Sensing Temperature with Heat

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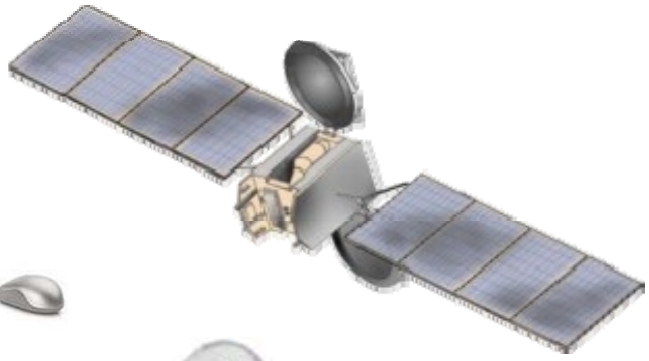
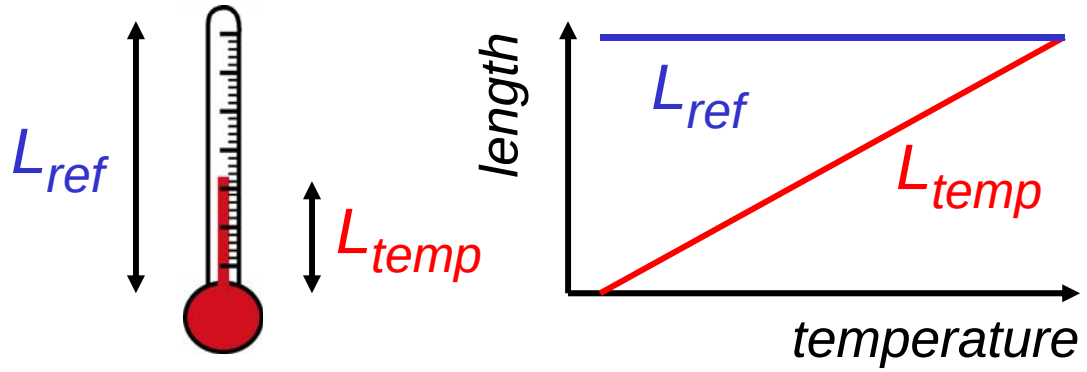
Temperature Sensors are Everywhere!

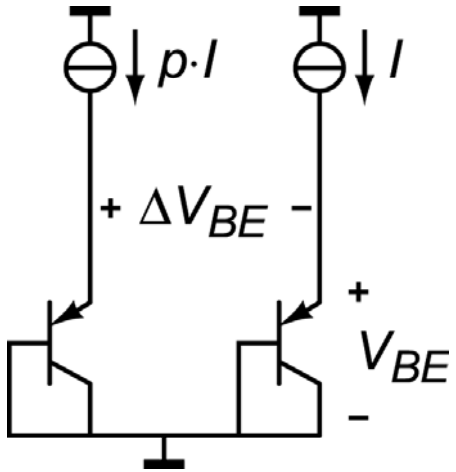


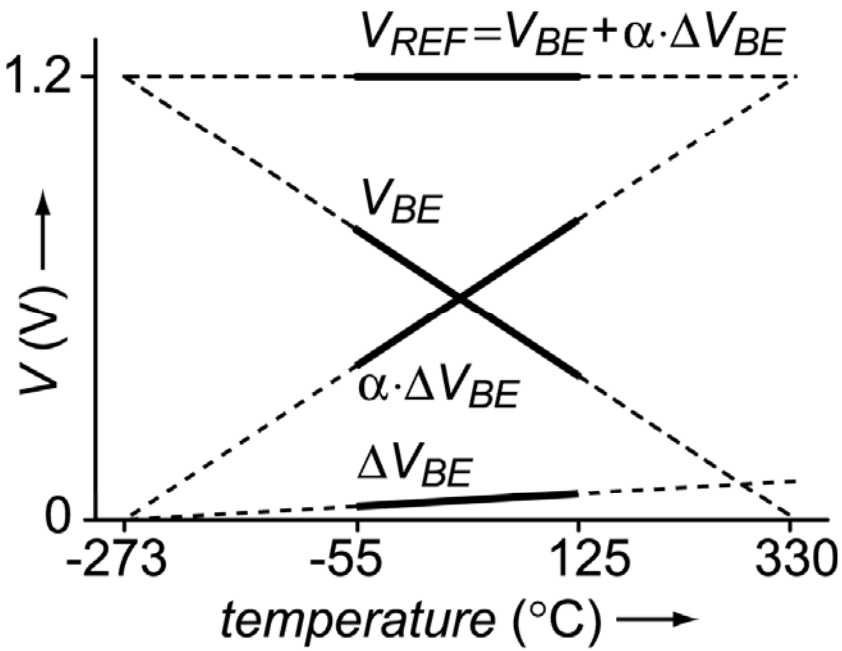
On-Chip Temperature Sensors

- Most properties of silicon are temperature dependent!
  $\Rightarrow$ resistors, diodes and transistors are all “sensors”
- But **good** temperature sensors require **two** signals:
  - a temperature dependent signal
  - a reference signal



The Band-Gap (BG) Principle

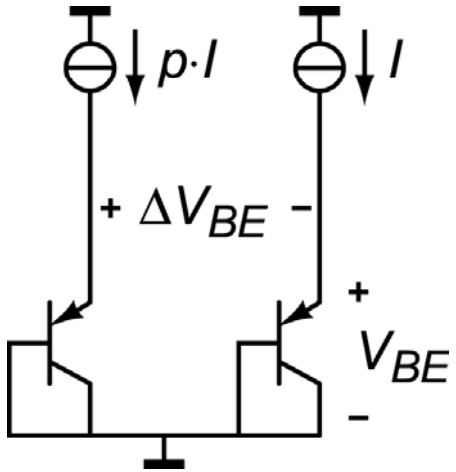




- substrate PNPs generate:
  - ΔV_{BE} proportional to absolute temp. (PTAT)
  - V_{BE} complementary to absolute temp. (CTAT)
- Combining these:

$$\mu = \frac{\alpha \cdot \Delta V_{BE}}{V_{BE} + \alpha \cdot \Delta V_{BE}} = \frac{V_{PTAT}}{V_{REF}}$$

Dominant Error Sources



$$V_{BE} = \frac{kT}{q} \ln \frac{I_C}{I_S}$$ ← **Spread!**

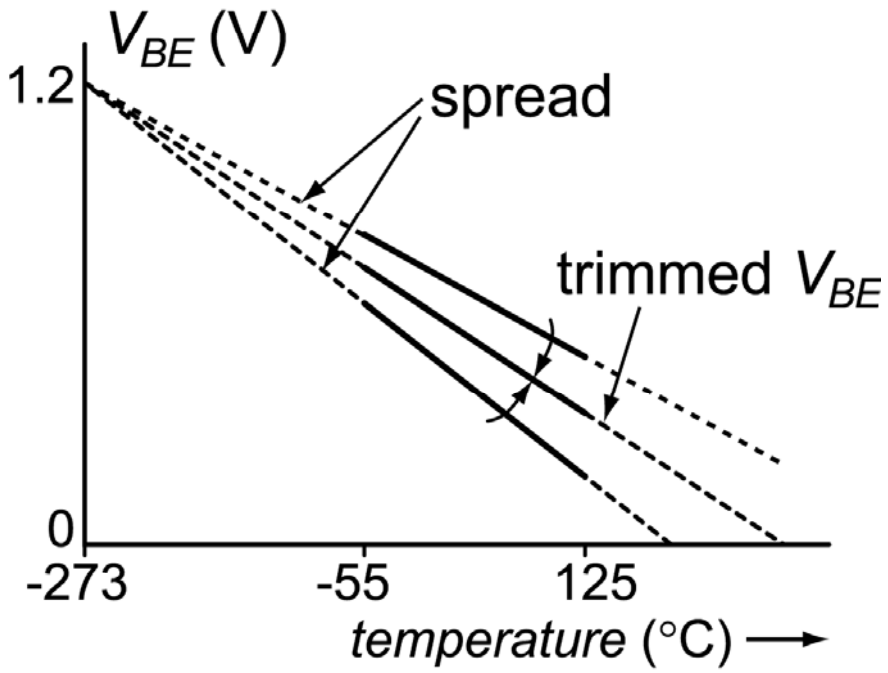
$$\Delta V_{BE} = \frac{kT}{q} \ln(p)$$ **~ 200μV/°C ⇒ Small!**

$$V_{REF} = V_{BE} + \alpha \cdot \Delta V_{BE}$$

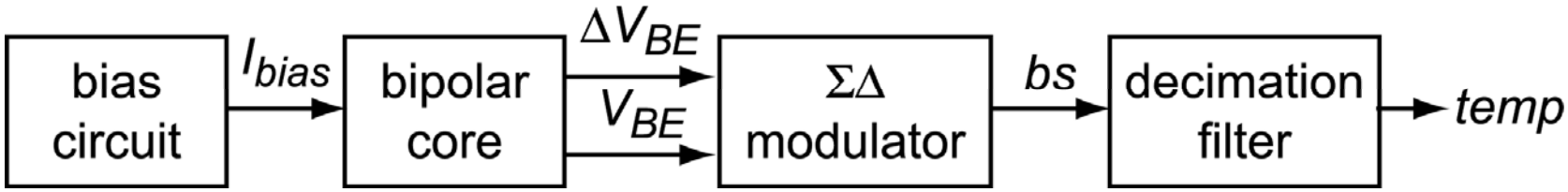
- **process spread** of V_{BE} ⇒ errors of ~3°C
- **offset** in ΔV_{BE} read-out: 10μV ⇒ 0.1°C error
- **errors** in ln(p) term and gain α: 0.1% ⇒ 0.2°C error

Single-Temperature Calibration

- process spread
  $\Rightarrow$ PTAT error in V_{BE}
- So single-temperature trim is sufficient
  e.g. by trimming I_C
- But all other (circuit) errors must be made negligible …

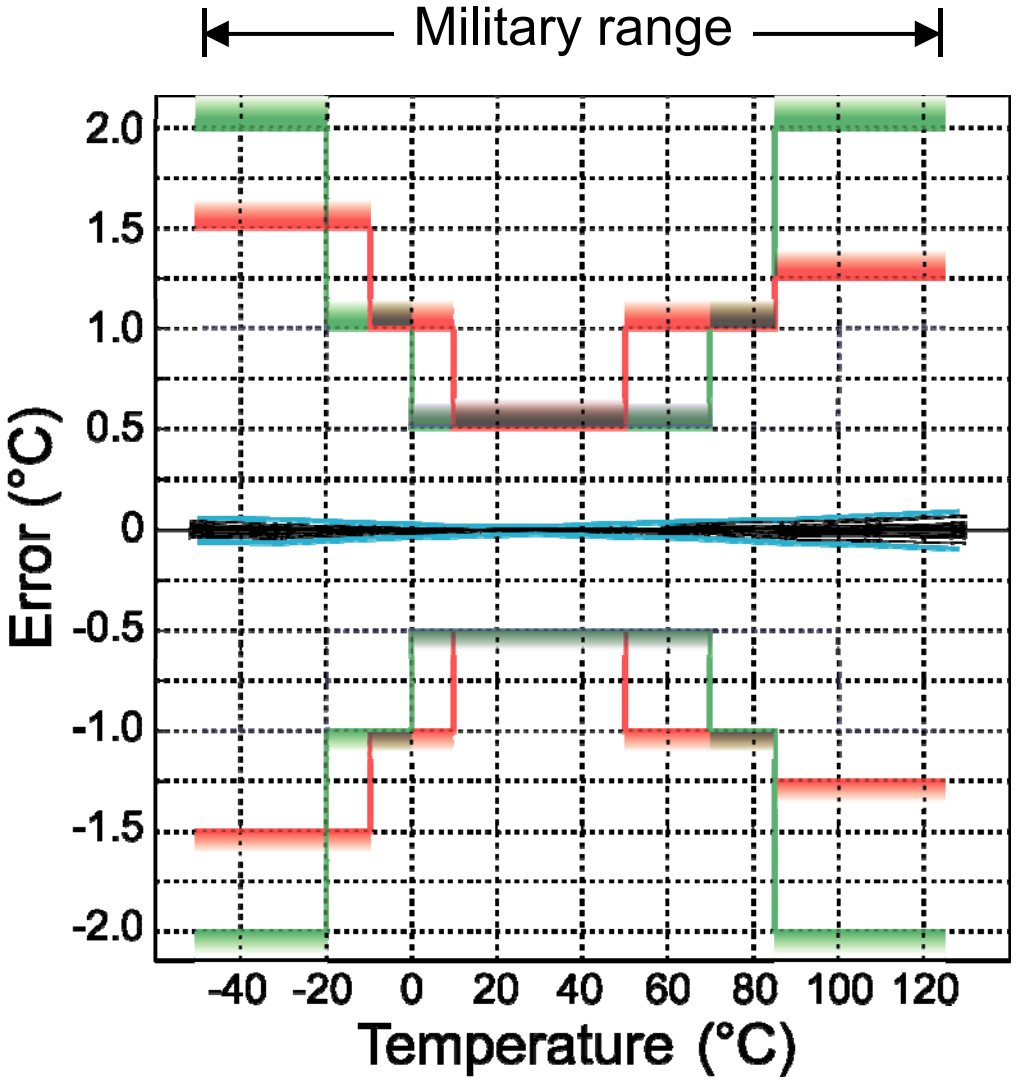


BG Temp Sensor: Block Diagram



- Bipolar core = two PNP transistors
- Bias circuit generates a programmable current I_{bias}
  $\Rightarrow$ Room temperature V_{BE} trim
- ΣΔ modulator outputs a bitstream *bs* that is filtered and **scaled** by decimation filter
- Chopping, CDS and DEM minimize offset and errors in the current ratios and gain factor α

Measurement Results

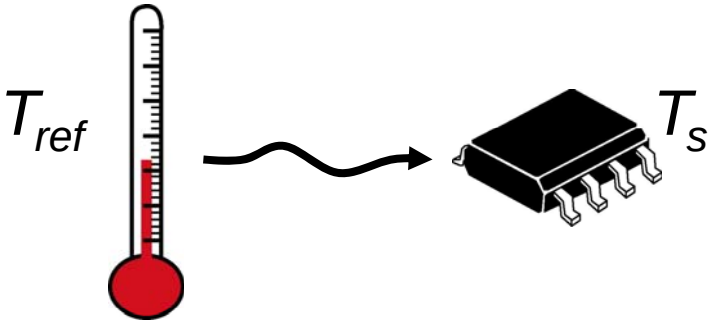


- TI TMP275
- National LM92
- Maxim DS1626
- Our design
  ±0.1°C (±3σ)
  State-of-the-art!

Pertijs, JSSC ’05

The Calibration Problem

- Process spread $\Rightarrow V_{BE}$ must be trimmed



- Thermal time constant of package = several **seconds**
  $\Rightarrow$ calibration and trimming takes several minutes
- BUT time = money!

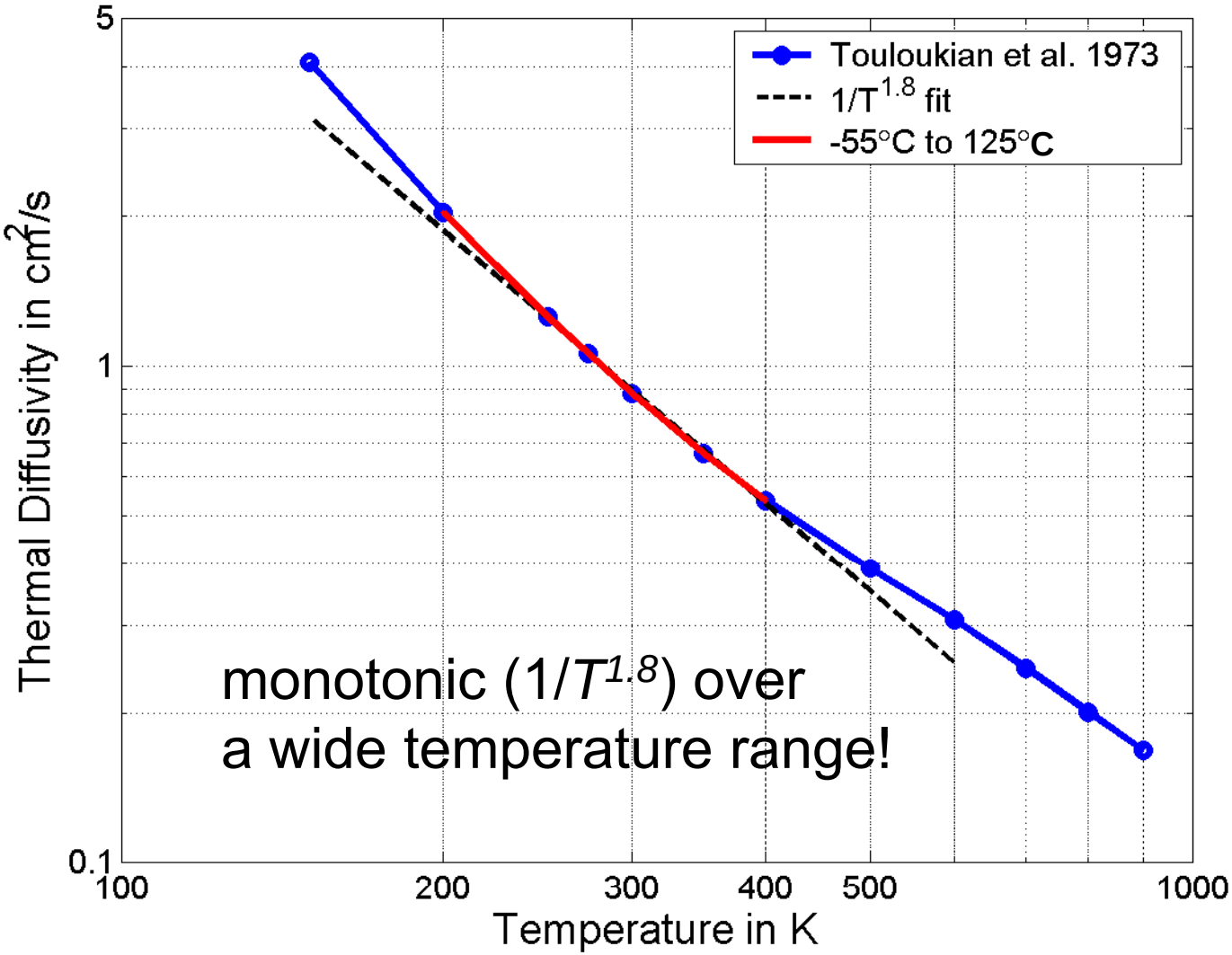
  So most commercial sensors are calibrated in <1s at one temperature $\Rightarrow$ inaccuracies of ~ 0.5°C

Better Temperature Sensors?

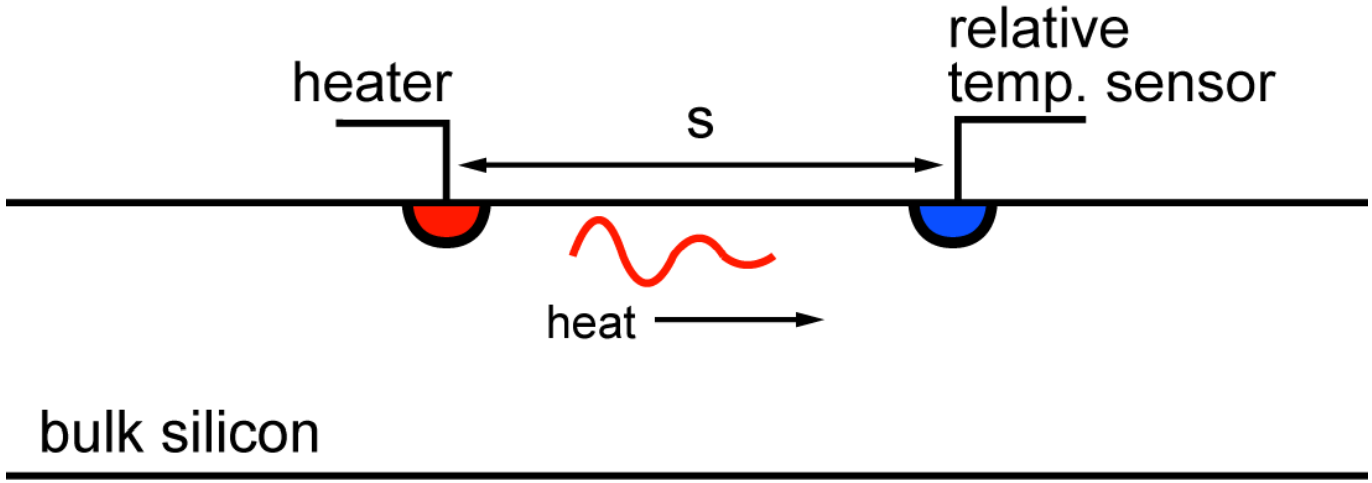
- Should exploit the strengths of nanometer CMOS
  - Fast switches (tens of picoseconds)
  - Accurate lithography (nanometers)
  - Pure silicon substrate (10^{-8})

- But the **electrical** properties of silicon are strongly affected by doping variations
- Why not measure one of the **other** physical properties of the substrate?

Thermal Diffusivity of Silicon



Thermal Diffusivity Sensing

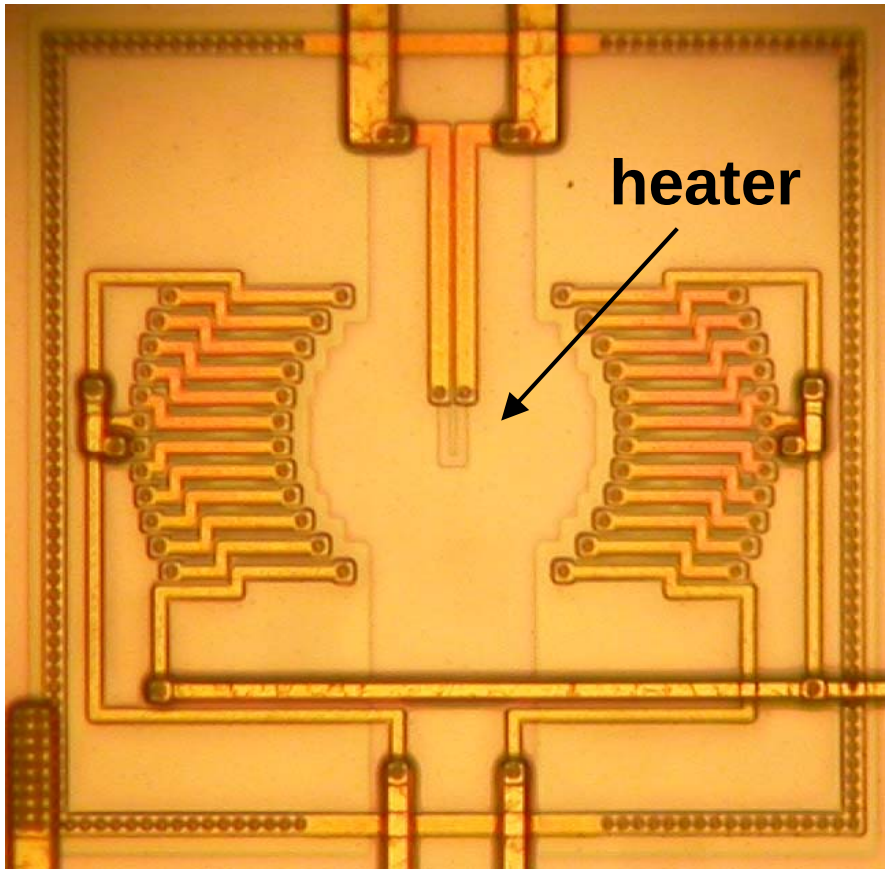


- Thermal diffusivity, D, is a function of T_{abs}
  $\Rightarrow$ temperature-dependent ***delay***
- Lithography $\Rightarrow$ accurate spacing **s**
- Pure silicon substrate $\Rightarrow$ D is well-defined

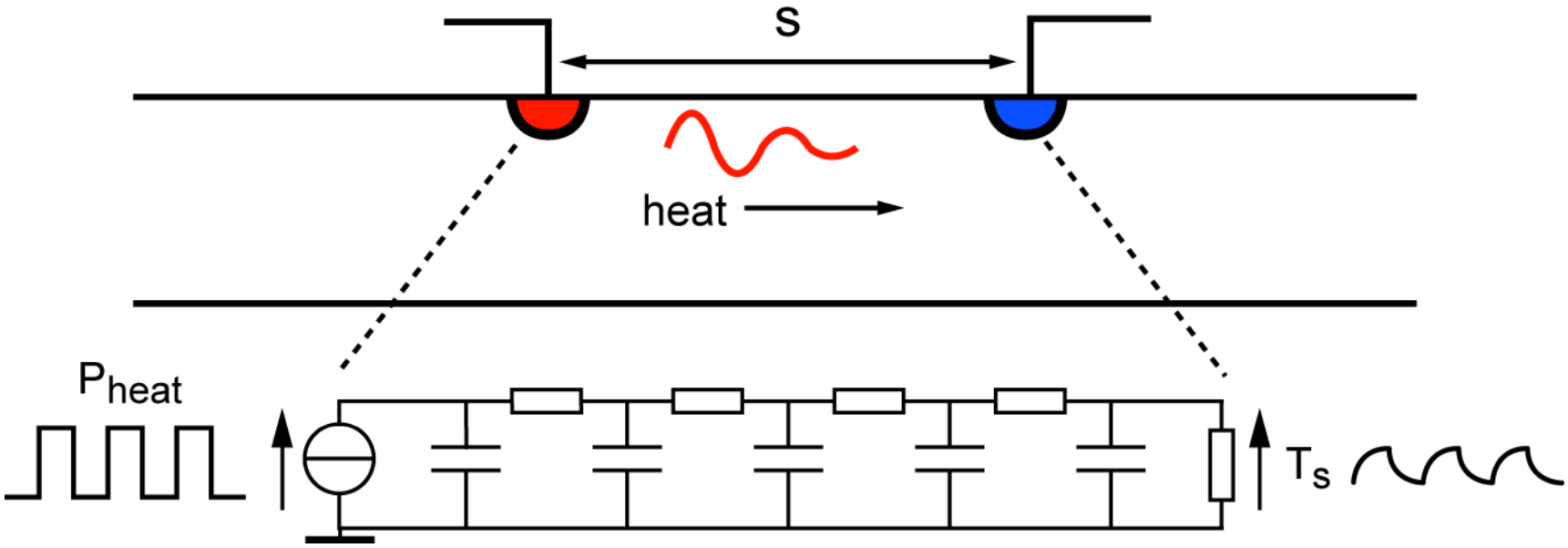
CMOS Implementation

- Heater
  = n^+ resistor
- Temp. sensor
  = p^+/Al thermopile

- Silicon is a good heat conductor
  $\Rightarrow$ sub-mV output!
- Self-heating < 1°C
  $\Rightarrow P_{heat}$ < 10mW



Sensor Characteristics

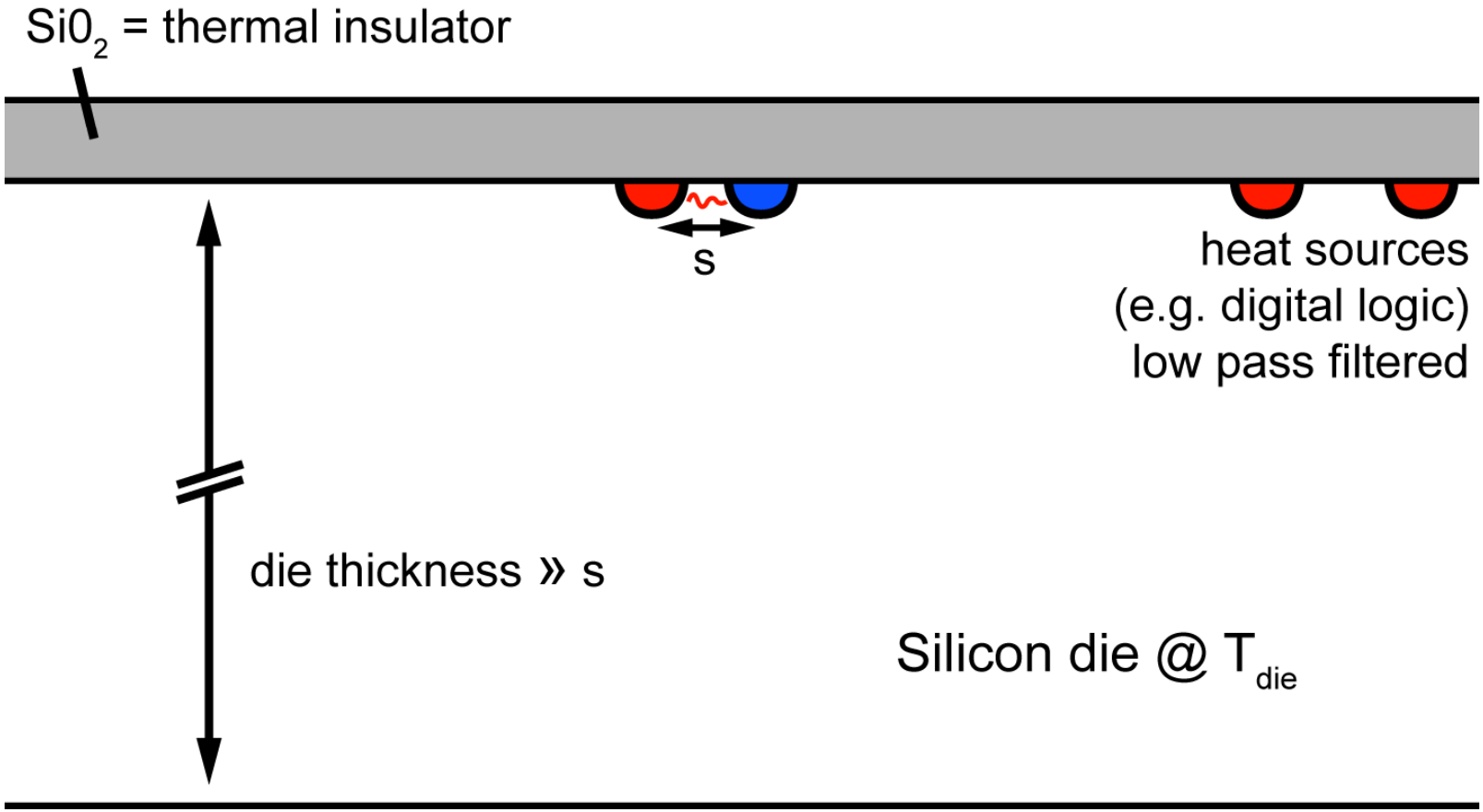


- This is actually an **electrothermal** filter (ETF) with a *temperature-dependent* phase shift

$$\phi_{ETF} \propto s\sqrt{f / D}$$

- At room temp, s =20μm, f = 100kHz $\Rightarrow$ $\phi_{ETF} \sim 90°$

CMOS Compatibility



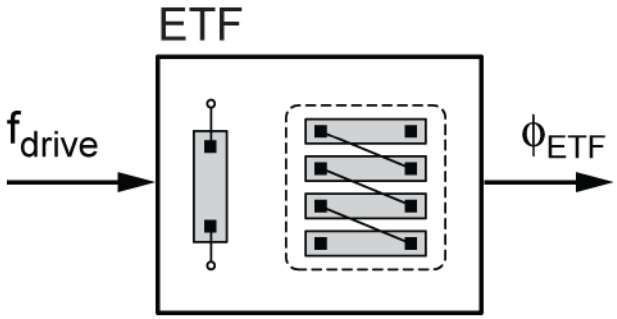
- ETFs sense ***local, AC*** temperature signals and are well insulated from the chip's packaging

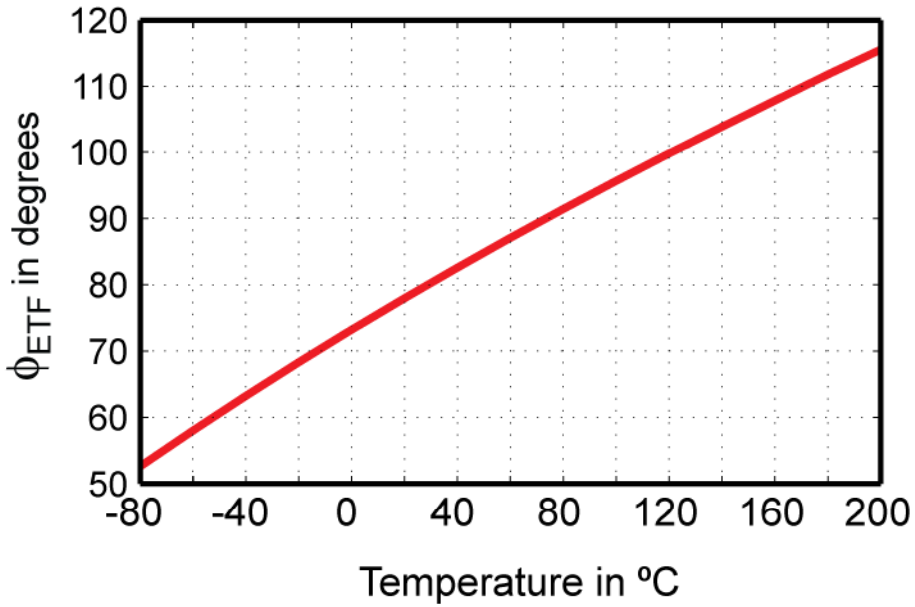
ETF Phase Response

- f_{drive} = const
  $\Rightarrow \phi_{ETF}(T)$ is
  nearly linear

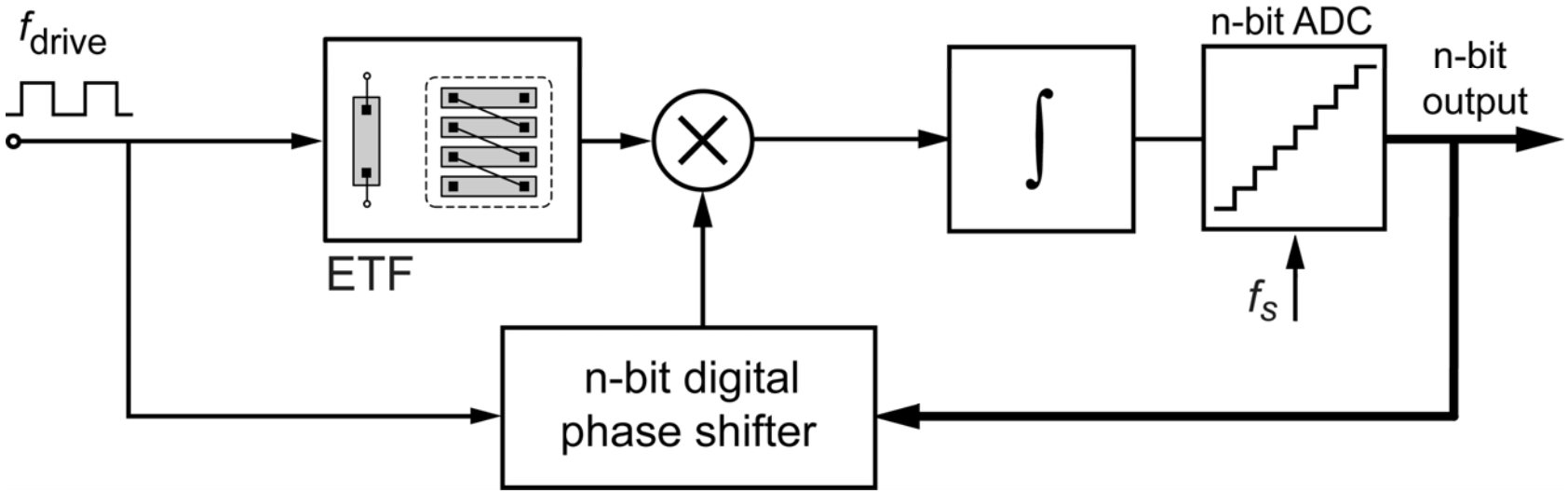
- In the military range:
  60º < ϕ_{ETF} <100º
- Sensitivity: **0.2º/K**

- So we need a precision phase detector …



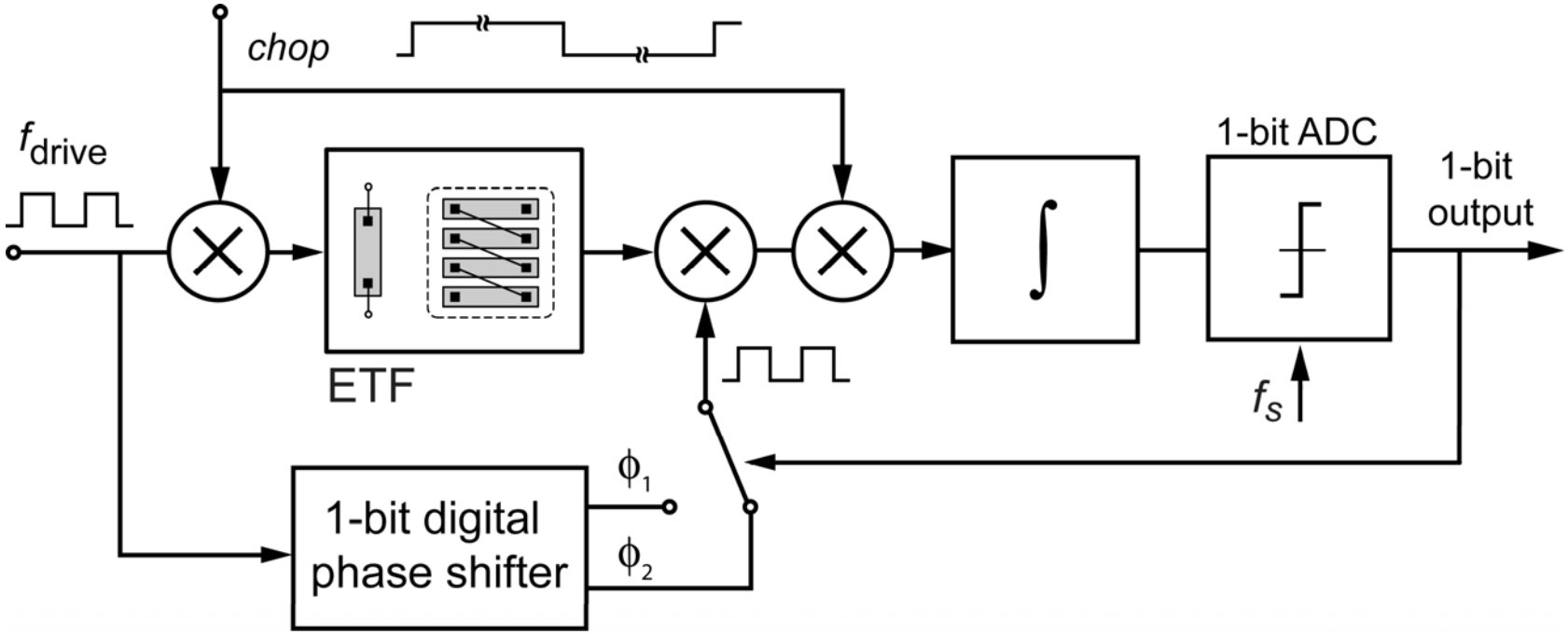


Phase-Domain ΣΔ Modulator



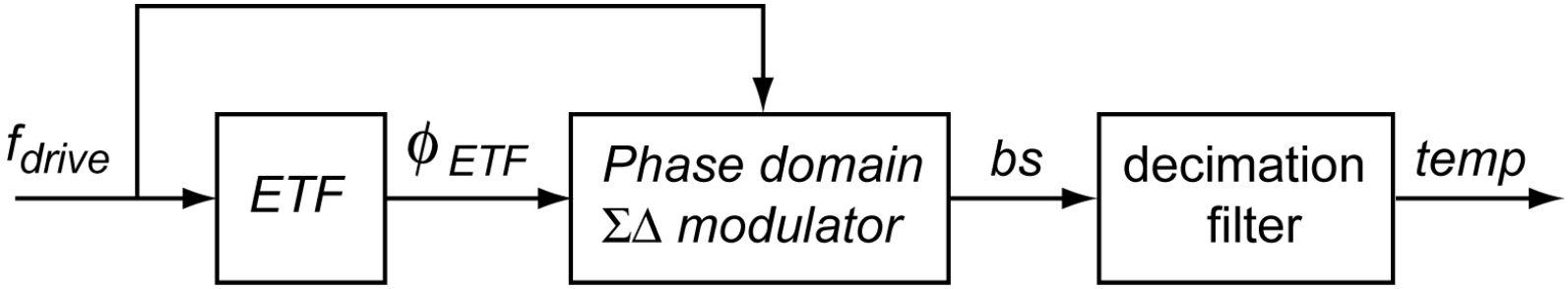
- Low ETF output (~1mV$_{pp}$) ⇒ synchronous phase detector
- Accuracy ⇒ null balancing with digital feedback
- Slow sensor ⇒ Over-sampling ⇒ simple 1-bit ADC
- Phase detector offset? 10μV ⇒ ~10°C error!

Chopped PD-ΣΔ Modulator



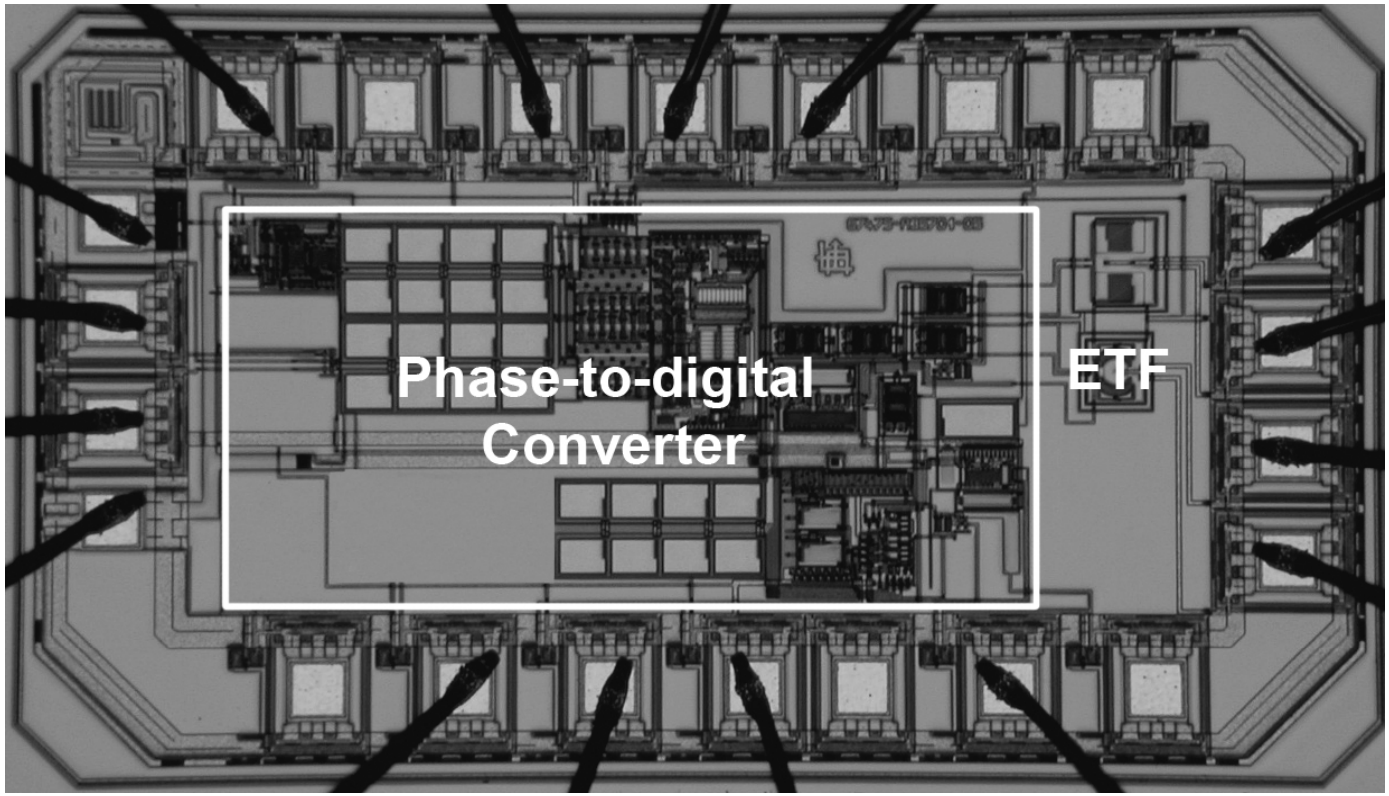
- Phase detector (chopper) offset $\propto f_{drive} \sim 100kHz$
- Low frequency (20Hz) chopping of phase detector
  $\Rightarrow$ 100nV offset $\Rightarrow$ < 0.1°C error

Smart Thermal Diffusivity Sensor



- Quartz-crystal clock generates f_{drive}
  (its 100ppm inaccuracy ⇒ 0.05°C error)
- ϕ_{ETF} is digitized by a *phase-domain* ΣΔ modulator
- ETF's resolution is limited by thermal noise
- Decimation filter limits noise BW to < 1Hz
  ⇒ < 0.1°C resolution

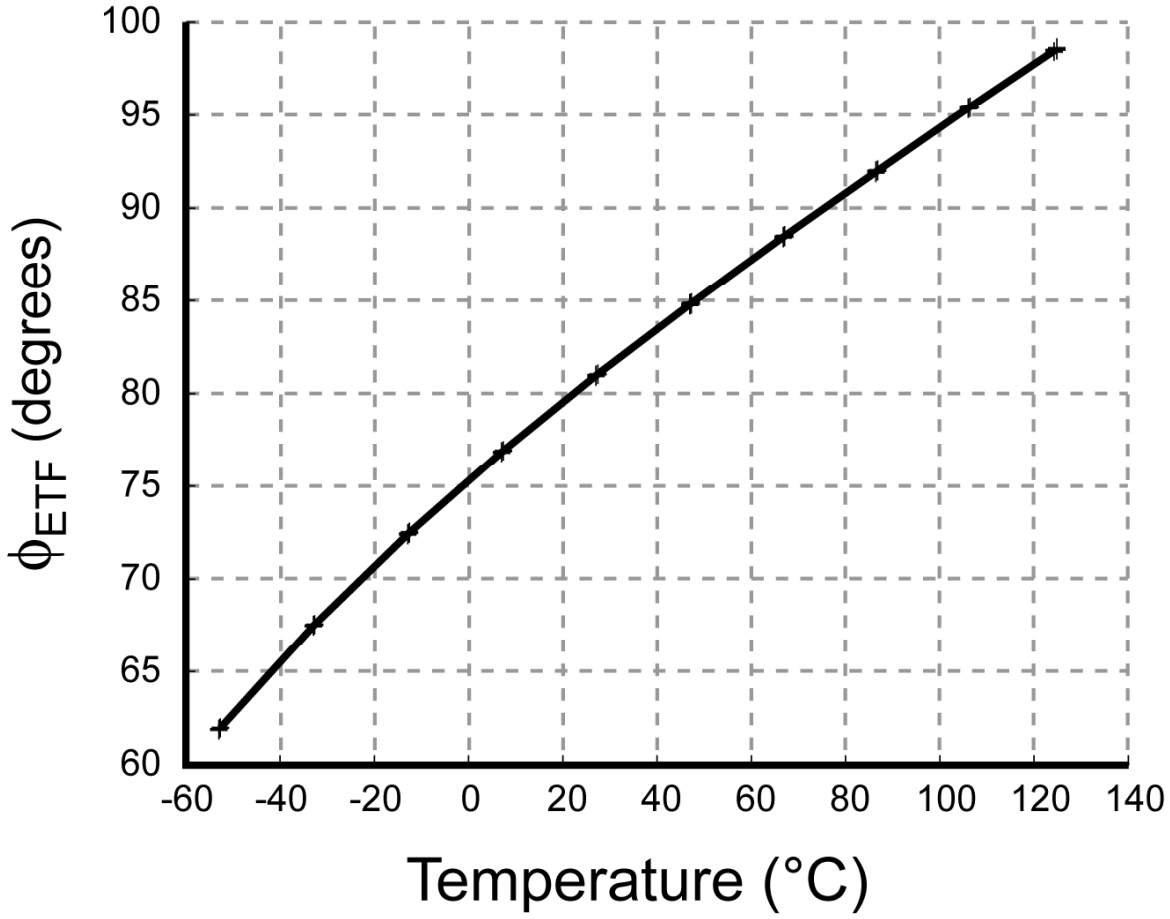
Chip Photo



- 0.7µm CMOS, active area 0.5mm^2
- $P_{circuit}$ = 2.5mW, P_{ETF} = 2.5mW

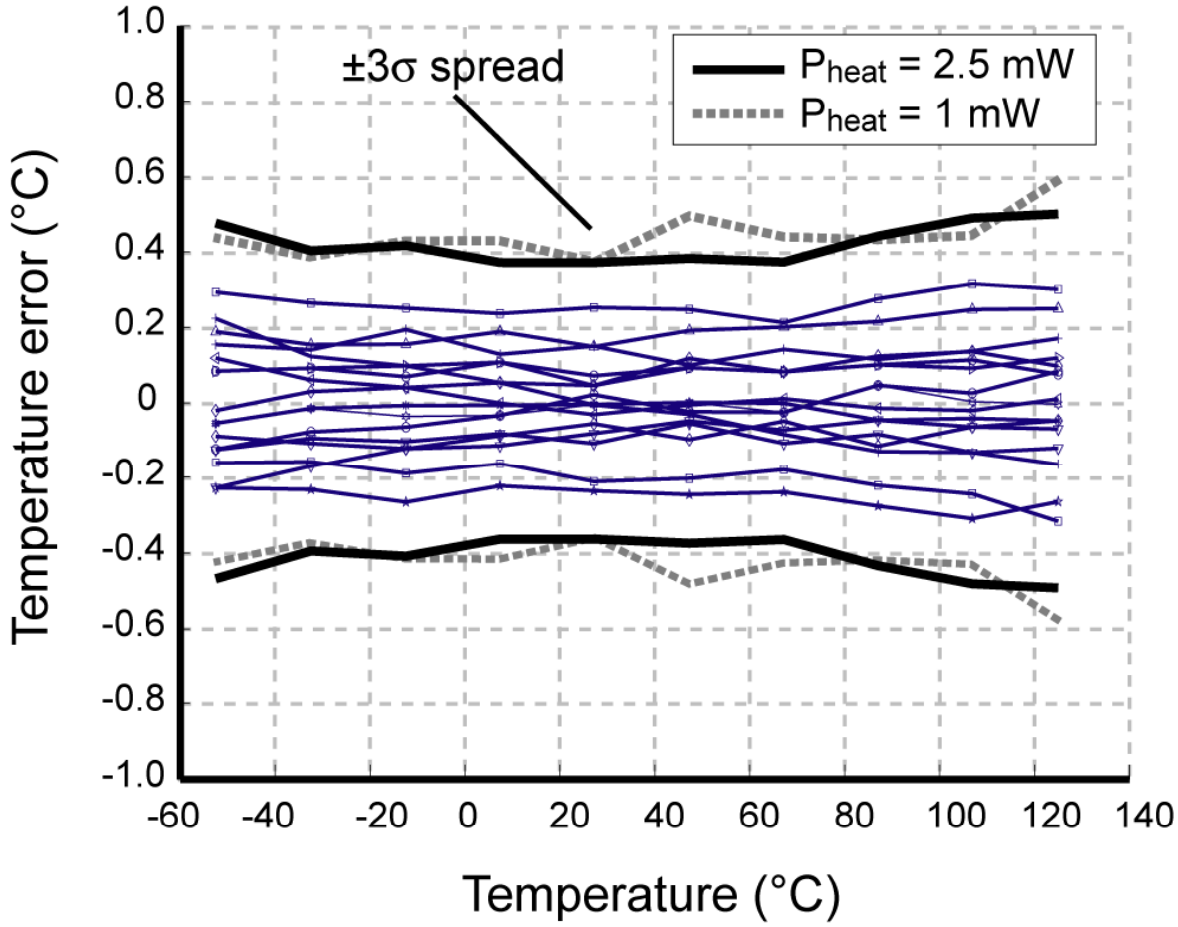
Measurement Results (1)

- f_{drive} = 85kHz
- Near-linear characteristic
- As predicted!



Measurement Results (2)

- 16 samples
- NO trimming!
- Spread is < 0.5°C (3σ)
- Comparable to batch-calibrated BG sensors

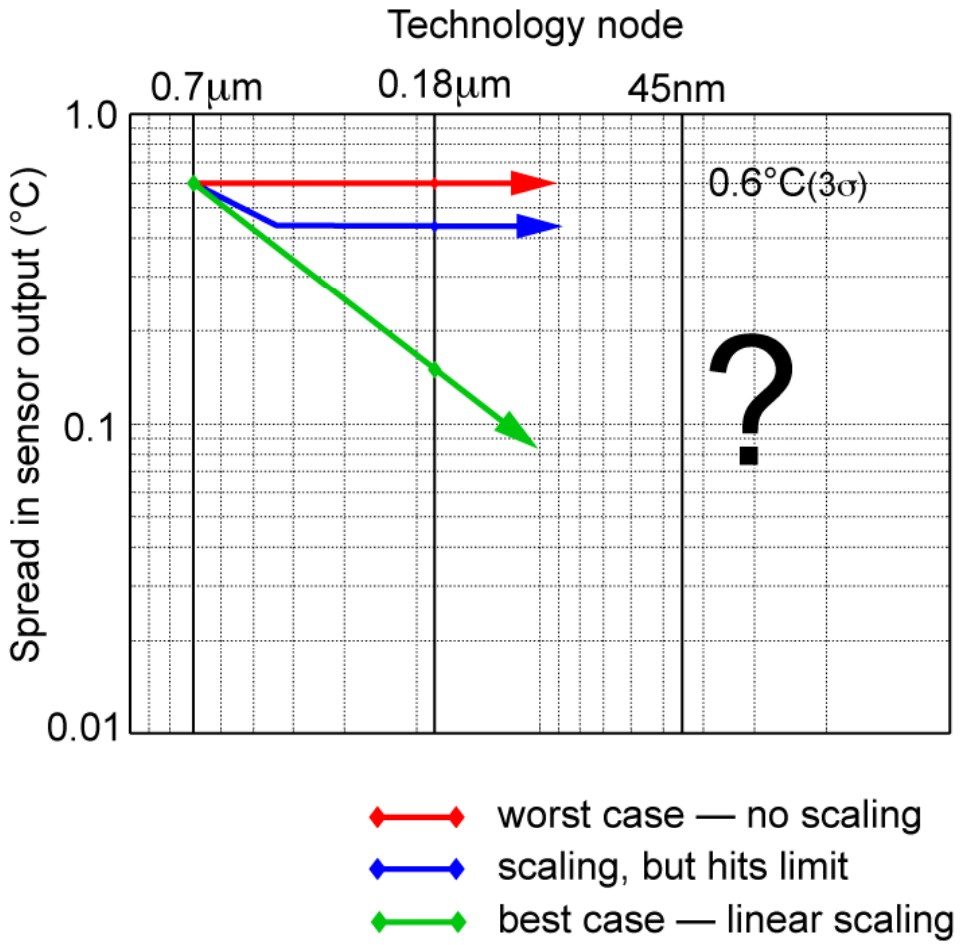


Van Vroonhoven, ISSCC08

But Does it Scale?

- Hypothesis: spread is lithography limited
- So spread in 0.18µm CMOS should be less ~ 0.15°C

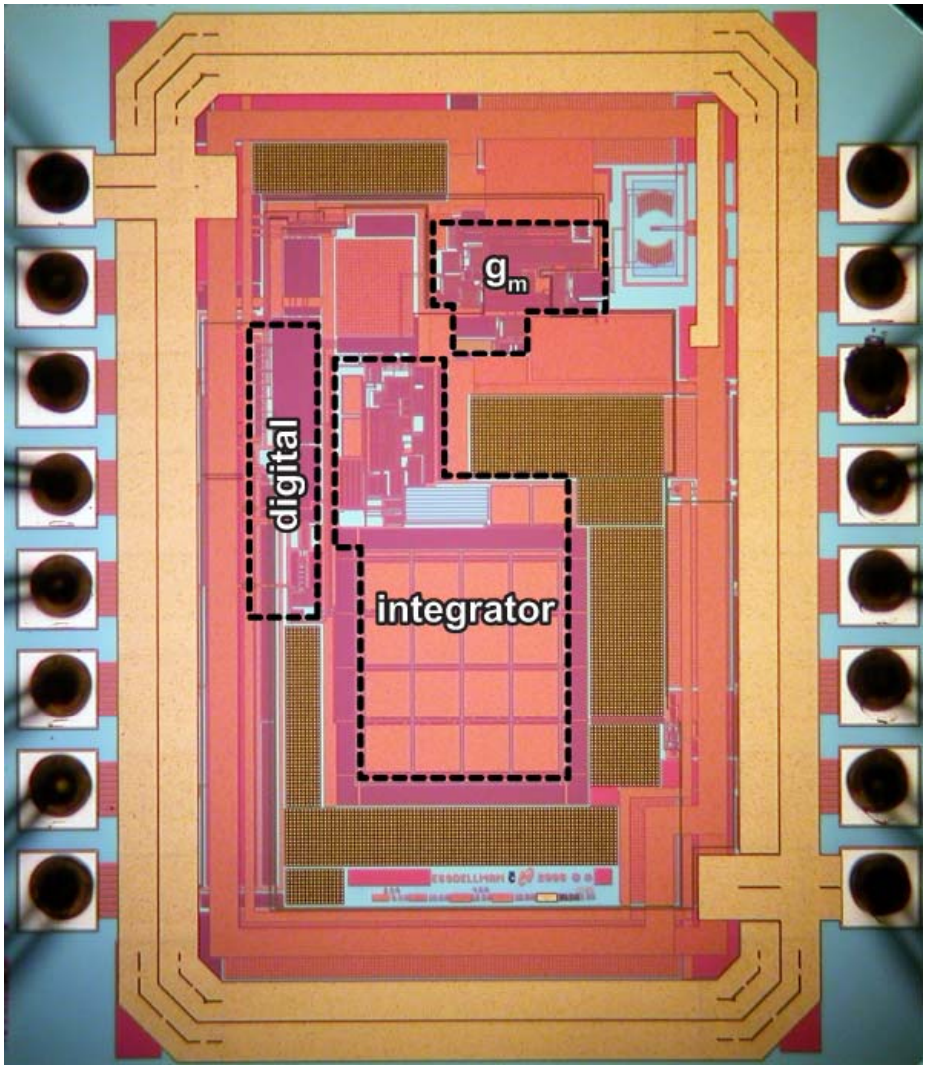
- Showstoppers?
  - Spread in *D?*
  - Packaging stress?



Chip photo

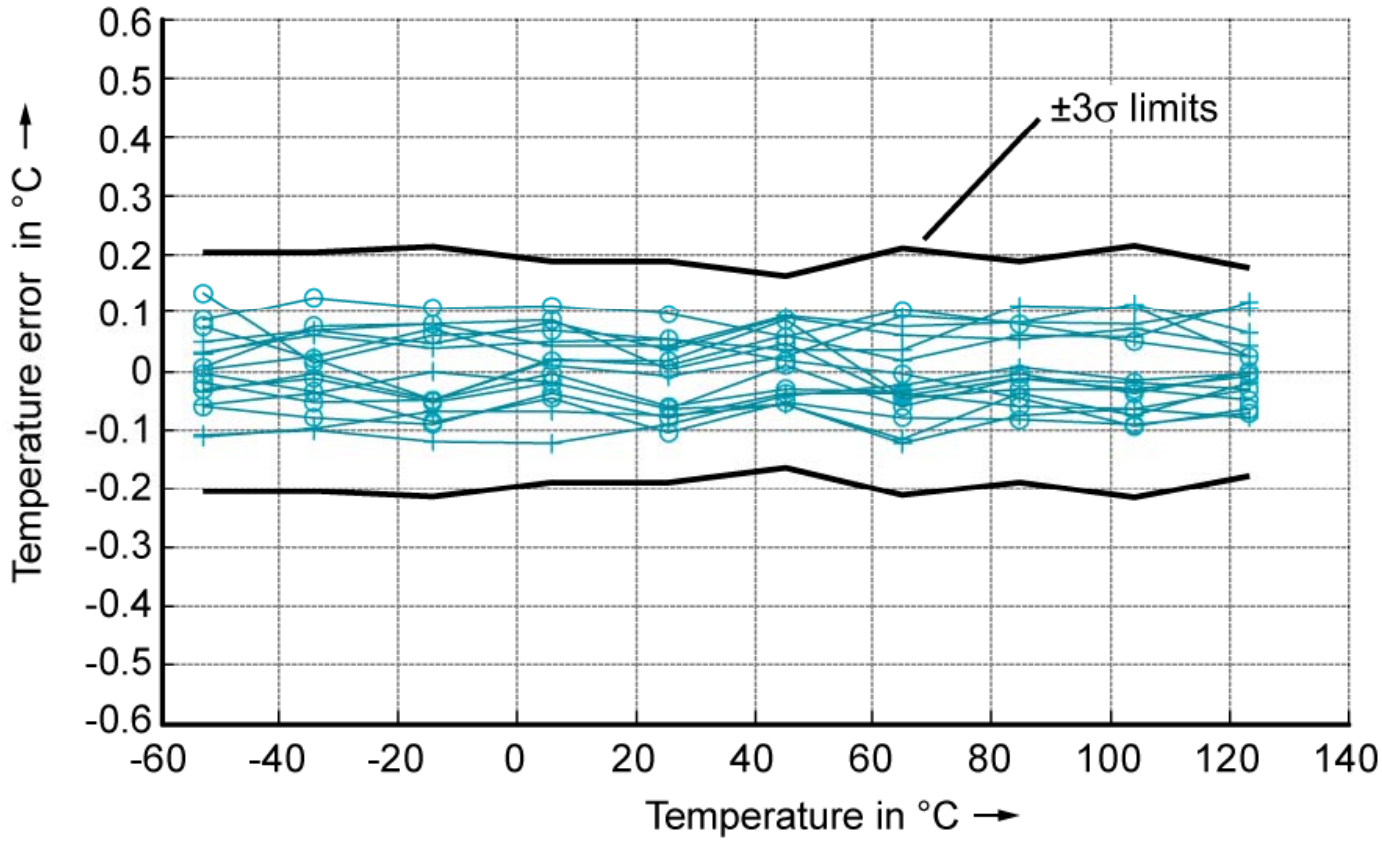
- 0.18μm CMOS
- Active circuit area ~ 0.2mm^2
- $P_{circuit}$ = 0.5mW
- P_{ETF} = 2.5mW

- Circuit power (5x) and area (3x) scale down



Yes it Does!

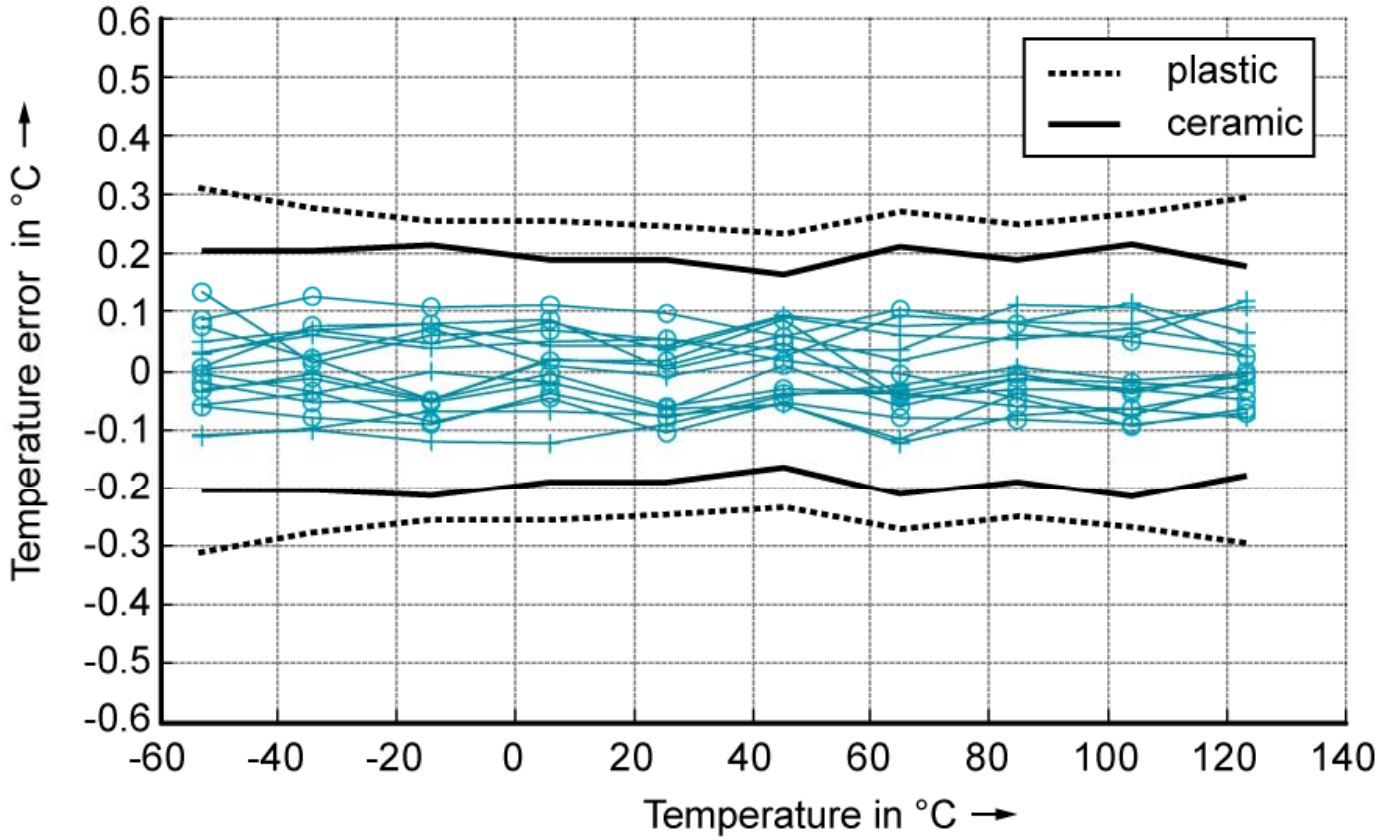
van Vroonhoven, ISSCC10



- Untrimmed device-to-device spread ±0.2ºC (3σ)
  ⇒ 3x improvement

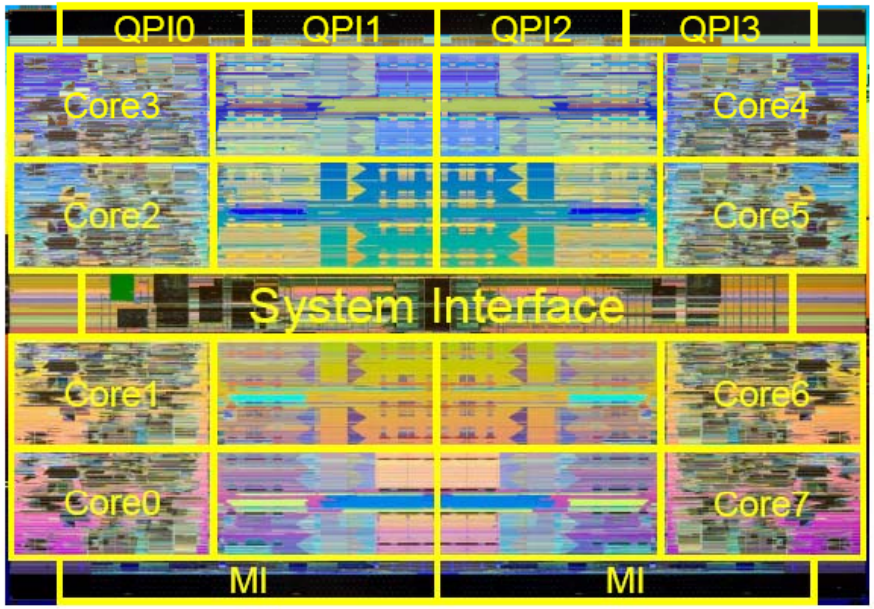
Plastic Packaging

van Vroonhoven, ISSCC10

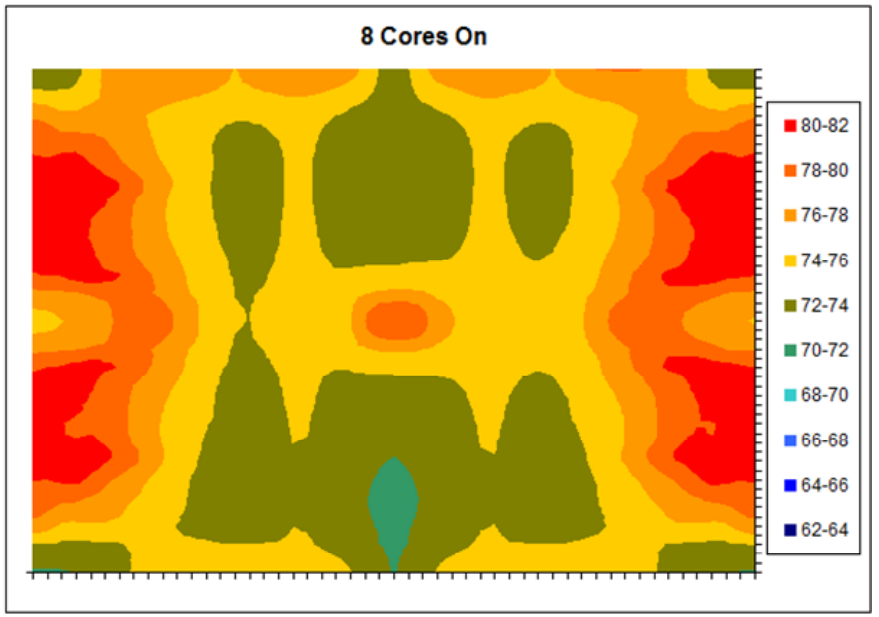


- 16 devices in plastic TSSOPs (no stress coating)
  ⇒ Slightly more spread, but no shift!

The Killer Application?



Intel 45nm Xeon



Courtesy of S. Rusu Intel

- Multi-core processors ⇒ multiple hot spots
  ⇒ multiple temperature sensors!
- Key requirement = no trimming ⇒ TD sensors
- But they need to be faster and more robust …

Conclusions

- Thermal diffusivity-based temperature sensors:
  - Are fully CMOS-compatible
  - Performance (accuracy, speed) scales with process

- Achieve 0.2ºC (3σ) inaccuracy without trimming
- Comparable to the best trimmed BG sensors

- Are thus well suited for temperature sensing in nanometer CMOS processes

Acknowledgements

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  - NXP Semiconductors
  - National Semiconductor
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- Michel Pertijs, Martijn Snoeij,
  Caspar van Vroonhoven
  Cheng Zhang & Mahdi Kashmiri

- Thank-You for Your Attention!

Back-Up Slides