High Frequency GaN-Based Power Conversion Stages

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Anatomy of a power device driven revolution in power electronics

Enabling Rapid Commercialization of Switch Mode Power Supply

In 3-5 years, expect 1-2% of applications to adopt GaN technology

Enabling higher levels of integration for dense and efficient power conversion
GaNpowIR – An Introduction

• A Commercially Viable GaN-based power device platform
• The result of 5 years of R+D effort at IR
• Based on Proprietary GaN-on-Si Hetero-epitaxy
• Utilizes low cost high quality 150 mm Si wafer substrates
• Highest throughput (multi-wafer) epitaxial systems used
• Device manufacturing process is CMOS compatible
• Device structure and process leverages significant silicon expertise
• Standard high volume manufacturing disciplines applied
• Industry standard quality systems utilized
• Extensive intrinsic reliability studies performed
• Standard product reliability tests applied to device qualification
Heterogeneous Growth is actually on AlN layer, which is grown on substrate.

To be competitive, epitaxial process and substrate cost must be

\[ < \$ 2 / \text{cm}^2 \]

High volume requires mature process platform

Current power device material demand

\[ > 10^7 \text{ 6 inch wafers per year} \]
MOCVD technology is the most mature and scalable to volume production. All commercial electronics have so far been produced with MOCVD systems (especially LED).

Silicon substrates are the most scalable and cost effective for volume production.

Adequate epitaxial film uniformity, defect levels, device reliability and process cost structure must be achieved to permit the use of GaN on Si based devices to achieve widespread use in power electronics.

Device processing should be CMOS compatible to achieve commercially viability.
Power Delivery

Power Stage

POWER CONVERSION STAGE
Value realization in power conversion

Value = efficiency * density/cost

The value proposition is driven to a large measure by the performance of the power device.

Conversion architecture and control schemes are developed to take advantage of the capabilities of the power devices and mitigate their deficiencies.

Radically improved device performance therefore drives a revolution in power electronics in terms of both architectures and control schemes.
Dramatic Improvements in Power Device FOM

Comparison of $R_{on}$ for Si, SiC, and GaN

Ecrit: $Si = 20 \text{ V}/\mu\text{m}$, $GaN = 300 \text{ V}/\mu\text{m}$
Application -- CPU Transient Current $> 1000 \text{ A/\mu s}$

Low Frequency Leads to Parasitic Power Loss

Loop 1 di/dt < 350A/\mu s
Control Loop & Output Inductance

Loop 2 di/dt < 100A/\mu s
Electrolytic Bulk Capacitors

Loop 3 di/dt < 400A/\mu s
Ceramic Bulk Capacitors

Loop 4 di/dt > 1200A/\mu s
Ceramic Caps Underneath Socket
Eliminate Cost, Size, Improve Reliability

Power Stage Function

Loop 1 di/dt ≈ 300A/us
Control Loop & Output Inductance

Loop 4 di/dt > 1200A/us
Ceramic Caps Underneath Socket

Effective Output Inductance (3-phase)

PCB Parasitics

Effective Output Inductance

Loop 1 @ Fsw = 3MHz

Loop 3 di/dt < 400A/us
Ceramic Bulk Capacitors

Loop 4 @ Fsw = 5MHz

CPU Socket

CPU Package

Ceramic Bulk 22uF

CPU Caps 0.1uF

Eliminate Cost, Size, Improve Reliability
Eliminate Board Parasitics and Wasted Space

The Power Stage Function becomes part of the CPU Socket!

Loop 1 di/dt = 6600A/us
Control Loop & Output Inductance
Realistic Expectations for Projected Evolution of $R_{on}*Q_g$ FOM for LV GaNpowIR FETs

Based on Device Modeling
Application: High Current LV POL (VRM)

Can Achieve > 91% efficiency from 10A to 100A – 4 phase

700 kHz  \( V_{in} = 12 \text{ V}, \ V_{out} = 1.2 \text{ V} \)  

Circuit Simulations
Enabling High Density LV Point of Load Converters

12V to 2V, 10A Load, Power Conversion Loss

- Std Current Benchmark (2006)
- GaNpowIR Gen 1.0
- GaNpowIR Gen 1.1
Application: POL - Early Prototypes realize potential of GaN

6 times Higher Frequency over Si Solution with similar efficiency!

Linear Tech POL Si Solution:
15 mm x 15 mm

1MHz, 10A

IR GaNpowIR Gen 1.1 Solution:
6 mm x 9 mm....

75 +% Smaller!

6MHz, 12A

Output Inductor Integrated with Power Stage
\( \eta = 85\% \)
12 V to 1.2 V
iP2007 Switching Waveforms at 4 MHz  Vin = 12 V, Vout = 1.3 V, Iout = 20 A
GaN based HEMT basic device structure

- S Contact
- AlGaN
- GaN un-doped
- D Contact
- Substrate (GaN, Sapphire, SiC, Si, Others)

Piezoelectric effects create 2 DEG electron sheet $n_s = 10^{13}$ cm$^{-2}$
6” GaNpowIR Device Fabrication
Comparison of IR prototype GaN HV diode function Qrr and SiC

GaN device performs very much the same as SiC Diode
• No sign of dynamic Rdson is seen.
Transfer Characteristics of Large Early LV GaN HEMT

High Current Device, $I_d > 100$ A

$V_{GS}$ (V)

$I_d$ (A)

(Wg/Lg=1.6m/0.4um), AA = 7 mm$^2$  

$Ta = 25 \degree C$
Early Enhancement Mode Device Results
Breaking the Compromise – Radical Improvement in RQ

Realistic Expectations for Projected Evolution of Ron*Qg FOM for LV GaNpowIR FETs

Based on Device Modeling
Potential LV DC-DC Power Stage Roadmap

Optimized Performance – Without tradeoff

12Vin, 1.2Vout, 100A

Based on Circuit Simulation
Density:

Freq: 10 to 100 MHz (L > 20 to 2 nH)

J > 5 A/mm²

Efficiency

Rs < 5 mohmm²
Achieving significantly improved density at high efficiency and commercially viable costs requires increased switching frequency and a higher degree of integration of the power conversion stage.

Silicon based power devices are reaching their inherent performance limitations.

New power devices based on new materials such as SiC and GaN are clearly leading candidates to achieve breakthrough performance gains.

Since solution costs are fundamental to adoption, it appears that SiC will have only a marginal role to play in the larger volume of power device materials requirements (\(< 10^6\) out of \(> 10^9\) cm\(^{-2}\)).

GaN based devices (HEMT) on silicon substrates look like a promising candidate to meet this opportunity.

High density magnetic components, capable of supporting high currents with low loss are required for conversion switching frequencies > 10 MHz.
Thank You
for
Your Kind Attention