Wide Bandgap Integration Trends and Opportunities

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Motivation

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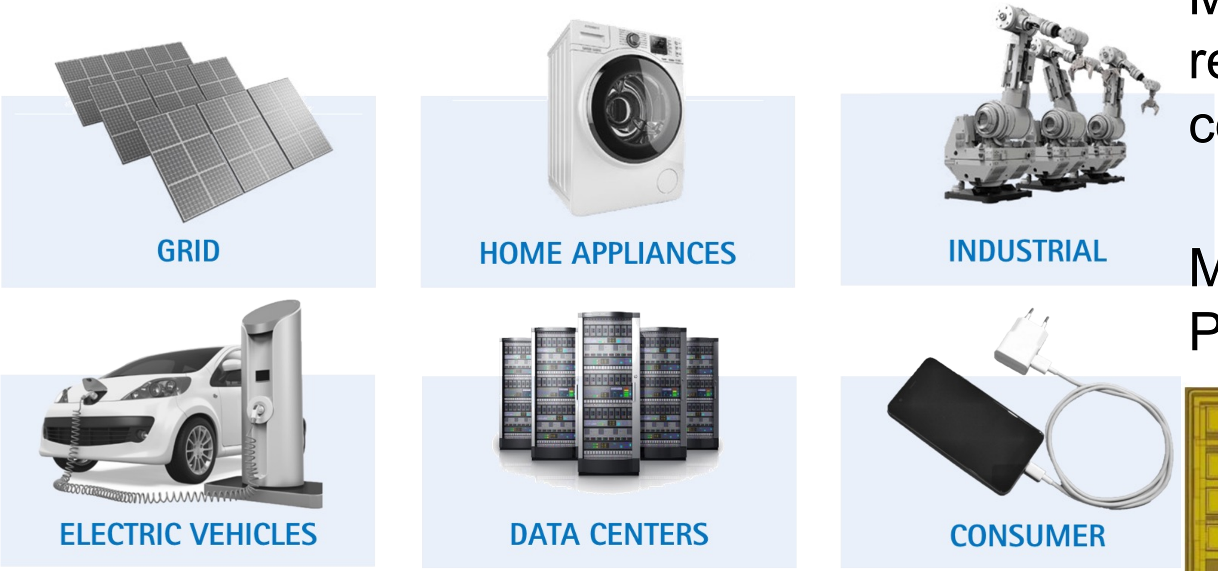
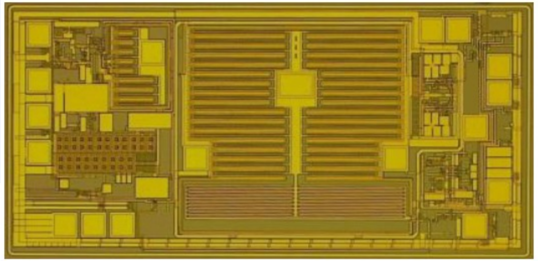
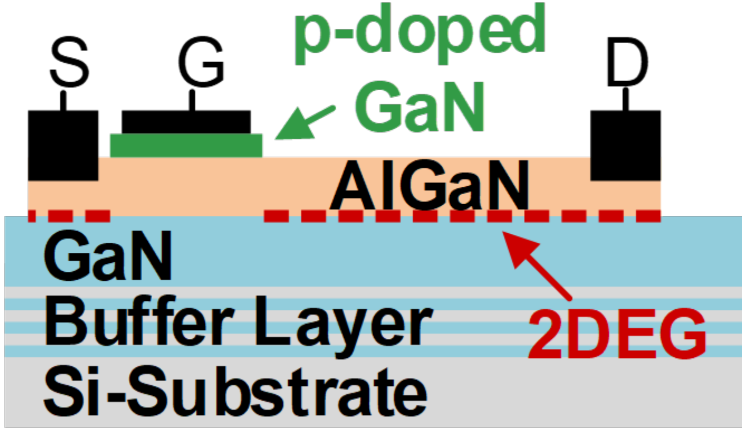


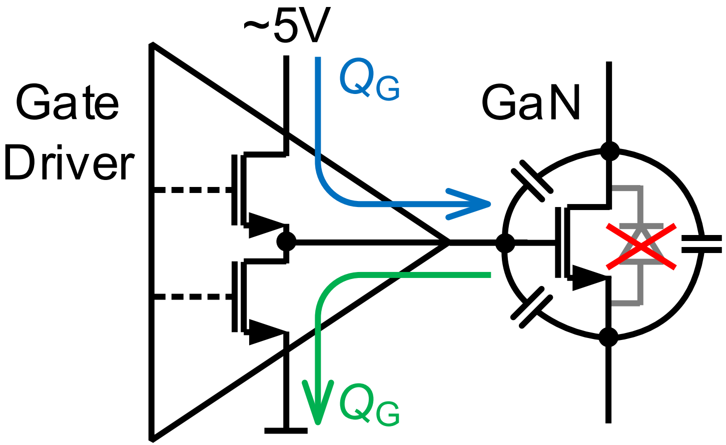
Miniaturization, effciency, reliability & controllability, cost

Monolithic GaN integration: Power + Control



The E-Mode GaN Device

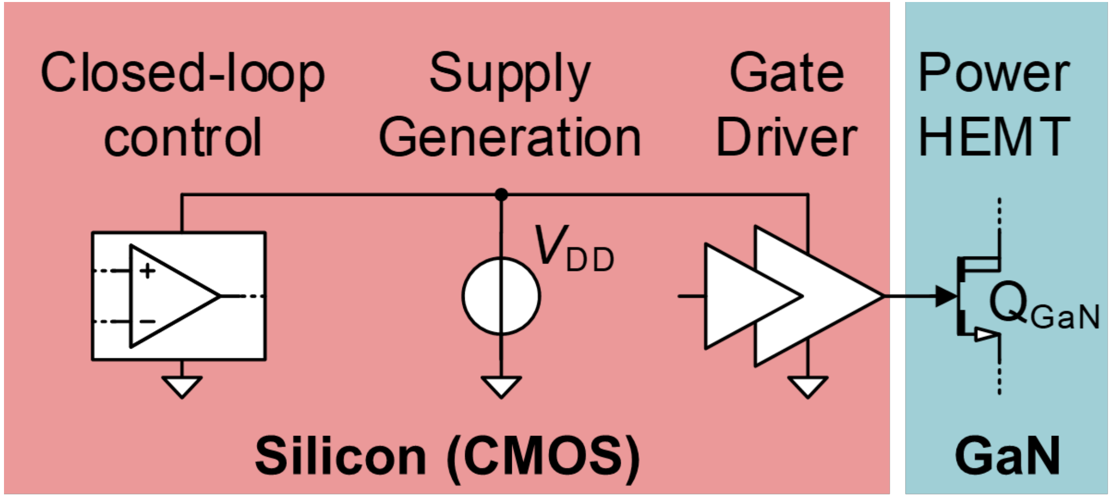




- Utilizes high electron mobility of GaN: Small chip area → lower parasitic capacitance → high speed, efficiency, miniaturization, lower system cost
- No junction → no body diode, zero reverse recovery charge Q_{RR}
- >10x lower gate charge Q_G vs. silicon
- Lateral device: Simpler monolithic integration and packaging → GaN ICs

System Integration: The Conventional Approach

GaN + Silicon Gate Driver and Control



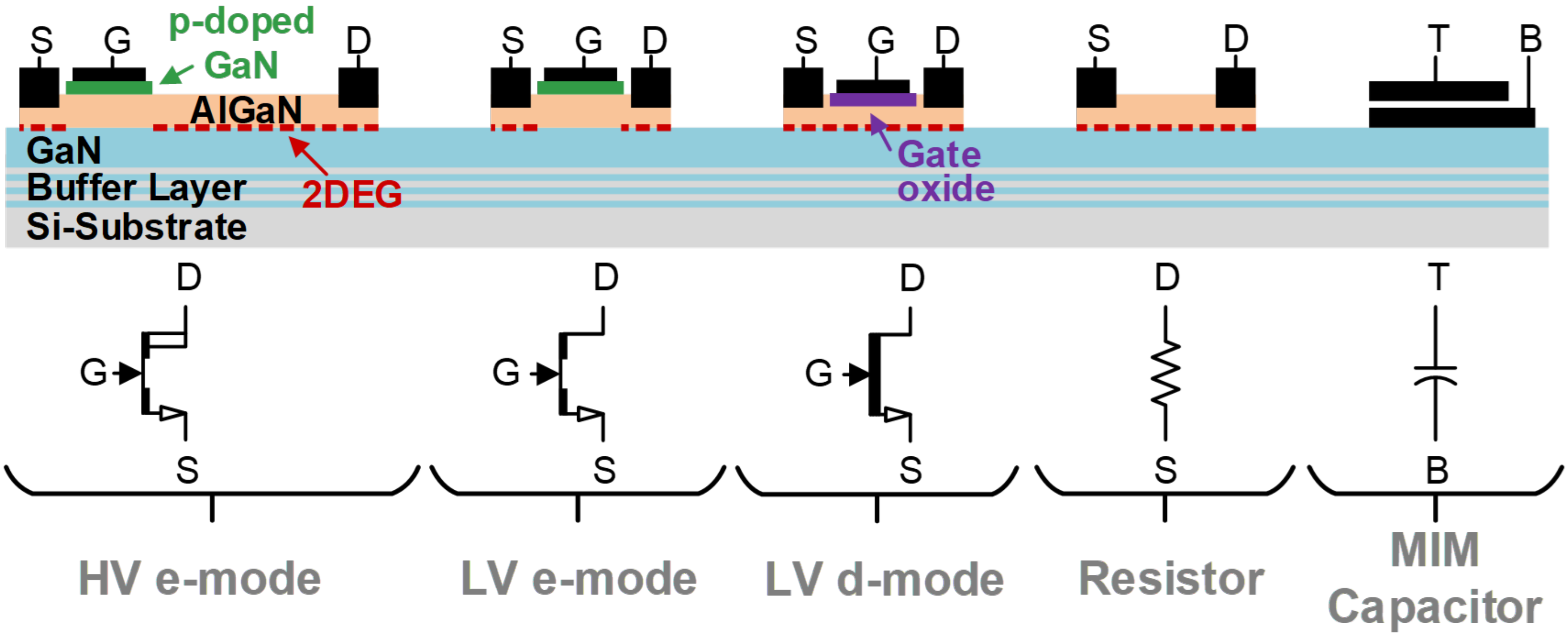
Recent products: LMG341xR050 (TI 2020), MASTERGAN1 (ST 2020)

Monolithic GaN Integration

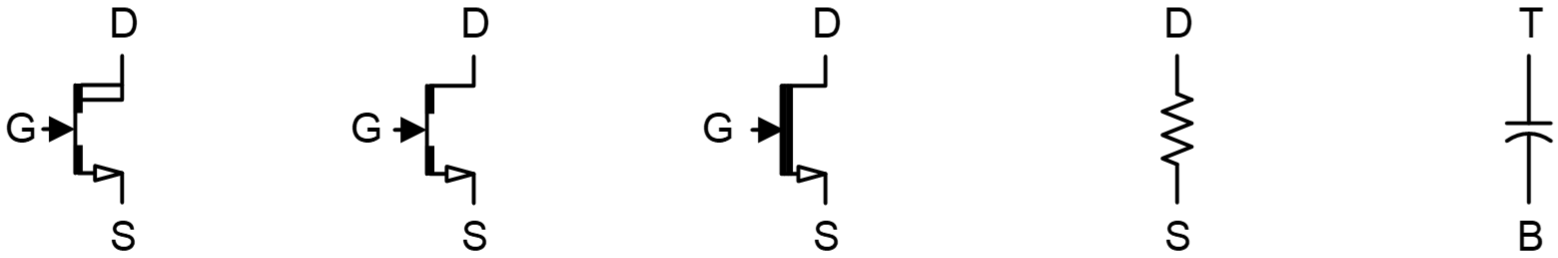
Monolithic GaN-ICs – Foundries and Vendors

tsmc
imec
EXAGAN
Accelerate Power Transition
Navitas
GaN Systems
ON
ON Semiconductor
ST
intel
EPISIL
dialog
SEMICONDUCTOR
EPC
EFFICIENT POWER CONVERSION
Sanan IC

Monolithic GaN Integration: Available Devices



Monolithic GaN Integration: Opportunities and Challenges



- Monolithic integration: Gate loop inductance → 0
- Tracks PVT variations of the driving voltage for the integrated GaN power device

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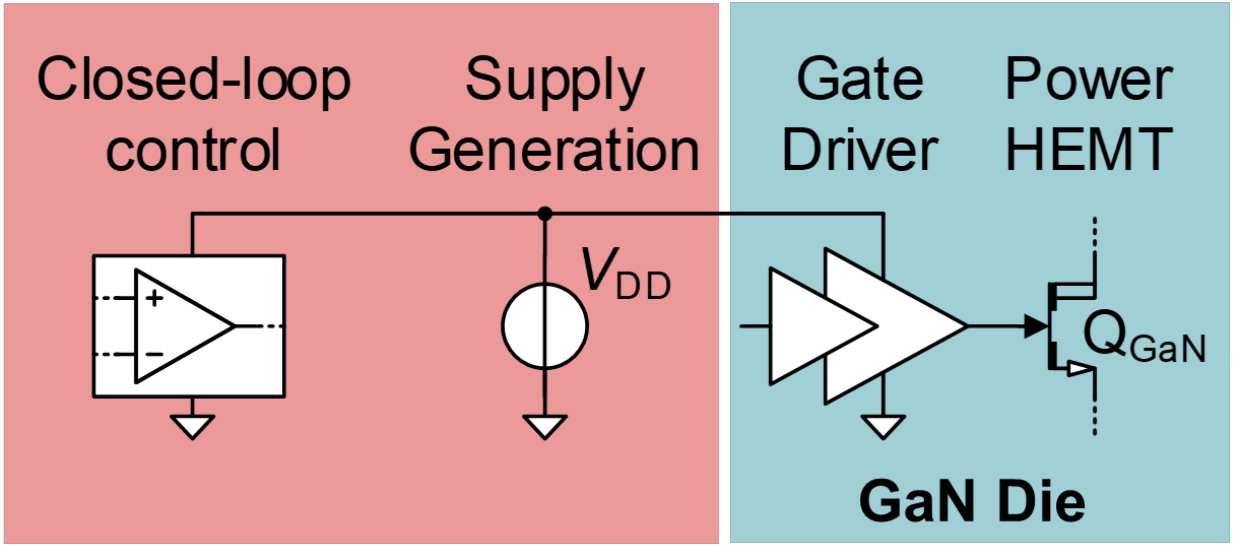
- Limited device types and options, no p-type
- No diodes, neither designed nor parasitic
- Immature technology with poor analog properties (gain, matching, noise)

To be addressed on system and circuit level: *"learning from the 1970s"*

Monolithic GaN Integration: System Partitioning

Gate driver and power transistor in GaN → nearly zero gate loop inductance:



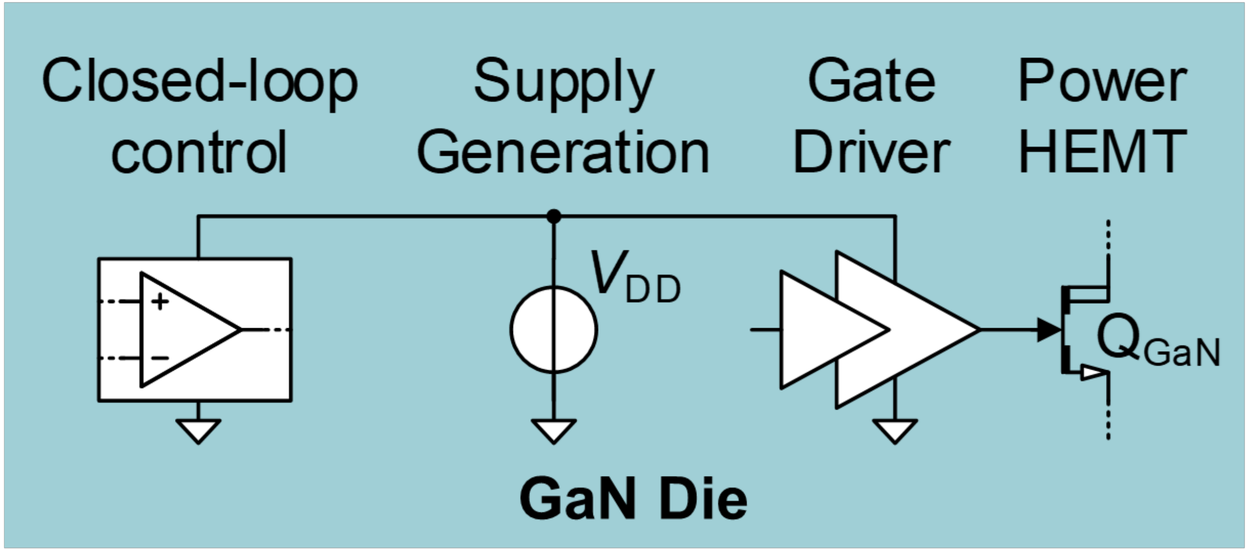
Xue et al. (Navitas), APEC 2017 [4]

Recent products:

- GaNFast™ Power IC (Navitas 2020) → includes supply regulator
- ePower™ Stage 80 V, 15 A (EPC 2021) → includes bootstrap rectifier

Monolithic GaN Integration: System Partitioning

Full system in GaN:

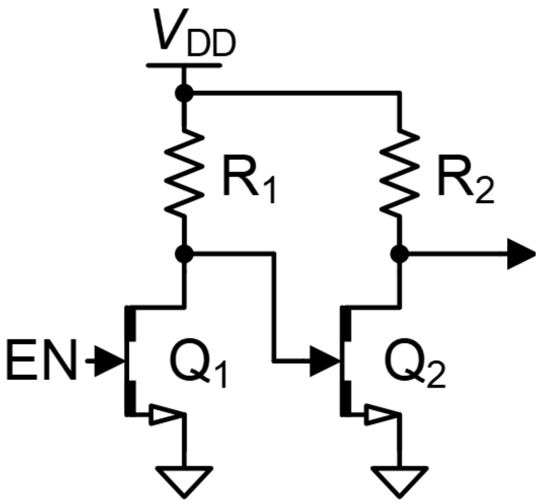


Kaufmann et al., ISSCC 2020 [5], [6]

GaN Gate Drivers

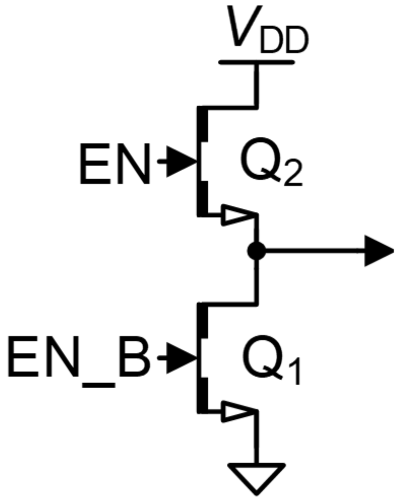
Gate Driver without p-Type Device

Resistor Pull-Up



- Large quiescent current
- Nearly rail-to-rail output

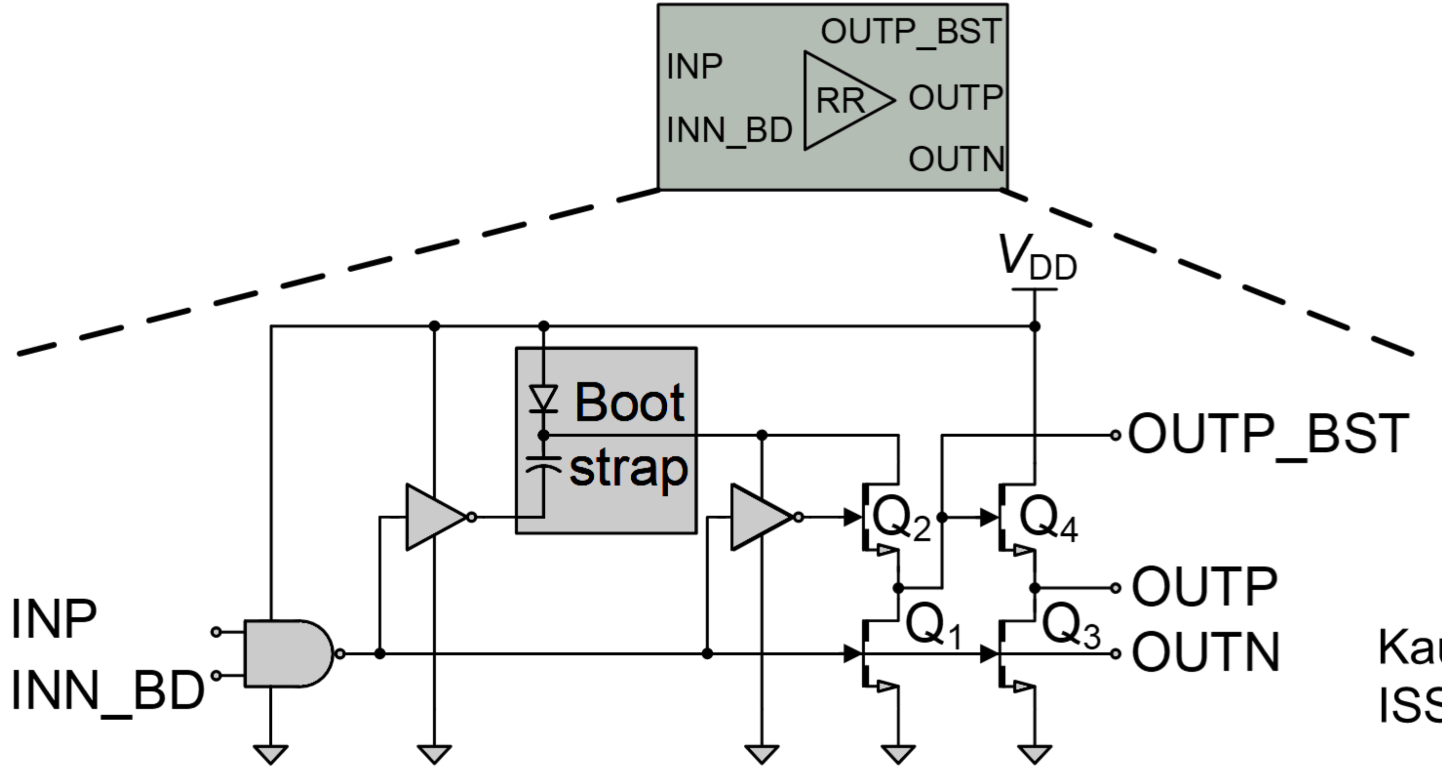
N-Type Pull-Up



- Low quiescent current
- Output GND … VEN-Vth2

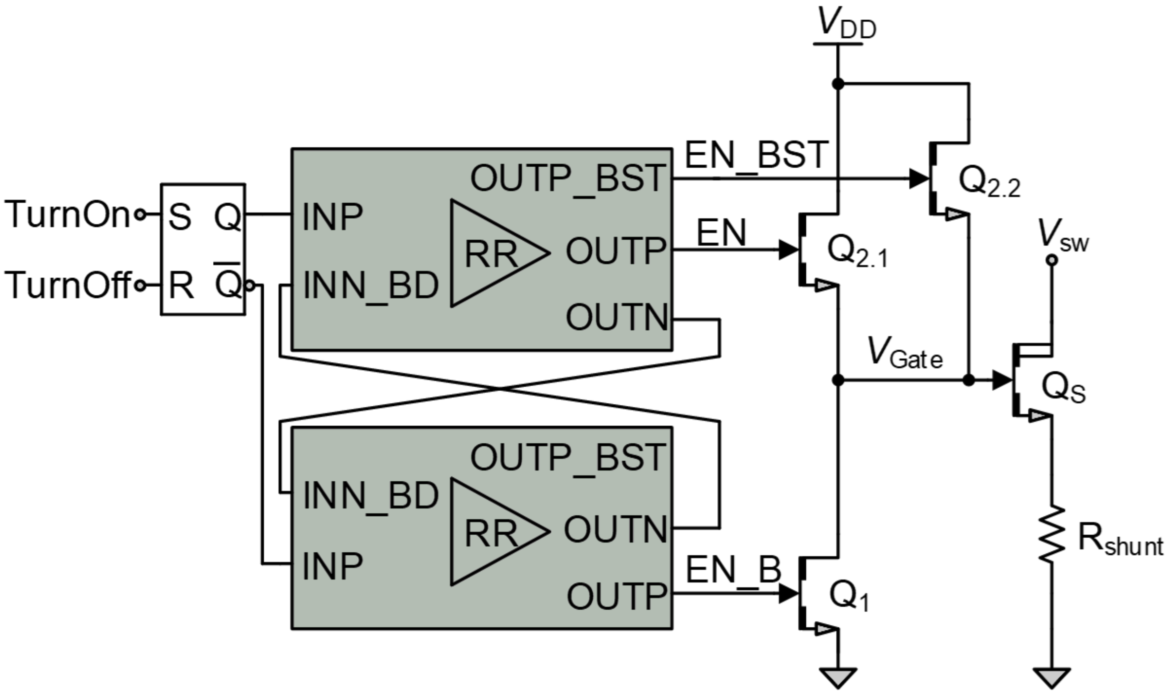
→ Bootstrapped EN signal (V_{DD}+V_{th}) required for rail-to-rail operation

Bootstrapped n-Type Rail-to-Rail Gate Driver



Kaufmann et al., ISSCC 2020 [5], [6]

Gate Driver Toplevel

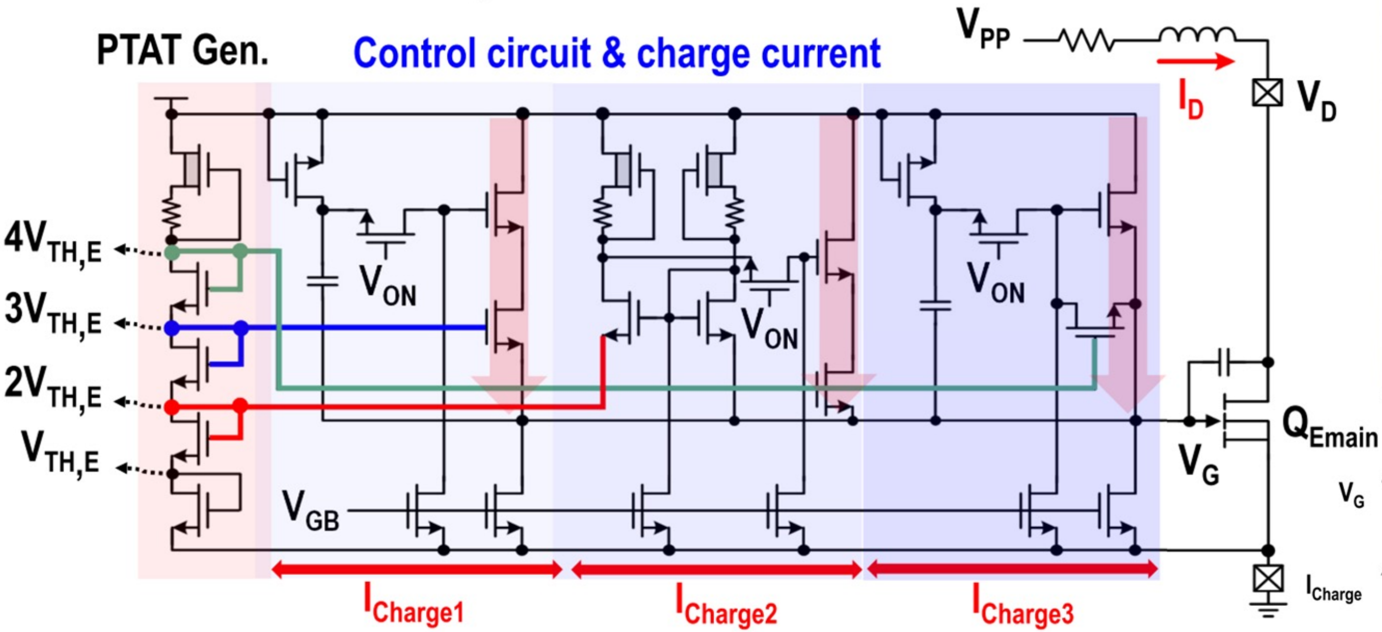


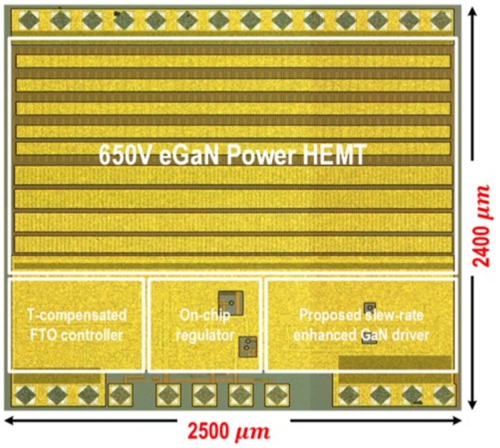
Kaufmann et al., ISSCC 2020 [5], [6]

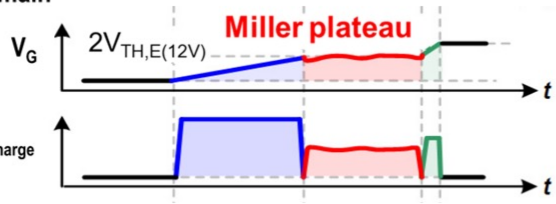
- Split pull-up Q2 for quick and efficient turn-on
- Identical rail-to-rail driver for pull-up and pull-down

Gate Driver with Miller-Plateau Tracking

Based on Vth-sensing and PTAT circuit in GaN



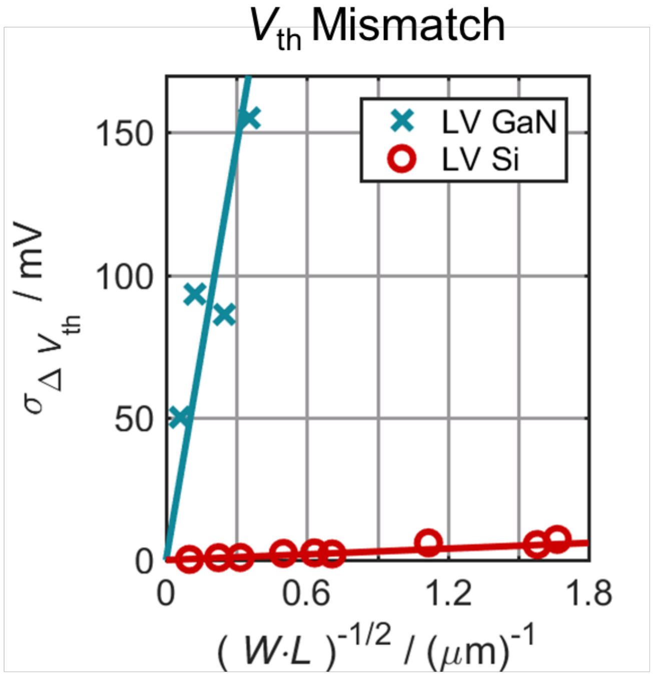


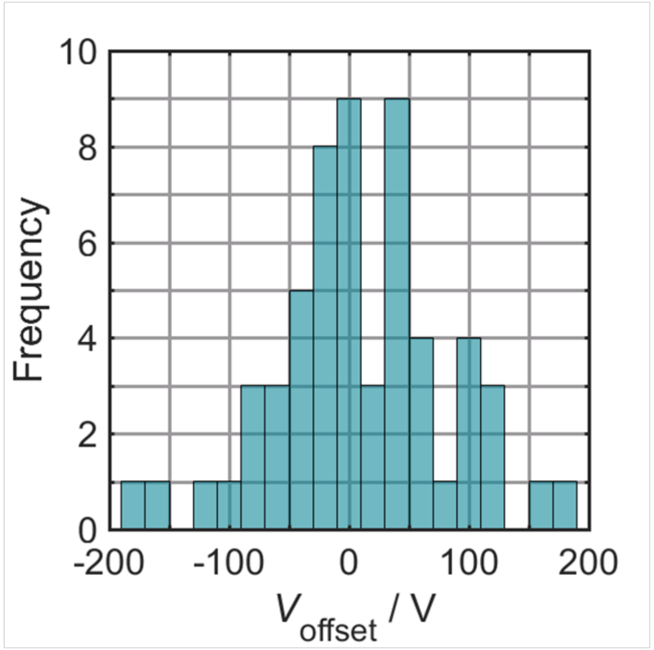


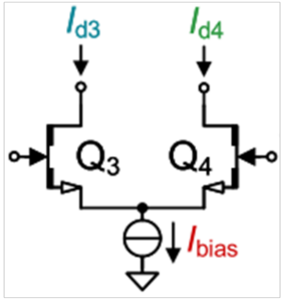
H.-Y. Chen et al. ISSCC 2021 [7]

Sensing and Control

Technology Challenges: Matching

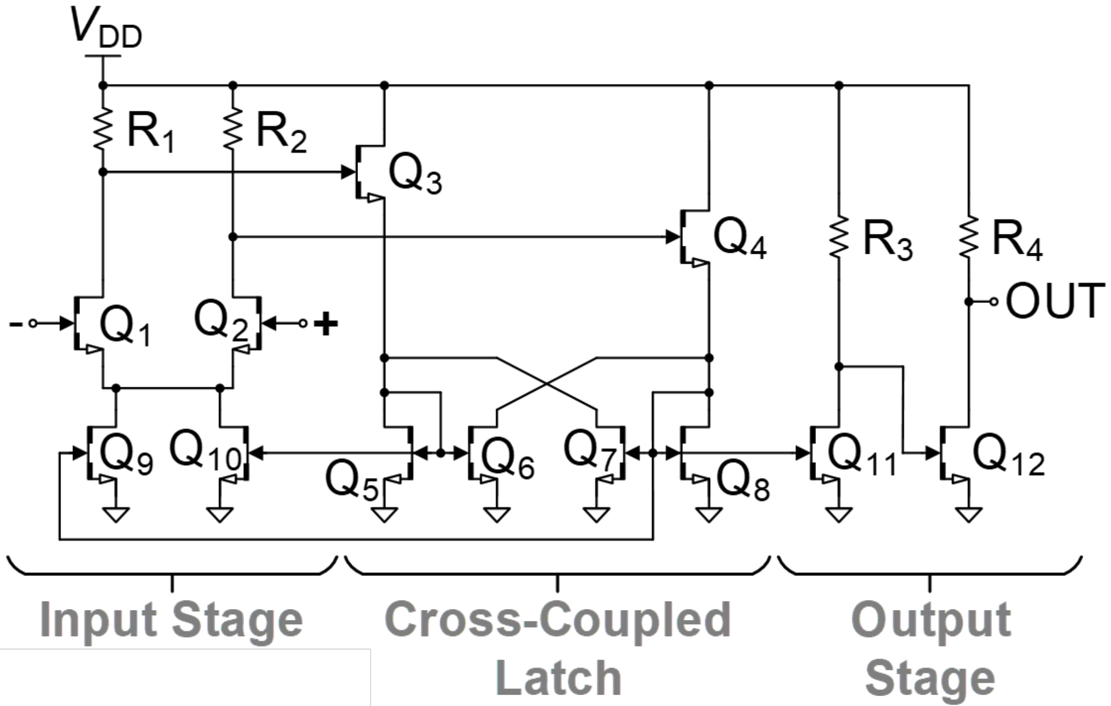






- Pelgrom's matching law $\sigma_{\Delta Vth} \propto 1/\sqrt{W \cdot L}$ (JSSC 1989) is also valid for GaN
- Much larger mismatch of GaN leads to +/- 200mV Offset

Comparator with Autozeroing (all in GaN)

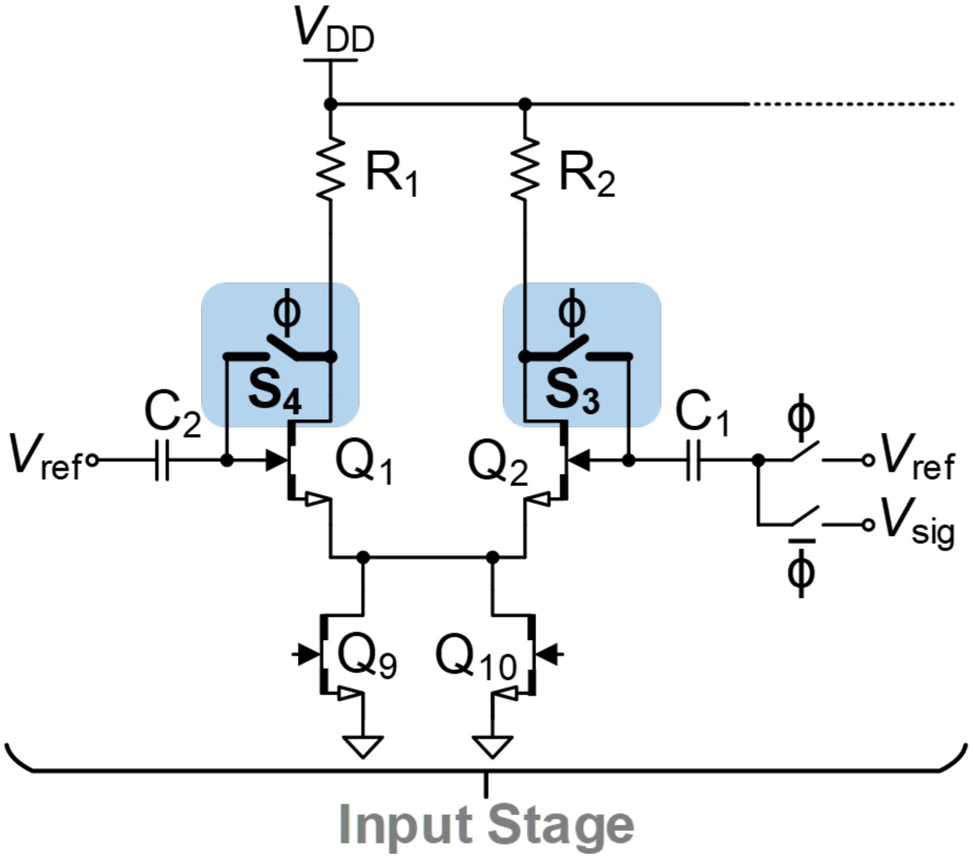


- Input stage
- Common-mode feedback for self-biasing
- Cross-coupled latch
- Full-swing output stage $Q_{11,12}$ and $R_{3,4}$

Inspired by Tsividis et al., JSSC 1980 [8]

Challenges:
Low input common mode < Vth, poor matching → offset ~200mV

Autozeroing



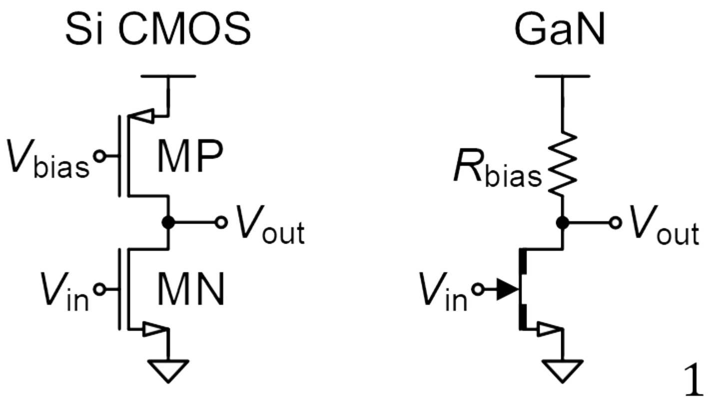
ϕ=1: Differential pair in unity gain

- Input referred offset sampled on $C_{1,2}$
- $C_{1,2}$ additionally used for level shifting to support input common-mode < V_{th}

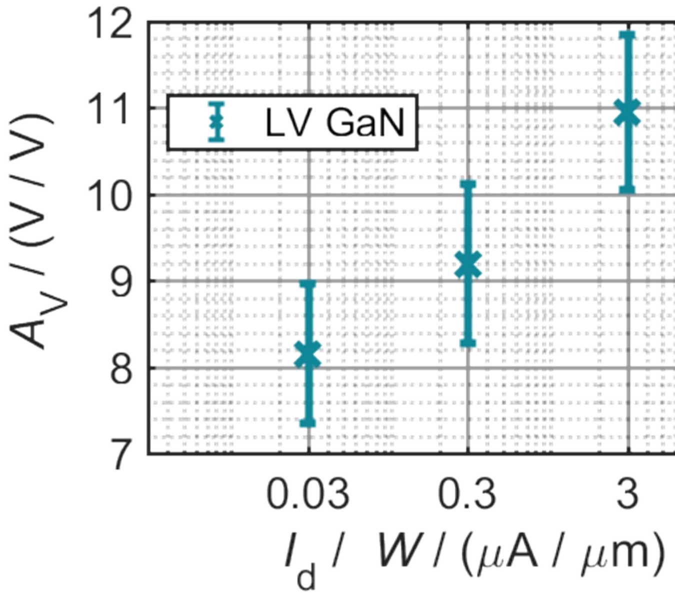
ϕ=0: Regular comparator operation

→ Switches $S_{3,4}$ implemented as bootstrapped n-type transistors

Technology Challenges: Voltage Gain



$$r_{load} = R_{bias} \sim \frac{1}{10} \cdot r_{ds}$$

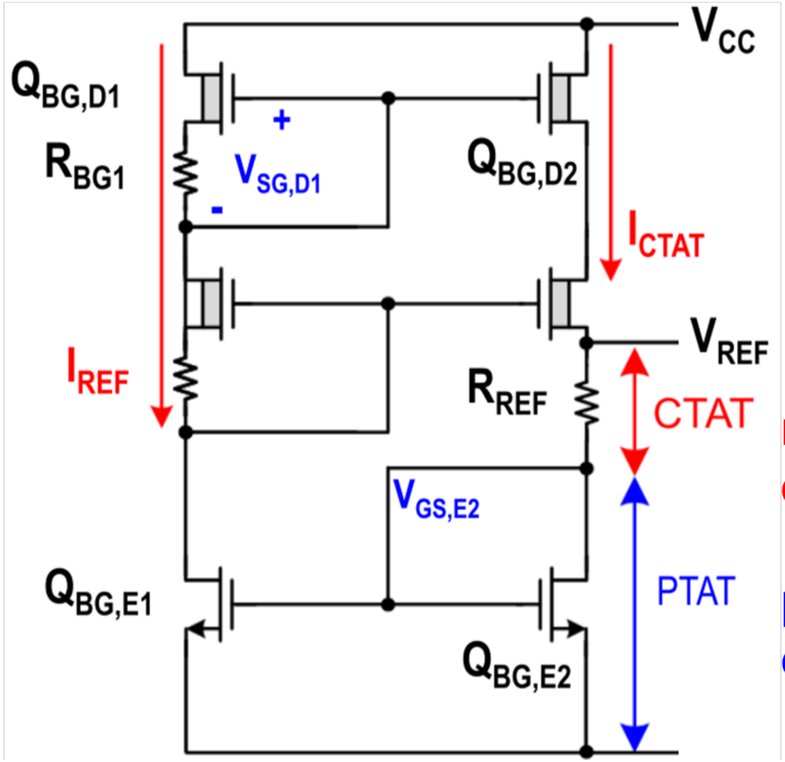


Lack of p-type device:

- Similar intrinsic gain, but GaN has low single stage gain ~ 10 V/V due to load resistor
- High power consumption for slow resistor-transistor logic gates
- Pull-up resistor requires significant layout area

Reference Voltage Generator

H.-Y. Chen et al. (NYCU) ISSCC 2021 [7]

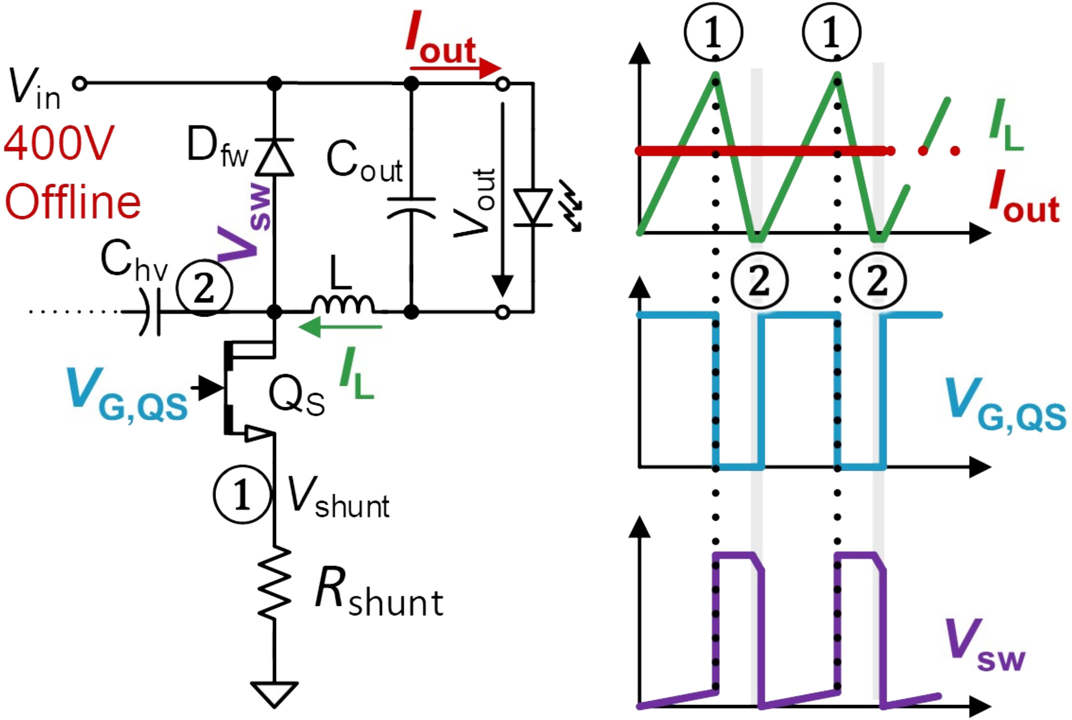


negative temperature coefficient
of a d-mode current source

positive temperature coefficient of an
e-mode transistor’s threshold voltage

A Monolithic GaN Converter

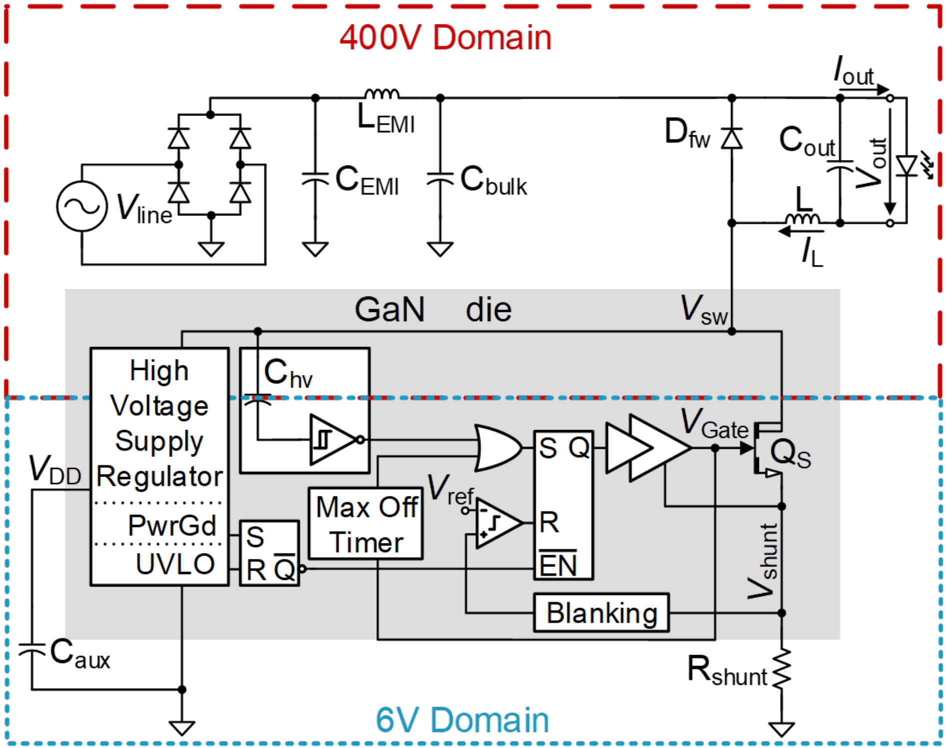
Monolithic GaN Integration: 400V Offline Buck Converter



- Constant current output for LED load
- Hysteretic control:
  - ① Cycle-by-cycle peak current control
  - ② Boundary conduction mode
- Asynchronous rectifier

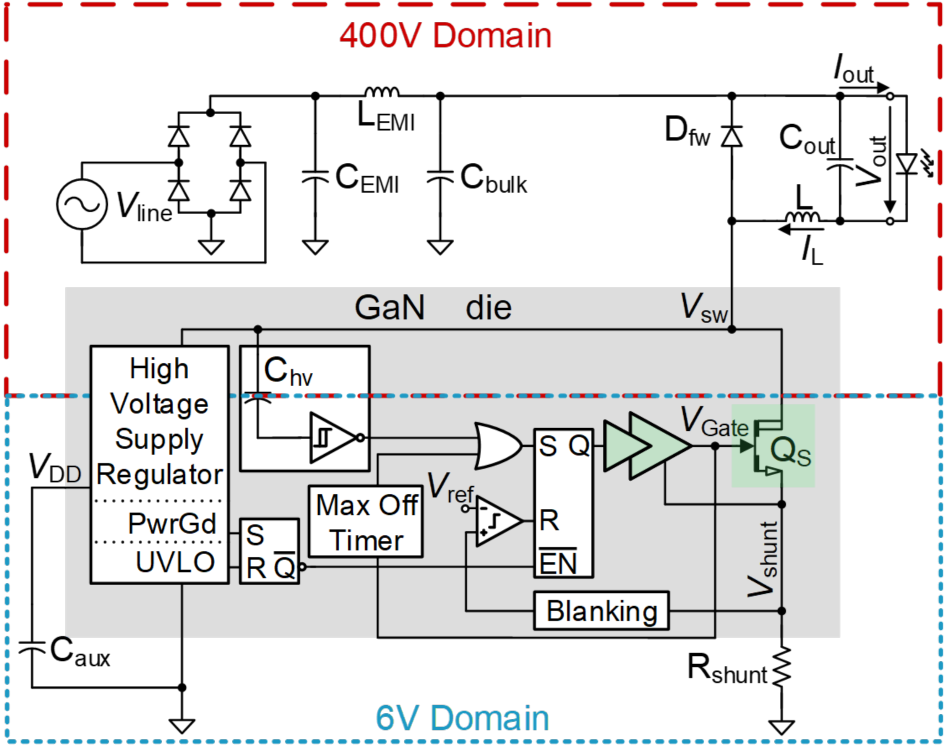
Kaufmann et al., ISSCC 2020 [5], [6]

A Monolithic GaN Offline Buck Converter



Kaufmann et al., ISSCC 2020 [5], [6]

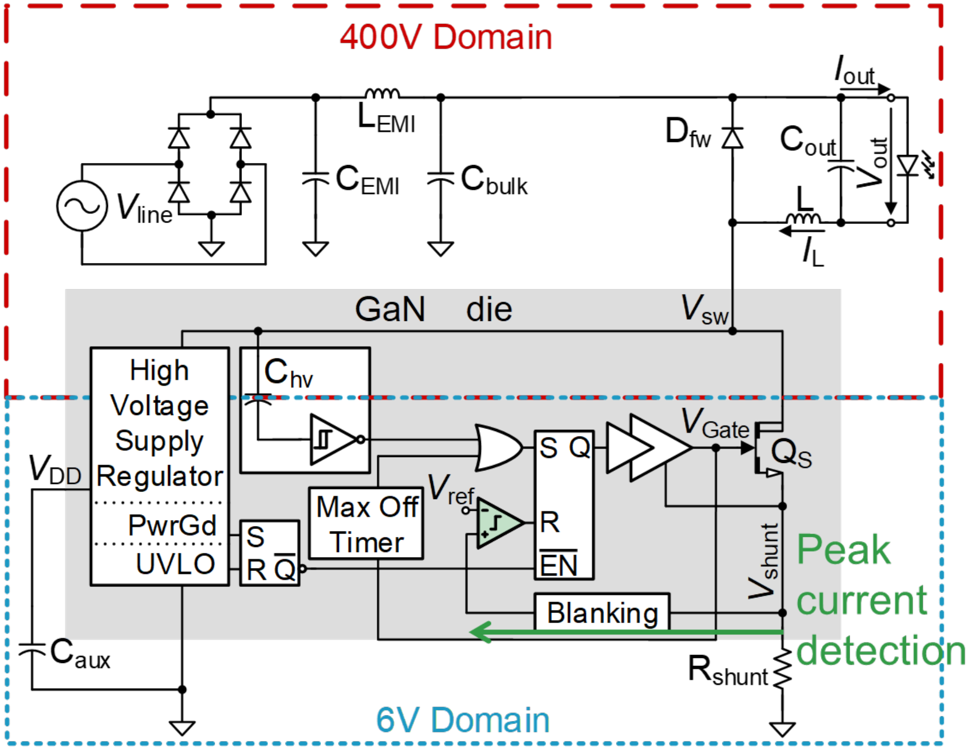
A Monolithic GaN Offline Buck Converter



- **Gate driver and high voltage power HEMT**

Kaufmann et al., ISSCC 2020 [5], [6]

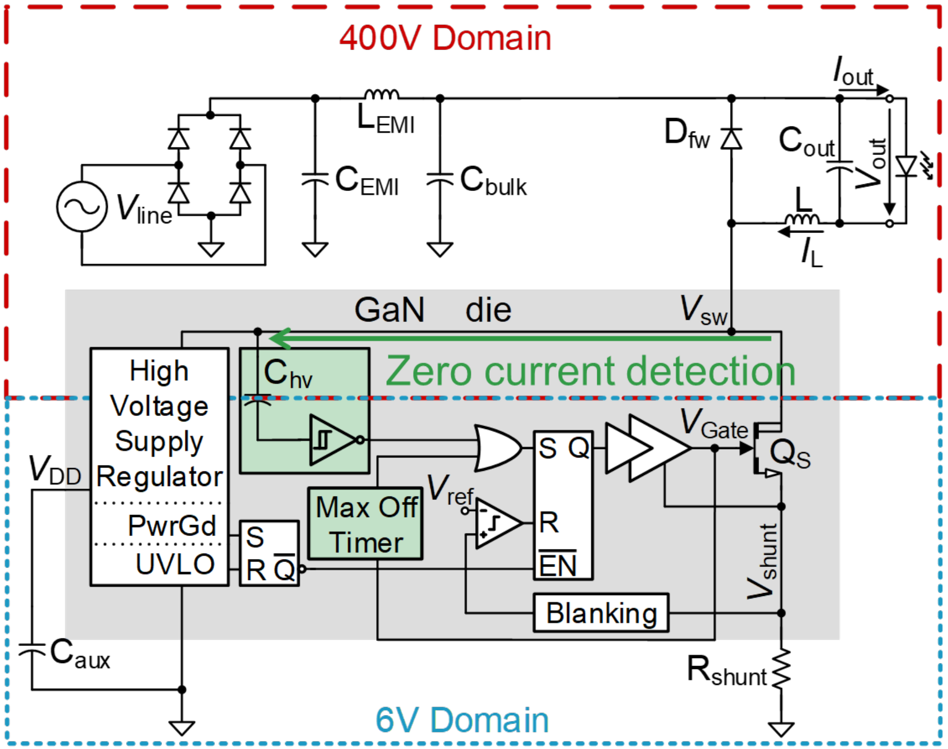
A Monolithic GaN Offline Buck Converter



- Gate driver and high voltage power HEMT
- **Peak current comparator with autozeroing**

Kaufmann et al., ISSCC 2020 [5], [6]

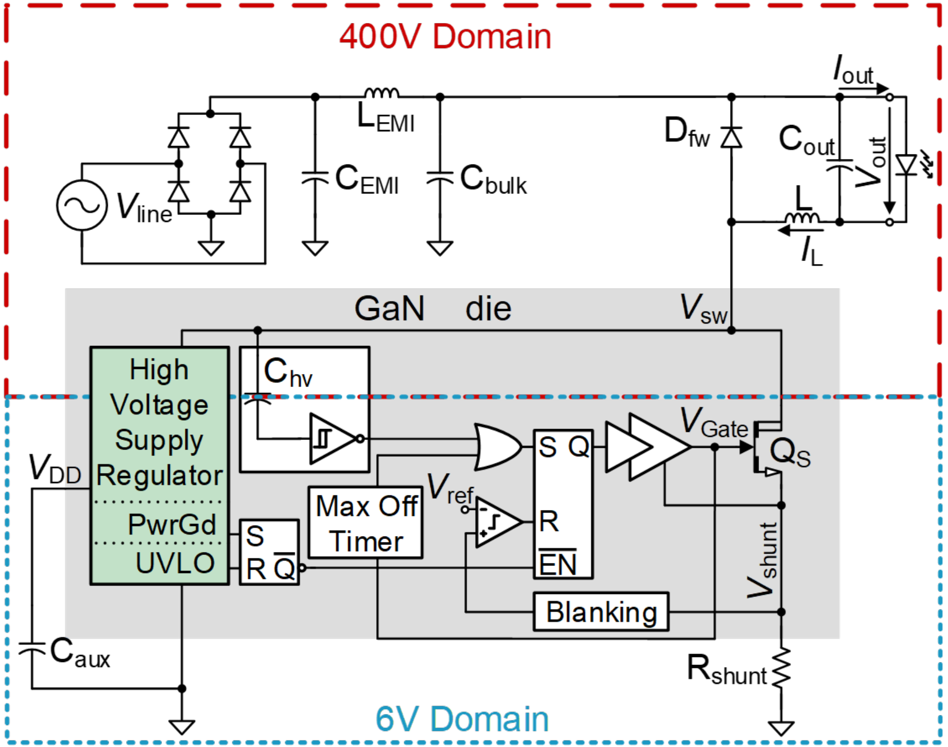
A Monolithic GaN Offline Buck Converter



- Gate driver and high voltage power HEMT
- Peak current comparator with autozeroing
- **Zero current detection for boundry conduction mode**
- **Max off timer for startup**

Kaufmann et al., ISSCC 2020 [5], [6]

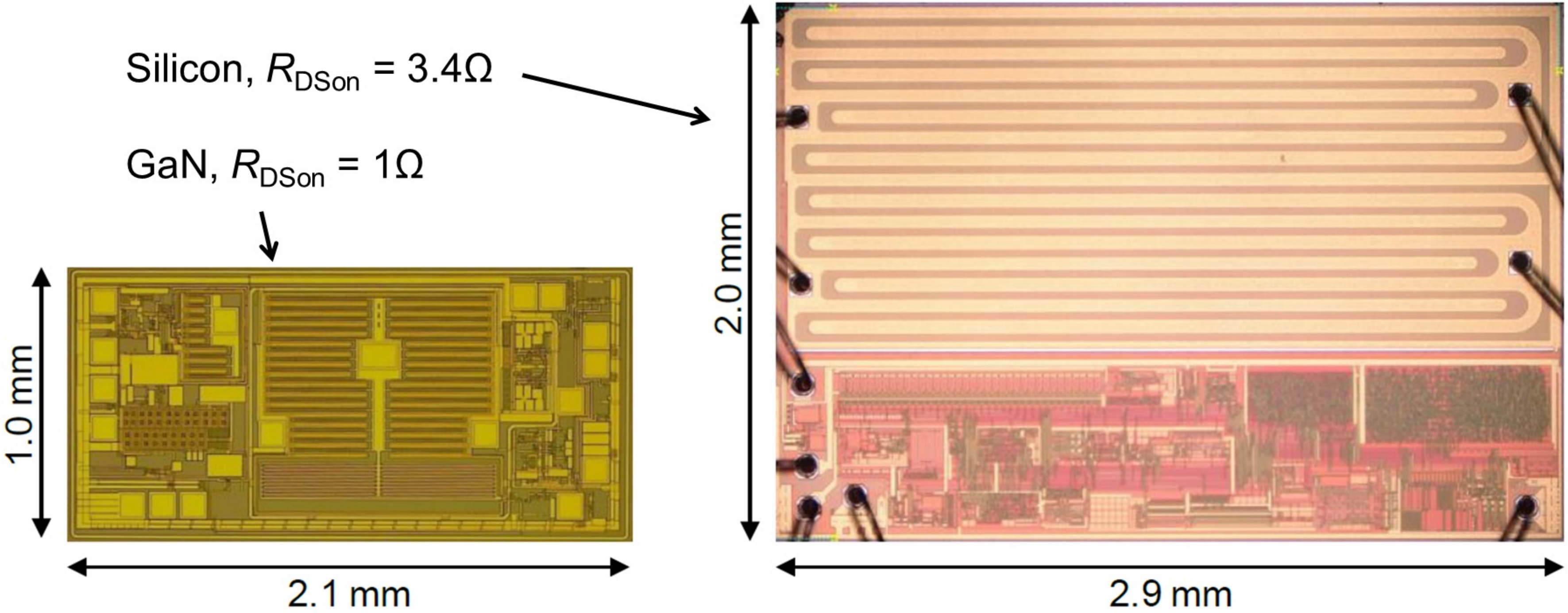
A Monolithic GaN Offline Buck Converter



- Gate driver and high voltage power HEMT
- Peak current comparator with autozeroing
- Zero current detection for boundry conduction mode
- Max off timer for startup
- **HV supply regulator for self-biased offline operation**

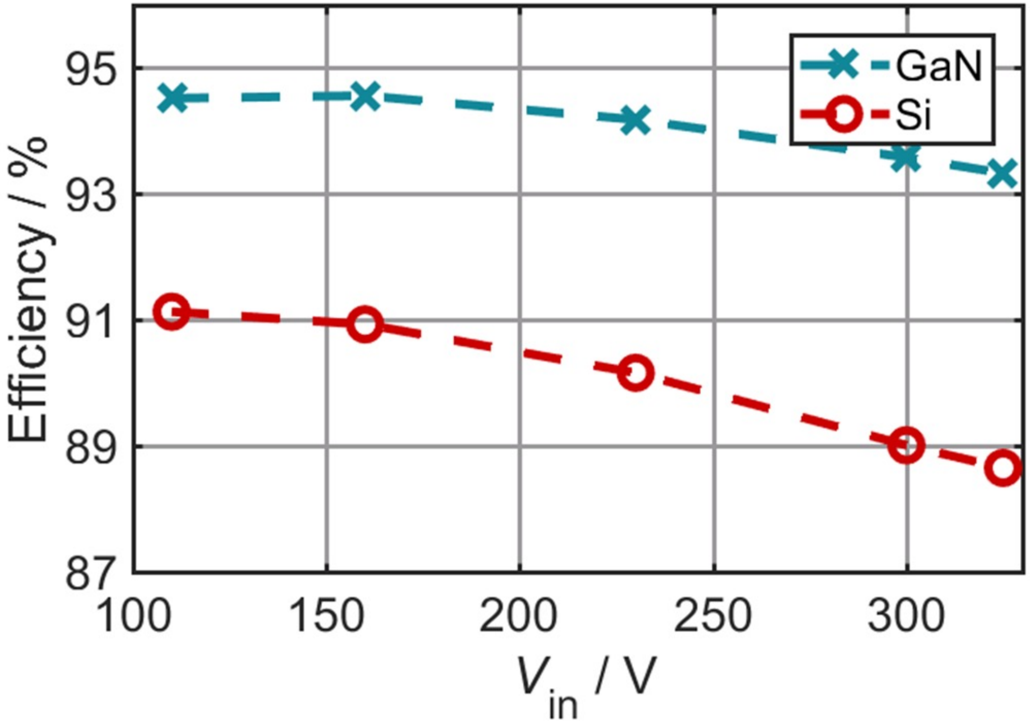
Kaufmann et al., ISSCC 2020 [5], [6]

Comparison: Die Micrograph



GaN achieves 1/3 on-resistance using only 1/3 die area

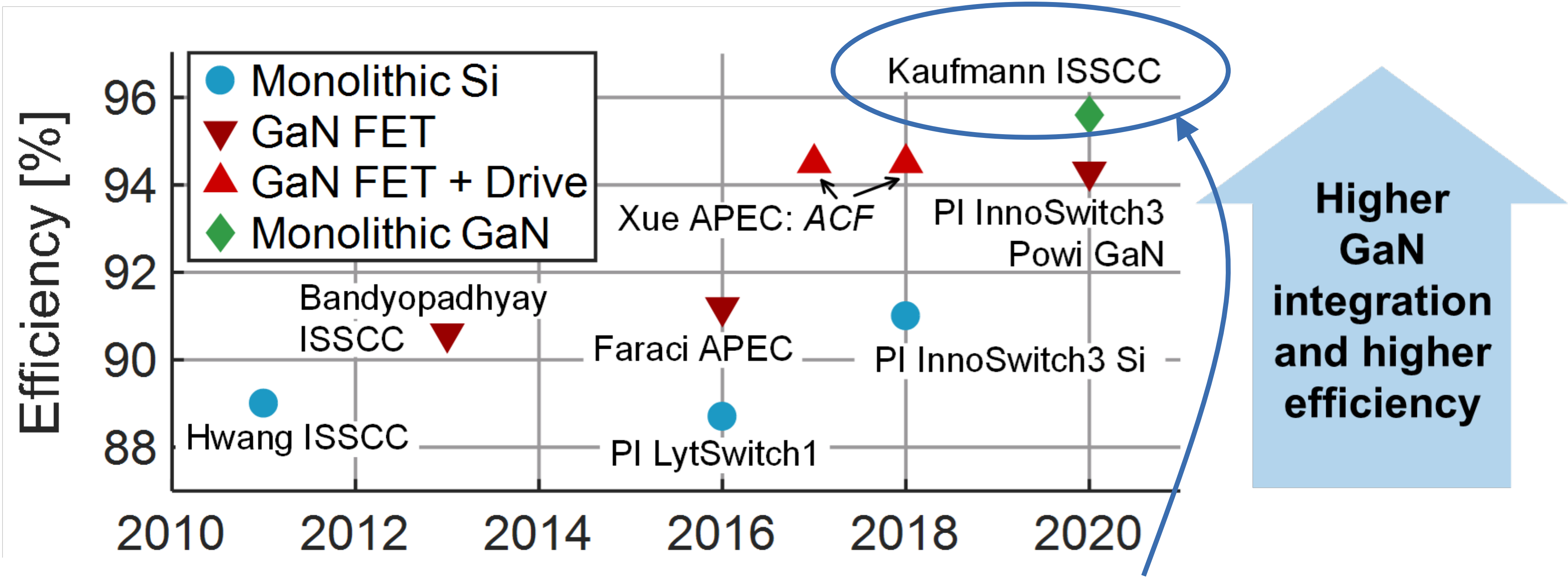
Comparison: Efficiency over V_{in}



L_{out} = 470uH
f_{sw} = 89.1 … 131.3 kHz

GaN implementation achieves higher efficiency under various operating conditions

10-50W Offline Converter Integration Trends



- 95.6% peak efficiency → highest achieved with fully integrated power stage
- Low component count and small passives → 44W/in^3 power density

Conclusion - Monolithic Integration in GaN

- Power + sensing + control on one single die
- Eliminates gate loop parasitics
- Tracks PVT variations of the GaN gate drive voltage
- Analog properties (gain, matching, etc.) still worse than silicon

The presented GaN circuits show high levels of integration for compact and efficient high-voltage power supplies

References

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