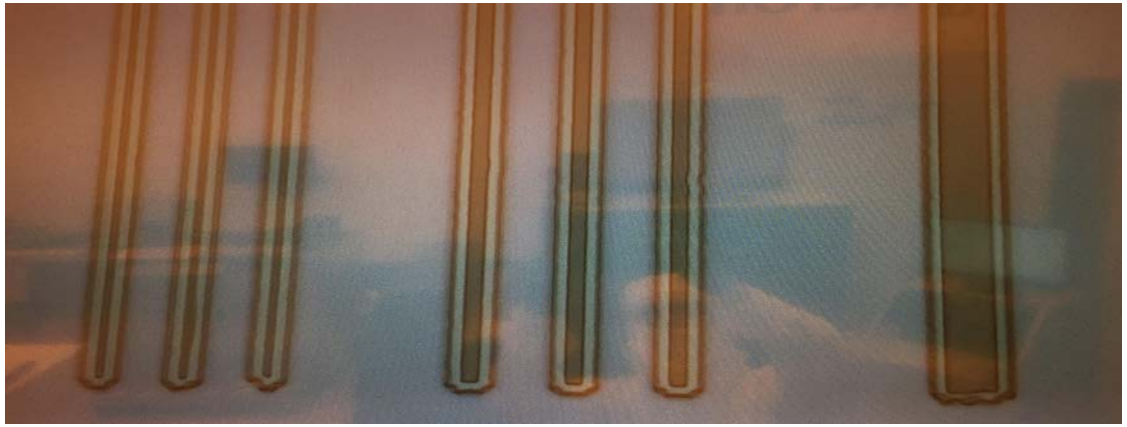
Cross-section

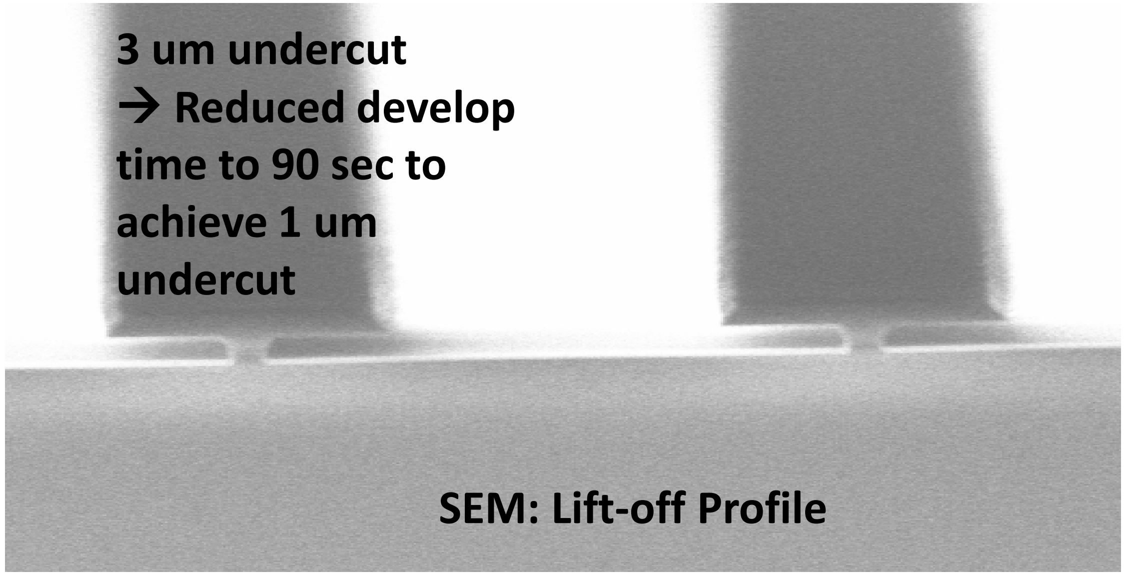


Process – Lift-off

Bi-Layer Lift-off:

- Coat LOR 5A: (~1.0 – 1.1 um thickness)
  - Spin speed: 1000 rpm
  - Softbake 150 C for 60 sec (or 60 sec/1 um layer (if multilayered))
- Coat OiR620: (~1.0 um thickness)
  - NOHMDS.RCP recipe on SII track
  - Spin speed: 3400 rpm (5 sec) and 2000 rpm (25 sec)
  - Softbake: 93 C for 60 sec
- Exposure: Karl Suss MA 150 – 250 mJ, ~60 sec
- PEB: 112 C for 60 sec
- Develop: Puddle 90 sec
- No hardbake (can destroy undercut profiles)



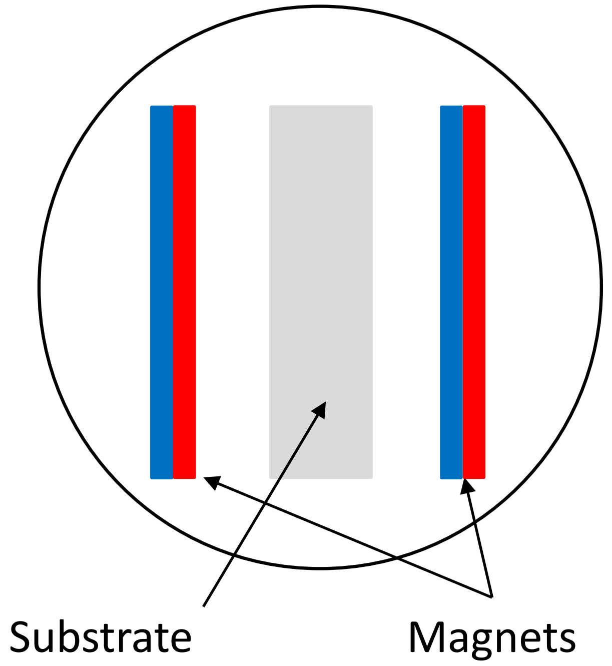


3 um undercut
→ Reduced develop time to 90 sec to achieve 1 um undercut

SEM: Lift-off Profile

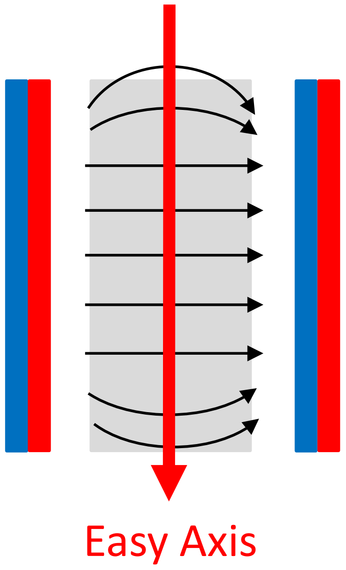
Process - Deposition

Custom
Sample Holder



Red: North
Blue: South

Magnetic Field
Uniformity



Deposition via e-beam evaporation in presence of magnetic field

- Overcomes shape anisotropy
- Induce transverse anisotropy

Constructed custom substrate holder

- Two magnets: neodymium
- 2.5 in. spacing generates 45 mT of magnetic field @ center
- Accommodates 2 in. wide and 4 in. long substrates
- Magnet Spacing adjustable to change field strength

Process Modifications

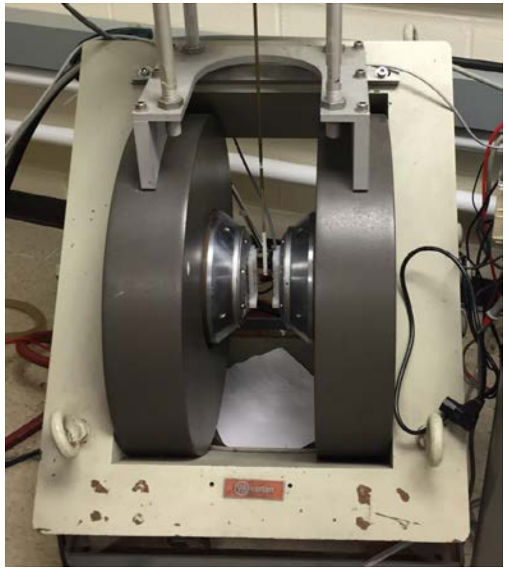
- Permalloy exhibited stress and adhesion issues
  - Added Titanium layer to reduce film stress
  - Descum and hardbake added for adhesion issues
- Ti layer changes film resistivity difference
  - Reduction in performance

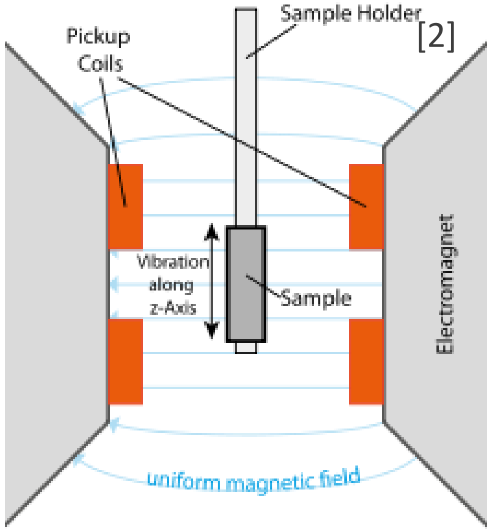
Run #	Hardbake 60 sec @ 140C	Descum 30 sec	2x LOR Thickness	Ti Seed Layer	Magnet Spacing	Process as Piece	Comments
1	0	0	0	0	0	0	Permalloy & resist peeled off
2	**X**	0	0	0	0	0	"
3	0	**X**	**X**	**X**	0	0	Less visible peeling
4	**X**	**X**	**X**	**X**	0	0	"
5	0	0	**X**	**X**	0	0	"
6	**X**	0	**X**	**X**	0	0	"
7	0	0	**X**	**X**	**X**	0	"
8	0	0	**X**	**X**	**X**	**X**	Significant improvement for peeling, able to salvage some devices

Testing Part 1

Domain Alignment Testing

- Tested using a Vibrating Sample Magnetometer
- Vibration generates an electromotive force (EMF)
- EMF picked up by sense coils
- Signal conditioned by amplifier to readout magnetic moment vs. field (hysteresis loop)

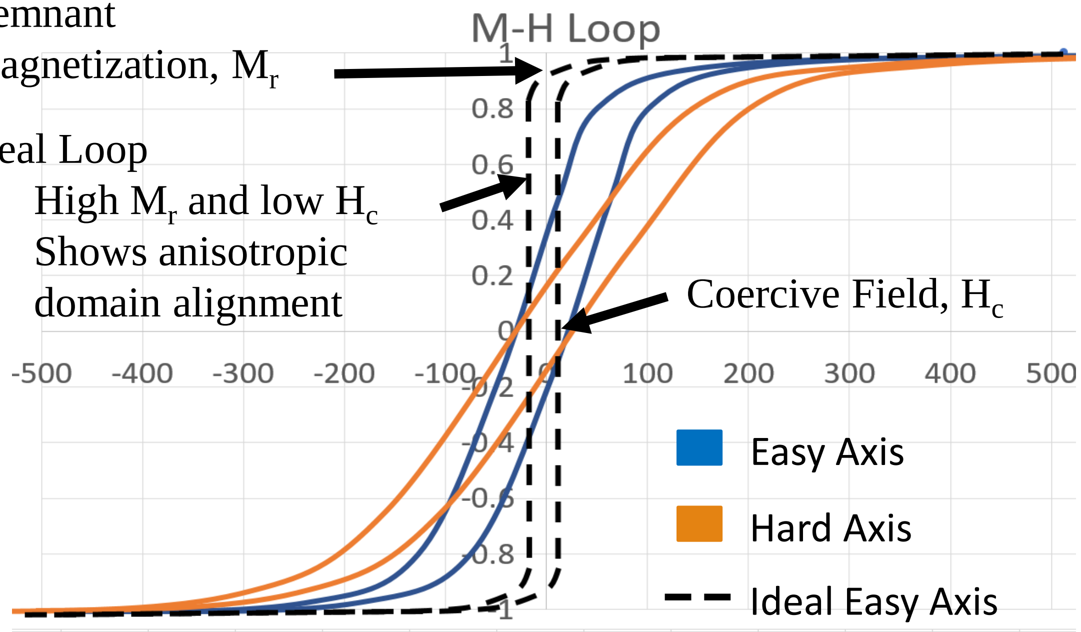




Remnant Magnetization, M_r

Ideal Loop

- High M_r and low H_c
- Shows anisotropic domain alignment

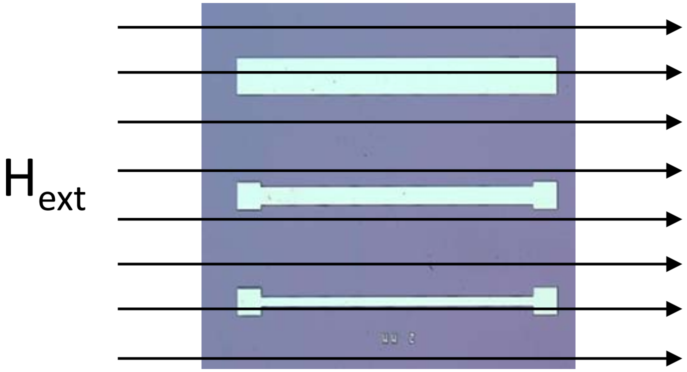


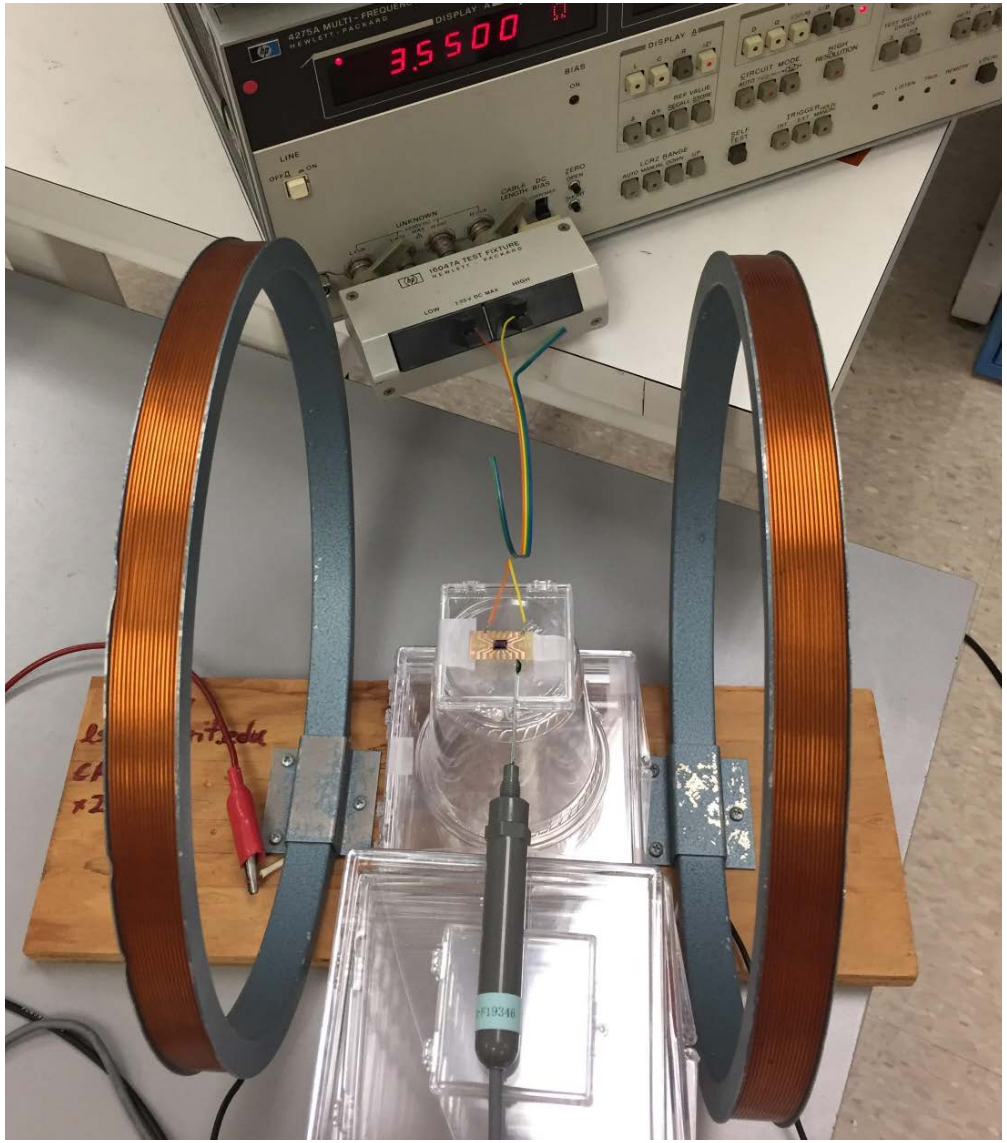
Coercive Field, H_c

Testing Part 2

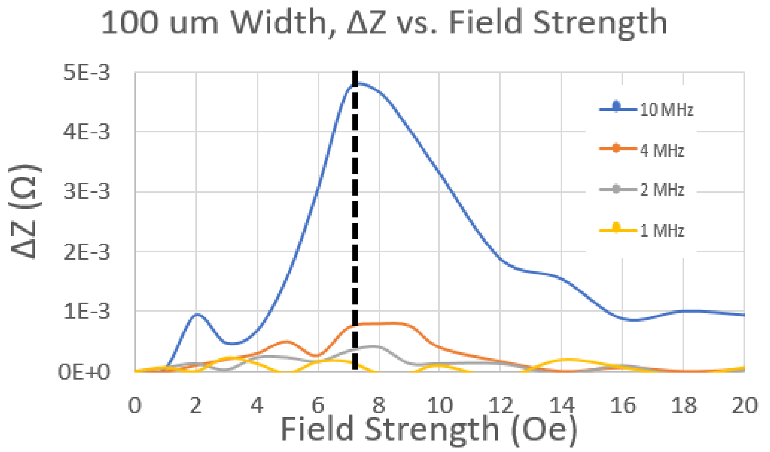
Impedance Test Setup

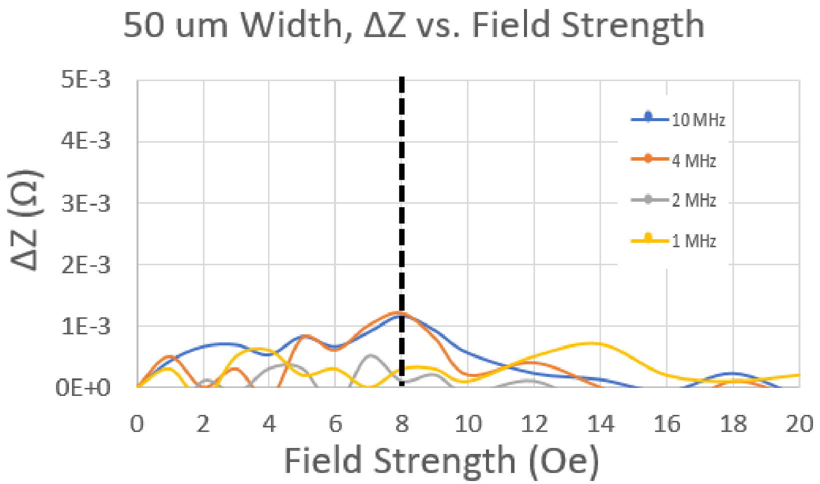
- Applied uniform magnetic field using Helmholtz coil set
- Mounted sample in the center of the coils
- Wirebond GMI sensor onto PCB
- Sweep field 0 – 20 Oe, measured Z at multiple frequencies

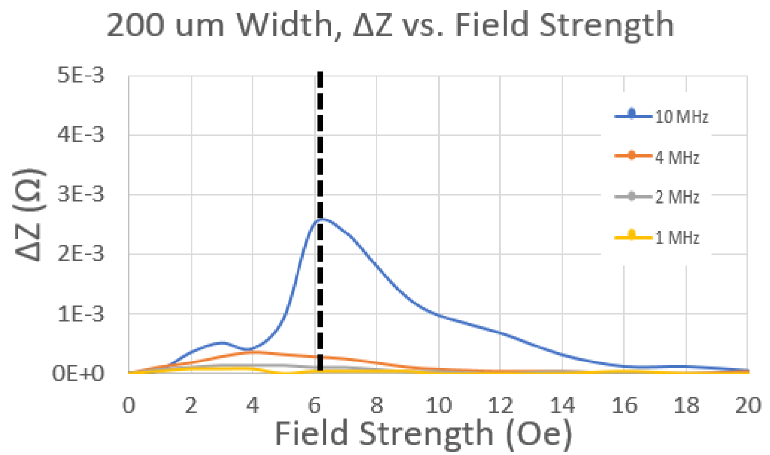




Testing Part 2







- Measured only 2 mm sensors due to process issues
- Sensors made for higher frequencies of 300 -500 MHz
- 100 um feature width @ 10 MHz exhibits best ΔZ response
- Max ΔZ between 6 – 8 Oe
  - Ferromagnetic resonance occurs in this range for 10 MHz
  - Here δ is significantly smaller than conductor thickness
- 50 and 200 um features showed smaller ΔZ
  - Due to difficulty overcoming shape anisotropy

Testing Part 2

2 mm Sensor Performance				
	Experimental @ 10 MHz		Calculated @ 500 MHz	
Width	**GMI Ratio**	**Sensitivity**	**GMI Ratio**	**Sensitivity**
50 um	0.015 %	0.009 %/Oe	-	-
100 um	0.028 %	0.01 %/Oe	1.43 %	0.5 %/Oe
200 um	0.007%	0.002 %/Oe	-	-

Applications

- **Electronic Compasses** – Low power and size reduction solution to currently used flux-gate sensors for geomagnetic field sensing. Highly used in boats/the motor industry. [4]

- **High-Density Magnetic Memory** – Reading module in magnetic storage drives. Reads localized remnant magnetization bits from write operation. Currently lower sensitivity GMR sensors used for magnetic memory. [4]

- **Magnetic Immunoassay** – Detection of pathogens and other biomolecules with magnetic bead labels in blood samples. [4]

- **Automated Highway System** – Research in Japan proposes automated driving using a magnetic guidance system, which employs a GMI sensor to sense magnetic markers fixed in the road. [4]

Conclusion

- Processing Permalloy was proven very difficult and resulted in loss of test structures for experimental design
- Successfully fabricated GMI sensors of 2 mm length and varying width
- Best performance seen in 100 µm wide sensor
- Failed to meet performance expectations
- Performance lower than expected due to insufficient domain alignment and inclusion of Titanium layer

Future Work

- Determine functional process without Titanium seed layer → Significantly improve performance
- Perform DOE on sensor geometries to find optimum performance criteria
- Study the effect of inter-dielectric material between conductor and magnetic layers, which is hypothesized to produce better performance @ lower frequencies

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Thank You