Designing Interface Electronics for Smart Sensors

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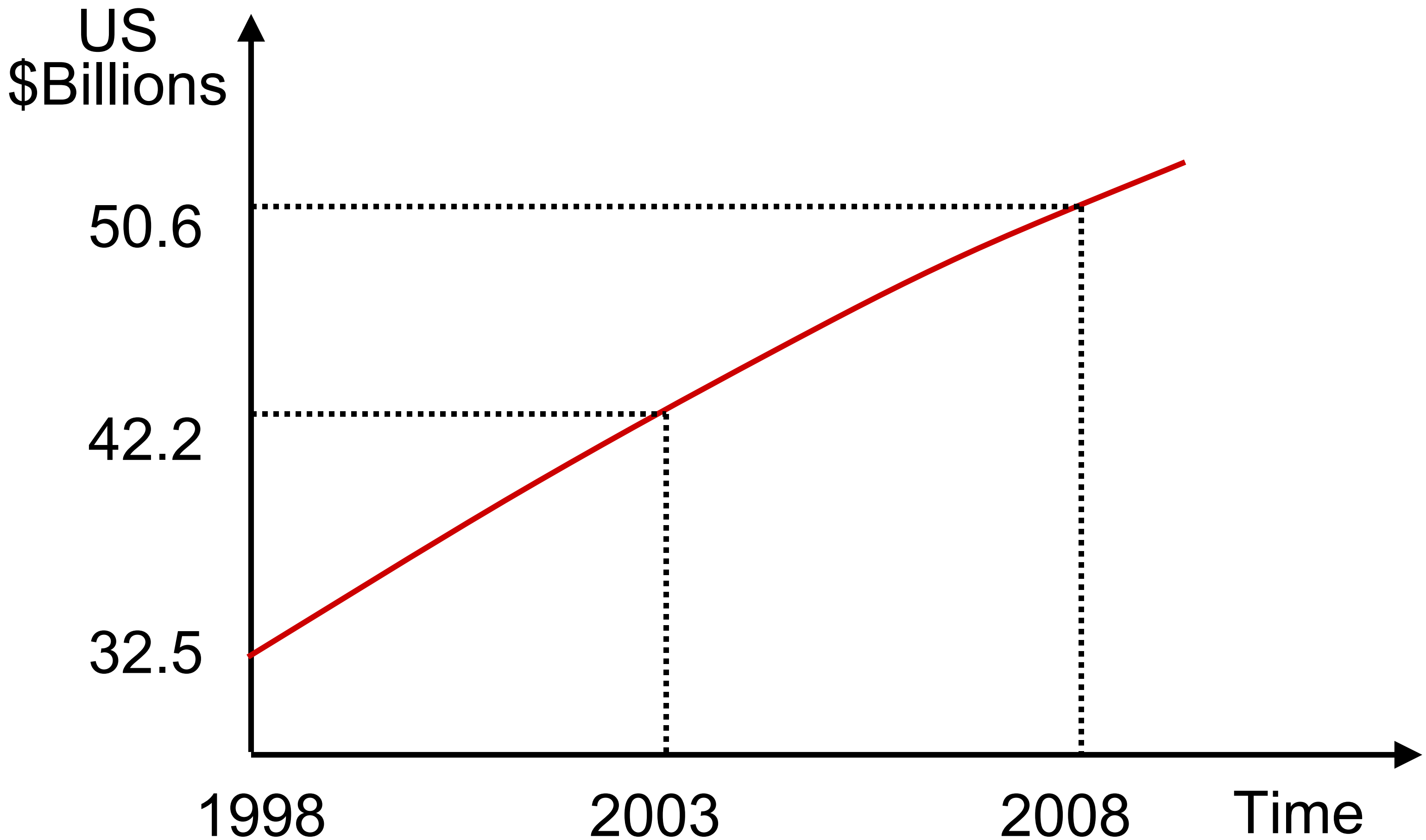
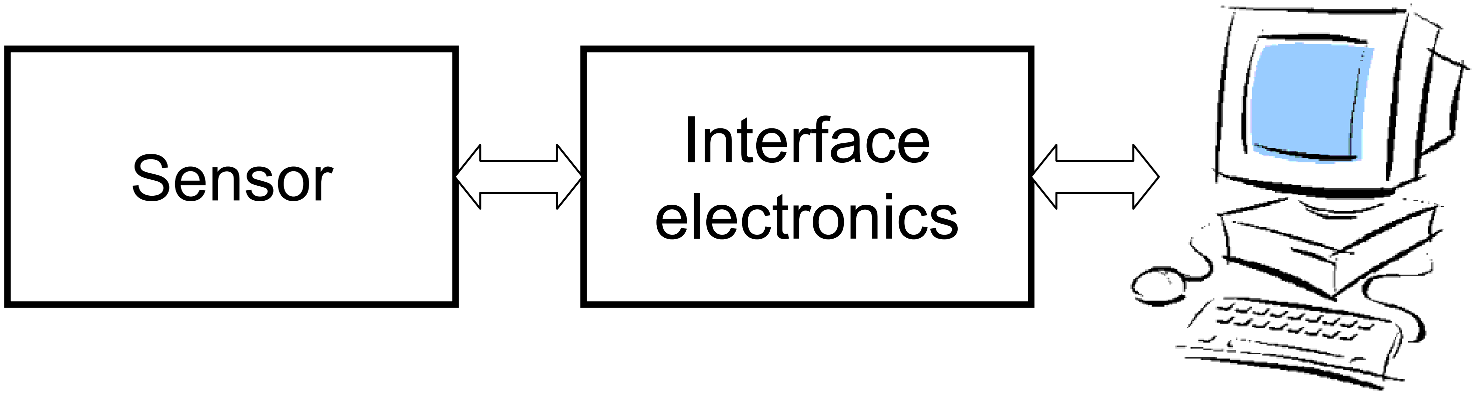
Sensors are Everywhere!

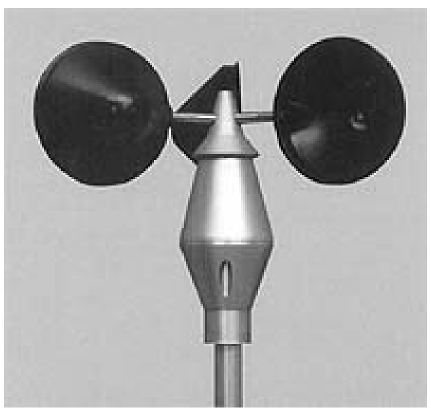
World Sensor Market

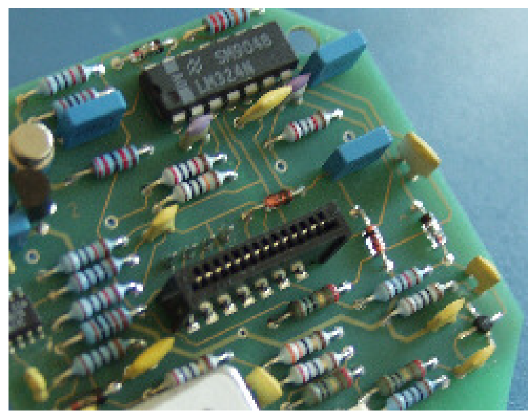


Courtesy of InTechno Consulting

Traditional Sensor Systems

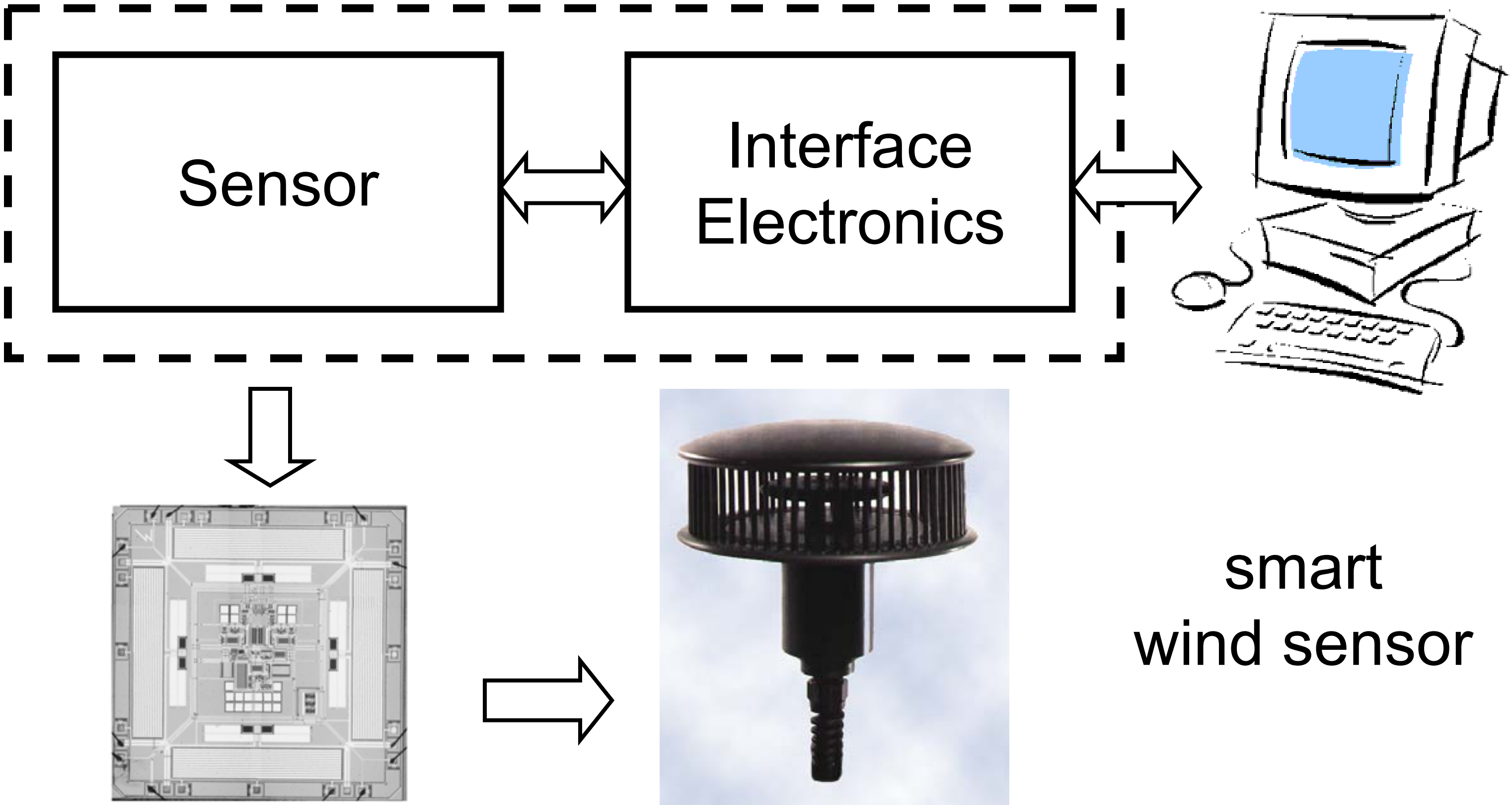






traditional wind sensor

Smart Sensors



- Sensor + Interface electronics in **one** package
- Robust microprocessor compatible interface

Silicon Sensors

Silicon sensors cover the following domains:

- Thermal $\Rightarrow$ resistors, transistors & thermopiles
- Magnetic $\Rightarrow$ Hall-plates & magFETs
- Optical $\Rightarrow$ photo-diodes
- Chemical $\Rightarrow$ ISFETs
- Electrical $\Rightarrow$ resistors, capacitors & inductors
- Mechanical (requires micro-machining!)
  $\Rightarrow$ moveable proof mass or diaphragm

Silicon is a versatile material!

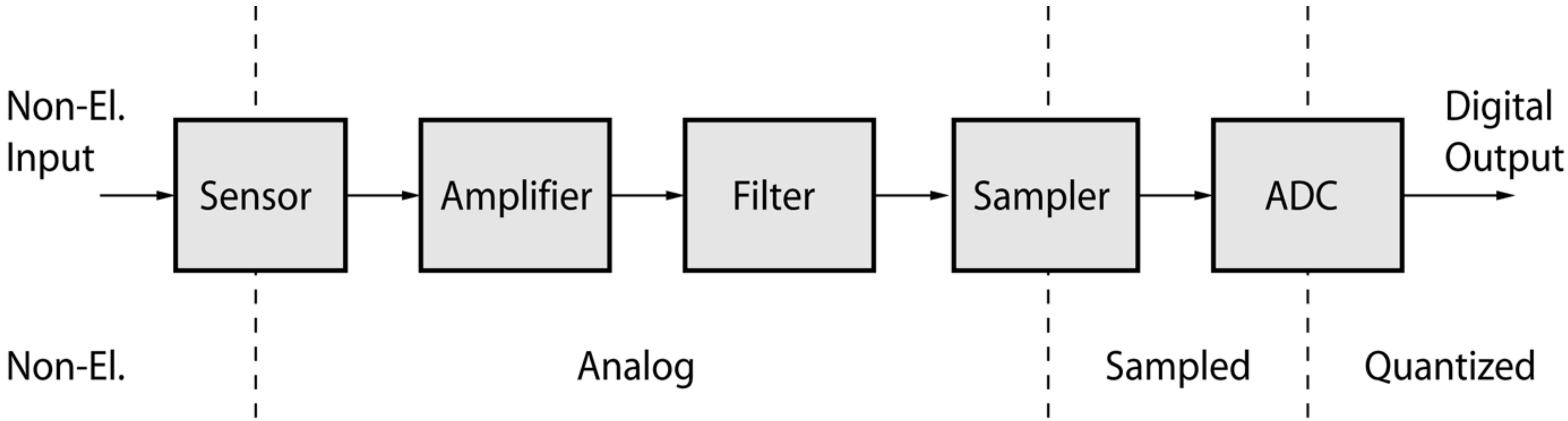
Interface Electronics?

- Term refers to ***electronic circuits*** that connect ***sensors*** to ***computers***.

Implements the following functions

- sensor excitation\powering
- signal conditioning
- analog-to-digital conversion
- Facilitates calibration and compensation
- (Standard) interfaces to the outside world

Signal Processing Chain



- Amplifier boosts weak sensor signals
- Filter rejects interference, noise and aliases
- ADC converts sensor signal to a digital format
- Tolerances add up $\Rightarrow$ system calibration and trimming

Typical Sensor Characteristics

In general, sensors

- Output a **variety** of **small** analog quantities: microvolts (Hall sensors, thermopiles), microamps (photodiodes), atto-farads (inertial sensors)
- Are relatively **slow** – at least compared to the switching speed of transistors

In addition, silicon sensors

- Are sensitive to **process spread**, **temperature** & (packaging) **stress**
- Are rather average as sensors go, so good system performance ⇒ good interface electronics

Interface Design Methodology (1)

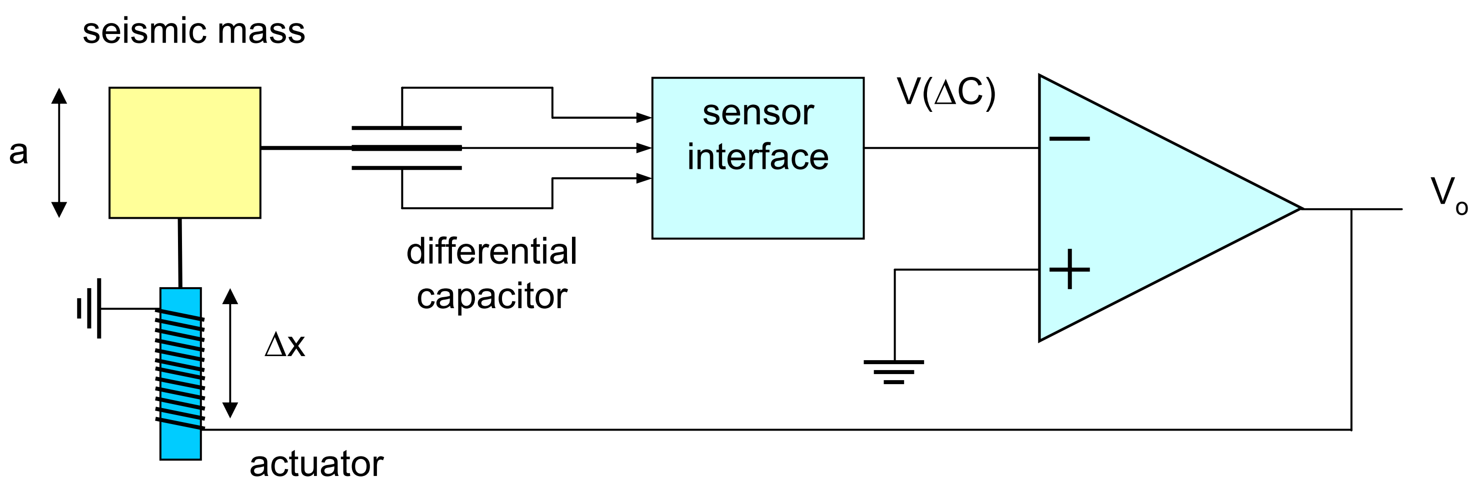
Do no harm!

- Interface electronics should be <u>transparent</u> i.e. should not impair **sensor** performance
- An error budget for key specs should be made : resolution, accuracy, bandwidth, dynamic range etc

Interface Design Methodology (2)

Do system design!

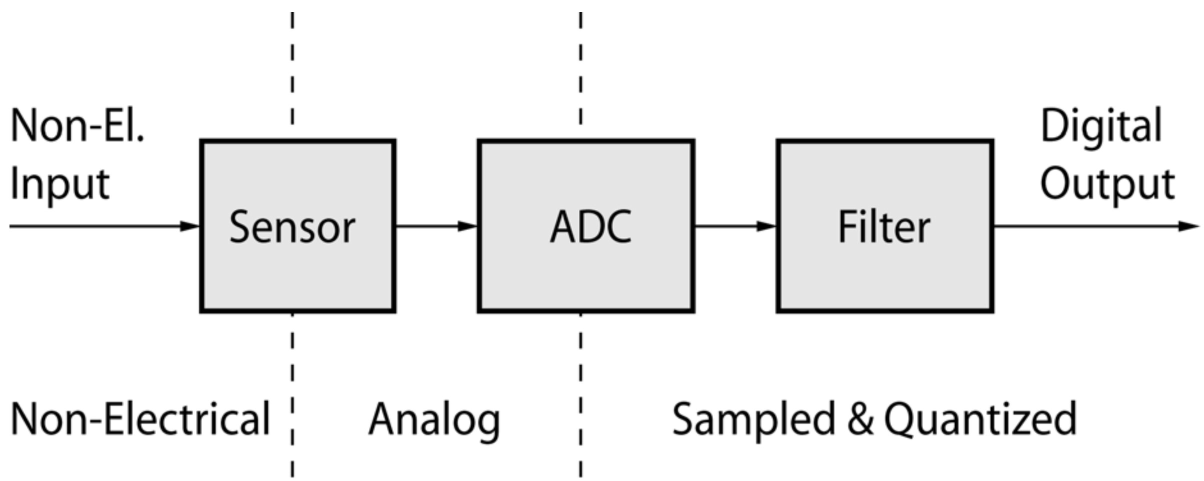
- Regard the combination of sensor and interface electronics as **one** system
- Appropriate biasing may compensate for non-idealities e.g. force feedback improves accelerometer linearity



Interface Design Methodology (3)

Digitize early!

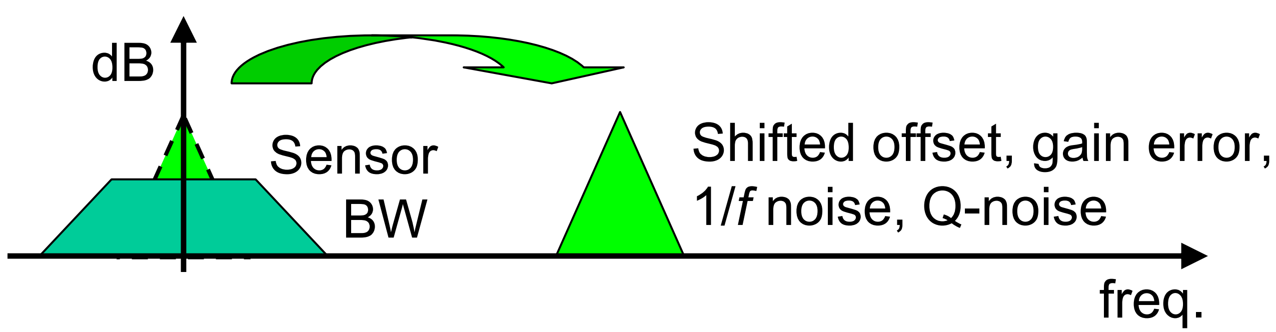
- Analog signal processing is sensitive to process spread (but power efficient at low resolution)
- Digital signal processing is accurate, flexible and increasingly cheap (Moore's Law)
- High resolution ΣΔ ADCs bridge the gap!



Interface Design Methodology (4)

Be dynamic!

- Slow sensors ⇒ dynamic techniques can be used to mitigate analog errors
- Gain errors ⇒ Dynamic element matching (DEM)
- Offset and 1/f noise ⇒ auto-zeroing, chopping
- Quantization noise ⇒ ΣΔ modulation

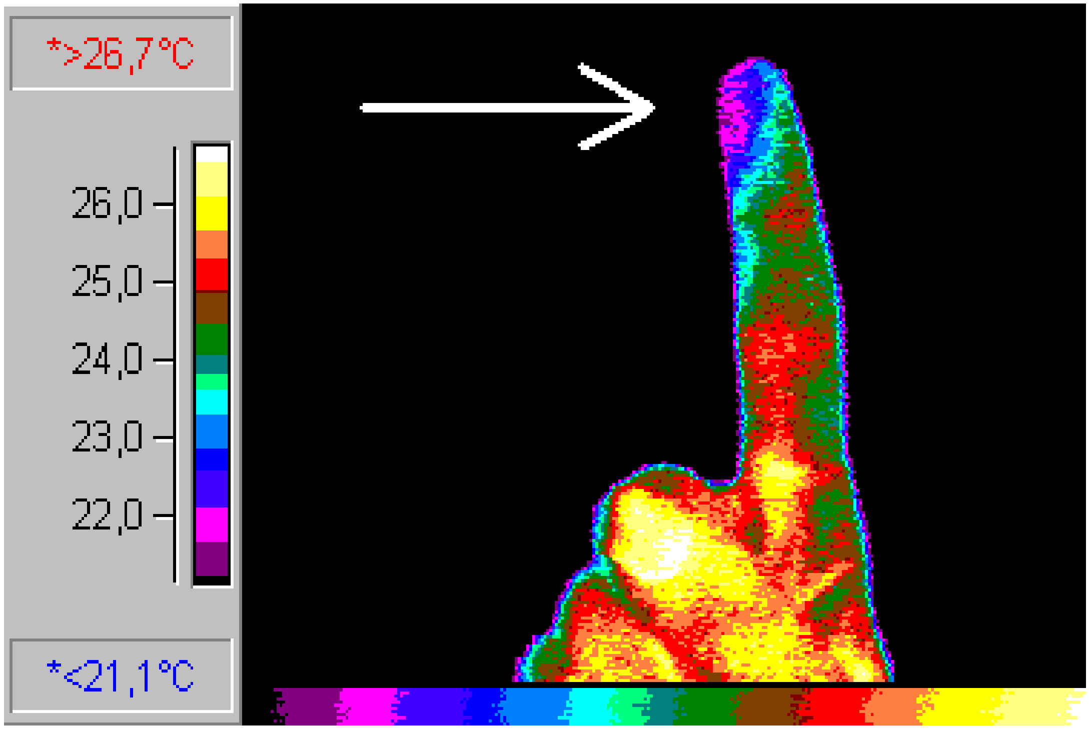


Interface Design Methodology

1. Do no harm!
2. Do system design!
3. Digitize early!
4. Be dynamic!

Three case studies: a smart wind sensor, a smart Hall-effect sensor and a smart temperature sensor

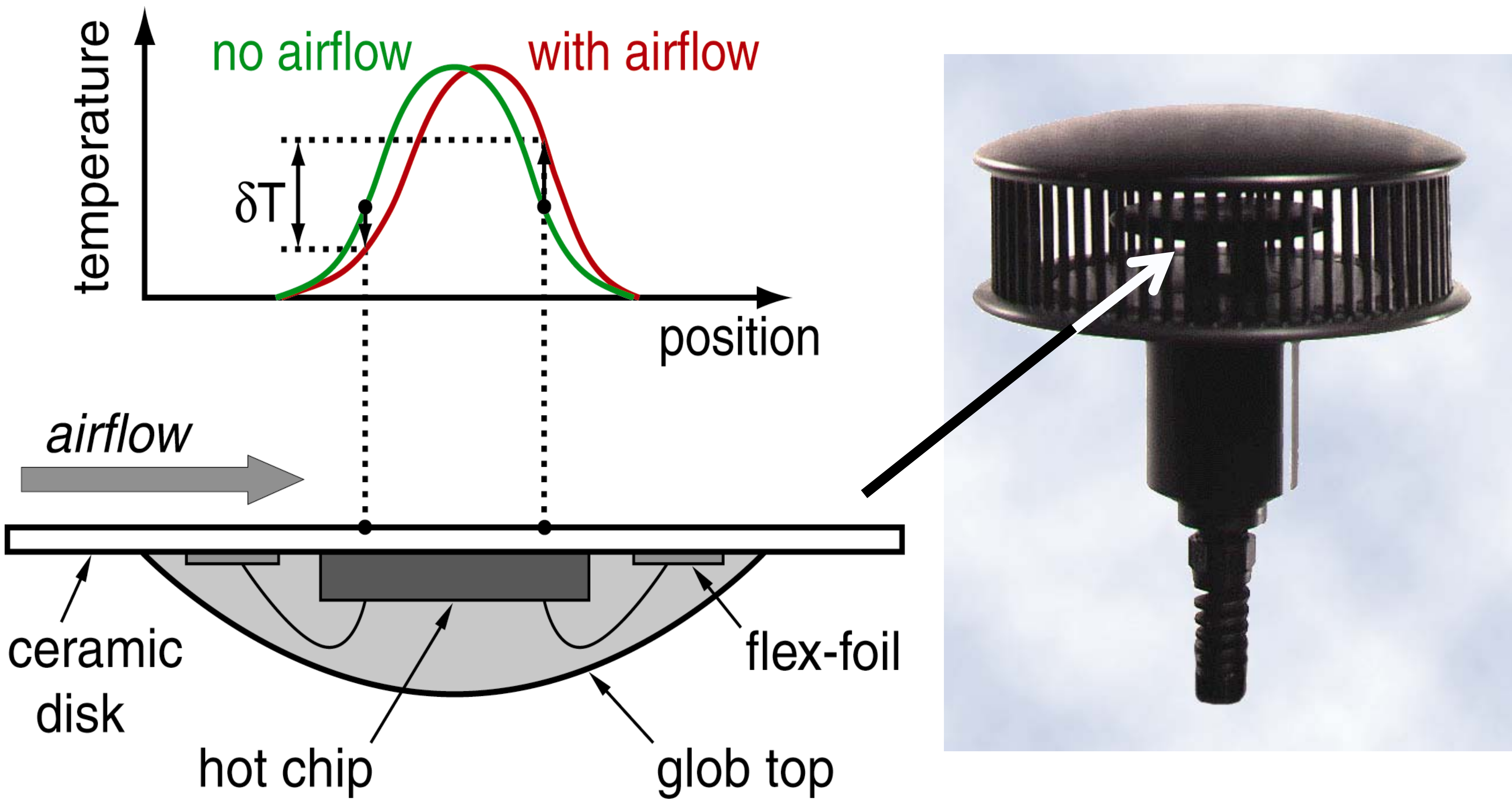
A Smart Wind Sensor!



Convective cooling ⇒ temperature gradient

⇒ wind speed and direction

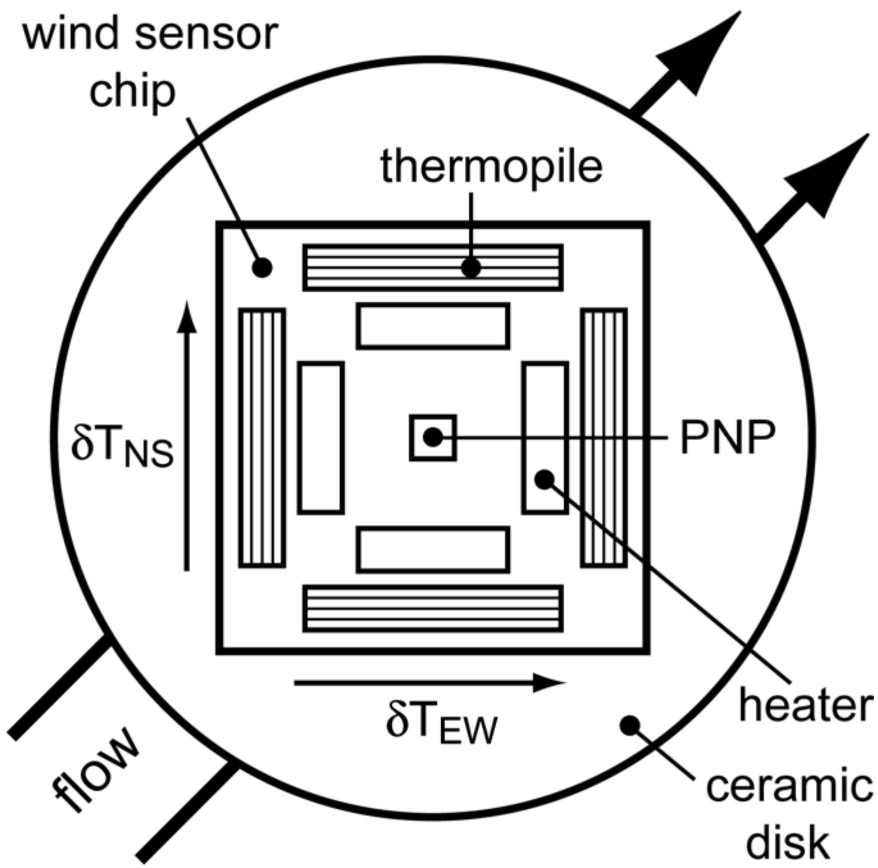
An Electronic Wind Sensor



Wind Sensor Chip

- On-chip heaters
- PNP: measures chip temperature T_{chip}
- Thermopiles: measure temperature differences δT_{NS} and δT_{EW}

$\Rightarrow$ wind speed and direction

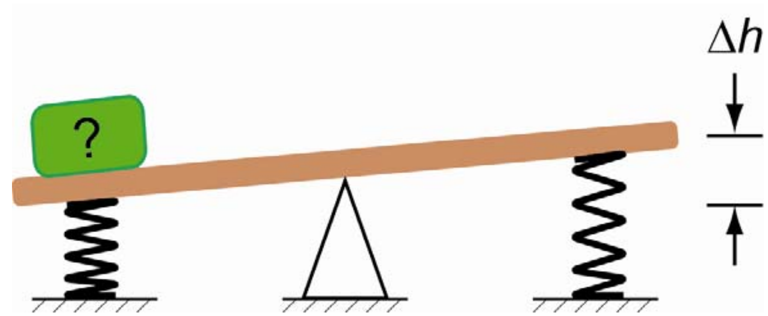


Sensor Characteristics

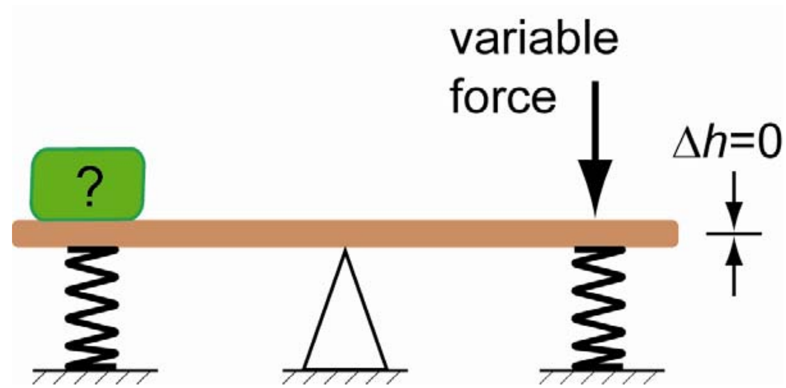
- Slow (~1s time constant)
- Thermopile output is small (microvolts)
- Output is proportional to $\Delta T = T_{chip} - T_{amb}$ ⇒ regulation
- Sensor suffers from packaging offset (chip is not perfectly centered on disc) ⇒ calibration and trimming
- Sensor achieves ~2° angle error ⇒ thermopile outputs must be digitized with > 8-bit resolution
- Sensor characteristics depend on chip area ⇒ same chip area ⇒ simple interface circuitry

Thermal Balancing

- Old principle: **measure** temperature difference δT

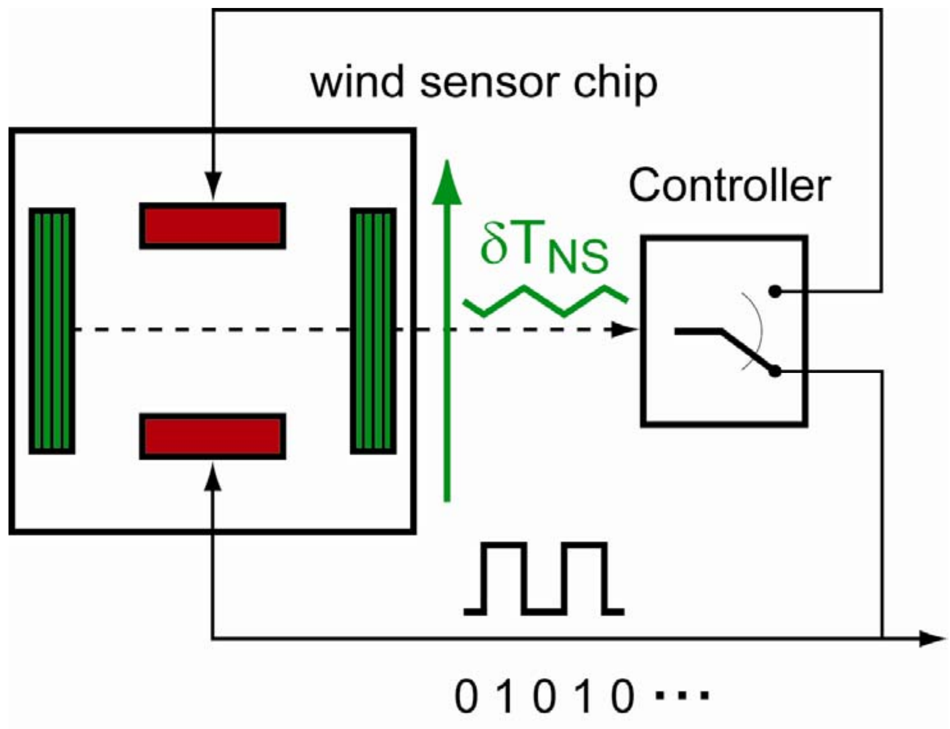


- New principle: **cancel** temperature differences
- Measure difference in heater power δP
  ⇒ wind speed & direction



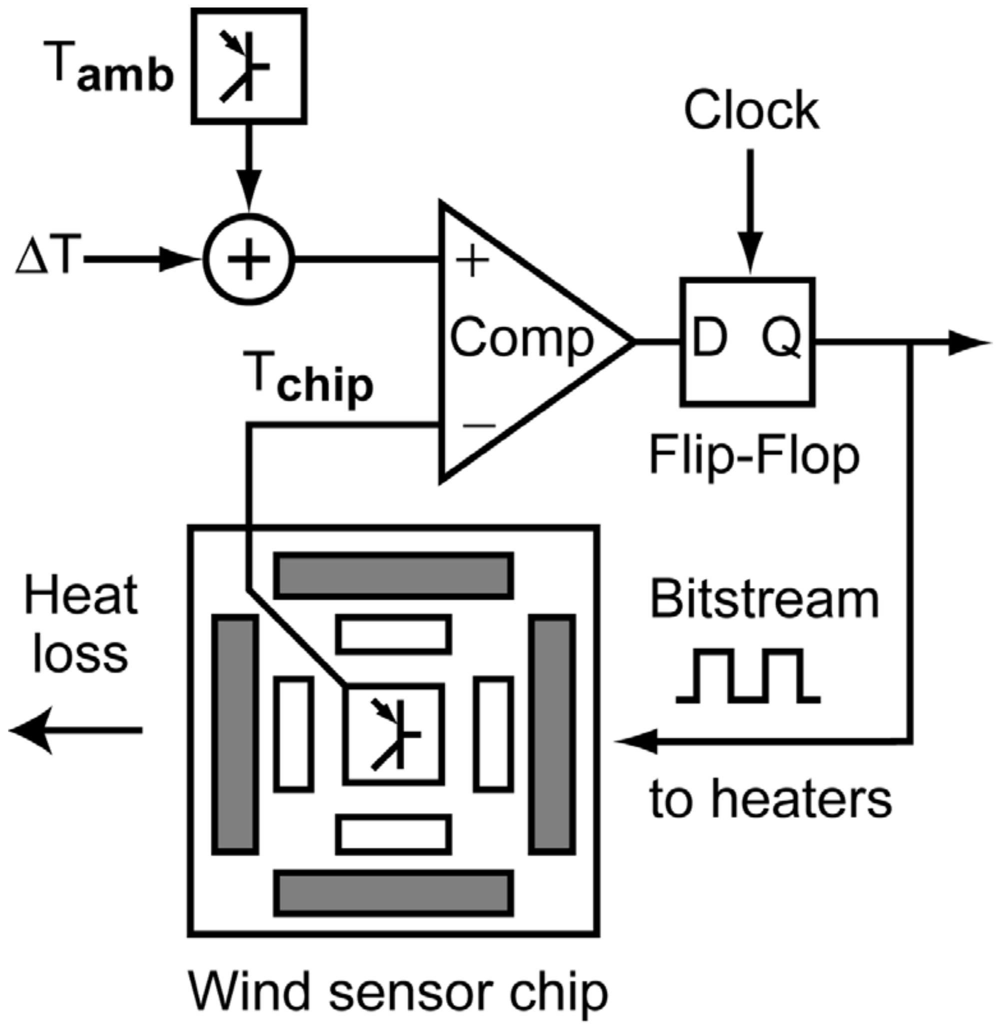
Thermal ΣΔ Modulation

- Heaters are pulsed by bitstream
- Pulses are thermally low-pass filtered $\Rightarrow \delta T_{NS} \sim 0$
- Requires only a simple comparator!
- Is a ΣΔ modulator $\Rightarrow$ digital output!

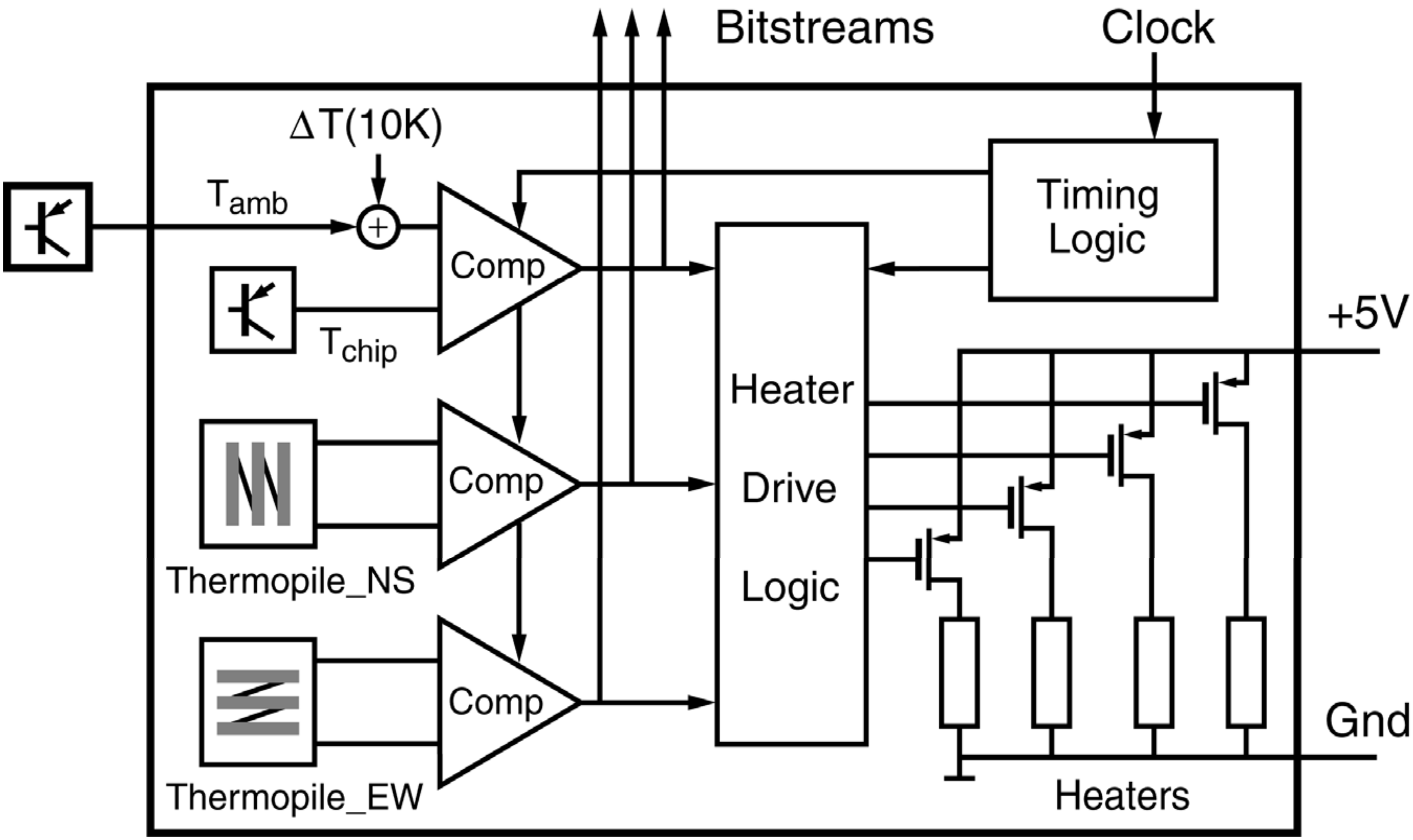


CM Thermal ΣΔ Modulator

- Keeps $T_{chip} \cong T_{amb}$+10°C
- $T_{chip} \Rightarrow$ on-chip PNP
- $T_{amb} \Rightarrow$ external PNP

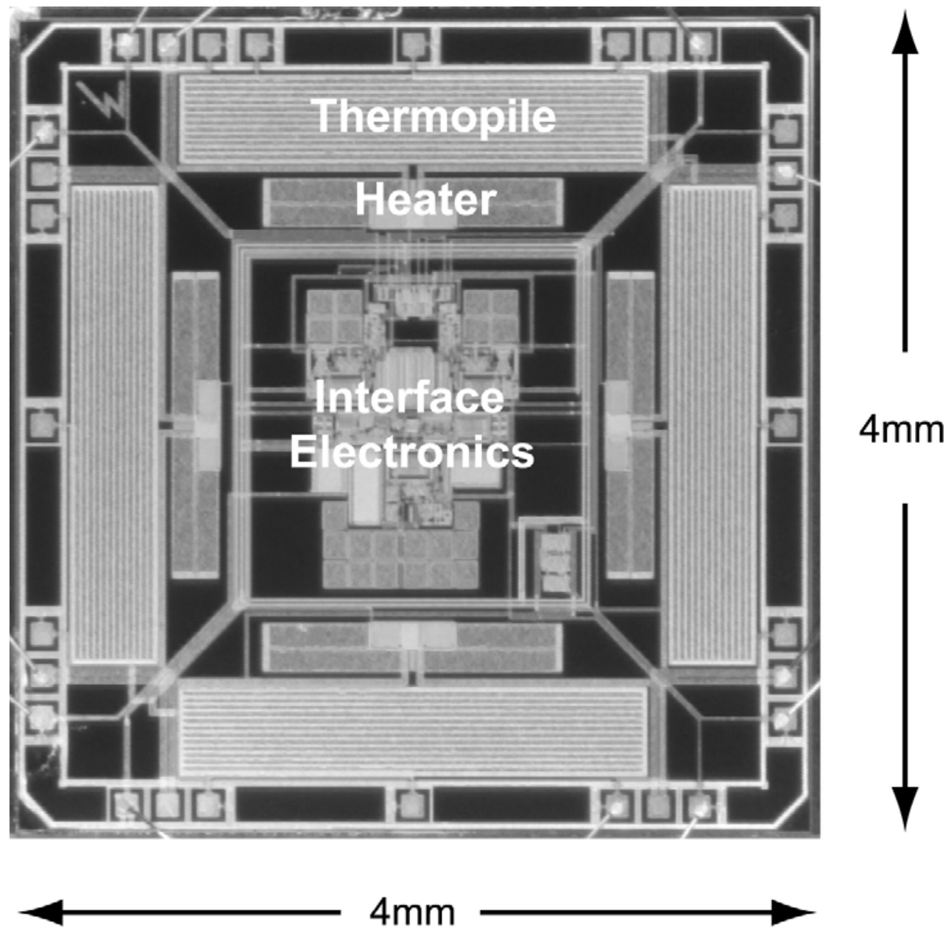


Smart Wind Sensor



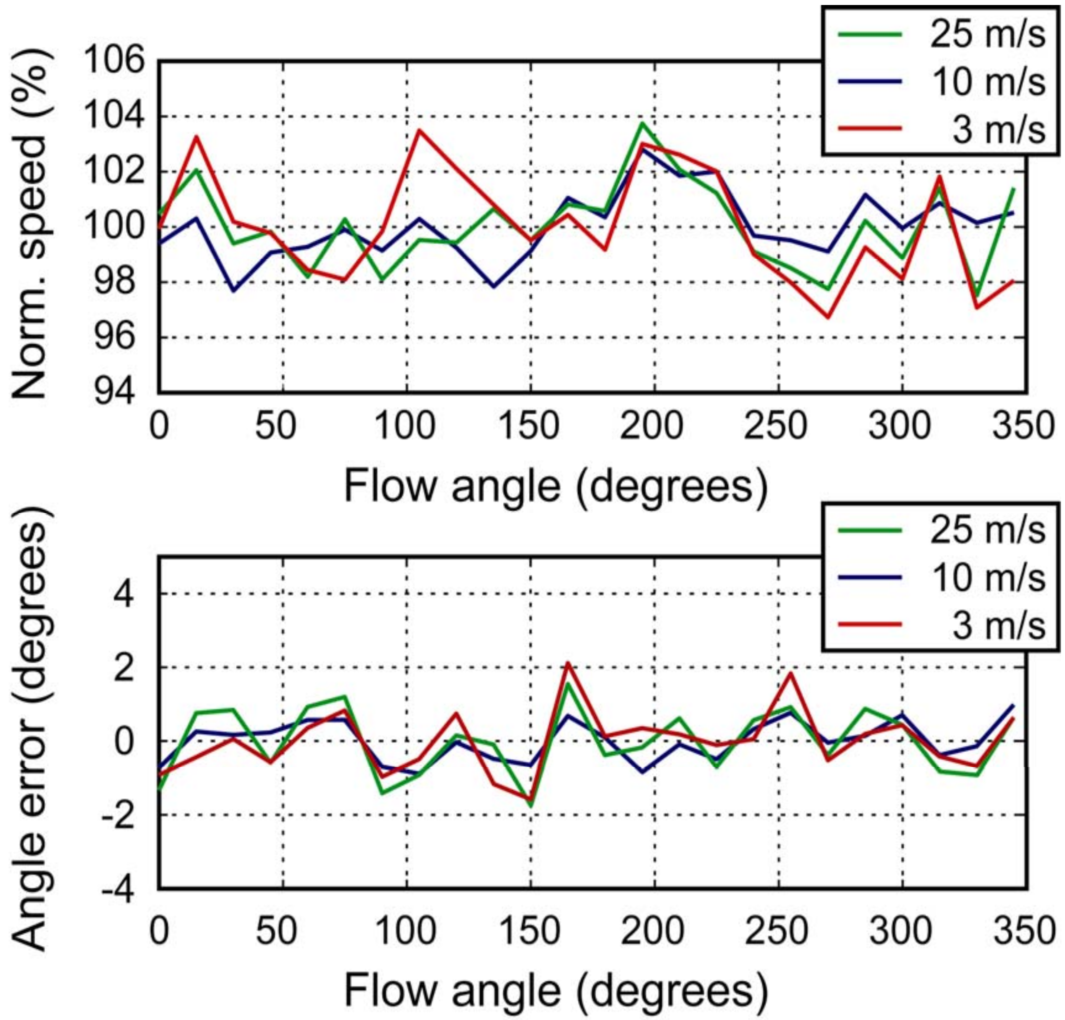
Smart Wind Sensor Chip

- Same area as original sensor
- Even in a 1.6μm CMOS process!
- Thermal ΣΔ modulators
  ⇒ 10-bit resolution
- Bitstream output



Wind Sensor Performance

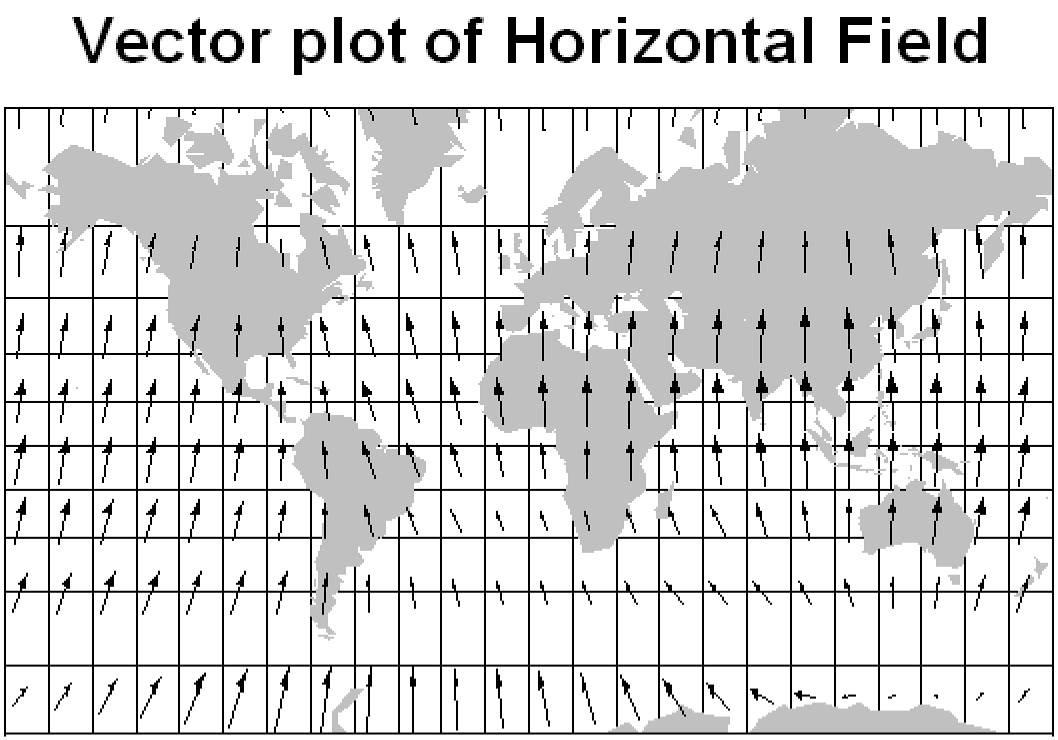
- After calibration:
  Speed error: ± 4%
  Angle error: ± 2°
- *Same* as for original sensor
- But, with on-chip electronics
- Is being commercialized

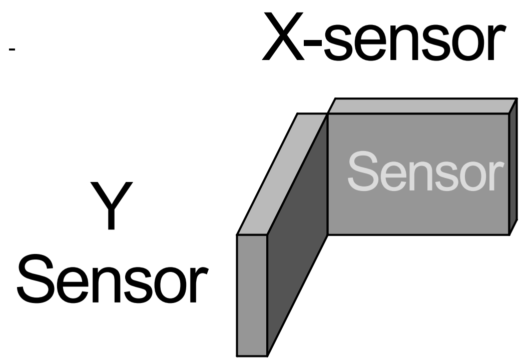


Design Summary

1. Do no harm: performance **is** limited by sensor!
2. System design: sensor's thermal inertia is used to realize **simple** thermal balancing control loops
3. Digitize early: sensor is embedded in a $\Sigma\Delta$ modulator
4. Be dynamic: Auto-zeroing cancels offset and1/*f* noise

A Smart Hall Sensor





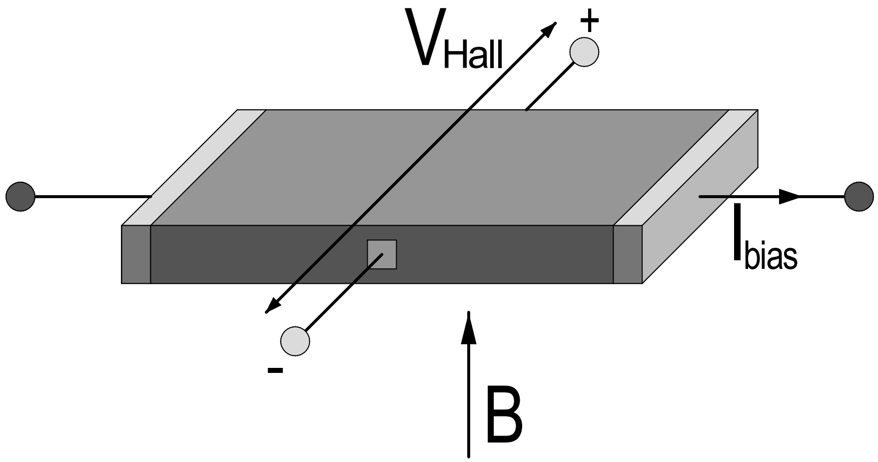
- Compass senses at least two components of earth's field
- Field strength < 45μT

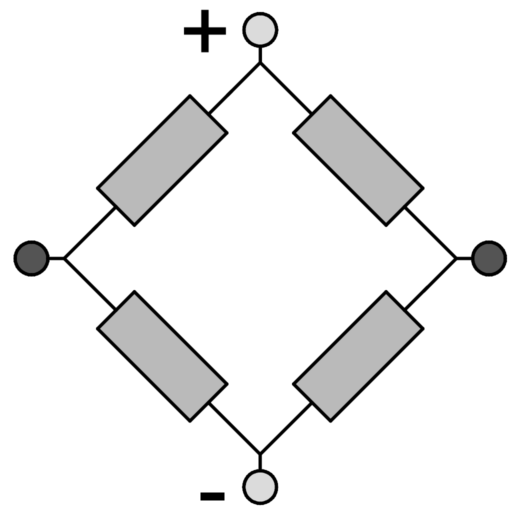
Goal: Hall-sensor based compass with 1° angle error

⇒ Hall-sensor precision < 0.5μT

⇒ Precision of readout electronics < 25nV!

Hall Effect





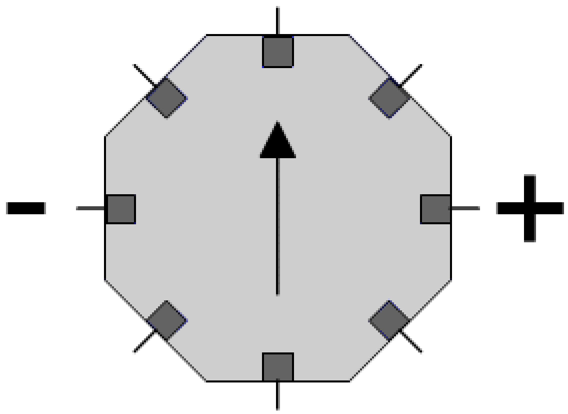
$$V_{Hall} = S_H I_{Bias} B$$

Wheatstone bridge model

Resistances in bridge model

- Are mismatched ⇒ Offset (10mT typical)
- **Change** due to changes in temperature and packaging stress ⇒ Offset drift

Spinning-Current Technique



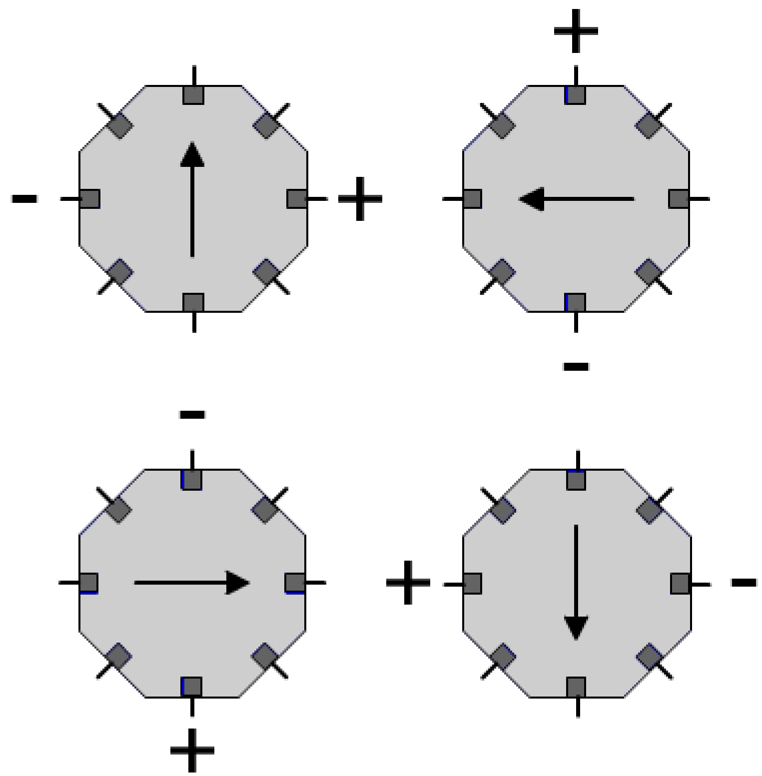
- Bias current rotated, while Hall voltages are summed
- Cancels offset due to **static** bridge mismatch

⇒ 10 - 100μT offset

- **But** thermal settling ⇒ tens of milliseconds per spin cycle

⇒ Time-varying offset e.g. due to temperature and stress remains a problem

Hall Sensor Offset Reduction

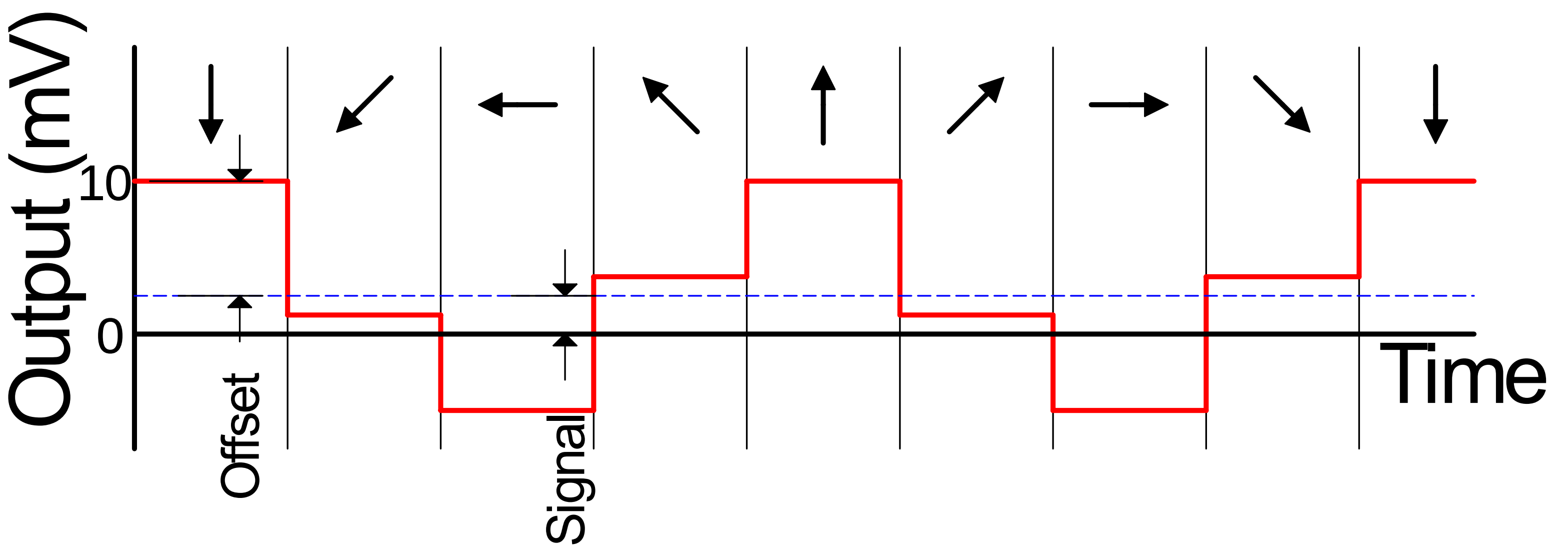


- Orthogonal coupling
  - 4 sensors are biased in 4 different directions
  - Hall voltages are summed

⇒ Instantaneous compensation of time-varying offset

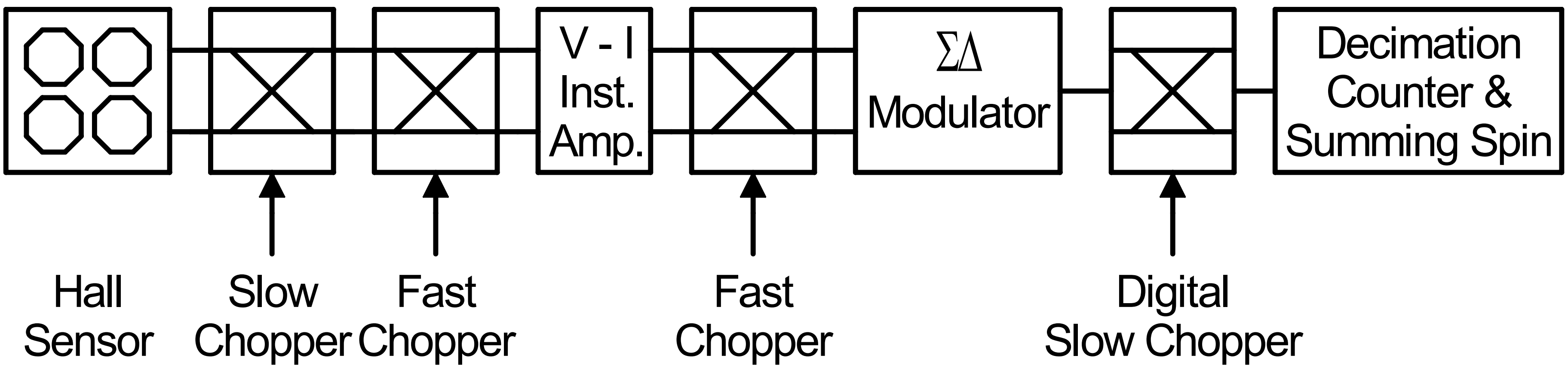
- **Stable** offset < 10μT
  ⇒ can be trimmed!
- Also compensates for errors due to nearby metal objects

Spinning-Current Sensor Output



- Typically 10mV worst case offset
- But offset **drift** < 25nV is required after spinning
  $\Rightarrow$ Interface electronics with sub-microvolt offset
  $\Rightarrow$ Good linearity over an 80 - 100dB dynamic range

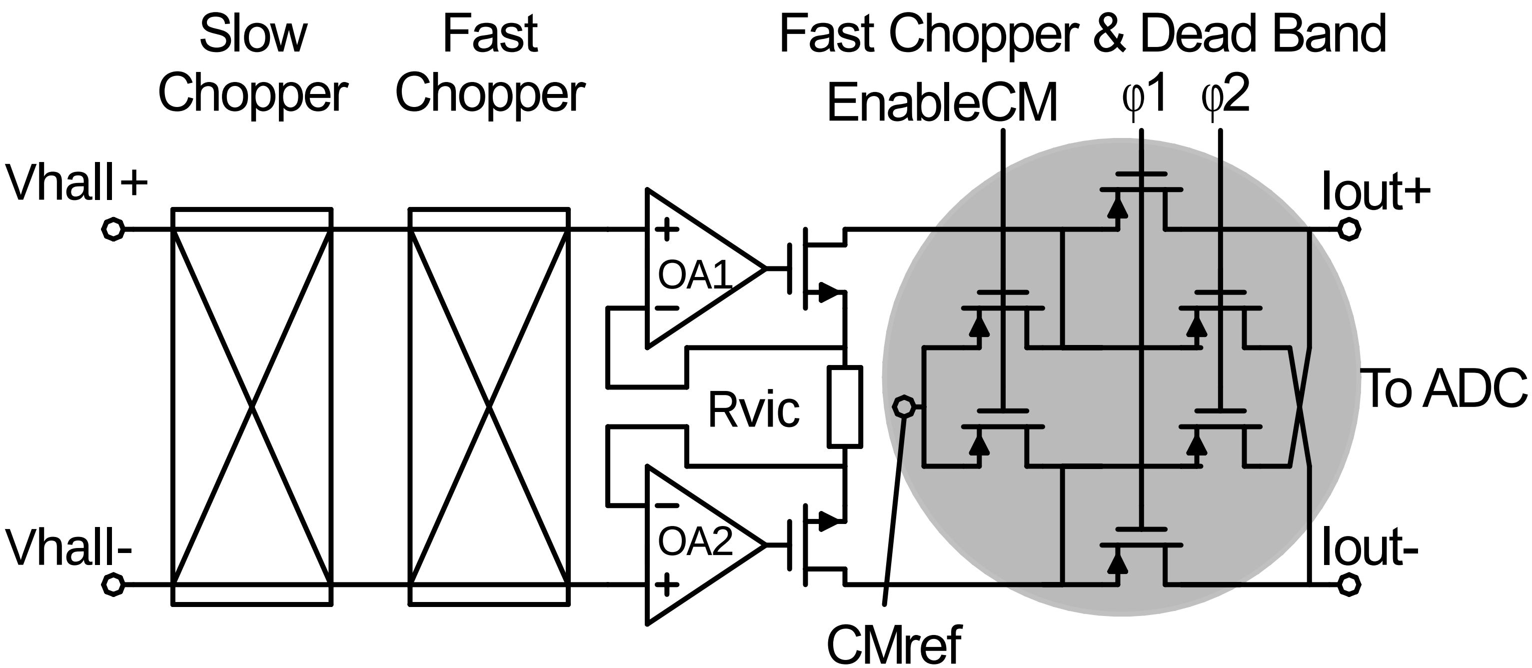
System Architecture



Sub-microvolt offset ⇒ nested chopping

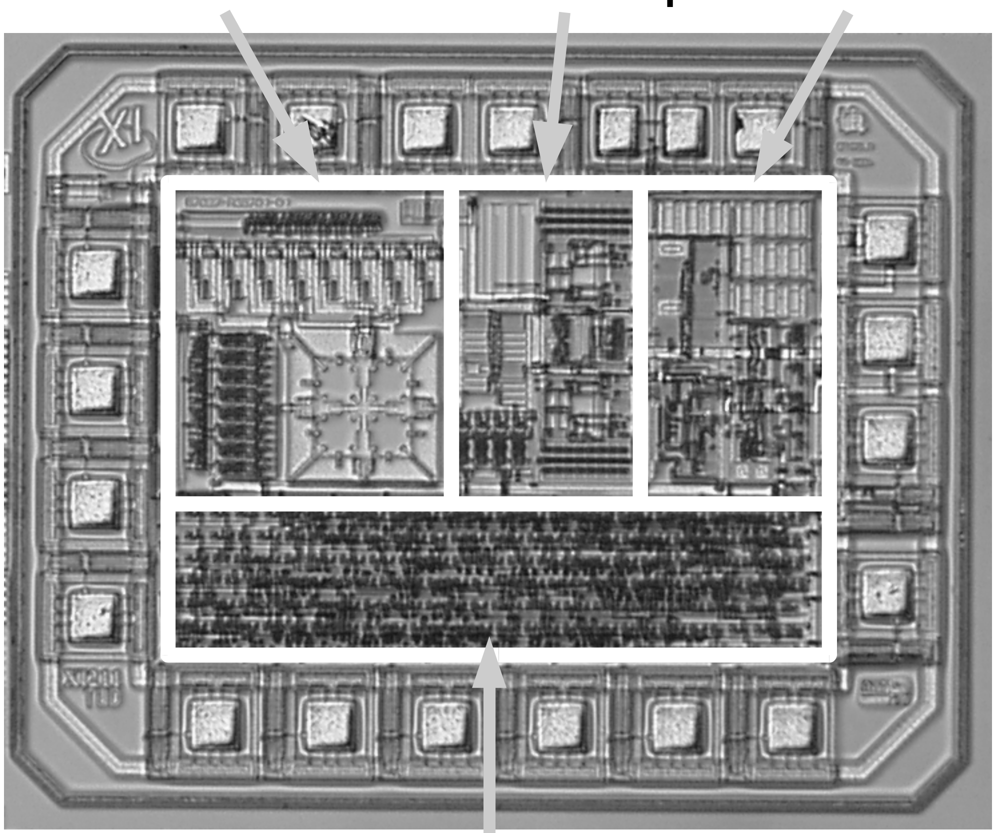
- Hall-voltages converted to currents by chopped instrumentation amplifier (fast choppers)
- ΣΔ Modulator digitizes resulting currents
- Entire front-end is again chopped (slow choppers)
- Decimation filter sums and averages Hall-voltages

Precision V-I Converter



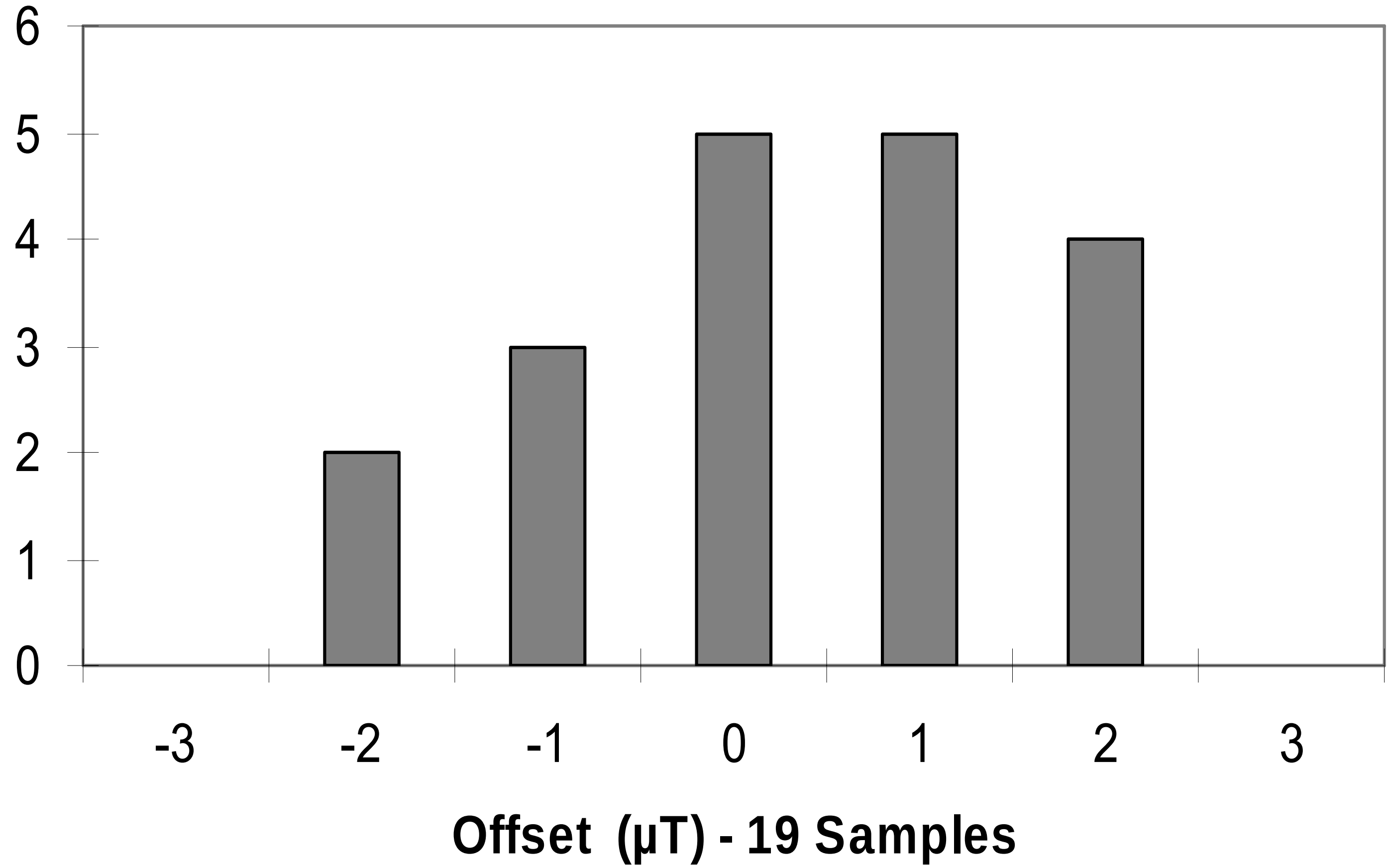
- Fast output chopper implements dead-bands
- During dead-bands, output current flows into a CM node
- Slow output chopper implemented in ADC

Chip Micrograph



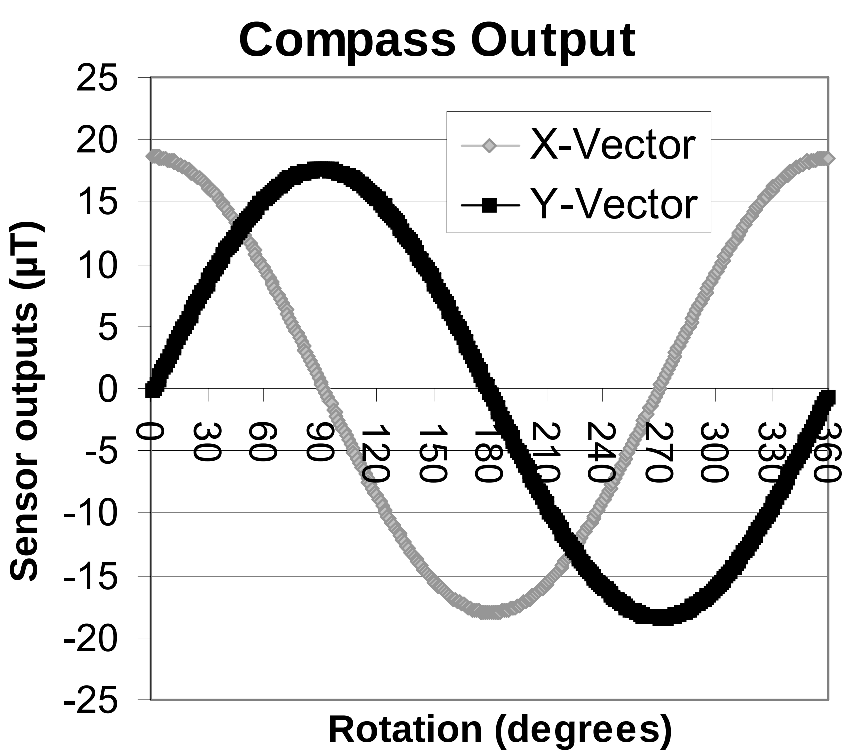
- 0.5µm CMOS
- Area: 2.9 mm²
- Dissipates 21mW (4.2mA @ 5V)
- RS232, SPI/µwire and PWM interface
- Commercial product

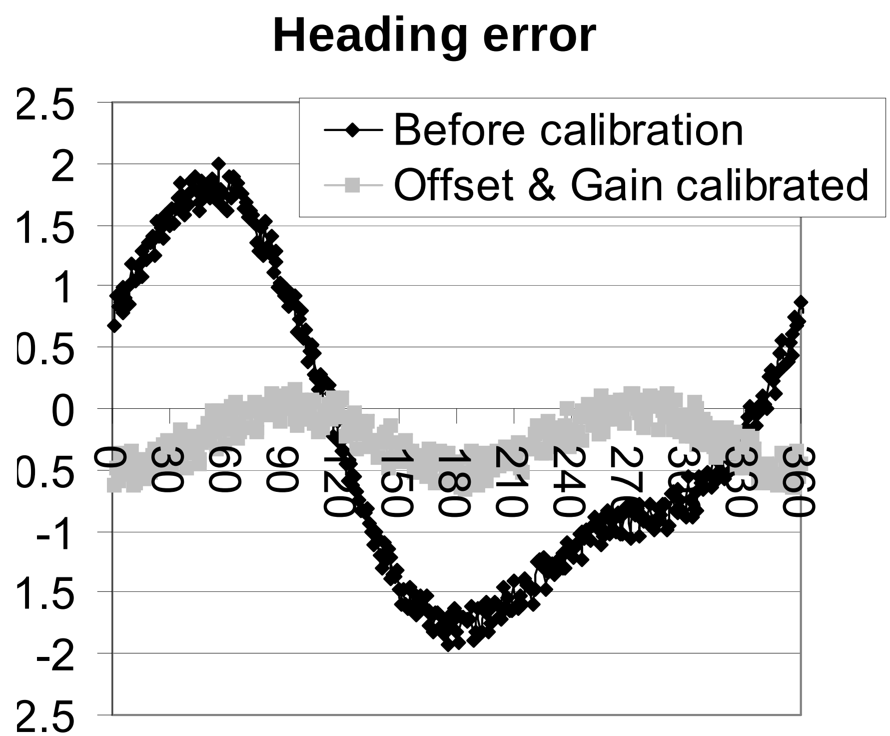
Sensor Offset Distribution



Sensor offset (3σ) < 4µT, but offset drift < **5nT** per week!

System Response Measurement



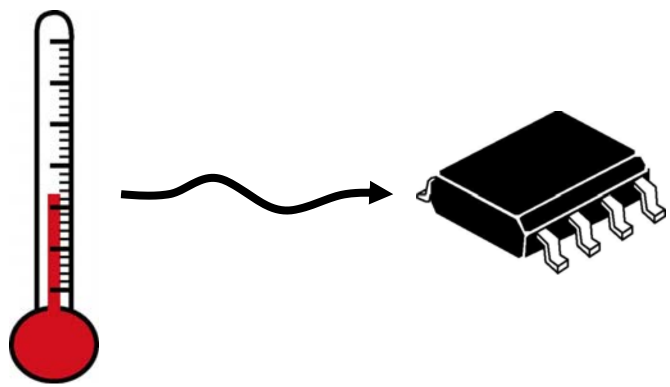


- Angle error < 1° after calibration and trimming!
- State-of-the-art performance!

Design Summary

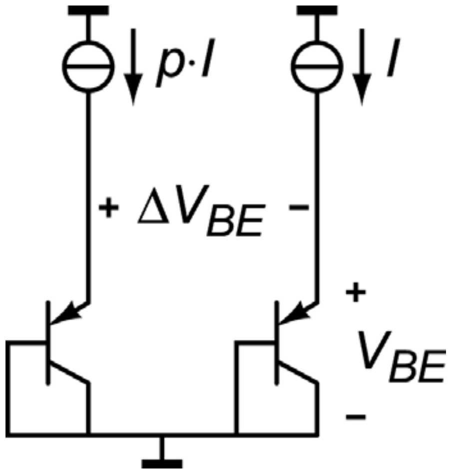
1. Do no harm: performance **is** limited by Hall sensors!
2. System design: spinning current technique + quad Hall sensor reduces and **stabilizes** sensor offset
3. Digitize early: sensor output is converted to a current and then digitized by a $\Sigma\Delta$ modulator
4. Be dynamic: nested chopping is used to cancel offset and1/*f* noise

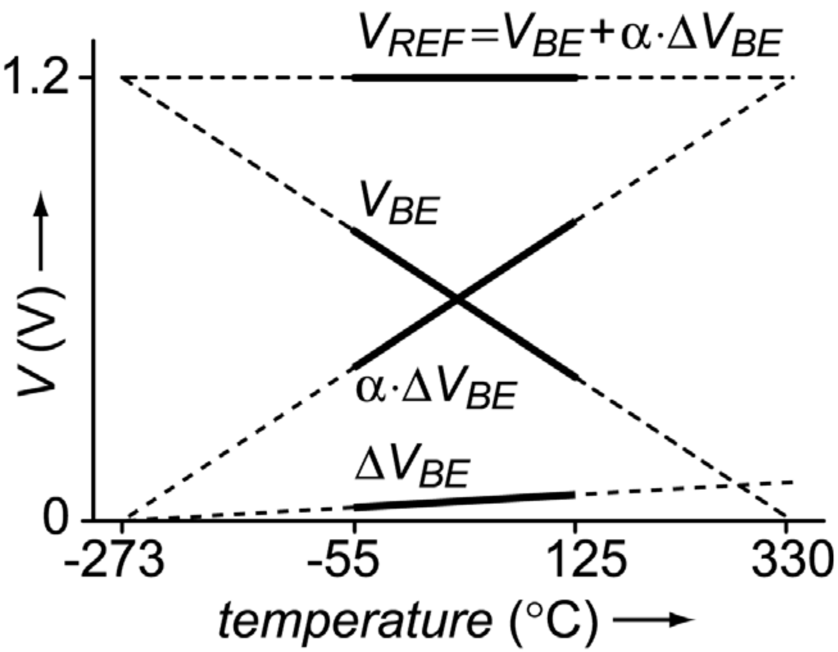
A Smart Temperature Sensor



- *Commercial* smart temperature sensors are not very accurate (±1.0°C from –55°C to 125°C)
- By comparison: class-A Pt100 ±0.5°C
- Our goal: ±0.1°C from –55°C to 125°C with only a single-temperature trim

Operating Principle

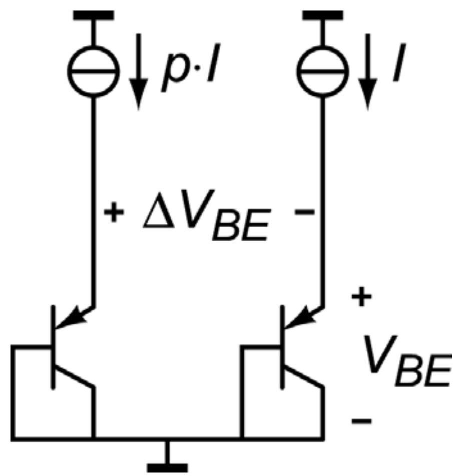




- substrate PNPs generate:
  ΔV_{BE} proportional to absolute temp. (PTAT)
  V_{BE} complementary to absolute temp. (CTAT)

- ratiometric measurement: $\mu = \dfrac{V_{TEMP}}{V_{REF}} = \dfrac{\alpha \cdot \Delta V_{BE}}{V_{BE} + \alpha \cdot \Delta V_{BE}}$

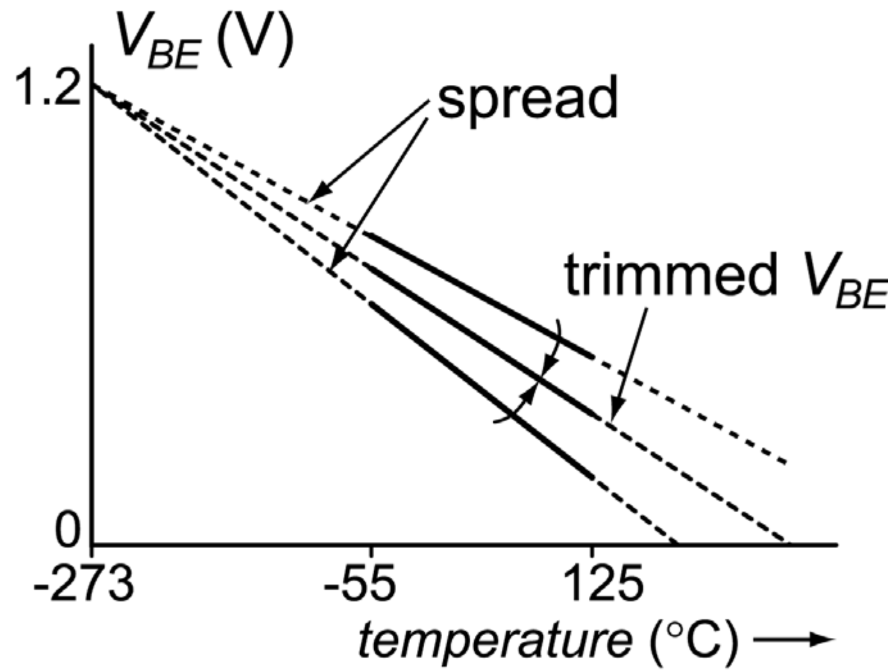
Dominant Error Sources



- **process spread** of $V_{BE} \Rightarrow$ errors of ~3°C
- **offset** in ΔV_{BE} read-out: 10μV $\Rightarrow$ 0.1°C error
- **mismatch** in 1:p current ratio
  and gain α: 0.1% $\Rightarrow$ 0.2°C error

Single-Temperature Calibration

- process spread
  $\Rightarrow$ PTAT error in V_{BE}
- So single-temperature trim is sufficient, *provided* all other errors are negligible

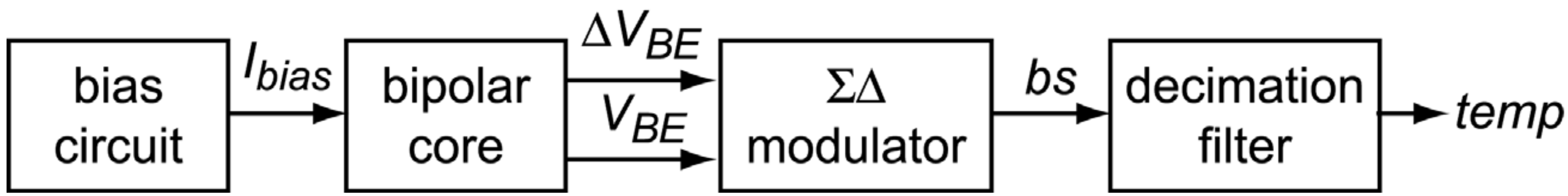


Approach:

- reduce all errors except spread to 0.01°C level

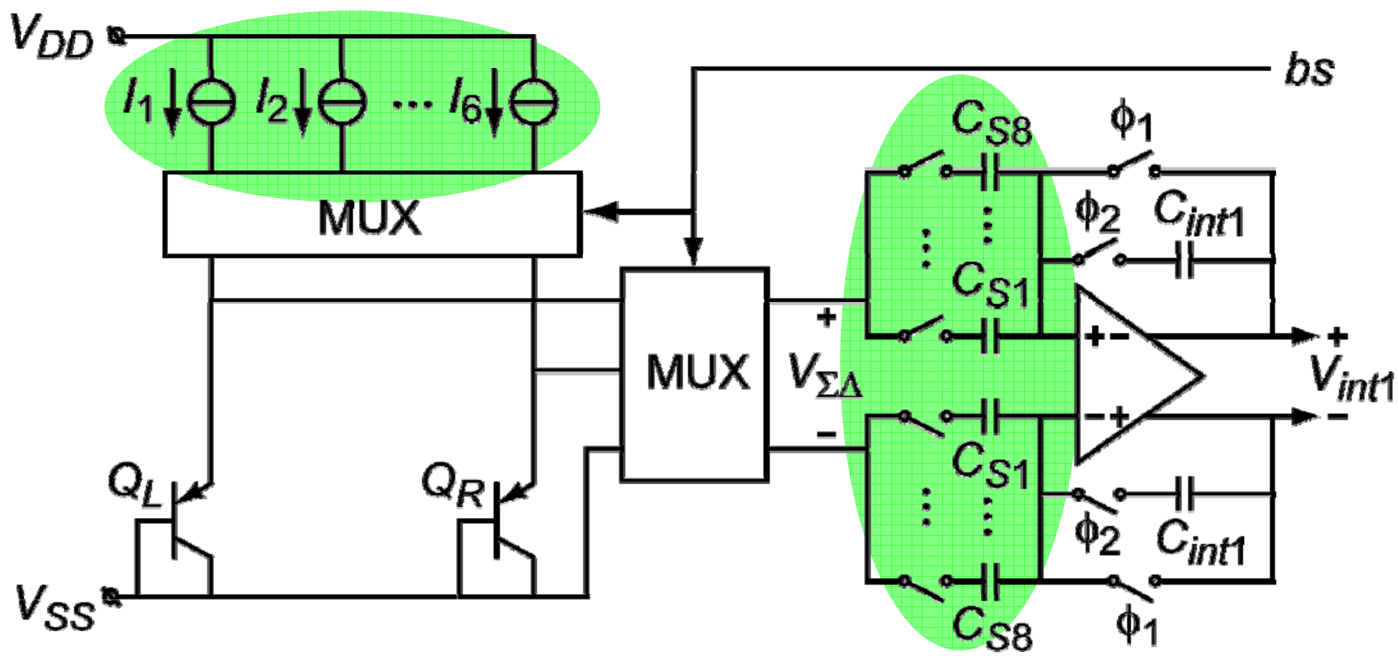
- correct spread by trimming the bias current

Block Diagram



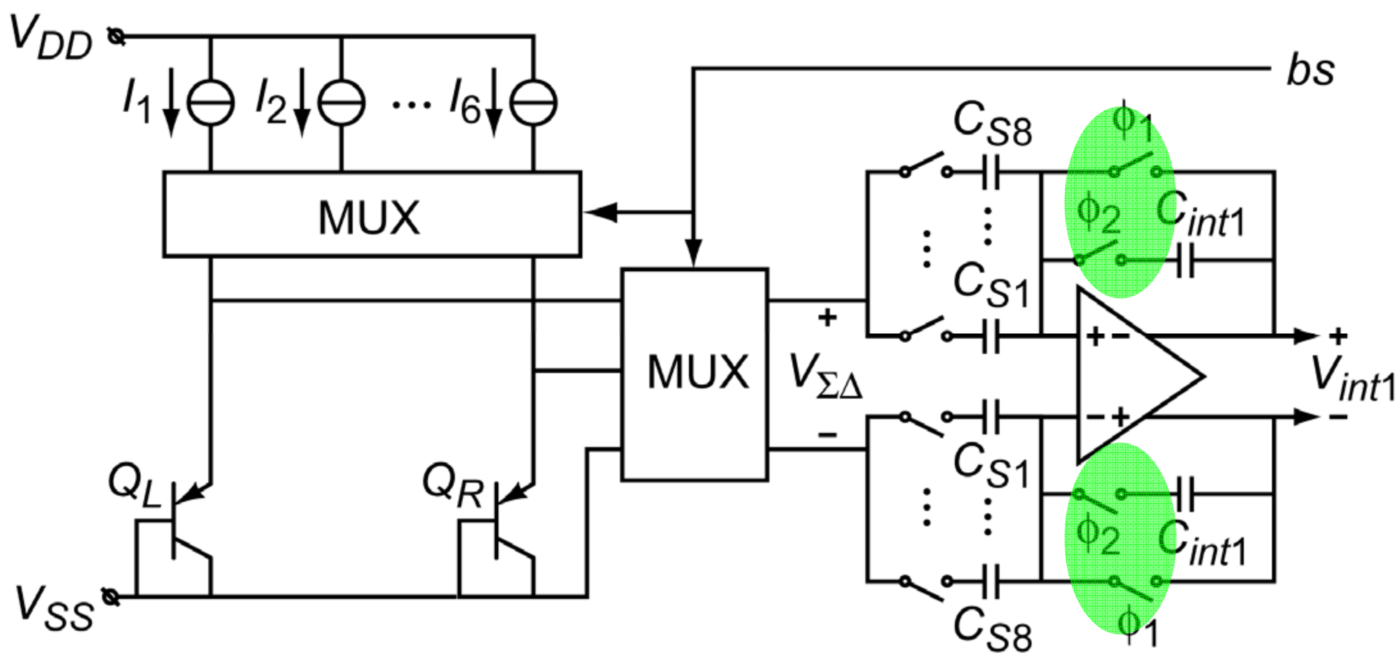
- Bipolar core = two PNPs
- ΣΔ modulator produces bitstream *bs* that is a digital representation of temperature
- bitstream is filtered and scaled by decimation filter to produce binary reading in °C

Dynamic Element Matching



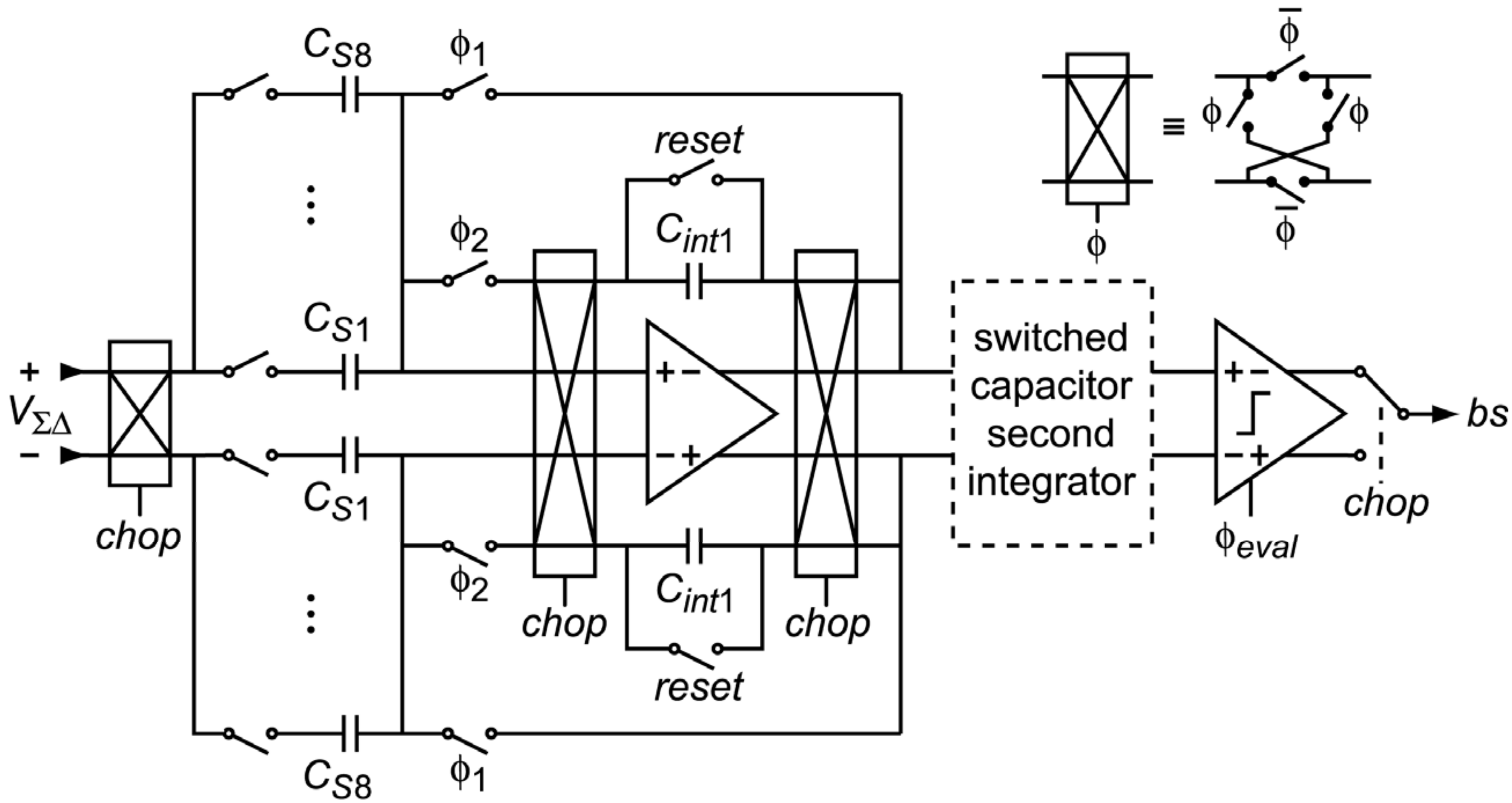
- Accurate 1:5 current ratio for ΔV_{BE}
  $\Rightarrow$ rotate current sources
- Accurate 1:8 sampling capacitor ratio
  $\Rightarrow$ rotate sampling capacitors

Switched-Capacitor Front-End



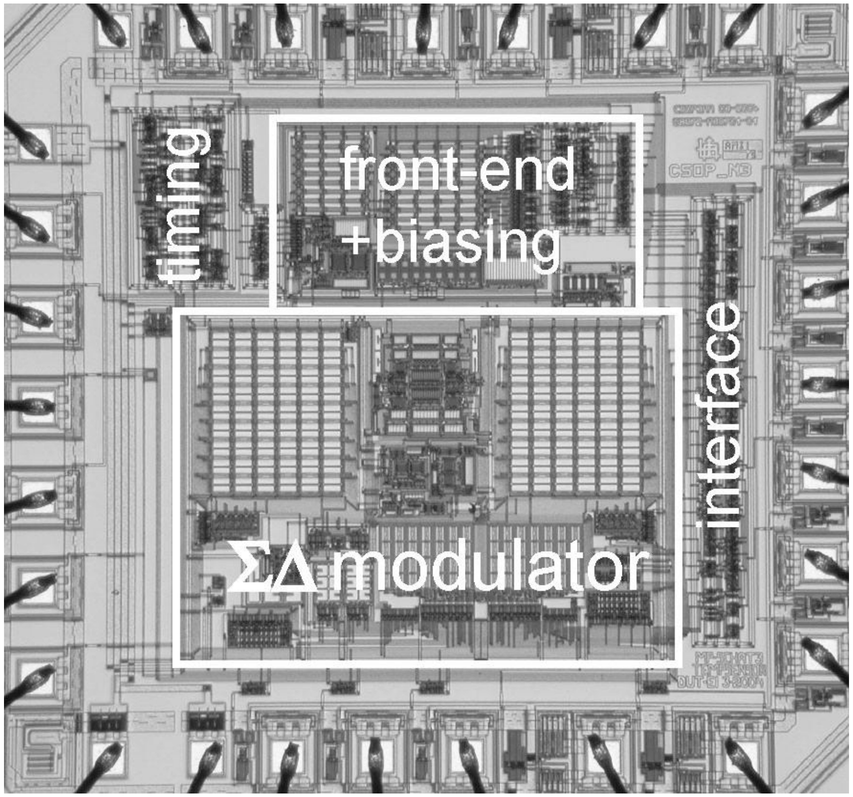
- Correlated double-sampling (CDS) cancels offset and 1/*f* noise of 1st integrator

Chopped ΣΔ Modulator



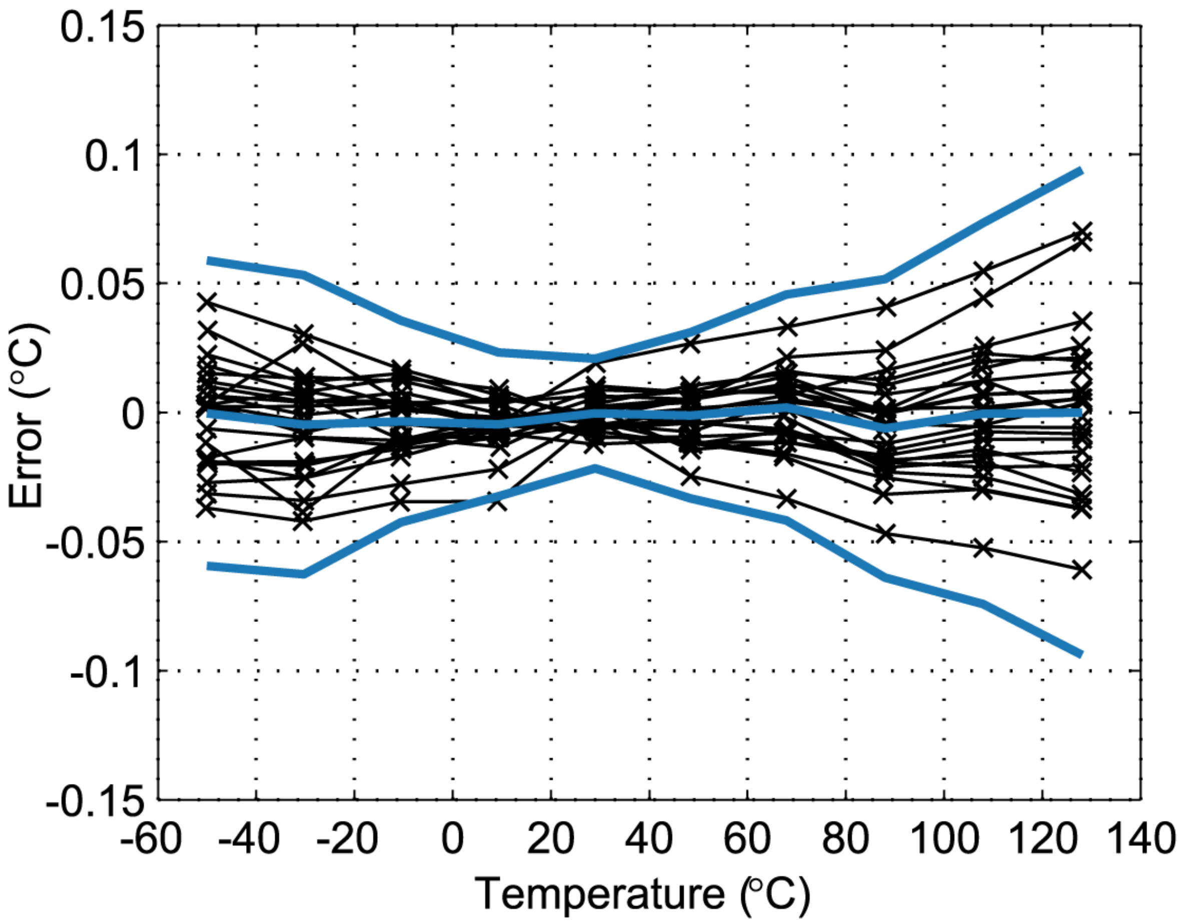
- After CDS, offset of 1st integrator is still > 10μV
  ⇒ further offset reduction by system-level chopping

Chip Micrograph



- 0.7μm CMOS
- Area: 4.5mm^2
- supply voltage: 2.5..5.5V
- supply current: 75μA
- Bitstream output

Measurement Results



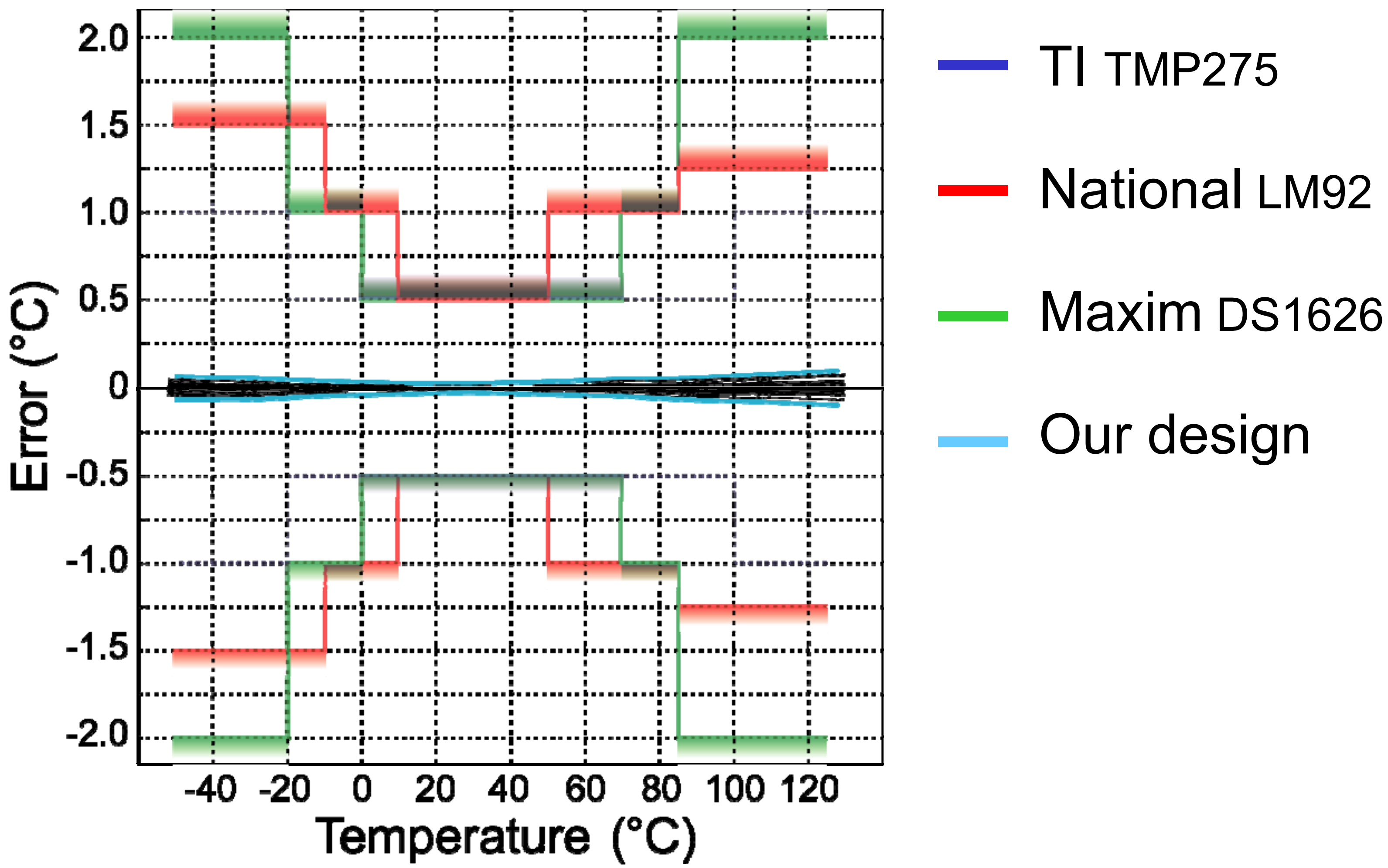
24 samples
from 1 batch

inaccuracy (±3σ)
after calibration
& trimming at 30°C:

±0.1°C –55..125°C

State-of-the-art
performance!

Benchmarking



Design Summary

1. Do no harm: accuracy **is** limited by sensor (but resolution is still limited by the ADC)
2. System design: nature of V_{BE} spread is exploited to permit cheap single temperature trimming
3. Digitize early: ΔV_{BE} and V_{BE} are input directly into a charge-balancing $\Sigma\Delta$ modulator
4. Be dynamic: CDS, nested chopping and dynamic element matching are used to cancel offset, 1/*f* noise and gain errors

Summary

- A variety of smart sensors can be made in silicon
- But the resulting sensors are only average
  $\Rightarrow$ require good interface electronics!
- The following design methodology helps
  - Do no harm!
  - Do system design!
  - Digitize early!
  - Be dynamic!
- Used to realize a unique wind sensor and state-of-the-art magnetic field and temperature sensors

Acknowledgements

- Mierij Meteo
- Xensor Integration
- NXP Semiconductors
- Dutch Technology Foundation (STW)

- Thank-You for Your Attention!

- Any questions?

Background Reading

1. K.A.A. Makinwa and J.H. Huijsing, “A smart wind sensor using thermal sigma-delta modulation techniques,” *Sensors and Actuators A*, vol. 97-98, pp. 15 – 20, April 2002.
2. K.A.A. Makinwa and J.H. Huijsing, “A smart CMOS wind sensor,” *Digest of Technical Papers ISSCC,* pp. 432 – 479, Feb. 2002.
3. J. van der Meer, F.R. Riedijk, K.A.A. Makinwa and J.H. Huijsing, “A fully-integrated CMOS Hall sensor with a 4.5uT, 3σ offset spread for compass applications,” *Digest of Technical Papers ISSCC,* pp. 246 – 247, Feb. 2005.
4. M. A. P. Pertijs, K. A. A. Makinwa, and J. H. Huijsing, “A CMOS smart temperature sensor with a 3σ inaccuracy of ±0.1°C from −55°C to 125°C,” *JSSC*, vol. 40, no. 12, pp. 2805 – 2815, Dec. 2005.
5. C.P.L. van Vroonhoven and K.A.A. Makinwa, “A CMOS Temperature-to-Digital Converter with an Inaccuracy of ±0.5°C (3σ) from –55 to 125°C,” *Digest of Technical Papers ISSCC*, pp. 576 – 577, Feb. 2008.
6. K.A.A. Makinwa and M.F. Snoeij, “A CMOS temperature-to-frequency converter with an inaccuracy of ±0.5°C (3σ) from –40 to 105°C,” *J. Solid-State Circuits,* vol. 41, is. 12, pp. 2992 – 2997, Dec. 2006.
7. K.A.A. Makinwa, M.A.P. Pertijs, J.C. van der Meer and J.H. Huijsing, “Smart sensor design: The art of compensation and cancellation,” *Proc. ESSCIRC*, pp. 76 – 82, Sept 2007.

