Outline
RFMD GAN TECHNOLOGY

- RFMD introduction
- 650V GaN Technology and Products
- Device Characteristics
- Application Performance
- 1200V+ Devices
- Reliability Investigation
- Summary
Delivering CS’s to Multiple Industries

Cellular Products Group
- Amplifiers and Switches
- Transmit Modules
- RF Platforms
- ASMs and SFMs
- RF Power Management ICs

Compound Semiconductor Group
- Leveraging industry-leading GaN and GaAs process technologies in products targeting non-RF market applications

Multi-Markets Products Group
- Broadband CATV
- Wireless Infrastructure/P2P
- Smart Energy/AMI
- Aerospace and Defense
- High Performance WiFi
- Custom Foundry Services
A long-standing commitment to fulfilling the GaN promise

- 1995: Fundamental GaN R&D Begins at Cornell/RF Nitro
- 2001: RFMD Acquires GaN Start-up RF Nitro
- 2007: GaN Process Lock and Technology Transfer to High Volume MFG Begins
- 2009: 1st GaN RF Technology Production Qualified
- 2010: 2nd GaN RF Technology (high linearity) Production Qualified
- 2010: GaN for Power Electronics Effort Begins
- May, 2012: RFMD Announces rGaN-HV™ technology for efficiency sensitive power conversion applications up to 900V
WIDE-BANDGAP TECHNOLOGIES
GAN TECHNOLOGY PUSHING INTO SiC FOM LIMITS

GaN Challenges
- $R_{ds(on),sp}$ and dynamic effects
- Increase BV field strength
- Maintain performance and yield at larger die size
- High Reliability
- BV-Rdson not the only FOM:
  - $Q_{rr}$, $E_{oss}$, $Q_{oss}$, $I_{rrp}$
- Cost? Yield? Si substrates?
HV GAN SUBSTRATE / TECHNOLOGY OPTIONS
GAN ON SIC OR SI??

**Substrate Cost**
- Must have performance...
- But at what cost?
- Long term projections...

**SiC**
- Electrical Performance
- Thermal Performance
- Packaging Flexibility
- Epitaxy Cost
- Intangibles

**Si**
- Substrate Cost

**But at what cost?**

**Intangibles**
RFMD PRODUCT HIGHLIGHTS

650V GAN CASCODE

**RFJS3006F**

- Isolated TO-247
- \( V_{DS} \): 650V
- \( I_D(25^\circ C) \): 30A
- \( R_{DS(ON)} \): 45mΩ

- Standard TO-247
- Isolated – EMI, assembly $
- R_{th,jc}$ – 1.6 K/W

**RFJS1506Q**

- 8x8 PQFN
- \( V_{DS} \): 650V
- \( I_D(25^\circ C) \): 15A
- \( R_{DS(ON)} \): 85mΩ

- 8 x 8mm PQFN format
- Pin compatible with SJ MOS
- Kelvin source connection
- Low \( R_{th,jc} \) ~ 1 K/W
RFMD RFJS3006F: 45mΩ TO-247

SWITCHING WAVEFORMS

- $R_g=1\,\Omega$, $V_{gs}=12\sim0\,V$, $I_{D\text{off}}=20\,A$
- No oscillations even at very high $dV/dt$, $dl/dt$

![Waveform Diagram]

- $E_{on} = 4\,\mu J$
- $E_{off} = 11\,\mu J$
- $V_{DS} = 400\,V$
- $I_D = 20\,A$
- $V_{DS} = 400\,V$ (100V/div)
- $I_D = 19\,A$ (10A/div)
- 10ns/div
RFMD RFJS3006F: 45mΩ TO-247

SWITCHING PERFORMANCE

- Soft switching FOM
- Hard switching FOM

1R. Mitova et al., PCIM 2013, pp. 49-56.
## RFJS3006: High Power Product

Comparison to closes competitor datasheet ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Si SJ MOSFET</th>
<th>Si SJ MOSFET</th>
<th>RFMD GaN SSFET</th>
<th>rGaN Advantage</th>
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<tr>
<td>Part Number</td>
<td>IPW65R045C7</td>
<td>STW69N65M5</td>
<td>RFSJ3006F</td>
<td>-</td>
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<tr>
<td>Breakdown Voltage</td>
<td>650 V</td>
<td>650 V</td>
<td>650 V</td>
<td>Same</td>
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<tr>
<td>On-Resistance</td>
<td>45 mΩ</td>
<td>45 mΩ</td>
<td>45 mΩ</td>
<td>Same</td>
</tr>
<tr>
<td>Eoss @ 400V</td>
<td>12 uJ</td>
<td>13 uJ</td>
<td>6 uJ</td>
<td>2X lower Eoss</td>
</tr>
<tr>
<td>Qg,typ</td>
<td>93 nC</td>
<td>143 nC</td>
<td>31 nC</td>
<td>3-5X lower Qg</td>
</tr>
<tr>
<td>Ron * Qg</td>
<td>4.2 nCΩ</td>
<td>6.4 nCΩ</td>
<td>0.95 nCΩ</td>
<td>4-6X better FOM</td>
</tr>
<tr>
<td>Eon / Eoff</td>
<td>90uJ / 25uJ  @20A; Rg=10Ω</td>
<td>-</td>
<td>20uJ / 30uJ @ 20A; Rg=1Ω</td>
<td>2X-5X lower switching energies</td>
</tr>
<tr>
<td>Qrr</td>
<td>13 uC</td>
<td>1.8 uC</td>
<td>0.06 uC</td>
<td>50X low Qrr</td>
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<tr>
<td>trr</td>
<td>250 ns</td>
<td>200 ns</td>
<td>12 ns</td>
<td>20-40X faster trr</td>
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<tr>
<td>Irrm</td>
<td>15 A @ di/dt = 100 A/us</td>
<td>18 A @ di/dt = 100A/us</td>
<td>6 A dl/dt = 1000 A/us</td>
<td>2-5X better @ 10X higher dl/dt</td>
</tr>
</tbody>
</table>
RFJS3006Q: 3L TO-247 Design

HIGH POWER PRODUCT

- Dynamic on-resistance
- Can cause significant system level efficiency degradation
- Difficult to measure accurately
- May contain many time constants

- Measurements taken in resistive switching measurement board
- Custom voltage limiting circuitry
- Held at dc bias for > 2min prior to measurement

Dynamic Resistance During Operation

- Lot 52: > 3X
- Lot 52: > 1.7X
- Lot 78: ~ 1.3X
- Lot 90: ~ 1.1X
GaN:Si Devices

GAN:SI HV DEVELOPMENT

- 650V+ / 85mΩ GaN:Si Cascode
- Excellent BV yield > 90%

- Non-insulating substrate for Gan:Si adds to Coss
GaN:Si Product Results

RFJS1506Q

- Performance similar to GaN:SiC devices
- Dynamic on-resistance low even sub-us timescales
2.4kW Boost Converter

HIGH EFFICIENCY PERFORMANCE

- $V_{\text{IN}} = 200V$, $V_{\text{OUT}} = 386V$, $f_{\text{sw}} = 133kHz$
2.4kW Boost Converter

HIGH EFFICIENCY PERFORMANCE

- $V_{IN} = 220V$, $V_{OUT} = 386V$, $f_{sw} = 133kHz$

$\eta = 99\%$
3kW Totem-Pole PFC

HIGH EFFICIENCY PERFORMANCE

- Totem-Pole PFC excellent application for 650V GaN switches
- Bridgeless topology enabled by lower reverse recovery Qrr
- 100kHz switching frequency
- CCM digital control  Vin = 85V to 265V

See it in booth #9-256
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1200V GaN:SiC Devices

HIGH POWER PRODUCT

- 100mΩ / 1200V GaN:SiC
1200V GaN:SiC Devices

HIGH POWER PRODUCT

- 100mΩ / 1200V GaN:SiC
GaN:Si Devices
HIGH POWER PRODUCT

- 200mΩ / 1200V GaN:Si

- Leakage currents:
  - 20μA @ 600V
2.6kV GaN HEMT
ULTRA-HIGH VOLTAGE

- 1700V devices feasible with lateral GaN technology
High Voltage GaN Reliability

ACCELERATED TESTING

- Reliability must be proven
- Gate Reliability, IPE, passivation

Typical use condition:
95% FIT = $10^{-7}$
$\Rightarrow$ $E_a > 2\text{eV}$
GaN Application Level Reliability Testing

- Key to satisfying customer new technology reliability averseness
- HTOL: SEPIC Converter
  - Application level reliability: **3000hrs+ at Tj=125°C**
  - Voltage / Current Stress = 400V/20A
  - Switching frequency = 109kHz
  - No performance degradation

![HTOL Results](image)

```
+-----------------+-----------------+
| Hours           | On-Resistance   |
| 0               | 30              |
| 500             | 35              |
| 1000            | 30              |
| 1500            | 35              |
| 2000            | 30              |
| 2500            | 35              |
| 3000            | 30              |
| 3500            | 35              |

+-----------------+-----------------+
|                 | Drain Leakage   |
| 0               | 0.0E+00         |
| 500             | 1.0E-04         |
| 1000            | 2.0E-04         |
| 1500            | 3.0E-04         |
| 2000            | 4.0E-04         |
| 2500            | 5.0E-04         |
| 3000            | 6.0E-04         |
| 3500            | 7.0E-04         |
```

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**2014 PCIM**

**Power Conversion Devices**

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Summary

GAN POWER

- 650V GaN HEMT technology enables significant efficiency advantages over existing Si superjunction technology
  - Hard switching / soft switching topologies
  - Further enable new topologies (totem pole PFC, matrix converters..)

- Dynamic on-resistance issues have been minimized
  - Do not pose roadblock for wide market adoption

- Higher voltage GaN devices are in the future
  - 1200V and potentially 1700V devices for specific applications

- Reliability and qualification data show high reliability is possible
  - More work needed in understanding fundamental activation physics
THANK YOU!