Unlocking the Invisible:

A Deep Dive into Modern Magnetic Sensing Technology

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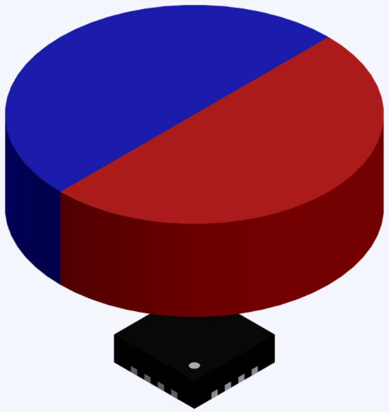
February 2026

Why Magnetic Sensing

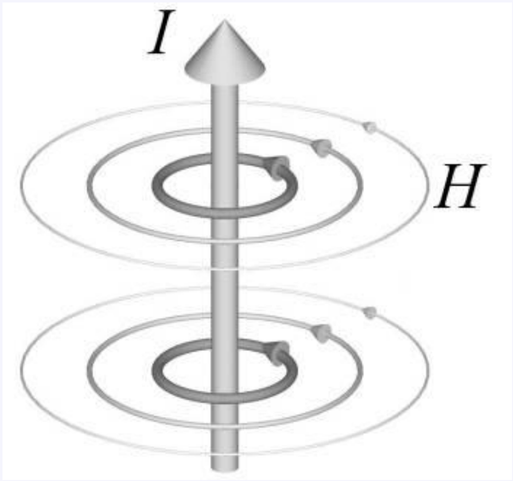
Position Sensors

The position of a moving (usually rotating) magnet is tracked via magnetic sensor(s).



Current Sensors

An electric current always has an associated magnetic field proportional to the amplitude of the current.



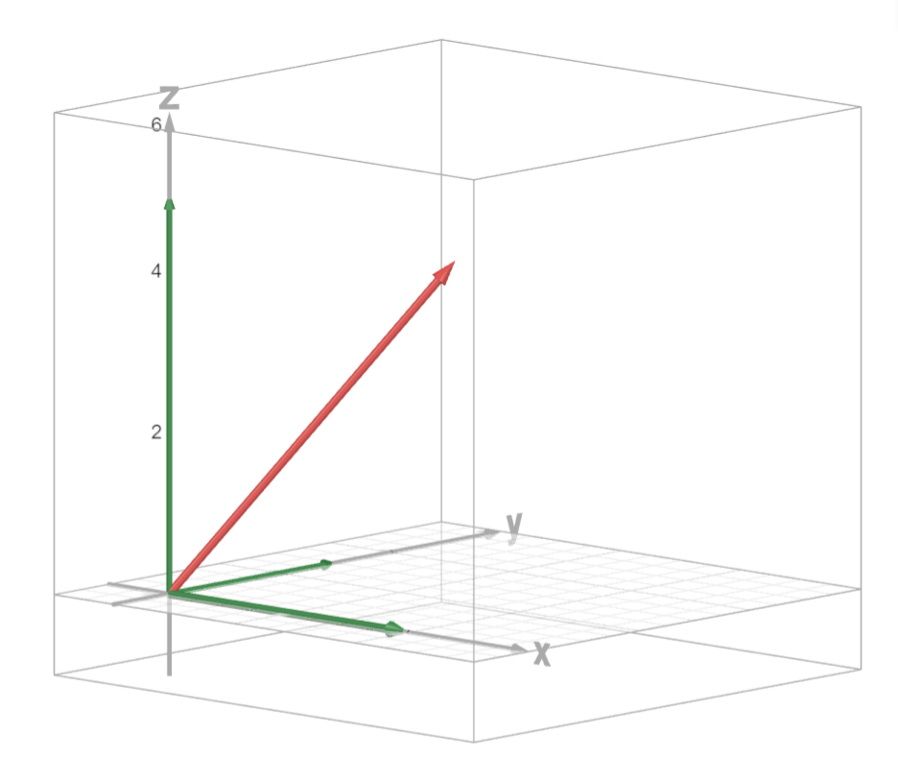
Others

- Lab measurement
- Navigation
- Medical safety
- Music (e.g. guitar pickups, etc.)

Terminology and Magnetic Field Basics

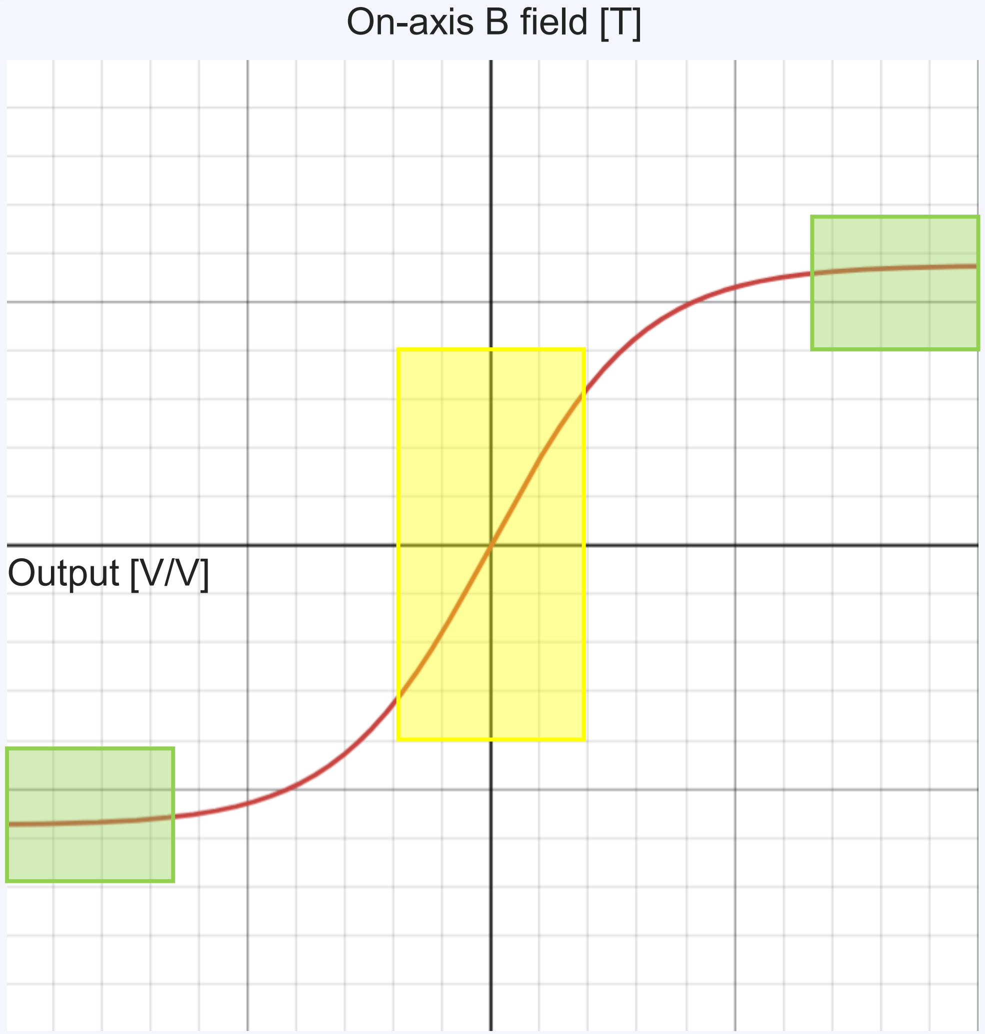
With a magnetic sensor, we are trying to "see" the magnetic field vector (or, more likely, one of its components) at a given point in space.

- Some sensors tell us only the direction of the field
- Some sensors tell us the direction and amplitude of the field



General Field		Field Related to Magnetized Matter		Material Property	
B (T) Magnetic Flux Density (magnetic induction, magnetic field)	H (A/m) Magnetic Field Strength (magnetic field, magnetic field intensity)	J (T) Magnetic Polarization (intrinsic flux density, intrinsic induction, ferric induction)	M (A/m) Magnetization (magnetic polarization)	μr (unitless) Relative Permeability	χ (unitless) Susceptibility

Linear vs Saturated



In general, this graph applies to xMR sensors. Hall sensors do not saturate (however the amplifiers and A/D converters *can* saturate.)

When referring to *liner mode*, we are usually speaking in the context of current sensing.

When referring to *saturated mode*, we are usually speaking in the context of angle sensing.

Hall Effect Sensors

Silicon-Based and III-V Based

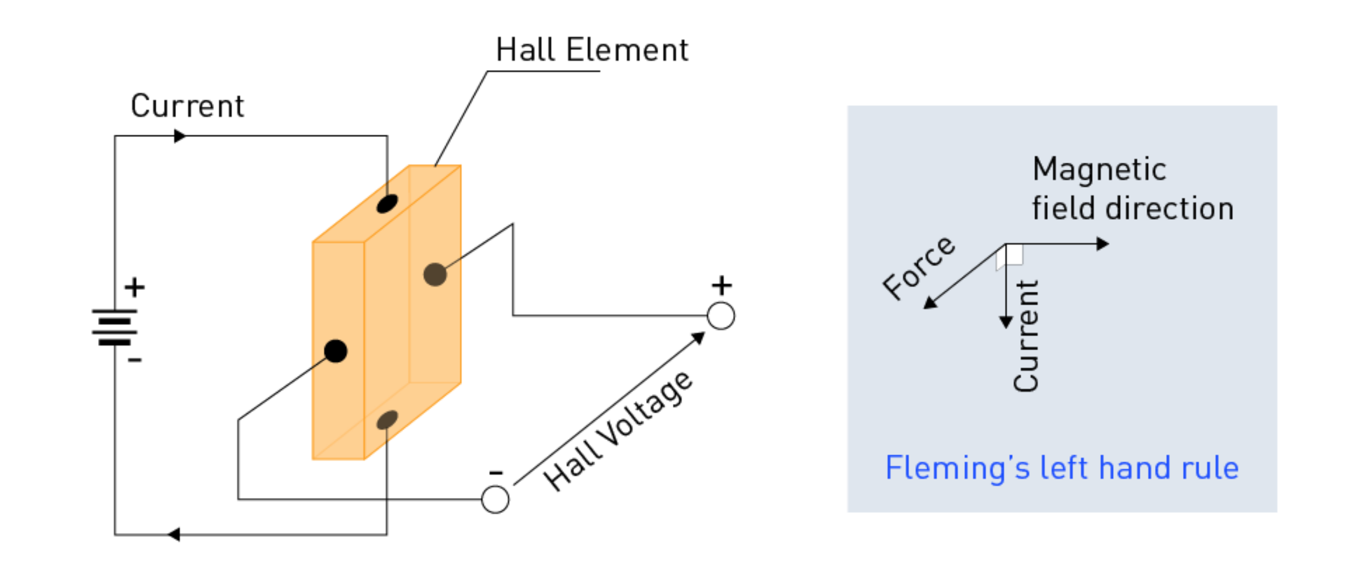
Silicon Hall-Effect Sensors: The Workhorse

Silicon Hall Sensors

- Based on the classical Hall effect
- Lorentz force deflects charge carriers
- Transverse voltage ∝ magnetic field

Why They Matter

- CMOS-compatible (inexpensive)
- Rugged and low cost
- Wide linear field range



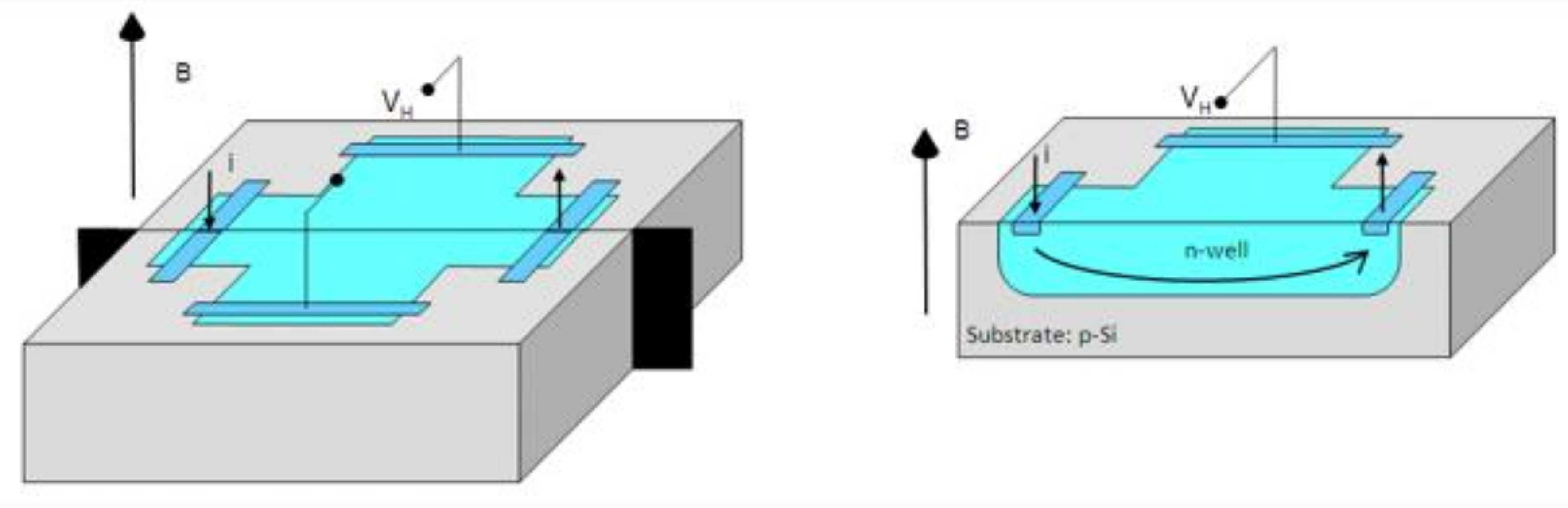
Advantages

- Full CMOS integration
- On-chip amplifiers and ADCs
- Low cost at volume
- Excellent temperature range (-40°C to +150°C)

Limitations

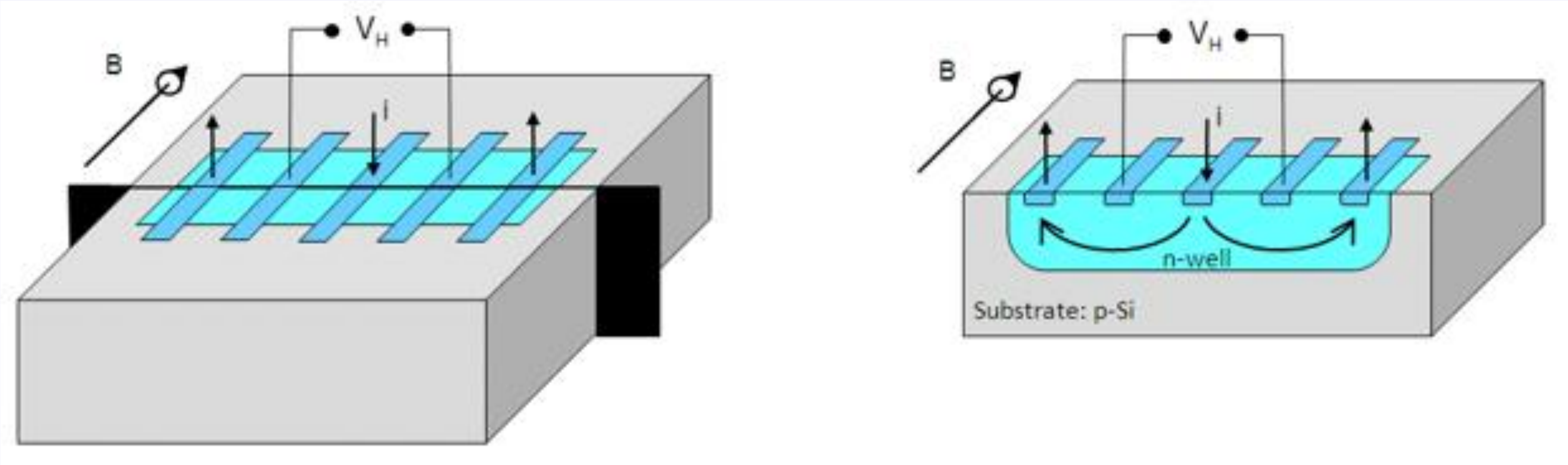
- Lower carrier mobility than III-V
- Lower raw sensitivity
- Higher intrinsic noise

Hall-Effect Sensors: The Workhorse *(continued)*



Planar Hall Device

Vertical Hall Device



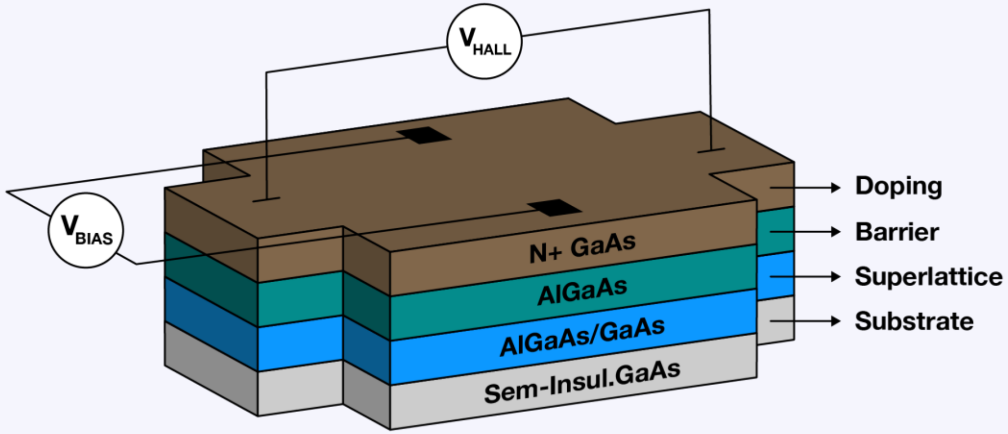
III-V Hall Sensors: Same Physics, Better Material

III-V Semiconductor Hall Sensors
(GaAs, InSb, InAs)

- Classical Hall effect
- High-mobility compound semiconductors
- Higher sensitivity than silicon Hall

Why They Exist

- When silicon Hall is not sensitive enough
- Precision current and field measurement

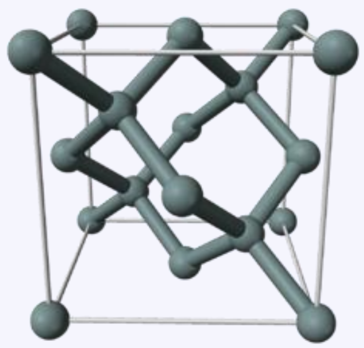


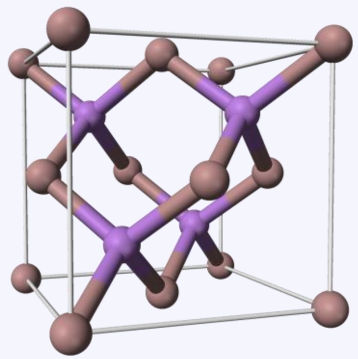
Material	Electron Mobility ($cm^2/V \cdot s$)
Silicon	~1,400
GaAs	~8,500
InSb	~70,000

Impact

- Higher Hall coefficient
- Higher sensitivity
- Lower thermal noise

Hall vs. Hall: (Silicon vs. III-V)





Feature	Silicon Hall	III-V Hall (GaAs)
Sensitivity	Low to Medium	High
Noise	μT/√Hz	100nT/√Hz
Integration	Excellent	Complex
Cost	Low	Medium
Temp Robustness	Excellent	Moderate

Magnetoresistive Sensors

AMR, GMR, TMR

AMR Sensors: When Resistance Depends on Direction

Anisotropic Magnetoresistance (AMR)

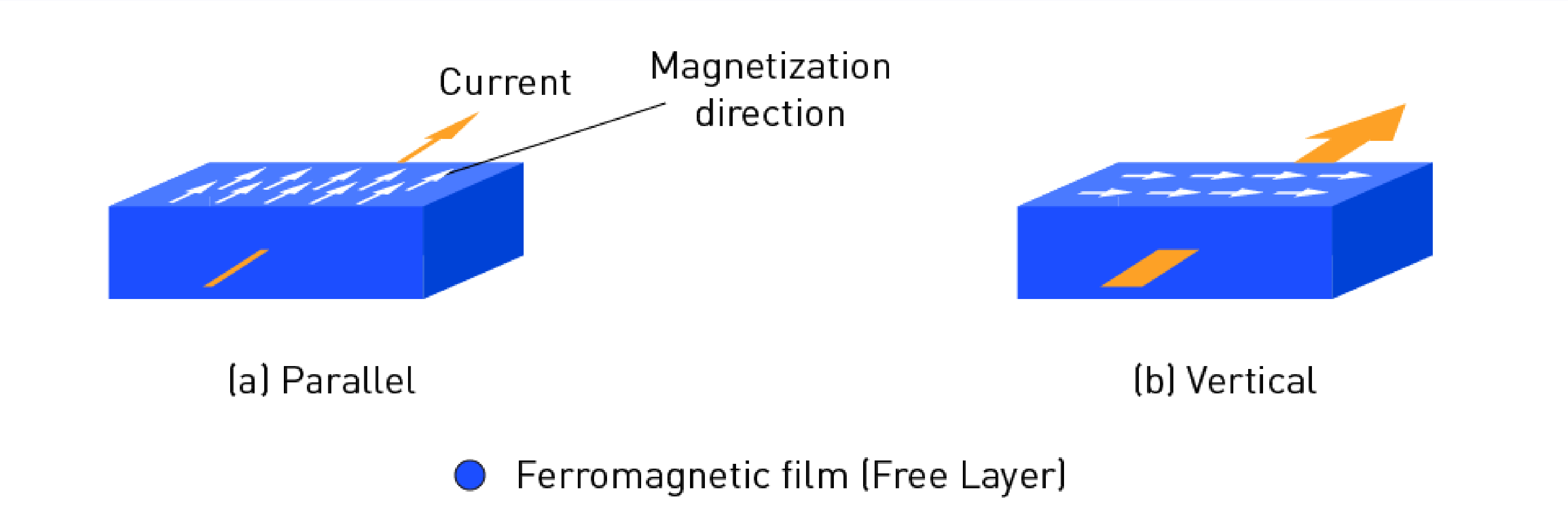
- Discovered in ferromagnetic metals (Permalloy)
- Resistance depends on the angle between:
  - Magnetization direction
  - Direction of current flow

Why AMR Matters

- First practical spin-based magnetic sensor
- Much higher sensitivity than Hall
- Excellent linearity for angle sensing

Physical Principle: Spin-Orbit Coupling

- Electron scattering depends on spin orientation
- Resistance varies with magnetization angle
- Maximum resistance when current ∥ magnetization
- Minimum resistance when current ⊥ magnetization



AMR Sensors *(continued)*

AMR Performance	
Magnetoresistance Ratio	2% to 4%
Sensitivity	1%/mT to 10%/mT
Noise Density	10nT/√Hz to 100nT/√Hz
Linear Range	± 1mT to 10mT
Offset Drift	Low to moderate

Set/Reset Requirements

- Magnetic domains drift
- External shocks reorient magnetization
- On-chip set/reset coils
- Periodic re-magnetization pulses
- Effects
  - Power consumption
  - Transient output glitches

AMR Limitations

- Saturates easily in stray fields
- Requires magnetic biasing
- Limited dynamic range
- Offset can jump after large field exposure

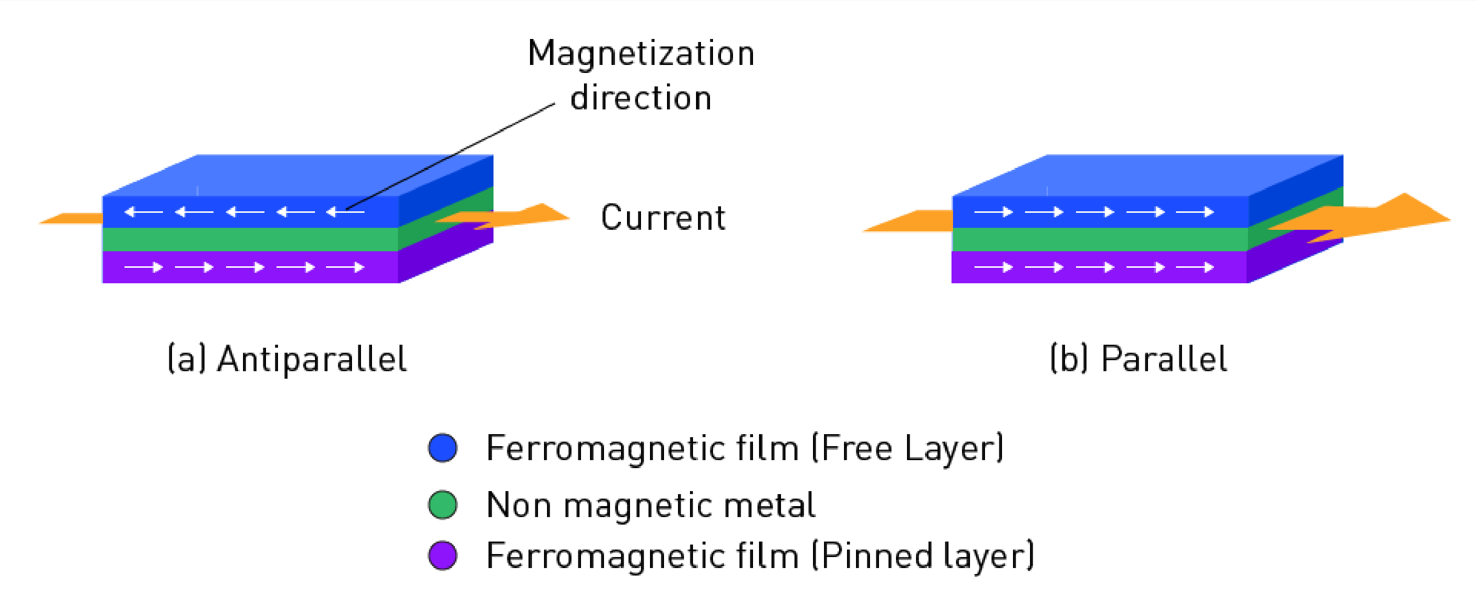
GMR Sensors: When Layers Talk through Spin

Giant Magnetoresistance (GMR)

- Discovered in multilayer thin films (1988)
- Nobel Prize winning effect
- Resistance depends on relative magnetization of layers

Why GMR Matters

- Much larger signal than AMR
- First high-sensitivity thin-film magnetic sensor
- Foundation of modern spintronics



GMR Sensors *(continued)*

GMR Performance	
Magnetoresistance Ratio	5% to 20%
Sensitivity	5%/mT to 20%/mT
Noise Density	5nT/√Hz to 50nT/√Hz
Linear Range	± 0.5mT to 5mT
Offset Drift	Moderate

Biasing/Linearization

- Raw response is nonlinear
- Symmetric around the zero field
- Magnetic bias layers are used
- Exchange bias pinning
- Various bridge configurations used

GMR Limitations

- Narrow linear range
- Easily disturbed by stray fields
- Temperature-dependent magnetization
- Requires careful magnetic design
- Offset shifts after large field exposure

TMR Sensors: Quantum Tunneling in Production

Tunnel Magnetoresistance (TMR)

- Based on quantum mechanical tunneling
- Two ferromagnetic layers separated by an insulator
- Resistance depends on relative magnetization

Why TMR Matters

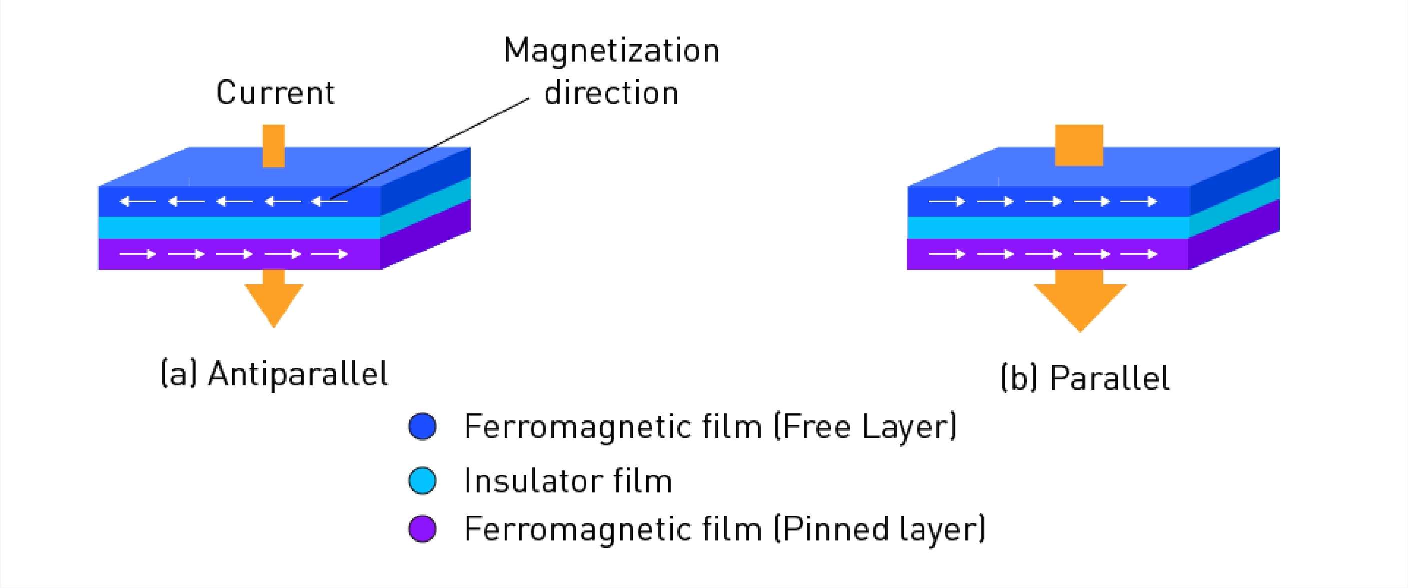
- Highest sensitivity of any production magnetic sensor
- Extremely low noise
- Foundation of modern high-resolution encoders

Physical Principle: Spin-Dependent Quantum Tunneling

- Two ferromagnetic electrodes
- Ultra-thin insulating barrier (≈1nm MgO)
- Electrons tunnel through barrier
- Tunneling probability depends on spin alignment

Key Effect

- Parallel magnetization → low resistance
- Anti-parallel magnetization → high resistance



TMR Sensors *(continued)*

TMR Performance	
Magnetoresistance Ratio	100% to 300%
Sensitivity	10%/mT to 100%/mT
Noise Density	1nT/√Hz to 10nT/√Hz
Linear Range	± 0.1mT to 1mT
Offset Drift	Moderate

Biasing/Linearization

- Raw response is nonlinear
- Extremely sensitive to offset
- Narrow linear region
- Integrated bias magnets
- Integrated “closed-loop” coils
- Temperature compensation

TMR Limitations

- Very narrow linear range
- Easily saturated by stray fields
- Sensitive to magnet/magnetic component placement
- Can be damaged by high field exposure

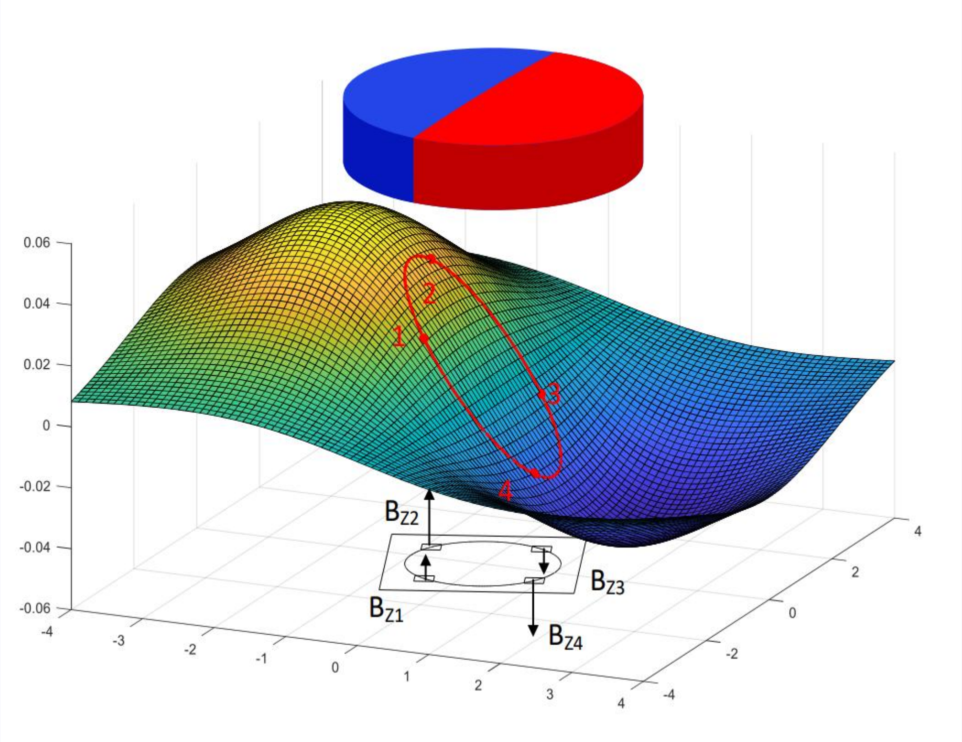
Technology Comparison - Saturated

Technology	What "saturation" means here	Typical field needed at die	Angular response	Notes
Silicon Hall	No magnetic saturation; SNR-limited	**~20–100 mT** (practical)	sin/cos	Low sensitivity → needs strong field
GaAs (III-V) Hall	No magnetic saturation; higher mobility	**~5–30 mT**	sin/cos	Better than Si Hall, still weaker than MR
AMR	Magnetization fully aligned with field (single-domain)	**~1–2 mT** (with bias / set-reset)	$\cos^2(\theta)$	Needs biasing; 180° periodicity
GMR	Free layer aligned, smooth rotation	**~2–8 mT**	$\sim\cos(\theta)$	Moderate signal, more drift
TMR (IP-TMR)	Free layer saturated, rotates with field	**~1–15 mT** (up to ~10 mT)	$\cos(\theta)$	Huge signal, true 360°

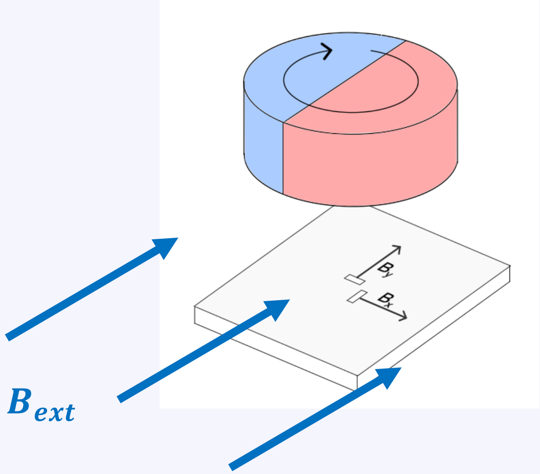
Technology Comparison - Linear

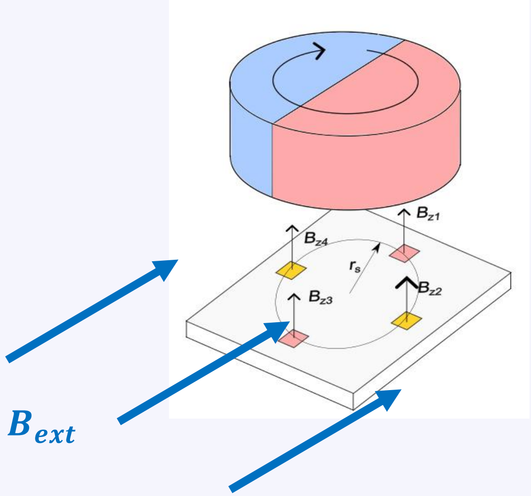
Technology	What limits linear operation	Typical linear field range	Noise floor (order-of-mag)	DC accuracy
Silicon Hall	Amplifier offset & noise	**±50–200 mT**	~1–10 μT/√Hz	Good
GaAs (III-V) Hall	Amplifier & thermal drift	**±30–150 mT**	~0.3–3 μT/√Hz	Very Good
AMR	Free-layer rotation & hysteresis	**±1–5 mT**	~50–200 nT/√Hz	Very good
GMR	Partial saturation, drift	**±2–10 mT**	~20–100 nT/√Hz	Very good
TMR	Free-layer saturation	**±1–5 mT**	~5–50 nT/√Hz	Excellent

Differential Technique



In the presence of a homogeneous external magnetic field B_{ext}:





$$out = \text{atan}\frac{B_y + \boldsymbol{B_{ext,y}}}{B_x + \boldsymbol{B_{ext,x}}}$$

$$out = \text{atan}\frac{B_{z4} + \boldsymbol{B_{ext,z}} - (B_{z2} + \boldsymbol{B_{ext,z}})}{B_{z3} + \boldsymbol{B_{ext,z}} - (B_{z1} + \boldsymbol{B_{ext,z}})}$$

The largest error occurs when both fields are perpendicular thus:

$$error = \text{atan}\frac{\boldsymbol{B_{ext}}}{B}$$

The common mode external field is cancelled:

$$error = 0$$

Why Your Sensor Spec Lies (A Love Letter to Datasheets)

MPS

What the Datasheet Assumes

- Perfect magnet, uniform magnetic field
- Mechanical tolerance stack up = 0
- Lab-grade power supply
- No PWM, no dV/dt, no EMI
- 25°C environment
- No nearby ferromagnetic materials

Example Motor Position Sensing/Phase Current Sensing

- Multi-axis, rotating, non-uniform fields
- Magnet tilt, airgap variation, mechanical runout
- PWM edges at 20kHz to 100kHz
- Ground bounce and common-mode noise
- Temperature gradients across the IC
- Steel, copper, and current everywhere

Specs Most Likely to Betray You

- Sensitivity – measured at small-signal B
- Noise density – ignores system-level noise
- Linearity – assumes no saturation or cross-axis coupling
- Offset drift – quoted without mechanical effects
- Bandwidth – small signal, not large signal

When Theory Meets Practice

- Temperature drift beats noise outside the lab
- Mechanical tolerances matter more than sensor specs
- A perfect sensor will show you all the flaws in your magnet
- “The universe is the best simulator”

Q&A

Thank you for joining!