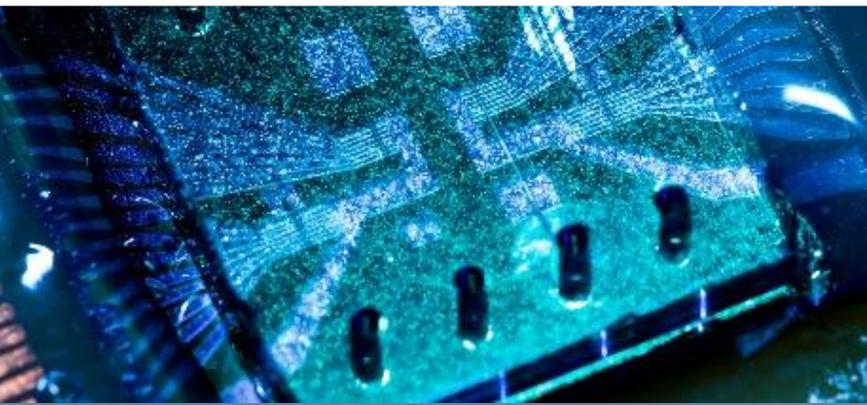
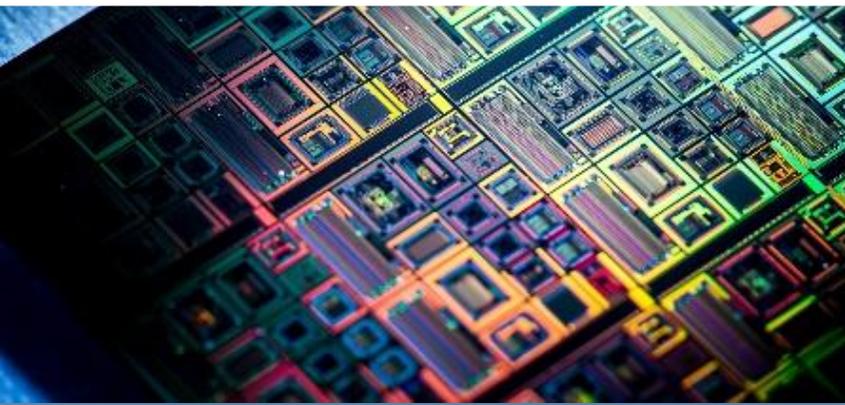


# TMR-Based Angular Magnetoresistive Sensors

Stoner-Wohlfarth Modeling, Simulation, and Experimental Validation

**Author:** Pedro Macedo

**Supervisor:** Susana Cardoso Freitas



## Tunnel Magnetoresistance (TMR)

- Quantum mechanical phenomenon in magnetic tunnel junctions
- Resistance changes based on relative magnetization orientation
- Spin-dependent tunneling effect
- Ideal MTJ resistance follows cosine dependence

$$R(\theta_{FL}, \theta_{RL}) \propto \cos(\theta_{FL} - \theta_{RL})$$

## Key Principles

- Low resistance when magnetizations are parallel
- High resistance when magnetizations are anti-parallel
- Non-volatile magnetic state

## MTJ Architecture

- **Free Layer:** Rotates with external field
- **Reference Layer:** Fixed magnetization direction
- **Barrier Layer:** Insulating tunnel barrier
- **Synthetic Antiferromagnet:** Coupled layers for stability

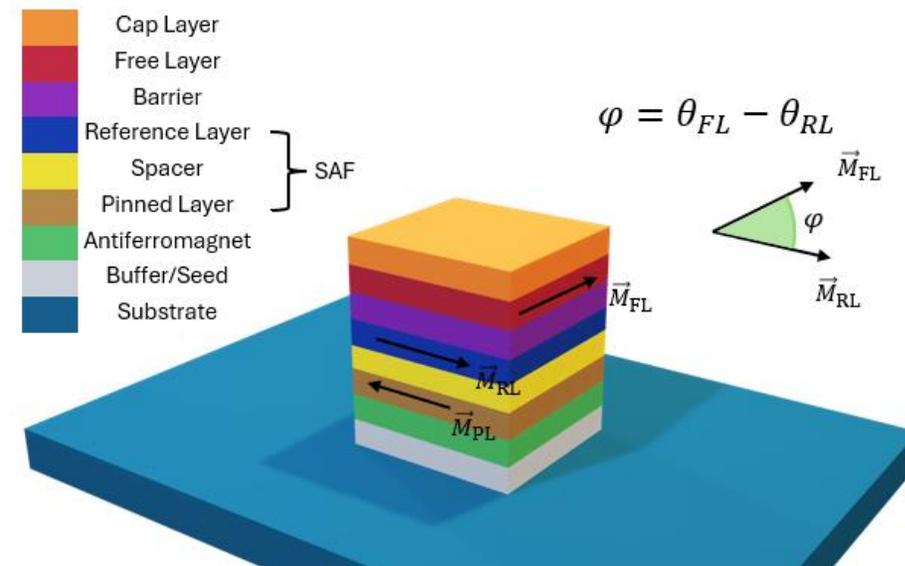


Figure 1: Multilayer MTJ structure

## Simulation Approach

- SW macrospin model with energy minimization
- Each magnetic layer → one macrospin
- Python GUI for interactive parameter sweeps

$$E(\theta, \phi, H, \varphi_H) = g(\theta, \phi) - \mu_0 M_s H \cos(\theta - \theta_H)$$

## Capabilities

- Linear field sweeps → hysteresis & operating windows
- Angular sweeps → response curves & error analysis
- Julliere model → resistance from magnetization angles
- Design optimization → predict performance before fabrication

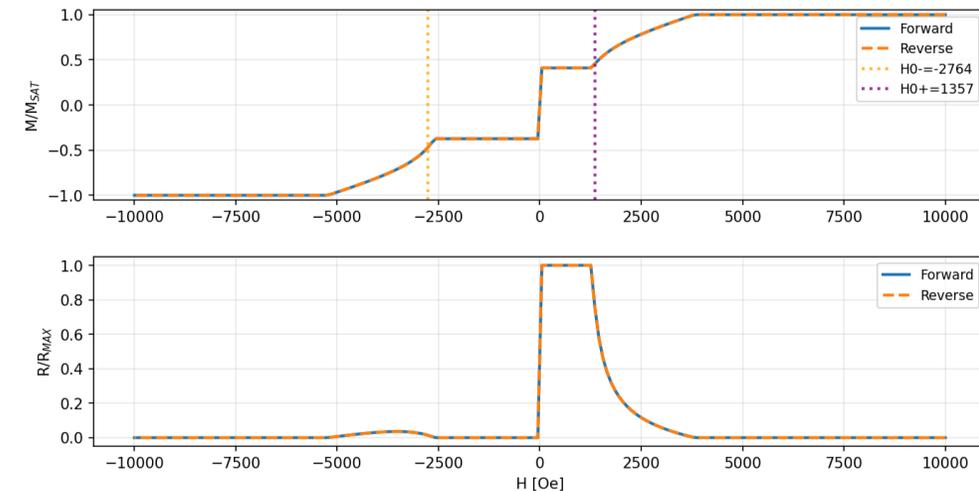


Figure 2: Field sweep showing  $M/M_{SAT}$  and  $R/R_{MAX}$  vs. magnetic field  $H$

## Field Sweep Procedure

- Sweep field from negative to positive values
- Record magnetization response  $M/M_{sat}$
- Measure resistance variations  $R/R_{max}$
- Identify coercive fields

## Angular Sweep Concept

- **Method:** Field rotation 0-360° at constant H
- **Resistance Calculation:** Based on relative angle  $\varphi = \theta_{FL} - \theta_{RL}$ :

$$\frac{\Delta R(\theta_H)}{R_{\perp}} = -\frac{TMR}{2} \cos(\varphi)$$

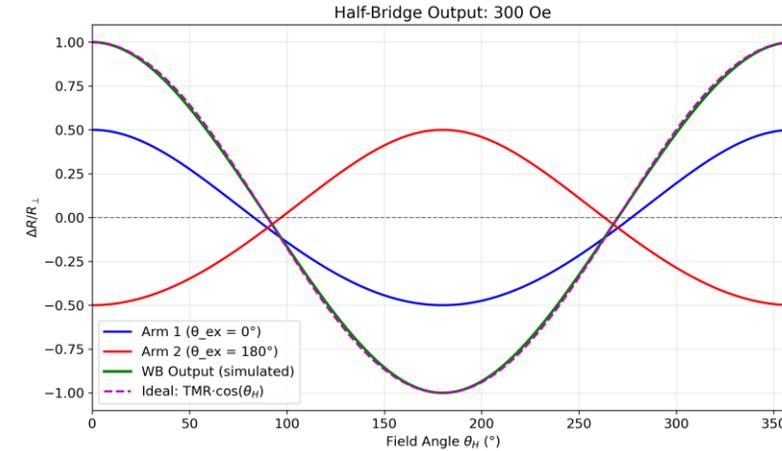


Figure 3: Comparison of single-element and Wheatstone bridge angular responses

## Differential Resistance Error

$$\Delta R(\theta_H) \equiv R(\theta_H) - R_{\cosine}(\theta_H)$$

## Angle Reconstruction

$$\theta_H = \arctan\left(\frac{\delta R_y}{\delta R_x}\right)$$

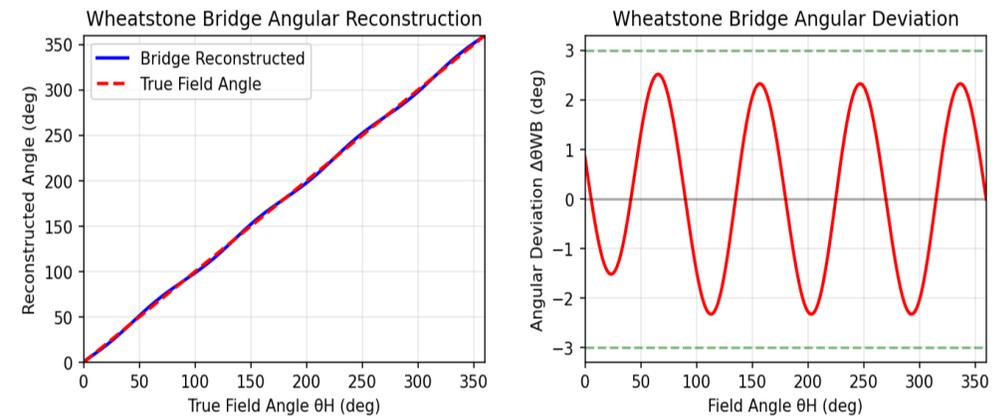


Figure 4: Angular error analysis for  $H=300$  Oe

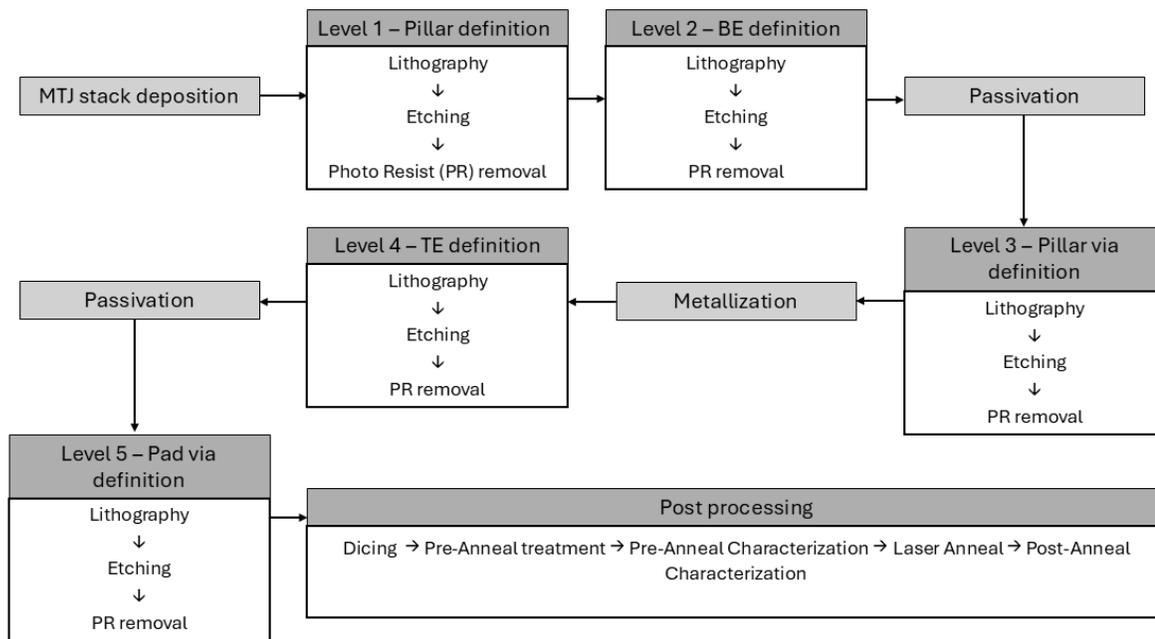


Figure 5: Overview of the microfabrication process

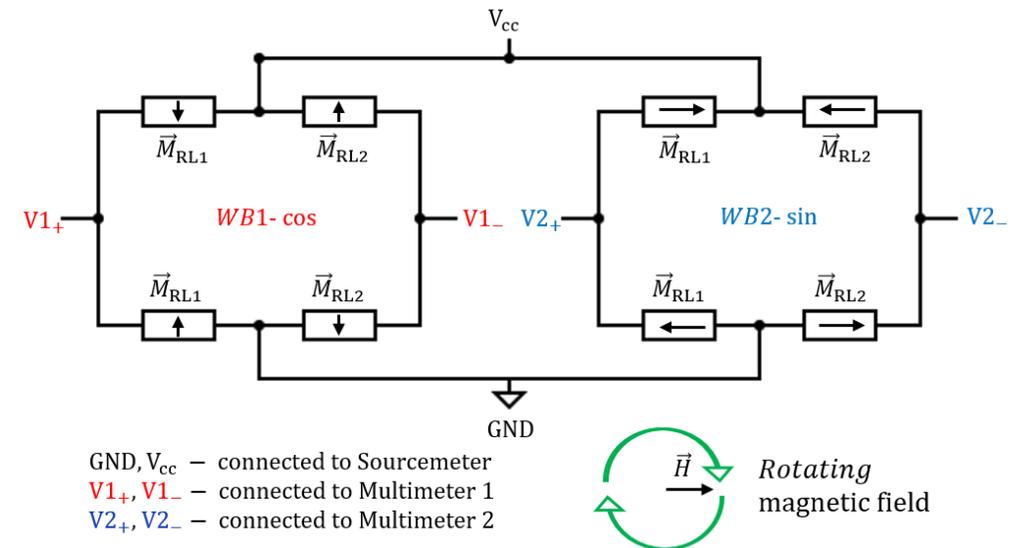


Figure 6: Six-probe Wheatstone bridge measurement configuration

## Bridge Output Measurements

- Excellent sinusoidal behavior for both signals
- Consistent amplitude across full rotation
- Clean 90° phase shift confirmed
- Minor variations from element mismatches

## Angle Reconstruction

$$\theta_{\text{reconstructed}} = \arctan\left(\frac{V_{\text{sine}}}{V_{\text{cosine}}}\right)$$

## Angular Error

$$\Delta\theta = \theta_{\text{reconstructed}} - \theta_{\text{expected}}$$

### Key Findings

- ✓ Four-peak pattern (second-harmonic distortion)
- ✓ Consistent with simulation predictions
- ✓ Error structure matches SW model behavior

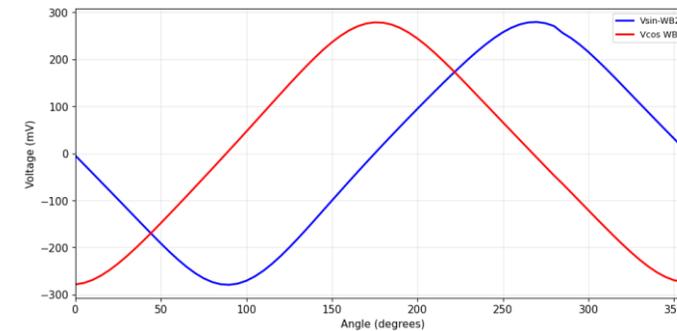


Figure 7: Measured sine-cosine bridge outputs

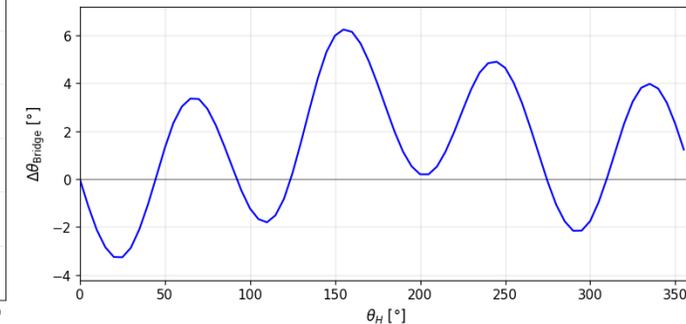
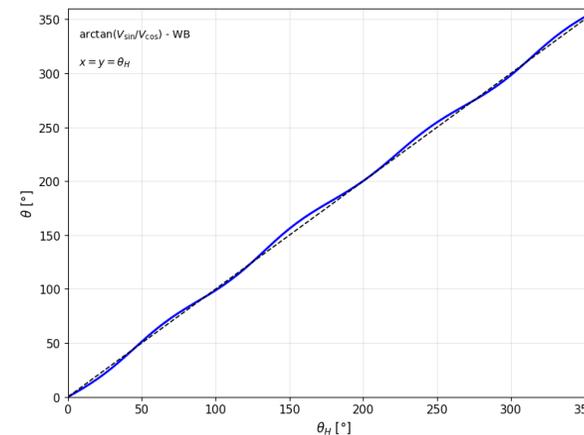


Figure 8: Reconstructed angle (left) and error (right)

- P. Ripka. *Magnetic Sensors and Magnetometers*. Artech House, 2010.
- S. Yuasa et al. "Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions." *Nature Materials* 3 (2004): 868-871.
- S. Ikeda et al. "Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion." *Applied Physics Letters* 93 (2008): 082508.
- A. Silva et al. "Linearization strategies for high sensitivity magnetoresistive sensors." *European Physical Journal Applied Physics* 72 (2015).
- P. D. Araujo et al. "Impact of the synthetic antiferromagnet in TMR sensors for improved angular-dependent output." *IEEE Sensors Journal* 24.11 (2024): 17588-17595.
- H. Jaffrès et al. "Angular dependence of the tunnel magnetoresistance in transition-metal-based junctions." *Physical Review B* 64 (2001): 184427.
- D. C. Mendonça Júnior. "Magnetic sensors with superior performance: material and design optimization for angular sensing." MSc Thesis, Universidade de Lisboa, 2025.
- K. M. Krishnan. *Fundamentals and Applications of Magnetic Materials*. Oxford University Press, 2016.
- C. Zheng, K. Zhu, S. de Freitas et al. "Magnetoresistive sensor development roadmap (non-recording applications)." *IEEE Transactions on Magnetics* 55.4 (2019): 0800130.
- P. P. Freitas et al. "Magnetoresistive sensors." *Journal of Physics: Condensed Matter* 19 (2007): 165221.
- S. Cardoso et al. "Spintronic sensors." *Journal of Physics D: Applied Physics* 48 (2015): 163001.
- M. Julliere. "Tunneling between ferromagnetic films." *Physics Letters A* 54.3 (1975): 225-226.
- S. S. P. Parkin et al. "Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers." *Nature Materials* 3 (2004): 862-867.
- J. M. D. Coey. *Magnetism and Magnetic Materials*. Cambridge University Press, 2010.
- A. Maignan et al. "Ion beam etching effects in magnetic tunnel junction nanopillars." *Journal of Applied Physics* 109 (2011): 103910.