Newcastle University

Microelectronics System Design Group

Intra-chip Physical Parameter Sensor for FPGAs using Flip-Flop Metastability

Ghaith Tarawneh, Terrence Mak and Alex Yakovlev

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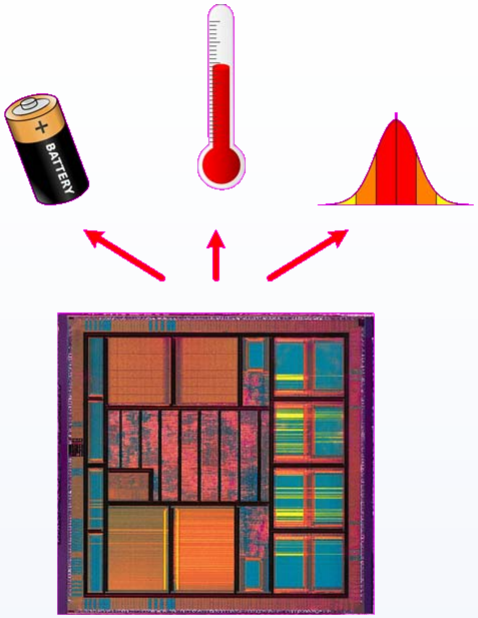
Presentation Overview

- Introduction
- Ring Oscillator Sensing
- Proposed Sensor
- FPGA Measurements
- Conclusion

Introduction

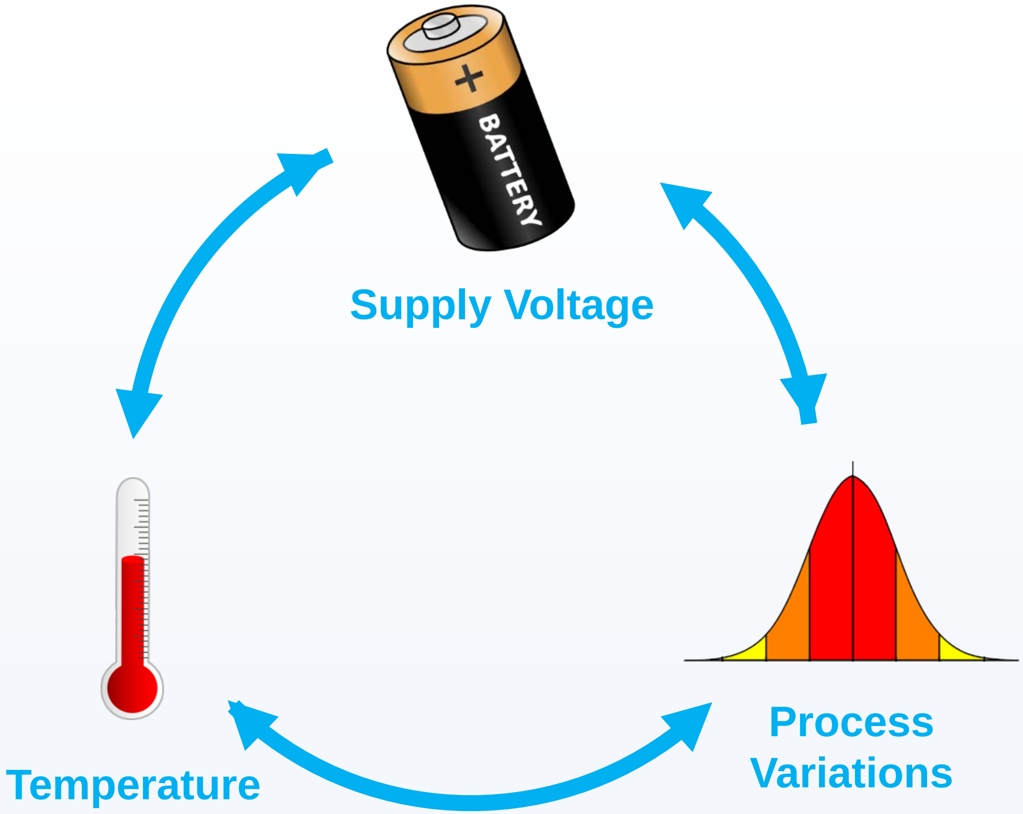
- **Physical parameter sensing in FPGAs:**

  1. Dynamic power and thermal management
  2. Development of power and thermal models
  3. Variation-aware component placement
  4. Monitoring and performance profiling



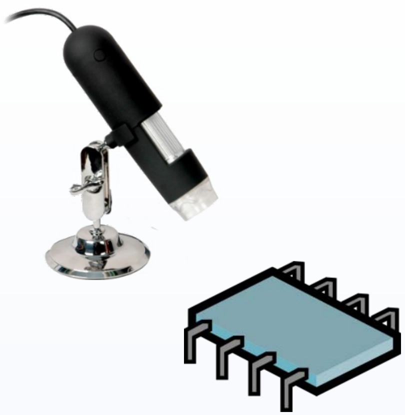
Introduction

- Intra-chip physical parameters are strongly interlinked.

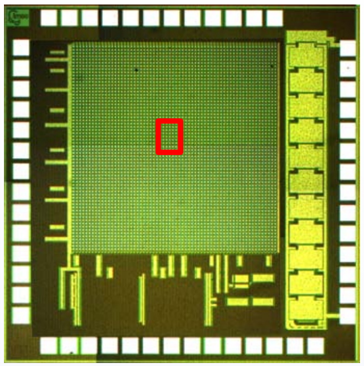


Introduction

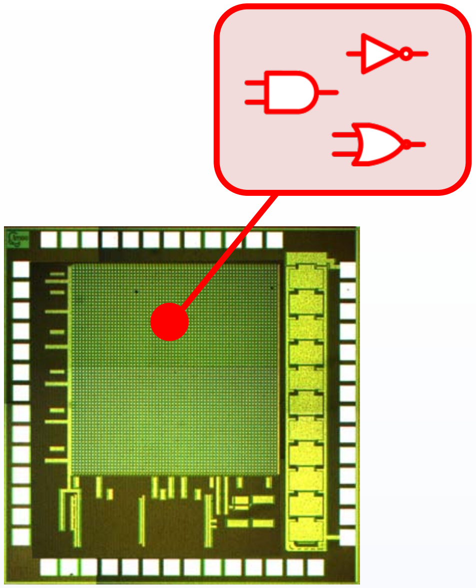
- **Physical parameter sensing in FPGAs:**



External



Built-in Sensors

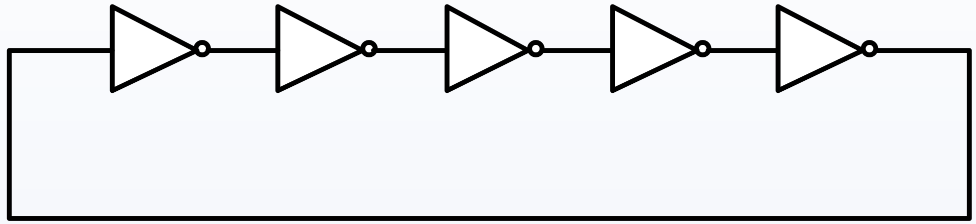


Soft Sensors

1 2 3

Introduction

- **Ring Oscillators:**
  - Oscillation frequency inversely proportional to element delay
  - Higher VDD → lower element delay → higher frequency



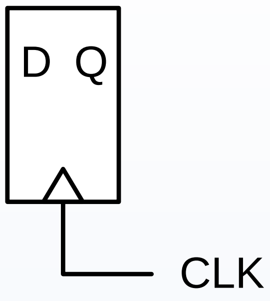
$$f = \frac{1}{2 \times n \times t_d}$$

n : number of elements in loop

t_d : delay of single element

Proposed Sensor

- **Flip-flop Metastability:**
  - When the setup and hold time conditions of a flip-flop are not met, the flip-flop may become **metastable**.
  - A metastable flip-flop will take extra time to decide whether to go logic high or low.
  - Extra decision time = higher clock-to-q delay



Proposed Sensor

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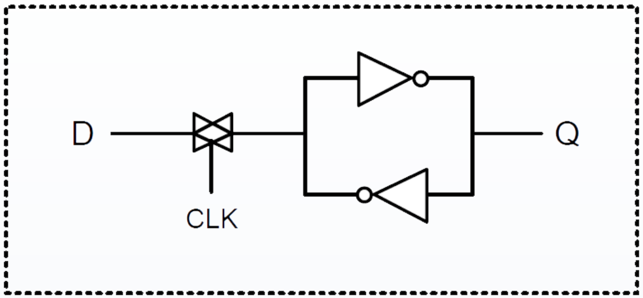
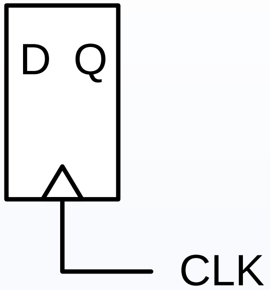




$$Q(t) = Q' \times e^{t/\tau}$$

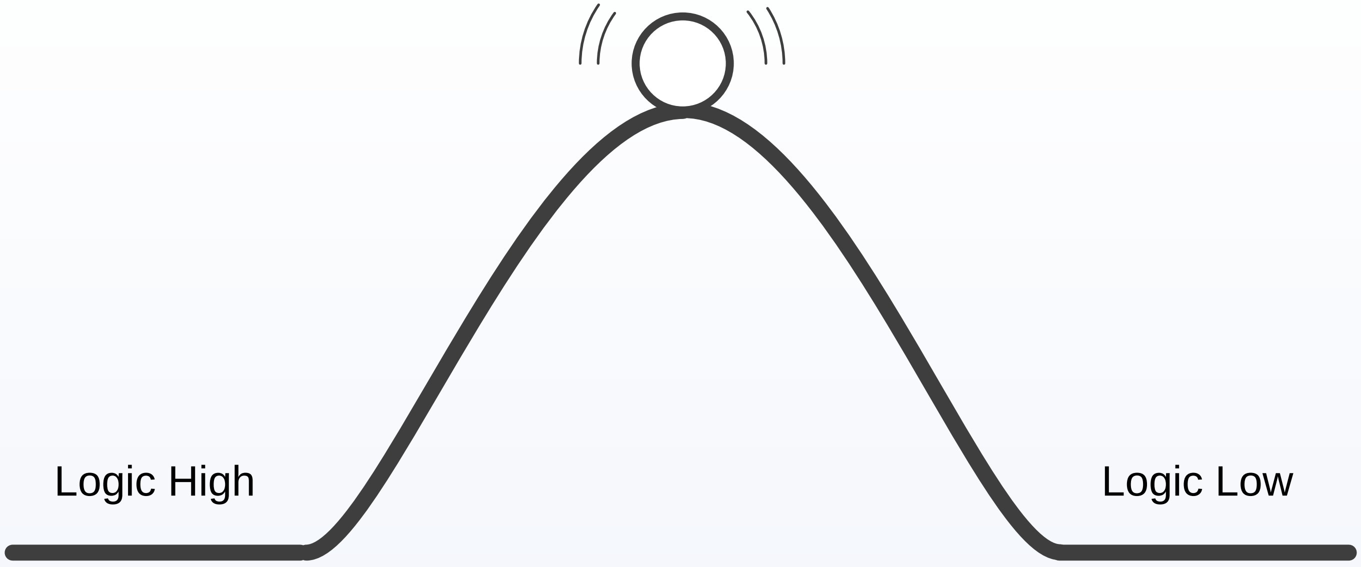
  - The time constant τ is a function of the flip-flop's transconductance.

Proposed Sensor

- **Flip-flop Metastability:**
  - The probability that the flip-flop’s clock-to-q delay will exceed *t* seconds depends exponentially on the value of the time constant Tau.

Proposed Sensor

- **Flip-flop Metastability:**



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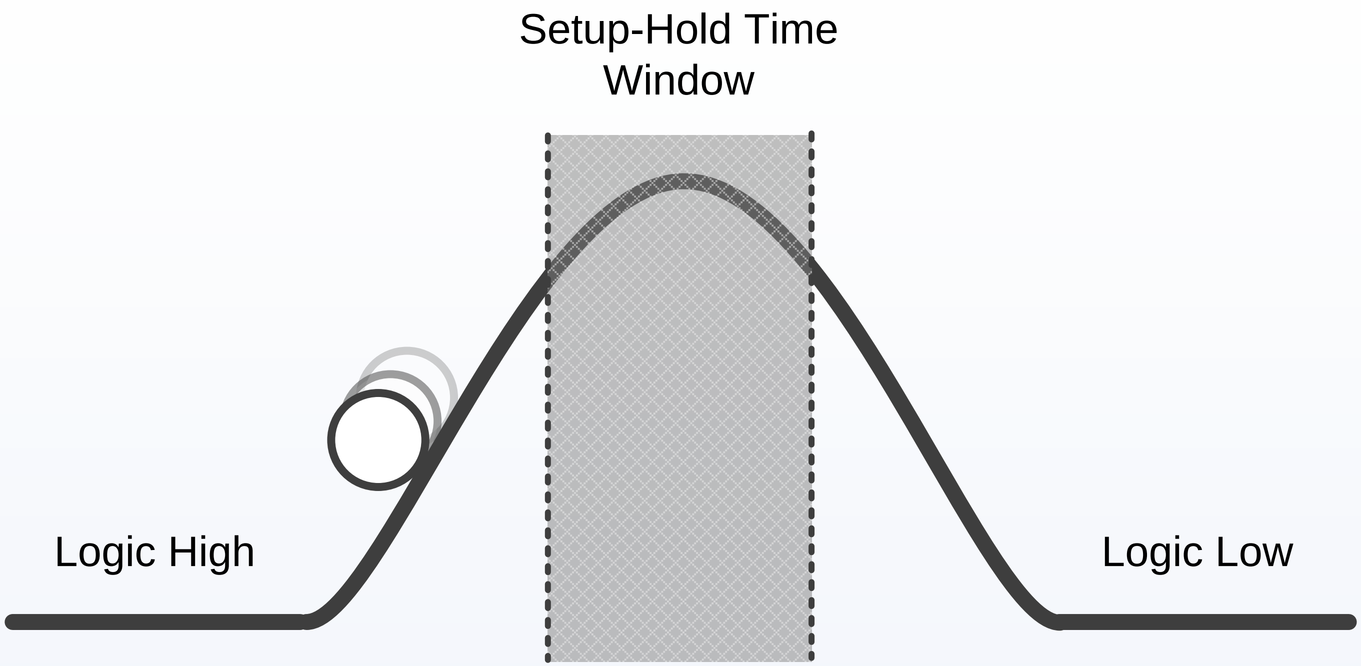

Proposed Sensor

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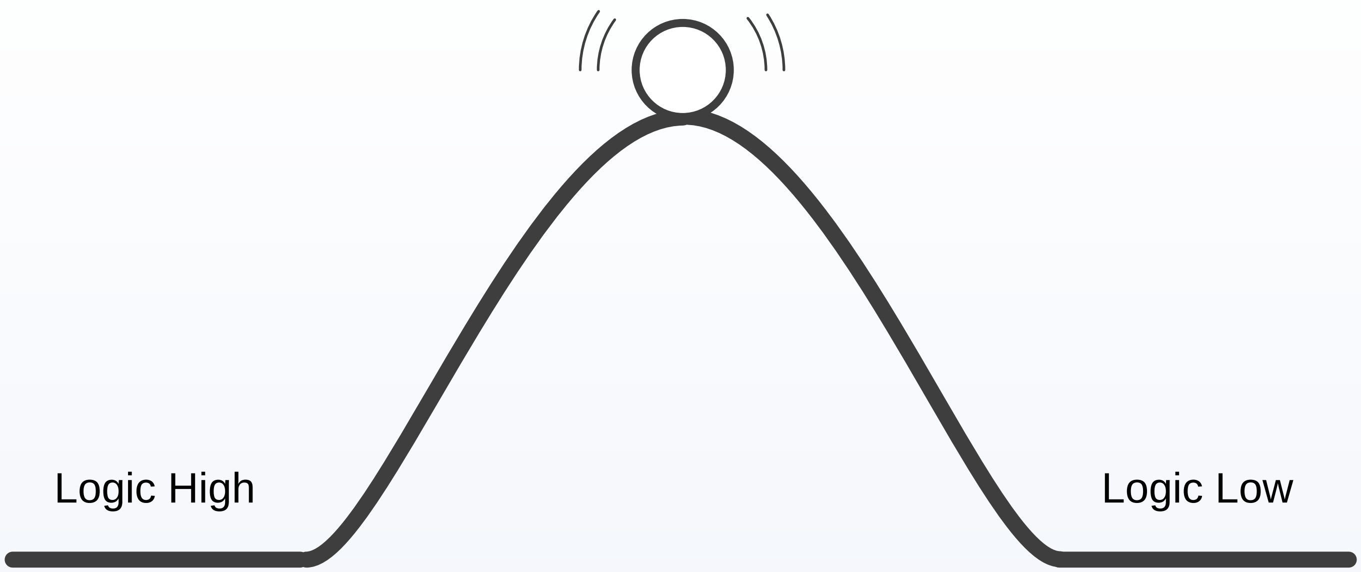

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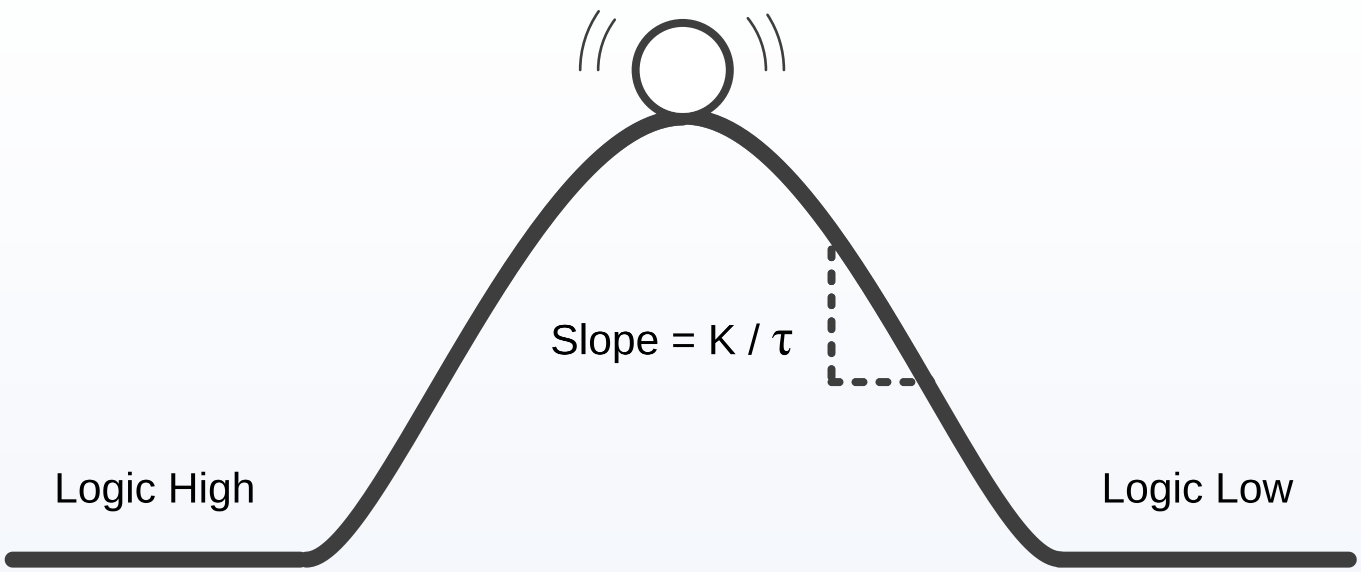

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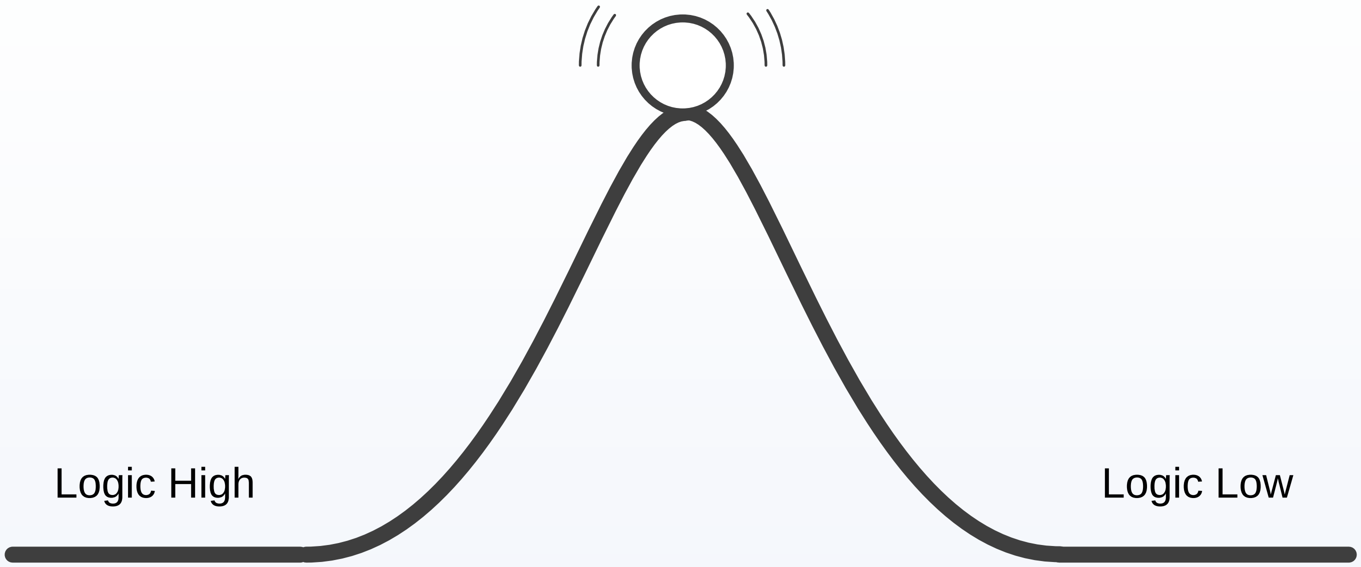

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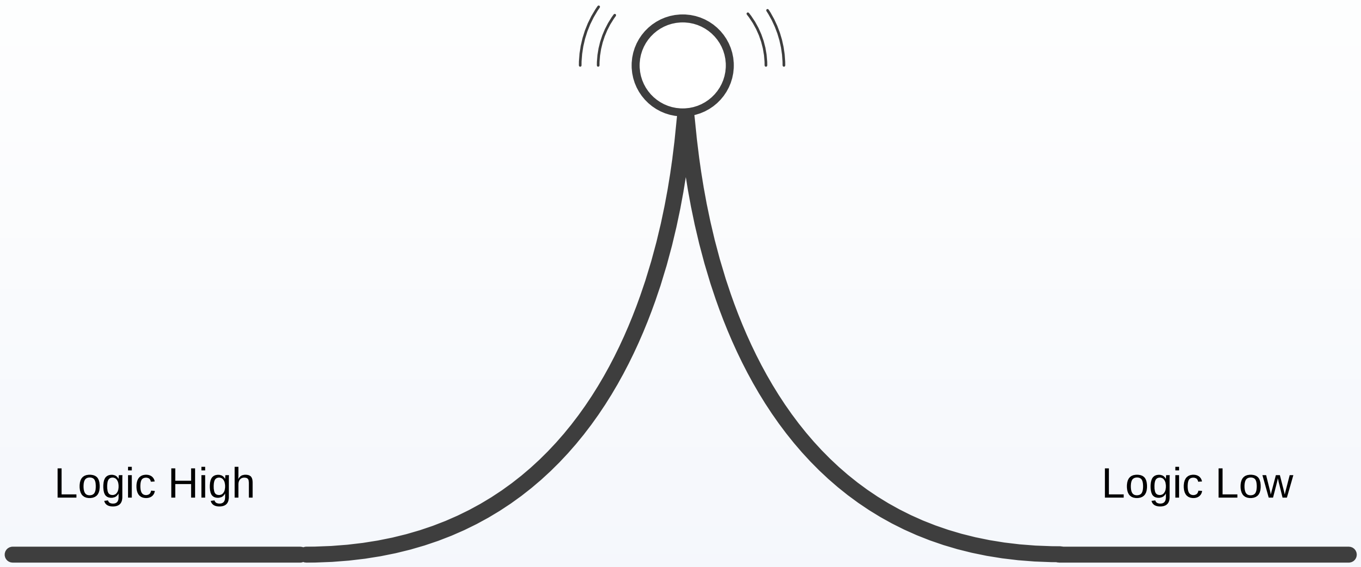

Proposed Sensor

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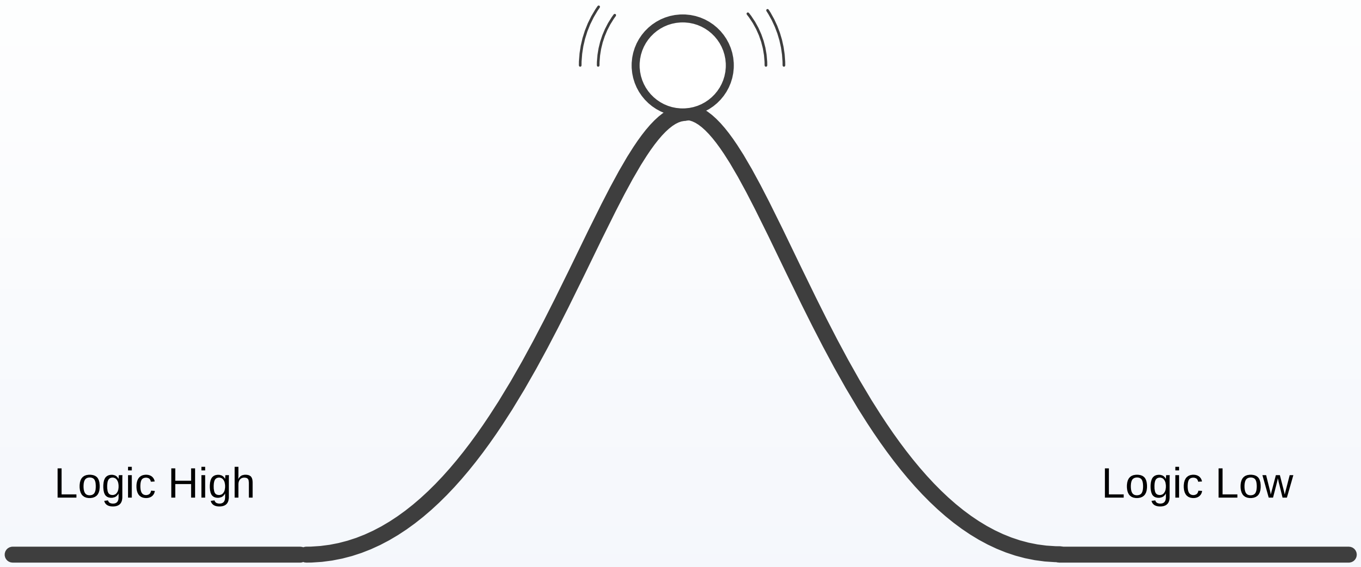
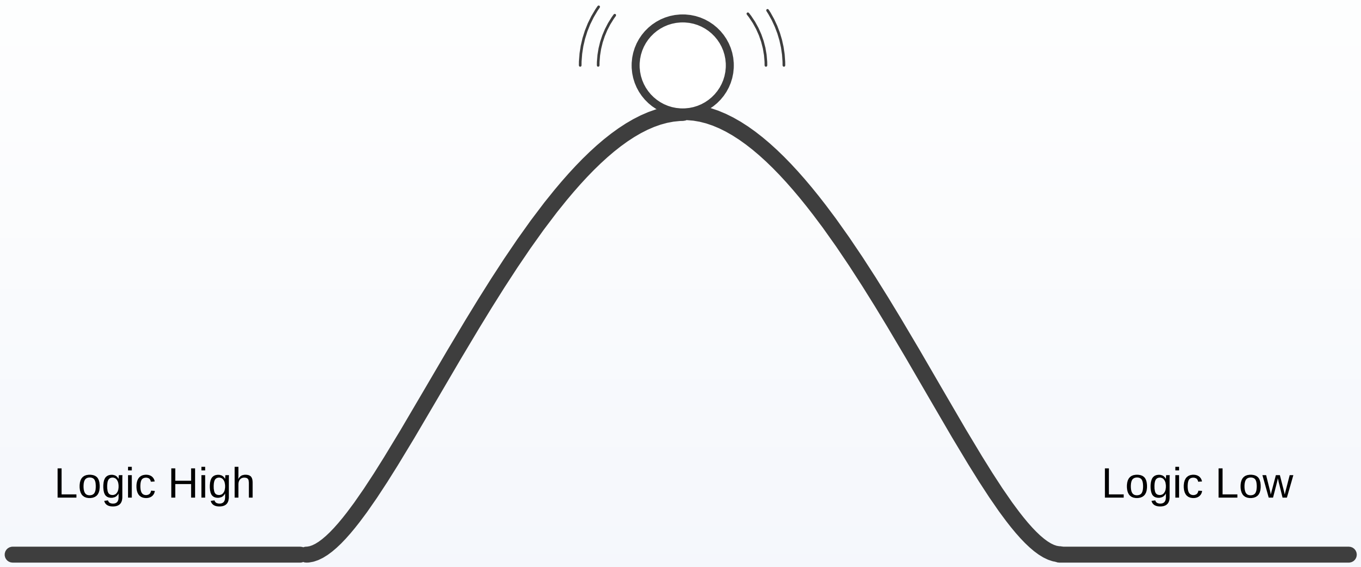


Proposed Sensor

- **Flip-flop Metastability:**

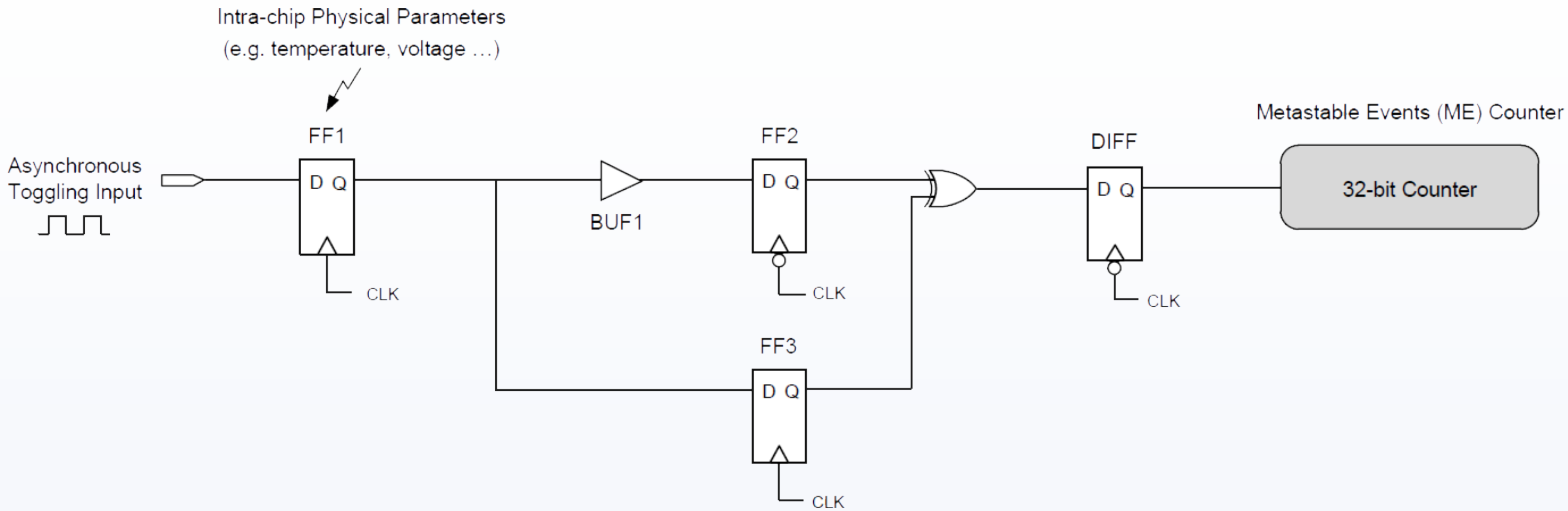


Proposed Sensor

- **Flip-flop Metastability:**
  - Tau (the slope of the hill) is a function of the cross-coupled gates transconductance.
  - Tau is influenced by physical parameter variations similar to propagation delay.

Proposed Sensor

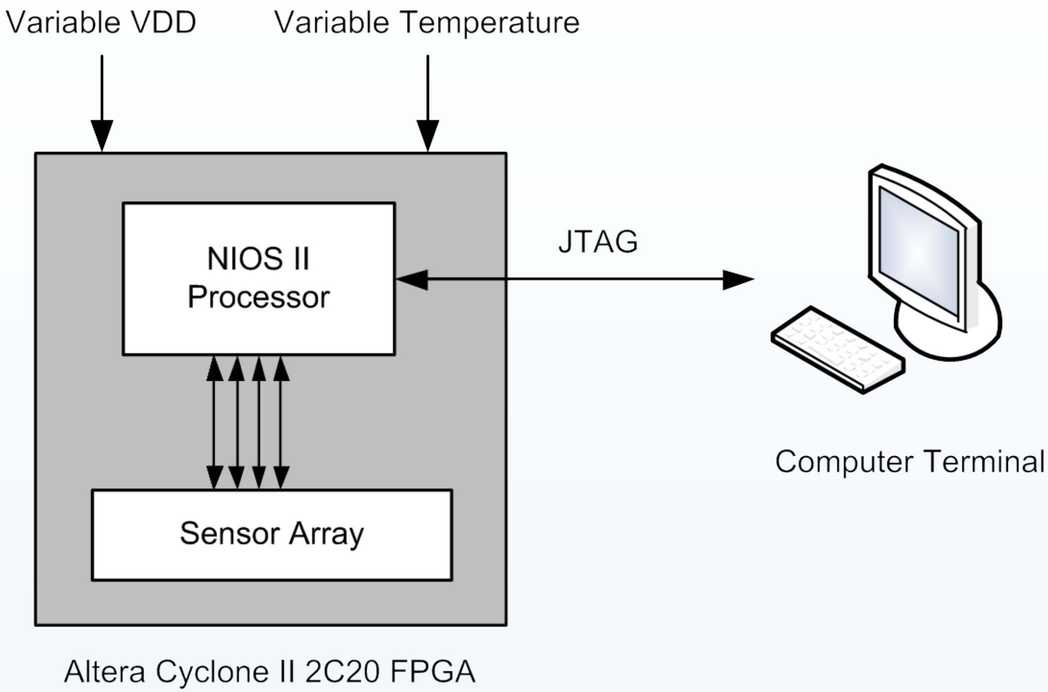
- **Proposed Design:**



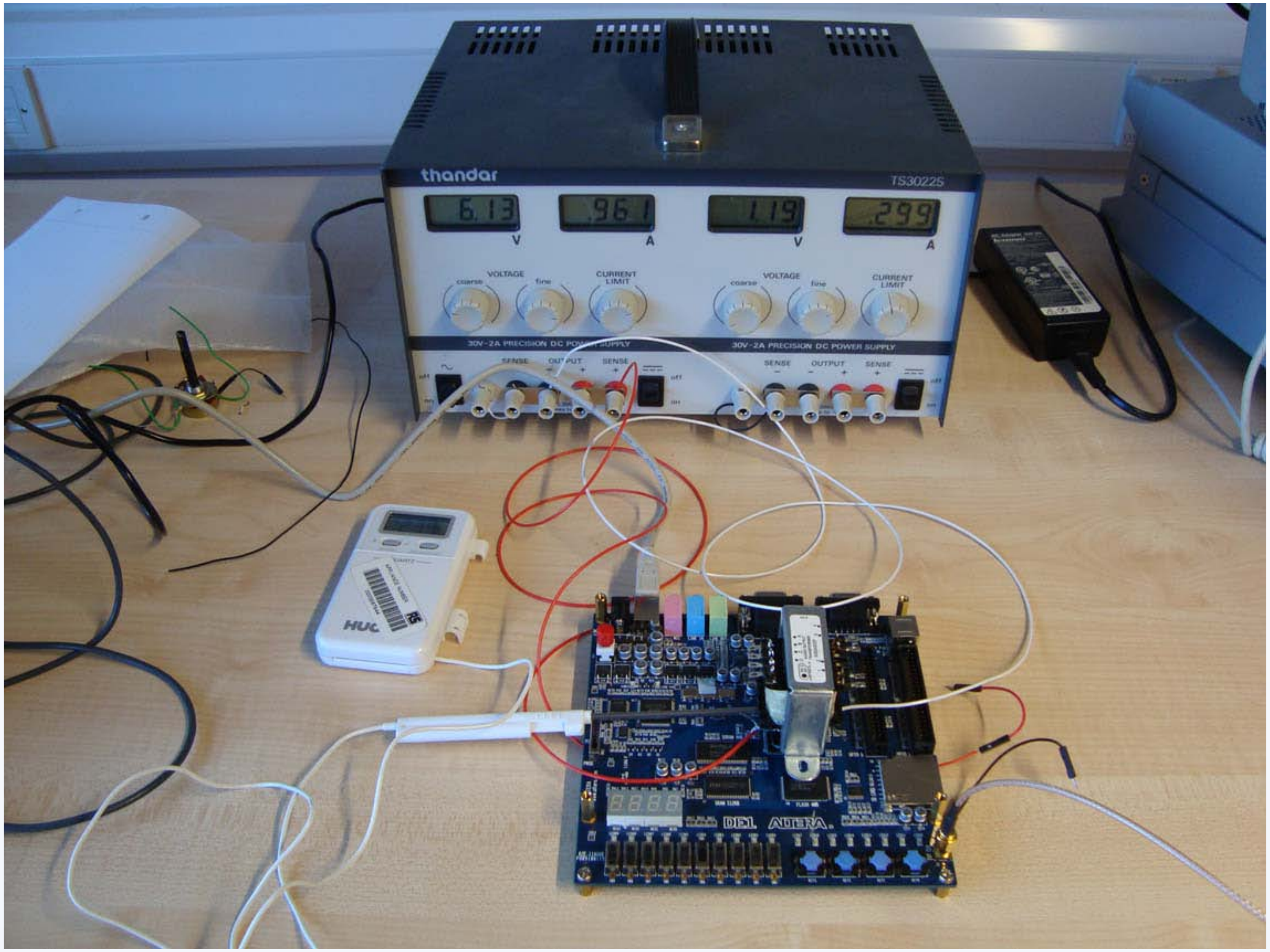
$$\text{Count} = n \times K \times e^{Sp}$$

FPGA Measurements

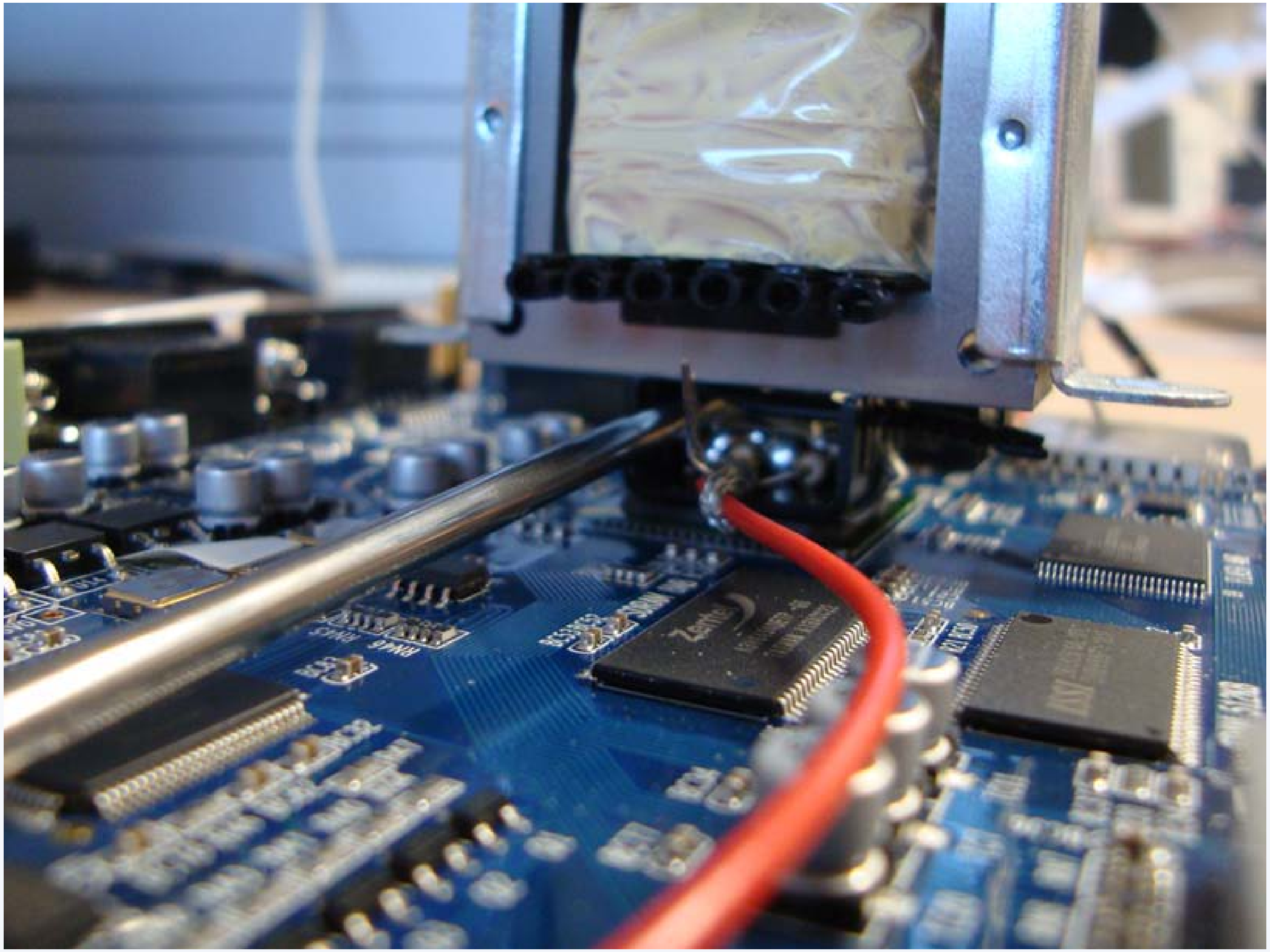
- **Sensor characterization system:**



FPGA Measurements



FPGA Measurements



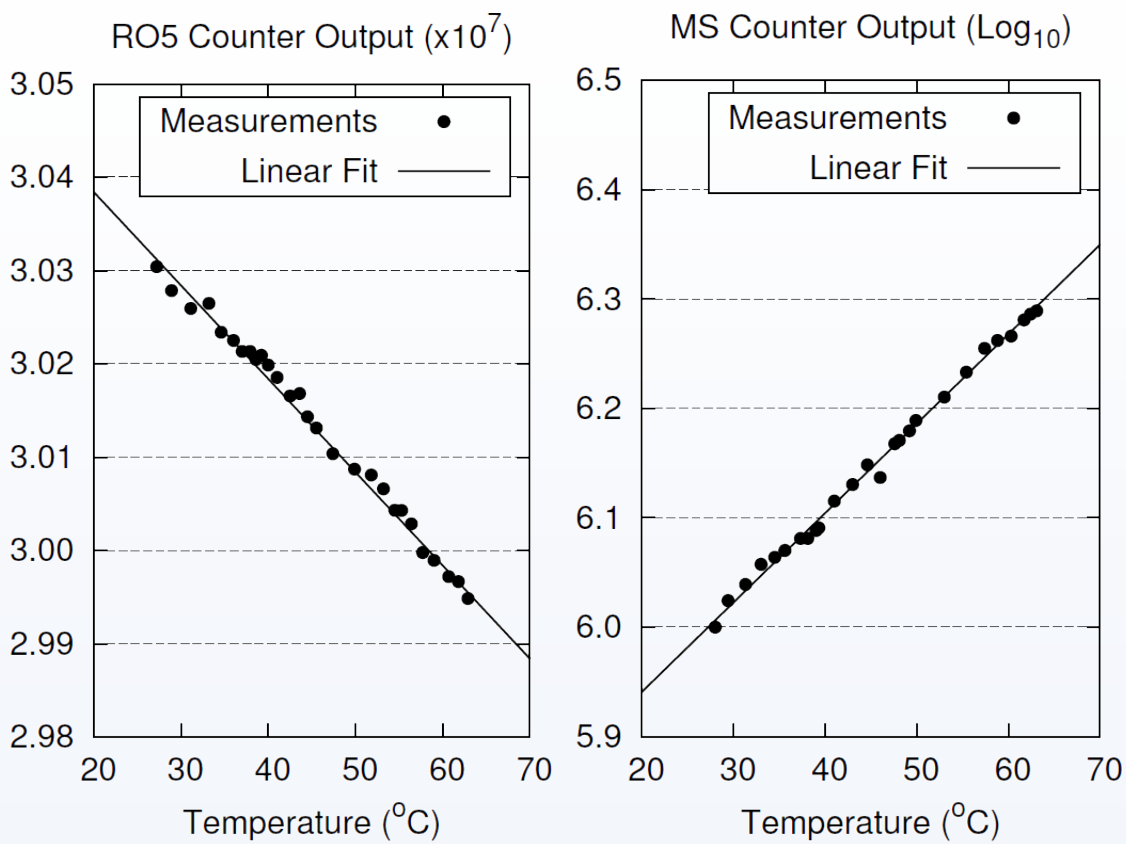
FPGA Measurements

- **Compared Sensors:**

Sensor	Description	LUTs	FFs
RO5	5-stage RO with 3 decimation stages	9	5
RO11	11-stage RO with 3 decimation stages	15	5
RO17	17-stage RO with 3 decimation stages	21	5
MS	metastability-based sensor (proposed)	2	4

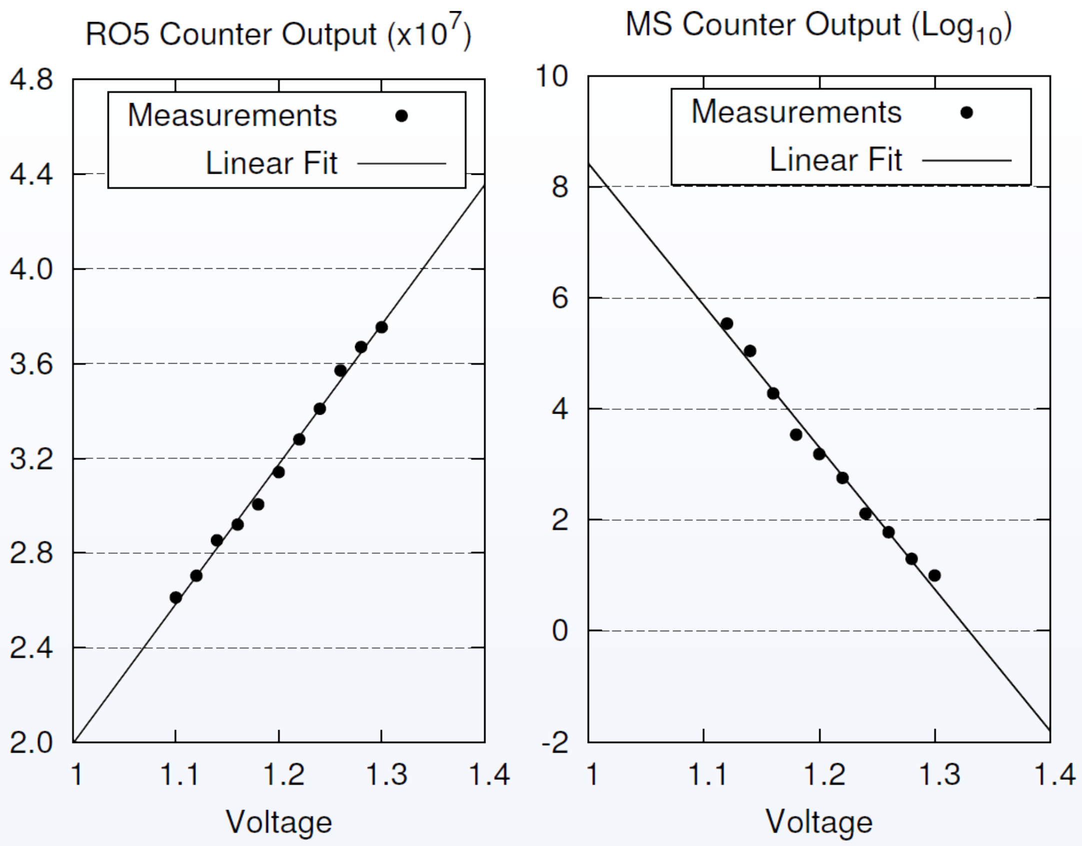
FPGA Measurements

- **Output Response (Temperature):**



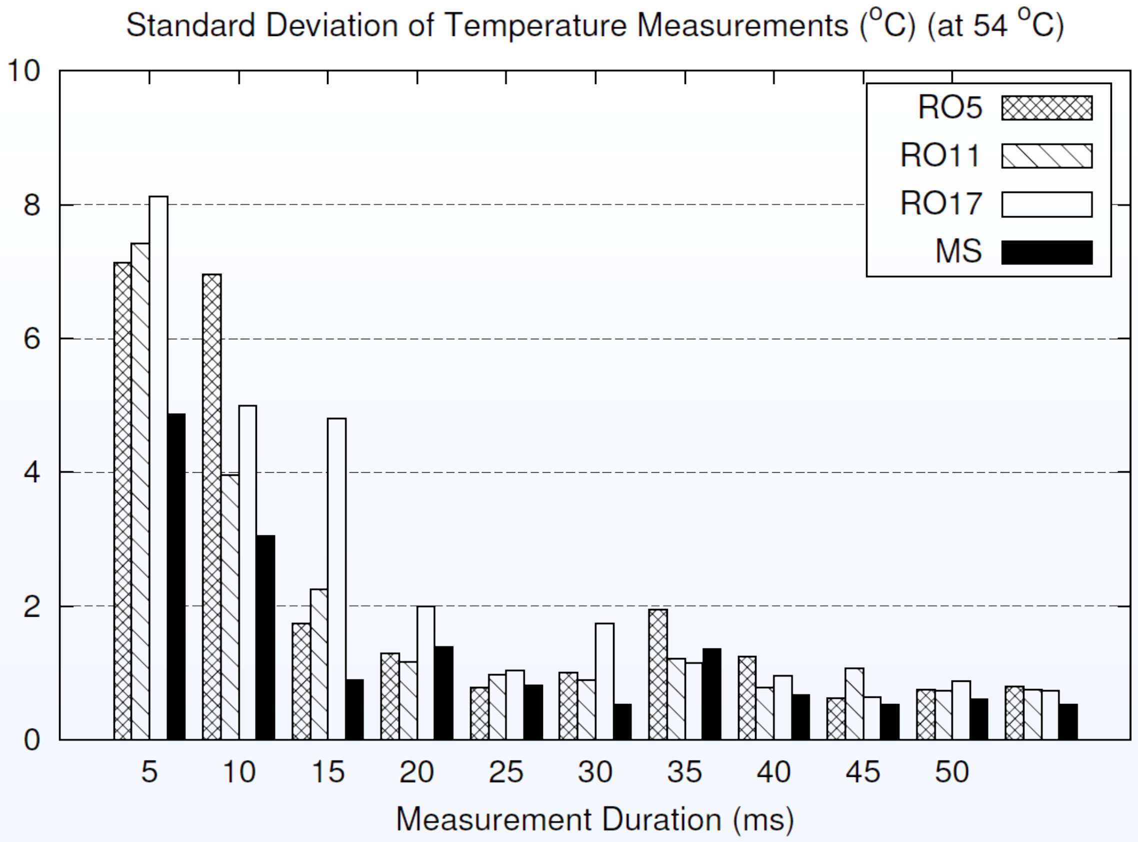
FPGA Measurements

- **Output Response (Voltage):**



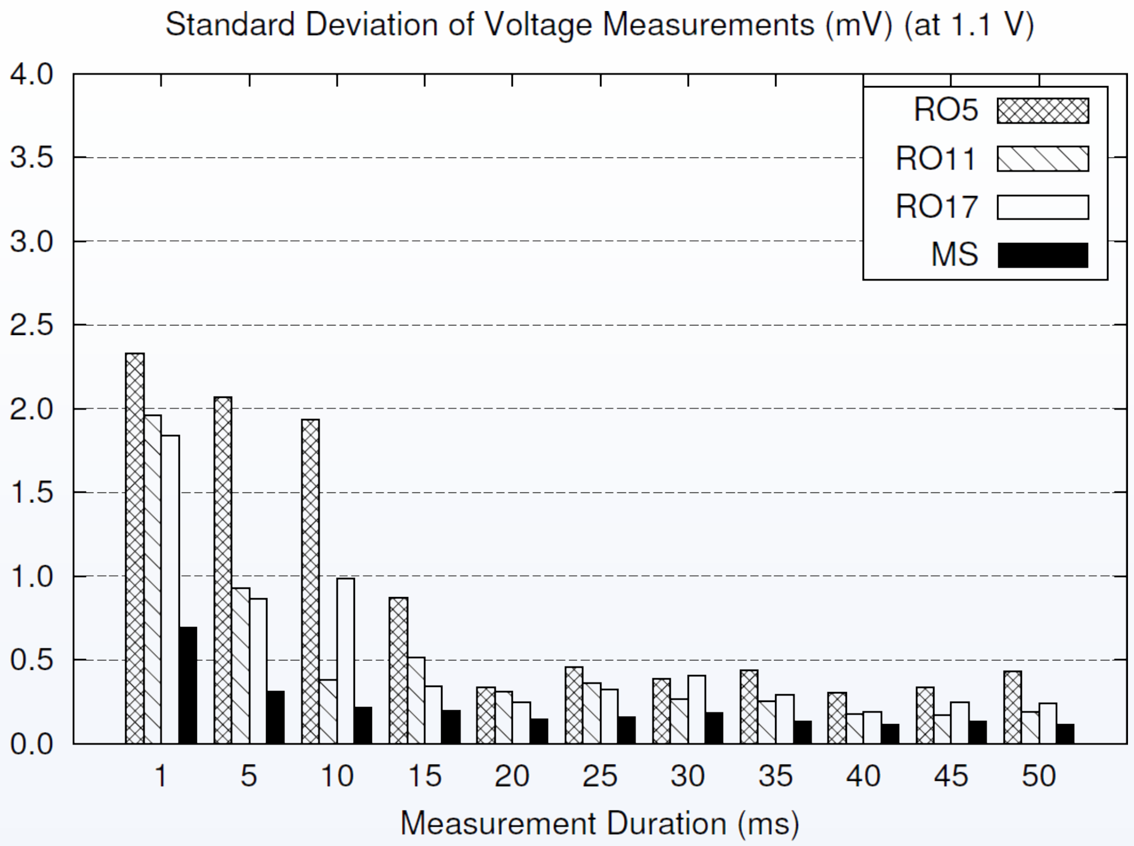
FPGA Measurements

- **Precision (Temperature): 60% average increase**



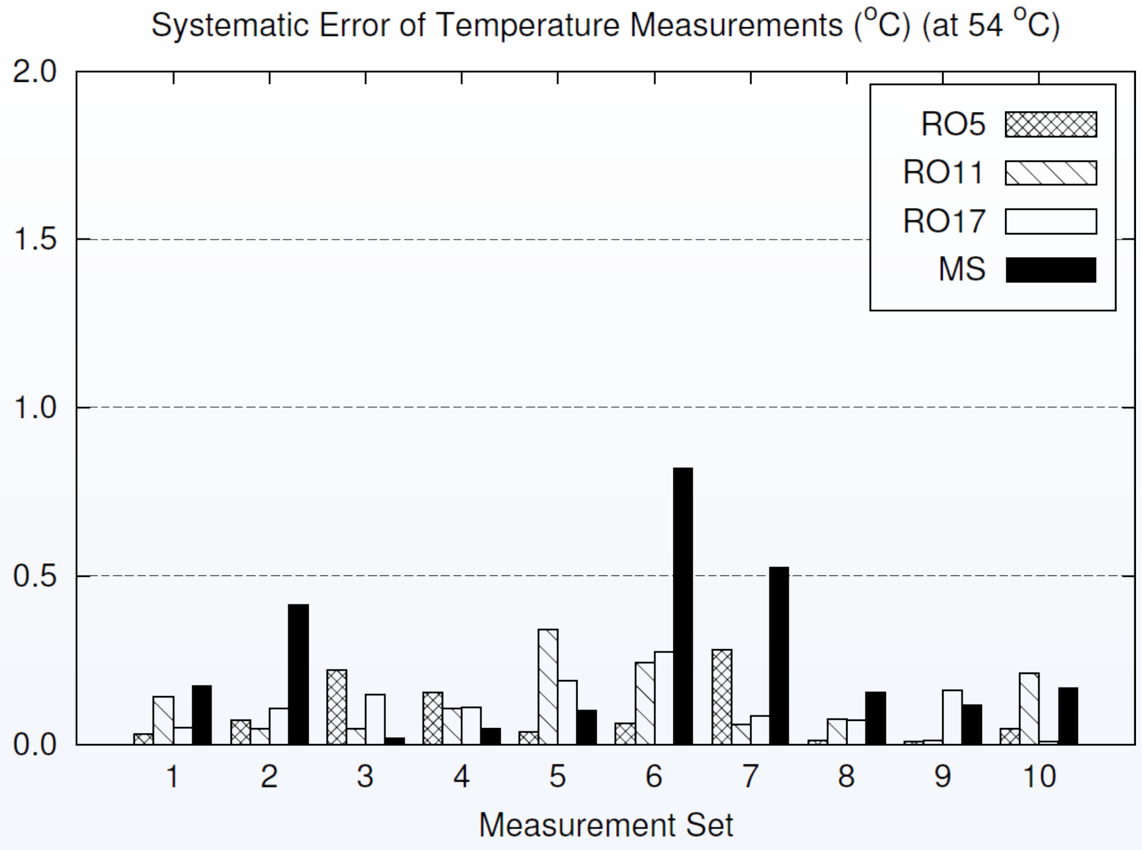
FPGA Measurements

- **Precision (Voltage): 173% average increase**



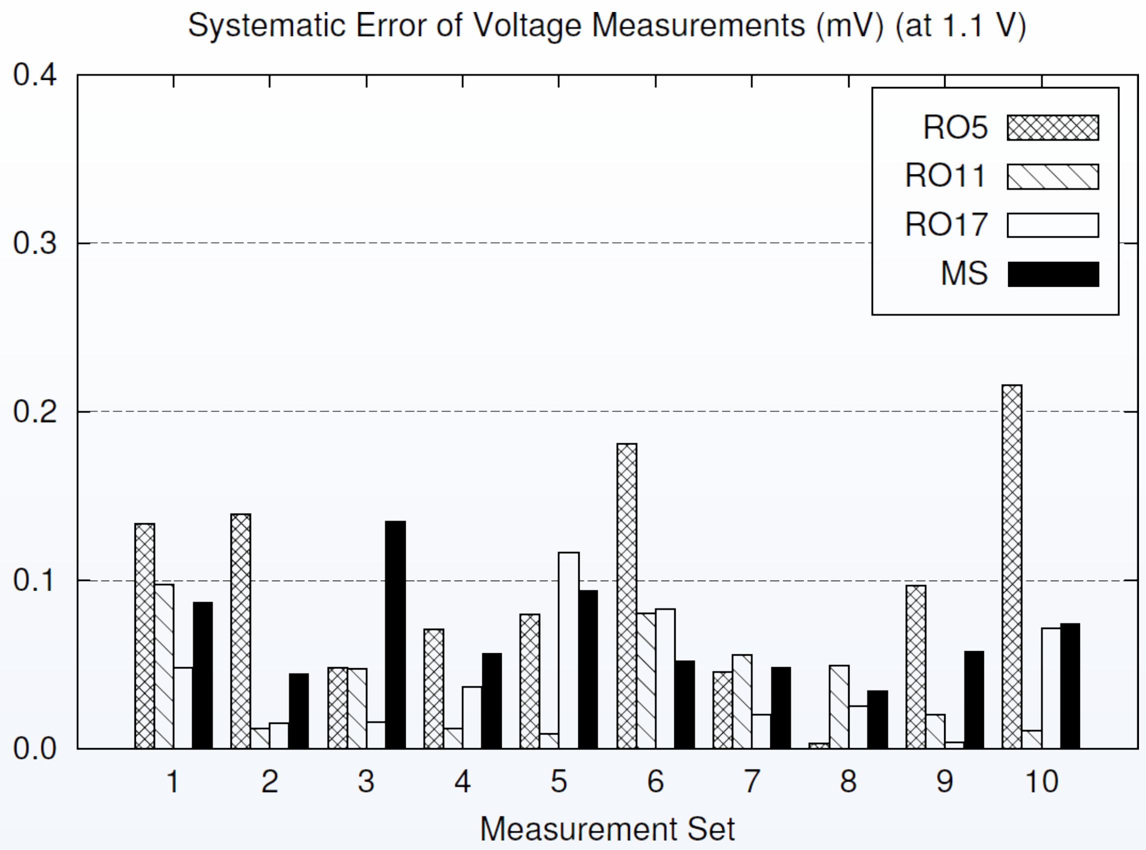
FPGA Measurements

- **Accuracy (Temperature): no significant difference**



FPGA Measurements

- **Accuracy (Voltage): no significant difference**



Conclusion

- Physical parameter sensing supports adaptive, reconfigurable and self-aware applications.
- Presented a novel intra-chip physical parameter sensor based on the phenomenon of flip-flop metastability.
- Proposed design consumes 20% less flip-flops, 75% less LUTs and demonstrated precision improvements of 60% in temperature sensing and 173% in voltage sensing.

End of Presentation