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A 3.12pJ°C² Ultra-Low-Power Direct-ADC Multi-Range Temperature Sensor for IoT Nodes

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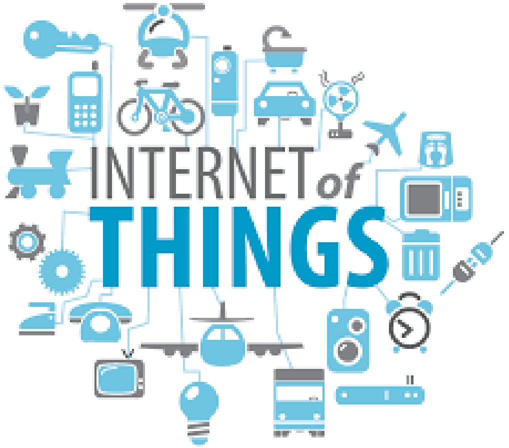
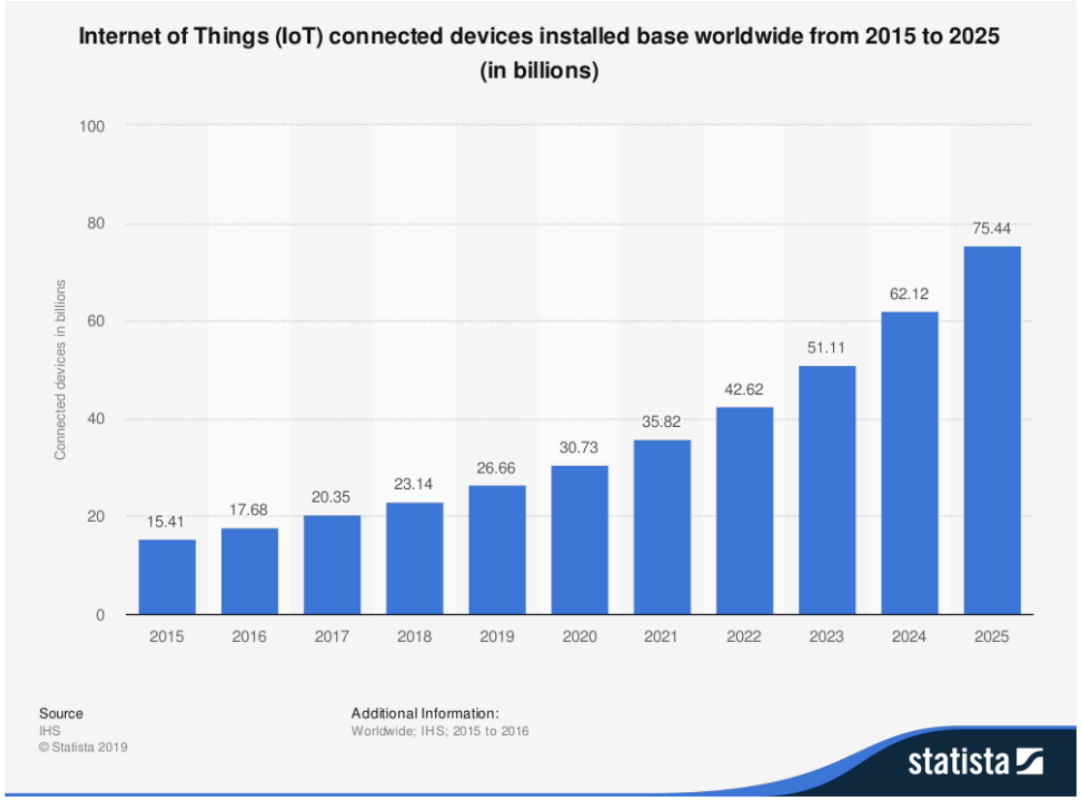
Outline

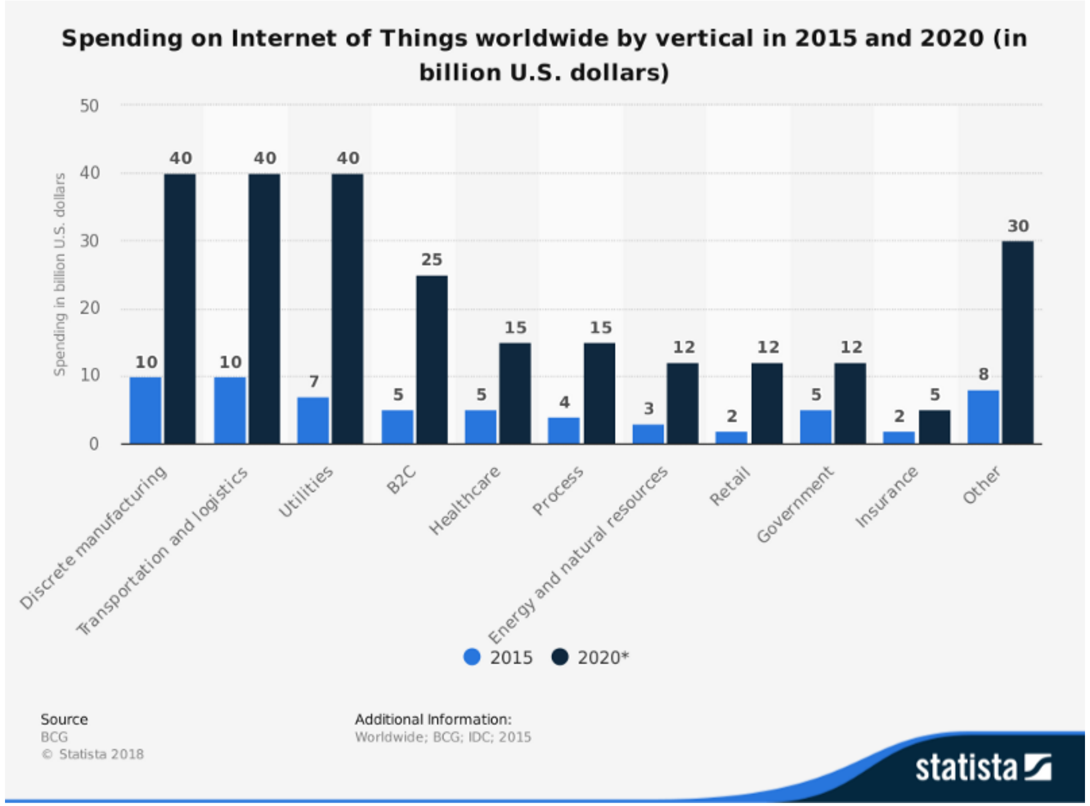
- Introduction
  - Internet of Things definition and challenges
  - Temperature sensing elements
- BJT-based Temperature sensors
  - BJT-based sensor: conventional structure (operation principles)
  - Challenges of the Convectional Structure
- Proposed BJT-based Temperature sensors
  - Proposed structure
  - Dynamic range utilization improvement
  - Temperature dependent linear parameter
  - Non-ideality sources
- ADC design
  - Architecture selection
  - MATLAB system-level implementation
  - Circuit level implementation
  - Results

Internet of Things definition and Challenges



- IoT: system of interrelated computing devices
  - Increasing demand for low-power wireless sensor nodes
  - Temperature sensors: Highly-utilized modules in IoT devices.
- Wireless nature: Minimum possible power consumption





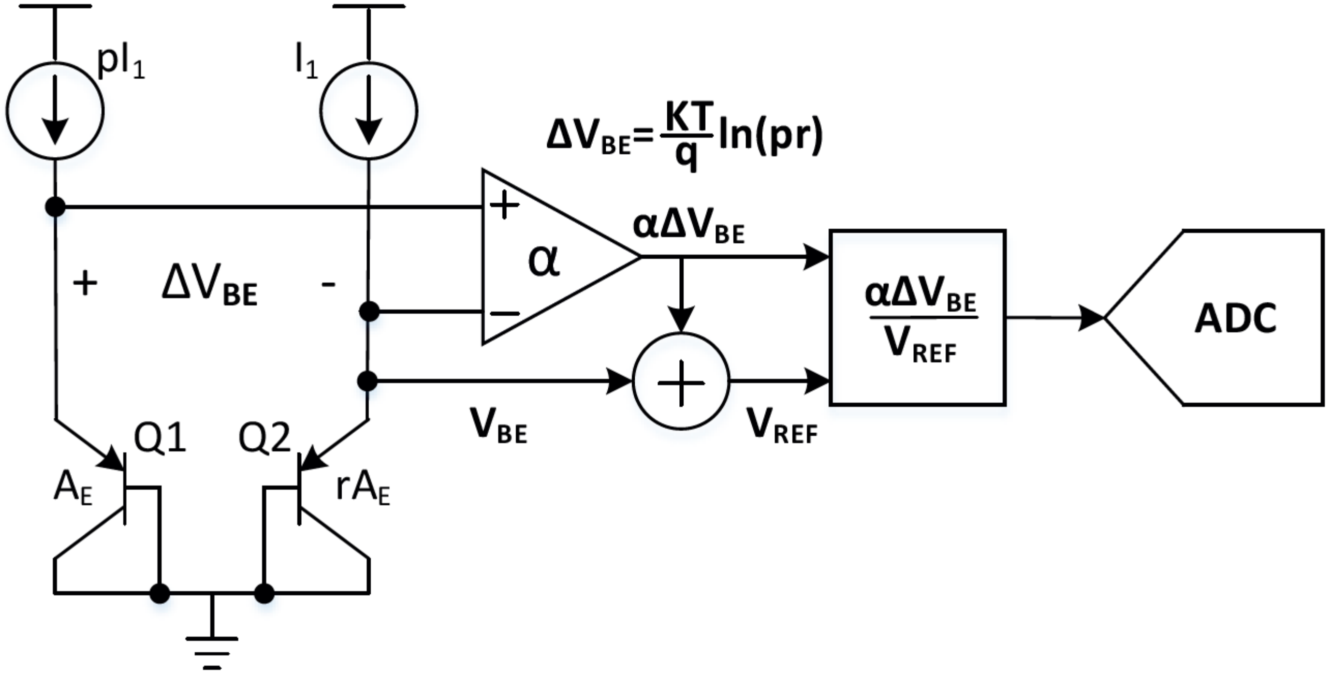
Temperature Sensing Elements

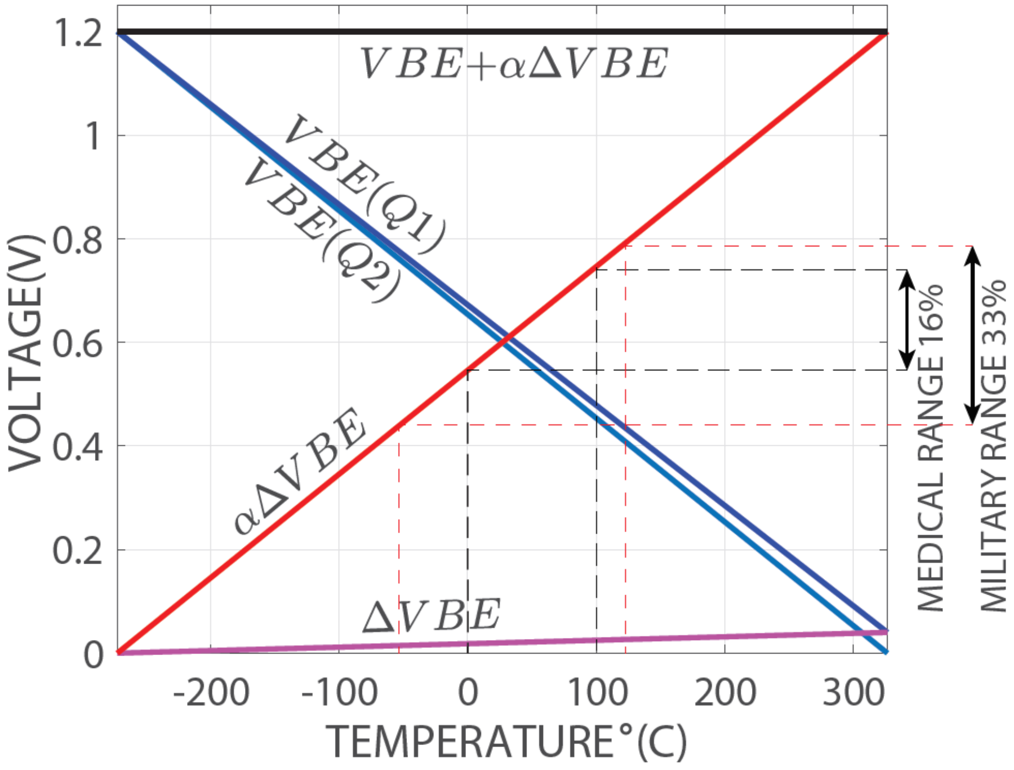
- CMOS compatible temperature sensing element
  - Cost effective
  - Reliable performance
  - Compact physical size
- Available sensing element in CMOS technology:
  - Resistors, BJTs, MOSFET, and DTMOST.

Ref	Tech (μm)	Temperature range	resolution	Conversion time (ms)	FOM pJK^2	Sensor type
VLSI(2011)	0.18	0ºC - 100 ºC	0.25 ºC	0.012	19	Resistor
SSC(2013)	0.16	-55 ºC - 125 ºC	0.02 ºC	5.3	11	BJT
JSSC(2014)	0.18	0 ºC - 100 ºC	0.3 ºC	30	190	MOSFET
ISSCC(2014)	0.16	-40 ºC - 125 ºC	0.063 ºC	6	14.1	DTMOST

Outline

BJT-based sensor: Conventional Structure (Operation Principles)





$$\Delta V_{BE} = \frac{KT}{q}\ln(pr)$$

$$\mu = \frac{\alpha\Delta VBE}{V_{BE} + \alpha\Delta VBE}$$

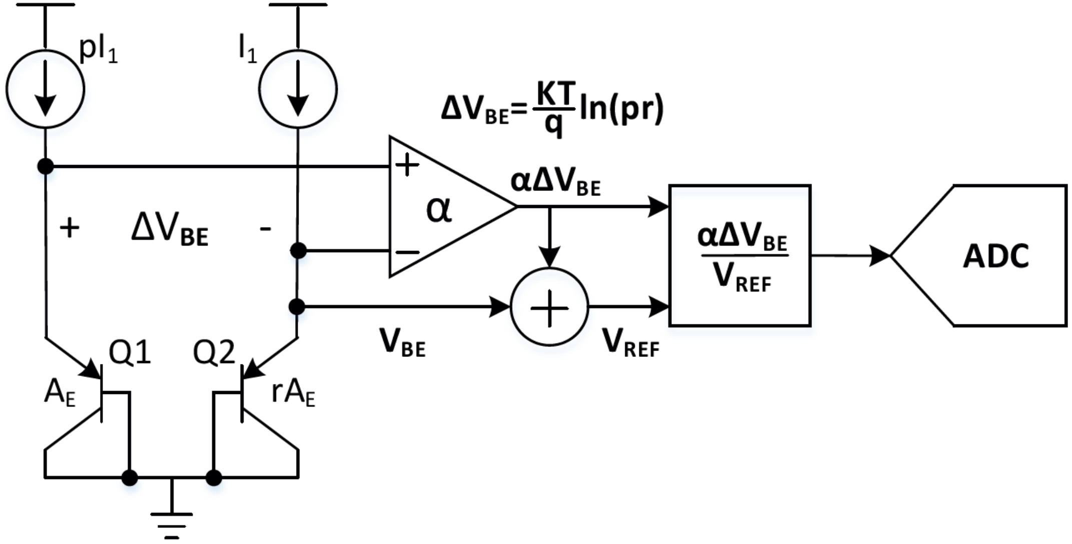
$$T = A.\mu + B$$

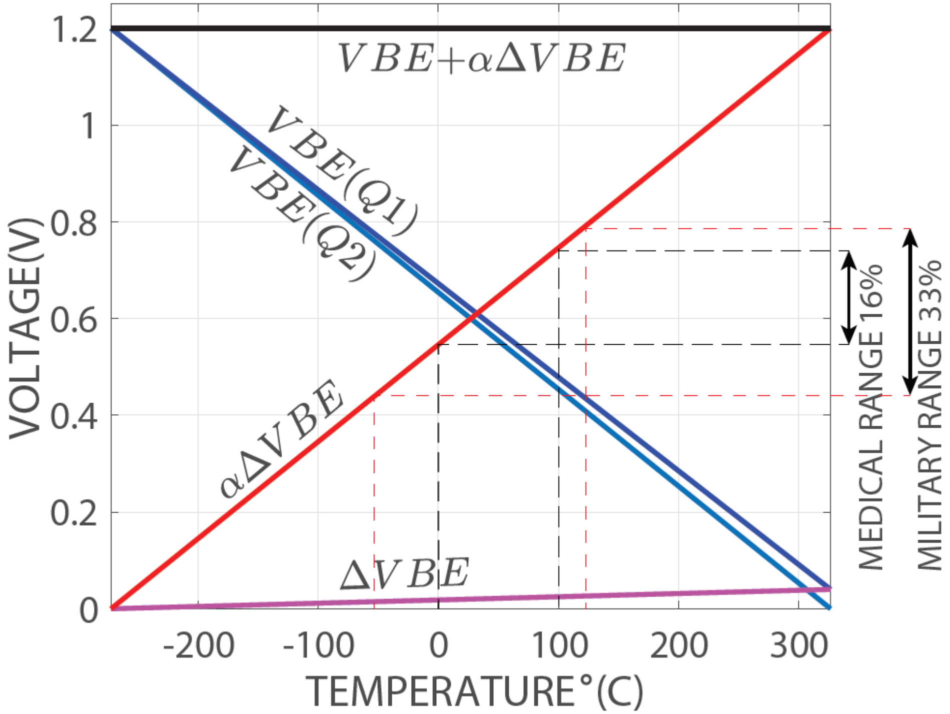
$$T = A \approx 600K \quad \& \quad B \approx -273K$$

Challenges of the Convectional Structure

- ΔV_{BE}: Small temperature to voltage conversion gain
  - Constant gain is required (α)
- α: Process dependent value
  - Require a temperature independent variable-gain amplifier
- Utilizing only small percentage of the ADC dynamic range
  - High accuracy ADC
  - High power consumption

$$\alpha = \frac{S^{T}_{V_{BE}}}{\frac{KT}{q} ln(pr)}$$





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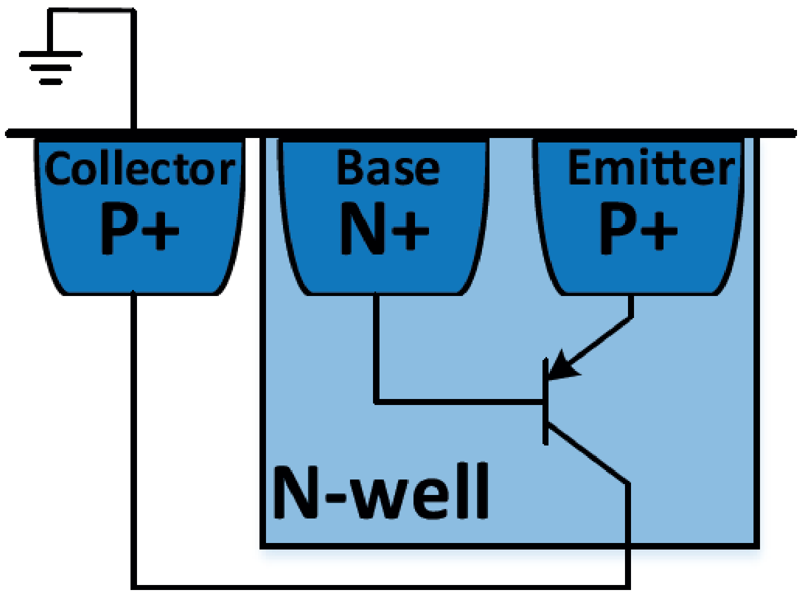
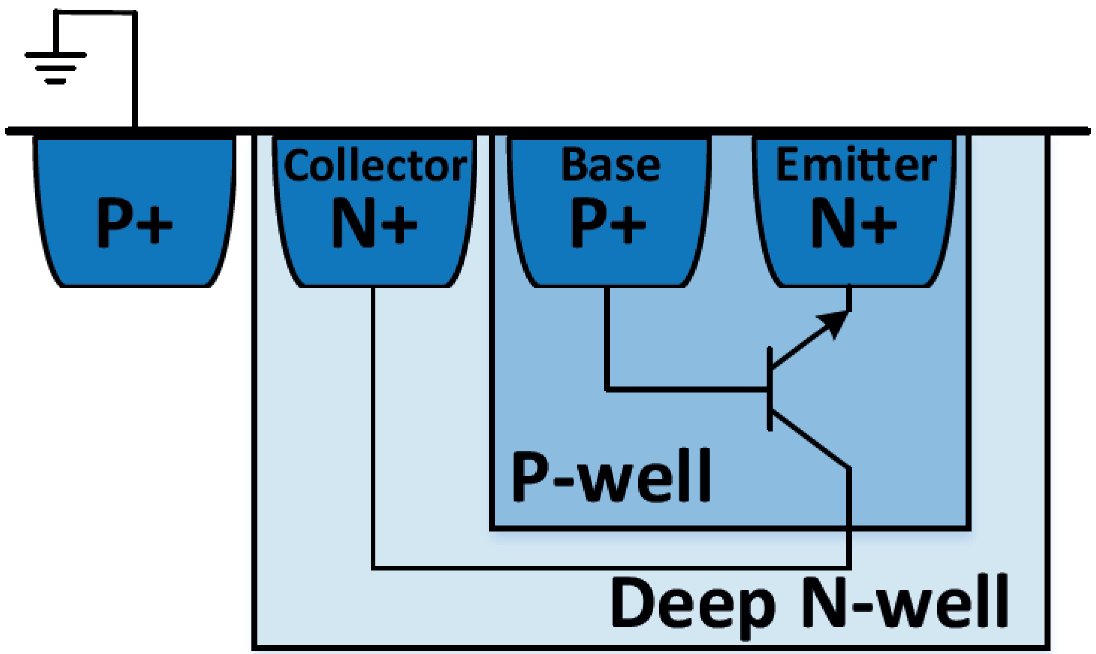
NPN-based vs PNP-based Temperature Sensor

- Cross section view of PNP transistor.
- Collector terminal is the substrate.
  - Collector can only be grounded



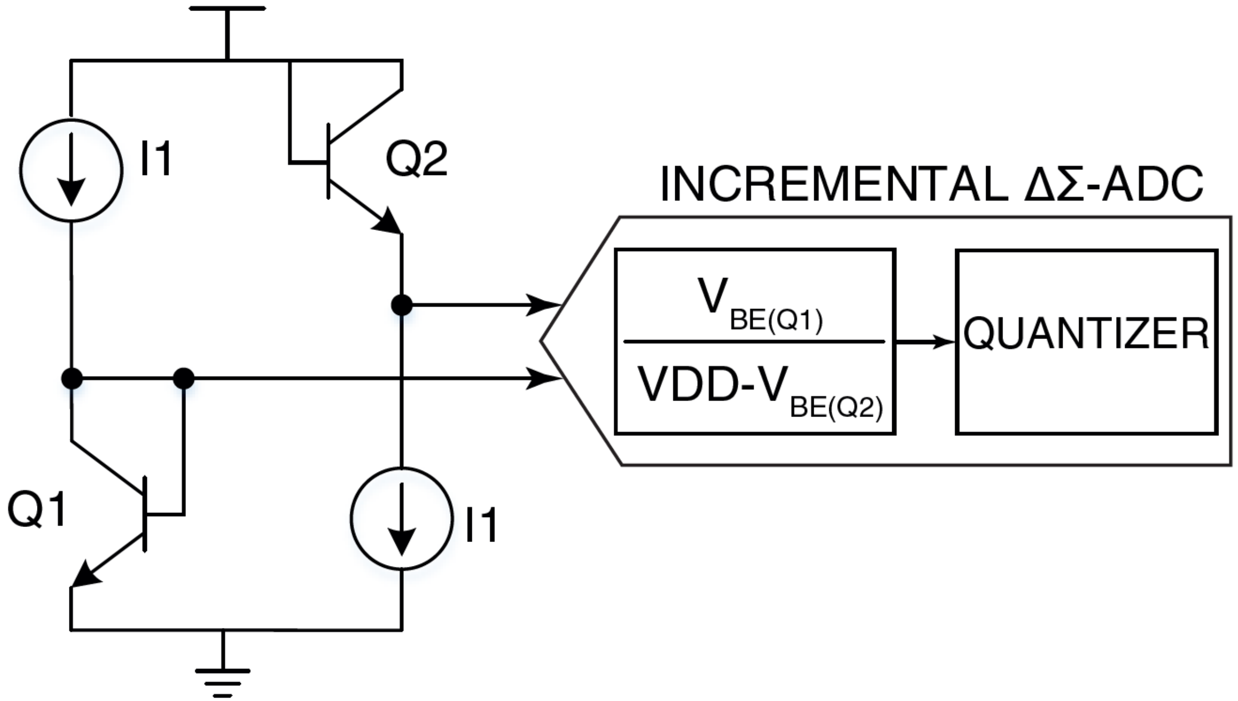
- Cross section view of NPN transistor.
- Require Deep N-well
  - Only available in more recent technologies.
- No limit in connection of terminals

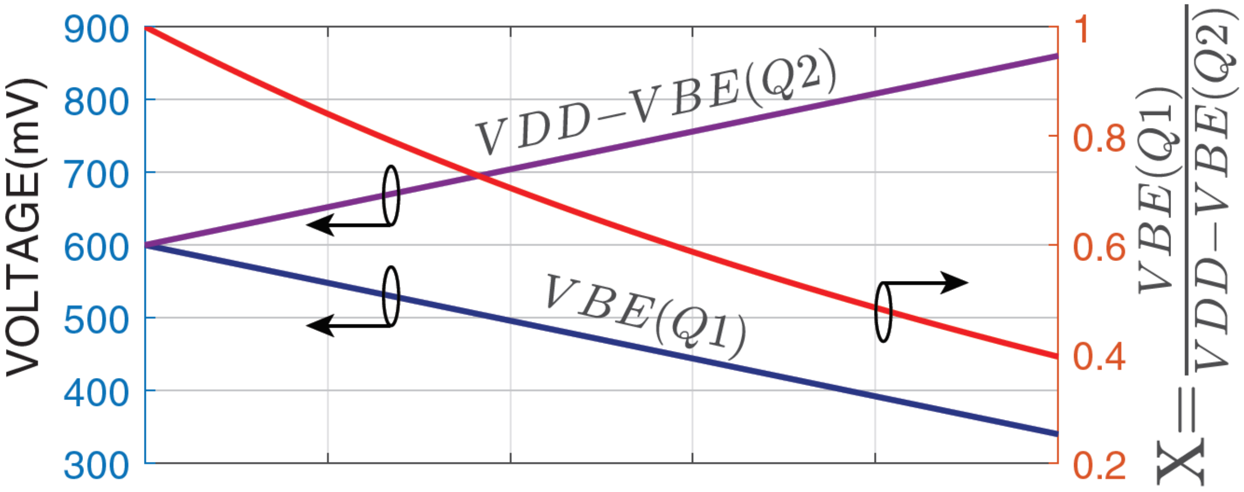


Proposed Structure

- NPN-based structure.
- Significant higher temperature to voltage conversion rate.
  - Lower ADC resolution
    - Lower power consumption
- Needless of temperature independent processing
  - Can be directly fed to the ADC

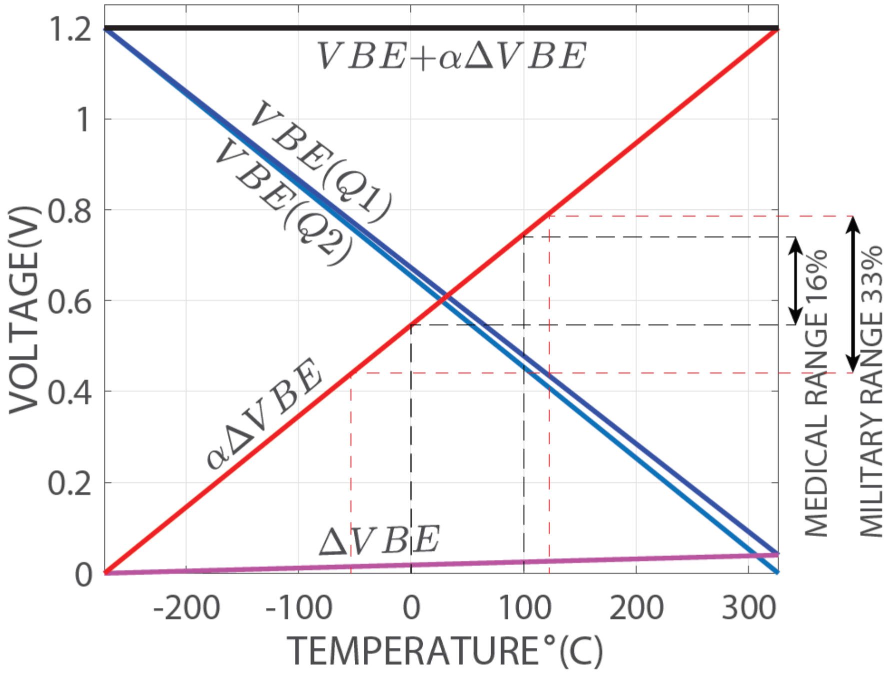
$$X = \frac{V_{BE}(Q1)}{VDD - V_{BE}(Q2)}$$

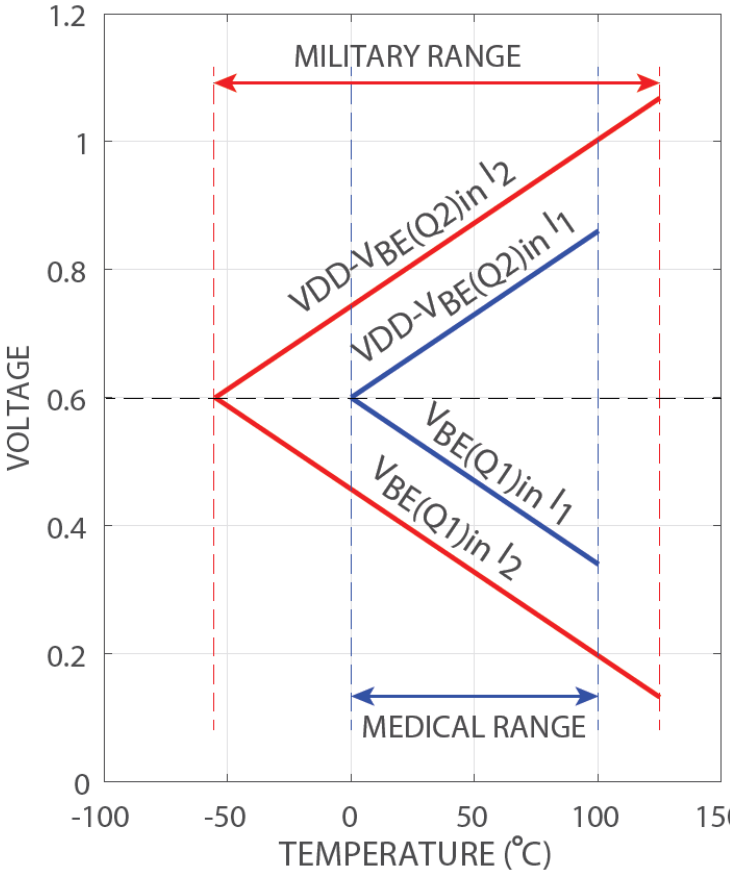


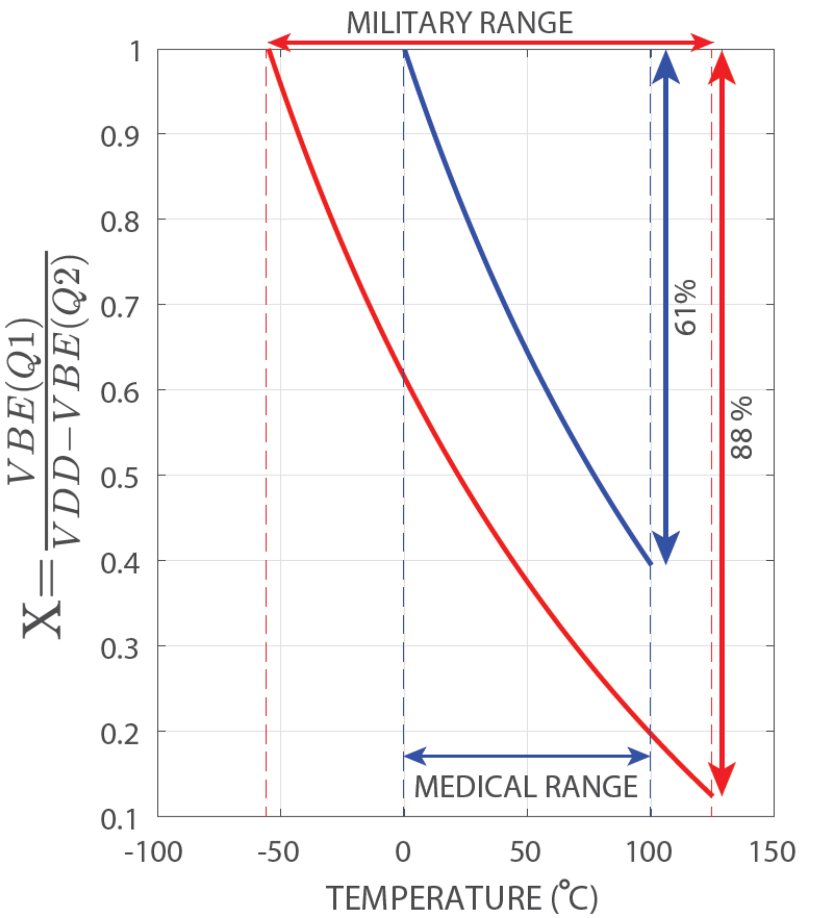


Dynamic Range Utilization Improvement

- Low percentage of DR utilization
  - 16% medical range
  - 33% military range
- Adjustable for different ranges
- Improved DR utilization
  - 61% medical range
  - 88% military range







Temperature Dependent Linear Parameter

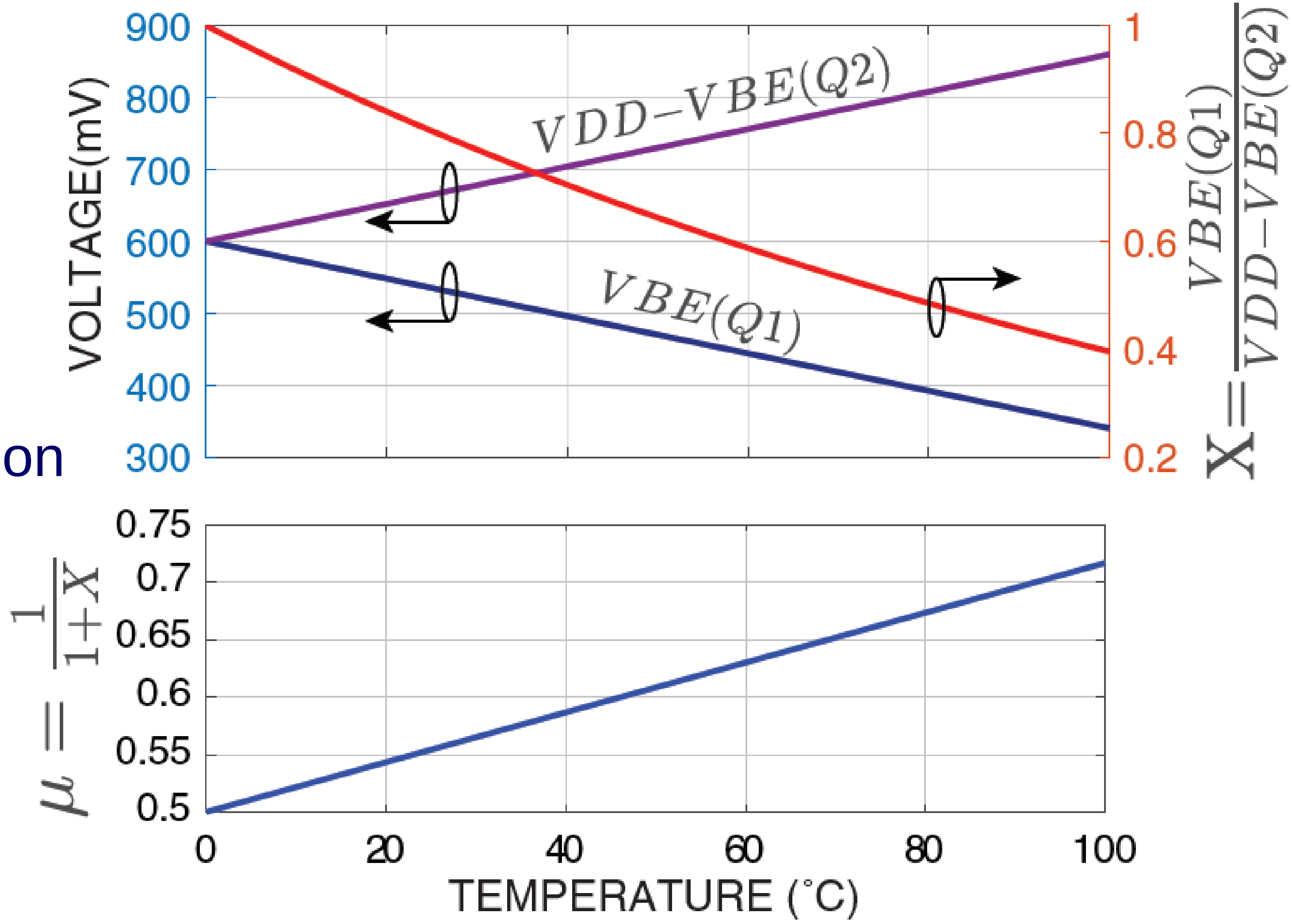
Non-linear temperature-dependent variation

$$X = \frac{V_{BE}(Q1)}{VDD - V_{BE}(Q2)}$$

linear temperature-dependent variation

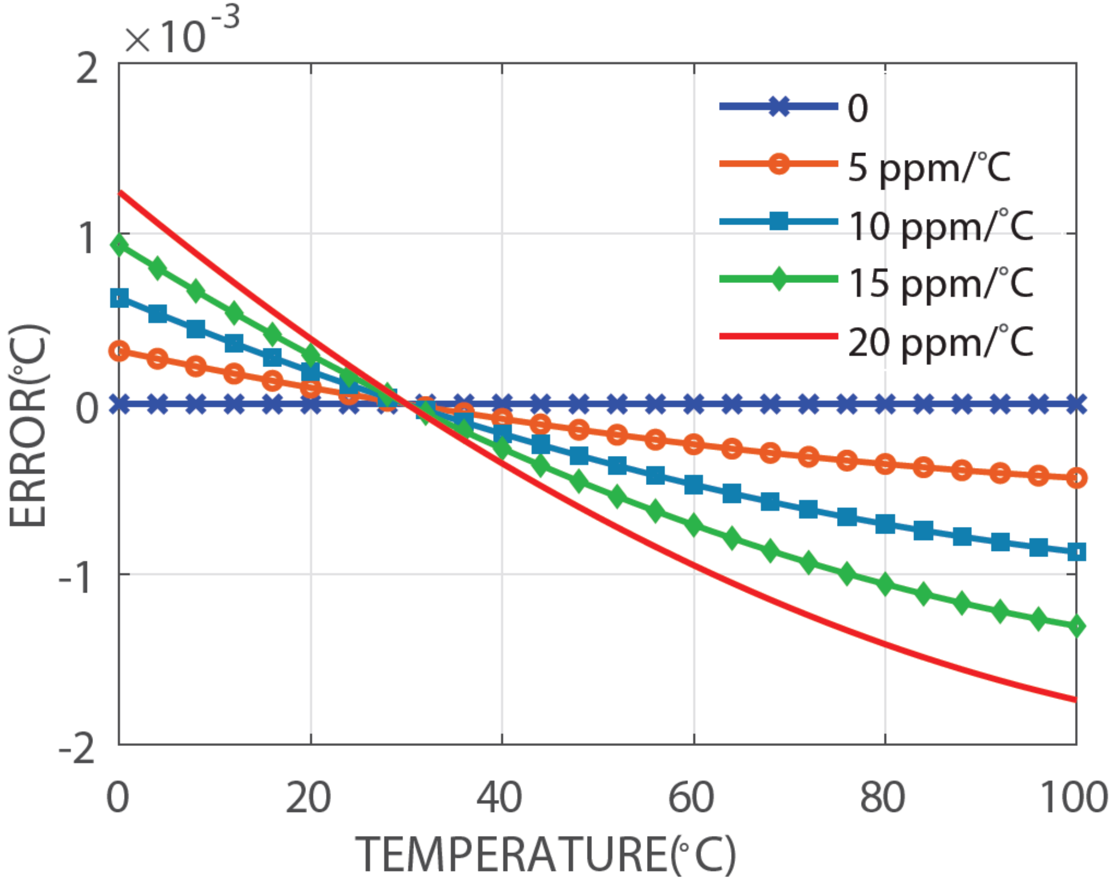
$$\frac{\partial VBE(Q1)}{\partial T} = \frac{\partial VBE(Q2)}{\partial T}$$

$$\rightarrow \mu = \frac{1}{1+X}$$

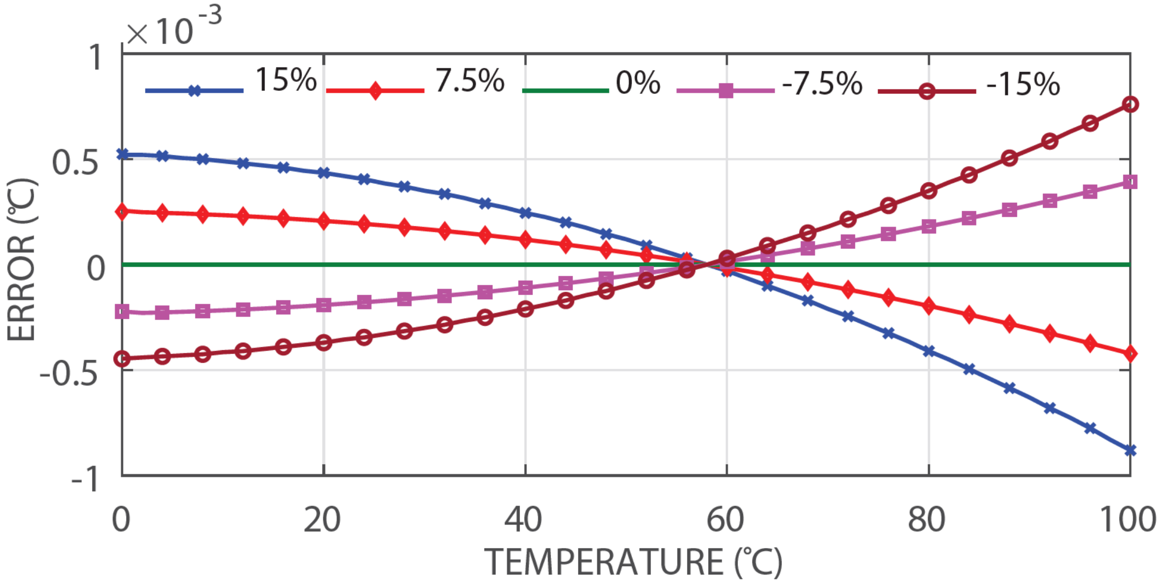


Non-ideality Sources

- Temperature invariant VDD is required
  - Usually required by other blocks as well
  - Bandgap voltage

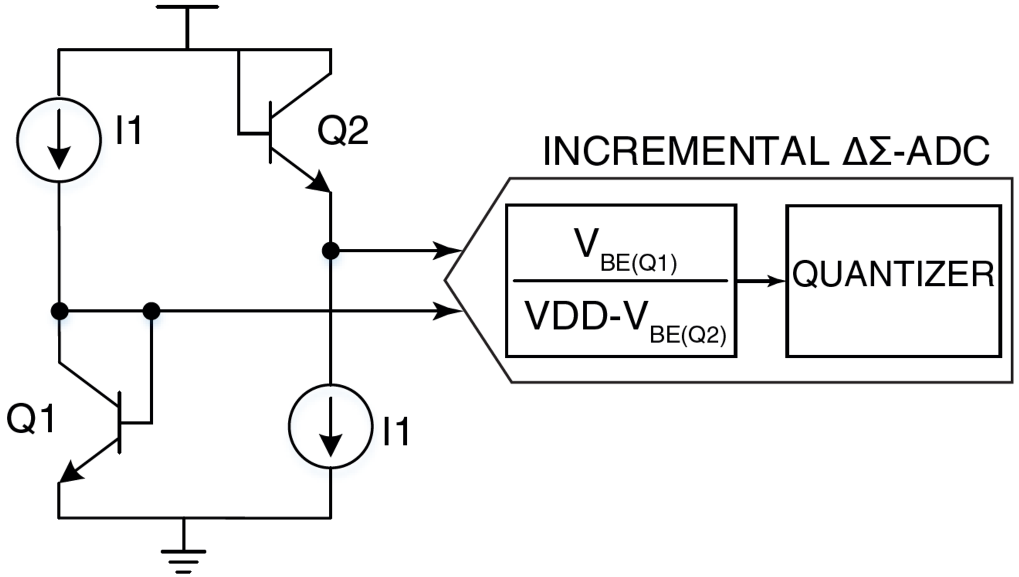


- Perfect matching between the two branches of the transducer core is required.
- Careful Layout:
  - Transistor matching
  - Current Sources matching



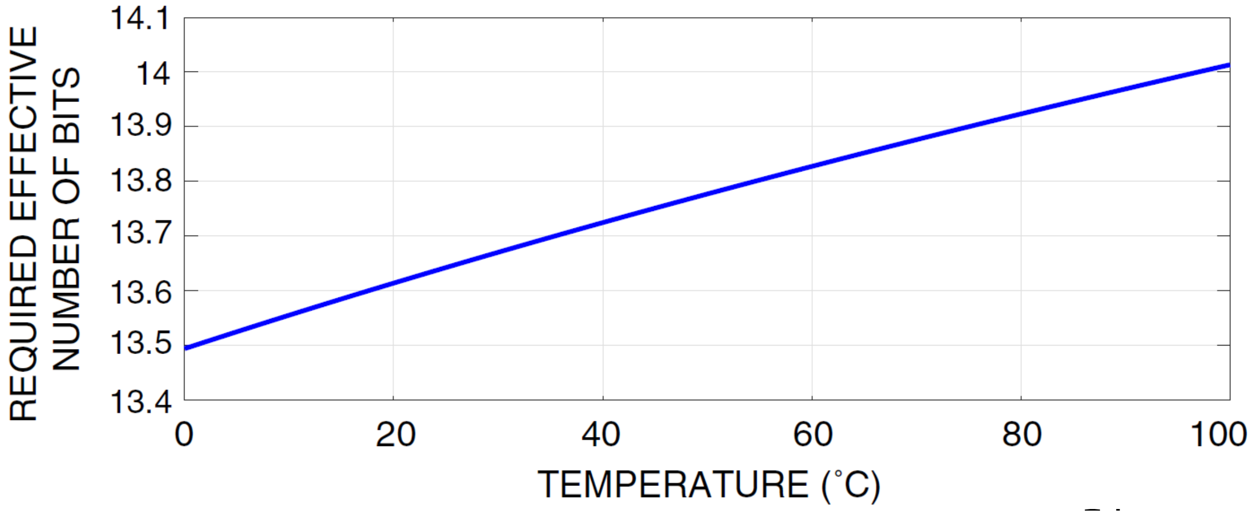
ADC Design Requirements

$$X = \frac{V_{BE}(Q1)}{VDD - V_{BE}(Q2)}$$



- Non-linear temperature dependent parameter
  - Temperature dependent ENOB requirement

$$ENOB = \log_2\left(\frac{Full\ scale\ of\ temperature\ variation}{Targeted\ resolution}\right)$$



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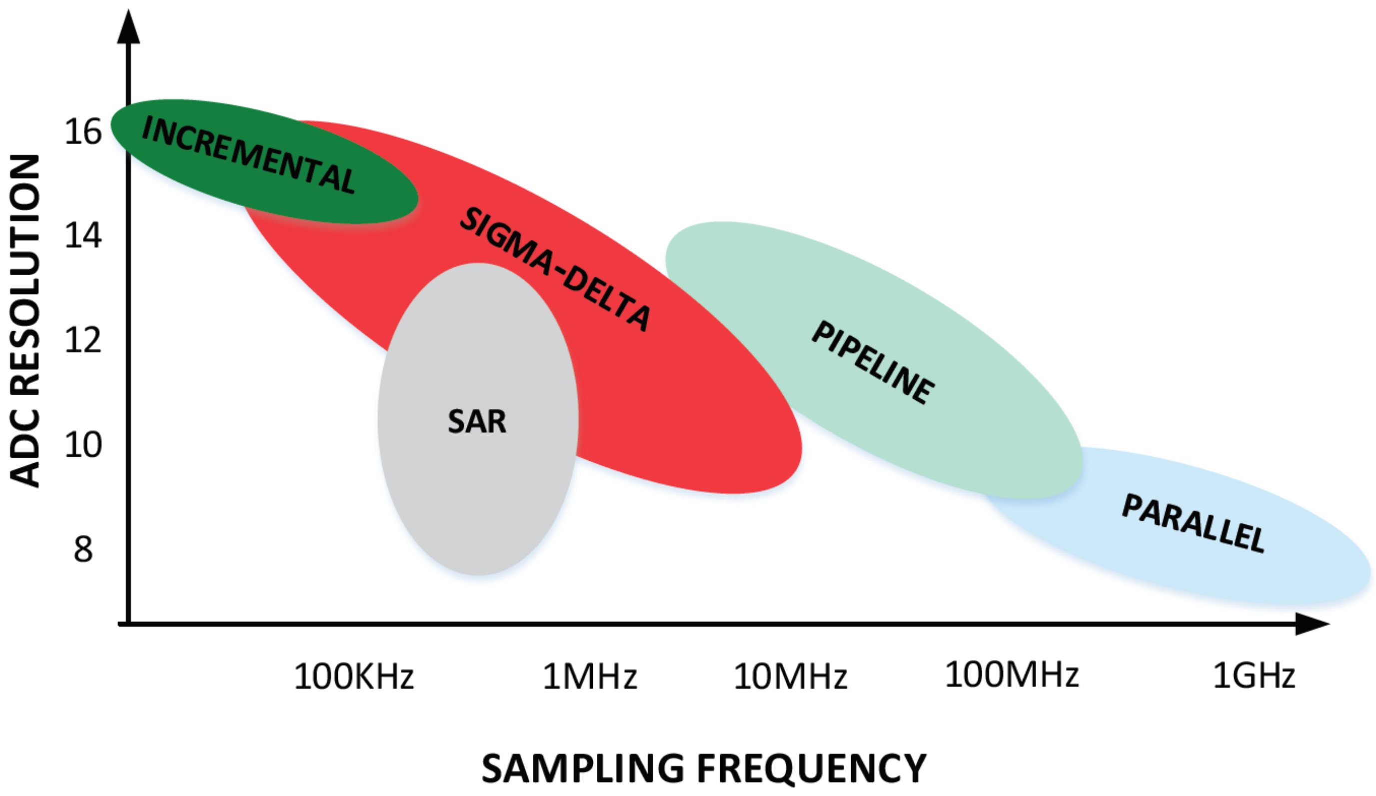
ADC Architecture Selection

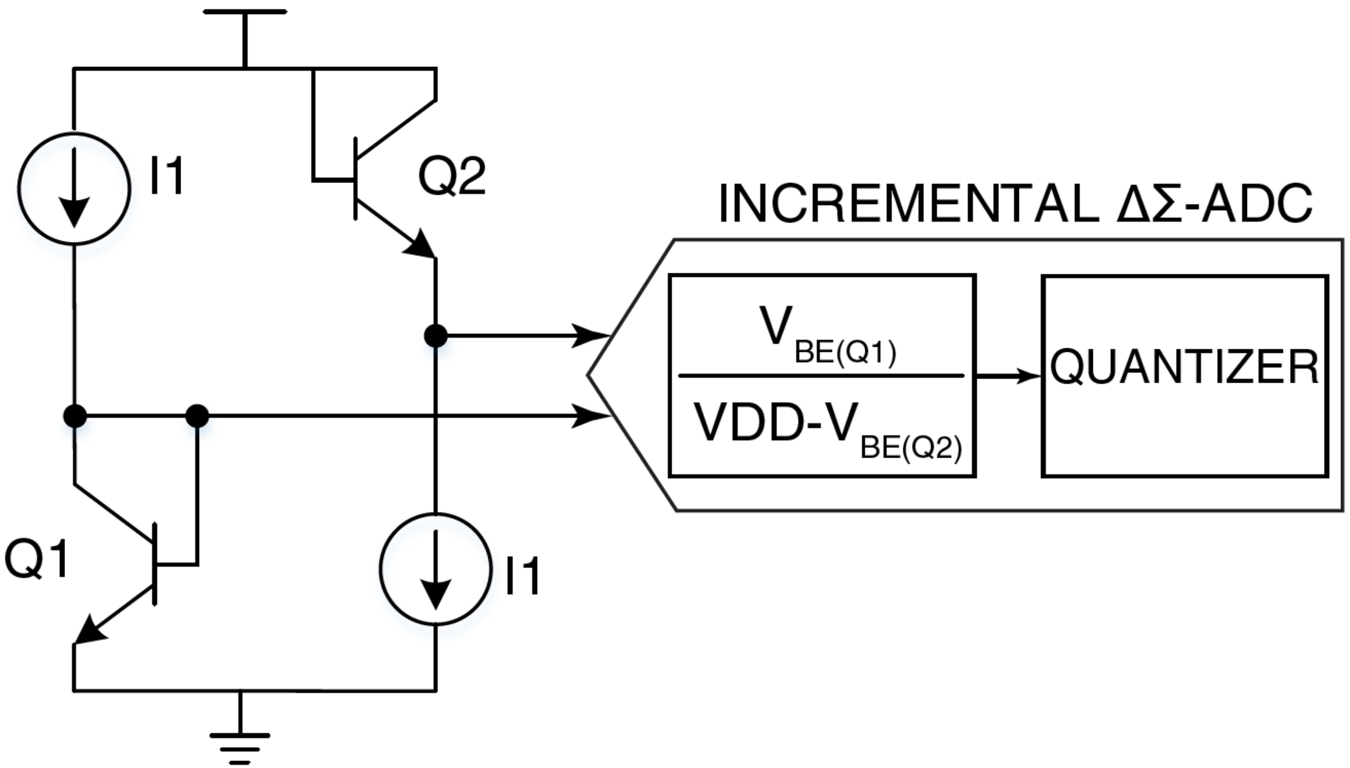
- ADC requirements
  - Low power consumption
  - High resolution
- Options:
  - Regular Delta-Sigma ADC
  - Incremental Delta-Sigma ADC
- Decision is the Incremental ADC
  - Inherent dividing capability
  - Simpler decimation filter



Division in Incremental ADC

- Incremental delta-sigma ADC
  - Receive two input voltages
  - Calculates the ratio of the two voltages.
  - Usually one of these voltages is the supply voltage (Normal digitization)
  - Both voltages can have variation

$$X = \frac{V_{BE}(Q1)}{VDD - V_{BE}(Q2)}$$

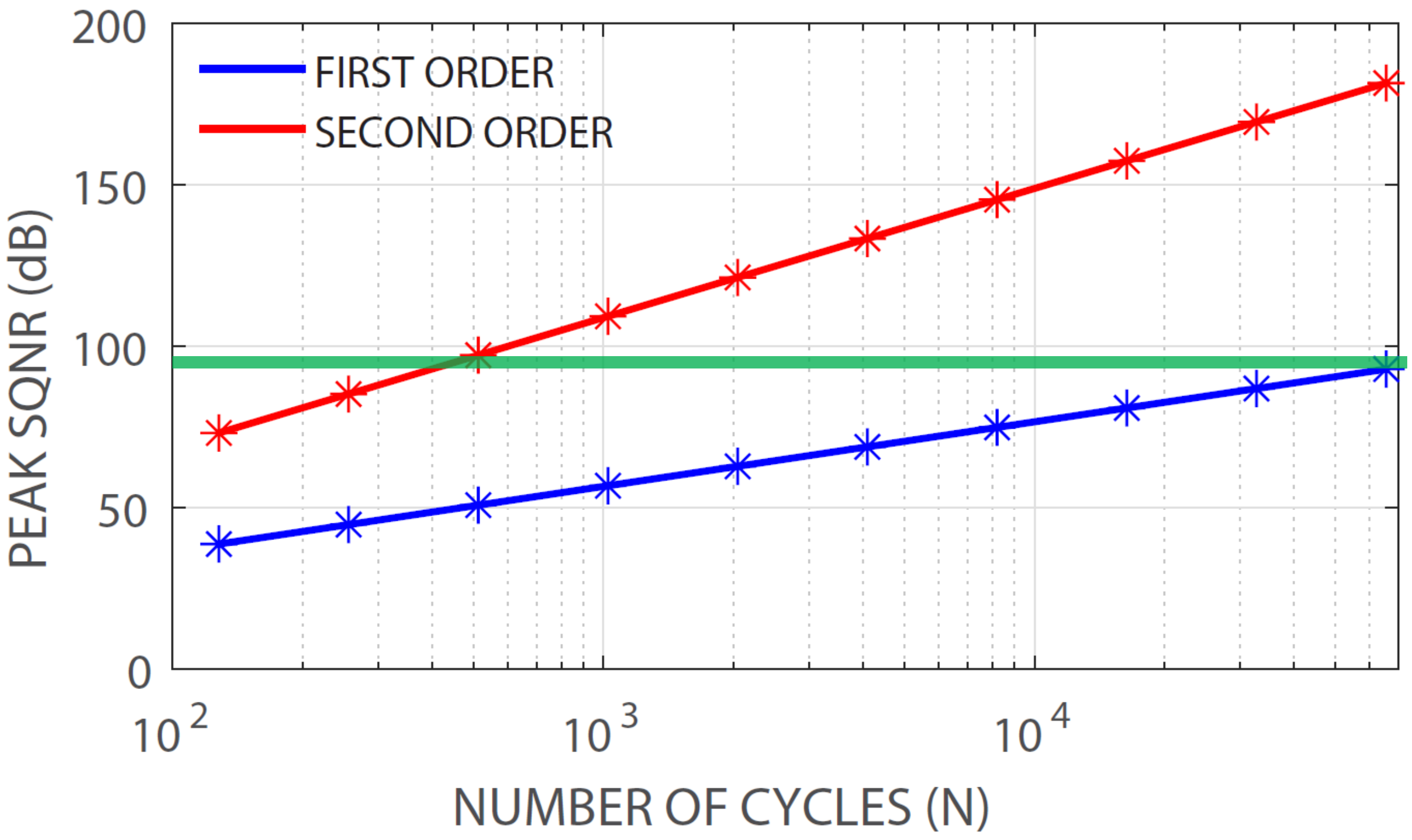


Incremental Delta-Sigma ADC Architecture

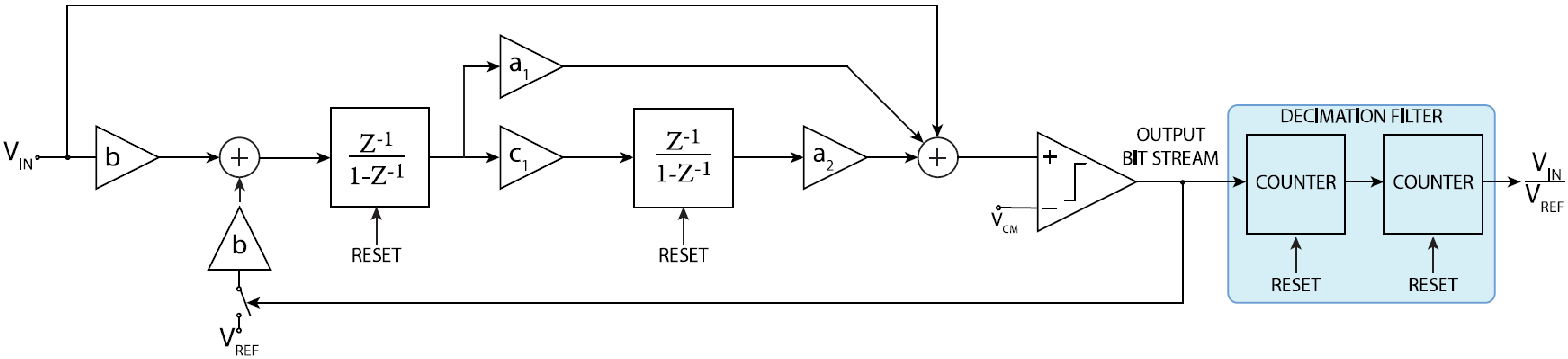
- Example: 15bit ENOB requires:
  - N = 500 in second order IΔΣ
  - N = 60000 in First order IΔΣ

- First order
  - Higher dynamic power consumption
  - Higher required opamp gain (90dB)
  - Simple design (No stability issue)

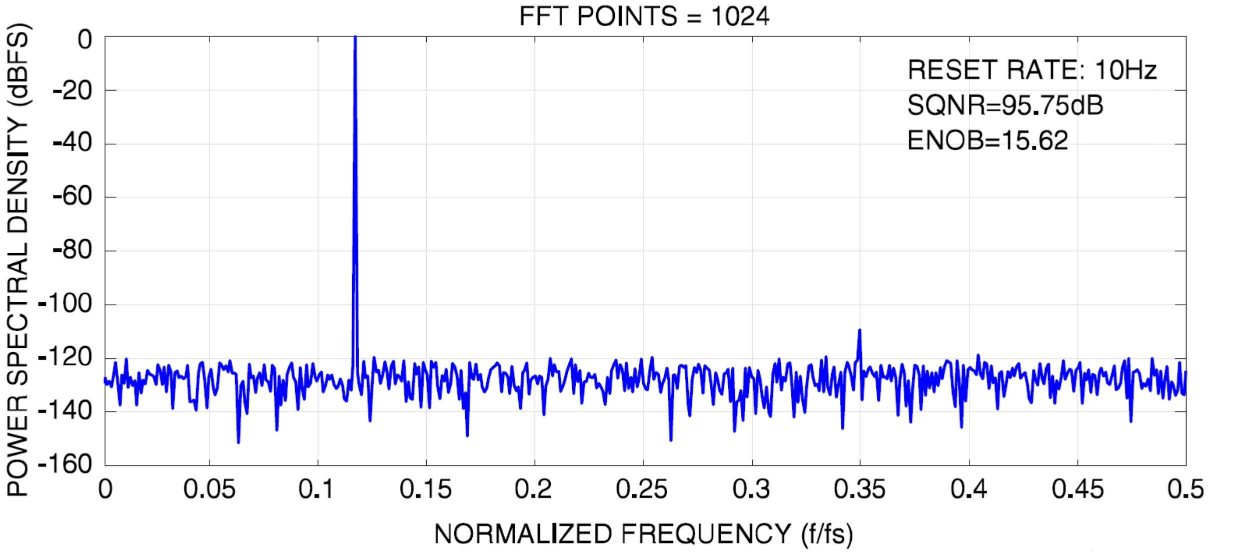
- Second order
  - Lower dynamic power consumption
  - Implementable with Simple opamp
  - Require stability consideration



MATLAB Implementation

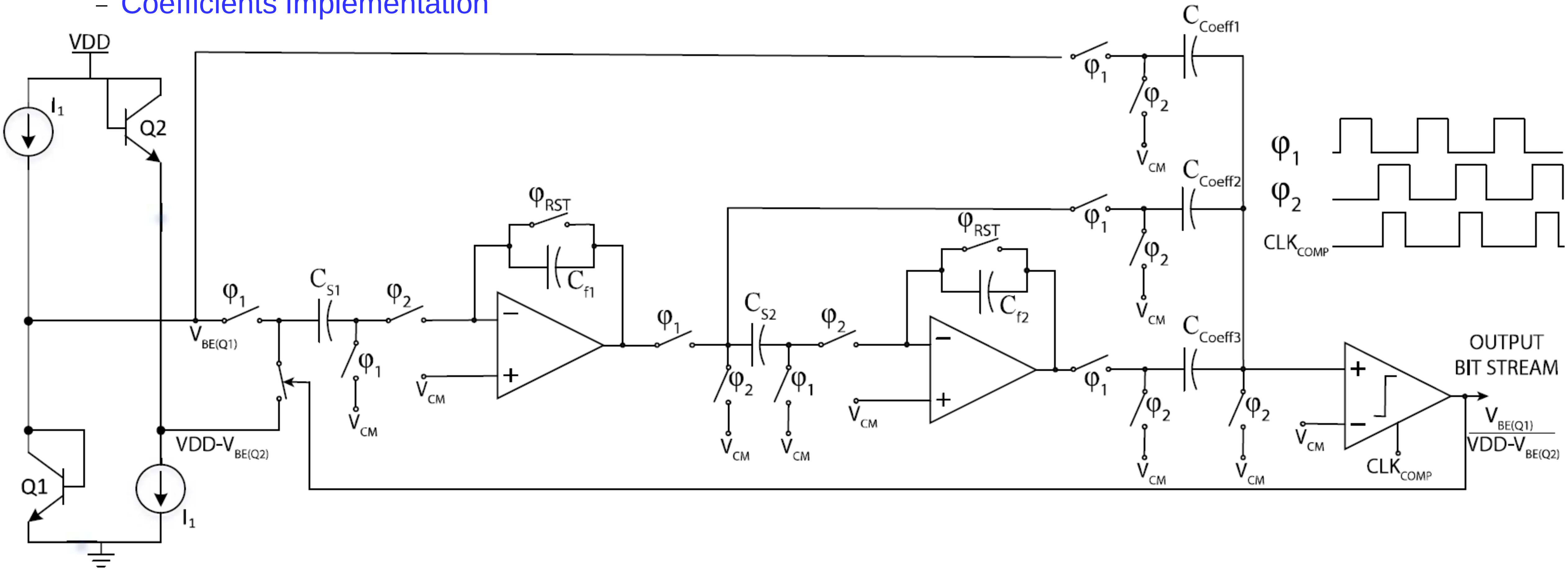


- System-level design in MATLAB
  - Design a second order CIFF Discrete-time ΔΣ using DELSIG MATLAB toolbox.
  - For stability consideration voltage swing of internal nodes is limited to a specific value.
  - Transfer the Discrete-time ΔΣ to the IΔΣ by a 3 step recursive procedure in order to get the same SNDR

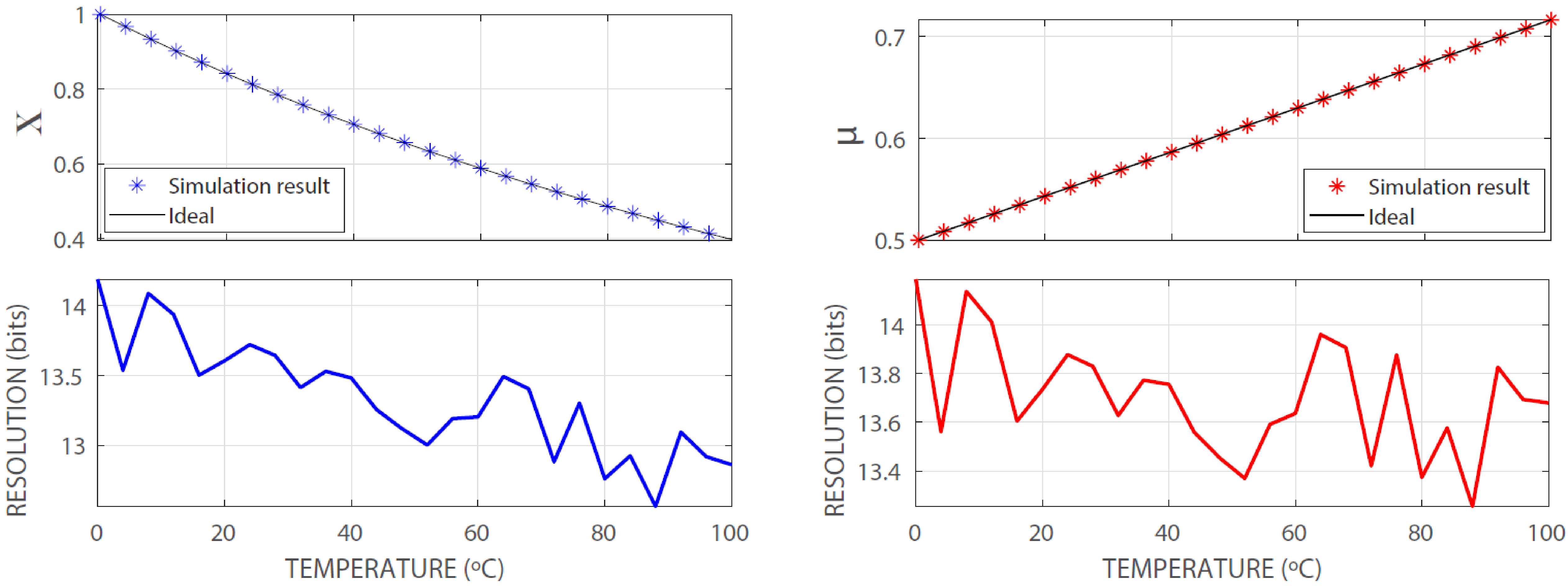


Circuit Implementation

- Circuit-level design (TSMC 0.13µm)
  - Integrator Implementation (settling time- open loop gain- output swing)
  - Comparator Design (Strong-arm architecture- mismatch cancellation)
  - Switch Implementation (Bootstrapping)
  - Coefficients Implementation



Simulation Results



$$X = \frac{V_{BE}(Q1)}{VDD - V_{BE}(Q2)}$$

$$\mu = \frac{1}{1 + X}$$

Comparison Table

	[7]	[8]	[3]	This work
Result	Measurement	Measurement	Measurement	Simulation
Sensor	BJT(PNP)	BJT(PNP)	BJT(PNP)	BJT(NPN)
Technology	0.7μm	0.16μm	0.16μm	0.13μm
Supply Voltage	2.9V-5.5V	1.6V-2V	1.5V-2V	1.2V
Supply Current	55μA	4.6μA	3.4μA	2.6μA
Resolution	0.003°C	0.015°C	0.005°C	0.01°C
t_{conv}	2.2ms	100ms	100ms	100ms
ADC	CT Duty cycle modulator	Zoom ADC (SAR+IΔΣ)	Zoom ADC (SAR+IΔΣ)	IΔΣ
Res.FoM	$3.6pJ^{\circ}C^2$	$170pJ^{\circ}C^2$	$11J^{\circ}C^2$	$3.12pJ^{\circ}C^2$

$$Res.FoM = (Resolution)^2 \times Power \times t_{conv}$$

Thank You !