High voltage GaN cascode switches shift power supply design trends

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Outline for Today’s PSMA PTR Presentation

• Why do we need GaN?
• 600V GaN cascode switches
• Comparison to existing Si technologies
• Application examples
  • Hard-switched topologies
  • Soft-switched and resonant topologies
• EMI
• System value
• Future roadmap, trends
• Summary
Why GaN for Power Electronics?

Today’s Silicon Options for 600V Switch:

- **Superjunction FET (Coolmos, MDMesh)**
  - *Pro*: Low Rds(on) per area; reasonable cost
  - *Con*: Very poor body diode; nonlinear Qoss
  - *Typical applications*: Power Supplies

- **Traditional Planar FET (FREDFET)**
  - *Pro*: low cost process; performance similar to superjunction
  - *Con*: large die area for a given Rds(on)
  - *Typical applications*: Legacy power supplies

- **IGBT (with co-packaged diode)**
  - *Pro*: Very low $$/Amp; short-circuit capable
  - *Con*: High Vce(on); no sync rect; switching loss limits freq.
  - *Typical applications*: Motor drives, UPS inverters
Normally Off Cascode

- Native GaN HEMT (depletion mode) has best performance
  - Performance is compromised to shift threshold positive
- Cascode has easy gate drive
- Cascode includes excellent body diode
- 2-chip solution no more difficult than IGBT

![Diagram of GaN HEMT and Low Voltage Si FET with body diode]

US Patents 8,017,978 and 8,368,120
Performance Optimized Cascode Packaging

- Two key factors for minimizing losses in hard-switched topology:
  - Minimize GaN – Si interconnect inductance
  - Eliminate common-source inductance with Kelvin connection

**GaN: First Generation 600V Cascode**

### Best Superjunction Available

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IRGAN 60S002HTR</th>
<th>IPP65R150CFD CoolMOS CFDII</th>
<th>STB25NM60ND FDMesh II</th>
<th>IRFPS35N50L Fast body diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package</td>
<td>6x8mm PQFN</td>
<td>TO-220</td>
<td>TO-220</td>
<td>TO-247</td>
</tr>
<tr>
<td>Vdss</td>
<td>600V</td>
<td>650V</td>
<td>600V</td>
<td>500V</td>
</tr>
<tr>
<td>Rdson typ 25°C</td>
<td>135mΩ</td>
<td>135mΩ</td>
<td>130mΩ f(I_D)</td>
<td>125mΩ</td>
</tr>
<tr>
<td>Rdson typ 125°C</td>
<td>225mΩ +67%</td>
<td>300mΩ +122%</td>
<td>244mΩ +88%</td>
<td>281mΩ +125%</td>
</tr>
<tr>
<td>Qg (10V Vgs, 480V Vds)</td>
<td>7.9nC</td>
<td>86nC</td>
<td>80nC</td>
<td>150nC</td>
</tr>
<tr>
<td>Qrr (100A/µs, 25°C)</td>
<td>49nC</td>
<td>700nC</td>
<td>1,000nC</td>
<td>670nC</td>
</tr>
<tr>
<td>Qrr (100A/µs, 125°C)</td>
<td>51nC</td>
<td>1,600nC</td>
<td>2,000nC</td>
<td>1,500nC</td>
</tr>
<tr>
<td>Coss (480V)</td>
<td>108pF</td>
<td>420pF</td>
<td>320pF</td>
<td>320pF</td>
</tr>
</tbody>
</table>

- Better Rds(on) characteristic in much smaller footprint
- **10X** lower Qg than best superjunction
- **40X** lower Qrr than best superjunction
- 3-4X lower Coss (nonlinear, depends on measurement method)
600 V Device Trr Performance Comparison

GaN Qrr independent of temperature

Rectifier of IR
GaN 600V
Prototype Switch
Trr = 20 nSec
Irec = 2.5A

600V IGBT
CoPak Diode
Trr= 150 nSec
Irec = 7.5A

600V Super Junction FET
body diode
Trr = 200 nSec
Irec = 53A

Vr= 300V
If = 6A
T = 125C
50 nSec / division
10 A / division
Comparing Qoss of GaN vs Superjunction

Fig. 5, Comparison of the charge stored in the output capacitance $Q_{\text{oss}}$ for different CoolMOS devices and potential SiC and GaN devices.

Nonlinear Qoss Causes Time Delay

3.3X longer charge-up time

Qoss Measurement Circuit

Volts

Time (µs)

Company Confidential
Qoss Stored Energy versus Vds

IPW60R045CP
25.7µJ @ 400V

IPW65R045C7
18.6µJ @ 400V

50mΩ GaN Cascode
17.1µJ @ 400V
Why GaN cascode - Summary

• Outstanding body diode performance
  • Much lower turn-on (switching) loss
  • Much lower conducted EMI (-45dB measured)
  • Enables many more half-bridge applications
• Low, linear output capacitance Coss
  • Enables much higher soft-switching frequency
  • Well-behaved dv/dt further mitigates EMI
• Low gate charge
  • 5-10X lower gate driver power loss
• Bidirectional conduction (sync rect capable)
Traditional Boost PFC Topology

• Major common-mode EMI problems

Twin Boost Bridgeless PFC Topology

- Reduces common-mode EMI – but look at all the diodes
- Can be operated CCM or CrCM/DCM

• Is it really bridgeless (look at all the diodes)?
• Low \( R_{ds(on)} \) bidirectional switch is challenging

Synchronous Bridgeless Boost Topology

High Frequency Half-Bridge

60Hz Polarity Switch

Q1
Q2
Q3
Q4

AC LINE
EMI Filter

DC Bus
Synchronous Bridgeless Boost Demo Board

GaN Cascode Switches

Driver IC
Synchronous Bridgeless Boost Performance

Output Power (W)

η

240V line, 385Vout, 70kHz, Fully Synchronous
Synchronous Bridgeless Boost Summary

- No diode drops – only switch conduction voltage
- Very high efficiency possible – approaching 99%
- Lower component count than other bridgeless topologies
- Solves EMI problems common to alternative topologies
- Topology is enabled by GaN cascode switches
  - Can not be achieved with only superjunction FETs
  - Superjunction FETs have far too large Qrr and Coss
ZVS Half Bridge Building Block

Input Caps

Output Caps

RF Inductor

Gate Driver

GaN Cascode Switches

\[ \begin{align*}
\text{Vin} & \quad \text{Q1} \\
+ & \quad - \\
\text{Q2} & \quad \text{Vout}
\end{align*} \]
Half-Bridge Voltage and Current @ 3.3MHz

Inductor Current

Switch Voltage

LeCroy

International Rectifier
Performance of Half-Bridge Boost

Boost Converter Efficiency, No Heatsink, 400V Out

High Efficiency Possible by Frequency Control

- 3.3 MHz
- 2.5 MHz
High-Frequency ZVS Boost Summary

- 500 Watts, 2.5MHz, 97% efficiency – NOT Possible with Silicon
- Very small magnetic – 18mm toroid inductor
- No heatsink – convection cooled
- Very low gate drive power – 0.72W consumed by gate driver
- Enables ZVS Boost PFC
LLC Resonant DC-DC Power Supply

Square wave generator

Resonant network

Rectifier network

Figure 3. Schematic of Half-bridge LLC Resonant Converter

Figure 4. Typical Waveforms of Half-bridge LLC Resonant Converter
LLC – GaN vs Superjunction @ 1MHz

- GaN losses significantly lower than Superjunction

<table>
<thead>
<tr>
<th></th>
<th>I² Primary</th>
<th>I² Secondary</th>
<th>Gate Drive</th>
</tr>
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<tbody>
<tr>
<td>GaN</td>
<td>3.84A²</td>
<td>48.0A²</td>
<td>0.24W</td>
</tr>
<tr>
<td>Superjunction</td>
<td>4.93A²</td>
<td>64.6A²</td>
<td>1.88W</td>
</tr>
<tr>
<td>Difference</td>
<td>+28.3%</td>
<td>+34.6%</td>
<td>+685%</td>
</tr>
</tbody>
</table>
GaN Switch \( \frac{dv}{dt} \) control via Gate Drive Modulation

2A Turn off

2A Turn on

Some applications, esp motor drives require \( \frac{dv}{dt} < 5V/\text{ns} \)
Conducted EMI benefits of GaN

- Test condition: single half-bridge 1.5A phase current 20kHz
- No EMI filter
- GaN is up to 45dB improvement over Si

GaN IR 20kHz

IGBT 20kHz Rg=2Ω

45dB Improvement at 1.5MHz

Test data courtesy of Schneider Electronic, Technology & Strategy Department
600V, 200A GaN 2-sided cooling package*

Device Active area = 35mm²

* = Package developed by Delphi

This material is partially based upon work supported by the Department of Energy, ARPA-E under Award Number DE-AR0000016, resulting from the collaborative development efforts of Delphi Automotive Systems, LLC; International Rectifier; and Oak Ridge National Laboratory.
GaNpowIR® Product Roadmap

2013

5x7.65mm LGA

100V, 35 mOhm Half Bridge

2014

135 mΩ

600V, Cascode Switch

2015

70 mΩ

8x9mm QFN

600V, Cascode Half Bridge with Driver

6x8mm PQFN with 2.7mm creepage
GaNpowIR® Technology Roadmap

**Product Family**

- **600V 70-200 mΩ Cascode Discretes**
- **100V 35mΩ Half Bridge**
- **100-300V 5-40mΩ Cascode**
- **600V 25-2000 mΩ Modules**
- **800-1200V GaNpowIR®**
- **GaNpowIR® IC FETs and Driver**
- **GaNpowIR® System on Chip**

**Years:**
- **2013**
- **2014**
- **2016**
- **2018**
• Integration – IPMs
• Multiphase Architectures
• Short-circuit capability
• 900 – 1200V GaN
• VHF Optimized 30MHz+