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

PSMA Industry Session, Semiconductors

Dan Kinzer, CTO/COO
dan.kinzer@navitassemi.com

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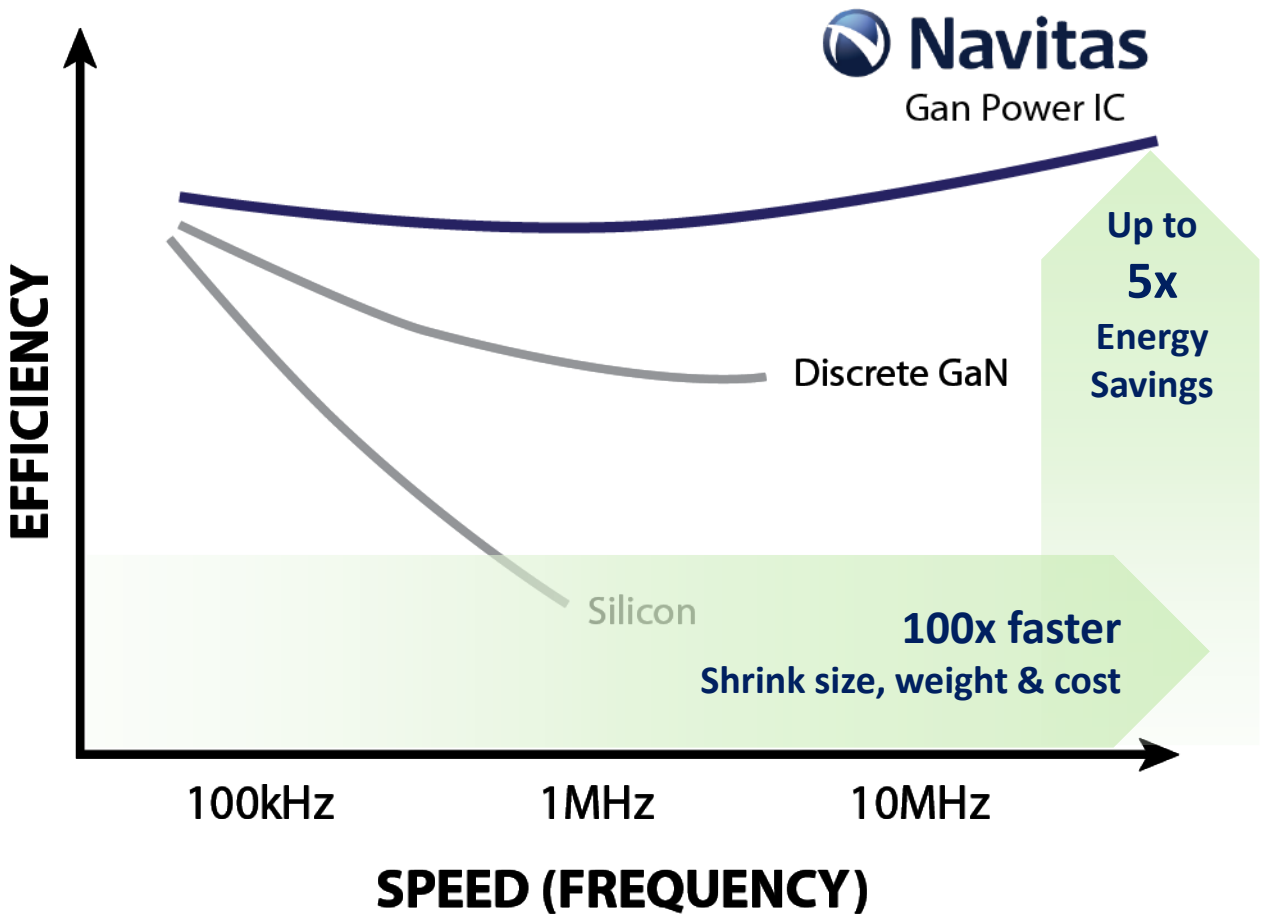
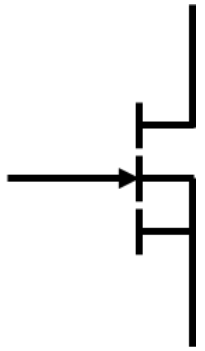
Power Electronics: *Speed & Efficiency are Key*

- **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**



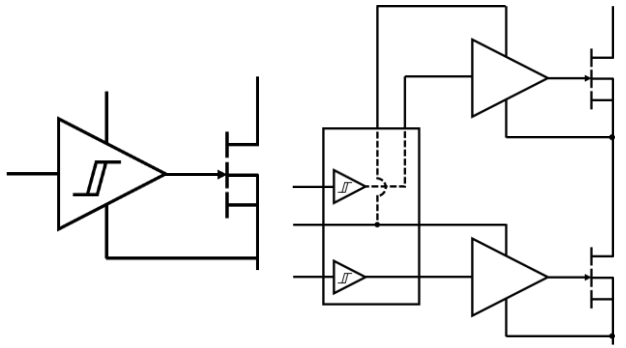
World's First AllGaN™ Power ICs

Fastest, most efficient GaN Power FETs



>20x faster than silicon
>5x faster than cascoded GaN
Proprietary design
15+ pending or issued patents

iDrive First & Fastest Integrated GaN Gate Drivers



>3x faster than any other gate driver
Proprietary design
8+ pending patents

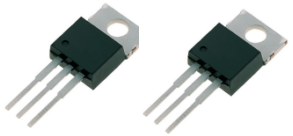
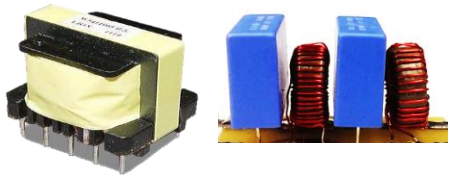
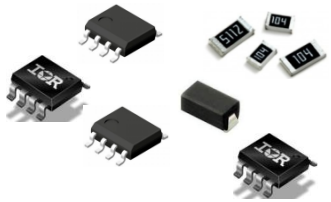
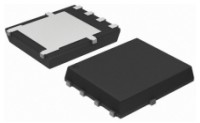
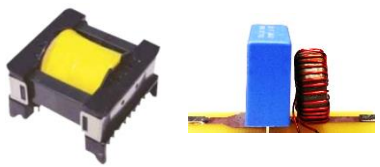
World's First AllGaN™ Power IC

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

The Power of GaN Power ICs

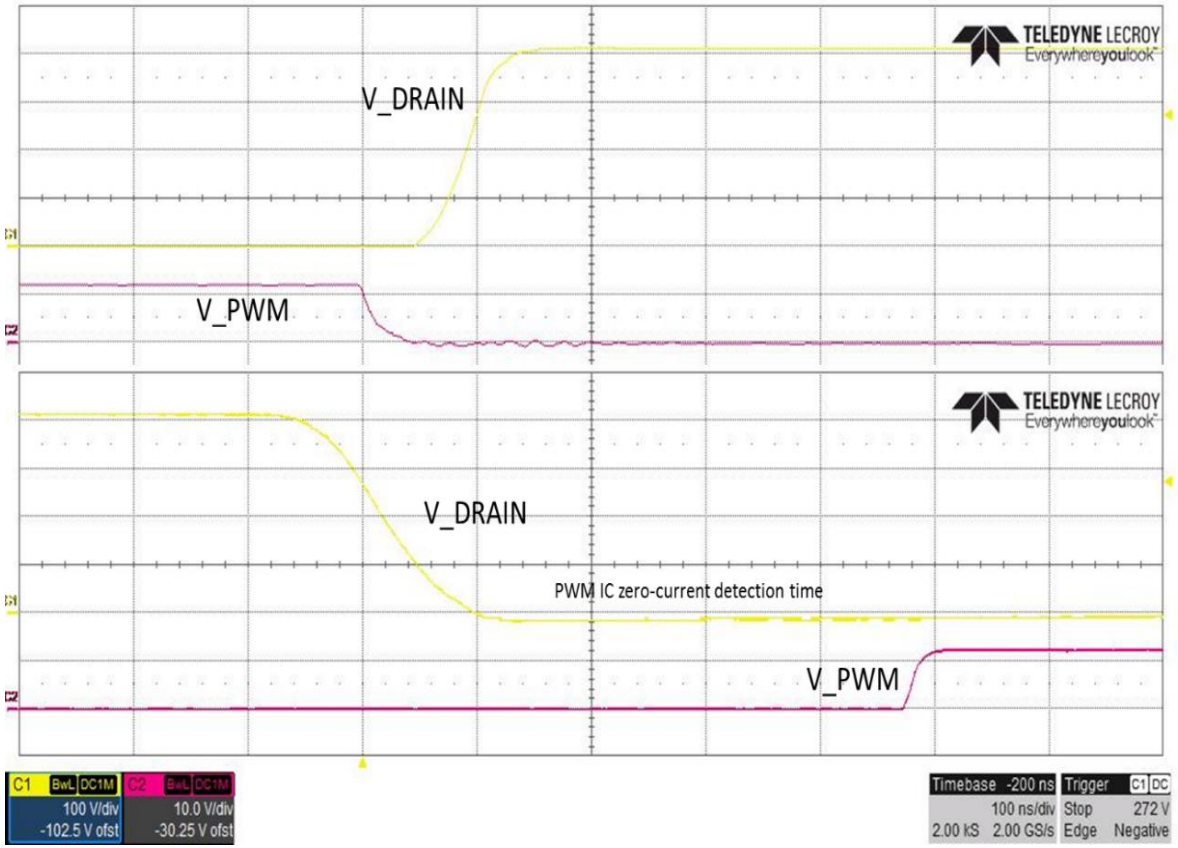
... Unequaled Speed & Efficiency

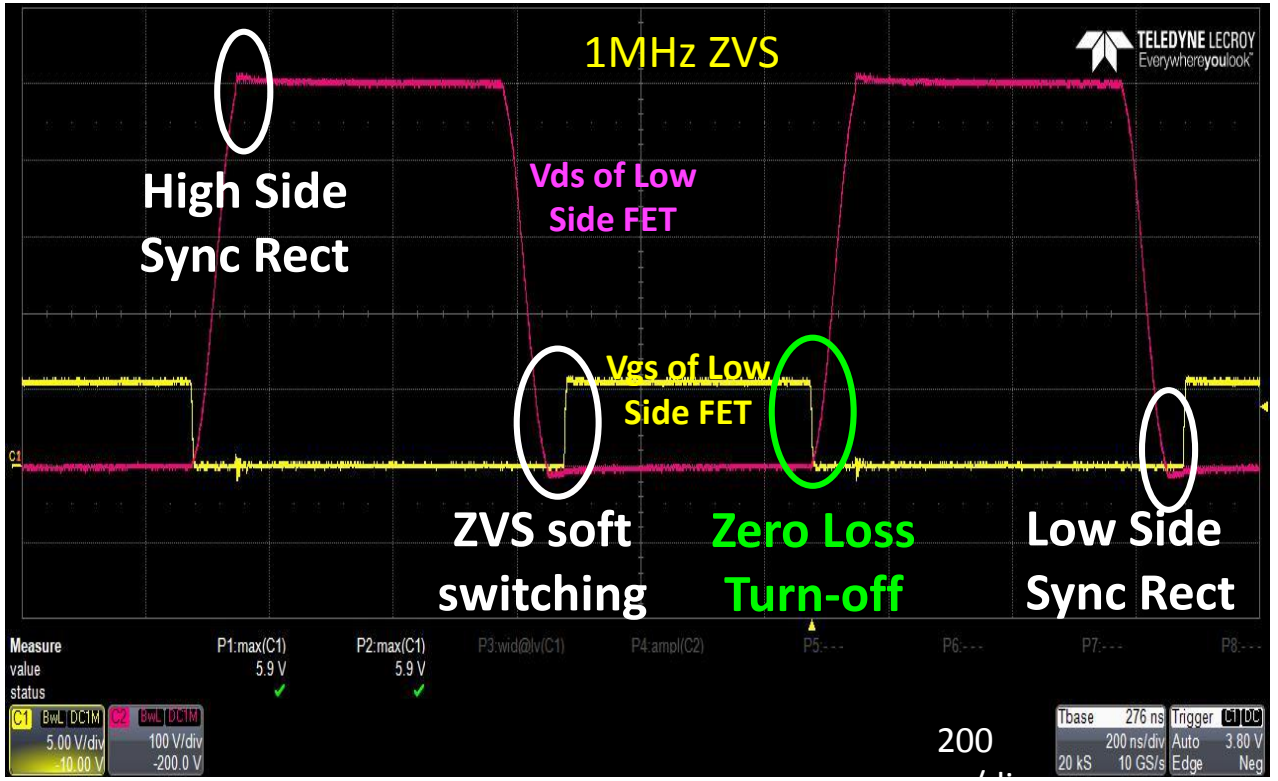
Navitas

	Driver Circuits	Power Devices	Passive Components	Switching Frequency	Energy Efficiency
Silicon				 *100kHz*	*85-90%*
Discrete GaN				 *500kHz*	*88-92%*
GaN Power ICs				 *1-10MHz*	*90-95%*

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)





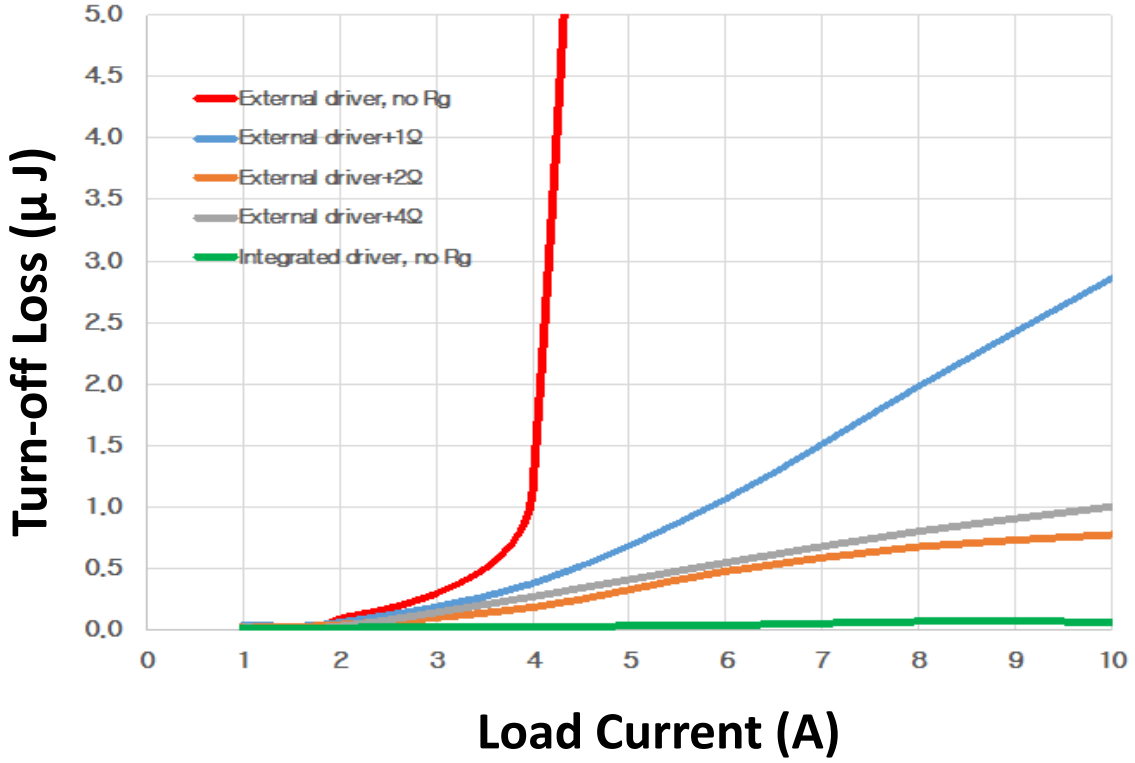
Speed & Integration → Eliminate Turn-off Losses

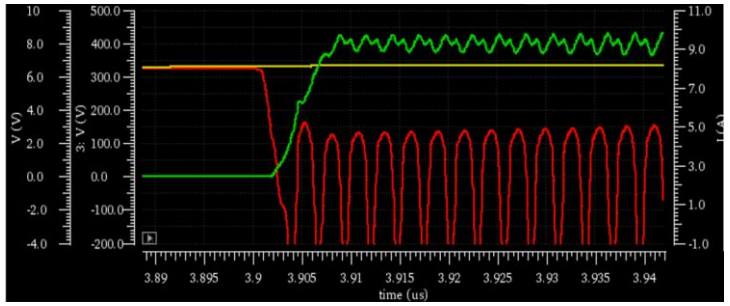
External drivers

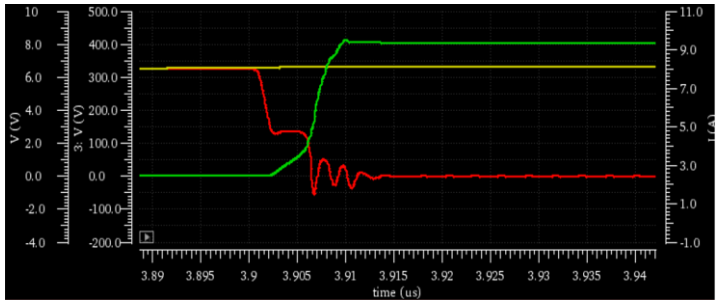
- Just 1-2 nH of gate loop inductance can cause unintended turn-on
- Gate resistors reduce spikes but create additional losses

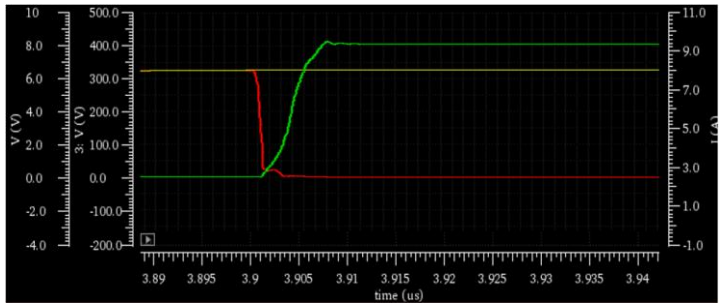
Integrated GaN drivers (iDrive™)

- Eliminate the problem
- Negligible turn-off losses



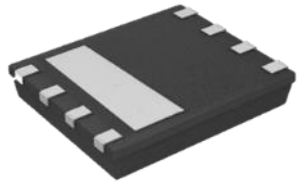




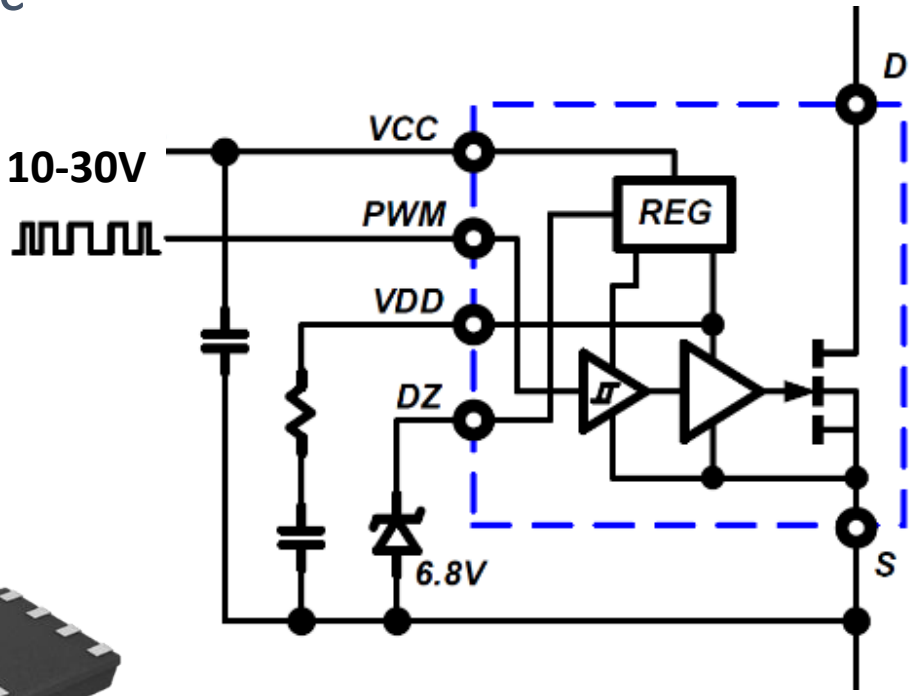


GaN Power IC: Hi-Speed FET, Drivers & More

- 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

Fast Chargers … *going "GaN Fast"*

3x Fast Charging with 50% Energy Savings

Navitas

Existing Si-based 15W	AllGaN™ 2016 25W	AllGaN™ 2017 25W
	2x Faster Charging	*3x Faster Charging*
		 25W 5W
100 kHz Up to 6.5 W/in³ 88%	300-500 kHz 11 W/in³ >92%	>1 MHz 17.5 W/in³ >95%

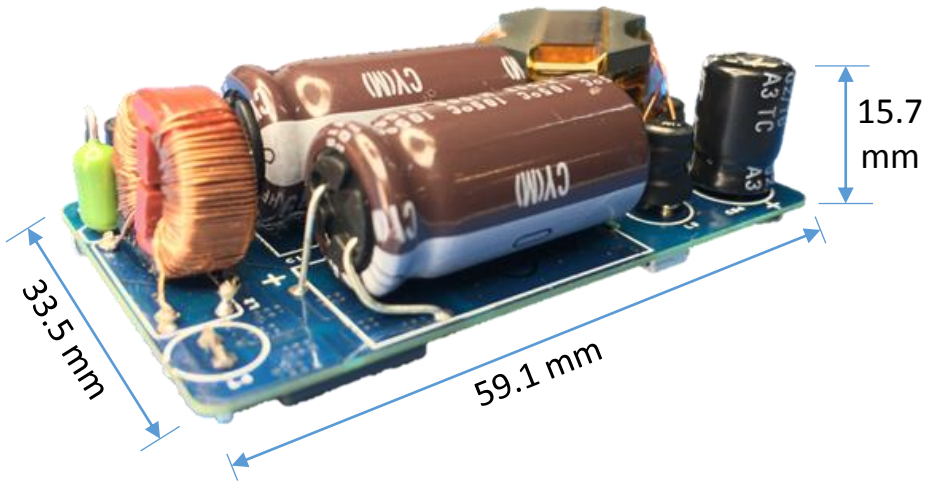
Smartphones & Tablets

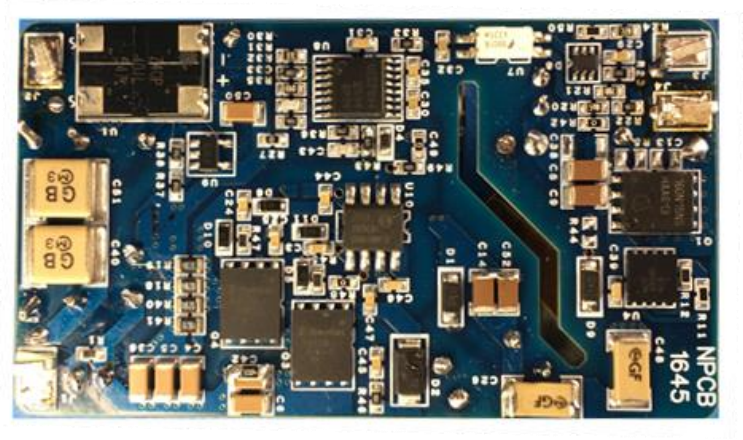
Fast-charging Drones

AR / VR & Wearables

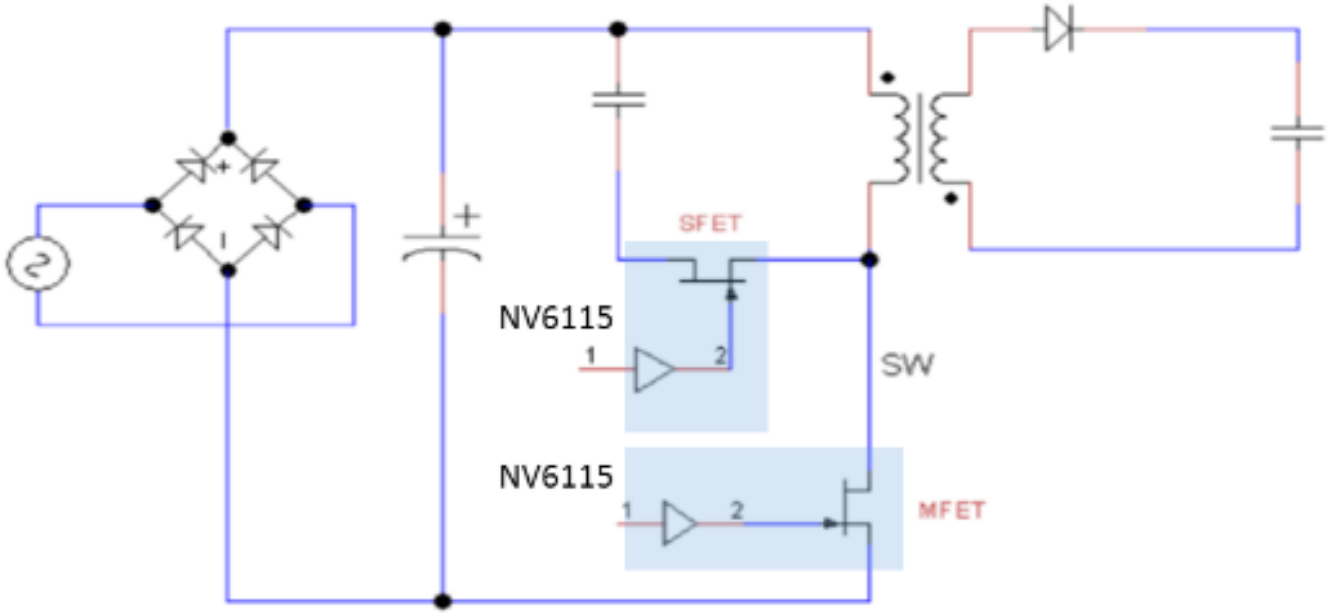
2016: Navitas; **2017**: Xiucheng Huang, "High Frequency GaN Characterization and Design Considerations," Ph.D Dissertation, Dept. Electr. Eng., Virginia Tech., Blacksburg, VA, USA, 2016.

45W Active Clamp Flyback & AllGaN Power ICs



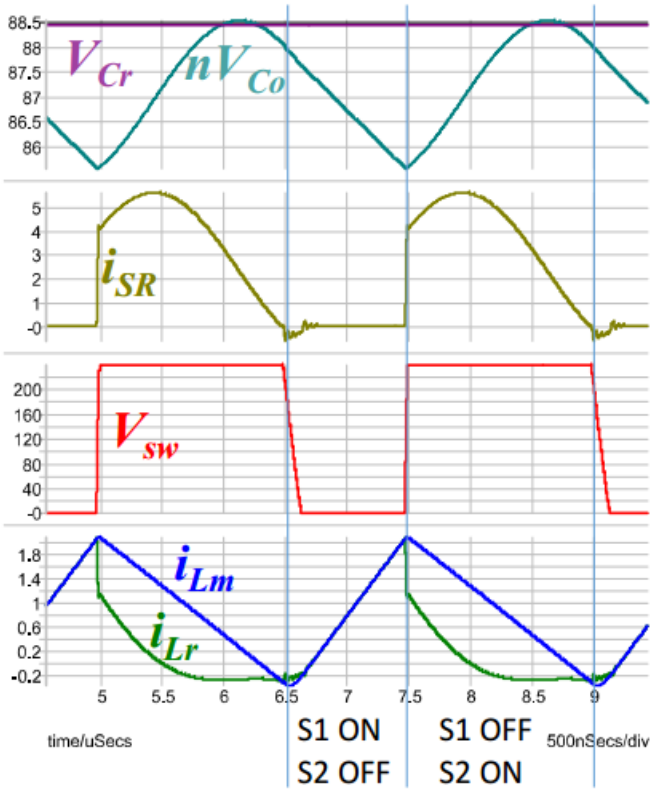


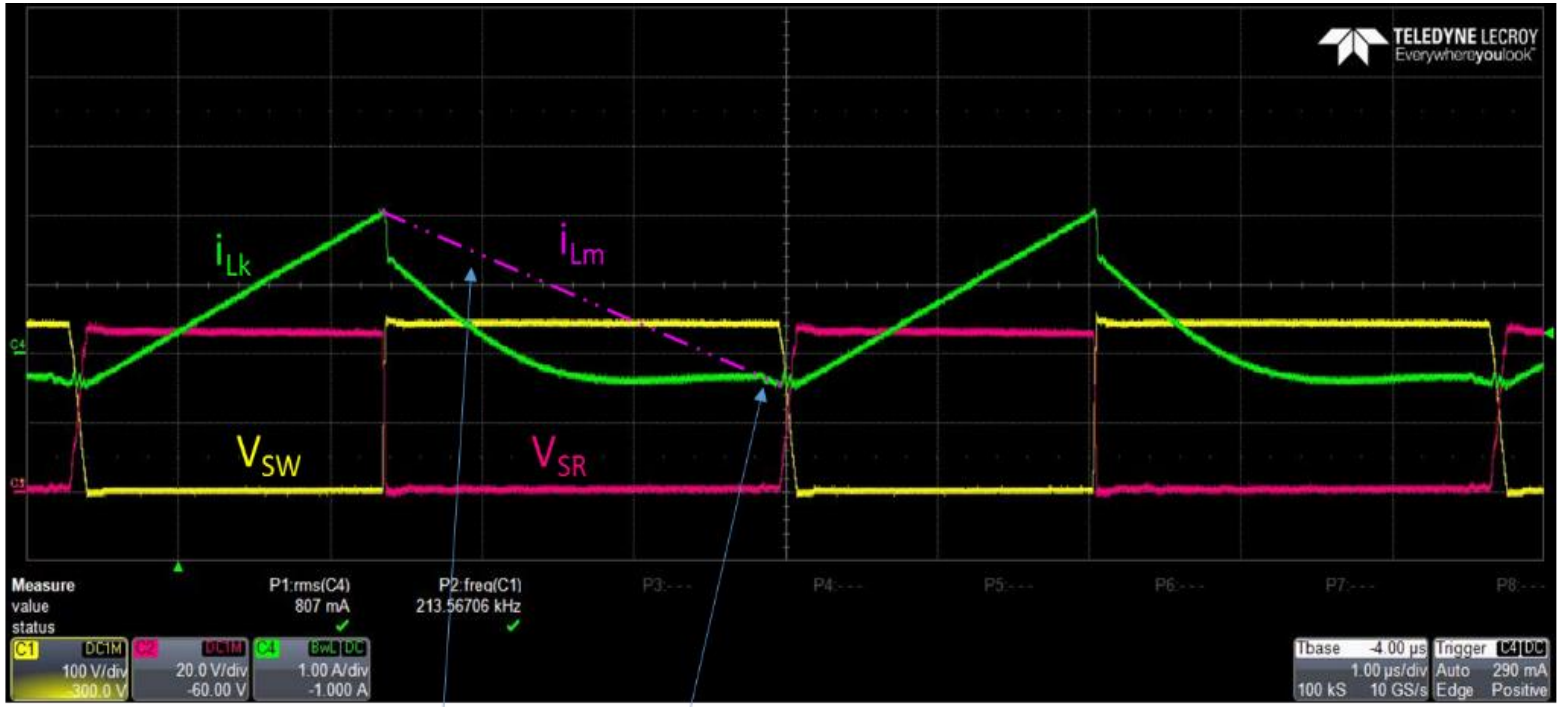
- 94.5% efficient at 220 V (94.2% at 120 V_{AC}, 93.1% at 90 V_{AC})
- 23.7 W/in^3 density (uncased)
- 15.7 mm profile



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





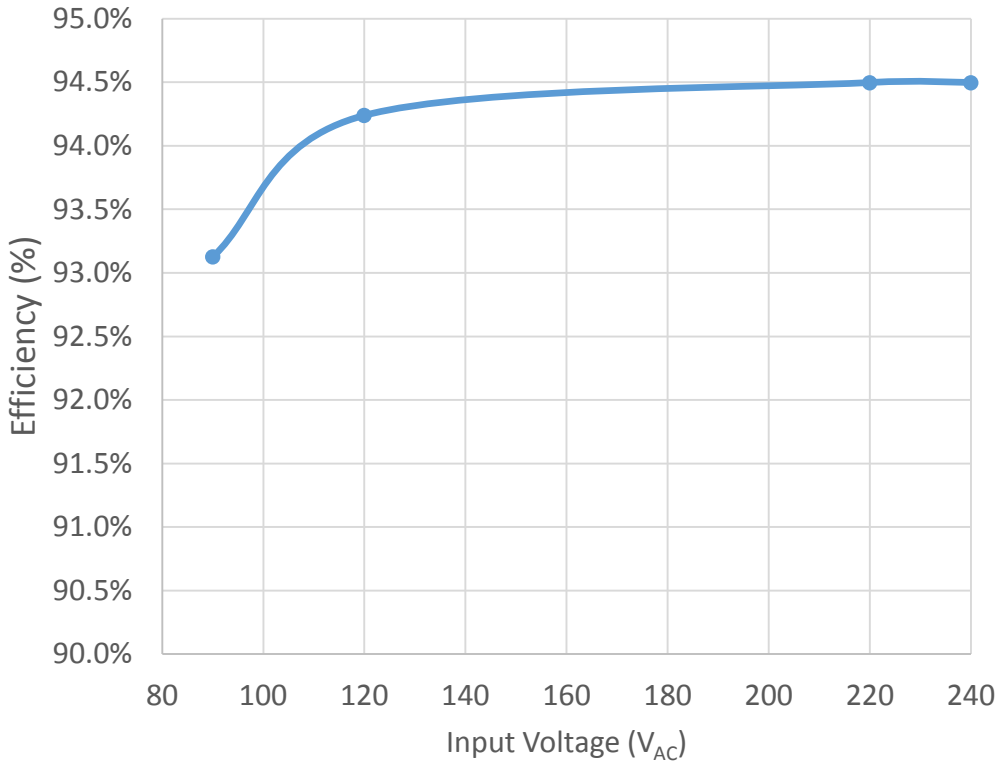
Magnetizing current (drawing)

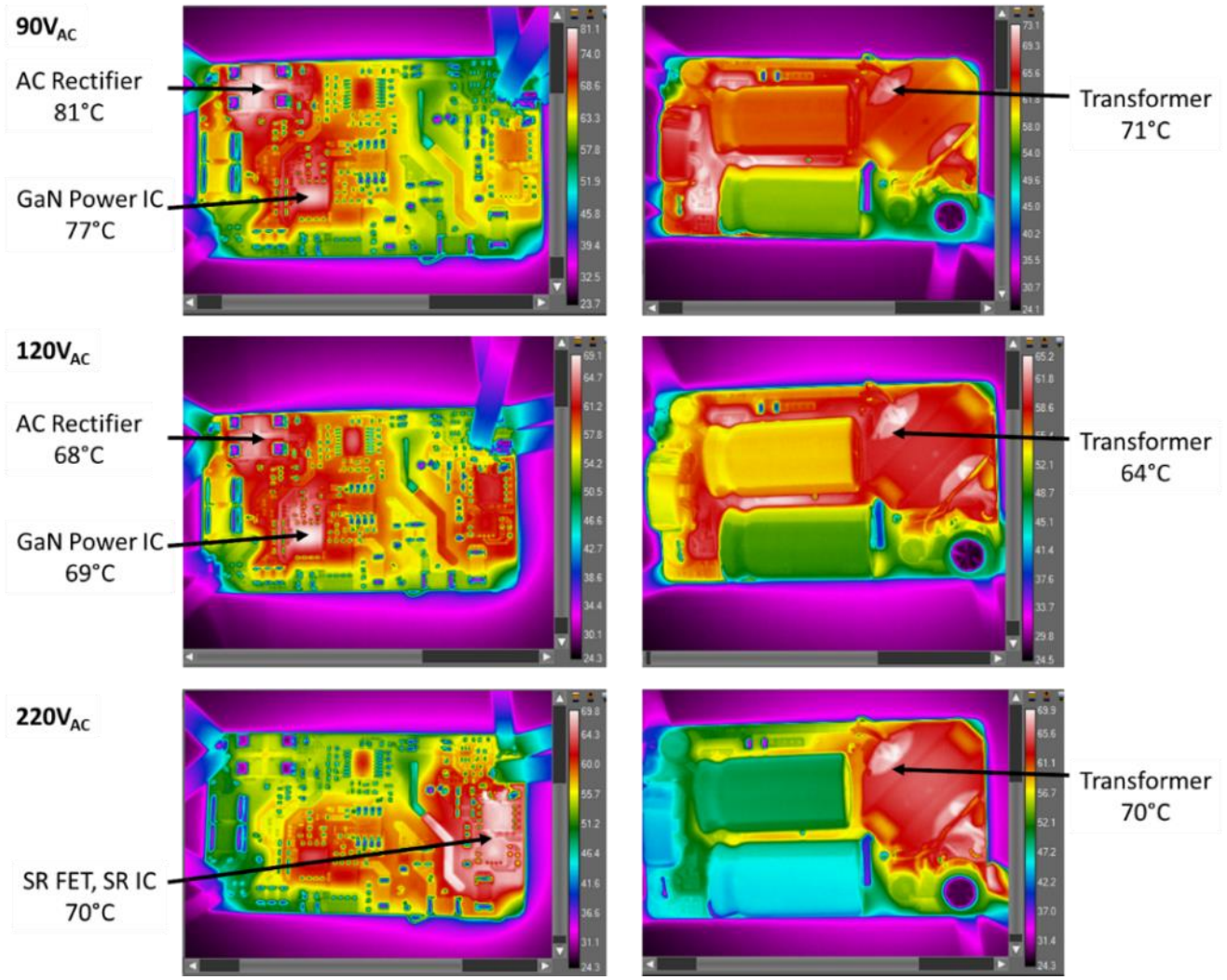
Inductor current merges with magnetizing current, achieves SR ZCS turn-off

- 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

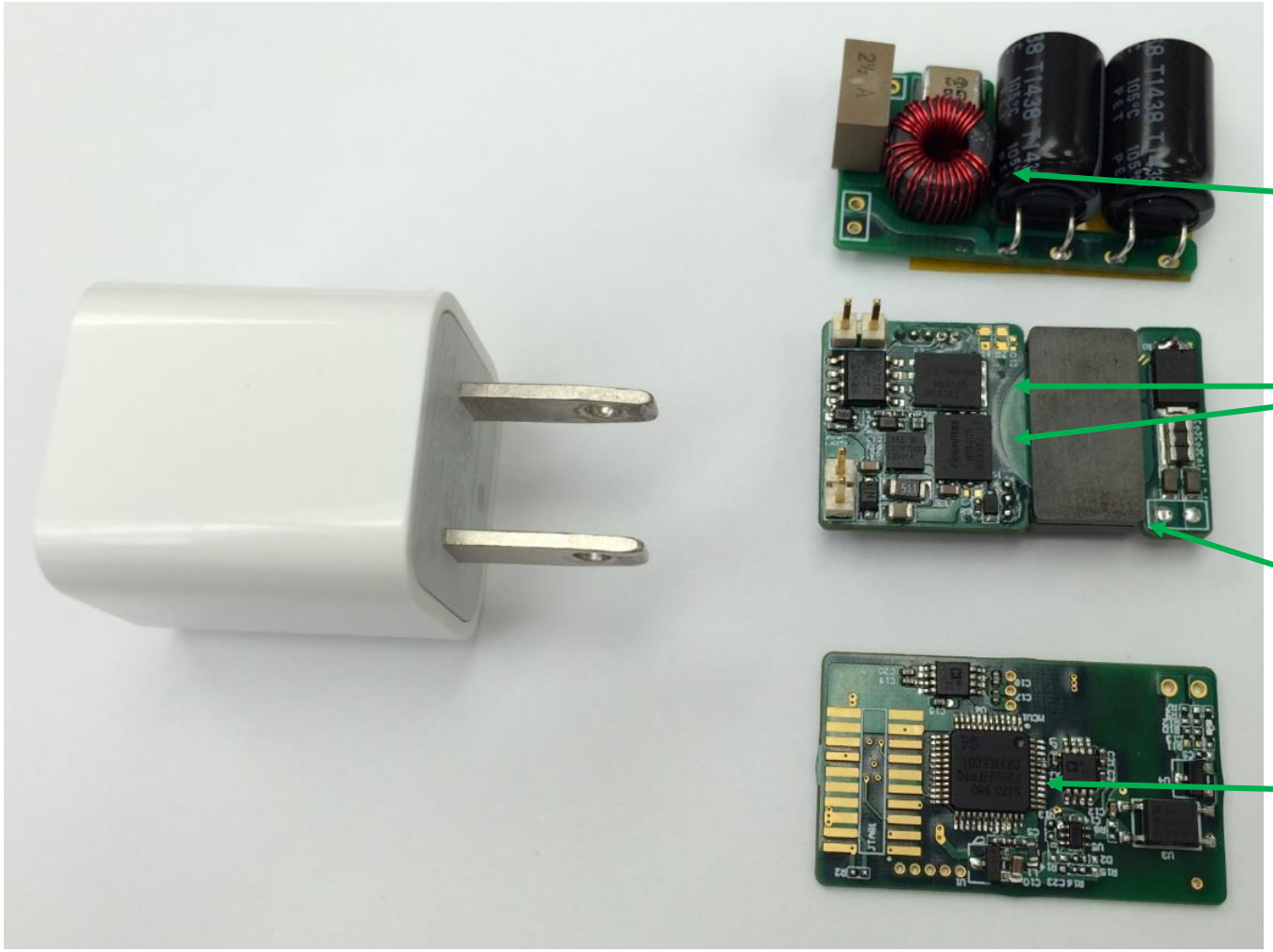
45 W ACF: High Efficiency, Cool Temperatures





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

AllGaN 2017: 1 MHz, 25 W ACF in 5W Size

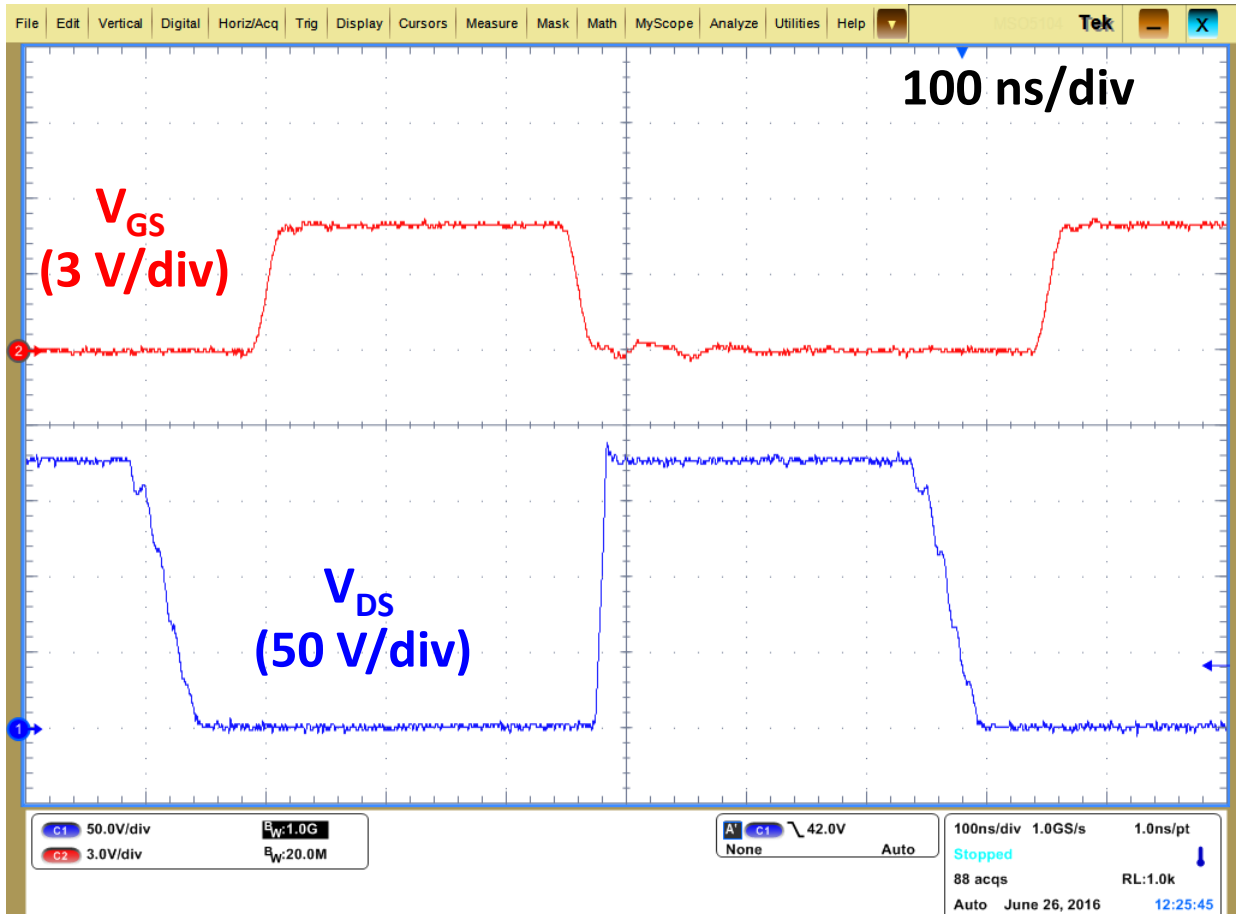


- Single-stage EMI
- Navitas GaN Power ICs
- Planar transformer
- DSP (for prototype)

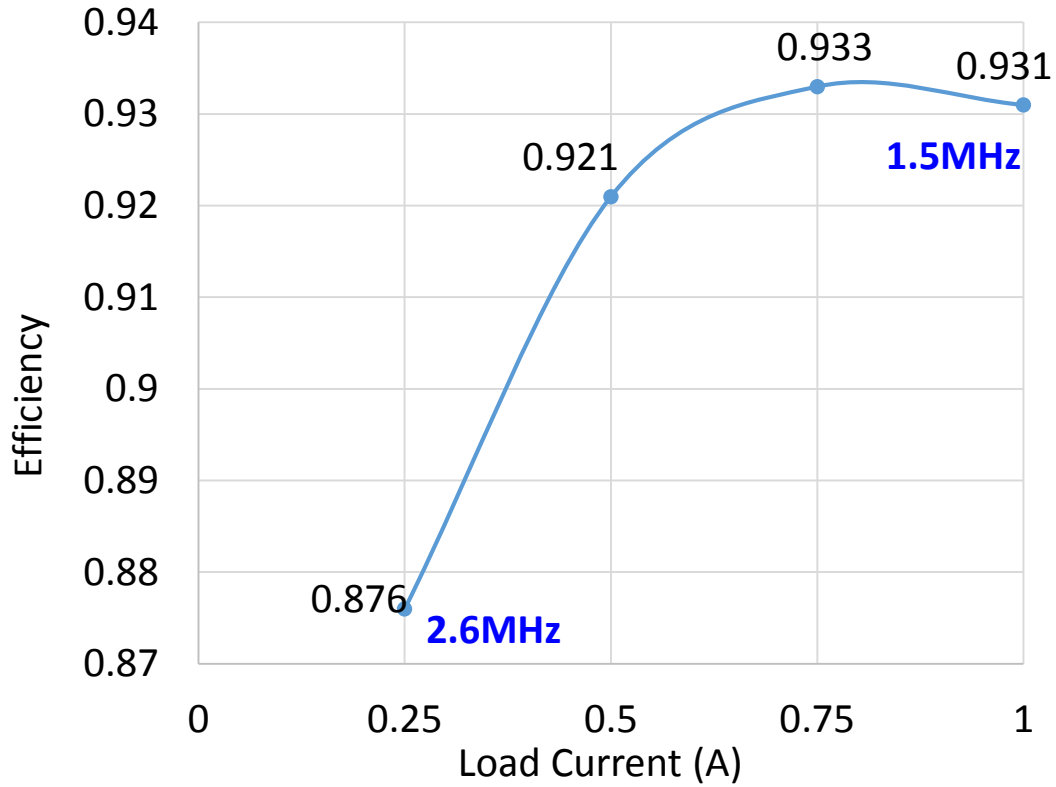
Xiucheng Huang, "High Frequency GaN Characterization and Design Considerations," Ph.D Dissertation, Dept. Electr. Eng., Virginia Tech., Blacksburg, VA, USA, 2016.

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.

GaN Power ICs enable Hi-Density Adapters

3x Higher Density with 50% Energy Savings

Navitas

Existing Si-based 150W	AllGaN™ 2016 150W	AllGaN™ 2017 150W
	*2x Higher Density* 	*3x Higher Density* 
100 kHz 5-10 W/in^3 88%	300-500 kHz 17 W/in^3 >93%	>1 MHz 26.5 W/in^3 >95%

Ultra-thin LED TV

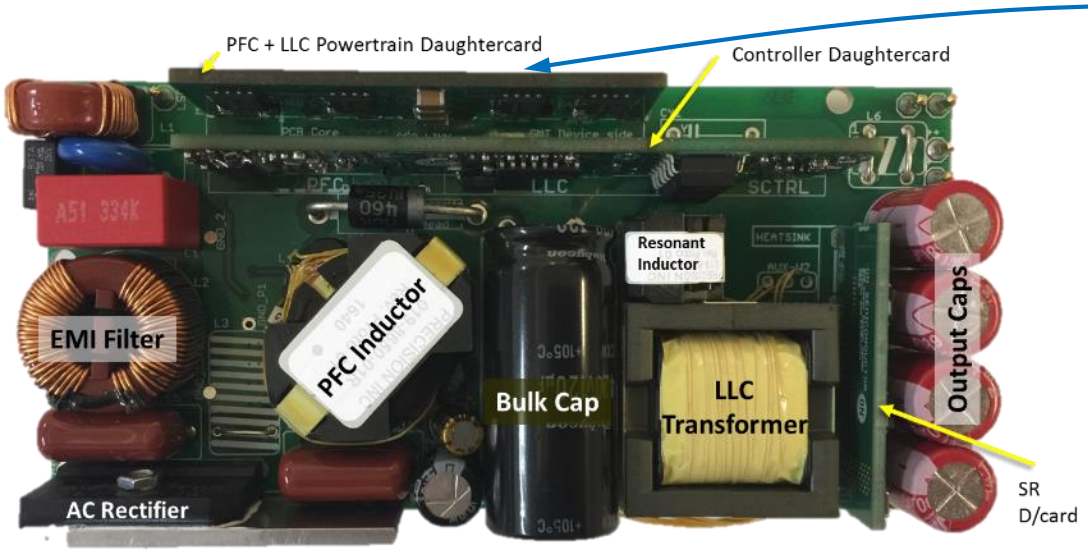
All-in-One PCs

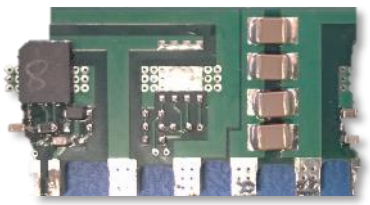
Next-Gen Gaming Consoles

2016: Navitas + On Semiconductor; **2017**: Xiucheng Huang, "High Frequency GaN Characterization and Design Considerations," Ph.D Dissertation, Dept. Electr. Eng., Virginia Tech., Blacksburg, VA, USA, 2016.

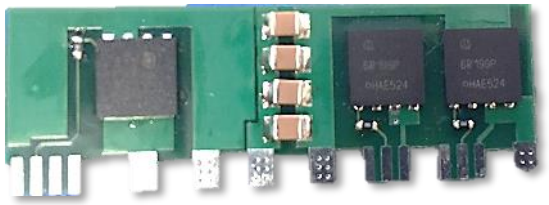
150 W, 19 V: GaN Power IC vs. Si

Part#	Technology	V	Pack	$R_{DS(ON)}$ (typ. mΩ)	Q_G (typ. nC)	C_{OSS}(er) (typ. pF)	R x Q_G (mΩ.nC)	R x C_{OSS}(er) (mΩ.pF)
STL34N65M5	Si FET	650	8x8	99	62.5	63	6,187	6,237
IPL60R199CP	Si FET	600	8x8	180	32	69	5,760	12,420
IPL60R299CP	Si FET	600	8x8	270	22	46	5,940	12,420
NV6115	GaN Power IC	650	5x6	160	2.5	30	400	4,800
NV6117	GaN Power IC	650	5x6	110	4	45	440	4,950
GaN Benefit							***14x***	***1.5-2.5x***





Navitas GaN Power ICs (5x6mm QFN)
PFC = 1x NV6117, LLC = 2x NV6115

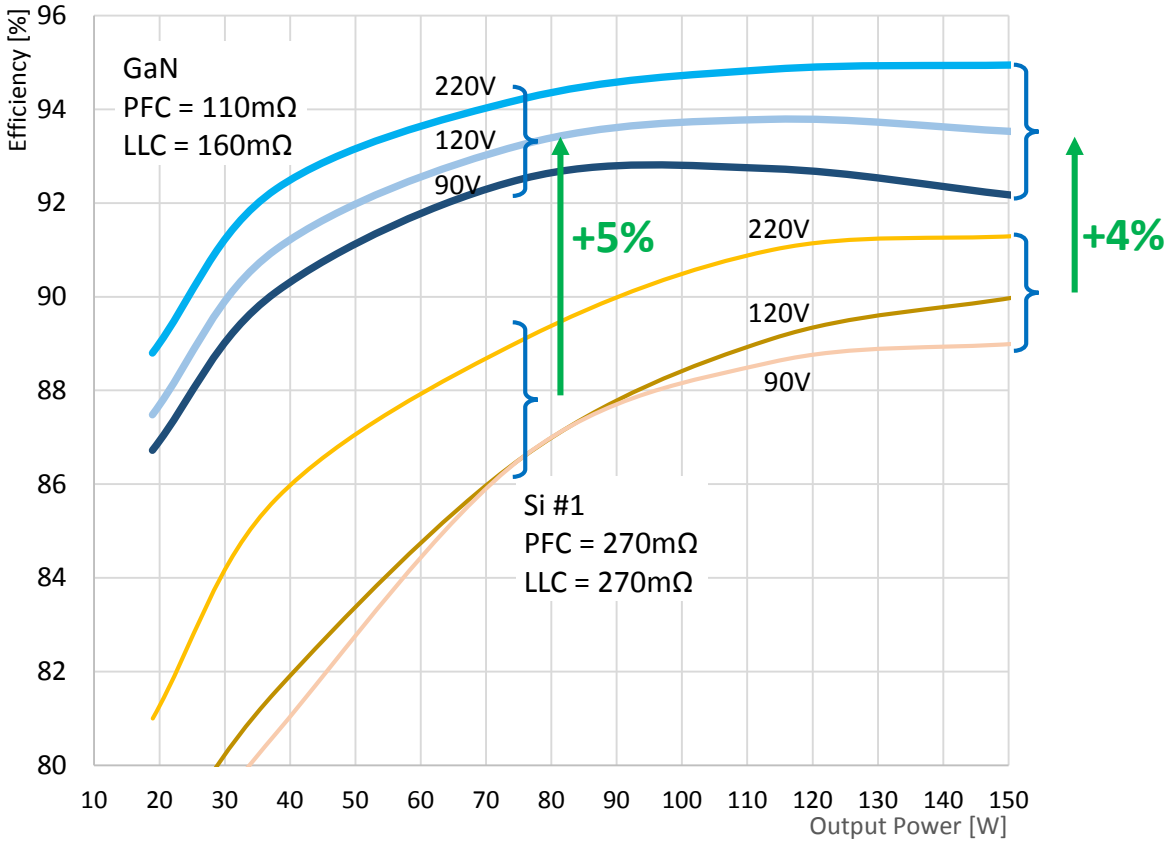


Si FETs (8x8mm QFN)
a) PFC = 1x IPL60R299CP, LLC = 2x IPL60R299CP
b) PFC = 1x IPL60R199CP, LLC = 2x IPL60R299CP

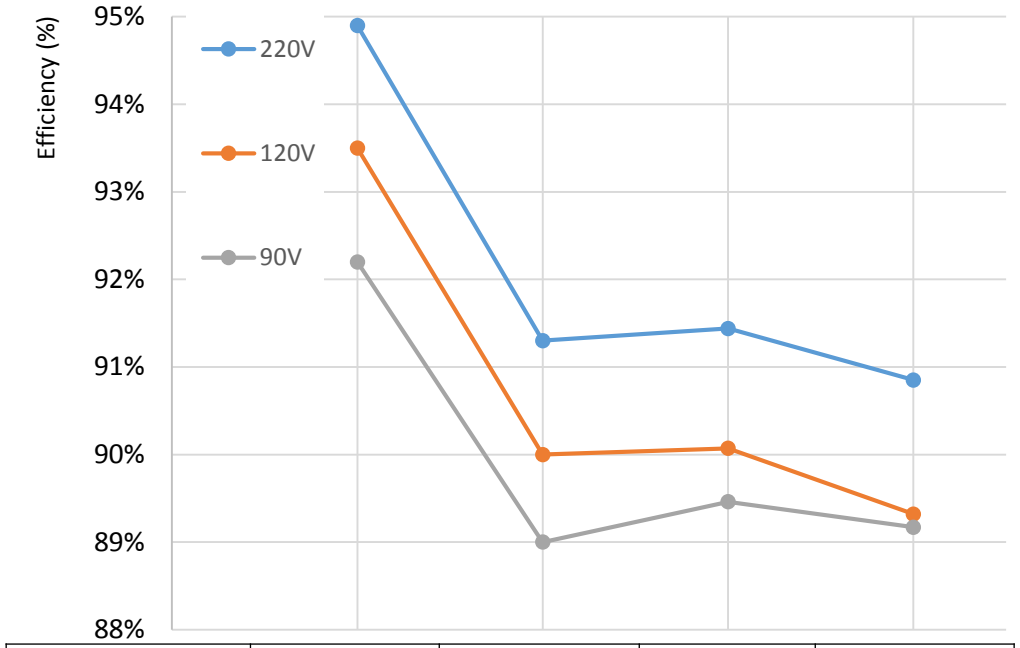
For further details of the 150 W, 21 W/in3 board, please see APEC 2017 Industry Session "State-of-the-Art Mobile Charging: Topologies, Technologies and Performance" (Mobile Applications)

Frequency-related Loss Kills Si

PFC = free-running 63-200 kHz, LLC = 300 kHz



Efficiency vs. Output Power, AC Line Voltage

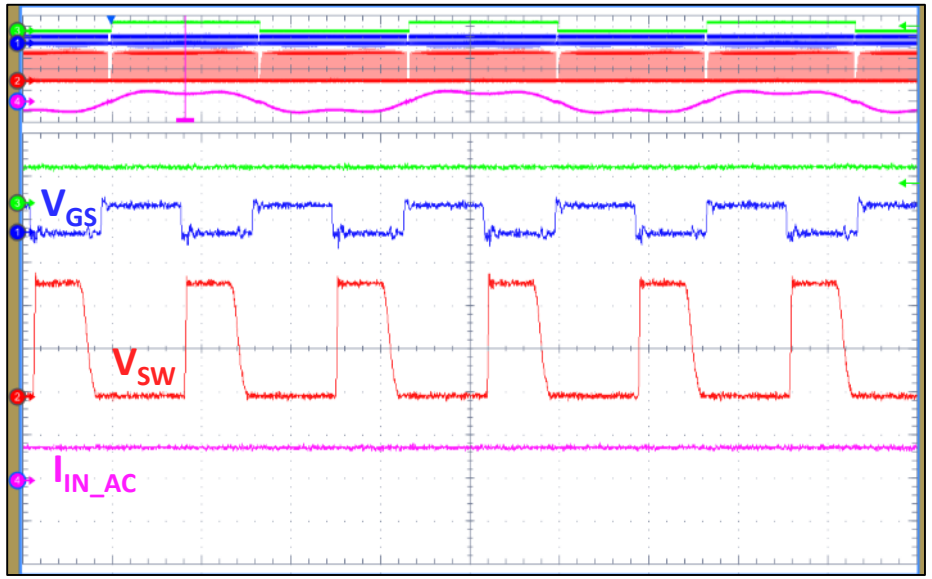


Powertrain	GaN	Si #1	Si #2	Si #3
PFC (mΩ)	110	270	180	99
LLC (mΩ)	160	270	270	270

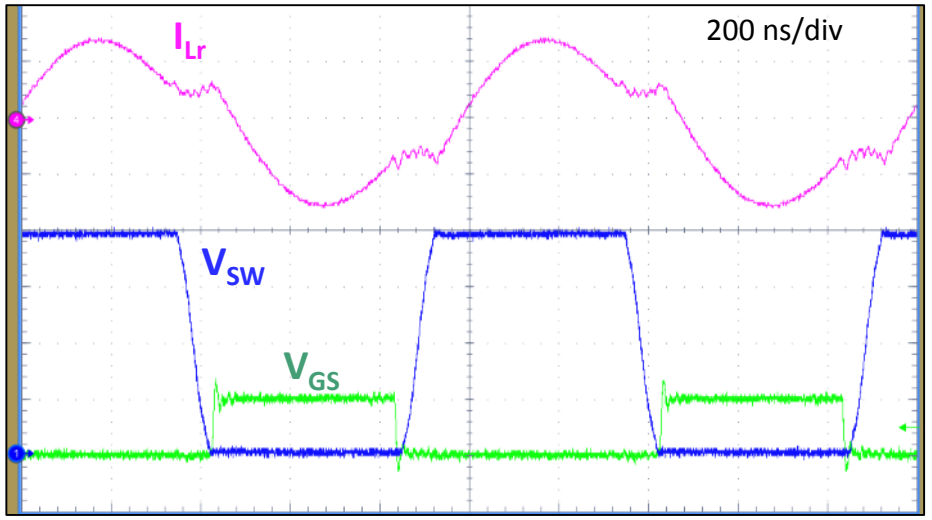
Efficiency vs. AC Line Voltage (150W Full Load)

AllGaN 2017: MHz 150W Totem-pole + LLC

PFC

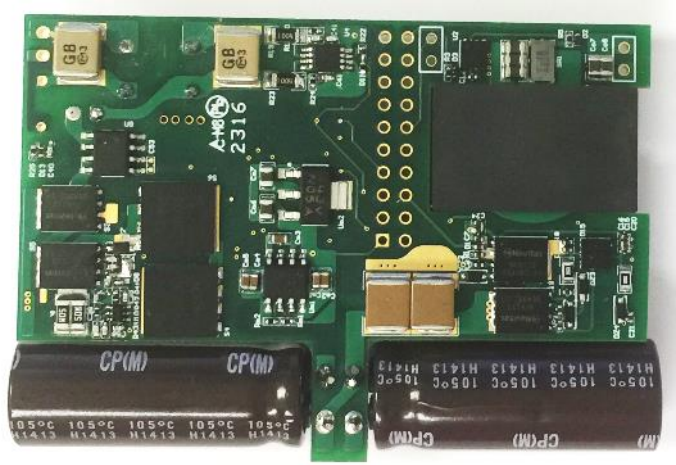


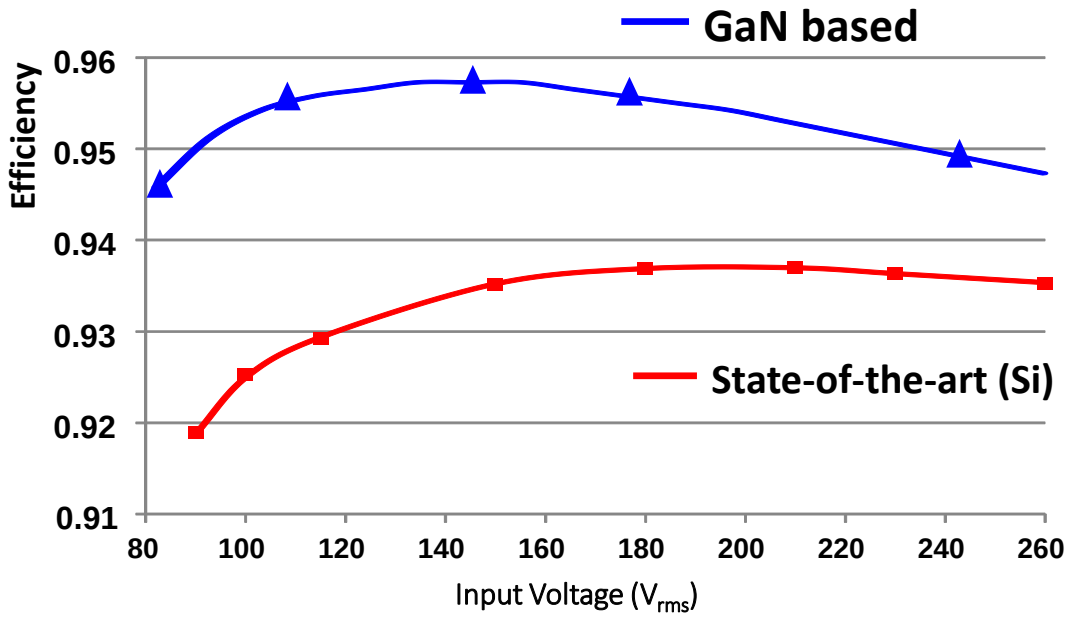
LLC



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

(Best commercial benchmark
= 12W/in3)



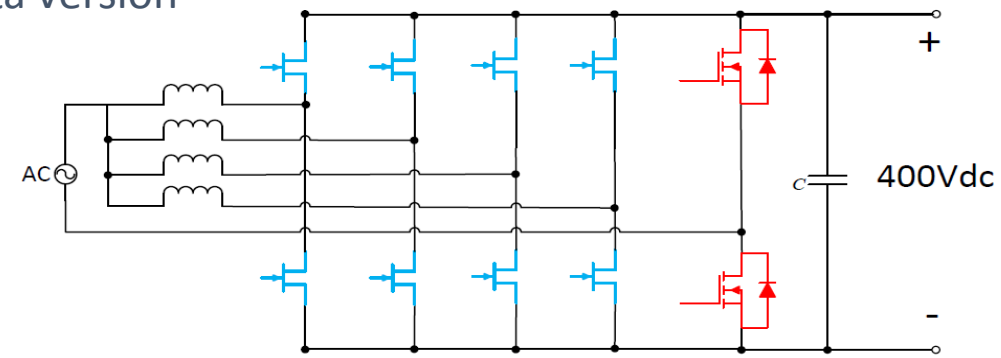


1 MHz, 3.2 kW Server Supply – 70 W/in³

- Multi-phase Totem-Pole CrCM + 2-phase Full-Bridge LLC
- Input : 220 V_{AC} (47-63 Hz)
- Output : 48 V, 3.2 kW
- Target Size : 200 x 80 x 41.5 mm (uncased)

PFC Beta version

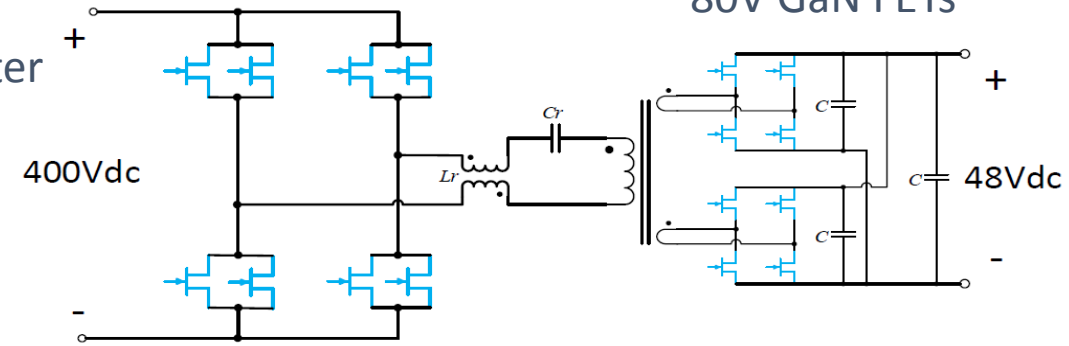
650V GaN Power ICs



650V GaN Power ICs

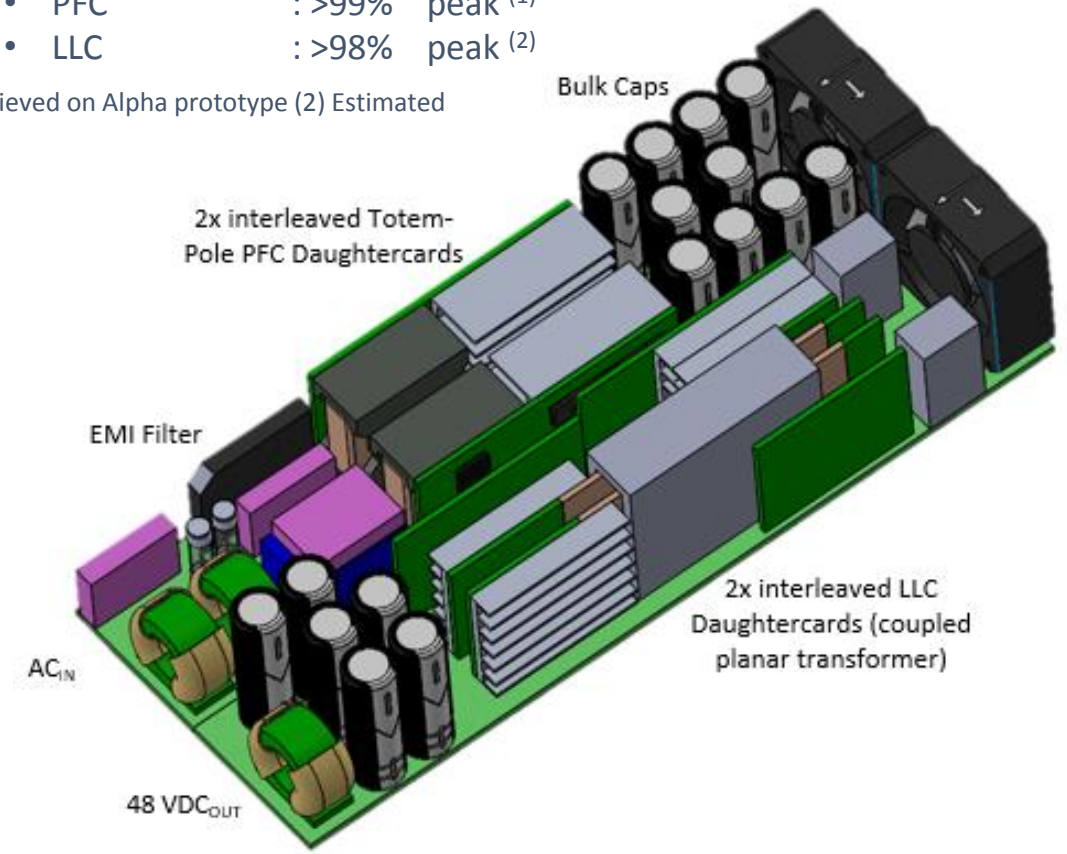
80V GaN FETs

LLC converter



- Target Frequency:
  - PFC = Variable frequency interleaving (500 kHz – 1.5 MHz)
  - LLC = Fixed-frequency interleaved 1 MHz
- Target Efficiency:
  - PFC : >99% peak (1)
  - LLC : >98% peak (2)

(1) Achieved on Alpha prototype (2) Estimated



Quasi-Square Wave PFC Full-range ZVS Operation

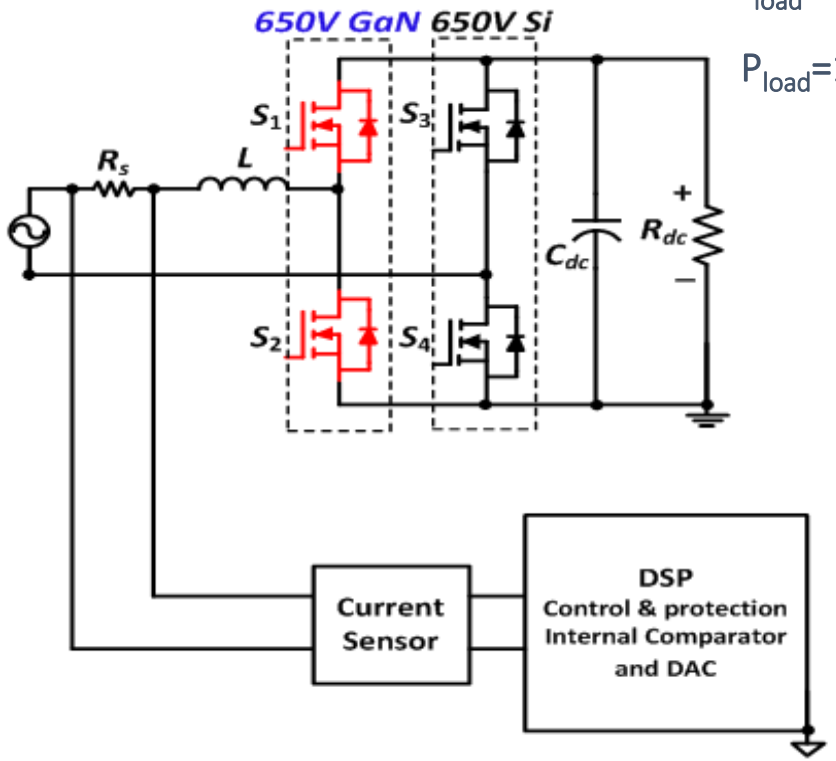
- Totem Pole Configuration
- Current Mode Control
- Constant ZVS current point
- Simple rule: only change the current reference waveforms

V_{DC}=385V

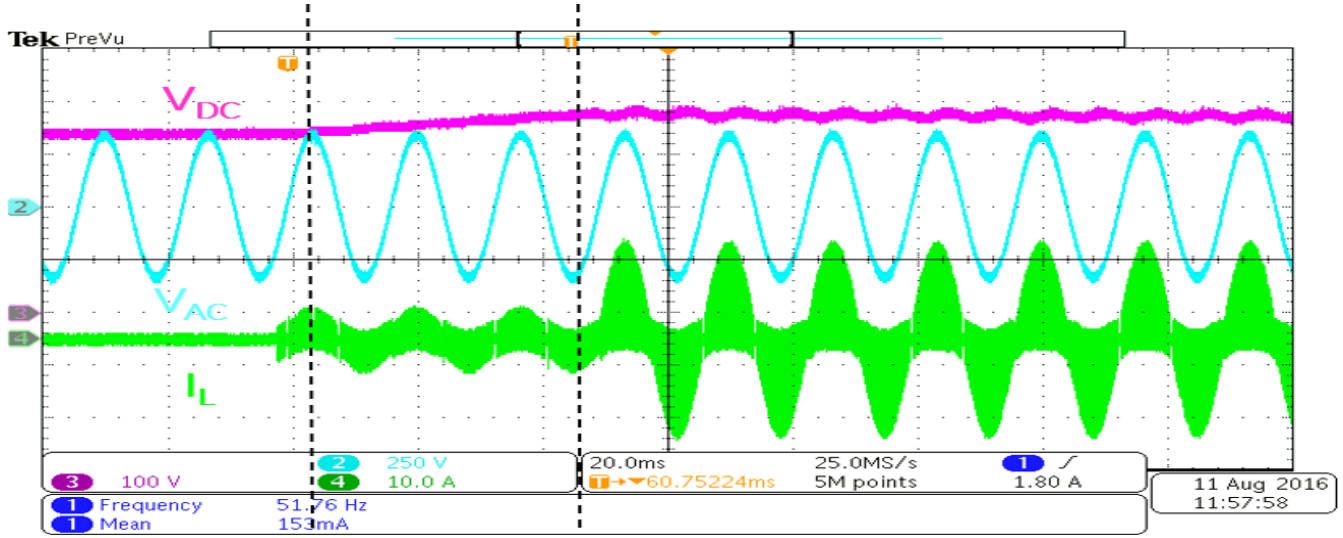
V_{AC}=240V/RMS

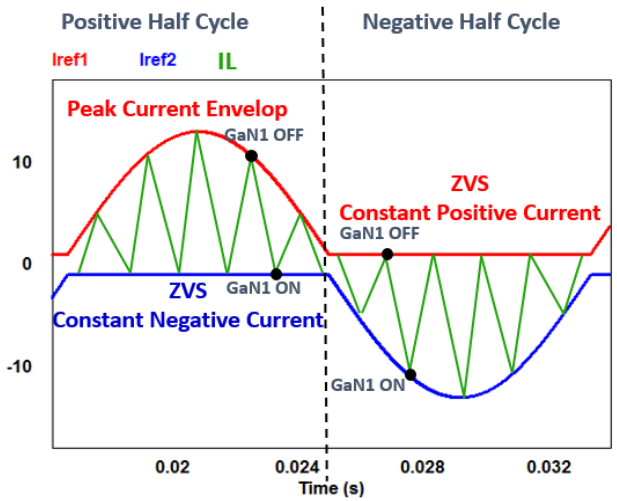
R_{load}=102ohm

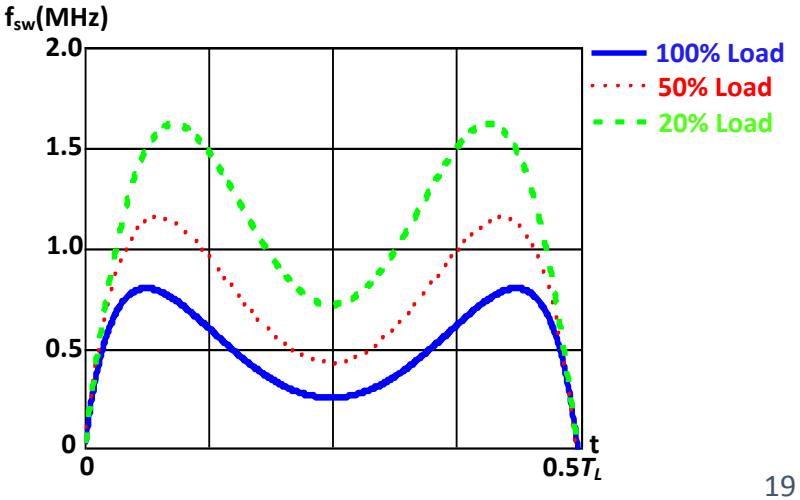
P_{load}=1450W



Zero Load Soft Start Full Load 1.45kW



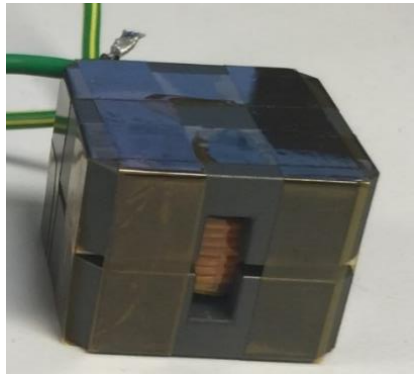


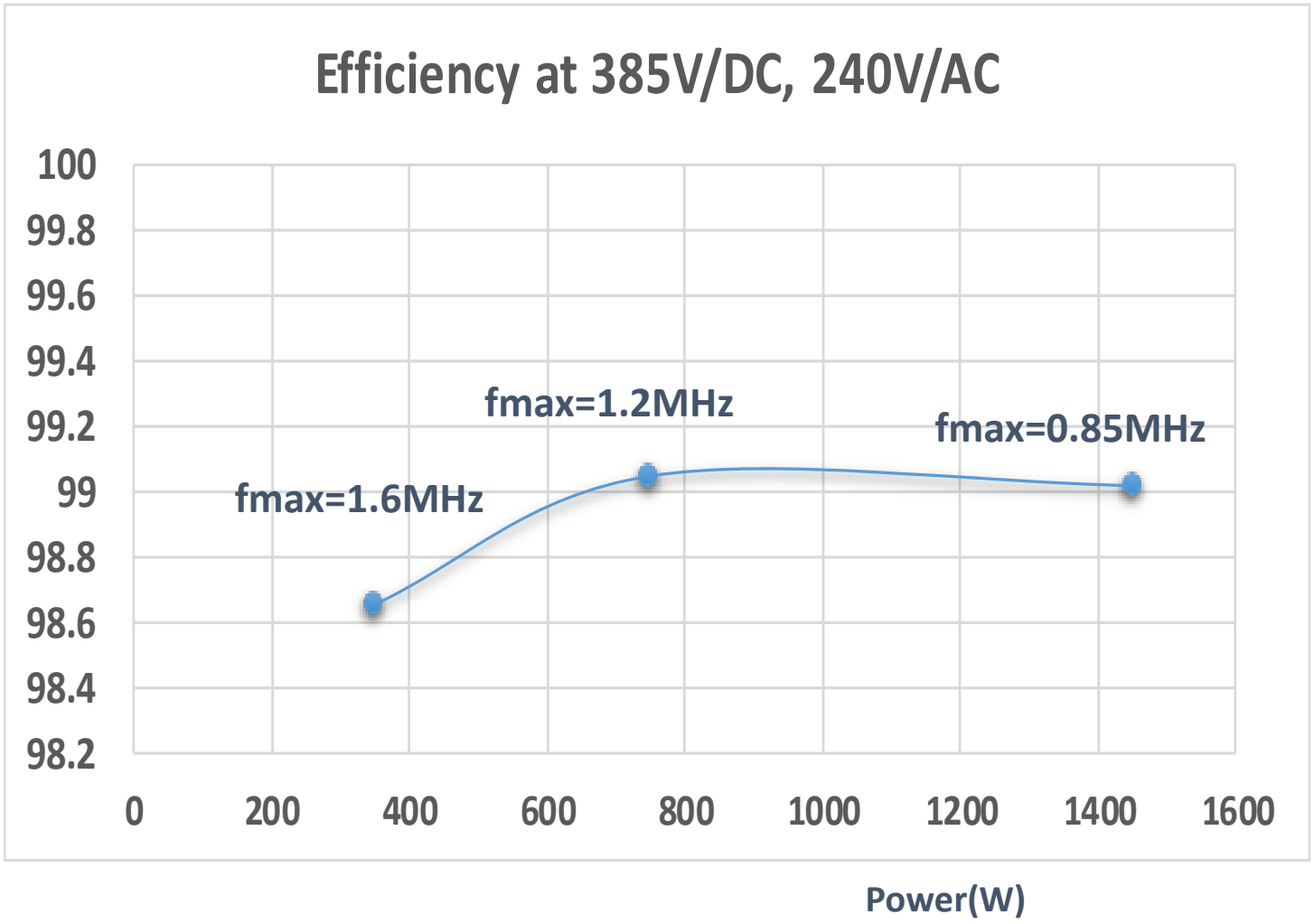


AllGaN Achieves Over 99% PFC Efficiency

3 GaN in Parallel, Vdd=6V

9.5uH, 7 Turns, Litz 46/660





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

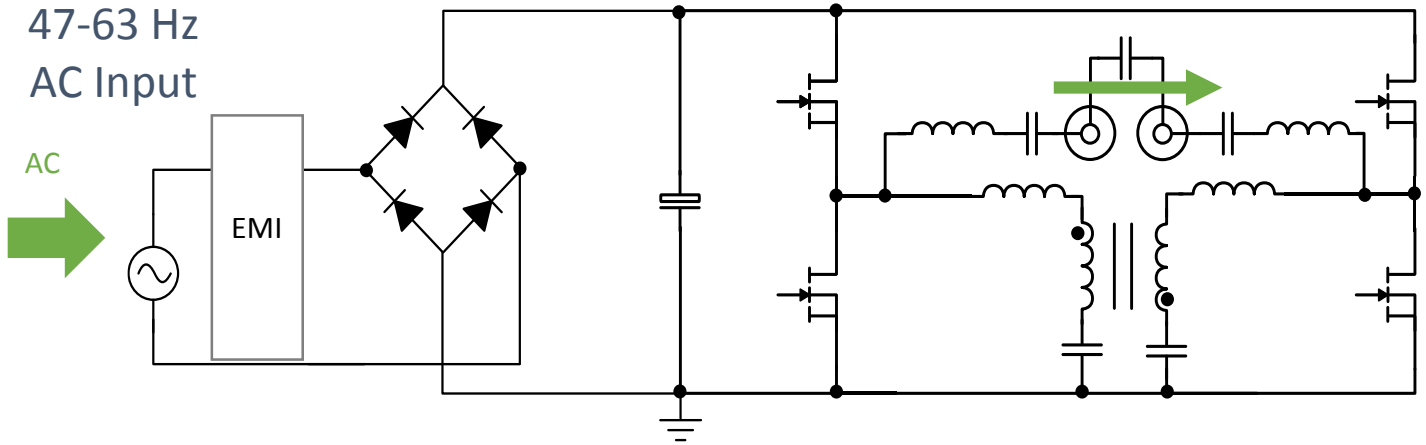
- 650V GaN Power ICs
- 3-stages integrated in 1-stage
- 6.78MHz Operation
- High-Efficiency

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

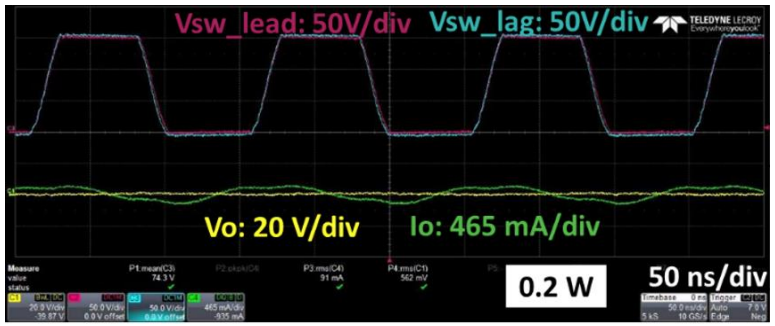
AC-RF Single Stage, Efficient & Cost-effective

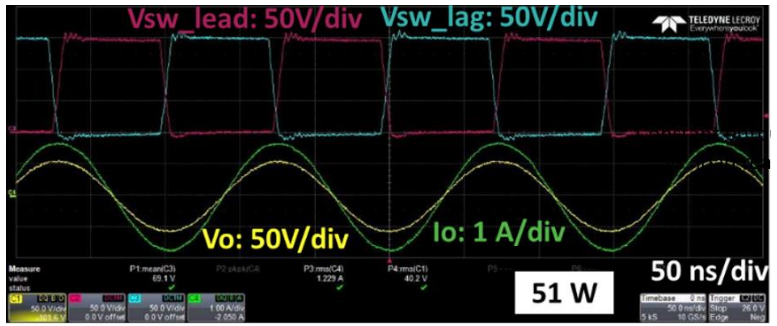
400V Phase-shifted Full Bridge with ZVS Coupled Inductors

6.78 MHz Output Direct to Transmitter Antenna

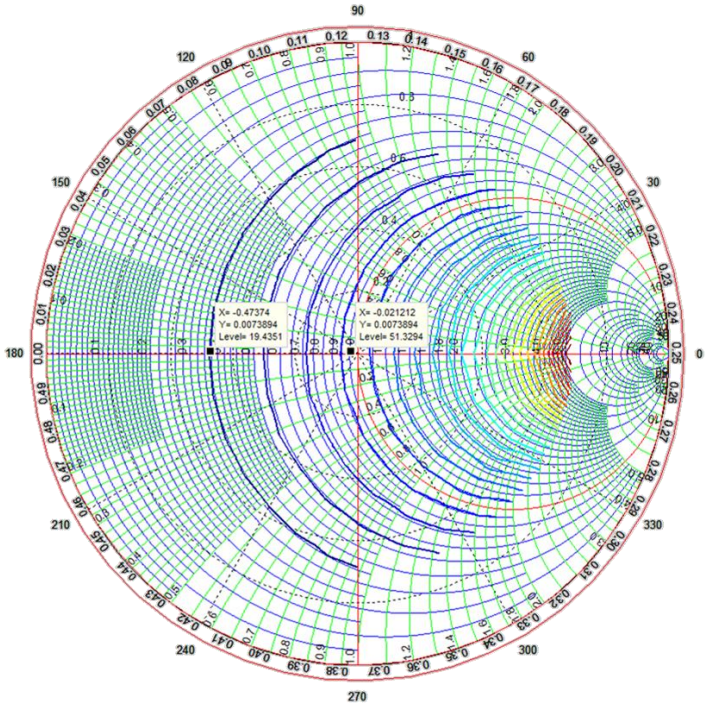


GaN Phase-Shift vs. Load





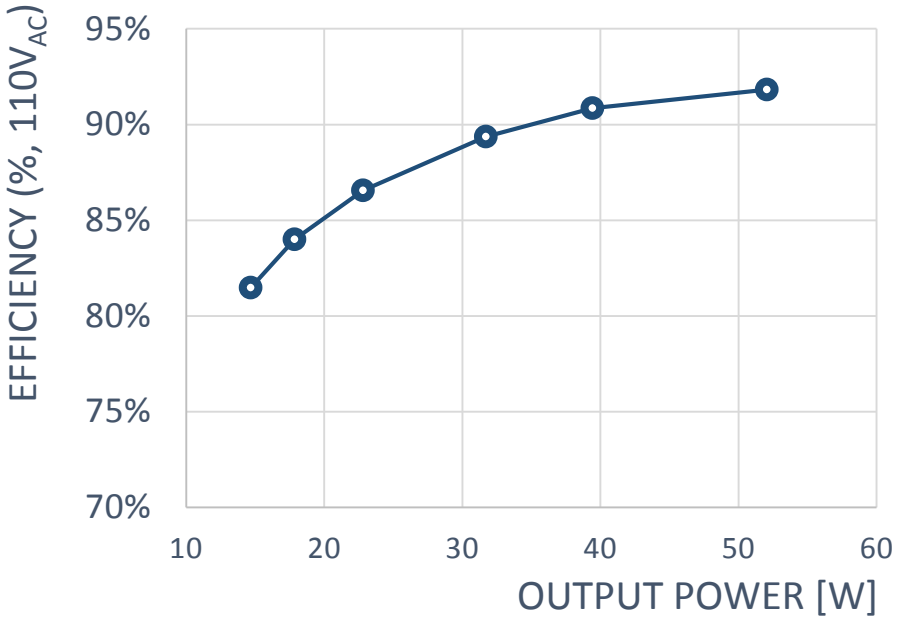
Meets Key System Requirements:
Constant output current vs. load reactance



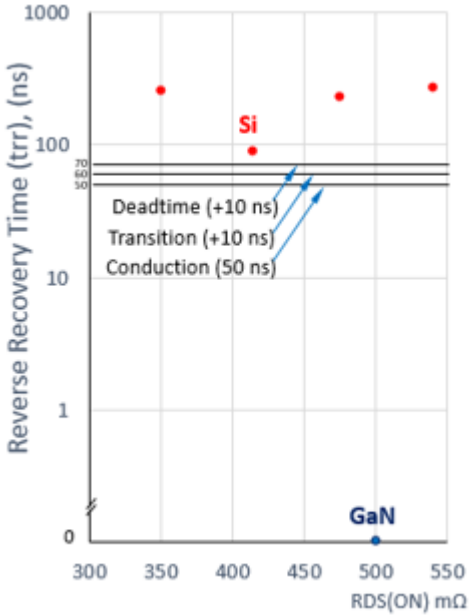
For further details, please see APEC 2017 technical paper “Single-Stage 6.78 MHz Power-Amplifier Design Using High-Voltage GaN Power ICs for Wireless Charging Application”, Xue, Zhang

Cool AllGaN, No Chance for Silicon

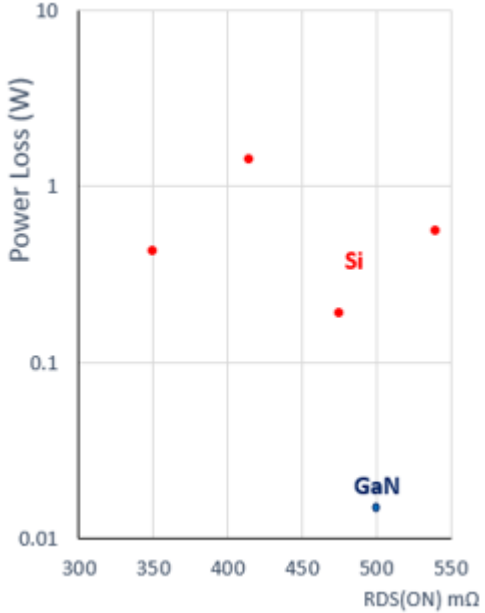
Efficiency from AC line to Transmitter Coil



Device Speed



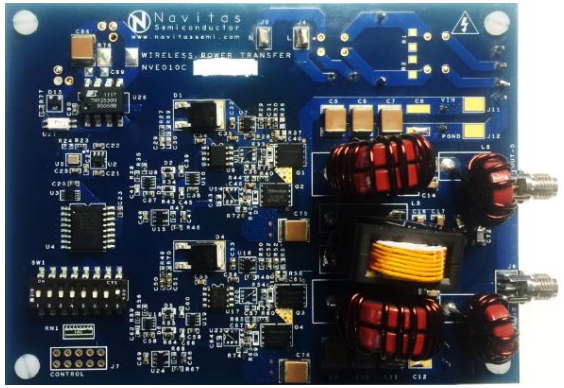
ZVS Current-Induced Loss

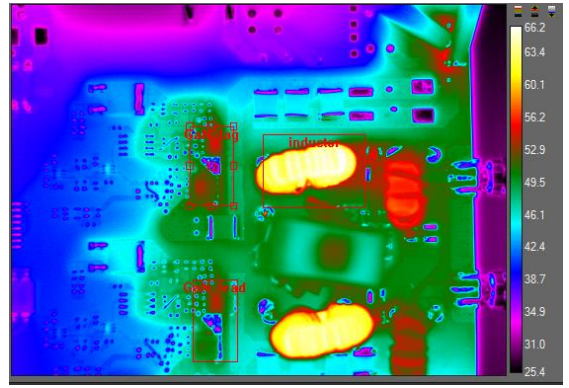


50W Prototype Board:

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

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

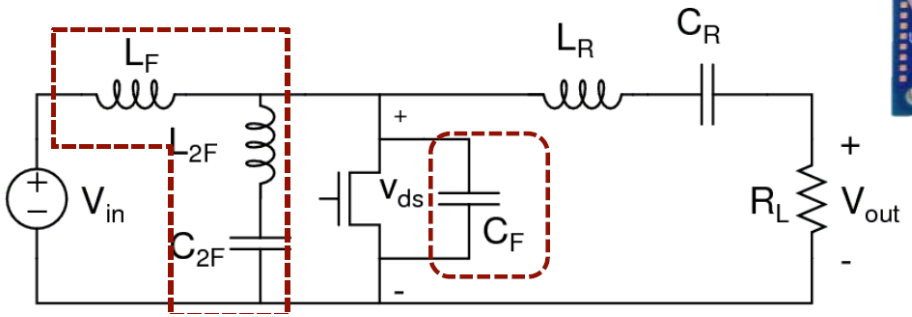


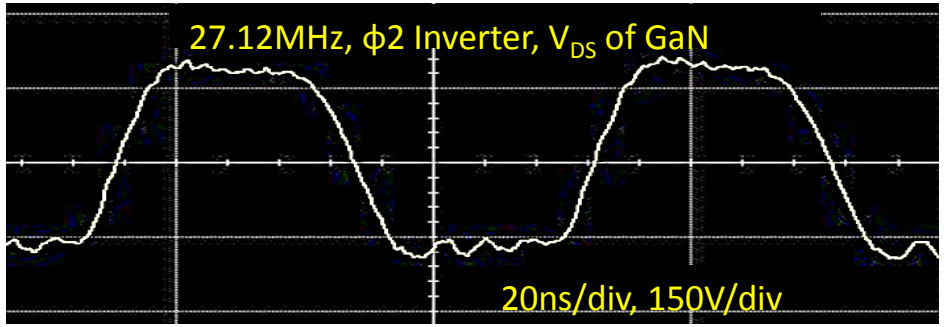


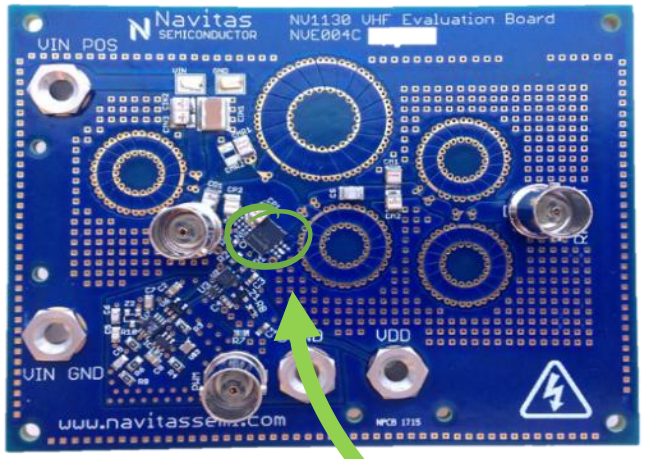
27 MHz, 40 MHz…

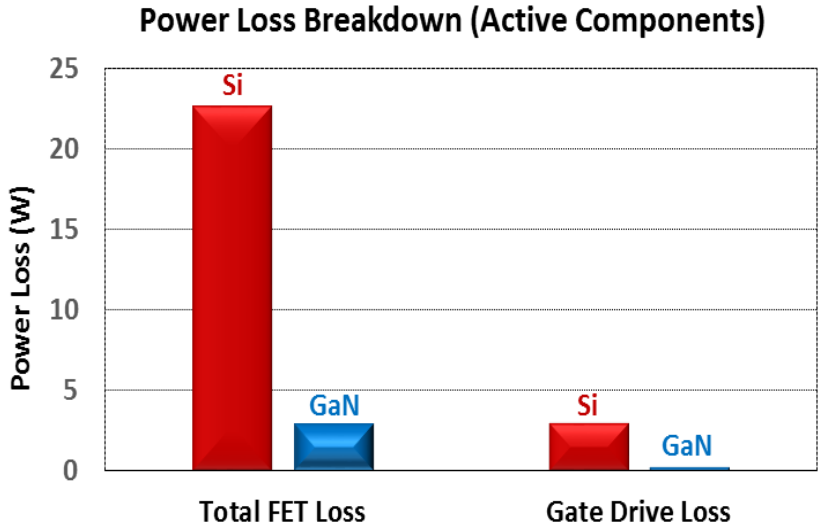
Class Phi-2 DC/AC converter

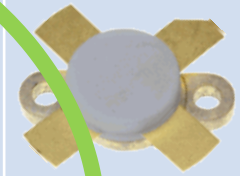
- 50% less loss than RF Si
- 16x smaller package
- Air-core inductors
- Minimal FET loss
- Negligible gate drive loss

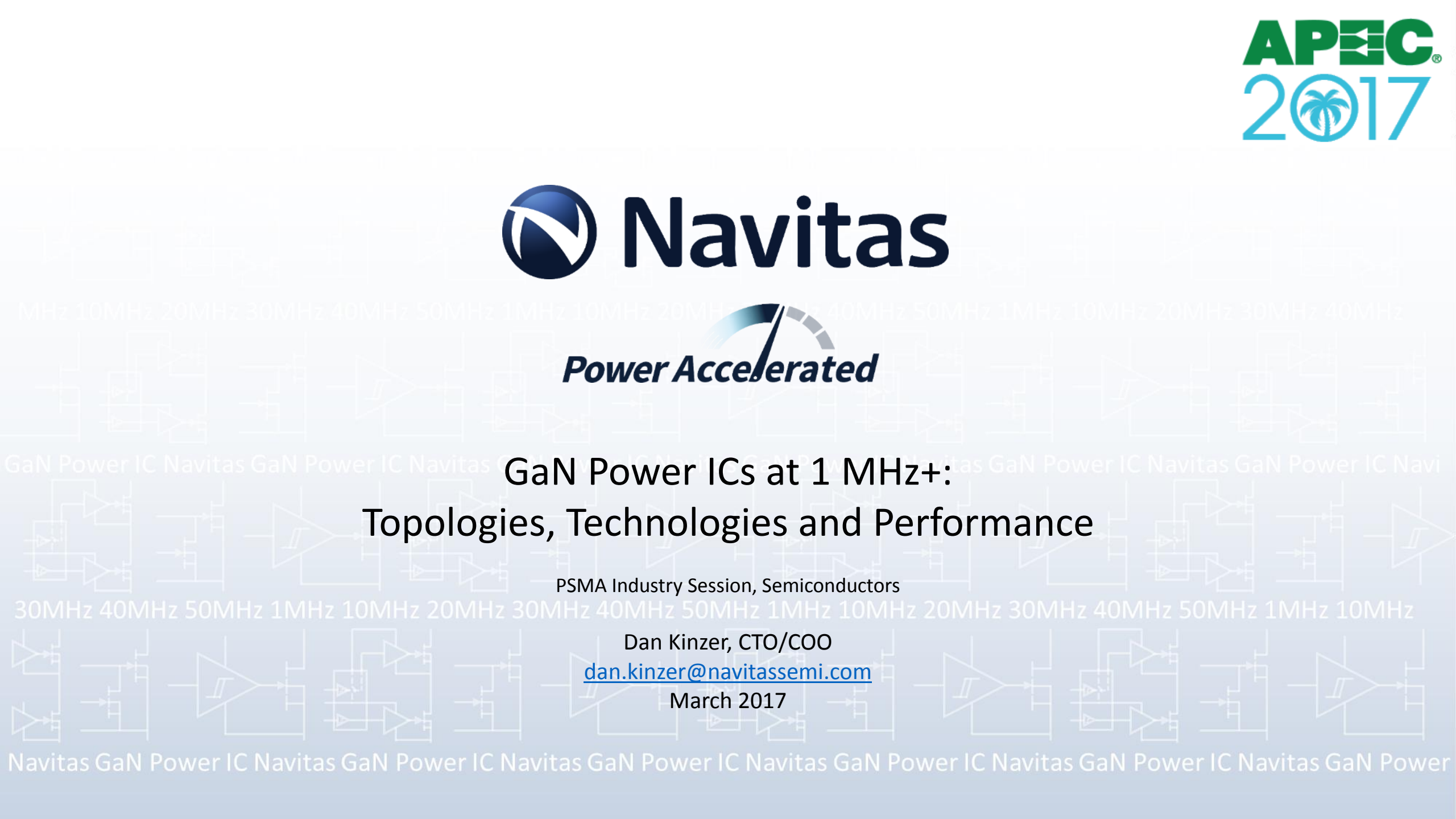








Technology	V	Pack (mm)		F_{SW} (MHz)	Eff. (%)	Power (W)
RF Si (ARF521) Microsemi POWER PRODUCTS GROUP	500	M174 22x22		27.12	91%	150
Navitas	650	QFN 5x6		27.12	96%	150
				40.00	93%	115



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

PSMA Industry Session, Semiconductors

Dan Kinzer, CTO/COO
dan.kinzer@navitassemi.com

March 2017