CoPEC

Monolithic High Frequency GaN Switched-Mode Power Converters

Dragan Maksimovic
maksimov@colorado.edu
Colorado Power Electronics Center (CoPEC)
ECEE Department, University of Colorado - Boulder

IEEE PELS Chapter meeting, UC Berkeley, February 1, 2016

Outline

- CoPEC: Colorado Power Electronics Center
- Introduction to wide bandgap semiconductors
- Monolithic VHF GaN converters
  - Application of interest: drain supply modulation for RFPA's
  - Half-bridge power stage with integrated gate drivers in GaN process
  - Experimental results: 10-400 MHz switching, up to 50V, >10W power
- Conclusions

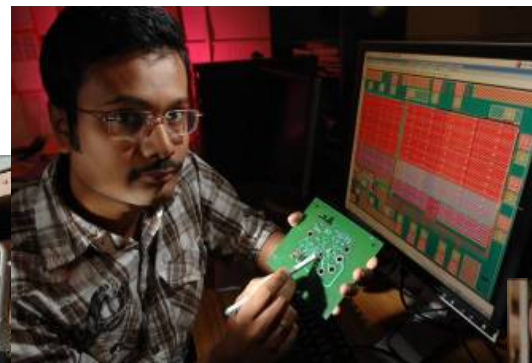
Colorado Power Electronics Center (CoPEC)

CoPEC faculty:

Prof. Bob Erickson
Prof. Dragan Maksimovic
Prof. Khurram Afridi
Prof. Hanh-Phuc Le (PMIC’s)
Prof. Zoya Popovic (RF/Microwaves Lab)
Dr. David Jones (Post-Doc Research Associate)

Research and education programs
in smart power electronics for energy efficiency and renewable energy applications and systems

From digital power control for components and systems…



…to custom power management ICs …

… to energy harvesting and wireless power transfer …

…energy efficient lighting systems, renewable energy systems, and automotive (EV) applications

Research projects:

- Sponsored by industry via CoPEC membership
- Sponsored by industry and agencies as separately directed contract projects

CoPEC Educational Program

Comprehensive power electronics curriculum

- Introduction to power electronics
- Resonant and soft-switching techniques
- Modeling and control of power electronics
- Power electronics and photovoltaic systems lab
- Power electronics for electric drive vehicles
- Adjustable speed ac drives
- Analog and mixed-signal integrated circuit design

Graduate certificates in (1) PE and (2) EV Technologies

Courses can be taken online through

beboulderanywhere.colorado.edu

Specialization in power electronics available through Coursera

www.coursera.org/specializations/power-electronics

CoPEC Research Directions

Transportation Electrification

U.S. DEPARTMENT OF ENERGY

DOE VT Incubator

(Erickson/Maksimovic/Afridi)

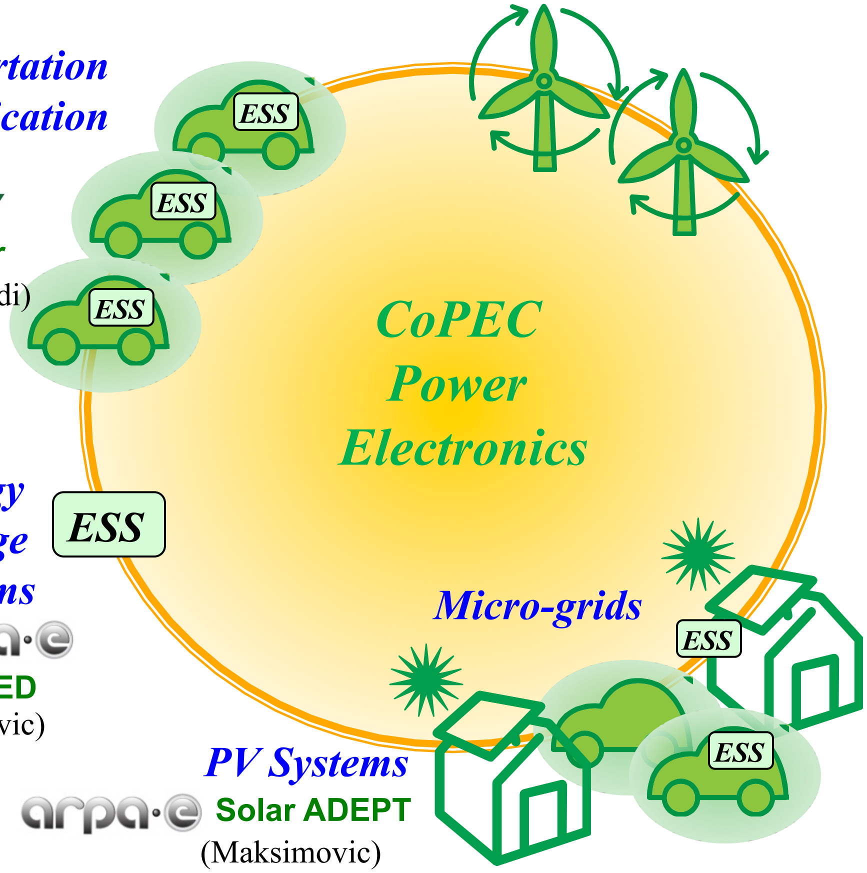
DOE GATE Center of Excellence

Energy Storage Systems

arpa-e

AMPED

(Maksimovic)



PV Systems

arpa-e Solar ADEPT

(Maksimovic)

Energy Efficiency and Consumer Electronics

- *Lighting*
- *Data centers, servers*
- *RF Transmitters* — DARPA MPC (Popovic/Maksimovic)
- *POL conversion*
- *Mobile electronics*
- *Wireless power* — arpa-e IDEAS, NSF (Afridi)
- *Energy harvesting*

- Research projects sponsored by industry through CoPEC, and by various agencies
- Collaborations with National Renewable Energy Laboratory

Introduction to wide bandgap semiconductors

Switch on-resistance R_{on} as a function of breakdown voltage V_B

$$R_{on} = k \frac{V_B^2}{A} \frac{1}{\mu_n \varepsilon_s E_c^3}$$

A = device area

V_B = device breakdown voltage

E_c = critical electric field for avalanche breakdown

μ_n = electron mobility

ε_s = semiconductor permittivity

$$\frac{AR_{on}}{V_B^2} = \frac{R_{on,sp}}{V_B^2} = \frac{k}{\mu_n \varepsilon_s E_c^3} =$$

Semiconductor material figure of merit (FOM) for majority-carrier devices (e.g. MOSFETs)

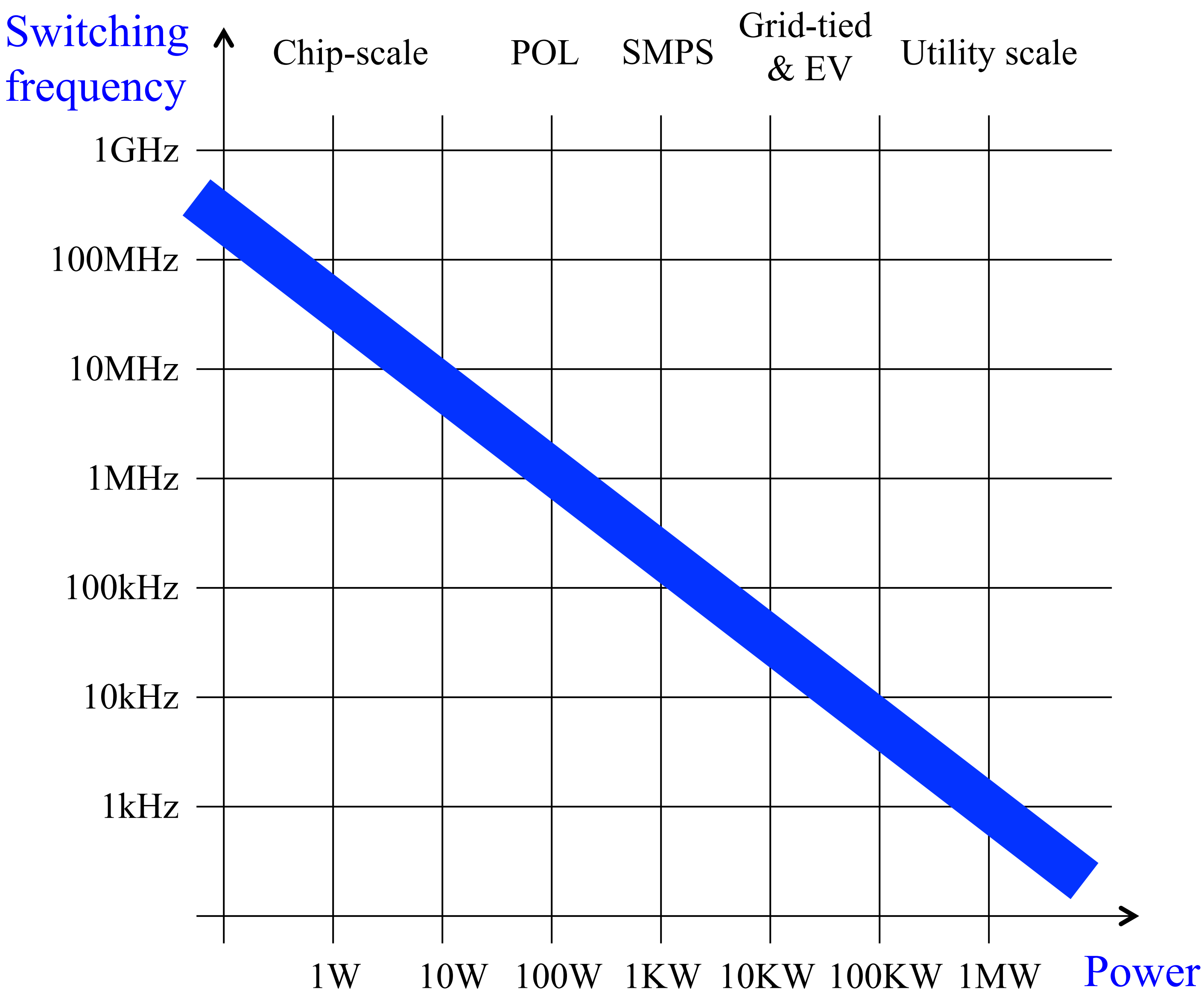
Comparison of semiconductor materials

Material	Bandgap [eV]	Electron mobility μ_n [cm^2/Vs]	Critical field E_c [V/cm]	Thermal conductivity [W/m°K]
Si	1.12	1400	3×10^5	130
SiC	2.36-3.25	300-900	**$1.3\text{-}3.2 \times 10^6$**	700
GaN	3.44	900 1500-2000 (AlGaN/GaN)	**$3.0\text{-}3.5 \times 10^6$**	110

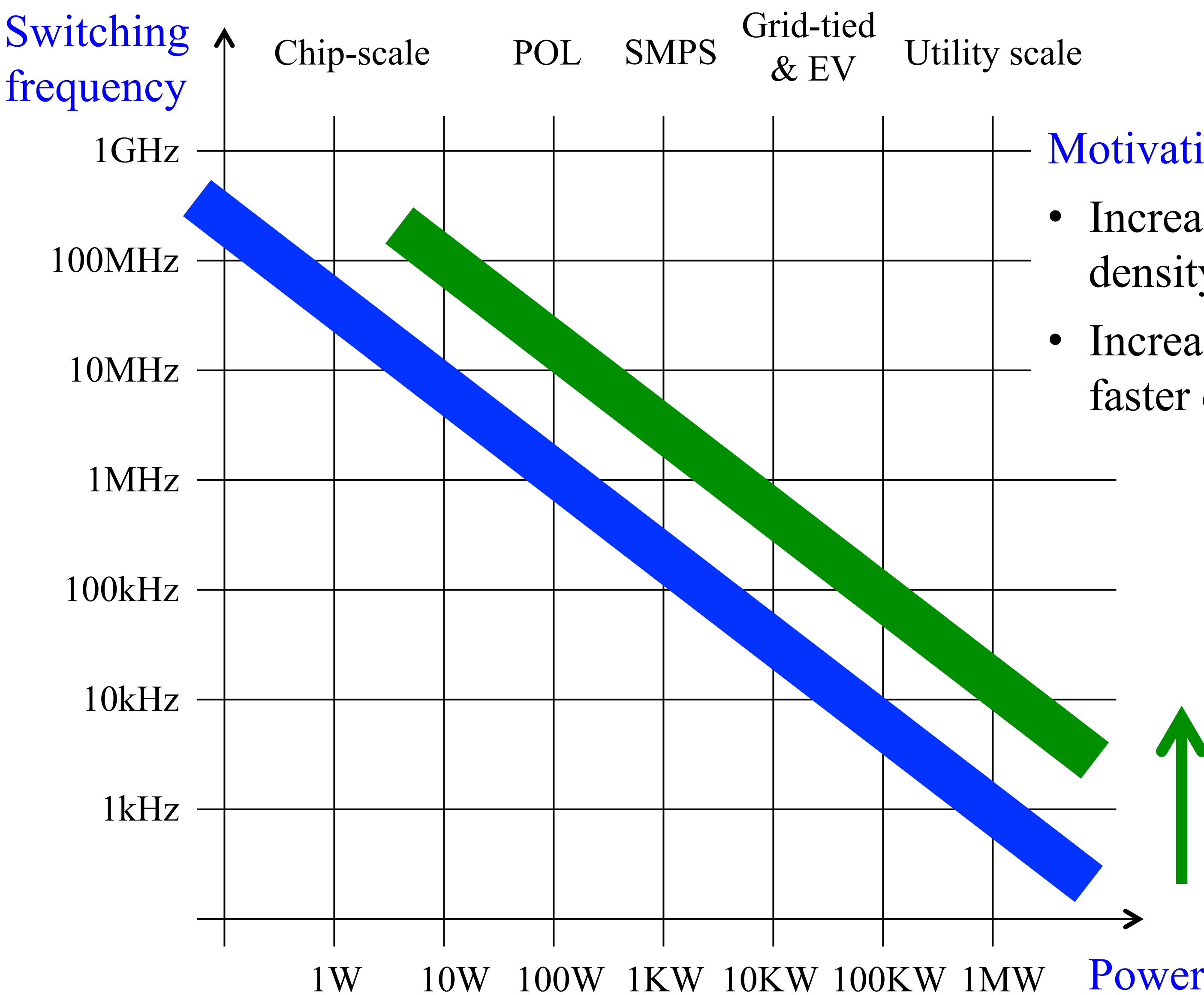
Advantages of wide bandgap (SiC, GaN) power semiconductors

- Much better FOM, reduced resistive voltage drops at higher breakdown voltages
- Much reduced stored charge (MOSFET), much reduced reverse-recovery related switching losses (high-voltage Schottky diodes)
- Capability of operation at increased junction temperature

Power electronics applications



Increased switching frequency: motivation

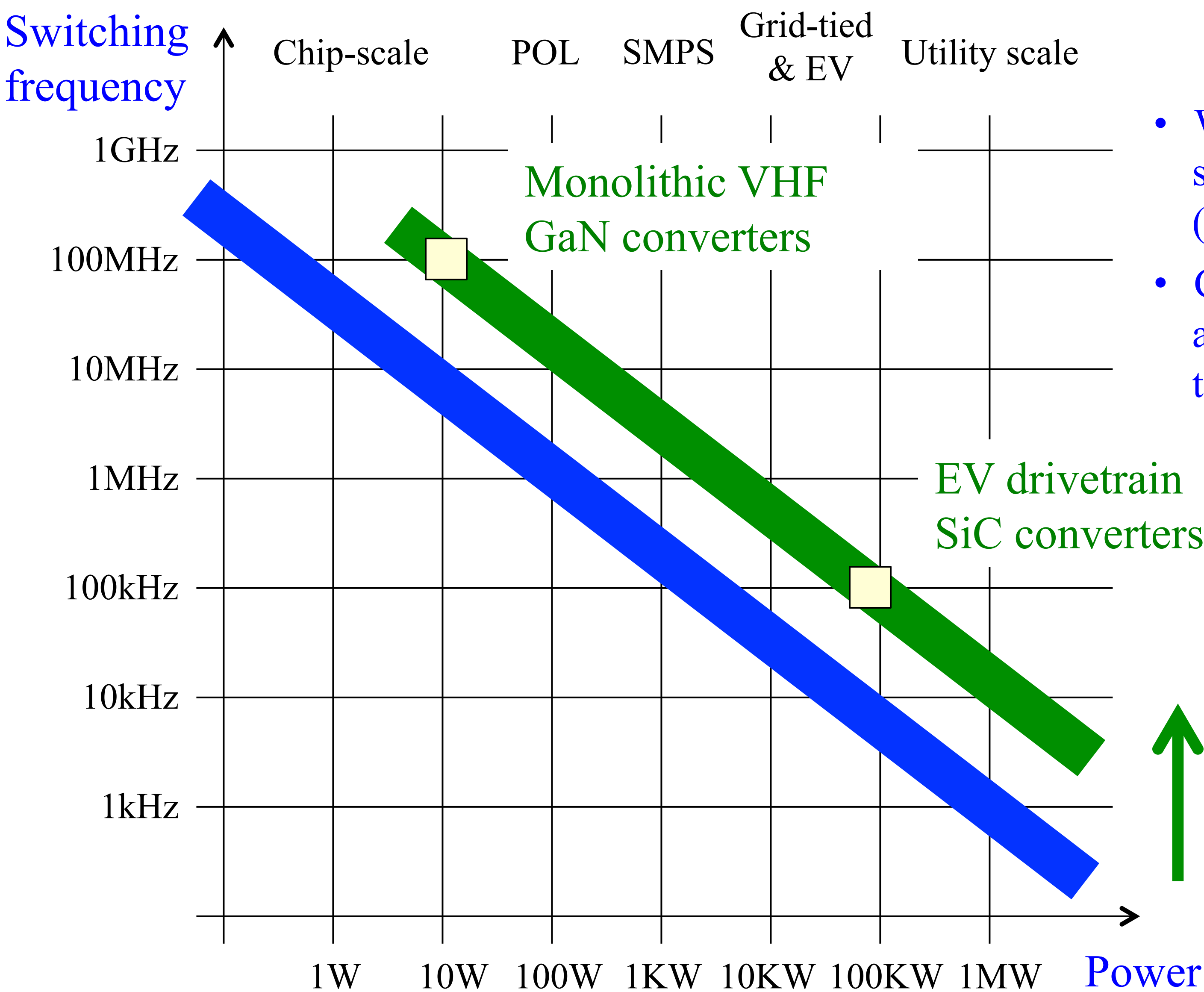


Motivation:

- Increased power density
- Increased bandwidth, faster dynamics

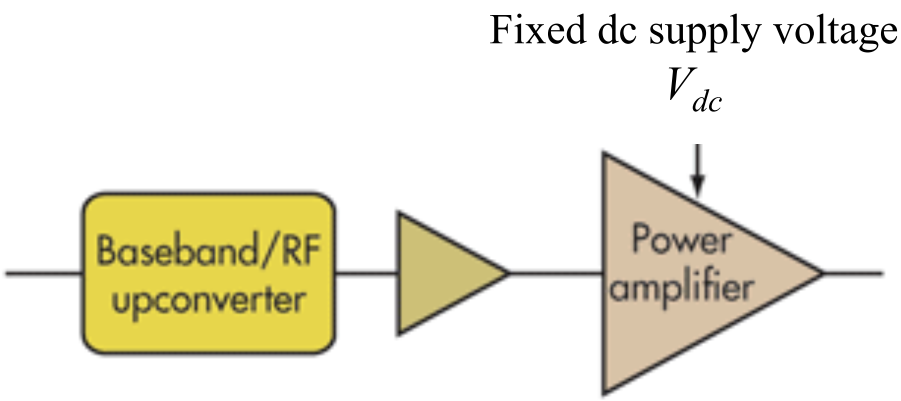
- Wide bandgap semiconductors (GaN, SiC)
- Circuit topologies and design techniques

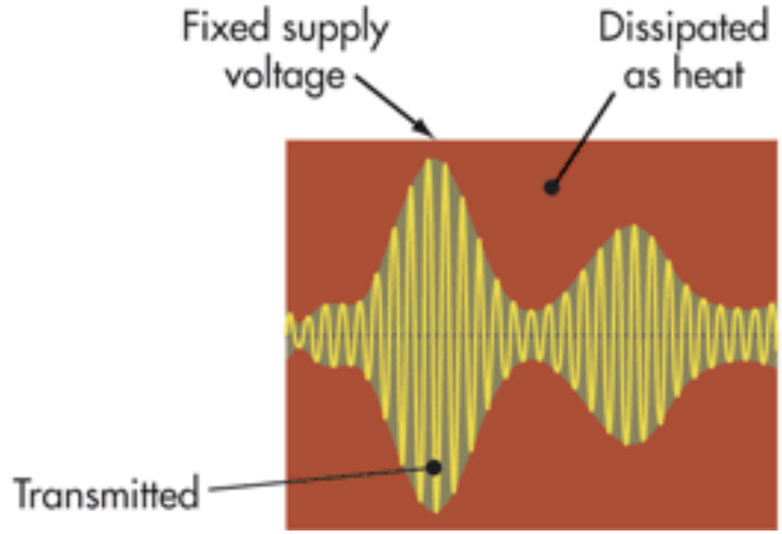
Application examples from our recent projects



- Wide bandgap semiconductors (GaN, SiC)
- Circuit topologies and design techniques

Application: RF transmitters

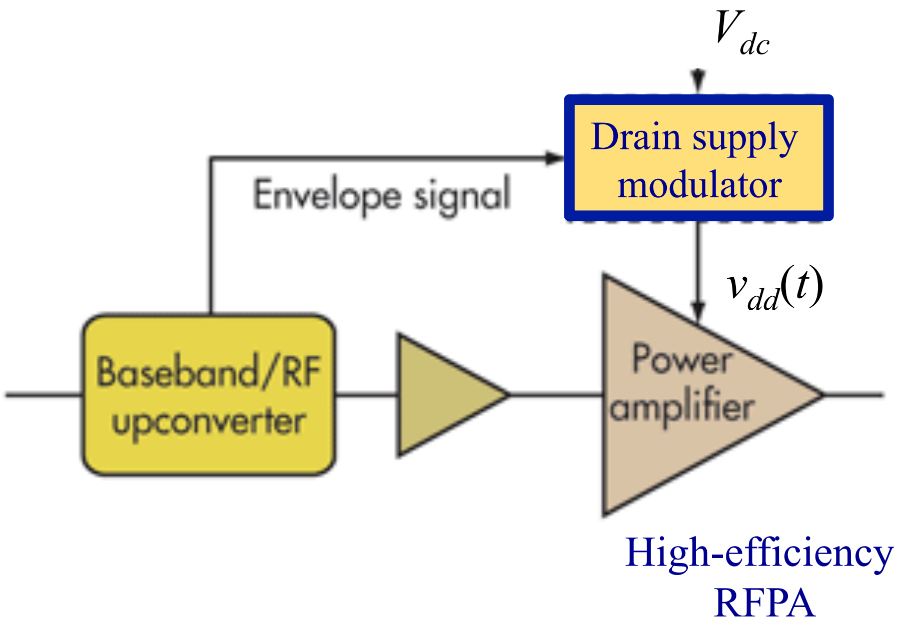


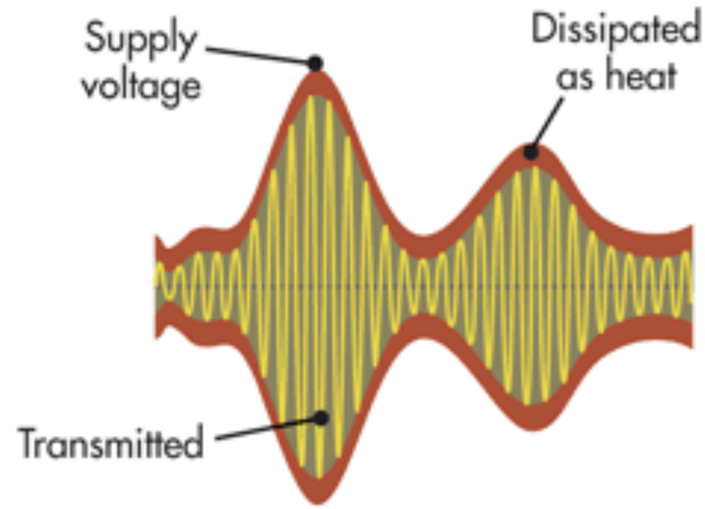


Problem: low efficiency of conventional RF transmitters in mobile, base station, and other wireless infrastructure systems

- High peak-to-average ratio (PAR) signals
- Continuous-wave (CW) or low-PAR signals at average power levels below peak

Objective: high-efficiency, flexible RF transmitters

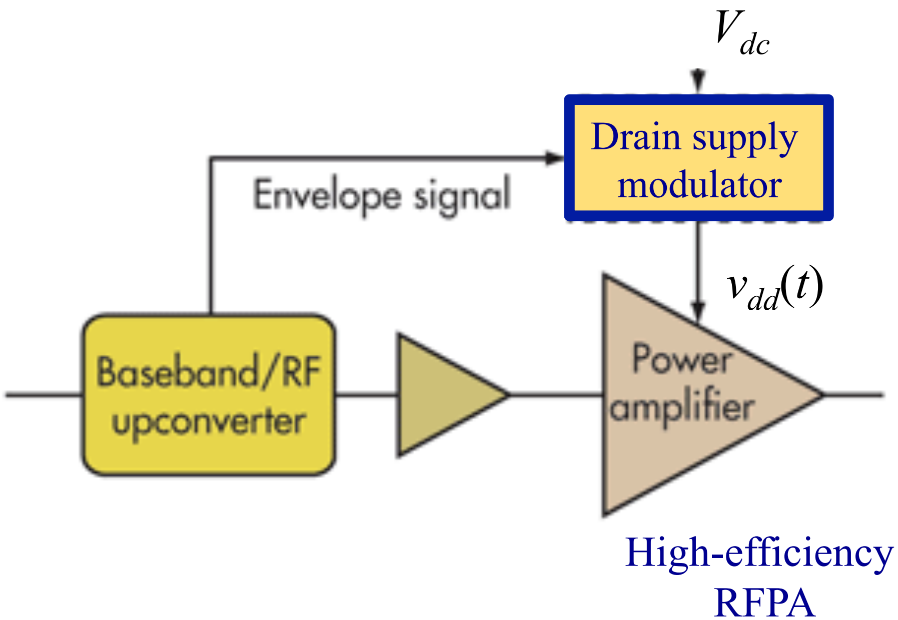


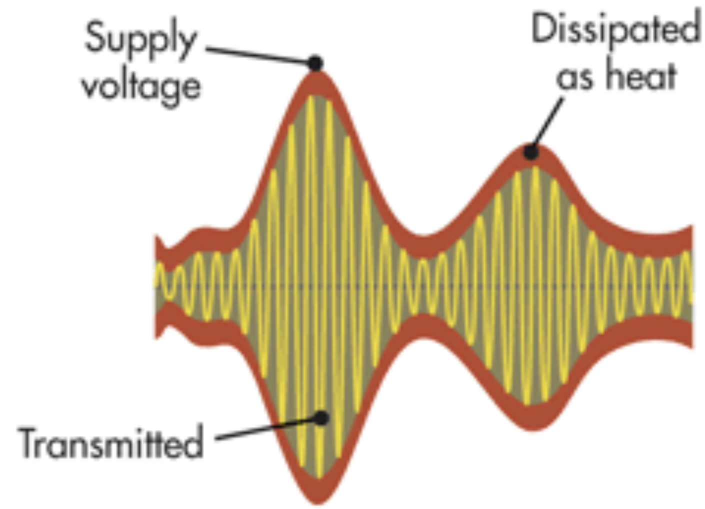


One possible system efficiency improvement approach:
"envelope tracking" transmitters based on drain supply modulation

- High-efficiency RFPA
- High-efficiency, wide-bandwidth envelope-tracking drain supply modulator
- System co-design and integration

Objective: high-efficiency, flexible RF transmitters



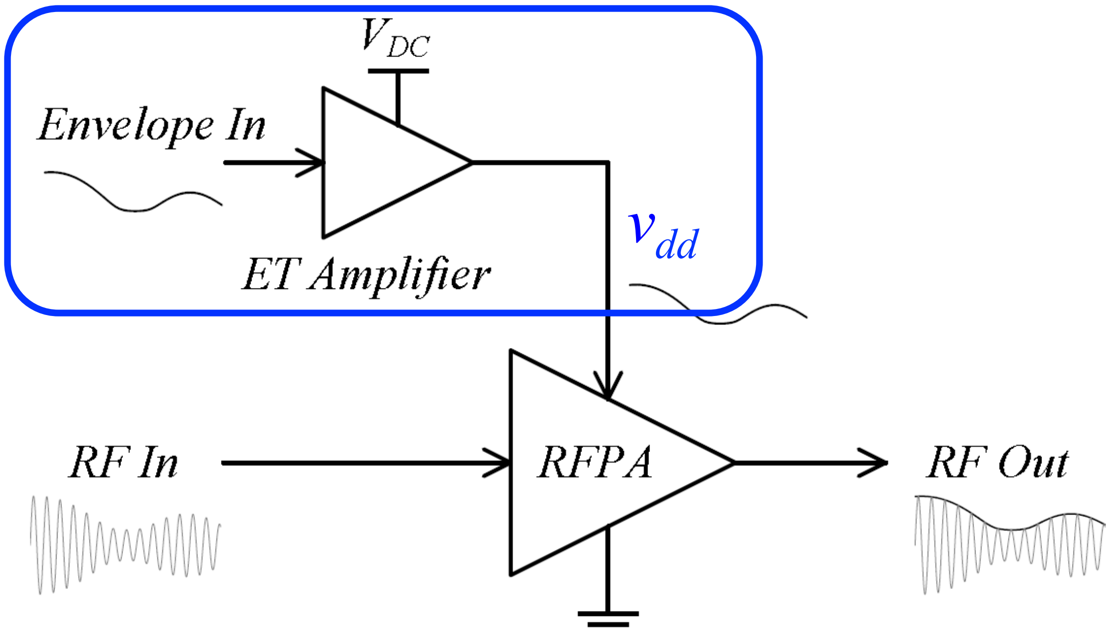


One possible system efficiency improvement approach:
"envelope tracking" transmitters based on drain supply modulation

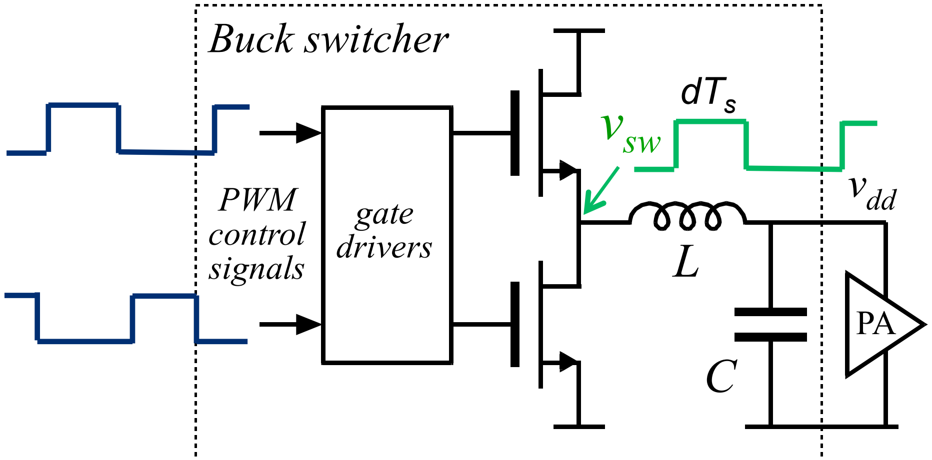
- High-efficiency RFPA
- **High-efficiency, wide-bandwidth envelope-tracking drain supply modulator**
- System co-design and integration

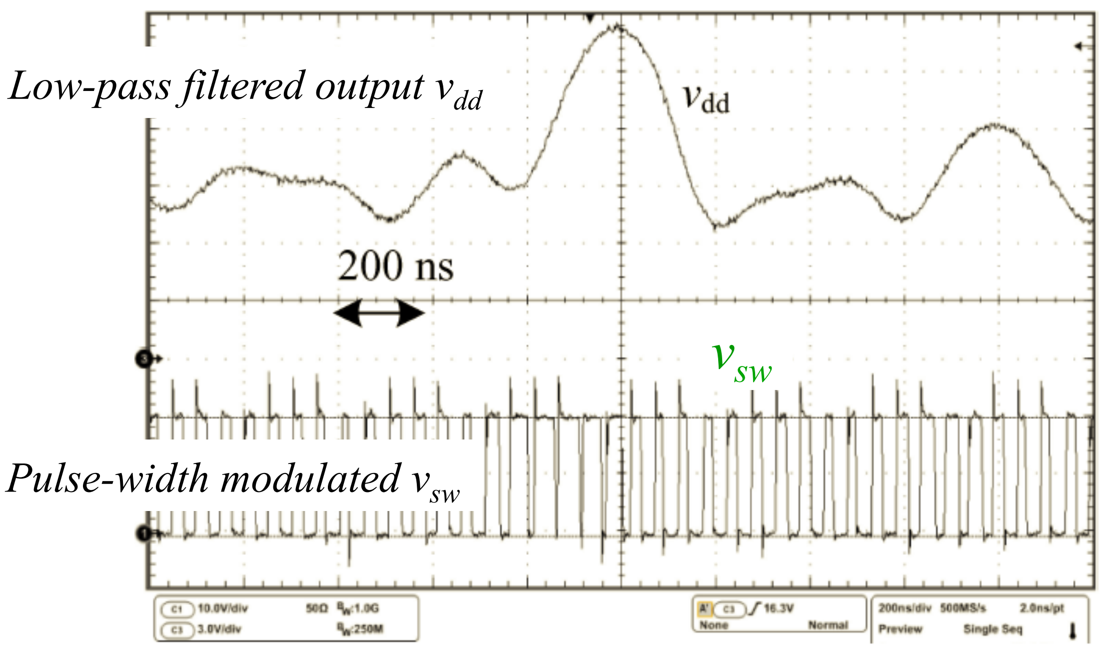
Drain supply modulator design challenges

- Wide tracking bandwidth [$BW_{tracking}$ = 10's to 100's of MHz]
- High output voltage slew rate [dv_{dd}/dt = several V/ns]
- High efficiency to realize system-level efficiency improvements



Basic approach: PWM buck dc-dc converter





LC filter corner frequency

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

$$f_o > BW_{tracking}$$

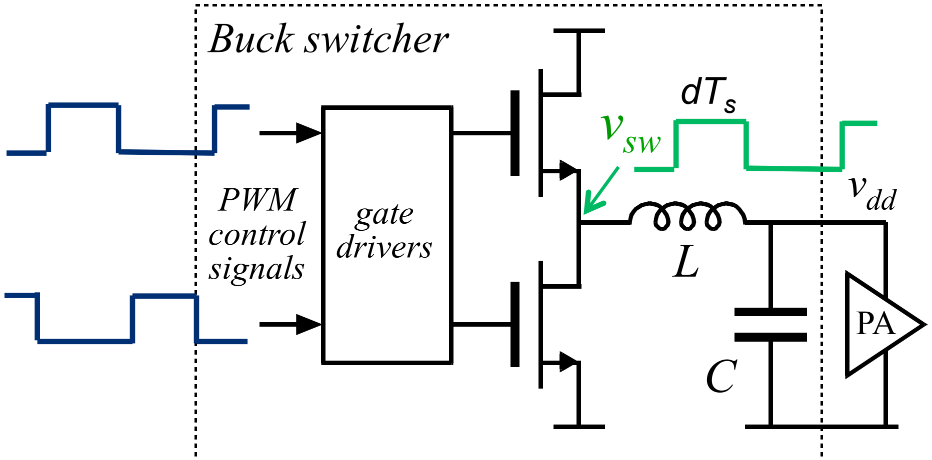
Filtered output voltage

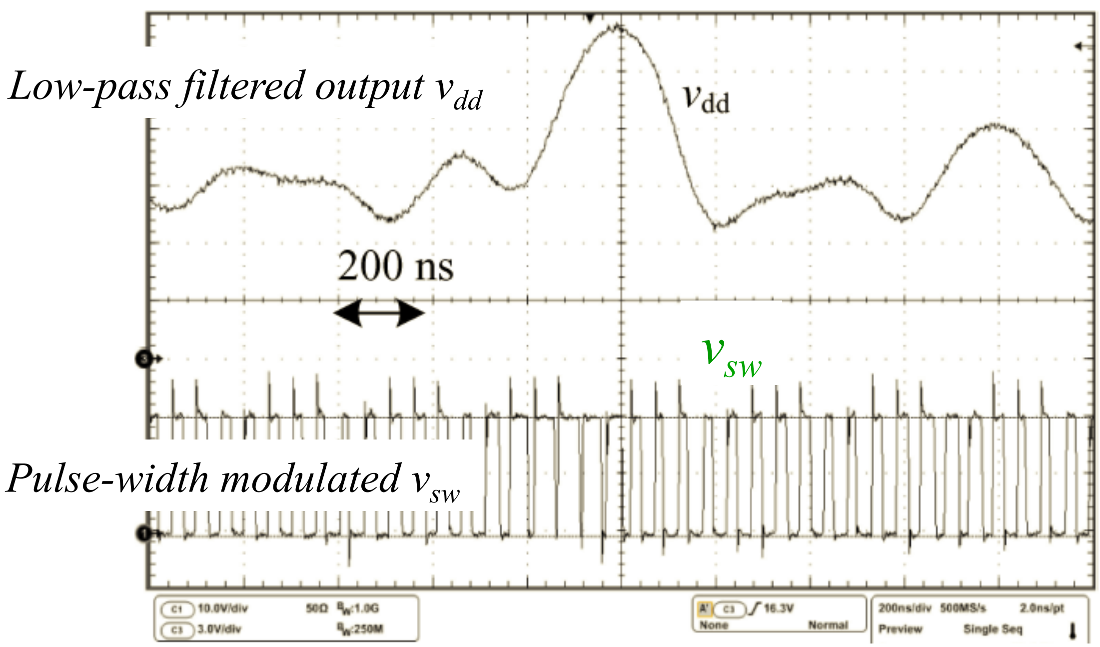
$$v_{dd}(t) \approx d(t)V_{in}$$

Switching frequency requirement

$$f_s >> BW_{tracking}$$

Challenge: high-efficiency at high switching frequency





LC filter corner frequency

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

$$f_o > BW_{tracking}$$

Filtered output voltage

$$v_{dd}(t) \approx d(t)V_{in}$$

Switching frequency requirement

$$f_s >> BW_{tracking}$$

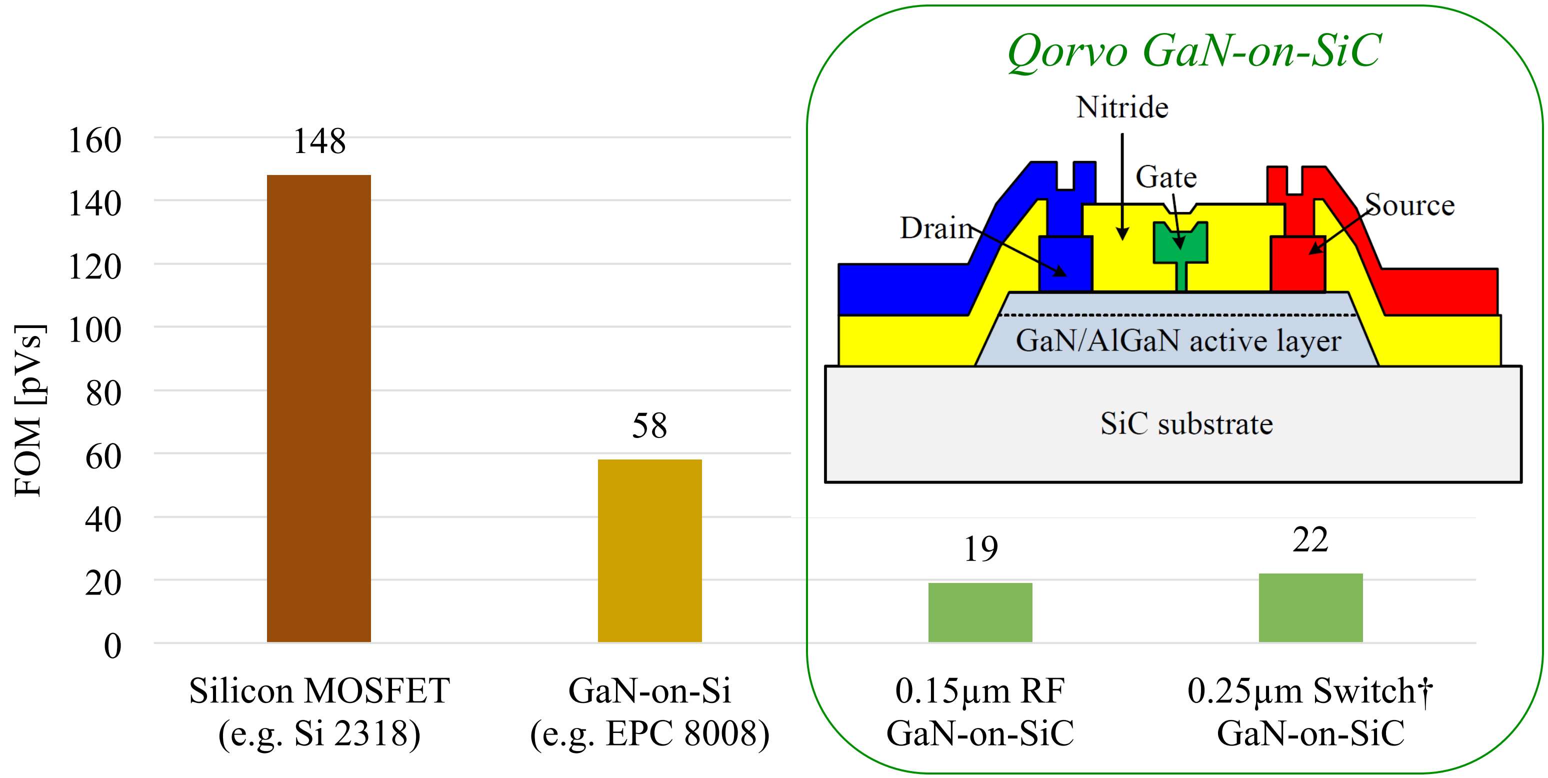
Conventional switched-mode power converter designs are limited to low switching frequencies (MHz) due to switching losses proportional to f_s

Approach: monolithic VHF GaN switchers

Switched-mode converter design techniques in GaN process

- Gate-drive integration
  - Enables efficient PWM of high-bridge power stage at VHF
  - Enables logic-level inputs to monolithic GaN switcher chip
- Zero-voltage switching
  - Reduces switching losses
- Multi-phase conversion
  - Improves tracking bandwidth to switching frequency ratio
  - Enables power scaling
  - Reduces ripple

GaN-on-SiC process: switch FOM = $R_{on,s}Q_{g,s}$

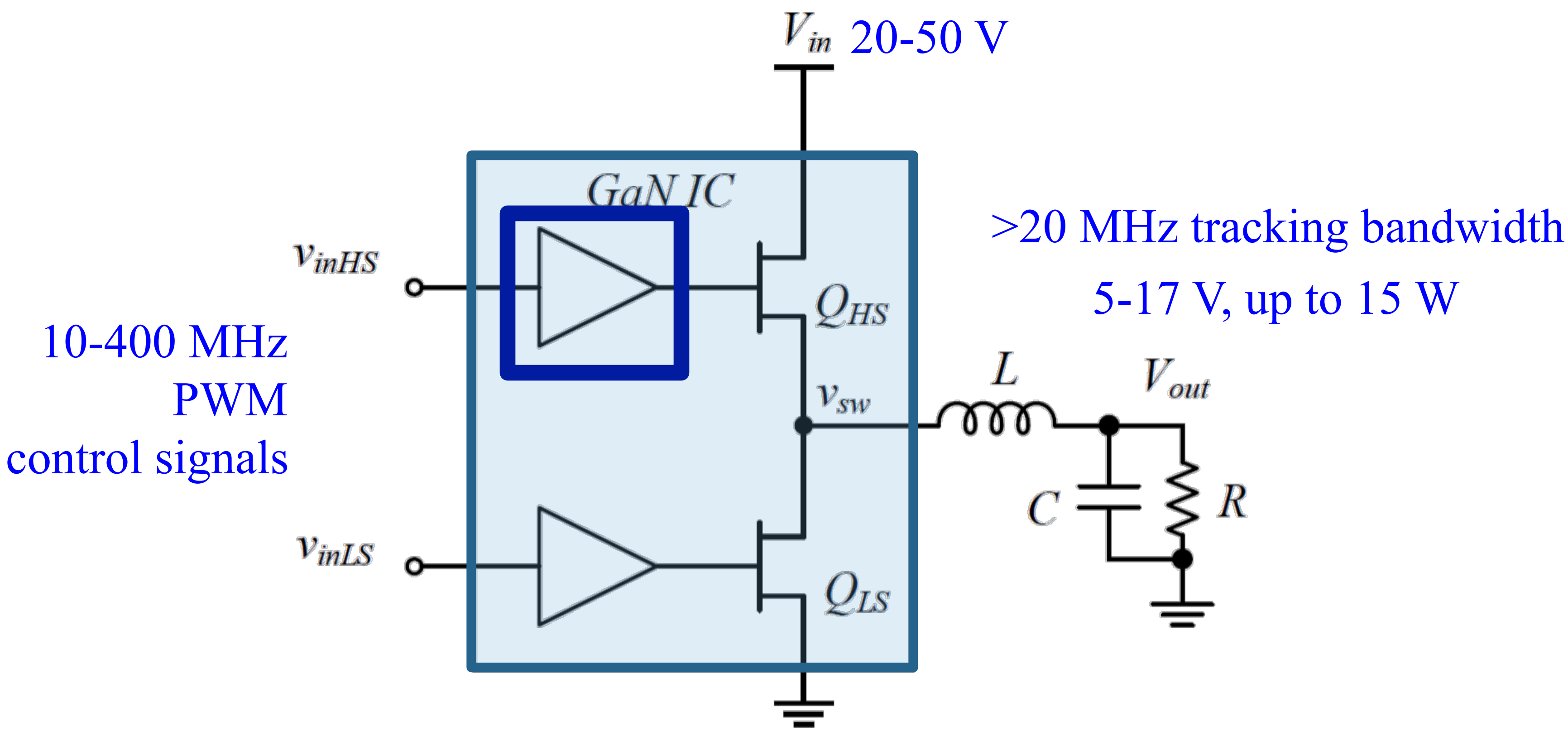


Superior figure of merit allows switched-mode converter circuit design techniques leading to high efficiencies at very high switching frequencies

Integrated converter circuits tested at 10-400 MHz switching frequencies, up to 20V in the 0.15µ RF process, and up to 50V in the 0.25µ Switch process

NMOS-only process: circuit design challenges

10-400 MHz Integrated GaN PWM Buck Converters

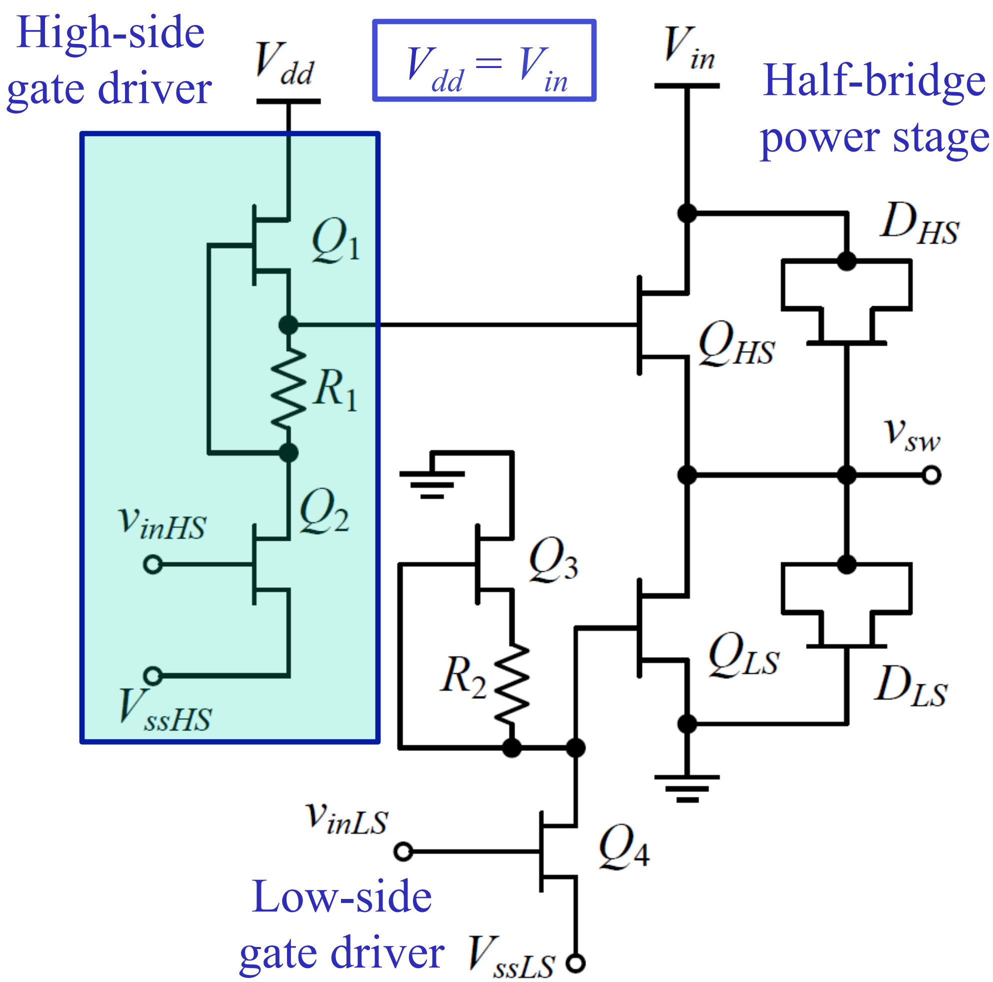


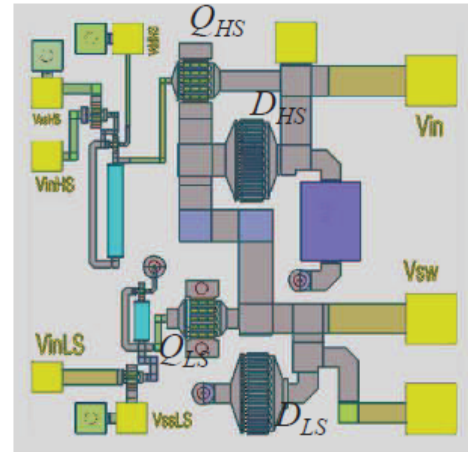
<u>Key circuit innovation:</u> level-shifting high-side gate driver in GaN-on-SiC process to support very high frequency PWM control

Integrated Gate Drivers for Half-Bridge Power Stage

- Active pull-up driver
- Bootstrap drive
- Modified active pull-up driver

Active pull-up driver





Chip layout: 2.4 × 2.3 mm

Half-bridge power stage
Q_{HS}/D_{HS}, Q_{LS}/D_{LS}

High-side gate driver
Q_1, R_1, Q_2

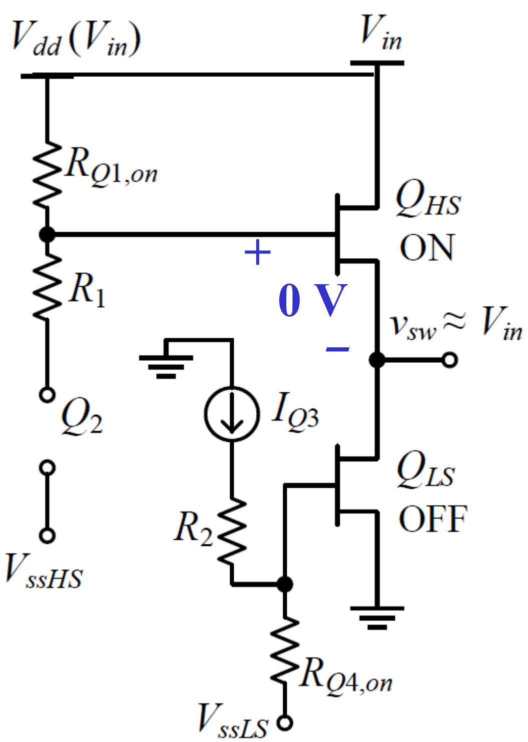
Low-side gate driver
Q_3, R_2, Q_4

Q_{HS}, Q_{LS}	D_{HS}, D_{LS}	Q_1, Q_3	Q_2, Q_4	R_1	R_2
10x125μm	10x120μm	2x25μm	4x50μm	300 Ω	125 Ω

Active pull-up driver operation

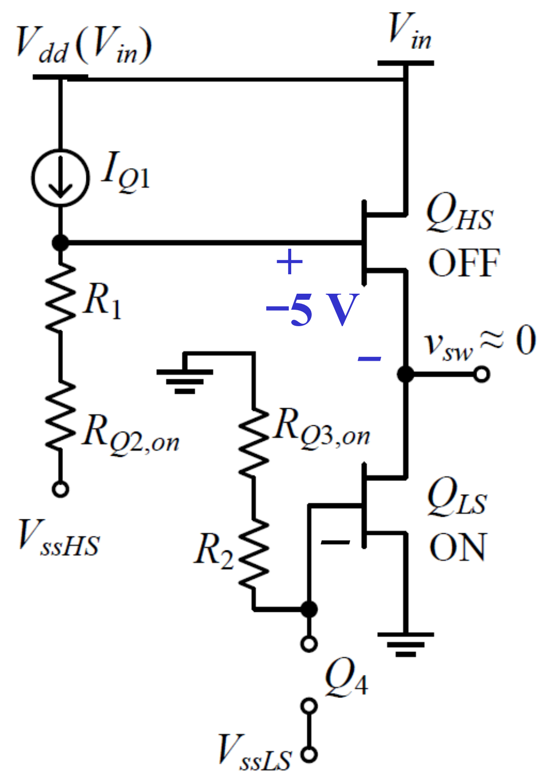
Q_{HS} on, Q_{LS} off

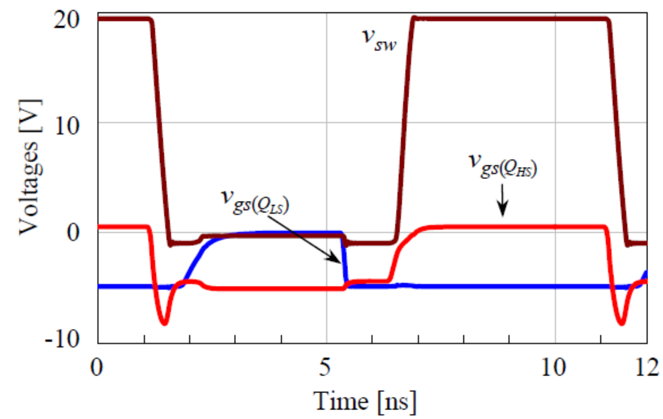
I_{Q3}=13.2 mA

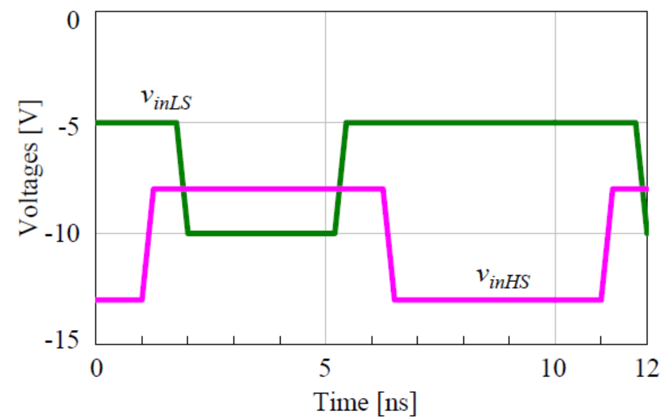


Q_{HS} off, Q_{LS} on

I_{Q1}= 8.5 mA





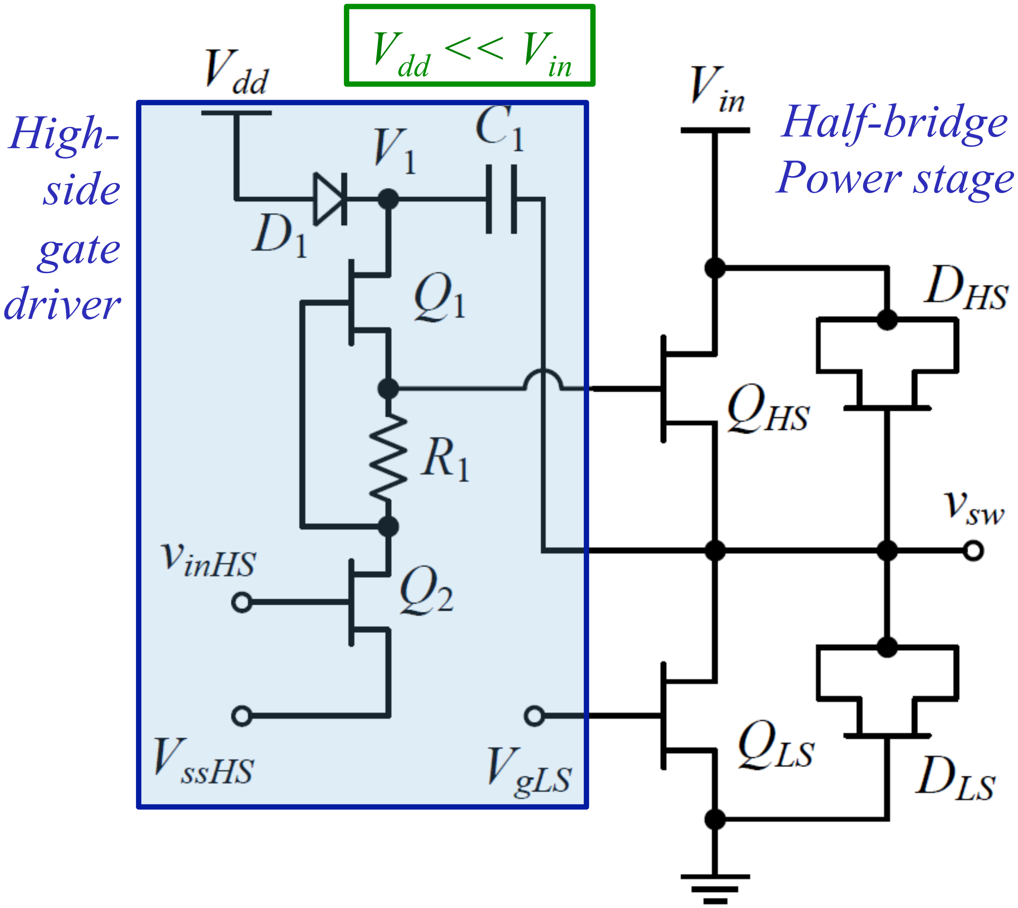


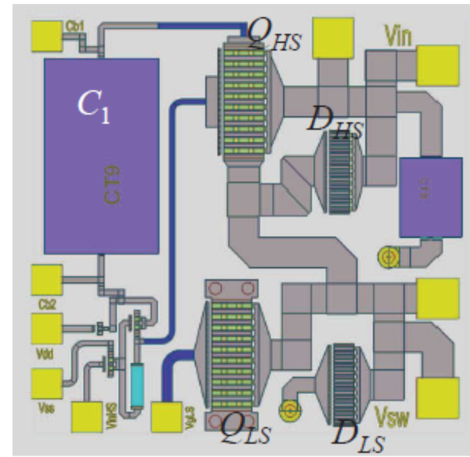
D=0.5, I_o=0.25 A

$$P_{d,conduction} = -DV_{ssLS}I_{Q3}+(1-D)(V_{in}-V_{ssHS})I_{Q1}$$

HIGH

Bootstrap driver





Chip layout: 2.4 × 2.3 mm

Q_{HS}, Q_{LS}	D_{HS}, D_{LS}	Q_1, Q_2	D_1	C_1	R_1
20x200μm	20x100μm	4x25μm	2x25μm	126 pF	175 Ω

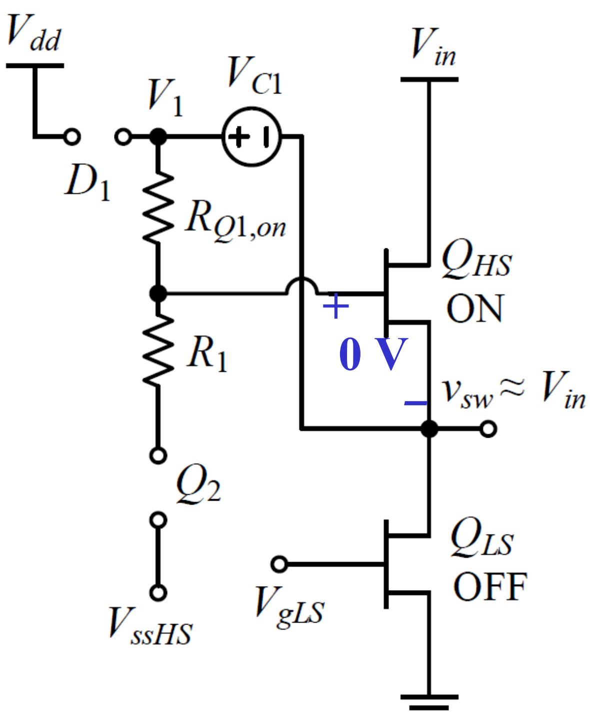
Half-bridge power stage
Q_{HS}/D_{HS}, Q_{LS}/D_{LS}

High-side gate driver
Q_1, R_1, Q_2, D_1, C_1

Low-side gate driver
Q_3, R_2, Q_4

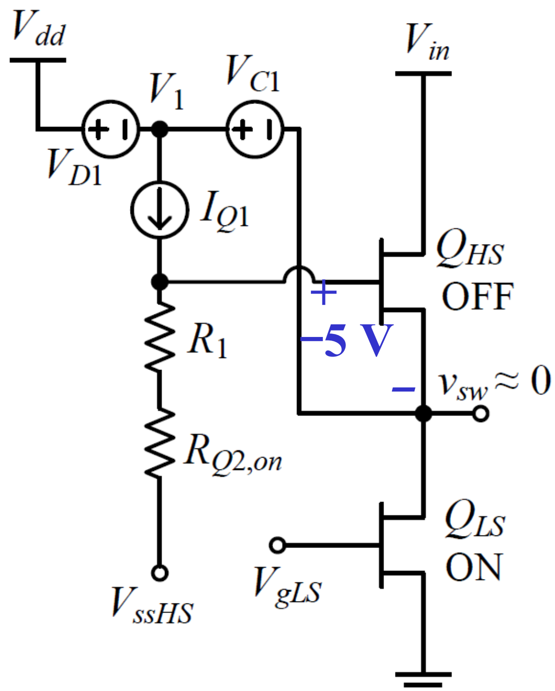
Bootstrap driver operation

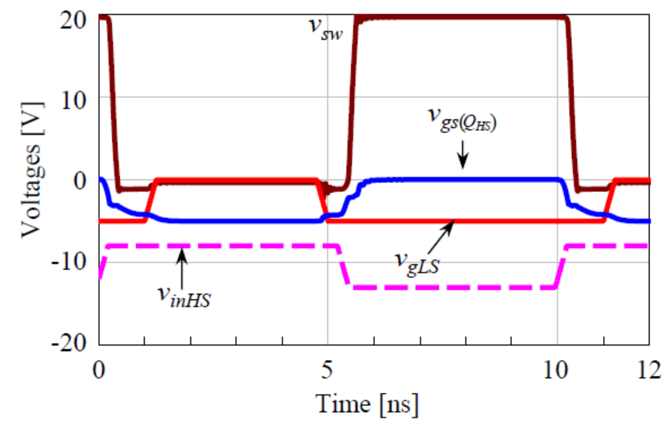
Q_{HS} on, Q_{LS} off



Q_{HS} off, Q_{LS} on

$I_{Q1} = 13.5\ mA$





D=0.5, I_o=0.25 A

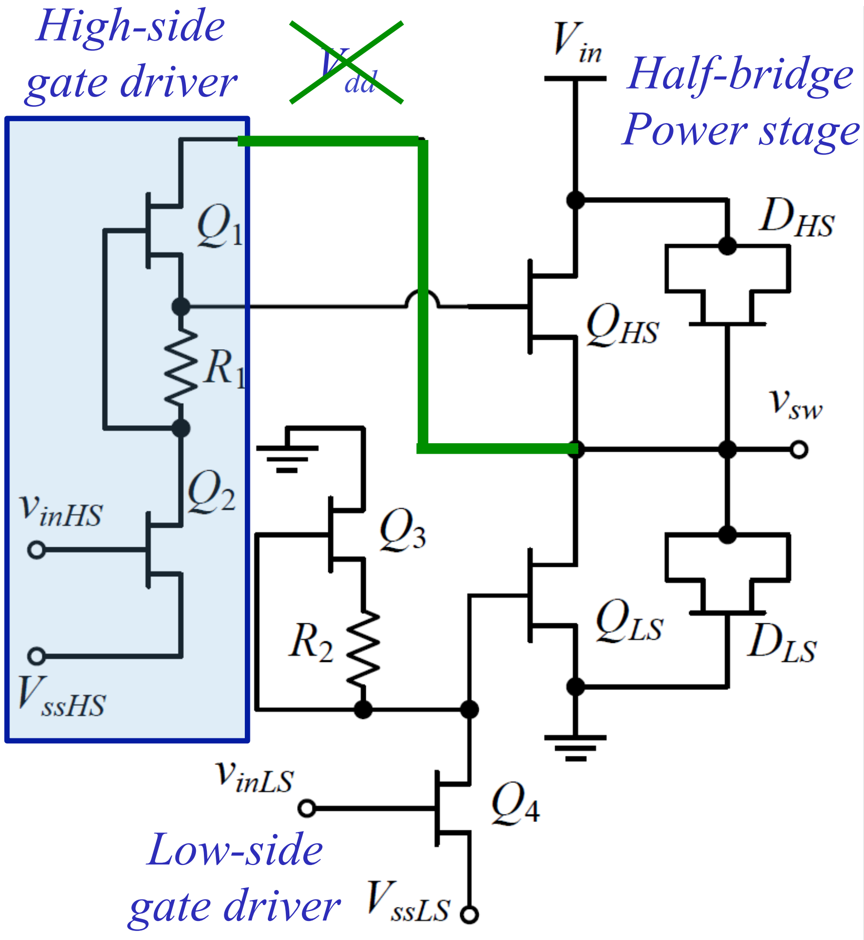
$$P_{d,conduction} = -DV_{ssLS}I_{Q3} + (1-D)(-V_{ssHS})I_{Q1}$$

LOW

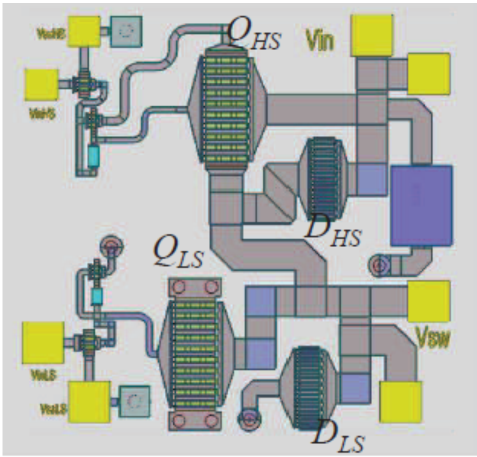
Low driver power loss,

but a bootstrap capacitor is required (large chip area, or external)

Modified active pull-up driver



Q_{HS}, Q_{LS}	D_{HS}, D_{LS}	Q_1, Q_3	Q_2, Q_4	R_1	R_2
20x200μm	20x100μm	4x25μm	4x50μm	100 Ω	75 Ω



Chip layout: 2.4 × 2.3 mm

Half-bridge power stage
Q_{HS}/D_{HS}, Q_{LS}/D_{LS}

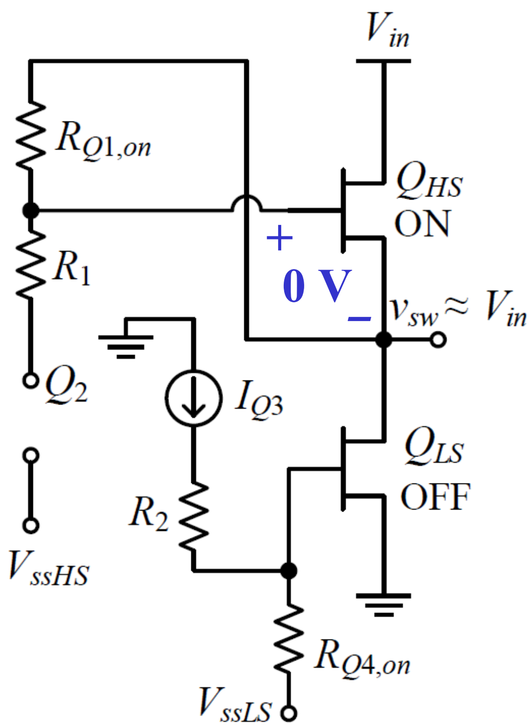
Half-side gate driver
Q_1, R_1, Q_2

Low-side gate driver
Q_3, R_2, Q_4

Modified active pull-up driver operation

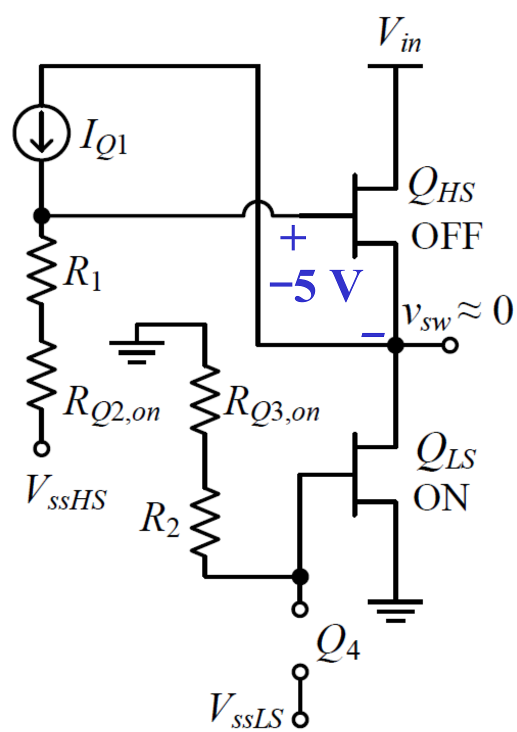
Q_{HS} on, Q_{LS} off

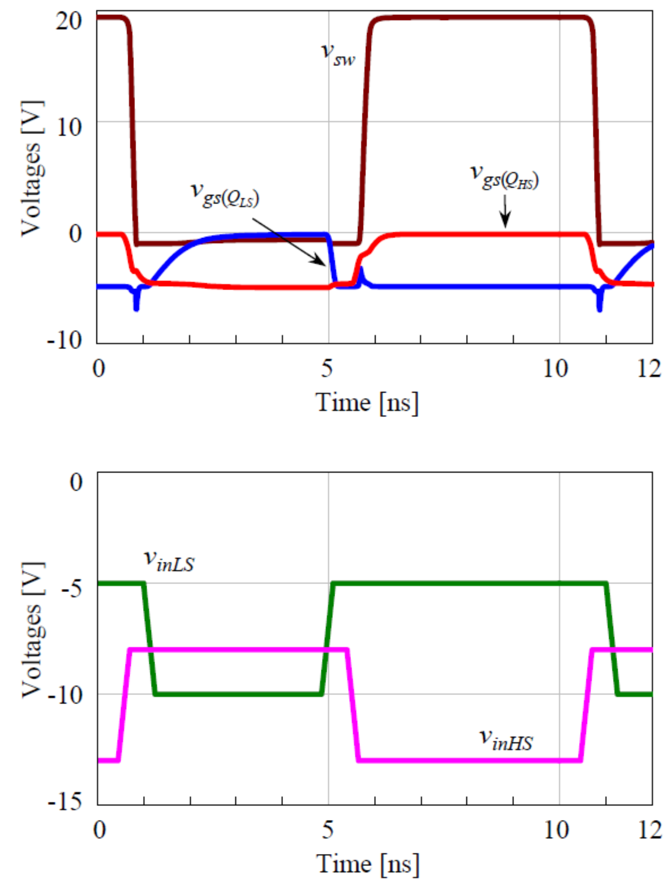
I_{Q3}=25.6 mA



Q_{HS} off, Q_{LS} on

I_{Q1}= 23.3 mA





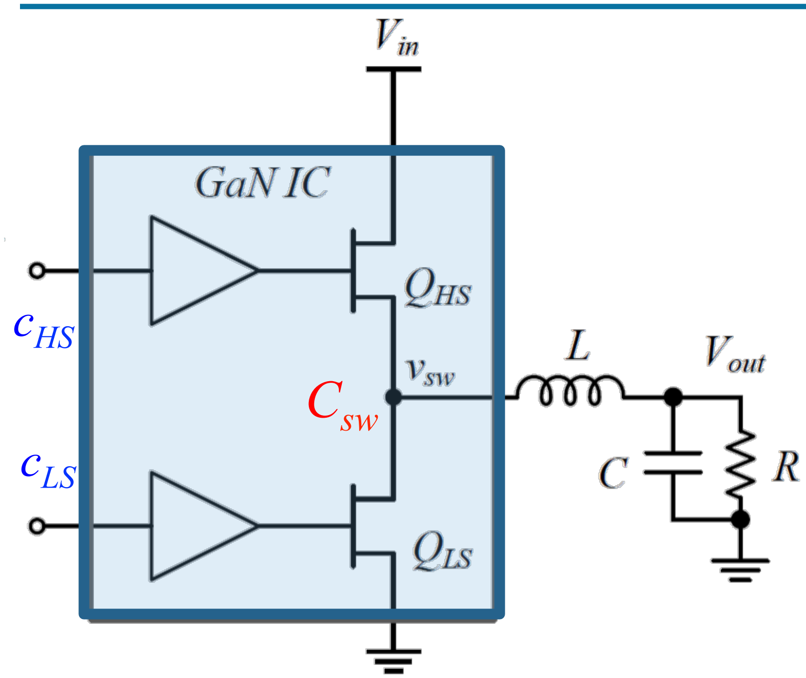
D=0.5, I_o=0.25 A

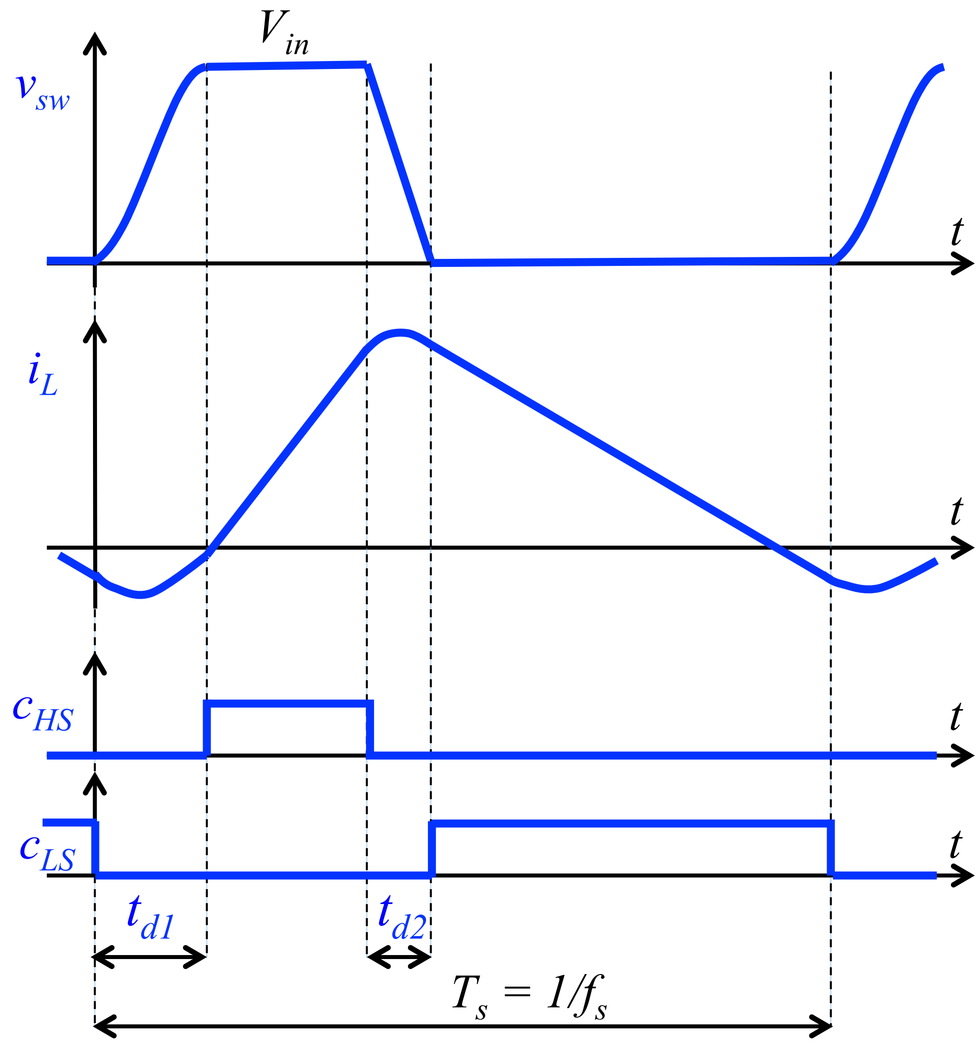
$$P_{d,conduction} = -DV_{ssLS}I_{Q3} + (1-D)(-V_{ssHS})I_{Q1}$$

LOW

Low driver power loss, and no bootstrap capacitor required

Zero-voltage-switching (ZVS) operation

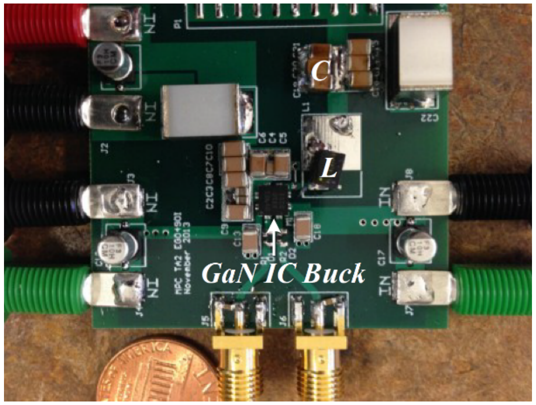


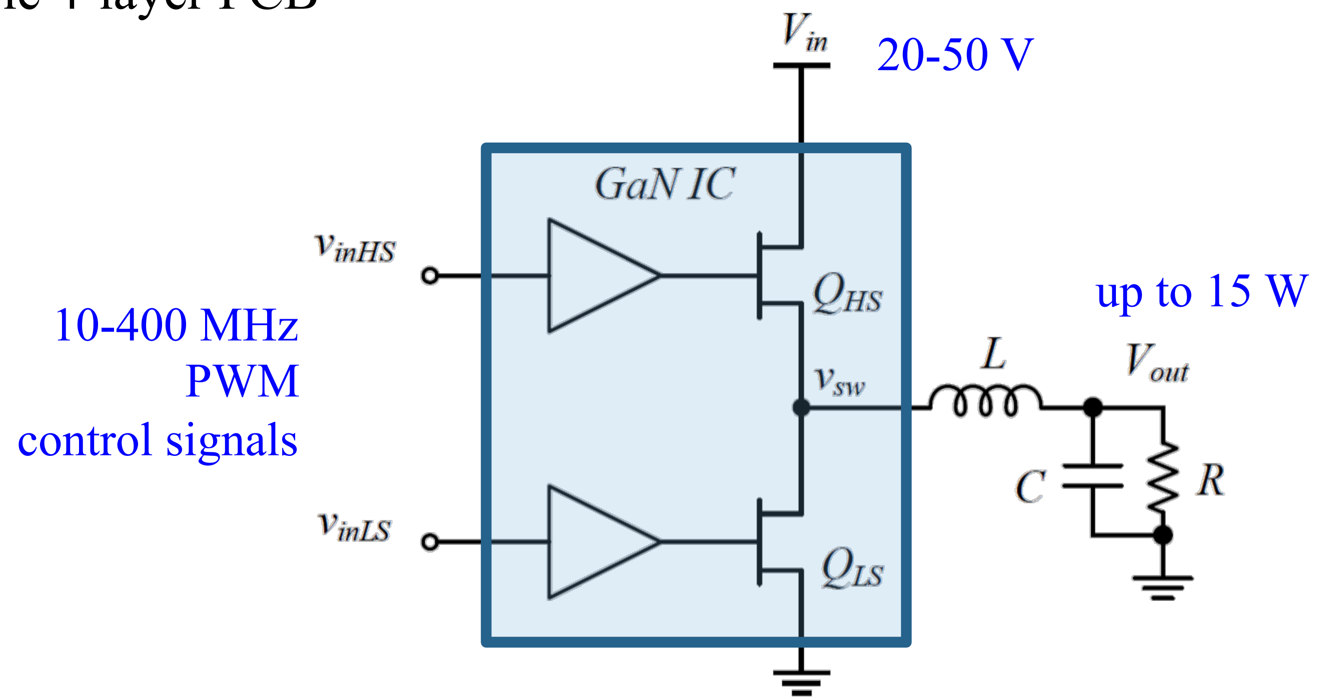


- L-C_{sw} resonant ZVS transitions
- Much reduced switching losses
- Dynamically adjusted dead-times t_{d1}, t_{d2} , with around 100ps resolution

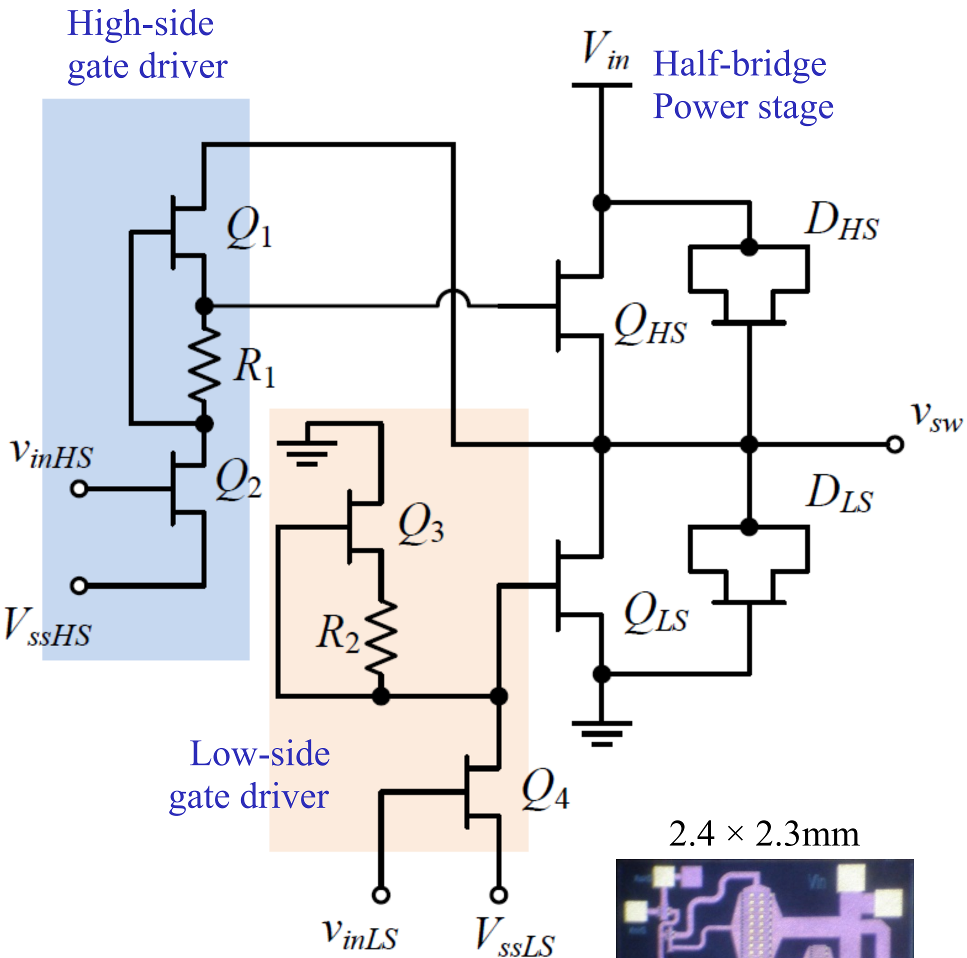
Experimental results

- 10-400 MHz PWM switching, mostly ZVS operation
- Control: Altera Stratix IV FPGA, 125 ps resolution
- Chips packaged in: 20-pin 4x4mm QFN package
- Filter components
  - Low-ESR capacitors (ATC)
  - High-*Q* air-core inductors (Coilcraft), 10-400 nH
- Simple 4-layer PCB

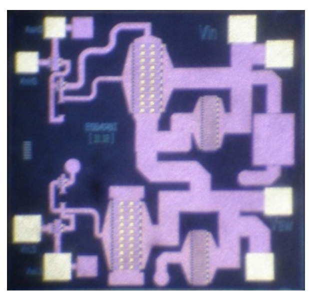


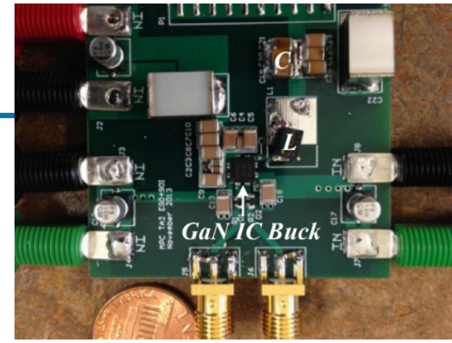


Switching waveforms

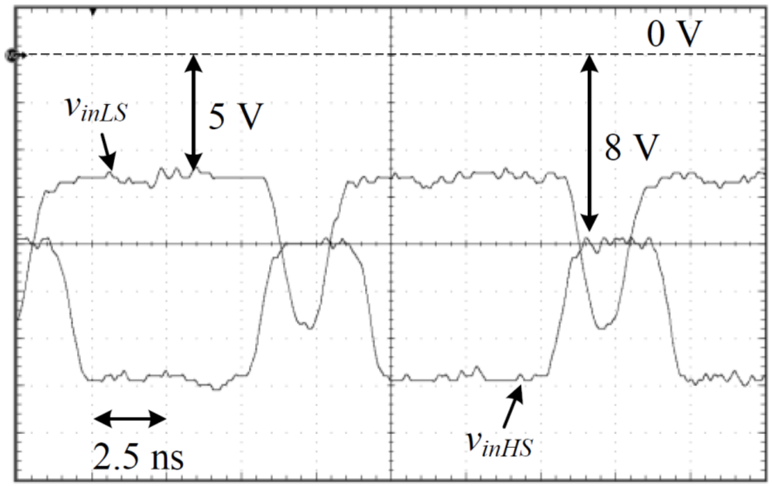


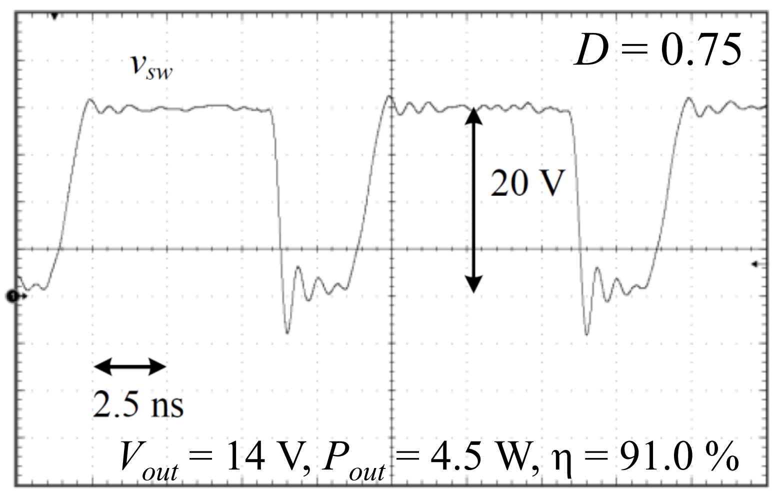
2.4 × 2.3mm



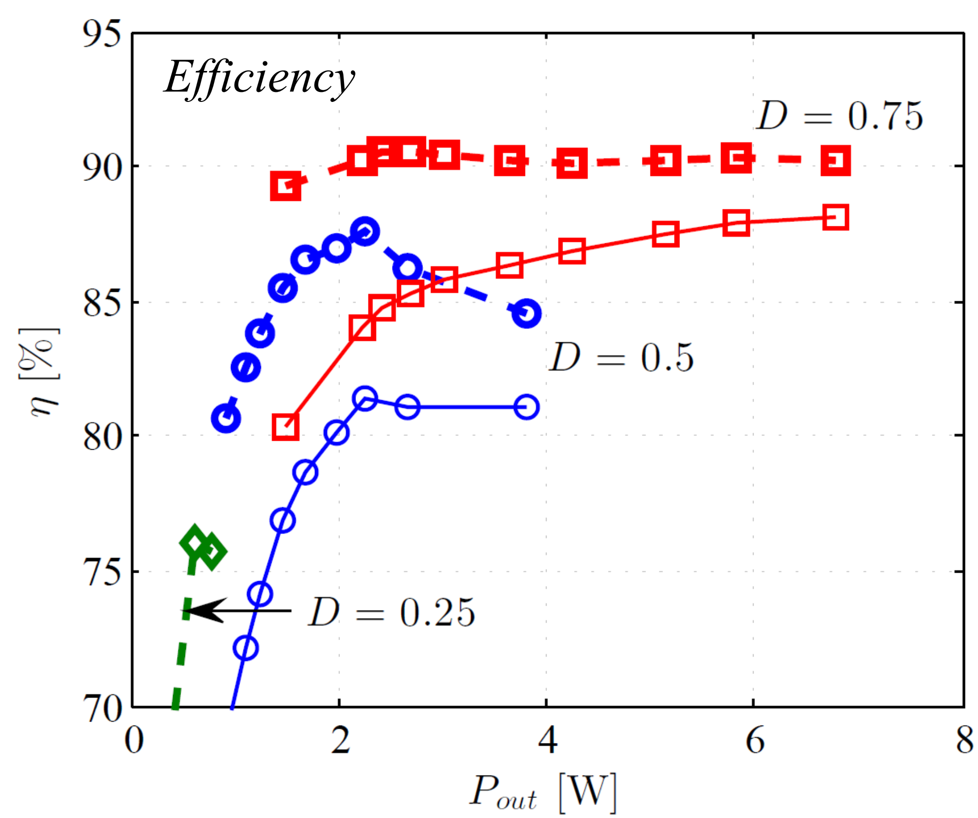


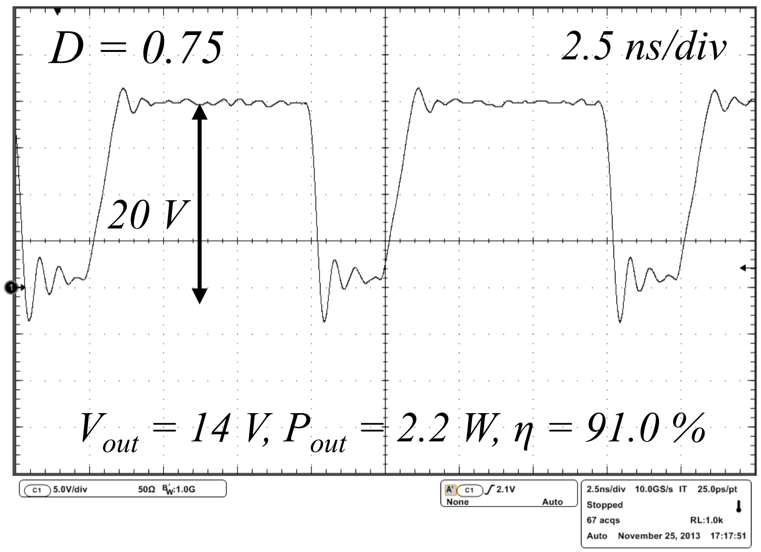
100 MHz switching waveforms

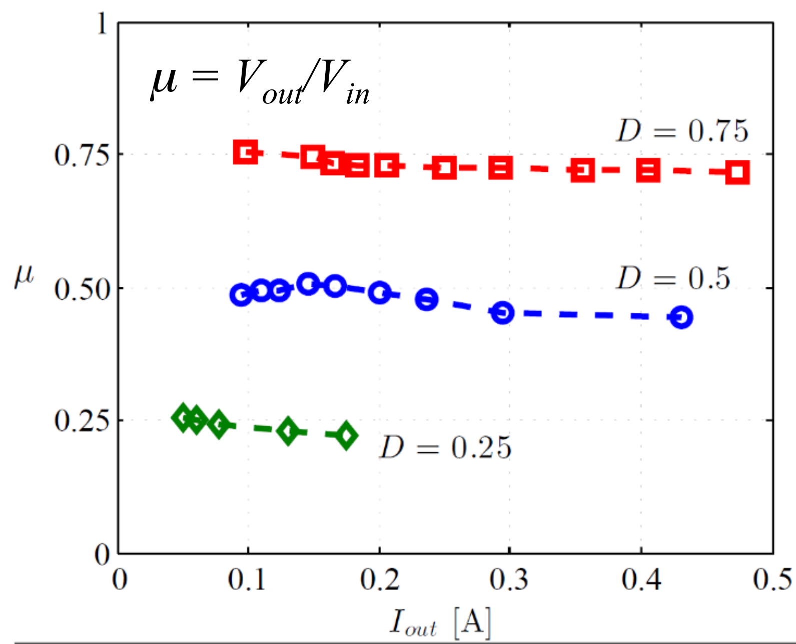




Experimental results: 100 MHz switching

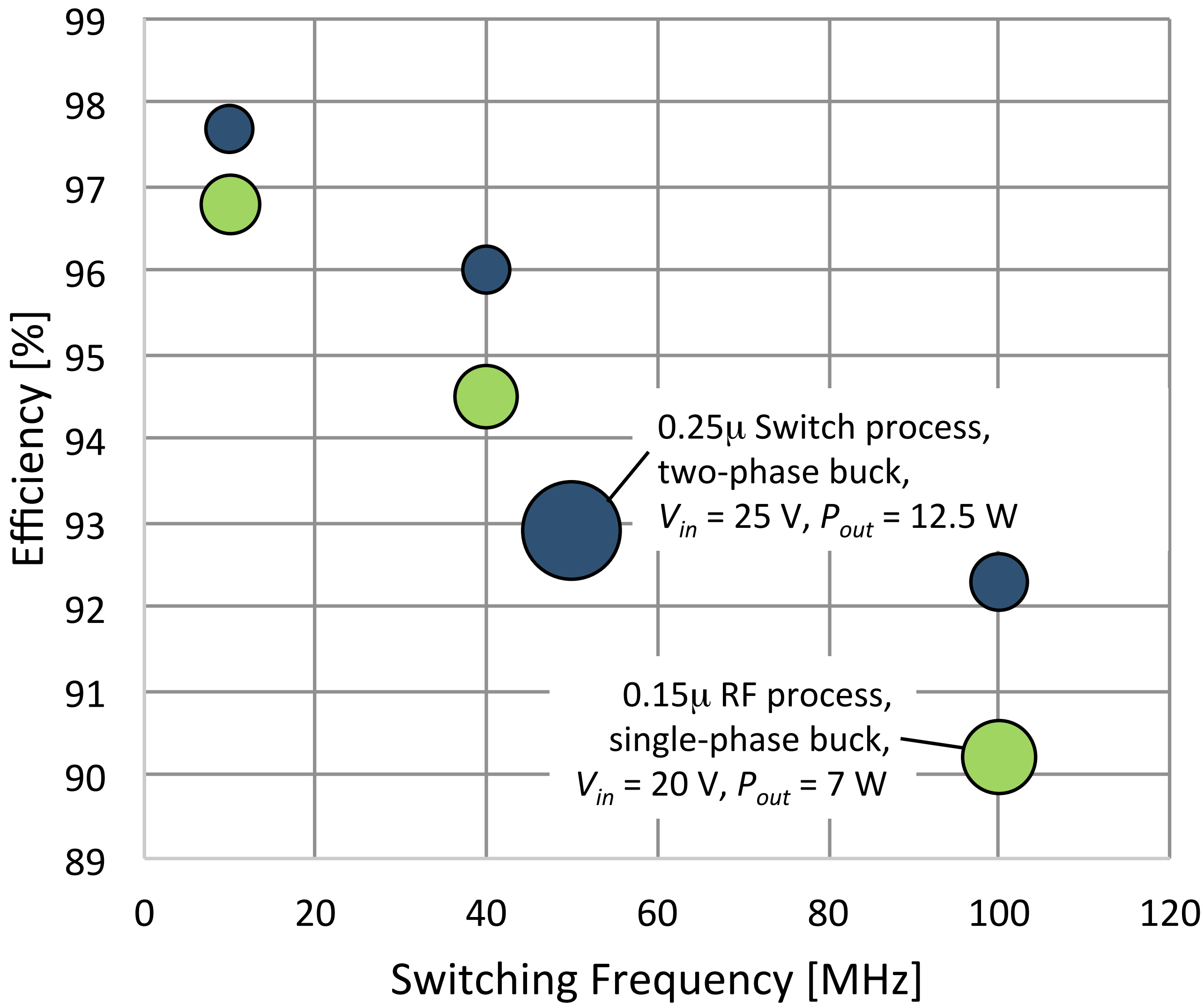




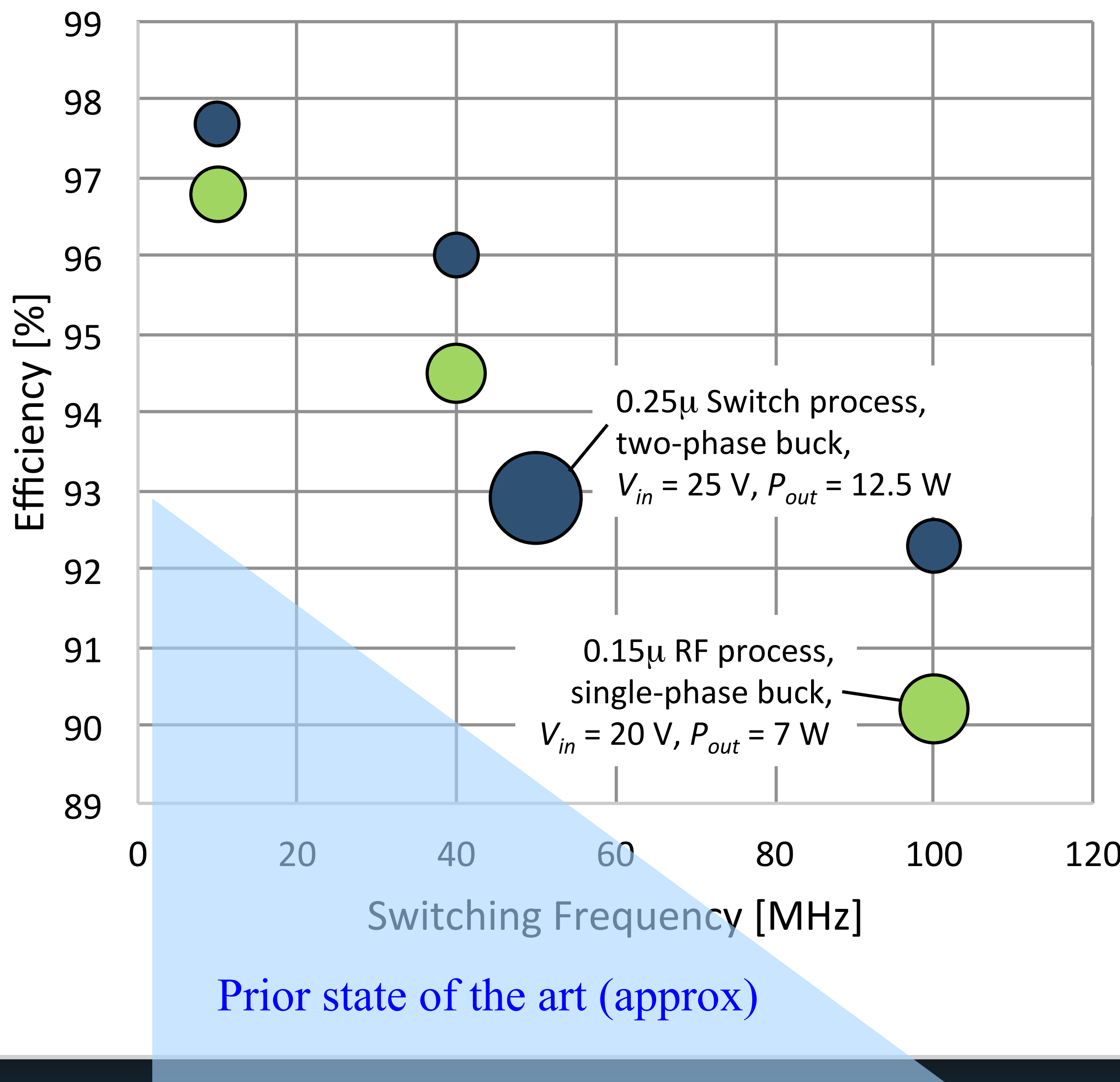


- 100 MHz switching
- P_{out} up to 7 W
- 91% peak power-stage efficiency
- < 0.2 W driver loss

Monolithic GaN switchers: efficiency versus sw. frequency

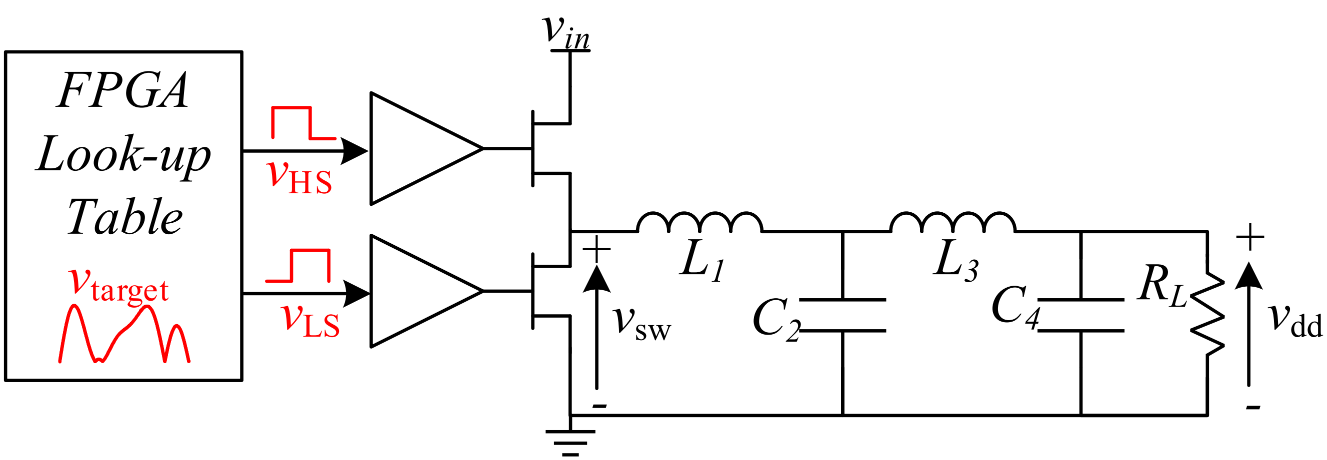


Monolithic GaN switchers: efficiency versus sw. frequency



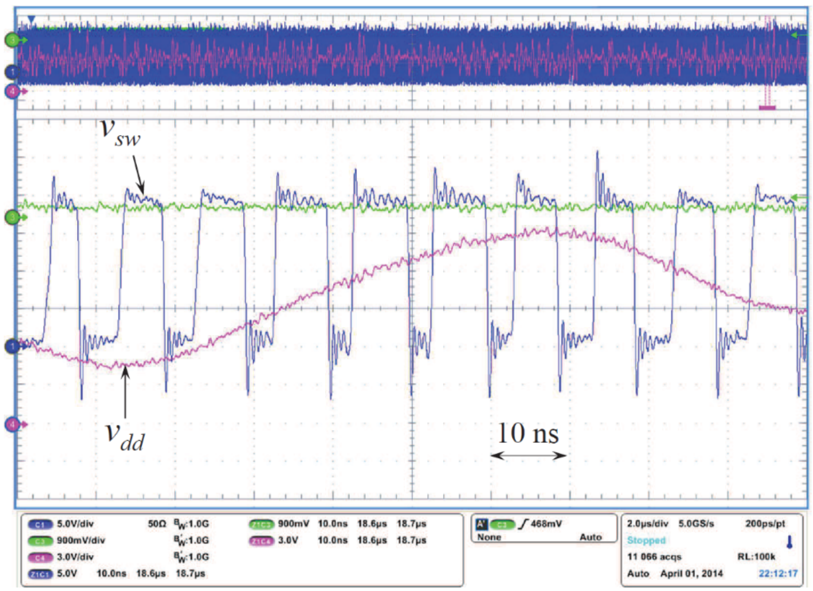
Application: envelope tracking supply for RFPAs

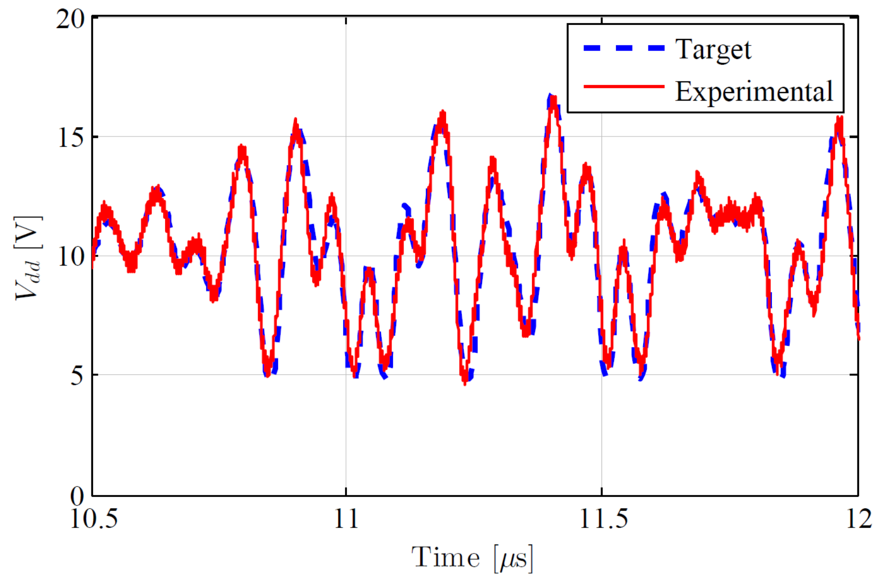
- Target signal: 20 MHz bandwidth LTE envelope
- 4^{th} order filter, 25 MHz cut-off frequency
- 100 MHz switching frequency



L_1	C_2	L_3	C_4	R_L	V_{in}	$P_{out,pk}$
28 nH	820 pF	307 nH	270 pF	30 Ω	20 V	10 W

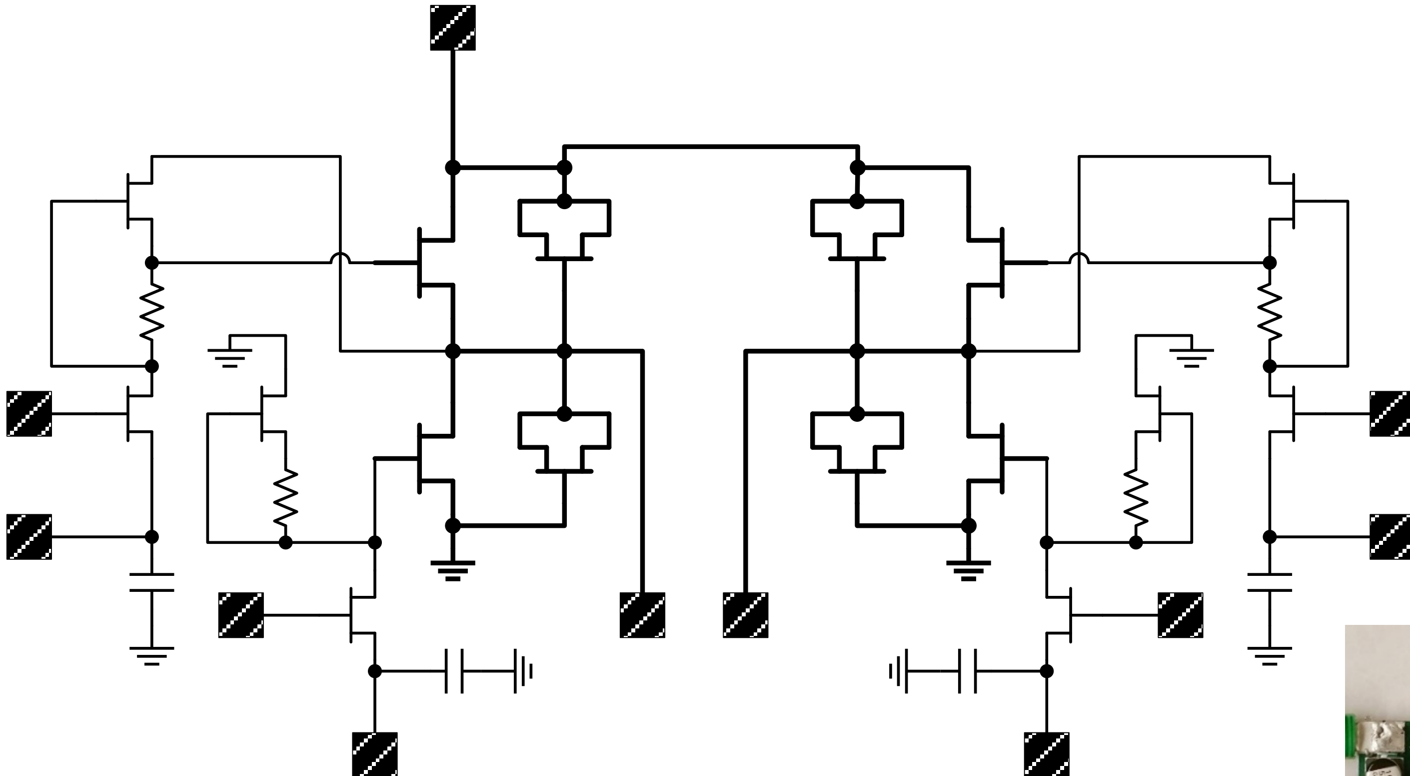
Envelope tracking experimental results



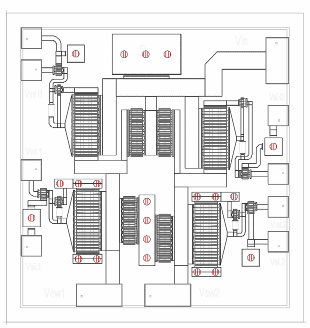


- 20 MHz LTE envelope, 100 MHz switching frequency
- Power stage efficiency: 83.7%
- Total efficiency: 80.1% (including on-chip driver loss)
- Normalized RMS error: 5.4%

Integrated two-phase GaN buck converter chip



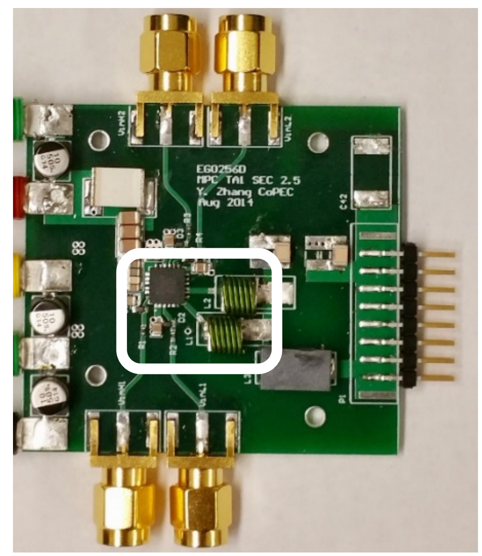
2.6 x 2.7 mm



0.25µ GaN-on-SiC switch process

20-pin QFN package

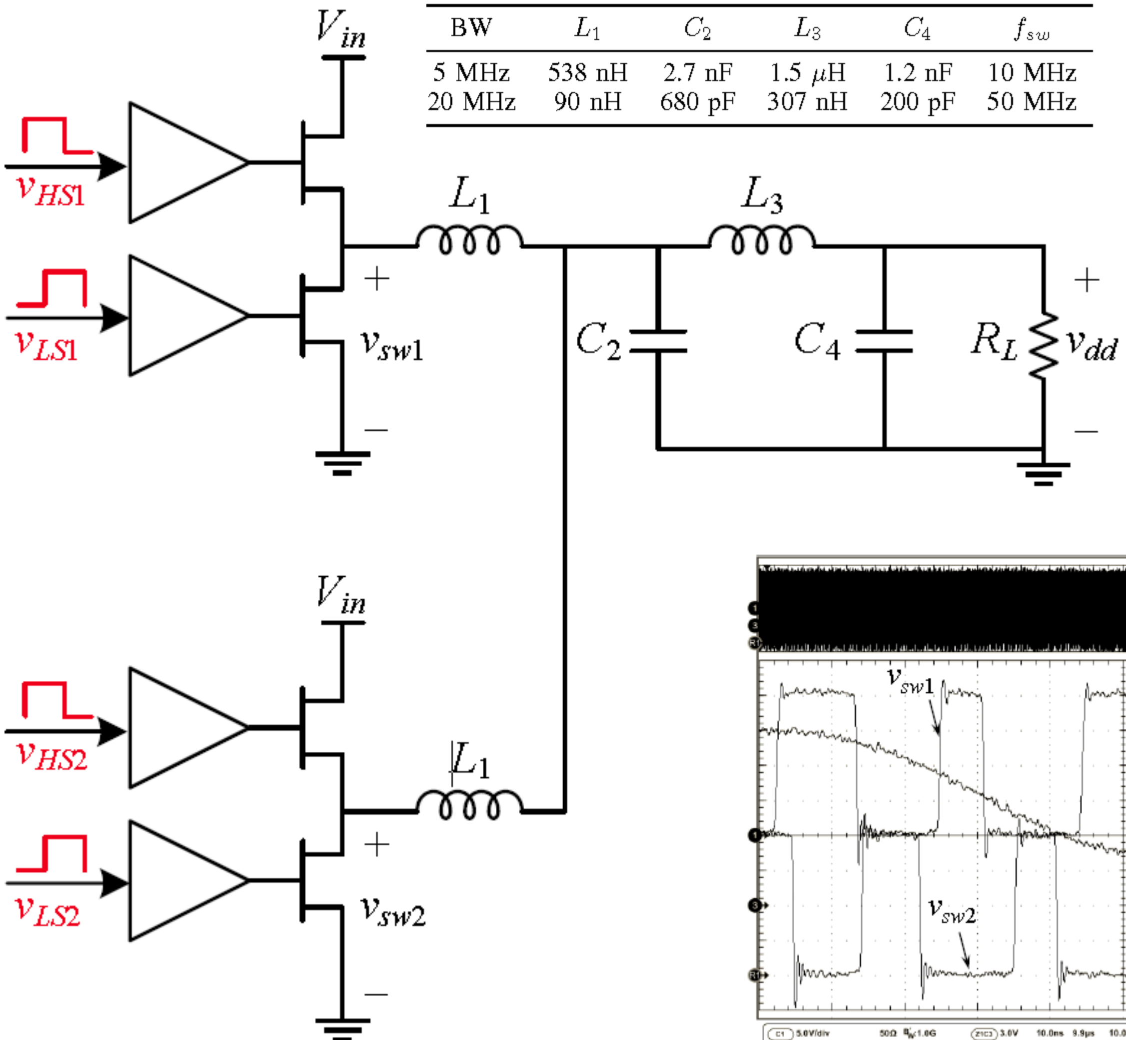
Air-core inductors



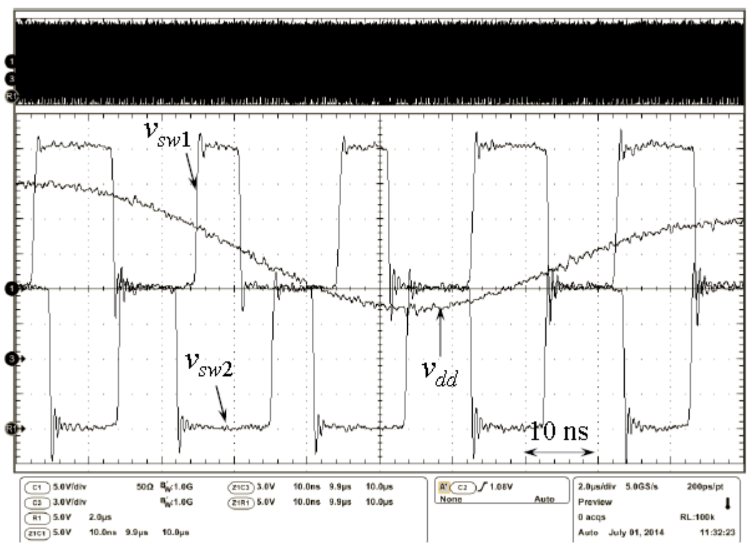
Two-phase switching drain supply modulator

FOURTH-ORDER FILTER DESIGNS FOR TWO PHASE CONVERTERS.

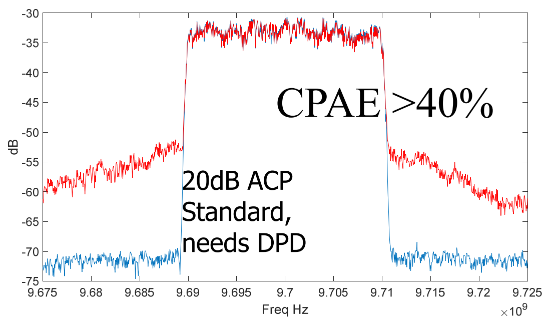
BW	L_1	C_2	L_3	C_4	f_{sw}
5 MHz	538 nH	2.7 nF	1.5 μH	1.2 nF	10 MHz
20 MHz	90 nH	680 pF	307 nH	200 pF	50 MHz



- 50 MHz per-phase switching frequency
- 20 MHz tracking bandwidth
- 3.4% RMSE tracking 20MHz LTE envelope
- **93.2% peak, 85% total efficiency**

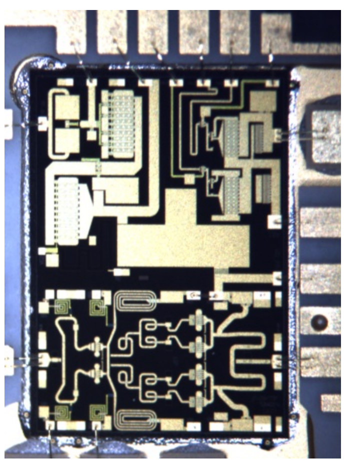


System integration: monolithic high-efficiency RF PA



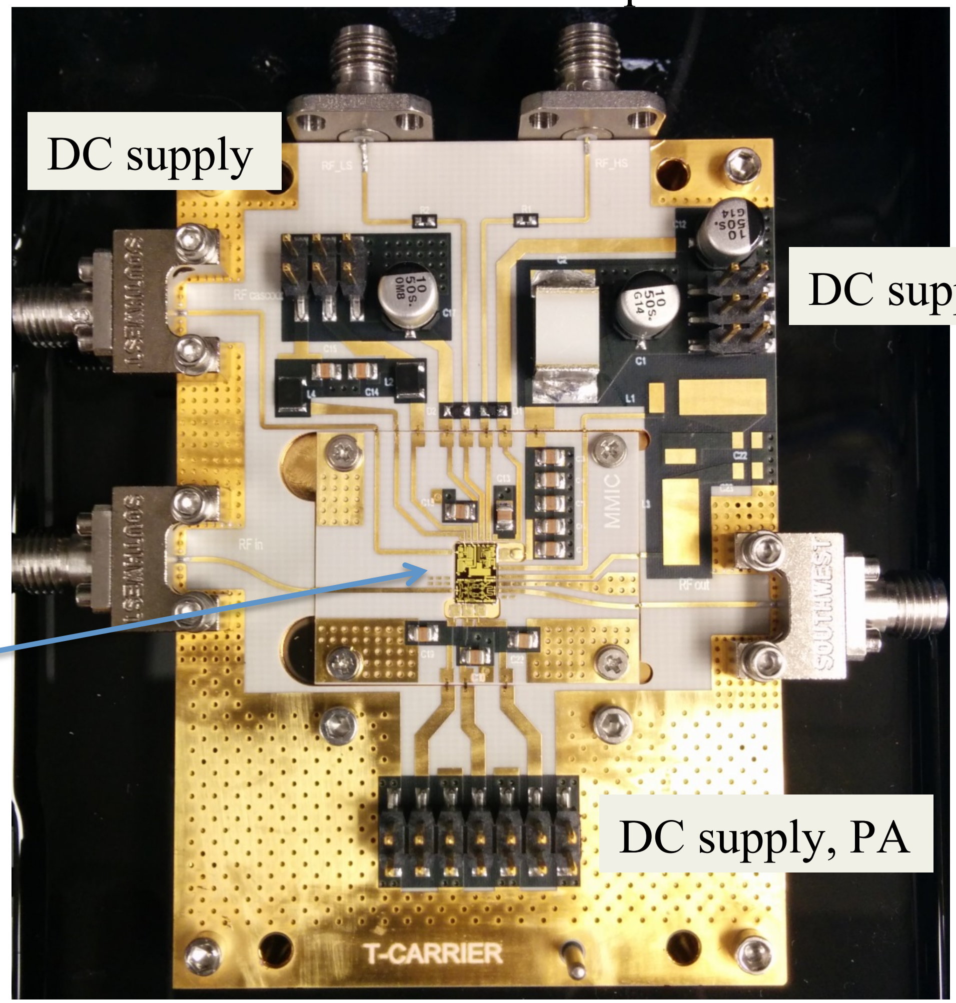
RF VHF/ UHF input

X-band input



5.4 x 3.8 mm MMIC

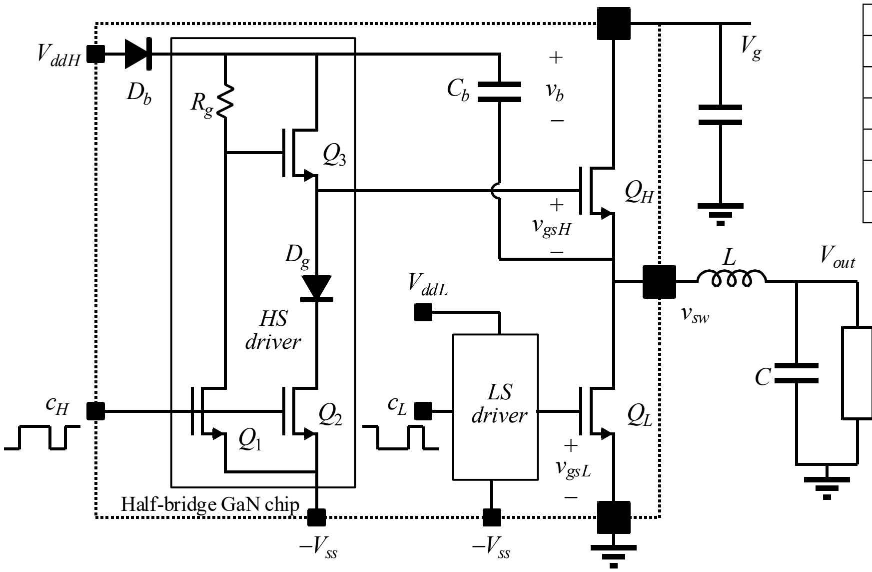
Switcher drive inputs



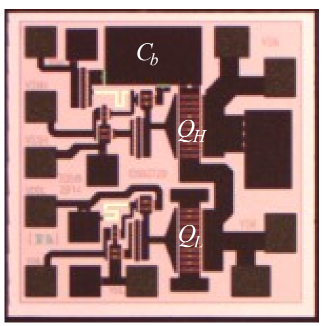
X-band modulated output

MMIC carrier board

Monolithic GaN switchers in an E-mode process

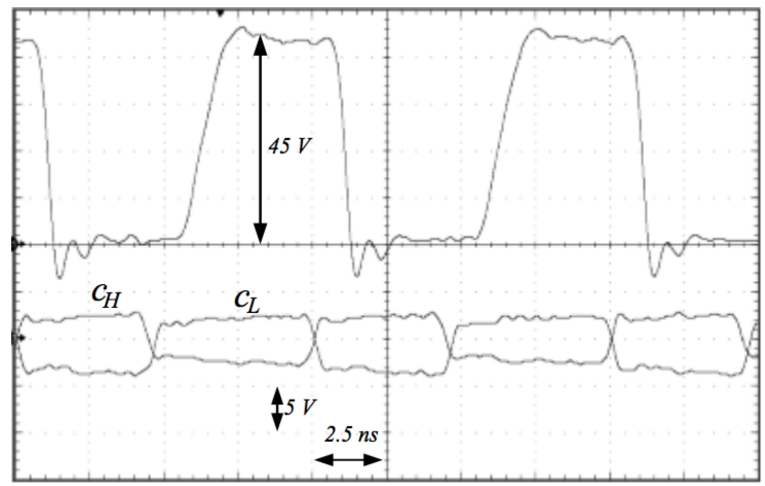


(a)



(b)

Switching frequency, f_s [MHz]	20	50	100	200	400	100
Input voltage [V]	25	25	25	25	20	45
Maximum output power [W]	16.0	10.1	7.1	3.4	5.0	6.0
Peak power stage efficiency [%]	95.0	94.2	93.2	86.5	72.5	91.7
Peak total efficiency [%]	92.5	91.7	89.2	82.0	67.0	90.2
Inductance (L) [nH]	160	90	47	22	12.5	90
Duty cycle (D) [%]	75	75	75	75	50	50

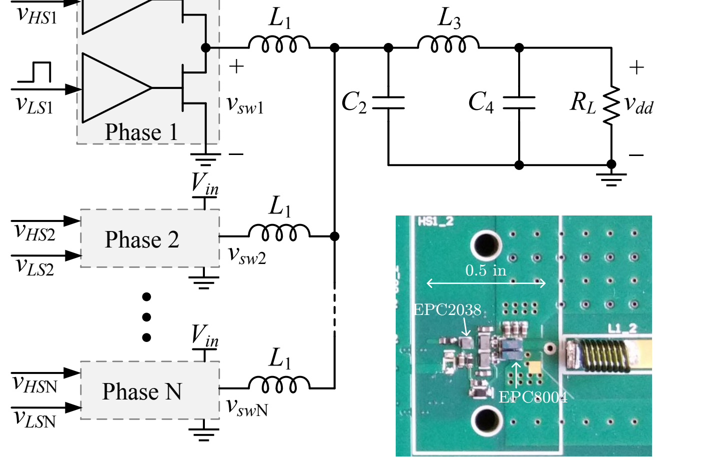


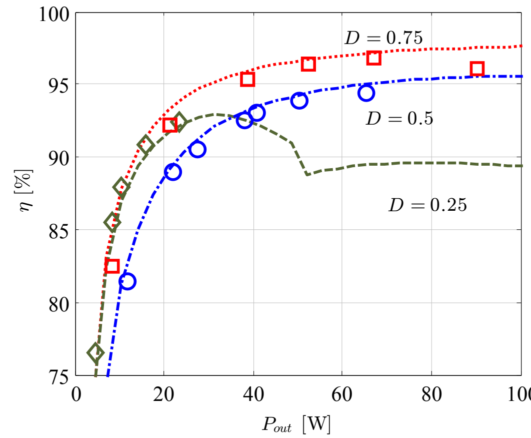
V_{out} = 23.1 V, P_{out} = 6 W, η = 91.7 %

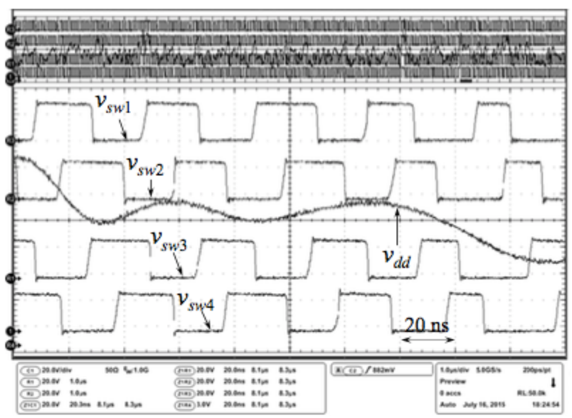
A.Sepahvand, Y.Zhang, D.Maksimovic, "High Efficiency 20-400 MHz PWM Converters using Air-Core Inductors and Monolithic Power Stages in a Normally-Off GaN Process," IEEE APEC 2016

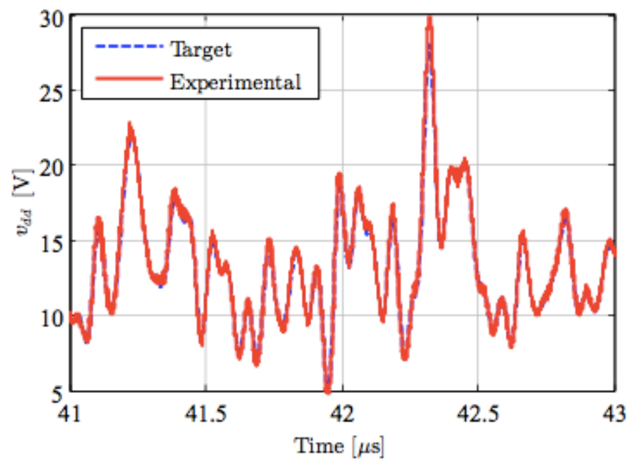
Scaling to higher power levels

BW	L_1	C_2	L_3	C_4	R_L
20 MHz	68 nH	5 nF	22 nH	1.6 nF	2.6 Ω









- 4-phase envelope tracker using EPC GaN fets
- Bootstrap driver with GaN fet synchronous bootstrap diode
- 25 MHz per-phase switching frequency
- 20 MHz tracking bandwidth for LTE signals
- 92.3% average efficiency at 67 W average output power

Y.Zhang, J.Strydom*, M.Rooij*, D.Maksimovic, "Envelope Tracking GaN Power Supply for 4G Cell Phone Base Stations," IEEE APEC 2016. *EPC

Conclusions

- Wide bandgap semiconductor technologies open new opportunities in power electronics, but benefits of brute-force replacements of Si devices are limited
- Opportunities for innovations in power electronics
  - Converter circuit topologies and architectures
  - Magnetics
  - Soft switching
  - Control
  - Integration
  - Packaging
  - System architectures and system design

Selected references: VHF GaN converters

[1] J. Hoversten, S. Schafer, M. Roberg, M. Norris, D. Maksimovic, Z. Popovic, “Co-design of PA, Supply and Signal Processing for Linear Supply-Modulated RF Transmitters,” *IEEE Trans. Microwave Theory and Techniques, Special Issue on PAs,* pp. 210-220, April 2012.

[2] M. Rodriguez, Y. Zhang, and D. Maksimovic, “High-frequency PWM buck converters using GaN-on-SiC HEMTs,” *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2462–2473, 2014.

[3] Y. Zhang, M. Rodriguez, and D. Maksimovic, “High-frequency integrated gate drivers for half-bridge GaN power stage,” *in Control and Modeling for Power Electron.*, IEEE COMPEL 2014

[4] Y. Zhang, M. Rodriguez, and D. Maksimovic, “100 MHz, 20 V, 90% efficient synchronous Buck converter with integrated gate driver,” *in Proc. IEEE Energy Convers. Congr. Expo.*, 2014.

[5] Y. Zhang, M.Rodriguez, D.Maksimovic, “Very high frequency PWM buck converters using monolithic GaN half-bridge power stages with integrated gate drivers,” *IEEE Trans. Power Electron.*, 2016.

[6] A.Sepahvand, Y.Zhang, D.Maksimovic, “High Efficiency 20-400 MHz PWM Converters using Air-Core Inductors and Monolithic Power Stages in a Normally-Off GaN Process,” IEEE APEC 2016

[7] Y.Zhang, J.Strydom*, M.Rooij*, D.Maksimovic, “Envelope Tracking GaN Power Supply for 4G Cell Phone Base Stations,” IEEE APEC 2016