Development of GaN-based Power Electronics for PV Inverters

--- an important BoS cost driver

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Chairman and CTO, Transphorm Inc., (a UCSB Start-up)
“Moore’s Law” of Power Electronics

Output Power Density (W/cm³)

<table>
<thead>
<tr>
<th>Year</th>
<th>Output Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>0.01</td>
</tr>
<tr>
<td>1980</td>
<td>1</td>
</tr>
<tr>
<td>1990</td>
<td>10</td>
</tr>
<tr>
<td>2000</td>
<td>100</td>
</tr>
<tr>
<td>2010</td>
<td>1000</td>
</tr>
<tr>
<td>2020</td>
<td>10000</td>
</tr>
</tbody>
</table>

Industry goal = 1/40 volume in 10 years

- IGBT
- Si SJ
- GaN
- SiC
- BJT
- SCR

10-30 W/cm³
GaN is the next significant semiconductor alongside Silicon

- GaN has a direct and large bandgap
  - Enormous and growing photonics market which develops a large eco-system of infrastructure and human resources

- GaN is a lucky semiconductor; it performs reliably (in photonics and electronics)
  - Even while being an imperfect material (high dislocation density)

- In electronics it can also serve a large market
  - From KHz (power conversion) to GHz (RF amplification and communication)

- It has been proven reliable in both power conversion and RF applications
  - It is market ready

- GaN has a clear roadmap to lower cost and higher performance
  - Necessary for mass adoption

- Vertical GaN-on-GaN devices
  - Attractive for high power applications (>50kW)
Form and function is driven by frequency
Home Satellite Communication

C-Band
4-8 GHz

Ku-Band
12-18 GHz

Widespread distribution enabled by higher frequency

http://www.satsig.net/pointing/dish-pointing-images.htm
With High Efficiency at High Frequency Transphorm’s EZ-GaN Disrupts PV Inverters by Providing Enhanced Efficiency and Reduced Size at Reduced Cost

High Efficiency – Reduces Mechanical Size

High Frequency – Reduces Electrical Size

Analysis done for one class of inverters, will apply to other inverter classes in general
Current Inverter Technology (20 kHz)
Top Cost Drivers

**Mechanical**
- Switch Box $36.51, 17%
- Enclosure $63.53, 30%
- Other, $61.71, 29%

**Electrical**
- Electrolytic Capacitors $35.52, 14%
- Common Mode Chokes $12.48, 5%
- Other $84.53, 33%
- Boost Inductor $47.02, 19%
- Inverter Inductor $72.10, 29%
Transphorm’s EZ-GaN Provides High Efficiency with Simple Topology: Reduces Size and Cost

Enables:
- Shrinking of Heatsink
- Shrinking of Enclosure

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>96.8</th>
<th>97.5 (Current)</th>
<th>98.5 (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heatsink in inches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>12</td>
<td>8.4</td>
<td>5.5</td>
</tr>
<tr>
<td>Width</td>
<td>12</td>
<td>7.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Height</td>
<td>3</td>
<td>2.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

With GaN
- System Size
  - GaN, 2520 in³ (72%)
  - Saved, 1000 in³ (28%)

With GaN 15% system price reduction
Breakdown of PV system costs for a residential system

Figure 4. NREL modeled residential rooftop PV system prices (nationwide average, 5.2 kW)
The Advantage of GaN-on-Si for Power Conversion

- GaN enables increased output power density
- Higher efficiencies at higher power and higher frequencies
- PV inverter: 4.5kW > 98% efficiency at 50KHz (Yaskawa)
  - 10L (50% of Yaskawa’s Si IGBT-based product)
- 1U server solution: 2.2kW at 98% efficiency
  - Today’s current design is 1.2kW
Cascode HEMT implementation

**Advantage:**
- Robust
- High performance
- Compatible with Si drivers

**Disadvantage**
- Two-chip solution

---

Cascode Approach to achieve normally off

**Device Cell Cross-section**
- Source
- Gate
- Drain
- AlGaN Barrier
- GaN Buffer
- Substrate (SiC or Si)

**Device Layout**
- Source
- Gate
- Active Area
- Drain

**Effective CKT**
- Normally on
- Normally off
High Temperature Operating Life

Circuit: Boost converter
- Input Voltage: 200 V
- Output Voltage: 400 V
- Operating frequency: 300kHz

Operating conditions:
200/400V converter operation @ 175°C/300kHz/410W
Tested in hard-switched boost converter

Operating Temperature: Tcase = 150°C
Output Power: 410 W
Test time: 3000 hours
Quality and Reliability

- Transphorm has demonstrated JEDEC-qualified 650V GaN devices
- Extended reliability testing above and beyond JEDEC
- Established intrinsic lifetime for 650V rated GaN power chips

Over 1500 V breakdown voltage

With little dynamic R(on) collapse

Stable switching up to 1000 Volts
Temperature and Current Acceleration
- Devices tested at “high” range of nominal current levels
- \( T_j \) ranged from 330 to 380°C
- Results consistent with reported data
  - \( E_a = 1.84 \text{eV} \)
  - Lifetime at 150°C > 1X10^8hrs

Voltage Acceleration
- Cascode (product) devices tested
- High Voltages ranged from 1000 to 1300V
  - MTTF at 1050V = 6800hrs
  - Higher than expected voltage spikes during operation
- Nominal operating temperature = 82°C
- Lifetime at 600V > 1X10^8hrs

Tests provides credible and good lifetime projections
High-voltage Power Technology Transitions
GaN-on-Si based power conversion is ready

Significant inflection point in **CY18/CY19** timeframe for reliable >650V GaN-on-Si product
2014/15 World Wide Vehicle Sales by Region

- Europe is the fastest growing: 9.2 % growth
  - Three largest markets: DE, UK, FR, (Nor, SE, NL gov’t programs supporting EV’s)
- China is the largest: 9.1 % growth
  - Reduced taxes on vehicles with less than 1.6 liter engines
- Japan contracted by 10.1 %

Source: VDC
Why is GaN Targeting Auto

Figure 11. Electric vehicle market 2013-2020.
GaN’s Value Proposition

- Bridgeless Totem Pole PFC
- Higher Frequency
- Increased Power
- Lower System Cost

650 V / SMD & TO packages AEC-Q101

Higher Efficiency
**Value of GaN is Realized in Different Topologies**

<table>
<thead>
<tr>
<th>Topology</th>
<th>Higher Performance</th>
<th>Higher Power Density</th>
<th>Lower System Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard boost PFC</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interleaved boost PFC</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridgeless totem-pole PFC</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
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![Diagram of GaN topologies]

[Diagram showing different GaN topologies with standard boost PFC, interleaved boost PFC, and bridgeless totem-pole PFC.]
GaN Value Shown Via Customer Solution

- Project: 1.2kW power supply
- Competition: Superjunction (silicon)
- Result: Higher efficiency, lower BOM cost
  - Reduction in part count, magnetics, EMI filter

<table>
<thead>
<tr>
<th>Parameter Results</th>
<th>Interleaved PFC</th>
<th>Bridgeless Totem Pole PFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>97.8%</td>
<td>98.7%</td>
</tr>
<tr>
<td>Total cost</td>
<td>100%</td>
<td>93.7%</td>
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</table>
GaN Value Shown Via Customer Solution

- **Project:** 3.3kW power supply
- **Competition:** Superjunction (silicon)
- **Result:** Higher efficiency, lower BOM cost
  - Reduction in part count, magnetics, EMI filter

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<tr>
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<td>98.7%</td>
</tr>
<tr>
<td>Total cost</td>
<td>100%</td>
<td>60%</td>
</tr>
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</table>
Vertical design advantages over lateral design

- Grow thick GaN layers: High BV \(>>\) 1200V
- Realize **high current** (\(>> 20\)A) devices
- **Normally-off** operation
- Reduced number of defects: **Improved Reliability**, Large \(E_C\)
- Breakdown occurs in bulk **Avalanche capability**
- GaN on GaN takes less chip area \(\rightarrow\) **Lowers die cost**

![](image)

Optimum design of GaN vertical device as guided by FOM.

*KIZILYALLI et al.: VERTICAL POWER p-n DIODES BASED ON BULK GaN*
State of the art vertical devices: CAVET

CAVET
(UCSB, ASU, Avogy, Toyota, UC Davis)

Best Performance: - 1.5 kV, 2.2 mΩ.cm² (Avogy)

Best Performance: - 380 V, 1.5 mΩ.cm² (UCSB)
Vertical GaN in a simple device topology is attractive for 1200V markets soon.

\[ R_{ON} = 2.5 \text{ m\Omega.cm}^2 \]

\[ V_{BR} = 990 \text{ V} \]
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Sustained funding from UC Solar for both the PV module and the PV Inverter will Drive higher performance lower cost systems in the coming decades
Yes we GaN!