APEC 2017

Navitas

Power Accelerated

GaN Power ICs at 1 MHz+: Topologies, Technologies and Performance

PSMA Industry Session, Semiconductors

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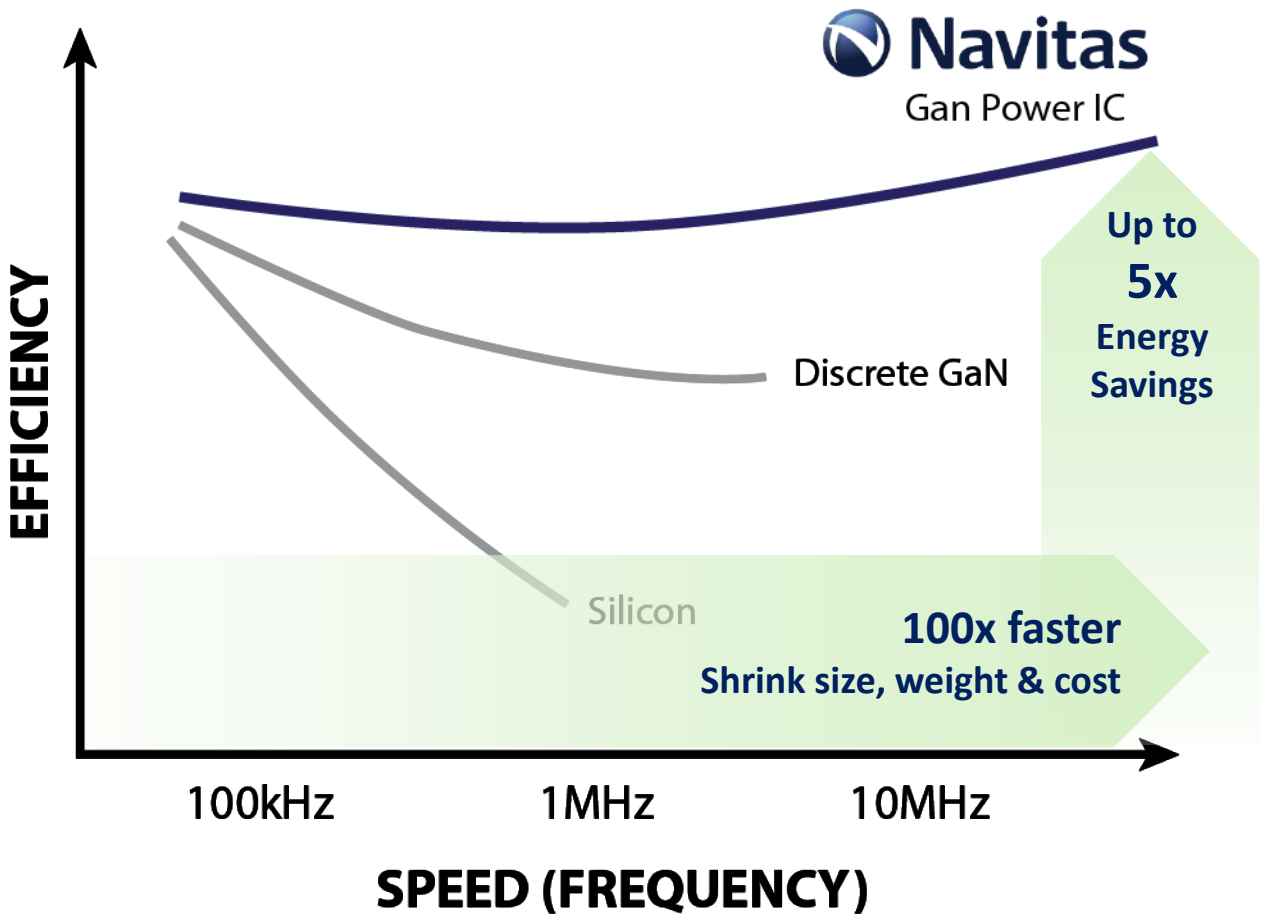
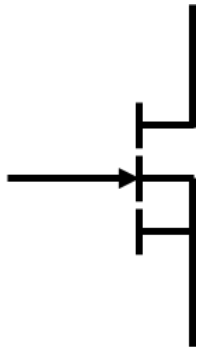
Power Electronics: *Speed & Efficiency are Key*

- **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*** with unequaled **Speed & Efficiency**



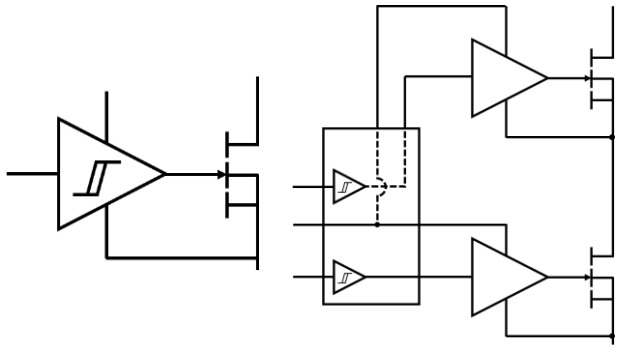
World's First AllGaN™ Power ICs

Fastest, most efficient GaN Power FETs



>10x faster than silicon
>5x faster than cascoded GaN
Proprietary design
5+ pending or issued patents

iDrive First & Fastest Integrated GaN Gate Drivers



>2x faster than any other gate driver
Proprietary design
15+ pending or issued patents

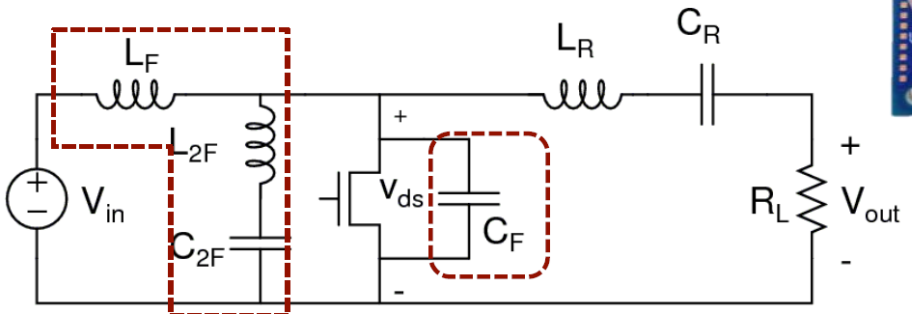
World's First AllGaN™ Power IC

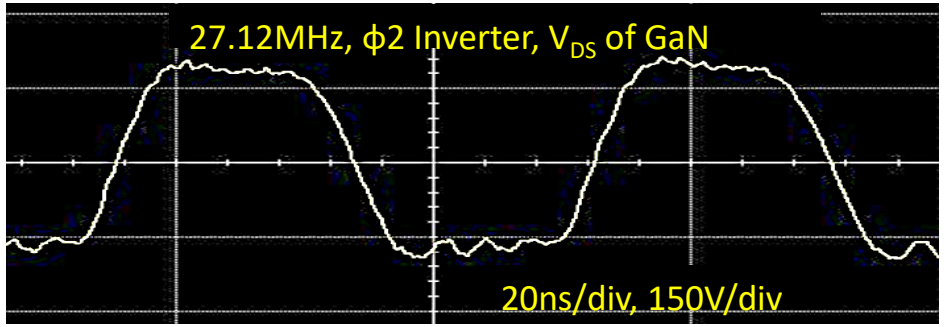
Up to 40MHz switching, 5x higher density & 20% lower system cost

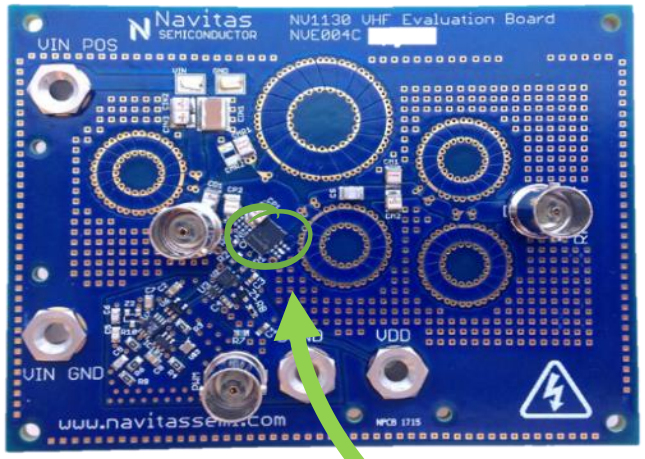
27 MHz, 40 MHz…

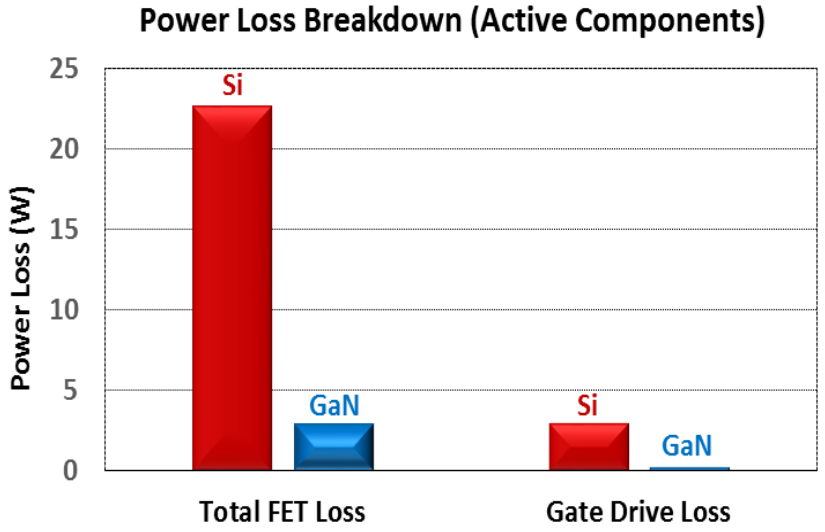
Class Phi-2 DC/AC converter

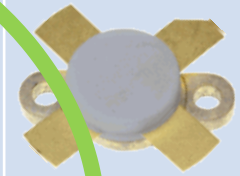
- 50% less loss than RF Si
- 16x smaller package
- Air-core inductors
- Minimal FET loss
- Negligible gate drive loss







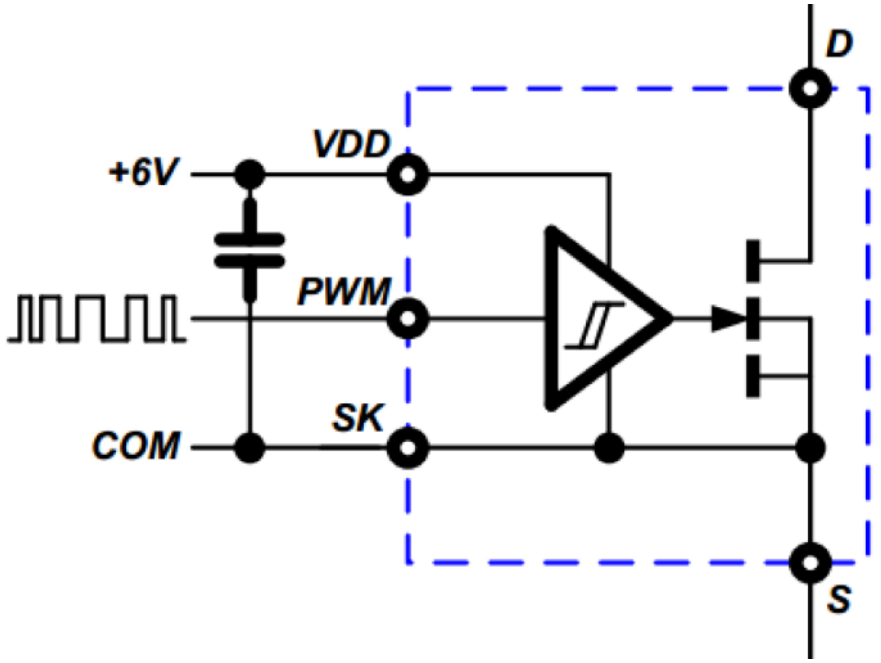


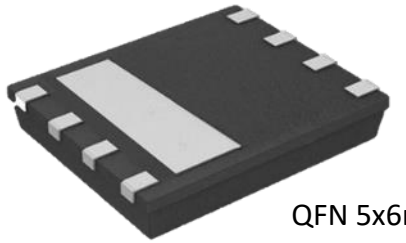
Technology	V	Pack (mm)		F_{SW} (MHz)	Eff. (%)	Power (W)
RF Si (ARF521) Microsemi POWER PRODUCTS GROUP	500	M174 22x22		27.12	91%	150
Navitas	650	QFN 5x6		27.12	96%	150
				40.00	93%	115

Removing Speed Limits:

Navitas GaN Power IC

- **Monolithic** integration
- 20X lower drive loss than silicon
- Driver impedance matched to power device
- Shorter prop delay than silicon (10ns)
- Zero inductance turn-off loop
- Digital input (hysteretic)
- Rail-rail drive output
- Layout insensitive





QFN 5x6mm

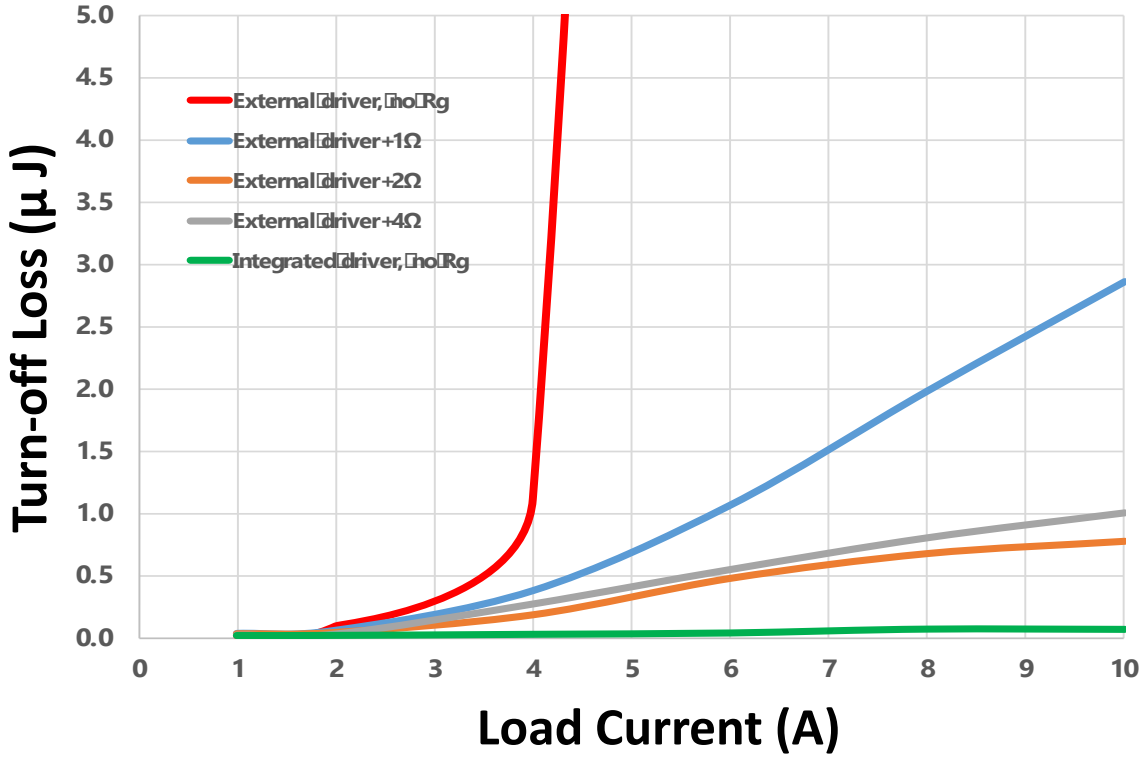
Speed & Integration → Eliminate Turn-off Losses

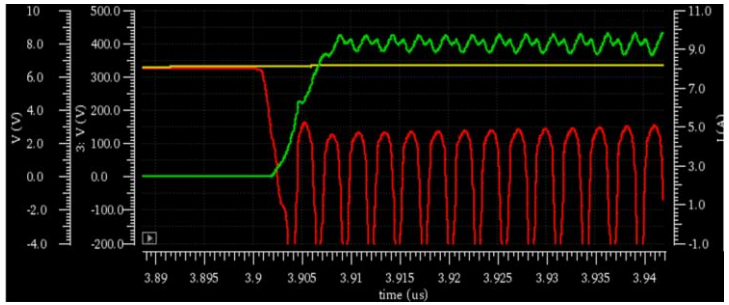
External drivers

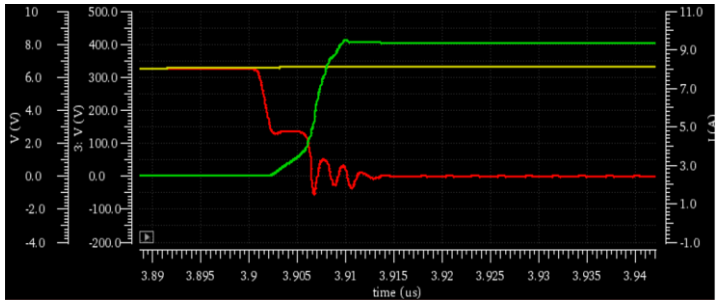
- Just 1-2 nH of gate loop inductance can cause unintended turn-on
- Gate resistors reduce spikes but create additional losses

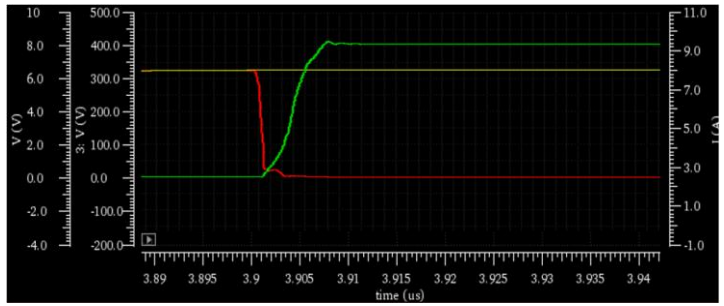
Integrated GaN drivers (iDrive™)

- Eliminate the problem
- Negligible turn-off losses



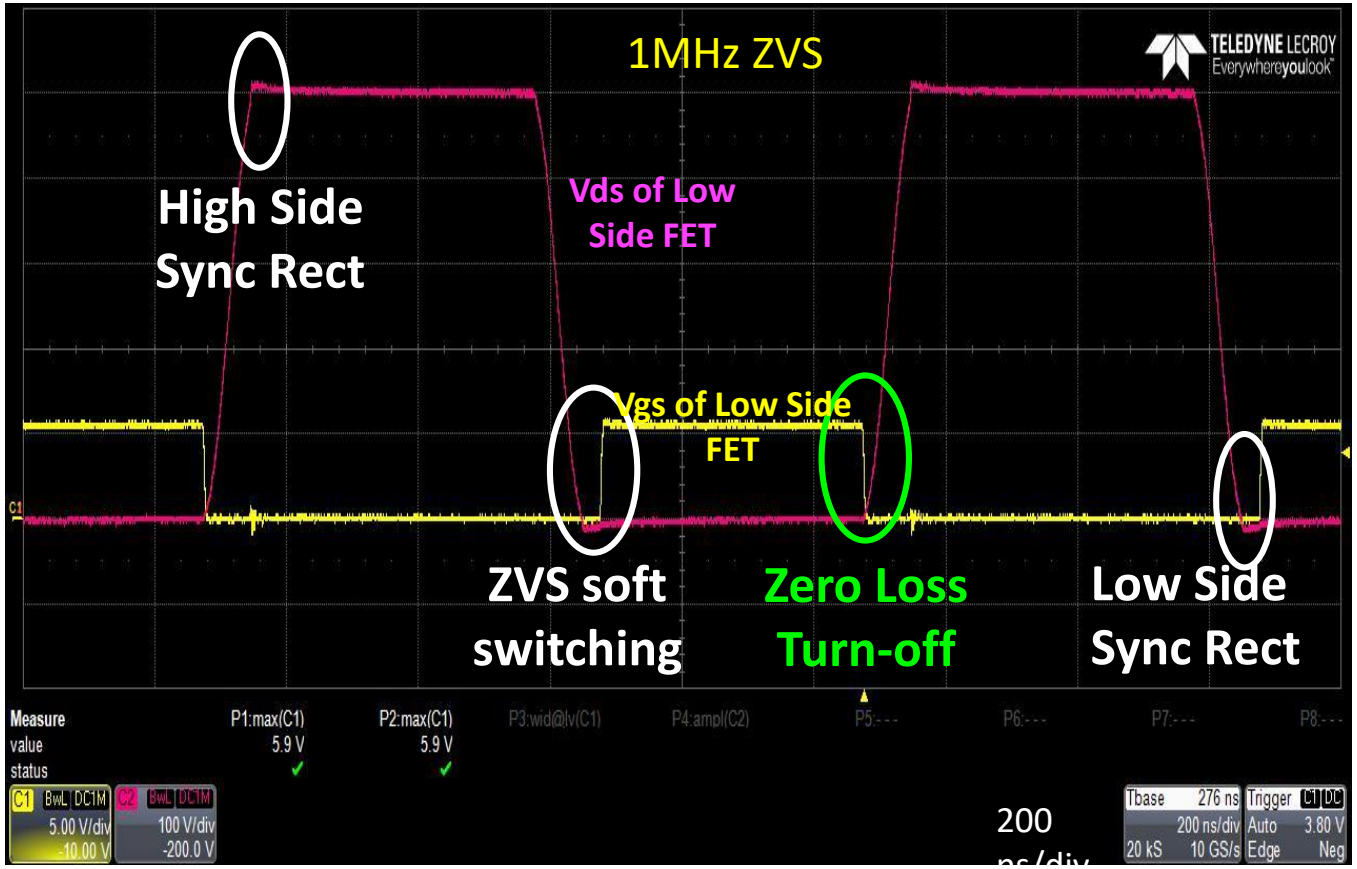






GaN Power IC – *Fast & Efficient*

- No overshoots, No spikes, No oscillations , S-curve' transitions,
- Zero Loss Turn-on (Soft switching) Zero Loss Turn-off (Integrated Gate Drive)



Wireless Power ... *Accelerated*

Navitas

AirFuel™ Alliance

Existing Silicon-based multi-stage wireless power

AirFuel™ Alliance

AC-DC Adapter
88% Efficiency

DC-DC
94% Efficiency

Power Amplifier
93% Efficiency

Wireless Transfer
90% Efficiency

Single-Stage Amplifier
90% Efficiency

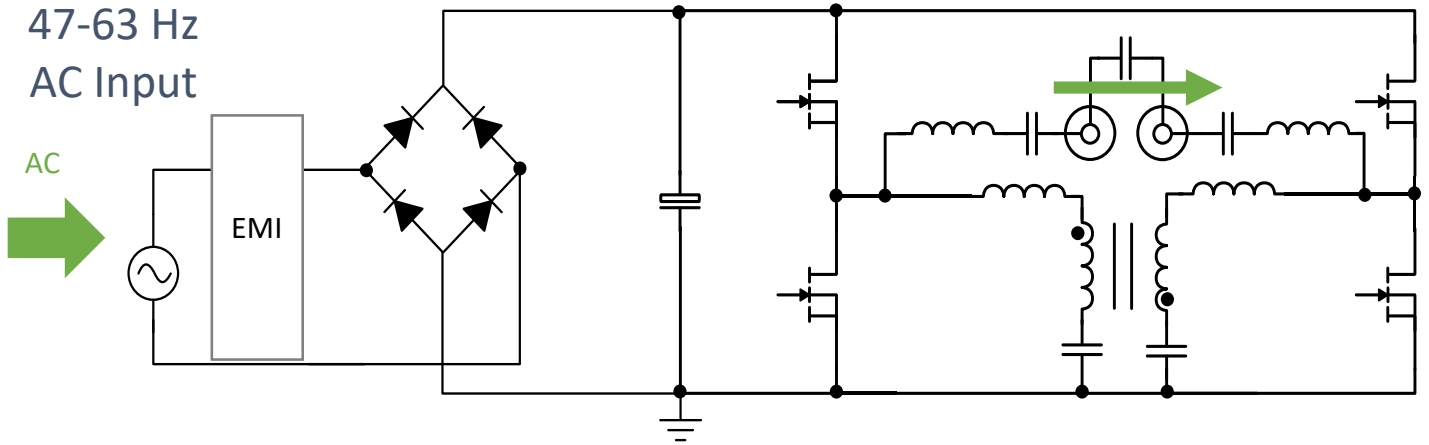
- 650V GaN Power ICs
- 3-stages integrated in 1-stage
- 6.78MHz Operation
- High-Efficiency

- **Multi-stage Efficiency: 77%**
- **GaN-enabled single stage: 90%**
- **20% lower system cost**
- **3x faster charging**

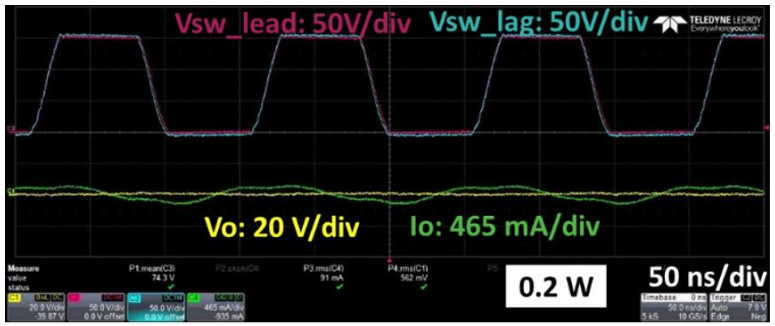
AC-RF Single Stage, Efficient & Cost-effective

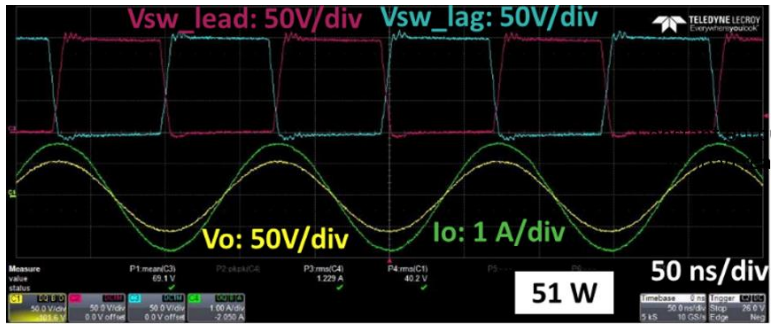
400V Phase-shifted Full Bridge with ZVS Coupled Inductors

6.78 MHz Output Direct to Transmitter Antenna

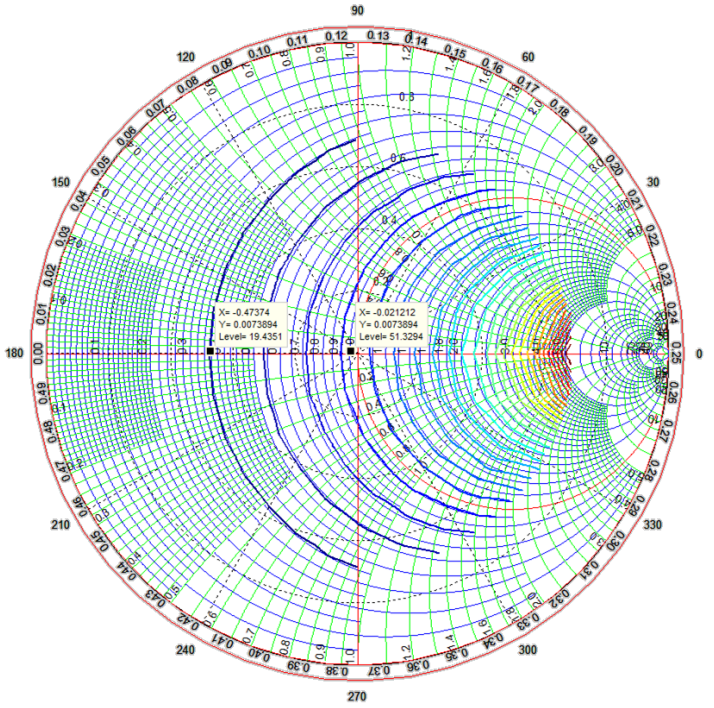


GaN Phase-Shift vs. Load





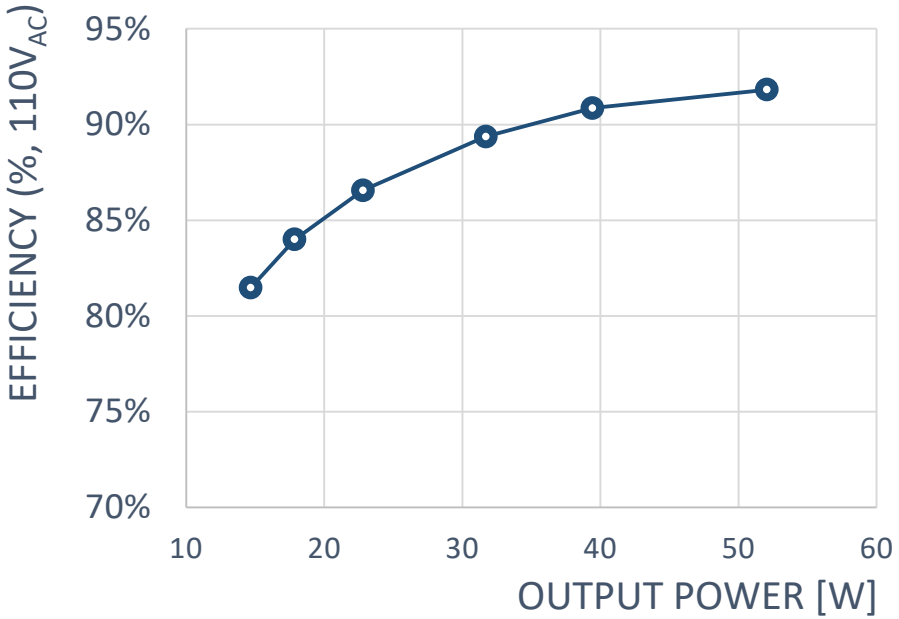
Meets Key System Requirements:
Constant output current vs. load reactance



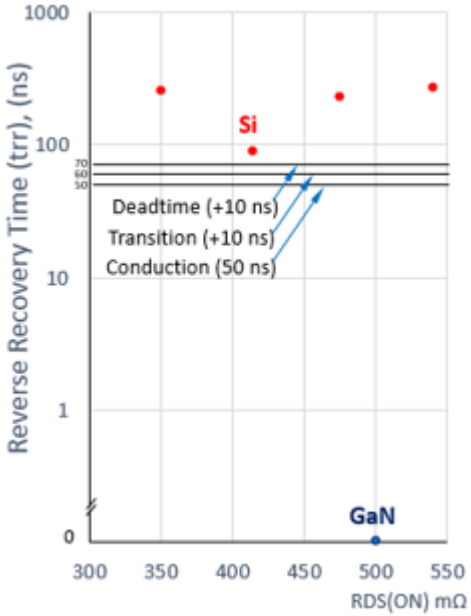
For further details, please see APEC 2017 technical paper “Single-Stage 6.78 MHz Power-Amplifier Design Using High-Voltage GaN Power ICs for Wireless Charging Application”, Xue, Zhang

Cool AllGaN, No Chance for Silicon

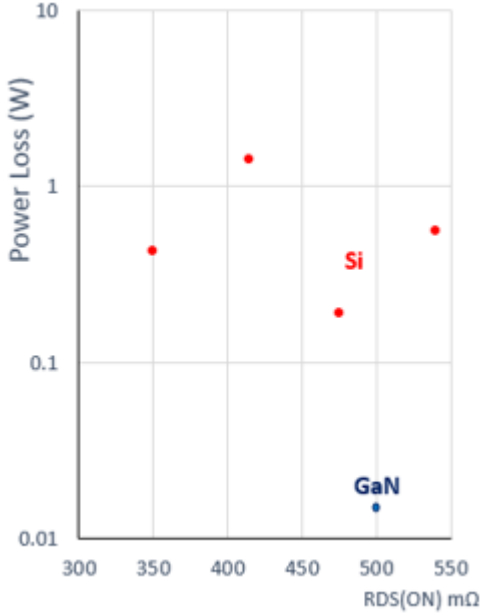
Efficiency from AC line to Transmitter Coil



Device Speed



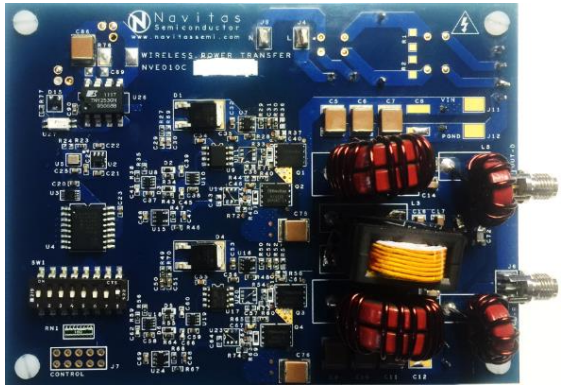
ZVS Current-Induced Loss

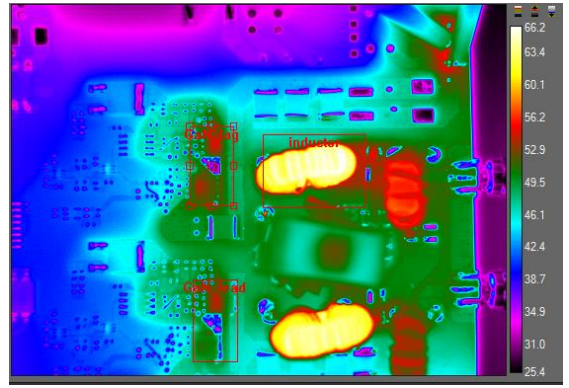


50W Prototype Board:

a) Significant potential for further integration (control & GaN Power IC)

b) Thermal performance (50W):
Max GaN Power IC T_{CASE} = 53°C

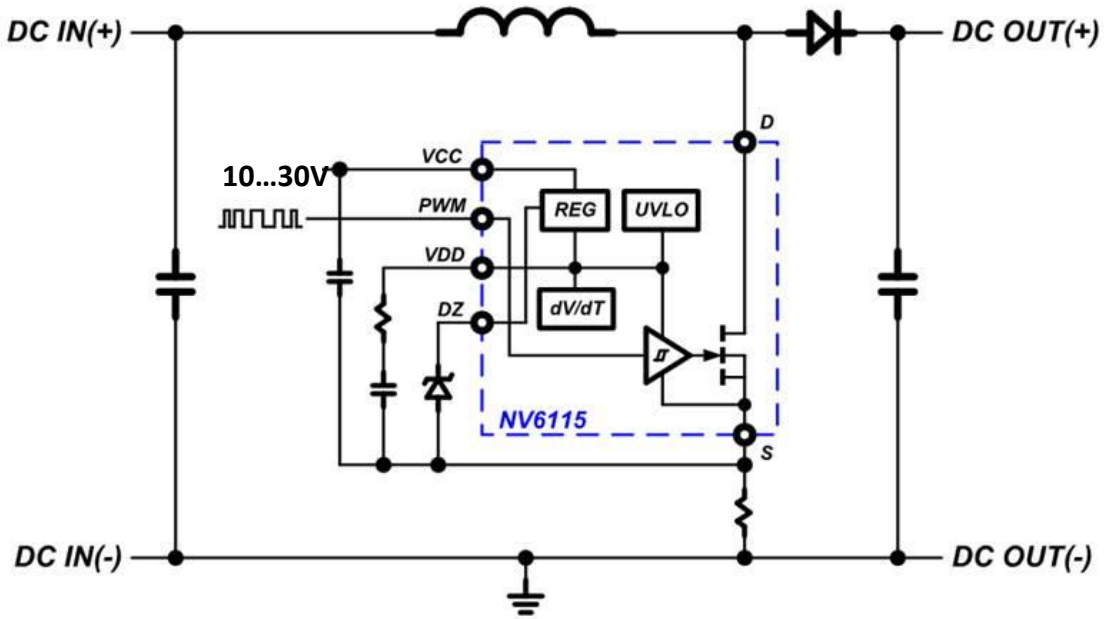


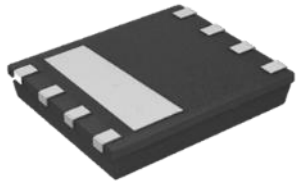


The Road Ahead (as per APEC 2016…)

GaN Power IC: Hi-Speed FET, Drivers & More

- Proprietary AllGaN™ technology
- **Monolithic** integration of GaN FET, GaN Driver, GaN Logic
- 650 V eMode
- 20x lower drive loss than silicon (<35 mW at 1 MHz)
- Driver impedance matched to power device
- Very fast (prop delay and turn-on/off of 10-20 ns)
- Zero inductance turn-off loop
- High dV/dt immunity (200 V/ns) with control
- Digital input
- Complete layout flexibility

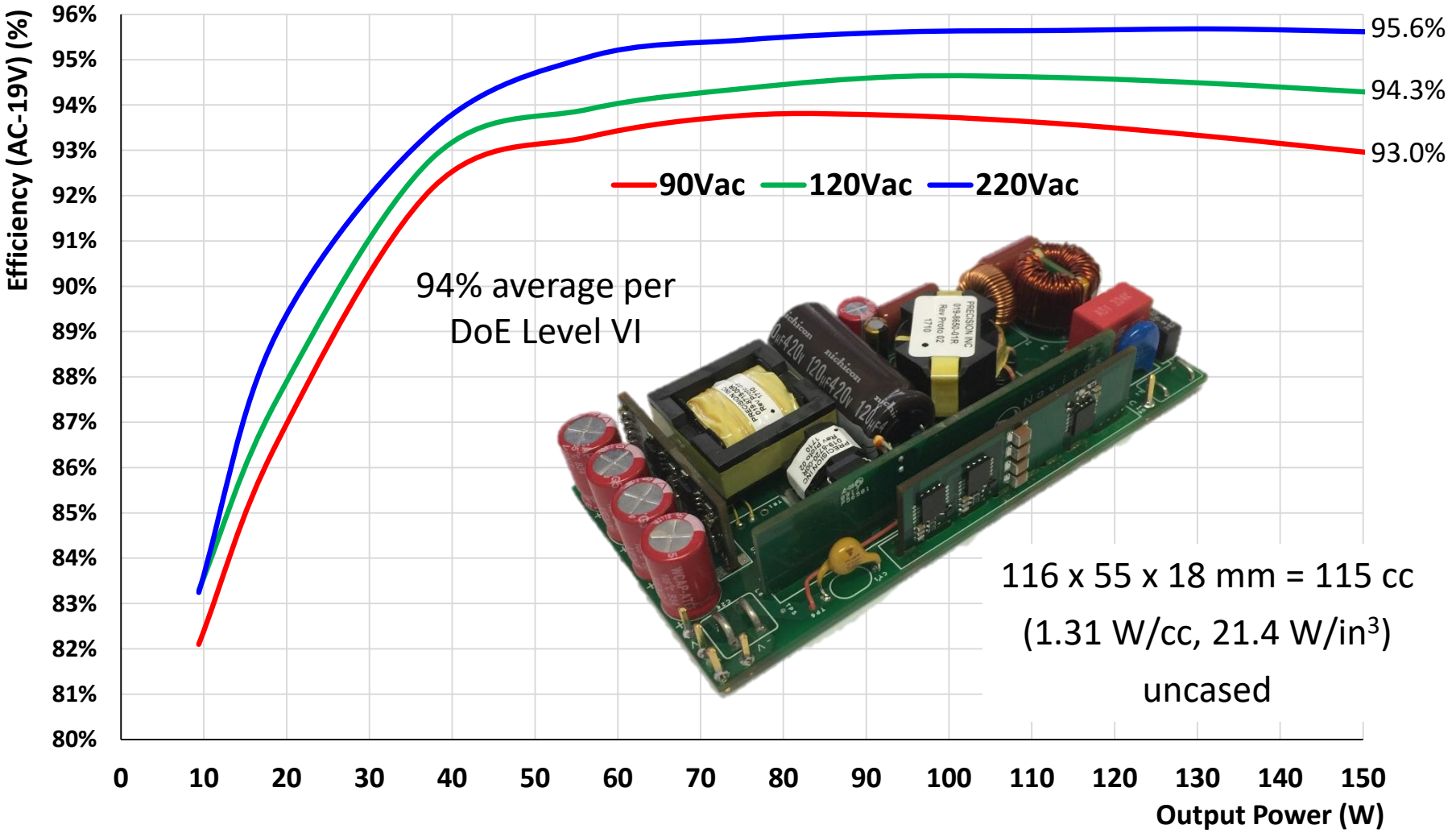


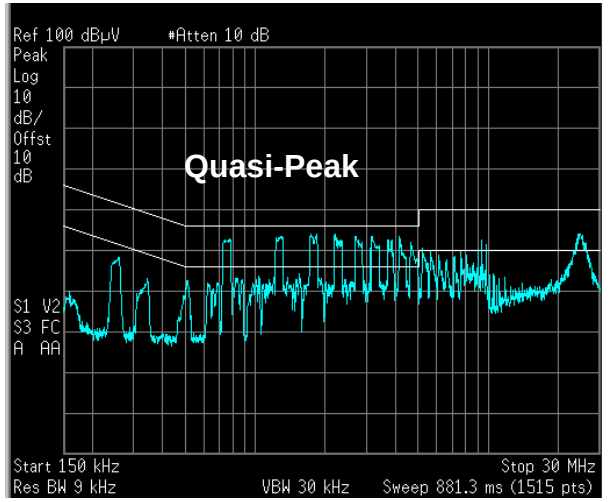


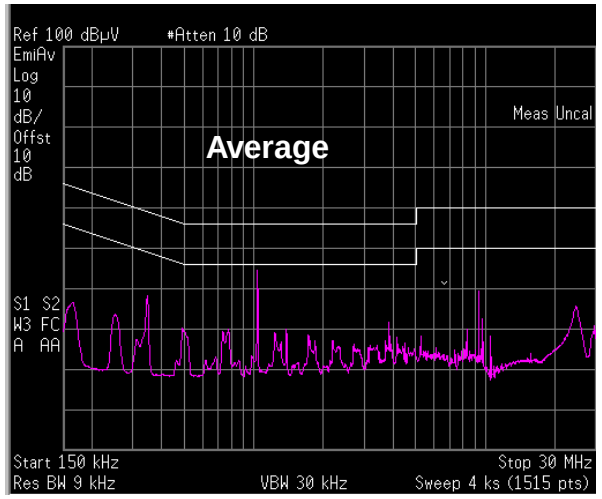
QFN 5x6mm

D. Kinzer, S. Oliver "Monolithic HV GaN Power ICs" in *IEEE PELS Power Electronics Magazine*, vol. 3, no. 3, pp. 14-21, September 2016

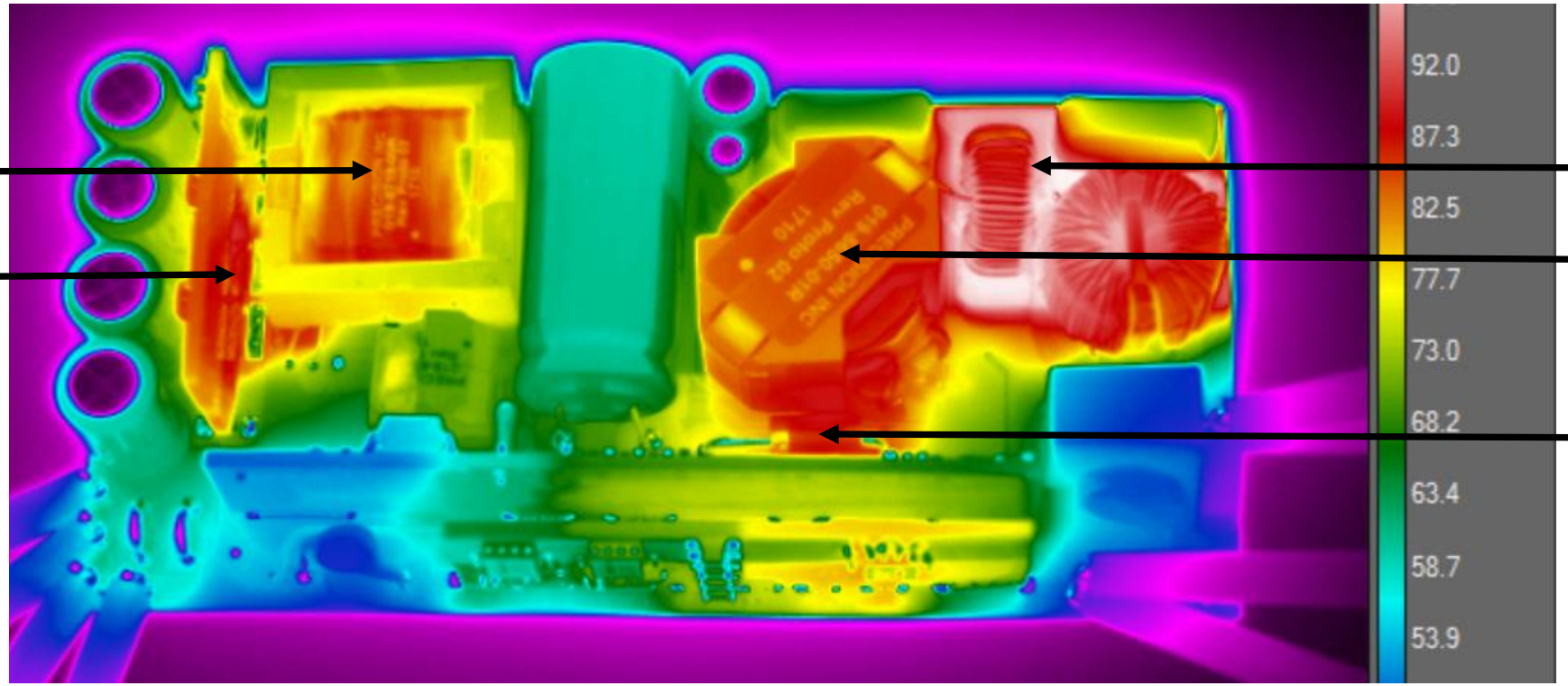
150W AC-19V, ~300 kHz

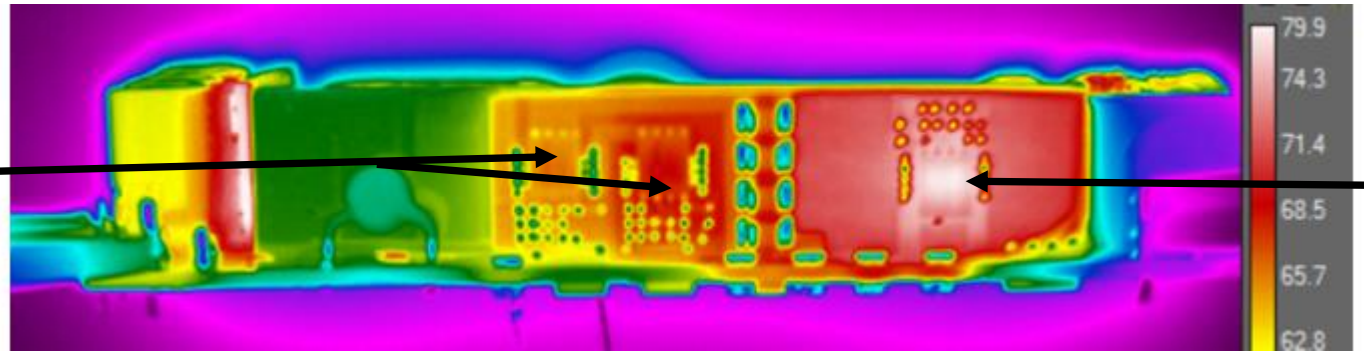






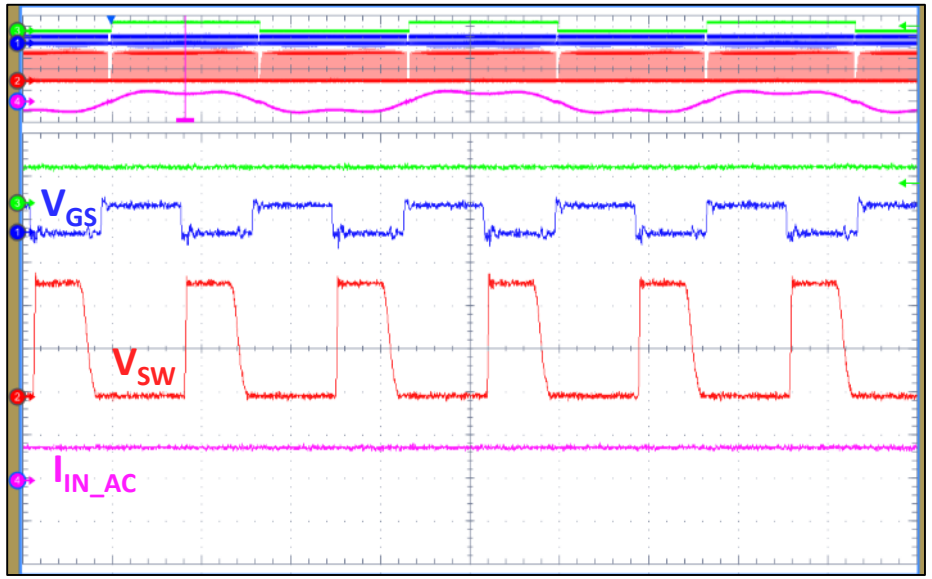
150W: Running Cool



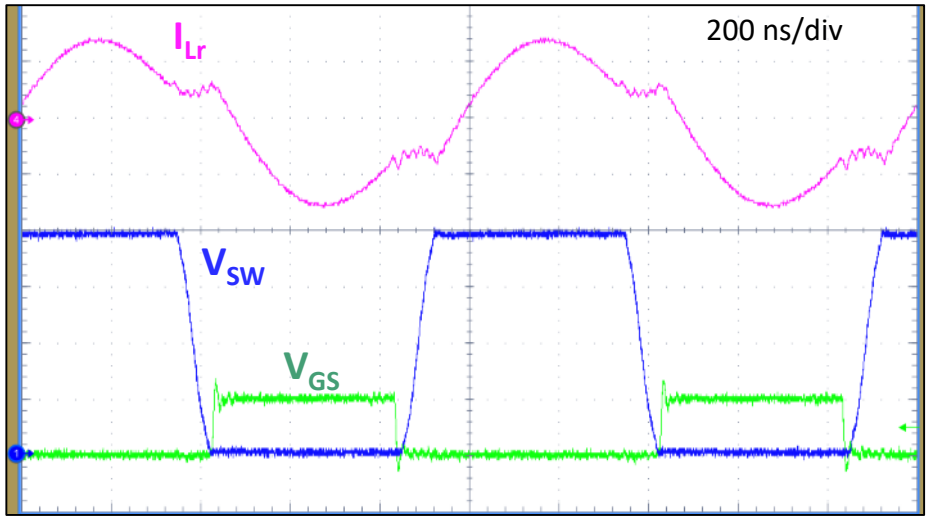


AllGaN 2017: MHz 150W Totem-pole + LLC

PFC

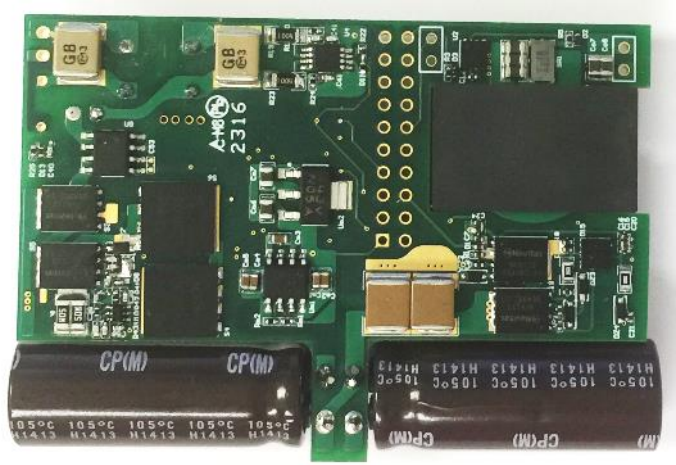


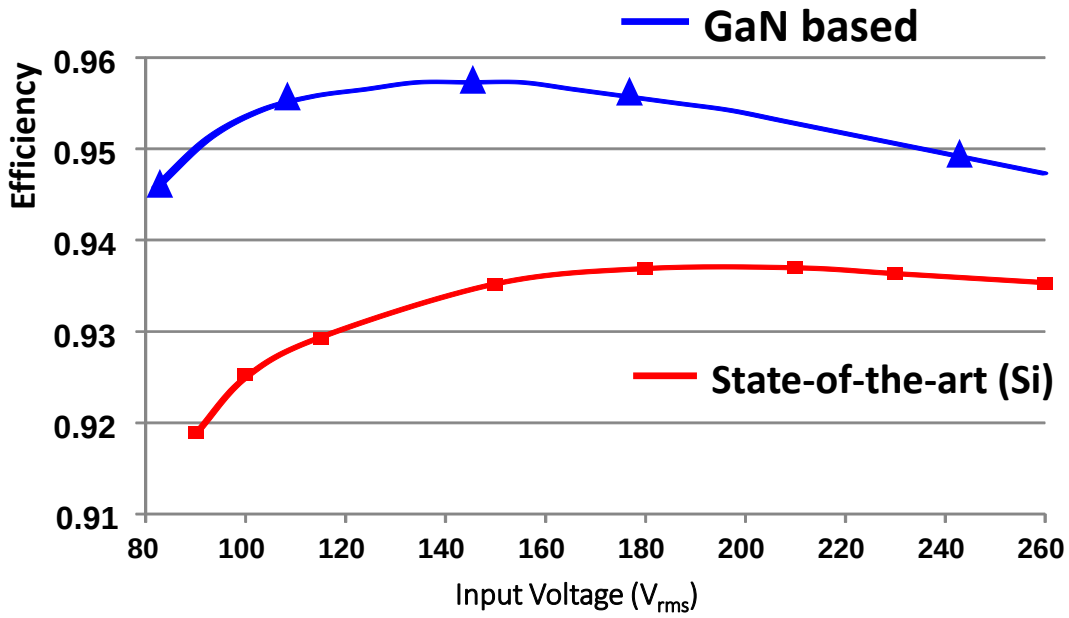
LLC



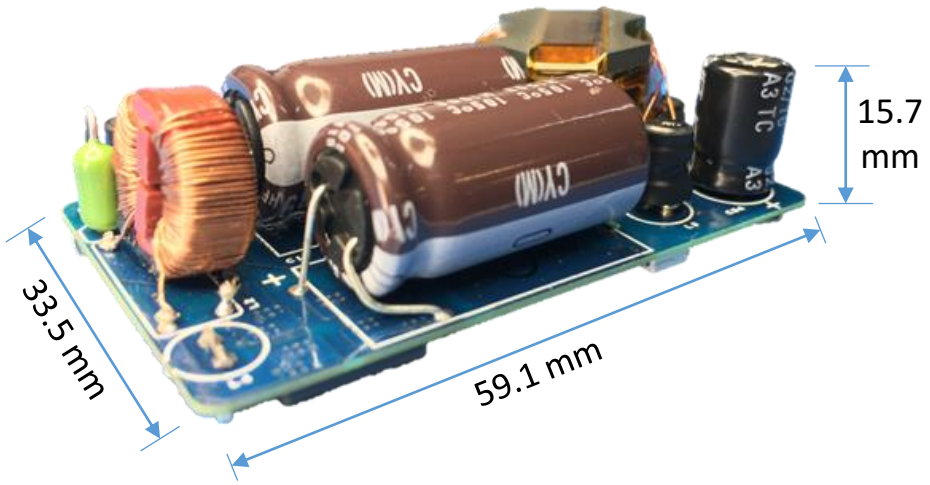
GaN-based
Power Density
= 35 W/in^3

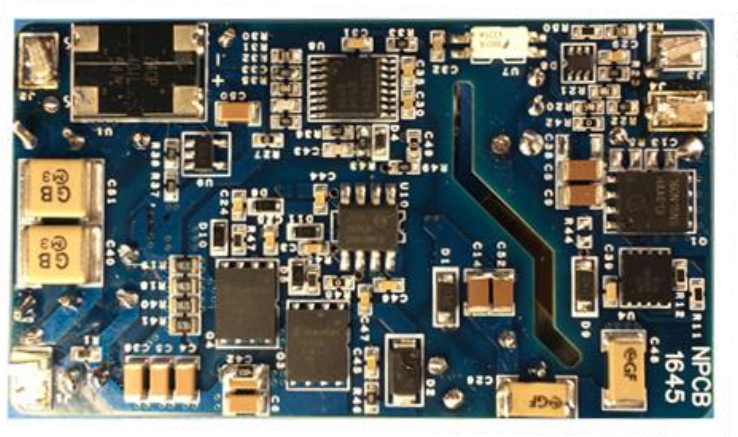
(Best commercial benchmark
= 12W/in3)



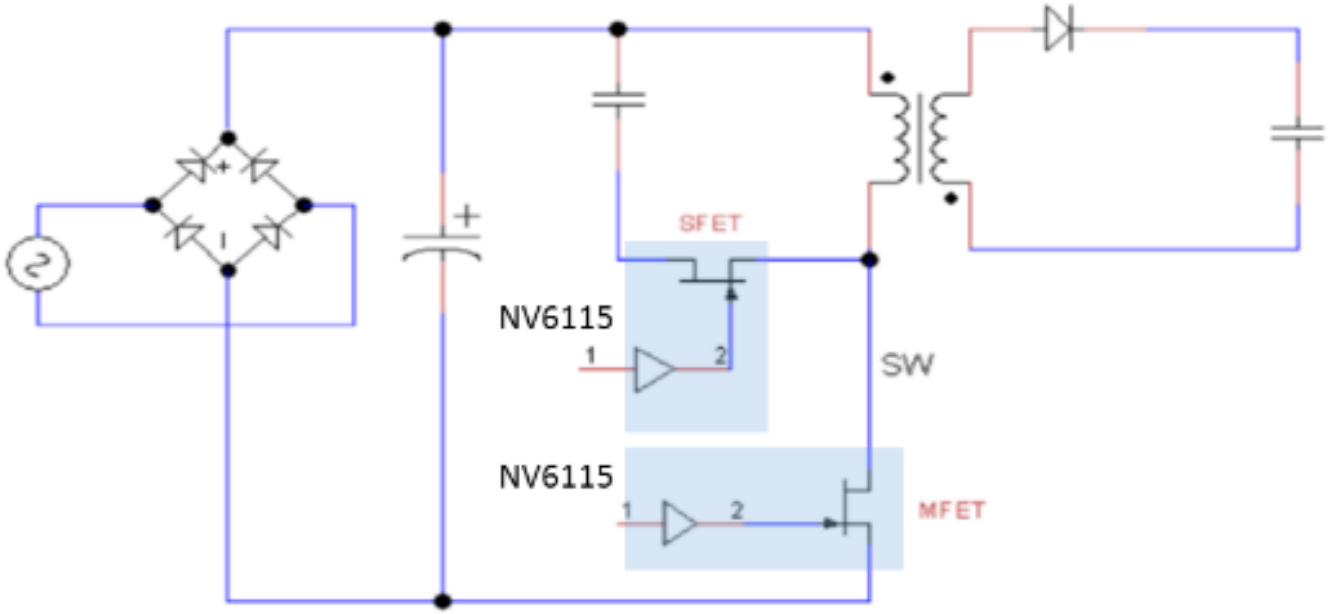


45W Active Clamp Flyback & AllGaN Power ICs



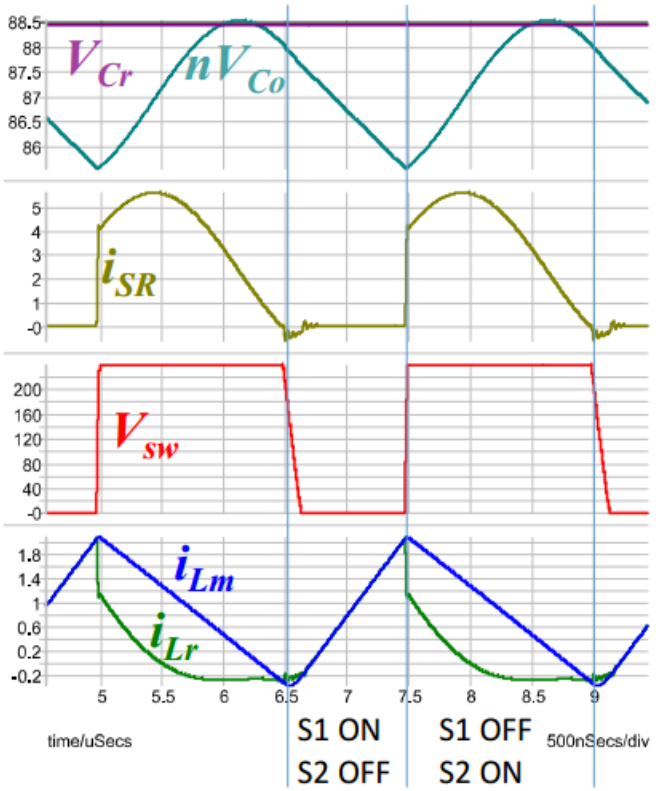


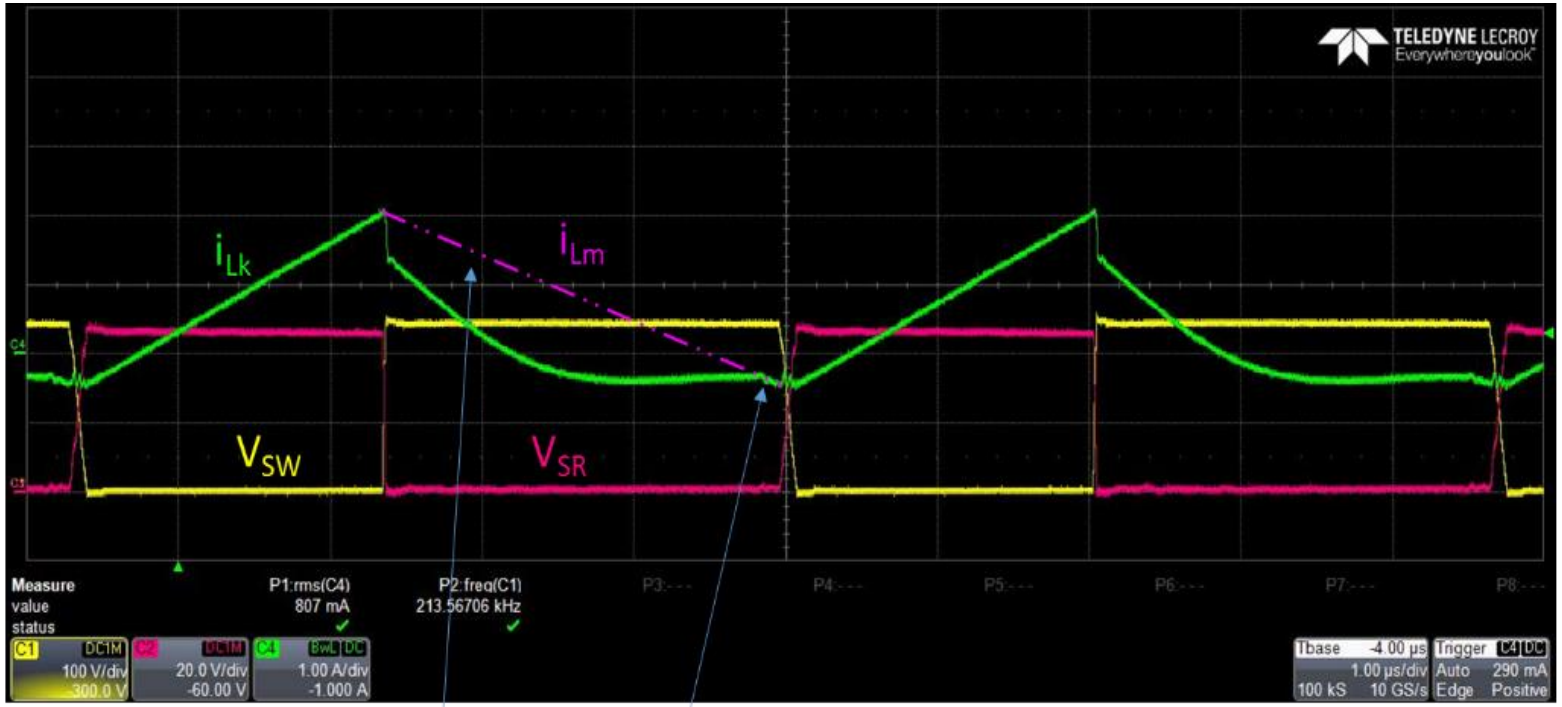
- 94.5% efficient at 220 V (94.2% at 120 V_{AC}, 93.1% at 90 V_{AC})
- 23.7 W/in^3 density (uncased)
- 15.7 mm profile



For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang

45W CrCM ACF Operation





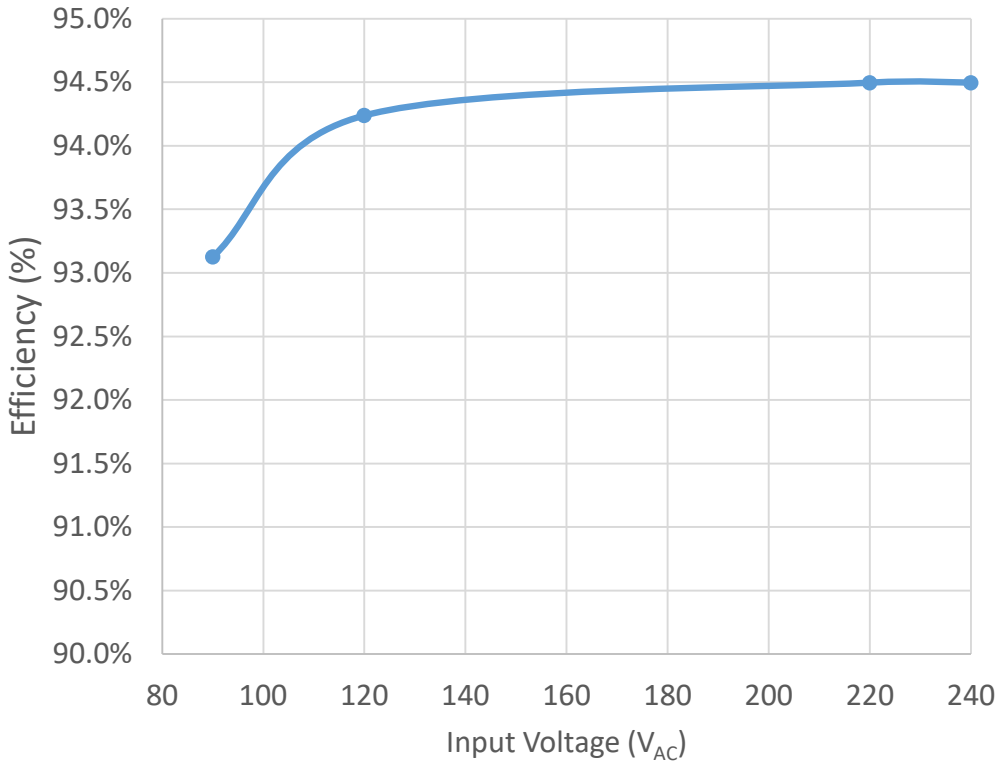
Magnetizing current (drawing)

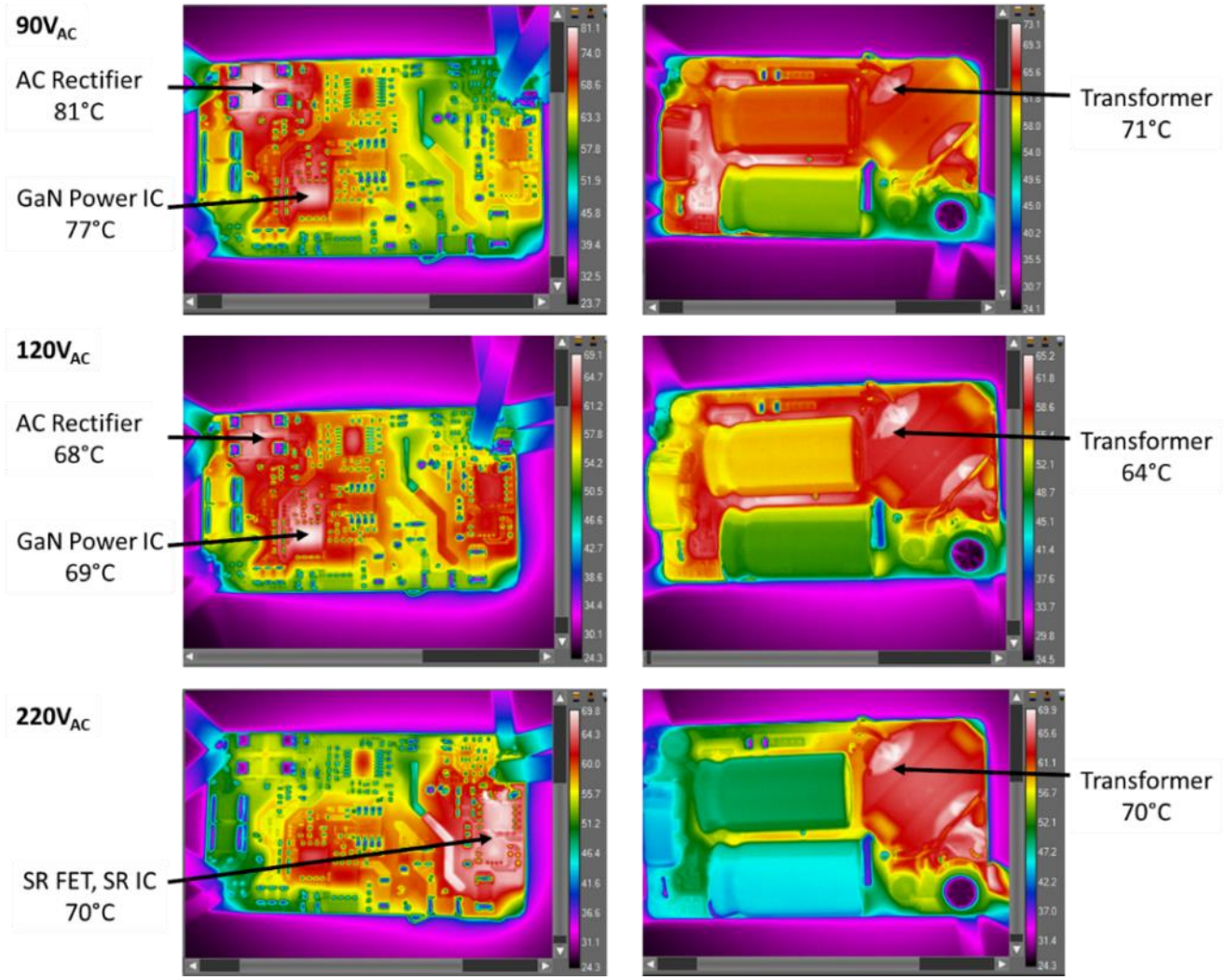
Inductor current merges with magnetizing current, achieves SR ZCS turn-off

- Switch-node voltage (V_{SW}), SR FET voltage (V_{SR}), leakage current (i_{LK}) and magnetizing current (I_{Lm})
- $120V_{AC}$, 0.2A load, F_{SW} = 210kHz, Circulating Current minimized using Secondary Resonance

For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang

45 W ACF: High Efficiency, Cool Temperatures





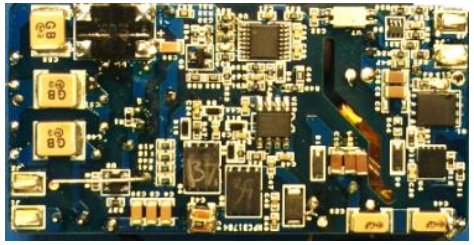
For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang

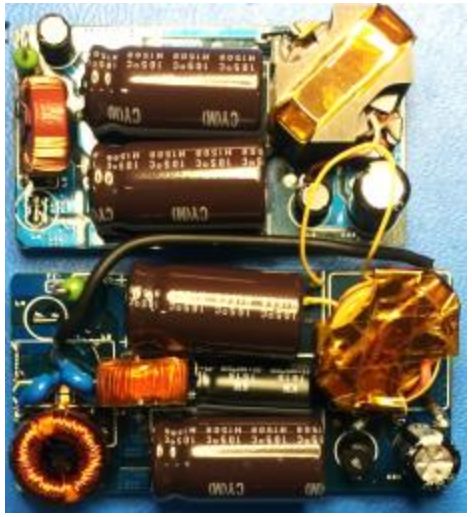
45W→65W ACF
Just 13% longer for 44% more power

45W = 59.1 x 33.5 x 15.7 mm = 24 W/in^3 (uncased)
2x NV6115 (160mΩ)

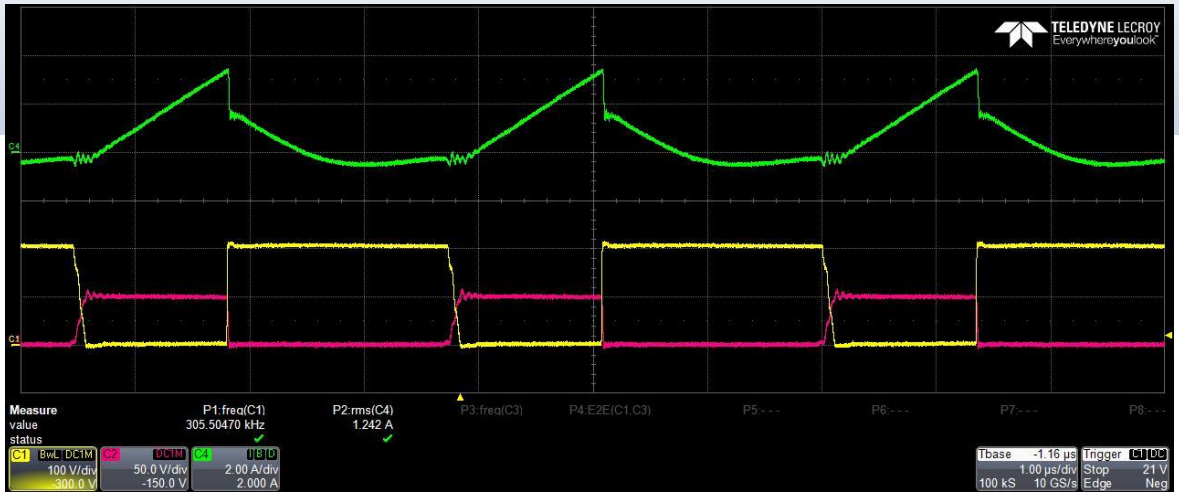
45W

65W

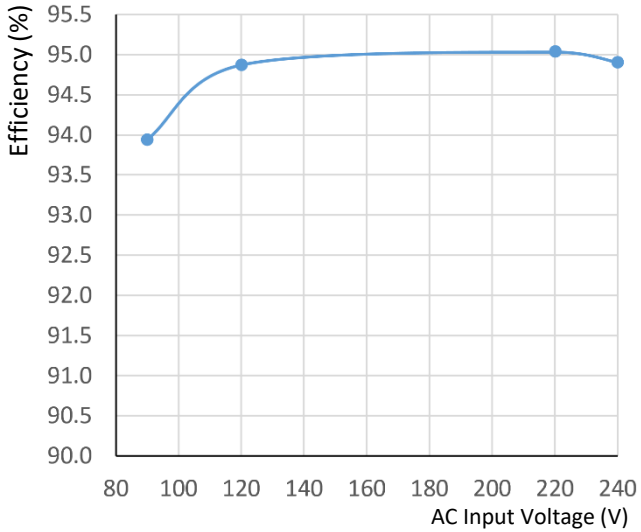




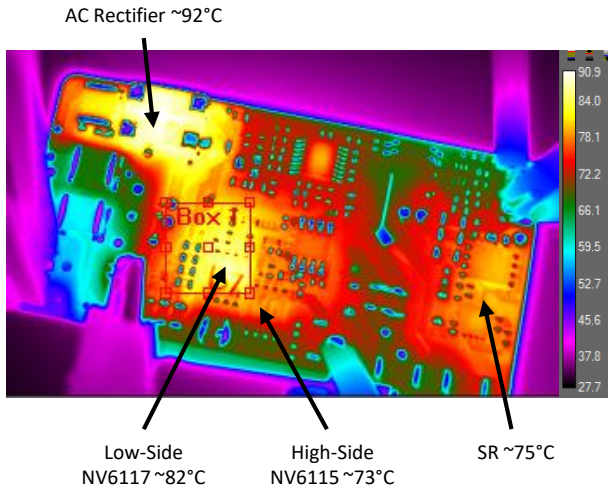
65W = 66.7 x 33.5 x 15.7 mm = 30 W/in^3 (uncased)
1x NV6115 (160mΩ) + 1x NV6117 (110mΩ)



ACF switching waveforms, 300 kHz

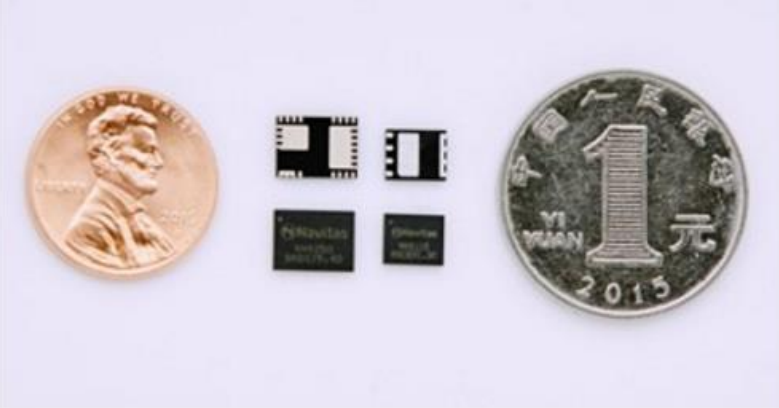


65W Efficiency *(excluding EMI)* vs. AC line
(25°C ambient, no airflow, full load

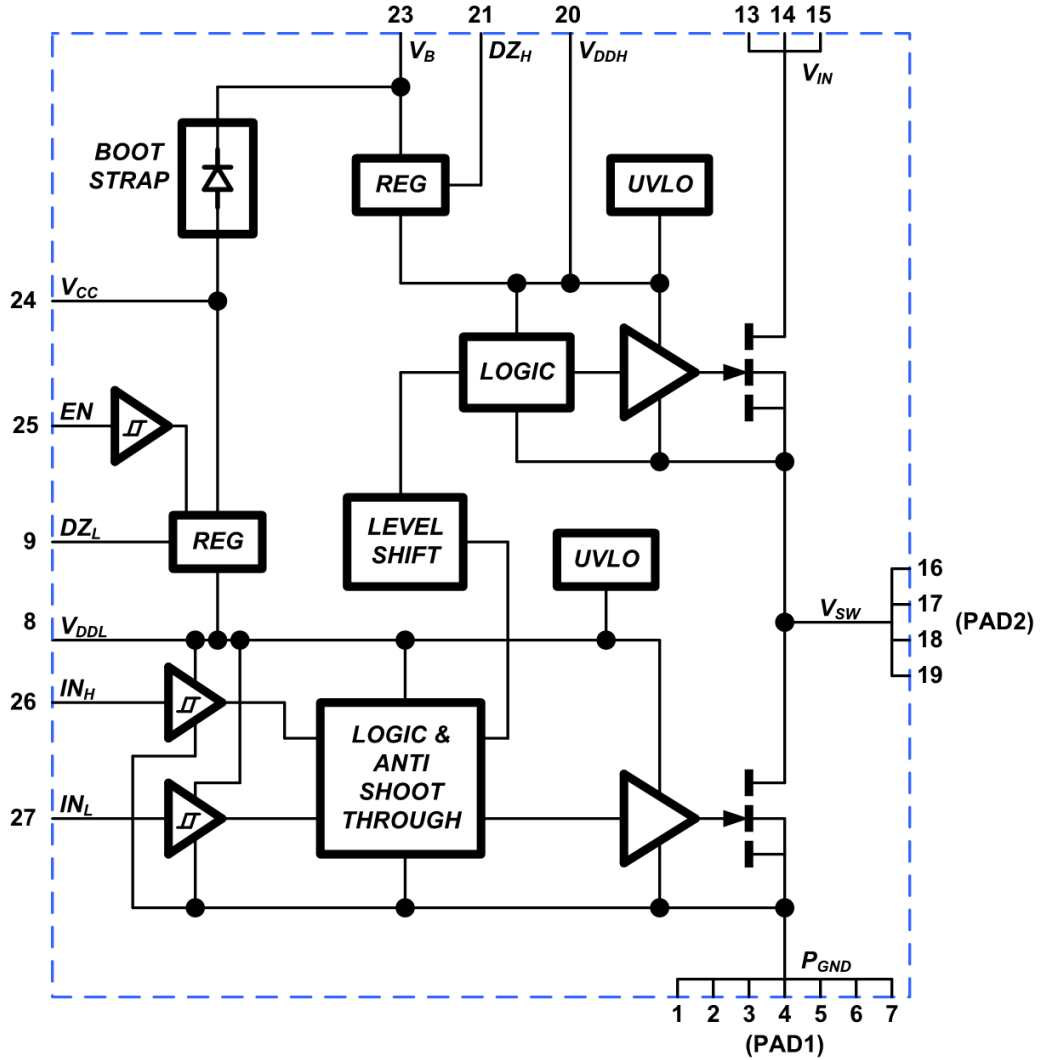


65W Thermal Performance
(90VAC, 25°C ambient, no airflow, full load)

650V Half-Bridge AllGaN™ Power IC

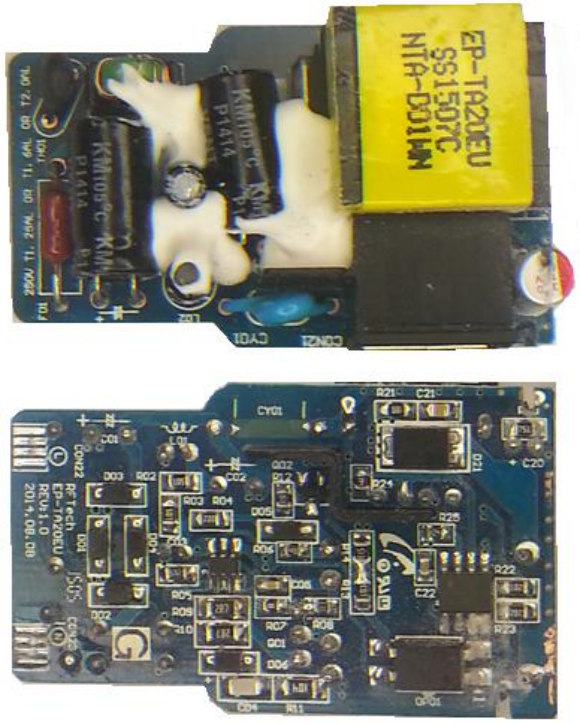


- Proprietary AllGaN™ technology
- Monolithic integration of 650V eMode GaN FET, driver, logic
- Internal level-shift, bootstrap
- Ground-referenced, digital input
- High dV/dt immunity (200 V/ns)
- Zero inductance turn-off loops
- ESD, UVLO, shoot-through protection
- Flexible topologies: Active Clamp Flyback, Half-Bridge, LLC, etc.

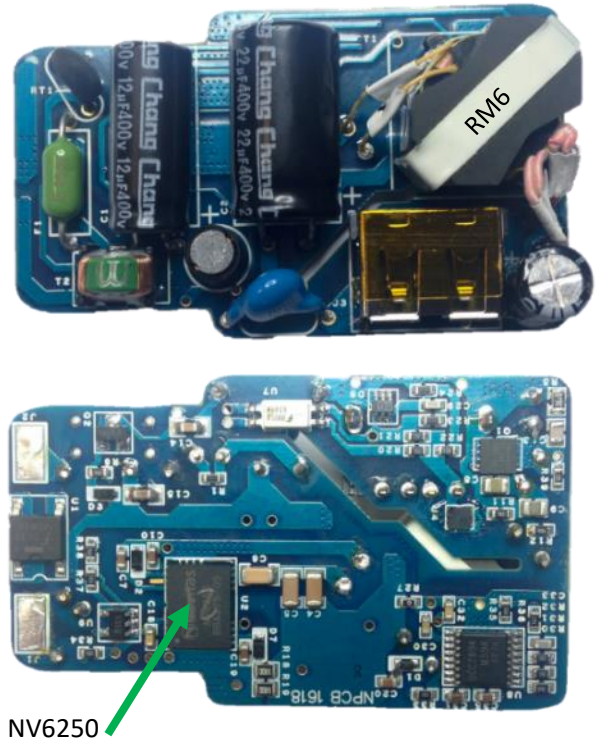


66% Higher Power with Half-Bridge GaN Power IC

a) Original 15 W AC charger case

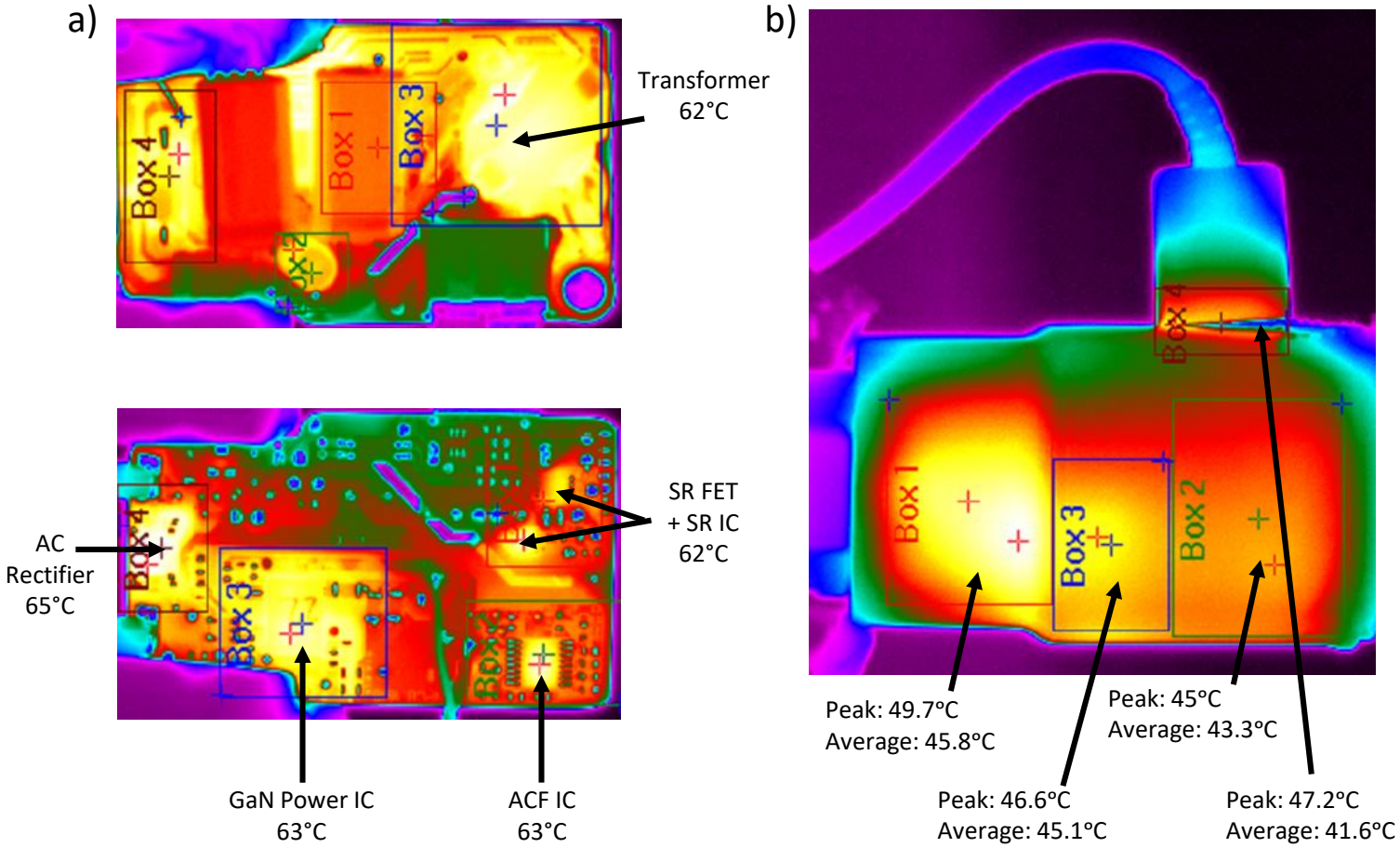


b) Original 15 W, Si-based QR Flyback, ~100 kHz



c) Upgraded 25 W, Half-Bridge GaN Power IC ACF, ~400 kHz

25W Cool Thermals (12.5V, 2A)

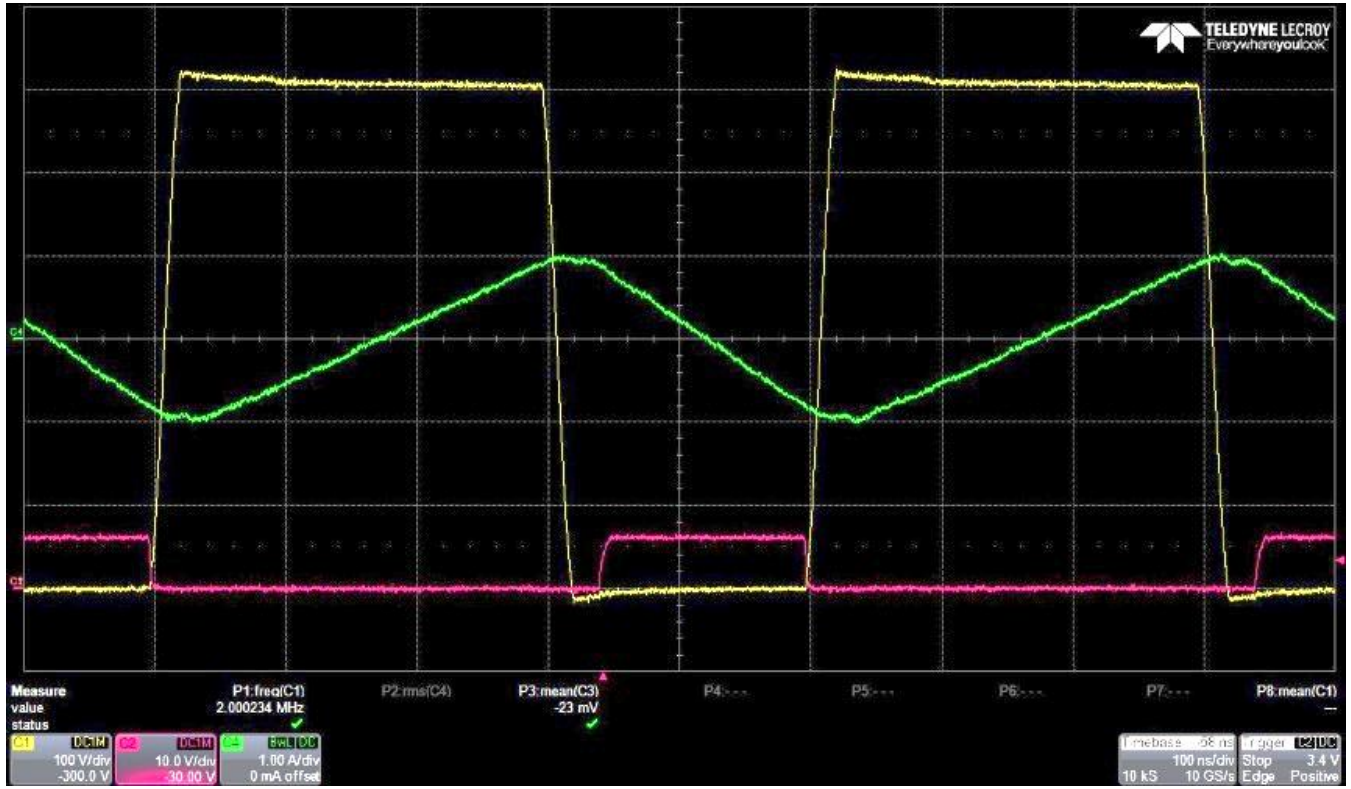


a) No case, 25°C ambient, full load, 90 V_{AC} input, no heatsinking.

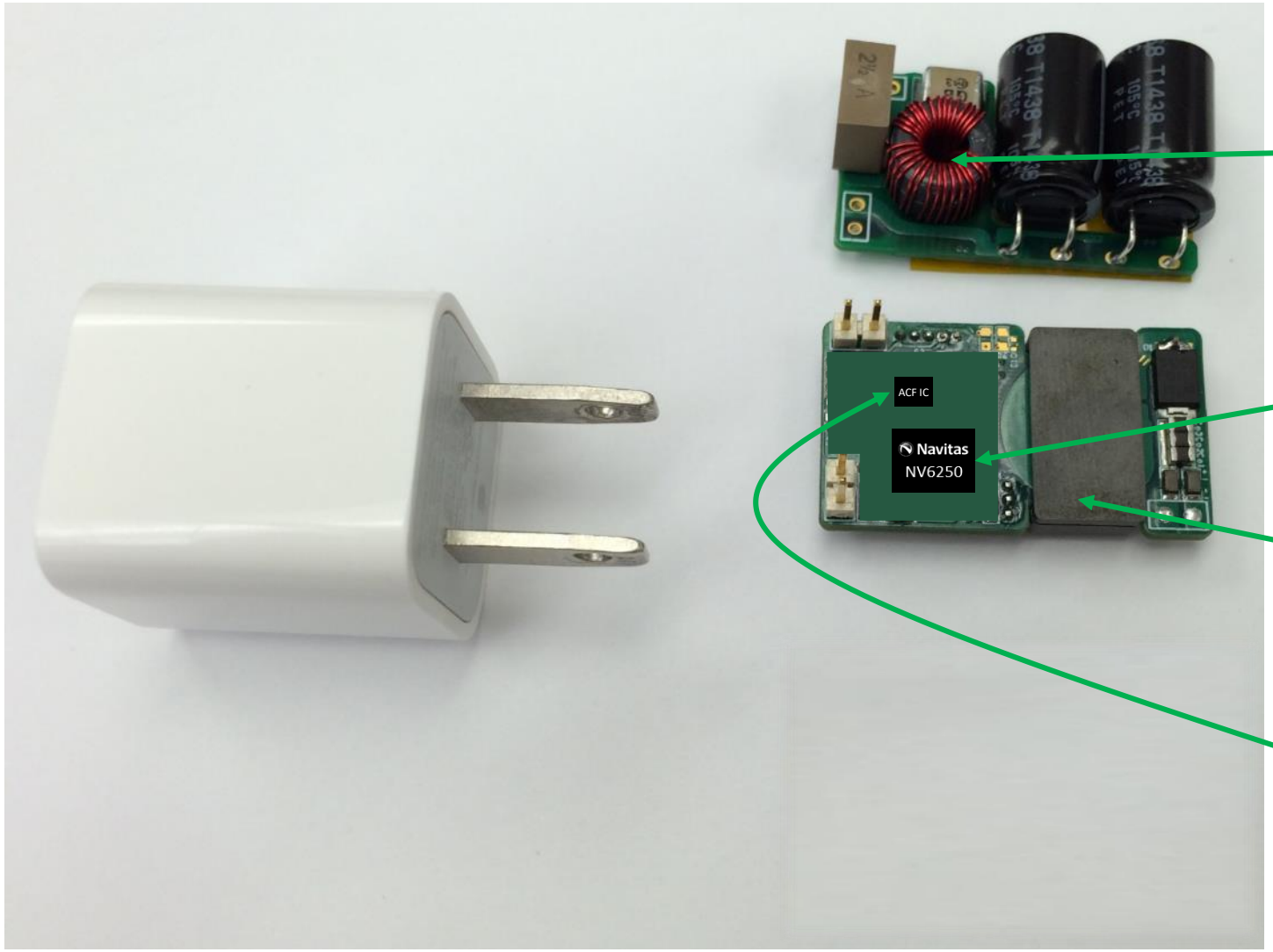
b) Cased, 25°C ambient, full load, 90 V_{AC} input, no heatsinking.

Clean 600V ZVS switching at 2 MHz

- Demonstration board with half bridge AllGaN™ Power IC driving an LC resonant load
- Nearly perfect, loss-free half bridge switching up to 650V with a single part
- Only 5V PWM logic signals are needed
- No diode recovery losses
- No turn-on losses
- Nearly zero turn-off losses



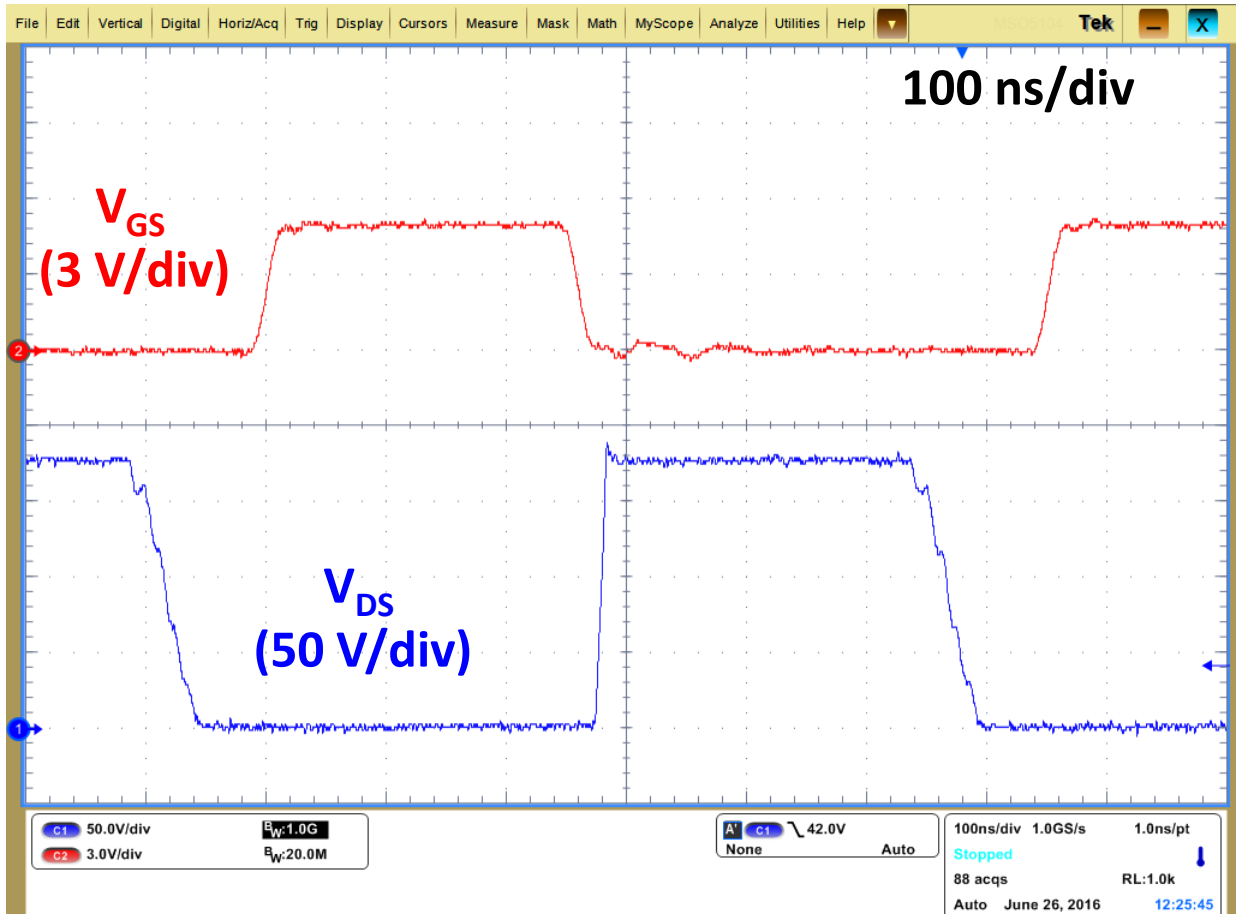
1 MHz, 25 W ACF – Next Step



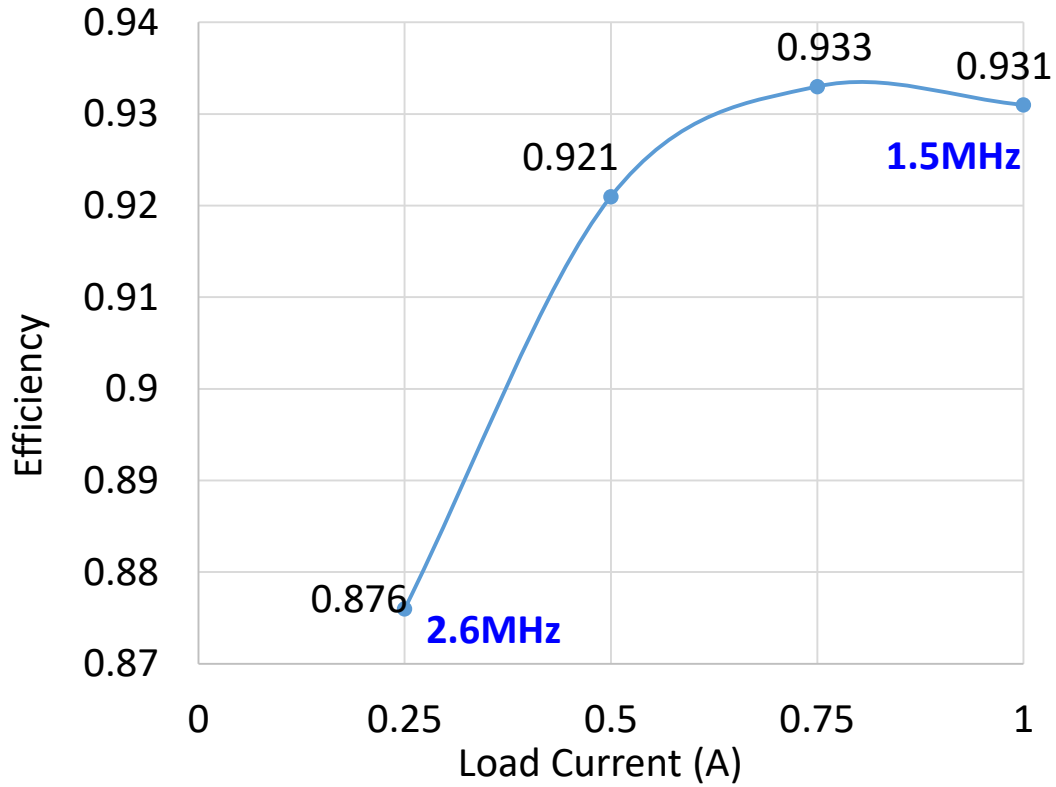
- Single-stage EMI
- 1x Navitas Half-Bridge GaN Power IC
- Planar transformer
- ACF IC

MHz+ 25 W ACF Prototype Performance

F_{SW}=1.5MHz



Efficiency vs. Load

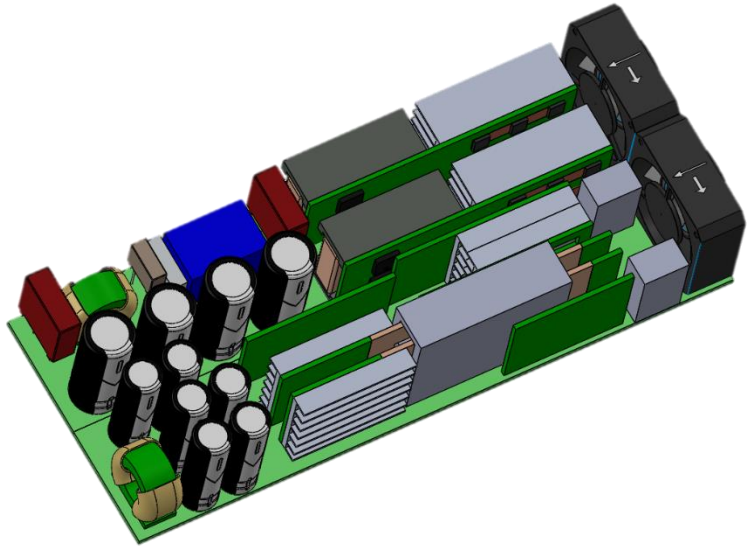


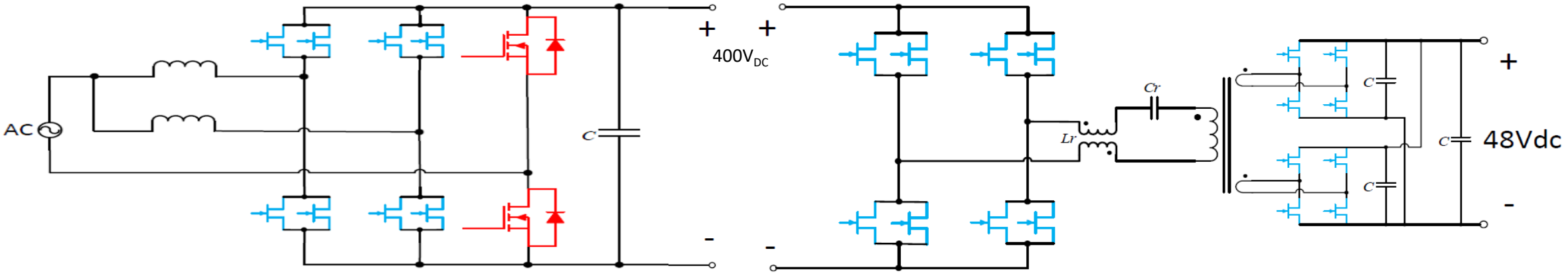
** Exclude bridge and EMI filter loss*

Xiucheng Huang, "High Frequency GaN Characterization and Design Considerations," Ph.D Dissertation, Dept. Electr. Eng., Virginia Tech., Blacksburg, VA, USA, 2016.

1 MHz, 3.2 kW Server Supply – 65 W/in³

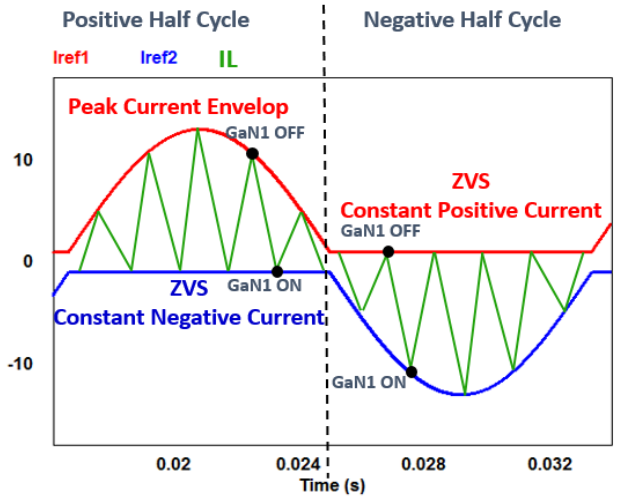
- 220 V_{AC} (47-63 Hz) to 48 V, 3.2 kW
  - Target > 97.5% efficiency (<80W loss)
  - >99% efficiency demonstrated on PFC alpha version
- Multi-phase Totem-Pole CrCM
  - Variable frequency interleaving (500 kHz – 1.5 MHz)
- 2-phase full-bridge LLC with full-bridge SR
  - Fixed-frequency interleaved 1 MHz

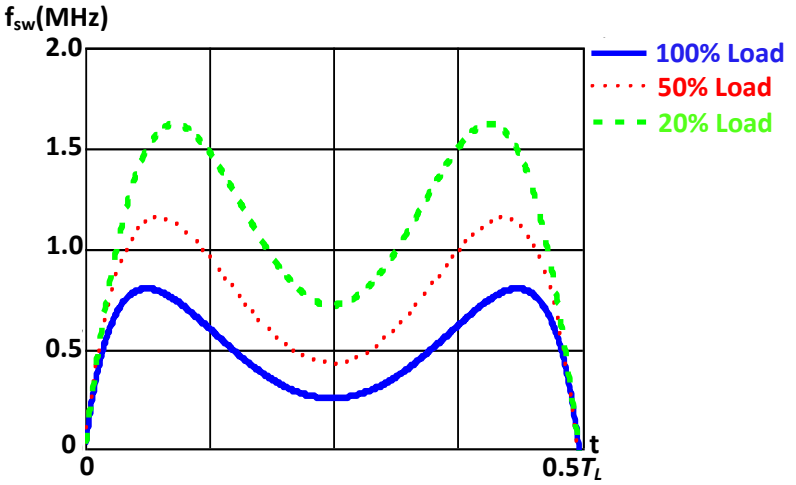




Quasi-Square Wave PFC Full-range ZVS Operation

- Totem Pole Configuration
- Current Mode Control
- Constant ZVS current point
- Alpha version waveforms





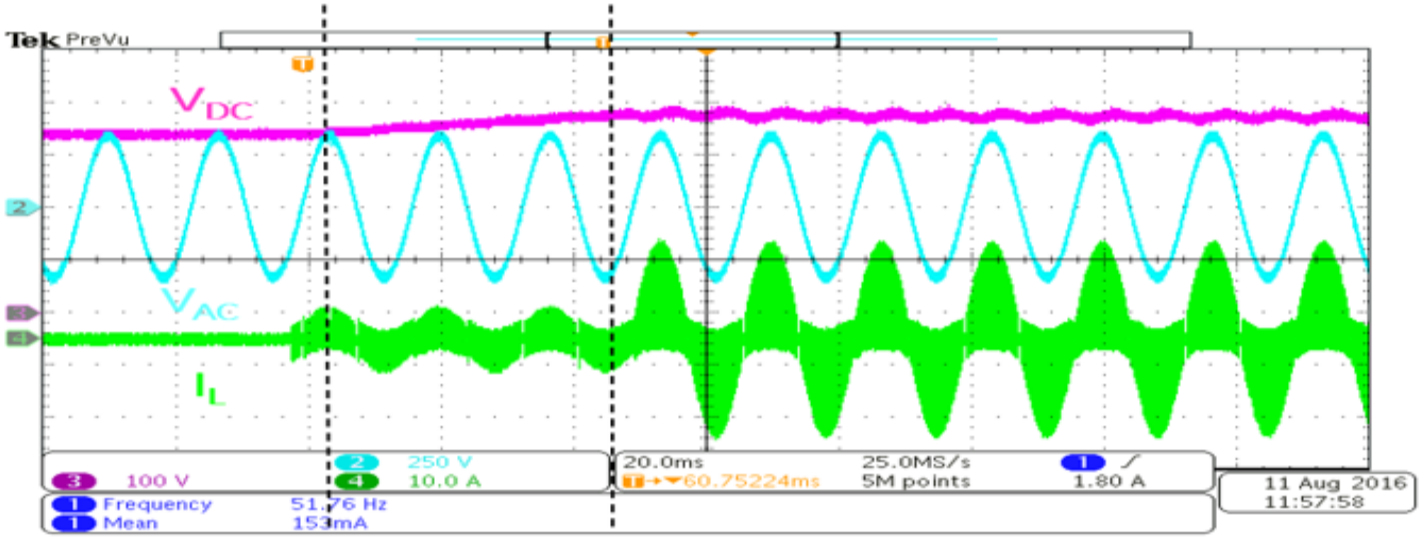
Zero Load Soft Start Full Load 1.45kW

V_{DC}=385V

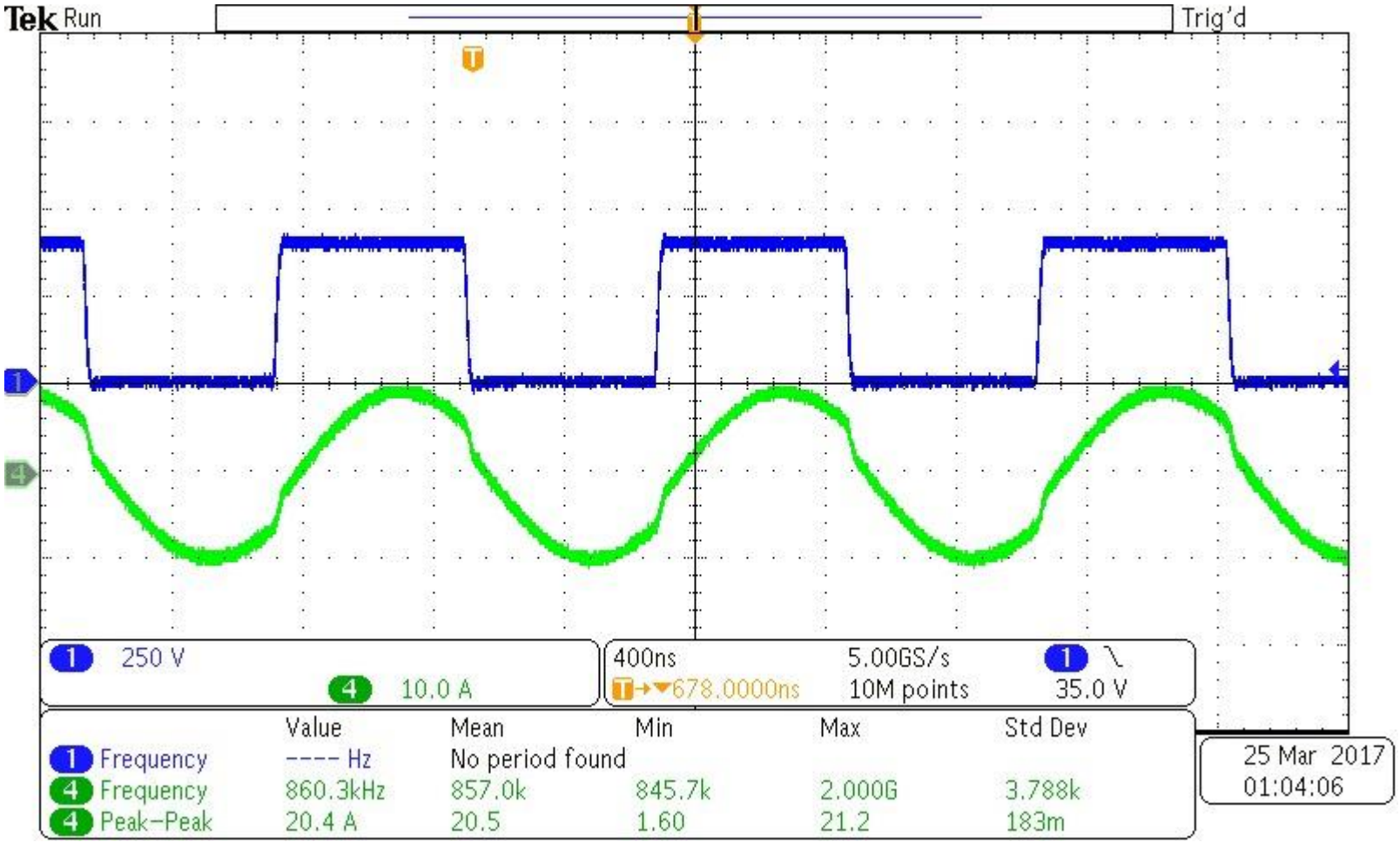
V_{AC}=240V/RMS

R_{load}=102ohm

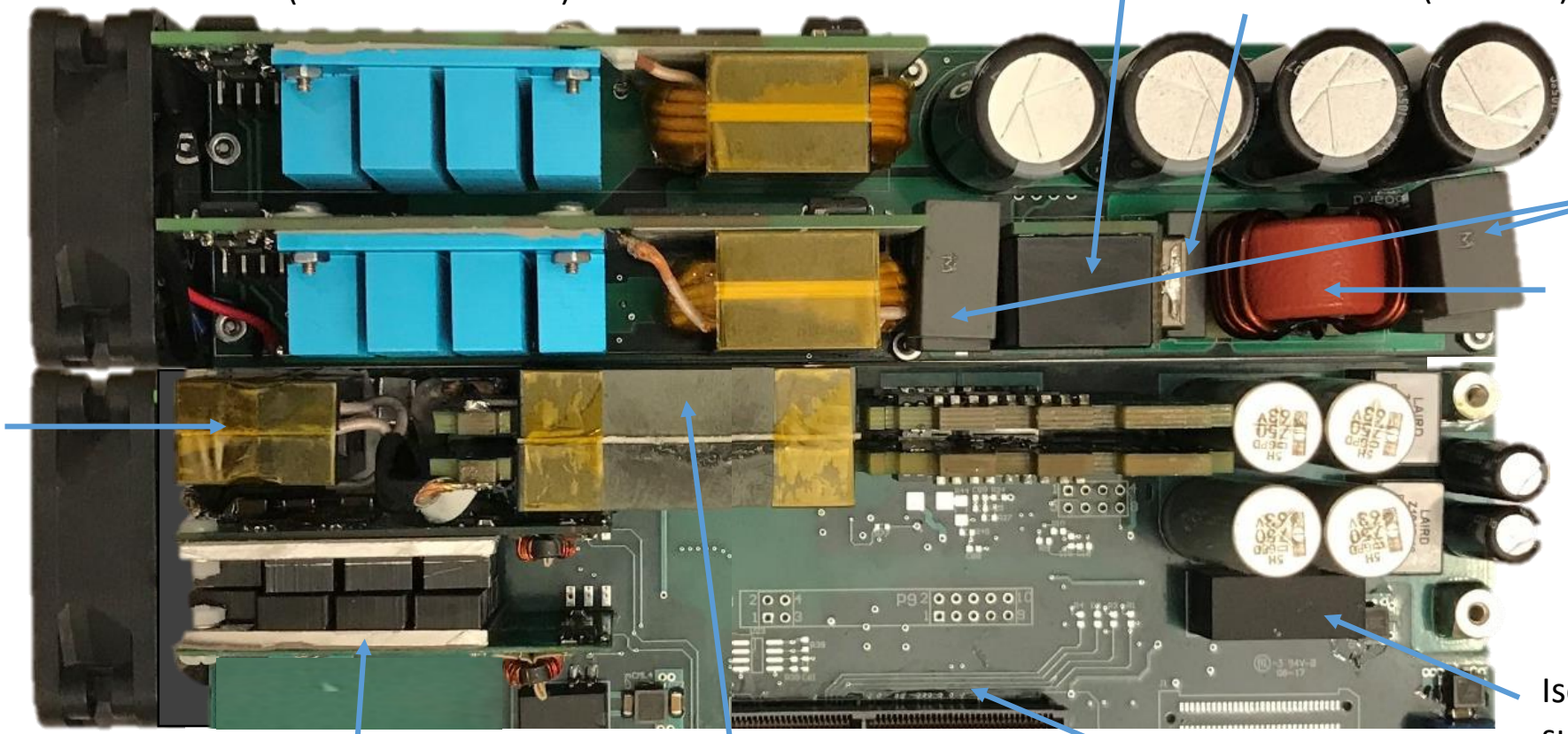
P_{load}=1450W



Preliminary LLC Waveforms at 400V, 2.4kW



1 MHz, 3.2 kW – 100% GaN



Work in progress, rendered image

We Have Arrived!

- GaN Power ICs are now delivering these desired features and more
- System designers are taking a major step forward to deliver more power with less loss in smaller form factors than ever before
- It's time to go "GaN Fast"

GaN Power ICs at 1 MHz+: Topologies, Technologies and Performance

PSMA Industry Session, Semiconductors

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March 2017