A Batteryless Thermoelectric Energy-Harvesting Interface Circuit with 35mV Startup Voltage

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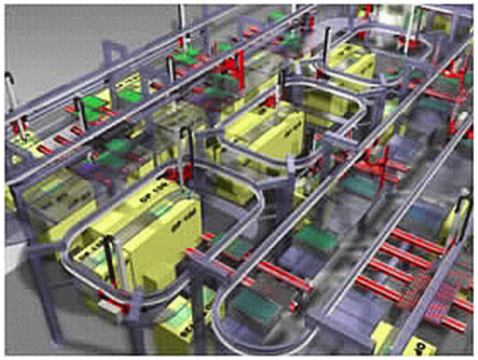
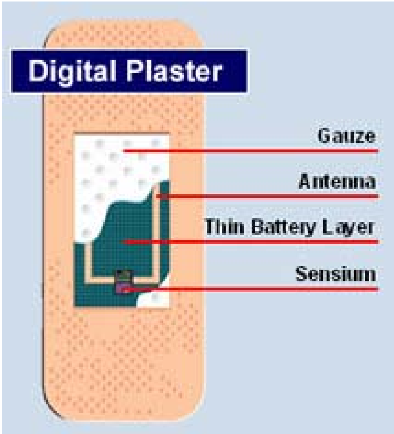
Self-Powered Applications

Pipeline/Exhaust Sensors

Industrial Automation



Wearable Medical Devices

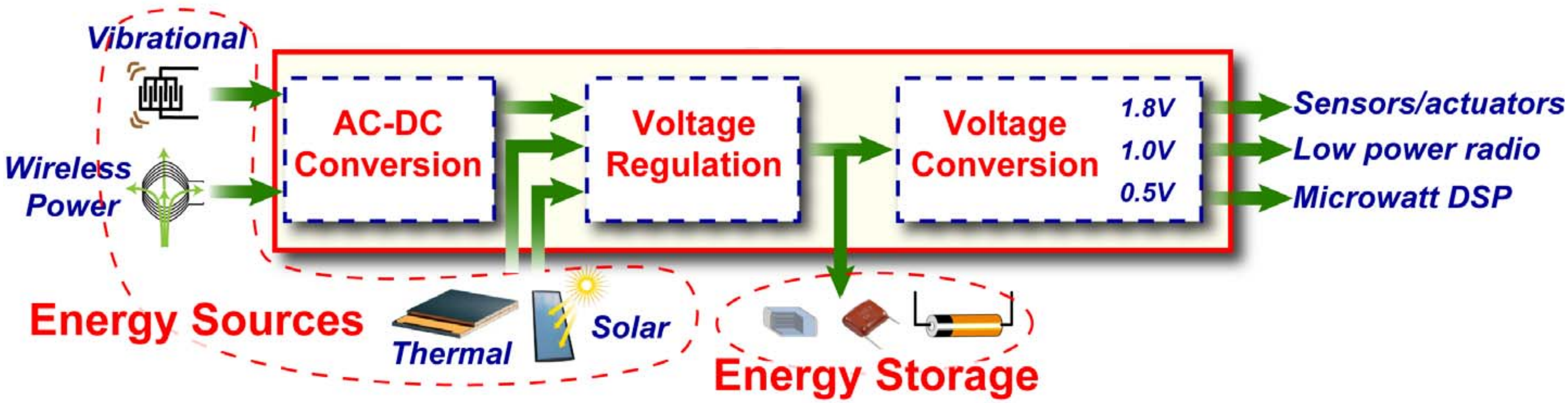


[Toumaz]

- Energy efficiency of IC's is crucial
- Micro-power sensor systems

Batteryless solutions desirable

Energy Processing Circuits



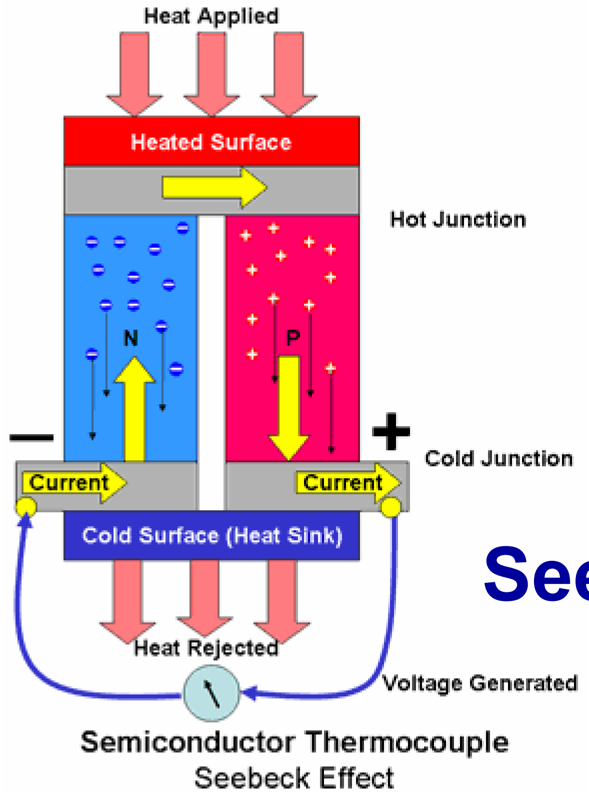
- **Amount of electrical power obtained – better metric for energy harvesters**

End-to-end efficiency is critical

Outline

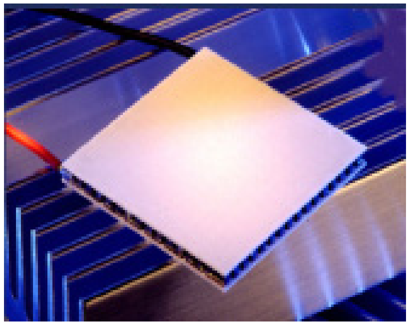
- Thermoelectric Energy Harvesters
- Startup Technique
- Architecture and Energy Transfer Circuits
- Measurement Results
- Conclusion

Thermoelectric Energy Harvesters



[Micropelt]

[Tellurex]

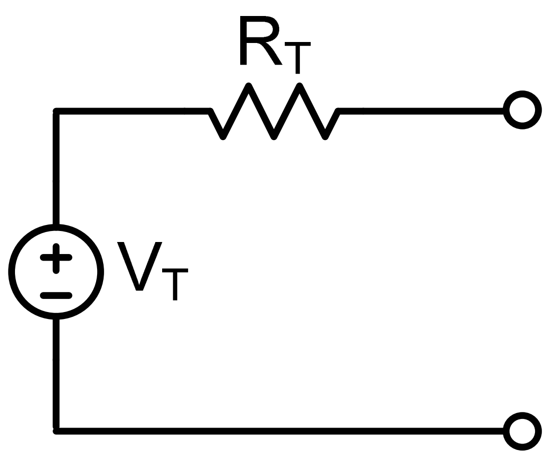


Seebeck Effect

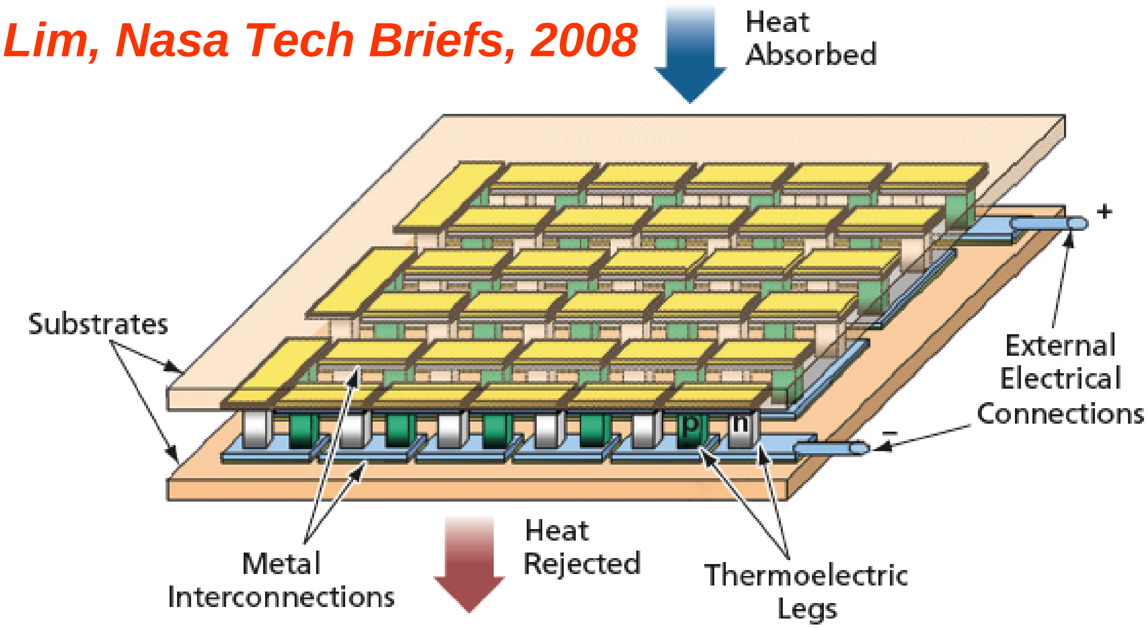
- **Convert heat energy to electrical energy**
- **Consists of p- and n-type Bismuth Telluride**
- **One p-n leg generates ~ 0.2mV/K**

Equivalent Circuit of Thermal Harvester

$$V_T = S\Delta T$$

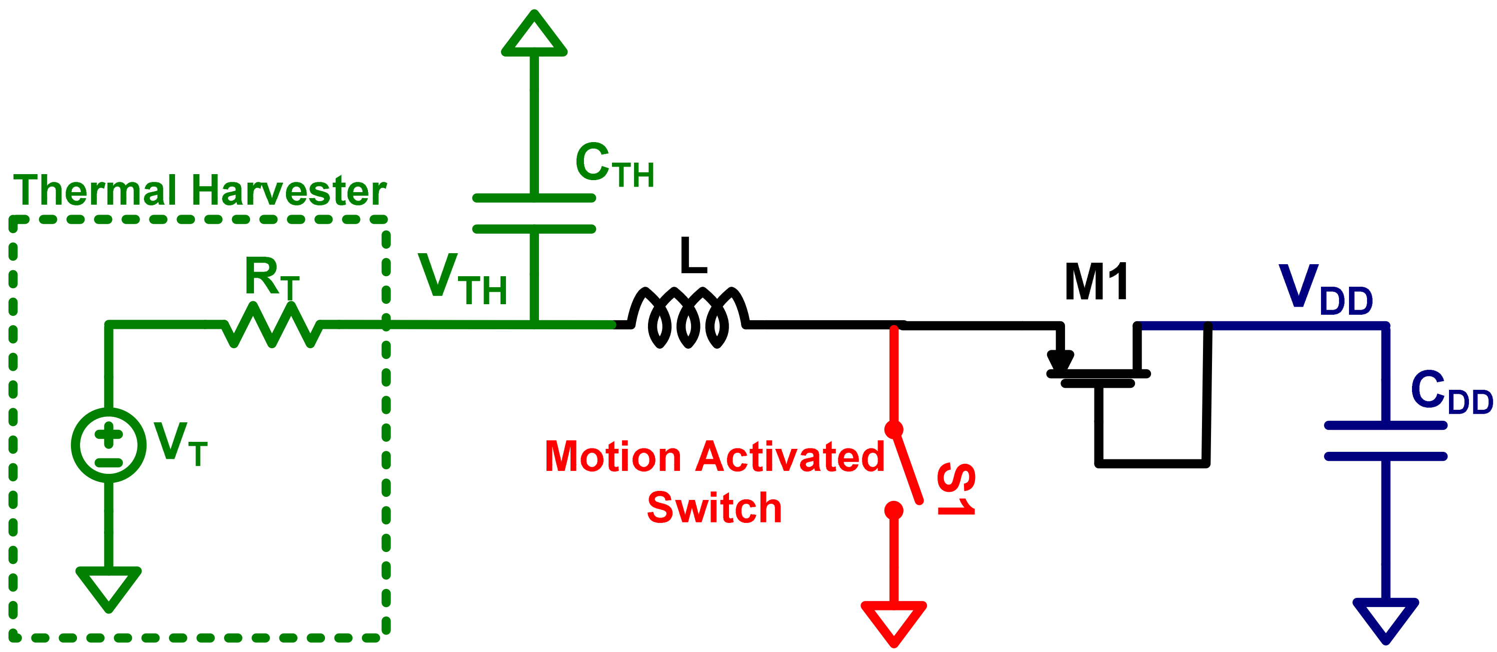


Lim, Nasa Tech Briefs, 2008



- **Electrically in series, Thermally in parallel**
- **For a 10cm² harvester, S = 23mV/K, R_T = 5Ω**
- **Extremely low voltage output**

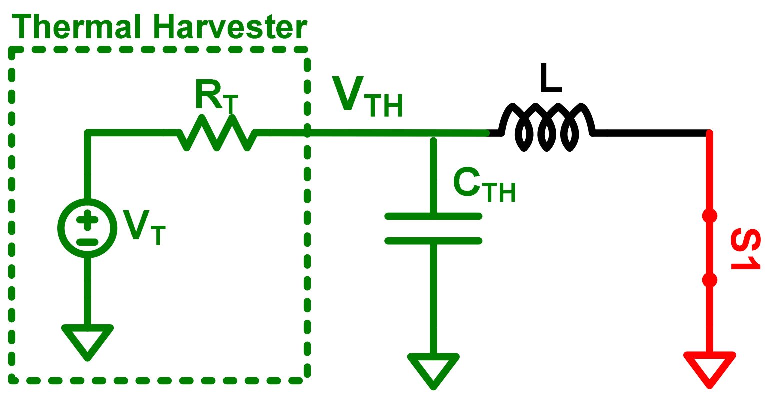
Mechanically Assisted Startup



- Small vibrations present in human motion
- Vibration driven switch kick-starts energy transfer

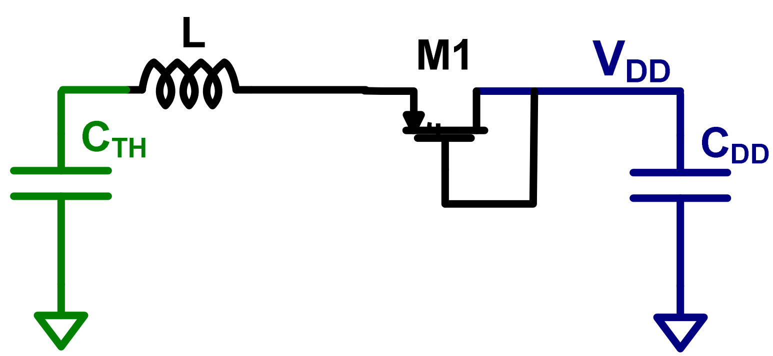
Mechanically Assisted Startup

S1 ON



$$i_L = \frac{V_T}{R_T}$$

S1 OFF

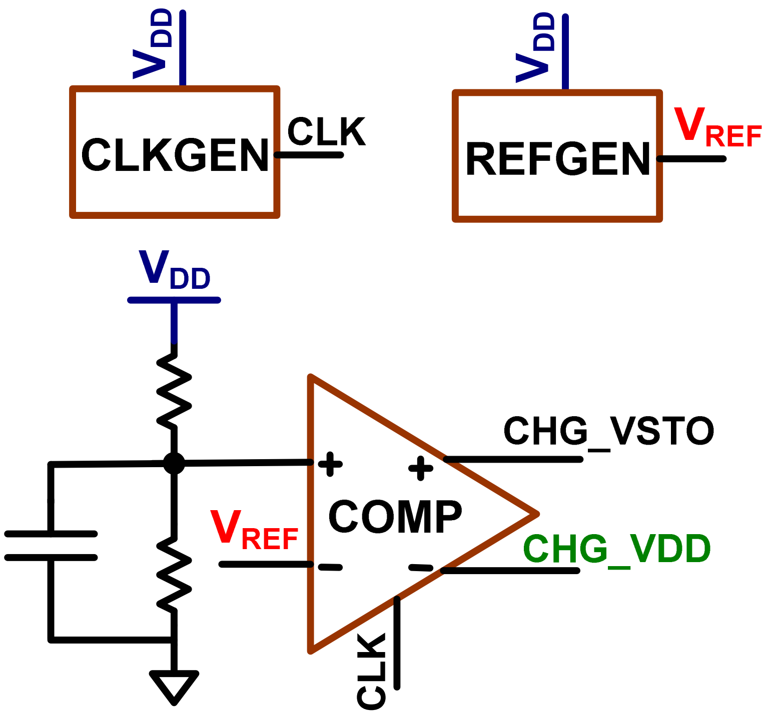


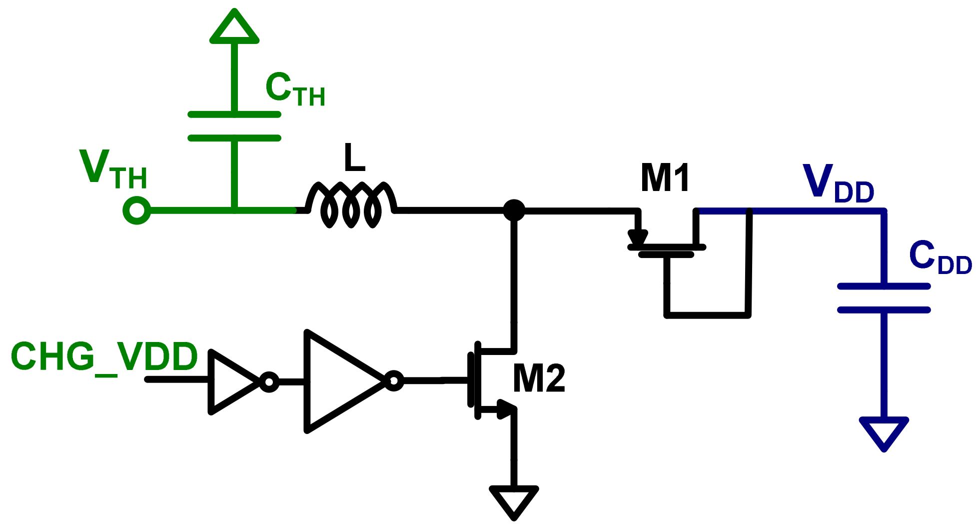
$$V_{DD} = \left(\frac{\sqrt{L / C_{DD}}}{R_T} \right) V_T$$

- $L = 20\mu H$, $C_{DD} = 470pF$ and $R_T = 5\Omega$

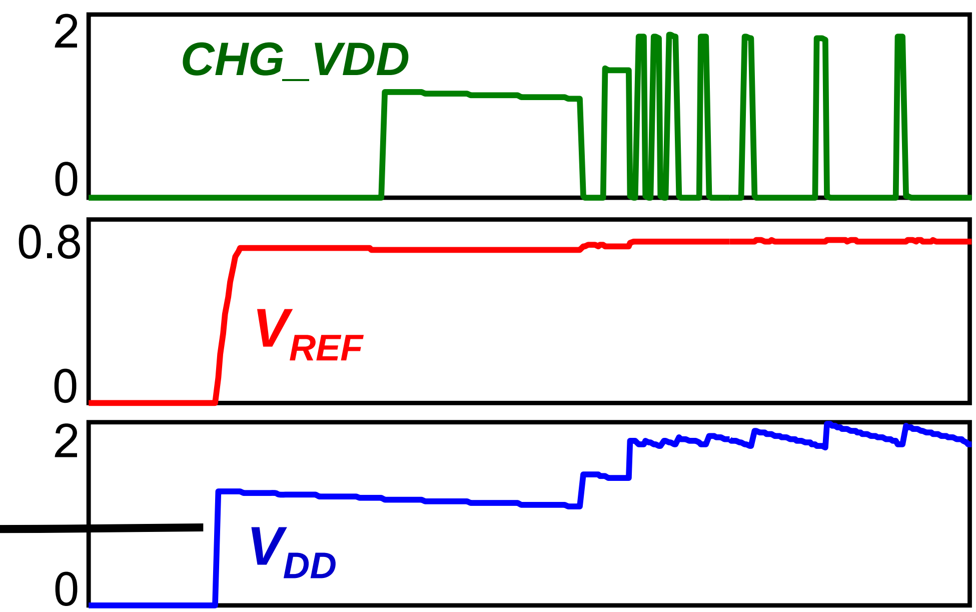
35mV input needed to get 1V at V_{DD}

Startup Block

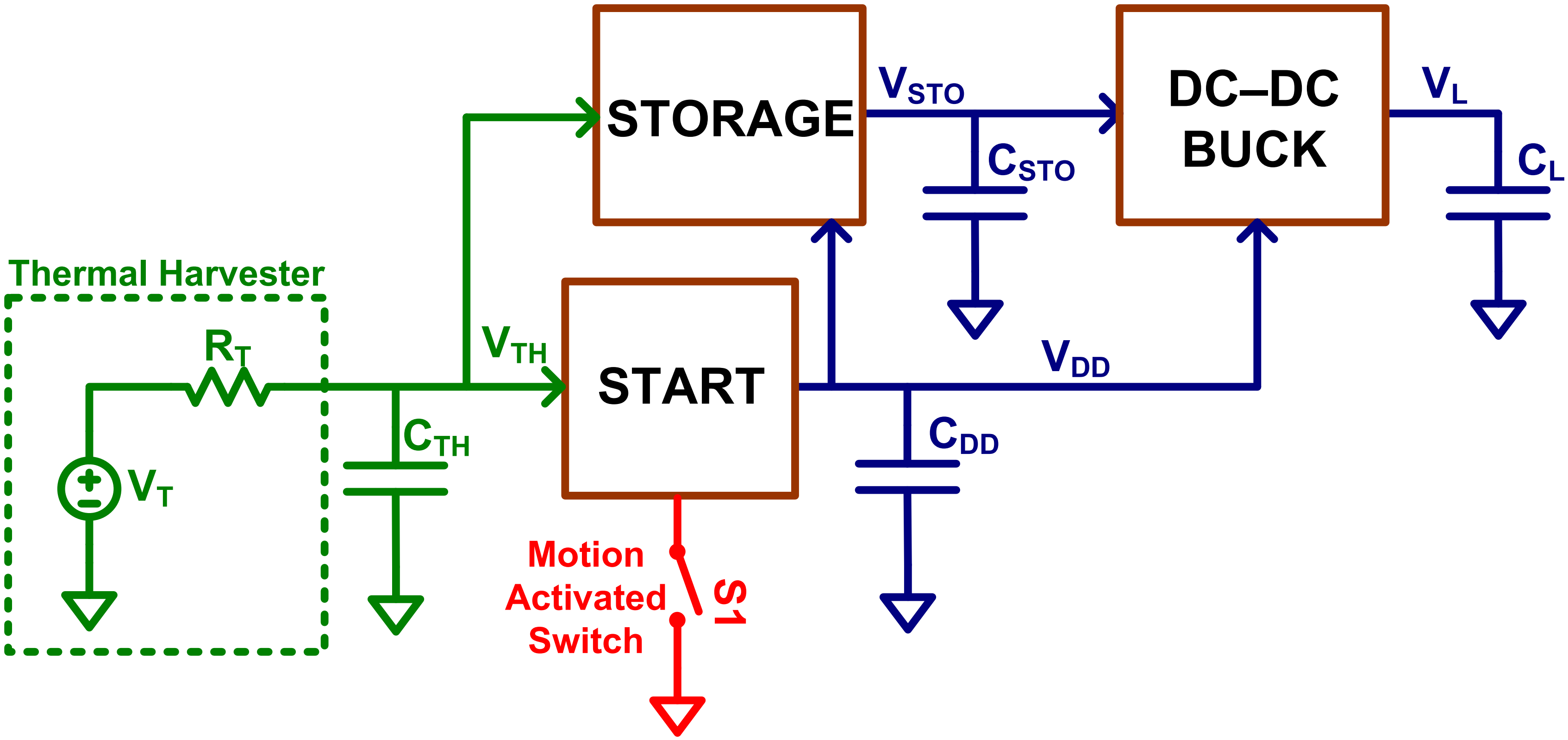




Mechanical Startup

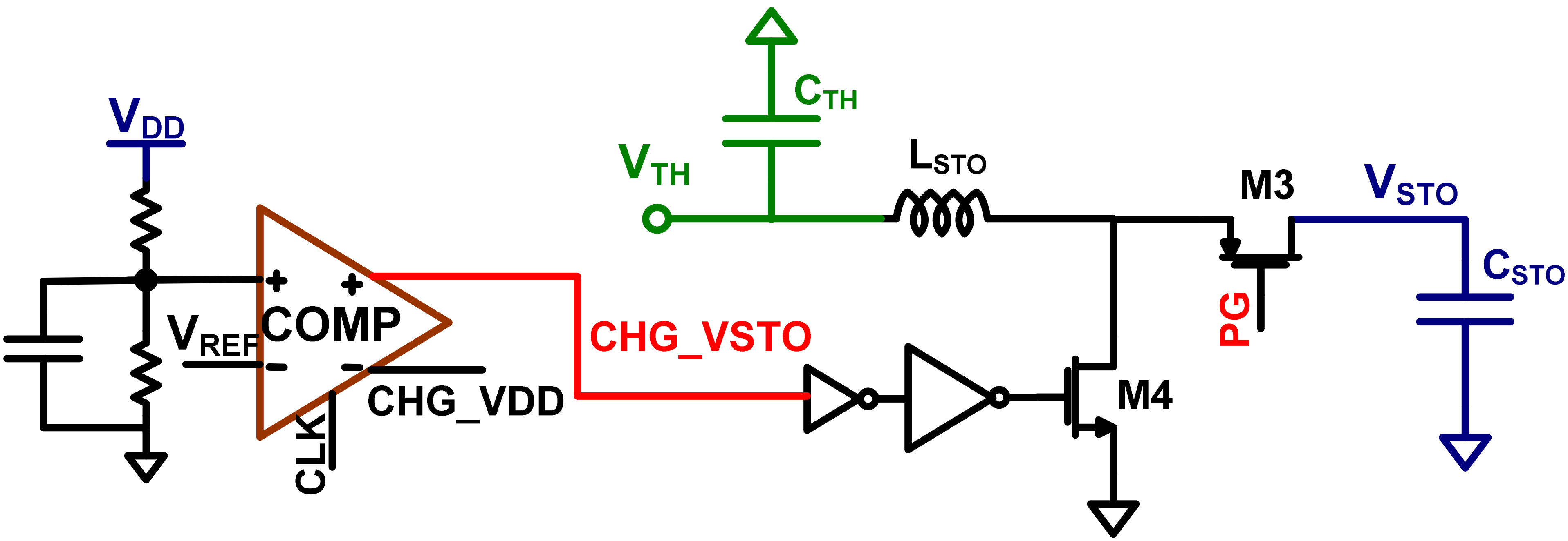


Architecture



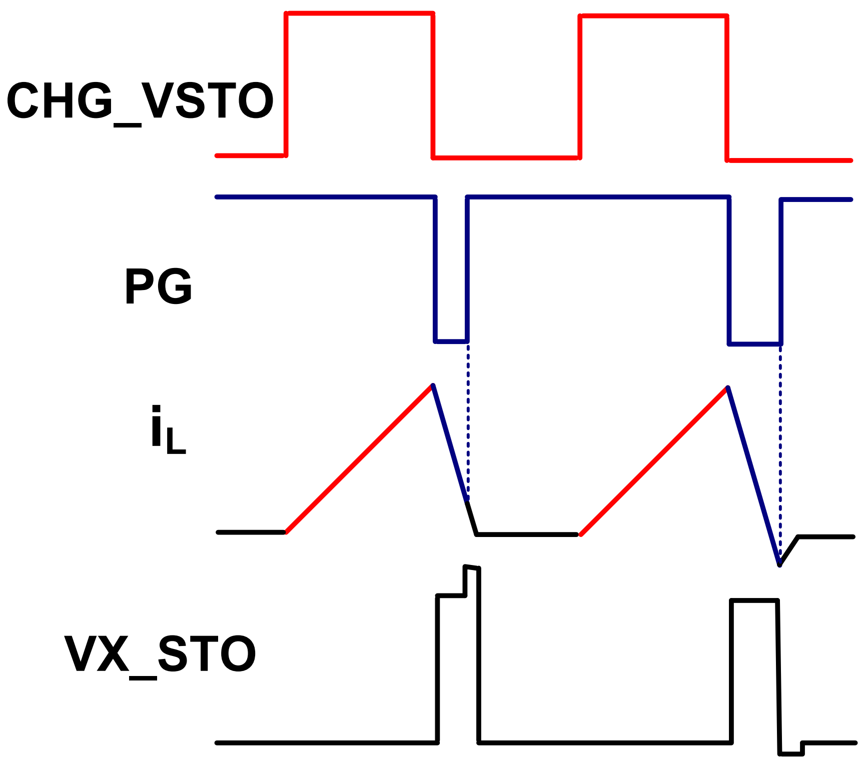
- Digitally assisted control
- Storage block acts as energy buffer
- Buck converter outputs a 1.8V regulated supply

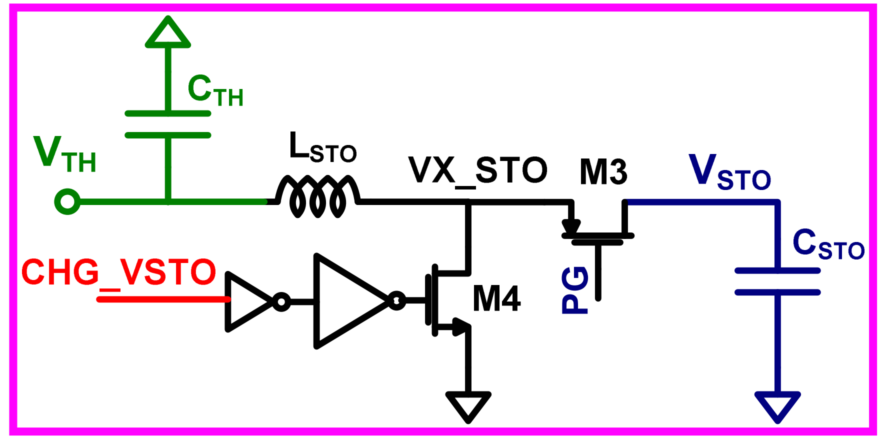
Storage Block – Boost Converter

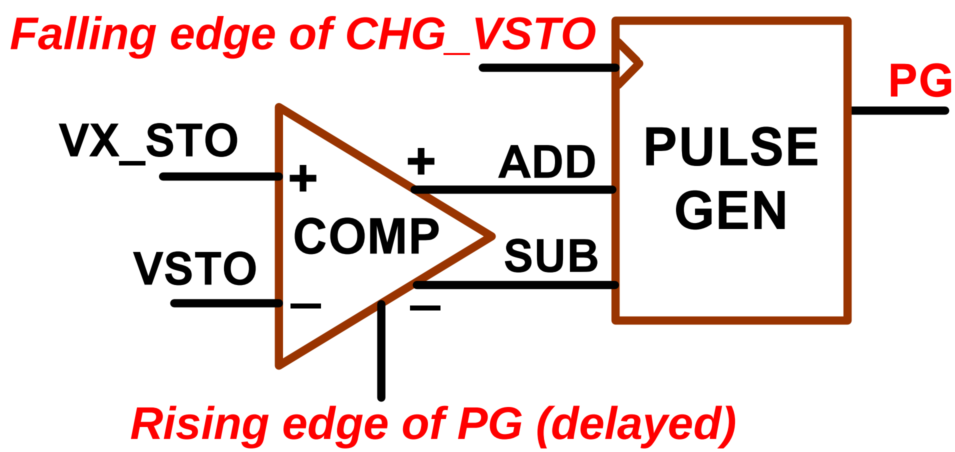


- Activated when V_{DD} > 1.8V
- M3 is actively turned ON
- Storage voltage is unregulated

Zero Current Switching

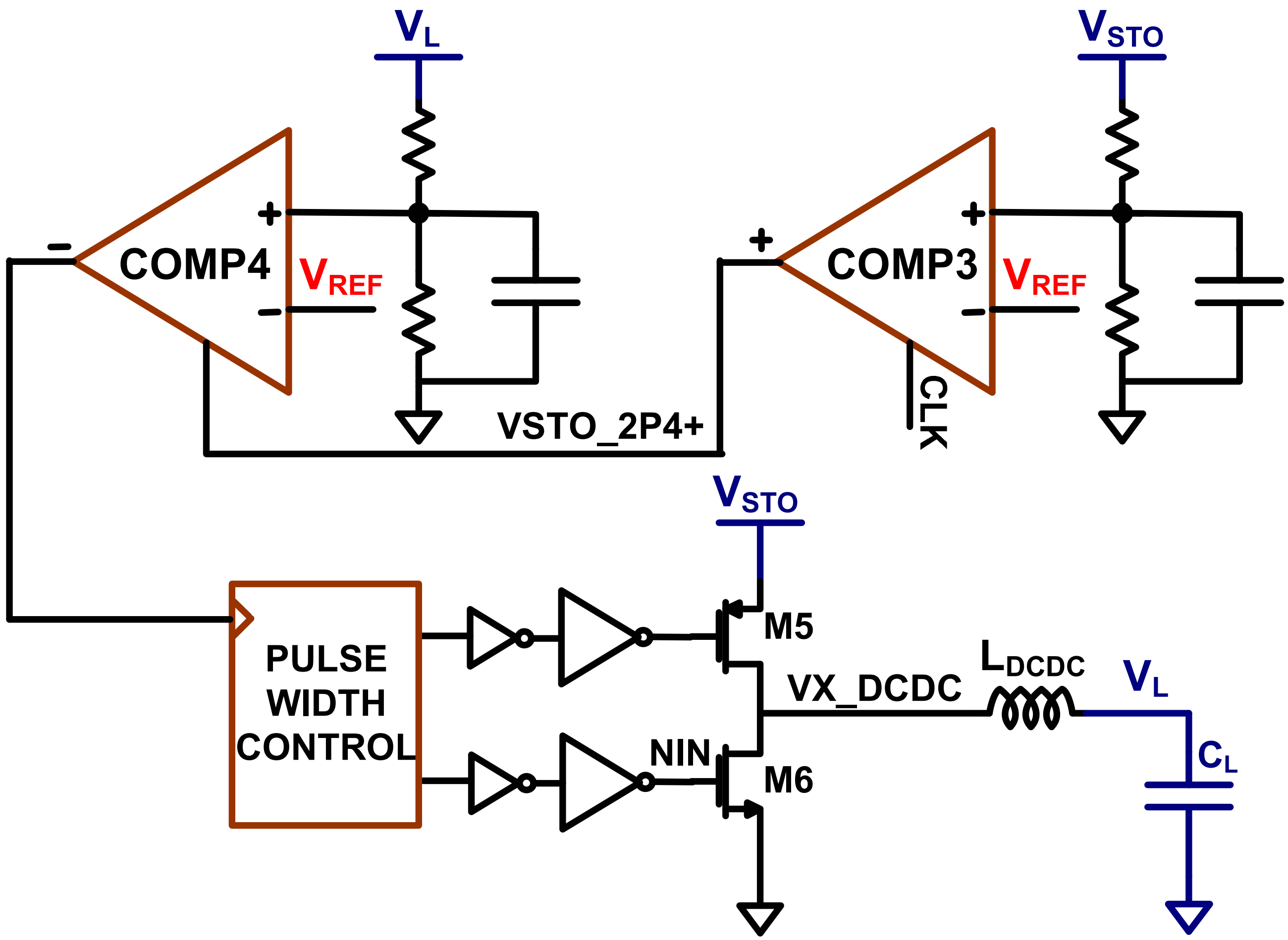






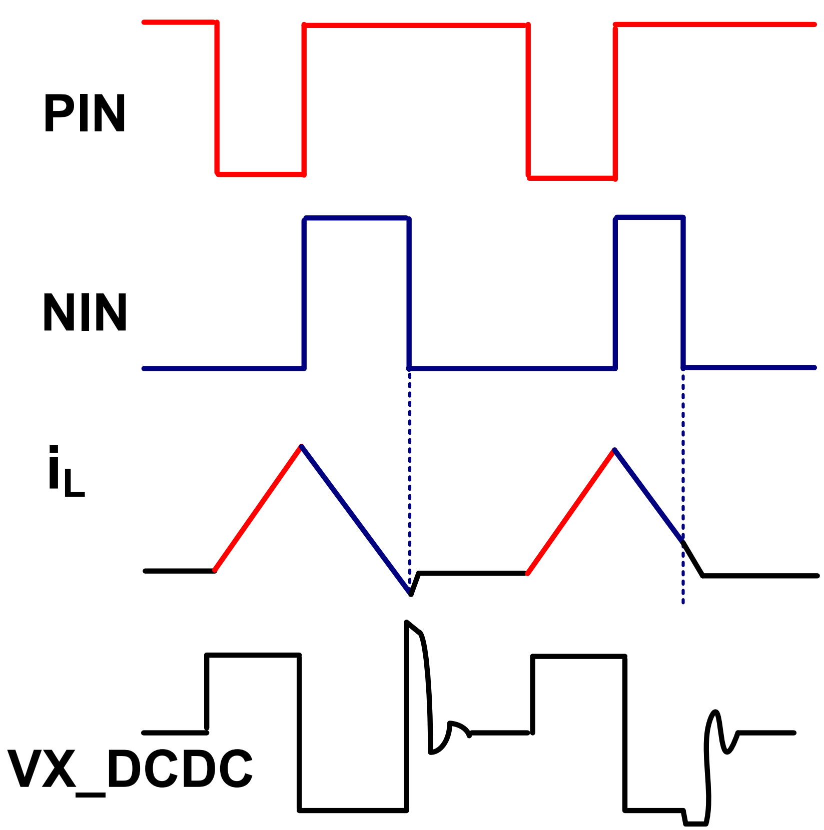
- **Pulse-width of PG is adjusted closed-loop to achieve zero current switching**

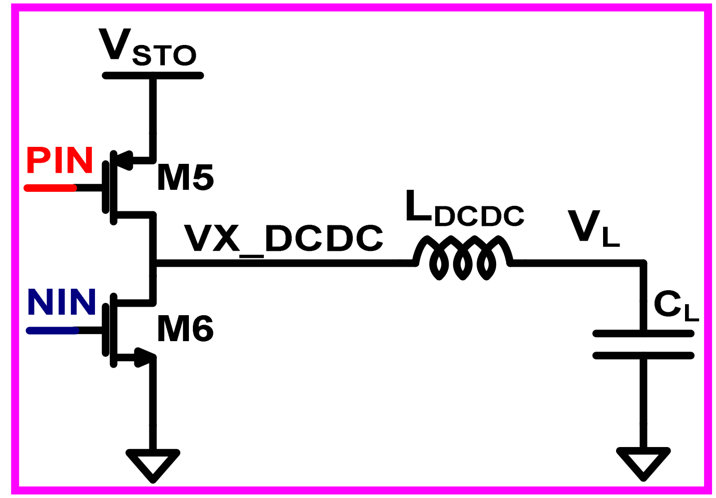
DC-DC Buck Converter

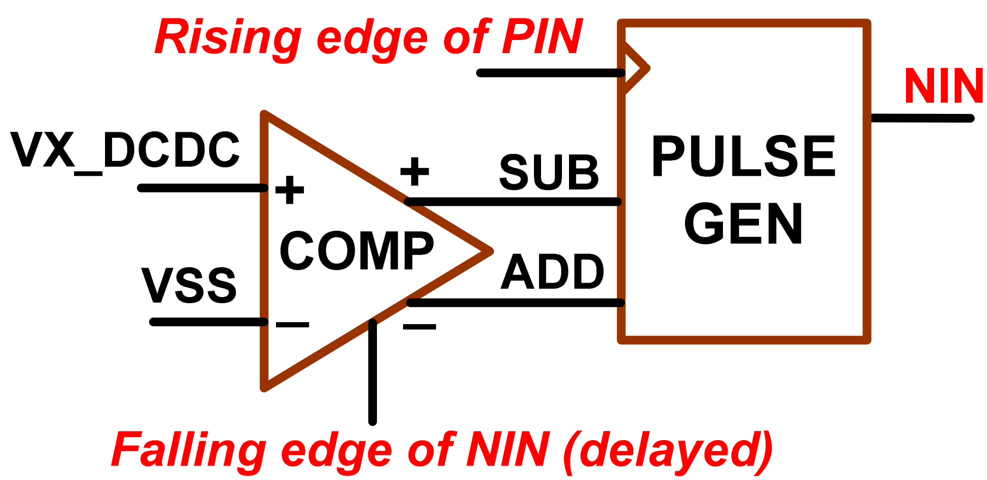


- DC-DC is activated only after V_{STO} > 2.4V
- Pulse Frequency Modulation mode of control

DC-DC – ZCS

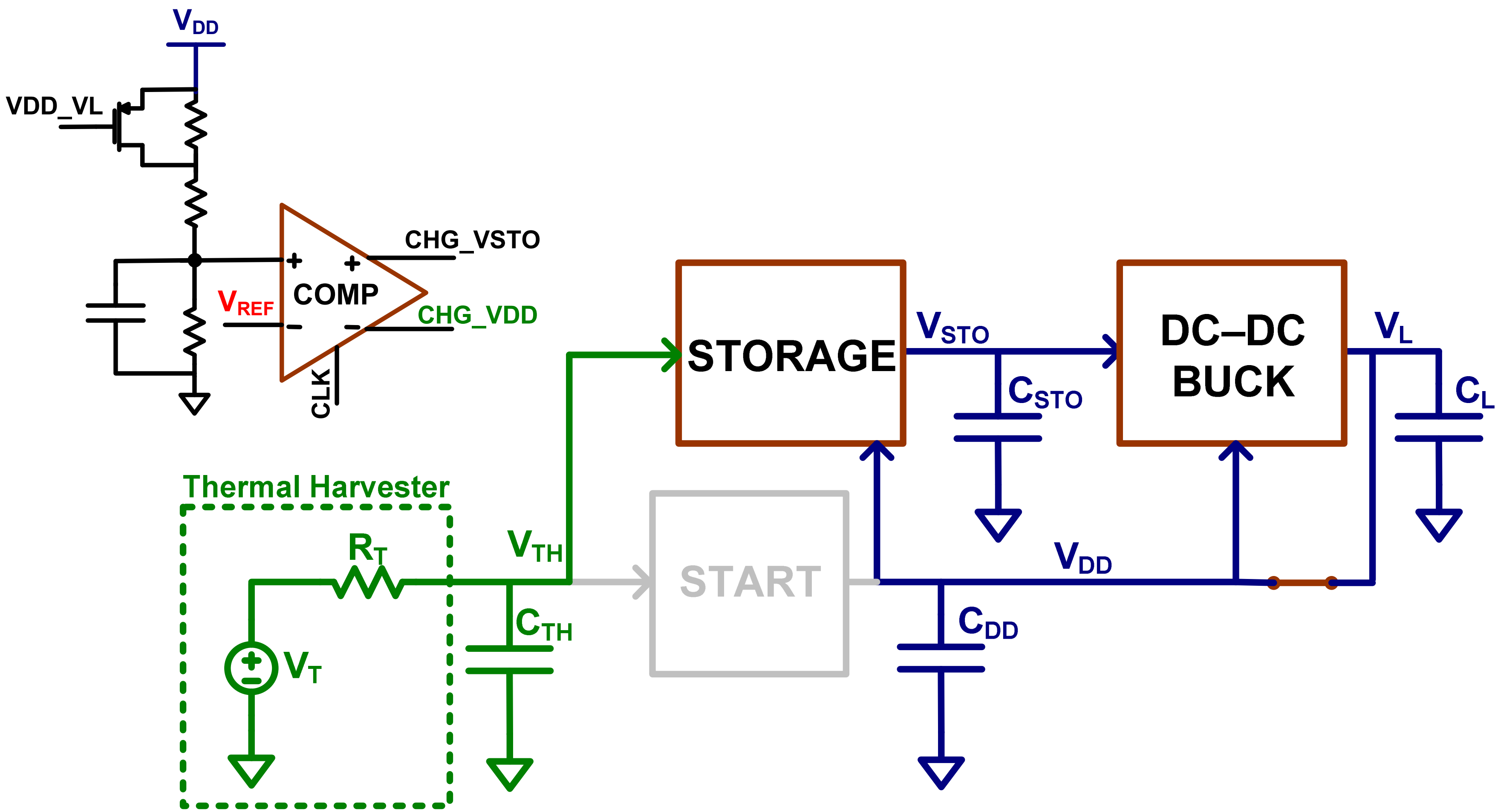






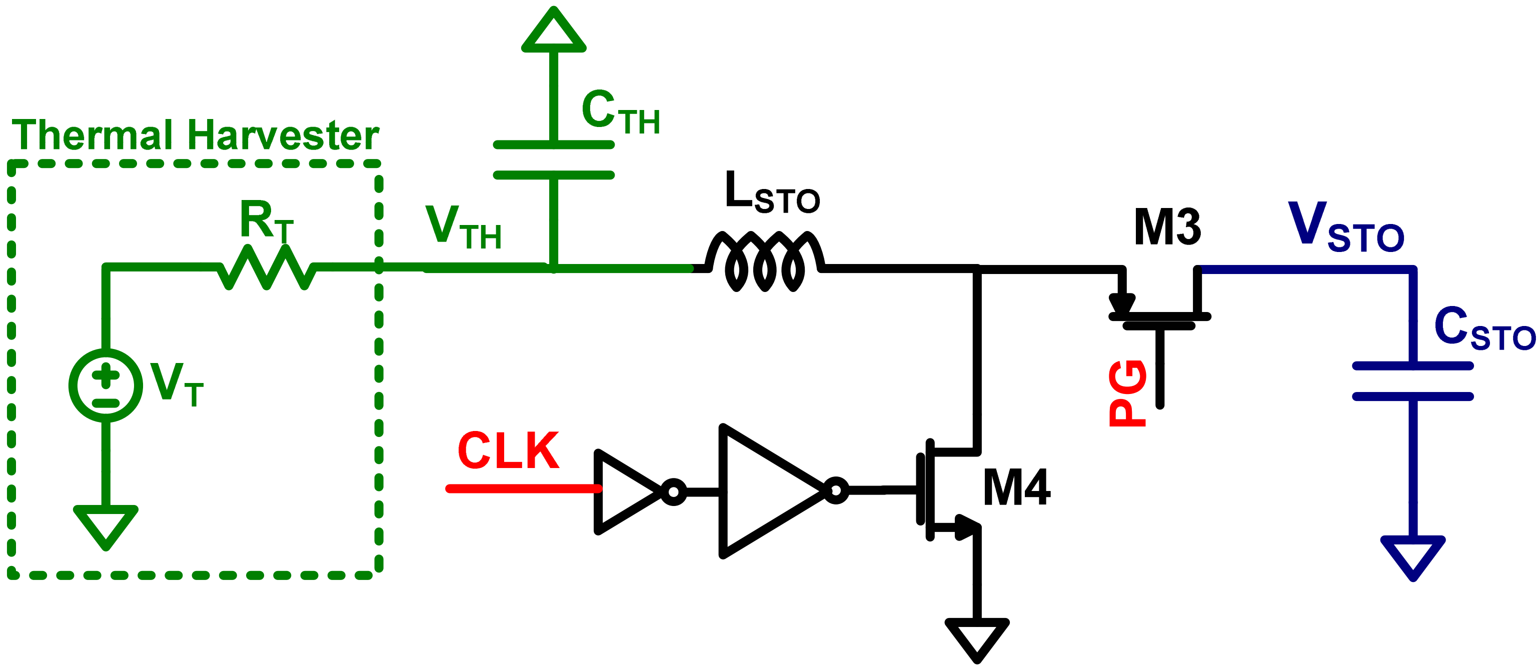
- **Pulse-width of NIN is adjusted closed-loop to achieve zero current switching**

Disabling Start Block



- V_{DD} shorted with V_L once $V_L > 1.8V$
- Start block is disabled

Maximum Power Transfer

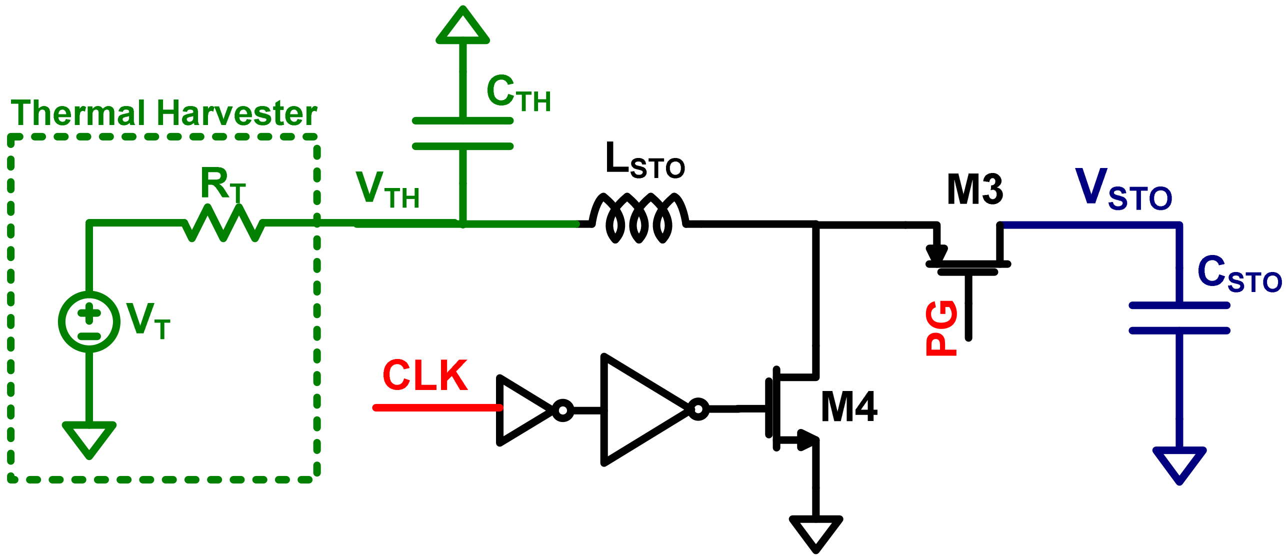


$$P_{max} = \frac{V_{TH}^{2}}{R_{T}}$$

$$P_{STO} \approx \frac{V_{TH}^{2}}{8 L_{STO} f_{s}}$$

- **Free running boost converter switching at f_s**

Maximum Power Transfer



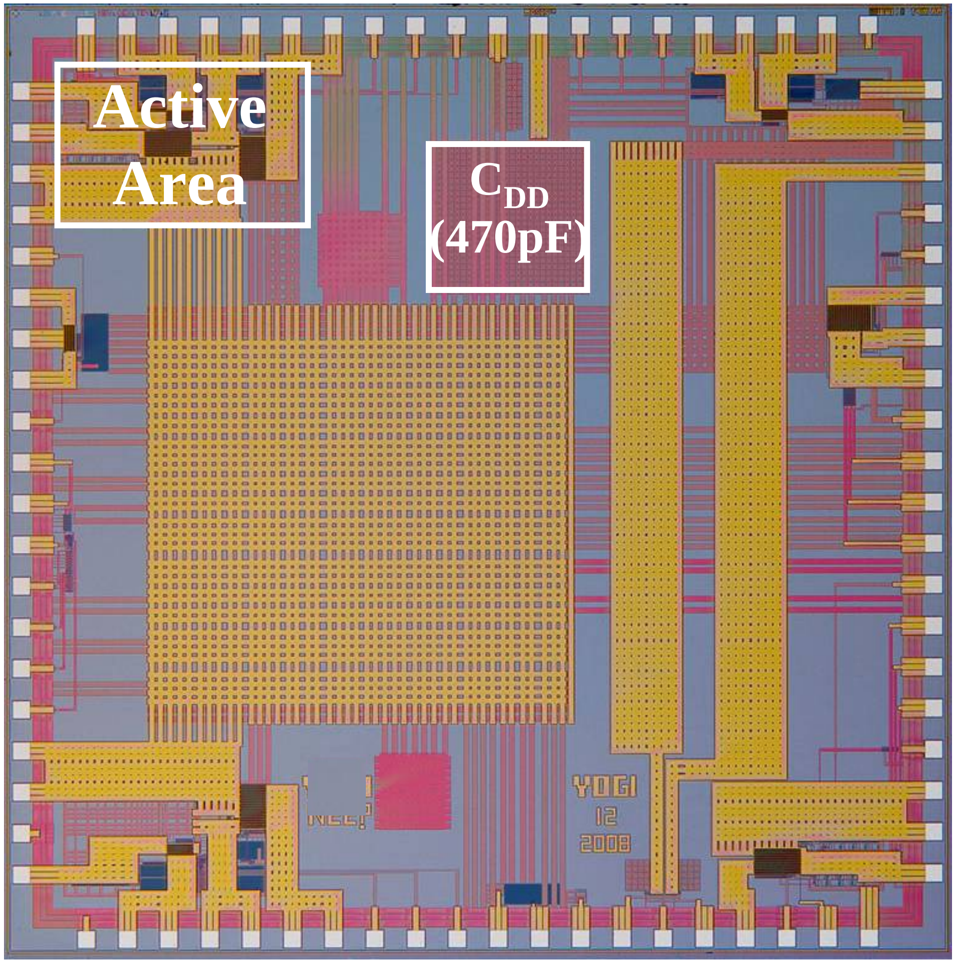
$$\frac{V_{TH}^2}{R_T} = \frac{V_{TH}^2}{8 L_{STO} f_s}$$

⇒

$$f_s \approx \frac{R_T}{8 L_{STO}}$$

- **Maximum power transfer obtained by just choosing f_s appropriately**

Test-Chip



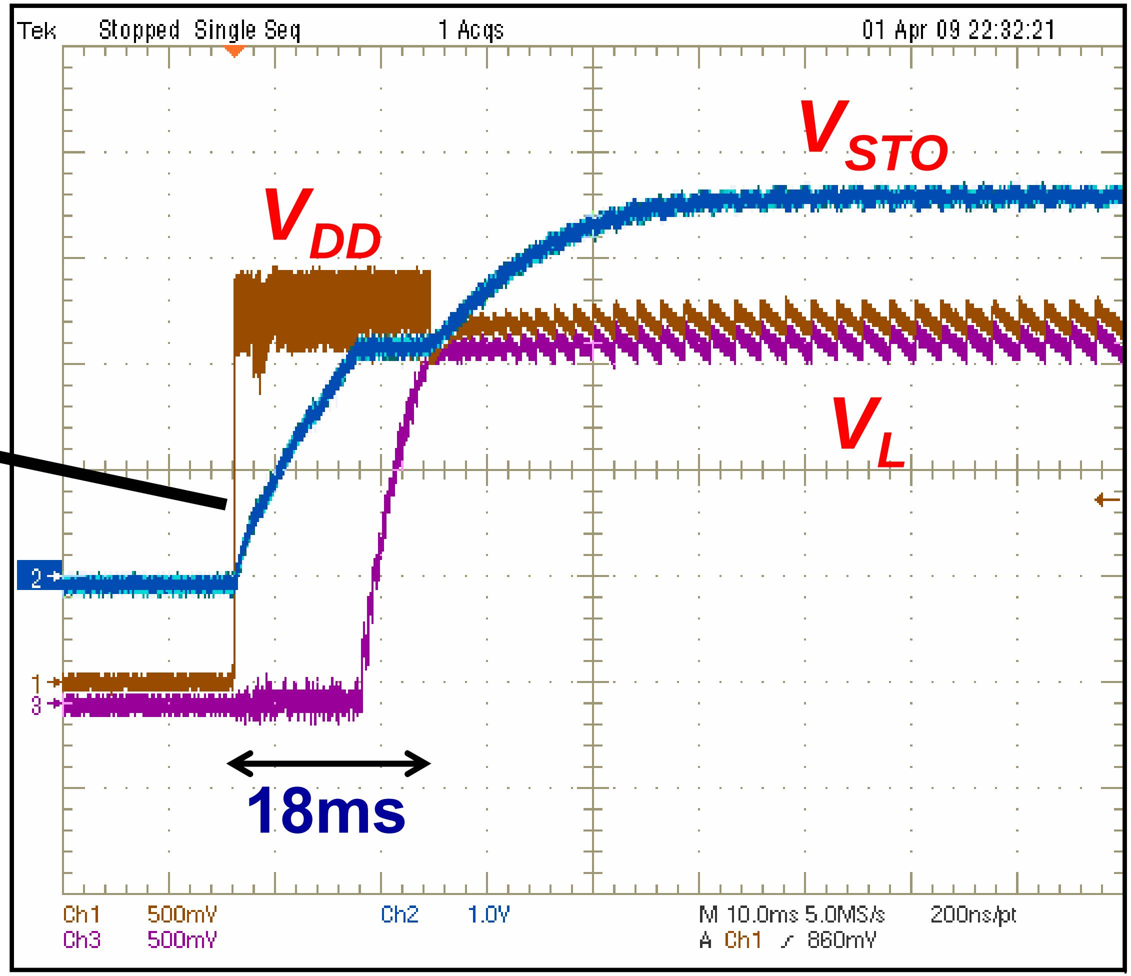
[Tellurex]

- 0.35µm digital CMOS process
- Active area = 1.7mm^2

Measured Startup Waveform

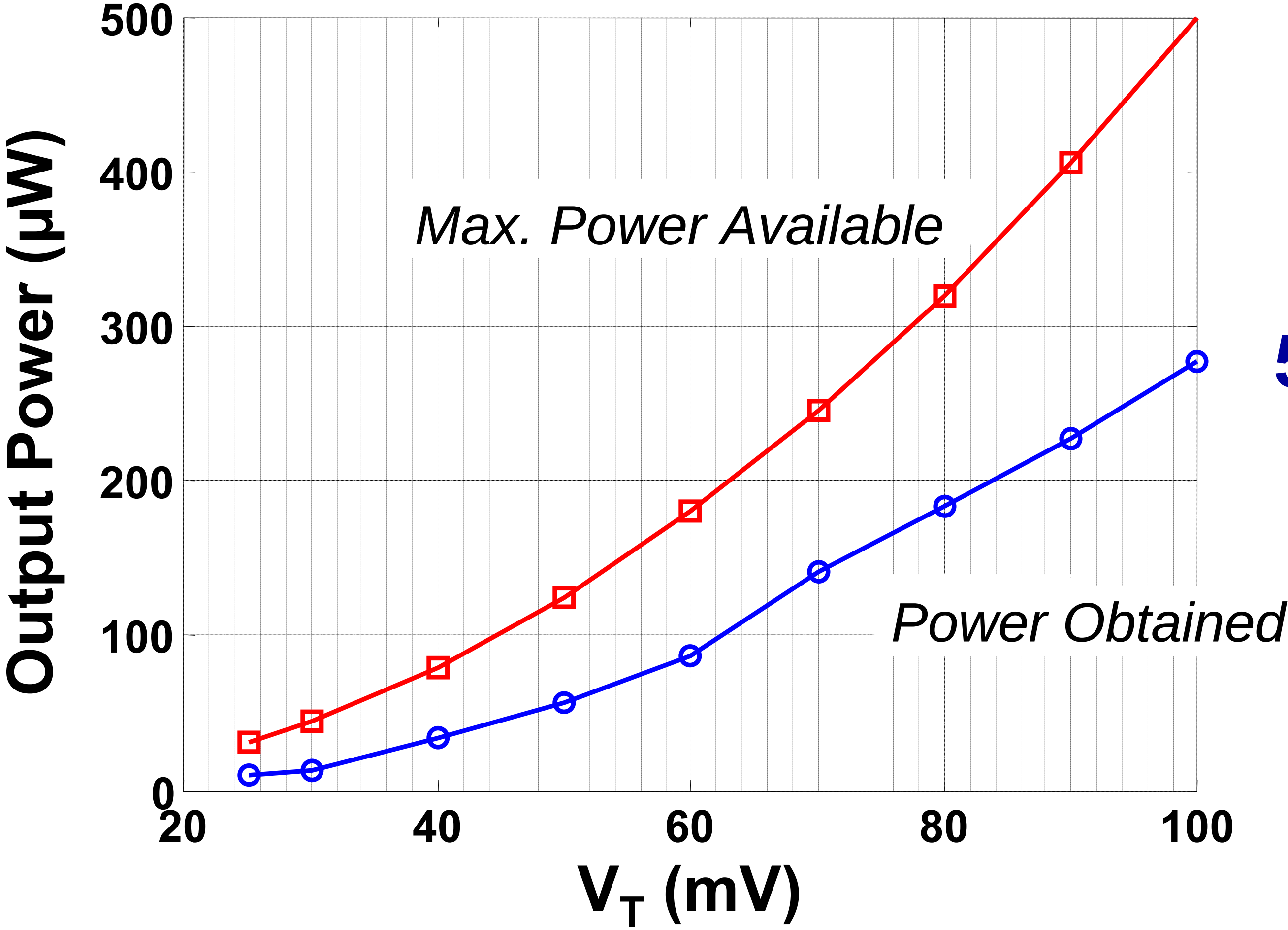
Mechanical Startup

2K Temperature Difference



- $V_T = 50mV$; $R_T = 5\Omega$

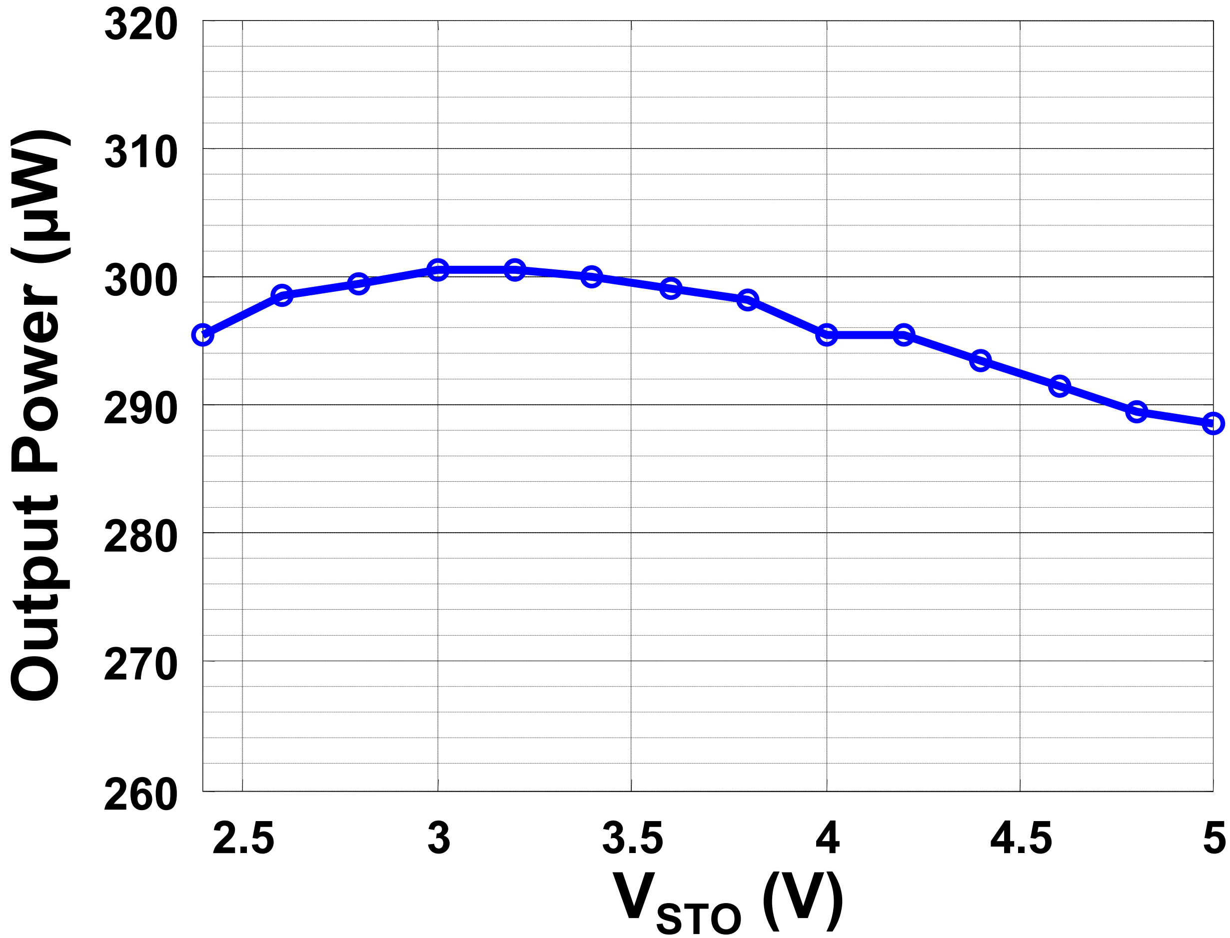
Measured Output Power



58% Maximum End-to-End Efficiency

- **Voltage source with 5Ω resistance**
- **Startup – 35mV; Operational down to 25mV**

Power Obtained at Storage Capacitor



V_T = 100mV

R_T = 5Ω

- Obtained power stays constant from 2.4V – 5V
- Verifies operation of ZCS block

Comparison with state-of-the-art

Parameter	Lhermet ISSCC 2007	Doms ISSCC 2009	Carlson VLSI 2009	EnOcean	This work
Process	0.35µm	0.35µm	0.13µm	n/a	**0.35µm**
Min. input voltage	1V	0.6V	20mV	20mV	**25mV (35mV to startup)**
External voltage?	None	2V battery	Minimum of 650mV	None	**None**
Output Voltage	1.75V-4.3V	2V	1V regulated	4V-4.5V	**1.8V regulated**
Peak efficiency	50% (just boost converter)	70% (just boost converter)	52% (end-to-end)	20% (end-to-end)	**58% (end-to-end)**
Maximum Power Tracking?	No	Yes	No	No	**Yes**

Conclusions

- **Batteryless thermoelectric energy harvesting interface circuit with 35mV startup voltage**
- **Provides end-to-end efficiency of 58% with maximum power point tracking**
- **Optimized interface circuits are a key enabler of self powered systems**

Acknowledgements : MIT Energy Initiative