Monolithic High Frequency GaN Switched-Mode Power Converters

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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 energy harvesting and wireless power transfer ...

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

...to custom power management ICs ...

...energy efficient lighting systems, renewable energy systems, and automotive (EV) applications
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
- Energy Efficiency and Consumer Electronics
  - Lighting
  - Data centers, servers
  - RF Transmitters
  - POL conversion
  - Mobile electronics
  - Wireless power
  - Energy harvesting
- Energy Storage Systems
  - Micro-grids
  - PV Systems
  - Solar ADEPT
- DOE VT Incubator
  (Erickson/Maksimovic/Afridi)
- DOE GATE Center of Excellence
- DOE IDEAS
- AMPED
  (Maksimovic)
- DARPA MPC
  (Popovic/Maksimovic)
- NSF IDEAS
  (Afridi)
- 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

$\mu_n = $ electron mobility

$\varepsilon_s = $ semiconductor permittivity

$$\frac{A R_{on}}{V_B^2} = \frac{R_{on,sp}}{V_B^2} = \frac{k}{\mu_n \varepsilon_s E_c^3} = \text{Semiconductor material figure of merit (FOM) for majority-carrier devices (e.g. MOSFETs)}$$
**Comparison of semiconductor materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap [eV]</th>
<th>Electron mobility $\mu_n$ [cm²/Vs]</th>
<th>Critical field $E_c$ [V/cm]</th>
<th>Thermal conductivity [W/m⁰K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>1400</td>
<td>$3 \times 10^5$</td>
<td>130</td>
</tr>
<tr>
<td>SiC</td>
<td>2.36-3.25</td>
<td>300-900</td>
<td>$1.3-3.2 \times 10^6$</td>
<td>700</td>
</tr>
<tr>
<td>GaN</td>
<td>3.44</td>
<td>900</td>
<td>$3.0-3.5 \times 10^6$</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500-2000 (AlGaN/GaN)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Switching frequency

1GHz
100MHz
10MHz
1MHz
100kHz
10kHz
1kHz

1W  10W  100W  1KW  10KW  100KW  1MW

Power

Chip-scale  POL  SMPS  Grid-tied & EV  Utility scale
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

Switching frequency

1GHz
100MHz
10MHz
1MHz
100kHz
10kHz
1kHz

Power

1W 10W 100W 1KW 10KW 100KW 1MW

Chip-scale  POL  SMPS  Grid-tied & EV  Utility scale

Monolithic VHF GaN converters

EV drivetrain SiC converters
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 \([BW_{\text{tracking}} = 10\text{'s to 100's of MHz}]\)
- High output voltage slew rate \([d\nu_{dd}/dt = \text{several V/ns}]\)
- 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 0.15µm RF process, and up to 50V in the 0.25µm Switch process

NMOS-only process: circuit design challenges
10-400 MHz Integrated GaN PWM Buck Converters

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

10-400 MHz PWM control signals

$V_{in}$ 20-50 V

$V_{out}$

$L$

$C$

$R$

$>20$ MHz tracking bandwidth

5-17 V, up to 15 W
Integrated Gate Drivers for Half-Bridge Power Stage

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

- High-side gate driver
- Low-side gate driver

**Half-bridge power stage**

- $Q_{HS}$, $D_{HS}$
- $Q_{LS}$, $D_{LS}$

**Chip layout**: 2.4 \times 2.3 \text{ mm}

<table>
<thead>
<tr>
<th>$Q_{HS}$, $Q_{LS}$</th>
<th>$D_{HS}$, $D_{LS}$</th>
<th>$Q_1$, $Q_3$</th>
<th>$Q_2$, $Q_4$</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x125\mu m</td>
<td>10x120\mu m</td>
<td>2x25\mu m</td>
<td>4x50\mu m</td>
<td>300 \Omega</td>
<td>125 \Omega</td>
</tr>
</tbody>
</table>
Active pull-up driver operation

\[ Q_{HS \text{ on, } Q_{LS \text{ off}}} \]
\[ I_{Q3} = 13.2 \text{ mA} \]

\[ Q_{HS \text{ off, } Q_{LS \text{ on}}} \]
\[ I_{Q1} = 8.5 \text{ mA} \]

\[ P_{d, \text{conduction}} = -D V_{ssLS} I_{Q3} + (1-D)(V_{in} - V_{ssHS}) I_{Q1} \]

\[ D=0.5, \quad I_o=0.25 \text{ A} \]
Bootstrap driver

**Chip layout:** 2.4 × 2.3 mm

**Half-bridge power stage**

\[ Q_{HS}/D_{HS}, Q_{LS}/D_{LS} \]

**High-side gate driver**

\[ Q_1, R_1, Q_2, D_1, C_1 \]

**Low-side gate driver**

\[ Q_3, R_2, Q_4 \]

<table>
<thead>
<tr>
<th>Q_{HS}, Q_{LS}</th>
<th>D_{HS}, D_{LS}</th>
<th>Q_1, Q_2</th>
<th>D_1</th>
<th>C_1</th>
<th>R_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>20x200(\mu)m</td>
<td>20x100(\mu)m</td>
<td>4x25(\mu)m</td>
<td>2x25(\mu)m</td>
<td>126 pF</td>
<td>175 (\Omega)</td>
</tr>
</tbody>
</table>
Bootstrapping driver operation

\[ Q_{HS} \text{ on, } Q_{LS} \text{ off} \]

\[ Q_{HS} \text{ off, } Q_{LS} \text{ on} \]

\[ I_{Q1} = 13.5 \text{ mA} \]

\[ V_{dd} \]

\[ V_{in} \]

\[ V_{C1} \]

\[ V_{1} \]

\[ D_{1} \]

\[ R_{Q1,on} \]

\[ R_{1} \]

\[ Q_{2} \]

\[ V_{ssHS} \]

\[ V_{gLS} \]

\[ 0 \text{ V} \]

\[ v_{sw} \approx V_{in} \]

\[ Q_{LS} \text{ OFF} \]

\[ Q_{HS} \text{ ON} \]

\[ V_{D1} \]

\[ I_{Q1} \]

\[ V_{C1} \]

\[ 0 \text{ V} \]

\[ -5 \text{ V} \]

\[ v_{sw} \approx 0 \]

\[ Q_{LS} \text{ ON} \]

\[ Q_{HS} \text{ OFF} \]

\[ V_{ssHS} \]

\[ V_{gLS} \]

\[ D = 0.5, \ I_{o} = 0.25 \text{ A} \]

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

Low driver power loss, but a bootstrap capacitor is required (large chip area, or external)
Modified active pull-up driver

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
\( Q_3, R_2, Q_4 \)

<table>
<thead>
<tr>
<th>( Q_{HS}, Q_{LS} )</th>
<th>( D_{HS}, D_{LS} )</th>
<th>( Q_1, Q_3 )</th>
<th>( Q_2, Q_4 )</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20x200( \mu )m</td>
<td>20x100( \mu )m</td>
<td>4x25( \mu )m</td>
<td>4x50( \mu )m</td>
<td>100 ( \Omega )</td>
<td>75 ( \Omega )</td>
</tr>
</tbody>
</table>
Modified active pull-up driver operation

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

\( D = 0.5, I_o = 0.25 \, \text{A} \)

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

\[ T_s = \frac{1}{f_s} \]
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

![Diagram of GaN IC Buck converter](image)

- 10-400 MHz PWM control signals
- 20-50 V
- up to 15 W
Switching waveforms

High-side gate driver

Half-bridge Power stage

Low-side gate driver

100 MHz switching waveforms

\[ V_{out} = 14 \text{ V}, \quad P_{out} = 4.5 \text{ W}, \quad \eta = 91.0\% \]
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

- **0.25μ Switch process, two-phase buck,**
  - \( V_{in} = 25 \text{ V}, \ P_{out} = 12.5 \text{ W} \)

- **0.15μ RF process, single-phase buck,**
  - \( V_{in} = 20 \text{ V}, \ P_{out} = 7 \text{ W} \)
Monolithic GaN switchers: efficiency versus sw. frequency

Prior state of the art (approx)

0.25µ Switch process, two-phase buck,
\[ V_{in} = 25 \, \text{V}, \, P_{out} = 12.5 \, \text{W} \]

0.15µ RF process, single-phase buck,
\[ V_{in} = 20 \, \text{V}, \, P_{out} = 7 \, \text{W} \]
Application: envelope tracking supply for RFPAs

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

![Diagram of envelope tracking supply for RFPAs]

<table>
<thead>
<tr>
<th>$L_1$</th>
<th>$C_2$</th>
<th>$L_3$</th>
<th>$C_4$</th>
<th>$R_L$</th>
<th>$V_{in}$</th>
<th>$P_{out,pk}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 nH</td>
<td>820 pF</td>
<td>307 nH</td>
<td>270 pF</td>
<td>30 Ω</td>
<td>20 V</td>
<td>10 W</td>
</tr>
</tbody>
</table>
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

0.25μ GaN-on-SiC switch process
20-pin QFN package
Air-core inductors

2.6 x 2.7 mm
Two-phase switching drain supply modulator

**Fourth-order filter designs for two phase converters.**

<table>
<thead>
<tr>
<th>BW</th>
<th>$L_1$</th>
<th>$C_2$</th>
<th>$L_3$</th>
<th>$C_4$</th>
<th>$f_{sw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MHz</td>
<td>538 nH</td>
<td>2.7 nF</td>
<td>1.5 μH</td>
<td>1.2 nF</td>
<td>10 MHz</td>
</tr>
<tr>
<td>20 MHz</td>
<td>90 nH</td>
<td>680 pF</td>
<td>307 nH</td>
<td>200 pF</td>
<td>50 MHz</td>
</tr>
</tbody>
</table>

- 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

Switcher drive inputs

DC supply

RF VHF/UHF input

X-band input

5.4 x 3.8 mm MMIC

MMIC carrier board

DC supply, modulator

X-band modulated output

DC supply, PA

CPAE >40%

20dB ACP Standard, needs DPD

Pout

av

Pout_pk

CPAE_av

1.4 W

1 0 W

8 . 7 0 %

90% efficiency

region

CW measurement at 9.7GHz
(best efficiency) used to extract trajectory

20dB ACP Standard, needs DPD

CPAE is >40%

This number includes all the board loss
Monolithic GaN switchers in an E-mode process

Scaling to higher power levels

- 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

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


