How GaN helps power supplies achieve extraordinary levels of efficiency

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Application map for Si, SiC, GaN

- Silicon
  - Remains mainstream technology

- SiC
  - Central PV*

- GaN
  - String PV*
  - OBC*

* PV = photovoltaic inverter; ** OBC = onboard charger
What is GaN – the technology

• GaN is a “wide-bandgap” semiconductor material that can be fabricated into high-performance power transistors

• Infineon makes devices by epitaxially growing layers of GaN (with other elements) onto Silicon substrates

Cross-section view of 600 V Lateral Hybrid Drain Gate Injection Transistor.
This is an enhancement-mode (normally-off) device
CoolGaN™ die and package example

Note substrate is connected to source potential:
How is CoolGaN™ better performing than Si or SiC?

The 3 key benefits of GaN transistors:

1. GaN transistors conduct in the reverse direction (third quadrant) like a diode, but there is **zero** reverse-recovery charge
   • This is a huge benefit that enables hard-switching with low-loss and low EMI

2. GaN transistor capacitance/charge is much smaller than comparable Si or SiC transistor
   • Both gate charge and output charge are lower than any competing technology – enabling fast, low-loss switching

3. Because of low charge and no minority-carriers, GaN switching speed can be **very** fast (single-digit ns range)
   • Especially at turn-off, the channel current can be cut-off in a few ns making turnoff losses extremely low
## Comparing 600 V transistor key parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CoolGaN (IGT60R070)</th>
<th>CoolMOS (CFD7)</th>
<th>SiC (SCT3060AL)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{DS(on),typ}$ (m$\Omega$)</td>
<td>55</td>
<td>57</td>
<td>60</td>
<td>Very close typical room-temp Rds(on) ±5%</td>
</tr>
<tr>
<td>$Q_{rr,typ}$ (nC)</td>
<td>0</td>
<td>570</td>
<td>55</td>
<td>CoolMOS max &gt;1000</td>
</tr>
<tr>
<td>$Q_{OSS,typ}$ @ 400 V (nC)</td>
<td>41</td>
<td>400</td>
<td>~60</td>
<td>SiC estimated from chart</td>
</tr>
<tr>
<td>$E_{OSS,typ}$ @ 400 V (µJ)</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>Relatively small differences!</td>
</tr>
<tr>
<td>$t_r/t_f$ typ (ns)</td>
<td>7/10</td>
<td>23/6</td>
<td>37/21</td>
<td>SiC has large internal $R_G$</td>
</tr>
<tr>
<td>$I_{D,pulse}$ (A)</td>
<td>60</td>
<td>129</td>
<td>97</td>
<td>@25°C. GaN is 35 A @ $T_C = 125°C$</td>
</tr>
<tr>
<td>$R_{thJC}$ (MAX) °C/W</td>
<td>1.0</td>
<td>0.8</td>
<td>0.91</td>
<td>Not significant differences</td>
</tr>
</tbody>
</table>

› Note: Rohm SiC MOSFET is rated at 650 V, GaN and Si are rated at 600 V  
› CoolMOS $t_f$ looks deceptively fast because it does not include the time spent 0-10% $V_{DS}$ (measurement is from 10-90%)
Why are these key transistor characteristics?

• What makes these so important?

• Consider the main loss mechanisms in power transistors:

• Conduction loss: nearly the same for these 3 examples

• Switching loss – dominated by 3 factors:
  1. “crossover” loss – during the switching interval, both $I_D$ and $V_{DS}$ are simultaneously large creating high peak power loss
     • GaN has fastest turn-on time = lowest loss
  2. $E_{OSS}$ – the $C_{OSS}$ energy is dissipated during hard turn-on
     • GaN is lowest, but not by much compared to CoolMOS or SiC
  3. Reverse-recovery loss: in hard-switched half-bridge topology this can be a huge loss for superjunction
     • SiC is 10X better than CoolMOS, but GaN is far better than either
Benefit of GaN in single-ended topologies

• Body-diode performance does not matter – so benefit is limited:
  • Current flow is unipolar in each case
    • So body diode never conducts – its performance is irrelevant
  • CoolMOS is typically the best choice for these applications
    • Any small improvement in switching loss using GaN is likely not worth the additional cost
Circuits where GaN *does* provide significant benefit

- **Topologies based on the half-bridge:**
  - Totem-pole PFC
  - LLC converter
  - Phase-shifted bridge converter
  - Active-clamp flyback converter
  - Inverters

- **The benefit provided by GaN depends on 2 key factors:**
  1. **Control strategy – hard or soft-switching?**
     - For all hard-switching, GaN is clear choice due to zero Qrr
     - For resonant/soft switching, CoolMOS for <250 kHz, GaN >250 kHz
  2. **Operating frequency:**
     - For Hard-switching, losses $\propto$ frequency, so lower frequency is used for maximum efficiency
     - For soft-switching, advantage of GaN is at >250 kHz
3rd quadrant conduction characteristic

- HEMT turns back ON when drain goes below G, S

\[ T_j = 25^\circ C \]

\[ T_j = 125^\circ C \]
4 possible half-bridge commutation conditions

**Positive \( V_{SW} \) Transition**

- High-side ZVS turn-on following low-side turnoff
  - \( V_{GS} \) upper
  - \( V_{GS} \) lower
  - \( V_{SW} \)
  - Slope depends on \( |I_L| \)

**Negative \( V_{SW} \) Transition**

- Low-side hard turn-on following high-side turnoff
  - \( V_{GS} \) upper
  - \( V_{GS} \) lower
  - \( V_{SW} \)
  - Slope depends on gate drive

**High-side hard turn-on following low-side turnoff**

- \( V_{GS} \) upper
- \( V_{GS} \) lower
- \( V_{SW} \)
- Slope depends on gate drive

**Low-side ZVS turn-on following high-side turnoff**

- \( V_{GS} \) upper
- \( V_{GS} \) lower
- \( V_{SW} \)
- Slope depends on \( |I_L| \)
Minimizing 3\textsuperscript{rd} quadrant losses

- Power dissipated in 3\textsuperscript{rd} quadrant “diode mode” proportional to $V_{SD} \times I_{SD} \times \text{time} \times \text{frequency}$

- Minimize $V_{SD}$ by using only as much negative gate drive as necessary to prevent shoot-through

- Minimize time spent in diode mode:
  - Use shortest deadtime possible, or
  - Employ adaptive deadtime optimization
    - Look-up table or calculate pulse-by-pulse
Example 20 A hard-switching waveforms
The Results:

• 2.5 kW GaN Reference Design
• CCM Full-Bridge PFC operating @ 65 kHz
• >99% efficiency over most of the load range
GaN 2.5 kW PFC measured efficiency

S/N 035 – no external power supplies – everything included. Vin = 230 V ac, Vout = 390 V dc, 25 °C Ambient
GaN 2.5 kW PFC loss breakdown

• At 1000 W output power:
  • GaN conduction loss 1.5W
  • GaN switching loss 1.1 W
  • Coolmos conduction loss 0.7 W
  • EMI filter, cap ripple loss 0.5 W
  • PFC inductor total loss 2.0 W
  • Bias supply + control circuit 1.3 W
  • (fan not running at this load)
  • Total losses ~7.1 W
## Example high-density resonant application

### Main Specifications:
- Input: 350-400 V DC, 385 V nominal
- Output: 52 V @ 70 A, 3600 W
- Power density: 160 W/in$^3$
- LLC resonant frequency: 350 kHz

### Components Used:
- CoolGaN: 70 mΩ IGT60R070D1
- SR: 2.6 mΩ Optimos BSC026N08NS5
- HV Driver: 1EDI20N12AF
- LV Driver: 2EDN7524R
- Controller: ICE2HS01G
- Aux Supply: ICE2QR2280Z

### Performance:

![Efficiency versus output load graph]

Efficiency versus output load

Demoboard available
CoolGaN™ and EiceDRIVER™ in production now

The new power paradigm: ultimate efficiency and reliability

- The most reliable GaN solution delivering highest performance amongst all available GaN devices
- Manufacturing expertise throughout the entire supply chain
- Global application design support
- Broad portfolio including drivers
- Volume capability
- Attractive price projection

CoolGaN™ 600 V

- DSO-20-87
- IOT60R070D1
- 70 mΩ

- DSO-20-85
- IOT60R070D1
- 70 mΩ

- DFN 8x8
- IGLD60R070D1
- 70 mΩ

- HSOF-8-3
- IG60R070D1
- 70 mΩ

- HSOF-8-3
- GST60R190D1S
- 190 mΩ

1) Top-side cooling
2) Bottom-side cooling
4) Reinforced (safe) isolation

GaN EiceDRIVER™

- NB DSO 16-pin
- 150 mil
- 1EDF5673F

- WB DSO 16-pin
- 300 mil
- 1EDS5663H

- 5x5 LGA 13-pin
- 1EDF5673K

3) Functional isolation
Summary

• 3 key features of GaN transistors enable high performance:
  • Zero reverse-recovery charge
  • Lower charge than competing technologies
  • Capable of faster switching

• These features are of particular benefit to half-bridge topologies
  • Lowest loss in hard-switching applications
  • Lowest rms current in soft-switching and resonant applications

• CoolGaN can be driven by off-the-shelf gate drivers

• In production and available now

• (See production power supply example in session IS16.5)