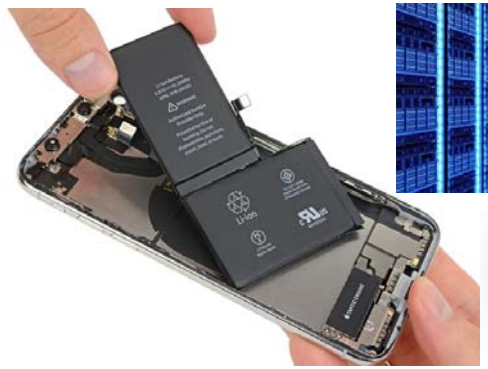
Hybrid Converters for Mobile and IoT Applications

Patrick Mercier
University of California, San Diego

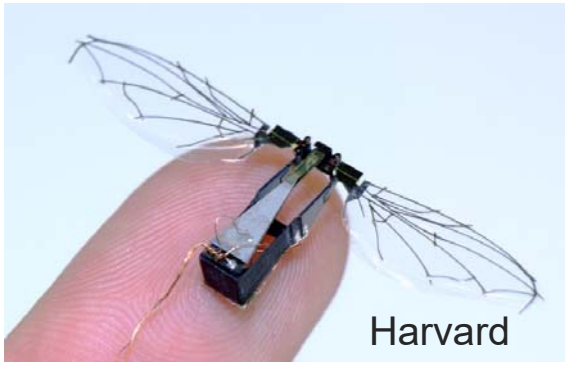
Power Management Research Focus Areas

High Power Density Hybrid Converters:
Mobile phones, data centers, automotive



RF Power Amplifiers
5G, Wi-Fi 6, Long Range IoT

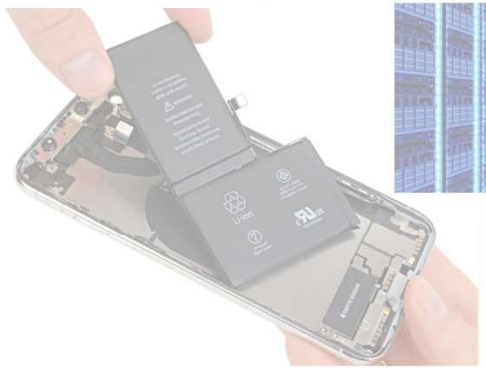

Integrated High-Voltage Conversion
Microrobotics, Neural Implants

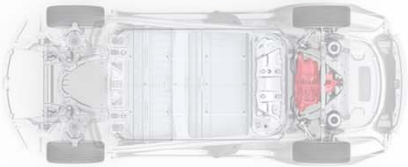


Wide Dynamic Current Range Converters
IoT, Wearables

Power Management Research Focus Areas

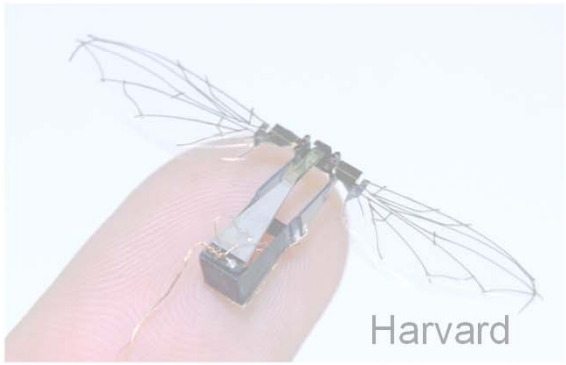
High Power Density Hybrid Converters:
Mobile phones, data centers, automotive

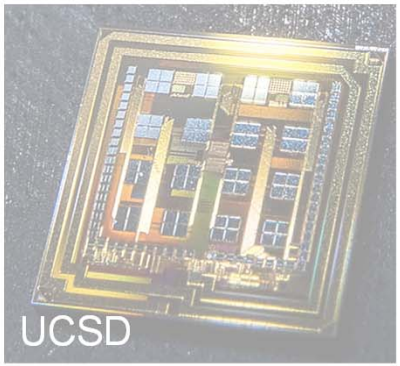




RF Power Amplifiers
5G, Wi-Fi 6, Long Range IoT

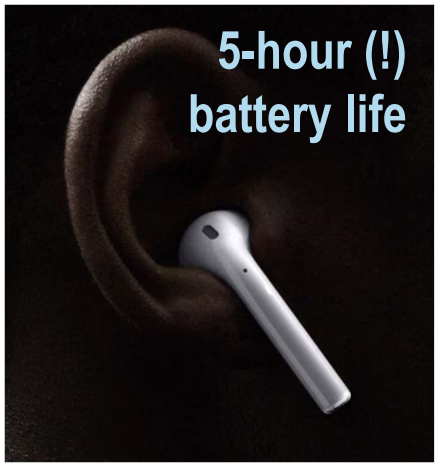

Integrated High-Voltage Conversion
Microrobotics, Neural Implants





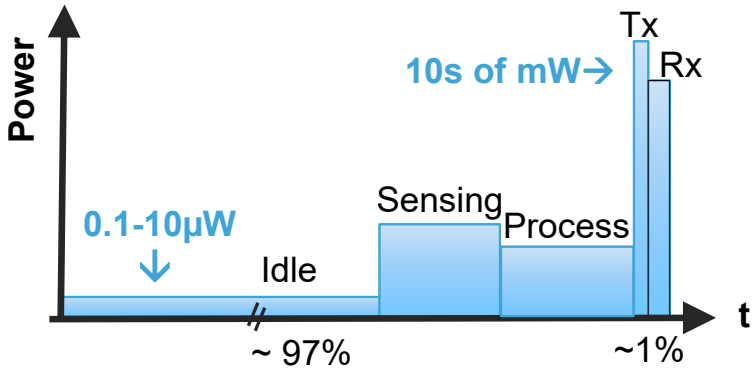
Wide Dynamic Current Range Converters
IoT, Wearables

Major limiter in IoT devices: battery size / battery life



Challenge: Not a lot of room for large passives/converters

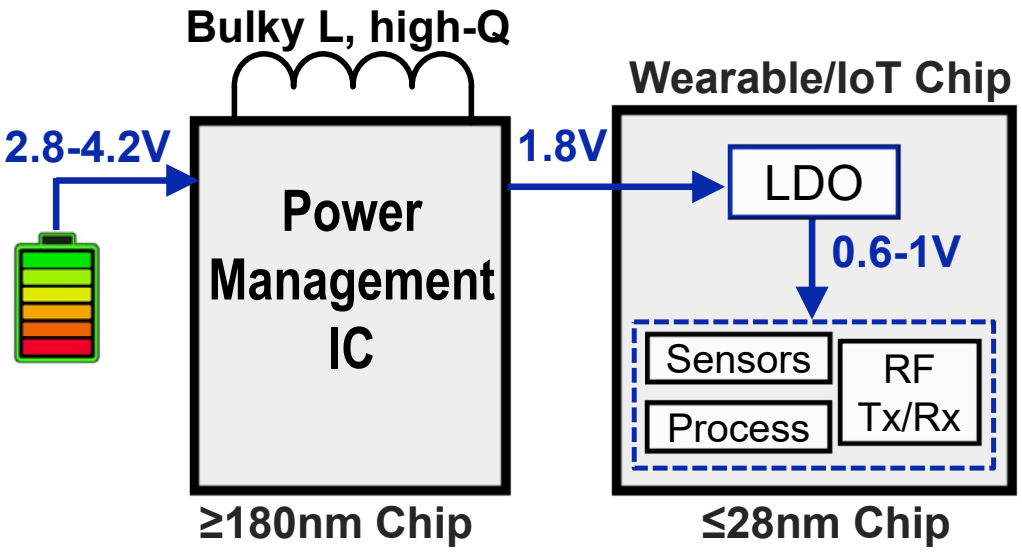
Challenge: Require high efficiency over 1,000,000x dynamic range



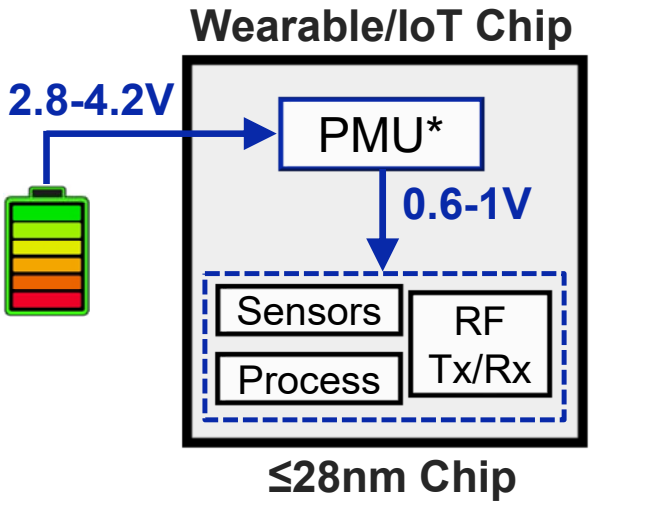
Research goal:
Simultaneously increase efficiency *and* power density over a wide dynamic range

Powering IoT and Wearables in Scaled-CMOS

Conventional



Goal

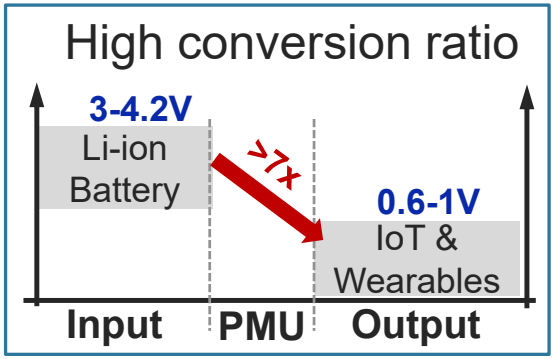


PMU*: Power Management Unit
with or without off-chip inductor

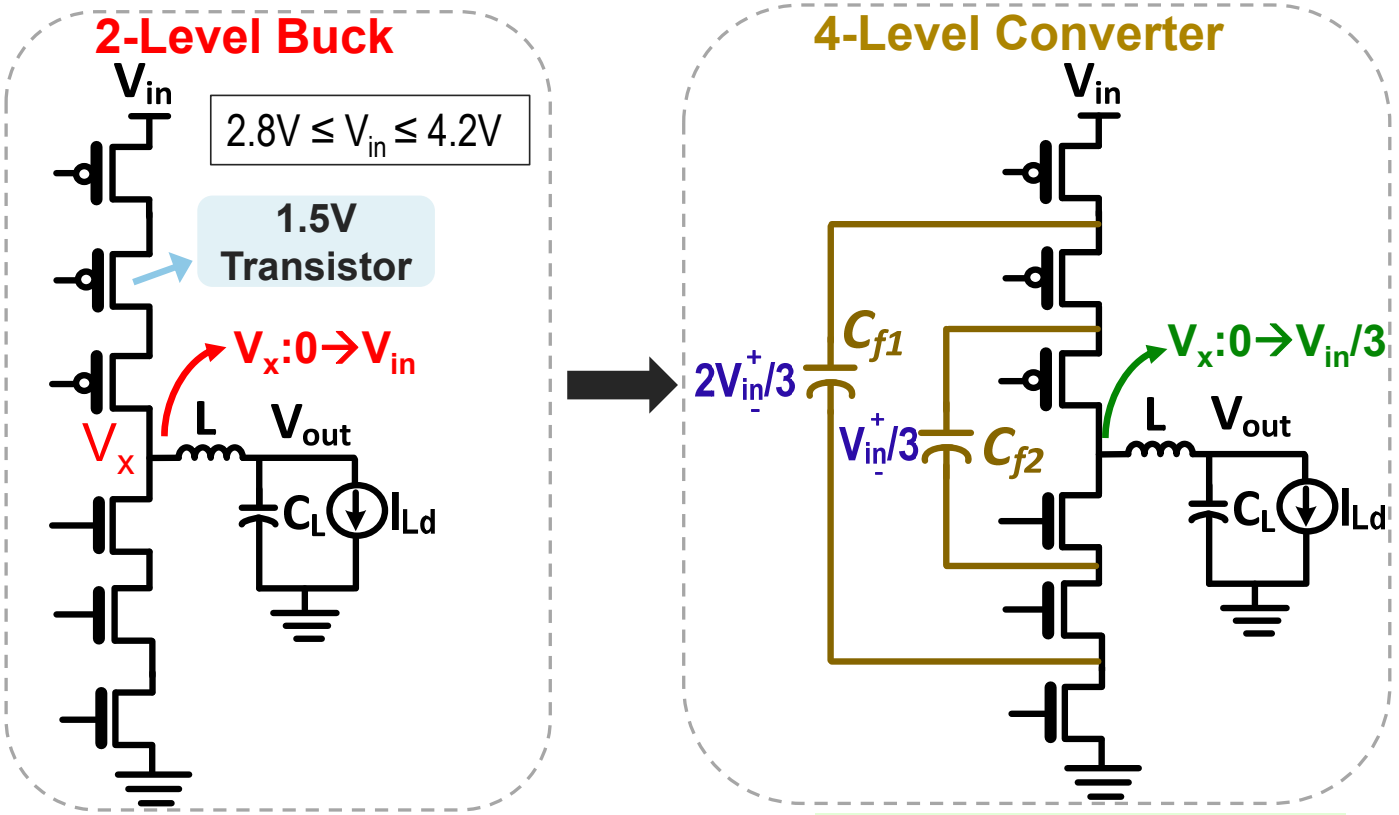
Li-ion Fully-Integrated PMU Challenges in 28nm FDSOI

Scaled-CMOS Challenges

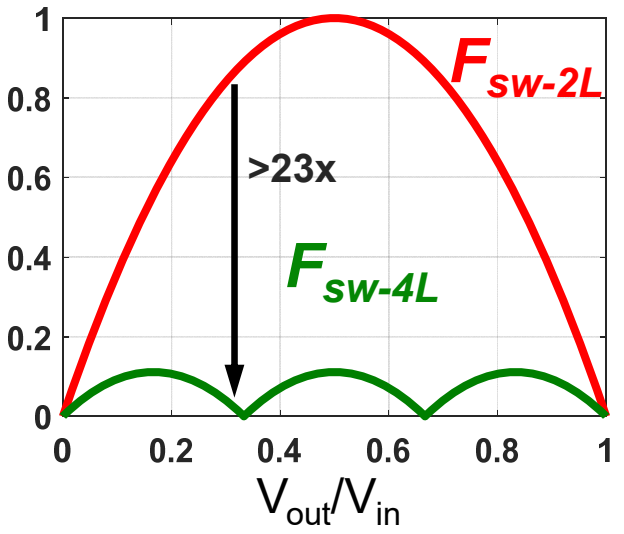
- Only Low-V transistors available
  - Transistors stacking required
    - High switching & conduction losses
    - Complex power-hungry drivers
    - Many level shifters
  - **Poor efficiency**
- Only Low-V capacitors available
  - Capacitors stacking required
    - Large area
  - **Low power density**
- Poor quality on-chip passives
  - Large ESR, parasitic cap
  - Low density
  - **Poor efficiency**
  - **Low power density**



Towards Fully-Integrated Li-ion PMU in Scaled CMOS



DCM-operated
Constant I_{pk}
Normalized Switching Frequency



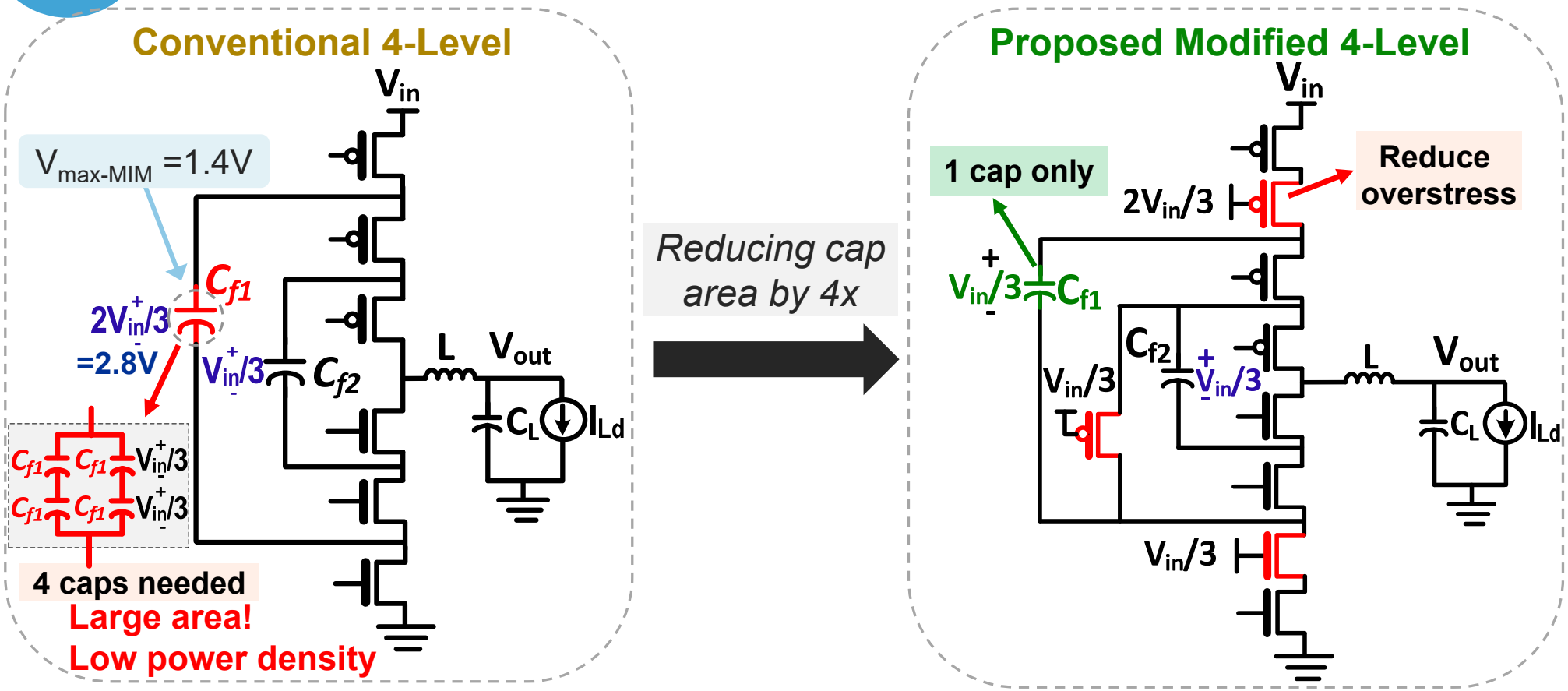
$$\frac{F_{sw\_4L}}{F_{sw\_2L}} = \frac{1/3 - V_{out}/V_{in}}{1 - V_{out}/V_{in}}$$

Small on-chip L, large ESR
-High Switching & conduction losses
-Poor efficiency

Reduced swing at Vx
F_{sw} reduced by > 23x
& efficiency by up to 33%

S.S. Amin et al., JSSC'19

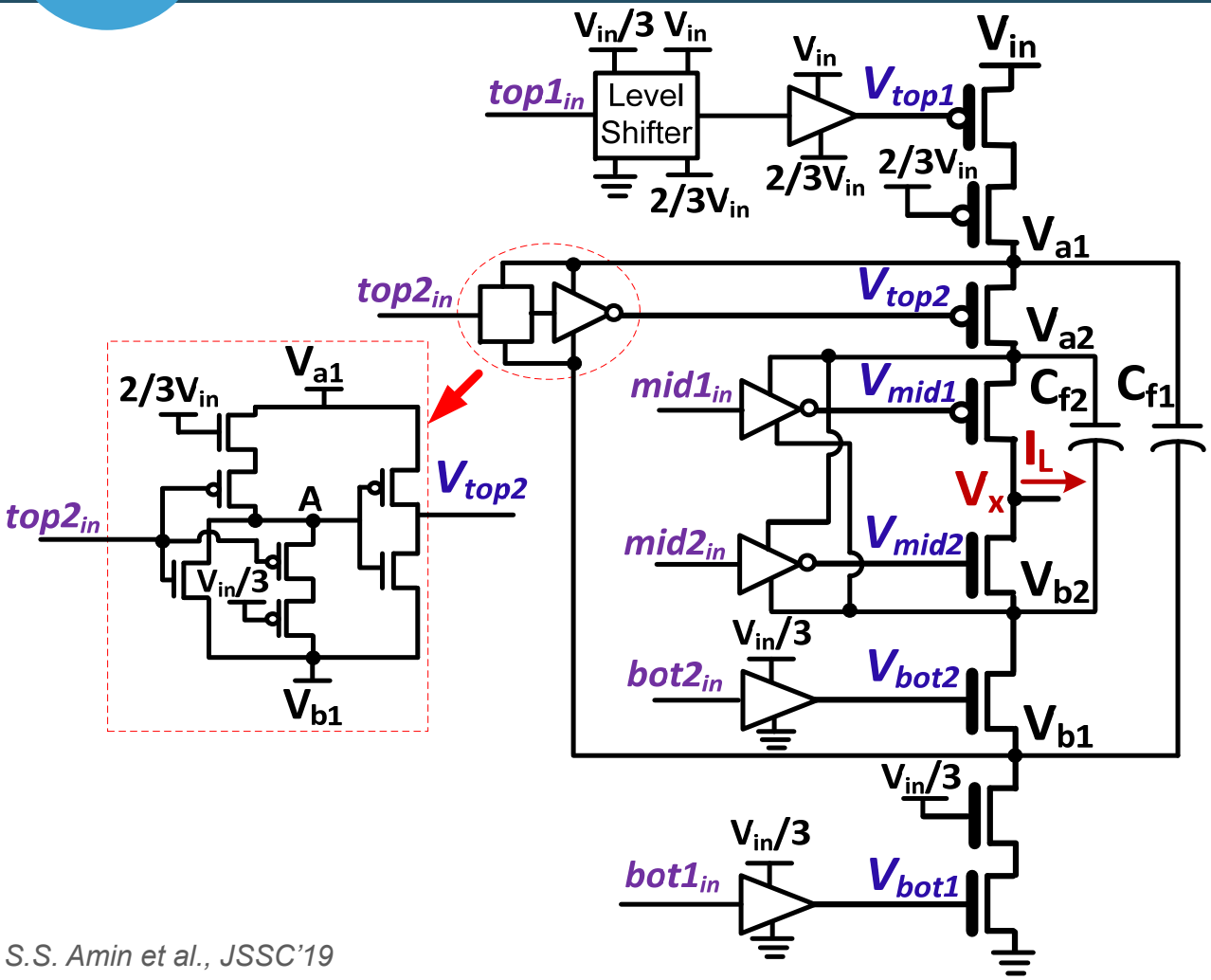
Conventional 4-Level Converter Area Penalty

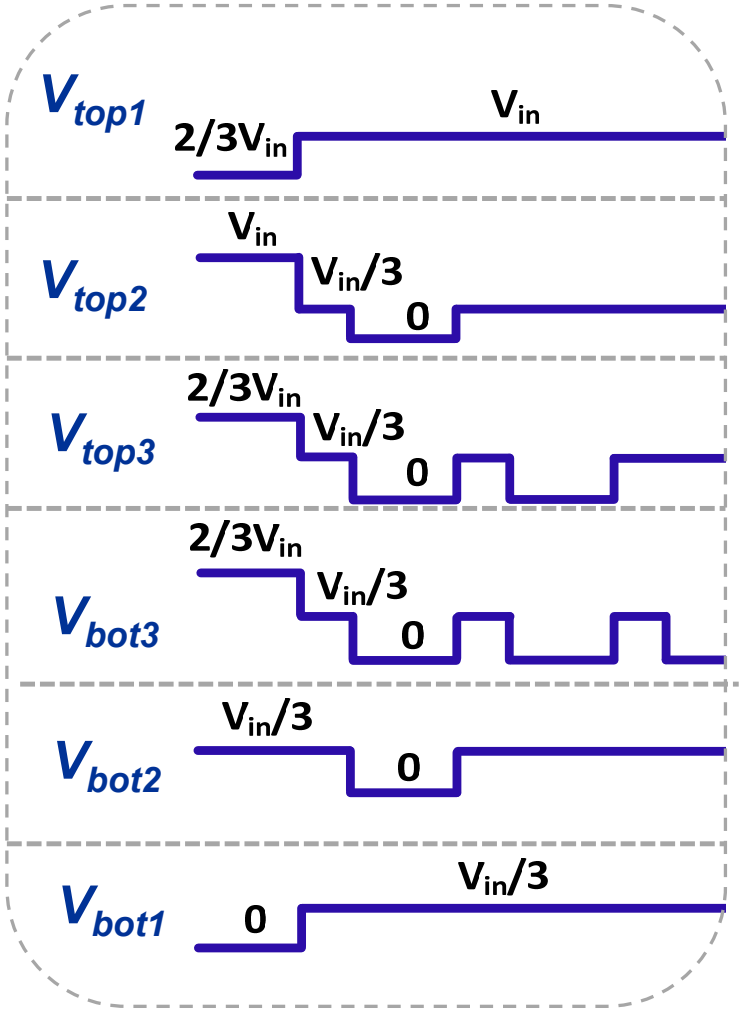


Changing the switching states of flying caps reduces the cap voltage stress

S.S. Amin et al., JSSC'19

Driver Architecture





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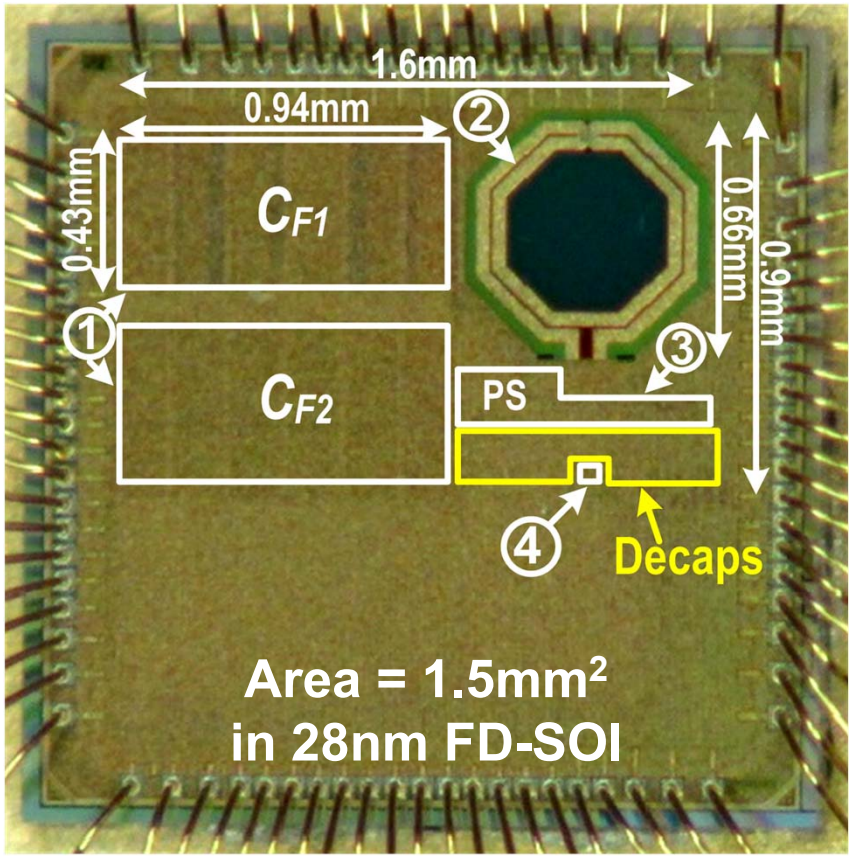
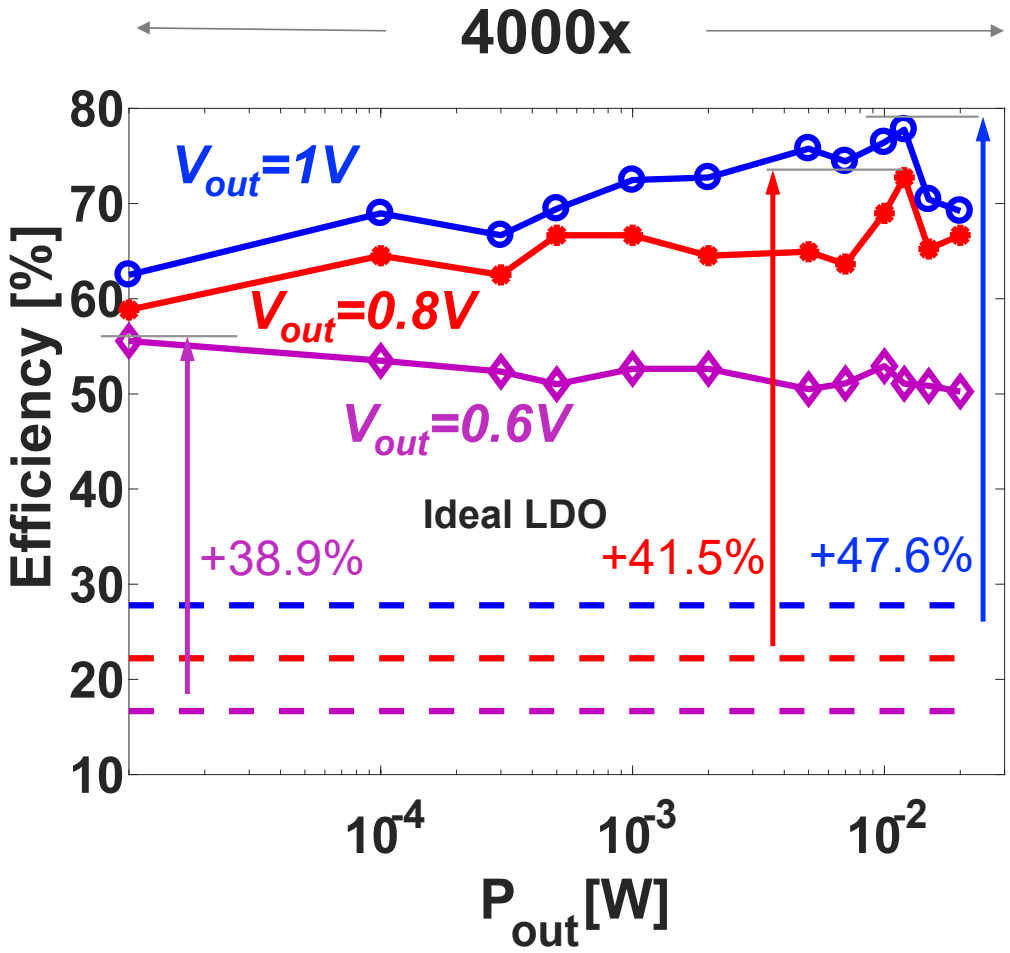
Center for Wearable Sensors

Measurement Results





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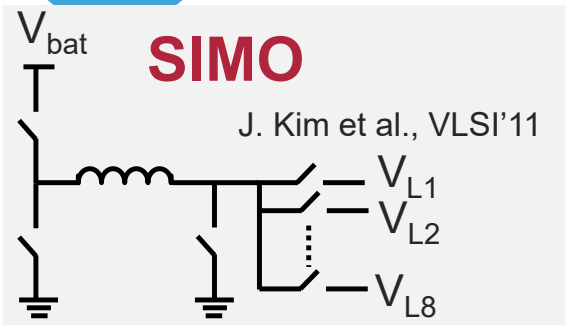
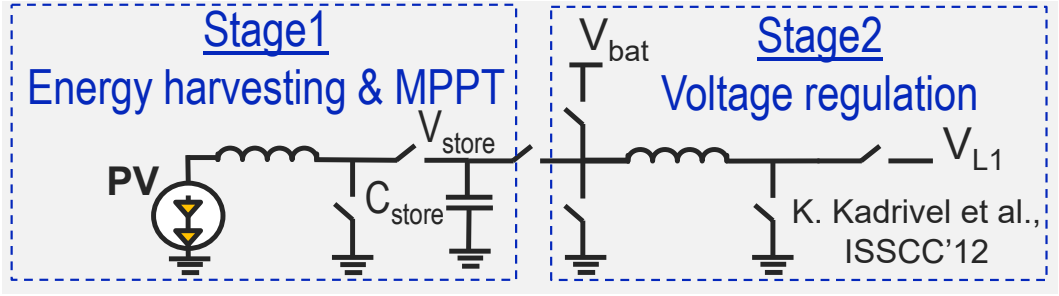
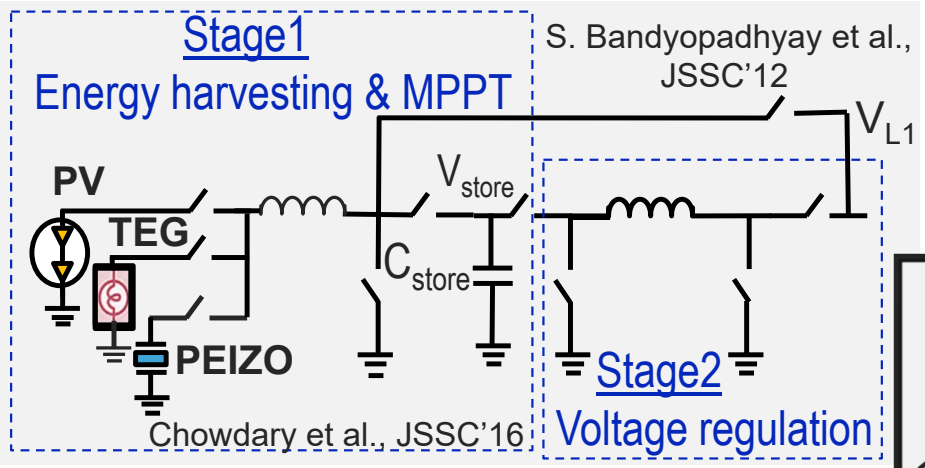
Towards Small Form-Factor Single-Inductor Converters

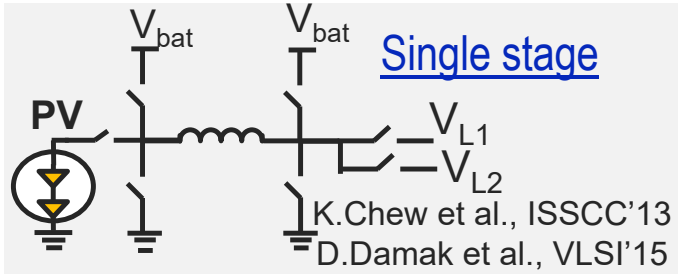




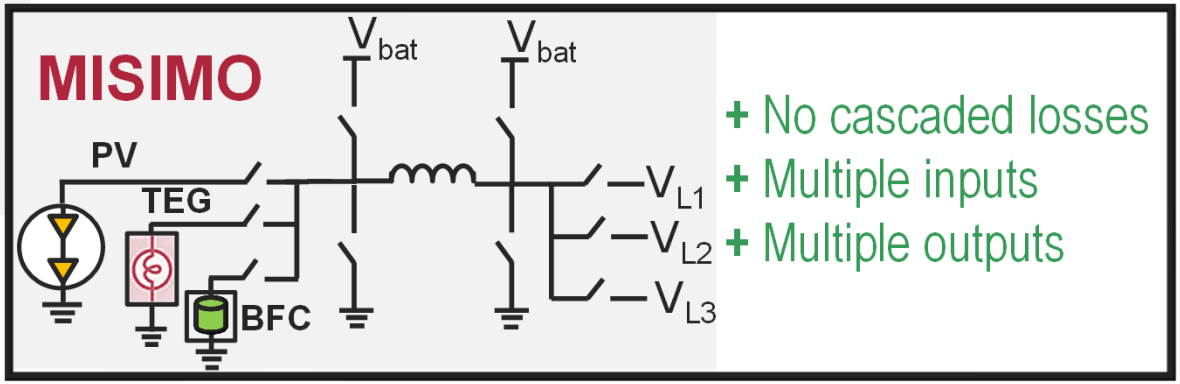
- Single input
- Single output
- Cascaded losses



+ Multiple inputs
- Cascaded losses
- Single output



+ No cascaded losses
+ Multiple outputs
- Single input



+ No cascaded losses
+ Multiple inputs
+ Multiple outputs

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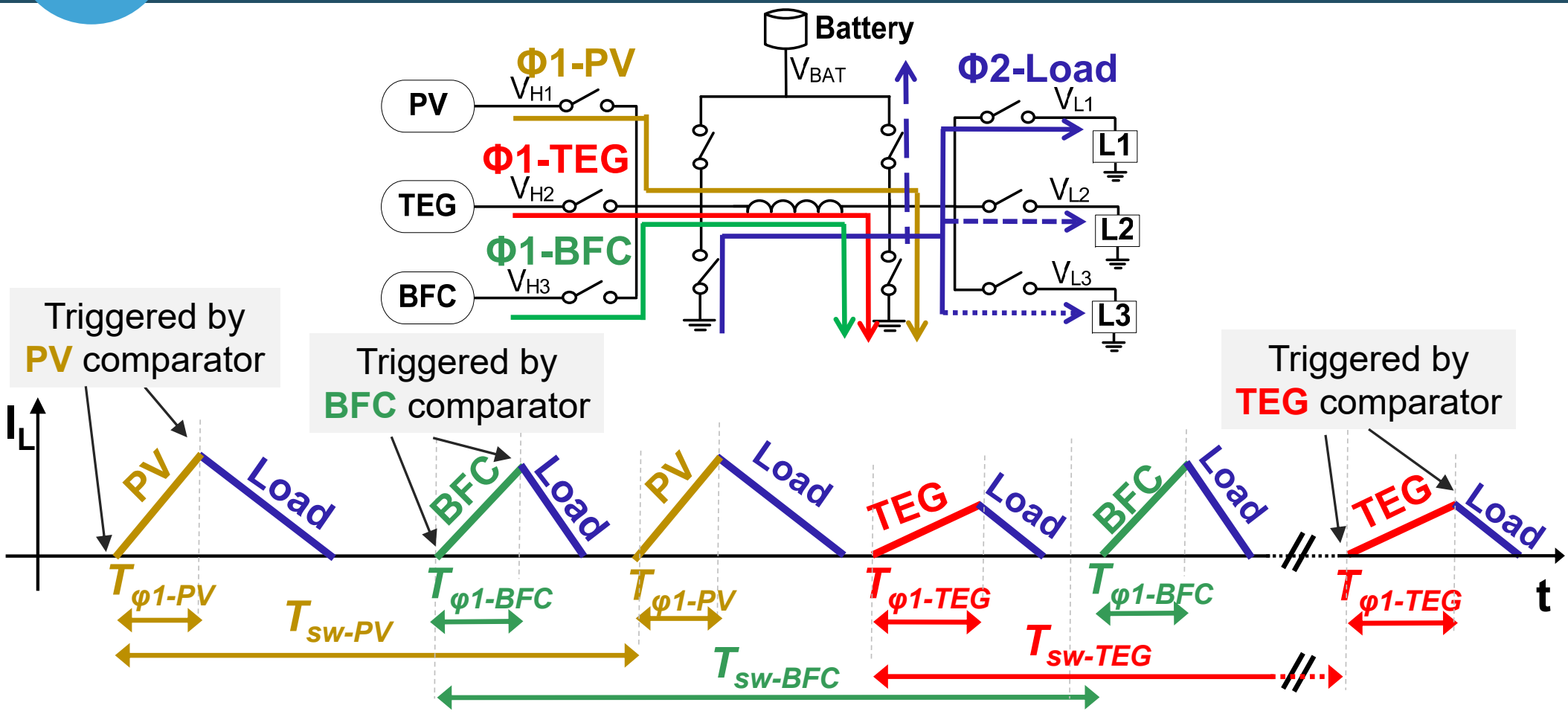
Time-Shared Inductor for Multi-Input Harvesting



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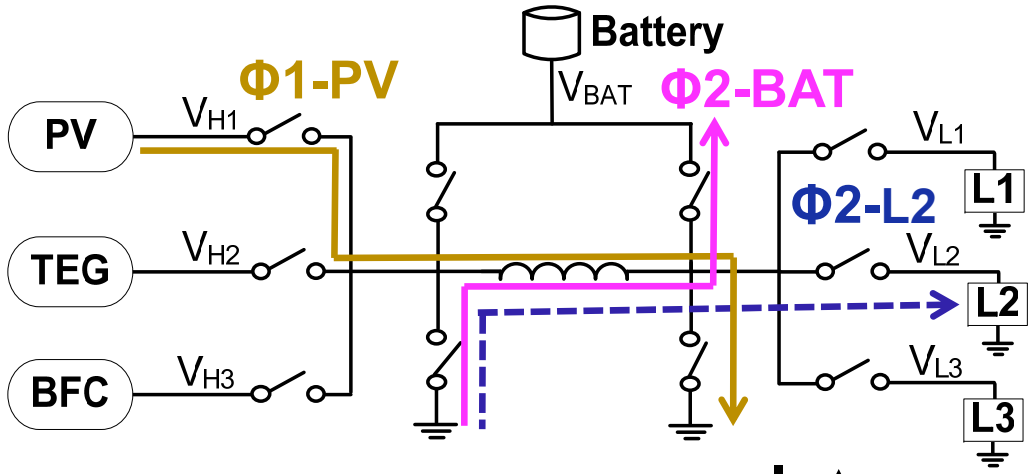
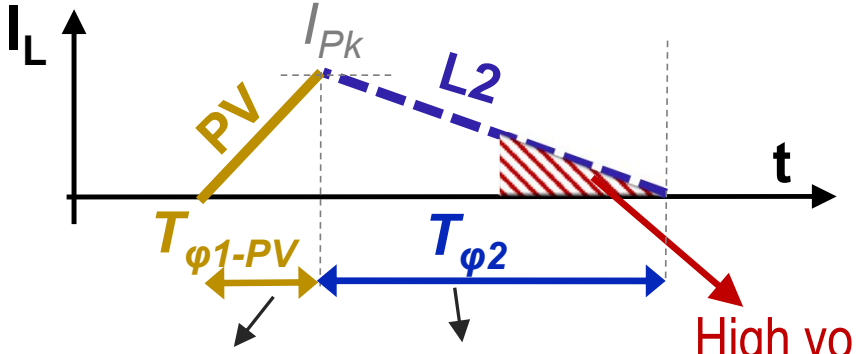
Challenge: decoupling MPPT and Load Regulation





$T_{\varphi 1}$ set for MPPT

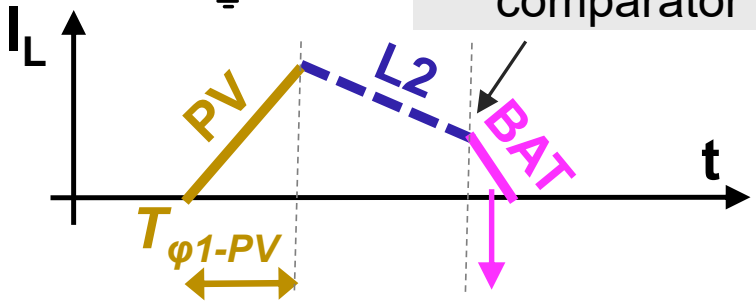
$T_{\varphi 2}$ set by ZCD

High voltage ripple

Degraded load regulation

Trade off in "K. Chew et al., ISSCC 2013"

Proposed



Triggered by load comparator

Extra charge recycled to battery

MPPT & load regulation decoupled

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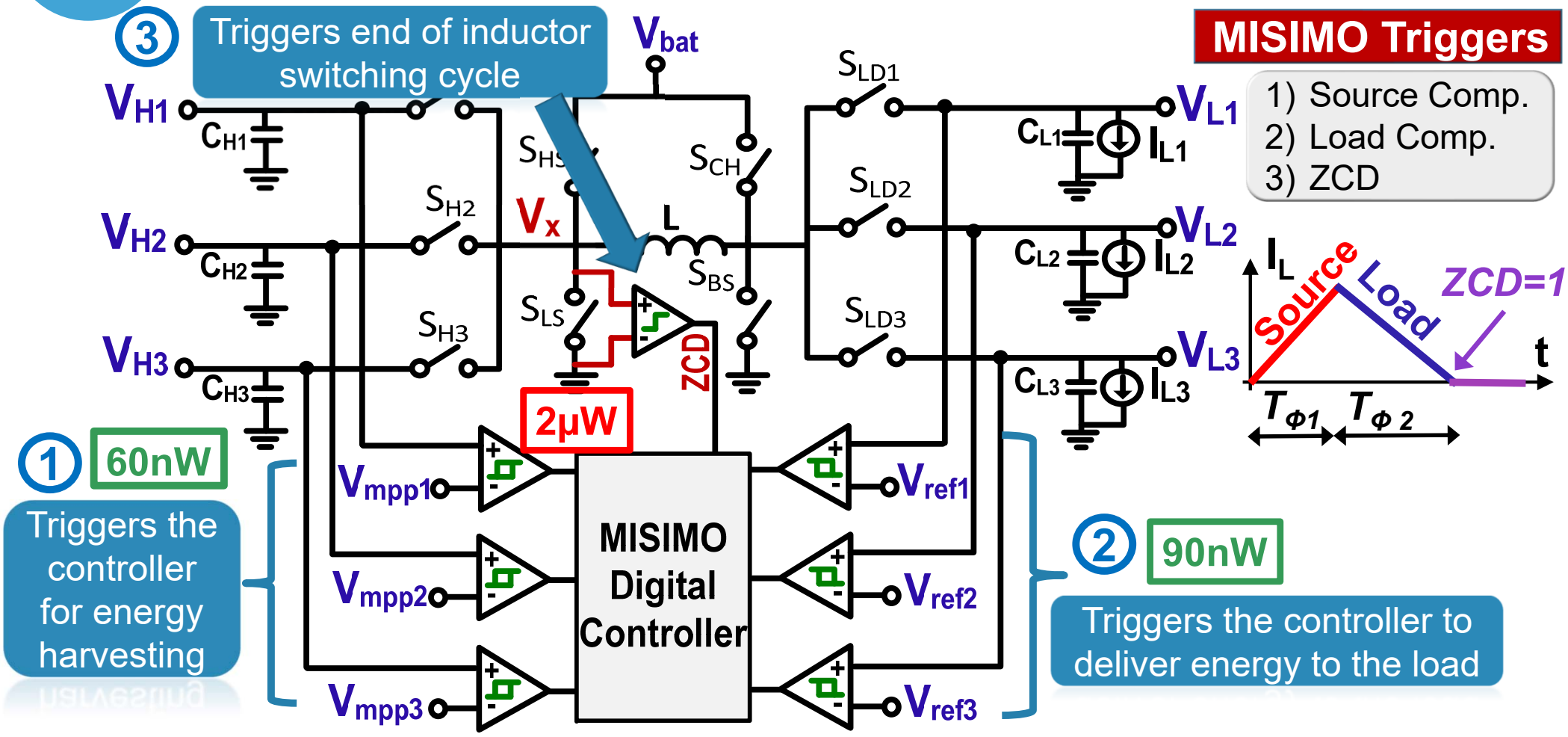
MISIMO Event Driven Controller



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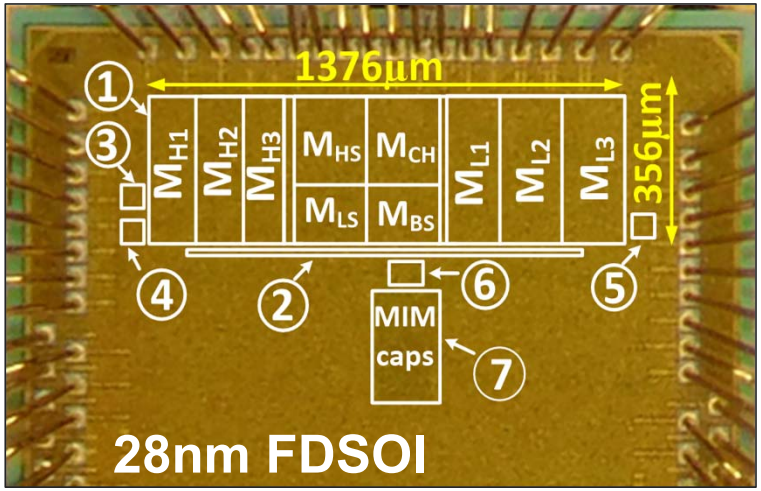
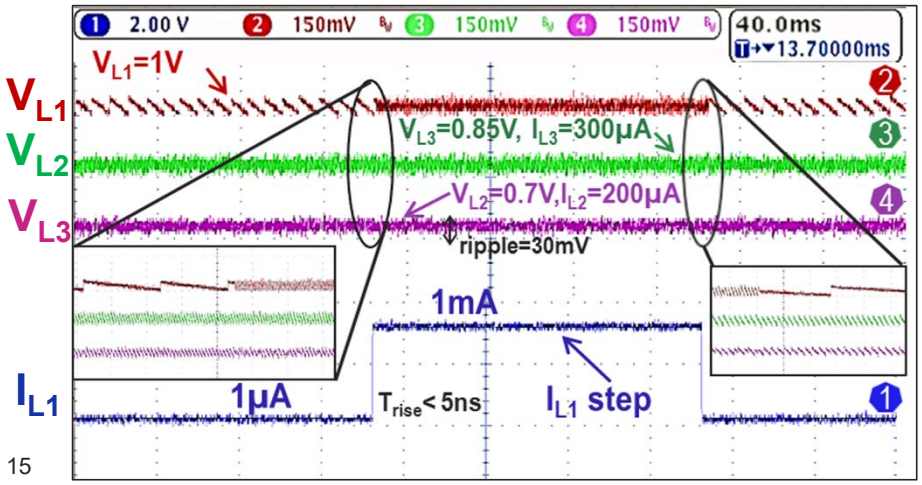
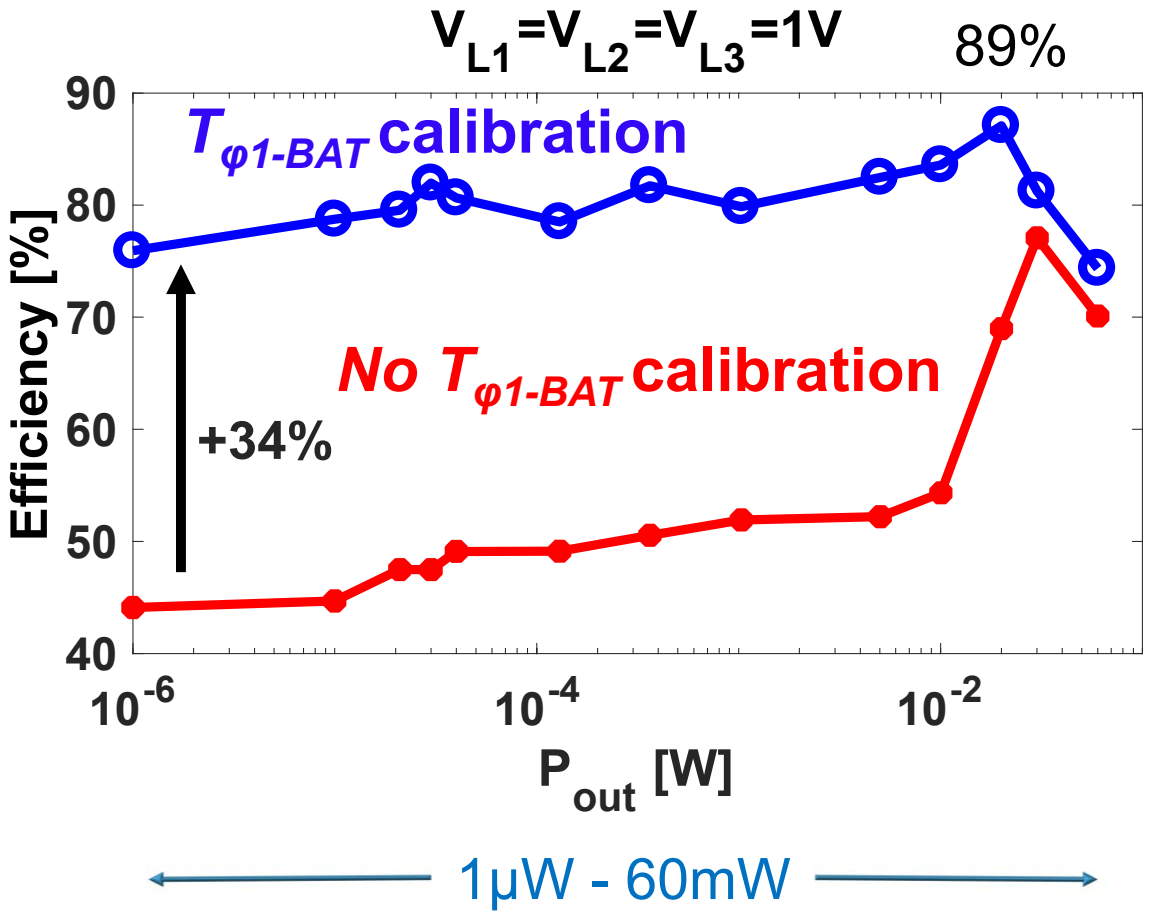
MISIMO Measurement Results







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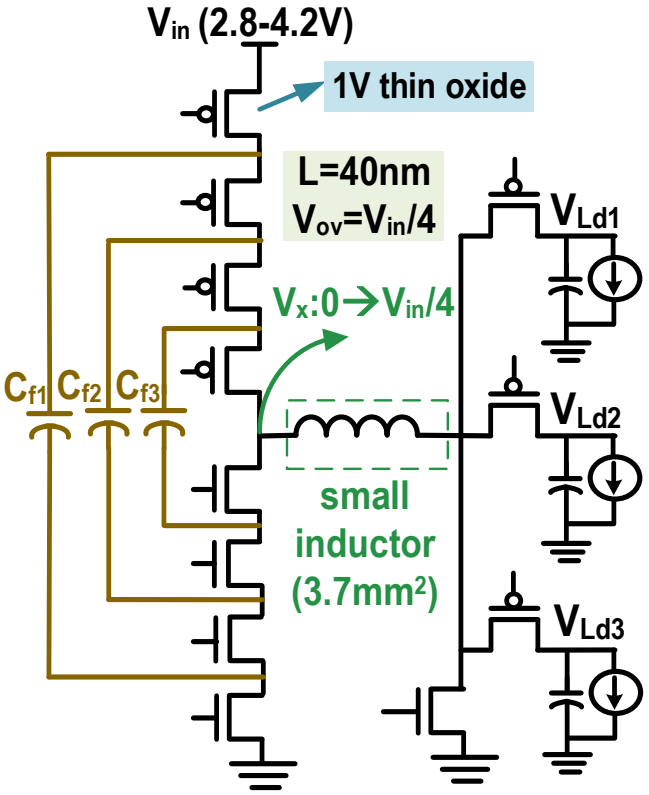
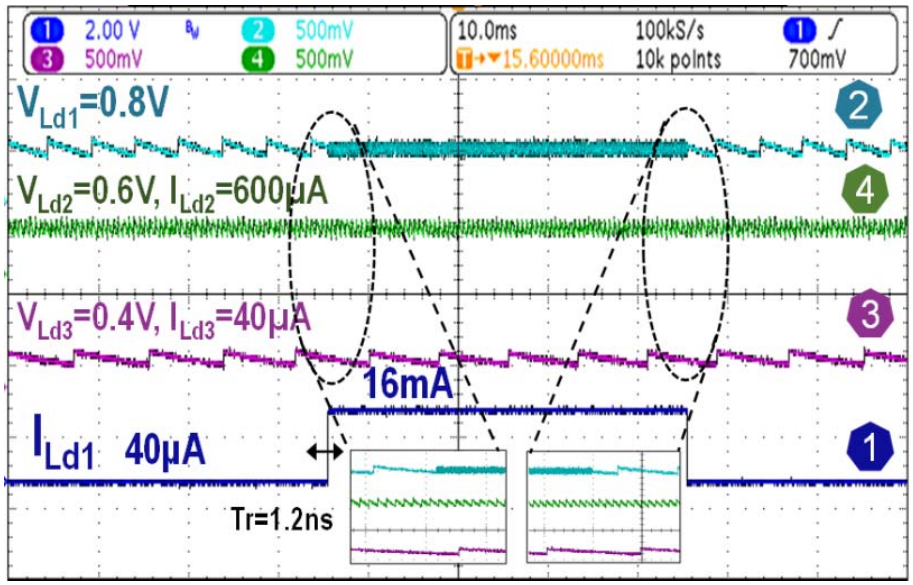
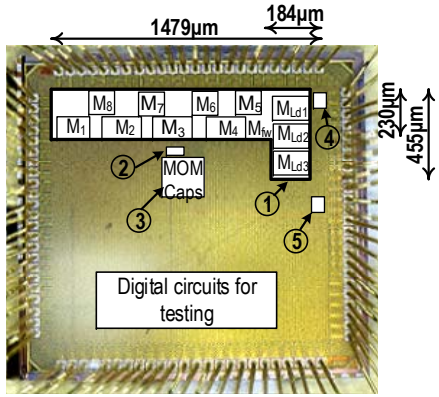
Hybrid SIMO

H-SIMO: Hybrid SIMO







- Li-ion compatible in 28nm FDSOI
- Simultaneously regulates 3 loads w/ one inductor
- Peak efficiency = 91.4%
- 4,000x dynamic range w/ >70% efficiency

S.S. Amin et al., CICC'20

Power Management Research Focus Areas

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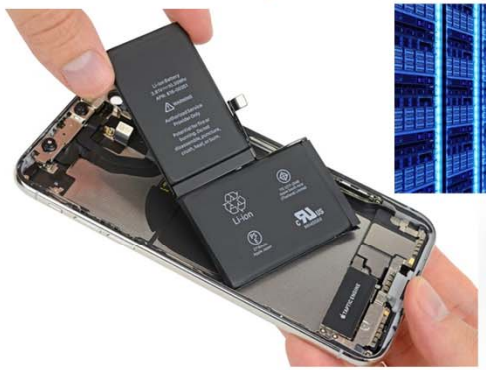

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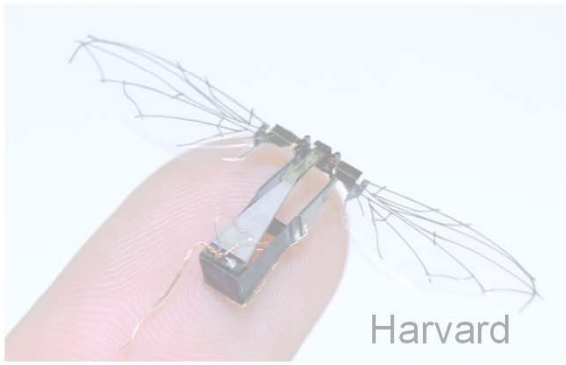
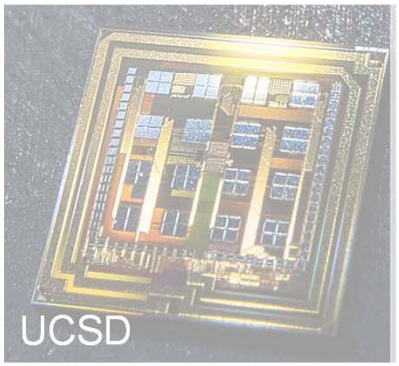
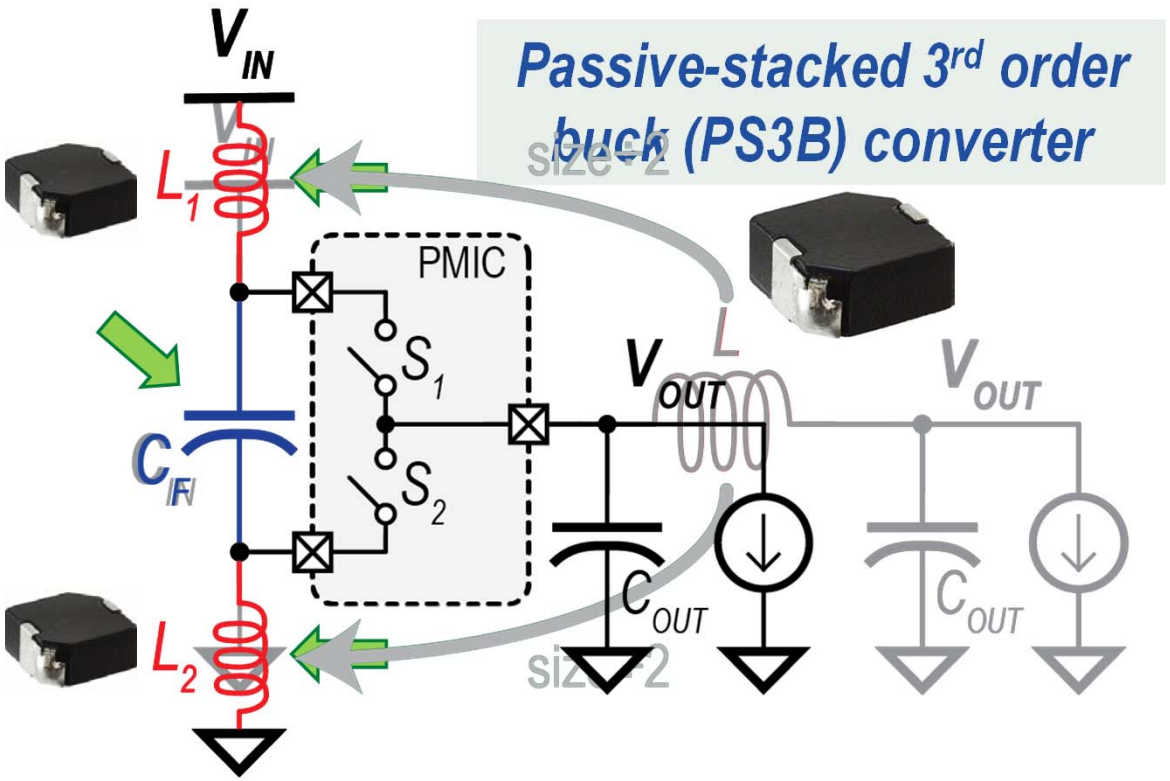
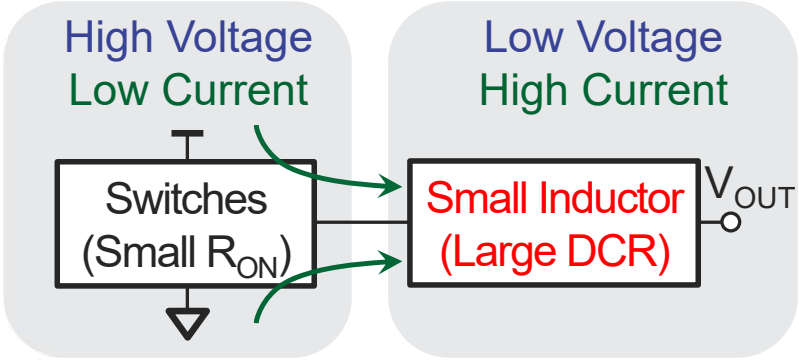




Wide Dynamic Current Range Converters
IoT, Wearables

Inductor-first conversion





Split into two half-sized inductors and stack at input

The input capacitor is now flying

All passives are stacked at input

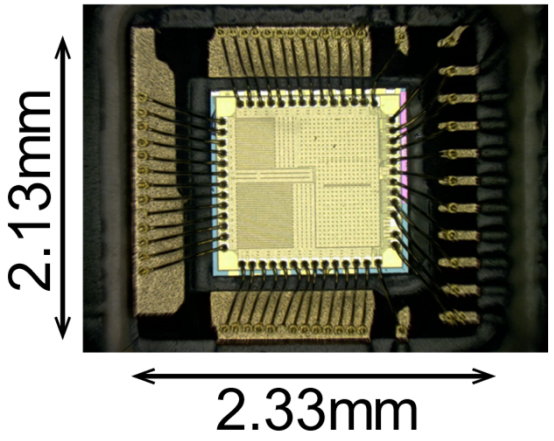
Inductors are placed at the low-current side of the converter

A. Abdulslam et al., ISSCC'19

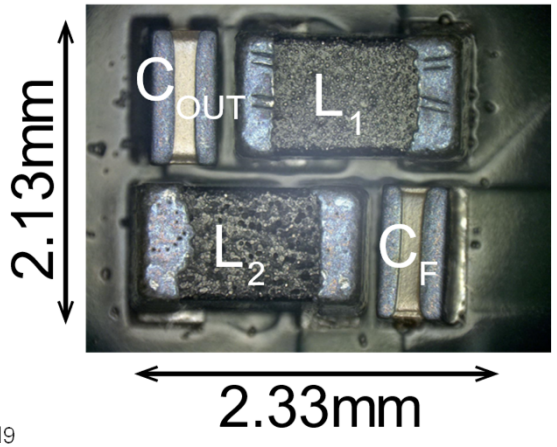
PS3B Measurement Results

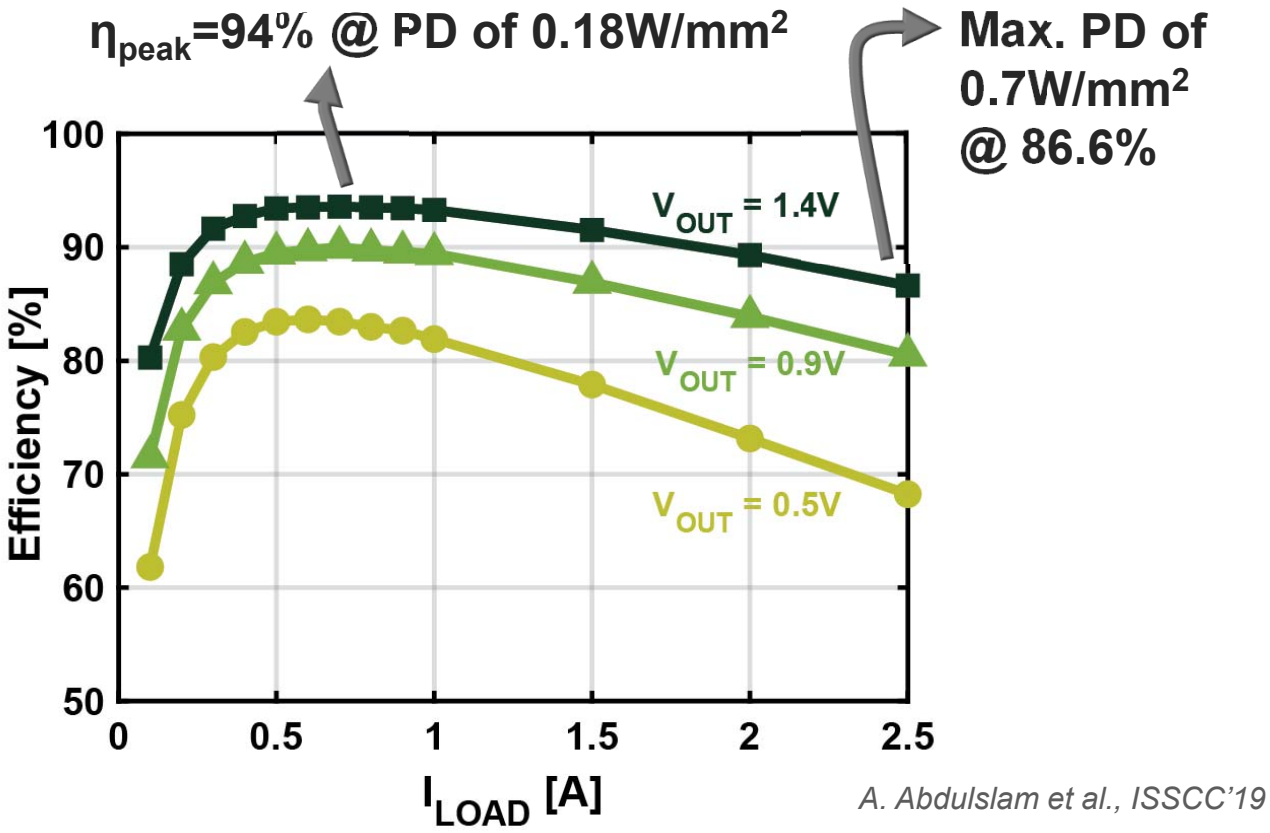
Center for Wearable Sensors

Top-side



Bottom-side





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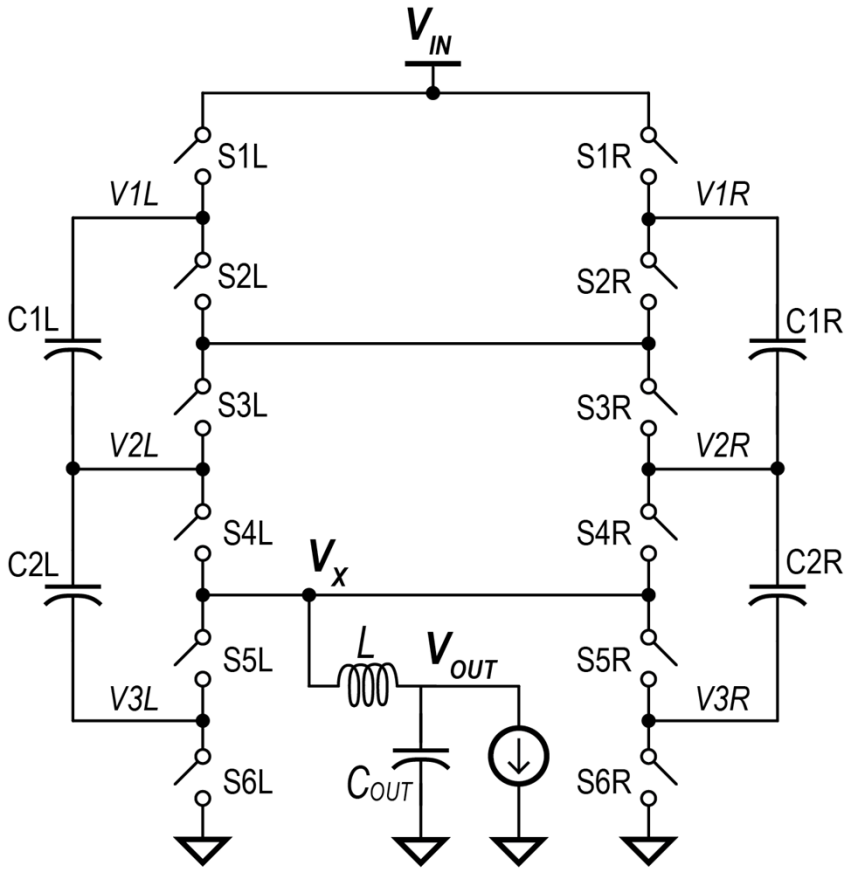
Benefits: reduced EMI and input noise, area-efficient stacked-passives, smaller inductors volume

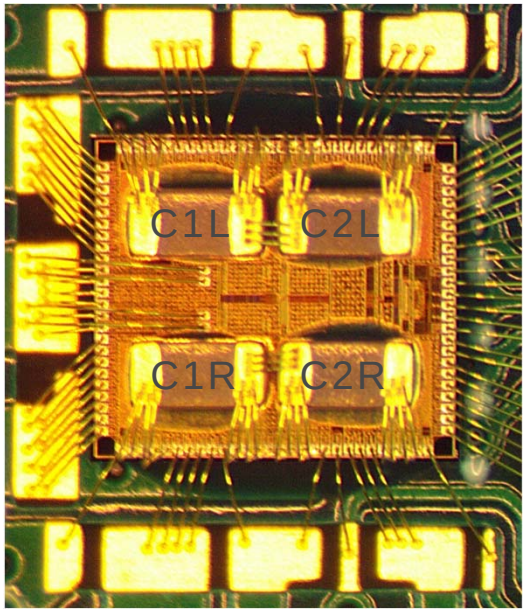
Li-ion-compatible SMML Converter

- A symmetric modified multilevel ladder (SMML) converter:
  - Consists of two sides each with 2 capacitors and 6 switches.
- Features:
  - ✓ **Decreased conduction losses** due to inherent phase interleaving.
  - ✓ **Minimum blocking voltage** on all switches/capacitors.
  - ✓ **No need for voltage balancing modules** flying capacitors are naturally stable.
  - ✓ **All necessary supplies are generated internally** to power drivers and level shifters.

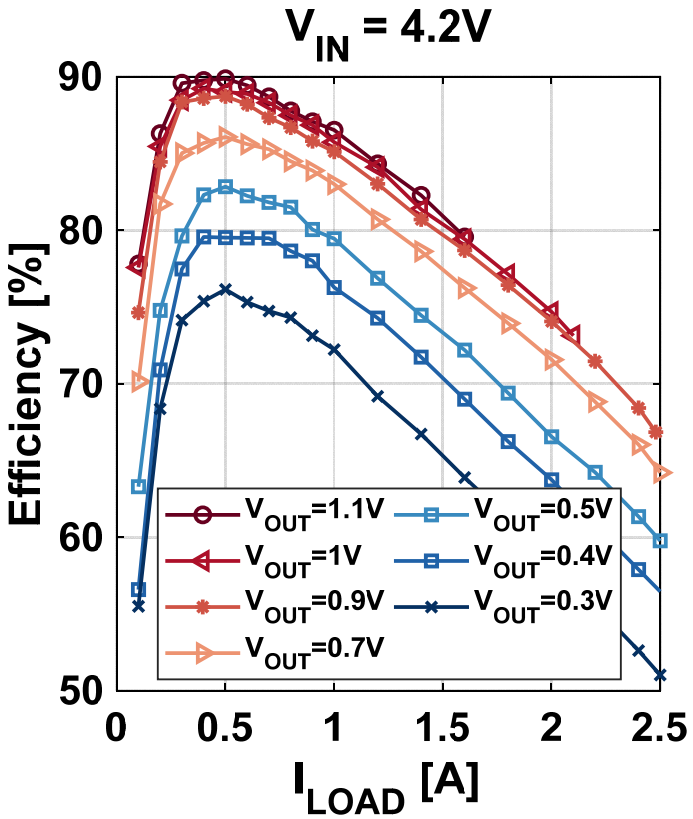


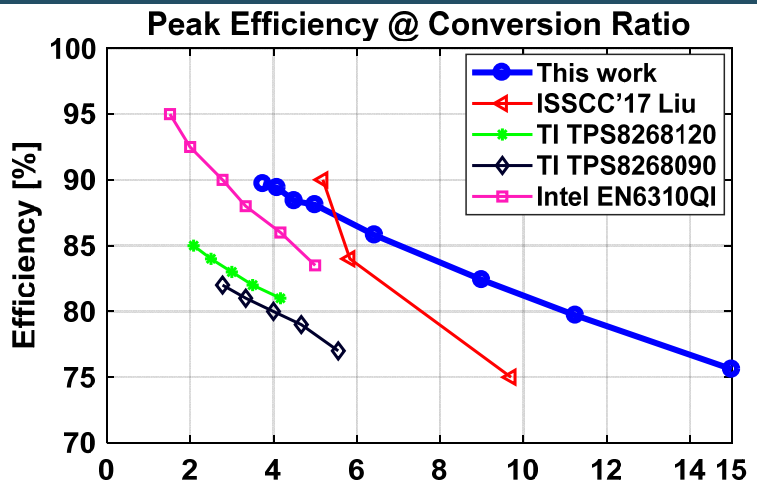
A. Abdulslam et al., JSSC'20

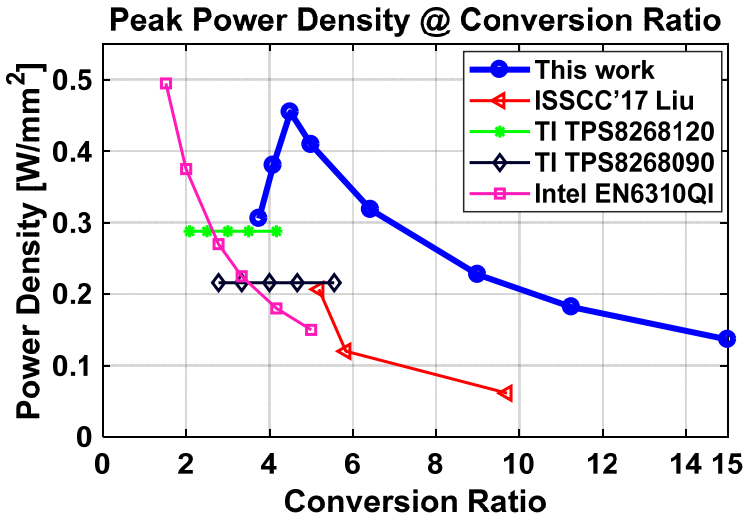
SMML Measurement Results



The inductor and the output capacitor are mounted under the chip







A. Abdulslam et al., JSSC'20

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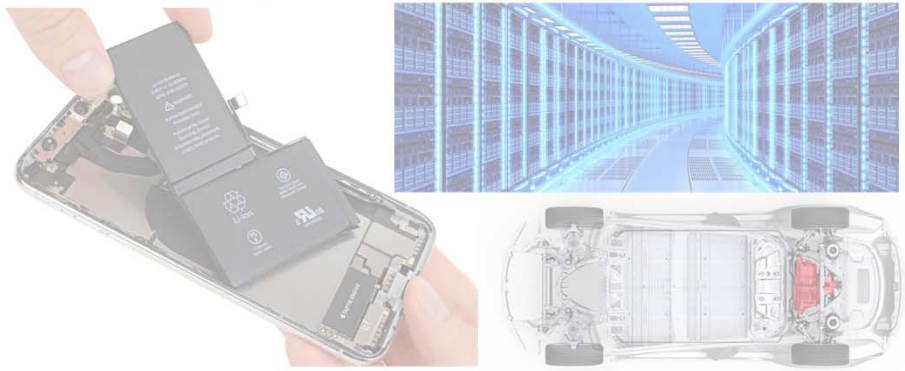

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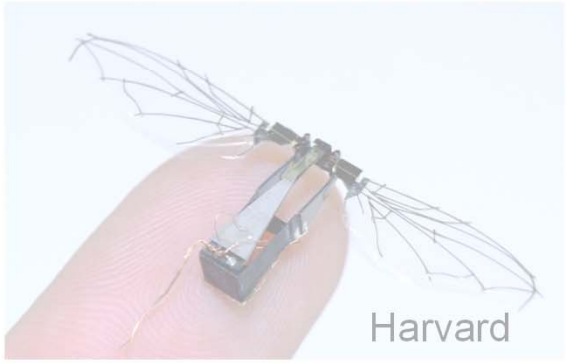

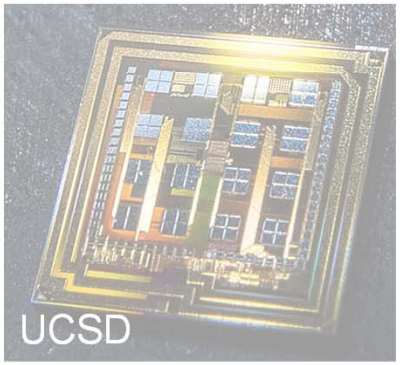

Wide Dynamic Current Range Converters
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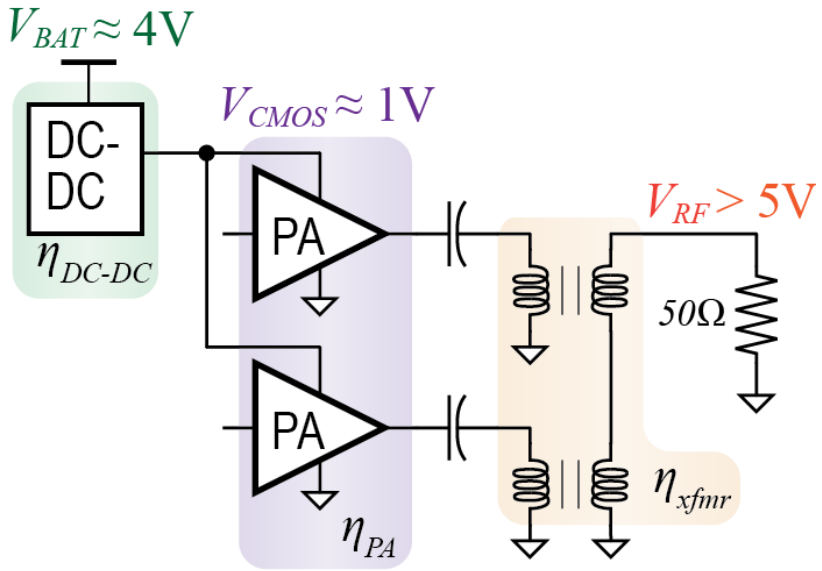
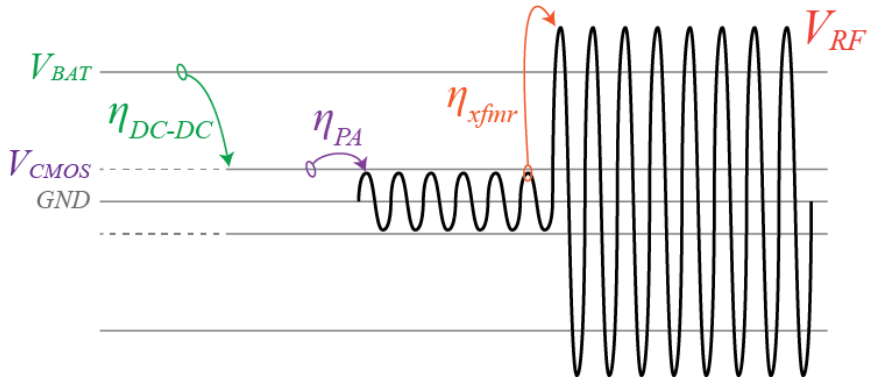
CMOS Power Amplifier Voltage Challenge





Idea: utilize many efficient ~1V class-D PAs and combine power with transformers

Problem: three voltage conversion stages leads to cascaded losses:

$$\eta_{tot} = \eta_{DC-DC}\,\eta_{PA}\,\eta_{xfmr} < 30\%$$

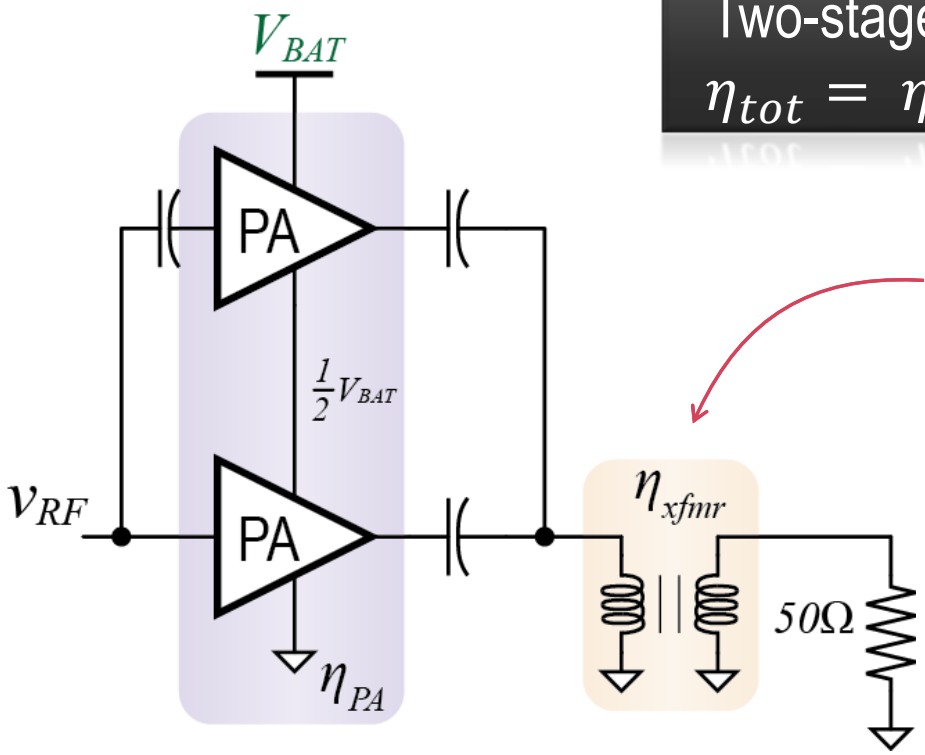
Why do we go down, then back up in voltage?
There must be a better way!

Partial Solution: PA Stacking

Stack entire class-D PAs for current re-use:

~100% efficient *implicit* DC-DC conversion

(each PA sees only $V_{BAT}/2$)



Two-stage cascade:

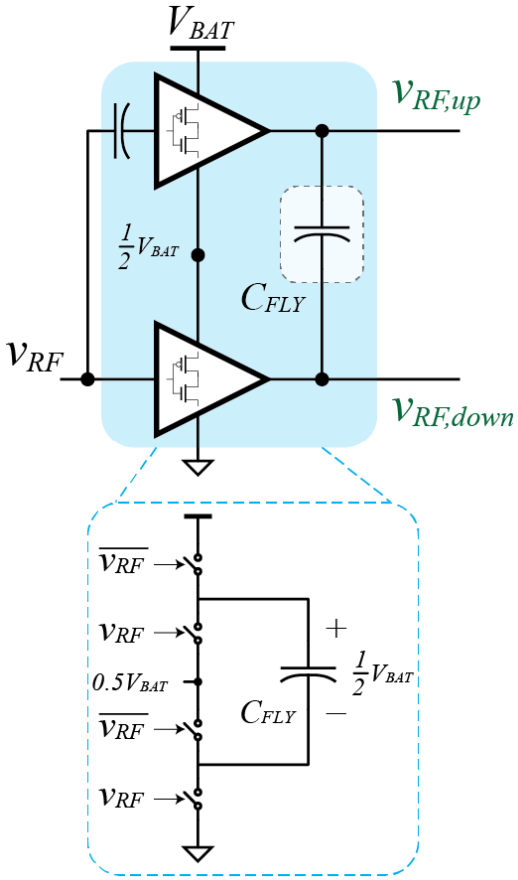
$$\eta_{tot} = \eta_{PA}\,\eta_{xfmr}$$

Problem: still require lossy transformer to achieve high output power in scaled CMOS

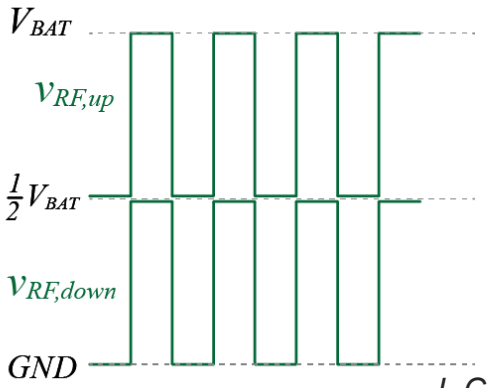
L.G. Salem et al., JSSC'17

Solid-State RF Impedance Transformation

Idea: generate large RF voltages directly from a battery using ~1V devices by stacking PAs, then flying subsequent PAs between the rails of the prior stages in a *House-of-Cards* Topology



Animation not seen in print



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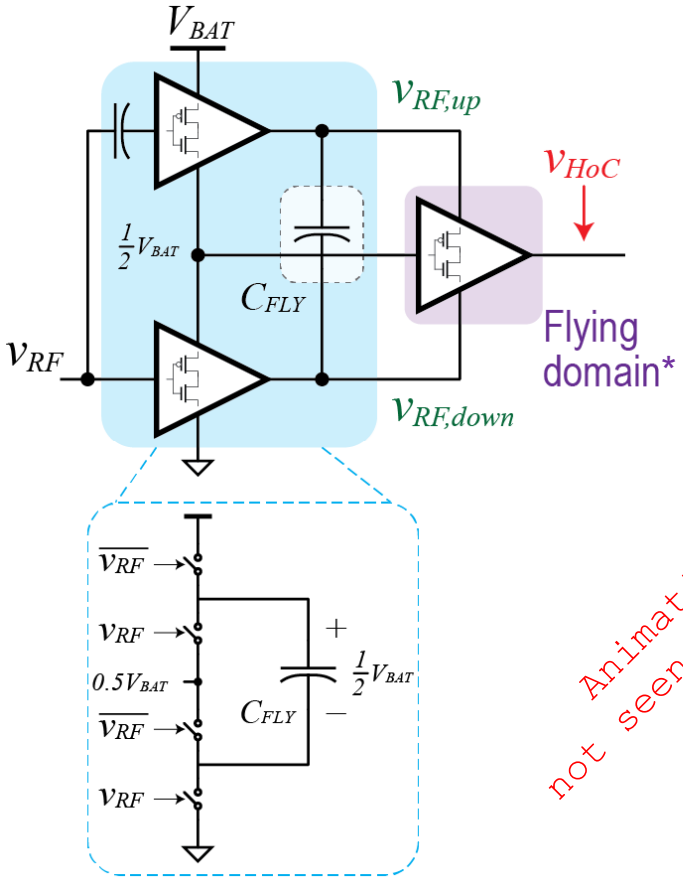

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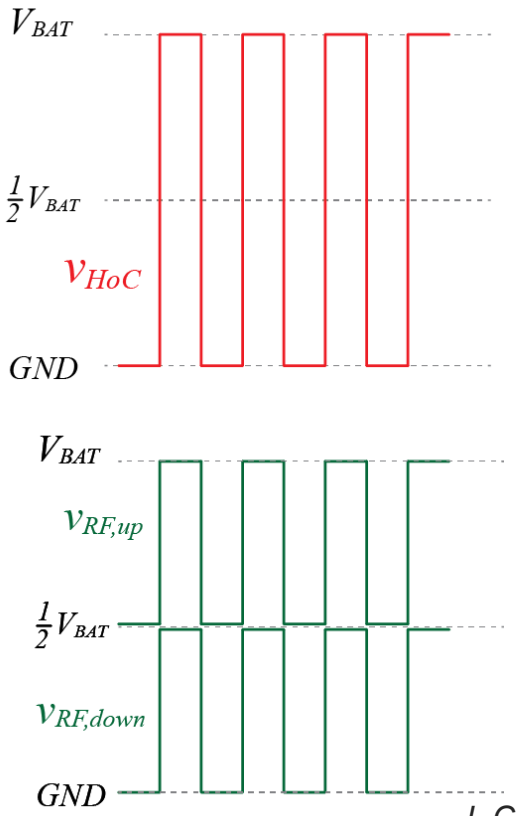

*For more information, see Salem et al., ISSCC'16

L.G. Salem et al., JSSC'17

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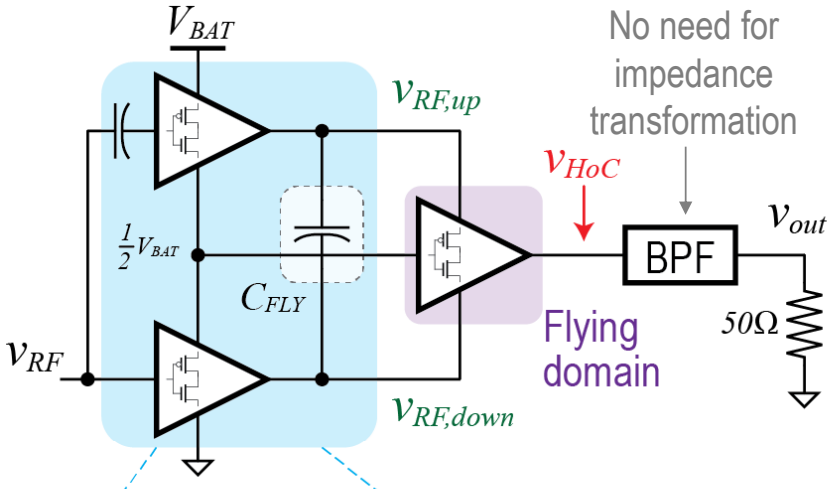

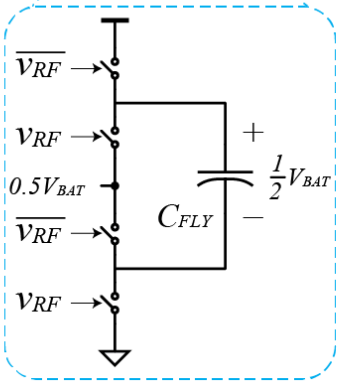

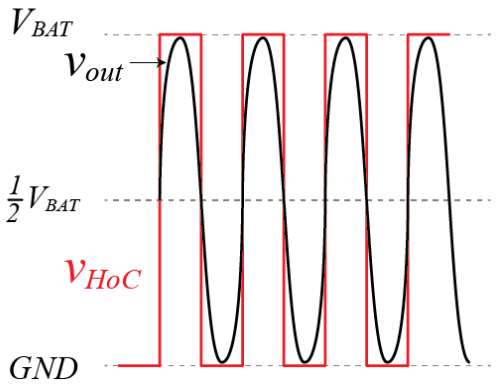

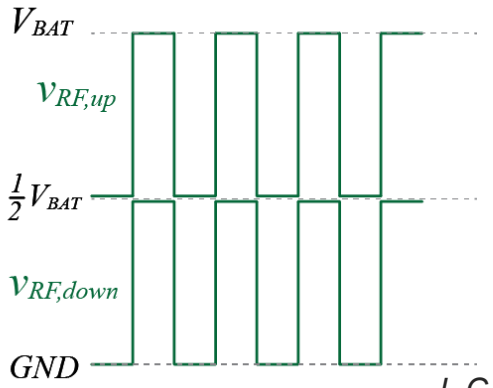

High power RF waveform synthesized directly from V_{BAT} using low-voltage transistors

*For more information, see Salem et al., ISSCC'16

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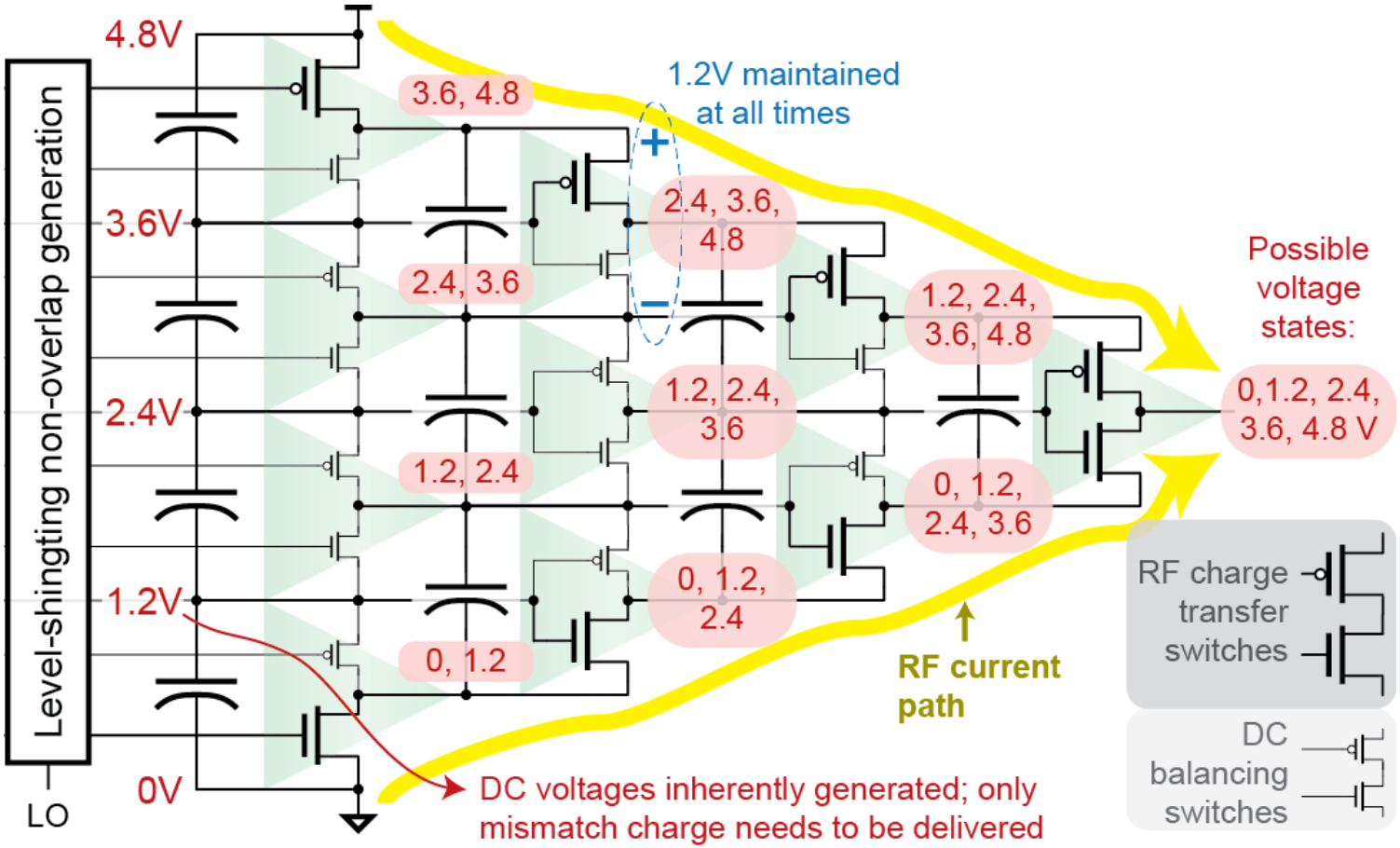
House-of-Cards (HoC) Schematic



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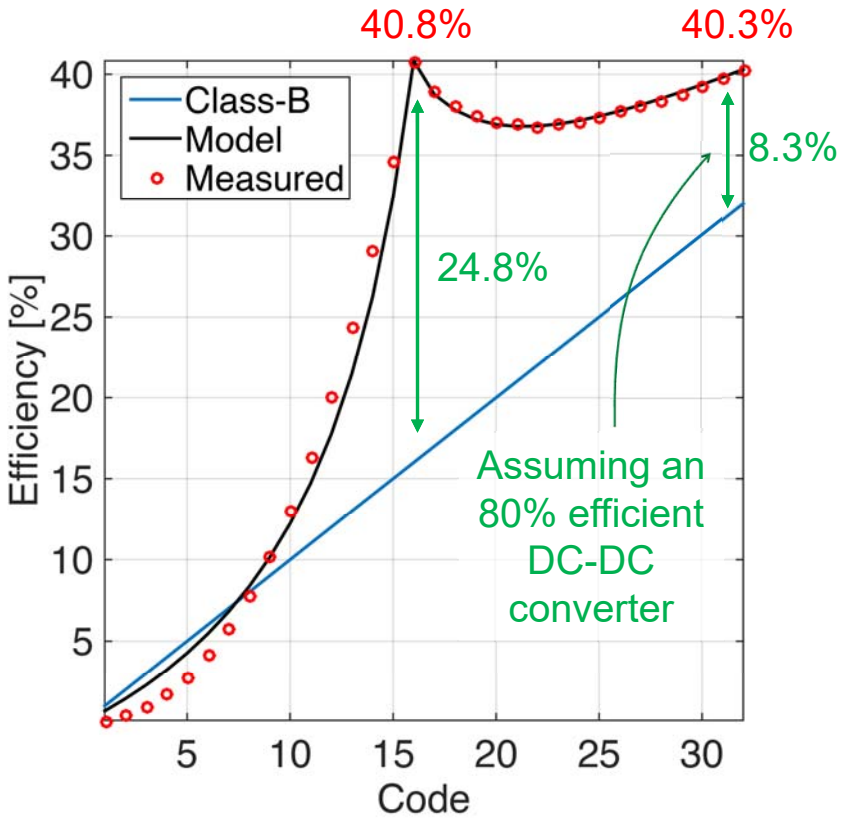
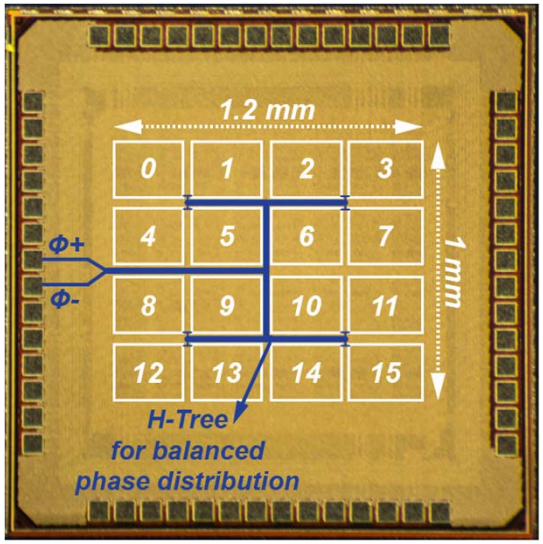
Measurement results: PAE



65nm LP
1.2V transistors
Direct 4.8V Li-ion battery connection



>40% battery-to-RF power-added efficiency at both peak power (23dBm) and at 6dB backoff

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Acknowledgements

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