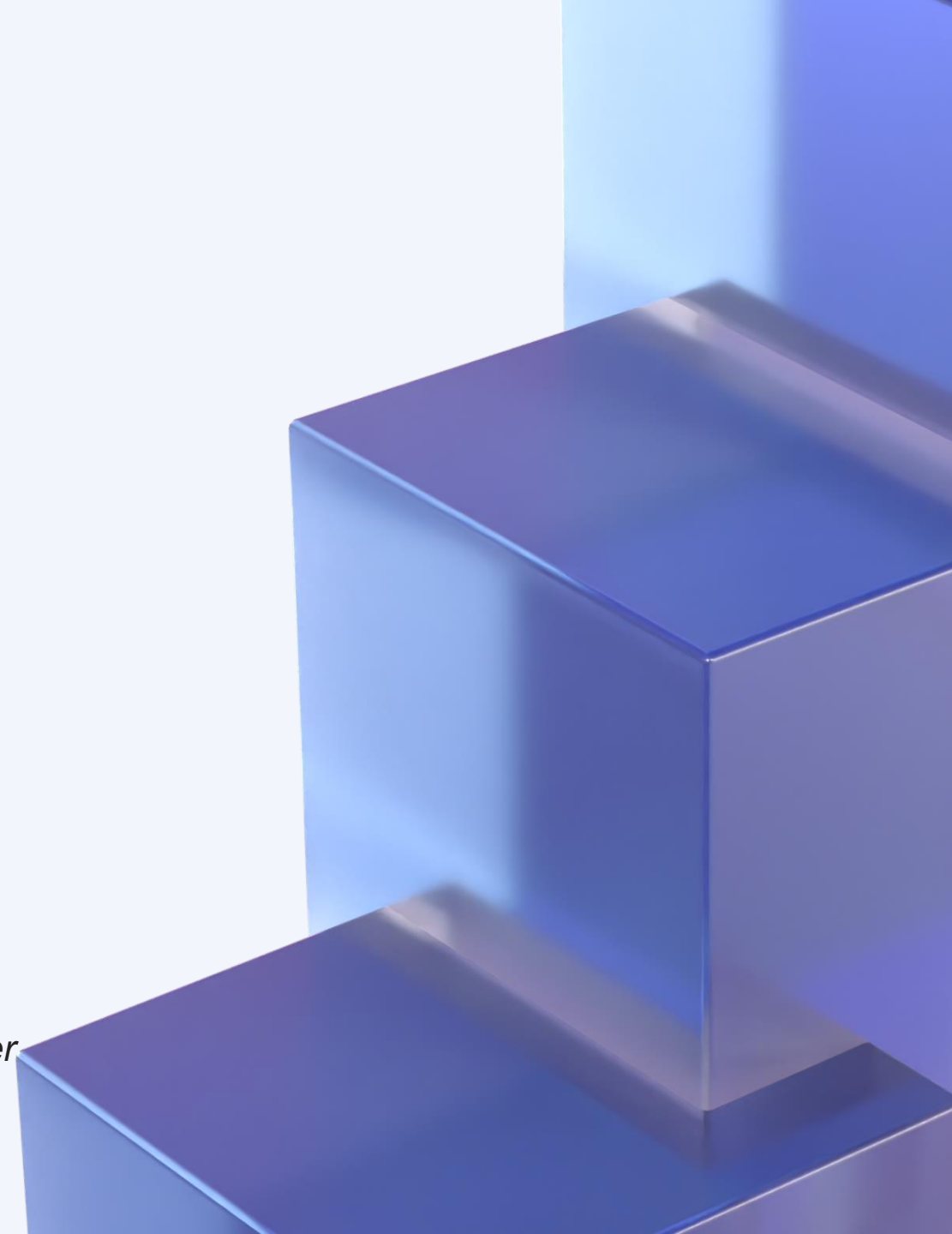
“看见”磁场

—— 磁传感器技术从原理到实战

Elena Xie, Sr. Application Engineer

English version: *Unlocking the Invisible: A Deep Dive into Modern Magnetic Sensing Technology, Ted Smith, Sr. Field Applications Engineer*

Nov 2026

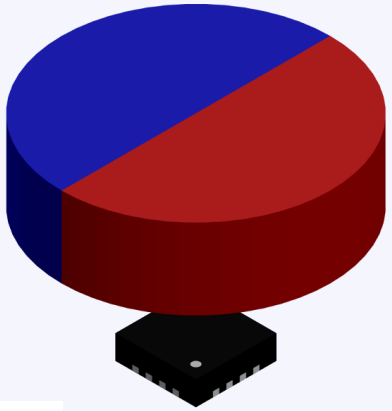


Content

- Why Magnetic Sensing
- Hall Effect sensors
- Magnetoresistive Sensors
- MPS Sensor Solution

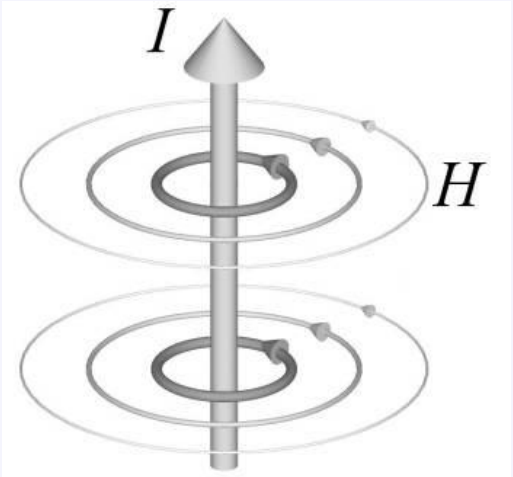
Position Sensors

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

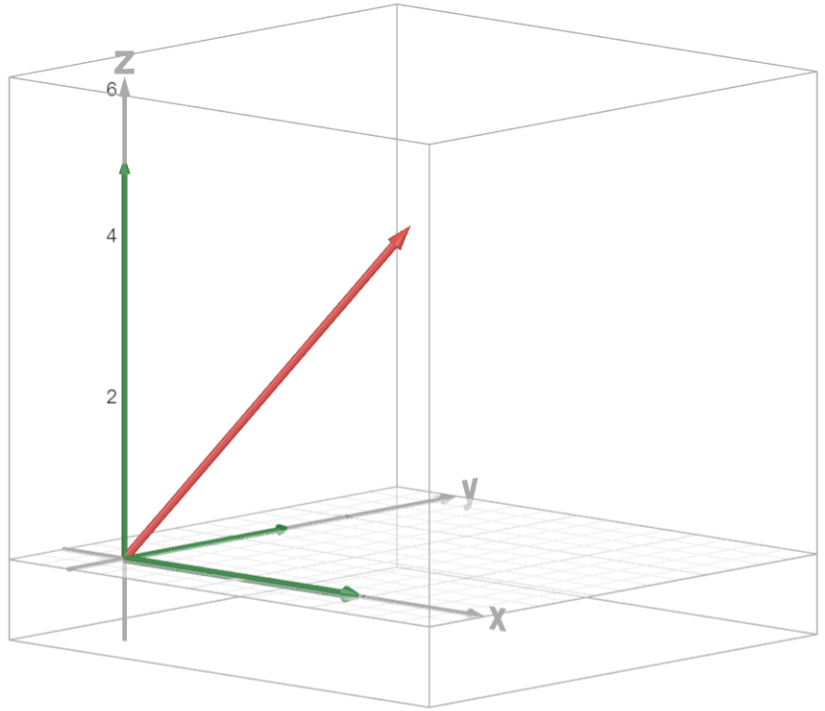
- Lab measurement
- Navigation
- Medical safety
- Music (e.g. guitar pickups, etc.)

Non-contact, penetrable, and naturally occurring

Terminology and Magnetic Field Basics

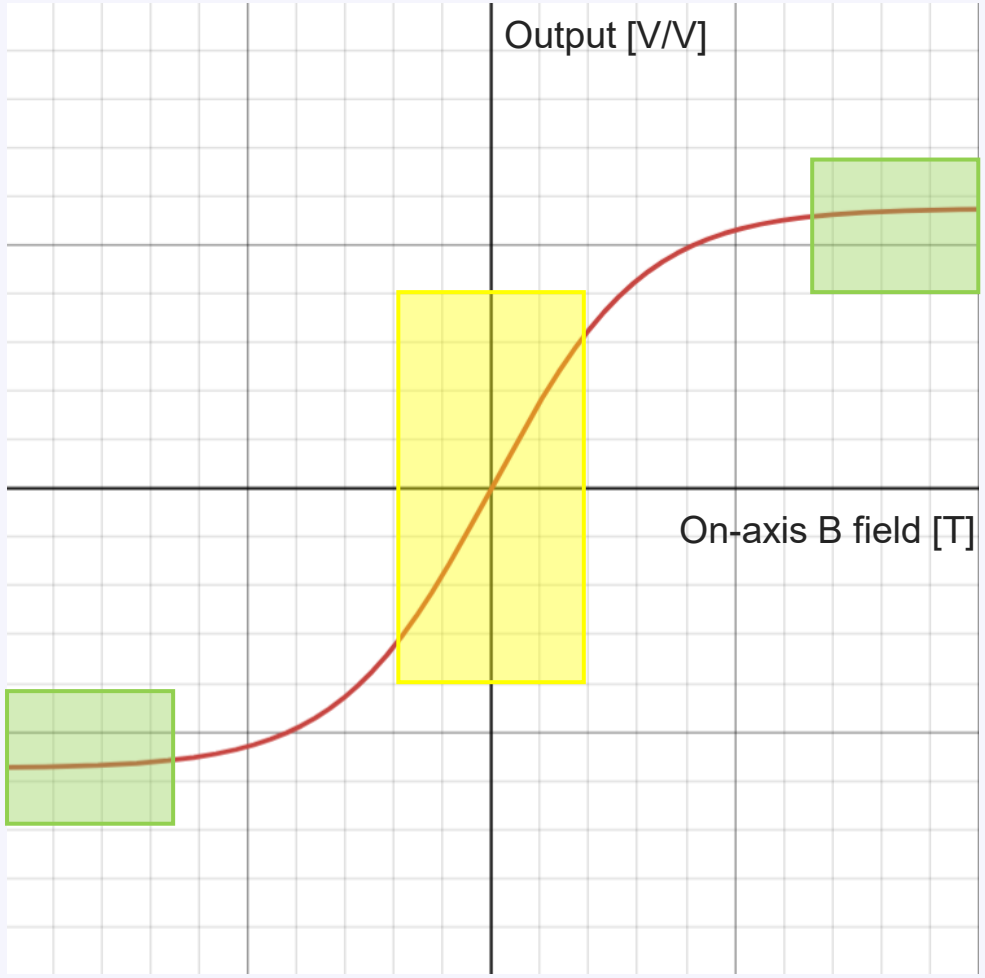
With a magnetic sensor, we are trying to "see" the magnetic field vector (or, more likely, one of its components) at a given point in space.

- 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

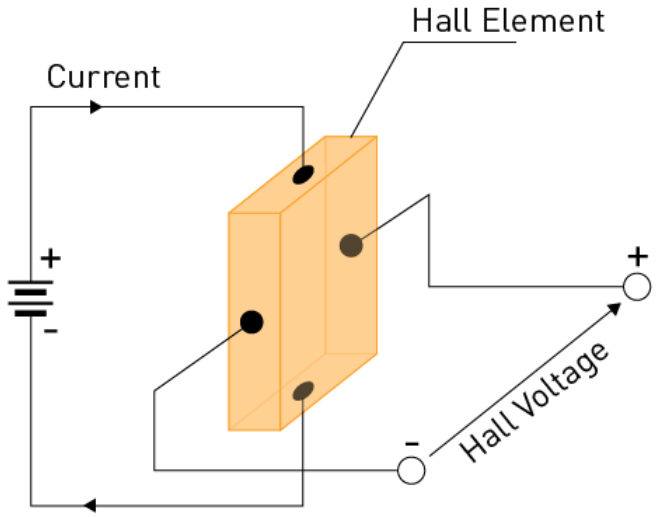
Silicon Hall-Effect Sensors: The Workhorse

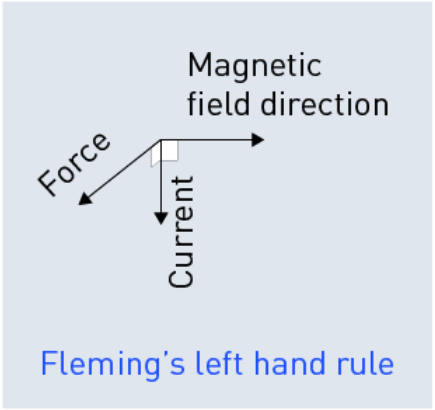
Silicon Hall Sensors

- 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





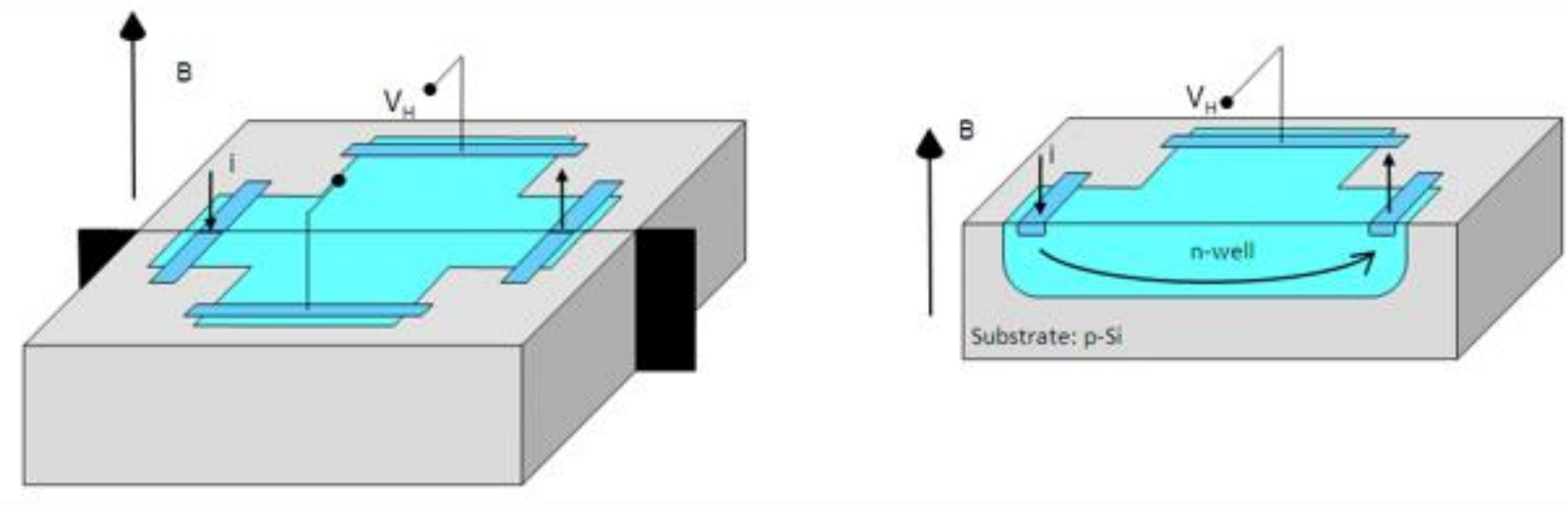
Advantages

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

Limitations

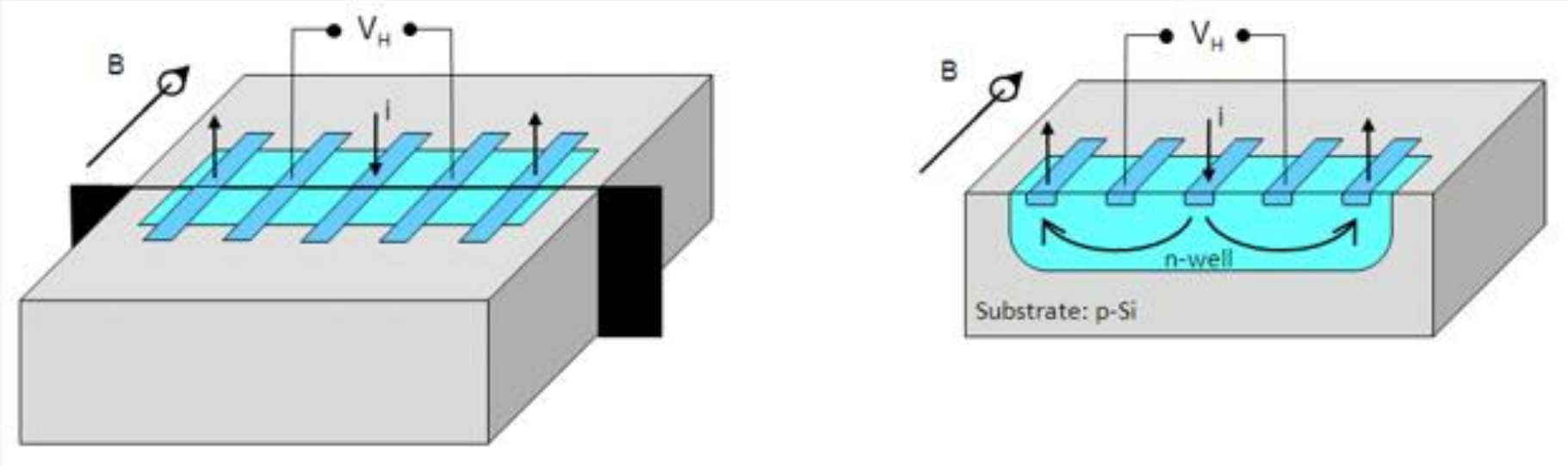
- Lower carrier mobility than III-V
- Lower raw sensitivity
- Higher intrinsic noise
- Large offset

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



Planar Hall Device

Vertical Hall Device



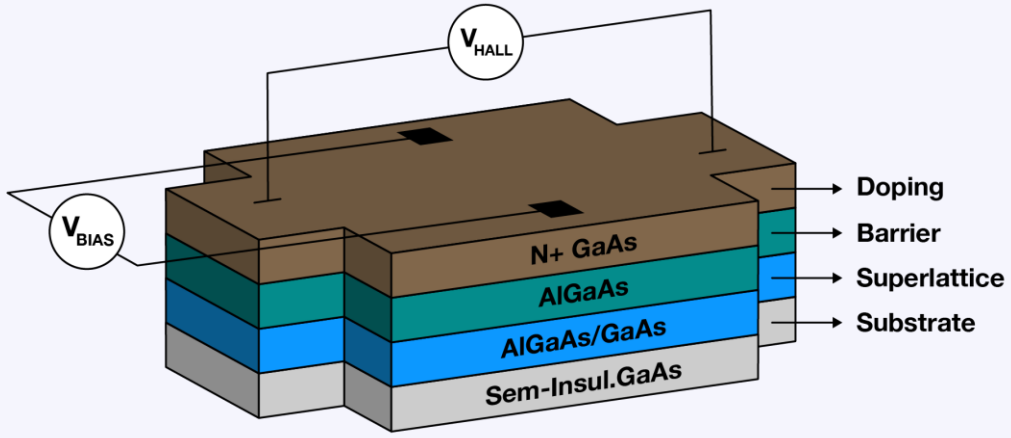
III-V Hall Sensors: Same Physics, Better Material

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

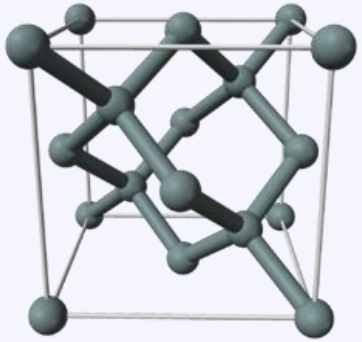


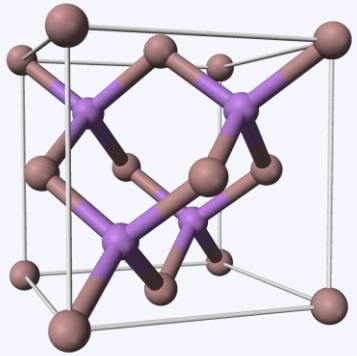
Material	Electron Mobility ($cm^2/V \cdot s$)
Silicon	~1,400
GaAs	~8,500
InSb	~70,000

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 density	μT/√Hz	100nT/√Hz
Integration	Excellent	Complex
Cost	Low	Medium
Temp Robustness	Moderate	Excellent

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

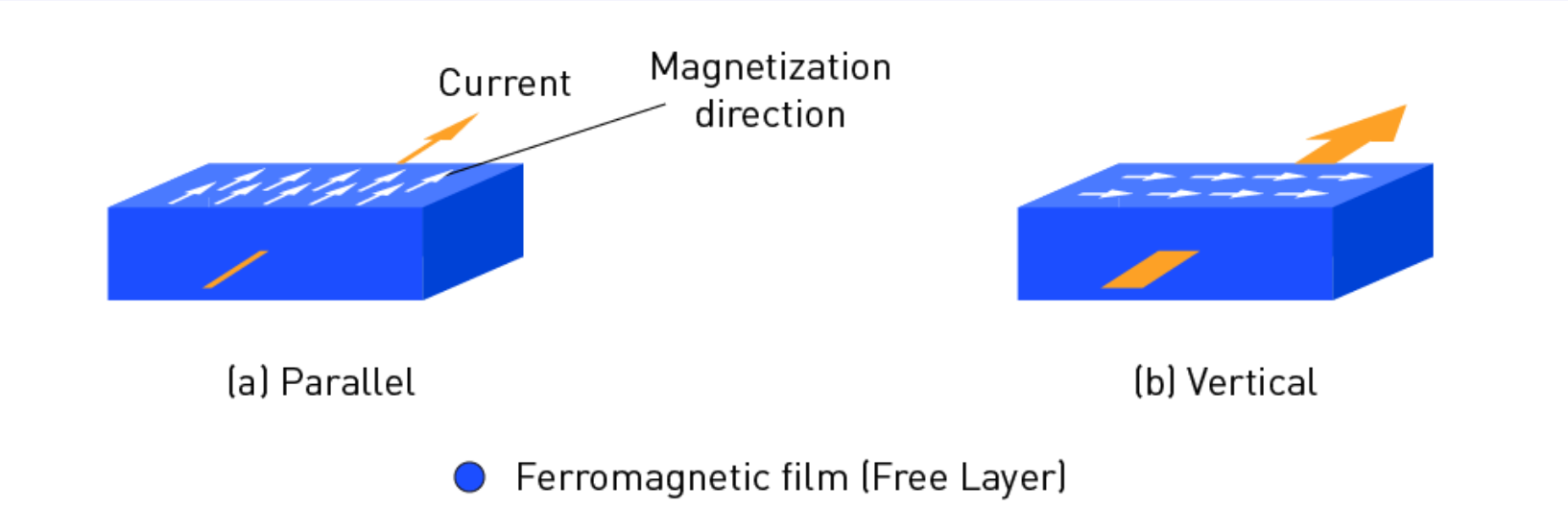
Why AMR Matters

- 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

$$R(\theta)=R_{\perp}+\Delta R\cos^2\theta$$



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
- Limited dynamic range
- Requires magnetic biasing
- Offset can jump after large field exposure

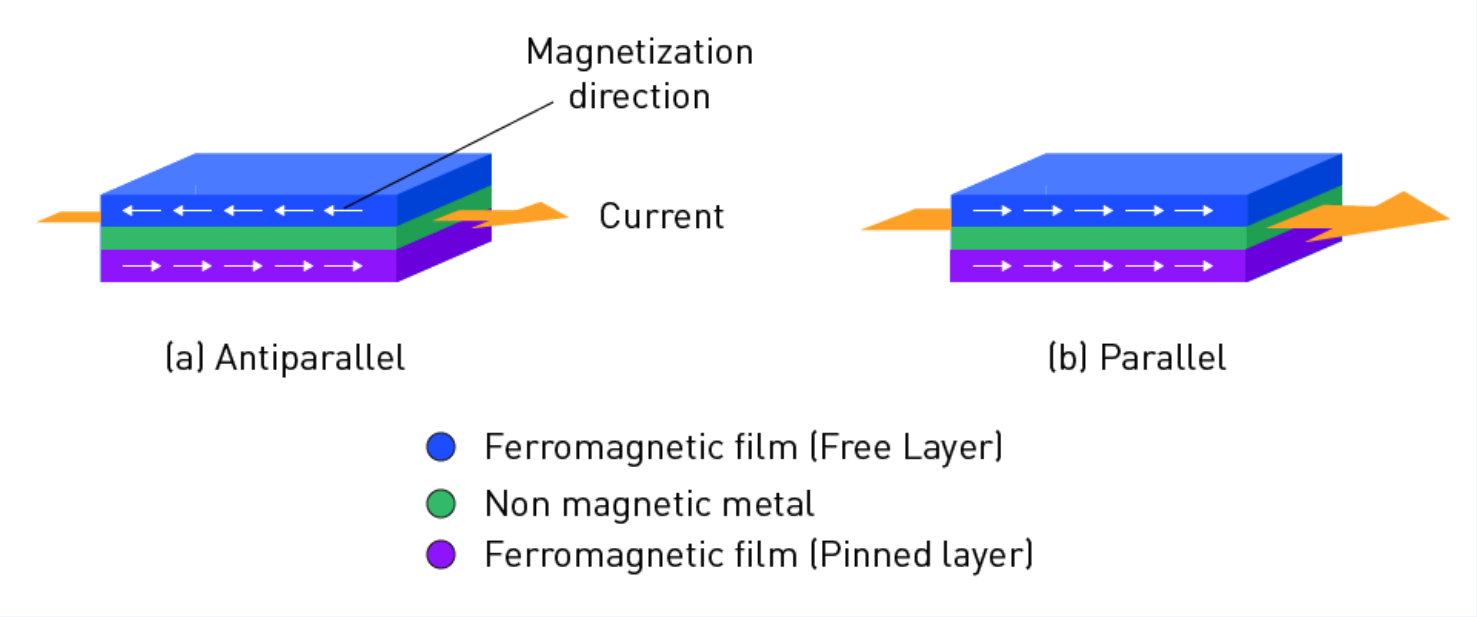
GMR Sensors: When Layers Talk through Spin

Giant Magnetoresistance (GMR)

- Discovered in multilayer thin films (1988)
- Nobel Prize winning effect (2007)
- 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

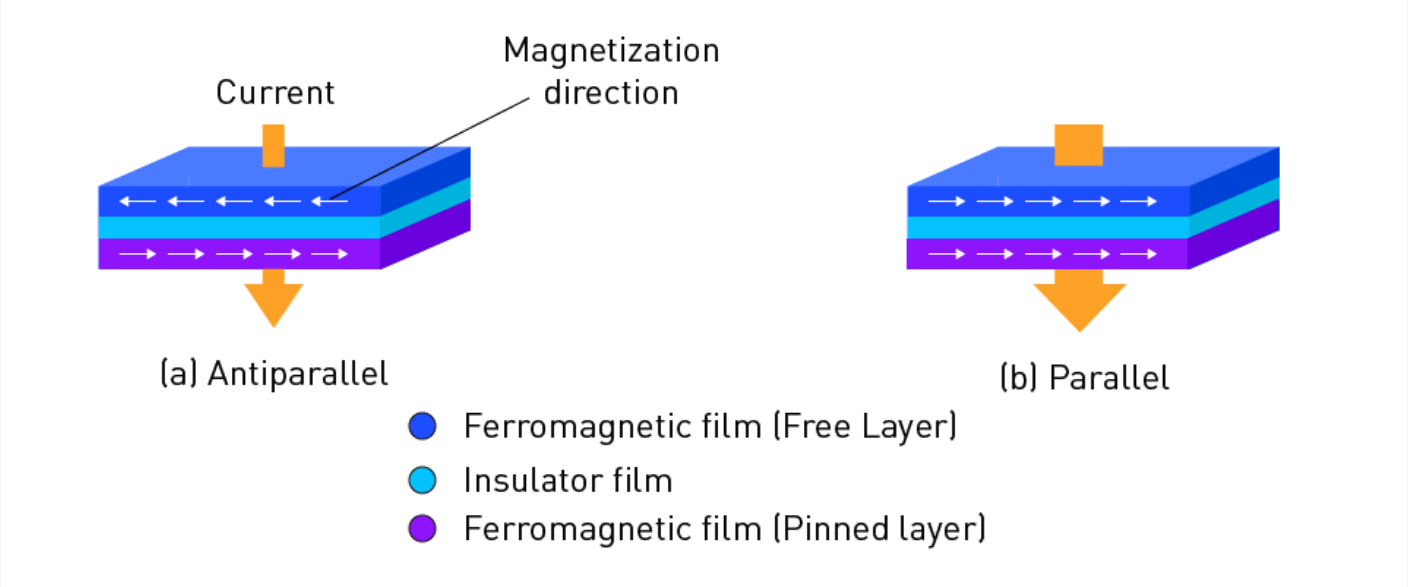
- Highest sensitivity of any production magnetic sensor
- Extremely low noise
- Foundation of modern high-resolution encoders

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 5mT
Offset Drift	Moderate

Biasing/Linearization

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

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 – Angle Sensing (Saturated)

Technology	*Typical field needed at die*	*Angular response*	*INL temperature drift*	*Noise floor (order-of-mag)*	*Notes*
Silicon Hall	*~20–100 mT (practical)*	*sin/cos*	★	*~1–10 µT/√Hz*	*Low sensitivity → needs strong field*
GaAs (III-V) Hall	*~5–30 mT*	*sin/cos*	★★	*~0.3–3 µT/√Hz*	*Better than Si Hall, still weaker than MR*
AMR	*~1–2 mT (with bias / set-reset)*	*$\cos^2(\theta)$*	★★	*~50–200 nT/√Hz*	*Needs biasing; 180° periodicity*
GMR	*~2–8 mT*	*~cos(θ)*	★★	*~20–100 nT/√Hz*	*Moderate signal, more drift*
TMR	*~1–15 mT (up to ~10 mT)*	*cos(θ)*	★★★	*~5–50 nT/√Hz*	*Huge signal, true 360°*

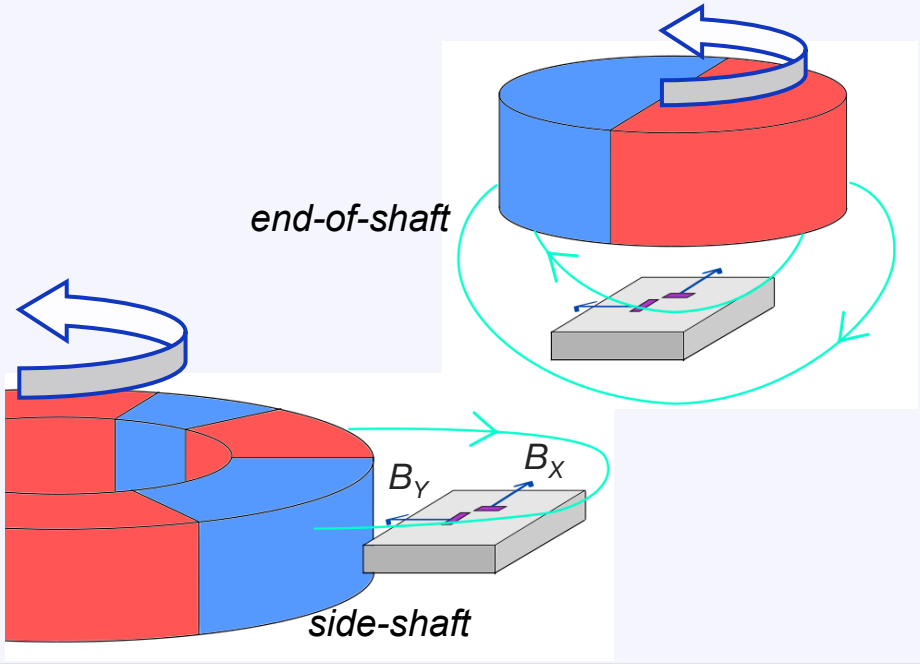
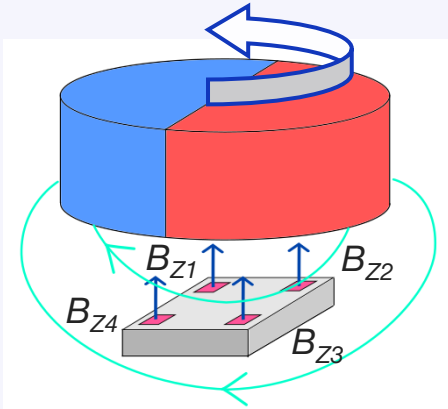
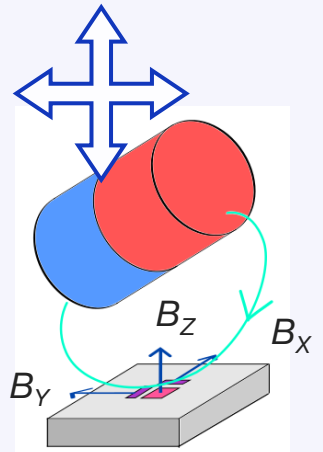
Technology Comparison – Current Sensing (linear)

Technology	*What limits linear operation*	*Typical linear field range*	*BW (product in the mkt)*	*Accuracy over temperature*	*Irreversibility after exposure to large field*
Silicon Hall	*Amplifier offset & noise*	*±50–200 mT*	*~1MHz*	★	*No*
GaAs (III-V) Hall	*Amplifier & thermal drift*	*±30–150 mT*	*~4MHz*	★★	*No*
AMR	*Free-layer rotation & hysteresis*	*±2–10 mT*	*~3MHz*	★★	*No*
GMR	*Partial saturation, drift*	*±2–10 mT*	*~1MHz*	★★	*Yes*
TMR	*Free-layer saturation*	*±2–10 mT*	*~10MHz*	★★★	*Yes*

MPS Sensors

Angle sensor & Current sensor

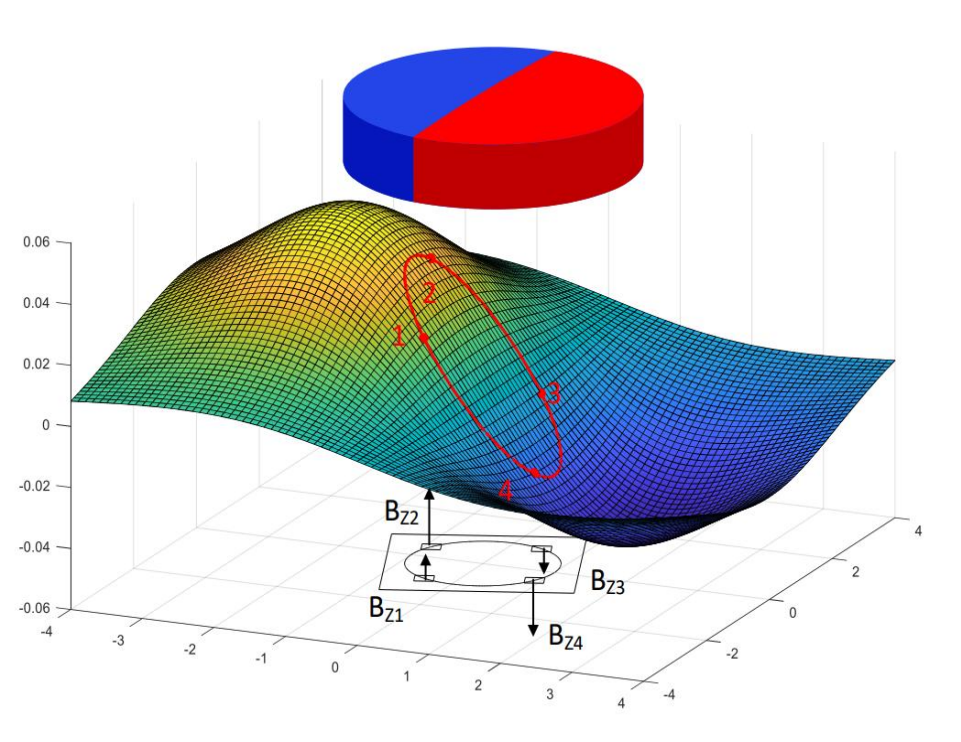
Position Sensor Overview

	MagAlpha™	MagDiff™	MagVector™
Part Numbers	MA732, MA735/6, MA702, MA302, MA782, MAQ600A, MA(Q)6xx, MAQ430, MAQ470/3	MA900, MA98x, MAQ900/900B, MAQ79010FS, MAQ79xxxFS	MV300, MV(Q)3xx
Magnetic Configuration		 end-of-shaft	 anywhere
Qty Measured	B_x, B_y	$B_{z1}, B_{z2}, B_{z3}, B_{z4}$	B_x, B_y, B_z
Sensor Output	$angle = \text{atan}\frac{B_y}{B_x}$	$angle = \text{atan}\frac{B_{z4} - B_{z2}}{B_{z3} - B_{z1}}$	B_x, B_y, B_z

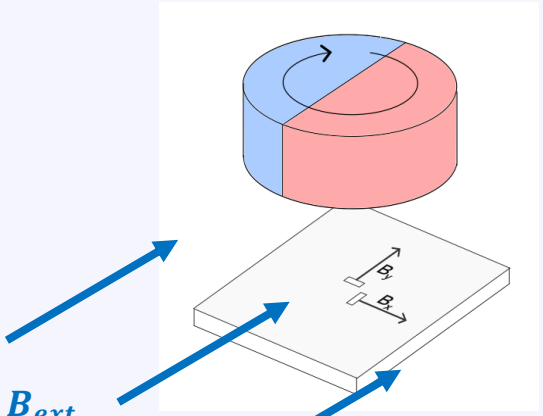
Magnetic field lines Direction of motion

Sensitivity direction

Differential Technique



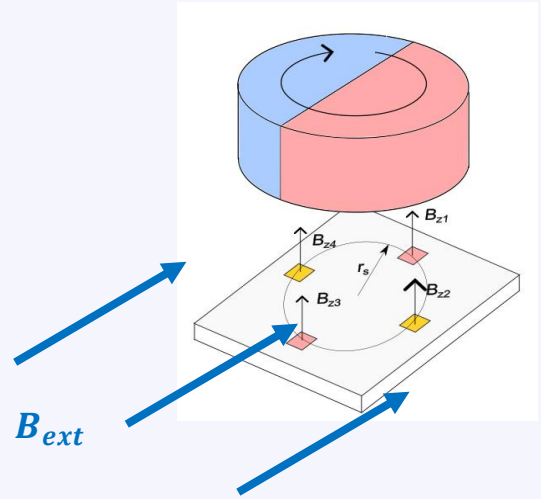
In the presence of a homogeneous external magnetic field B_{ext}:



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

The largest error occurs when both fields are perpendicular thus:

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



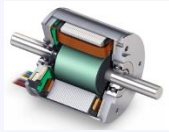
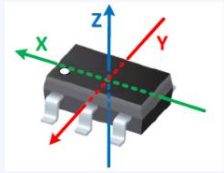
$$out = \text{atan}\frac{B_{z4} + \boldsymbol{B_{ext,z}} - (B_{z2} + \boldsymbol{B_{ext,z}})}{B_{z3} + \boldsymbol{B_{ext,z}} - (B_{z1} + \boldsymbol{B_{ext,z}})}$$

The common mode external field is cancelled:

$$error = 0$$

Position Sensor Solutions

Home page

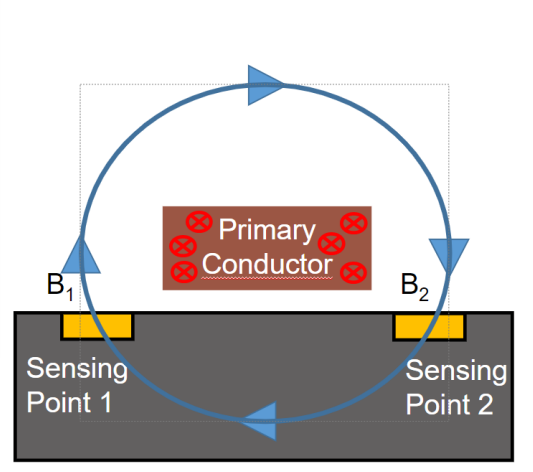
MagAlpha™ Sensors for Motors & Rotary Encoders	MA330 14-bit, Digital, Contactless, ABZ & UVW MA732 14-bit, Digital, Contactless, ABZ Incremental & PWM Outputs  MA780/2 8 to14-bit Res SPI auto wake/sleep MA(Q)600A 12 to 15-bit, 0.6°(0.1°) INL High BW, No Latency SPI, SSI, UVW, ABZ, PWM TMR		MA(Q)6xx 12 to 15-bit, 0.6°(0.1°) INL, High BW, No Latency SPI, SSI, UVW, ABZ, PWM TMR
MagDiff™ Differential Position Sensors		MA(Q)900/B 14-bit, SPI, I²C, PWM, SSI, UVW, ABZ MAQ79010FS 14-bit, SPI, I²C, UVW, SENT, ABZ ASIL B MPSafe  MA(Q)98x 9 to 13-bit SPI Out	MAQ79xxxFS 14-bit, Differential SPI, I²C, UVW, SENT, ABZ ASIL D MPSafe MA(Q)98x 9 to 13-bit, Hall, Differential, Low Power, SPI Out
MagVector™ 3D Position Sensors	MV300 3D Mag Sensor 12-bit data I2C, SPI	 MV(Q)3xx 3D Sensor; 12-bit data I²C, SPI	

New Release | Production | Sampling | Development

Integrated Coreless Magnetic Current Sensors

Differential Sensing

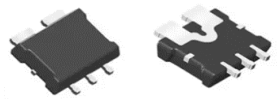
Ampere's Law: B ∝ I



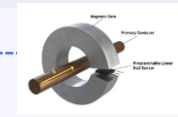
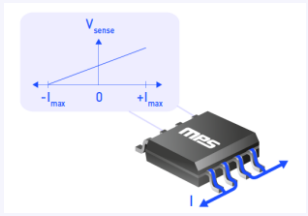
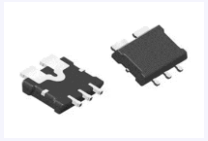
$$V_{OUT} = V_{OUT(Q)} + G(B_2 - B_1)$$

Immune to constant external stray fields

Packages

 *(0.6mΩ)*	*3mm x 3mm QFN-12*
 *(0.5mΩ min)*	*SOIC-8*
 *(0.45mΩ)*	*SOIC16 WB*
 *(0.3mΩ)*	*SOIC16-10 WB*
 *(0.2mΩ)*	*PSOF-7*

Current Sensor Solutions

Isolation Voltage (V_{RMS}) >3kV		MCS(Q)1810/12/14 3.3V/5V, 2%, <1µs Fast OCD Flag WSOIC-10 and 16 5kV$_{RMS}$ | 1100V$_{PEAK}$ 	MCS(Q)185x 3.3/5V,1%, 1MHz BW MCS(Q)183x Programmable Linear Hall-Effect Current Sensor, 200k to 380kHz BW 
Isolation Voltage (V_{RMS}) ≤3kV	MCS(Q)1805 3.3V/5V, 2.5%, OCD Flag 3kV$_{RMS}$ | 580V$_{RMS}$ MCS(Q)1806 3.3V/5V, 2.5% 3kV$_{RMS}$ | 500V$_{RMS}$ MCS1800/1801 3.3V/5V, 2.5-3% 1kV | 250V$_{RMS}$ MCS1802/1803 3.3V/5V, 2.5-3% 2.2kV$_{RMS}$ | 250V$_{RMS}$		MCS(Q)180x 3.3/5V,2%, V_{REF}, 350kHz 3.5kV$_{RMS}$ | 800V$_{RMS}$
Basic Isolation 100V	MCS(Q)1823 MCS1826 3.3V/5V, 2.5-5% 100V Isolation 	 MCS(Q)18xx 3.3V/5V, 2% PSOF-7 Package 350kHz BW, OCD 100V Isolation	

New Release | Production | Sampling | Development

Why Your Sensor Spec Lies – Engineering Practice

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
- 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

- Noise density – ignores system-level noise
- Linearity – assumes no magnet imperfection 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!