# Faster, Higher, Monolithic – Efficient Energy Conversion with GaN

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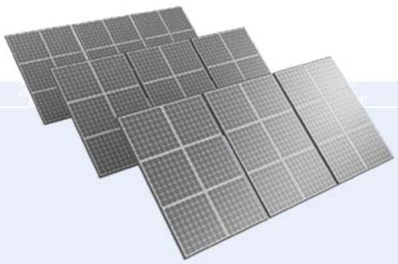
# Introduction

# Motivation



GRID

HOME APPLIANCES

INDUSTRIAL

ELECTRIC VEHICLES

DATA CENTERS

CONSUMER

# Demands on Modules and Components

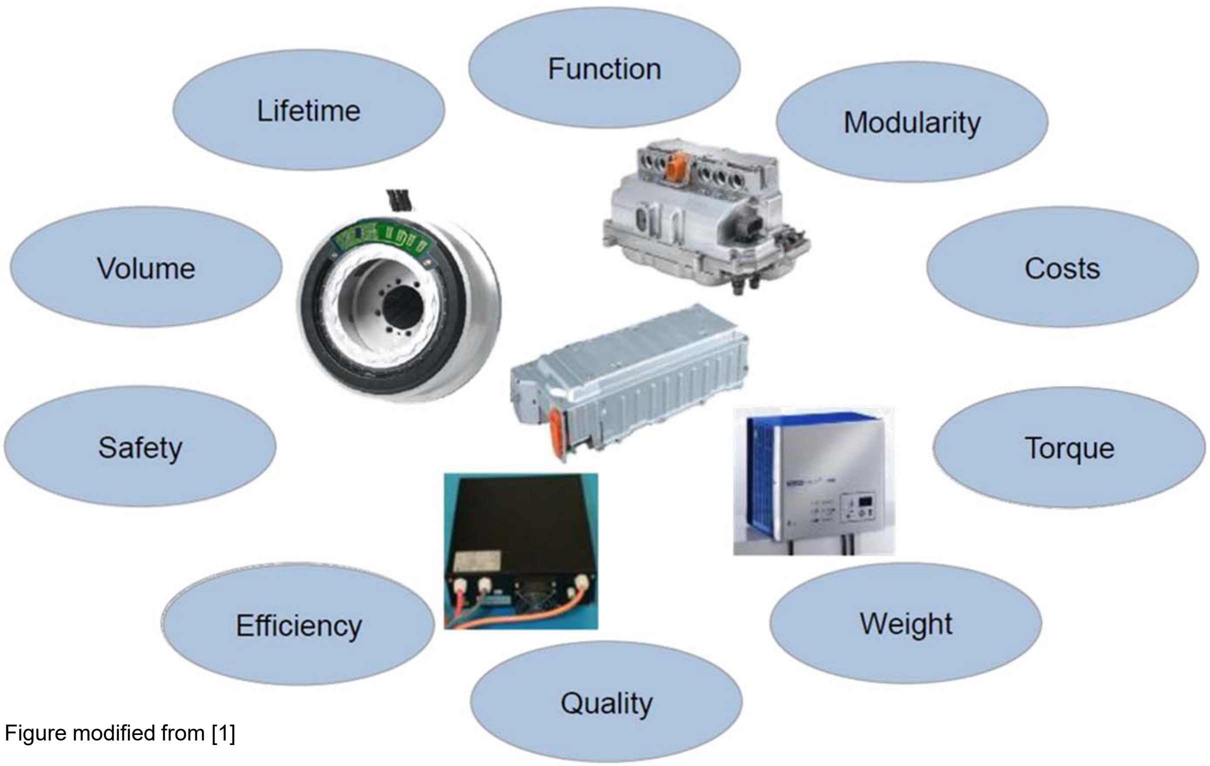
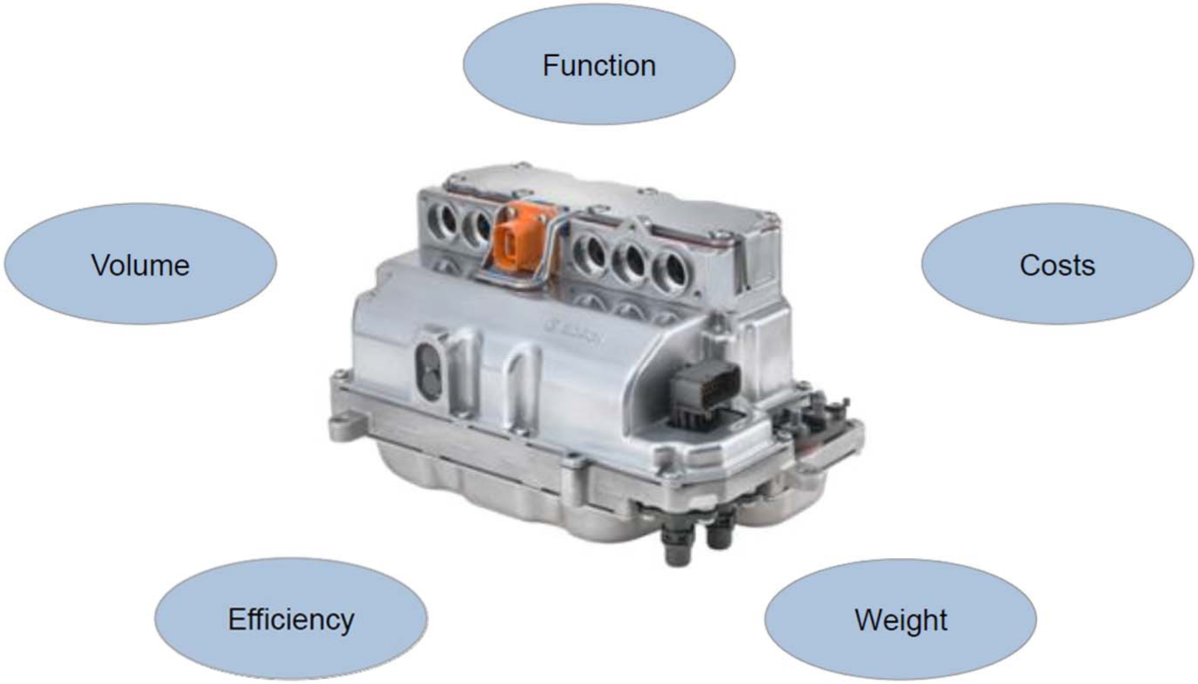



Figure modified from [1]

# Success Factors

→ Miniaturization, effciency, reliability & controllability, cost



# Success Factors

→ Miniaturization, effciency, reliability & controllability, cost

Function
reliability, controllability

miniaturization
Volume
W/in³

Costs
$ per W

Efficiency

Weight
miniaturization

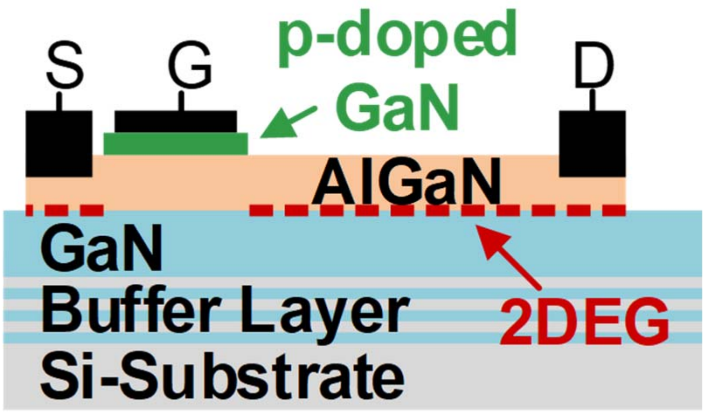
Figure modified from [1]

➡ FASTER switching

➡ HIGHER efficiency

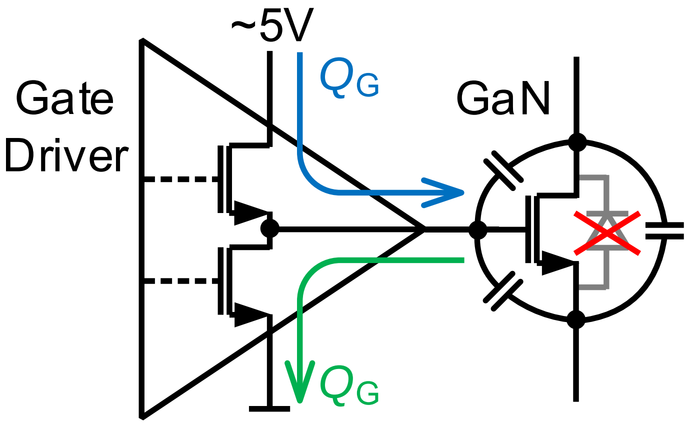
➡ STRONGER performance

# 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 $Q_{RR}$
- Lateral device: Simpler monolithic integration and packaging → GaN ICs

# GaN for Power Electronics




| | Si CoolMOS C7 * (650V / 52mΩ / 33A) | GaN Transistor ** (650V / 55mΩ / 30A) |
|---|---|---|
| $V_{GS}$ | 15V | **~5V** |
| $V_{th}$ | 3.5V | **1.6V** |
| $Q_G$ | 64nC | **5.8nC** |
| $Q_{RR}$ | 10µF | **0** |

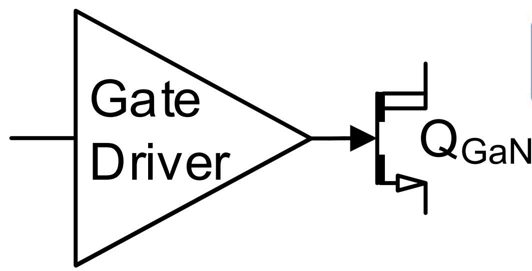
>10x

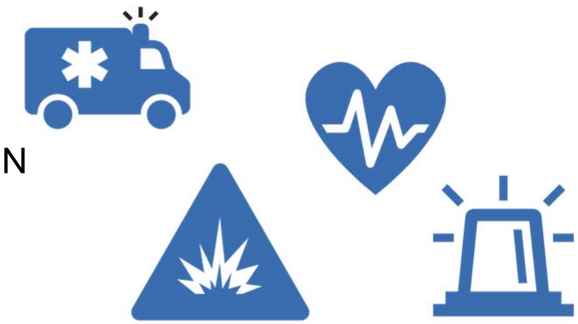
*IPP65R065C7, **GS66508T

Key parameters of GaN transistors:

- ~5V gate drive, low threshold voltage $V_{th}$
- >10x lower gate charge $Q_G$, zero reverse recovery charge $Q_{RR}$

# GaN Driver Requirements: Faster, Higher, Stronger



FASTER switching:
Miniaturization

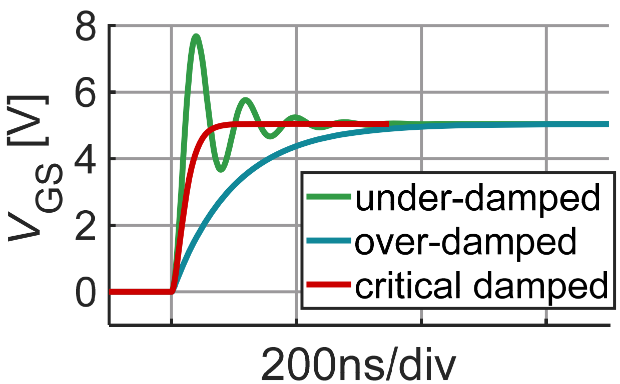
HIGHER efficiency:
Low switching losses,
high dVDS/dt

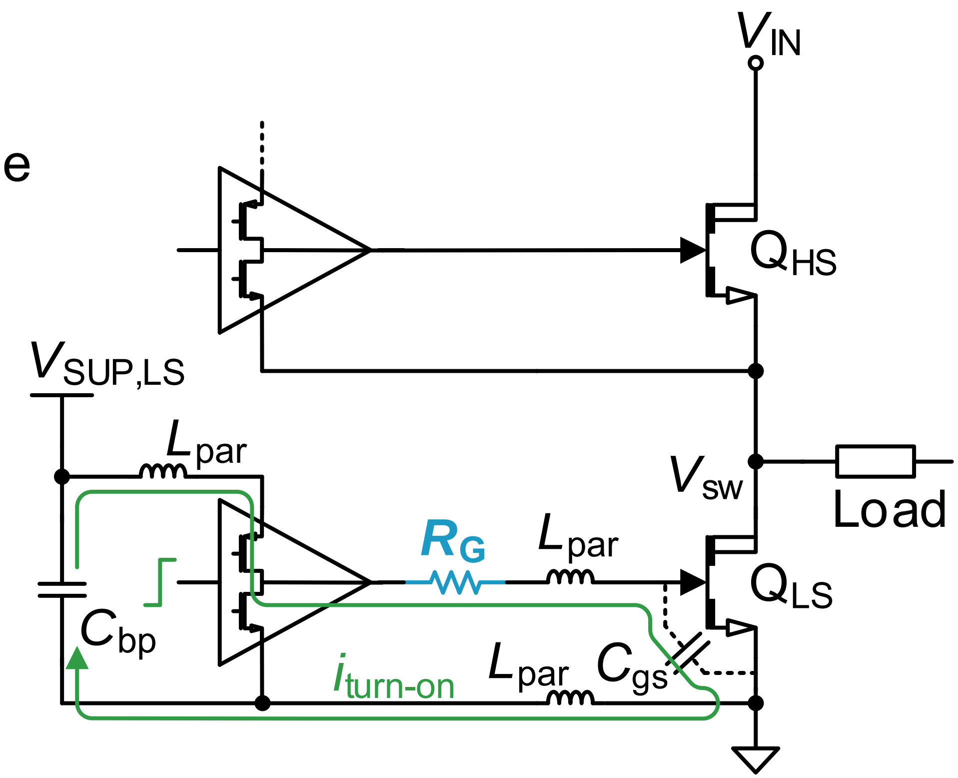
STRONGER performance:
Reliability and save operation

- Save on- and off-state
- Low $V_{GS}$ overshoot

# Gate Driver – Turn-on Behavior

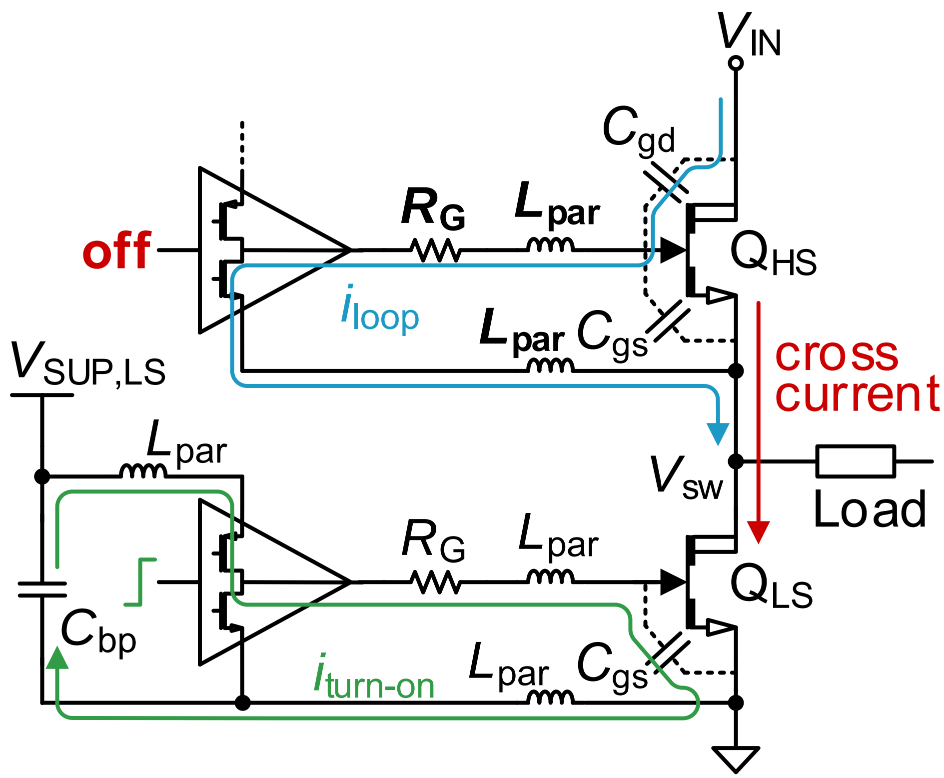
- $L_{par}$, $C_{bp}$ and $C_{gs}$ form a resonant tank
  → $V_{GS}$ overvoltage and ringing
- Gate resistor to prevent gate overvoltage
  → slows down the driver



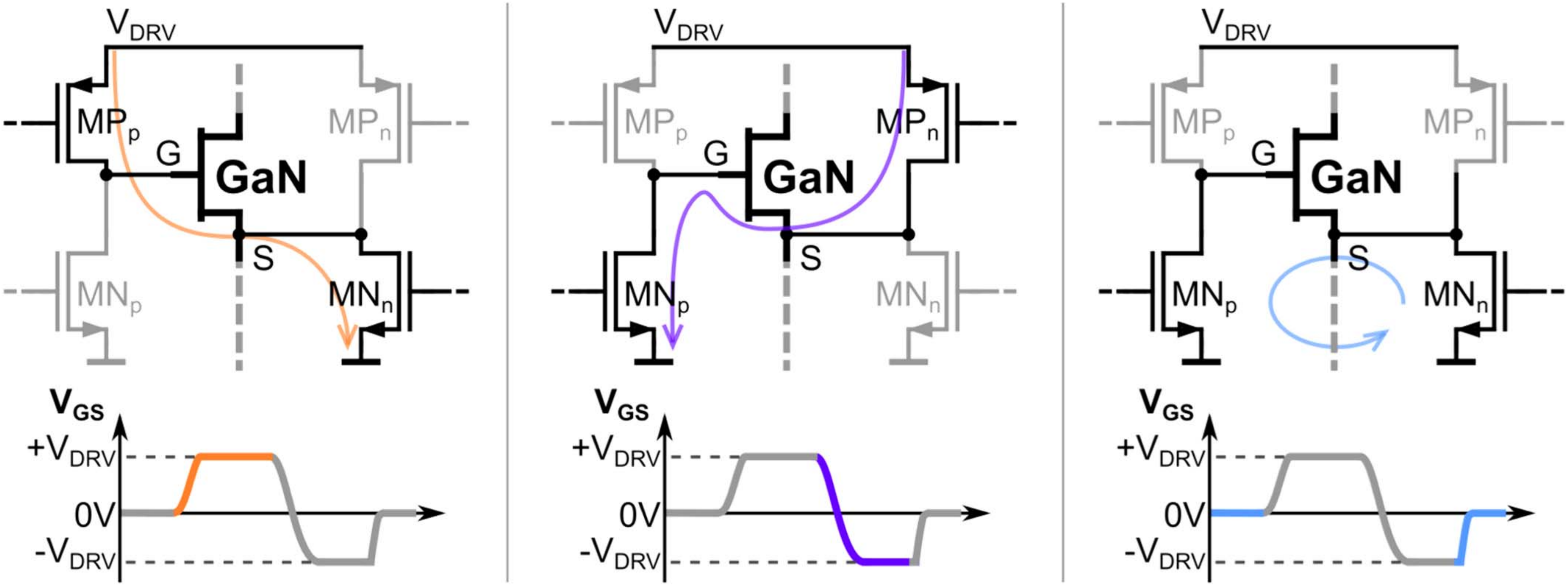



# Gate Driver – Save Off-State

- $dV_{DS}/dt \gg 100V/ns$ (GaN)
  → large current $i_{loop}$ through $C_{gd}$
- $R_G$ and $L_{par}$ → risk for $Q_{HS}$ to turn on
  → cross current
- Addressed by:
  – Bipolar gate drive ($V_{GS}$ < 0V)
  – Larger $C_{gs}$
  → reduced efficiency and speed



# Full-Bridge Gate Driver for Bipolar and Three-level Driving



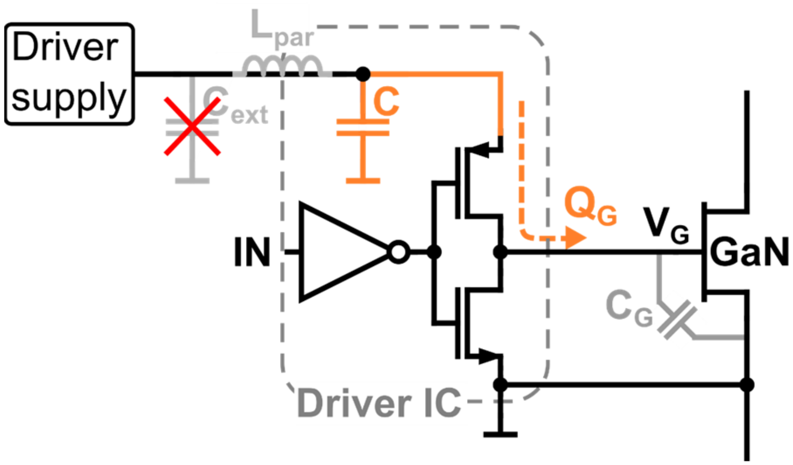

**On: $V_{GS}$ = 5V** **Off: $V_{GS}$ = -5V** **Off: $V_{GS}$ = 0**

IC level integration: 5V devices result in a compact (layout) and fast driver

# High-Voltage Energy Storing (HVES)

# Gate Drivers for GaN

Integration of the buffer capacitor → fewer interconnections, smaller parasitics, smaller footprint, fast switching




$$Q_G = \Delta V_C \cdot C$$

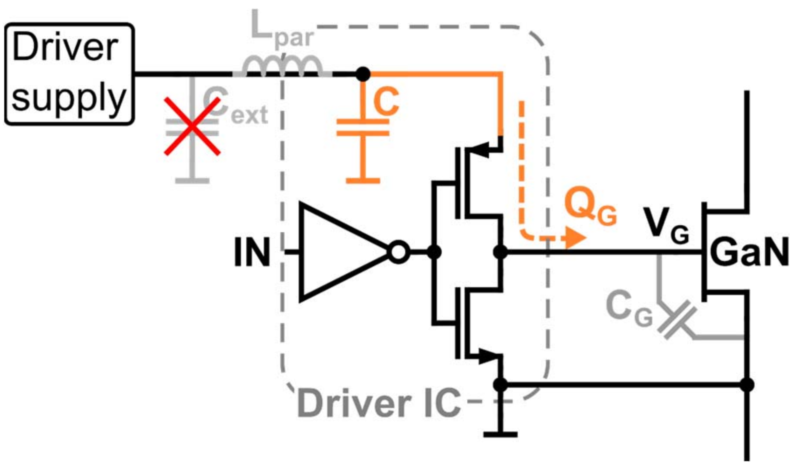
Example:

$Q_G$ = 10nC, $\Delta V_c$ = 0.1V → C ≥ 100nF

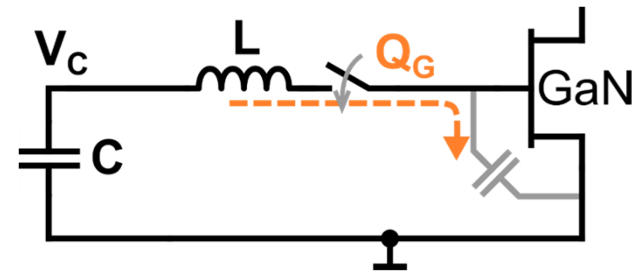
→ How to integrate a capacitor of this size?

# Gate Drivers for GaN: High Voltage Energy Storing (HVES)

Integration of the buffer capacitor → fewer interconnections, smaller parasitics, smaller footprint, fast switching




High-Voltage **Energy** Storing (HV**ES**)




$$Q_G = \Delta V_C \cdot C$$

*Seidel et al.,*
*ISSCC 2017, 2018* [2], [3]

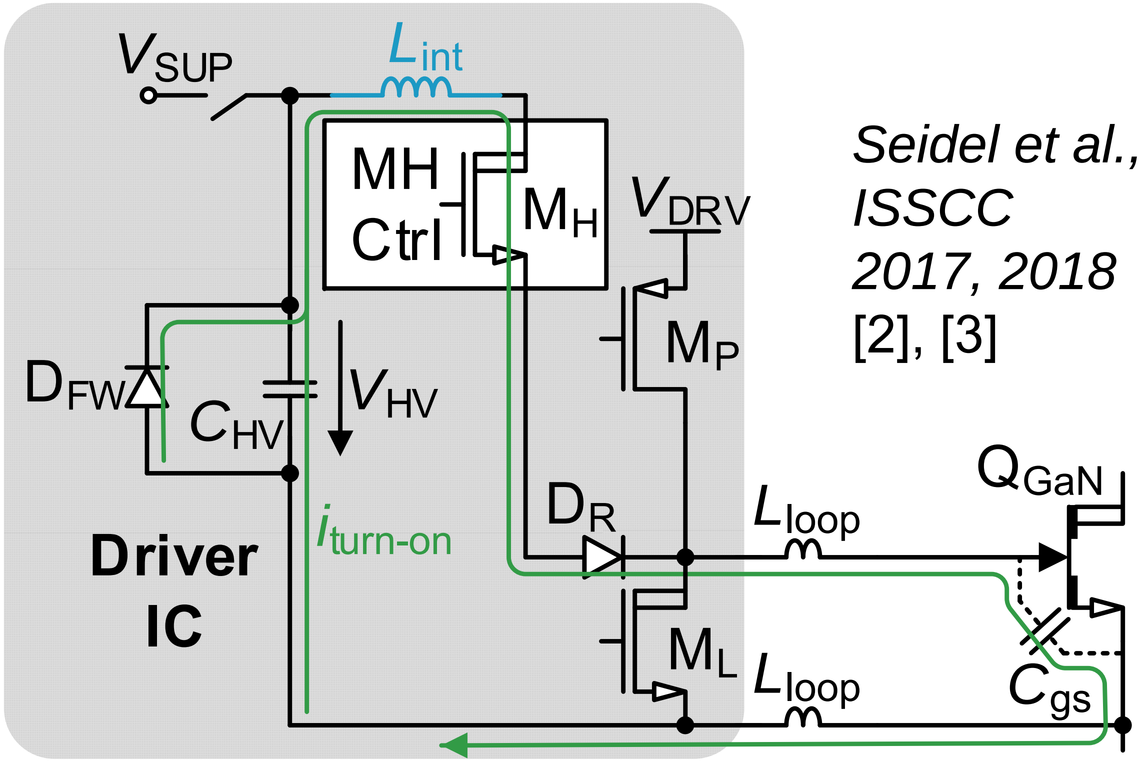
HVES reduces cap size to reasonable values for on-chip integration:


>10x higher gate charge without any external components

# Gate Driver with High Voltage Energy Storing (HVES)

- $V_{HV}$ = 15V, $C_{HV}$ = 0.6nF, $L_{int}$ = 14nH
  → 11nC gate charge
  → fully integrated on IC
- $C_{HV}$ dominates
  → faster turn-on:

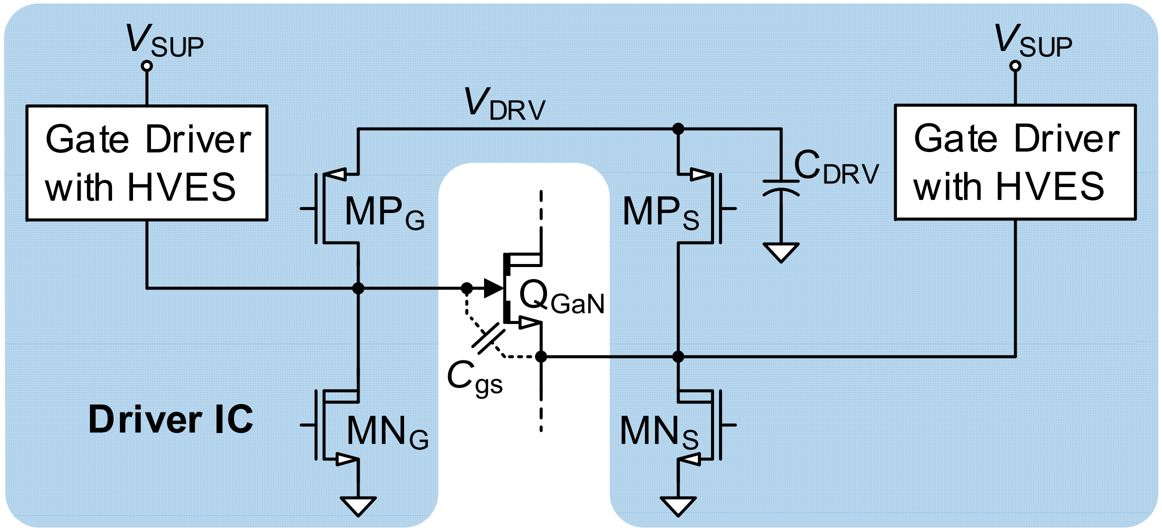
$$f_{res} \approx \frac{1}{2\pi\sqrt{L_{par} \cdot C_{HV}}}$$




DR: Block reverse current
DFW: Freewheeling

*Seidel et al., ISSCC 2017, 2018* [2], [3]

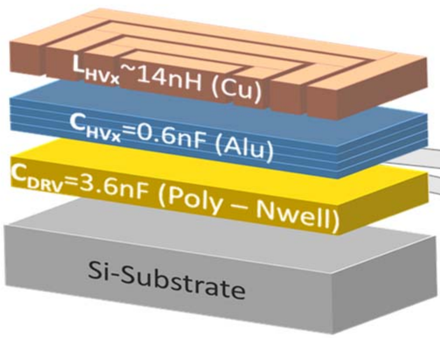
# Gate Driver with HVES – Toplevel

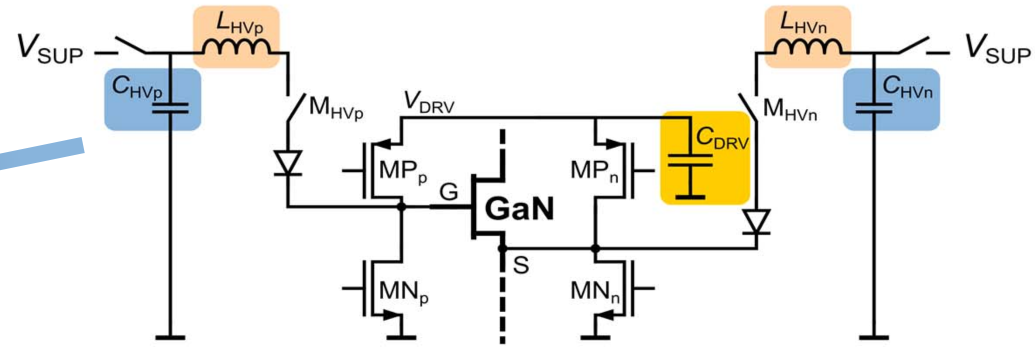



- Full-Bridge for bipolar and three-level driving and stable DC level
- HVES at gate and source for fast on / off transitions

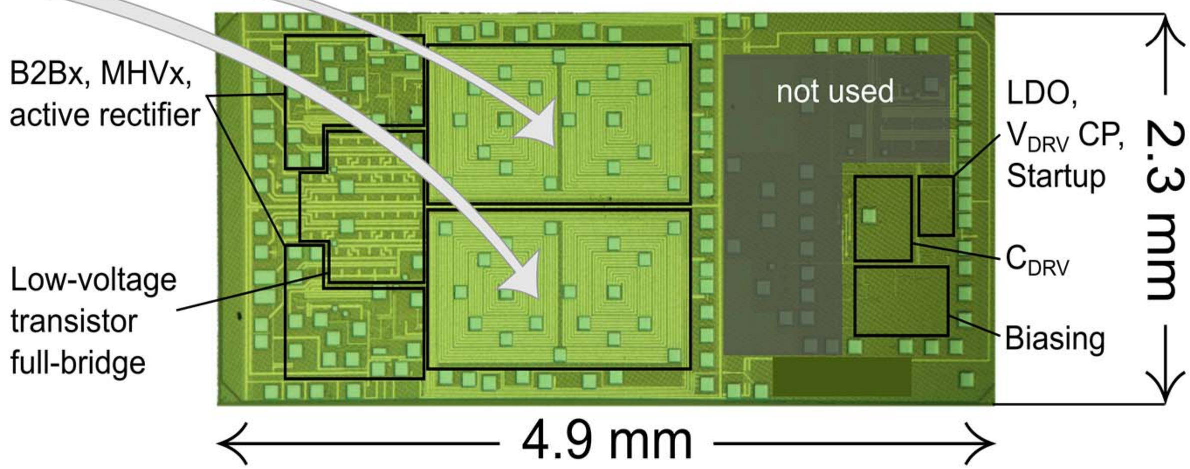
# Gate Driver IC with High Voltage Energy Storing (HVES)

**Fully integrated**



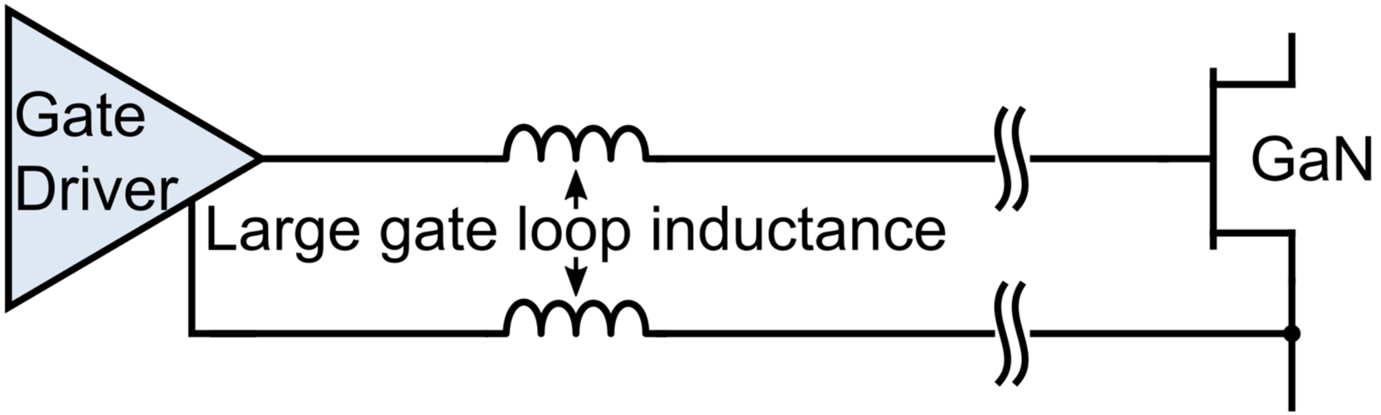




Manufactured in a 180nm BCD technology



# Large Gate Loops

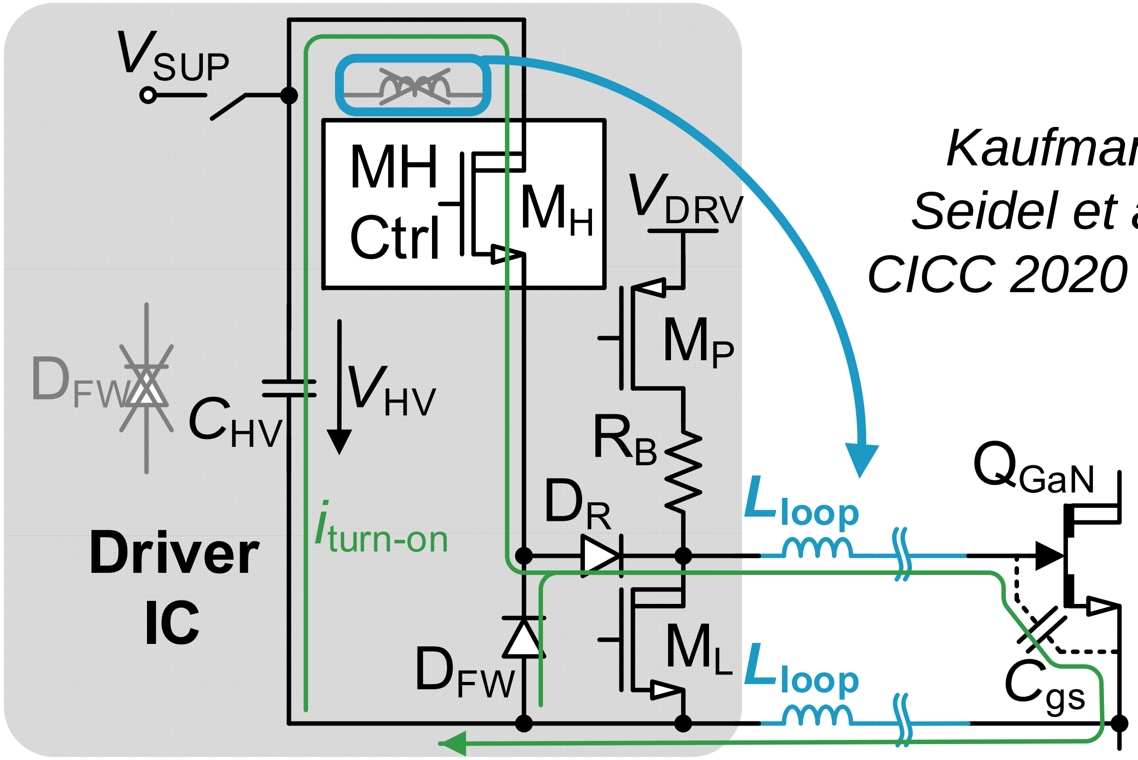
# Flexible Driver Placement: Large Gate Loop




| | |
|---|---|
| Lower temperature | High temperature |
| Multi-layer PCB | High-current substrate |
| Space restrictions | Optimized transistor and heat sink placement |
| Modularity | Modularity |

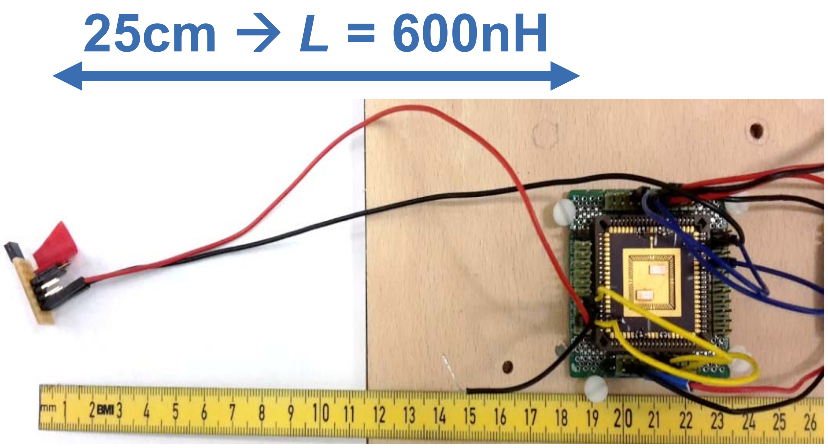
# Flexible Driver Placement: HVES Applied to Large Gate Loop

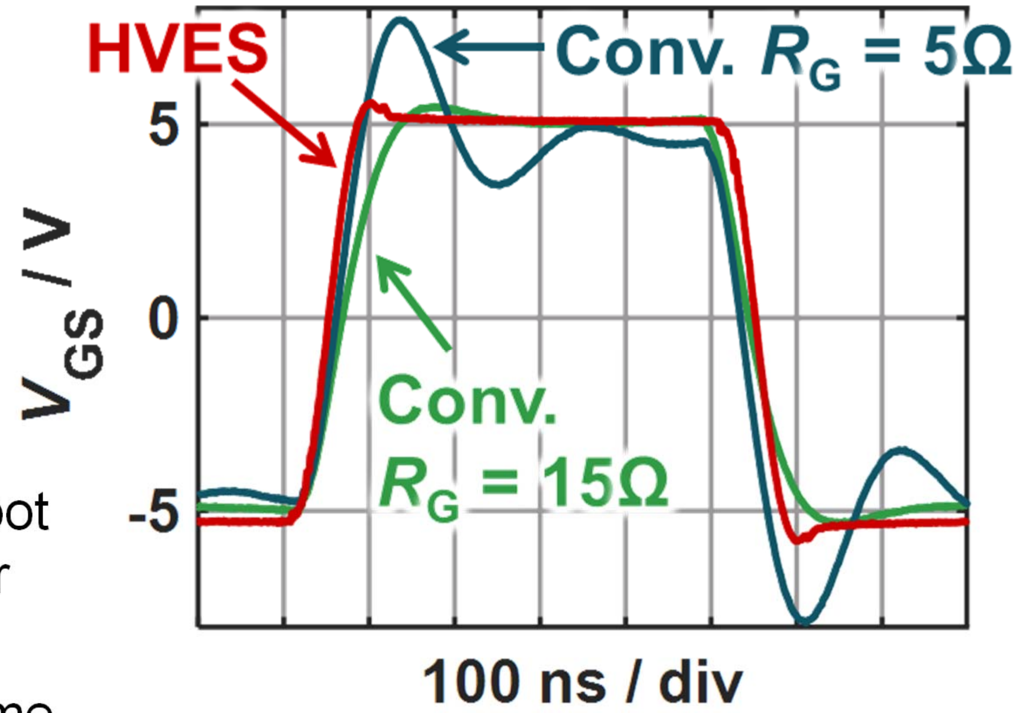
- Loop inductance utilized for resonant gate driving
- Fully integrated solution with small $C_{HV}$ in turn-on loop




*Kaufmann, Seidel et al., CICC 2020* [4]

# Gate Driver with HVES – Experimental Results

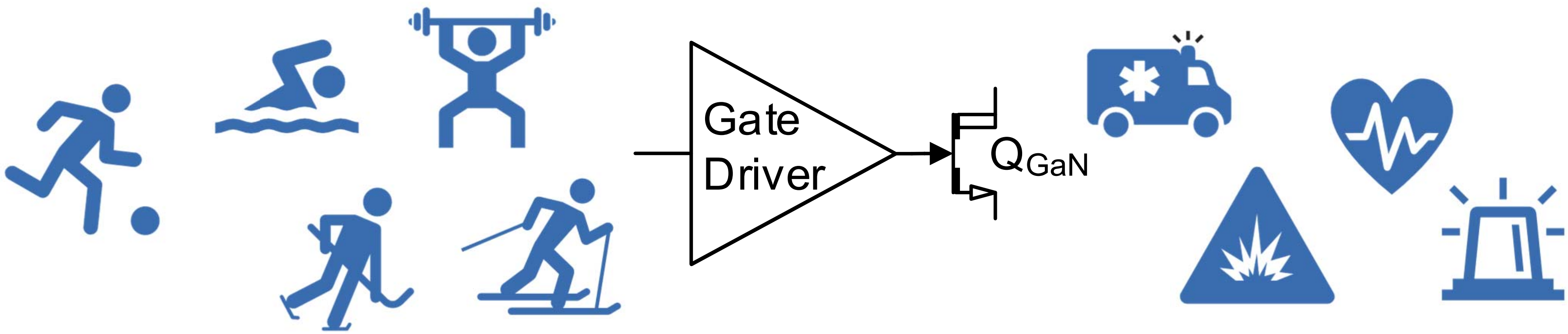



- HVES achieves 80% lower overshoot than conventional driver with similar rise time
- HVES achieves 45% shorter rise time than conventional driver with similar overshoot

*Kaufmann et al., CICC 2020* [4]

# Gate Driver with HVES: Faster, Higher, Stronger




**Miniaturization:**

- Integrated buffer caps
- Use of parasitic Lloop

**Low switching losses, high dVDS/dt:**

- Fast switching due to small integrated high-voltage cap

**Reliability and save operation:**

- Bipolar / 3-Level gate drive for increased margin
- Low VGS overshoot with resonant driving

# Monolithic GaN Integration

# Monolithic GaN-ICs – Foundries / IDMs

tsmc

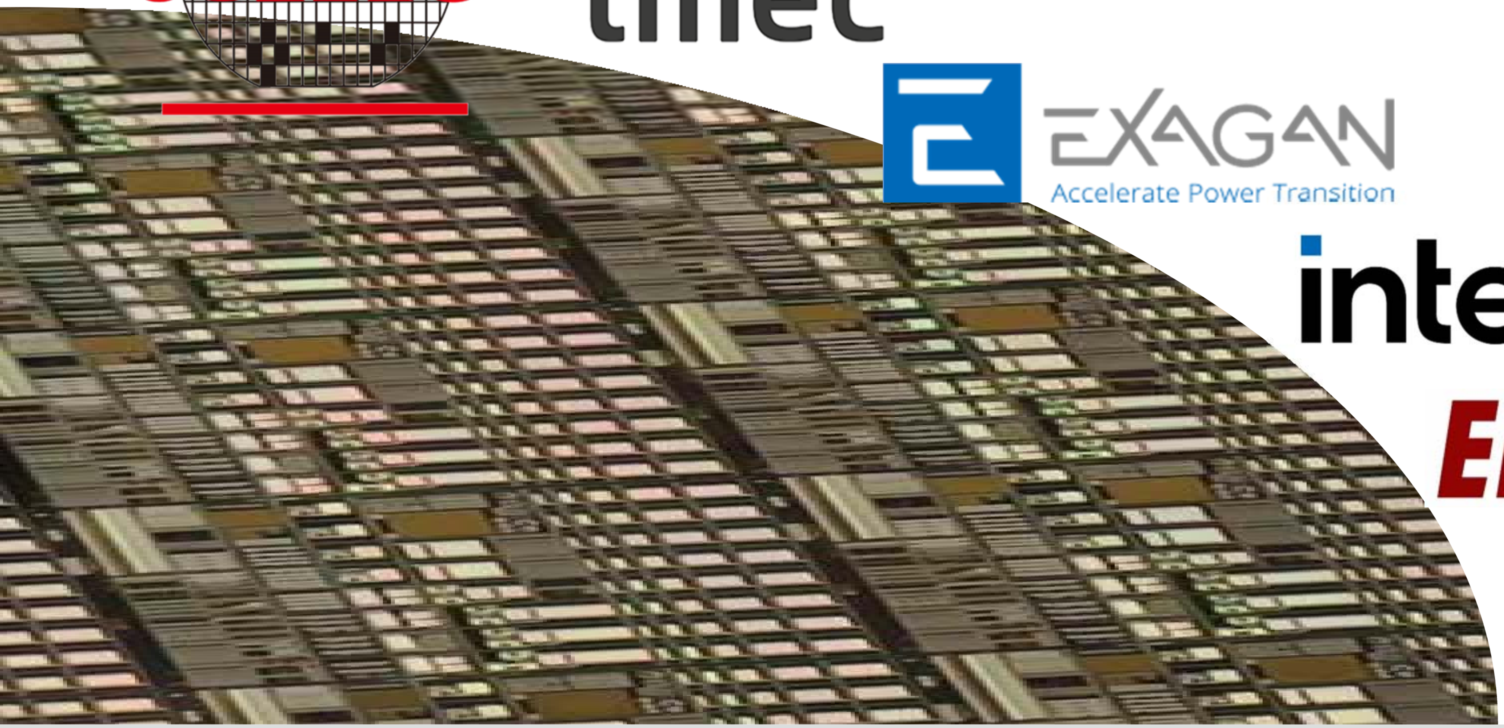
imec

EXAGAN
Accelerate Power Transition

intel®

EPISIL

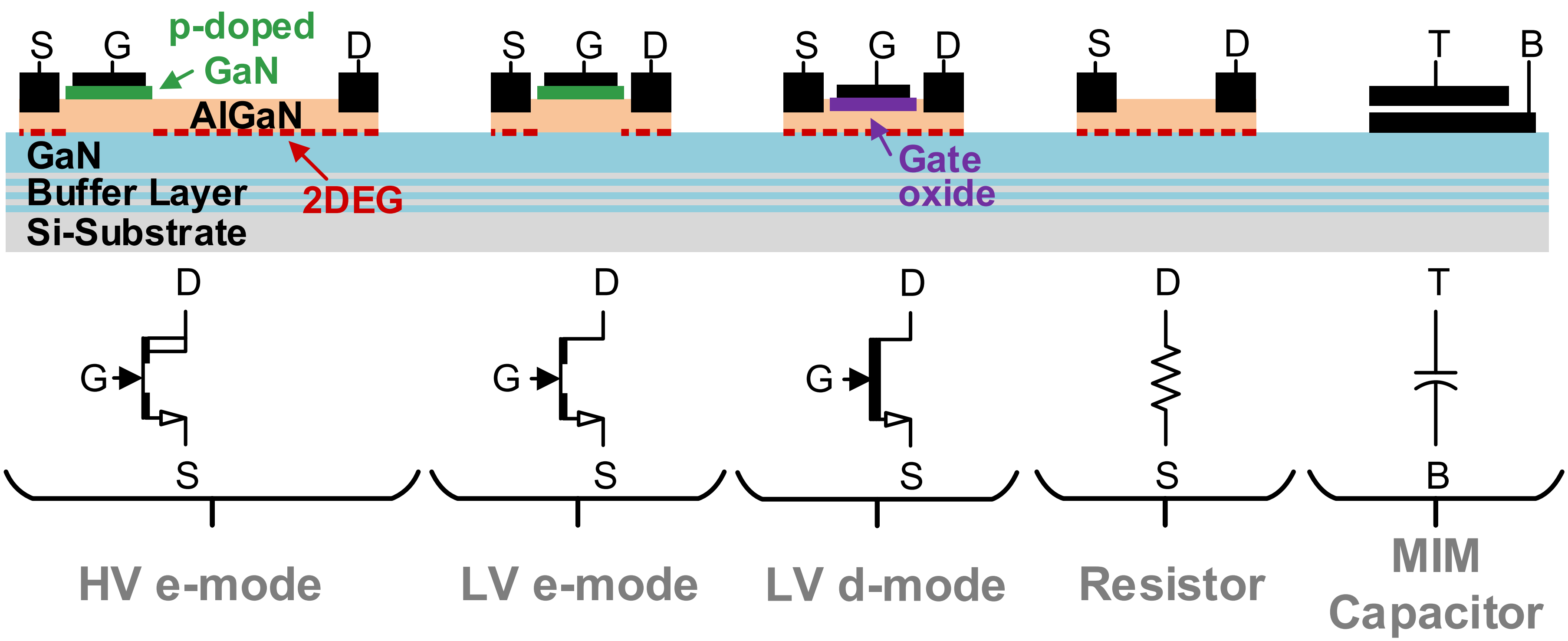
Sanan IC



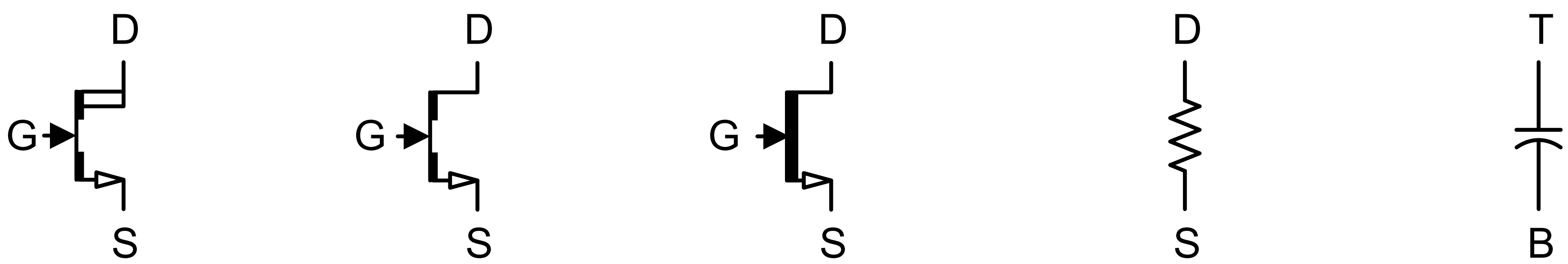
# Monolithic GaN-ICs – Foundries / IDMs and GaN Industry

tsmc
imec
EXAGAN
Accelerate Power Transition
Navitas
GaN Systems
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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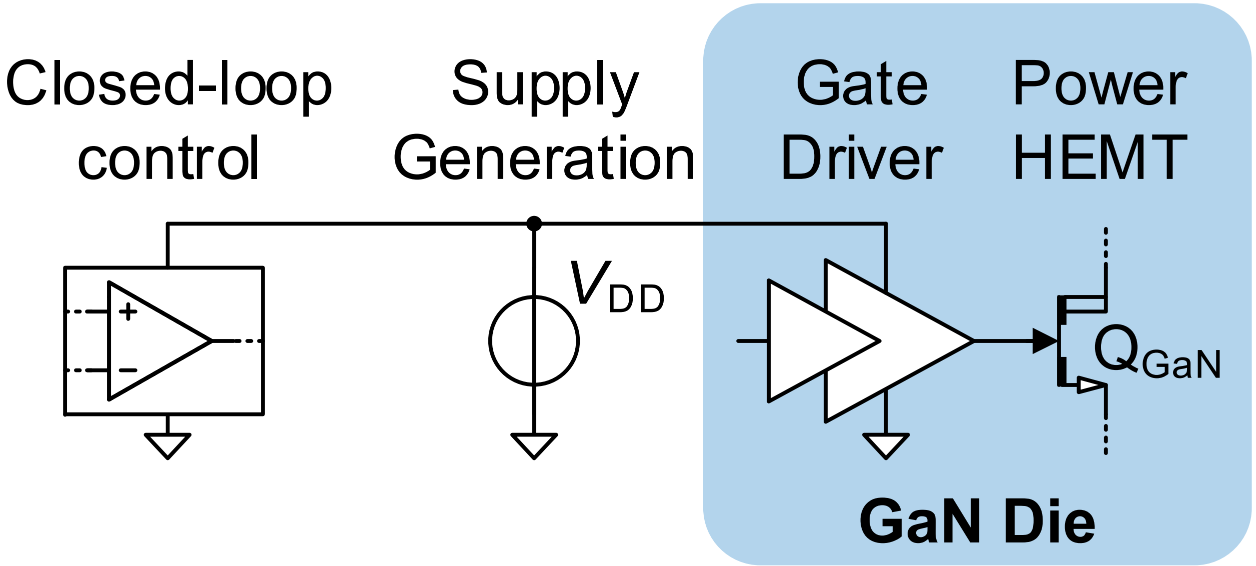
- Limited device types and options, no p-type
- No diodes, neither designed nor parasitic
- Immature technology with poor matching properties

To be addressed on system and circuit level → *learning from the 1970ies*

# Monolithic GaN Integration: System Partitioning

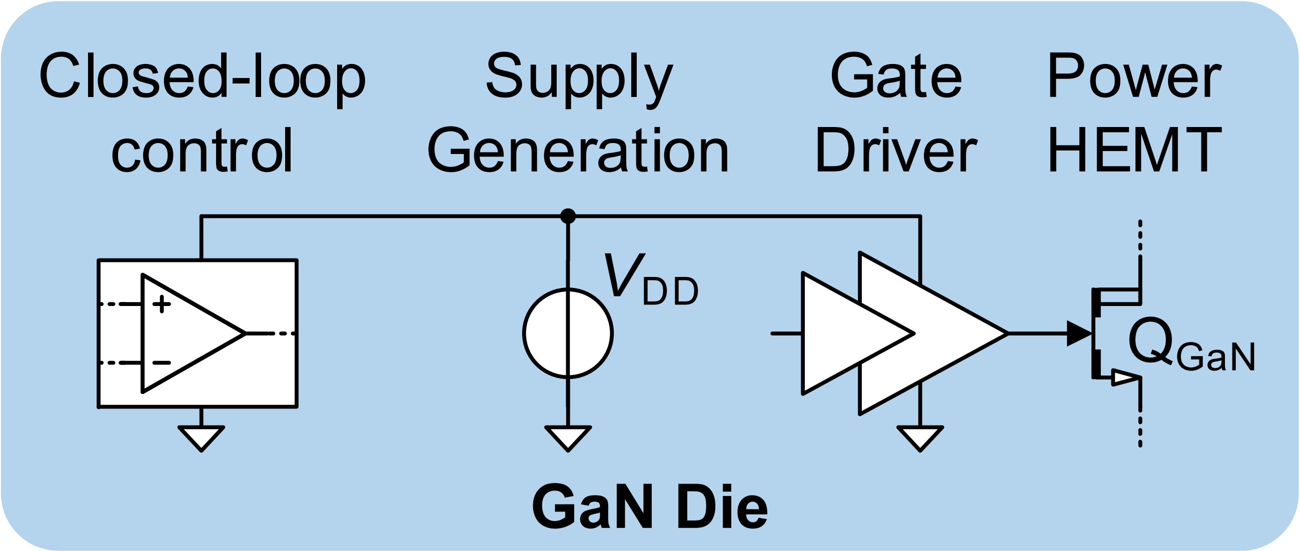
Gate driver and power transistor in GaN:




*Xue et al. (Navitas), APEC2017* [5]

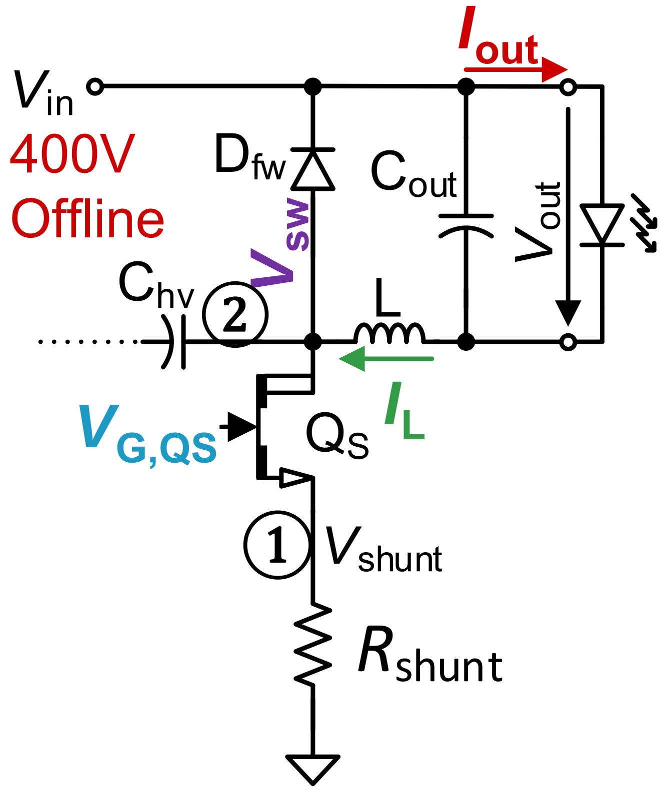
# Monolithic GaN Integration: System Partitioning

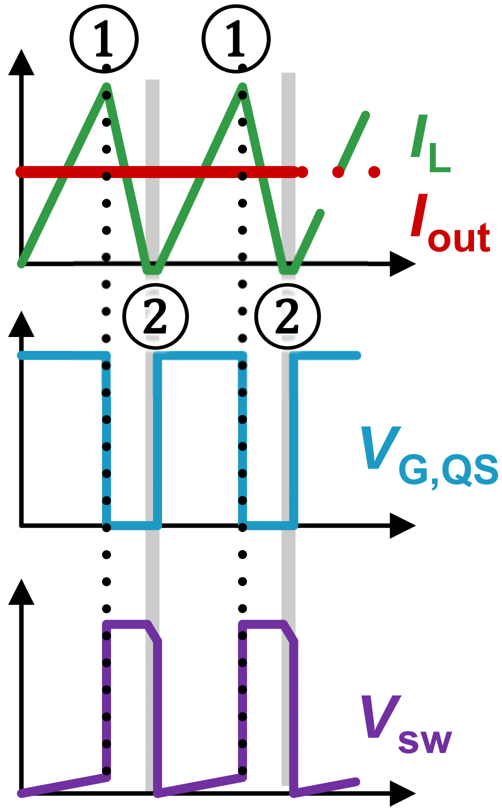
Full system in GaN:




*Kaufmann et al., ISSCC 2020* [6], [7]

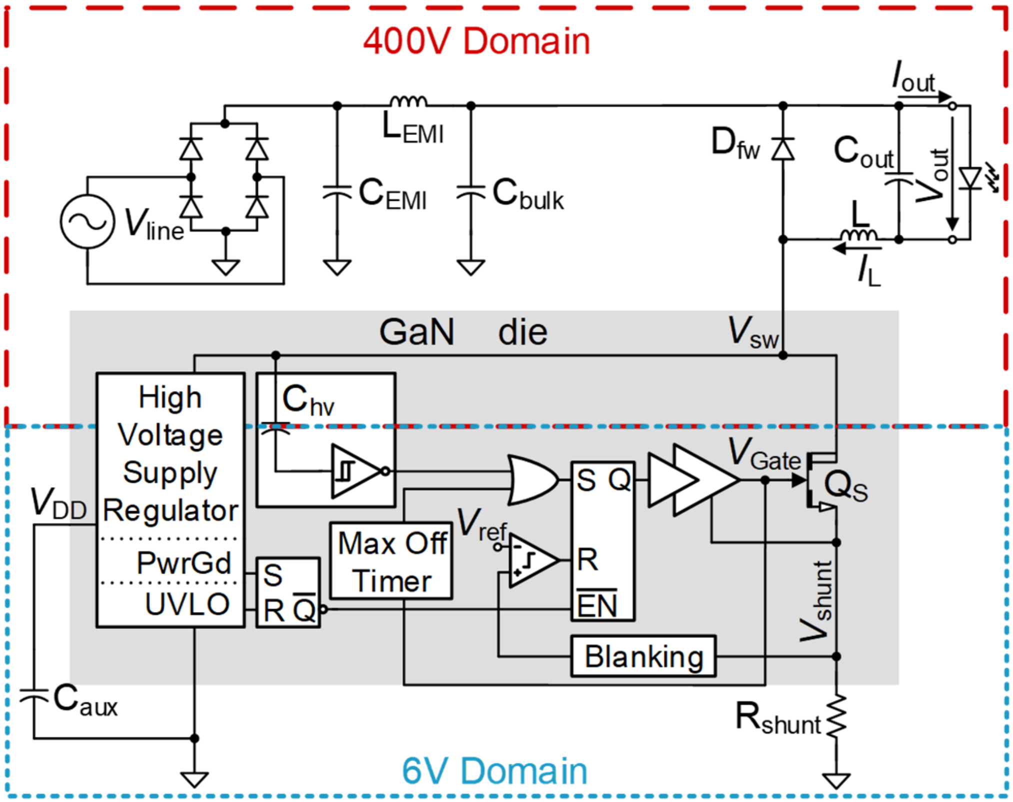
# Monolithic GaN Integration: 400V Offline Buck Converter



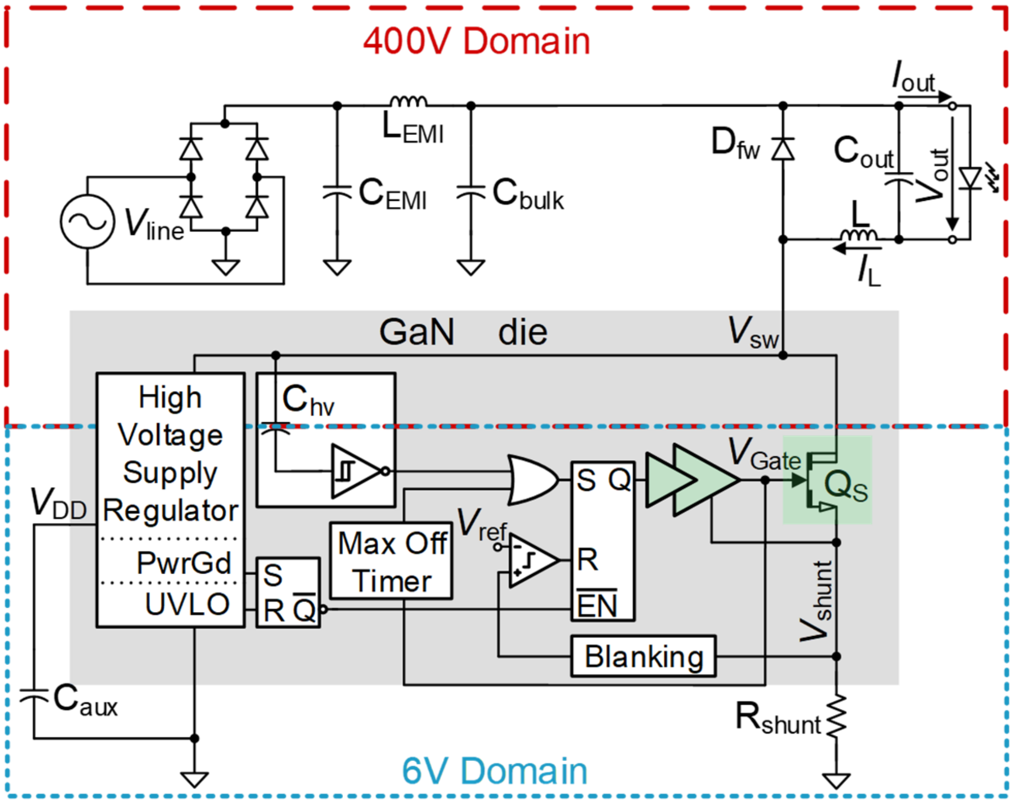




- Constant current output for LED load
- Hysteretic control:
  - ① Cycle-by-cycle peak current control
  - ② Boundary conduction mode
- Asynchronous rectifier

# Monolithic GaN Offline Buck Converter

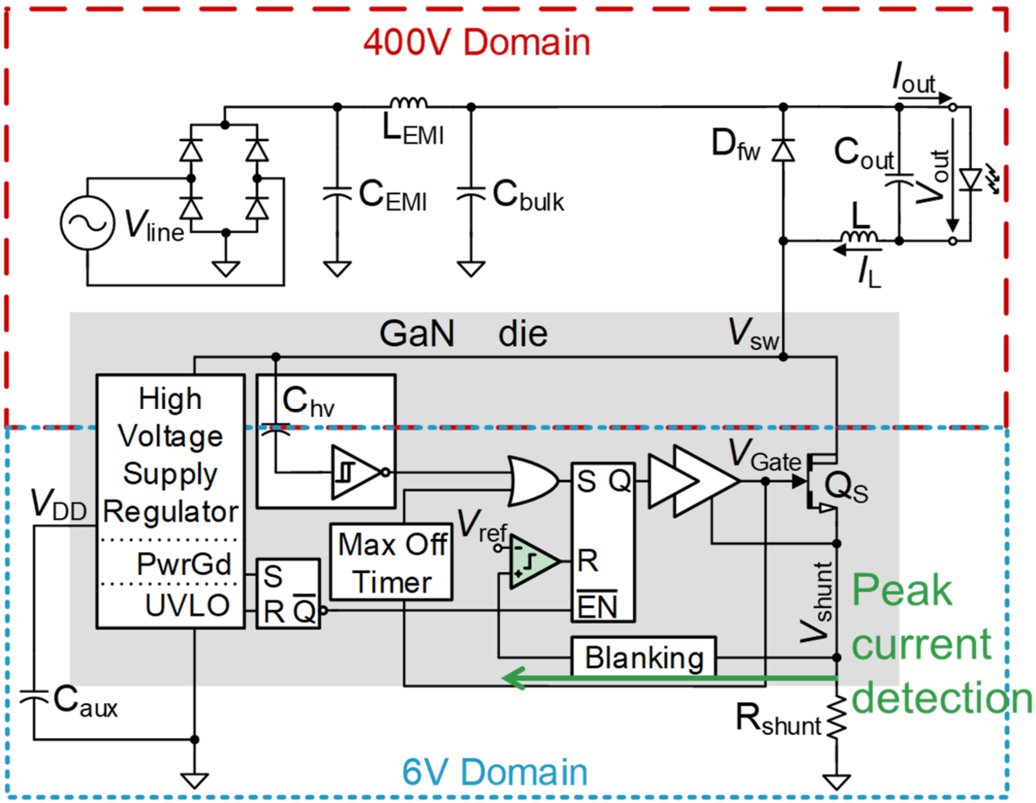


# Monolithic GaN Offline Buck Converter



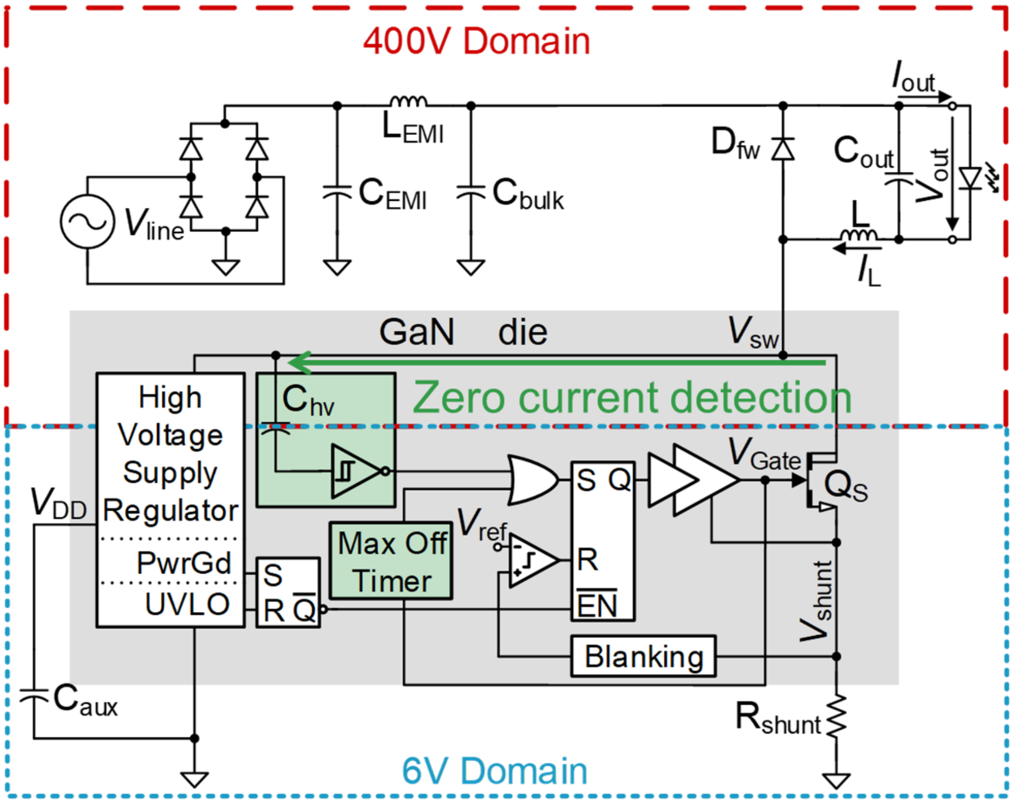

- **Gate driver and high voltage power HEMT**

# Monolithic GaN Offline Buck Converter



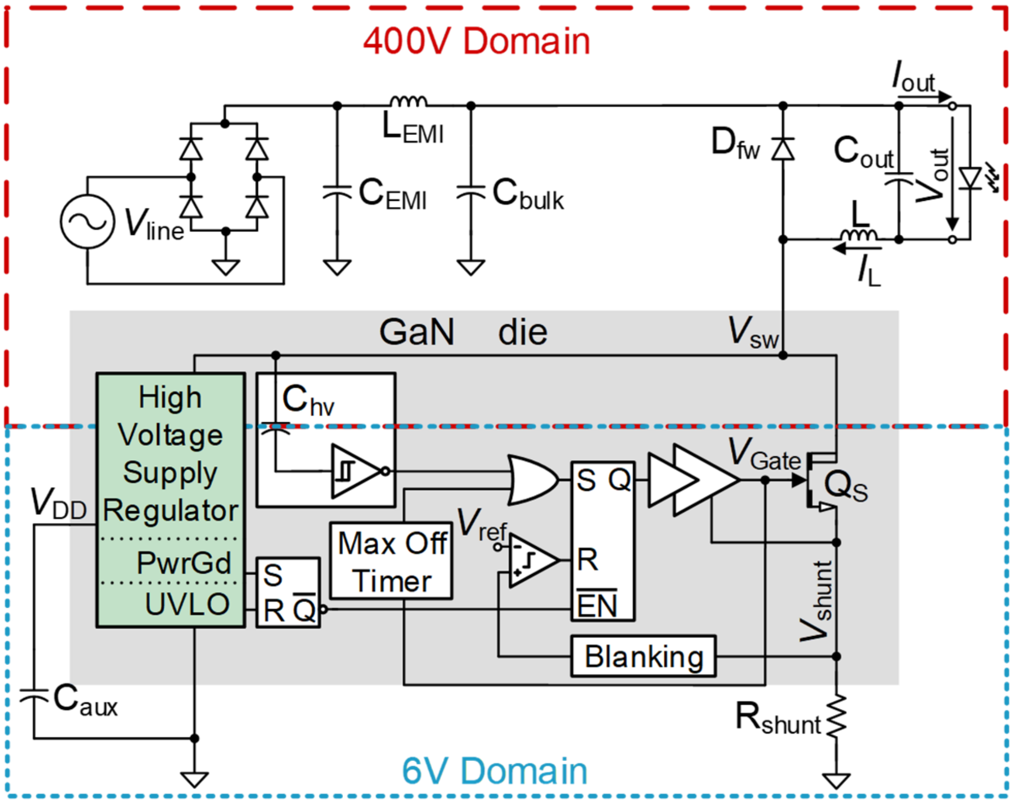

- Gate driver and high voltage power HEMT
- **Peak current comparator with autozeroing**

# Monolithic GaN Offline Buck Converter



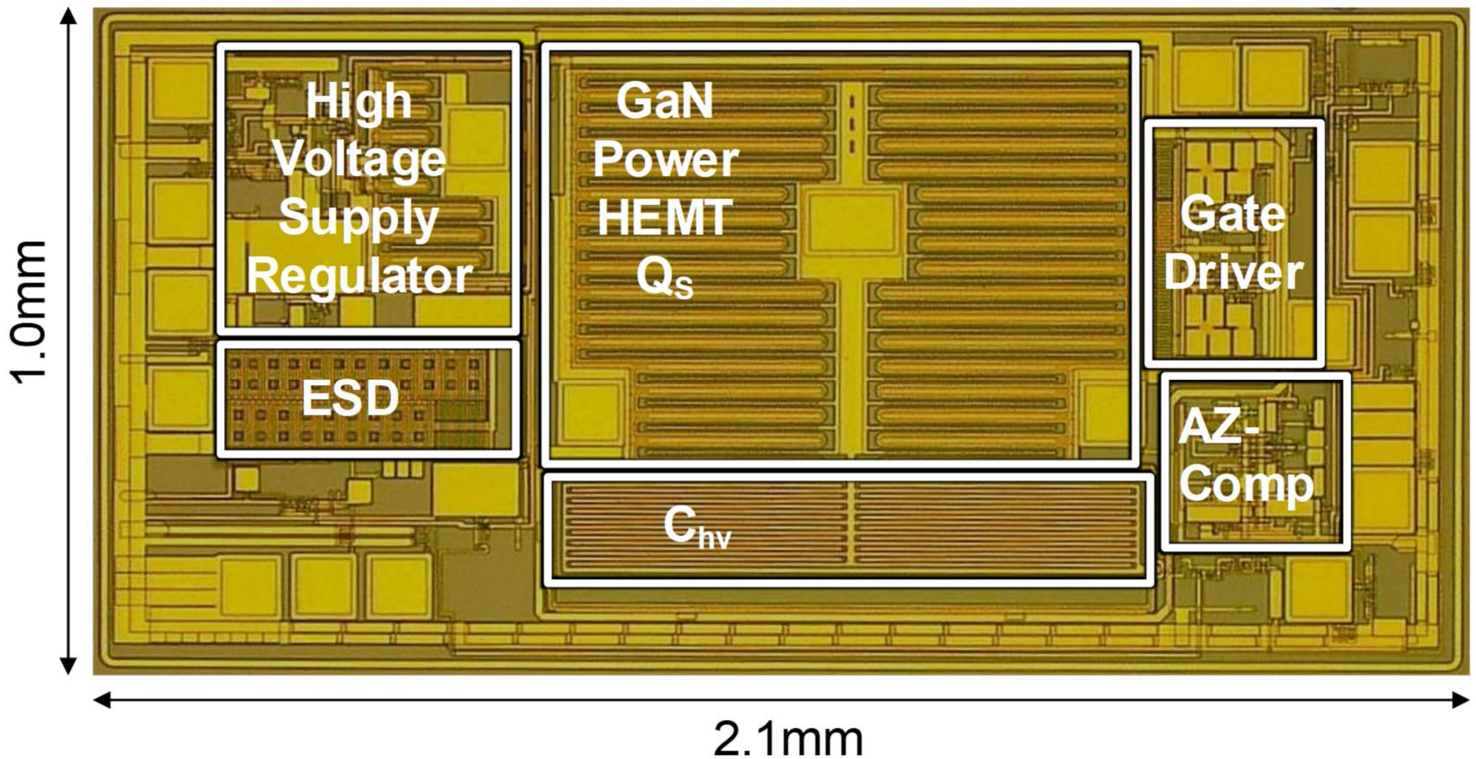

- Gate driver and high voltage power HEMT
- Peak current comparator with autozeroing
- **Zero current detection for boundry conduction mode**
- **Max off timer for startup**

# Monolithic GaN Offline Buck Converter



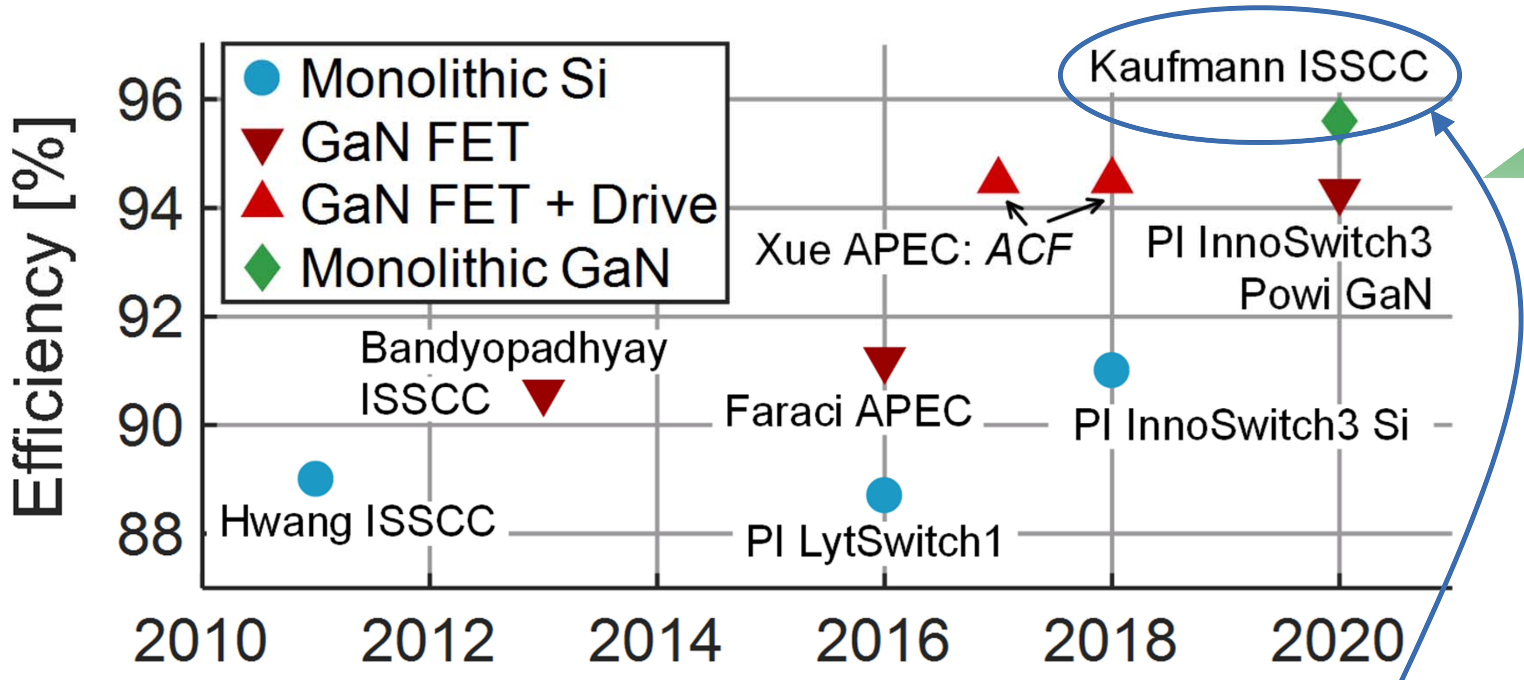

- Gate driver and high voltage power HEMT
- Peak current comparator with autozeroing
- Zero current detection for boundry conduction mode
- Max off timer for startup
- **HV supply regulator for self-biased offline operation**

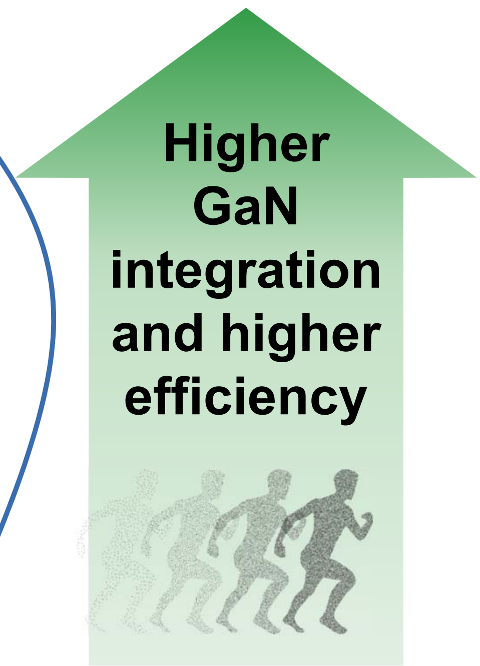
# Monolithic GaN Offline Buck Converter




**650V**
**GaN-on-Si**

# 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

- GaN enables highly efficient and compact power conversion ***BUT*** gate driving is more challenging
- High-voltage energy storing (HVES) gate driver actively uses gate loop inductance for quick and robust resonant switching
- Monolithic integration with GaN eliminates gate loop parasitics and tracks PVT of the driving voltage for the GaN HV-HEMT

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

# References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