GaN Offers Advantages to Future HEV

Yifeng Wu
ywu@transphoromusa.com
Transphorm Inc.
115 Castilian Dr.
Goleta, CA 93117, USA
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Key Considerations For HEV

1. Resistance-capacitance figure of merit at high voltages
2. Over-voltage, $dV/dt$ & $dl/dt$ capabilities
3. High temperature tolerance
4. Extended power capability
5. Hard-switched H-bridge simplicity & performance
6. System benefit
GaN Is Inherently a Highly Reliable Material

- GaN is inherently reliable
  Wurtzite Crystal: high bonding energy
- Dislocations in GaN is benign
  Lasers stable with 100x more dislocation than other semiconductors
- Intrinsic device reliability has been proven in RF applications
- Learn from experience in RF devices
  Epi quality for high μ & low leakage
  Passivation guidelines for low trapping
  Principle of electric field management
  Basic fabrication process

- Challenges:
  High voltage epi / device designs & process realization
  New operation space exceeding traditional package schemes
  Stringent qualification requirement
GaN HEMT Spike Tolerance Test at Vdc=600V Using Artificially-High Parasitic Inductance

Vdc = 600V, Inductor current = 16A

- GaN HEMTs successfully turned on and off 16A current at 600V bus with parasite inductor loop of 4cm² (90nH with current probe on).
- Voltage transient up to 380V/ns and spikes up to 850V.
- Device has no functionality change after 100,000 shots of 850V spikes.
- Datasheet spike rating 750V for safety margin.
600V Converter Operation at 100kHz

• GaN-on-Si HEMT achieves 99% 1:2 boost efficiency at 100kHz
• Low on-resistance, low charge and high speed are key in obtaining high efficiency for compact systems running at high PWM.
600V GaN-on-Si HEMT Voltage Blocking Capability at 175°C

- kV capability at 175°C.
200:400V, 400W, $T_J=175^\circ C$

- CoolMOS 60R385: $\Delta \text{loss}=2.1\text{W}$
- GaN 310mΩ HEMT: $\Delta \text{loss}=1.4\text{W}$

- GaN devices show lower increase of loss at high $T$.
- Due to less heating & lower temperature sensitivity.
GaN-on-Si Hybrid HEMT High Temperature Operation up to 1.5kW at $T_C=187^\circ C$ ($T_j=215^\circ C$)

- GaN-on-Si can operate at high volt & high current at $T_j=215^\circ C$ with ease
- HT performance lends support for inherent robustness
Preliminary Life Time Indication

Tj=215°C

10^6 hr for Eff. to degrade by 0.2%
(By no means device life time prediction)
Device Paralleling for Extended Power Without Reducing Speed and Efficiency

- Scalable unit cell
- Equal-length fan-in
- Low-impedance diode termination
- Equal-length inductive fan-out
• Roughly 4x increase in output power
• No loss in efficiency
1. GaN’s potential as a efficient kV class devices
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7. Summary
GaN HEMT Offers Low Qrr in Reverse Conduction Mode, Enables Simple Hard-switched Bridge Operation

\[ Q_{rr} = 1000\text{nC} \text{ at } 9\text{A}, 400\text{V} \]
\[ Q_{rr} = 54\text{nC} \text{ at } 9\text{A}, 400\text{V} \]

- Both measured in the same test board
- Transphorm GaN HEMT was tested at 450A/\mu s with little ringing
- CoolMOS was not stable at 450A/\mu s. \(\text{d}I/\text{d}t\) reduced to 100A/\mu s for stability.
- GaN HEMT has Qrr of ~20x less than CFD-type CoolMOS (Low Qrr design).
## Device Suitability for Hard-switched Bridge Applications

### Bridge configurations

<table>
<thead>
<tr>
<th>Device</th>
<th>IGBT</th>
<th>GaN HEMT</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Bridge configuration diagram" /></td>
<td><img src="image" alt="Bridge configuration diagram" /></td>
<td><img src="image" alt="Bridge configuration diagram" /></td>
</tr>
</tbody>
</table>

### Bridge operation properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Si MOSFET</th>
<th>Si IGBT</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial forward drop ($V_f$)</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Ron Resistance ($R_{ON}$)</td>
<td>Low</td>
<td>Extremely Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Reverse conduction</td>
<td>Yes</td>
<td>No (Need FW-Diode)</td>
<td>Yes</td>
</tr>
<tr>
<td>Reverse Qrr (body diode)</td>
<td>High (hard switch bridge impractical)</td>
<td>NA</td>
<td>Low</td>
</tr>
<tr>
<td>Operation speed*</td>
<td>Fast</td>
<td>Slow to Medium</td>
<td>Very fast</td>
</tr>
<tr>
<td>Overall bridge performance</td>
<td>Poor</td>
<td>Good</td>
<td>Superior</td>
</tr>
</tbody>
</table>

*Operation speed* indicates the speed at which the device can operate efficiently.
Performance Benchmarking Between IGBT and GaN Bridges

- Buck converter is configured from a half bridge
- 2 state-of-the-art HF IGBTs + 2 state-of-the-art SiC SBDs were used in IGBT bridge
- 2 Transphorm GaN HEMTs were used in GaN bridge

<table>
<thead>
<tr>
<th>Spec comparison:</th>
<th>IGBT</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vbd</td>
<td>600 V</td>
<td>600 V</td>
</tr>
<tr>
<td>Imax at 25°C</td>
<td>23 A</td>
<td>19 A</td>
</tr>
<tr>
<td>Imax at 100°C</td>
<td>12 A</td>
<td>14 A</td>
</tr>
<tr>
<td>Vce (Ron)</td>
<td>2.1 V at 12A</td>
<td>(0.15 Ω)</td>
</tr>
</tbody>
</table>
Output Waveforms Between IGBT and GaN Bridges

Rise time:
- GaN = 2.8 nS \((1.5-2\text{ns})\)
- Si IGBT = 7 nS

Fall time:
- GaN = 8 nS
- Si IGBT = 42 nS

- GaN has 3-5x less rise time: Reduced commutation loss
- GaN has 5x less fall time: Much less output charging loss
400-200V Buck Performance as a Function of Frequency

- Si IGBT loss escalates as frequency increases (breaking down at 400kHz)
- GaN bridge converter maintains >98% at 300kHz
  High PWM frequencies enable inductor/capacitor size reduction
GaN Diode-free™ 3-Phase Bridge Modules

Module Schematics

Module Package

Module spec:
• 6 in 1 switches
• 600V, 14A capability
  at $T_C = 100^\circ C$
Transphorm’s High-Frequency 3-Phase GaN Motor Drive Inverter

- High frequency design enables compact filter
- Pure Sine-wave output eliminates un-wanted PWM stresses on motor

Available as Demo kit from Transphorm

Project supported by ARPA-E
Output Current Waveform Comparison

- GaN inverter operating at 100 kHz with compact filter & pure Sine-Wave output
- IGBT inverter operating at only 15kHz with PWM output
- GaN inverter output current is spike-free, ideal for motor drive
GaN Motor-drive at 100kHz with Filter Vs. State-of-the-art IGBT at 15 kHz w/o Filter

- GaN Inverter efficiency exceeded IGBT:
  - GaN: 100kHz, include filter loss
  - IGBT: 15kHz, w/o filter loss

- Superior efficiency margin of GaN allows high PWM and filter losses
Motor Drive System Efficiency: GaN Vs. State-of-the-art IGBT

Motor Efficiency

System Efficiency

- Pure Sine-Wave output from GaN inverter significantly improved motor efficiency
- Overall system benefit is compelling:
  2.5% at full load, ~4% at mid load and ~8% at low load
10kW GaN Converter At 600V Bus

- GaN can push power conversion to new power/frequency space
Summary

1) GaN-on-Si have shown superior performance including low Ron, kV-level breakdown voltages, high spike tolerance and high temperature robustness at >200 C.

2) Device paralleling at high speed demonstrated with 4x increase in power and no loss in efficiency at 100 kHz.

2) GaN enables diode-free bridge hard-switched at 5-10x higher PWM than conventional IGBT, yet offering high efficiency.

3) Compact on-board filtering realized with high PWM, boosting motor system efficiency by 2-5%.

4) 10-kW GaN-based converter demonstrated with a single H-bridge, further scaling will enable HEV level applications.