GaN Power IC Enable Next Generation Power Adaptor Design

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Navitas Semiconductor Inc.

- World’s first & only GaN power IC company
- Founded January 2014
- HQ in El Segundo, CA, USA
- World-class team
- World-class manufacturing partners
- www.navitassemi.com
The First Revolution in Power Electronics

- **Power Density (W/in^3)**
  - (AC-DC converters ~300W)
  - 0.1
  - 1
  - 10
  - 100

- **Efficiency**
  - 40%
  - 80%
  - 90%

- **Frequency**
  - 50 Hz
  - 30 kHz
  - 65 kHz

- **1977**
  - Linear Regulators
  - Si BJTs
  - 40% efficiency

- **1987**
  - Switching Regulators
  - • 5x Lower Loss
  - • 3x Lower $/W
  - • Si BJTs → Si FETs
  - • New Magnetics
  - • New Controllers
  - • New Topologies

- **2017**
  - Switching Regulators
  - • Better Si FET (Super junction)
  - • SR
  - • QR

- **<10%/yr improvement over 30 years**

**5x Increase in 10 years**
Today’s Power Revolution

- **Linear Regulators**
- **Switching Regulators**
- **Switching Regulators**
- **HF Switching Regulators**

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**Power Density (W/in³)**

- 50 Hz
- 30 kHz
- 65 kHz
- 1 MHz

- **40% efficiency**
- **80%**
- **90%**
- **95-98%**

**5x Increase in 10 years**

- **Si BJT → Si FETs**
- **New Magnetics**
- **New Controllers**
- **New Topologies**

- **5x Lower Loss**
- **3x Lower $/W**

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**<10%/yr improvement over 30 years**

- **Better Si FET (Super junction)**
- **SR**
- **QR**

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- **2x Lower Loss**
- **3x Lower $/W**

- **New GaN Power ICs**
- **New Magnetics**
- **New Controllers**
- **New Topologies**

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- **1977**
- **1987**
- **2017**
- **2027**
Key Factors for Next Generation Power Adaptor

- **HF Power Switch**
  - GaN Power IC, GaN FET, SiC FET
- **HF Magnetics**
  - 300kHZ~2MHz
- **HF Controllers**
  - ASIC ACF (up to 2MHz)
  - ASIC TP PFC (up to 2MHz)
  - ASIC LLC (up to 2MHz)

HF Power Switch: Navitas GaN Power IC

- **Speed** enables *small size, low-cost* and *faster charging*

- **Efficiency** enables *energy savings*

- With Silicon or Discrete GaN power devices, you can get one *or* the other

- With GaN power ICs, you get *both at the same time*, unequaled Speed & Efficiency
Hard-Switch $\rightarrow$ Soft-Switch with eMode GaN

**Primary Switch Power Loss:**

$P_{\text{FET}} = P_{\text{COND}} * k + P_{\text{DIODE}} + P_{\text{T-ON}} + P_{\text{T-OFF}} + P_{\text{DR}} + P_{\text{QRR}} + P_{\text{QOSS}}$

- **k-factor** > 1 due to increased circulating current, duty cycle loss (deadtime)
- **$P_{\text{T-On}}$** = 0 (soft-switch)
- **$P_{\text{DR}}$** ↓ 10X (GaN $P_{\text{DR}}$ negligible up to 2Mhz)
- **$P_{\text{QRR}}$** = 0 (NO Reverse recovery)
- **$P_{\text{DIODE}}$** ↓ 2X (reverse conduction loss reduced due to short deadtime)
- **$P_{\text{QOSS}}$** ↓ 10X (GaN Coss charging/discharging loss negligible up to 2Mhz)
- **$P_{\text{T-OFF}}$** = Reduced (limited by I-V crossover loss due to drive loop impedance)
Hard-Switch $\rightarrow$ Soft-Switch with Navitas 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 (deadtime)
- **$P_{\text{T-On}}$**: $= 0$ (soft-switch)
- **$P_{\text{DR}}$**: $\downarrow 10X$ (GaN $P_{\text{DR}}$ negligible up to 2Mhz)
- **$P_{\text{QRR}}$**: $= 0$ (NO Reverse recovery)
- **$P_{\text{DIODE}}$**: $\downarrow 2X$ (reverse conduction loss reduced due to short deadtime)
- **$P_{\text{QOSS}}$**: $\downarrow 10X$ (GaN Coss charging/discharging loss negligible up to 2Mhz)
- **$P_{\text{T-OFF}}$**: $= 0$ (Due to driver Integration, No gate loop impedance)
Ideal Switching = No Switching Loss @ High $F_{SW}$

Navitas GaN ICs provide Ideal Switching

How?
HF Power Switch: World’s First AllGaN™ Power ICs

Fastest, Most Efficient GaN Power FETs

- >20x faster than silicon
- >5x faster than cascoded GaN
- Proprietary design

iDrive First & Fastest Integrated GaN Gate Drivers

- >3x faster than any other gate driver
- Proprietary design
- 30+ patents granted/applied

World’s First AllGaN™ Power IC

Up to 40MHz switching, 5x higher density & 20% lower system cost
AllGaN™: Monolithic GaN Power IC

- Monolithic integration at 650 V
  - GaN FET (range 110-560 mΩ)
  - GaN Driver (iDrive™)
  - GaN Logic
- “Digital In, Power Out”
Integrated Drive – Simple & Robust

Wide-range $V_{CC}$ (10-30 V)

Regulator ensures $V_{GS}$ within SOA

PWM hysteresis for noise immunity

No inductance or ringing in gate loop

Total layout flexibility & simplicity

Gate protected from external noise

PWM (5 V/div)

$V_{GS}$ (2 V/div)
Clean, Controlled FET Gate

• **Discrete driver**
  - Gate loop inductance creates overshoot (even with good layout)
  - Reliability concern

• **iDrive™ GaN Power IC**
  - No gate loop parasitic
  - Clean and fast gate signal
Fast & Clean Hard Switching

- IC prevents noise coupling into gate
- Zero gate-loop inductance
- Eliminate turn-off loss
- Clean HV hard switching
- Prop delay 10-20 ns
- PWM
- HV power FET
- VDD
- Gate driver loop
- Clean HV hard switching
- ~100 V/ns dV/dt
- V_{PWM} (2 V/div)
- V_{DRAIN} (100 V/div)
- PWM
- 500 V
- I_{Load} = 5 A
- 50 ns/div
• External drivers
  • Just 1-2 nH of gate loop inductance can cause unintended turn-on
  • Gate resistors reduce spikes but create additional losses

• Integrated GaN drivers (iDrive™)
  • Eliminate the problem
  • Negligible turn-off losses
  • Removes unintended dV/dt turn-on

Discrete FET and drive, no $R_g$ = out of control
Discrete FET and drive, with $R_g$ = slow, lossy
Integrated FET and drive, no $R_g$ = fast, efficient
Hard-Switch → Soft-Switch with Navitas GaN Power IC

Primary Switch Power Loss:

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

- **Minimized**
  - \( k \) factor: >1 due to increased circulating current, duty cycle loss (deadtime)
  - \( P_{\text{T-ON}} \): = 0 (soft-switch)
  - \( P_{\text{DR}} \): ↓ 10X (GaN \( P_{\text{DR}} \) negligible up to 2Mhz)
  - \( P_{\text{QRR}} \): = 0 (NO Reverse recovery)
  - \( P_{\text{DIODE}} \): ↓ 2X (reverse conduction loss reduced due to short deadtime)
  - \( P_{\text{QOSS}} \): ↓ 10X (GaN Coss charging/discharging loss negligible up to 2Mhz)
  - \( P_{\text{T-OFF}} \): = 0 (Due to driver Integration, No gate loop impedance)

- **Reduced**
High Power Density = More Integration
AllGaN™ Half-Bridge GaN Power IC

• Monolithic integration at 650V
  • 2x GaN FETs (110-560 mΩ)
  • 2x GaN drivers (iDrive™)
  • GaN Logic (level-shift, bootstrap, UVLO, shoot-through, ESD)
• “Digital In, Power Out”
**GaN Level-Shift: Low Loss, High-Frequency**

**Disparate Technologies**
Hybrid isolator, discrete driver, discrete power, bootstrap diode

**High Power Loss**
- Driver loss, $R_G$ loss
- Bootstrap diode $Q_{RR}$, $V_F$
- Pulsed high current level shifter power (?)

**Low Power Loss**
- No gate driver loop parasitics, matched driver-FET capability, negligible loss vs. frequency
- Zero $Q_{RR}$, low $V_{DS}$ in synchronous charging
- Very fast, low-power loss, MHz+

**Monolithic Platform**
Lateral GaN-on-Si, Half-Bridge GaN Power IC

**AllGaN™ Technology**
Lateral 650V GaN-on-Si
Complex Design ↠ Easy-to-Use

**Half-Bridge *Discrete* GaN**

- PCB Area: 24 x 42 ~ 1,000 mm²

**Half-Bridge GaN *Power IC***

- 20x smaller PCB area
- Lower cost
- Robust & protected
- Simple
- Easy layout

PCB Area: 6 x 8 = 48 mm²
HF Topology for Low Power Adaptor(<75W)

Active Clamp Flyback
QR vs ACF

- RCD loss (leakage loss)
- Hard switching loss (high Line)
- Switching loss increases with high fsw

QR Flyback

- No RCD loss (leakage loss)
- ZVS over all AC line, all load conditions
- ZCS achieved
- ACF operates at > 1MHz

Active Clamp Flyback
ACF Operation (S1 ON)

- S1 ON, linearly charging $L_m$, like a QR flyback
ACF Operation (S2 ON, S1 OFF)

- S2 ON with ZVS, effective clamping since current can go both direction, no overshoot
- Leakage resonates with clamping capacitor
- Rectifier diode conducts and delivers power
- Interval ends when rectifier current drops to zero
ACF Operation (Building Negative Lm)

- S2 current equals to magnetizing current
- Magnetizing current becomes negative
ACF Operation (S1 ZVS Transition)

- Negative $i_{Lm}$ discharge S1 $C_{OSS}$
- S1 can be turned on later in ZVS
ACF Enables ZVS and High Frequency Switching

- No snubber losses, all leakage energy is recovered
- ZVS turn-on over entire operation range
- ZCS turn-off for output rectifier
- Clean waveforms reduce EMI
- Enable small adapter design with high frequency switching
65W USB-PD ACF: World’s Smallest Adapter

- **Input**: Universal AC (85-265V<sub>AC</sub>, 47-63Hz)
- **Output**: USB-PD (5-20V) (65W)
- **Frequency**: 300~400kHz (Full Load)
- **Primary FET**: NV6115 (160 mΩ) + NV6117 (110 mΩ) GaN Power ICs
- **Controller (ACF)**: UCC28780
- **Magnetic Core**: N49
- **Size**: 38 x 46 x 15.5 mm = 27 cc uncased
  43 x 51 x 20.5 mm = 45 cc with 2.5 mm case
- **Efficiency**: 93.4% at 90 V<sub>AC</sub>, Full Load
- **Power Density**: 2.4 W/cc (39 W/in<sup>3</sup>) uncased
  1.5 W/cc (24 W/in<sup>3</sup>) cased
- **Construction**: 4-layer, 2-oz Cu PCB, SMT powertrain
  “No heatsink” design
65W USB-PD ACF

Efficiency at 20 $V_{OUT}$ (25°C, no airflow)

Efficiency measured at PCB
65W USB-PD ACF

Efficiency (25°C, no airflow)

• Standby: 25 mW at 115 V_{AC}, 40 mW at 230 V_{AC} (CoC Tier 2 spec is < 75mW, DoE Level VI spec <= 210 mW)

Efficiency measured at PCB

Controller (ACF) : UCC28780
600kHz 65W Planar Prototype

- **Input**: Universal AC (85-265V<sub>AC</sub>, 47-63Hz)
- **Output**: Fixed 20 V (65W)
- **Powertrain**: NV6115 (160 mΩ) + NV6117 (110 mΩ) GaN Power ICs
- **Control**: ACF = TI UCC28780
- **Frequency**: 500-600 kHz
- **Size**: 38 x 47 x 12.5 mm = 22 cc uncased
  43 x 52 x 17.5 mm = 39 cc with 2.5 mm case
- **Power Density**: 2.9 W/cc (47 W/in<sup>3</sup>) uncased
  1.7 W/cc (27 W/in<sup>3</sup>) cased
- **Construction**: 4-layer, 2-oz Cu PCB, SMT powertrain
  “No heatsink” design

*In progress, available Q2’18*
1MHz 150 W

State-of-the-art Si 12W/in³

1MHz GaN 35W/in³

Totem-Pole: 2 x Navitas Power ICs

2 x Si FETs

LLC transformer

LLC Primary 2 x GaN Power ICs

Microcontroller not shown

Efficiency

1MHz GaN Power IC

State-of-the-art Si

Input Voltage (V_{in})
1.2 MHz, 300W Totem-Pole PFC (Preliminary)

- **Input**: Universal AC (85-265V\textsubscript{AC}, 47-63Hz)
- **Output**: 400V (300W)
- **Fast FETs**: NV6117 (110mΩ) GaN Power ICs
- **Slow (AC) FETs**: Si Superjunction (62mΩ)
- **Frequency**: 300-1,200 kHz
- **Size**: 53.3 x 57.5 x 20 mm = 62 cc uncased \textit{(DSP controller board not included)}
- **Power Density**: 4.9 W/cc (80 W/in\textsuperscript{3}) uncased
- **Target Efficiency**: 98.5% @ 220V\textsubscript{AC}, 98% @ 110V\textsubscript{AC}, 97.5% at 90V\textsubscript{AC}, full load

\textit{In progress, report available APEC’18}
Summary

- **Navitas GaN Power IC**

  **Enable**
  - Market adoption of HF magnetics
  - ACF topology adoption in low power application
  - HF ASIC for ACF, TP-PFC, LLC, SR invention
  &
  Next Generation High Power Density Adaptor
GaN Power ICs: Integration Drives Performance