Chip-Scale High-Voltage Power Supplies

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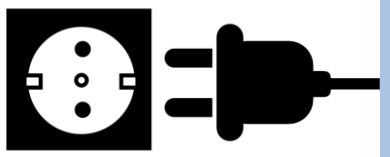
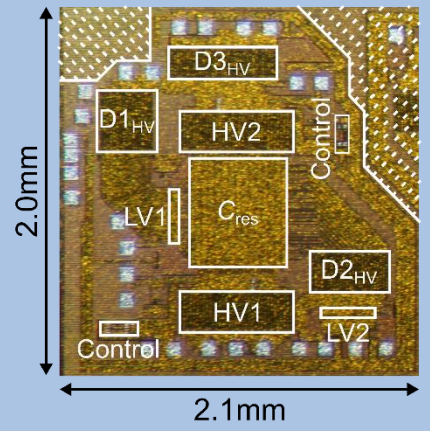
Overview



IC

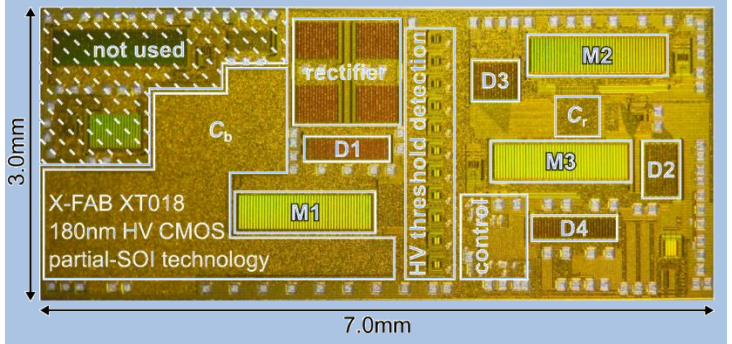
One-step resonant DC-DC
325V to 3.3-10V, <500mW
Options: SJ-FET / SJ-LIGBT



[ISSCC 2020, JSSC Nov. 2021]

HV AC-Interface

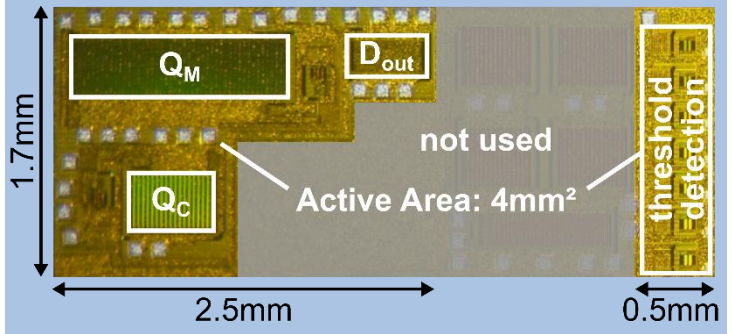
One-step DC-DC 15-325V
to 3.3-10V, <300mW



[ISSCC 2022]

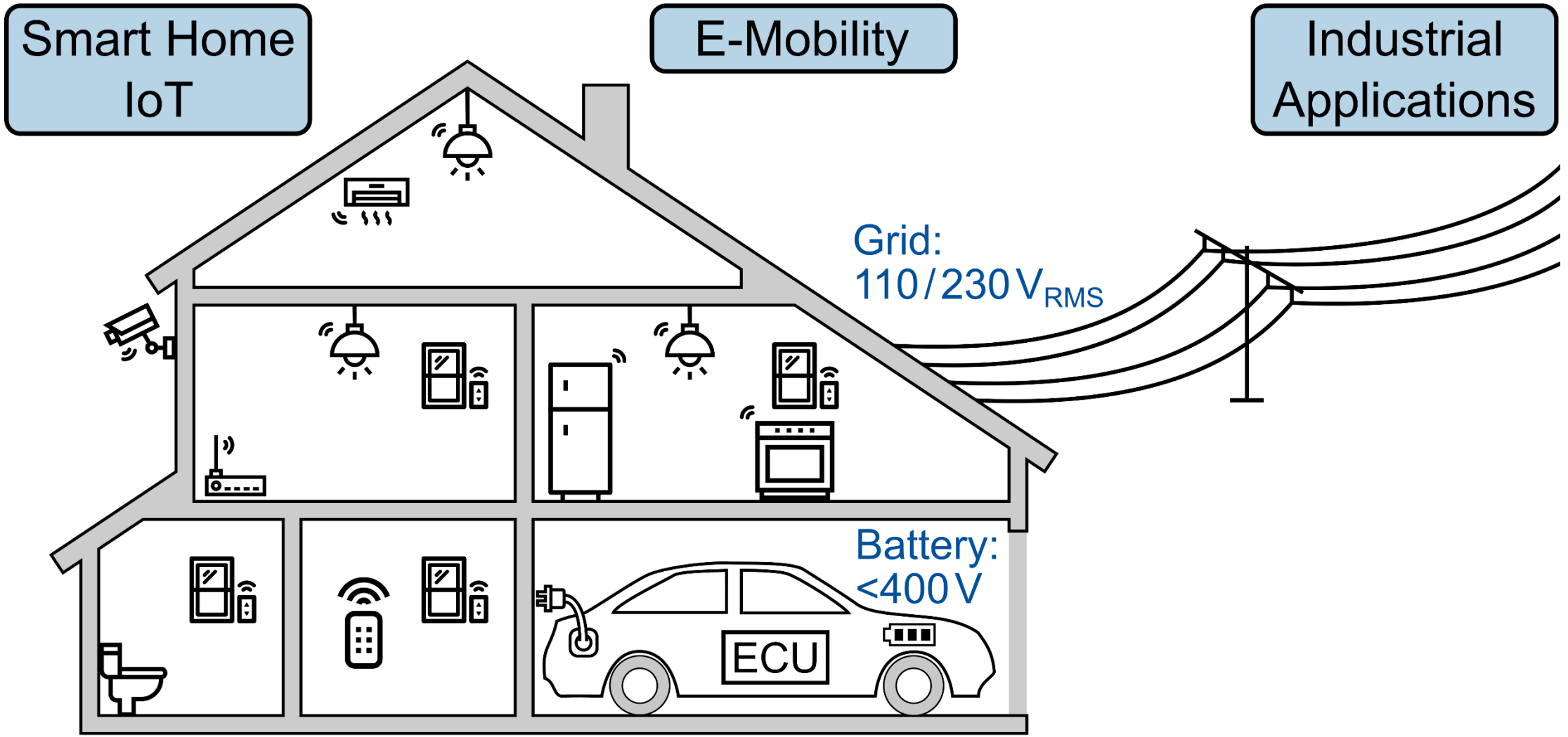
HV AC-Interface
(optional)

Active-Clamp Flyback
DC-DC 20-300V to 5V,
500mW

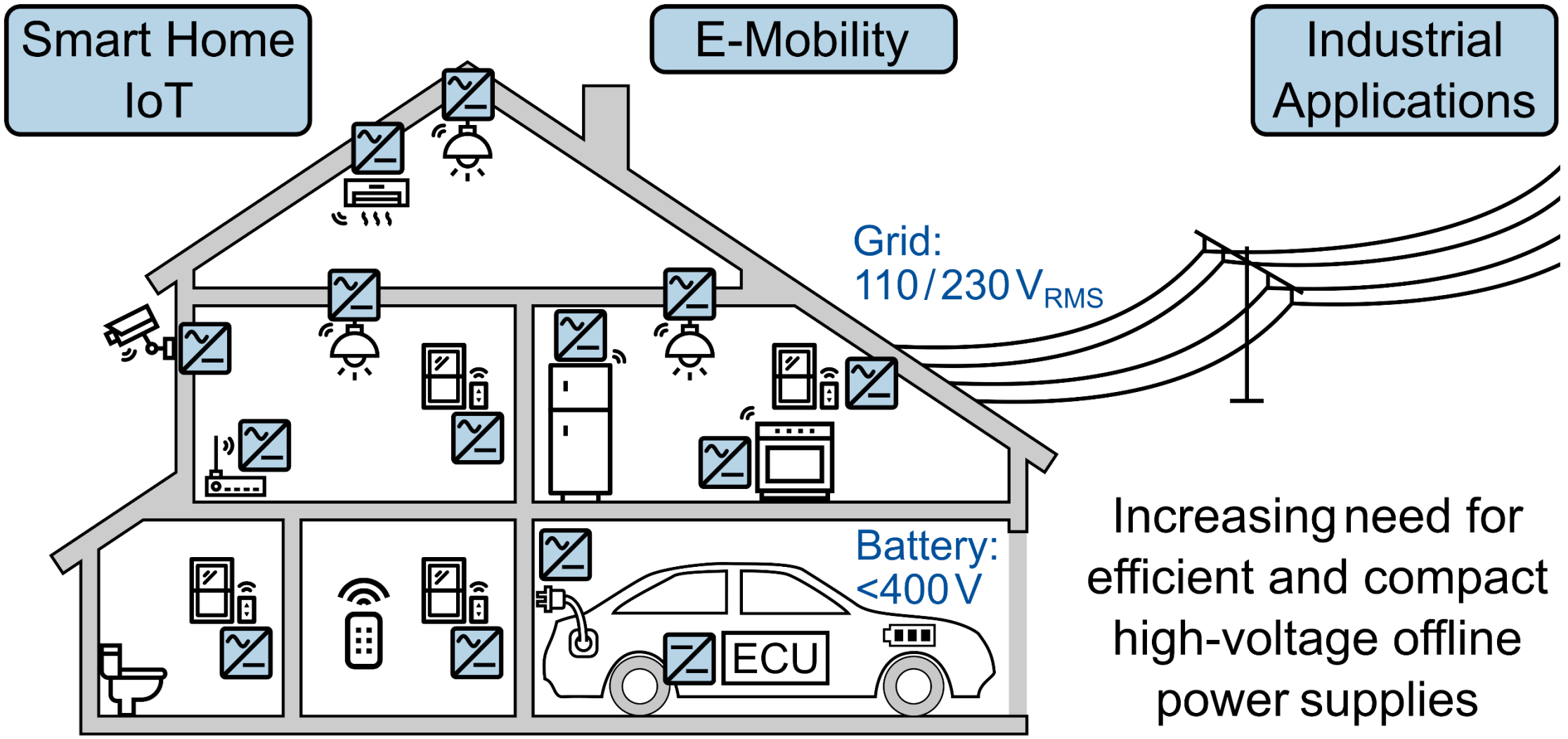


[CICC 2022]

The Need for High-Voltage Low-Power Converters



The Need for High-Voltage Low-Power Converters



Increasing need for efficient and compact high-voltage offline power supplies

Closing the Power-Supply Gap for IoT, …

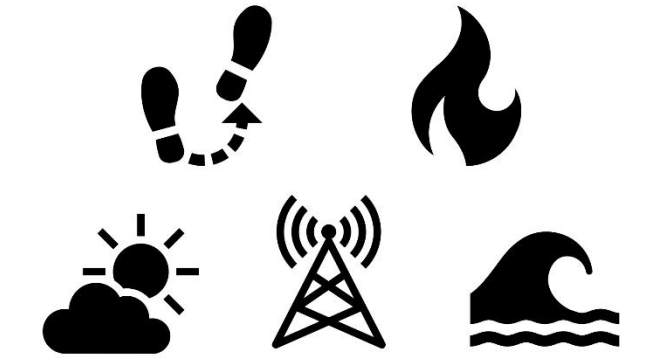
µ-Power & Energy Harvesting

Power density $<1 \frac{mW}{cm^3}$
not suitable for many applications

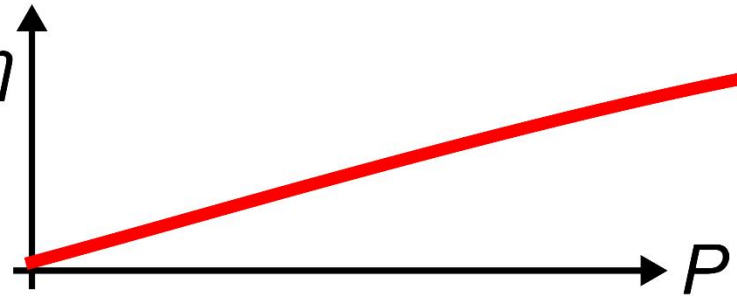
Closing the Power-Supply Gap for IoT, …

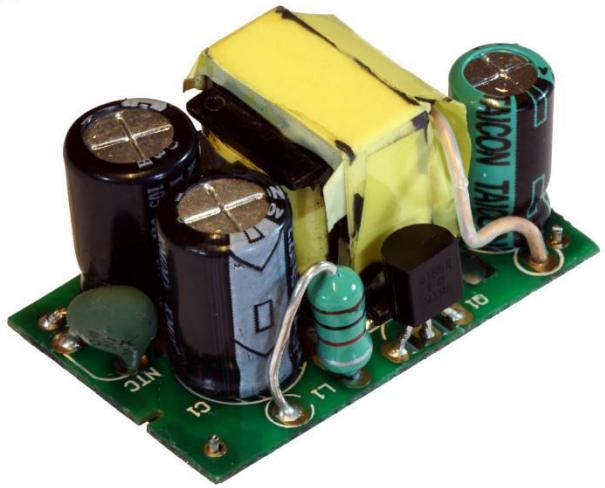
µ-Power & Energy Harvesting | **Discrete Power Modules**

1 mW | 500 mW



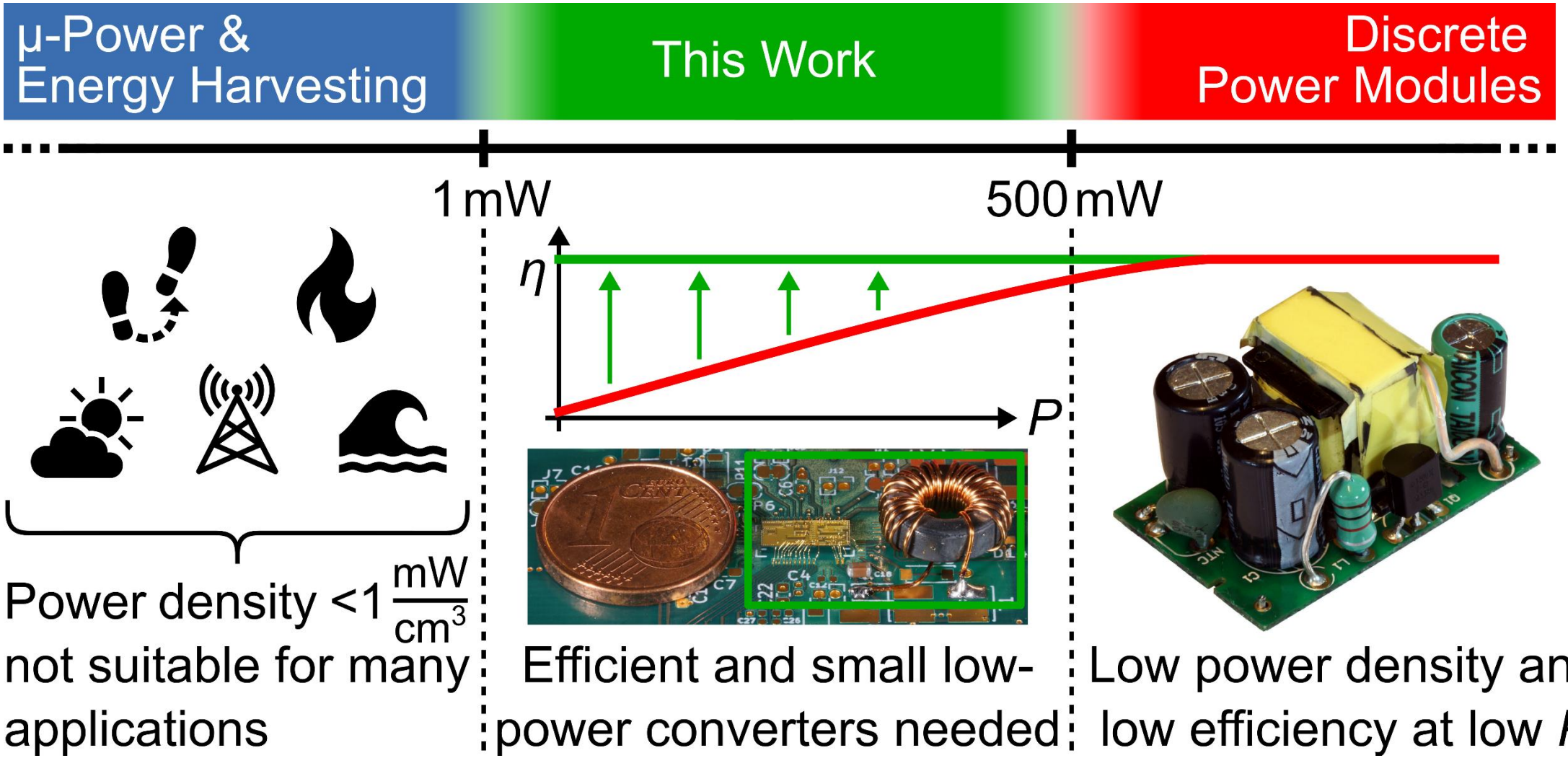
Power density <1 $\frac{mW}{cm^3}$
not suitable for many applications



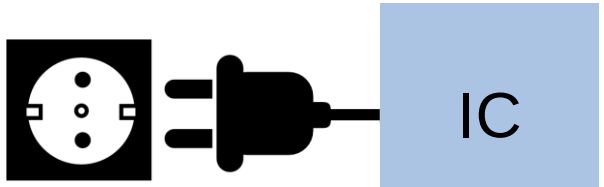


Low power density and low efficiency at low *P*

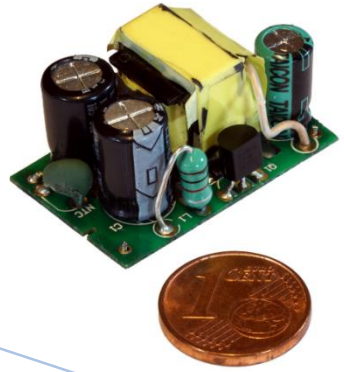
Closing the Power-Supply Gap for IoT, …

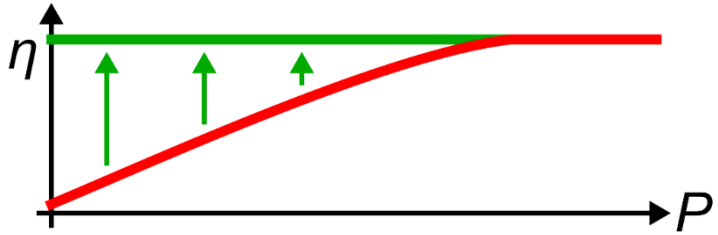


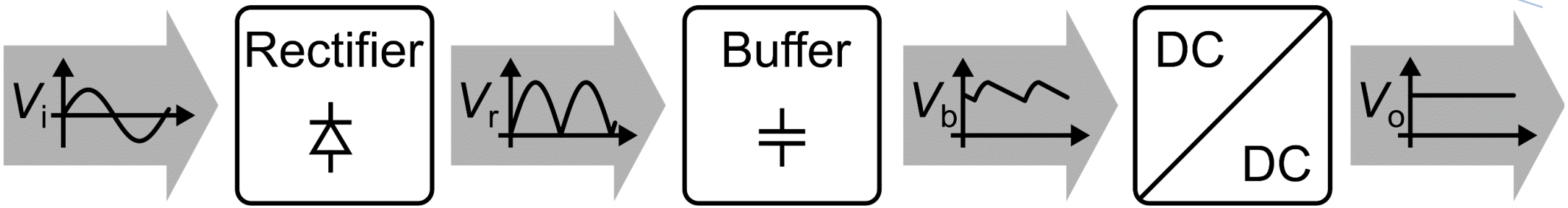
Towards Chip-Scale Offline Power Supplies



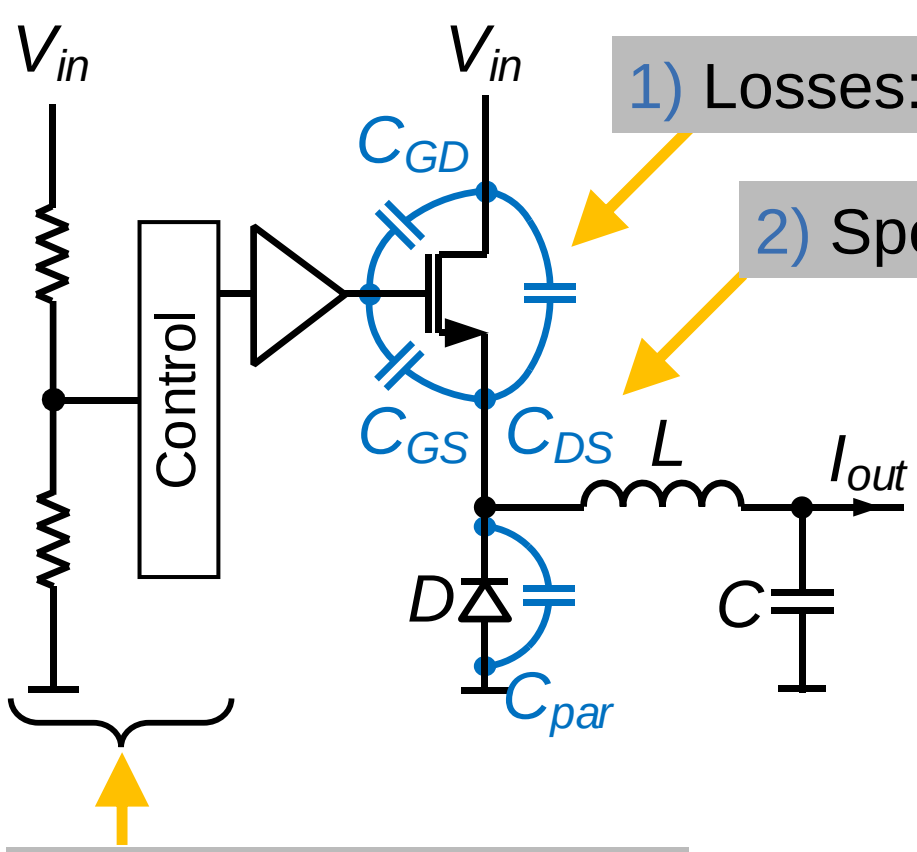
IC





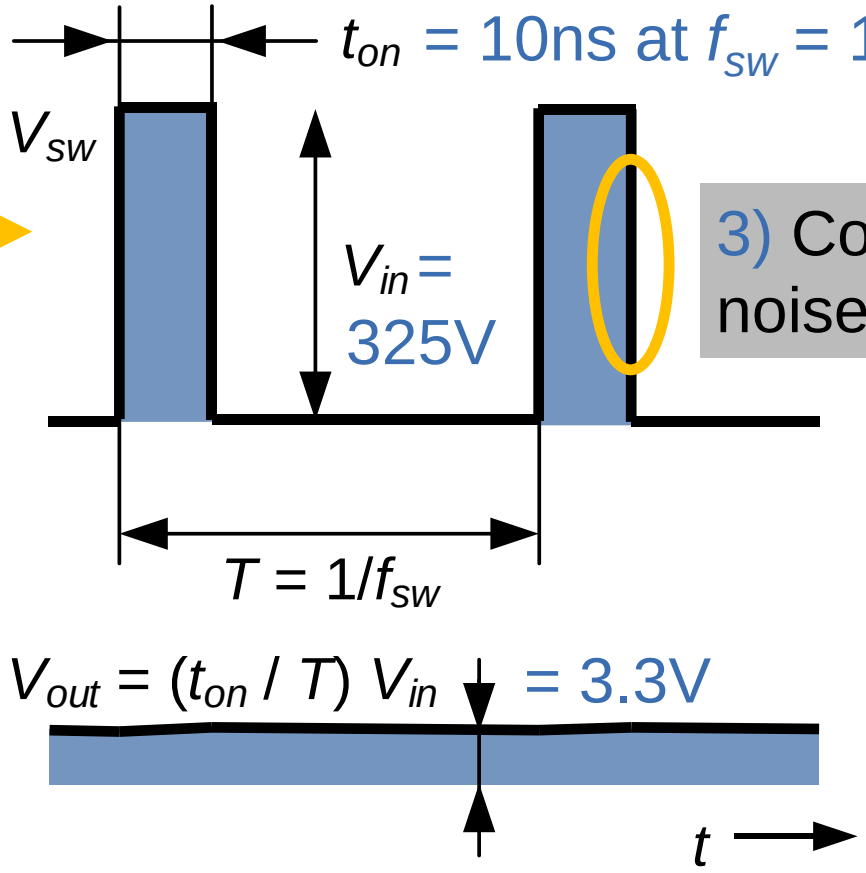


HV Challenges



1) Losses: C + I-V

2) Speed



3) Coupling, noise, EMC

4) Sensing and biasing
~100mW @ R = 1MΩ

HV Challenges

1) Losses
2) Speed
3) Substrate coupling, noise, EMC
4) Low-power biasing and sensing

…to be addressed by

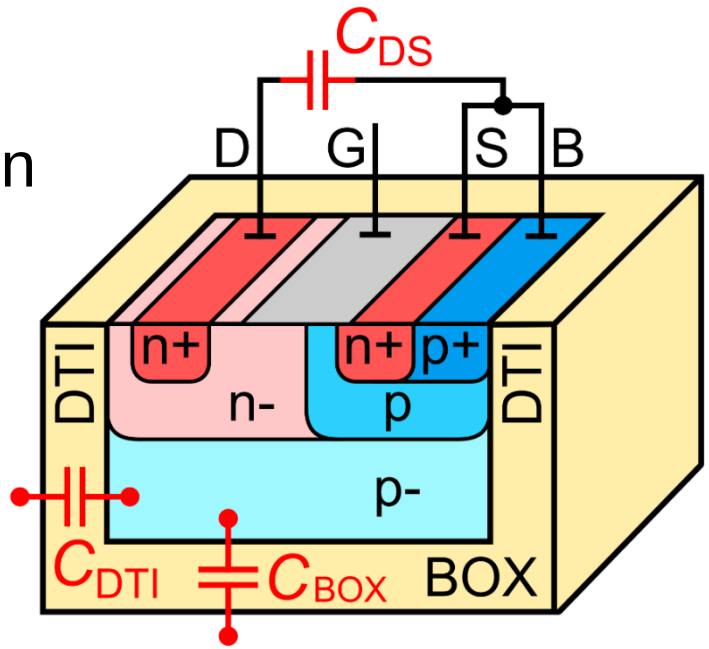
Topology and Design

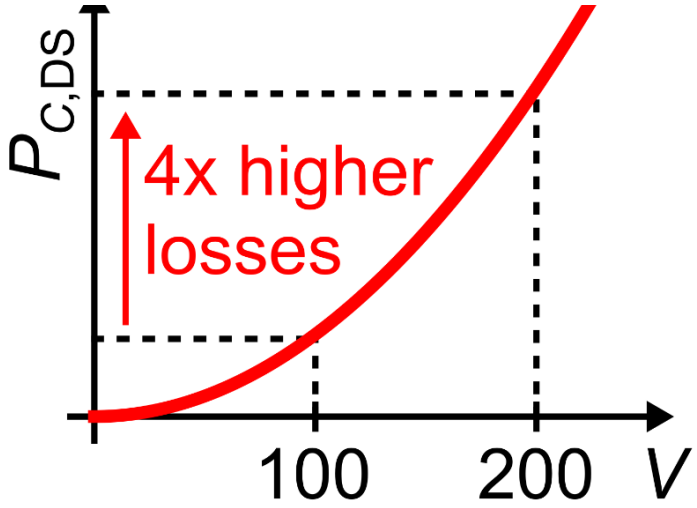
Technology and Layout

Why SOI?

- Oxide isolation instead of junction isolation
  - No parasitic bipolar effects
  - Negligible leakage currents
  - Smaller die size (narrow HV isolation)
- Small, low-resistive HV devices
- Super-junction MOSFET and IGBT

- But: Capacitive-loss-reduction techniques required

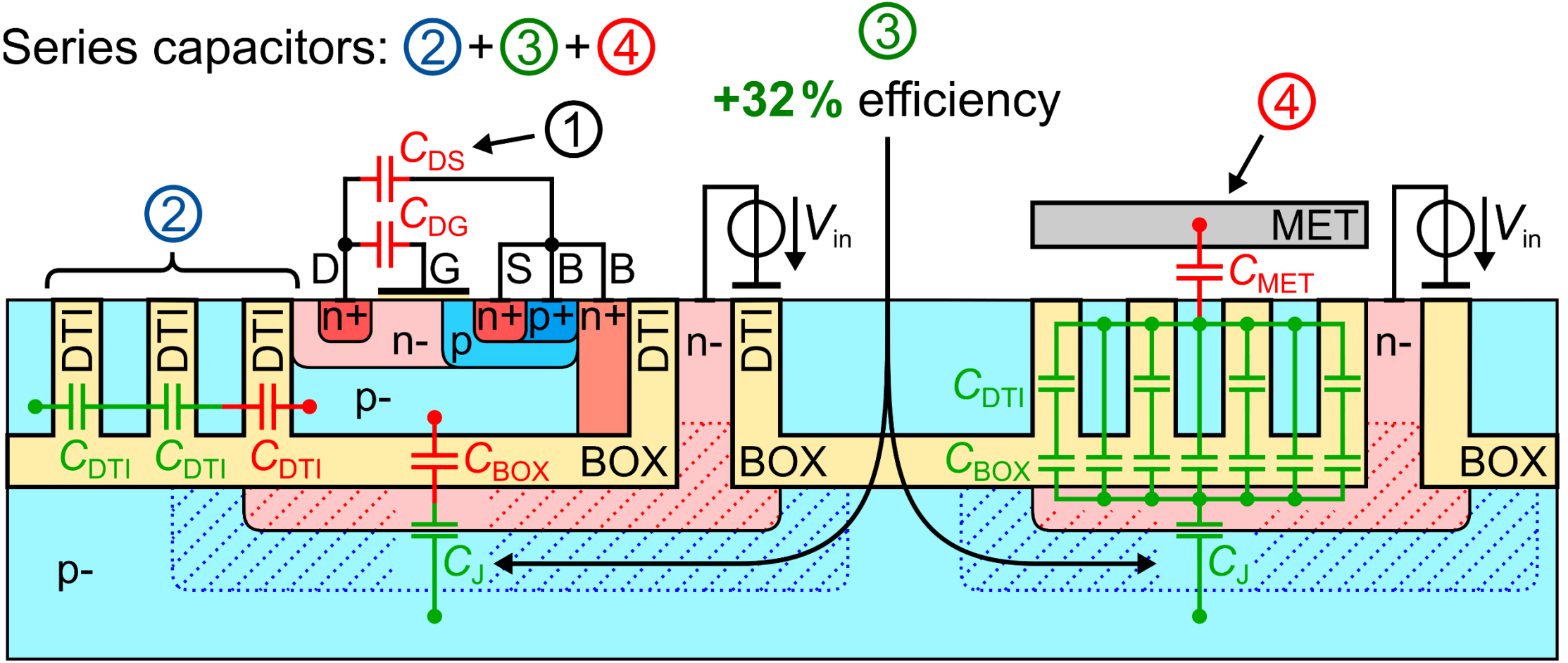




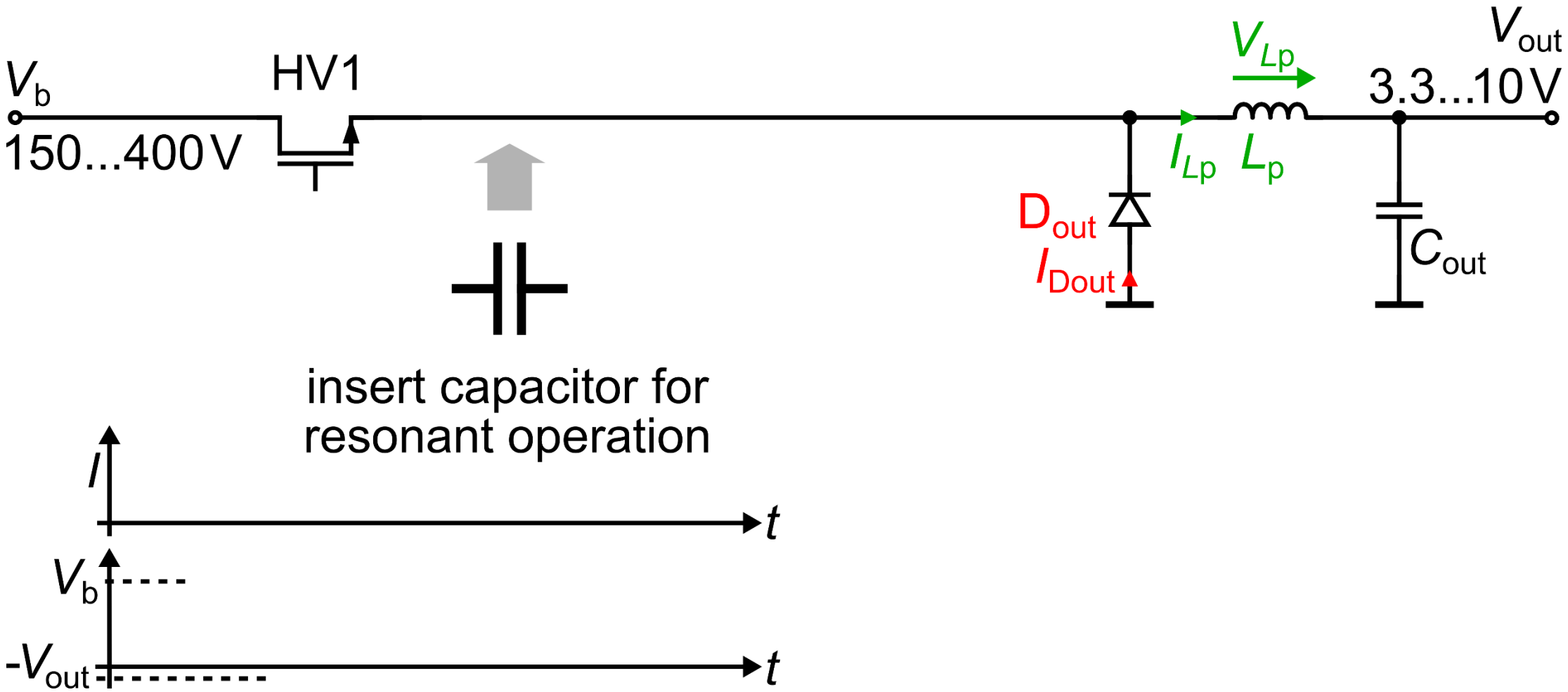
Capacitive-Loss-Reduction Techniques in SOI

Resonant switching: ①

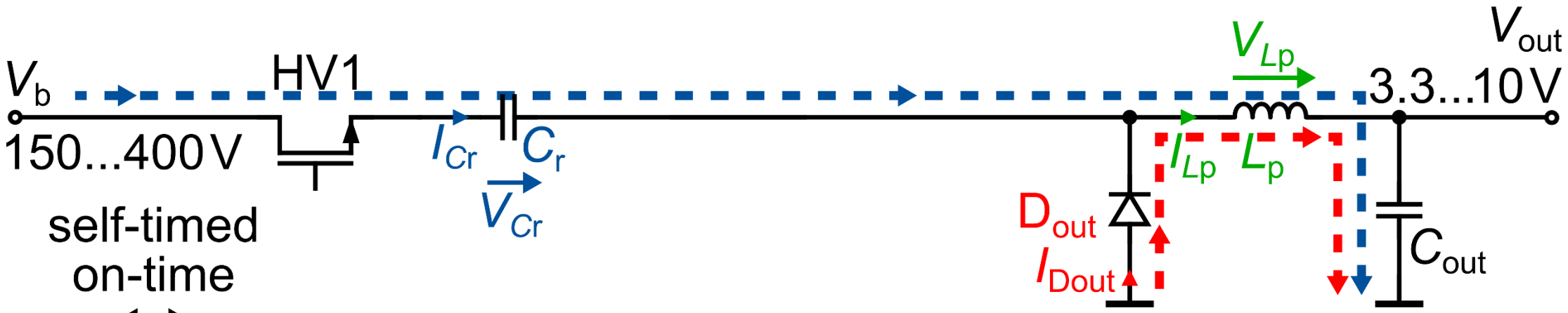
Series capacitors: ② + ③ + ④

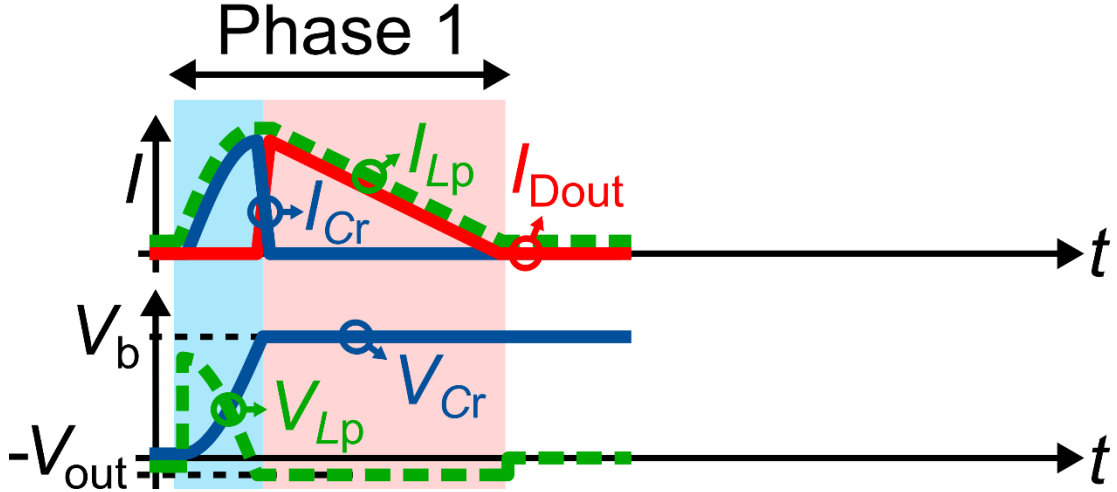


Self-Timed Resonant Operation (1)



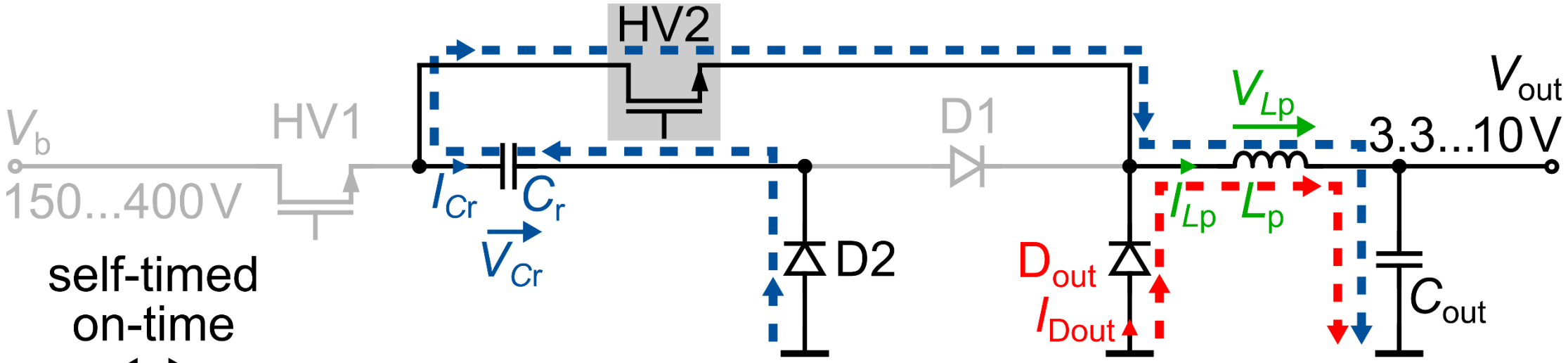
Self-Timed Resonant Operation (2)

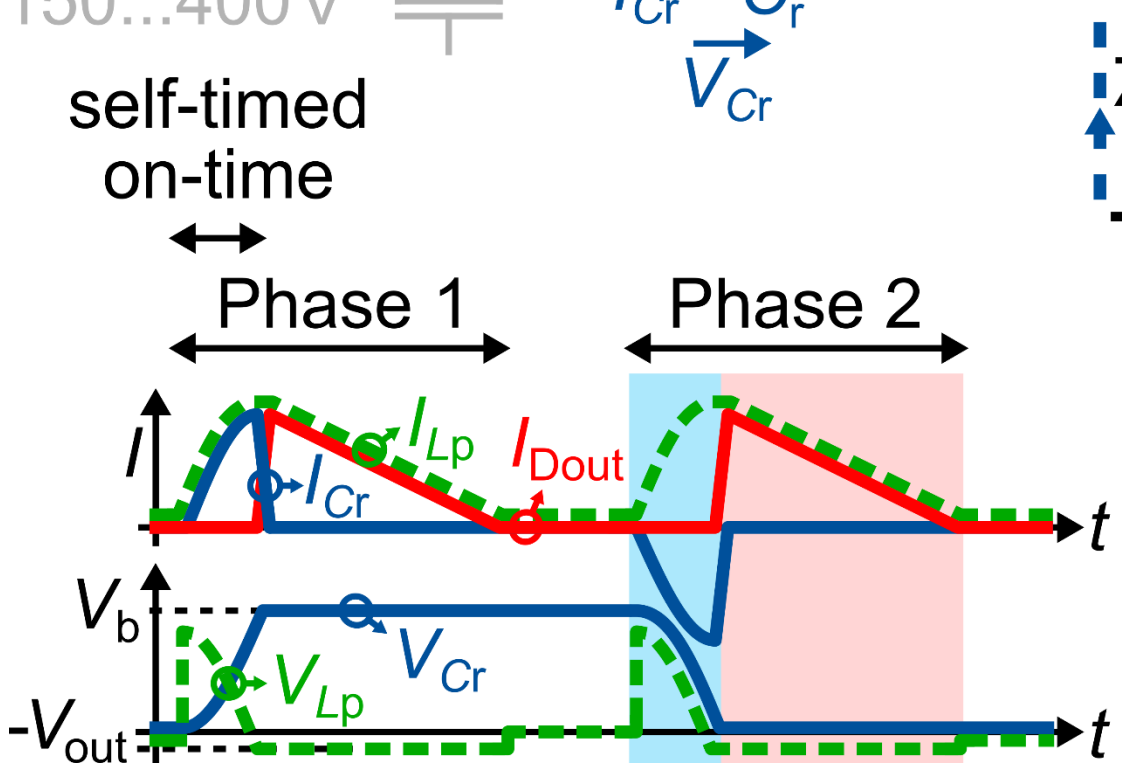




- C_r causes resonant behaviour
  - ➡ Self-timed on-time
  - ➡ ZVS / ZCS of HV1
  - ➡ Capacitive loss-reduction

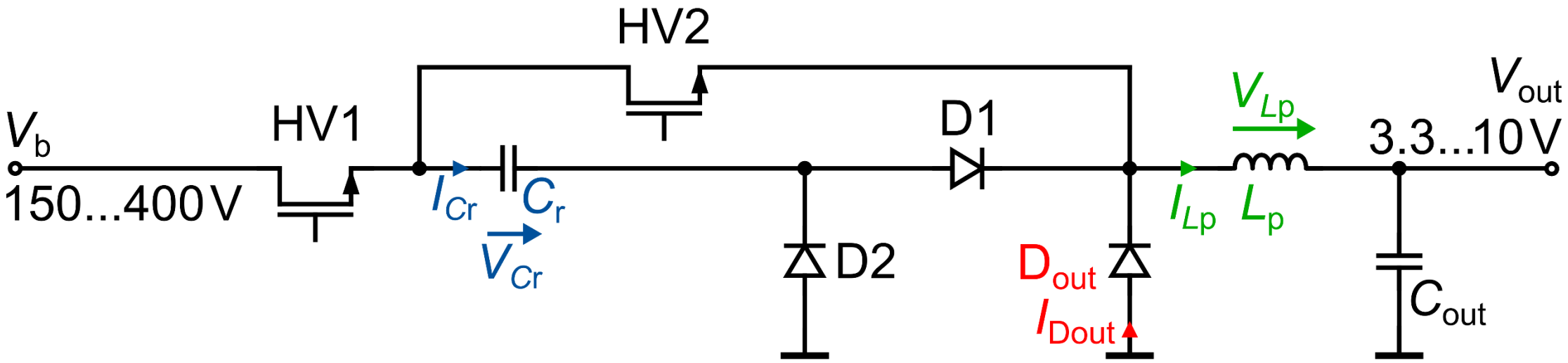
Self-Timed Resonant Operation (3)

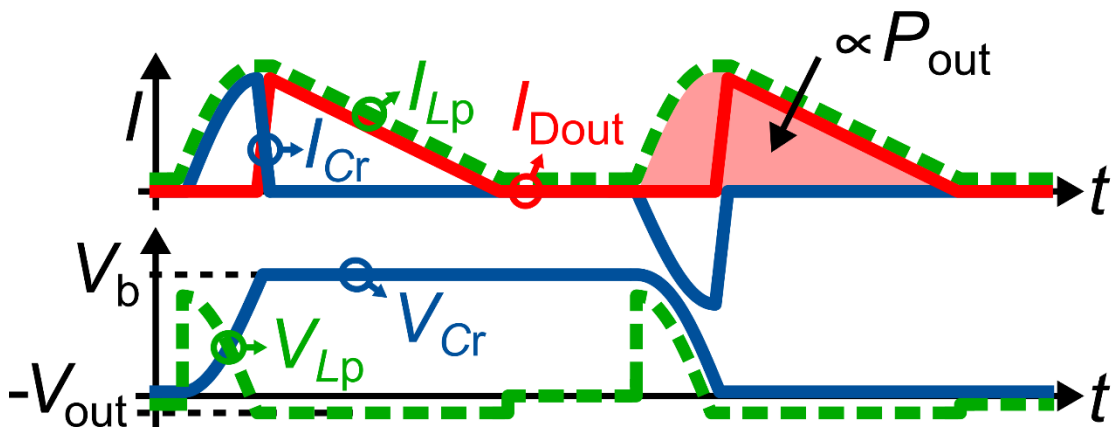




- C_r causes resonant behaviour
  - ➡ Self-timed on-time
  - ➡ ZVS / ZCS of HV1 / HV2
  - ➡ Capacitive loss-reduction
- HV2 enables reuse of energy stored in C_r

Self-Timed Resonant Operation: Output Power

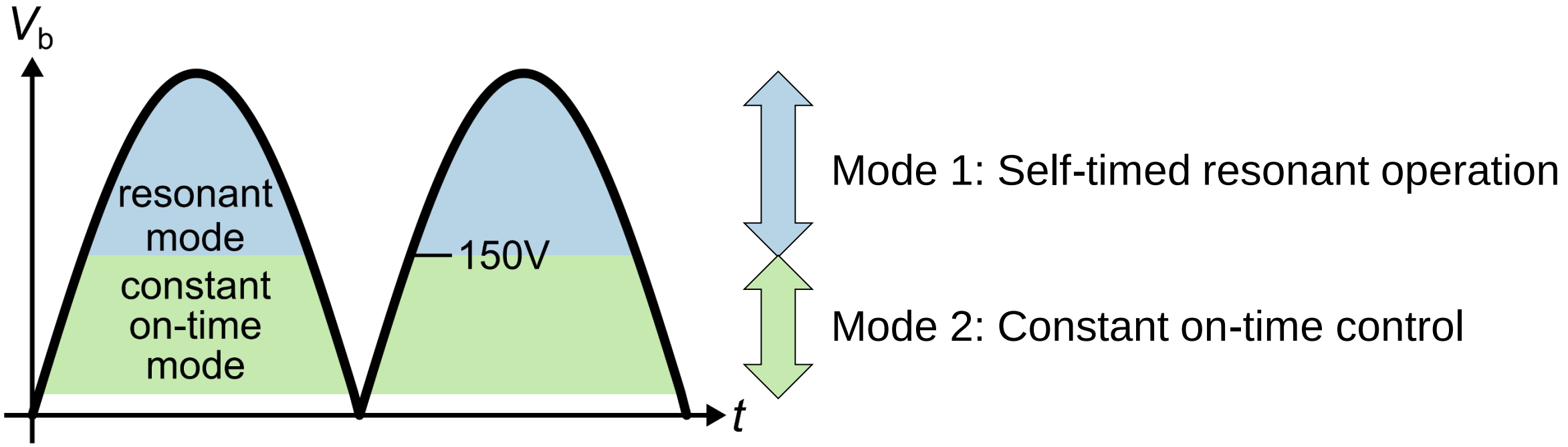




- $P_{out} \approx 0.5 \cdot C_r \cdot V_b^2 \cdot f_{sw}$
- Varying f_{sw} ➡ pulse-based control of P_{out}
- But: $P_{out,max}$ defined by $V_{b,min}$
  ➡ Second conversion mode for high P_{out} at low V_b required

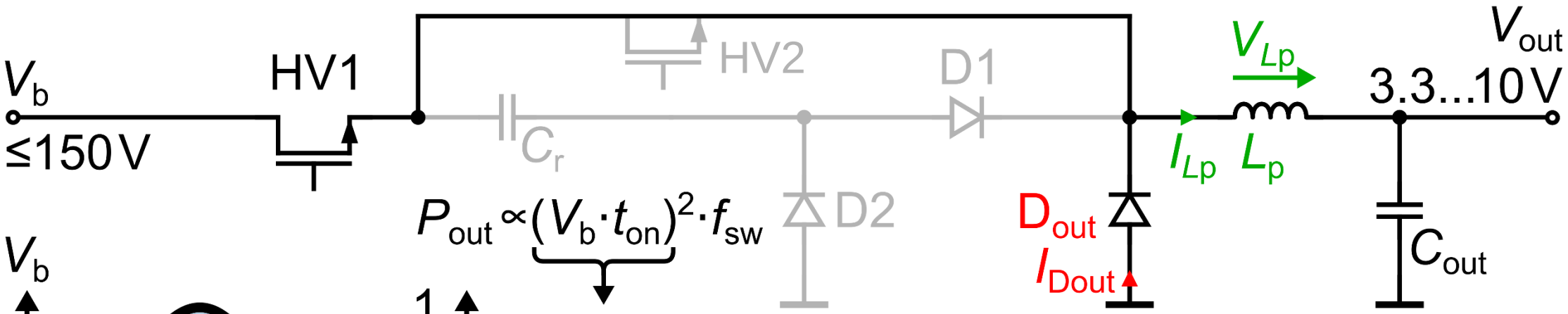
The Dual-Mode Buck Converter

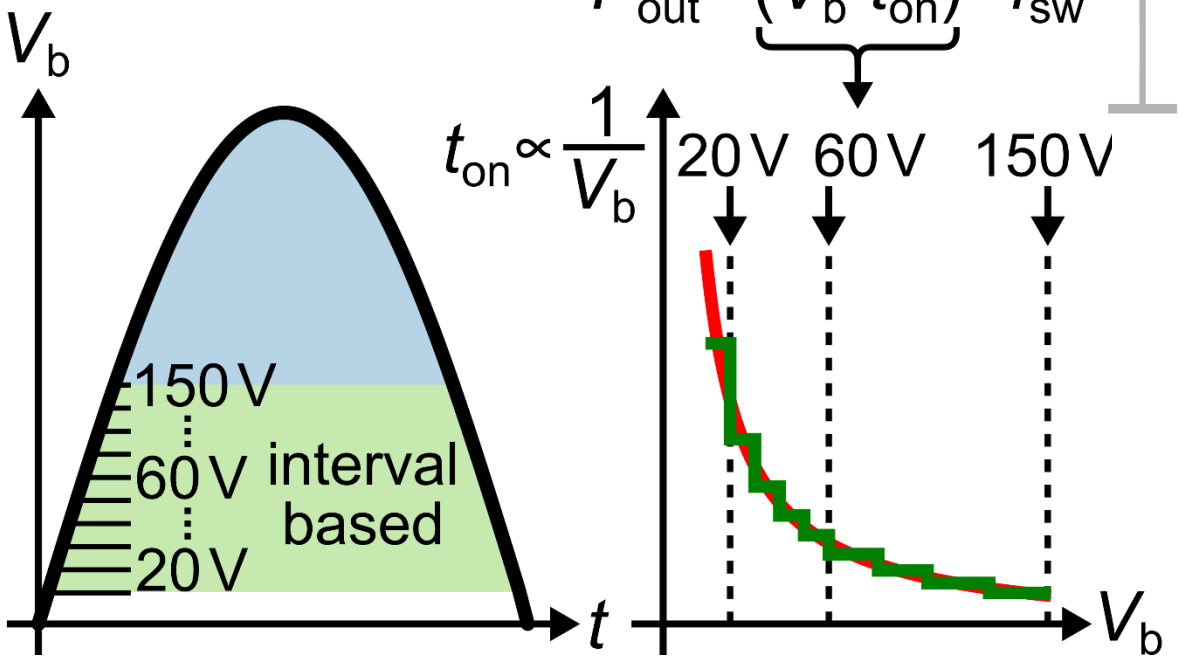
Suitable for DC-DC and AC-DC conversion



Mode 2: Interval-Based Constant-On Time Control

Conventional buck converter with HV2 permanently turned on (reuse from Mode 1)

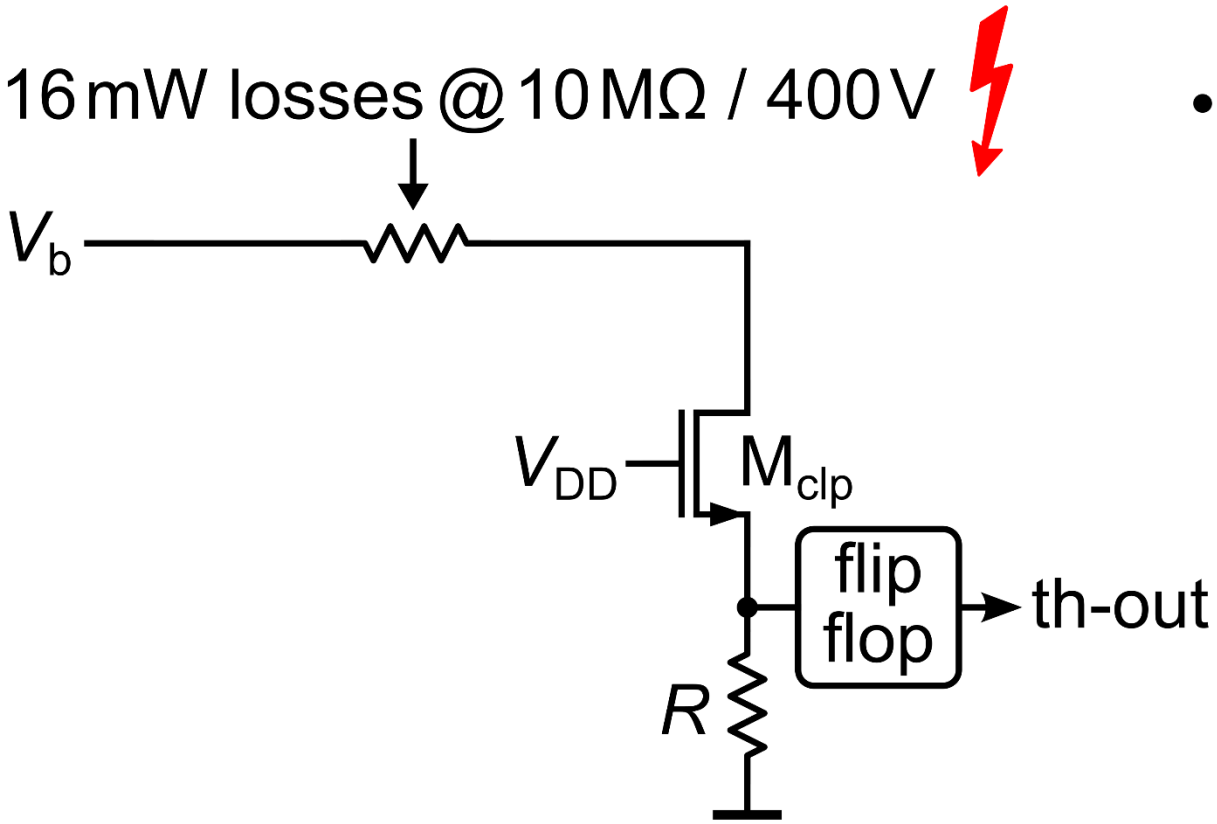




Interval-based control:

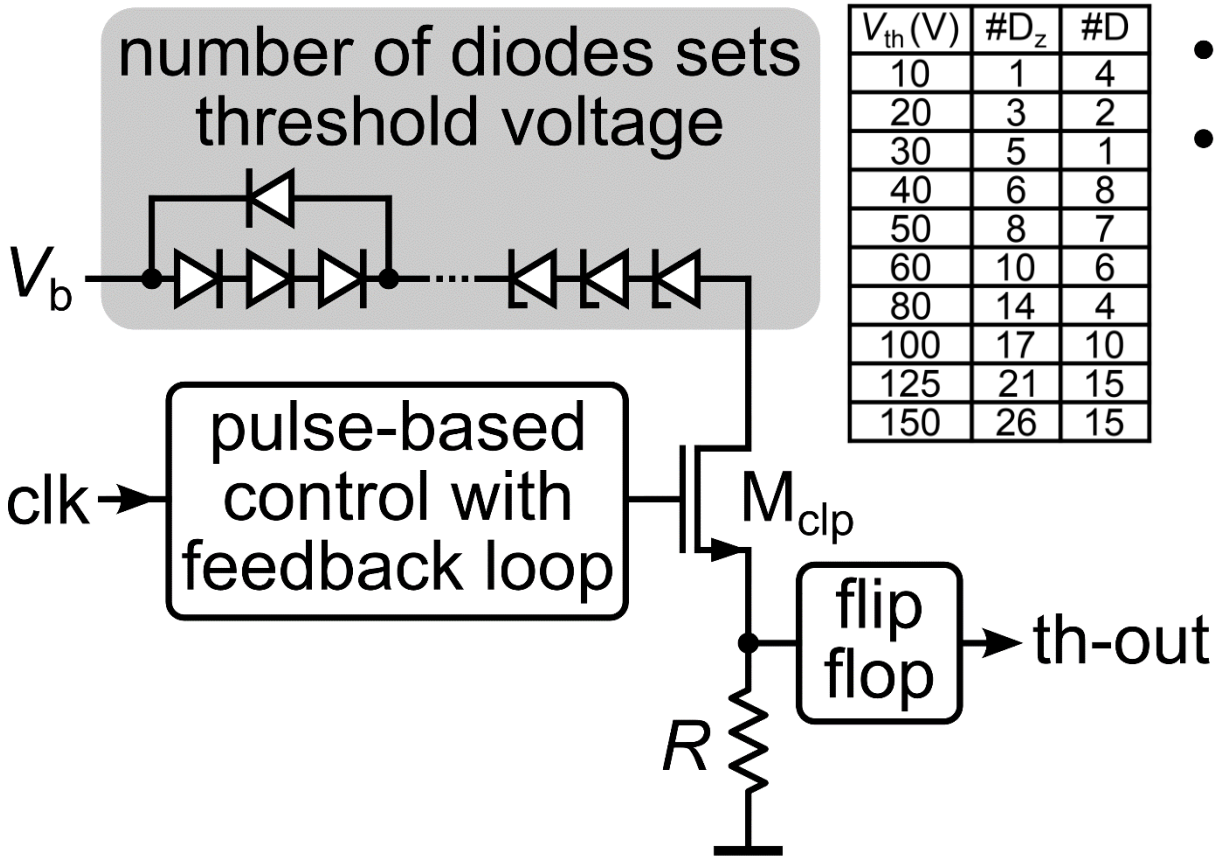
- Trade-off between control complexity and efficiency
- Lower losses than continuous control
- Look-up table, RC-delays in HS domain
- Sufficient P_{out} down to V_b ~ 0

Interval-Based Control: High-Voltage Threshold Detection



- Large efficiency impact due to resistive input-voltage sensing

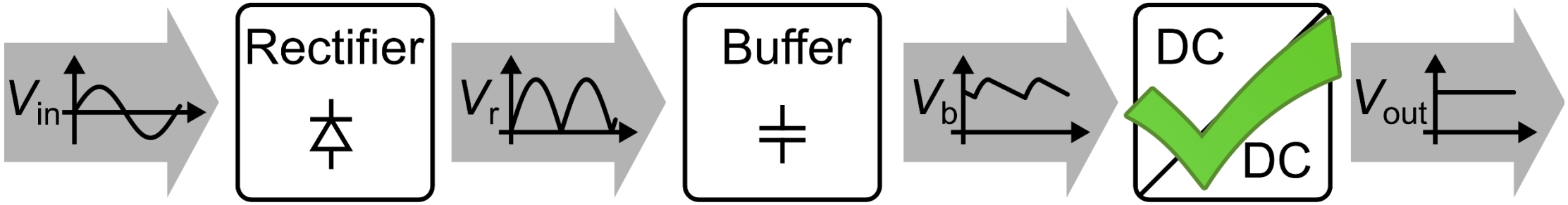
Interval-Based Control: High-Voltage Threshold Detection

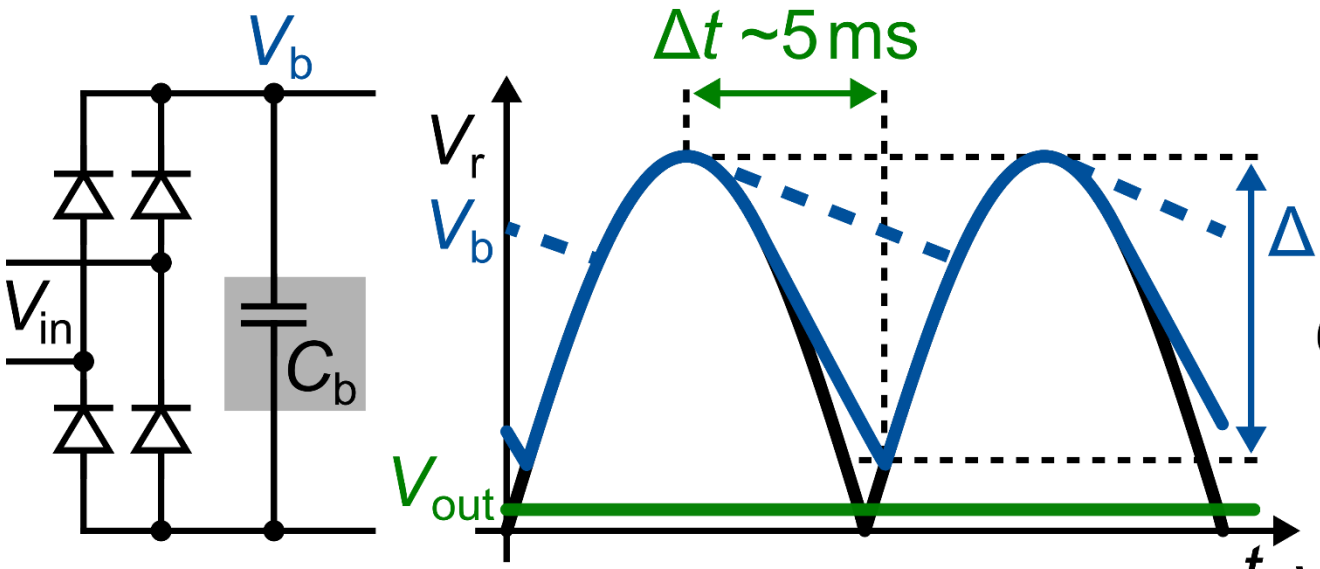


V_{th} (V)	#D_z	#D
10	1	4
20	3	2
30	5	1
40	6	8
50	8	7
60	10	6
80	14	4
100	17	10
125	21	15
150	26	15

- High-speed detection (~10 ns)
- 1000x lower power consumption
  - ➡ Negligible current below V_{th}
  - ➡ Large R reduces current above V_{th}
  - ➡ Pulse-based control with feedback loop further reduces losses

The Zero-Crossing Buffer Capacitor





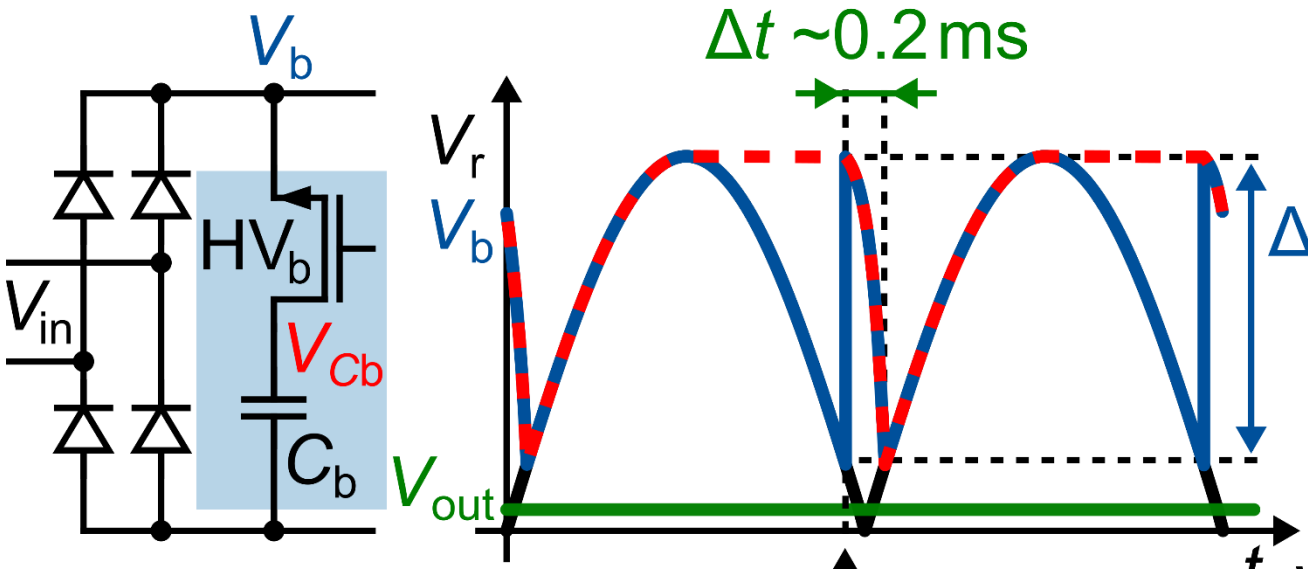
$$C_b = \frac{\Delta t \cdot I}{\Delta V_b} \propto P_{out} > 800\,\text{nF} @ 500\,\text{mW}$$

70 nF

V_b range of DC-DC converter down to 12.5 V

0.7 cm^3

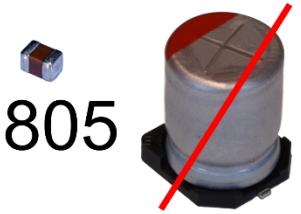
An Active Zero-Crossing Buffer



- Active zero-crossing buffer allows for higher integration

$$C_b = \frac{\Delta t \cdot I}{\Delta V_b} \propto P_{out}$$

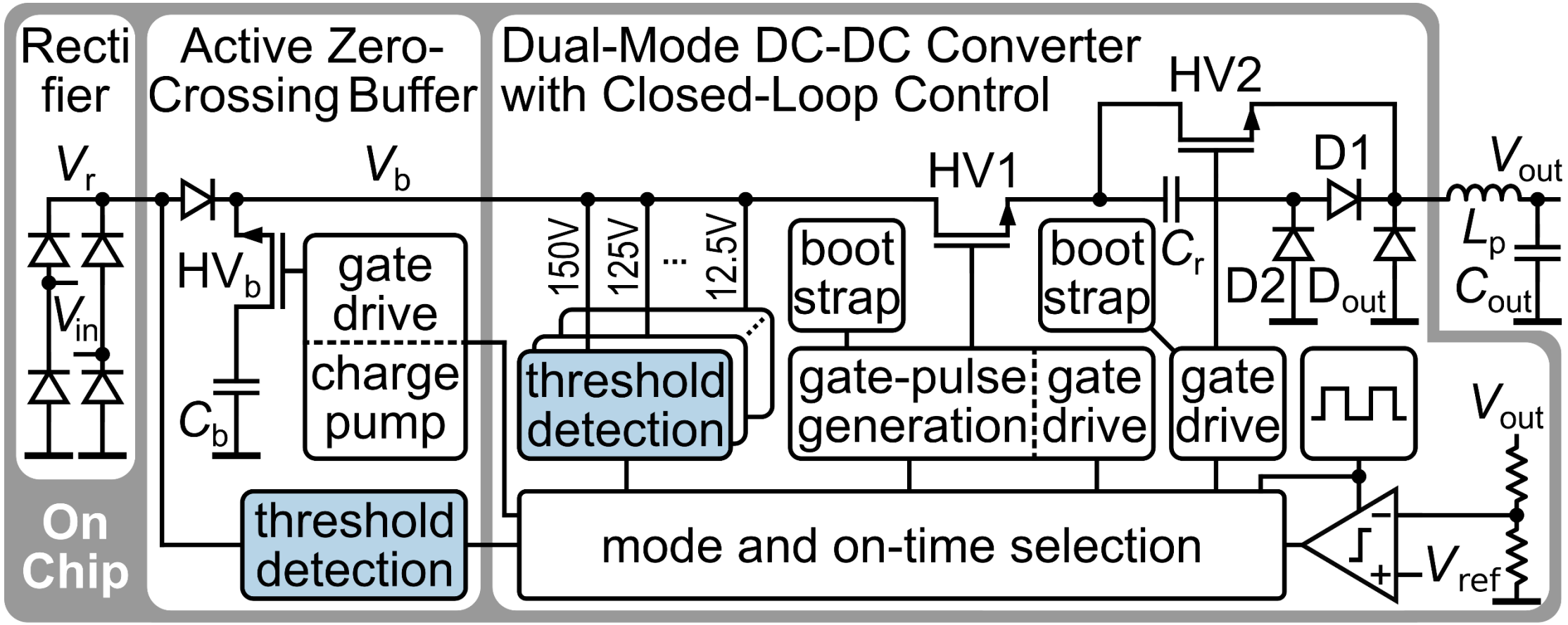
~~800 nF~~ @ 500 mW
~~70 nF~~
3.3 nF 0805



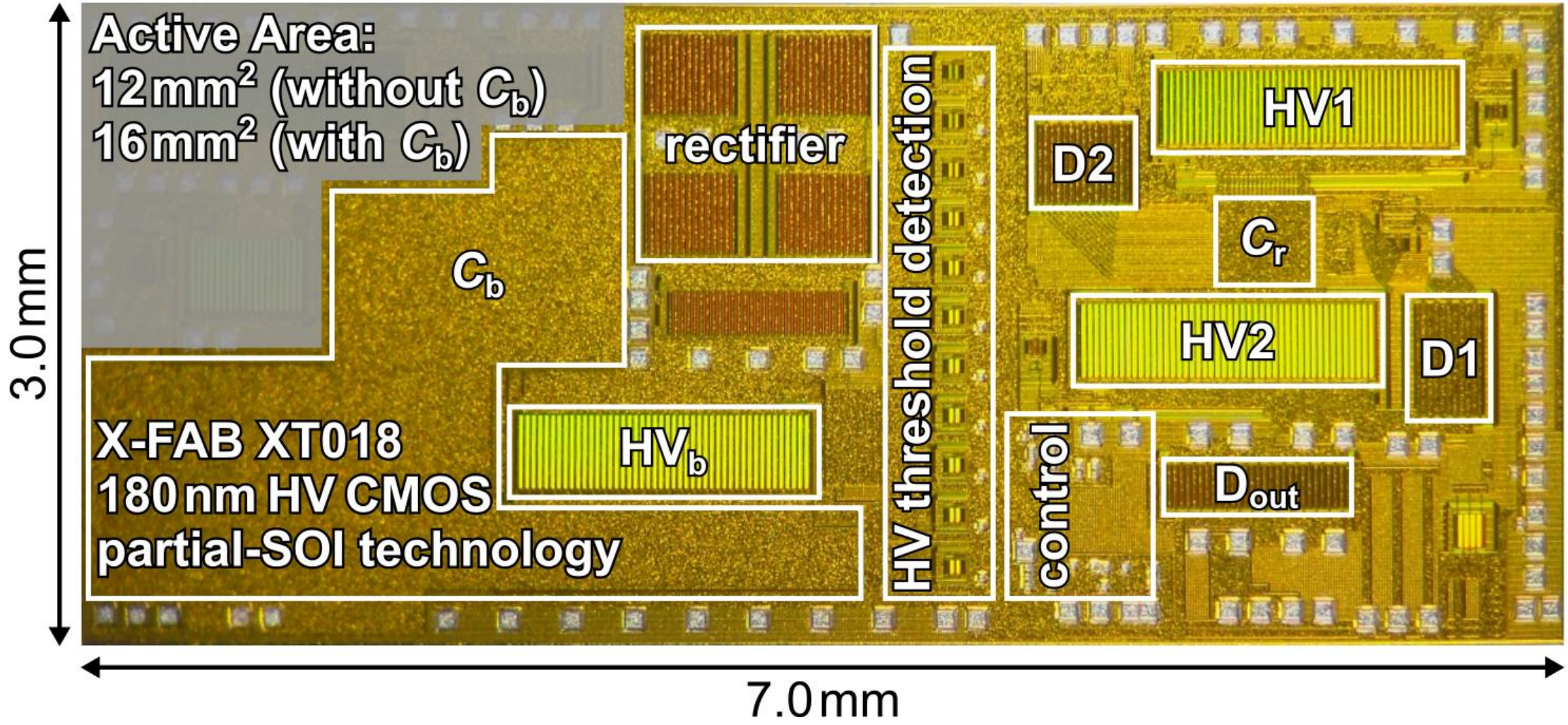
~~0.7 cm³~~

V_b range of DC-DC converter down to 12.5 V

Block Diagram of the AD-DC Converter IC

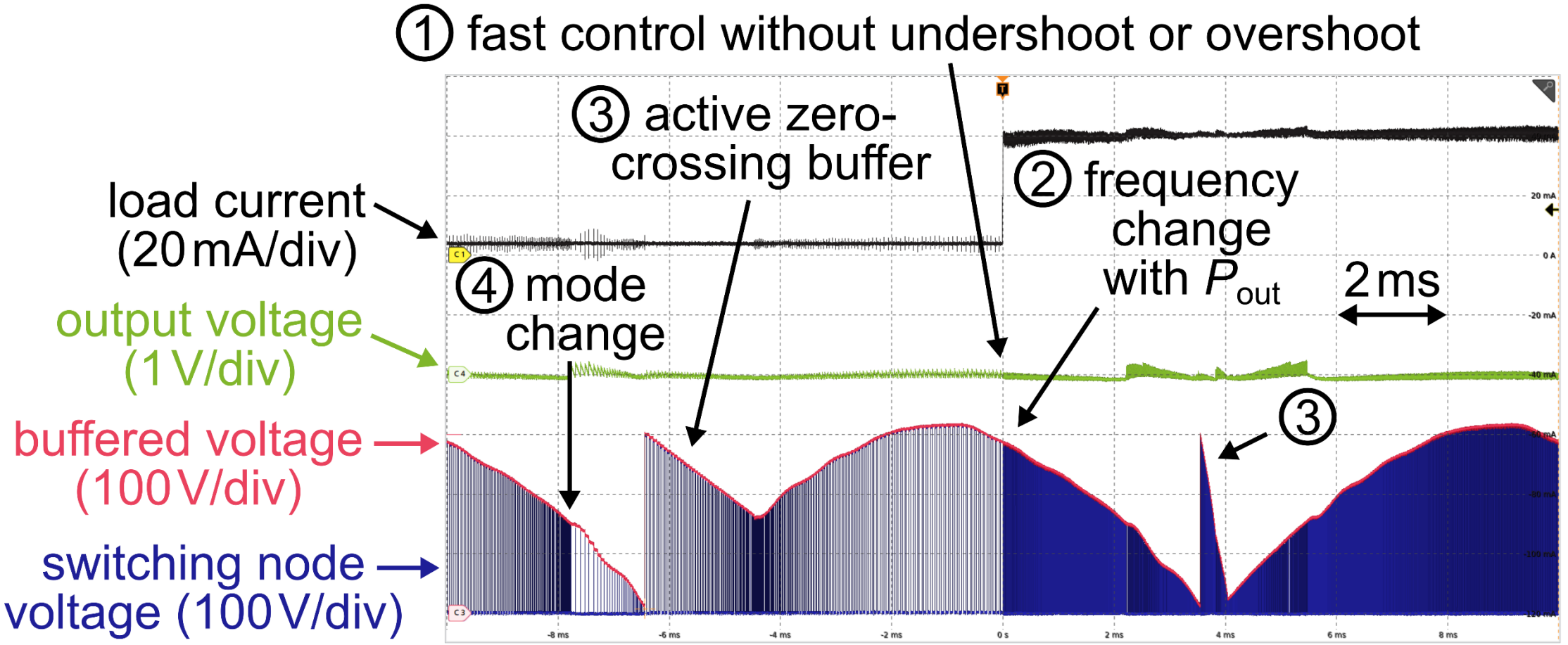


Die Photo

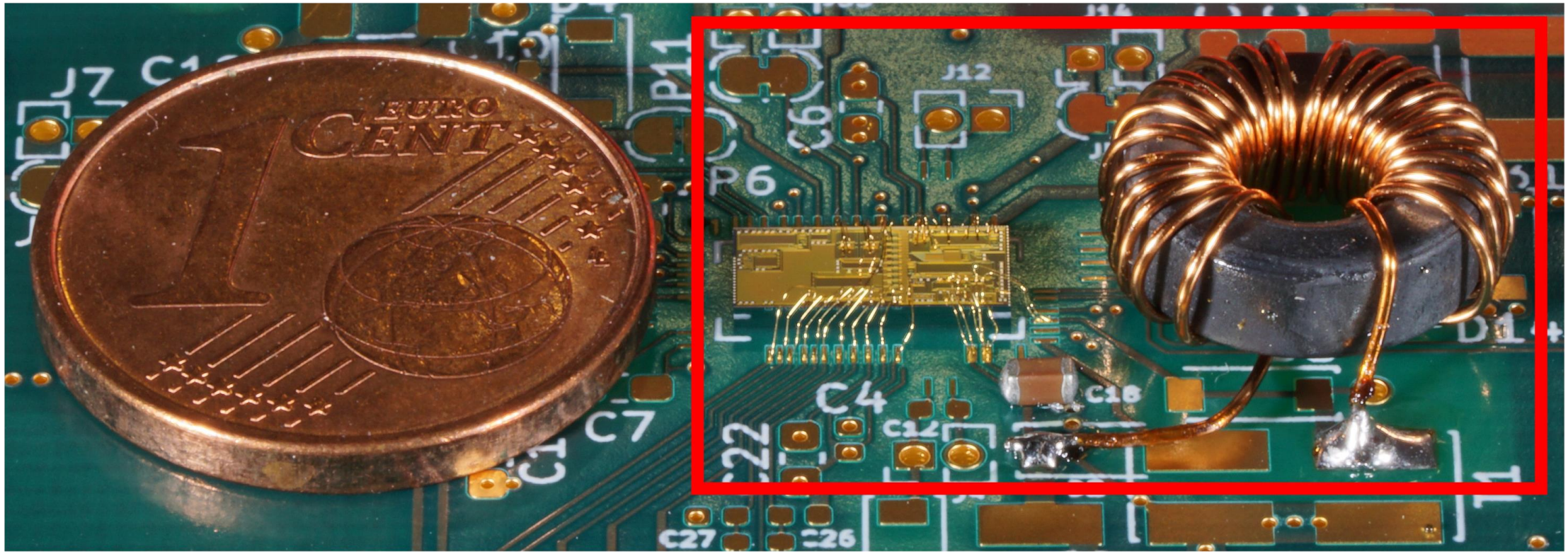

Active Area:
12 mm² (without C_b)
16 mm² (with C_b)
rectifier
C_b
HV threshold detection
D2
HV1
C_r
HV2
D1
HV_b
control
D_{out}
X-FAB XT018
180 nm HV CMOS
partial-SOI technology
3.0 mm
7.0 mm

Measured Transients – AC-DC Converter

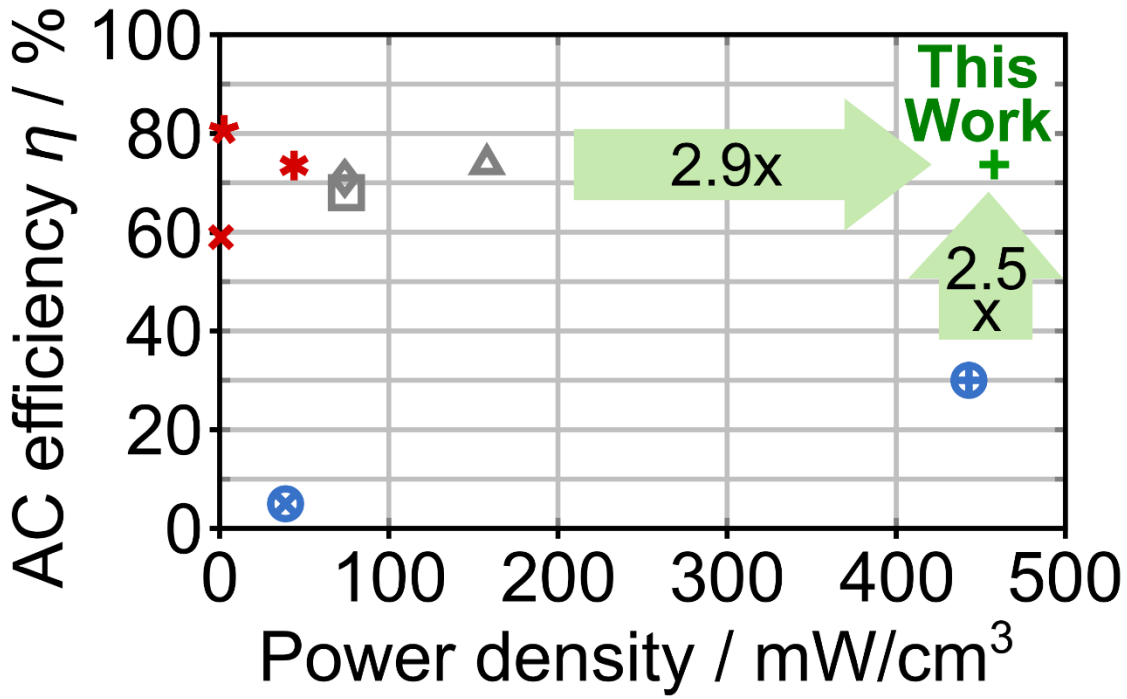
Load-step from I_{load}=4 mA to I_{load}=40 mA @ V_{in}=230 V_{RMS}, V_{out}=5 V



PCB Implementation

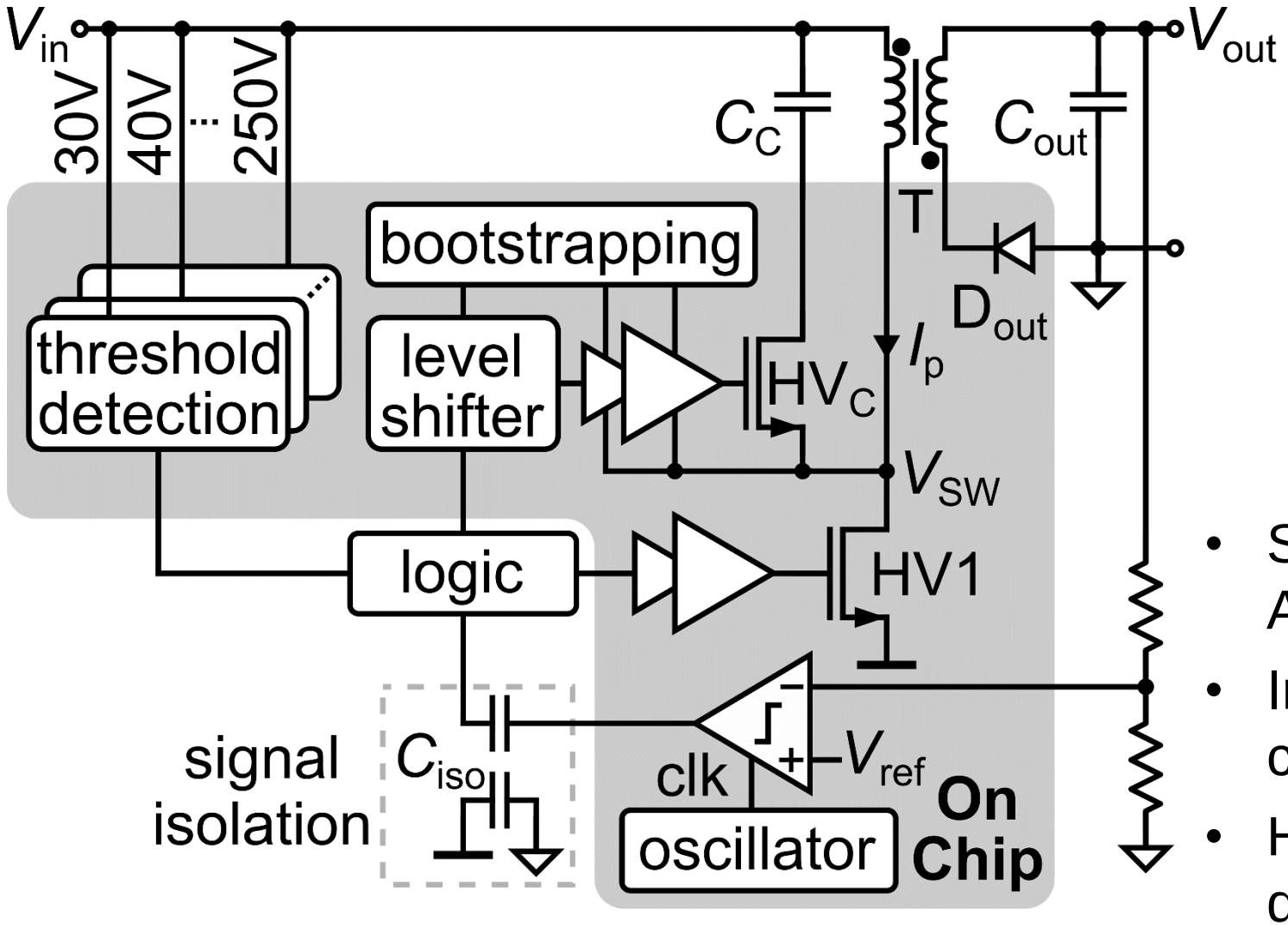


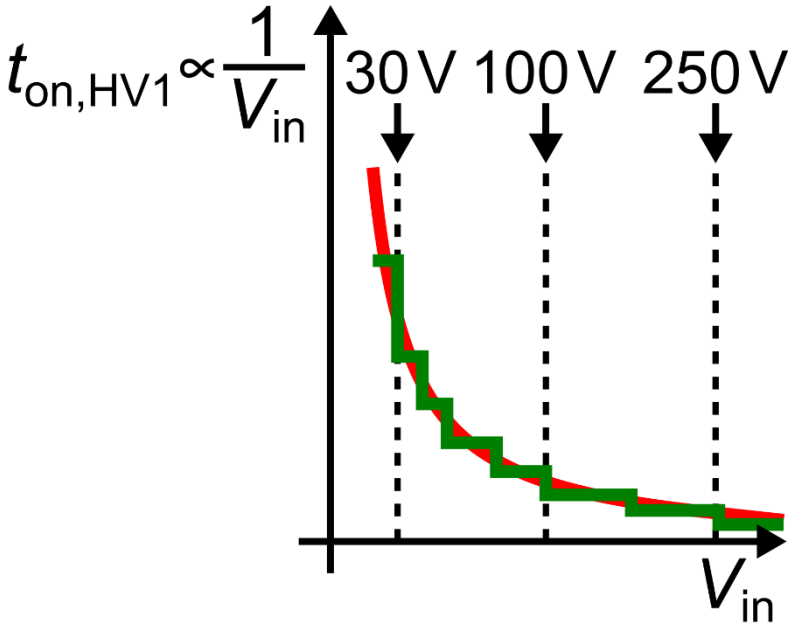
Comparison to State-of-the-Art



+ high power density: **458 mW/cm³**
+ high AC efficiency: **73.7 %**
+ high DC efficiency: **84 %**
+ all grid voltages: **110 / 230 V_{RMS}**
+ wide $V_{in,DC}$ range: **12.5 V - 400 V**

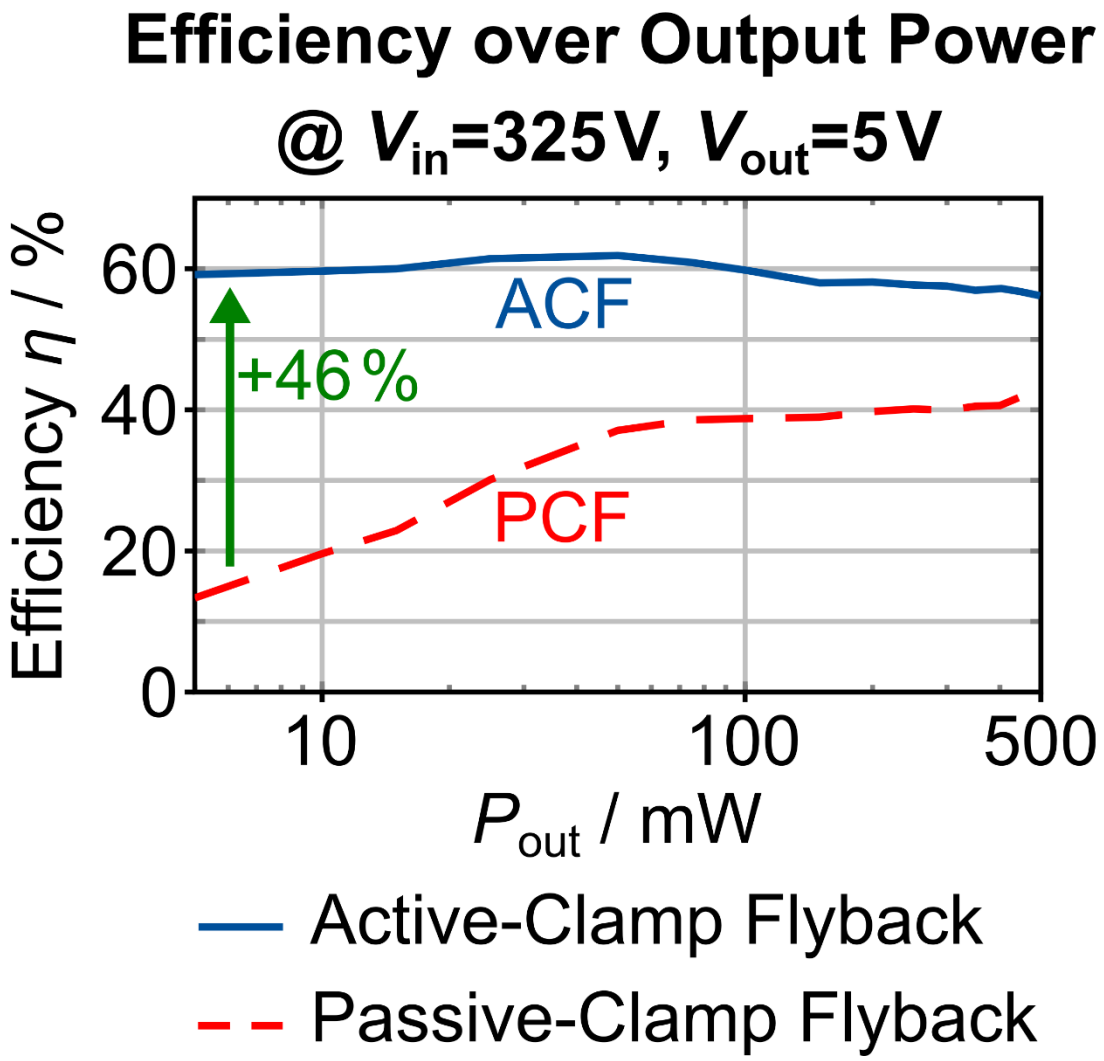
Active-Clamp Flyback



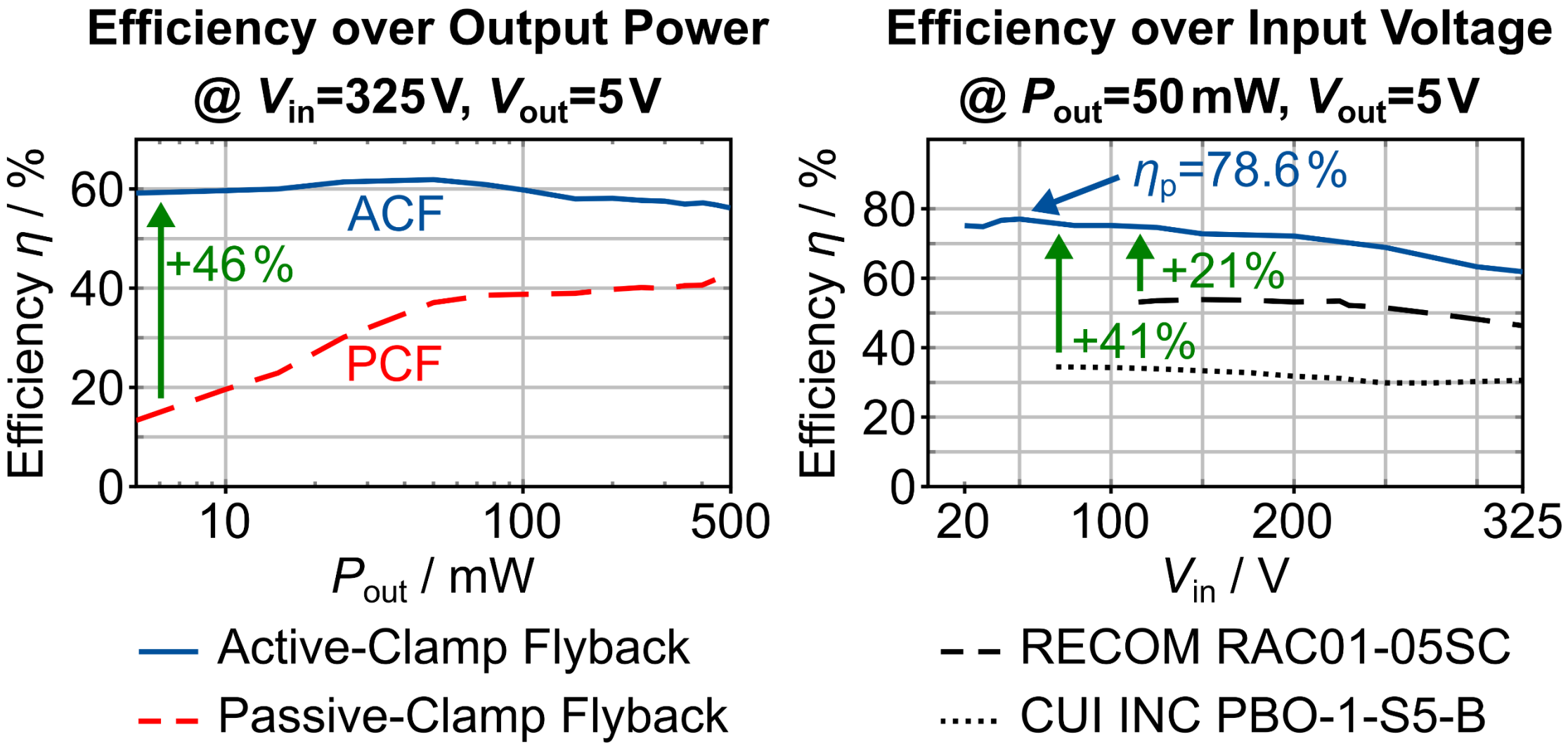


- Same block-level circuits as for AC-DC
- Interval-based constant on-time control
- High-speed, low-loss threshold detection

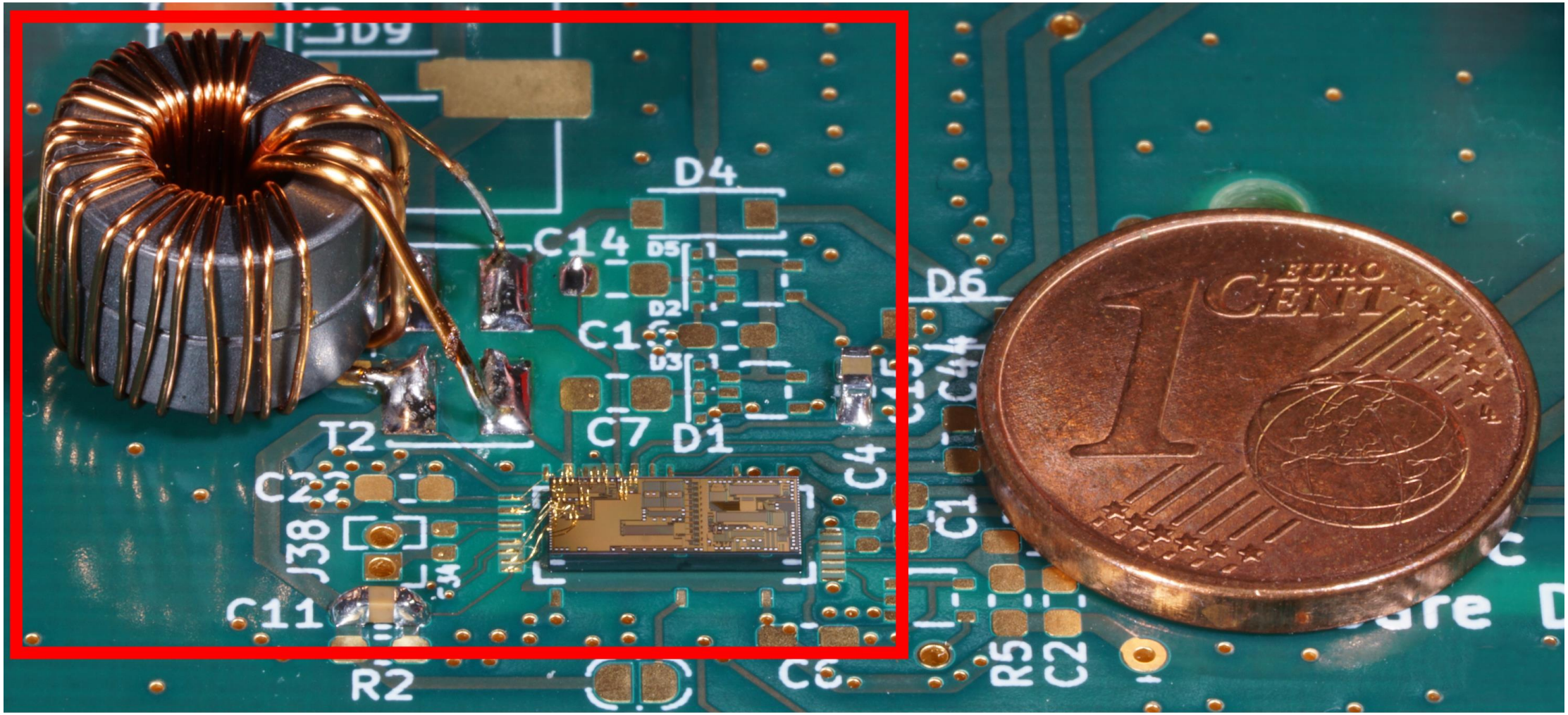
Measured Efficiency



Measured Efficiency

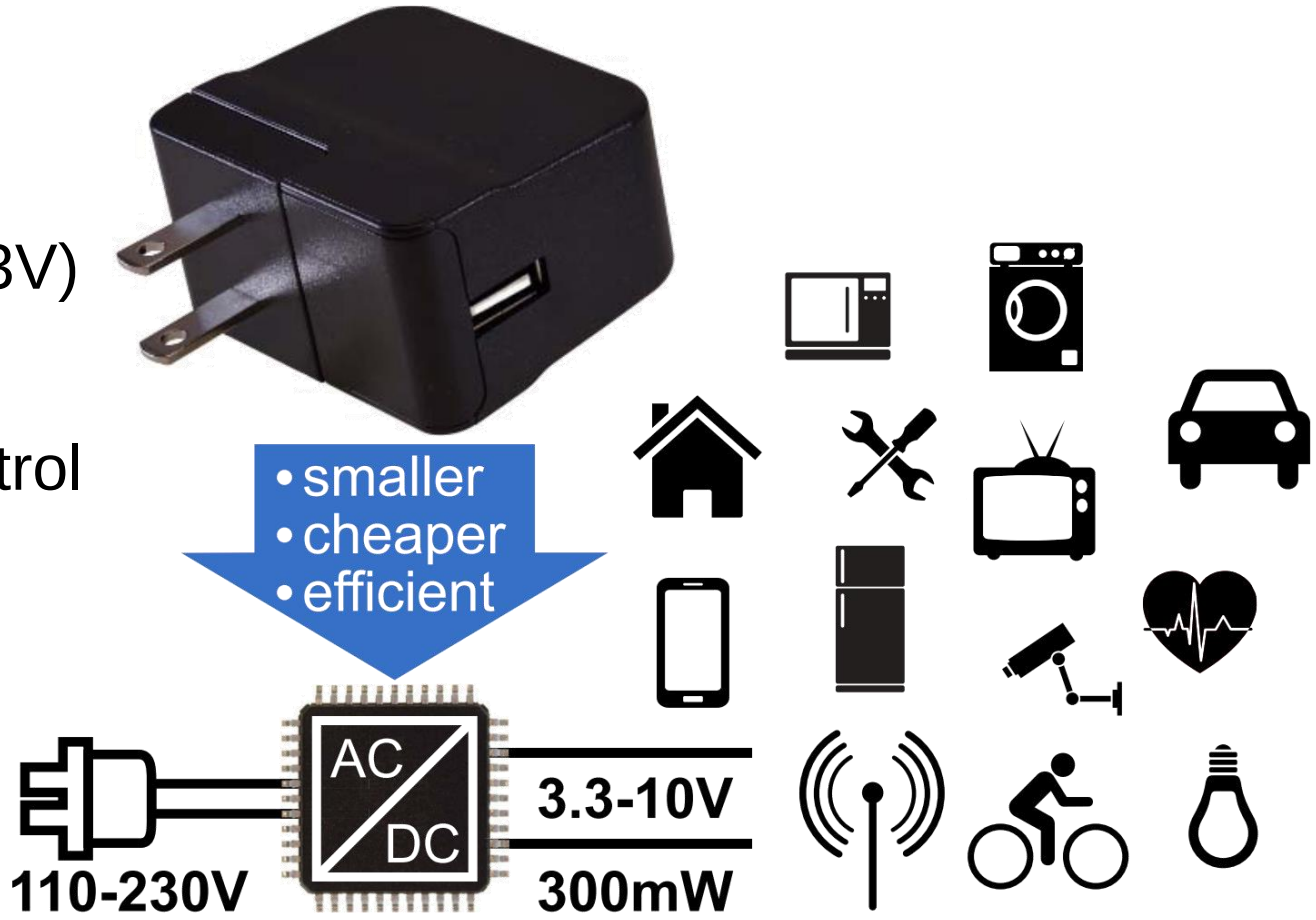


PCB Implementation



Conclusion

- Chip-scale DC-DC and AC-DC converter designs
- High conversion ratios (400V → 3.3V)
- Topology and Design:
  - Intervall-based control COT control
  - Low-power threshold detection
  - Buffer size reduction
- Technology and Layout:
  - SOI
  - Capacitive-loss reduction



Acknowledgement

This presentation is based on the Ph.D. research of Christoph Rindfleisch.

Thanks to X-FAB for partially supporting the IC fabrication and to Alexander Hölke and Elizabeth Tee for their advice and support.

References

[1] C. Rindfleisch and B. Wicht, “A 110/230 V AC and 15–400 V DC 0.3 W Power-Supply IC With Integrated Active Zero-Crossing Buffer,” JSSC, Dec. 2022

[2] C. Rindfleisch and B. Wicht, “A 110V/230V 0.3W Offline Chip-Scale Power Supply with Integrated Active Zero-Crossing Buffer and
Voltage-Interval-Based Dual-Mode Control,” ISSCC 2022

[3] C. Rindfleisch et al., “A Highly-Integrated 20-300V 0.5W Active-Clamp Flyback DCDC Converter with 76.7% Peak Efficiency,” CICC 2022

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