# A 550μm$^2$ CMOS Temperature Sensor Using Self-Discharging P-N Diode with ±0.1°C (3σ) Calibrated and ±0.5°C (3σ) Uncalibrated Inaccuracies


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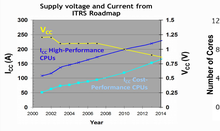
## Motivation and Background

While not always obvious, temperature sensors are everywhere!

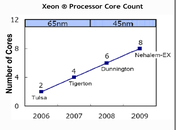
## Temperature Sensors in ICs?

Scaling, integration, and higher speeds demands more power consumption for system-on-chips (SoCs)

Supply voltage and Current from ITRS Roadmap



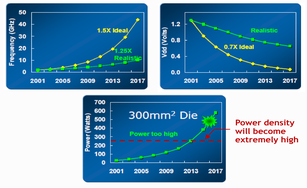

Xeon ® Processor Core Count




This trend suggests higher die temperatures for SoCs

## Intel CPU Power Projections

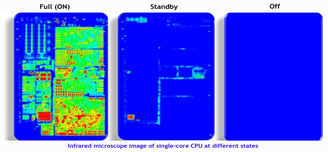
"Power management is job #1 for future designs!"




Source: T. Karnik, ISSCC 2012

## The Plot Thickens...

Power consumptions is inhomogeneous across the die

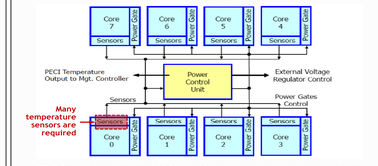



Infrared microscope image of single-core CPU at different states

Even with high-performance heat sinks implemented in the package we will have local "hotspots"

Source: T. Karnik, ISSCC 2012

## Monitoring and controlling on-chip temperature in a distributed fashion

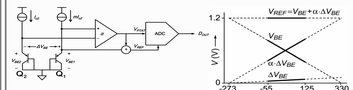



Distributed sensors should be small, low power, and easy to place

Source: T. Karnik, ISSCC 2012

## Previous Solution 1: BJT-Based Sensor

Idea: Use the forward bias current of two BJT transistors to create a proportional to absolute temperature (PTAT) voltage




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

$$V_{BE1} = \frac{\eta kT}{q} ln\left(\frac{pI}{I_S}\right)$$

$$V_{BE2} = \frac{\eta kT}{q} ln\left(\frac{I}{I_S}\right)$$

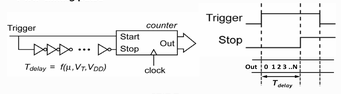
$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{\eta kT}{q} ln(m)$$

PTAT Output Voltage

M. Pertijs et al., IEEE JSSC, 2005.

## Previous Solution 2: MOSFET-Based Sensors

Idea: Use propagation delay of a chain of inverters to create a PTAT timing pulse




PTAT $T_{delay}$

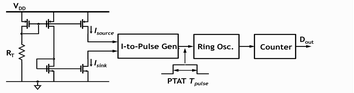
$$T_{delay} = \frac{2(L/W)C_L}{\mu C_{OX}(V_{DD} - V_{TH})} ln\left(\frac{3V_{DD} - 4V_{TH}}{V_{DD}}\right)$$

$$\mu = \mu_0 \left(\frac{T}{T_0}\right)^m, m = -1.2 \text{ to } -2.0$$

P. Chen et al., IEEE JSSC, 2005.

## Previous Solution 3: Resistor-Based Sensors

Idea: Use a resistor to create a temperature dependent current or voltage

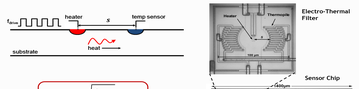



$$I_{source} \approx \frac{V_{DD} - V_{TH}}{R_T}$$ CTAT $I_{source}$

C. Kim et al., IEEE Microelectronics, 2005.

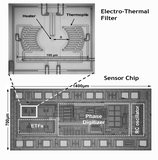
## Previous Solution 4: Si Thermal Diffusivity

Idea: Use temperature dependent property of silicon substrate diffusivity to create a PTAT phase-shift




$$\phi_{shift} \propto s\sqrt{\frac{f_{drive}}{D_{si}}} \propto T^{-0.9}$$

PTAT $\phi_{shift}$




M. Perrott et al., IEEE ISSCC, 2012.

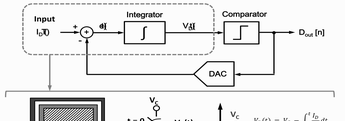
C. Vroonhoven et al., IEEE ISSCC, 2012.

## Summary of Previous Work

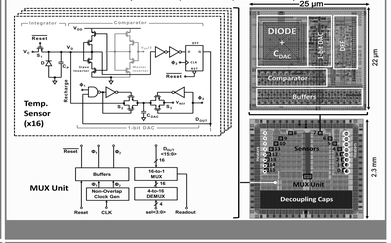
| Sensor Type | Area (Size) | Power | Accuracy | Design Effort | Limitations / Challenges |
|---|---|---|---|---|---|
| BJT | Large | High | Good | Very High | Calibration Trimming |
| MOSFET | Medium | Low | Medium | High | Aggressive Calibration Curvature Correction |
| Thermistor | Large | Medium | Good | Medium | Calibration at multiple temperature points, Curvature Correction |
| Si Thermal Diffusivity | Large | Very High | Good | Very High | Calibration Trimming |
| Our Goal | Ultra-Small | Ultra-Low | Good | Low | Calibration, Curvature Correction |

Quantitative comparison will be presented in a later slide

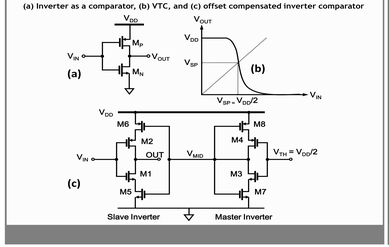
## This Work; Idea: Use reverse-bias diode as the input source and integrator of a continuous time Δ-Σ loop to create PTAT output pulse trains



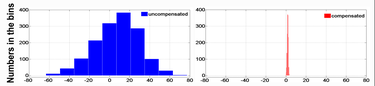

Circuit schematic and layout of the implemented temperature sensor system.



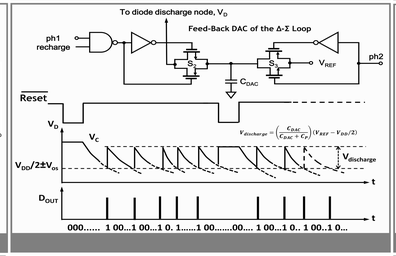

(a) Inverter as a comparator, (b) VTC, and (c) offset compensated inverter comparator



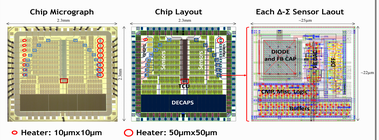

## Comparator Monte-Carlo Simulated Results



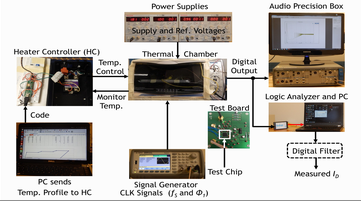

| Type | Mean (mV) | Std. Dev. (mV) | Min (mV) | Max (mV) |
|---|---|---|---|---|
| Uncompensated | 7.5 | 22 | -63 | 77 |
| Compensated | 1.7 | 0.604 | -0.55 | 3.4 |



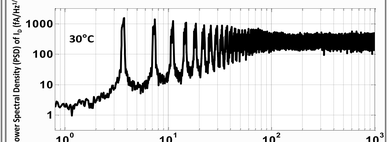

## Implementations in TSMC 180nm CMOS



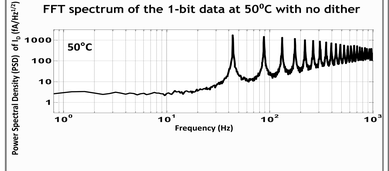

## Measurement Setup



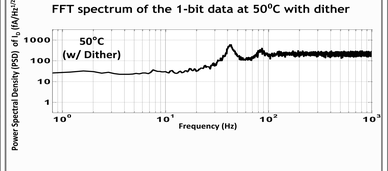

## FFT spectrum of the 1-bit data at 30°C with no dither



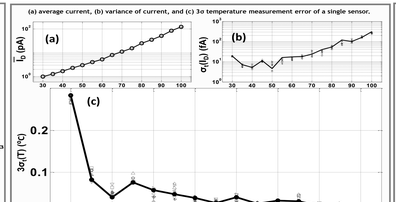

## FFT spectrum of the 1-bit data at 50°C with no dither



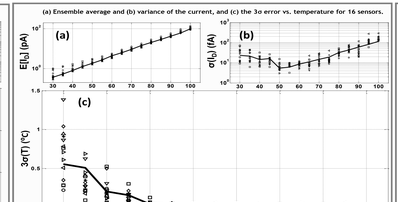

## FFT spectrum of the 1-bit data at 50°C with dither




(a) average current, (b) variance of current, and (c) 3σ temperature measurement error of a single sensor.

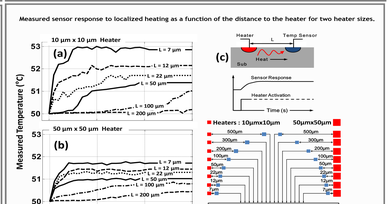



(a) Ensemble average and (b) variance of the current, and (c) the 3σ error vs. temperature for 16 sensors.




## Performance Comparison

| Parameter | This Work | ISSCC '14 [5] | ISSCC '14 [6] | JSSCC '13 [7] | VLSI '11 [8] | TCAS-II '12 [3] |
|---|---|---|---|---|---|---|
| CMOS Technology | 0.18μm | 0.16μm | 0.7μm | 0.16μm | 0.18μm | 32nm SOI |
| Area (mm$^2$) | 0.00055 | 0.085 | 0.8 | 0.08 | 0.18 | 0.001 |
| Transducer Structure | p-n diode | DTMOST | BJT | BJT | Resistor | p-n diode |
| Supply Voltage | 1.8V | 0.85 - 1.2V | 2.9 - 5.5V | 1.5 - 2.0V | 1.2 - 2.0V | 1.65V |
| Supply Current | 2.2nA | 700nA | 55μA | 1.4μA | 20μA | 60μA |
| Temperature Range | 35°C to 100°C | -40°C to 125°C | -45°C to 130°C | -55°C to 125°C | 0°C to 100°C | 0°C to 100°C |
| Inaccuracy (3σ) | ±0.5°C[1], ±0.1°C[2] | ±0.4°C[3] | ±0.15°C[4] | ±0.15°C[3] | ±0.5°C[4] | ±1.95°C[4] |
| Speed (samples/second) | 2 | 166 | N/A | 200 | 10 | N/A |

[1]Uncalibrated [2]Calibrated [3]Batch-Calibration and Trim [4]1-Point-Calibration [5]2-Point-Calibration

## Measured sensor response to localized heating as a function of the distance to the heater for two heater sizes.