GaAs PowerStages for Very High Frequency Power Supplies

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Agenda

- Case for Higher Power Density Voltage Regulators
- Limitations of Silicon MOSFETs
- GaAs as a Technology Platform for Very High Frequency VRs
- Prototype Results
- PSiP Vision
Growing Problem - VRs Consume Large Area and Height

11 VRs:
- 11 inductors
- 11 PowerStages
  - 2 discrete FETs per PowerStage
- Many capacitors
  (most on other side of board)

Example: Apple's MacBook Motherboard

Source: http://www.ifixit.com/Teardown/
The Goal – Small, Efficient PowerStages and PSiPs

Switching Frequency to Power Density

Best-in-class silicon-based VR

Dramatically Increase VR Switching Frequency

1MHz
3mm
150mm²

50MHz
1mm height
25mm²

Example: 12Vin
1.2Vout
10A

Height
Footprint

Large, thick L’s
Single Phase
Slow Response

Integrated L’s
Multiphase
Fast Response

How Do We Turn this Goal into Reality?
MOSFET Switching Losses Constrain Fsw of VR

Common MOSFET Figure of Merit:

\[ FOM = R_{ds(on)} \times Q_g \]

Better: \[ FOM_2 = R_{ds(on)} \times Q_{gd} \]

→ But…\( Q_{gd} \) ~ scales with \( Q_g \), so \( FOM \) is still a good indicator
Compound Semiconductors Enable Efficient High Fsw VRs

Compound Semiconductors (GaN, SiC, GaAs, etc) Have the Capabilities to Enable Efficient Very High Frequency (VHF) Power Converters

Attributes:
- Wide Bandgap Material
- High Electron Mobility
- Low Capacitance
- Low Gate Charge
- No Body Diode

A lot of recent Focus and Attention on GaN on Silicon as the enabling Compound Semiconductor material

Our Belief:
- GaAs is Superior to GaN in Low Voltage (<20V) Applications
- GaN has Tremendous Opportunities in Higher Voltage Applications

GaAs FET has Dramatically Lower FOM than Silicon

State-of-the Art Si MOSFETs FOM ~30
GaAs FET Prototypes FOM ~ 10
### GaAs FETs are Outstanding for VHF Low Voltage VRs

<table>
<thead>
<tr>
<th></th>
<th>Silicon MOSFETs</th>
<th>GaN on Silicon FETs</th>
<th>Prototype GaAs FETs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{DS(on)} \times \text{Area}$</td>
<td>mΩ-mm²</td>
<td>40+ (lateral)</td>
<td>&gt;20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 to 20 (vertical)</td>
<td></td>
</tr>
<tr>
<td>$R_{DS(on)} \times Q_G$</td>
<td>mΩ-nC</td>
<td>30 to 100+</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Electron Mobility</td>
<td>cm²/Vs</td>
<td>1,400</td>
<td>1,800</td>
</tr>
<tr>
<td>Input Voltage (max)</td>
<td>V</td>
<td>200</td>
<td>600</td>
</tr>
<tr>
<td>Body Diode</td>
<td></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>%/°C</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Manufacturing Scalability</td>
<td></td>
<td>• Production for 30+ years</td>
<td>• Immature technology • Low volume production</td>
</tr>
</tbody>
</table>

### So...What has been Holding Back the Industry from Employing GaAs?

- **Cost - Higher Unit Area Cost than Silicon**
  - Has prevented GaAs from successful commercialization in power conversion

- **Inherently Depletion-mode Devices**
  - Complicates gate drive
  - Enhancement mode devices possible with some tradeoffs
Lower Cost GaAs FETs

Basic Structure: Pseudomorphic High Electron Mobility Transistor (pHEMT)

Conventional GaAs Die for RF Application

Fujitsu 50 W L-Band FET
\[ W_g = 86 \text{mm} \]
\[ A = 4 \text{mm}^2 \]

Sarda’s GaAs Die

Prototype Die
\[ W_g = 86 \text{mm} \]
\[ A = 0.74 \text{mm}^2 \]
\[ R_{DS(on)} = 17 \text{ m}\Omega \]

Reducing Specific On-resistance makes GaAs Cost-effective for Power conversion
Highly Integrated PowerStage
Handles GaAs FET Drive Requirements

CMOS IC
- Drivers

3-D SiP
- (system in package)
- Integrates performance-critical components for high Fsw
- 4x4x1.3mm QFN

GaAs IC
- Integrates many high-speed FETs monolithically (lateral devices)
- Minimizes stray inductance

Unique 3D packaging, but in standard QFN footprint
### Prototype GaAs FET Characterization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GaAs FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown voltage</td>
<td>$B_{V_{DSS}}$</td>
</tr>
<tr>
<td>On-resistance</td>
<td>$R_{DS(on)}$</td>
</tr>
<tr>
<td>Gate charge total</td>
<td>$Q_g$</td>
</tr>
<tr>
<td>Gate-to-drain charge</td>
<td>$Q_{gd}$</td>
</tr>
<tr>
<td>Reverse recovery charge</td>
<td>$Q_{rr}$</td>
</tr>
<tr>
<td>Output Capacitance</td>
<td>$C_{OSS}$</td>
</tr>
<tr>
<td>Rise time</td>
<td>$t_R$</td>
</tr>
<tr>
<td>Fall time</td>
<td>$t_F$</td>
</tr>
</tbody>
</table>

**FOM = 10.8**  
**FOM2 = 4.1**  
**No Body Diode**  
**Fast rise/fall times**  
(Also function of Driver)

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Prototypes Manufactured in Standard High-Volume pHEMT 0.5$\mu m$ Process
10A, 2-phase PowerStage Module - Predicted Performance With Auto Phase Dropping

**GaAs: 2-ph Monolithic**
- UFETs: $R_{dson} = 50\, \text{m}\Omega$
  - $Q_g = 0.2\, \text{nC}$
- LFETs: $R_{dson} = 13\, \text{m}\Omega$
  - $Q_g = 0.8\, \text{nC}$

**Inductors:** Vishay IHLP2020CZ-11
- (1MHz) $470\, \text{nH, } 5.4\, \text{m}\Omega$
  - 5 x 5 x 3mm
- Vishay IHLP1616BZ-11
  - (2MHz) $220\, \text{nH, } 6.5\, \text{m}\Omega$
    - 4 x 4 x 3mm
10A, 4-phase Module Predicted Performance
Same GaAs FET Die Size Segmented for 4-Phase

**GaAs**: 4-ph Monolithic
- UFETs: $R_{\text{dson}} = 100\,\text{m}\Omega$
  - $Q_g = 0.1\,\text{nC}$
- LFETs: $R_{\text{dson}} = 26\,\text{m}\Omega$
  - $Q_g = 0.4\,\text{nC}$

**Inductors**: Coilcraft XPL2010-201
- 200nH, 24mΩ
- 1.9 x 2 x 1mm

**5MHz**
- $L$ height: 1mm
- 7x9mm

Vin=12V, Vout=1V
4-ph, 5MHz
GaAs Enables Efficient VHF Operation
Predicted VR Efficiency, including Inductor Loss

State-of-the-Art Silicon PowerStage
Vin = 12V, Vout = 1V

GaAs-based Module
Vin = 12V, Vout = 1V

Note: green curve is 3MHz

Note: green curve is 5MHz

Demonstrates why silicon MOSFETs are not typically pushed beyond 1MHz for this application

GaAs reduces FET switching losses
GaAs enables small multiphase topology monolithically – also key to reducing switching and inductor losses
GaAs Technology Proven Using Feasibility Boards

- **Discrete GaAs FET implementation:**
  1. 14mΩ upper FET
  2. 14mΩ lower FET
- **Discrete driver implemented** – deadtime adjustability via potentiometers
- **Low Cu thickness PCB** – due to fine pitch geometries of GaAs prototypes with Cu pillars

Buck converter circuit using Sarda's GaAs FETs (12Vin, 1Vout, up to 10A)
Accuracy of Efficiency Model

SFB3 Actual vs. Predicted
Vin=12V, Vout=1V, 1MHz

SFB3 Actual vs. Predicted
Vin=12V, Vout=1V, 2MHz

Provides Level of Confidence in Hitting Predicted Performance
Feasibility Board Waveforms

Discrete Implementation

Turn-on time ~ 4nsec
Turn-off time ~ 2nsec
VHF PSiP with Integration of Output Filter

Increase Fsw and Phase Count to ~50MHz to Integrate Output Filter ($L_{out}$ and $C_{out}$)

→ GaAs is an Enabling Technology for this Vision!

6x4x1mm
What Will it Take to Get There?

- Very Low FOM FETs

Case Study
Vin = 12V
Vout = 1V
Iout = 5A

- GaAs Gen1 – 2 years to commercialize PowerStage
- Gen 2, 3 – within 3-5 years (no new fundamental process or material R&D)

Multiphase Operation
- Many Small PowerStages, Inductors

High Levels of Integration
- Magnetics and Packaging Innovation
Summary

- GaAs Can Enable the PSiP Vision!
  - Small VRs Operating Efficiently at VHF
    - 5MHz is First Step
    - Roadmap to 50MHz+
  - Employ Multiphase Architecture
    - Lateral GaAs FET Device Structure
  - 3-D Packaging with Integrated Magnetics