Maximizing GaN Power Transistor Performance with Embedded Packaging

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Market opportunities for GaN power transistors

- Very rapid sales growth is expected within the next five years leading to sales exceeding $500M by 2020
- Yole has published a market research report and press releases (June 2014) that identifies EV/HEV applications as being a key element of the market opportunity
- According to Yole the "Ramp-up will be quite impressive starting in 2016, at an estimated 80% CAGR"
Motor power and source voltage for electric vehicles

- 650 and 900 V devices are required by 2 level inverters
- IGBT devices currently used
- SiC and GaN are regarded as potential replacements
- 650 V GaN – 3 level inverter, high performance, low-cost, the best choice for 900 V operation at present
- 900 V SiC MOSFETs will be expensive and are difficult to protect and drive
- IGBTs too inefficient

Annual Production 30 Million EV/HEV Cars by 2025

- Battery costs determine EV/HEV sales and the growth potential
- High volume production allows price to fall below 400 USD/kWh
- EV/HEV combined sales predicted to reach 30% of market by 2025
- Result – production exceeds 30 Million EV/HEV cars per annum by 2025!
Relative value of EVs in 2014 by application sector

- Light EV/HEV vehicles will constitute 32% of the market by 2025
- Other ‘electric vehicle’ markets are also expected to be substantial, but diverse
  - Busses: 13%
  - Military: 16%
  - Forklift: 15%

Adapted from IDTechEx
Fleet Emission Demands

- Strict CO$_2$ fleet emission pressures are being placed up on the automotive industry.
- Critical need to reach 95 gCO$_2$/km by 2020/2025.
- Move to introduce EV/HEV models more rapid than expected.

Traction Inverter: GaN e-Mode vs. FRD - IGBT

- Traction Inverter Semiconductor Modules account for 30% of total cost of the unit - the Inverter is the second most expensive component after the battery pack
- GaN e-Mode has lower losses due to the absence of the Offset Voltages of the Fast Recovery Diodes and IGBTs
- Lower losses lead to reduced cooling system costs
- GaN e-Mode system allows smaller battery packs to be used
• Reverse conduction is an intrinsic operational capability of an GaN e-Mode – no Fast Recovery Diodes are required
• When the GaN e-Mode active switch mode is used, as shown, very low losses are achieved because the ‘diode like’ offsets are eliminated
IGBT vs. GaN Loss Simulation 600/650V – 100A/400A

Adopted from: C. Assad, et al. CIPS 2012

<p>| 25°C, 400A | IGBT | GaN/Si Sim. |</p>
<table>
<thead>
<tr>
<th>Typ. values</th>
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<tbody>
<tr>
<td>$V_{os}$ (V)</td>
<td>1.45</td>
<td>0.4</td>
</tr>
<tr>
<td>$P_{on}$ (W)</td>
<td>580</td>
<td>160</td>
</tr>
<tr>
<td>$E_{off}$ (mJ)</td>
<td>13</td>
<td>0.25</td>
</tr>
<tr>
<td>$E_{on}$ (mJ)</td>
<td>2.9</td>
<td>0.42</td>
</tr>
<tr>
<td>$V_{F}$ (V)</td>
<td>1.55</td>
<td>0.4</td>
</tr>
<tr>
<td>$P_{VF}$ (W)</td>
<td>620</td>
<td>160</td>
</tr>
<tr>
<td>$E_{REC}$ (mJ)</td>
<td>3.6</td>
<td>0.9</td>
</tr>
<tr>
<td>$V_{os} @ 100A$ (V)</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>$P_{on} @ 100A$ (W)</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

- IGBT/FRD offset voltage greatly effects losses achieved at typical 100A running current
- Four parallel connected GaN e-Mode devices each 650V/4mΩ provides a 1mΩ on resistance a 10 to 1 improvement in power loss
• The GaN device can be built as a very large integrated single structure whereas the IGBTs usually are paralleled devices within a module which uses an external driver

• The GaN device shown is a 100 A/650 V design that includes an on-chip driver and it includes a yield enhancement scheme

• This device is a first step towards a totally integrated very large 400 A integrated GaN structure
The embedded lateral GaN devices have the smallest parasitic elements and the package interconnect significantly supplements the current carrying capacity of the GaN die.

The laminate packaged device shown is a 650 V - 50 mΩ GaN-on-Si e-mode transistor.
Device design strategies

GaNPX embedded packaging cross-section

Superior inductance, current handling, and thermal performance
Embedded device structure

- The embedding technique has completely removed any electromigration concerns because the package metal augments the RDL and on-chip metal.

- The total metal thickness exceeds 30 microns and the critical width is more than 5 times larger.
Performance comparison

Benefits of GaNpx packaging

- Superior in terms of area and thermal resistance
- Best package figure of merit (°C/W * mm²)
- Less than half the volume of the SuperSO8

Smaller and provides excellent thermal performance
Thermal simulation: Junction-to-case thermal resistance

Bottom-side cooled package comparison

<table>
<thead>
<tr>
<th>Package</th>
<th>Thermal Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS61004P</td>
<td>1.1 °C/W</td>
</tr>
<tr>
<td>GS61006P</td>
<td>0.75 °C/W</td>
</tr>
<tr>
<td>GS61008P</td>
<td>0.55 °C/W</td>
</tr>
</tbody>
</table>
Measurement and Thermal Simulation Results Comparison

- Good agreements between the measurement and the thermal simulation results were obtained
- Thermal simulation predicts slightly higher junction temperature (~4%)
- The thermal camera measures the average temperature, the temperature from thermal simulation is maximum temperature
Benefits of low inductance packaging

- Vital requirement for lowest losses
- Lowest EMI
- Minimal voltage overshoot
- Simplifies gate drive
- Faster operation

**GaNpx inductance is as low as an unpackaged part (LGA)**
Performance comparison: $R_{ON}$ & $Q_G$

- GaN transistors have lower switching charge requirements than SJ MOSFETs for a given specified on-resistance and blocking voltage.
- Cascodes and SiC devices have lower performance.
- Embedded E-mode devices have superior $R_{ON}$ & $Q_G$ performance.
1. **GaN e-Mode FOM is:**
   - 3 - 4 times better than Cascode
   - 25 - 30 times better than MOSFET
   - 40 - 50 times better than FRD/IGBT

2. **GaN e-Mode Hard Switching FOM is:**
   - 2 - 3 times better than Cascode
   - 20 - 30 times better than MOSFET
   - 30 - 40 times better than FRD/IGBT

3. **GaN e-Mode has no diode charge storage losses!**
Power transistor product family

- E-mode GaN-on-Silicon
- 650V and 100V families
- Robust gate drive
- Highest currents
- Best Figure-of-Merit
System Embedding for Automotive Inverters

- 10kW IGBT Embedded design has forced cooling
- 10kW GaN Embedded design can be finned HS cooled
- Future - Embedded 50kW module

Source: Advancing Microelectronics (IMAPS), JAN/FEB 2015, vol. 42, No.1
Conclusion

• The embedded lateral GaN devices have the smallest parasitic elements and the package interconnect significantly supplements the current carrying capacity of the GaN die

• Superior in terms of area and thermal resistance

• Best package figure of merit (°C/W * mm²)

• GaN\textsuperscript{PX} inductance is as low as an unpackaged part (LGA)
Thank you for your attention
1st GEN. GaN e-Mode vs. 5th GEN. IGBTs

- Capacitances: $C_{ISS}$ - 5 times lower, $C_{RSS}$ - 2 times lower
- Total Gate Charge 40 vs. 300 nC
- Gate Voltage Swing 6 vs. 15 volts
- GaN device has integrated driver
Automotive Investment

- Automaker spent $17.6 billion (US) around the world in 2013 to increase vehicle-making capacity
- In the past four years China spent $46.9 billion, Mexico spent $6.3 billion
- Even before 2010 transportation counted for 27% of total “end-use” energy and road vehicle CO₂ emission reached seven gigatons!!!
GaN - chip size advantages

650V transistors compared

- Chip area typically 40 times, and 15 times, smaller than Si-MOSFETS and Si-SJ MOSFETS respectively for the same $R_{ON}$
- Smaller chip size reduces gate charge $Q_G$ and capacitance