A $30.1\mu m^2$, $< \pm 1.1^{\circ}C$-3σ-Error, 0.4-to-1.0V Temperature Sensor based on Direct Threshold-Voltage Sensing for On-Chip Dense Thermal Monitoring

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Outline

- Motivation and Design Requirements
- Proposed Temperature Sensor
- Chip Design
- Measurement Results
- Conclusion

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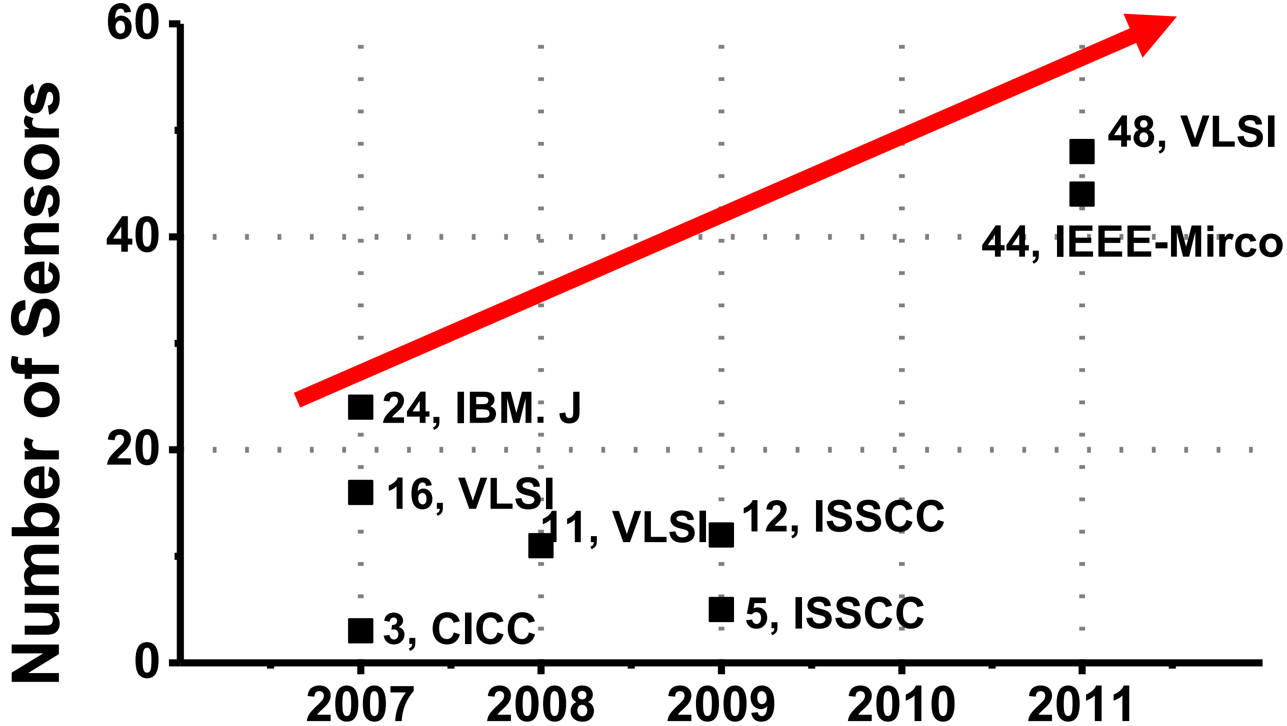
Motivation

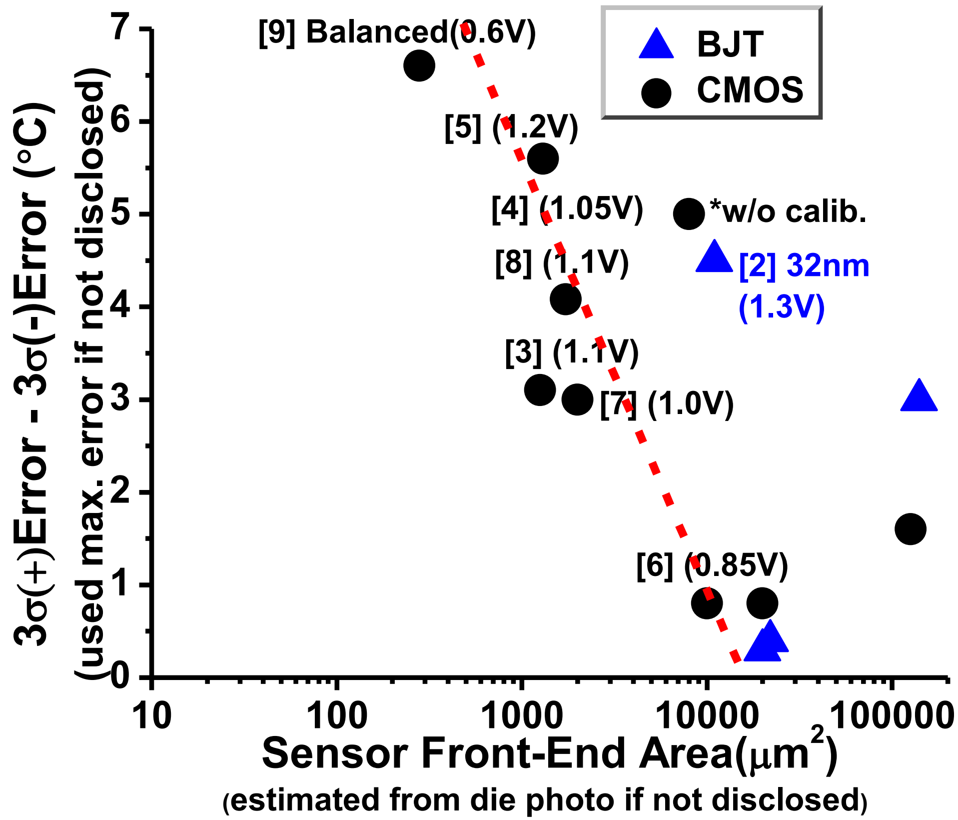


- Dynamic thermal management (DTM)
  - Address thermal hotspots, manage power…
- Trends show an increasing # of sensors on a chip

Design Requirement

- Small area
  - Trends require more # of sensors on a chip
    - Multi-core, 3D-ICs…
    - DTM efficiency improves with more # of sensors
  - Flexibility in placement; easily move and place sensors later in design phases
- Accuracy
  - DTM efficiency directly impacted by accuracy of each temperature sensor
- Voltage scalability
  - Commonly use dynamic voltage and frequency scaling (DVFS)
    - Ultra-dynamic voltage scaling (UDVS)

Motivation



- Trade-off between area and accuracy due to inevitable process variation, particularly mismatch
- Previous BJT-based sensors have limited voltage scalability

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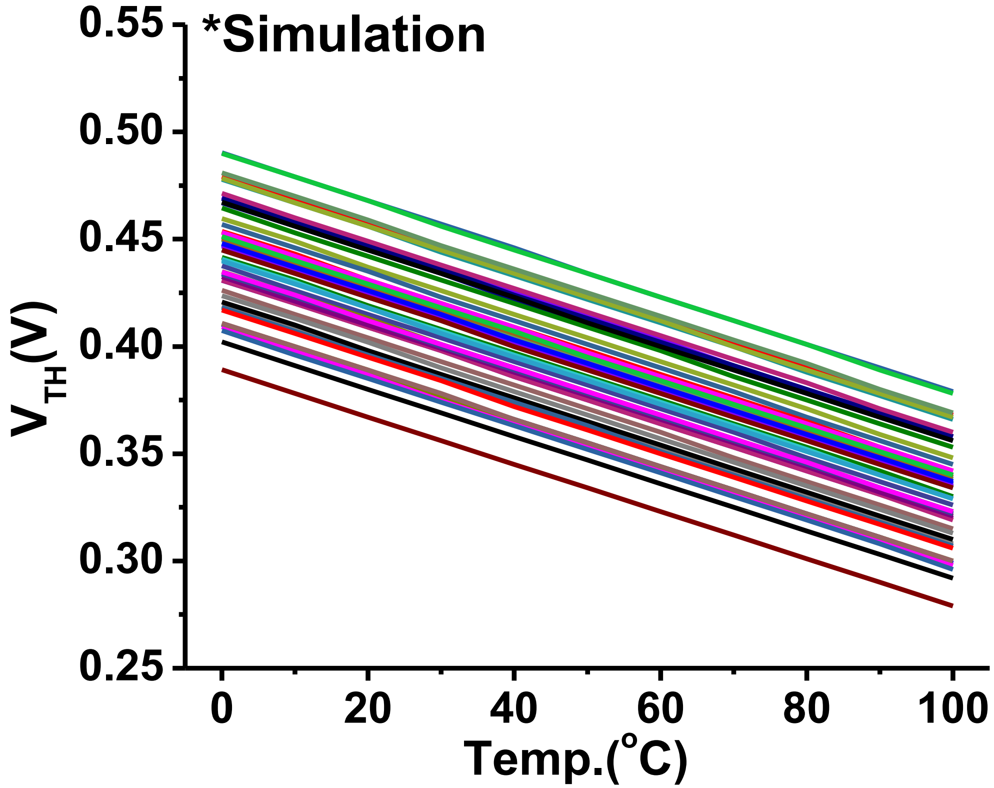
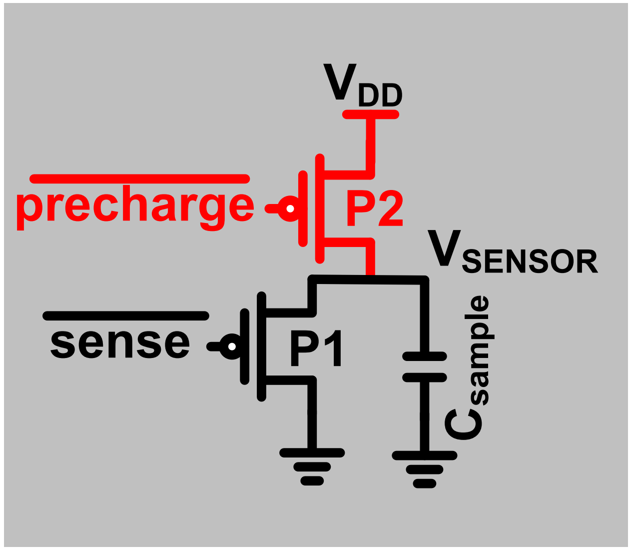
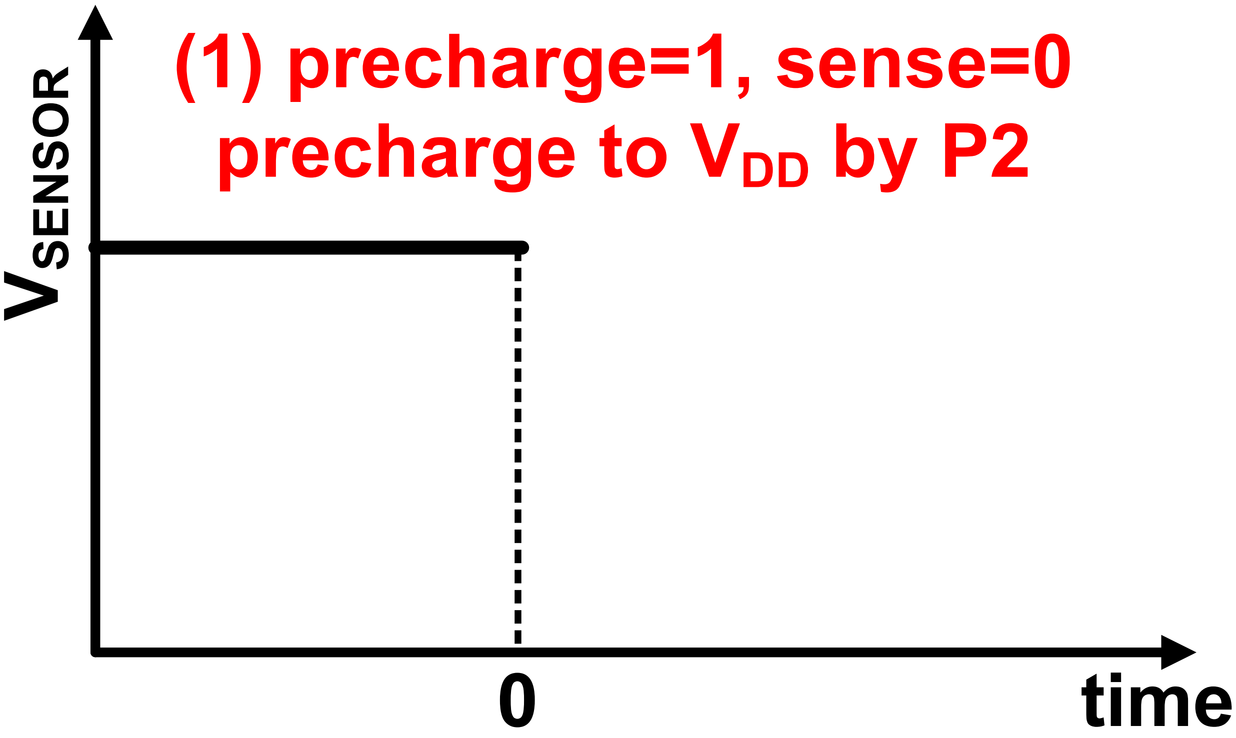
Temperature Dependency of V_{TH}



- $V_{TH}(T)=V_{TH}(T_{ROOM})+K_{VTH}(T-T_{ROOM})$
- K_{VTH} = -1.12mV/˚C, <u>stable against process variation</u>
- Linearity R^2>0.9999
- Well-suited for one-point-calibration (OPC)

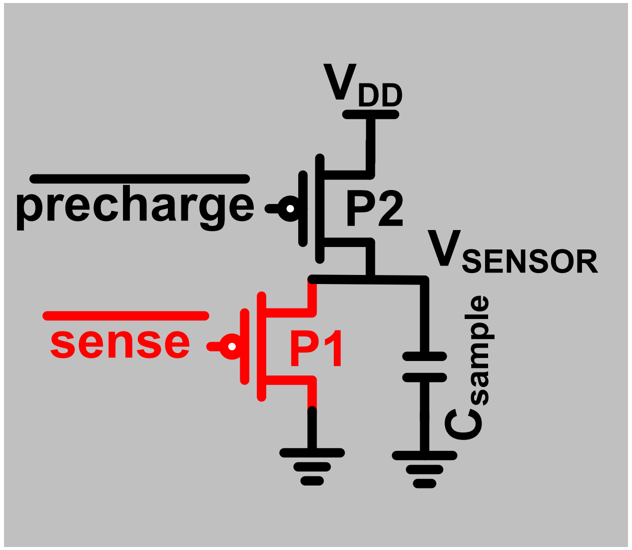
Proposed Temperature Sensor

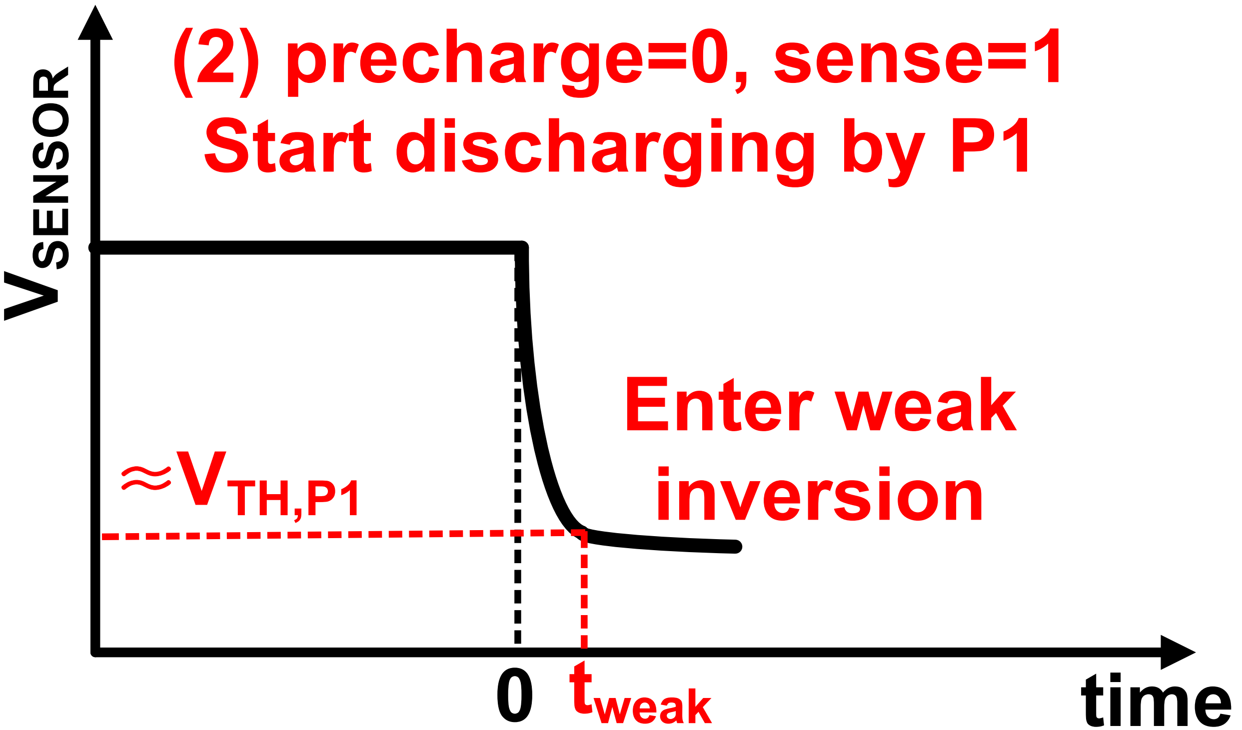




- Pre-charge PMOS P2

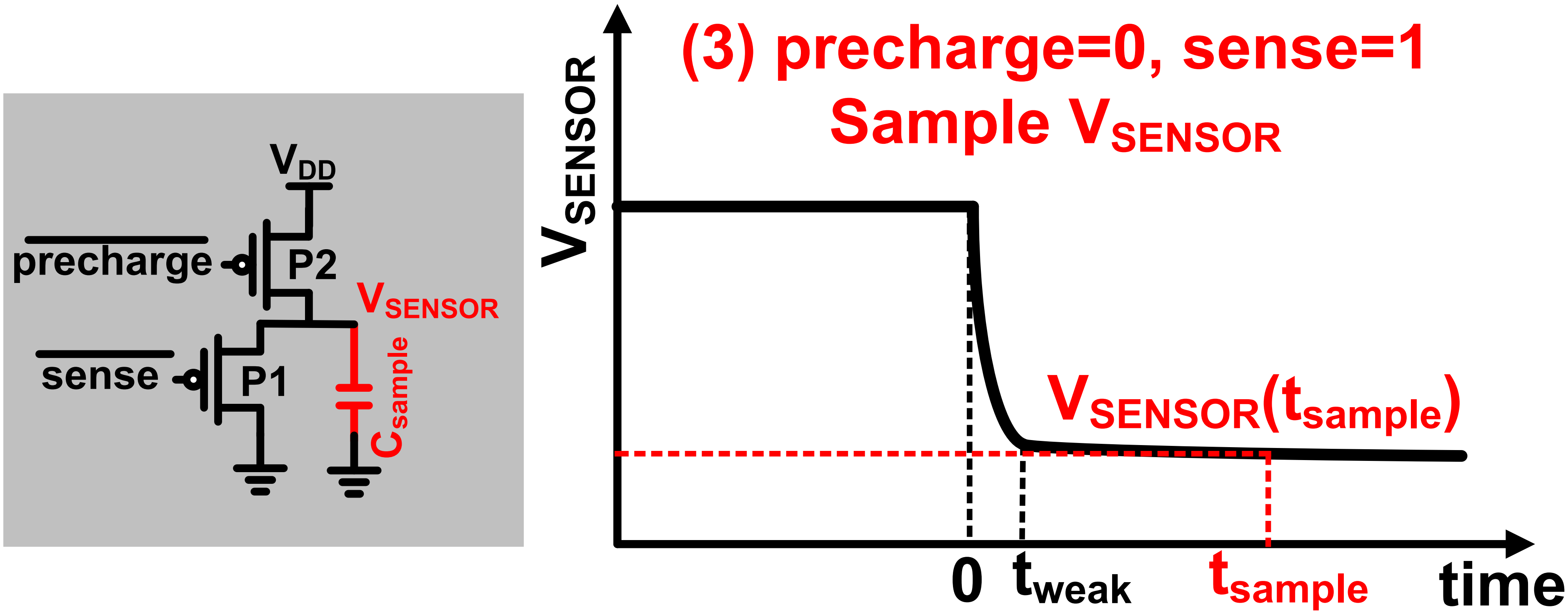
Proposed Temperature Sensor





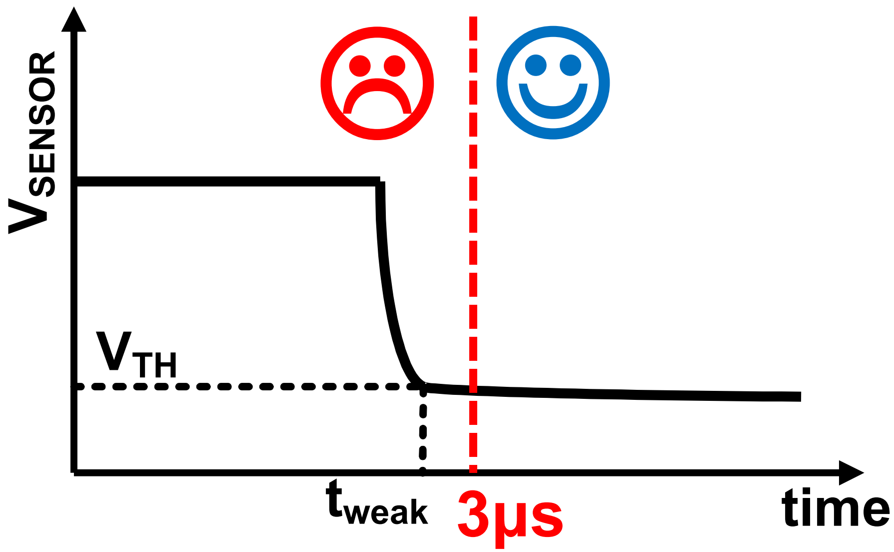
- Sensing transistor P1
  - Based on the dynamics often called V_{TH} drop
  - Use the temperature dependency of $V_{TH,P1}$ for temperature sensing

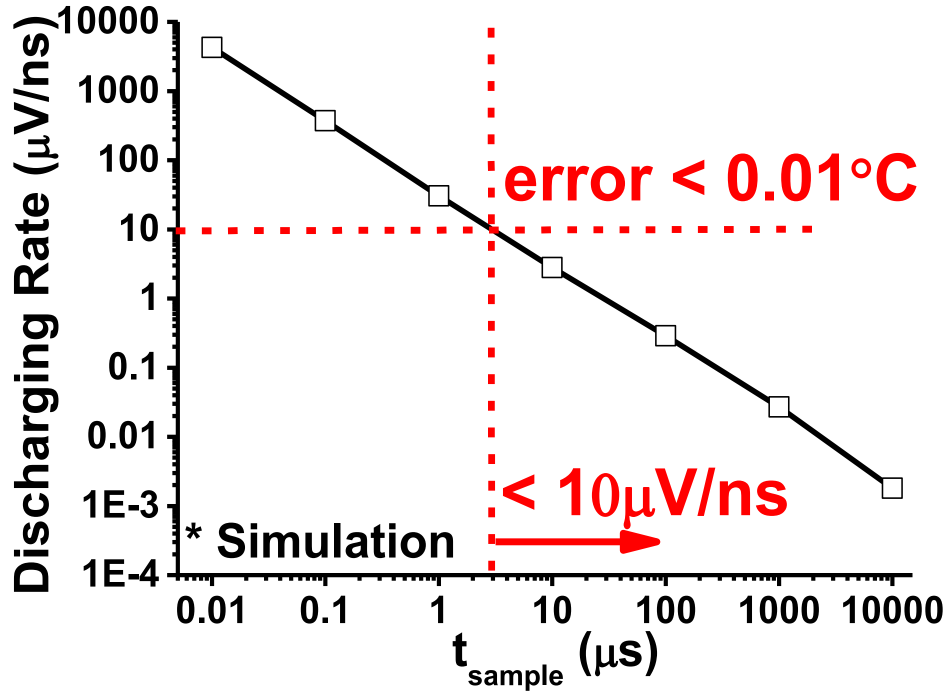
Proposed Temperature Sensor



- Wait and sample V_{SENSOR} at the optimal t_{sample}
- Sampling at optimal t_{sample} important for achieving high accuracy

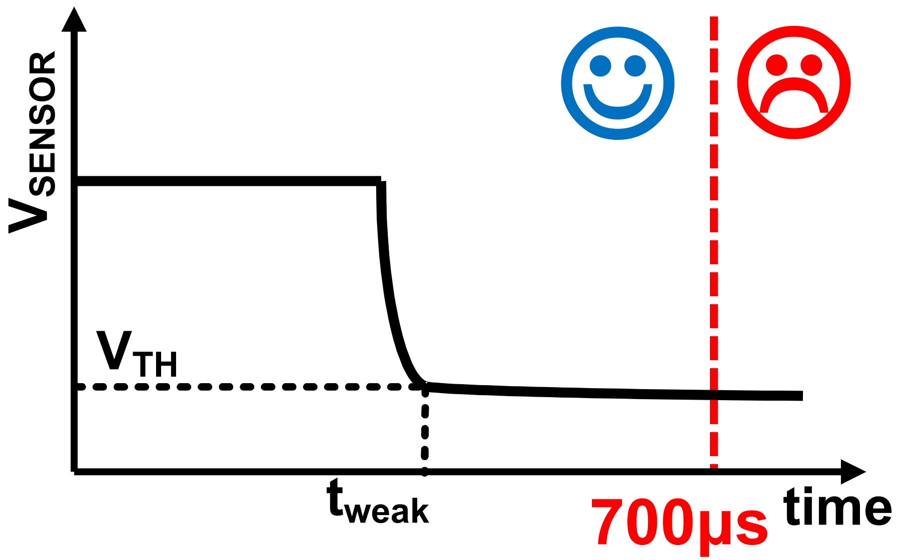
Optimal t_{sample}

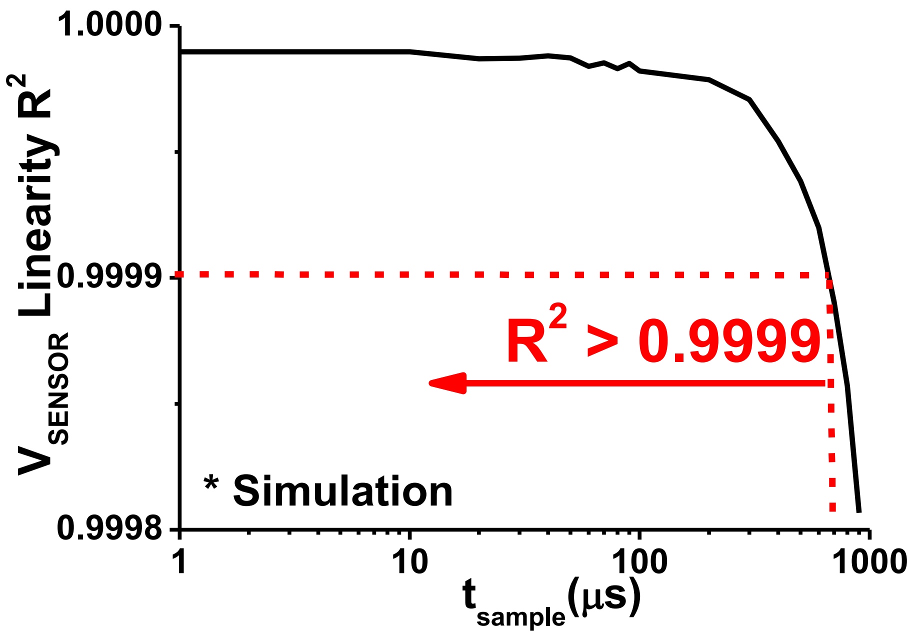




- Lower bound condition
- Low discharging rate is good against timing variation
  - E.g. t_{sample} variability due to PVT variations

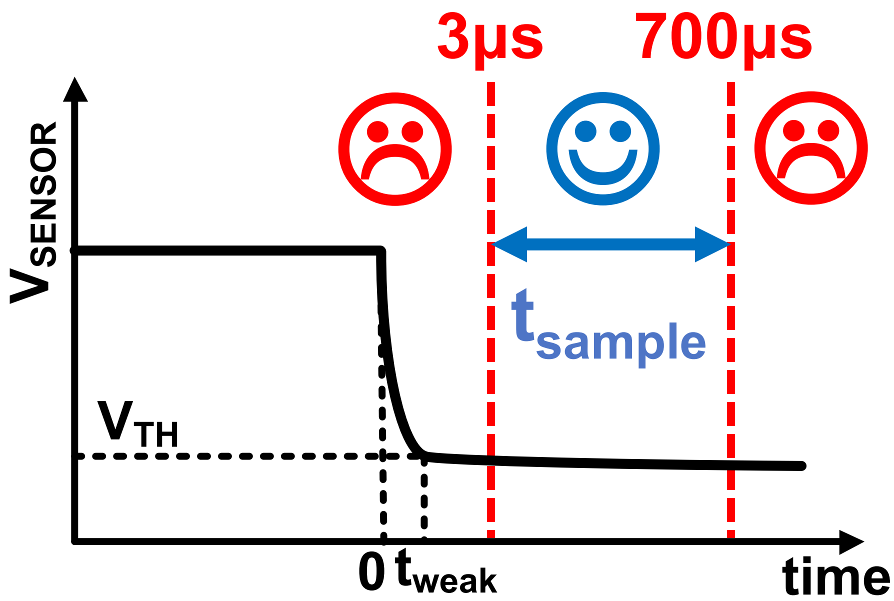
Optimal t_{sample}





- Upper bound condition
- Sampling too late can degrade linearity since leakage plays a bigger role

Optimal t_{sample}



$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot (t_{sample} - t_{weak})}{C_{sample}}$$

- Optimal sampling time: 3µs < t_{sample} < 700µs

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot (t_{sample} - t_{weak})}{C_{sample}}$$

$$V_{TH}(T) = V_{TH}(T_{ROOM}) + K_{VTH}(T - T_{ROOM})$$

V_{TH} is linear with temperature

$\approx t_{sample}$ ($\because t_{sample} >> t_{weak}$)

t_{weak}=100ns, t_{sample}=3μs-700μs

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot t_{sample}}{C_{sample}}$$

$$I_{weak} \approx \mu_0 \cdot \left(\frac{T}{T_{room}}\right)^{-k_u} \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{KT}{q}\right)^2 \cdot \exp\left(\frac{V_{GS} - V_{TH}(T)}{nV_T}\right)$$

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot t_{sample}}{C_{sample}}$$

$$I_{weak} \approx \mu_0 \cdot \left(\frac{T}{T_{room}}\right)^{-k_u} \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{KT}{q}\right)^2 \cdot \boxed{\exp\left(\frac{V_{GS} - V_{TH}(T)}{nV_T}\right)}$$

$V_{GS} \approx V_{TH}(T)$

$$\approx \mu_0 \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{K}{q}\right)^2 \cdot T_{room}^{k_u} \cdot T^{\boxed{K_0}}$$

$K_0 = -k_u + 2$

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot t_{sample}}{C_{sample}}$$

$$I_{weak} \approx \mu_0 \cdot \left(\frac{T}{T_{room}}\right)^{-k_u} \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{KT}{q}\right)^2 \cdot \exp\left(\frac{V_{GS} - V_{TH}(T)}{nV_T}\right)$$

$$\approx \boxed{\mu_0 \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{K}{q}\right)^2} \cdot T_{room}^{k_u} \cdot T^{K_0}$$

$$\approx \boxed{C} \cdot T_{room}^{k_u + k_0} \cdot \left(1 + \frac{T - T_{room}}{T_{room}}\right)^{k_0}$$

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot t_{sample}}{C_{sample}}$$

$$I_{weak} \approx \mu_0 \cdot \left(\frac{T}{T_{room}}\right)^{-k_u} \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{KT}{q}\right)^2 \cdot \exp\left(\frac{V_{GS} - V_{TH}(T)}{nV_T}\right)$$

$$\approx \mu_0 \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{K}{q}\right)^2 \cdot T_{room}^{k_u} \cdot T^{K_0}$$

$$\approx C \cdot T_{room}^{k_u+k_0} \cdot \boxed{\left(1 + \frac{T - T_{room}}{T_{room}}\right)}^{k_0}$$

$$\frac{T-T_{room}}{T_{room}} = -0.1 \sim 0.23 << 1$$

$$\approx C \cdot T_{room}^{k_u+k_0} \cdot \left(1 + k_0 \frac{T - T_{room}}{T_{room}}\right)$$

Taylor Series

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot t_{sample}}{C_{sample}}$$

$$\begin{aligned}
I_{weak} &\approx \mu_0 \cdot \left(\frac{T}{T_{room}}\right)^{-k_u} \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{KT}{q}\right)^2 \cdot \exp\left(\frac{V_{GS} - V_{TH}(T)}{nV_T}\right) \\
&\approx \mu_0 \cdot C_{ox} \cdot \frac{W}{L} \cdot (n-1) \cdot \left(\frac{K}{q}\right)^2 \cdot T_{room}^{k_u} \cdot T^{K_0} \\
&\approx C \cdot T_{room}^{k_u + k_0} \cdot \left(1 + \frac{T - T_{room}}{T_{room}}\right)^{k_0} \\
&\approx C \cdot T_{room}^{k_u + k_0} \cdot \left(1 + k_0 \frac{T - T_{room}}{T_{room}}\right) \\
&\approx C \cdot T_{room}^{k_u + k_0} \cdot \left[(1 - k_0) + \frac{k_0}{T_{room}} T\right] \\
&\approx A_{weak} + K_{weak} T
\end{aligned}$$

I_{weak} at optimal t_{sample} is linear with temperature

Optimal t_{sample}

$$V_{SENSOR}(t_{sample}) = V_{TH} - \frac{I_{weak} \cdot (t_{sample} - t_{weak})}{C_{sample}}$$

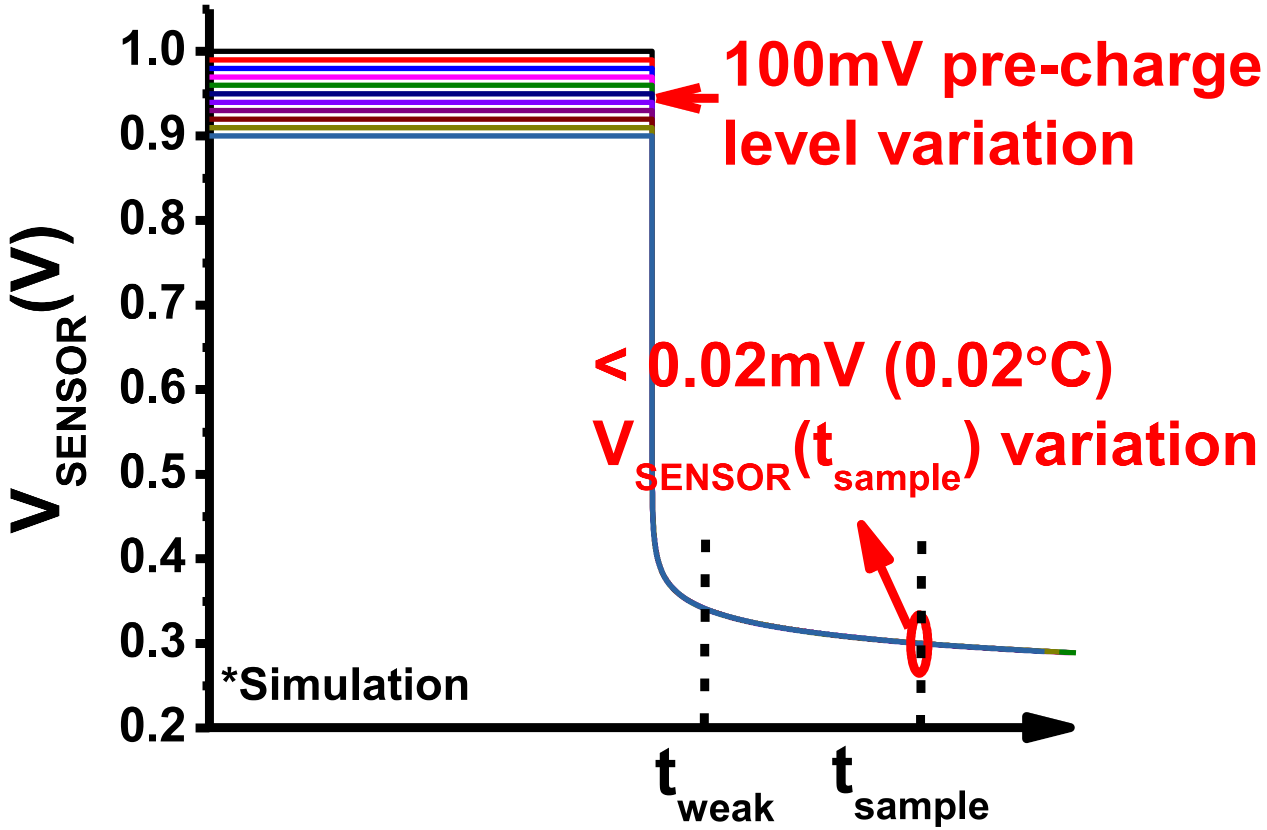
$$V_{SENSOR}(t_{sample}) \approx \left[V_{TH}(T_{room}) - K_{VTH} \cdot T_{room} - \frac{A_{weak} \cdot t_{sample}}{C_{sample}} \right] + \left(K_{VTH} - \frac{K_{weak} \cdot t_{sample}}{C_{sample}} \right) \cdot T$$

Calibrated via one-point-calibration

Dominant and stable against process variation

Much smaller than K_{VTH}
The variation in t_{sample}/C_{sample} makes little impact

Optimal t_{sample}



- V_{DD} noise can modulate t_{weak}
- V_{DD} noise has minimal impact since $t_{sample} >> t_{weak}$

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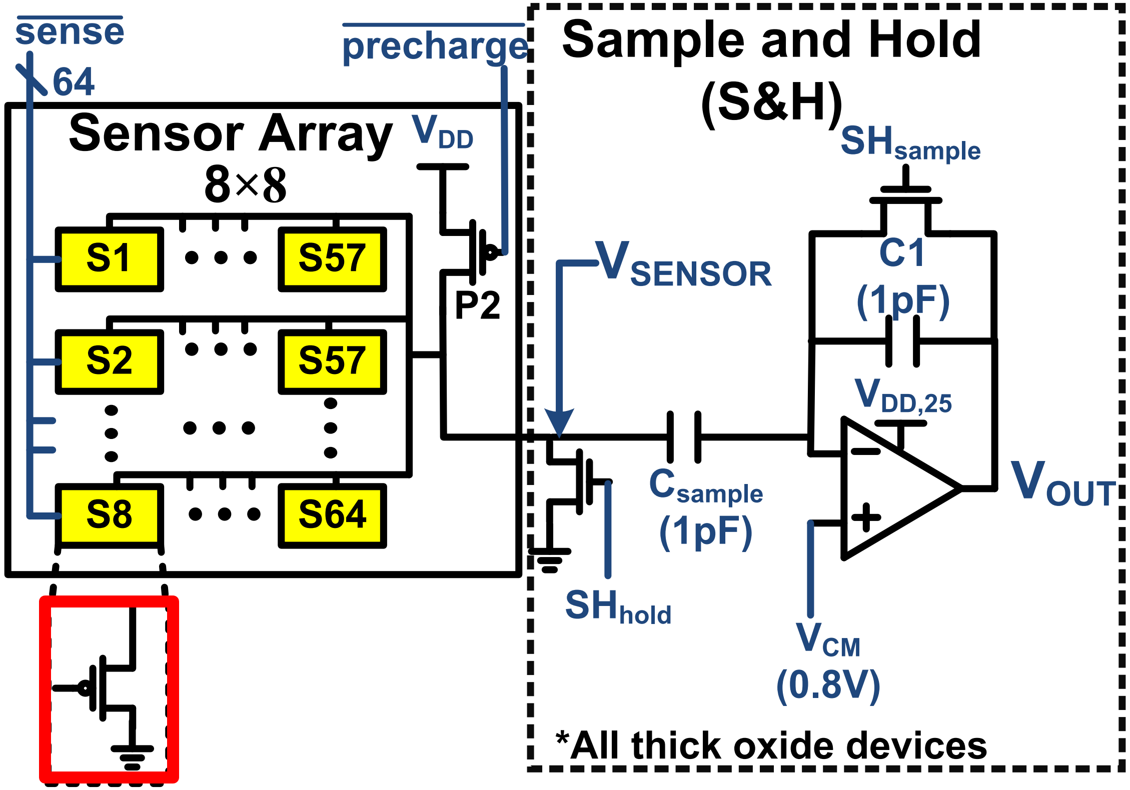
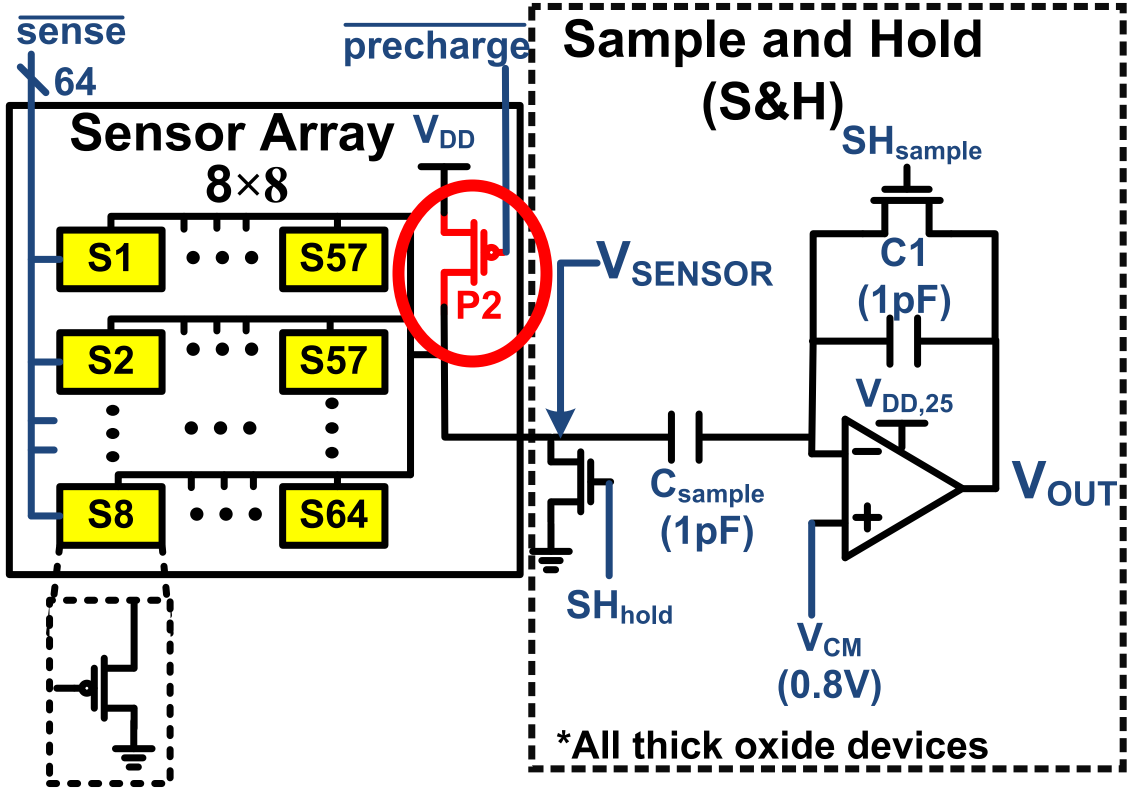
Chip Design



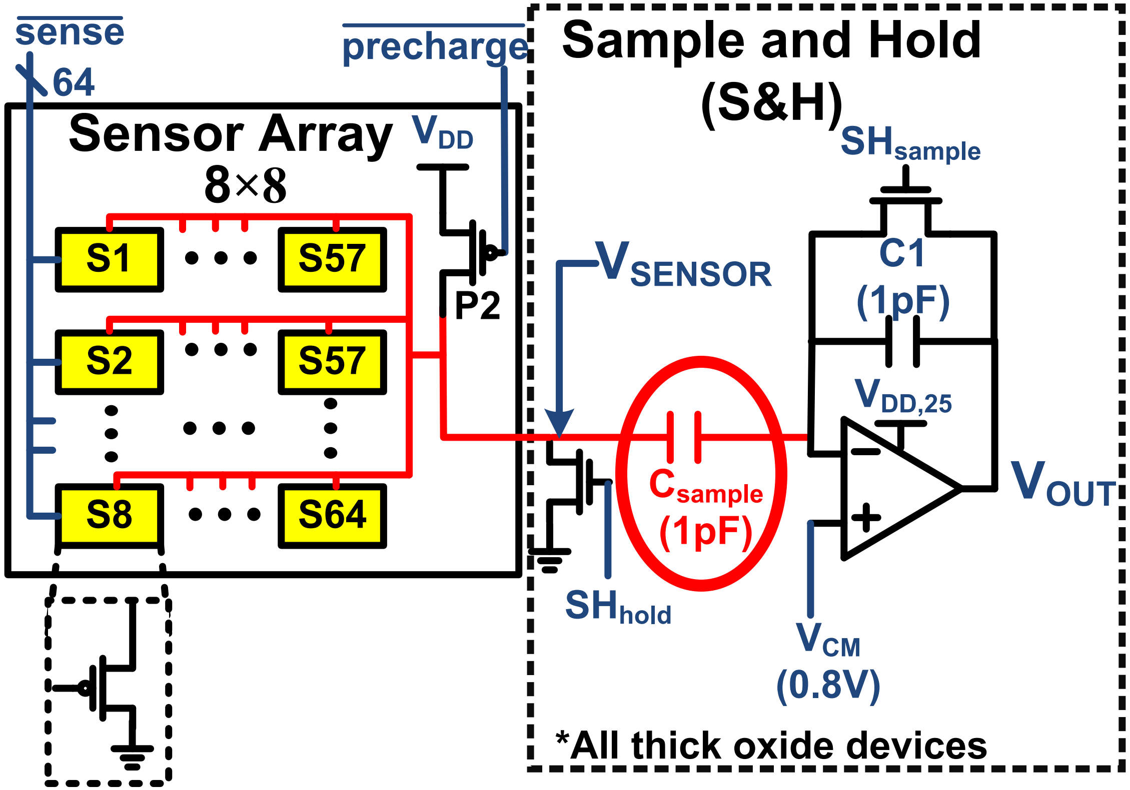
- Unit-size sensor array of 8x8
  - Unit-size sensor uses 3x-min.-sized thick-oxide PMOS
- Multiple unit-size sensors can be combined to form a larger size sensor front end

Chip Design



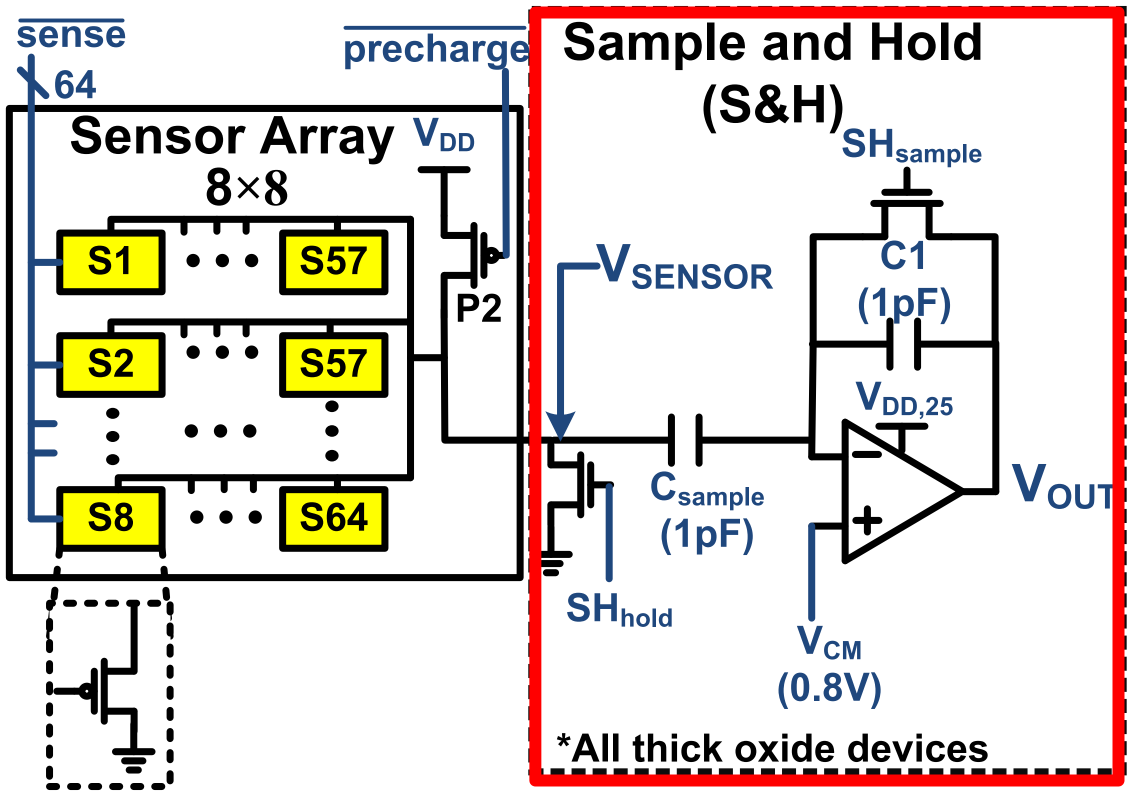
- Pre-charge PMOS (P2) is shared

Chip Design



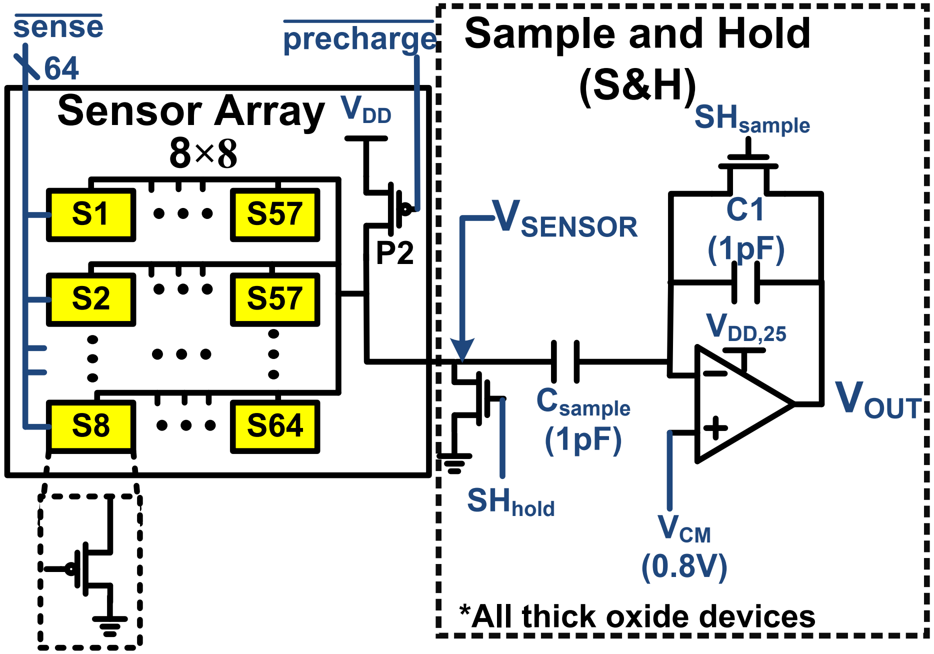
- Sampling capacitor (C_{sample}) is shared
  - ☺ Each sensor sees the identical load capacitance and temperature coefficient (i.e. K_{VTH}-$K_{weak}t_{sample}/C_{sample}$)
  - ☺ Robustness against manufacturing variation
  - ☺ Area savings

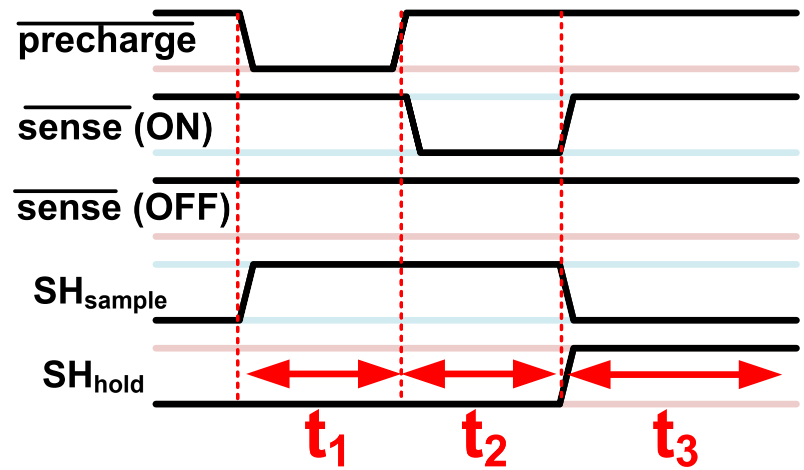
Chip Design



- Sample and hold circuits for off-chip measurement
- V_{OUT} (V_{SENSOR}+0.8V) is digitized with off-chip ADC (16bit, ±5V)

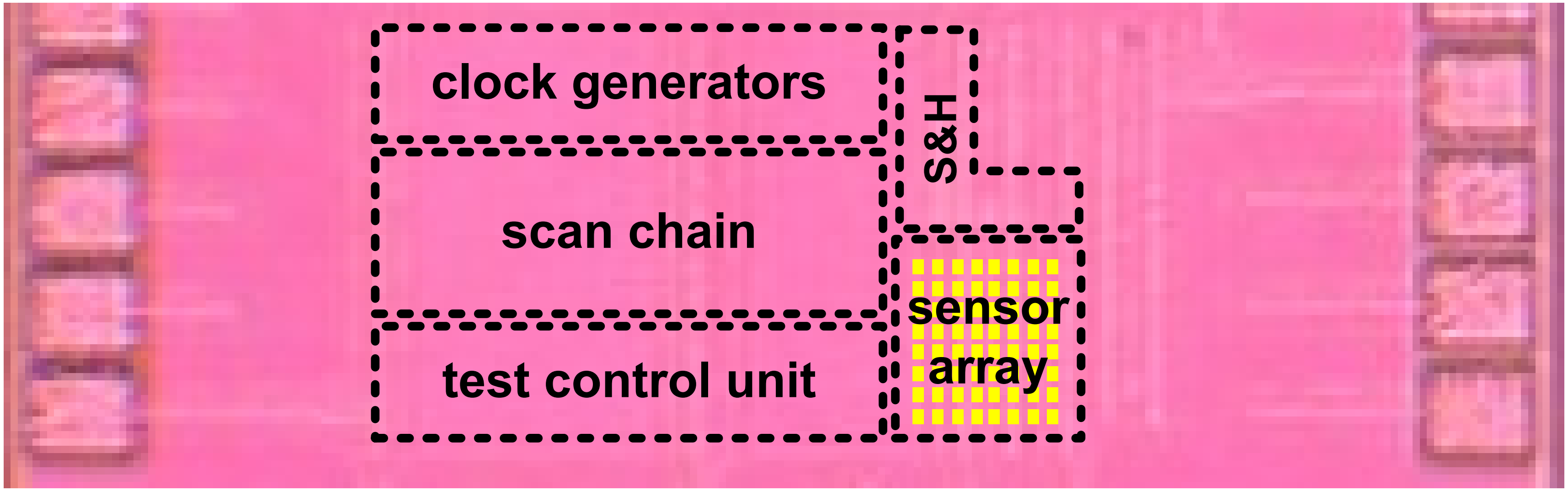
Chip Design





- t_1: pre-charge phase
- t_2: sampling phase ($=t_{sample}$)
- t_3: S&H captures V_{SENSOR} (t_{sample})

Chip Design



- Test chip die photo
- 65nm CMOS

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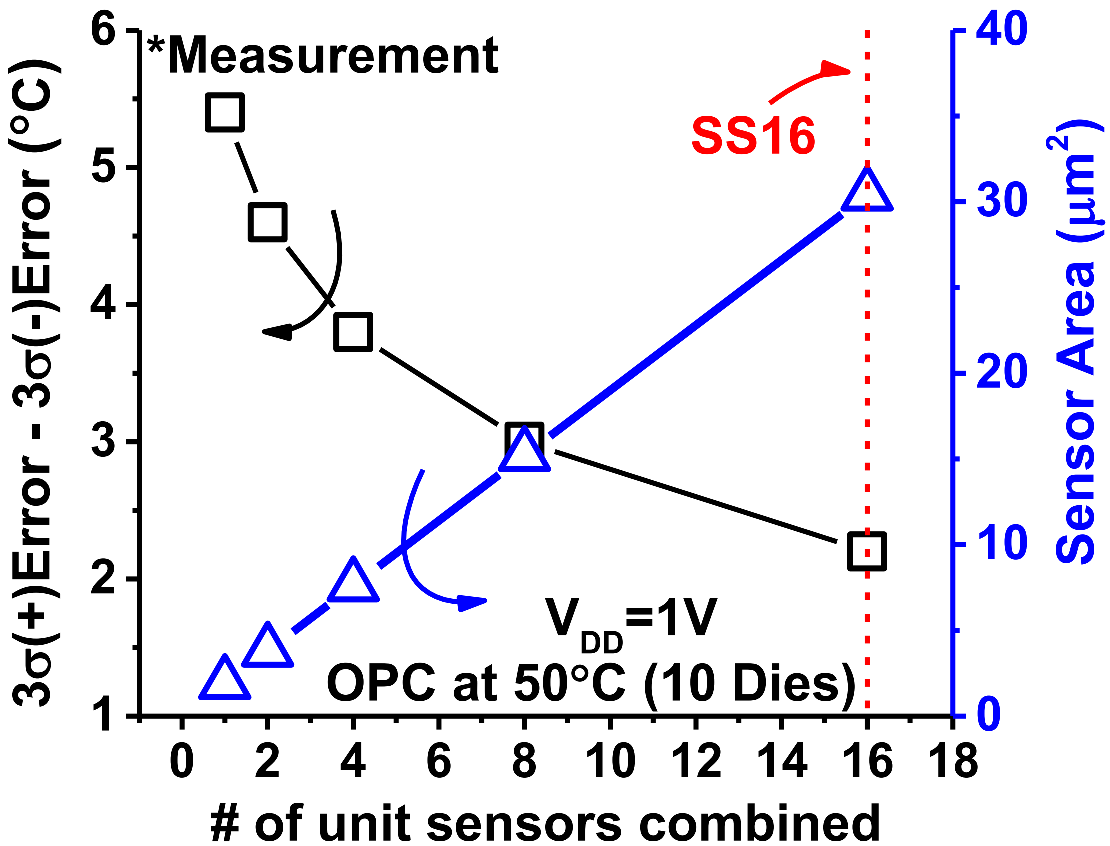
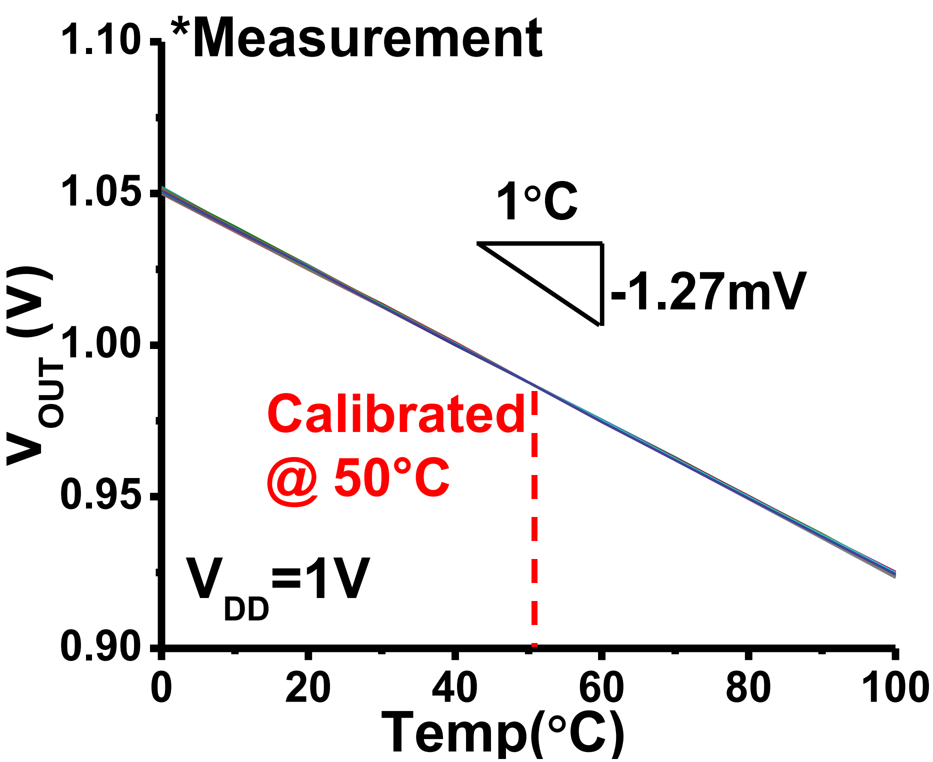
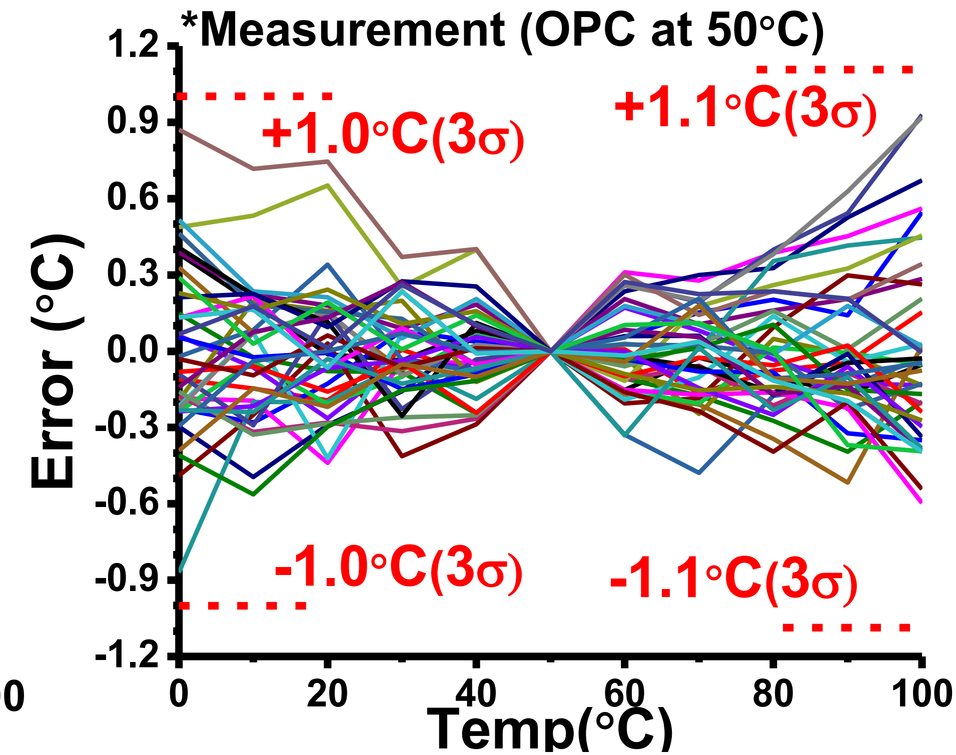
Measurement Results



- Accuracy improves with larger sensor size
- Sensor-size-16 (16 unit-size sensors combined)
  - 3σ worst-case error of ±1.1°C after one-point calibration
  - Footprint: 30.1μm^2

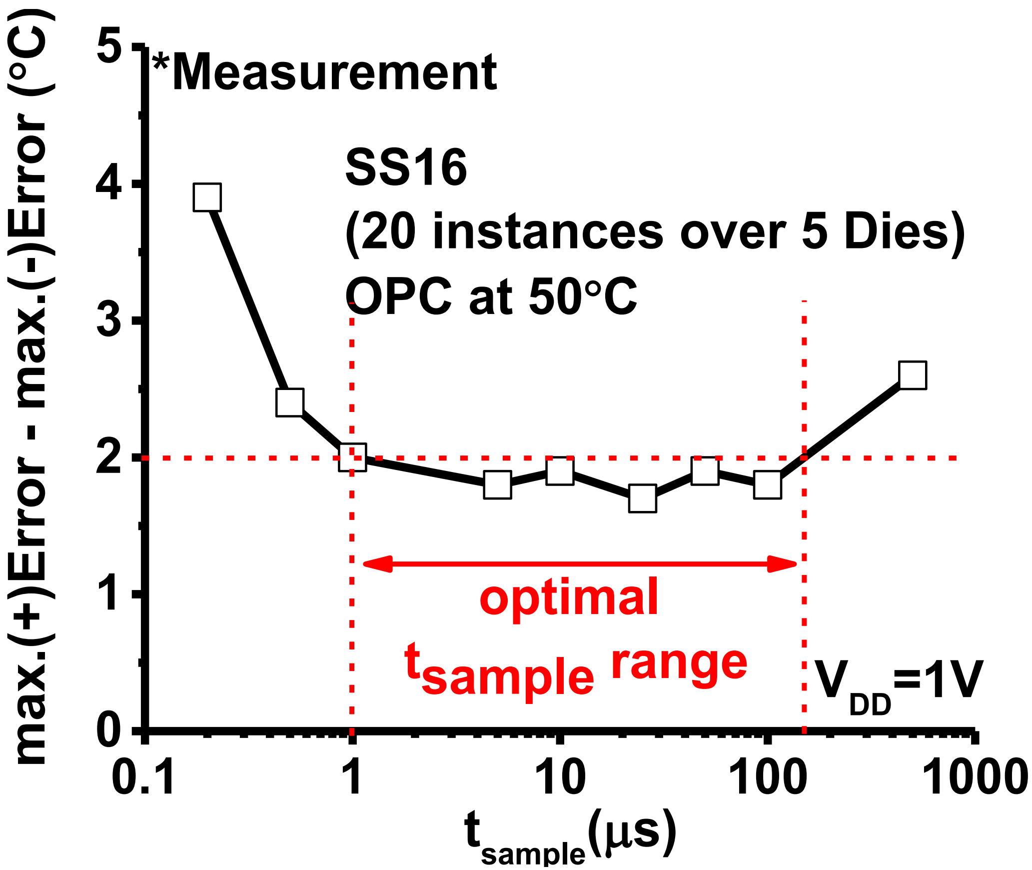
Measurement Results





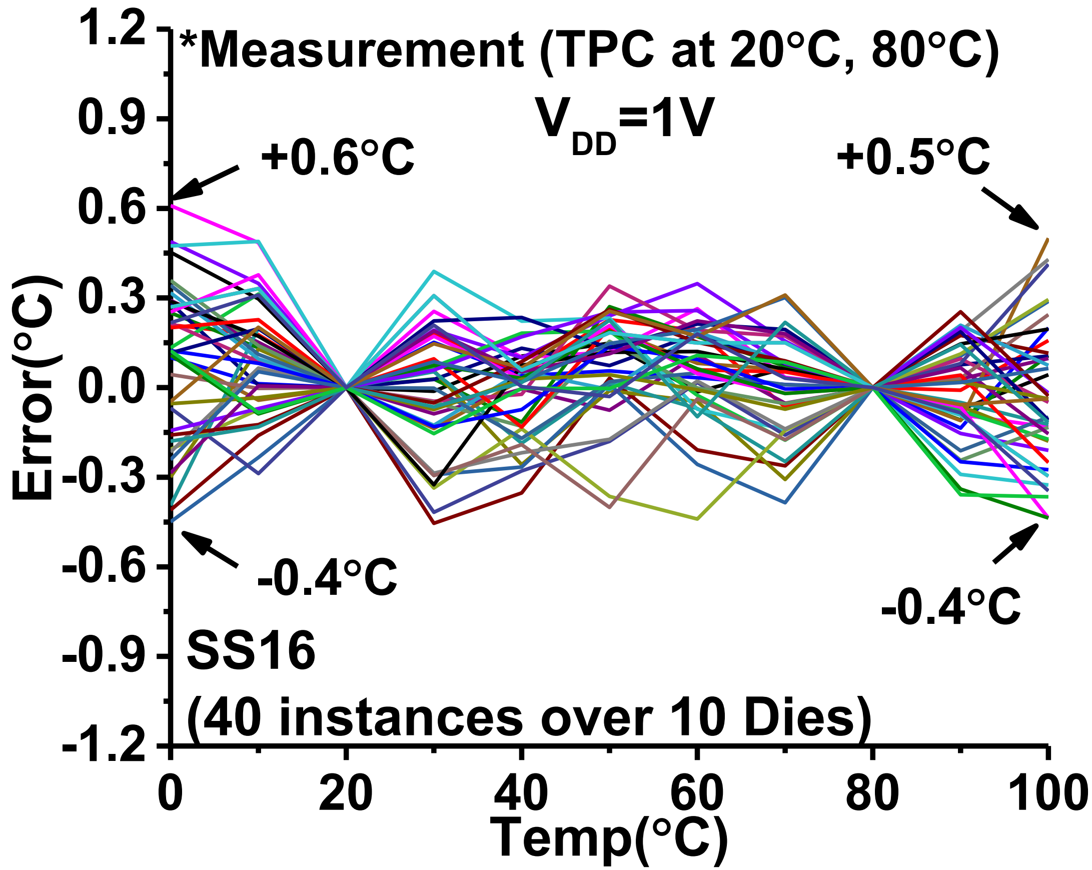
- Sensor-size-16 (SS16, 16 unit-size sensors combined)
- 40 SS16 (10 dies) one-point-calibrated at 50˚C
- 3σ errors of ±1.1˚C after one-point-calibration

Measurement Results



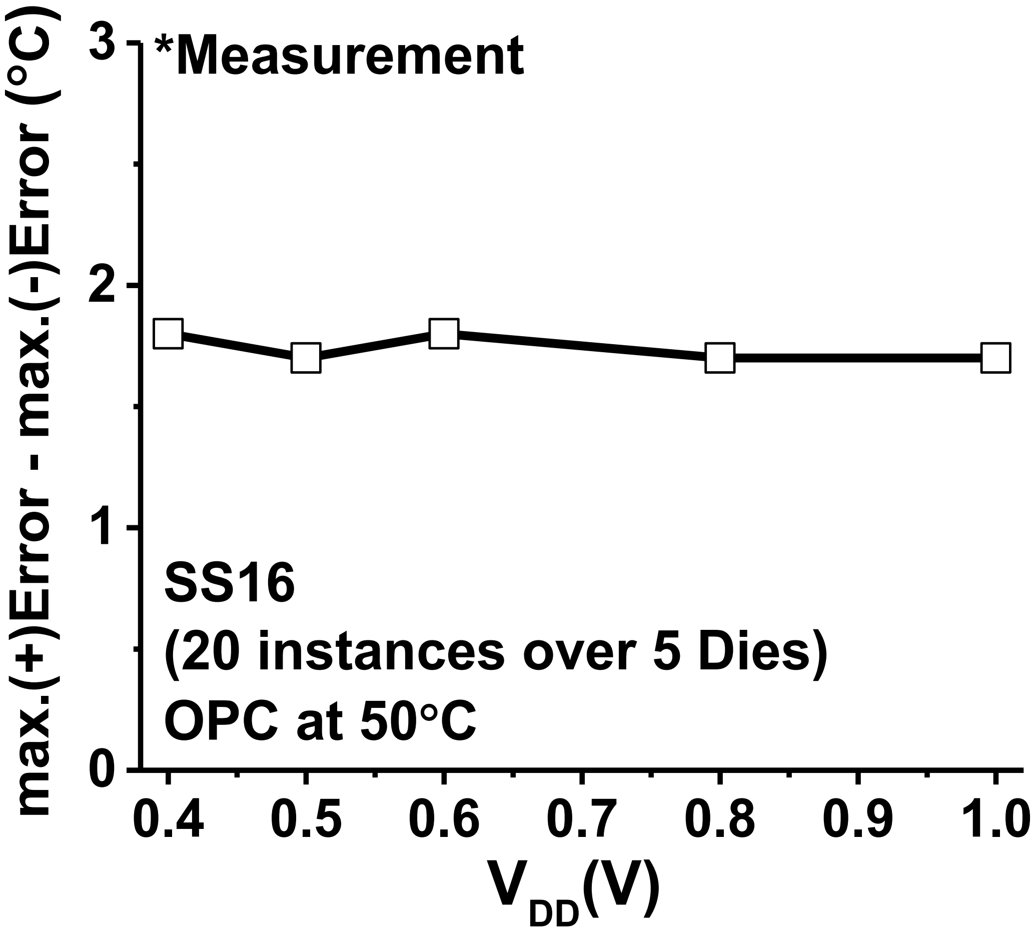
- Opt. t_{sample} range: 1μs to 100μs for the worst-case error < 2°C
- Sensor sampling rate at t_1=1μs, t_2=10μs: 91kS/s

Measurement Results



- Two-point-calibration can further reduce the worst-case error to 1°C (-0.4/+0.6°C)

Measurement Results

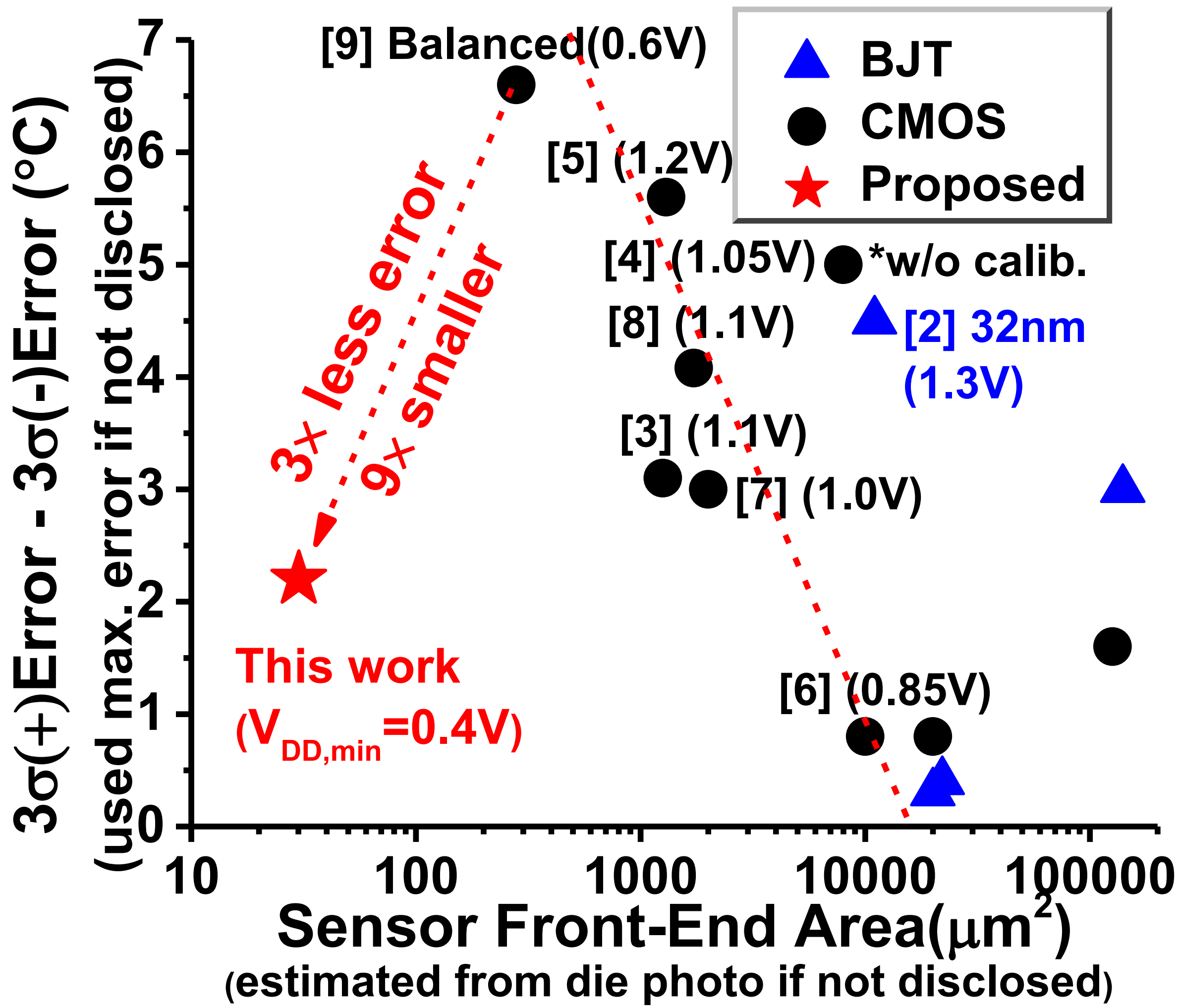


- Voltage scalability down to 0.4V
- Accuracy nearly constant across 0.4-1.0V
  - Using voltage specific TCs for one-point-calibration

Measurement Results

	[2]		[3]	[4]	[5]	[6]	[7]	[8]	[9] Balanced	[10]	**Proposed SS16**
Tech.	32nm	22nm	65nm	32nm	65nm	160nm	65nm	44nm	65nm	160nm	**65nm**
Area[1] (μm^2)	11000	4000	1255	8000*	1300*	10000*	2000*	1725	280	-	**30.1**
Area[2] (μm^2)	20000	6100	-	20000	6600	85000	8000	41300	-	4600	**-**
V_{DD} (V)	1.3-1.8	-	1.1	1.05	1.2	0.85-1.2	1	1.1	0.6~1	1.35	**0.4~1**
Temperature Coefficient	4.23 $[c/°C]$	3.82 $[c/°C]$	-	-	0.68 $[mV/°C]$	-	-	3.2 $[mV/°C]$	0.57 $[mV/°C]$	-	**1.27** $[\mathbf{mV/°C}]$
Range (°C)	-10~110		40~90	-10~110	-40~110	-40~125	0~110	0~110	0~100	-10~125	**0~100**
Error[3] (°C)	-	-	-	< 5	-	-	-	-	-	±6.5(3σ)	**-**
Error[4] (°C)	<4.5	-	<3.1	-	-2.7~2.9	±0.4(3σ)	±1.5(3σ)	-1.4~2.7	-3.4~3.2	±1.5(3σ)	**±1.1(3σ)**
Error[5] (°C)	<±1.2(3σ)	<±1.5	-	-	-	-	-	-	-1.5~1.6	-	**-0.4~0.6**
Sensor power	-	-	-	-	-	-	-	-	0.92uW	-	**1pJ******
Total power	3.78mW	1.4mW	-	1.6mW	0.4mW	0.6μW	0.5mW	0.4μW	-	3.6mW	**-**
Samples	50	5	-	750	15	16	20	61	64	80	**40**

Measurement Results



Conclusion

- Better sensors with *smaller* area, *higher* accuracy, and *lower* V_{DD} scalability are highly desirable

- A new temperature sensor architecture based on direct V_{TH} sensing is proposed

- The prototypes achieve 9× smaller footprint while having 3× better accuracy and 0.2V lower V_{DD} scalability down to 0.4V as compared to the previous state of arts