Smart Sensors:
No Signal too Small?

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Sensors are Everywhere!

Even In Our Pockets!

image sensor

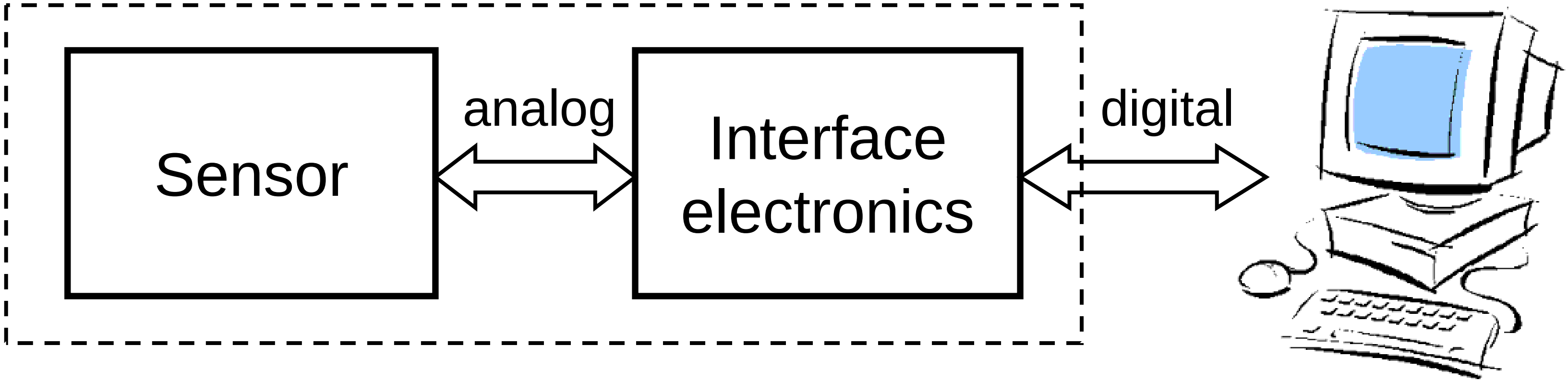
touch
screen

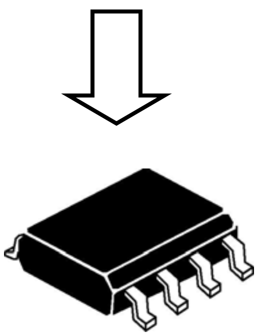
compass

inertial
sensors

microphone

Smart Sensor System





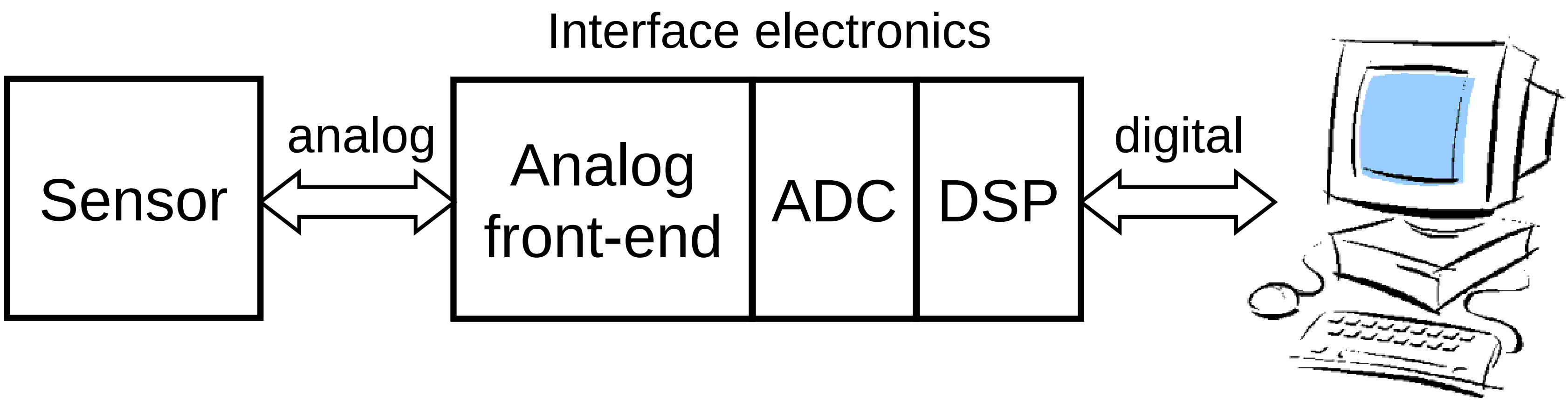
A smart sensor =

- Sensor + electronics in a single package
- Robust digital interface to the outside world

Silicon Sensors

- Generally **not** best-in-class
- Output **small** analog signals e.g.
  - microvolts (thermopiles, Hall sensors,)
  - microamperes (photodiodes)
  - atto-farads (inertial sensors)
- Are **slow** – compared to the speed of transistors
- Need **calibration** – because their characteristics depend on **temperature** and **process spread**

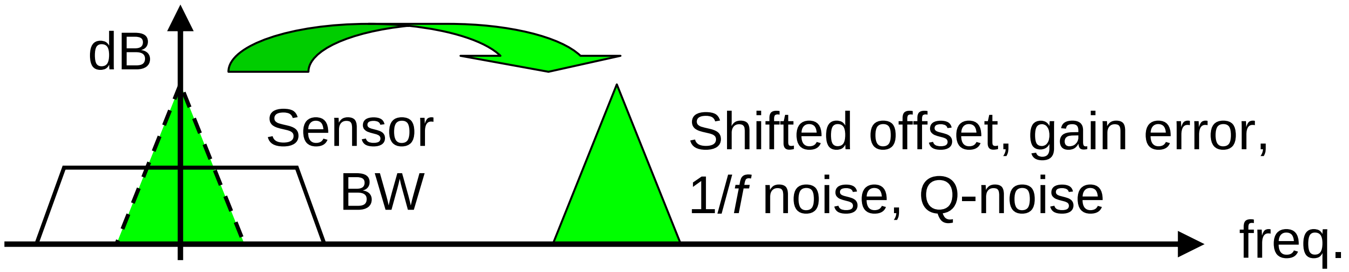
The Interfacing Challenge!



- Goal: **sensor** should limit system performance
  ⇒ Interface electronics should do no harm!
- Small sensor signals + CMOS
  ⇒ analog design **challenges**
- Mainly: offset, gain error, 1/*f* noise & process spread

Interface Design Methodology

1. Do system design! ⇒ use circuit techniques to compensate for sensor non-idealities
2. Digitize early! ⇒ less analog errors, more flexibility, more functionality (Moore's Law)
3. Be dynamic! ⇒ modulate errors (offset, gain, Q-noise) out of sensor bandwidth



K.A.A. Makinwa et al., "Smart sensor design: the art of compensation and cancellation," *Proc. ESSCIRC*, pp. 76 - 82, Sept 2007.

Interface Design Methodology

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Case study: A smart wind sensor

K.A.A. Makinwa et al., "Smart sensor design: the art of compensation and cancellation," *Proc. ESSCIRC*, pp. 76 - 82, Sept 2007.

Conventional Wind Sensors

Cup Anemometer

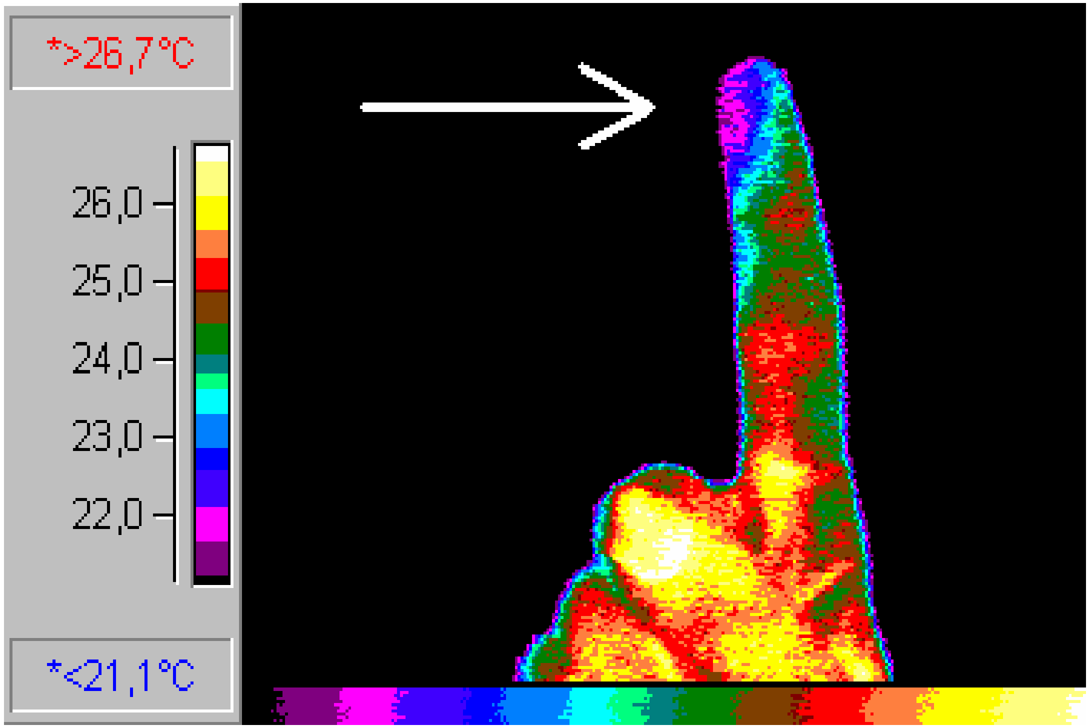
⇒ Wind Speed

Wind Vane

⇒ Wind Direction

- Typically have moving parts ⇒ maintenance
- Ideal solution: a wind sensor **without** moving parts

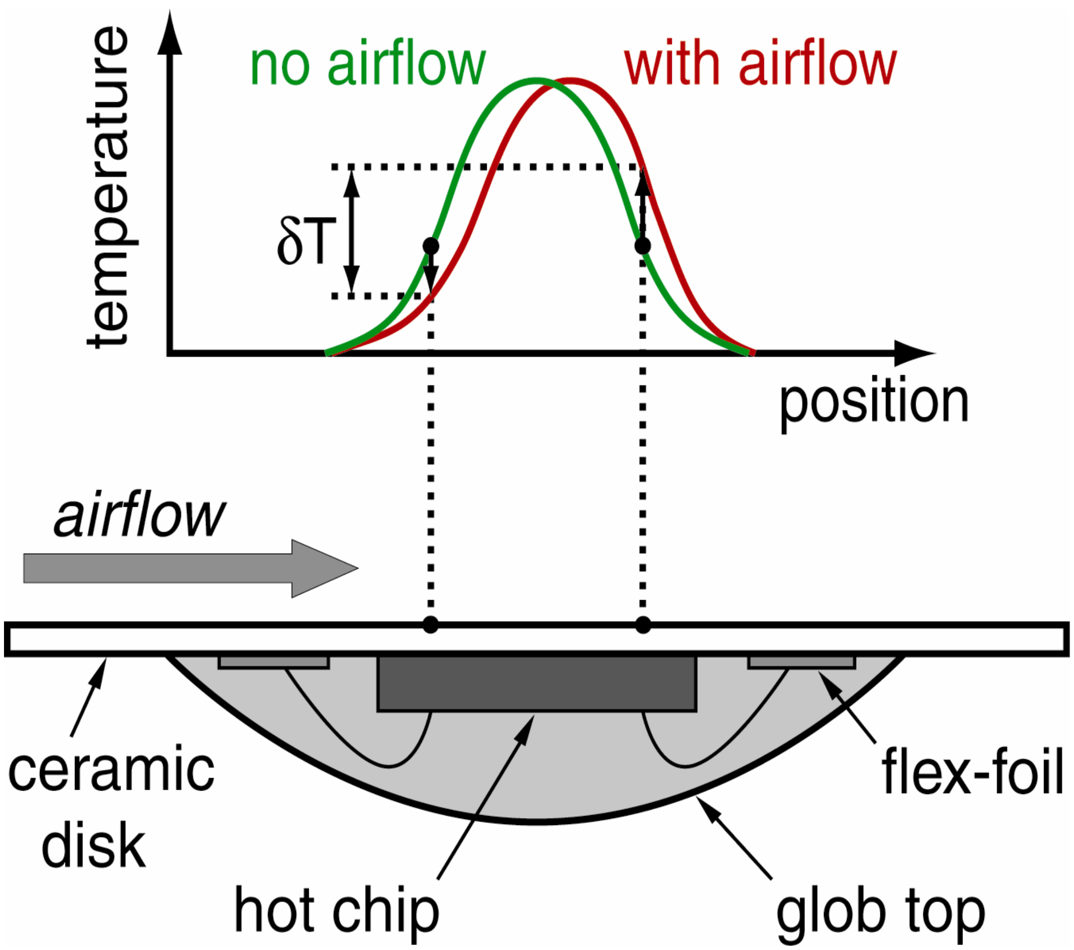
Inspiration From Nature

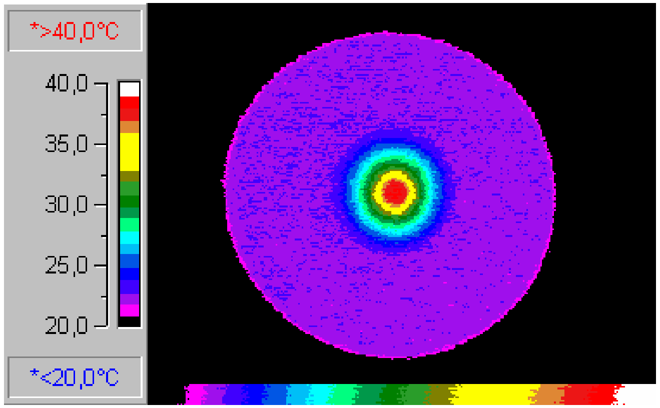


Convective cooling ⇒ temperature gradient

⇒ wind speed <u>and</u> direction

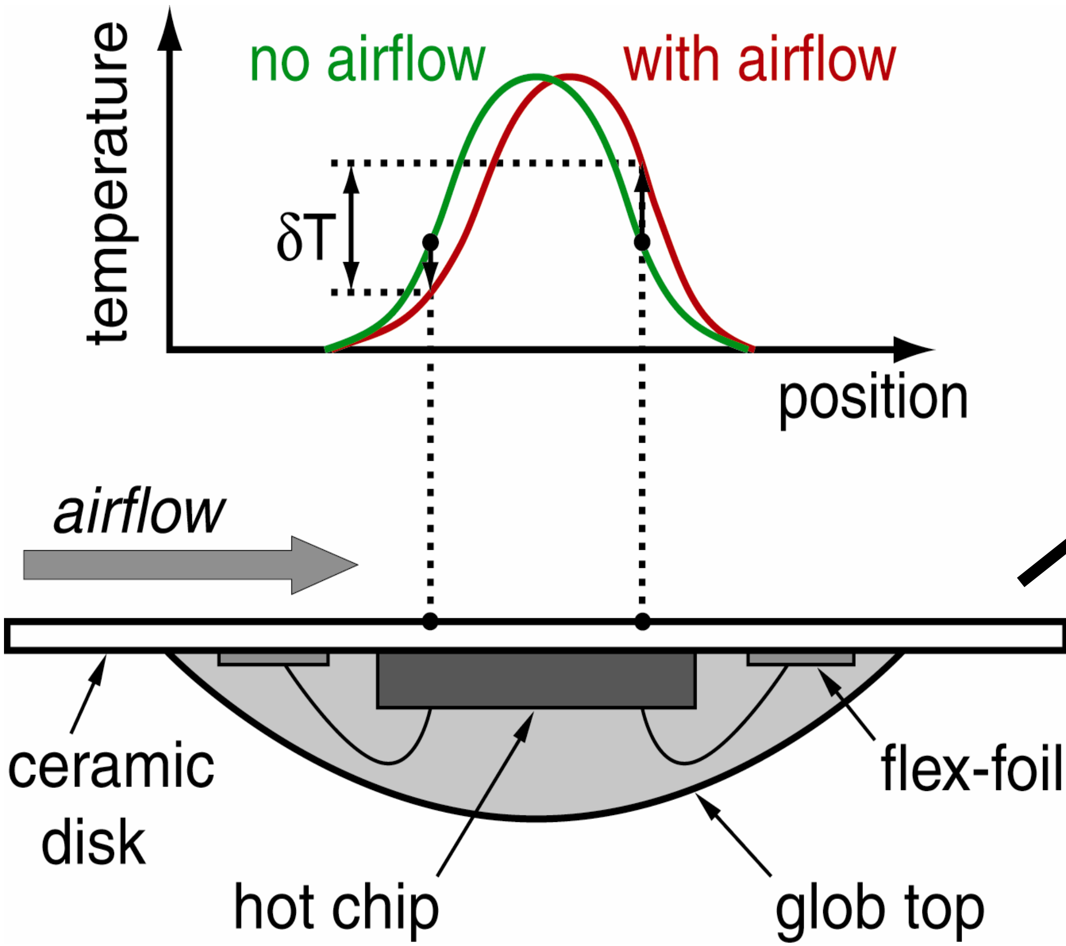
A Smart Wind Sensor





Circular hot-spot on disk surface

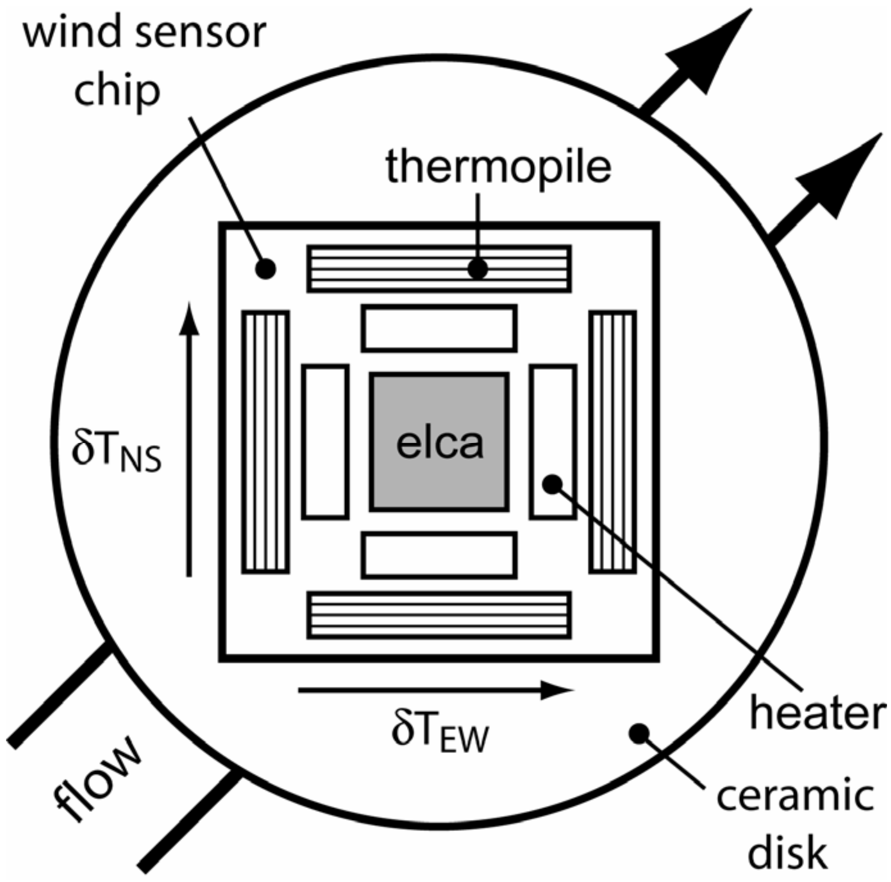
A Smart Wind Sensor



Plastic housing guides
wind over ceramic disk

Wind Sensor Chip

- Heater resistors
- Thermopiles (p^+/Al) sense temperature differences δT_{NS} & δT_{EW}
- On-chip electronics digitizes thermopile output



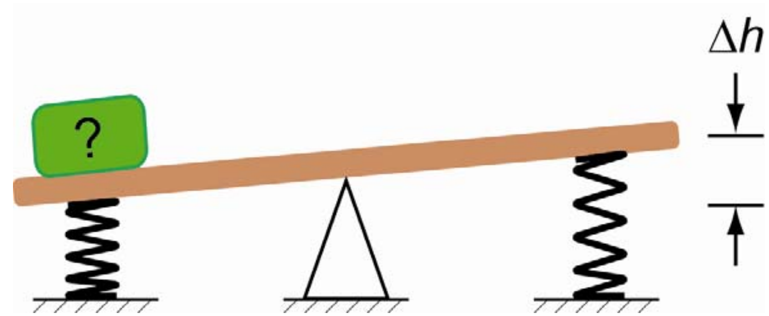
- $|\delta T| \Rightarrow$ wind speed
- $\arg(\delta T) \Rightarrow$ wind direction

Sensor Characteristics

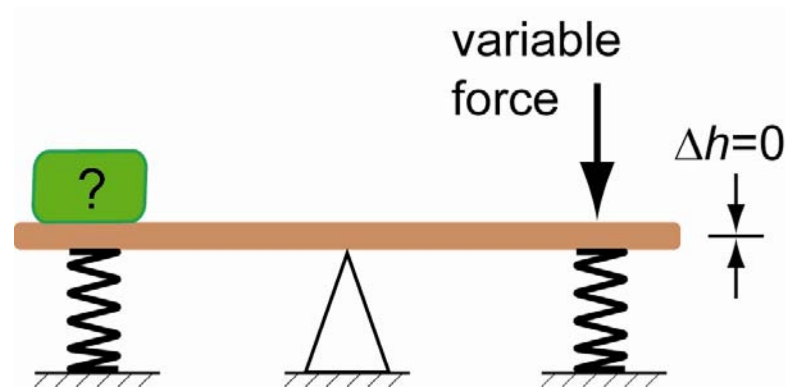
- Large thermal mass
  $\Rightarrow$ sensor is slow (~1s time constant)
- Silicon is a good conductor
  $\Rightarrow$ thermopile output V_{tp} is small (millivolts)
- Thermopile sensitivity S_{tp} depends on doping
- Square chip $\Rightarrow$ angle error ~2°
  $\Rightarrow$ thermopile outputs only require 8-bit resolution

System Design

- Directly digitizing V_{tp}
  $\Rightarrow$ precision amp + ADC
  $\Rightarrow$ too much area!



- Since V_{tp} is offset-free
  $\Rightarrow$ thermal balancing!
  $\Rightarrow$ S_{tp} does not matter!

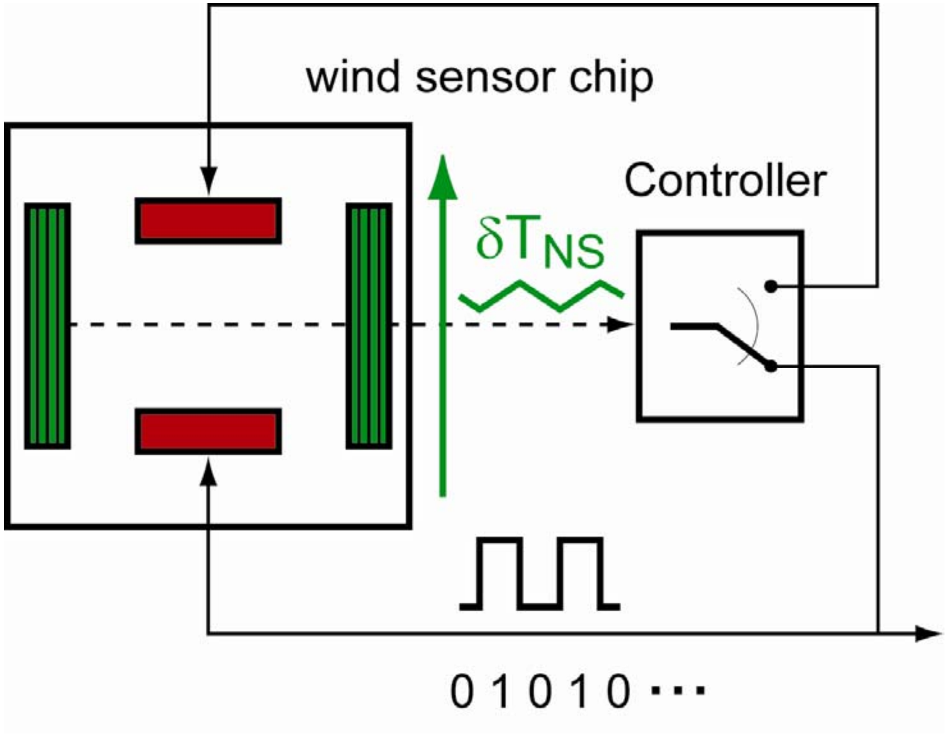


- Now heater **power** differences δP_{NS} & δP_{EW} **cancel** δT_{NS} & δT_{EW}

Thermal ΣΔ Modulation

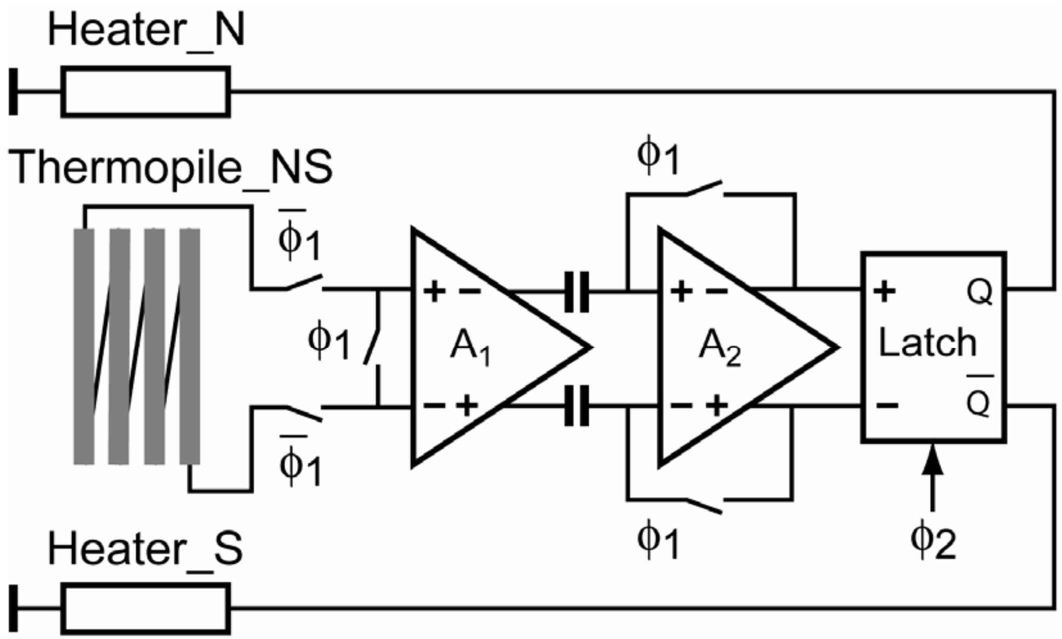
- Heaters are alternately pulsed $\Rightarrow$ digital output!
- Sensor's thermal mass filters pulses $\Rightarrow \delta T_{NS} \sim 0$
- Requires only a simple comparator!
- Result is a *thermal* ΣΔ modulator

δT_{NS} controller



Thermal ΣΔ Modulator: Circuit

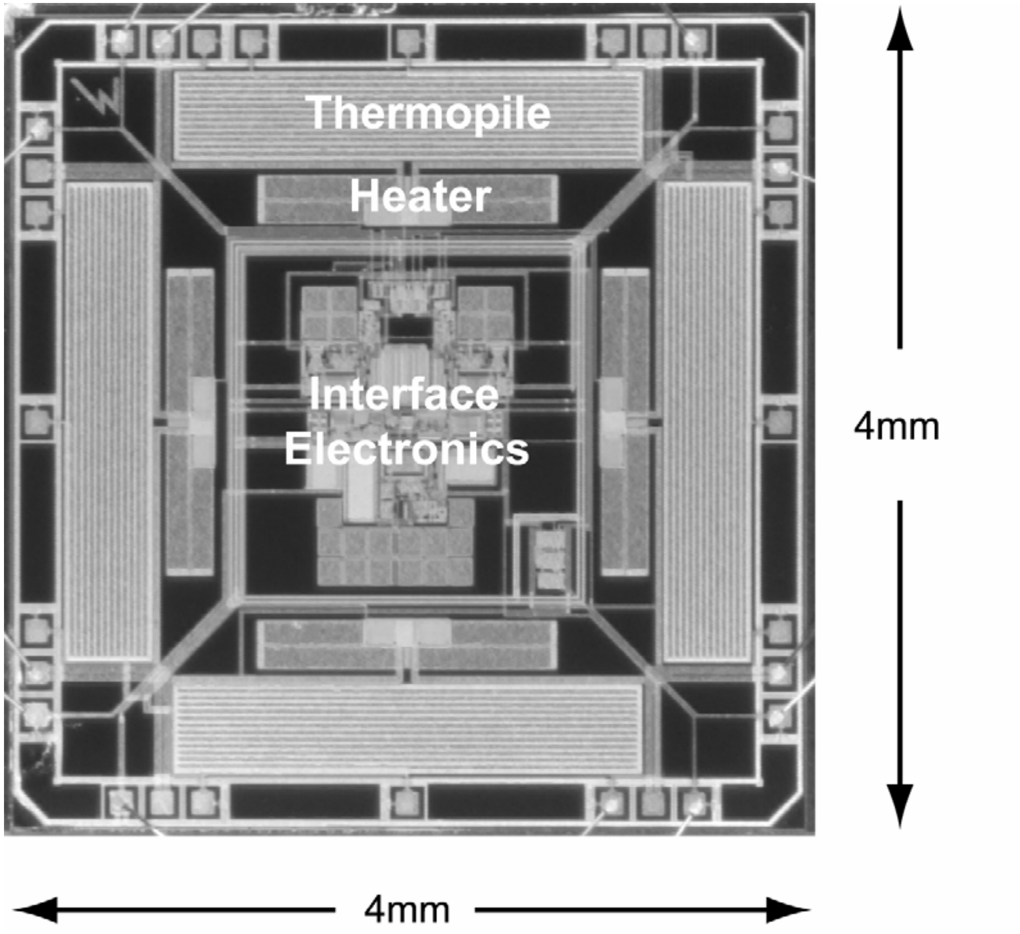
- Comparator offset << V_{tp} ⇒ auto-zeroed preamp + latch
- Preamp is AZ'ed before each comparison
- Comparator offset < 20μV



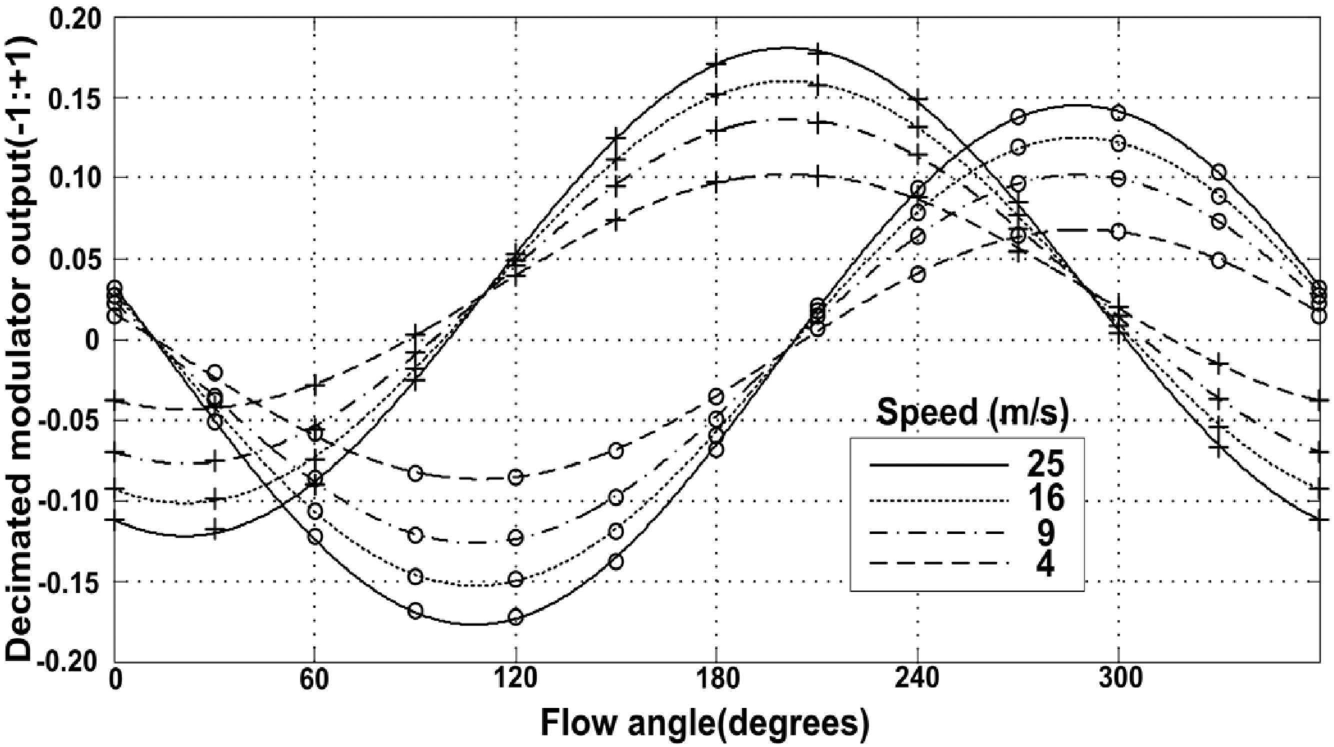
Smart Wind Sensor Chip

- (Mature) 1.6μm CMOS process
- Digital outputs: δP_{NS} & δP_{EW} bitstreams
- Chip dissipates 450mW
- Thermal ΣΔ modulators achieve 10-bit resolution

[Makinwa, ISSCC 2002]



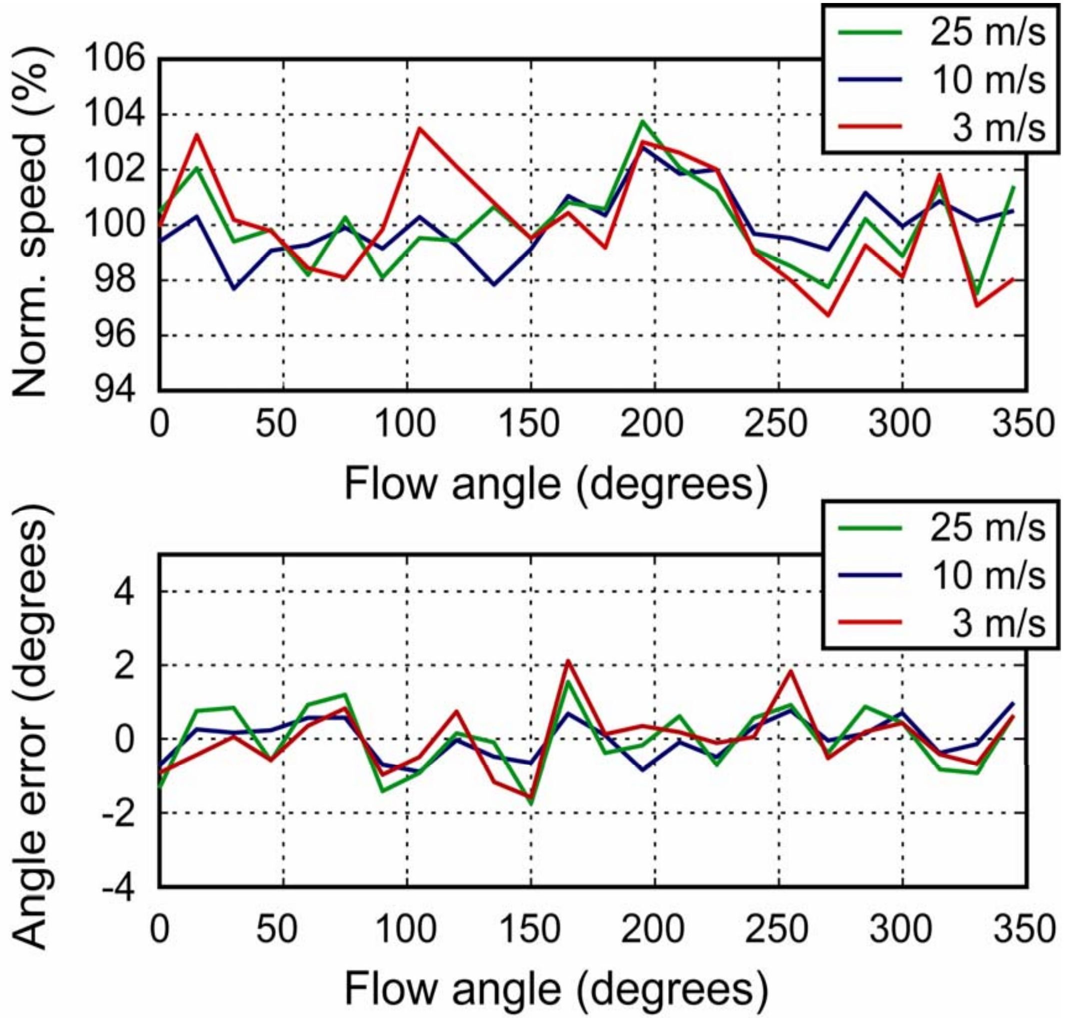
Wind Sensor Performance (1)



- Modulators output sine and cosine functions of wind speed and direction
- $|\delta P| \Rightarrow$ wind speed, $\arg(\delta P) \Rightarrow$ wind direction

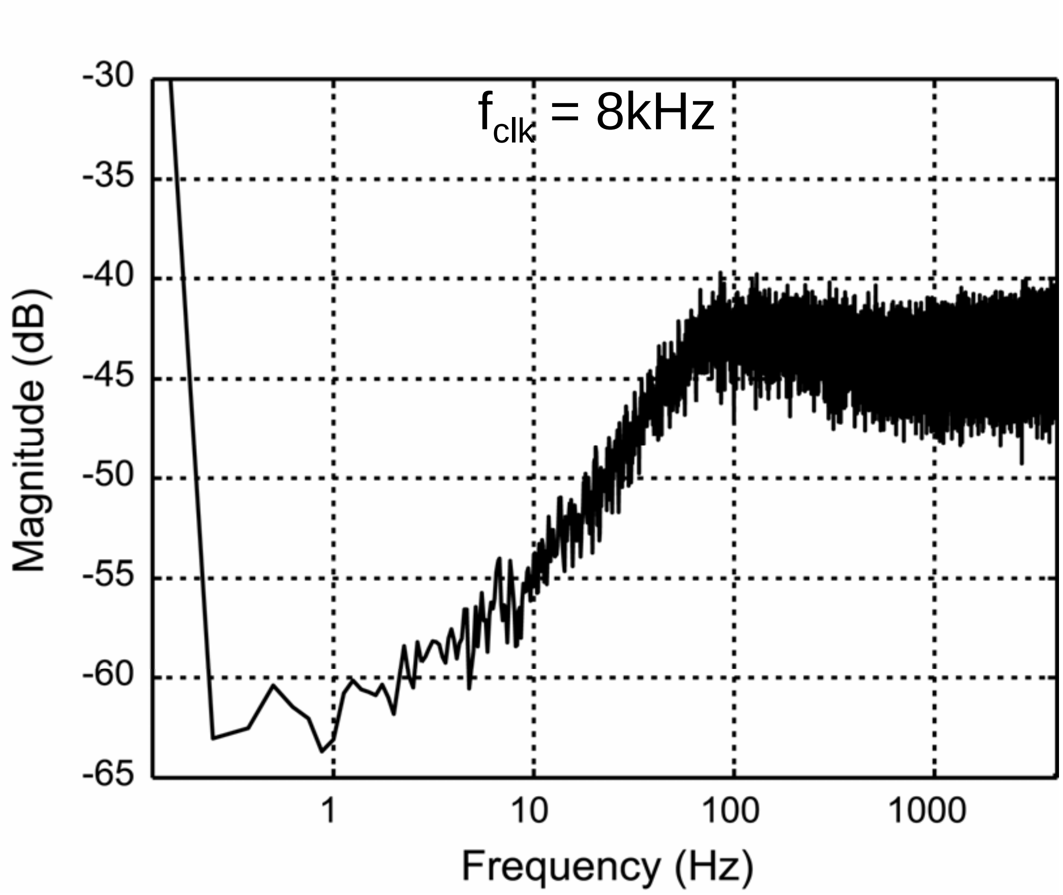
Wind Sensor Performance (2)

- Sensor is rotated in a wind tunnel
- After calibration:
  Speed error: ± 4%
  Angle error: ± 2°
- Comparable to conventional wind sensors
- But without moving parts!

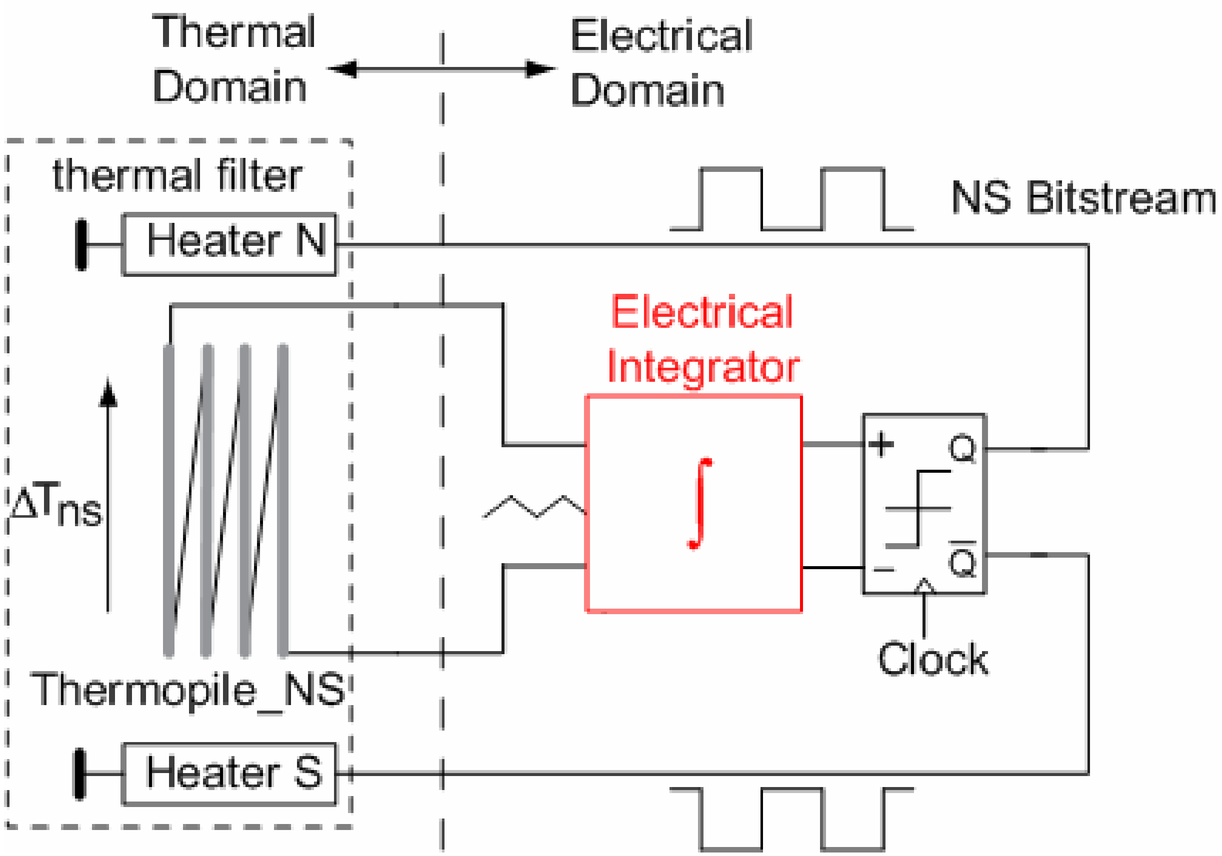


Modulator Output Spectrum

- Thermal LPF
  ⇒ Noise shaping!
- But the filter behaves like a **lossy** integrator
- So resolution is limited by Q-noise
  ⇒ wasted power!



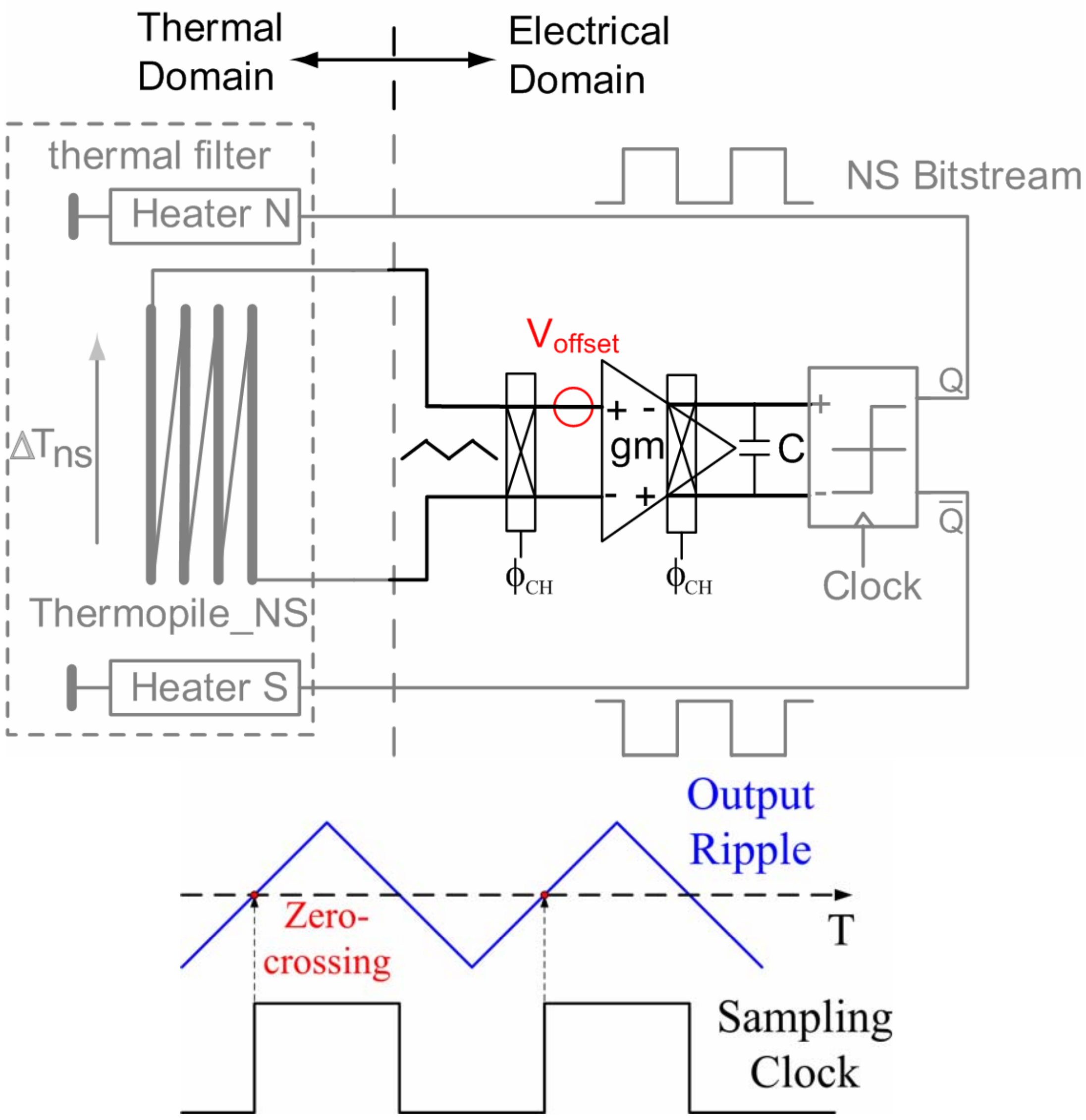
Improved Noise Shaping!



- Insert electrical Integrator after thermal LPF!

Improved Readout Electronics

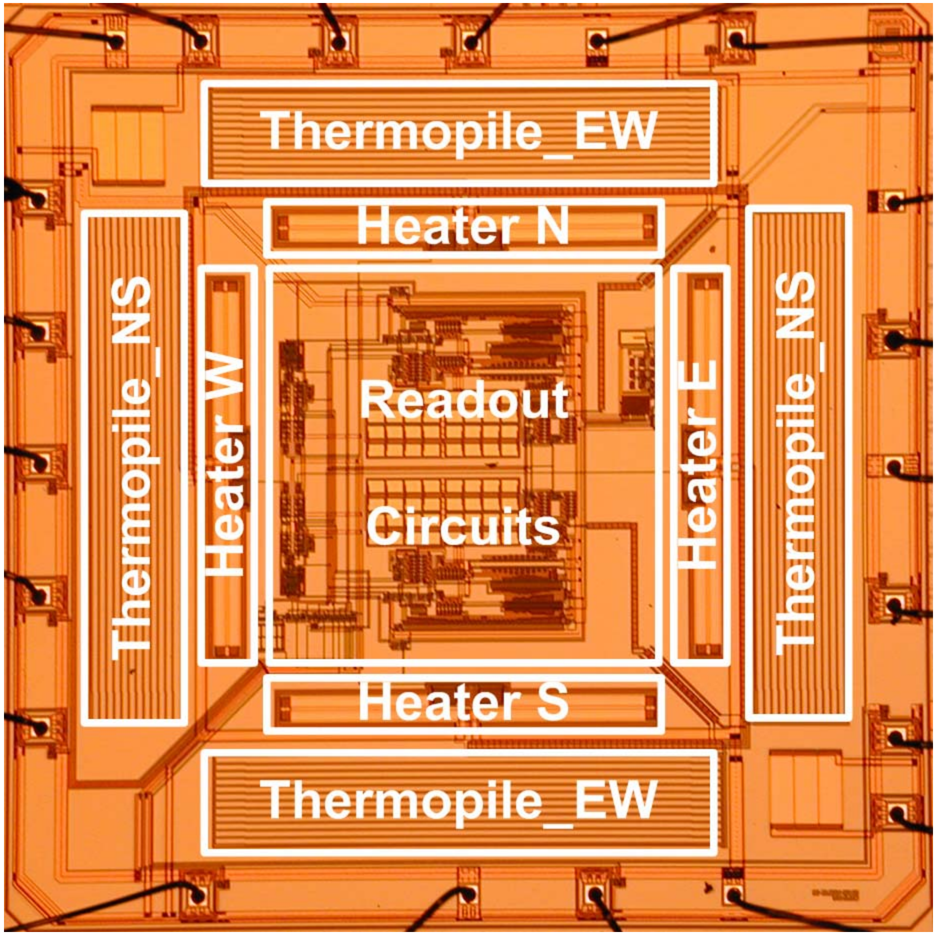
- Gm-C integrator
- Chopping instead of auto-zeroing $\Rightarrow$ lower noise and offset
- Chopper ripple? $\Rightarrow$ comparator samples ripple at zero-crossings



Smart Wind Sensor v2

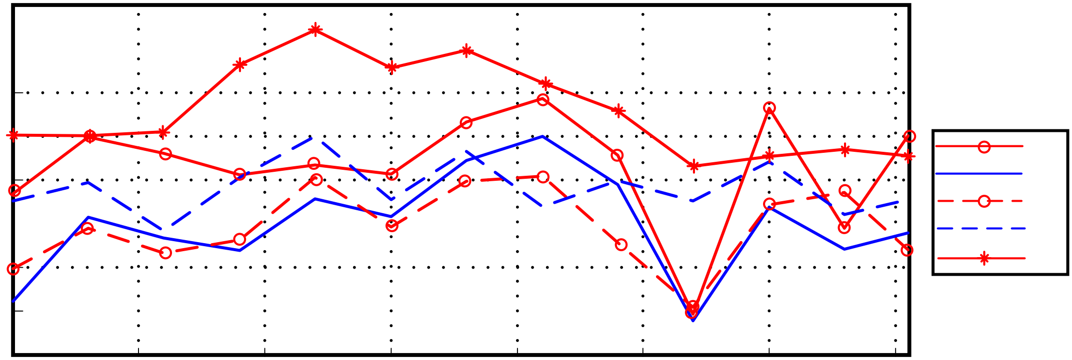
- Standard 0.7μm CMOS process
- Same size 4mm x 4mm
- But dissipates only 25mW ⇒ 18x less!
- Thermal ΣΔ modulators are now thermal-noise limited

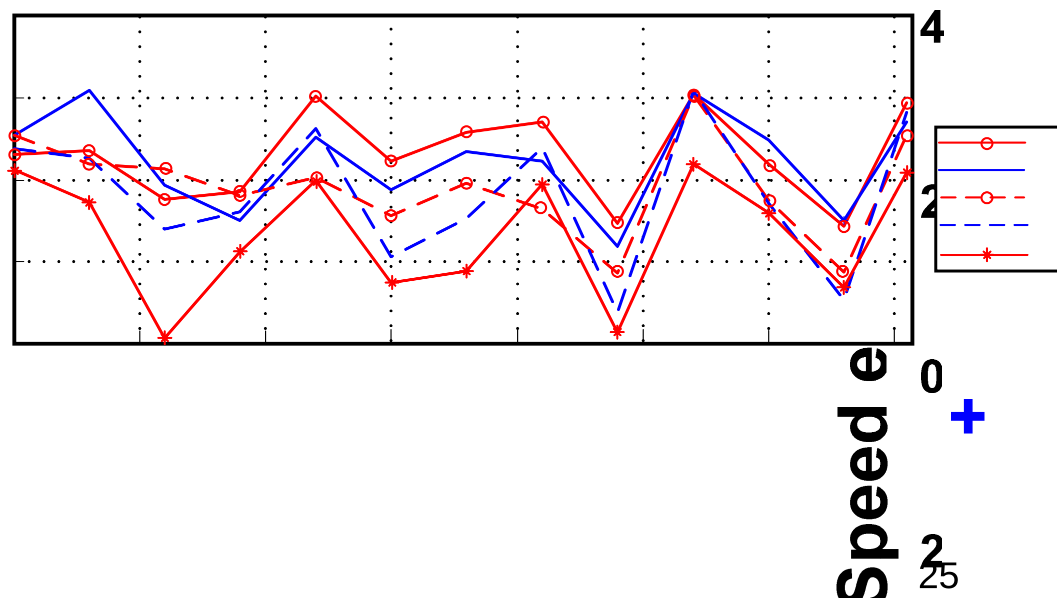
[Wu, ISSCC 2011]



Wind Sensor v2: Performance

- After Calibration:
  Speed error: ±4%
  Angle error: ±2°
- Same as before!





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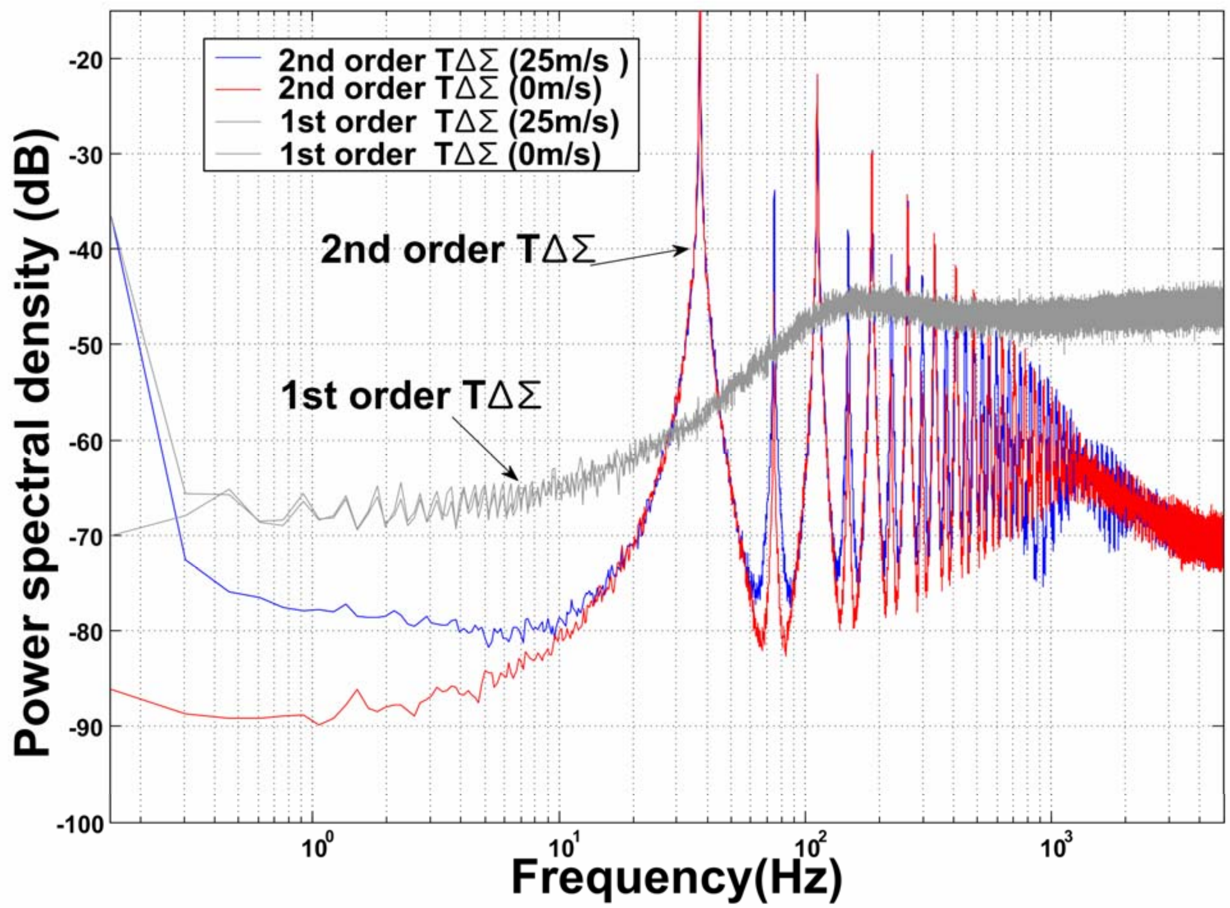
Stability?



- Thermal filter is lossy ⇒ modulator remains stable
- Noise floor is limited by wind turbulence!

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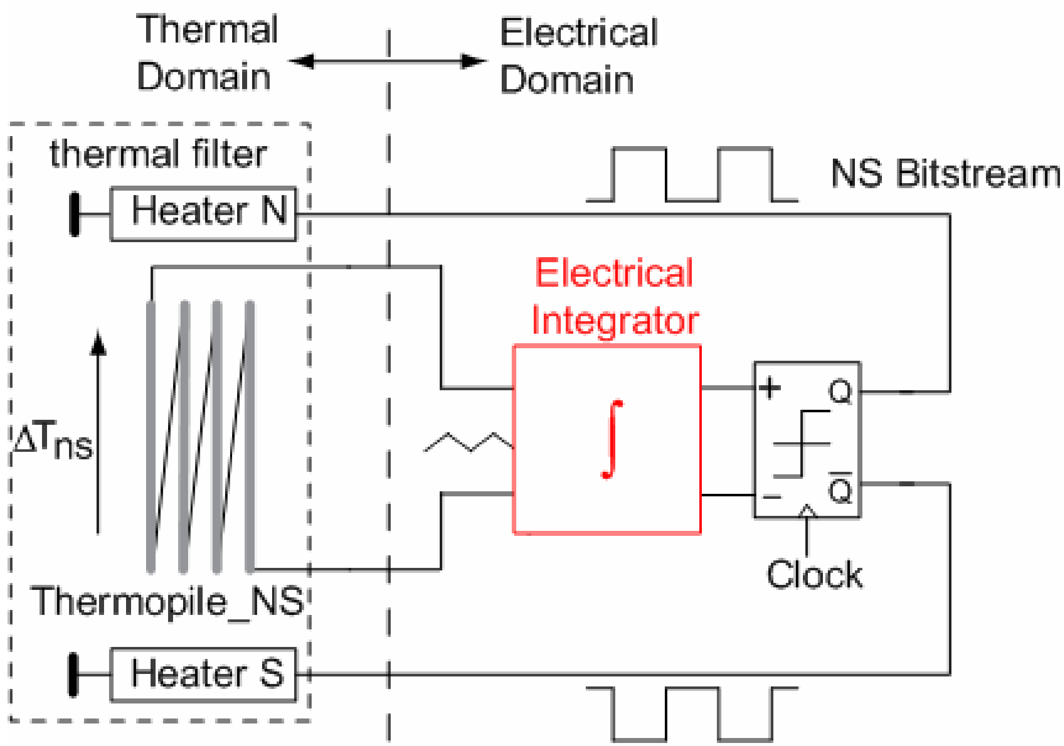
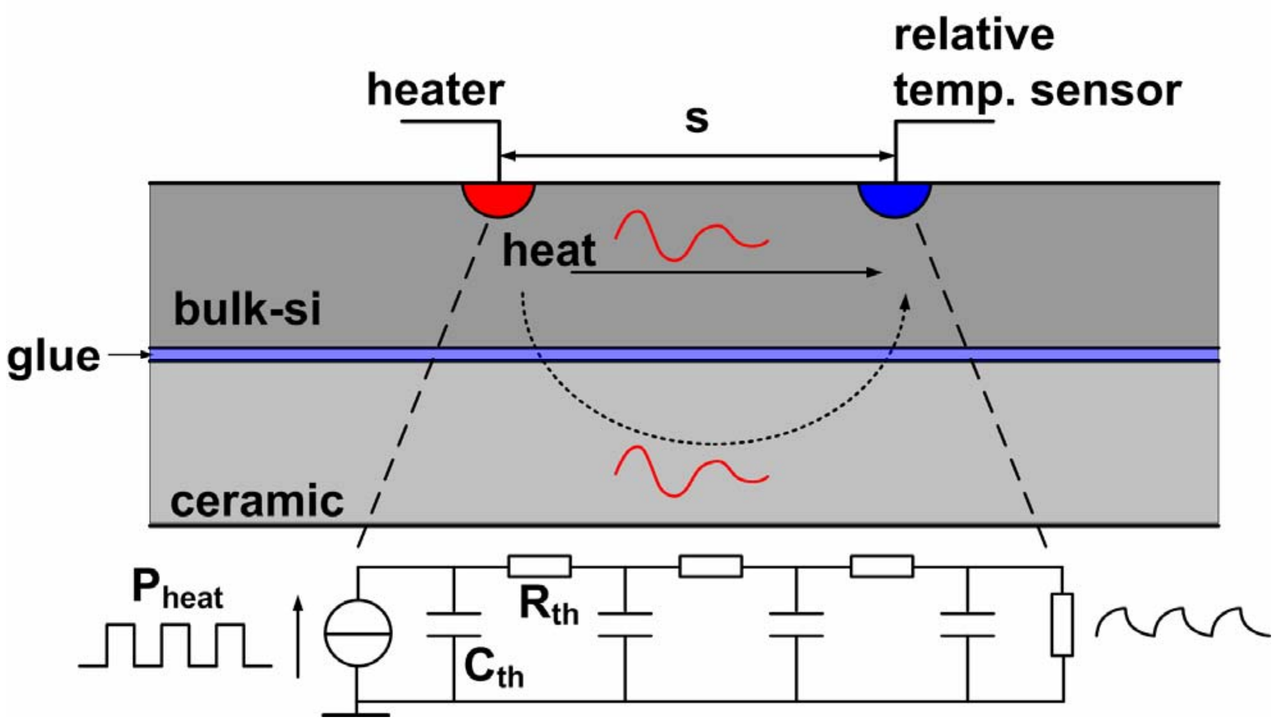
Tone Frequency?

- Strong tone occurs when $\Phi_{loop} = 180°$
- $\Phi_{integrator} = 90°$
  $\Rightarrow \Phi_{thermal} = 90°$
- So f_{tone} depends on the sensor's thermal properties



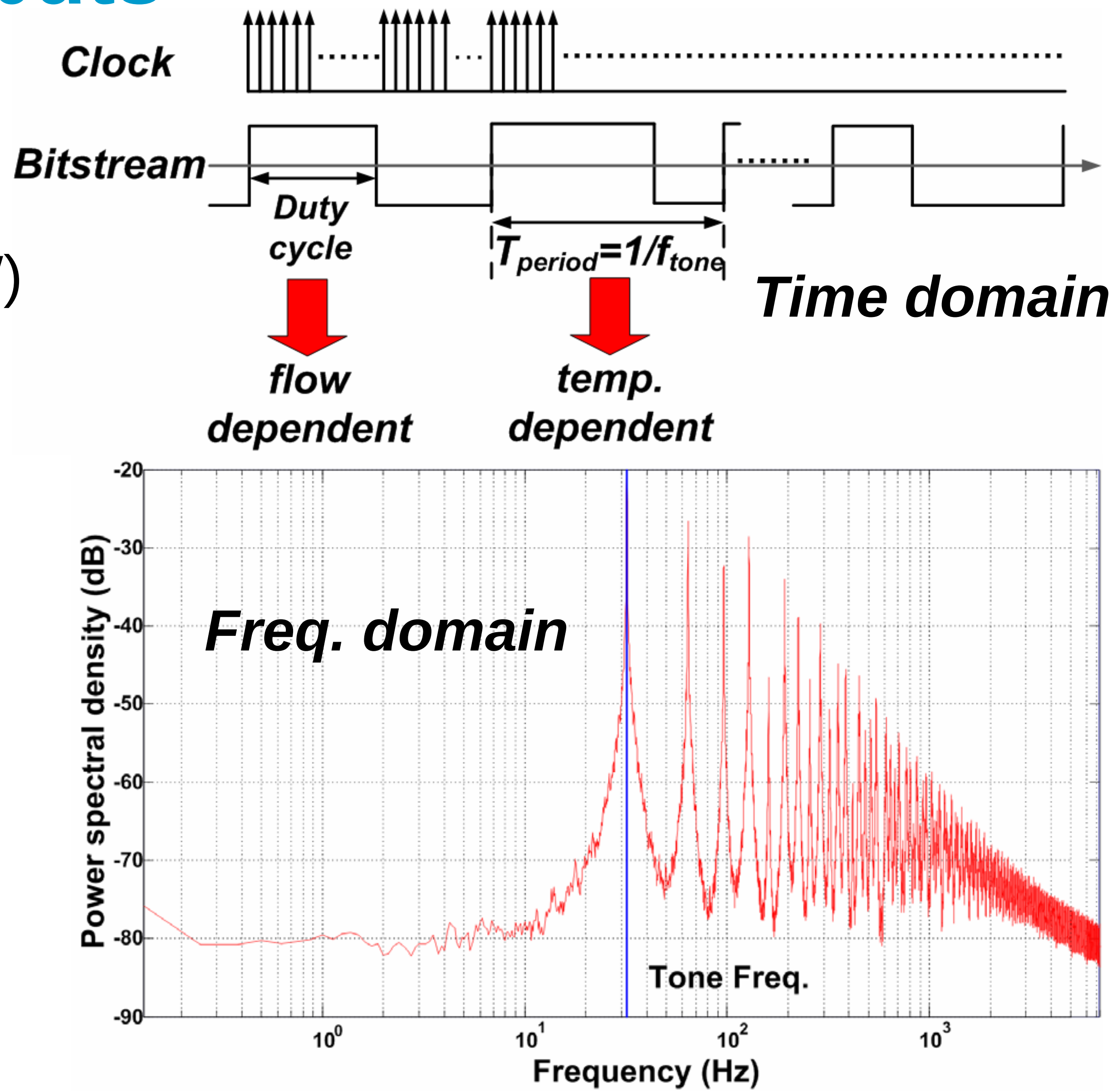
Thermal Filtering



- Heat diffuses through the silicon chip ⇒ thermal LPF
- Thermal diffusivity of silicon is *temperature-dependent* ⇒ $\Phi_{thermal}$ and f_{tone} will also be temperature-dependent

Sensor Outputs

- Sensor outputs two square waves (NS & EW)
- Duty-cycle is **flow** dependent
- Period T_{period} is **temperature** dependent !

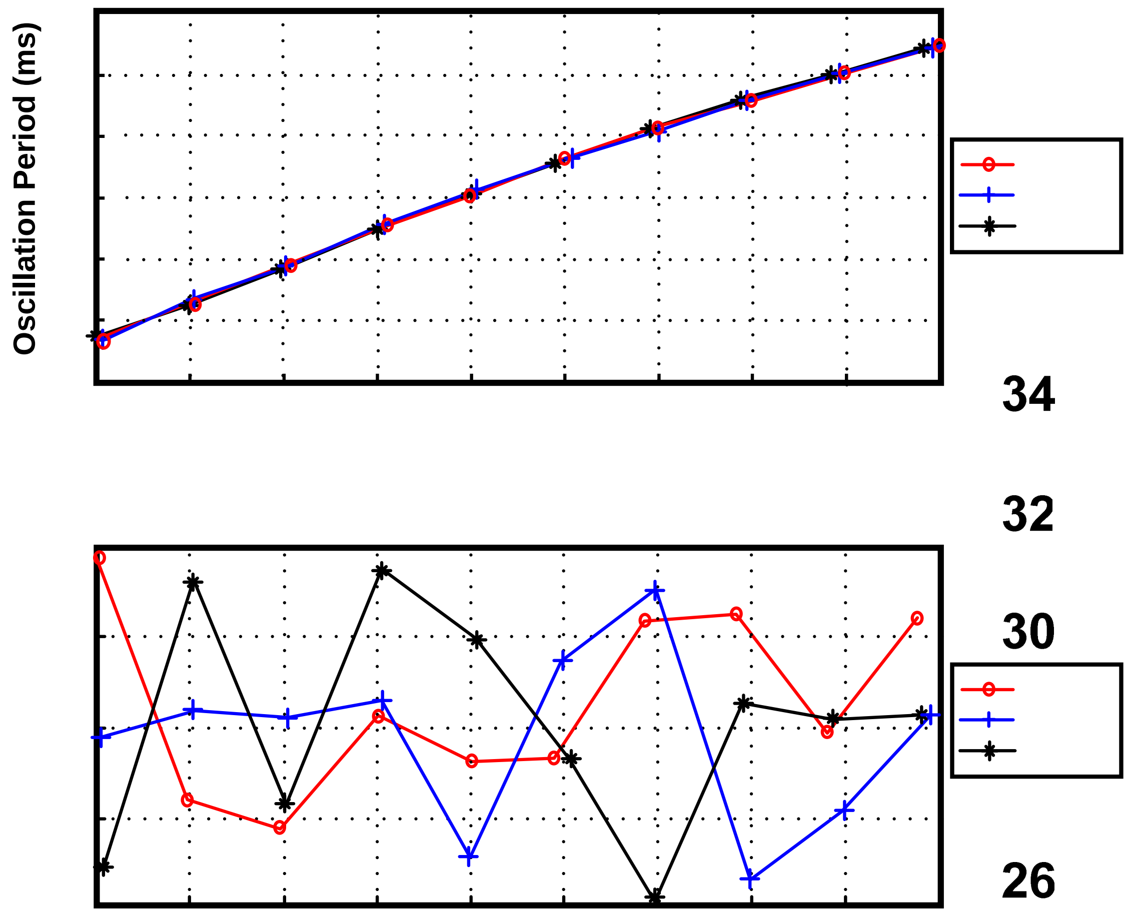


Measurement Results

- T_{period} is a monotonic function of temperature

- Equivalent temperature error ±1°C (-40 to 50°C)

- Self-heating? 25mW heater power ⇒ ~ 0.5°C



Design Methodology?

1. System design: sensor's thermal inertia is used to realize **simple** thermal balancing control loops

   Bonus: enables temperature-sensing functionality!

2. Digitize early: sensor is embedded in a $\Sigma\Delta$ modulator
3. Be dynamic: Chopping cancels offset and1/*f* noise

System accuracy and resolution are determined by the sensor $\Rightarrow$ interface does no harm!

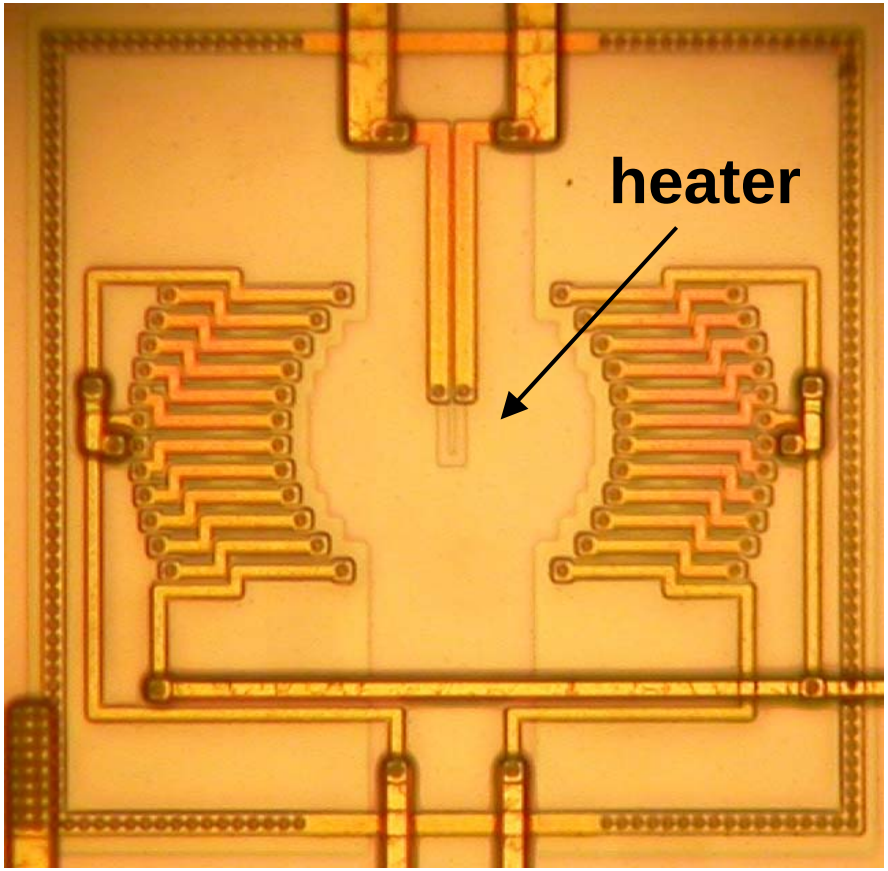
Better Thermal Diffusivity Sensor

- Thermopiles surround heater
- Reduced heater/sensor spacing = 24μm

⇒ better SNR

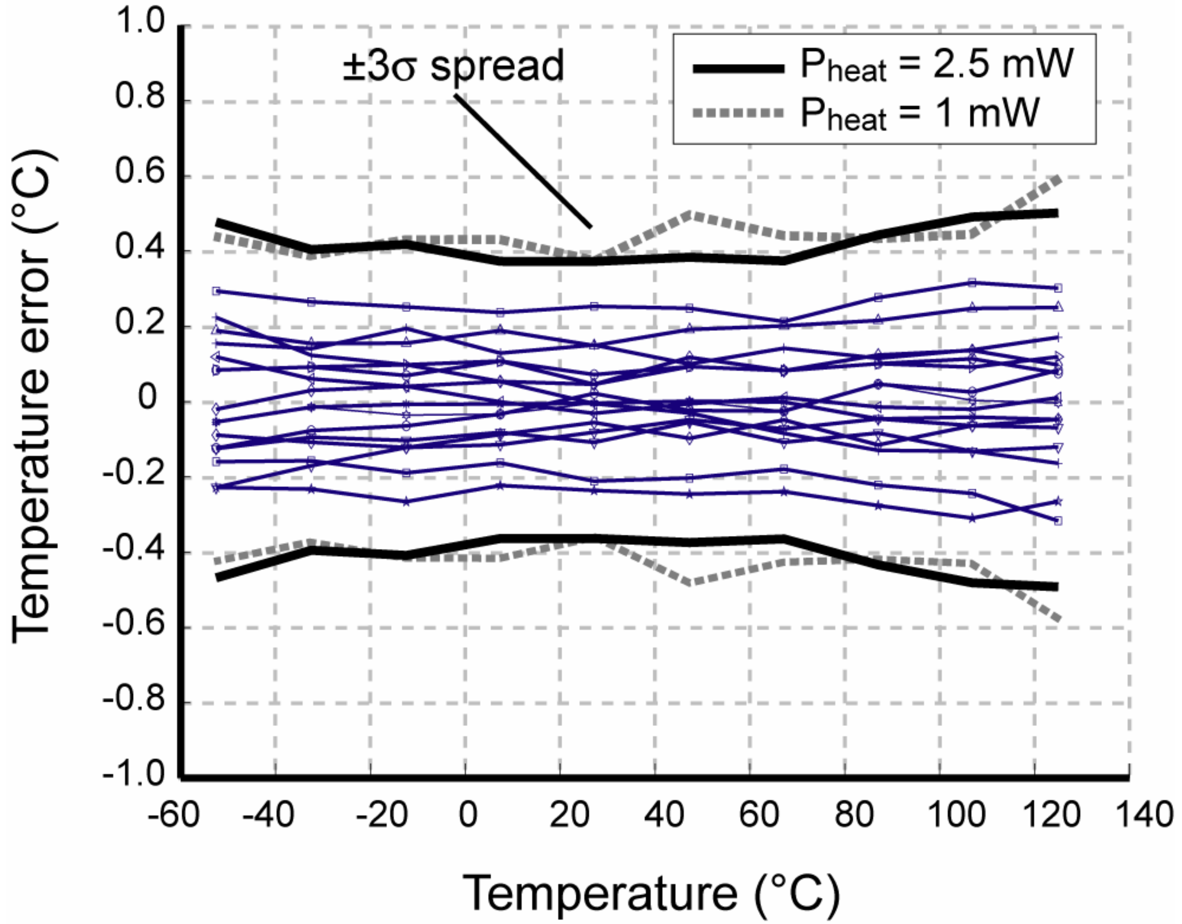
- Silicon is pure
- Spacing is fixed by lithography

⇒ $\Phi_{thermal}$ is well-defined?



Measurement Results

- 0.7μm CMOS
  ⇒ 0.5°C error
- 0.18μm CMOS
  ⇒ 0.2°C error
- Error **is** limited by lithography!
- More accurate than PNP-based temp sensors!



[van Vroonhoven, ISSCC '10, CICC '11]

Other Interfacing Examples

1. Temperature sensors [Pertijs, JSSC ’05, Souri, JSSC ’11]
   Trimming, chopping, CDS, DEM, $\Sigma\Delta$ modulation
   $\Rightarrow$ 0.1°C inaccuracy and mK resolution

2. Magnetic field sensors [van der Meer, ISSCC ’05]
   Trimming, chopping, CDS, $\Sigma\Delta$ modulation
   $\Rightarrow$ 4μT offset and nT resolution

3. Bridge readout ICs [Wu, ISSCC ’11]
   Nested chopping, DEM
   $\Rightarrow$ 50nV offset, 0.04% gain error

4. Precision chopper (bio-)amplifiers
   [Fan, JSSC ’11, Wu, JSSC ’11, Xu, TBioCAS ‘11]

Conclusions

- The use of **dynamic** techniques such as chopping, auto-zeroing & ΣΔ modulation enables the design of precision electronics in standard CMOS
- The following interface design **methodology** can then be used:
  - Do system design!
  - Digitize early!
  - Be dynamic!
- This has been illustrated by the design of a multi-functional **solid-state** wind sensor

Acknowledgements

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- Mierij Meteo BV
- Dutch Technology Foundation (STW)

- Thank-You for Your Attention!

- Any questions?

References

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