GaN Devices for Radio-Frequency Power Electronics

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Background: Power Electronics

- What is power electronics?
  - Convert and control electrical energy flow
  - Provide reliable and high quality electrical power
  - Target major system-level improvements
    - efficiency, performance, functions

- Many application areas
  - Renewable energy (solar, wind, lighting, fuel cells, etc.)
  - Transportation power generation and conversion
  - Power for computation, communication, and military application

Micro inverter for solar power conversion (manufactured by Enphase)
Alternator with integrated switched-mode rectifier (manufactured by Perreault, et al., MIT)
Server power supply (manufactured by Synqor)
Passive energy storage components are a major barrier to miniaturization
- Dominate converter size and cost
- Magnetics scale down in size poorly, and are difficult to integrate

**Objective:** To evaluate GaN devices and develop power electronics capable of dramatically increased operating frequencies (30 MHz – 300 MHz)
- Reduces requirements on passive components
Switching Frequency Limitations

- Loss mechanisms in conventional power electronics limit switching frequency (<1MHz)

- Minimize frequency dependent device loss, and switch fast enough (30MHz–300MHz)

- Switch should work at RF and have low $R_{ON}$ $C_{DS}$ and higher $V_{BR}$

Class E drain to source voltage ($f=25\text{MHz}$, $P_{out}=100\text{W}$, $V_{in}=200\text{V}$)

ZVS Soft Switching
GaN Device Overview

- **Advantages**
  - Very high frequency
  - High breakdown voltage
  - Low on resistance
  - Low parasitics

- **Disadvantages**
  - Normal ON device
  - Cost
  - Reliability
  - Not much research done in RF power electronics
Resonant Gating doesn’t like normal ON devices

Gate power loss (normalized by $C_{IS} V^2_{G, pk}$)

$C_{IS} = 276\mu F, V_{G, pk} = 8V$

Normal Off GaN Devices

- GIT: Gate Injection Transistor
  - P-AlGaN gate forms over undoped the AlGaN/GaN hetero-structure
  - P-AlGaN lifts up the potential at the channel, which enables normally-off operation

Fig. 7 (a) On-state and (b) Off-state at Vgs=0V Ids-Vds characteristics of the fabricated GIT (Vth=+1.0V, Ron·A=2.6mΩ·cm², Imax=200mA/mm, Breakdown voltage=800V).
GaN Device Example

- **Device Characteristics of CGH40045 from CREE**
  - $V_{BR} > 84$ V
  - $R_{ON} = 0.2 \, \Omega$
  - $C_{DS} = 10 \, \text{pF}$
  - Gate Threshold Voltage -3.0 to -1.8 V
  - $I_{DS} < 9.6 \, \text{A}$

- **Photovoltaic power conversion**
  - Input voltage = 25-40 V (72 cells)
  - Output voltage = 200 V
  - Output power < 200 W
### Displacement loss

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 MHz</td>
<td>&lt;0.1W</td>
</tr>
<tr>
<td>50 MHz</td>
<td>&lt;0.1W</td>
</tr>
<tr>
<td>100 MHz</td>
<td>&lt;0.1W</td>
</tr>
<tr>
<td>500 MHz</td>
<td>About 0.4 W</td>
</tr>
</tbody>
</table>
Vin=28 V; Vout=200 V; Pin=30-40 W; Fs=30 MHz, 100 MHz and 300MHz (Class E frequency limitation)
## Performance Comparison

<table>
<thead>
<tr>
<th>Frequency</th>
<th>30 MEG Hz</th>
<th>100 MEG Hz</th>
<th>300 MEG Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin</td>
<td>36.9 W</td>
<td>28.4 W</td>
<td>30.6 W</td>
</tr>
<tr>
<td>Pout</td>
<td>32 W</td>
<td>23.0 W</td>
<td>19.6 W</td>
</tr>
<tr>
<td>EFF (total)</td>
<td>86.7 %</td>
<td>81.0 %</td>
<td>64.0 %</td>
</tr>
<tr>
<td>Diode Loss</td>
<td>0.20 W (0.5%*)</td>
<td>0.20 W (0.7%*)</td>
<td>0.20 W (0.7%*)</td>
</tr>
<tr>
<td>Passive components Losses</td>
<td>3.58 W (10.1%*) (Ld has 3.6%)</td>
<td>4.32 W (15.2%*) (Ld has 10.8%)</td>
<td>9.7 W (31.7%*) (Ld has 23%)</td>
</tr>
<tr>
<td>GaN device Losses (total)**</td>
<td>1.01 W (2.7%*)</td>
<td>0.88 W (3.1%*)</td>
<td>1.12 W (3.6%*)</td>
</tr>
<tr>
<td>Conduction loss</td>
<td>0.85 W (2.3%*)</td>
<td>0.68 W (2.4%*)</td>
<td>0.73 W (2.4%*)</td>
</tr>
<tr>
<td>Displacement loss</td>
<td>0.15 W (0.4%*)</td>
<td>0.17 W (0.6%*)</td>
<td>0.30 W (1.0%*)</td>
</tr>
<tr>
<td>Gating Loss</td>
<td>0.01 W (0.03%*)</td>
<td>0.031 W (0.1%*)</td>
<td>0.093 W (0.3%*)</td>
</tr>
</tbody>
</table>

* Compare to Pin

** Device total losses include conduction, displacement and gating losses
Upper: drain to source voltage
Lower: rectifier input voltage
Conclusion

- GaN devices may have excellent performance in radio frequency power electronics
- GaN devices should be optimized for power applications (efficiency, frequency, $V_{BR}$, etc)
- Still a lot of work to do...
  - Normal ON
  - Cost
  - Reliability
  - Circuit design technique