Hardware Engineer's Guide

SENSORS

By Shimi Cohen

INTRODUCTION TO SENSORS

Core Definitions

A sensor converts physical phenomena into measurable electrical signals. The transducer performs the actual energy conversion. Every sensing system requires both components to function effectively. Modern electronics depend on accurate sensing for control, monitoring, and feedback systems. Board-level integration demands understanding sensor characteristics, interface requirements, and system constraints. The sensor element responds to stimulation. The transducer converts response into electrical output. Modern ICs often integrate both functions in single packages.

Sensor vs Transducer Distinction:

Component	*Function*	*Example*
Sensor	*Detects physical change*	*Thermocouple junction*
Transducer	*Converts energy forms*	*Voltage output circuit*
Complete System	*Detection + Conversion*	*Temperature Measurement IC*

ENERGY CONVERSION MECHANISMS

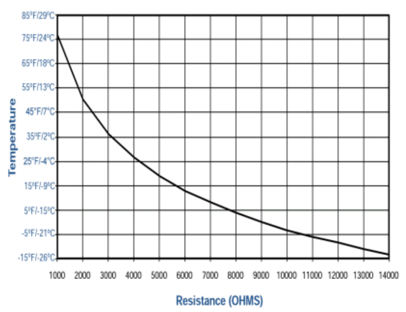
Common conversion mechanisms:

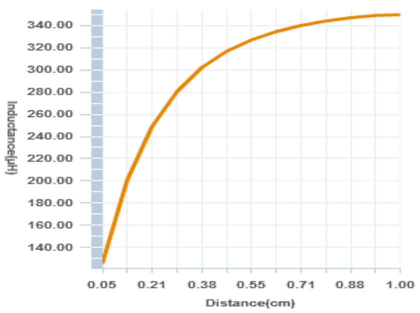
Resistive Changes: Temperature affects material resistance. Strain alters conductor geometry. Chemical exposure modifies surface properties.

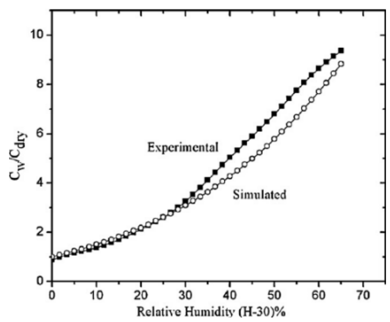
Capacitive Changes: Distance variations alter plate spacing. Dielectric property changes modify capacitance. Humidity affects dielectric constant.

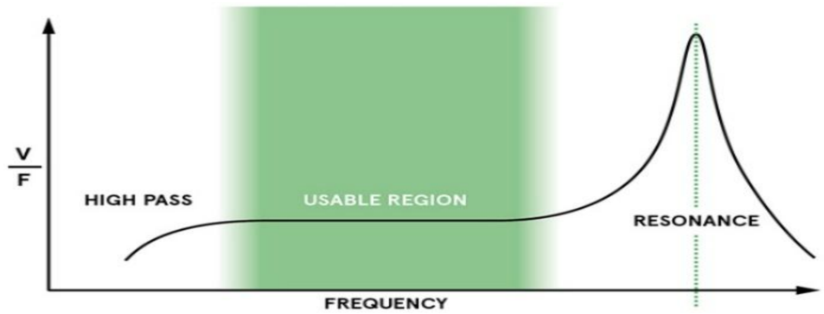
Inductive Changes: Magnetic field variations induce voltage. Position changes affect coupling. Eddy currents provide proximity detection.

Piezoelectric Effects: Mechanical Stress generates voltage. Crystal deformation produces charge separation. Acceleration creates measurable signals.









Physical vs Virtual Sensing

VIRTUAL SENSING IMPLEMENTATION

Virtual sensors calculate unmeasured parameters from available data.

Software algorithms process multiple sensor inputs.

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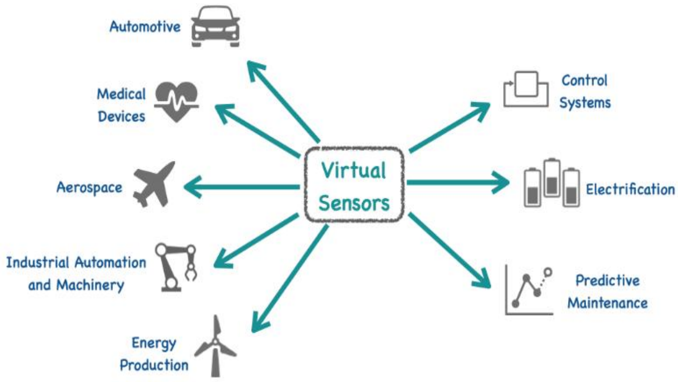
Applications include:

- Engine torque estimation
- Battery state-of-charge
- Tire pressure
- Structural Health Monitoring



PHYSICAL SENSING CHARACTERISTICS

Physical sensors directly interact with measured phenomena. Direct contact often provides highest accuracy. Environmental exposure affects reliability and lifespan.

Temperature sensors require thermal coupling. Pressure sensors need mechanical contact. Chemical sensors depend on material interaction.

Design considerations include:

- Environmental Protection Requirements
- Calibration stability over time
- Mechanical mounting constraints
- Electrical isolation needs

Active vs Passive Sensor Classification

PASSIVE SENSOR CHARACTERISTICS

Passive sensors require external excitation energy. Bridge circuits provide stable excitation. Constant current sources eliminate resistance effects.

Sensor Type	*Excitation Method*	*Output Signal*
RTD	*Constant current*	*Voltage drop*
Thermistor	*Voltage divider*	*Voltage ratio*
Strain gauge	*Bridge circuit*	*Differential voltage*
Potentiometer	*Reference voltage*	*Voltage division*

Passive sensors offer excellent stability. Temperature coefficients remain predictable. Aging effects develop slowly.

Power consumption stays low. No internal active components fail. Environmental sensitivity affects only sensing element.

ACTIVE SENSOR OPERATION

Active sensors generate output signals directly. Internal circuits amplify and condition signals. Power supply requirements increase system complexity.

Modern active sensors integrate:

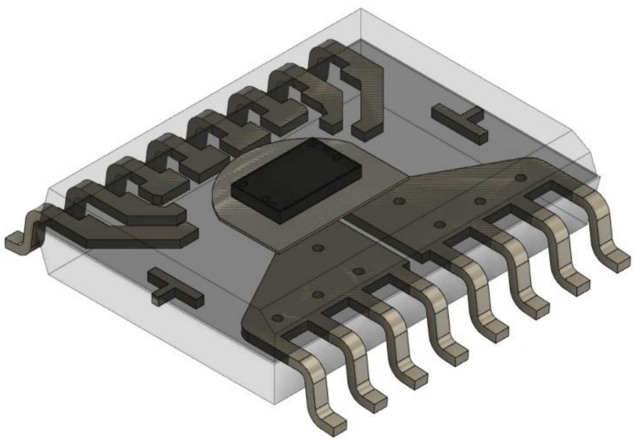
- Signal conditioning amplifiers
- Temperature compensation circuits
- Digital processing capabilities
- Communication interfaces

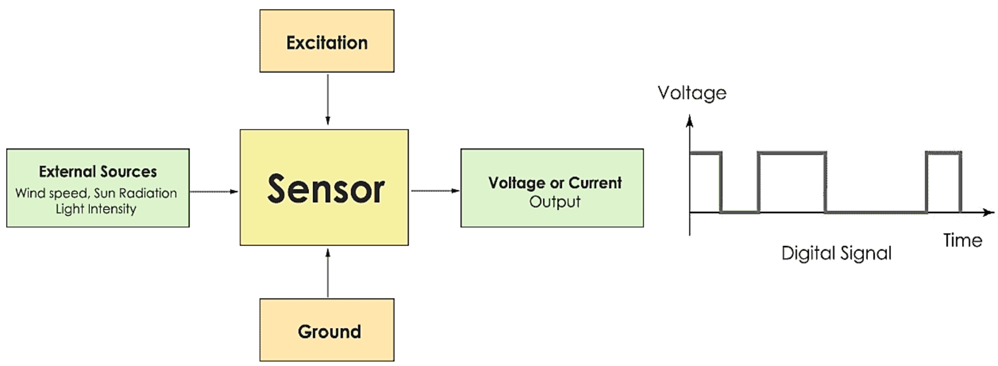
Advantages:

- High output signal levels
- Built-in signal conditioning
- Reduced External Circuitry
- Digital output options

Disadvantages:

- Higher power consumption
- Supply voltage sensitivity
- Electronic component aging
- EMI susceptibility





FUNDAMENTAL MEASUREMENT

Units and Measurement Standards

SI BASE UNITS FOR SENSORS

Engineering measurements require consistent unit systems. SI base units provide universal reference standards. Derived units combine base units for complex measurements.

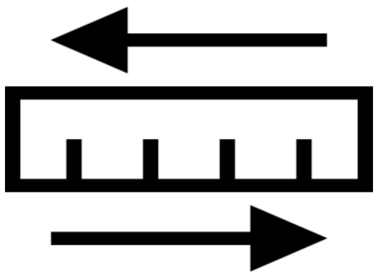
Quantity	*SI Unit*	*Symbol*	*Sensor Applications*
Length	*meter*	*m*	*Position, displacement*
Mass	*kilogram*	*kg*	*Force, acceleration*
Time	*second*	*s*	*Frequency, velocity*
Current	*ampere*	*A*	*Magnetic field, power*
Temperature	*kelvin*	*K*	*Thermal measurements*
Amount	*mole*	*mol*	*Chemical concentration*
Luminous	*candela*	*cd*	*Light measurements*

Measurement traceability links sensor readings to national standards. Calibration chains maintain accuracy across measurement systems.

ENGINEERING UNIT CONVERSIONS

Board design requires practical engineering units. Conversion factors ensure system compatibility. Microcontroller calculations need consistent units.

Common conversions for sensor applications:



- $Temperature: °C = K - 273.15$
- $Pressure: 1\ bar = 100\ kPa = 14.5\ psi$
- $Force: 1N = 0.225\ lbf$
- $Acceleration: 1\ g = 9.81\ m/s^2$

Range and Resolution Specifications

MEASUREMENT RANGE DEFINITION

Full-scale range defines maximum measurable values. Operating range specifies normal working conditions. Extended range allows temporary overload operation.

Range selection affects:

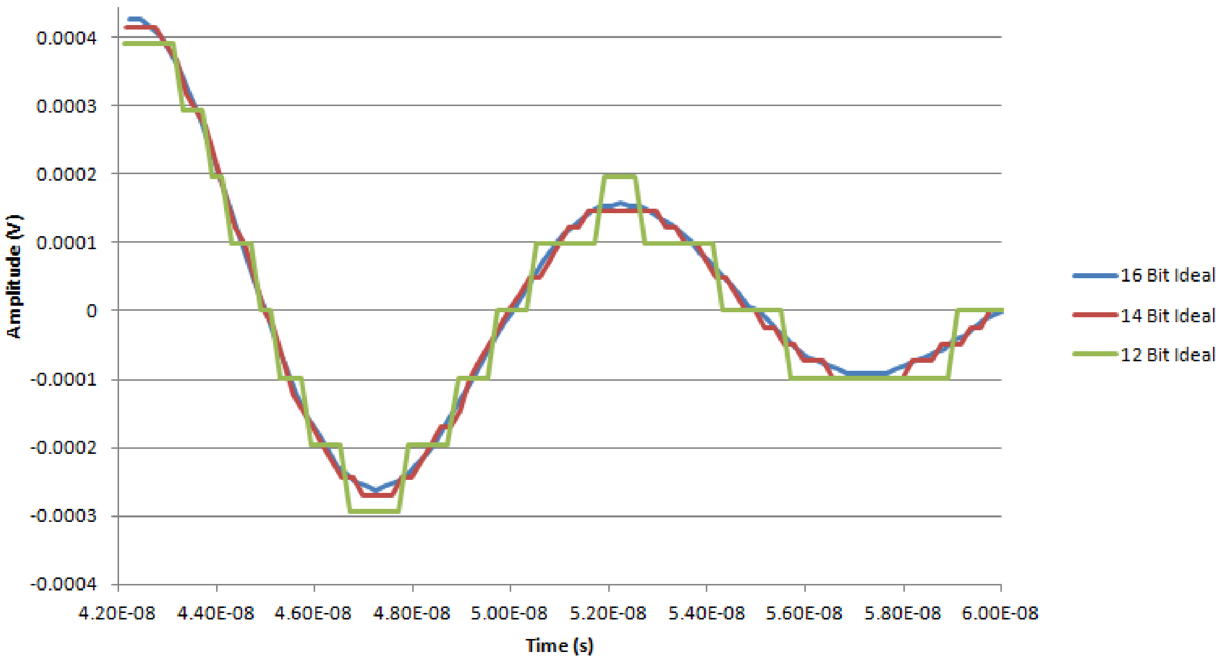
- ADC bit allocation
- Amplifier gain settings
- Power supply requirements
- Physical sensor sizing

RESOLUTION CHARACTERISTICS

Resolution determines smallest detectable change. Digital systems quantize analog signals. Bit depth limits resolution capabilities.

ADC Bits	*Resolution Steps*	*Typical Application*
8	*256*	*Basic control*
10	*1024*	*General purpose*
12	*4096*	*Precision measurement*
16	*65536*	*High accuracy*
24	*16.7M*	*Laboratory instruments*

Effective resolution differs from ADC resolution. Noise limits practical resolution. Oversampling improves effective bits.



Sensitivity and Accuracy Parameters

SENSITIVITY ANALYSIS

Sensitivity measures output change per input change. Units match output/input quantity ratio.

Higher sensitivity improves measurement precision.

Mathematical expression:

$$S = \Delta Output/\Delta Input$$

Temperature sensor example:

- Thermocouple: 40 μV/°C
- RTD: 0.385 Ω/°C per Ω
- Thermistor: -4%/°C

Sensitivity affects signal conditioning requirements. Low sensitivity needs high-gain amplification. High sensitivity requires careful noise management.

ACCURACY SPECIFICATIONS

Accuracy describes measurement correctness relative to true values. Systematic errors create offset problems. Random errors affect repeatability.

Error sources include:

- Calibration uncertainties
- Temperature coefficient effects
- Aging and drift phenomena
- Non-linearity deviations

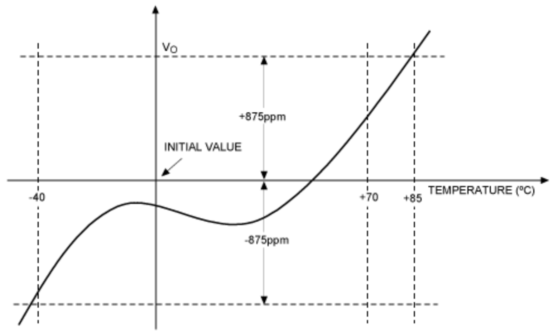
Accuracy specifications typically include:

- ±0.1% full scale (high precision)
- ±0.5% full scale (standard industrial)
- ±1.0% full scale (general purpose)
- ±2.0% full scale (basic applications)

Drift and Stability Considerations

TEMPERATURE DRIFT EFFECTS

Temperature changes affect all sensor components. Compensation circuits reduce drift errors. Digital correction algorithms improve performance.



Common drift mechanisms:

- Resistor temperature coefficients
- Semiconductor junction variations
- Mechanical expansion effects
- Chemical reaction rate changes

LONG-TERM STABILITY

Aging processes gradually change sensor characteristics. Material degradation affects accuracy over time. Periodic recalibration maintains performance.

Stability factors include:

- Component material properties
- Operating stress levels
- Environmental exposure conditions
- Manufacturing quality control

Signal-to-Noise Ratio Fundamentals

NOISE SOURCE IDENTIFICATION

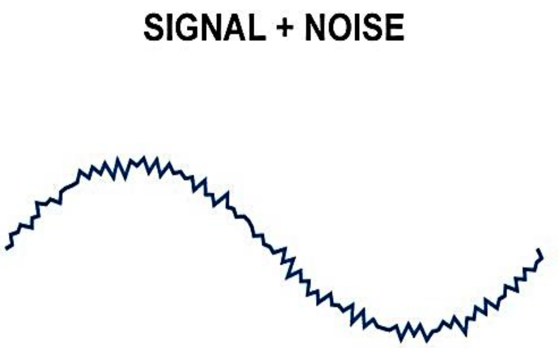
Electronic noise limits measurement precision. Thermal noise affects all resistive elements. Flicker noise dominates at low frequencies.

Noise Type	***Frequency Range***	***Characteristics***
Thermal	*All frequencies*	*White spectrum*
Flicker	*DC to 1 kHz*	*1/f spectrum*
Shot	*High frequency*	*Poisson statistics*
Interference	*Specific bands*	*External sources*

Signal conditioning improves SNR performance. Filtering removes out-of-band noise. Differential signaling reduces common-mode interference.

Design strategies:

- Maximize signal levels within safe limits
- Minimize noise bandwidth through filtering
- Use differential signal paths
- Implement proper grounding techniques
- Shield sensitive circuits from interference



Bandwidth and Frequency Response

DYNAMIC RESPONSE CHARACTERISTICS

Sensor bandwidth limits measurement speed. First-order systems show exponential responses. Second-order systems can exhibit resonance.

Response speed affects:

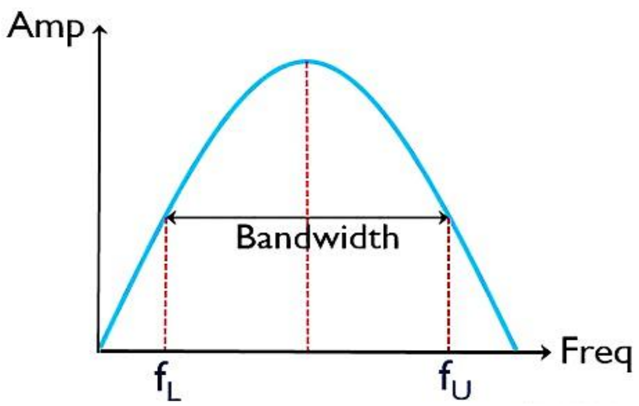
- Control system stability
- Data acquisition rates
- Anti-aliasing filter requirements
- Real-time processing capabilities

FREQUENCY DOMAIN ANALYSIS

Transfer functions describe sensor frequency response. Magnitude plots show gain versus frequency. Phase plots indicate timing relationships.

Bode plot analysis reveals:

- System stability margins
- Resonant frequency locations
- Roll-off characteristics
- Compensation requirements



Linearity and Calibration

LINEARITY SPECIFICATIONS

Linear sensors produce proportional outputs. Non-linearity creates calibration complexity. Piecewise linearization corrects systematic errors.

Linearity metrics:

- Best-fit straight line (BFSL)
- End-point linearity
- Independent linearity
- Least-squares fit

CALIBRATION STRATEGIES

Single-point calibration corrects offset errors. Two-point calibration adjusts gain and offset. Multi-point calibration handles non-linearity.

Calibration approaches:

- Factory calibration with stored coefficients
- Field calibration using known references
- Self-calibration with internal references
- Continuous calibration during operation

TEMP & HEAT SENSORS

Thermocouple Sensor

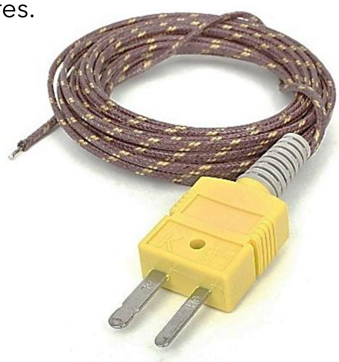
SEEBECK EFFECT PRINCIPLES

Thermocouple operation relies on the Seebeck effect. Dissimilar metals create voltage when temperature differs between junctions. Cold junction compensation ensures accurate readings.

$$V = \alpha(T_1 - T_2)$$

Where α represents the Seebeck coefficient and T_1, T_2 are junction temperatures.

Type	Materials	Range (° C)	Sensitivity (μV/° C)
K	Chrom-Alum	-200 to 1200	41
J	Iron-Const	-40 to 750	52
T	Copper-Const	-200 to 350	43
E	Chrom-Const	-200 to 900	68
R/S	Pt-PtRh	0 to 1600	6-10



COMMON THERMOCOUPLE TYPES

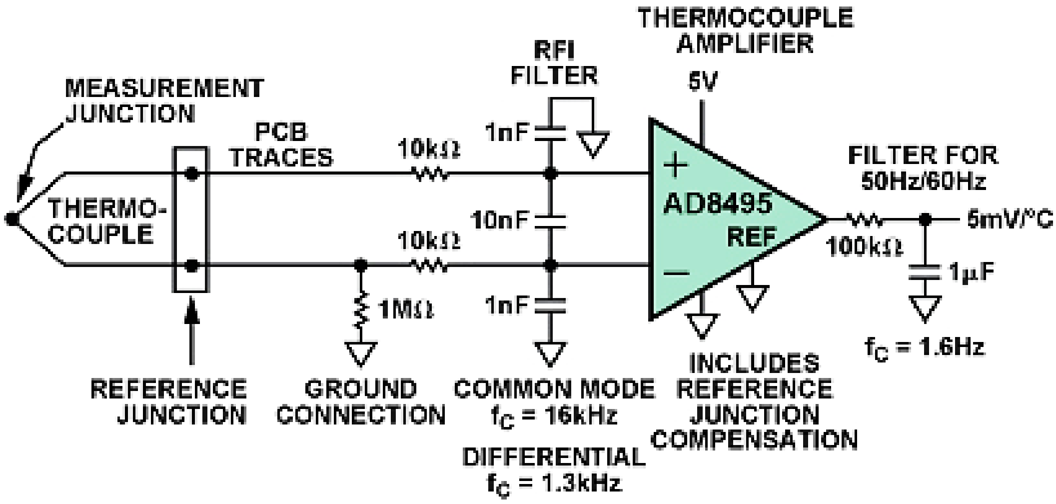
Type K thermocouples dominate industrial applications. Wide temperature range and good linearity make them versatile. Magnetic properties can affect readings near Curie point (354°C).

COLD JUNCTION COMPENSATION

Thermocouple circuits require reference temperature measurement. Ice bath reference provides 0°C baseline. Electronic compensation uses semiconductor temperature sensors.

Modern approaches include:

- Dedicated cold junction compensator ICs
- Microcontroller internal temperature sensors
- Thermistor-based reference measurement
- Software polynomial correction



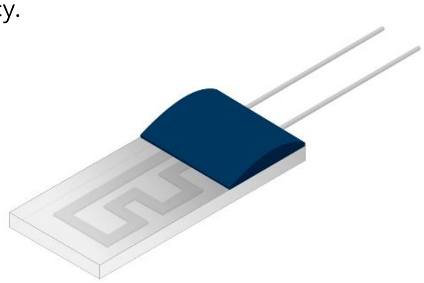
RTD - Resistance Temperature Detectors

RTD CONSTRUCTION AND MATERIALS

RTDs exploit predictable resistance changes with temperature. Platinum offers excellent stability and repeatability. Wire-wound construction provides highest accuracy.

Standard RTD configurations:

- Pt100: 100Ω at 0°C (most common)
- Pt1000: 1000Ω at 0°C (higher sensitivity)
- Pt500: 500Ω at 0°C (compromise option)



RTD RESISTANCE CHARACTERISTICS

Callendar-Van Dusen equation describes RTD behavior:

$$R(T) = R_0[1 + AT + BT^2 + C(T - 100)T^3]$$

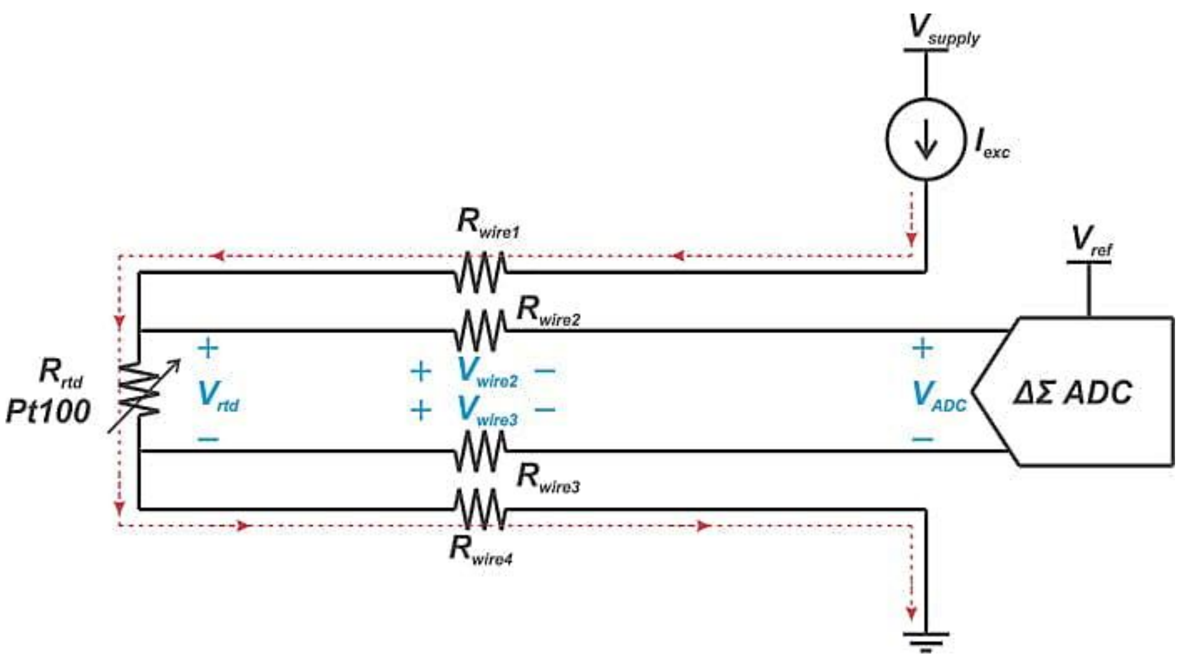
For temperatures above 0°C, C = 0, simplifying calculations.

Standard coefficients for Pt100:

- $A = 3.9083 \times 10^{-3} /°C$
- $B = -5.775 \times 10^{-7} /°C^2$

RTD Circuit Topologies:

Configuration	*Wires*	*Lead Resistance Effect*	*Accuracy*
2-wire	*2*	*Adds to measurement*	*±2°C*
3-wire	*3*	*Partially compensated*	*±0.5°C*
4-wire	*4*	*Fully compensated*	*±0.1°C*



NTC Thermistor

NTC THERMISTOR BEHAVIOR

Negative Temperature Coefficient (NTC) thermistors show decreasing resistance with increasing temperature. Exponential relationship provides high sensitivity.

Steinhart-Hart equation: $1/T = A + B(\ln R) + C(\ln R)^3$

Where T is absolute temperature (K) and R is resistance (Ω).

THERMISTOR SELECTION CRITERIA

Prime Parameters:

Parameter	*Typical Range*	*Selection Impact*
Resistance at 25C	*1k Ω to 100k Ω*	*Sets bias current*
Beta value	*3000K to 4500K*	*Determines sensitivity*
Tolerance	*±1% to ±20%*	*Affects calibration needs*
Time constant	*1s to 30s*	*Limits response speed*

Higher resistance values reduce self-heating effects.

Beta value determines temperature coefficient. Interchangeability grades affect replacement costs.

SELF-HEATING CONSIDERATIONS

Measurement current causes internal heating. Power dissipation must remain below thermal limits.

Dissipation constant relates power to temperature rise.

Maximum measurement current:

$$I\_max = \sqrt{(P\_max/R)}$$

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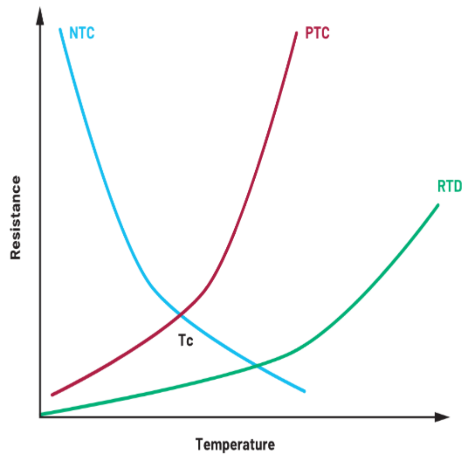


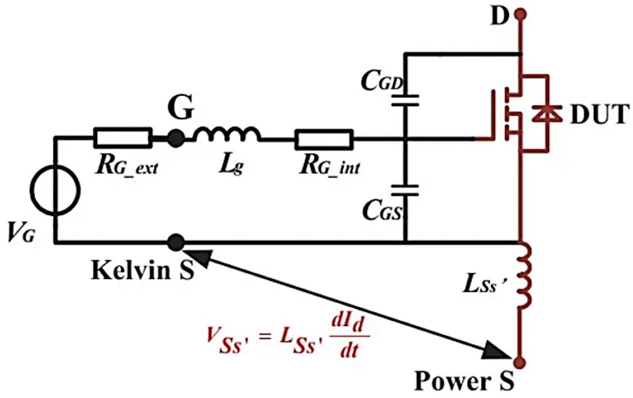
Semiconductor Temperature Sensors

REMOTE TEMPERATURE SENSING

Dedicated remote temperature sensor ICs monitor external diode-connected transistors.

Substrate PNP transistors in processors provide temperature feedback.

Kelvin connections eliminate lead resistance errors.



Applications include:

- CPU thermal management
- Power MOSFET monitoring
- Multi-point temperature sensing
- Thermal gradient measurement

PN JUNCTION TEMPERATURE DEPENDENCE

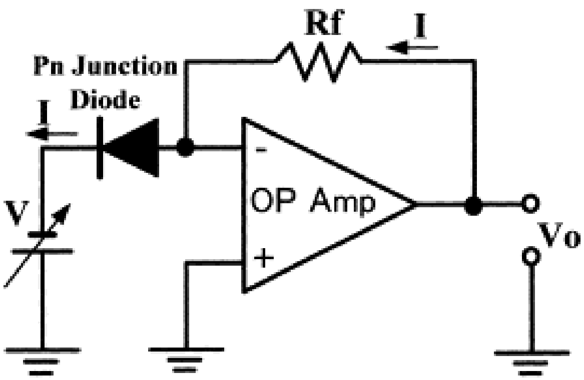
Forward-biased diode voltage decreases linearly with temperature. Silicon junctions show -2mV/°C temperature coefficient. Bandgap references provide stable voltage references.

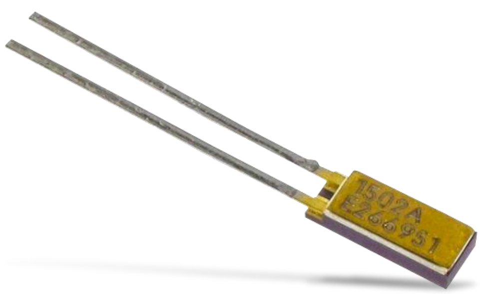
Modern ICs integrate signal conditioning, calibration, and digital interfaces.

Factory calibration eliminates user calibration requirements.

Integrated Temperature Sensor Types:

Output Type	*Resolution*	*Range (°C)*	*Interface*	*Applications*
Analog voltage	*10mV/°C*	*-40 to 125*	*Single wire*	*Simple monitoring*
Digital PWM	*12-bit*	*-55 to 125*	*Single wire*	*Microcontroller*
I²C/SPI	*16-bit*	*-55 to 150*	*2-3 wires*	*Multi-sensor*
1-Wire	*12-bit*	*-55 to 125*	*Single wire*	*Distributed sensing*





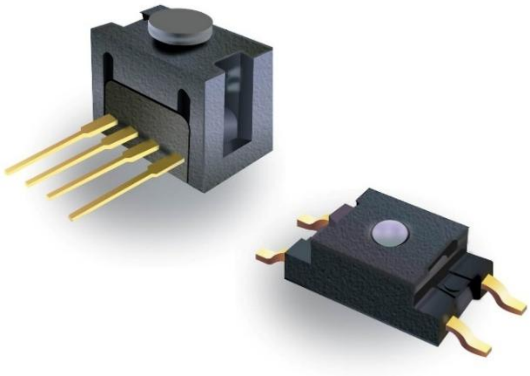
PRESSURE & FORCE SENSORS

PIEZORESISTIVE EFFECT

Mechanical stress changes material resistivity. Gauge factor relates resistance change to strain. Silicon piezo-resistors offer higher sensitivity than metal foil.

Gauge factor equation:

$$GF = (\Delta R/R)/(\Delta L/L)$$



Typical gauge factors:

- Metal foil: 2.0 to 2.5
- Silicon: 50 to 200
- Polysilicon: 10 to 40

STRAIN GAUGE CONFIGURATIONS

Wheatstone bridge circuits convert resistance changes to voltage signals. Quarter-bridge uses single active gauge. Half-bridge uses two active gauges. Full-bridge uses four active gauges.

Configuration	***Active Gauges***	***Temp Compensation***	***Output Sensitivity***
Quarter-bridge	*1*	*External required*	*Low*
Half-bridge	*2*	*Partial*	*Medium*
Full-bridge	*4*	*Complete*	*High*

Full-bridge configuration provides maximum sensitivity and natural temperature compensation.

FORCE MEASUREMENT APPLICATIONS

Load cells convert applied force to electrical signals. Compression, tension, and shear configurations suit different applications. Beam bending creates predictable strain patterns.

Design considerations:

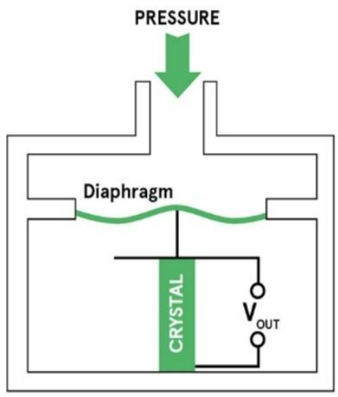
- Maximum load capacity
- Overload protection requirements
- Environmental sealing needs
- Mounting and alignment constraints

Piezoelectric Pressure Sensors

PIEZOELECTRIC MATERIALS

Quartz crystals generate charge when mechanically stressed.

Ceramic materials offer higher sensitivity. Polymer films provide flexibility.



Material	*Charge (pC/N)*	*Applications*
Quartz	*2.3*	*High temperature*
PZT ceramic	*150-400*	*General purpose*
PVDF polymer	*20-30*	*Flexible sensors*

CHARGE AMPLIFIER CIRCUITS

Piezoelectric sensors generate charge, not voltage. High-impedance charge amplifiers convert charge to voltage. Cable capacitance affects sensitivity.

Output voltage:

$$V = Q/C\_feedback$$

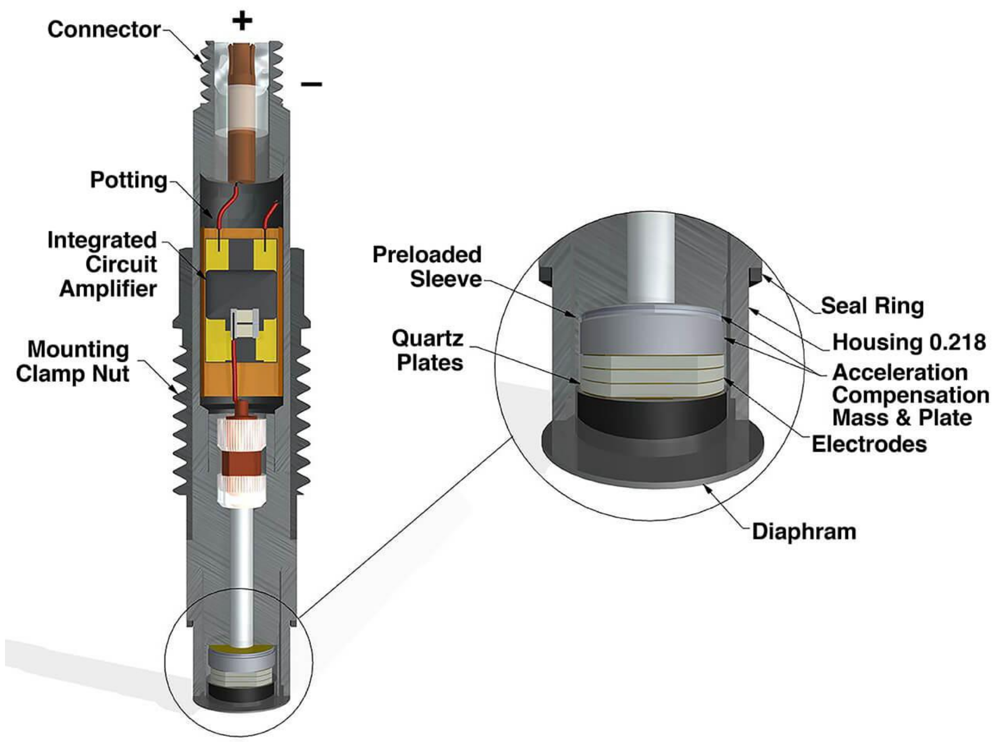
Where Q is generated charge and C_feedback is amplifier feedback capacitance.

DYNAMIC PRESSURE MEASUREMENT

Piezoelectric sensors excel at dynamic measurements. AC coupling eliminates static pressure effects. Frequency response extends from mHz to MHz.

Applications include:

- Engine knock detection
- Acoustic pressure monitoring
- Vibration analysis
- Impact force measurement



Capacitive Pressure Sensors

VARIABLE CAPACITANCE PRINCIPLES

Diaphragm deflection changes electrode spacing. Capacitance varies inversely with gap distance. Differential structures improve linearity.

Parallel plate capacitance:

$$C = \varepsilon_0 \varepsilon_r A/d$$

Where A is electrode area and d is gap spacing.

MEMS CAPACITIVE IMPLEMENTATION

Silicon micromachining creates precise structures. Sealed reference cavities enable absolute pressure measurement. Differential pressure measurement compares two pressures.

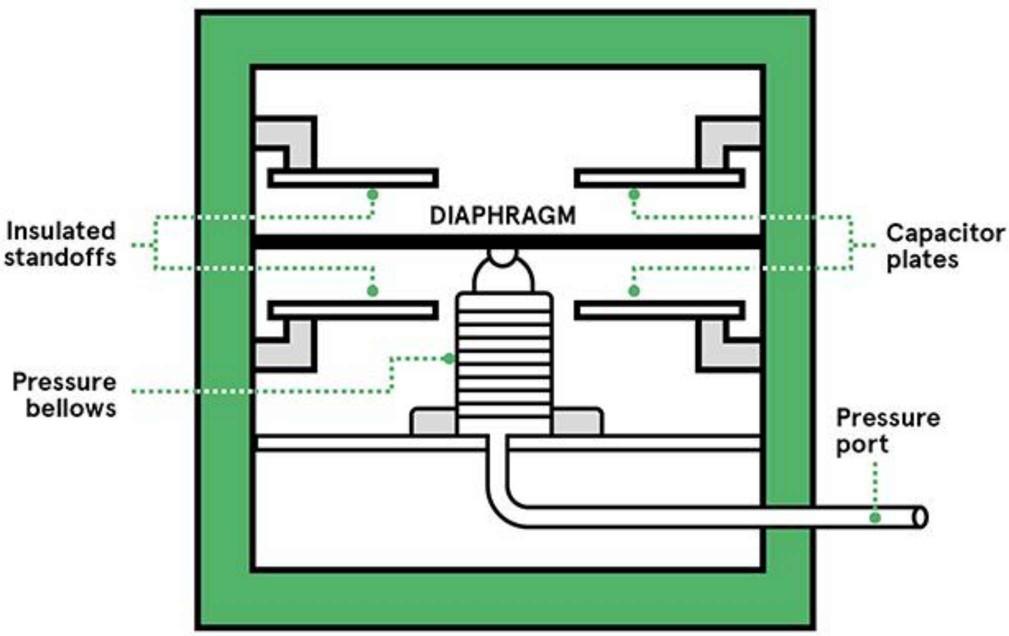
Pressure Type	***Reference***	***Applications***
Absolute	*Vacuum cavity*	*Altitude, weather*
Gauge	*Atmospheric*	*Tire pressure, HVAC*
Differential	*Second port*	*Flow, filter monitoring*

CAPACITANCE-TO-DIGITAL CONVERSION

Switched-capacitor circuits measure capacitance changes. Charge redistribution methods provide high resolution. Sigma-delta ADCs offer excellent noise performance.

Modern pressure sensor ICs integrate:

- MEMS sensing element
- Capacitance measurement circuit
- Temperature compensation
- Digital signal processing
- Calibrated output interface



POSITION SENSORS

Linear and Rotary Encoders

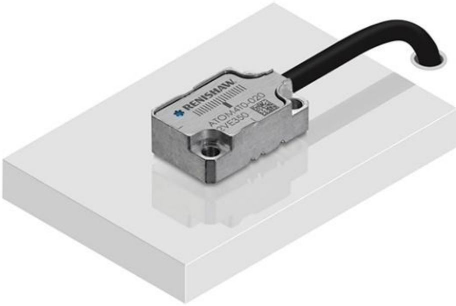
OPTICAL ENCODER TECHNOLOGY

Optical encoders use light interruption to detect motion. Code disks contain alternating transparent and opaque segments. Photodetectors convert light patterns to electrical pulses.

Resolution calculation: PPR = 2^n for n-bit absolute encoders

Incremental encoders provide:

- A channel: position pulses
- B channel: direction indication (90° phase shift)
- Z channel: once-per-revolution index



ABSOLUTE VS INCREMENTAL ENCODING

Type	*Output*	*Power Loss Recovery*	*Wiring*
Incremental	*Pulse train*	*Requires homing*	*3-5 wires*
Absolute	*Position code*	*Immediate*	*8+ wires*
Multi-turn absolute	*Position + turns*	*Complete recovery*	*Serial bus*

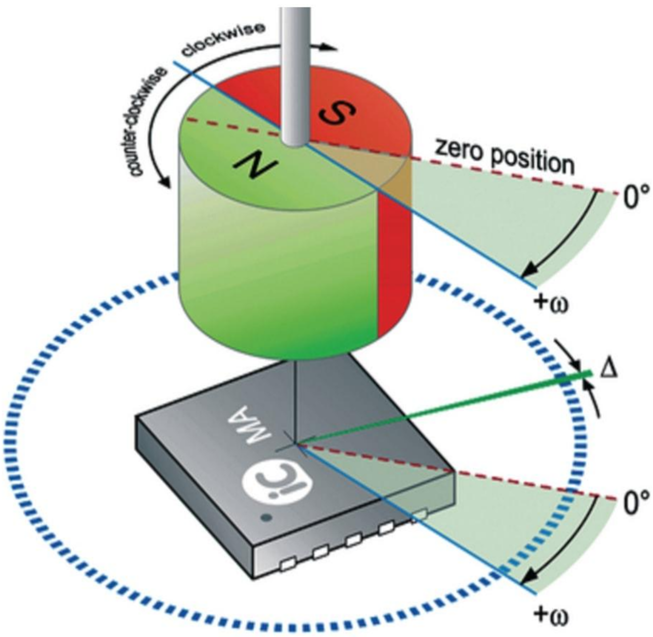
Incremental encoders suit continuous motion applications. Absolute encoders eliminate homing sequences. Multi-turn encoders track complete position history.

MAGNETIC ENCODER IMPLEMENTATION

Magnetic encoders detect magnetic field variations. Hall effect sensors respond to field strength changes. Magneto-resistive sensors detect field direction changes.

Advantages over optical:

- No optical alignment required
- Immune to contamination
- Operates in harsh environments
- Lower power consumption



Hall Effect Position Sensors

HALL EFFECT PHYSICS

Moving charges in magnetic fields experience Lorentz force. Hall voltage develops perpendicular to current and field. Voltage magnitude indicates field strength.

Hall voltage:

$$V\_H = (K\_H \times I \times B)/t$$

Where K_H is Hall coefficient, I is current, B is magnetic field, and t is thickness.

HALL SENSOR APPLICATIONS

Hall Sensors Types:

Sensor Type	***Output***	***Magnetic Field***	***Applications***
Digital switch	*On/off*	*10-100 gauss*	*Proximity detection*
Linear analog	*Proportional voltage*	*0-1000 gauss*	*Position measurement*
Programmable	*User-defined*	*Variable range*	*Custom applications*

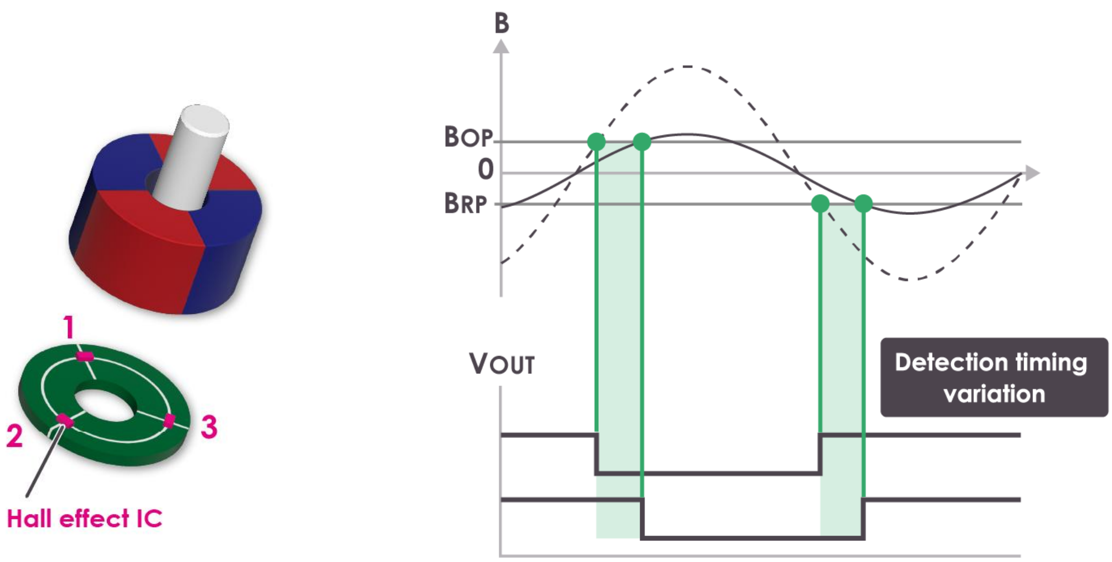
Digital Hall switches provide clean switching action. Linear Hall sensors enable continuous position measurement. Programmable versions offer application-specific optimization.

POSITION SENSING CONFIGURATIONS

Linear position measurement uses sliding magnet arrangements. Rotary position detection employs rotating magnetic assemblies. Multi-pole magnets increase resolution.

Design considerations:

- Magnet selection and placement
- Temperature coefficient matching
- Mechanical tolerance sensitivity
- EMI immunity requirements



Magnetoresistive Sensors

AMR TECHNOLOGY

Anisotropic Magnetoresistance (AMR) sensors detect magnetic field direction. Resistance changes with field orientation. Barber pole biasing improves linearity.

AMR sensors offer:

- High sensitivity (1 mV/V/gauss)
- Low power operation
- Wide frequency response
- Excellent temperature stability

TMR AND GMR TECHNOLOGIES

Tunneling Magnetoresistance (TMR) provides highest sensitivity. Giant Magnetoresistance (GMR) offers good performance at lower cost.

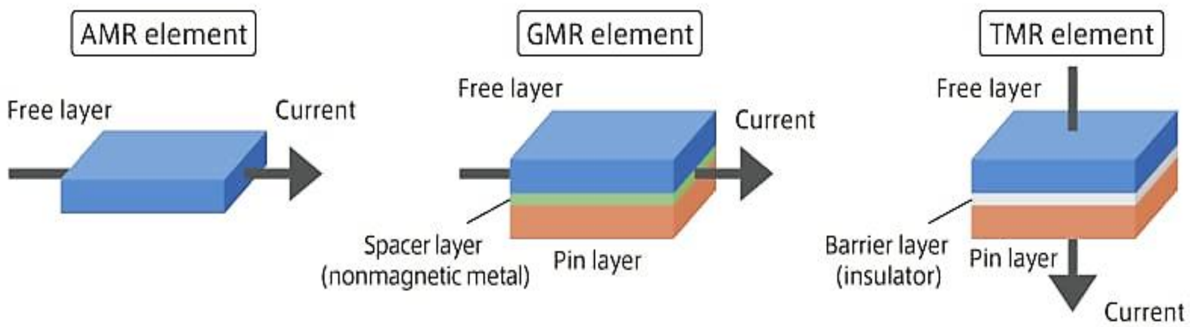
Technology	***Sensitivity***	***Power***	***Applications***
AMR	*Good*	*Low*	*Compass, position*
GMR	*Better*	*Medium*	*Hard disk heads*
TMR	*Best*	*High*	*Precision measurement*

ANGULAR POSITION MEASUREMENT

Magnetic encoders using magneto-resistive sensors achieve high resolution. Sin/cos output enables interpolation between poles. Arctangent calculation provides absolute angle.

Resolution enhancement techniques:

- Electronic interpolation
- Multi-pole magnet rings
- Differential sensing arrangements
- Temperature compensation algorithms



MOTION SENSORS

MEMS Accelerometer Technology

CAPACITIVE MEMS PRINCIPLES

MEMS accelerometers use suspended proof masses.

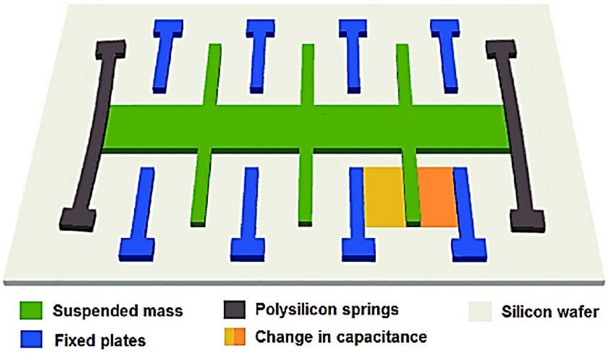
Acceleration causes mass displacement.

Capacitance change indicates acceleration magnitude.

Basic equation:

$$F = ma = kx$$

Where k is spring constant and x is displacement.



Accelerometer Specifications:

Parameter	*Typical Range*	*Selection Impact*
Full scale range	*±2g to ±400g*	*Application requirements*
Sensitivity	*16 to 16384 LSB/g*	*Resolution needs*
Bandwidth	*1 Hz to 5 kHz*	*Dynamic response*
Noise density	*25 to 400 μ g/ $\sqrt{}$Hz*	*Precision applications*

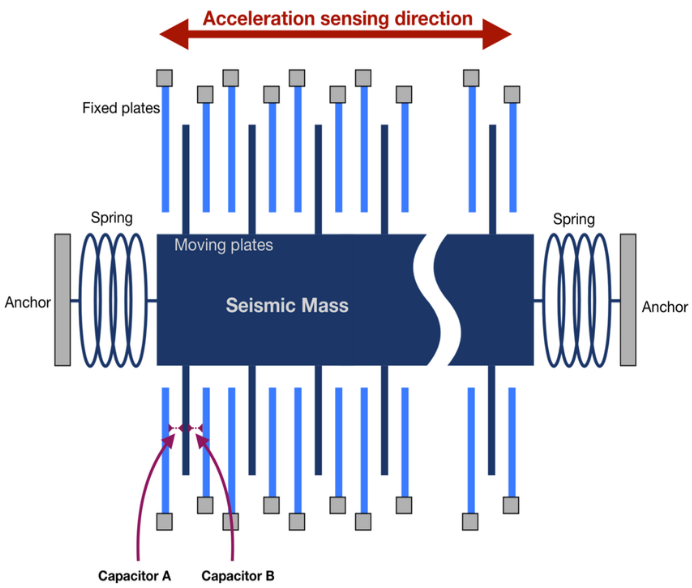
Consumer applications use ±2g to ±16g ranges. Industrial applications may require ±100g or higher. Shock sensors need ±1000g capability.

MULTI-AXIS INTEGRATION

Single-chip solutions integrate X, Y, and Z sensing. Orthogonal placement ensures axis alignment. Factory calibration corrects sensitivity and offset errors.

Tri-axis accelerometers provide:

- Complete motion vector measurement
- Tilt angle calculation capability
- Vibration analysis in all directions
- Compact PCB footprint



Gyroscope Technology

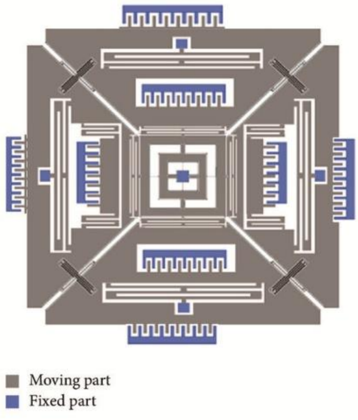
CORIOLIS EFFECT SENSING

MEMS gyroscopes detect Coriolis forces. Vibrating proof masses experience perpendicular forces during rotation. Capacitive sensing measures Coriolis-induced motion.

Coriolis force:

$$F\_c = 2m(\Omega \times v)$$

Where m is mass, Ω is angular velocity, and v is velocity vector.



GYROSCOPE PERFORMANCE PARAMETERS

Angular rate measurement accuracy depends on:

- Scale factor stability
- Bias drift characteristics
- Noise performance
- Temperature coefficient

Grade	*Stability (°/hr)*	*Applications*
Consumer	*10-100*	*Gaming, phones*
Industrial	*1-10*	*Robotics, drones*
Tactical	*0.1-1*	*Navigation aids*
Navigation	*<0.01*	*Inertial navigation*

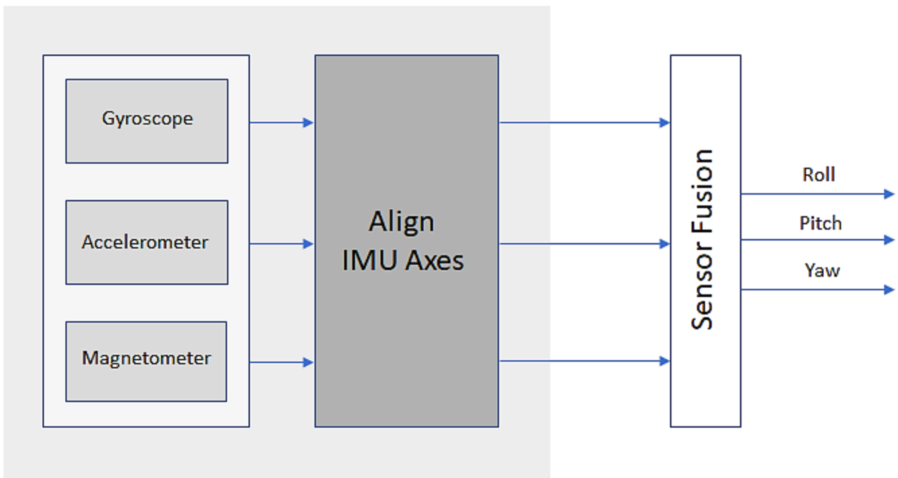
IMU INTEGRATION

Inertial Measurement Units combine accelerometers and gyroscopes. Six degrees of freedom provide complete motion sensing. Nine-axis IMUs add magnetometers for heading reference.

Sensor fusion algorithms combine measurements:

- Complementary filters for basic fusion
- Kalman filters for optimal estimation
- Quaternion mathematics for rotation
- Dead reckoning for position tracking

IMU Model



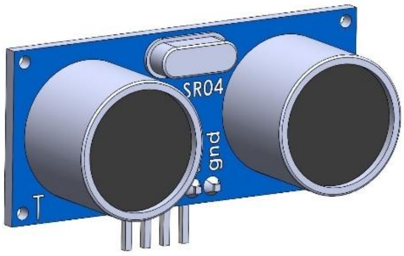
PROXIMITY SENSORS

Ultrasonic Distance Measurement

TIME-OF-FLIGHT PRINCIPLES

Ultrasonic sensors emit high-frequency sound pulses. Echo return time indicates target distance. Speed of sound varies depending on temperature and humidity.

Distance calculation:



$$d = (c \times t)/2$$

Where c is sound speed and t is round-trip time.

ULTRASONIC TRANSDUCER

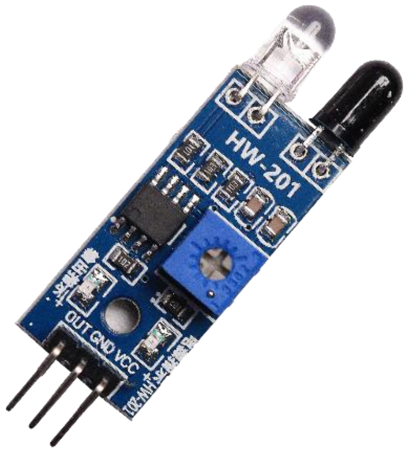
Transducer types:

Frequency	*Range*	*Resolution*	*Applications*
40 kHz	*2 cm to 4 m*	*±1 cm*	*General ranging*
200 kHz	*2 cm to 1 m*	*±2 mm*	*Precision measurement*
1 MHz	*1 mm to 10 cm*	*±0.1 mm*	*Thickness gauging*

Lower frequencies penetrate farther but offer less resolution. Higher frequencies provide better resolution but limited range.

Infrared Proximity Sensors

ACTIVE IR DISTANCE MEASUREMENT



IR LED emits modulated light. Photodiode receives reflected signal.

Triangulation or time-of-flight methods determine distance.

Triangulation advantages:

- Independent of target reflectivity
- Fast response time
- No ambient light interference
- Compact sensor design

PASSIVE IR DETECTION

PIR sensors detect thermal radiation changes. Fresnel lenses focus IR energy. Differential pyroelectric elements cancel common signals.

PIR sensor characteristics:

- Detection range: 3-12m
- Field of view: 90° to 120°
- Response time: 100-1000ms
- Power consumption: <100μA

OPTICAL DESIGN CONSIDERATIONS

Lens selection affects detection pattern. Multi-element lenses create multiple zones. Sensitivity varies with target temperature difference.

Design factors include:

- Fresnel lens focal length
- Pyroelectric element size
- Amplifier gain settings
- Environmental housing design

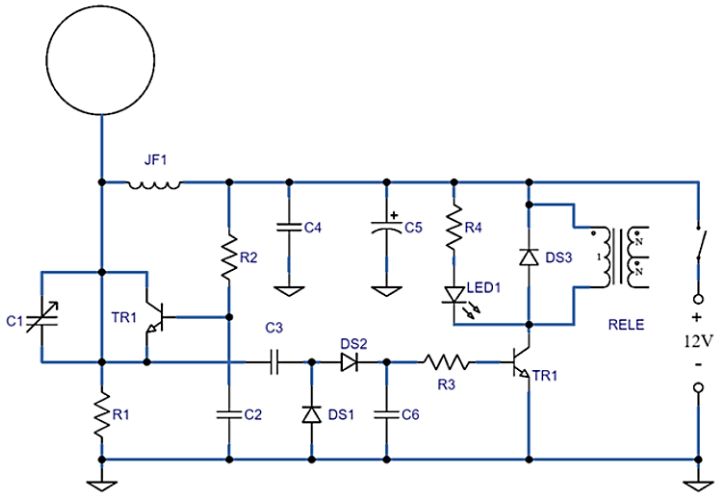
Capacitive Proximity Sensing

ELECTRIC FIELD SENSING

Capacitive sensors detect dielectric constant changes. Oscillator frequency changes with target proximity. Metal and non-metal targets both detectable.

Sensing range depends on:

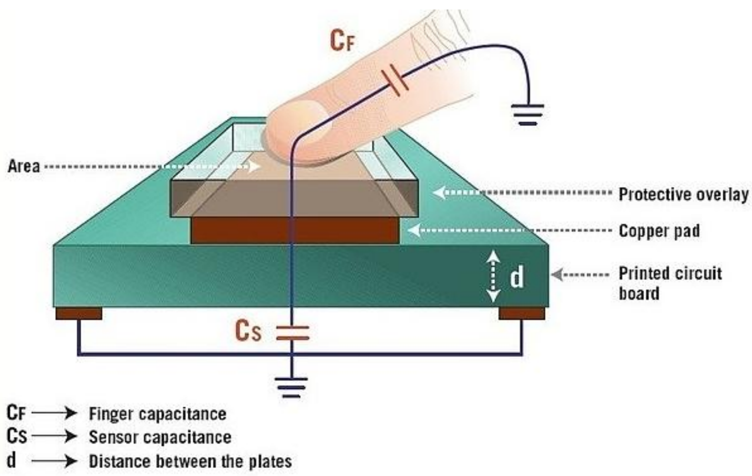
- Target dielectric constant
- Target size and shape
- Environmental conditions
- Sensor design parameters



TOUCH SENSING APPLICATIONS

Capacitive touch sensors detect finger proximity. Self-capacitance measures electrode-to-ground capacitance. Mutual capacitance measures electrode-to-electrode coupling.

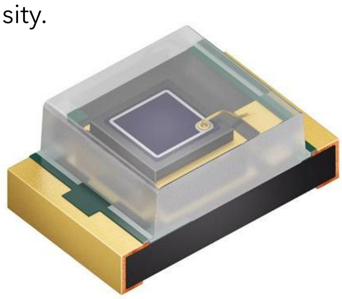
Method	***Advantages***	***Disadvantages***
Self-capacitance	*Simple design*	*Ghost touches*
Mutual capacitance	*True multi-touch*	*Complex routing*
Projected capacitance	*Through glass*	*Expensive*



OPTICAL SENSORS

Photodiode Technology

Photodiodes convert light energy to electrical current. Photons generate electron-hole pairs in semiconductor junctions. Current magnitude proportional to incident light intensity.



Photocurrent equation:

$$I\_ph = R \times \Phi$$

Where R is responsivity (A/W) and Φ is optical power (W).

PHOTODIODE CHARACTERISTICS

Photodiode types:

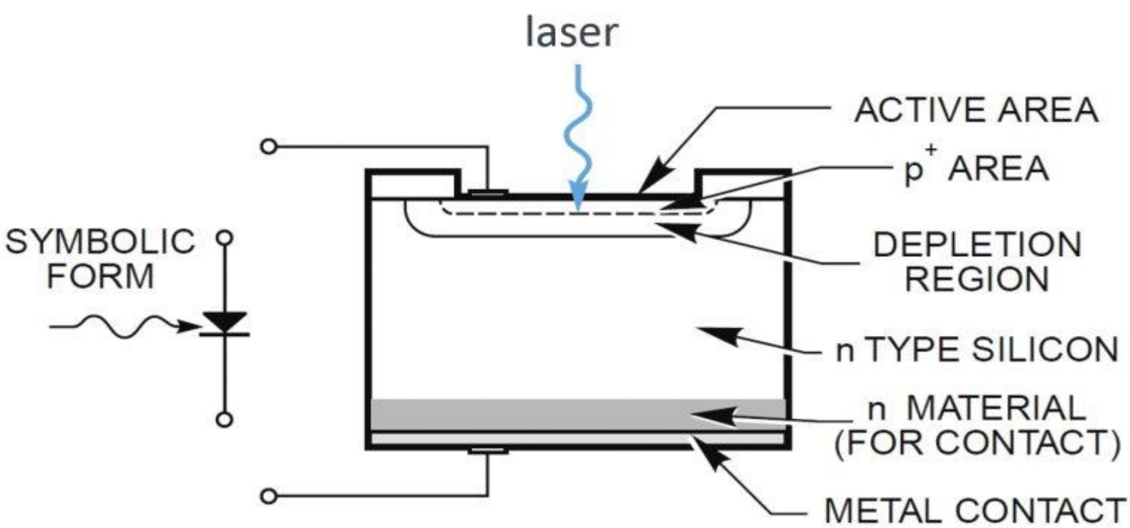
Type	Spectral Range (nm)	Responsivity (A/W)	Applications
Silicon	400-1100	0.4-0.6	Visible light
InGaAs	900-1700	0.8-1.0	Near infrared
Germanium	800-1800	0.5-0.7	IR communication
GaAsP	300-650	0.15-0.25	UV detection

Silicon photodiodes dominate visible applications. InGaAs sensors suit fiber optic communications. Germanium offers extended IR response.

OPERATING MODES

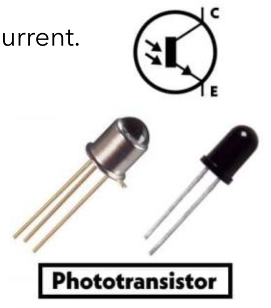
Photovoltaic mode generates voltage without bias. Photoconductive mode requires reverse bias for faster response. Dark current increases with reverse voltage.

Mode	Bias	Response Speed	Noise	Applications
Photovoltaic	0V	Slow (μs)	Low	Solar cells, meters
Photoconductive	Reverse	Fast (ns)	Higher	Communications



Phototransistor Applications

CURRENT AMPLIFICATION



Phototransistors provide internal current gain. Base photocurrent controls collector current.

Gain typically 100-1000× photodiode current.

Collector current:

$$I\_c = \beta \times I\_ph$$

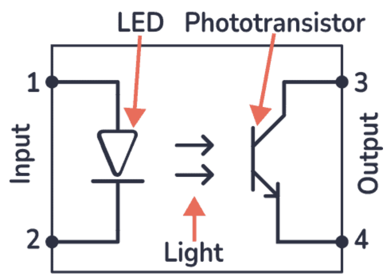
Where β is current gain and I_ph is photocurrent.

OPTOCOUPLER INTEGRATION

Optocouplers isolate electrical circuits. LED illuminates phototransistor across isolation barrier. Common-mode rejection exceeds 10kV.

Applications include:

- Power supply feedback isolation
- Digital signal isolation
- Motor drive protection
- Medical equipment safety



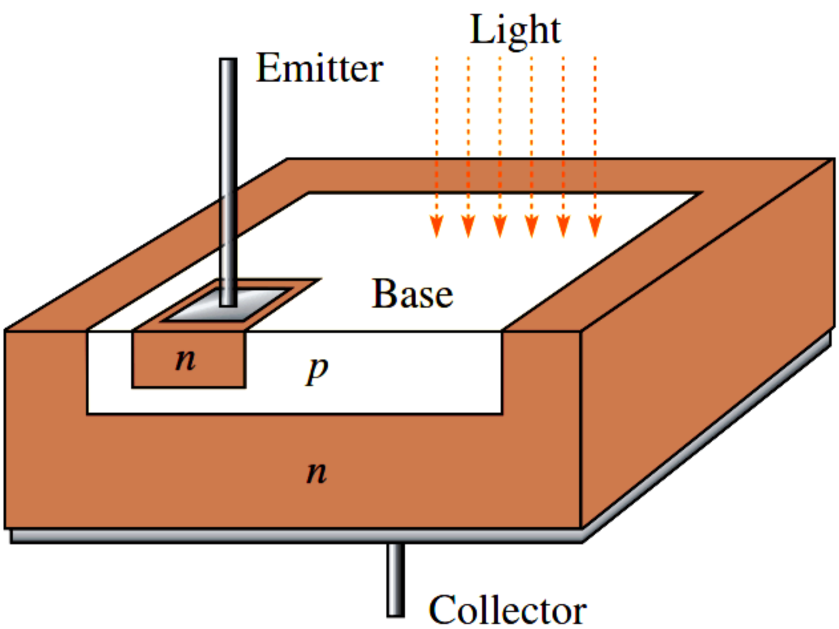
PERFORMANCE LIMITATIONS

Phototransistors exhibit slower response than photodiodes. Bandwidth typically limited to 100kHz.

Temperature affects gain characteristics significantly.

Design considerations:

- Load resistor selection affects speed
- Temperature compensation requirements
- Optical coupling efficiency
- Package light transmission



CCD and CMOS Image Sensors

PIXEL ARCHITECTURE

Image sensors contain arrays of photo detectors. Each pixel accumulates charge proportional to light intensity. Readout circuits convert charge to voltage.

Pixel specifications:

- Size: 1.4μm to 10μm pitch
- Full well capacity: 10,000 to 100,000 electrons
- Dark current: 1-100 electrons/second
- Quantum efficiency: 30-90%

CCD VS CMOS

Comparison:

Parameter	CCD	CMOS	Selection Criteria
Image quality	*Excellent*	*Good*	*Scientific vs consumer*
Power consumption	*High*	*Low*	*Battery applications*
Speed	*Medium*	*High*	*Video frame rates*
Cost	*High*	*Low*	*Volume production*
Integration	*Limited*	*High*	*System-on-chip*

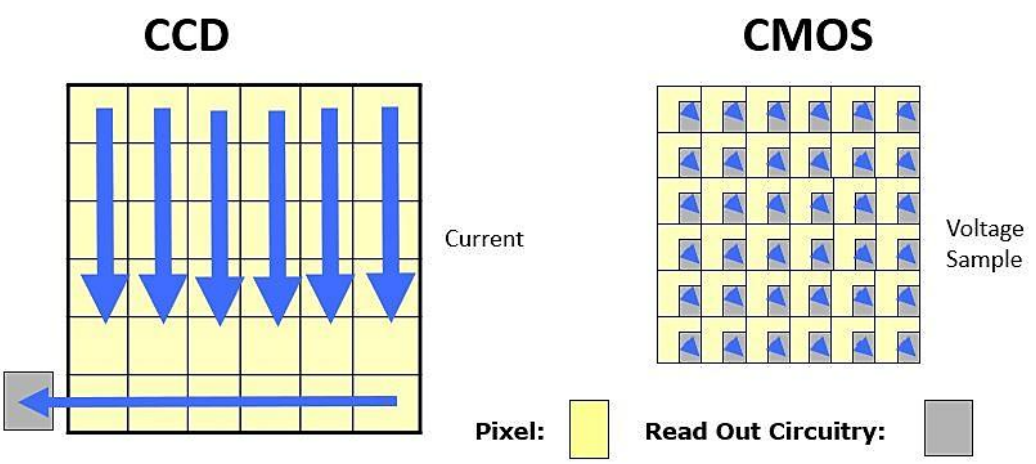
CMOS sensors dominate consumer applications. CCDs remain preferred for scientific imaging. Specialized applications may require either technology.

INTERFACE CONSIDERATIONS

Parallel interfaces provide maximum bandwidth. Serial interfaces reduce pin count. MIPI CSI-2 standard dominates mobile applications.

Common interfaces:

- 8/10/12-bit parallel
- I²C control + data
- SPI with separate data
- MIPI CSI-2 differential serial



Ambient Light Sensors

HUMAN EYE RESPONSE MATCHING

Ambient light sensors approximate human vision sensitivity. Photopic response peaks at 555nm (green). Scotopic response peaks at 507nm (blue-green).

Standard illuminants define measurement references:

- CIE Illuminant A: Tungsten (2856K)
- CIE Illuminant D65: Daylight (6504K)
- CIE Illuminant F2: Fluorescent (4230K)

LUX MEASUREMENT

Lux quantifies illumination intensity. One lux equals one lumen per square meter. Sensors convert optical power to lux-equivalent output.

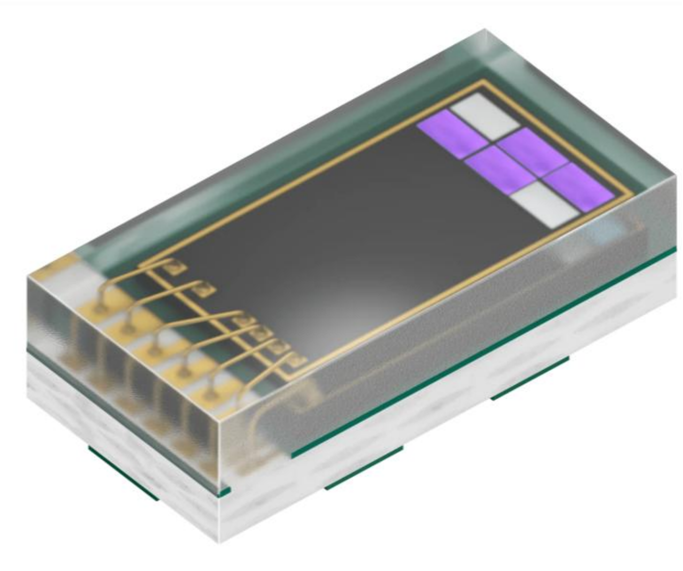
Environment	***Typical Lux***	***Sensor Range***
Starlight	*0.0001*	*0.01-100*
Moonlight	*0.25*	*0.1-1000*
Indoor office	*320-500*	*1-10000*
Bright sunlight	*100000*	*1000-100000*

DISPLAY BACKLIGHT CONTROL

Automatic brightness control saves battery power. Light sensor feedback adjusts display intensity. Hysteresis prevents oscillation.

Implementation considerations:

- Sensor placement relative to display
- IR rejection filter requirements
- Response time for user comfort
- Power management integration



CURRENT SENSORS

Hall Effect Current Sensing

MAGNETIC FIELD CONCENTRATION

Current-carrying conductors generate magnetic fields. Ferromagnetic cores concentrate fields for measurement. Air gaps allow Hall sensor insertion.

Ampere's law:

$$\oint B \cdot dl = \mu_0 I$$

Core design concentrates field at sensor location while minimizing reluctance variations.

CURRENT SENSOR TOPOLOGIES

Type	*Isolation*	*Bandwidth*	*Accuracy*
Open loop	*Yes*	*DC-100kHz*	*±1-3%*
Closed loop	*Yes*	*DC-200kHz*	*±0.2-1%*
Coreless	*Yes*	*DC-1MHz*	*±1-5%*

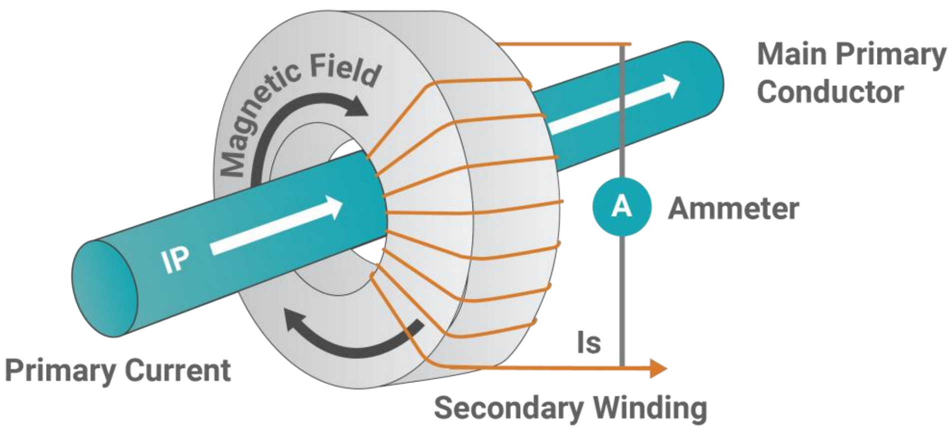
Closed-loop sensors use feedback windings for improved accuracy. Open-loop designs offer lower cost. Coreless sensors integrate easily on PCBs.

CURRENT SENSOR SELECTION

Primary current rating determines core size. Bandwidth requirements affect sensor choice. Isolation voltage rating impacts safety compliance.

Design parameters:

- Primary current range
- Secondary circuit isolation
- Frequency response requirements
- Temperature coefficient limits
- Physical size constraints



Current Transformer Technology

TRANSFORMER PRINCIPLES

Current transformers operate on electromagnetic induction. Primary current creates magnetic flux. Secondary winding generates proportional current.

Turns ratio:

$$I\_p/I\_s = N\_s/N\_p$$

Where I_p, I_s are primary/secondary currents and N_p, N_s are turns.

BURDEN RESISTOR SELECTION

Secondary current flows through burden resistor. Voltage drop must not saturate core. Burden resistance affects accuracy and phase angle.

Burden power:

$$P = I\_s^2 \times R\_burden$$

Standard burden resistances: 2.5Ω, 5Ω, 15Ω, 30Ω for different current ranges.

ACCURACY CLASSES

Current transformer accuracy depends on burden and frequency. IEEE and IEC standards define accuracy classes. Metering applications require higher accuracy than protection.

Accuracy Class	***Error Limit***	***Applications***
0.1	*±0.1%*	*Revenue metering*
0.2	*±0.2%*	*Precision measurement*
0.5	*±0.5%*	*General metering*
1.0	*±1.0%*	*Industrial monitoring*

Fluxgate Magnetometer

MAGNETIC SATURATION PRINCIPLES

Fluxgate sensors use periodic core saturation. Drive coil alternately saturates ferromagnetic core. External fields shift saturation timing.

Output signal contains second harmonic component proportional to measured field. Synchronous detection extracts field information.

SENSOR CONSTRUCTION

Ring core construction provides high sensitivity. Toroidal geometry minimizes external field effects. Drive and sense windings must maintain orthogonality.

Performance characteristics:

- Resolution: 0.1nT typical
- Range: ±100μT standard
- Bandwidth: DC to 1kHz
- Temperature stability: 0.1nT/°C

COMPASS APPLICATIONS

Three-axis fluxgate arrays measure Earth's magnetic field. Digital signal processing calculates heading angle. Tilt compensation corrects for sensor orientation.

Compass accuracy factors:

- Local magnetic declination
- Hard iron calibration
- Soft iron compensation
- Temperature coefficient correction
    -