Integrated Power Management Circuits for Energy-Efficient IoT Systems

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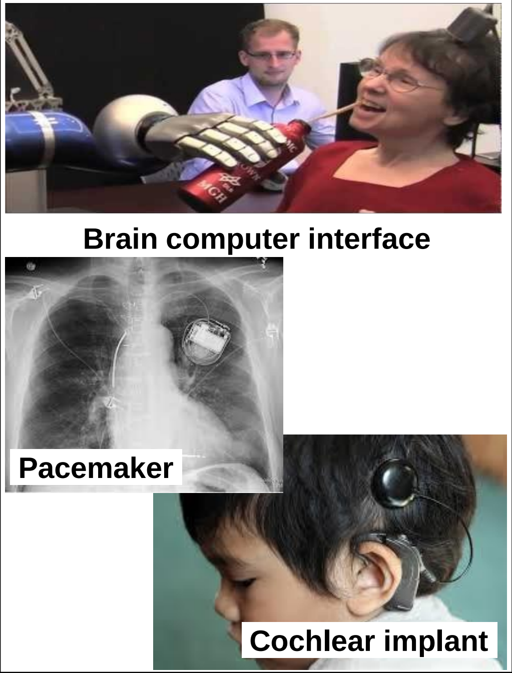
Outline

- Energy-efficiency in IoT systems
- 0.45-V input buck converter
- Wide I_{OUT} buck converter
- 80-mV input boost converter
- Switched capacitor DC-DC converter
  - Integration of MLCCs on die
- Summary

Multi-Layered Ceramic Capacitor (MLCC)

Emerging Applications

Area	IoT	Wearable	Implantable
			
Target	Environment, Things	Body surface	Inside the body
Applications	Management	Healthcare	Medical care

Requirements for IoT / Wearable Devices

Wearing-unconscious

(1) Ultra flexible / small-size

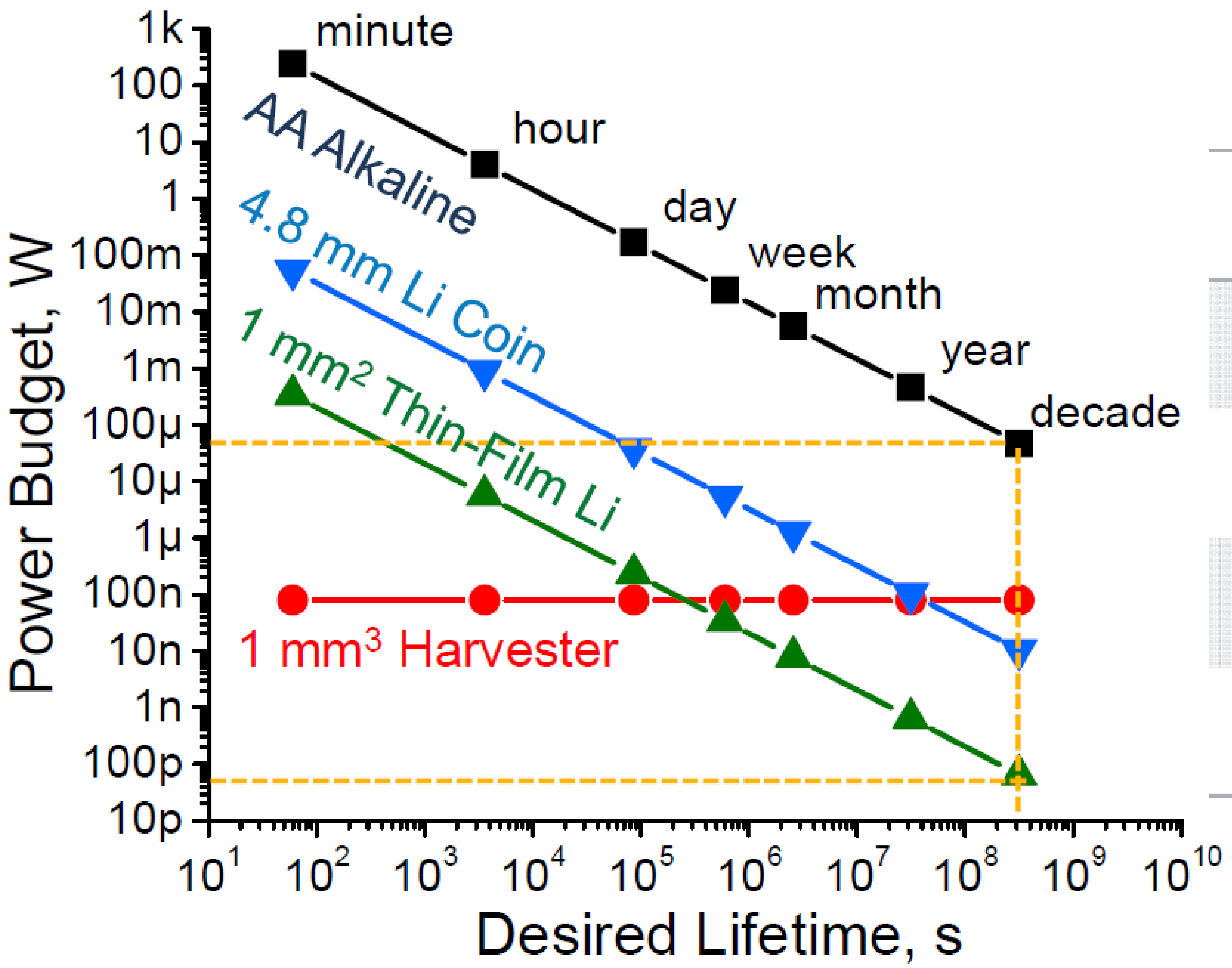
(2) Wireless

Maintenance-free

(3) Energy autonomy

(Low energy + Wireless powering/ Energy harvesting)

Ultra-Low Power for IoT

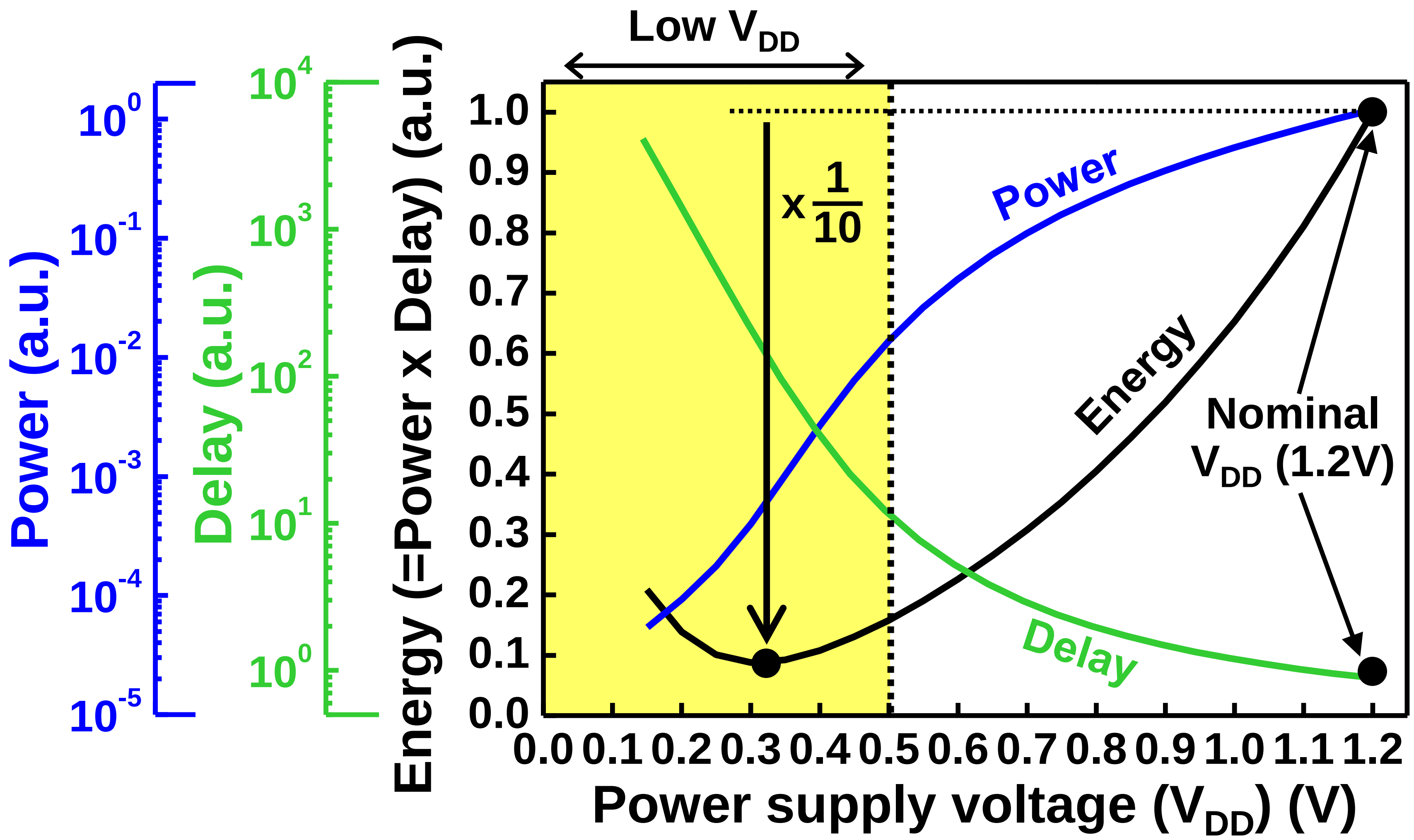


Battery	Peak Power
AA Alkaline	1.5 W
4.8 mm Li Coin	600 μW
1 mm² Thin-Film Li	40 μW
1 mm³ Harvester	80 nW

D. Blaauw (Univ. Michigan), ISSCC2011

- nW to μW are required.

Minimum Energy at Low V_{DD}

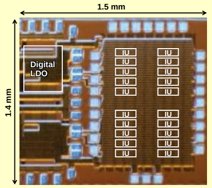


- Energy efficient operation at V_{DD} = 0.3V

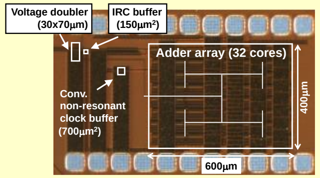
Our Sub-0.5V Circuits

Logic

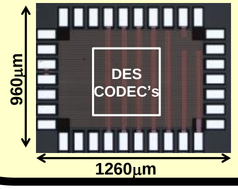
Adaptive V_{DD}
(ISSCC2012)



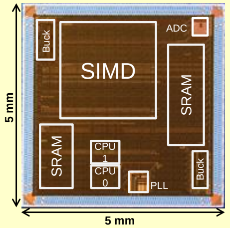
Resonant clock
(ISSCC2013)



Fine-grained V_{DD}
(ESSCIRC2011)
(ISQED2012)

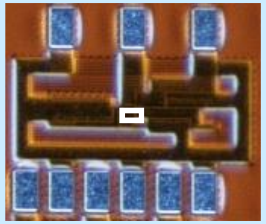


High V_{DD} clock
(VLSI2013)

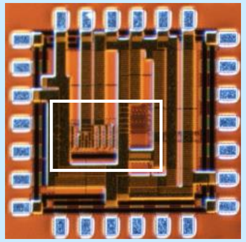


RF

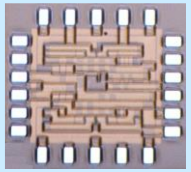
0.5V TX
(ESSCIRC2012)



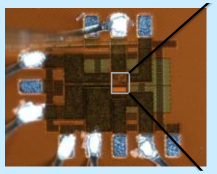
0.5V RX
(VLSI2012)



Power gated XO
(VLSI2013)

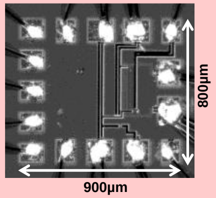


0.35V XO
(ISLPED2012)

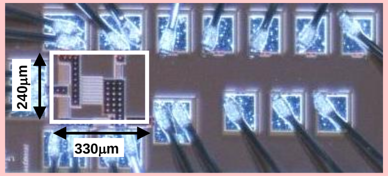


Power management

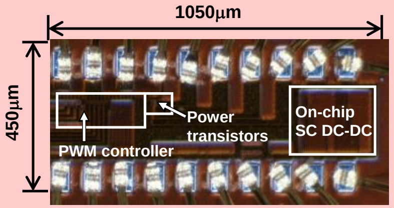
0.5V LDO
(CICC2010)



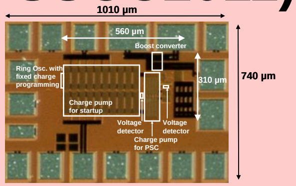
1V switched cap.
(VLSI2011)



0.45V buck
(VLSI2012)



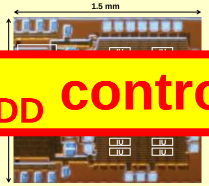
0.1V boost
(ISSCC2011)
(A-SSCC2011)



Key Techniques for Sub-0.5V Circuits

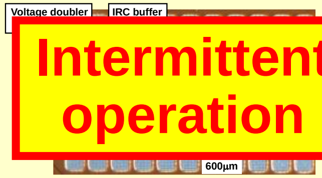
Logic

Adaptive V_{DD}
(ISSCC2012)



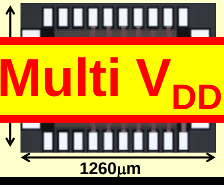
V_{DD} control

Resonant clock
(ISSCC2013)



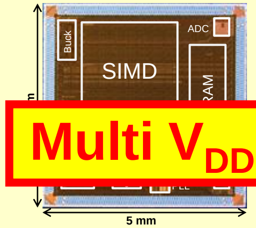
Intermittent operation

Fine-grained V_{DD}
(ESSCIRC2011)
(ISQED2012)



Multi V_{DD}

High V_{DD} clock
(VLSI2013)



Multi V_{DD}

RF

0.5V TX
(ESSCIRC2012)

Multi V_{DD}

0.5V RX
(VLSI2012)

Intermittent operation

Power gated XO
(VLSI2013)

Intermittent operation

0.35V XO
(ISLPED2012)

Gate width sizing

Power management

0.5V LDO
(CICC2010)

Analog → Digital

1V switched cap.
(VLSI2011)

Intermittent operation

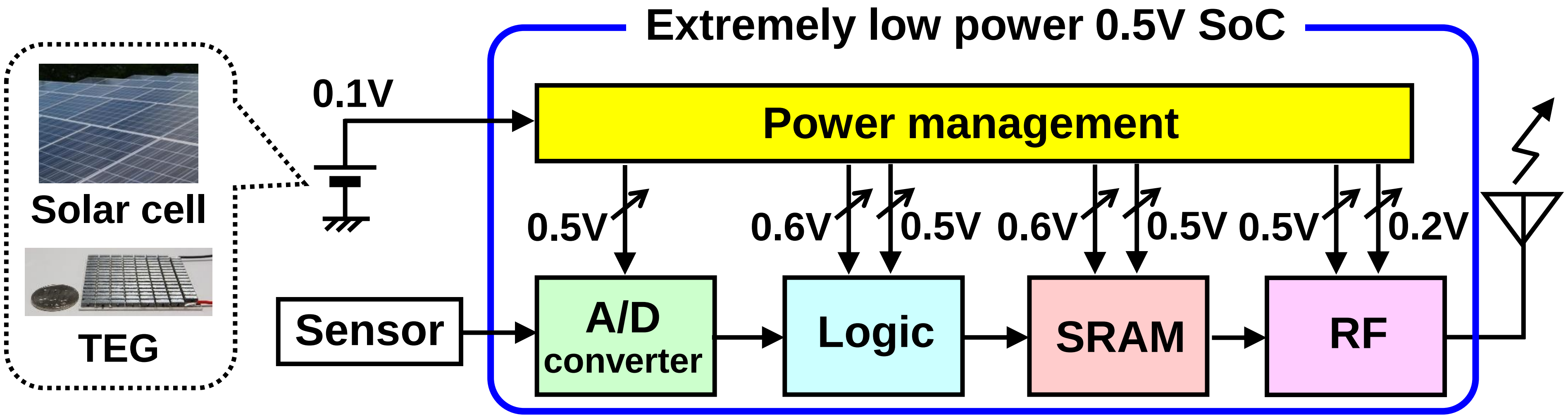
0.45V buck
(VLSI2012)

Local gate boost

0.1V boost
(ISSCC2011)
(A-SSCC2011)

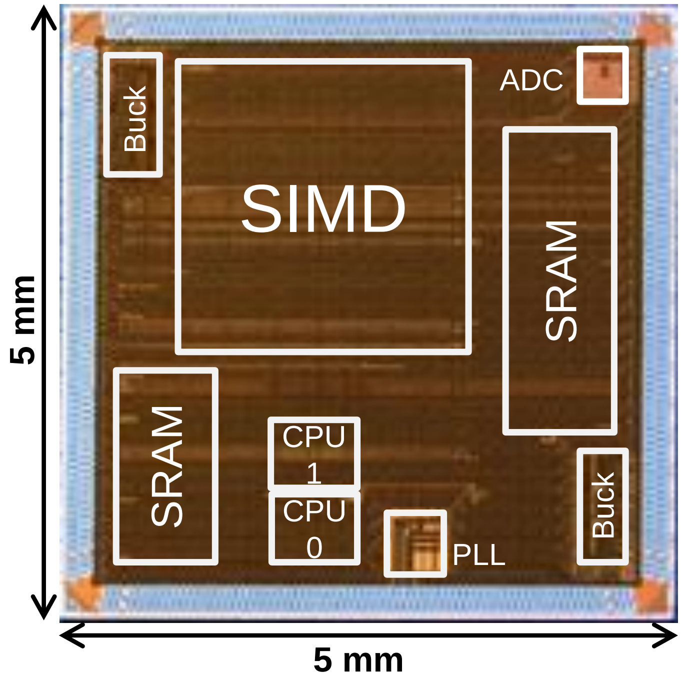
Local gate boost

0.5V SoC for Image Processing



TEG: Thermoelectric generator

Integrated power management circuits are important to achieve energy-efficient IoT systems.



M. Nomura, et al., VLSI Symp 2013

Outline

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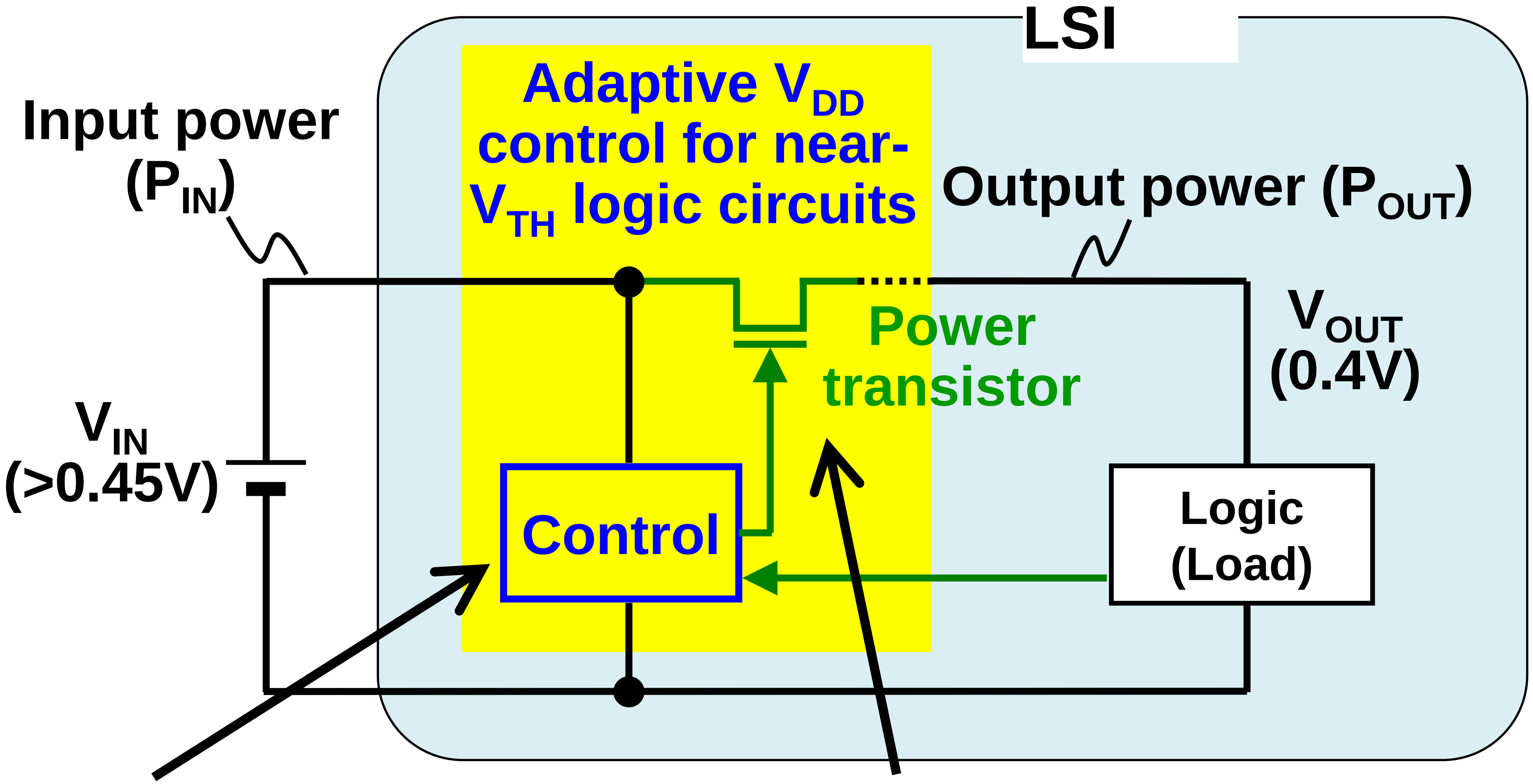
Multi-Layered Ceramic Capacitor (MLCC)

Target of Gate Boosted Buck Converter

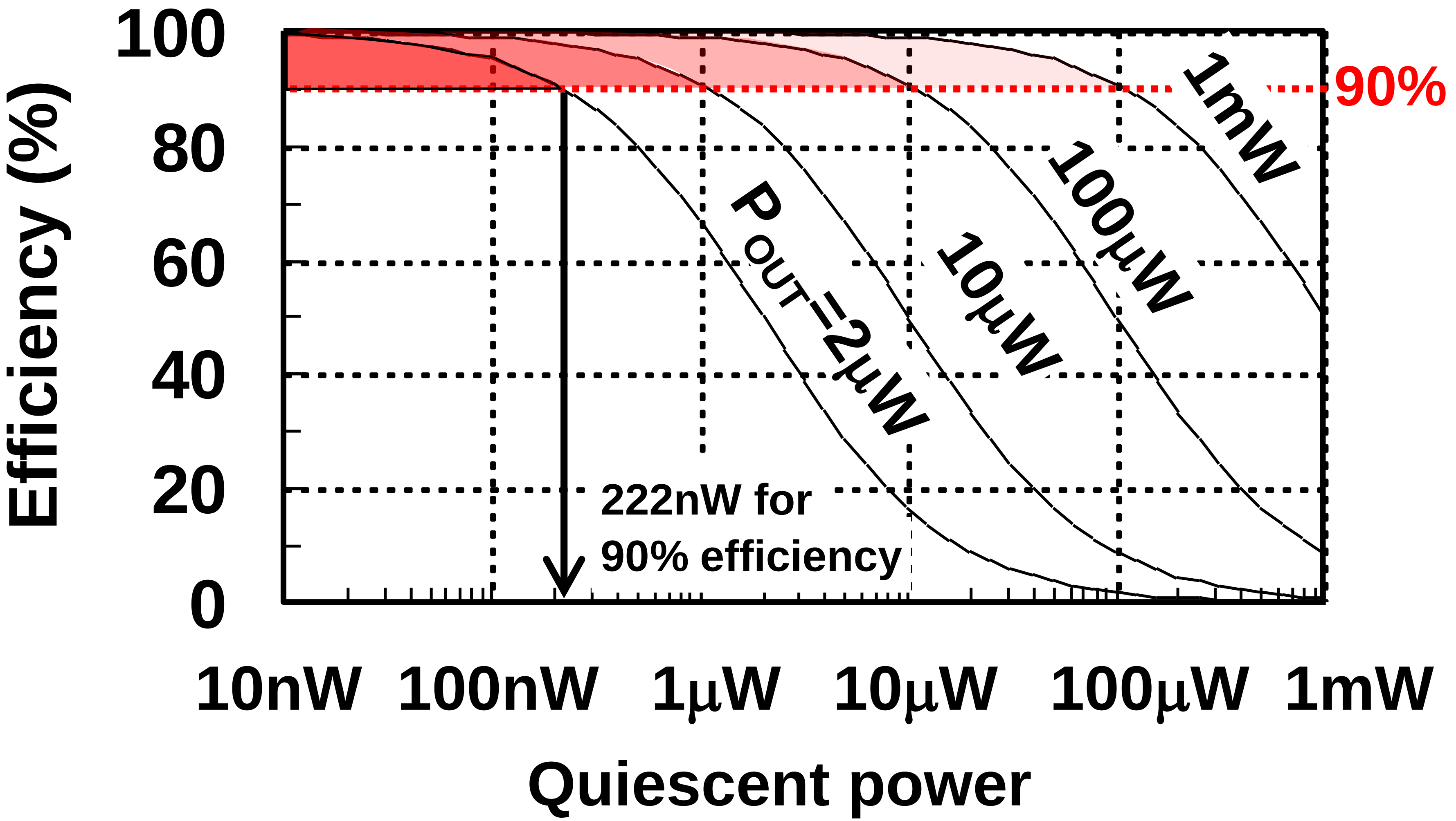
■ Target: P_{OUT}/P_{IN}>90% @ P_{OUT}=2μW~50μW



■ Low P_{OUT} → Controller power becomes dominant.

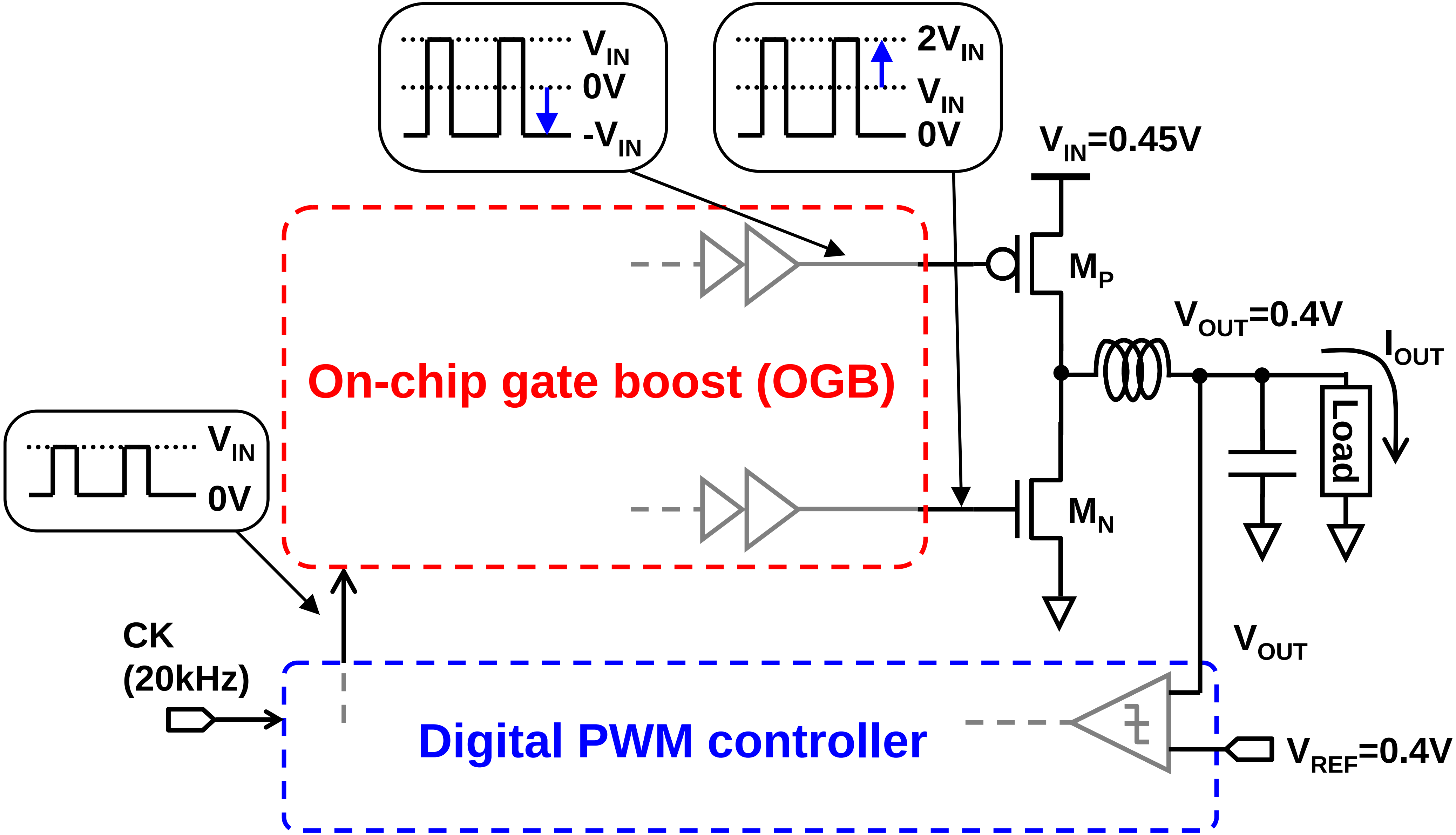
■ Low V_{IN} → Loss in power transistors increases.

Low Quiescent Power (≈ Controller Power)

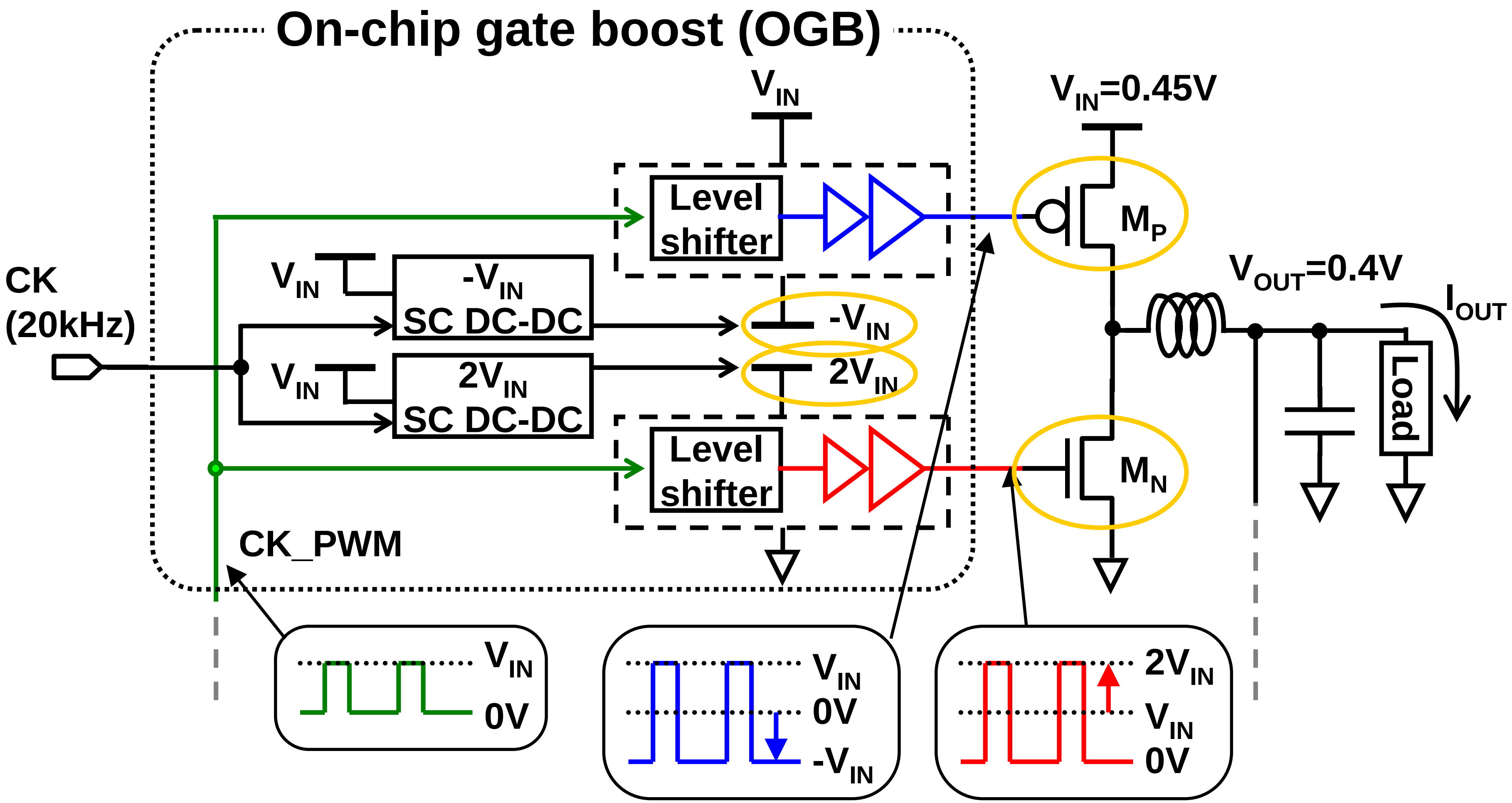


- As the quiescent power increases, the efficiency decreases.
- For 90% efficiency @ P_{OUT}=2µW, target quiescent power is 222nW.

Concept of Proposed Buck Converter



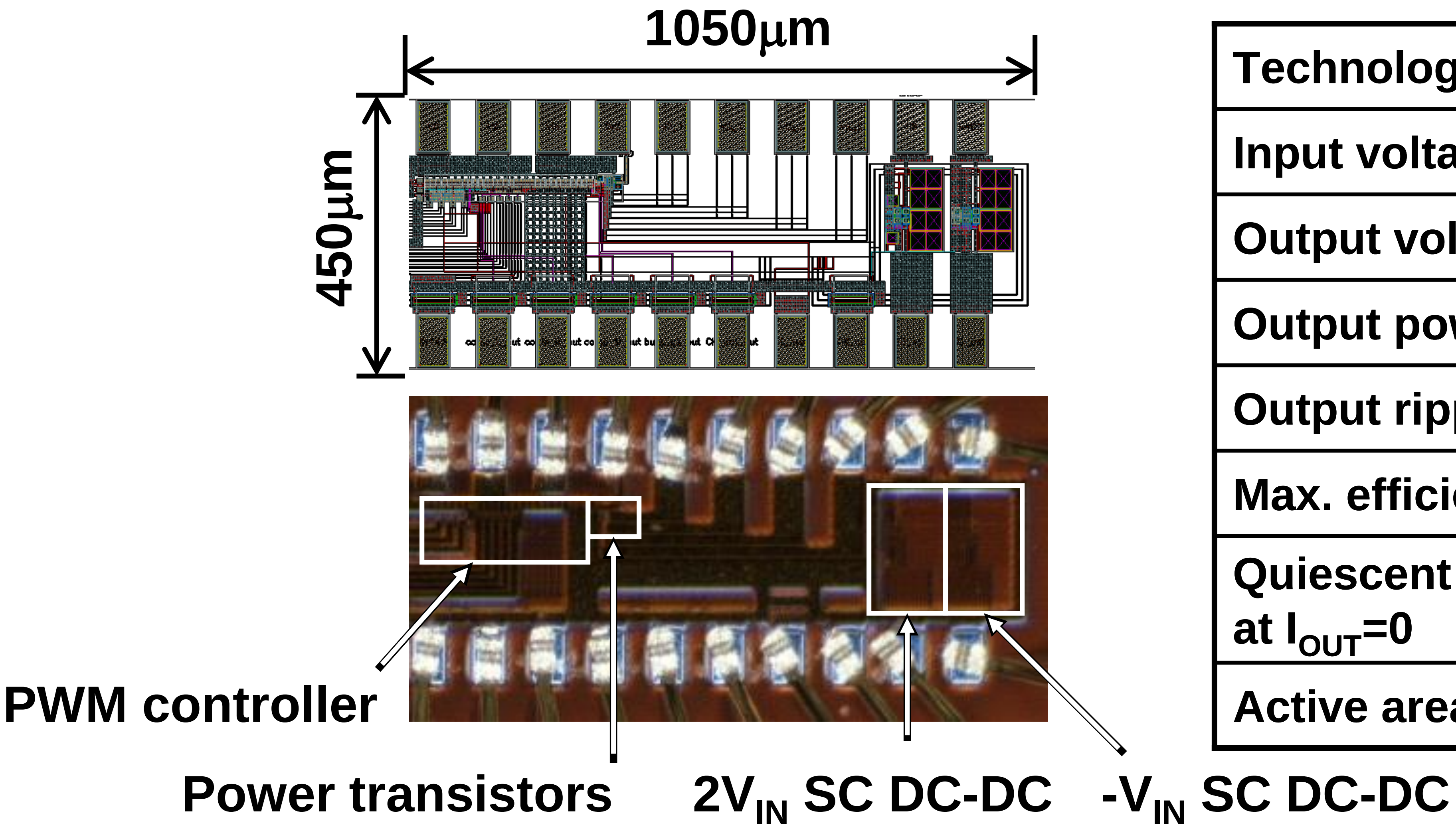
On-chip Gate Boost for Power Transistors



■ 2 power rails are generated by on-chip switched-capacitor (SC) DC-DC converters.

➔ Loss in M_P and M_N is reduced.

On-chip Gate Boosted Buck Converter

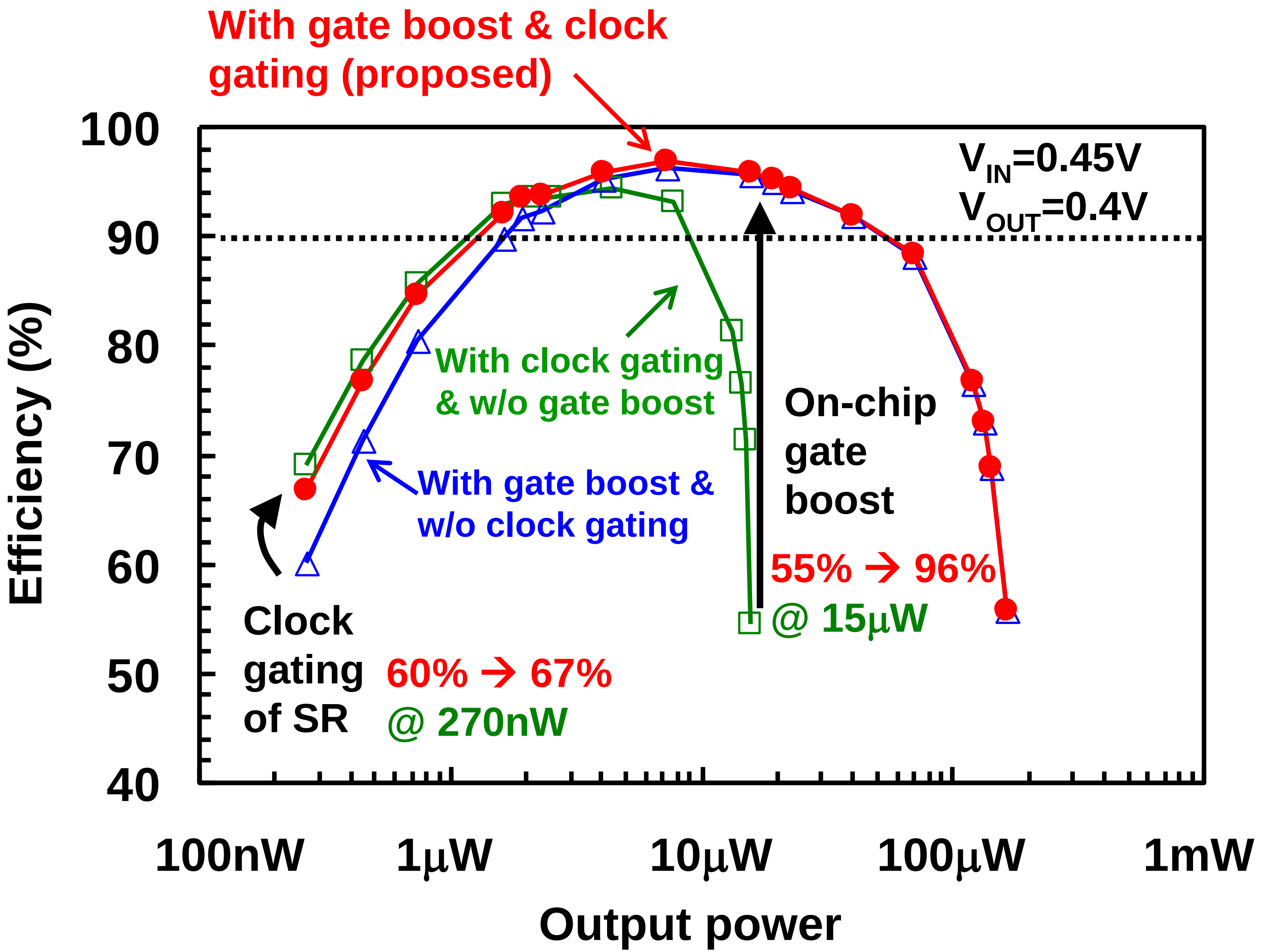


40nm CMOS

Technology	40-nm CMOS
Input voltage	0.45V
Output voltage	0.34V~0.44V
Output power	270nW~165μW
Output ripple	<5mV
Max. efficiency	97% at 7μW
Quiescent power at I_{OUT}=0	140nW
Active area	0.043 mm^2

X. Zhang, et al., VLSI Symp 2012

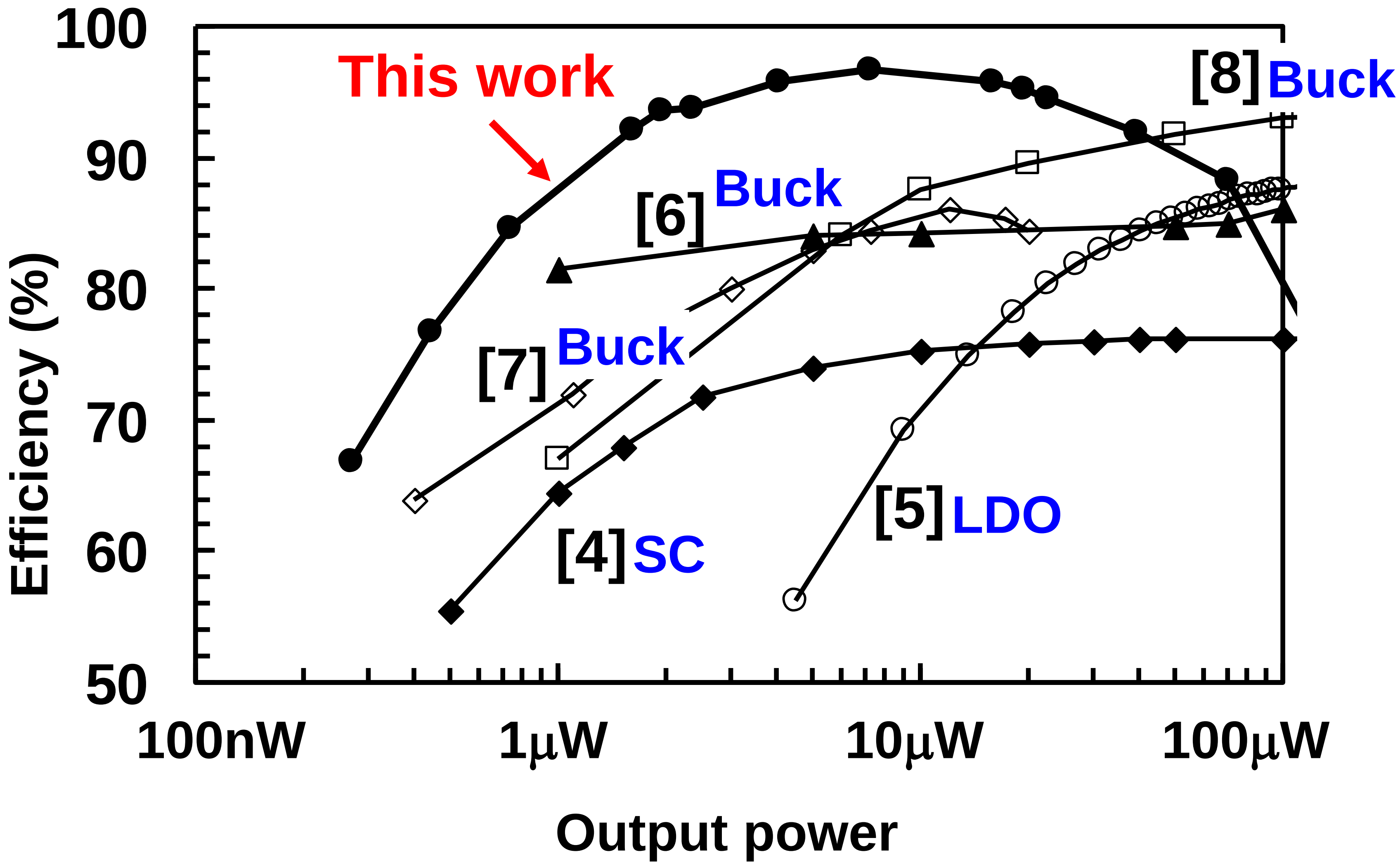
Measured Efficiency vs. Output Power



>90% efficiency is achieved from 2µW to 50µW.

(Ideal LDO= $\frac{0.4V}{0.45V}$ =89%)

Comparison with DC-DC Converters



■ By virtue of OGB and low-power controller (140nW), the highest efficiency (<40μW) is achieved.

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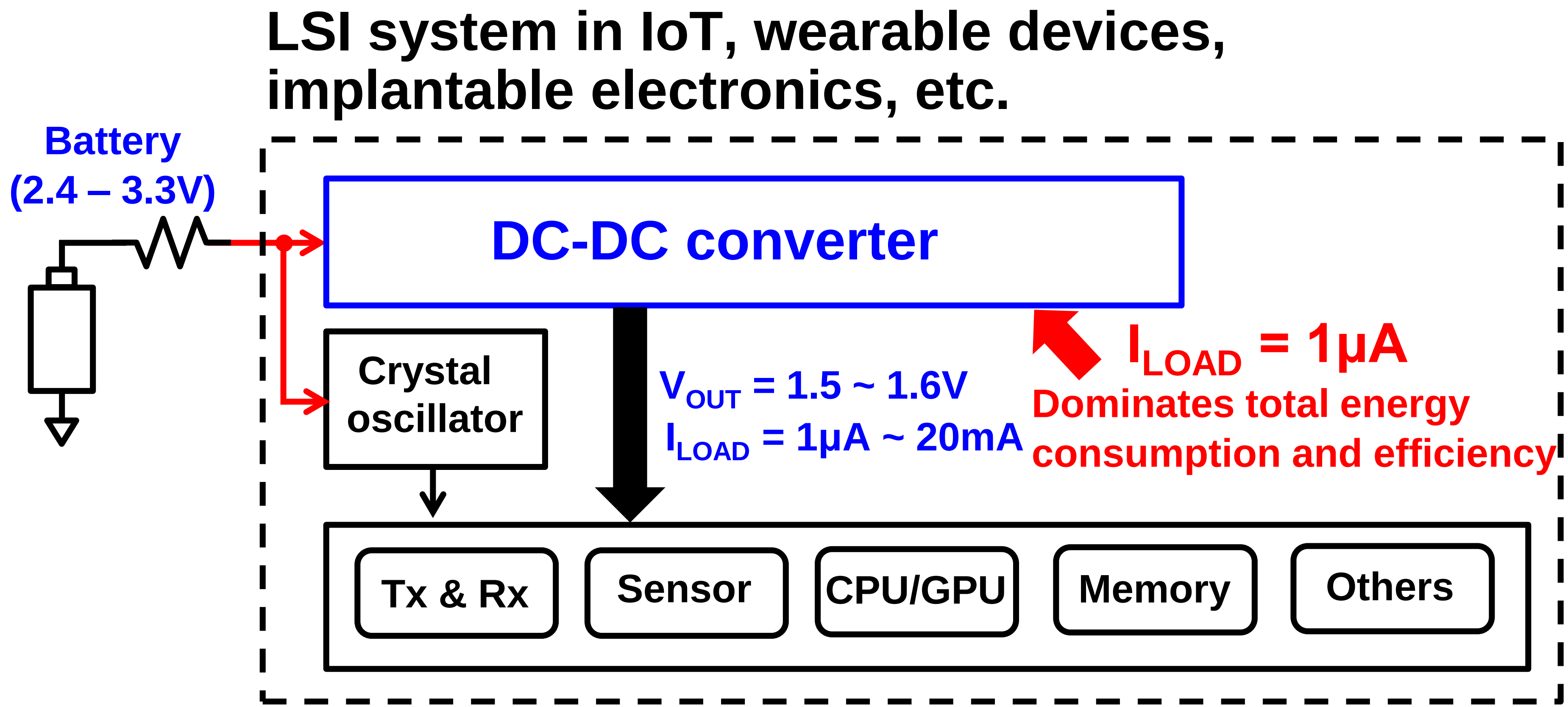
Multi-Layered Ceramic Capacitor (MLCC)

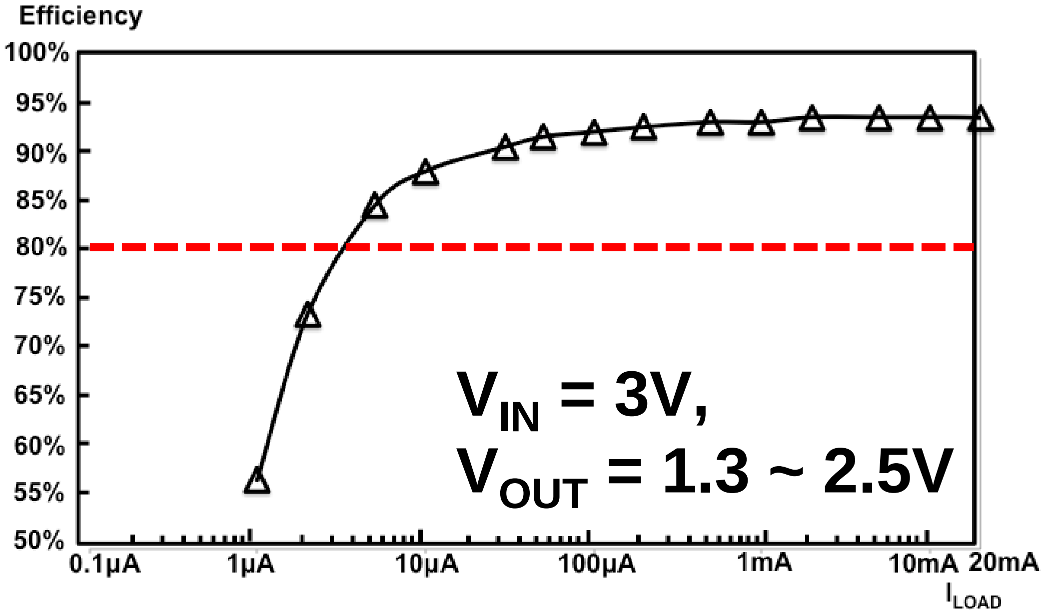
Buck Converter for Wide I_{OUT}

- Sleep mode consumes more than 95% energy
- BLE specifications: 15 mA (active), 1 μA (sleep)
- Load current range > 10^4



Low Efficiency at I_{OUT} < 1μA

Buck converter for IoT

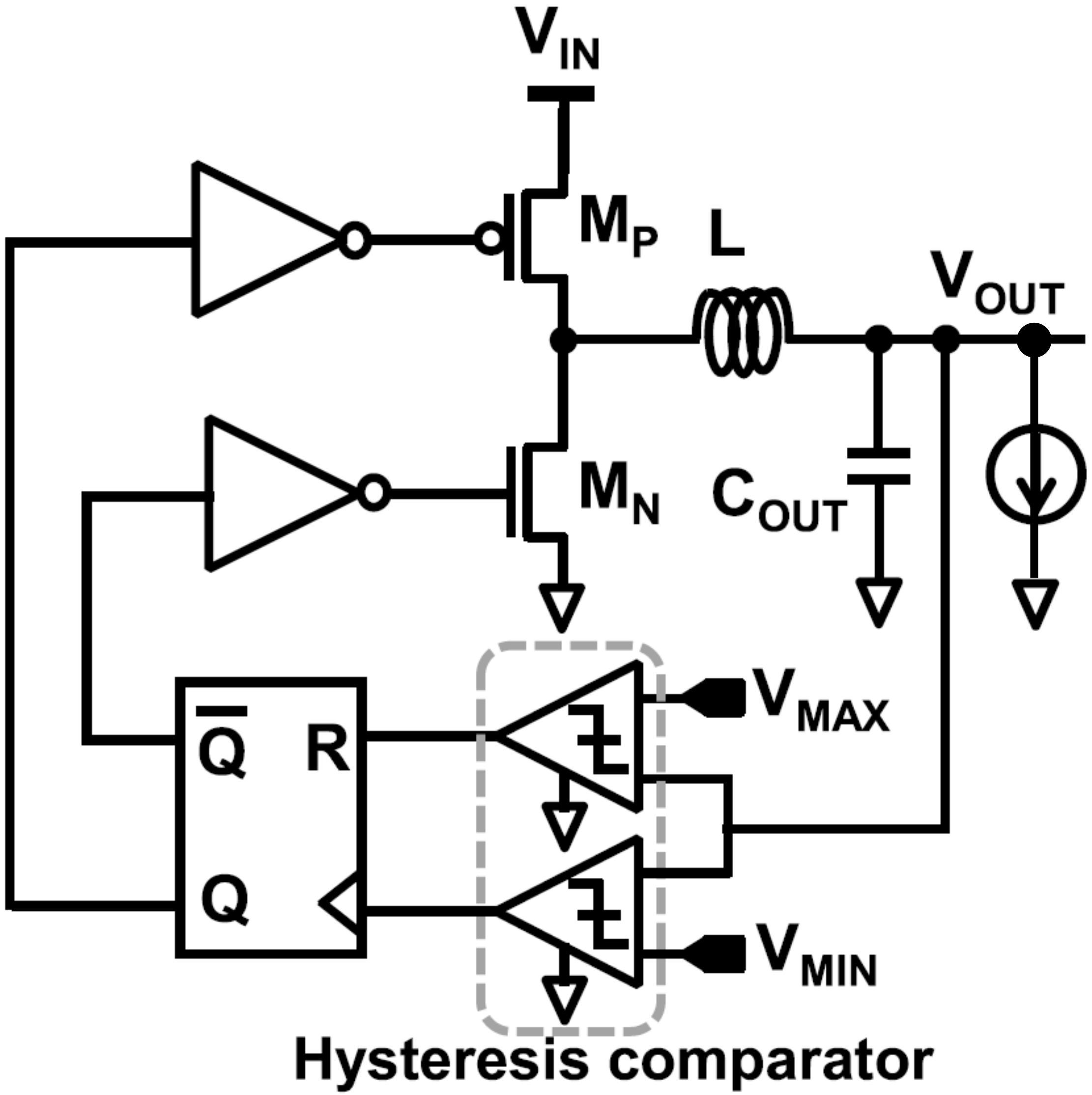


- ☐ I_{LOAD} range > 10^4
- ☐ η < 80% @ I_{LOAD} < 4μA
- ☐ η ~ 55% @ I_{LOAD} = 1μA

➢ **Efficiency should be improved in μ-A region**

→ **Save energy consumption and extend battery lifetime**

Conv. Buck Converter in DCM

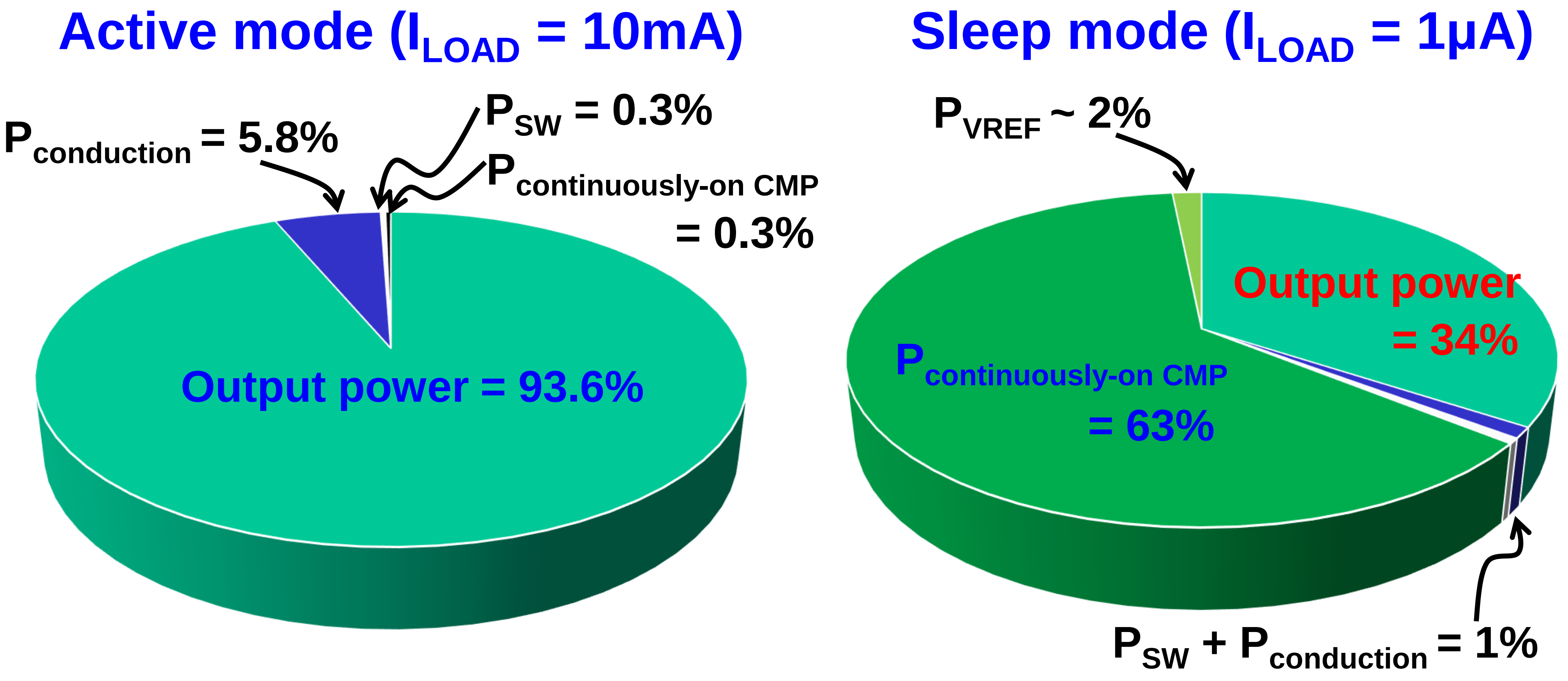


Discontinuous conduction mode (DCM)

DC power of the continuous-time comparator degrades the efficiency of buck converter.

Simulated Power Dissipation

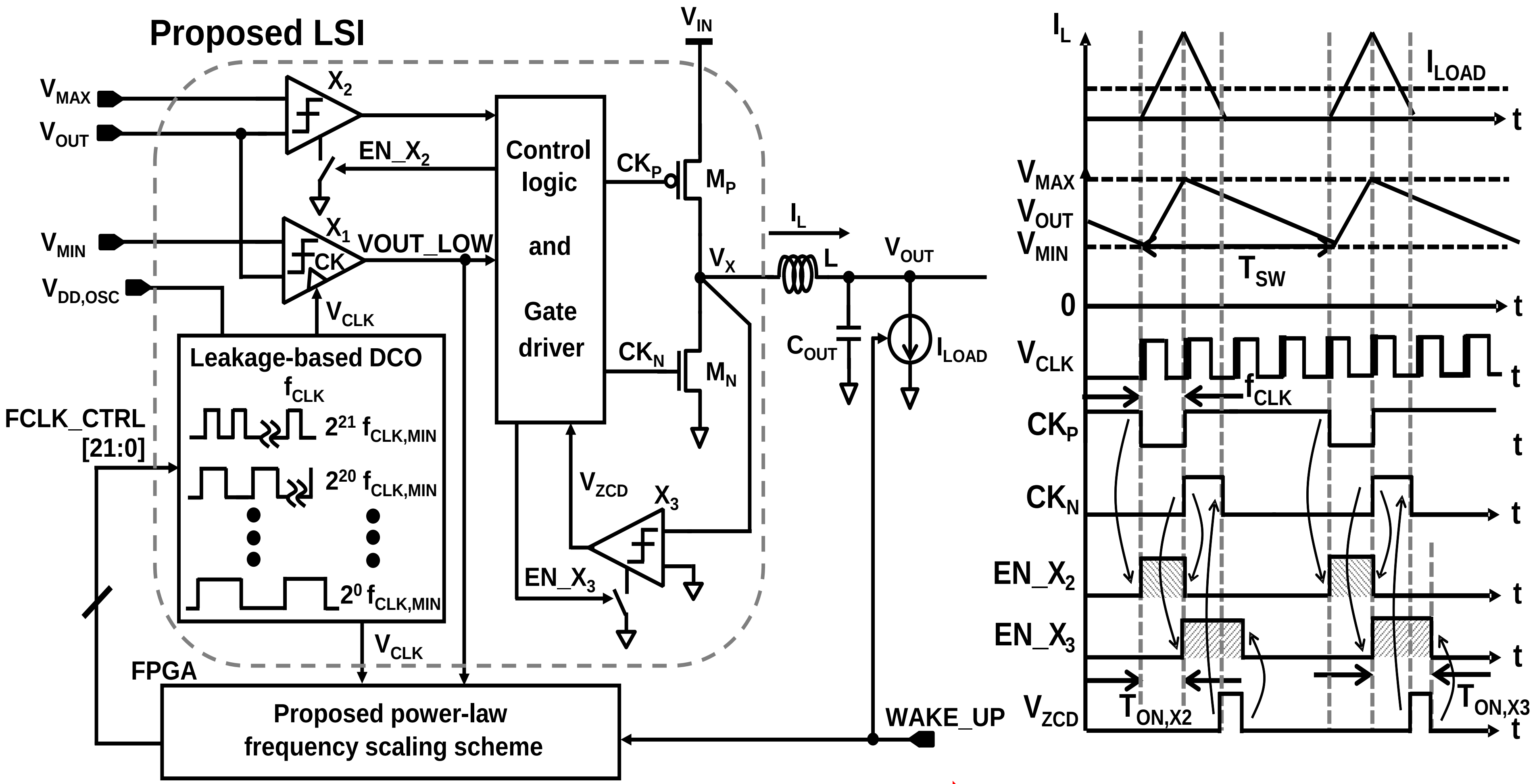
■ Power dissipation of hysteresis buck converter:



■ Even the I_{BIAS}=1μA also decreases η to 34% @ I_{LOAD}=1μA

➔ Remove the continuously-on Comparator

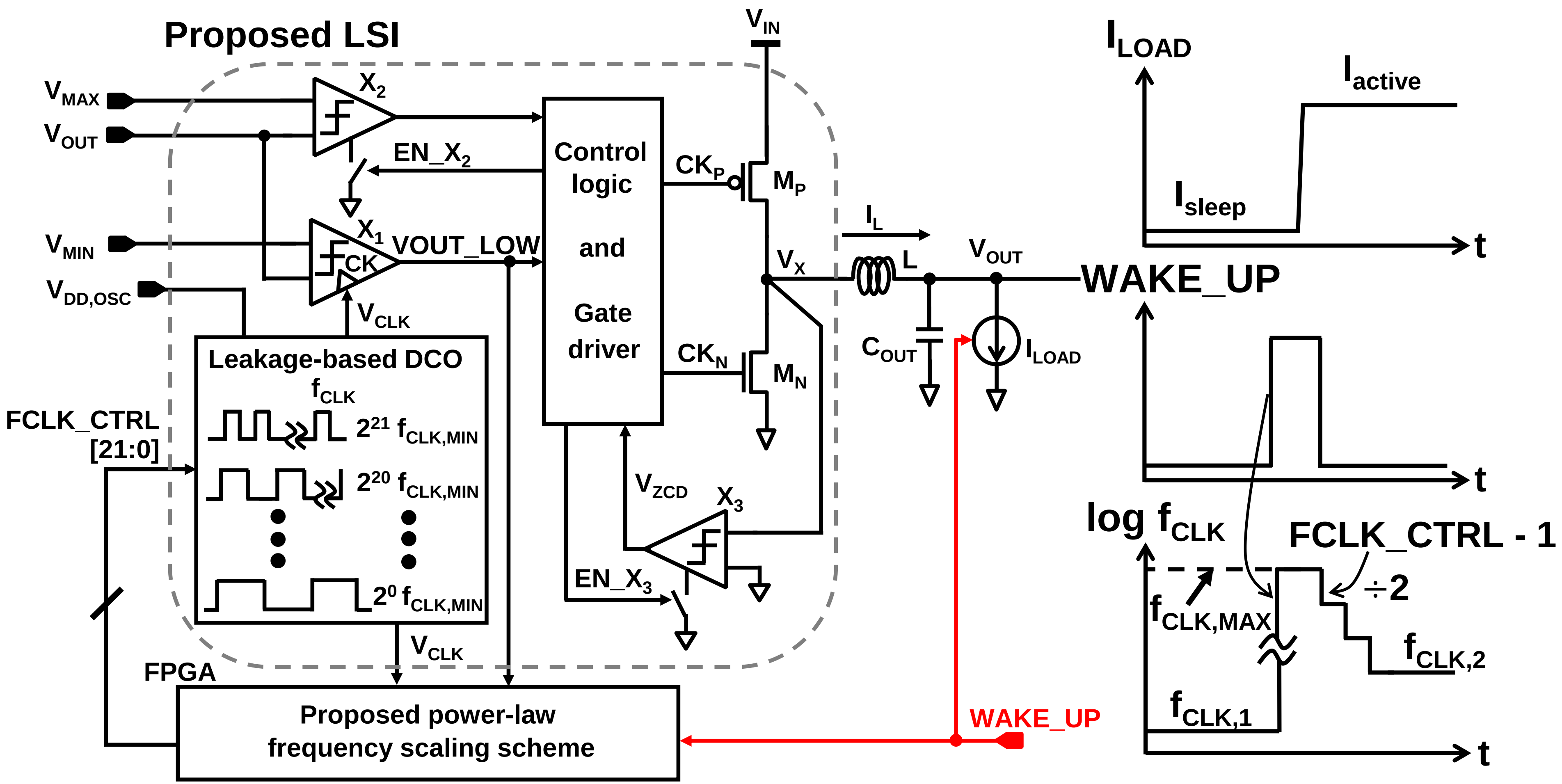
Proposed Clocked Hysteresis Control Buck Converter



- X_1: Clocked comparator
- X_2, X_3: Power-gated comparator

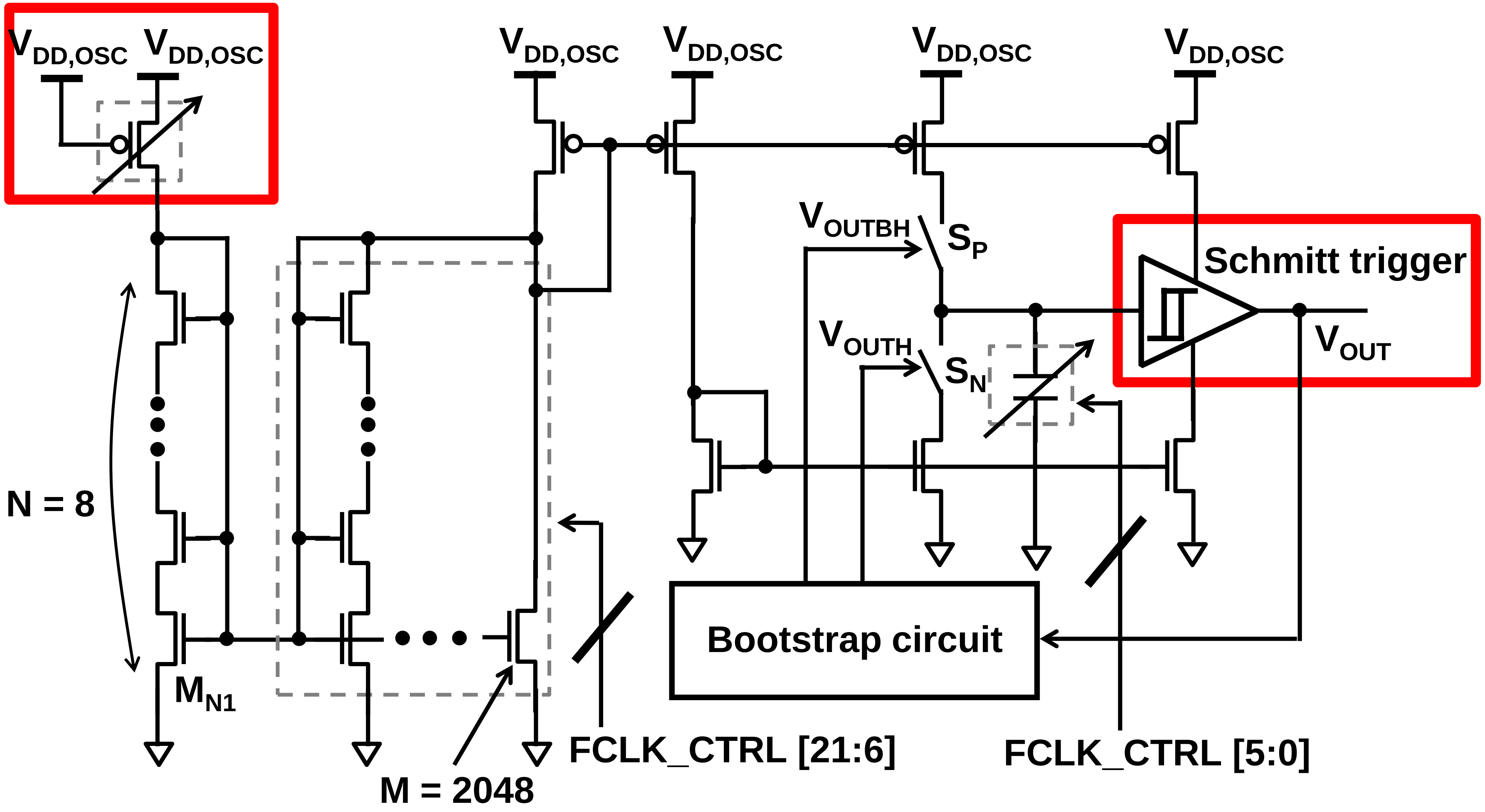
→ No DC power in comparators

Load Wake-up Operation



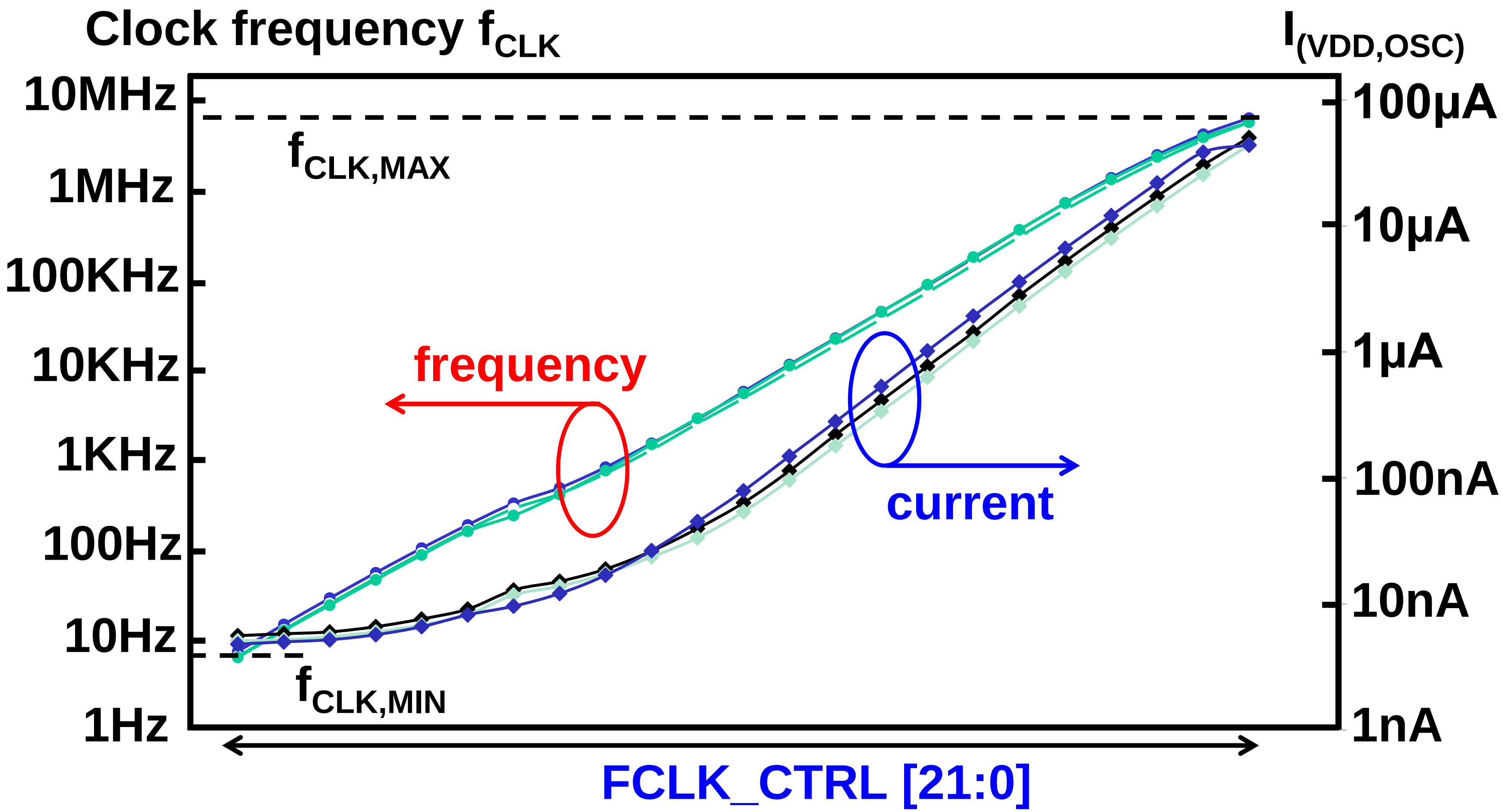
- WAKE_UP: reset f_{CLK} to highest frequency (2^{21} f_{CLK})
- Asynchronized logic can be designed to reset f_{CLK} immediately

Leakage-Based DCO



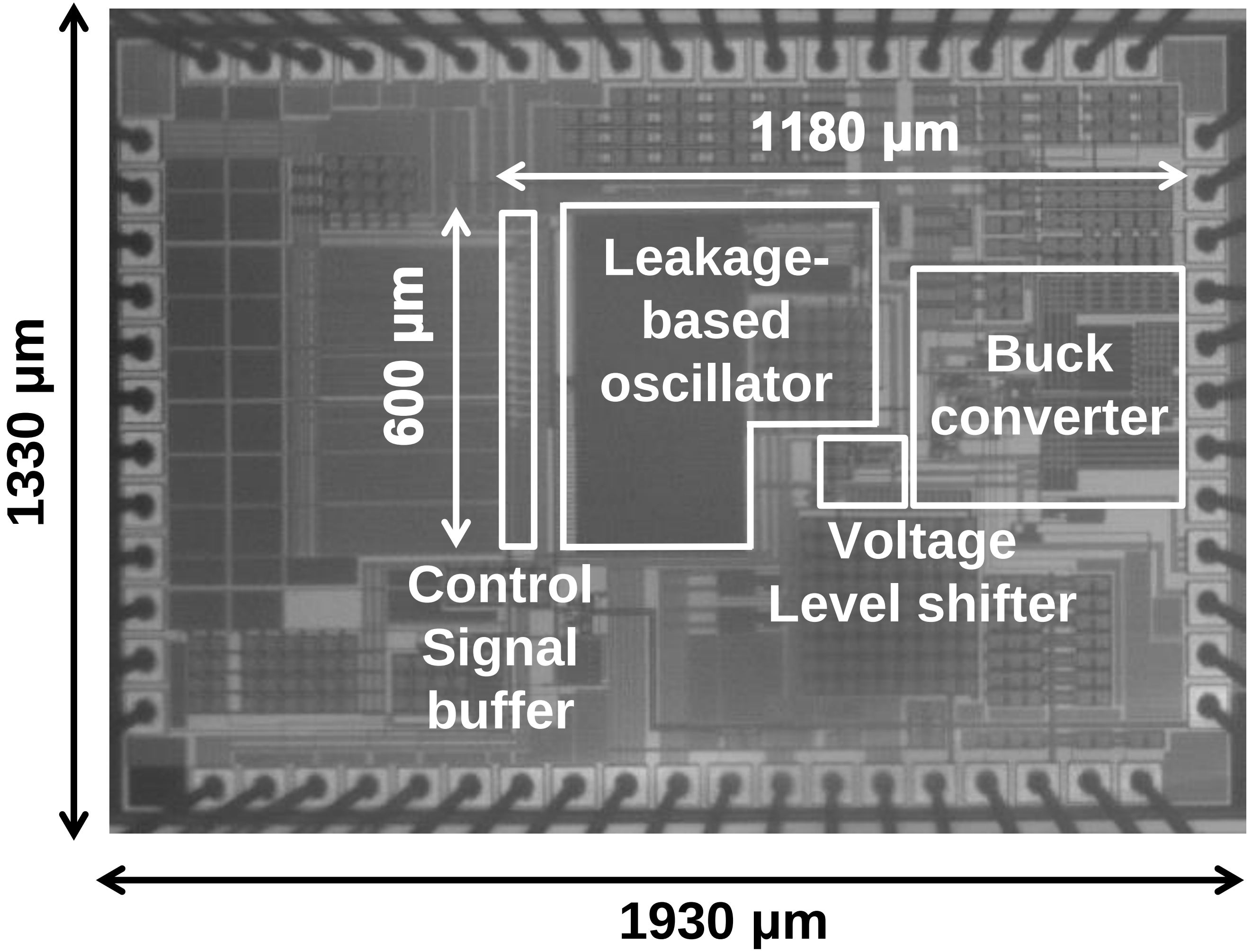
- Power: proportional to the oscillating frequency
- No additional voltage reference
- Leakage current is designed as bias

Measured Oscillator Power vs. Freq.



- Measured 3 chip showing small variation on $f_{CLK}/I_{(VDD,OSC)}$
- f_{CLK} = 7Hz ~ 6MHz controlled by 22 bits thermometer code
- $P_{(VDD,OSC)}$ = 3.5nW ~ 32μA when $V_{DD,OSC}$ = 0.6V

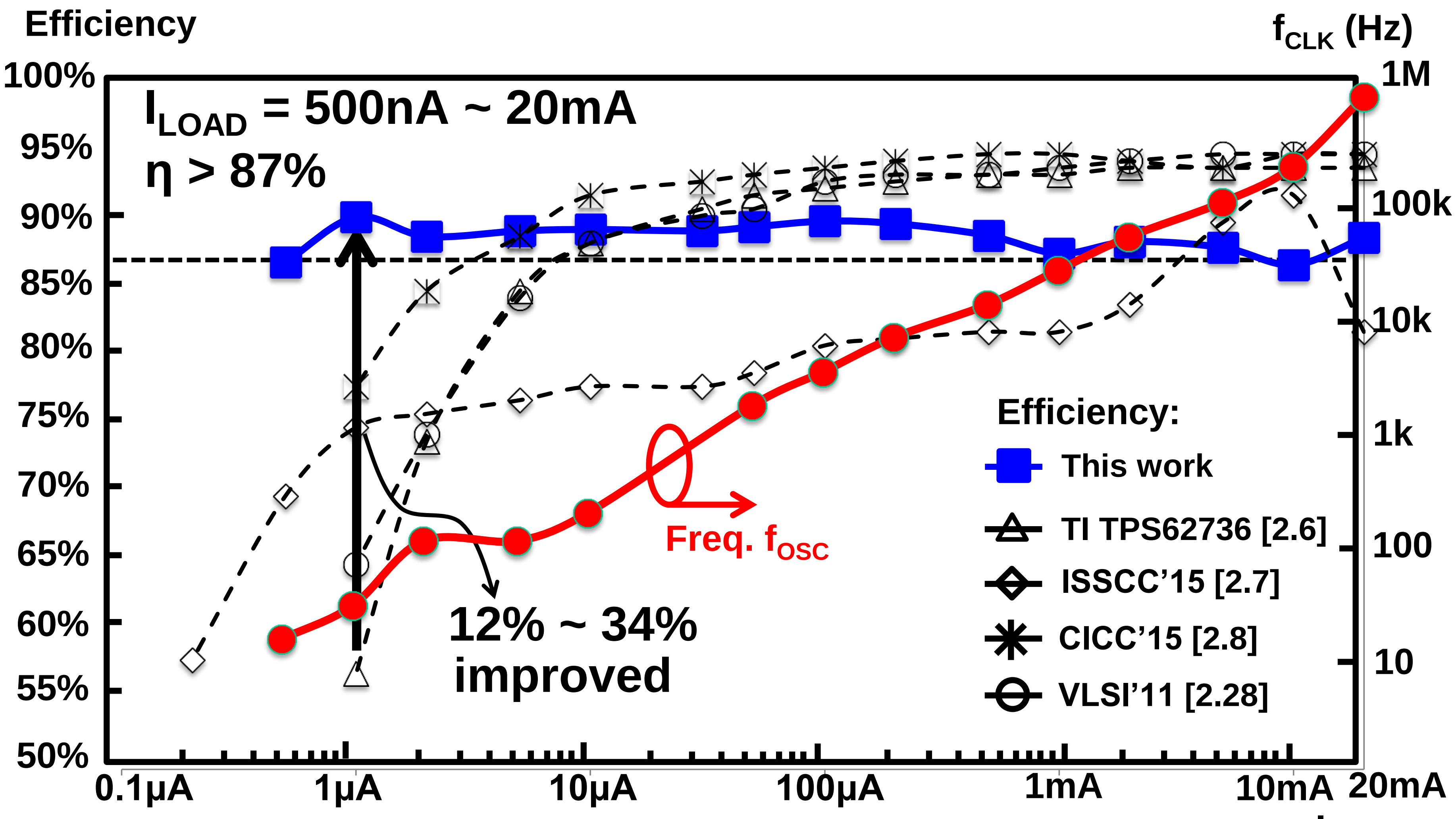
Chip Micrograph



- 0.18μm CMOS
- Active area: 0.71mm²
- V_{IN} = 2.4 – 3.3V, V_{OUT} = 1.5 – 1.6V
- Off-chip: 4.7-μH L, 1-μF C

C.-S. Wu, et al., IEEE Trans. on VLSI, 2018

Efficiency of Buck Conveter



V_{IN} = 3V, V_{OUT} ~ 1.58V

- η > 87% over 500nA to 20mA for BLE application
- 12% ~ 34% improvement is achieved @ I_{Load} = 1µA

Performance Comparison

	ISSCC'15 [2.7]	CICC'15 [2.8]	VLSI'15 [2.9]	VLSI'11 [2.28]	**This work**
Technology	180nm CMOS	350nm CMOS	180nm CMOS	250nm CMOS	**180nm CMOS**
Die size	1.44mm^2	2.88mm^2	2.42mm^2	0.21mm^2	**0.71mm^2 ***
V_{IN} (V)	0.6/1.2	2.2 – 6	3	1.2 – 2.5	**2.4 – 3.3**
V_{OUT} (V)	0.35 – 0.5	2.5	1	1	**1.5 – 1.6**
I_{LOAD}	100nA – 20mA	1µA – 100mA	10nA – 1µA	1µA – 100mA	**500nA – 20mA**
Peak eff. η_{PEAK}	92%	95%	87%	95.2	**90.4%**
η @ I_{LOAD} =1µA	75%	78%	87%	65%	**90.4%**
Inductor value L	4.7µH	2.2µH	47µH	1.5µH	**4.7µH**
Control methodology	PWM, PFM, and AM	Hysteresis control	Constant on-time	Dynamic on/off time	**Clocked hysteresis control**

* Active area

- **η > 87% over 500nA-20mA I_{Load} with the proposed clocked hysteresis control**

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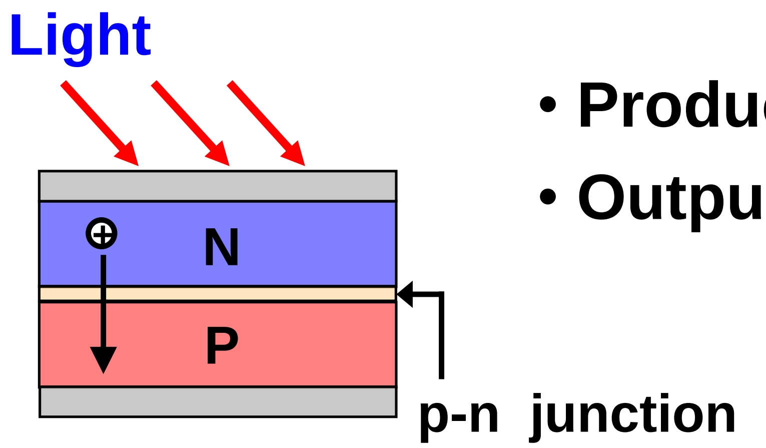
Multi-Layered Ceramic Capacitor (MLCC)

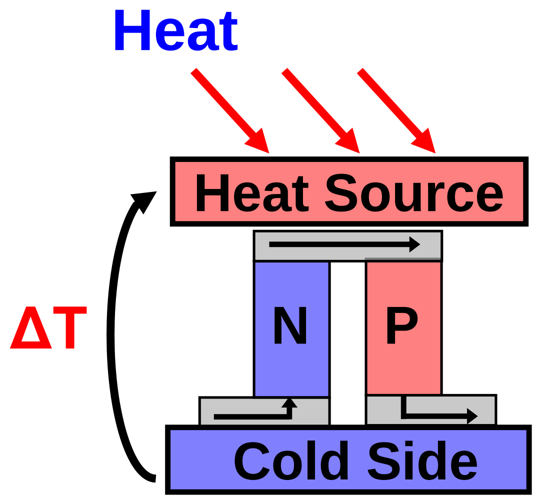
Energy Harvesters

Single-cell Solar Cell



- Producing electricity from light
- Output : 500~600mV (Outdoor),
  100~200mV (Dark office)

Thermoelectric Generator



- Producing electricity from heat
- Output : 10mV/K~50mV/K

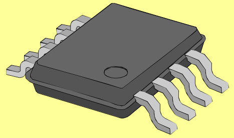
⇨ From body heat (2K) : 100mV

DC/DC for Energy Harvester

Startup voltage ($V_{Startup}$): The minimum V_{IN} that the converter starts to operate.

V_{IN}(<0.2V)

Step-up DC/DC Converter



V_{OUT}(>1V)

Energy Harvester

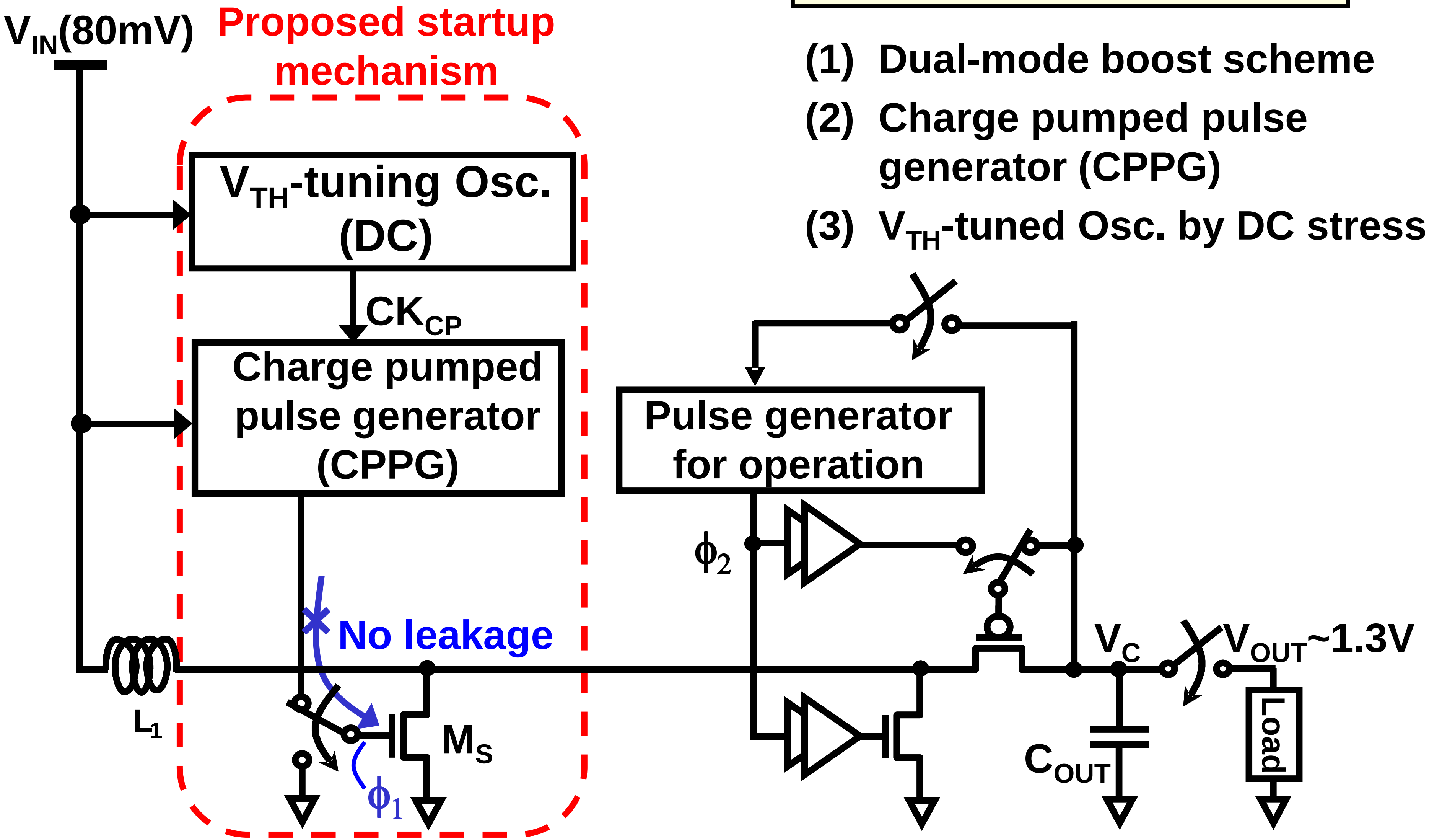
- Single-cell solar cell (100~200mV)

- Thermoelectric generator (100mV)

- Sensor nodes
- Healthcare devices

Target startup voltage of DC/DC converter is 100mV.

Proposed Dual-Mode Boost



Proposed Techniques

(1) Dual-mode boost scheme

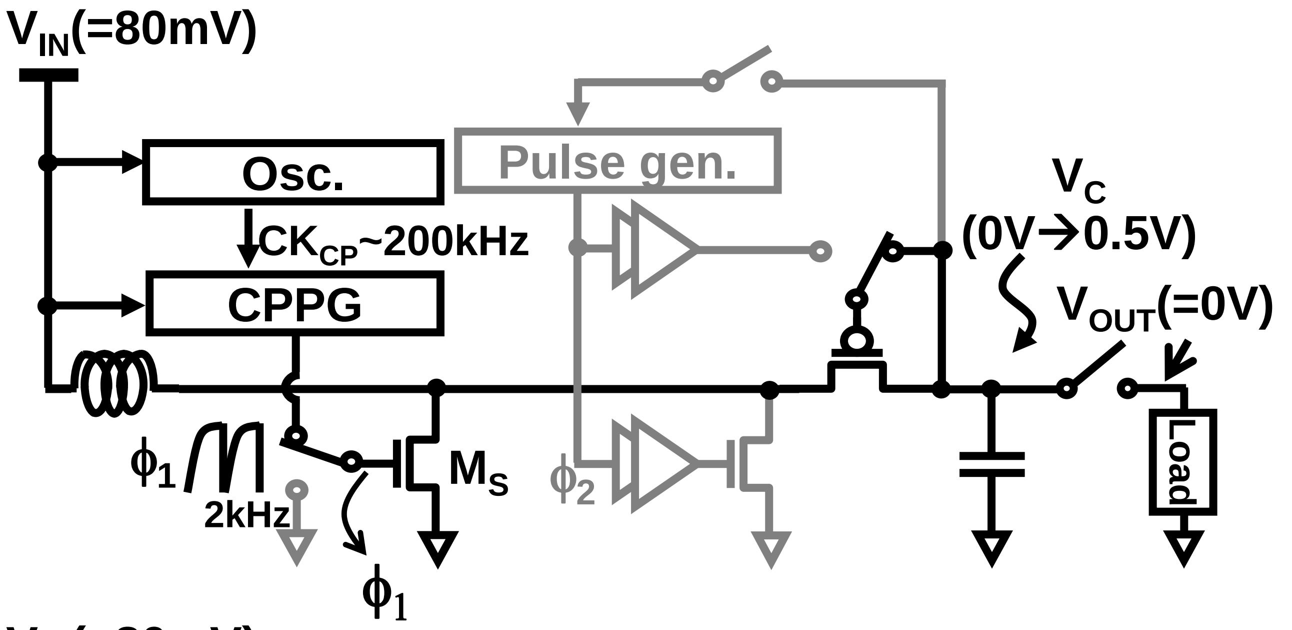
(2) Charge pumped pulse generator (CPPG)

(3) V_{TH}-tuned Osc. by DC stress

Dual Modes Operation

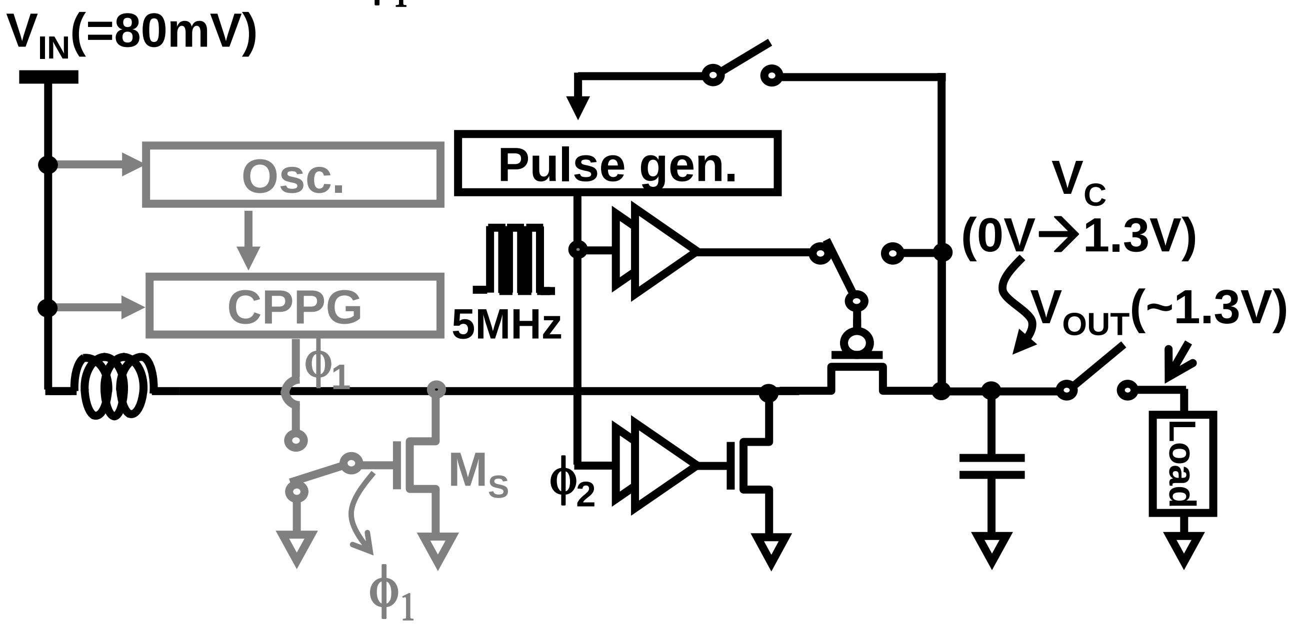
Startup mode

The system is kick-started by CPPG.

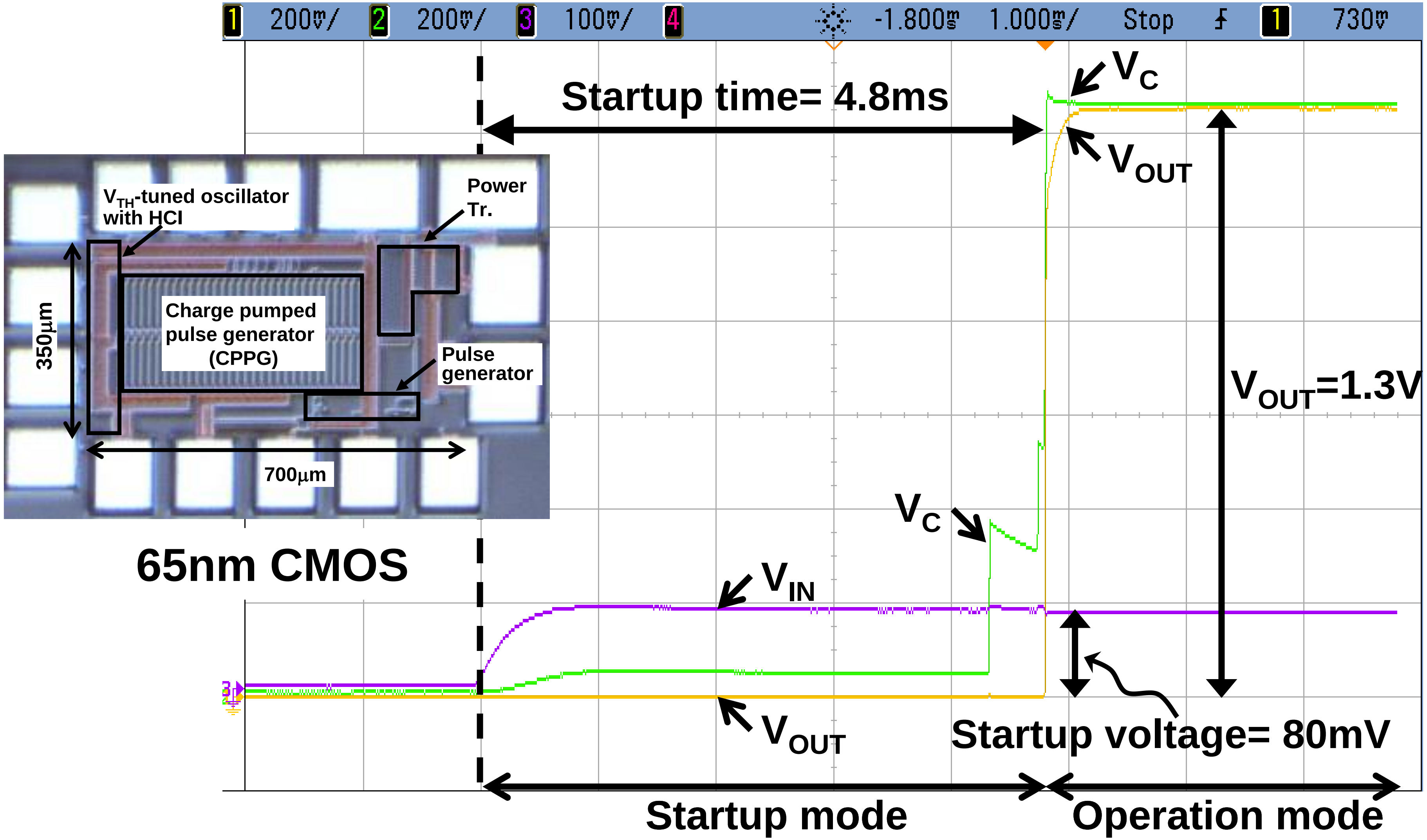


Operation mode

The power transistors are driven by output voltage for high efficiency.



Measured Boost Waveforms



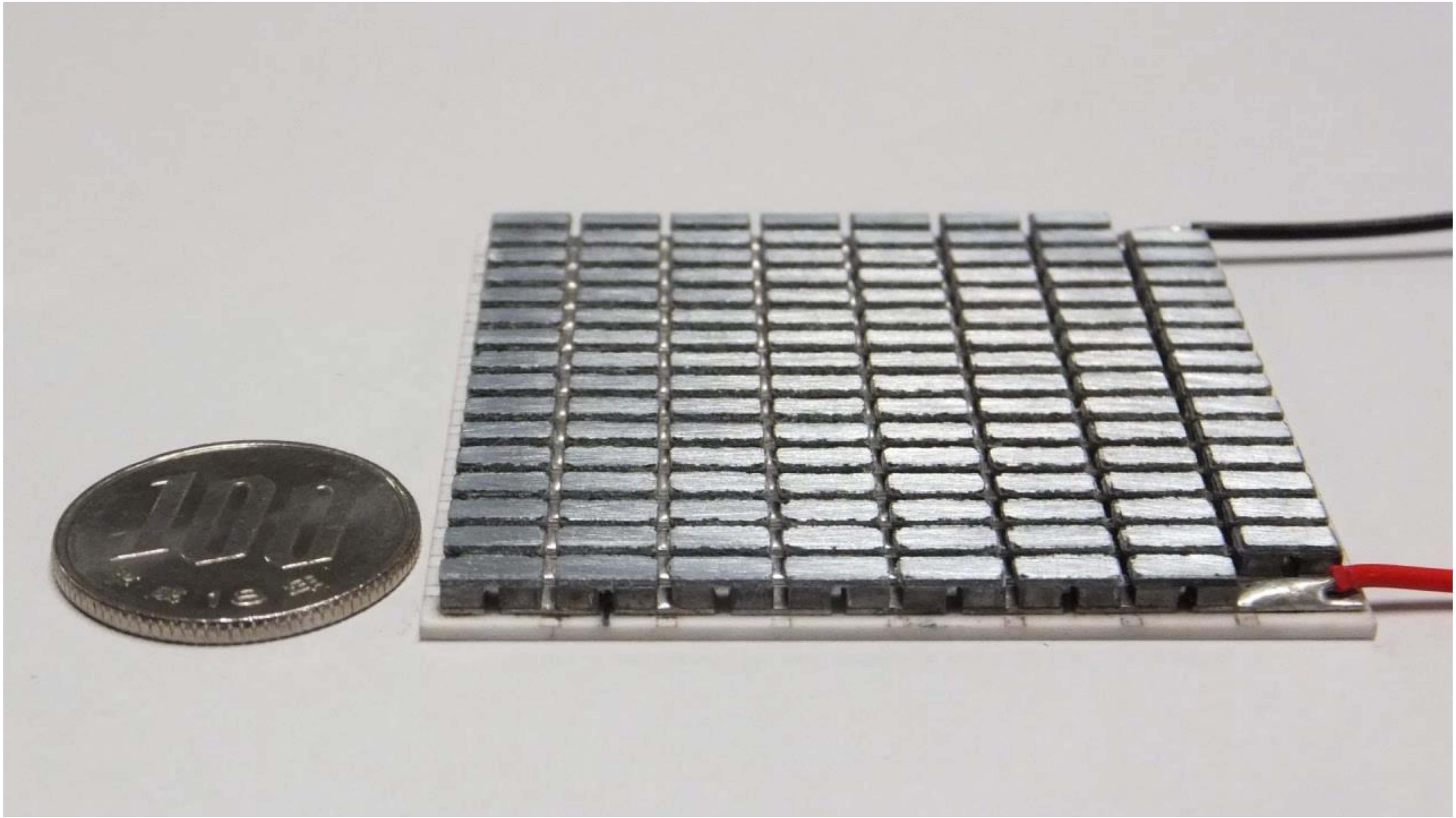
The step-up converter successfully startups from 80-mV V_{IN} with 4.8ms startup time.

P. -H. Chen, et al., A-SSCC 2011

Comparison of Startup Converter

Ref	Startup			Peak Efficiency	Program time for Osc.	CMOS process
	Mechanism	*Min. Voltage*	*Startup time*			
[3]	Boost with mechanical switch	35mV	18ms	58%@ V_{IN}=50mV	–	350nm
[4]	External Voltage	650mV	N/A	75%@ V_{IN}=100mV	–	130nm
[5]	Charge pump	95mV	262ms	72%@ V_{IN}=100mV	60min	65nm
This work	Boost with CPPG	80mV	4.8ms	60%@ V_{IN}=80mV	3min	65nm

Energy Harvesting from Thermoelectric Generator



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Multi-Layered Ceramic Capacitor (MLCC)

IVRs for Energy Efficient CPUs

Integrated Voltage Regulator (IVR)

Problems in CPU → **Solution by IVR**

Problems in CPU

(1) Increase of power

(2) Reduced V_{DD}
➔Circuits are sensitive to V_{DD} noise.

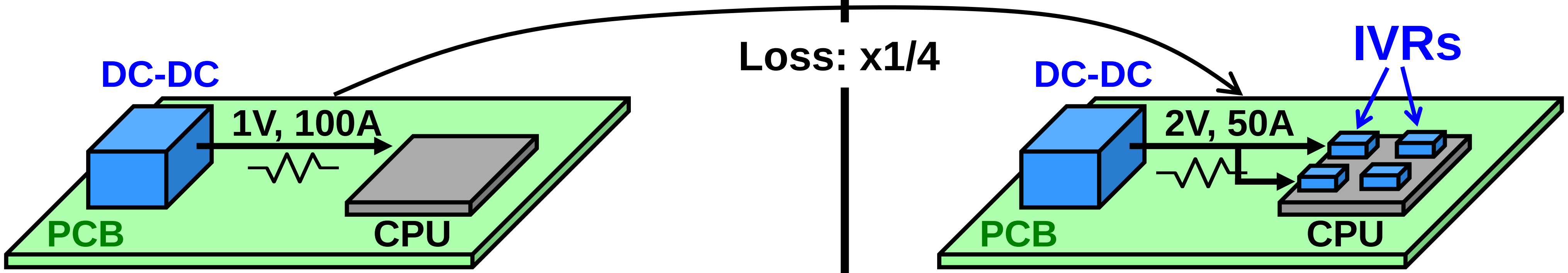
(3) Large I_{DD}
➔RI^2 loss on PCB increases.

Solution by IVR

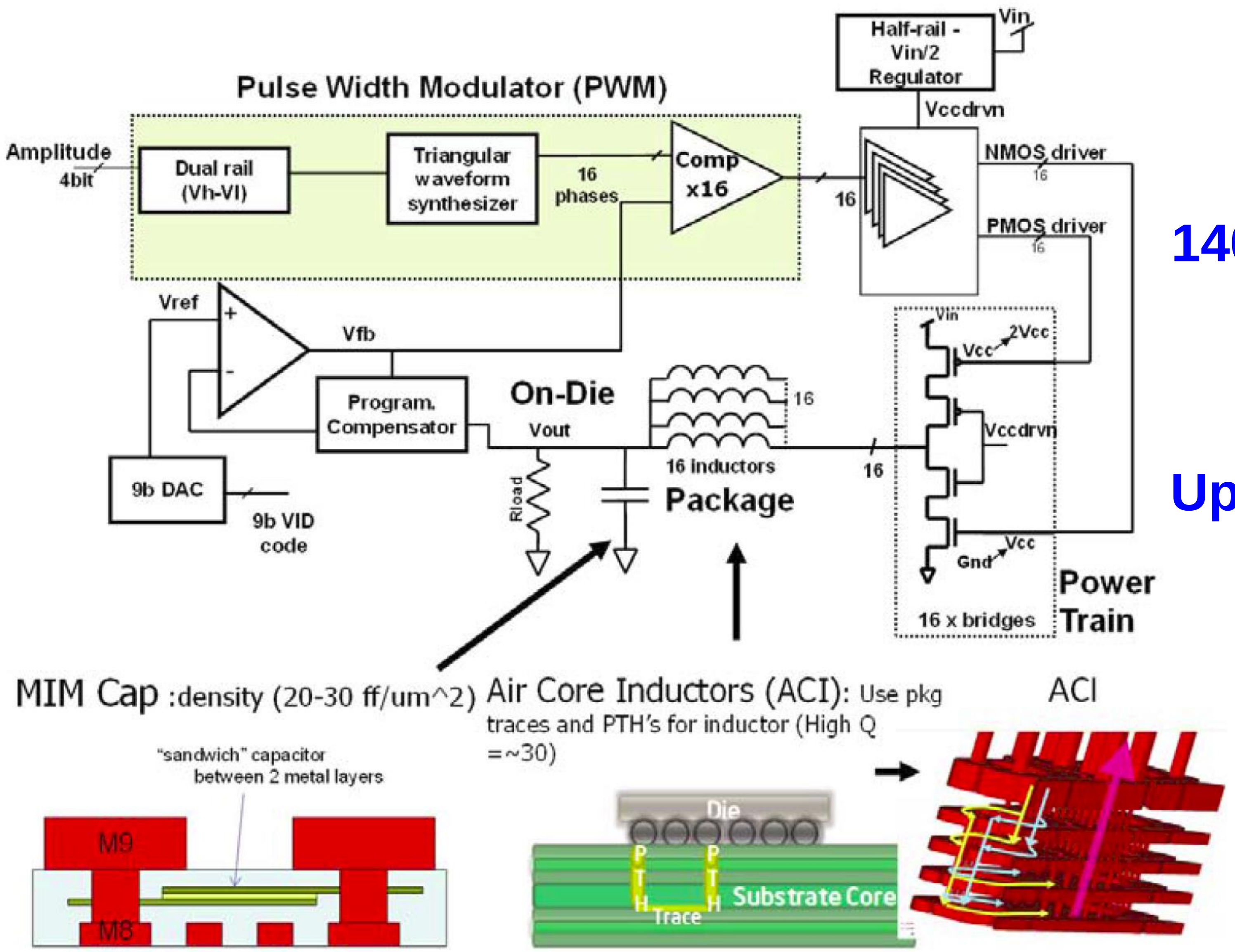
(1) Per-core dynamic voltage scaling
➔Low power

(2) Reduced V_{DD} noise

(3) Reduced I_{DD} on PCB
➔Reduced RI^2 loss



Integrated Buck Converter (Haswell)

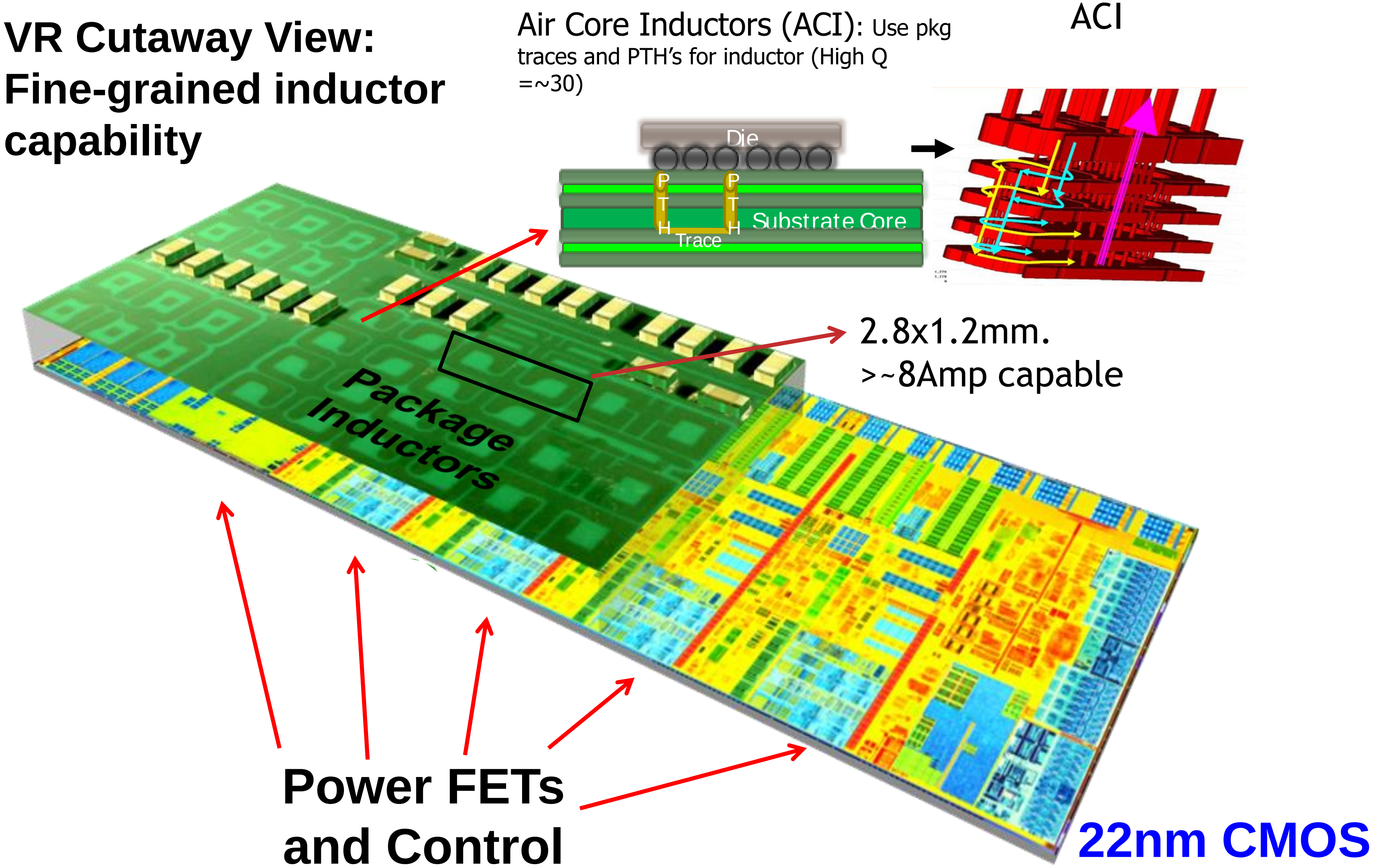


140MHz switching

Up to 16-phase

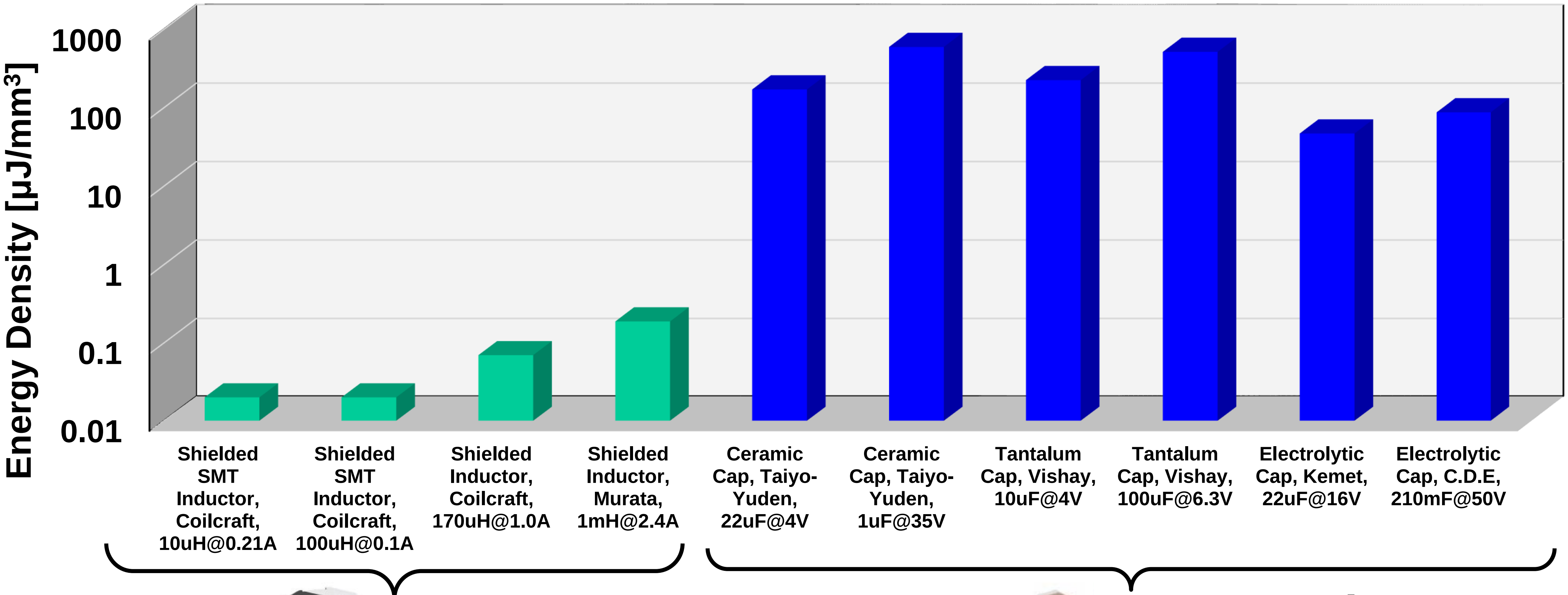
N. Kurd *et al.*, "Haswell: A Family of IA 22nm Processors," IEEE ISSCC, pp. 112-113, 2014. (Intel)

Inductors on PCB and On-die Capacitors



J. Douglas, "Fine-Grained Power Management Using Integrated DC-DC Converters," Short Course in IEEE Symposium on VLSI Circuits, 2014. (Intel)

Inductors vs. Capacitors



Inductor

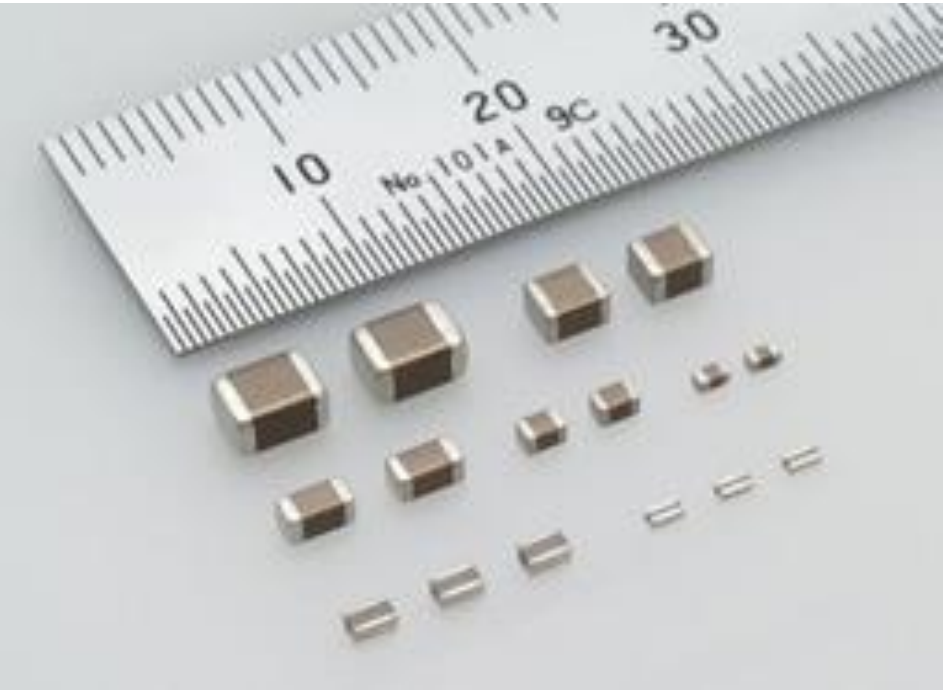
Capacitor

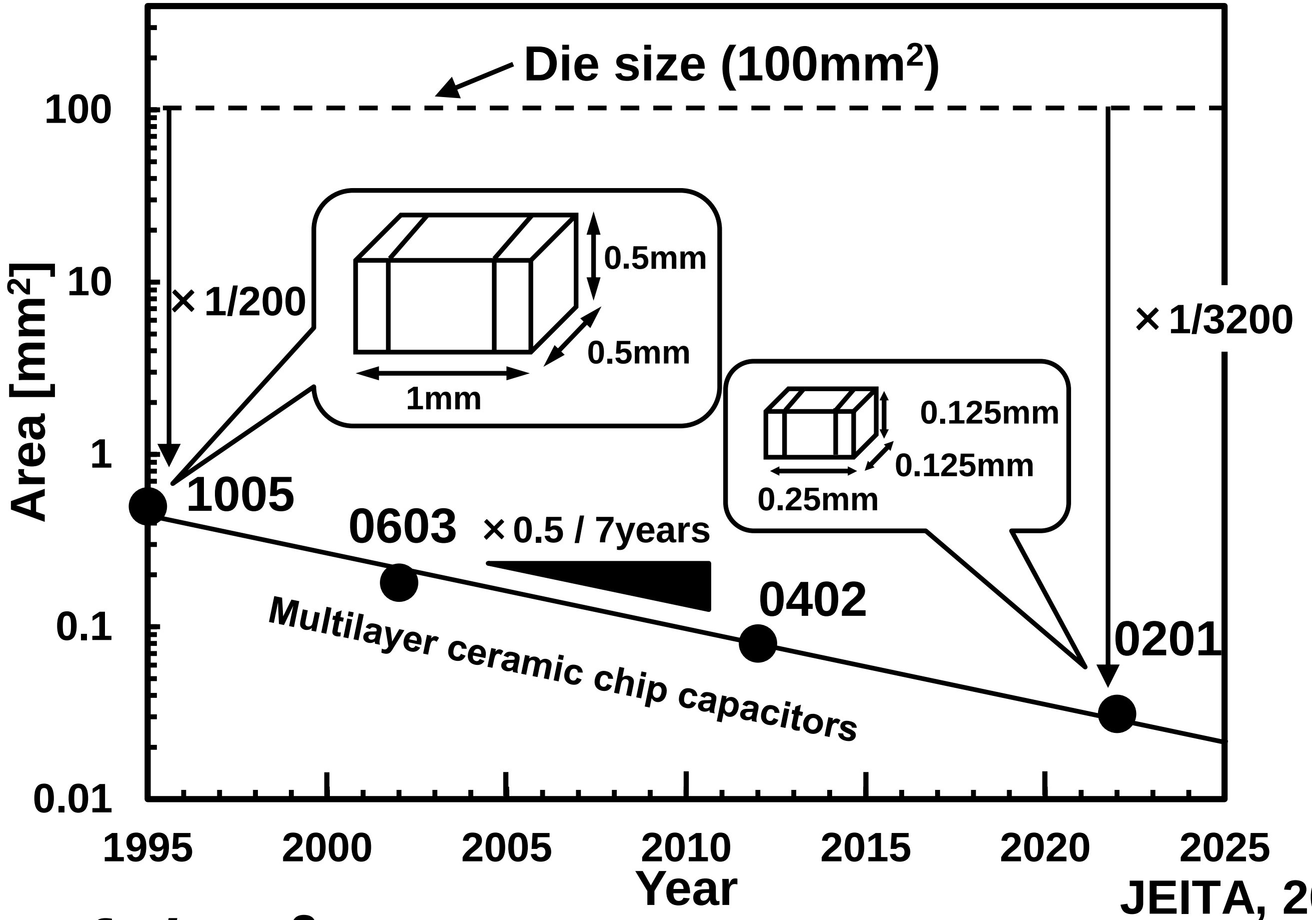
High energy density of capacitors than inductors.

S. Sanders *et al.*, TPEL 2013

Scaling of MLCCs

Multi-Layered Ceramic Capacitor (MLCC)



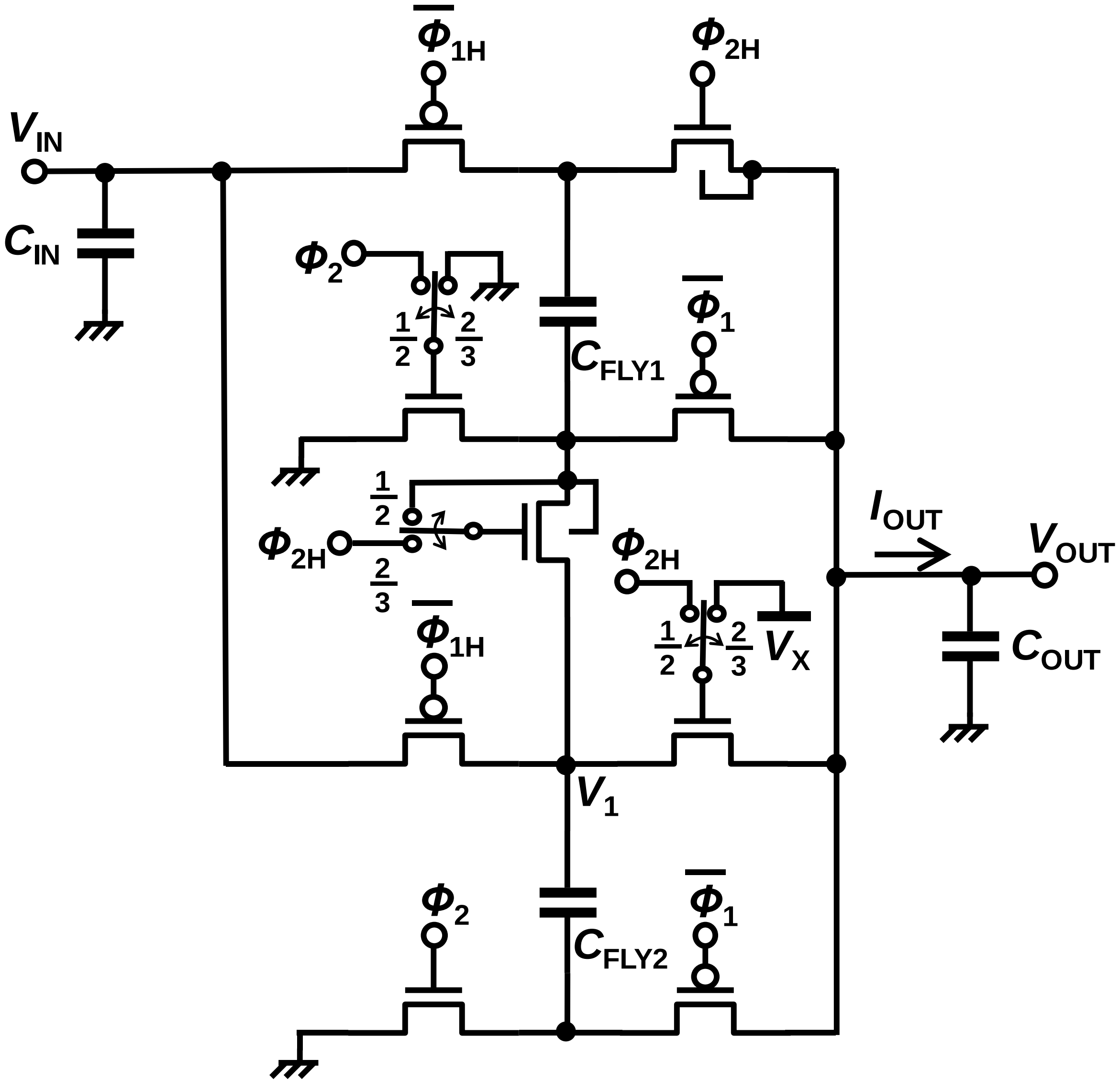


JEITA, 2015

0402 MLCC = 100nF ➔ 1250fF/μm²

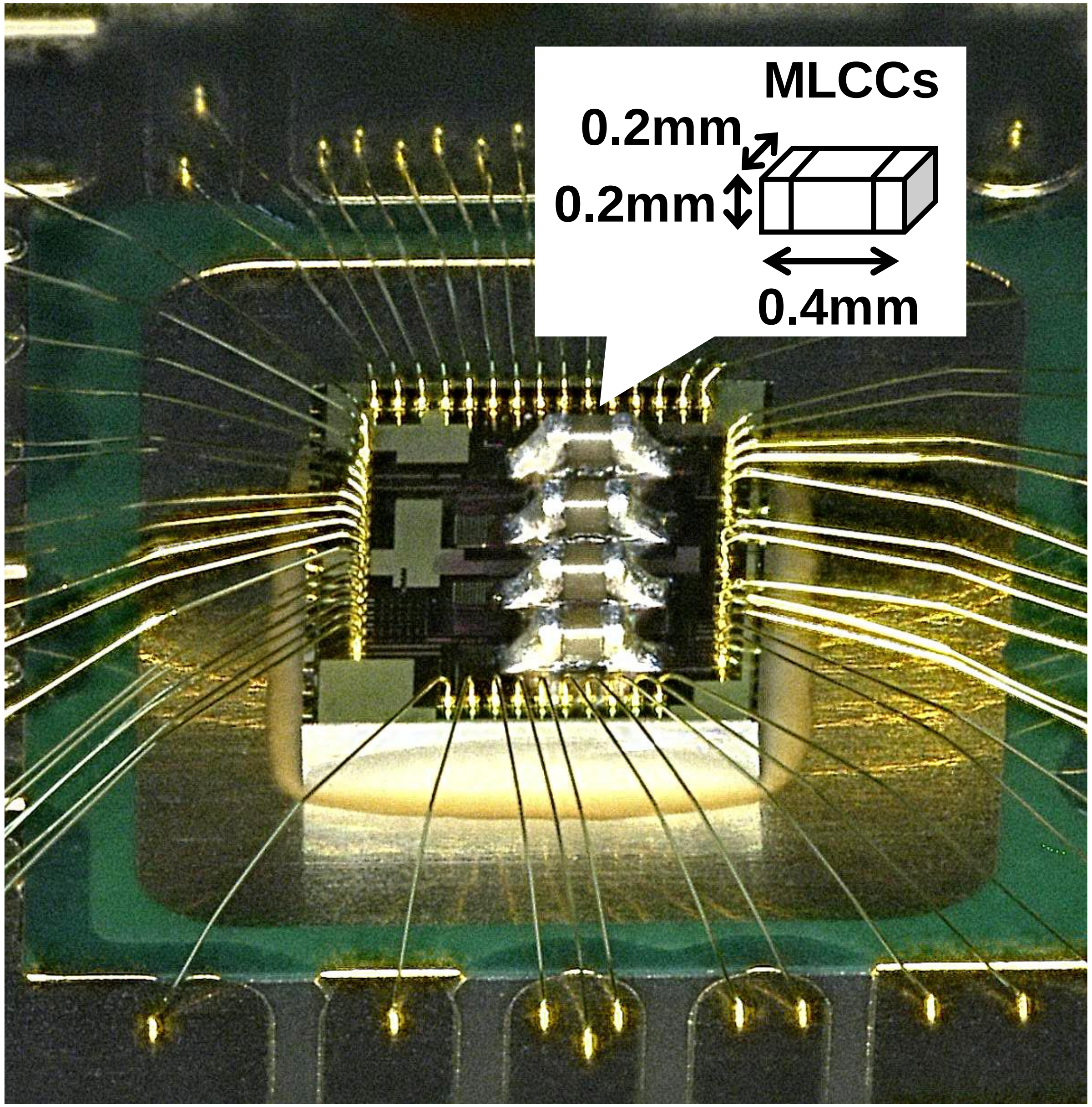
(e.g.) MIM 1-10fF/μm², MOS 10-20fF/μm², Deep Trench 200fF/μm²

Switched Capacitor (SC) DC-DC Converter



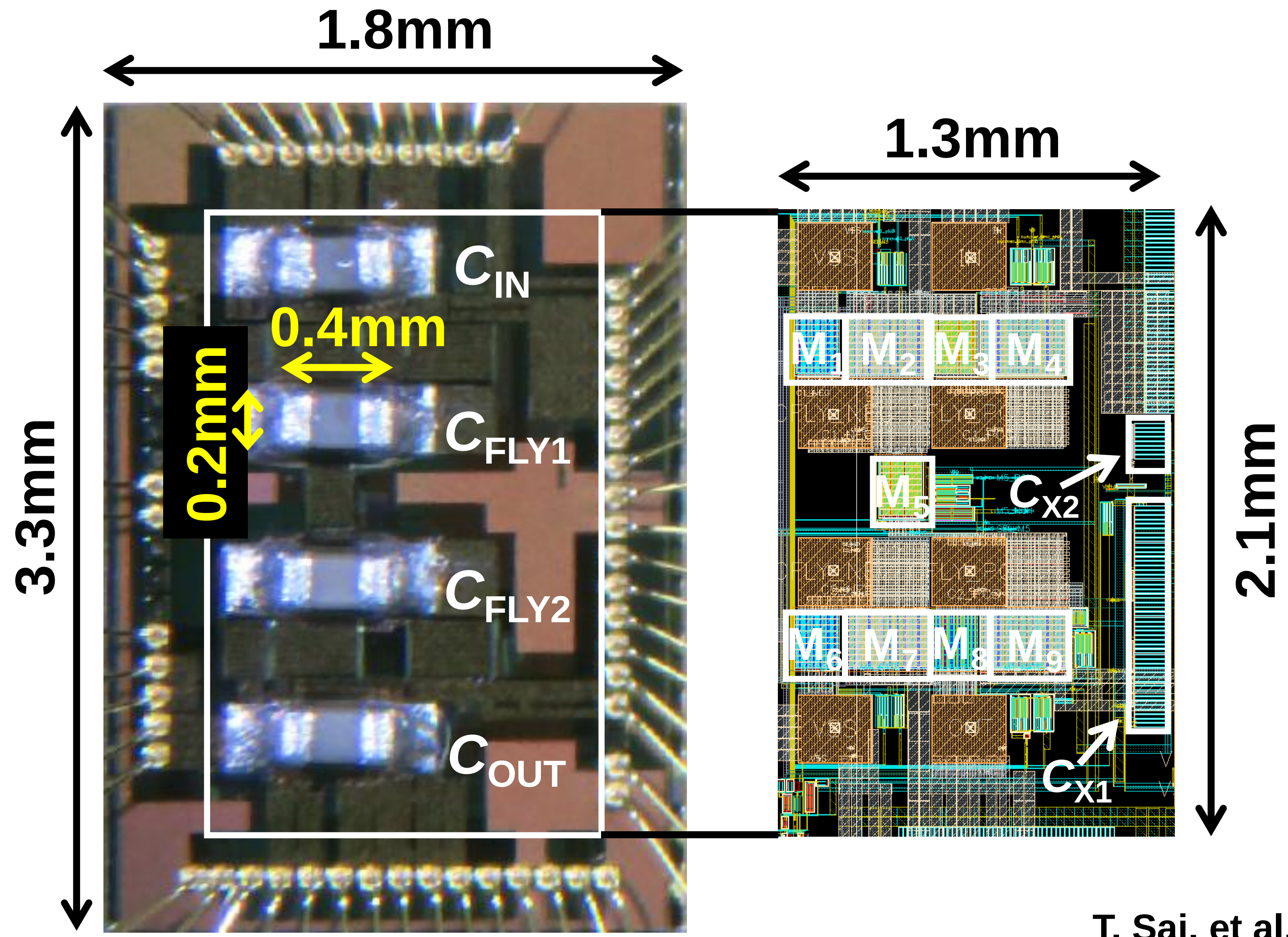
Technology	180nm bulk
Conversion ratio	2/3, 1/2
V_{IN}	2.7V
V_{OUT}	1.1V – 1.75V
P_{OUT} @ η_{MAX}	171mW
η_{MAX}	92.9%
Die area	2.73mm²
Capacitors	Off-chip MLCC x 4
C_{FLY}	100nF x 2
Power density (mW/mm²) @ η_{MAX}	62

Fabricated SC DC-DC Converter in 180nm



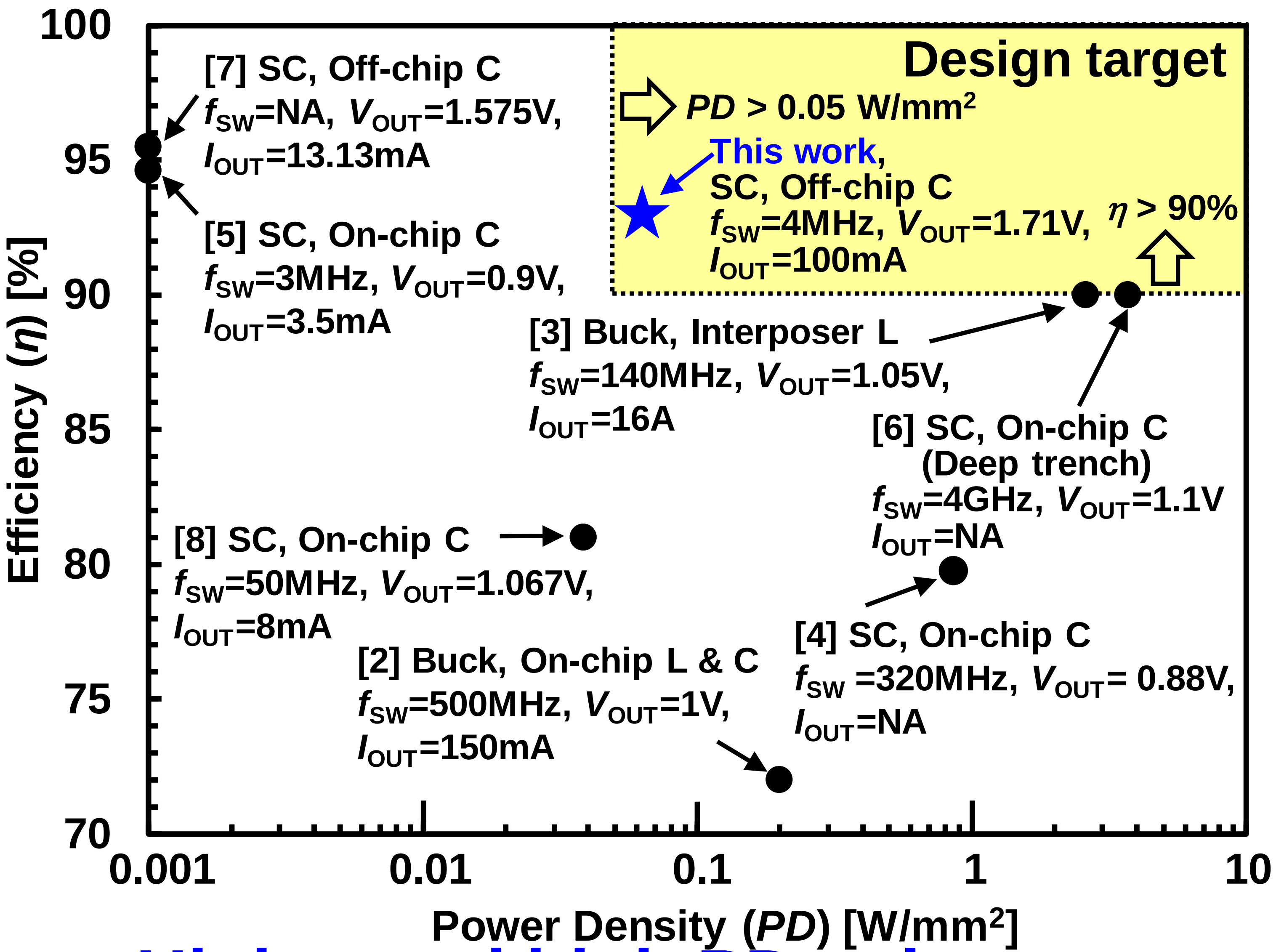
2.7-V input SC DC-DC converter mounting four 100-nF 0402 MLCCs on 180-nm CMOS die

Fabricated SC DC-DC Converter in 180nm



T. Sai, et al., IEEE TCAS II, 2018

Comparison in Step-down DC-DC Converters



High η and high PD at low-cost

Summary

- Integrated power management circuits for energy-efficient IoT systems
- Gate boosting for low V_{IN} DC-DC converters
- Clocked comparator for low I_{OUT} buck converter
- Integration of MLCCs on die for SC DC-DC converter