The Si Landscape

Si FETs
- Micro-inverters
- Commercial Solar String Inverters
- Server Power
- Industrial Drives, Welders, UPS, Inverters
- Wind Turbines
- Traction
- Utility

Si IGBTs
- On-board Battery Chargers & DC/DC Converters
- EV Inverters
- Laptop Adapters
- LED Lighting
- TV, Game Players
- Smartphone, Tablet Chargers
- TV, Game Players
- Industrial Drives, Welders, UPS, Inverters
- Wind Turbines
- Traction
- Utility

Application Power
- 1MW+
- 100kW
- 10kW
- 1kW
- 100W
- 10W

Device Voltage (V)
- 600V
- 1,200V
- 30V
- 100V
- 3,300V
- 6,500V+
The WBG Landscape

GaN (Lateral)

- 10W
- 100W
- 1kW
- 10kW
- 100kW
- 1MW+

SiC (Vertical)

- 30V
- 100V
- 300V
- 600V
- 1,200V
- 3,300V
- 6,500V+

Application Power

Device Voltage (V)

- Micro-inverters
- Mobile Wireless Power
- Class D Audio
- Laptop Adapters
- LED Lighting
- On-board Battery Chargers & DC/DC Converters
- TV, Game Players
- Smartphone, Tablet Chargers
- Industrial Drives, Welders, UPS, Inverters
- Server Power
- Wind Turbines
- Commercial Solar String Inverters
- EV Inverters
- Traction
- Utility
- 3,300V
- 6,500V+
- 10W
- 100W
- 1kW
- 10kW
- 100kW
- 1MW+
Driving to Higher Speeds

- 100kHz: Bulky, Heavy & Expensive
- 1MHz: Small, Light & Lower Cost
- 10MHz: Increasing efficiency

Switching Frequency vs. Efficiency Graph
Driving Styles

- **Switching Frequency**
  - 100kHz: Bulky, Heavy & Expensive
  - 1MHz: Small, Light & Lower Cost
  - 10MHz: Bulky, Heavy & Expensive

- **Efficiency**
  - Hard Switching
  - Soft Switching
Performance Limits of WBG Vertical Devices

Theoretical 1-D Limit for Vertical Devices

- **Si limit**
- **SiC limit**
- **Diamond limit**
- **GaN limit**

- **Rdson (mΩ-cm²)**
- **Maximum Voltage (V)**

- **High T° applications**
- **High frequency switching**

- **Electric Field (MV/cm)**
  - Si
  - SiC
  - GaN

- **Energy gap (eV)**
  - Si
  - SiC
  - GaN

- **Electron velocity (×107 cm/s)**
  - Si
  - SiC
  - GaN

- **Melting point (×1000 °C)**
  - Si
  - SiC
  - GaN

- **Thermal Conductivity (W/cm°C)**
  - Si
  - SiC
  - GaN

- **T = 300 K**
Lateral GaN Advantage for Off-line Applications

• WBG GaN material allows high electric fields so high carrier density can be achieved

• Two-dimensional electron gas with AlGaN/GaN heteroepitaxy structure gives very high mobility in the channel and drain drift region

• Lateral device structure achieves extremely low $Q_g$ and $Q_{OSS}$ and allows integration

• Integration on silicon substrates means mature low cost wafer fabrication is available
Performance Limits of WBG Materials

- **Current Performance**
  - Vertical Silicon
  - Lateral GaN

- **GaN 2-D Limit for Lateral Devices**
  - (with 400 ohm-sq 2-DEG)
  - 2.5MV/cm
  - 3.5MV/cm
  - Almost matches Diamond!
Hard-Switching

**Primary Switch Power Loss:**

\[
P_{\text{FET}} = P_{\text{COND}} + P_{\text{DIODE}} + P_{\text{T-ON}} + P_{\text{T-OFF}} + P_{\text{DR}} + P_{\text{QRR}} + P_{\text{QOSS}}
\]

Si: High $C_{OSS}$ = Long ZVS Transition = Trapped Energy

- Hard Switching loss: $P_{LOSS} = E_{OSS} \times F_{SW}$
- High $C_{OSS} \rightarrow$ Delay (limits $F_{SW}$)
- Too slow $\rightarrow$ partial ZVS $\rightarrow$ $E_{OSS}$ loss

- Si Superjunction $C_{OSS}$ is 50x-100x higher than GaN at $V_{DS} < 30V$
- Si SJ $E_{oss}$ is 3x higher than GaN at 200V (partial ZVS)
- Si SJ also has a high effective series resistance (ESR) and a lossy, hysteretic output capacitance, so even soft switching won’t save it at high frequency
Soft Switching with Si

**Primary Switch Power Loss:**

\[ P_{\text{FET}} = P_{\text{COND}} \times k + P_{\text{DIODE}} + P_{\text{T-ON}} + P_{\text{T-OFF}} + P_{\text{DR}} + P_{\text{QRR}} + P_{\text{QOSS}} \]

- **k-factor**
  - 2 (or more) due to increased *circulating* current, duty cycle loss, high \( C_{\text{OSS}} \)

- **\( P_{\text{T-On}} \)**
  - = 0 (soft, zero voltage switching)

- **\( P_{\text{Qoss}} \)**
  - \( \downarrow 2-3X \) (most energy stored in output capacitance is recovered)
ZVS LLC – Critical Parameters

<table>
<thead>
<tr>
<th>Partnumber</th>
<th>Voltage (V)</th>
<th>$R_{\text{DS(ON)}}$ (typ, mOhm)</th>
<th>$Q_S$ (typ, nC)</th>
<th>$C_{\text{OSS}}$ (er) (typ, pF)</th>
<th>$C_{\text{OSS}}$ (tr) (typ, pF)</th>
<th>$t_{\text{tr}}$ (typ, ns)</th>
<th>$Q_{\text{rr}}$ (typ, nC)</th>
<th>$R_{\text{DS(ON)}} \times C_{\text{OSS}}$ (er) (mOhm.pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPL60R199CP</td>
<td>600</td>
<td>180</td>
<td>32</td>
<td>69</td>
<td>180</td>
<td>340</td>
<td>5,500</td>
<td>12,420</td>
</tr>
<tr>
<td>TPH3206LD</td>
<td>600</td>
<td>150</td>
<td>6.2</td>
<td>64</td>
<td>105</td>
<td>17</td>
<td>54</td>
<td>9,600</td>
</tr>
<tr>
<td>Navitas</td>
<td>650</td>
<td>160</td>
<td>2.5</td>
<td>30</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>4,800</td>
</tr>
</tbody>
</table>

- Dead-time ($t_d$) and magnetizing current ($I_m$) discharge $C_{\text{OSS}}$ to achieve ZVS* ($C_{\text{OSS}} \approx \frac{I_m t_d}{2V_{\text{IN}}}$)
- eMode GaN has 2x-4x smaller $C_{\text{OSS}}$-related metrics than Si, cascode GaN
- Higher efficiency, higher frequency operation
- At 1MHz, GaN $Q_G$ is so low, *gate drive loss* ~zero

• Reverse Conduction
  • LLC converters need low stored energy in output capacitance to sustain resonant transitions at light load
  • Need low $Q_{rr}$ and fast, robust body diode characteristics to avoid shoot-through current, peak drain-source voltage, and reverse recovery $dv/dt$*
  • eMode GaN has no PN junction, so no minority carriers are injected and stored charge
  • $Q_{rr}$, $t_{rr}$, $i_{rr}$ ~ zero

* “New power MOSFET technologies optimized for efficient and reliable telecommunication power system”, W. Choi et al, Fairchild, APEC 2012
Soft-Switching with eMode GaN

Primary Switch Power Loss:

\[ P_{\text{FET}} = P_{\text{COND}} \times k + P_{\text{DIODE}} + P_{\text{T-ON}} + P_{\text{T-OFF}} + P_{\text{DR}} + P_{\text{QRR}} + P_{\text{QOSS}} \]

- k-factor > 1 (less than Si) due to increased circulating current, duty cycle loss
- \( P_{\text{T-On}} \) = 0 (soft-switch)
- \( P_{\text{Qoss}} \) ↓ 10X 2-3X (GaN \( C_{\text{OSS}} \) charging/discharging loss negligible up to 2MHz)
- \( P_{\text{DRIVER}} \) ↓ 10X (GaN \( P_{\text{DR}} \) negligible up to 2MHz)
- \( P_{\text{QRR}} \) = 0
- \( P_{\text{DIODE}} \) ↓ 2X (reverse conduction loss reduced by synchronous rectification)
- \( P_{\text{T-OFF}} \) = Reduced (limited by I-V crossover loss due to drive loop impedance)
Creating the World’s First AllGaN™ Power ICs

Fastest, most efficient GaN Power FETs + First & Fastest Integrated GaN Gate Driver = World’s First AllGaN™ Power IC

Up to 40MHz switching, 4x higher density & 20% lower system cost
GaN Power IC with Integrated Driver

- **Monolithic** integration
- 20x lower drive loss than silicon
- Driver impedance matched to power device
- Shorter prop delay than silicon (10ns)
- Zero inductance turn-off loop
- High $dV/dt$ immunity (200V/ns)
- Digital input (hysteretic)
- Rail-rail drive output
- Layout insensitive
GaN Power IC – Next Step in Integration

- Extended PWM input range
  - 3.3V, 5V, 15V, 20V input
- Wide $V_{CC}$ range (10V-20V)
- On-board (monolithic) regulator
  - Zener-selectable gate drive voltage
  - Safe start up, power down
  - Internal UVLO
- Resistor programmable turn-on dv/dt
- Standard QFN, simple layout
Fast, Low Cost, Industry-Standard QFN

- Leadframe-based 5X6mm power package outline
- Low profile, small footprint with HV clearance
- Kelvin source connection for gate drive return
- Low inductance power connections (~0.2nH)
- Low thermal resistance (<2°C/W)
- I/O pins enough for drive functions
- High volume
- Reliable
- Low cost
Soft-Switching with GaN Power IC

Primary Switch Power Loss:

\[ P_{\text{FET}} = P_{\text{COND}} \ast k + P_{\text{DIODE}} + P_{\text{T-ON}} + P_{\text{T-OFF}} + P_{\text{DR}} + P_{\text{QRR}} + P_{\text{QOSS}} \]

- **k-factor**: >1 due to increased circulating current, duty cycle loss
- **P_{T-On}**: = 0 (soft-switch)
- **P_{Qoss}**: ↓10X 2-3X (GaN C_{OSS} charging/discharging loss negligible up to 2MHz)
- **P_{DRIVER}**: ↓10X (GaN P_{DR} negligible up to 2MHz)
- **P_{QRR}**: = 0
- **P_{DIODE}**: ↓3X 2X (synchronous rectification with improved deadtime control)
- **P_{T-OFF}**: = 0 Reduced (near-zero drive loop impedance with integration)

>10x frequency increase possible with higher efficiencies
Crisp & Efficient Gate Control

- Eliminates gate overshoot and undershoot
- Zero inductance on chip insures no turn-off loss
GaN Power IC - Zero Loss Switching

- 500V Switching
- No overshoot / spike
- No oscillations
- ‘S-curve’ transitions
- ZVS Turn-on
- Zero Loss Turn-off
- Sync Rectification
- High frequency
- Small, low cost filter

1 MHz ZVS
- $V_{DS}$ of Low Side FET
- $V_{GS}$ of Low Side FET
- ZVS soft switching
- Zero Loss Turn-off
GaN vs Silicon in 500kHz CrCM PFC

- Critical Conduction Mode (CrCM)
- $120V_{AC} = 167-230kHz$
- $220V_{AC} = 230-500kHz$
- 265V peaks at 1MHz *PFC IC (L6562)* $F_{SW \ max}$

<table>
<thead>
<tr>
<th>Pack</th>
<th>Pack</th>
<th>$R_{D\text{S(ON)}}$</th>
<th>$Q_G$</th>
<th>$C_{OSS\text{ (er)}}$</th>
<th>$C_{OSS \text{ (tr)}}$</th>
<th>$R \cdot Q_G$</th>
<th>$R \cdot C_{OSS \text{ (tr)}}$</th>
<th>$R \cdot C_{OSS \text{ (er)}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navitas 5x6</td>
<td>5x6</td>
<td>160</td>
<td>2.5</td>
<td>30</td>
<td>50</td>
<td>400</td>
<td>8,000</td>
<td>4,800</td>
</tr>
<tr>
<td>Si CP Series 8x8</td>
<td>8x8</td>
<td>180</td>
<td>32</td>
<td>69</td>
<td>180</td>
<td>5,760</td>
<td>32,400</td>
<td>12,400</td>
</tr>
<tr>
<td>Si C7 Series 8x8</td>
<td>8x8</td>
<td>115</td>
<td>35</td>
<td>53</td>
<td>579</td>
<td>4,025</td>
<td>66,600</td>
<td>6,100</td>
</tr>
<tr>
<td>GaN Benefits</td>
<td>&gt;50%</td>
<td>n/a</td>
<td>&gt;10x</td>
<td>&gt;2x</td>
<td>&gt;10x</td>
<td>&gt;10x</td>
<td>&gt;7x</td>
<td>&gt;2.5x</td>
</tr>
</tbody>
</table>

Nanitas 5x6 160 x 50 x 10mm with 2-layer, 2 oz Cu
No heatsinks, no forced air, no glue, potting or heat spreaders
Cool GaN, not Cool Silicon: High Line, Full Load

220V\textsubscript{AC}, 150W

- GaN runs cool (61°C)

220V\textsubscript{AC}, 150W

- CP Si running >90°C
- C7 Si too hot to run at 220V\textsubscript{AC}

180V\textsubscript{AC}, 150W

Si C7 102.7°C

Navitas 61°C

AC Rectifier (58°C)

Aux V\textsubscript{cc} (77°C)

Boost Diode (63°C)

Si CP 89.2°C
Cool GaN, not Cool Silicon: Driving Frequency

- **Navitas GaN Power IC**
  - 5x6mm QFN, 160mΩ
  - 278kHz, 61°C
  - 278kHz, 86°C

- **Si Superjunction ‘CP’**
  - 8x8mm QFN, 180mΩ
  - 455kHz, 160°C

Graph showing AC-400V_{dc} Efficiency (%) vs. Output Power (W) with points at 450kHz, 70°C and 455kHz, 160°C.
AC-19V: GaN Power ICs in PFC, LLC

• Simple schematic
• Simple layout

Prototype shown, under optimization
CrCM PFC: High-Frequency, High Performance

- Excellent Power Factor - PF >99.5%
- High frequency operation
- Easy to achieve ZVS soft-switching
- Negligible switching loss during partial ZVS at high line with GaN
LLC: Smooth, Fast, Quiet

- No spikes, overshoot
- Smooth ‘S-curves’ with fast ~40V/ns slope
- Low EMI signature
High Efficiency at High Frequency

- AC-19V, 150W, 25°C, no airflow
- $110V_{AC} = 93\%, \ 220V_{AC} = 94.1\%$
$150\text{W}, 90\text{V}_{\text{AC}}, 500\text{kHz (no airflow, 25°C)}$
The MHz Eco-System

- **Navitas** GaN Power ICs plus...

- High-frequency controllers (PFC, PWM, DSP, LLC, SR)

- High-frequency magnetics

- High-frequency SR FETs
High Frequency Magnetics ‘GaN Optimized’

N59 optimized for 2MHz

3F & 4F up to 10MHz
Higher Frequency = Smaller, Cheaper

Cost Reduction

Normalized Cost ($)

- CM EMI
- DM EMI
- PFC

Size Reduction

Size (cm$^3$)

- CM EMI
- DM EMI
- PFC

Switching Frequency (kHz)

200kHz

1,000kHz

Magnetics & EMI Filters

- 40% reduction in cost
- 75% reduction in size
Frequency drives 2x-4x Power Density

- Typical adapters (65-150kHz) = 5-12W/in³
- Navitas demo (500kHz) = 13.5W/in³
- Navitas customer estimate = 20-25W/in³
**Soft-Switching: Active Clamp Flyback (ACF)**

- ACF* gives highest efficiency, highest power density for adapters 20W-75W
- No snubber loss
- Reduced voltage across primary FETs

Navitas 25W ACF: Frequency, Efficiency

- Existing ACF control IC
  - Uses variable frequency control to maintain critical DCM
  - Too high frequency loses soft switching
  - Too low frequency generates excessive negative current
  - Limited frequency
- New, higher frequency ACF controllers – expect +0.5%

Efficiency measured at PCB
Quiet EMI

- Conducted EMI (CISPR Class B)*
- Quasi-peak, 120$V_{AC}$, 285kHz
- Quiet performance
  - Controlled switching
  - No spikes, no overshoot
  - ‘S’-curve transitions
- Simple EMI filter design**

*In-house EMI equipment

**Refer also to: “Design Considerations of MHz Active Clamp Flyback Converter with GaN Devices for Low Power Adapter Application”, Huang, et al, VPT, APEC 2016
“Conducted EMI Analysis and Filter Design for MHz Active Clamp Flyback Front-End Converter”, Huang, et al, VPT, APEC 2016
ACF at 1MHz, 25W

CPES Prototype
25W

iPhone charger
5W

Loss (W)

<table>
<thead>
<tr>
<th>Component</th>
<th>Loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pri cond.</td>
<td>0.25</td>
</tr>
<tr>
<td>Pri sw</td>
<td>0.27</td>
</tr>
<tr>
<td>Sec Cond.</td>
<td>0.7</td>
</tr>
<tr>
<td>Core</td>
<td>0.33</td>
</tr>
<tr>
<td>Winding</td>
<td>0.23</td>
</tr>
<tr>
<td>Bridge</td>
<td>0.3</td>
</tr>
<tr>
<td>EMI filter</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Eff \approx 91.3\% @ P_0=25W

V_{AC}=90V
1MHz, 25W ACF

- Single-stage EMI
- Navitas GaN Power ICs
- Planar transformer
- DSP (for prototype)
1MHz 3kW PFC: 99%

- 2-phase Totem-Pole CrCM
- Input: 220V_{AC} (47-63Hz)
- Output: 400V, 3,000W

- Frequency*: 1MHz each phase
  - *Dual phase variable frequency interleaving (500kHz – 1.5MHz range)
- Efficiency: >99% @ 800kHz, 200-1,200W/phase (1)
  >98.8% @ 500kHz, 1,800W /phase (1)
- Power Factor: >0.995 (1)

---

(1) Achieved on Alpha prototype

---

3x 160mΩ GaN Power ICs, in 5x6 mm QFN
1MHz 3kW PFC: 135W/in³

- 2-phase Totem-Pole CrCM
- Input : 220V$_{AC}$ (47-63Hz)
- Output : 400V, 3,000W

- Frequency*: 1MHz each phase
  - *Dual phase variable frequency interleaving (500kHz – 1.5MHz range)
- Efficiency : >99% @ 800kHz, 200-1,200W/phase (1)
  - >98.8% @ 500kHz, 1,800W/phase (1)
- Power Factor : >0.995 (1)
- Power Density : 135W/in³

(1) Achieved on Alpha prototype, (2) Target for Beta prototype
eMode GaN at 27MHz & 40MHz

Class Phi-2 DC/AC converter: Stanford / Navitas demo

- 50% less loss than RF Si
- 16x smaller package
- Air-core inductors
- Minimal FET loss
- Negligible gate drive loss

27.12MHz, φ2 Inverter, V_{DS} of GaN

20ns/div, 150V/div

GaN Power ICs Enable High Frequency & Efficiency

Switching Frequency

- Bulky, Heavy & Expensive
- Small, Light & Lower Cost

Early’ GaN

Efficiency

100kHz  1MHz  10MHz