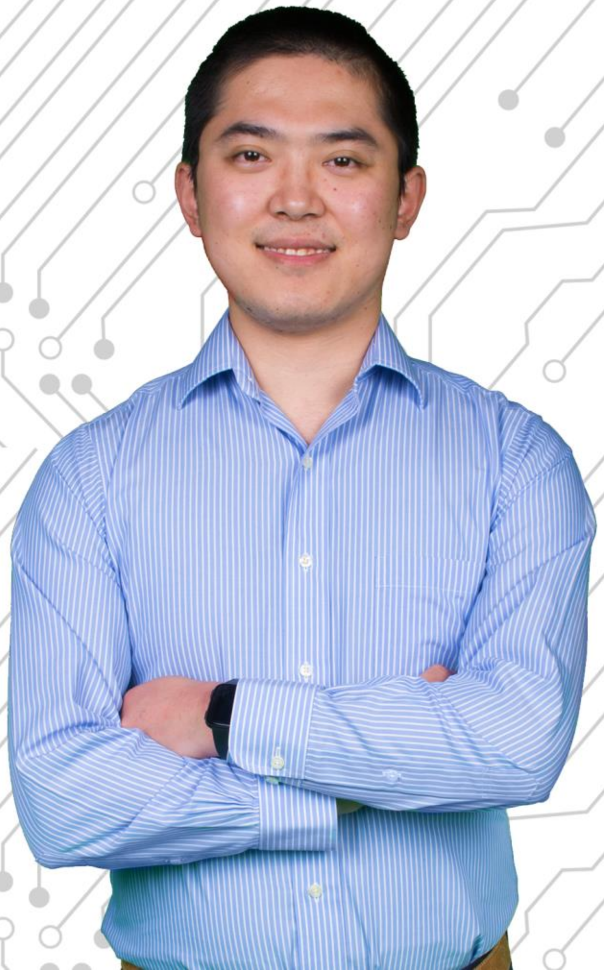
Texas Instruments

HIGH VOLTAGE SEMINAR

FEI YANG
GALLIUM NITRIDE

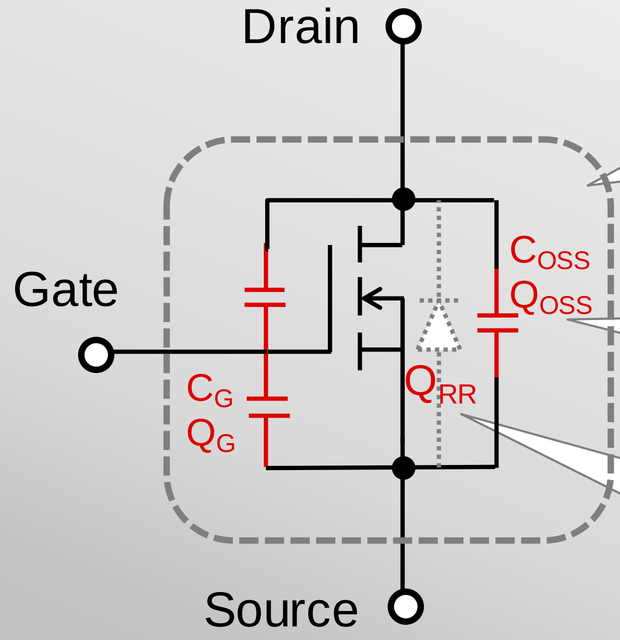
GaN FETS: HIGH POWER DENSITY AND EFFICIENCY IN PFC AND DCDC DESIGNS



Outline

- TI GaN: Engineered for high-frequency operation
- Applications driving for higher efficiency and density
  - Information technology power supplies
  - Automotive onboard chargers
- TI GaN for power factor correction (PFC) design
- TI GaN for DC/DC converter design
- TI GaN reference design and tools

GaN device: key advantages



Low C_G,Q_G gate capacitance/charge (1 nC-Ω vs Si 4 nC-Ω)
- ✓ faster turn-on and turn-off, higher switching speed
- ✓ reduced gate drive losses

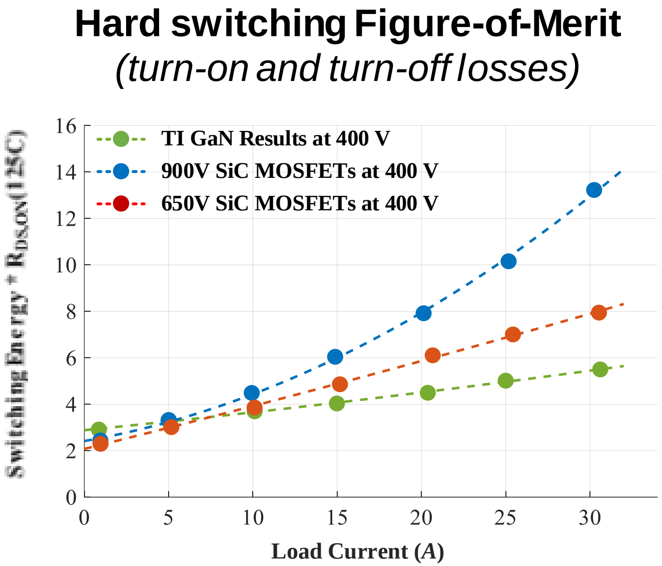
Low C_{OSS},Q_{OSS} output capacitance/charge (5 nC-Ω vs Si 25 nC-Ω)
- ✓ faster switching, high switching frequencies
- ✓ reduced switching losses

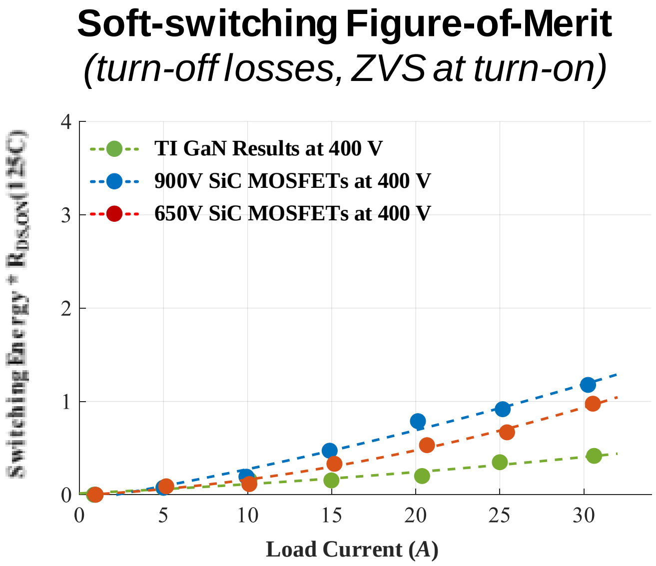
Low R_{DSON} (5 mΩ-cm^2 vs Si >10 mΩ-cm^2)
- ✓ lower conduction losses

Zero Q_{RR} No ‘body diode’
- ✓ No reverse recovery losses
- ✓ Reduces ringing on switch node and EMI

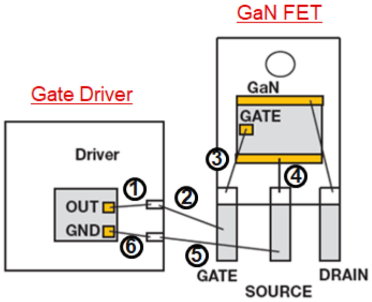
Low switching loss in TI GaN

- GaN offers best performance



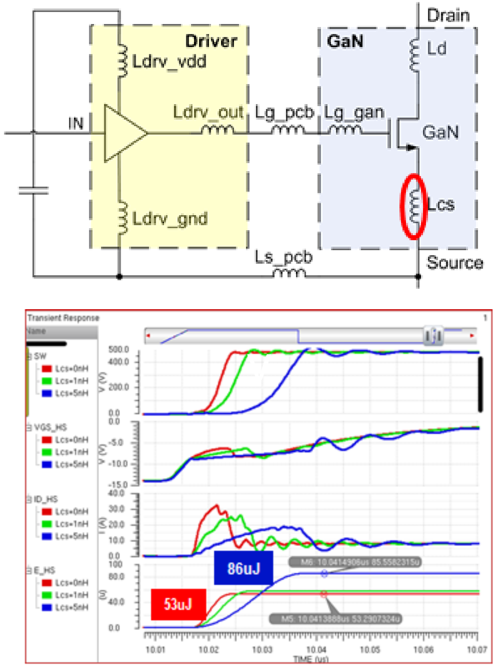


High-frequency design challenges with discretes



- **Common Source Inductance (CSI)**
  - Slows V_{DS} transitions.
  - Higher overlap losses (Hard-Switching).
  - Longer dead-times (Soft-Switching).
- **Gate Loop Inductance**
  - Limit peak gate current: slow down gate drive and induce high overlap losses in hard switching.
  - Gate overstress reliability risk.
  - Miller shoot-through risk.
- **White paper:** Optimizing GaN performance with an integrated driver

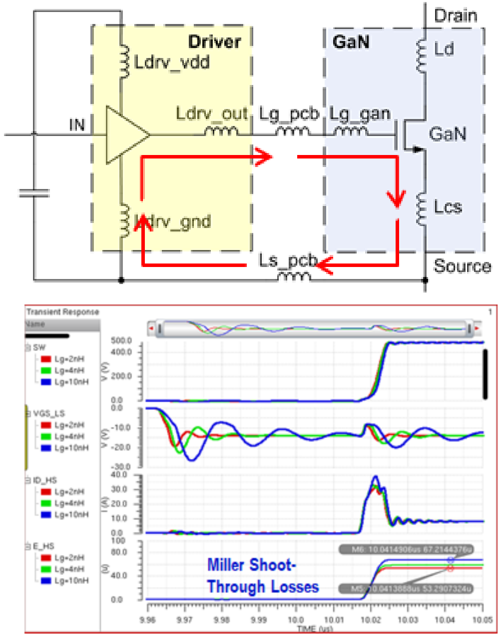
Common Source Inductance Effect



High-side turn on versus common-source inductance: red = 0 nH, green = 1 nH, blue = 5 nH

Limits peak I_{DS}, De-biases V_{GS}

Gate Loop Inductance Effect

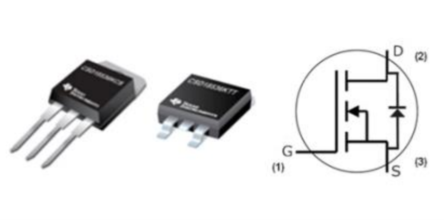
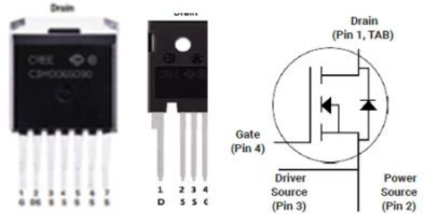
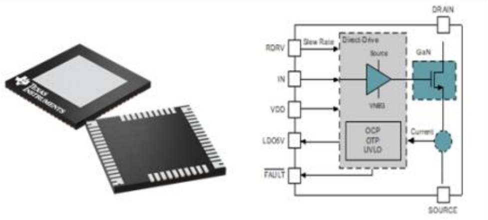


Low-side hold-off versus gate-loop inductance red = 2 nH, green = 4 nH, blue = 10 nH

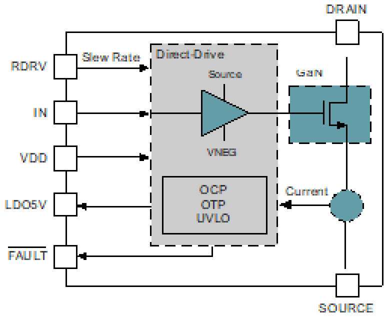
Limits peak I_{GATE} & slows down dV_{DS}/dt
Causes V_{GS} ringing & Miller shoot-through

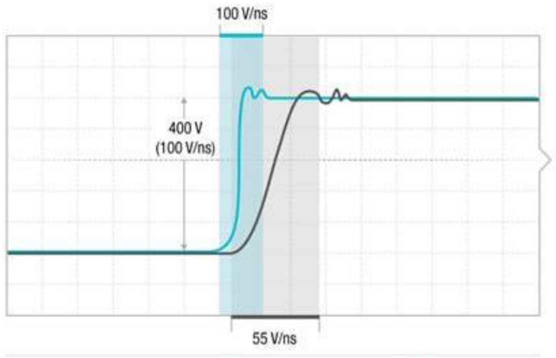
TI GaN engineered for high-frequency

- SMD (QFN) multi-chip module package offers **lowest parasitic inductance** for high frequency operation.

Standard Power Package	Kelvin Source Power Package	TI: GaN FET + Gate driver
		
Common Source: 2nH -10nH	Common Source: <1nH	Common Source: <1nH
Gate loop: 5nH – 20nH	Gate loop: 5nH – 20nH	Gate loop: 1nH – 4nH

TI GaN: Integrated for high frequency and robustness





Integrated GaN FET, gate driver, protection, reporting

- <1 nH common source inductance, <4 nH gate loop inductance
- On-chip V/I/T sensing, protections & reporting
- Advanced power management features

+

Compact SMD package

- Low parasitic lead inductance
- Enhanced thermal management with top/bottom-side cooling

=

Design simplicity & confidence

- Demonstrated d V_{ds}/dt capability of 150 V/ns
- dV_{ds}/dt adjustable between 30-150 V/ns for EMI vs efficiency
- Compact PCB footprint

TI GaN integration simplifies BOM and cost

TI GaN

FETs + Driver + Protection

Min area: 24x29mm

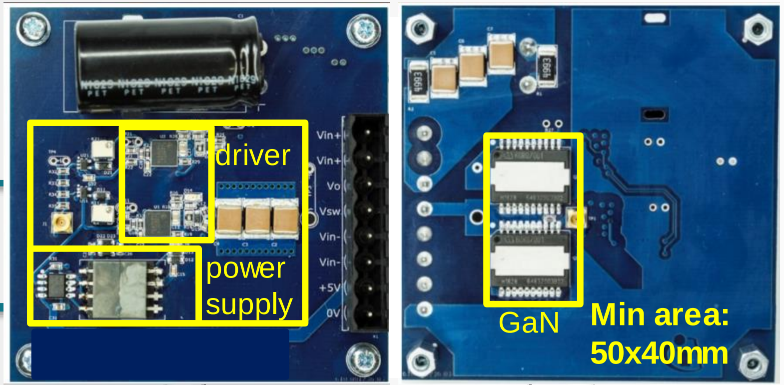
Only single 12-V unregulated supply needed

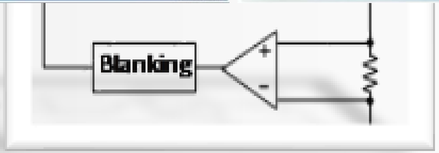
Discrete GaN

Gate drive circuitry

External power supply needed

External protection needed





TI GaN FET portfolio

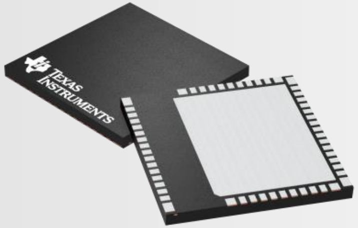
Gen-I

2x the power

RDS: 50/70/150 mΩ
Size: 8mm x 8mm
Cooling: Bottom
Rj-s: <5.5 C/W
Power Loop Inductance: <2.3 nH

https://www.ti.com/product/LMG3411R050

Gen-II Industrial

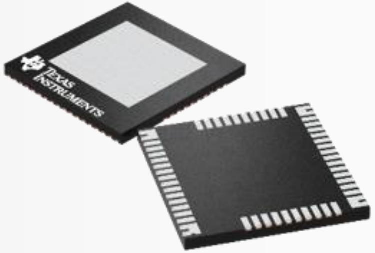


AECQ-100

RDS: 30/50 mΩ
Size: 12mm x 12mm
Cooling: Bottom
Rj-s: <2.6 C/W
Power Loop Inductance: <2.8 nH

https://www.ti.com/product/LMG3422R030

Gen II Automotive



RDS: 30 mΩ
Size: 12mm x 12mm
Cooling: Top
Rj-s: <2.3 C/W
Power Loop Inductance: <2.1 nH

https://www.ti.com/product/LMG3522R030-Q1

LMG342x/352x: TI Gen-II GaN FETs

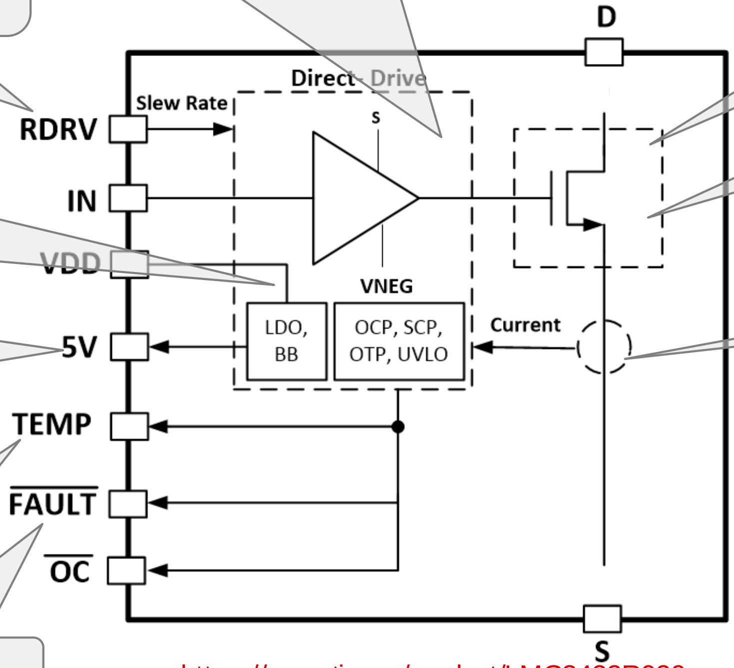
>150 V/ns Drain-Source Slew rate capability; **adjustable from 30 V/ns to 150 V/ns**

Integrated **2.2-MHz** gate driver with industry lowest CSI

LMG342x: 600-V GaN FET
LMG352x: 650-V GaN FET

Integrated gate driver bias generated from 7.5-18 V unregulated supply supporting **2.2-MHz switching**

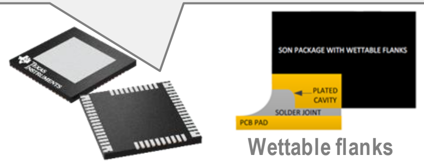
NEW LMG3425/3525 Ideal diode mode **reduces reverse conduction losses**



Overcurrent protection **Cycle-by-Cycle**
Short circuit protection **Latched**

5-V regulated output **for powering digital isolator**

NEW 12mm-by-12 mm QFN
LMG342x: bottom-cooled
LMG352x: top-cooled QFN with wettable flanks



Wettable flanks

NEW GaN FET temperature digital PWM reporting for **active power management**

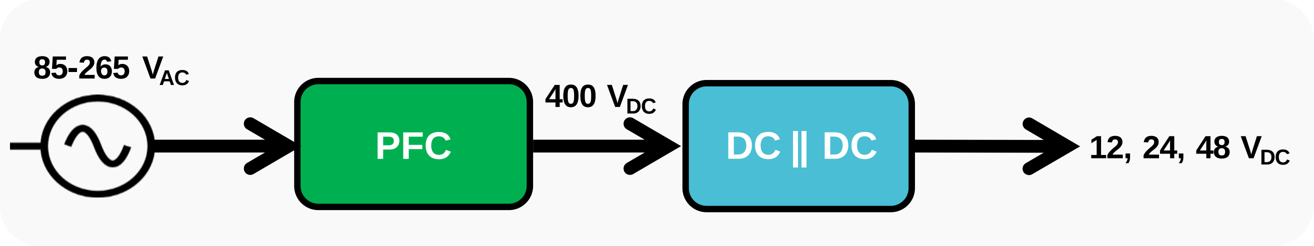
V/I/T **fault reporting**

https://www.ti.com/product/LMG3422R030
https://www.ti.com/product/LMG3522R030-Q1

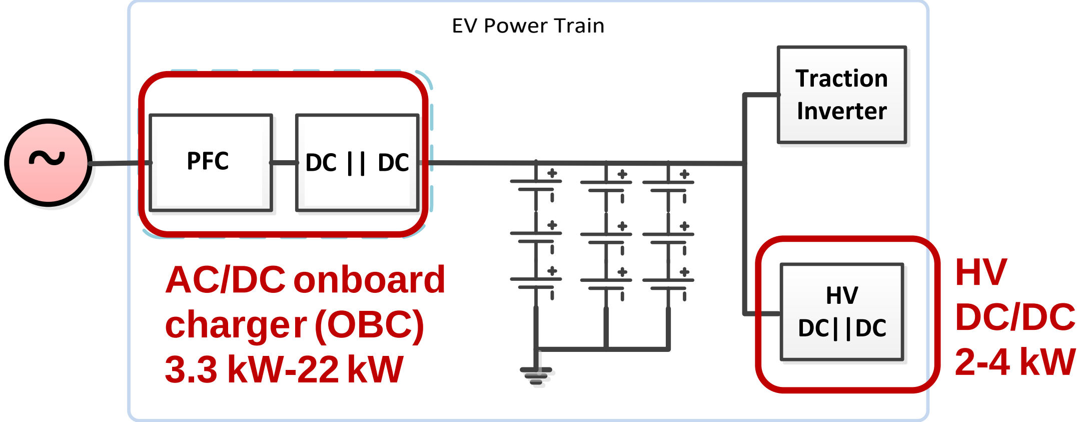
Outline

- TI GaN: Engineered for high-frequency operation
- Applications driving for higher efficiency and density
  - Information technology (IT) AC/DC power supplies
  - Automotive onboard chargers
- TI GaN for power factor correction (PFC) design
- TI GaN for DC/DC converter design
- TI GaN reference design and tools

Multi-kW applications demanding high efficiency & density



AC/DC power supply for datacenter, telecom, medical and industrial (up to 10 kW)



Automotive HEV/EV powertrain

AC/DC trends in datacenter and telecom

Energy Efficiency

Beyond 80+ Titanium
@ 50% & 100% load

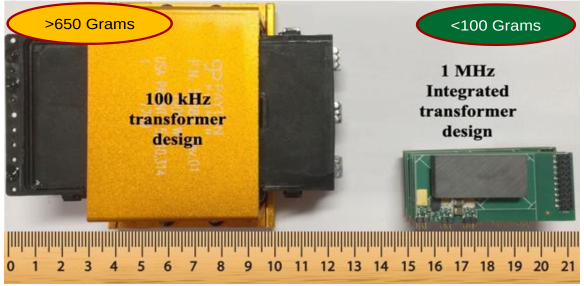
80 PLUS Certification	115V Internal Non-Redundant			230V Internal Redundant			
% of Rated Load	20%	50%	100%	10%	20%	50%	100%
80 PLUS	80%	80%	80%	N/A			
80 PLUS Bronze	82%	85%	82%	---	81%	85%	81%
80 PLUS Silver	85%	88%	85%	---	85%	89%	85%
80 PLUS Gold	87%	90%	87%	---	88%	92%	88%
80 PLUS Platinum	90%	92%	89%	---	90%	94%	91%
80 PLUS Titanium	---	---	---	90%	94%	96%	91%

80 PLUS | 80 PLUS BRONZE | 80 PLUS SILVER | 80 PLUS GOLD | 80 PLUS PLATINUM | 80 PLUS TITANIUM

- **PSU efficiency spec 2021:**
  - ITE-level PSU >**96.5%**
  - Rack-level PSU peak efficiency **> 97.5%** @ 230Vac

High power & Power density

3kW/4kW/5kW & >100W/in³



ITE-level PSU going up to 3kW+ in same FF
- Power density: 80W/in³ in Y19-Y20 → **115W/in³** in Y23-Y24

Rack-level PSU going up to 4kW+ in same form factor
- Power density: >**100W/in³** by Y23

Automotive trends in onboard charger & HV DC/DC

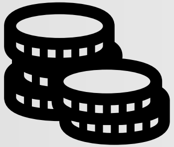
High power density

(1-2 kW/L → 3-5 kW/L)

Requires new topologies and design approaches:

- **PFC:** Totem-pole topology to achieve 2x density improvement
- **DC/DC:** >10x increase in switching frequency to achieve significant reduction in magnetics

Lower cost

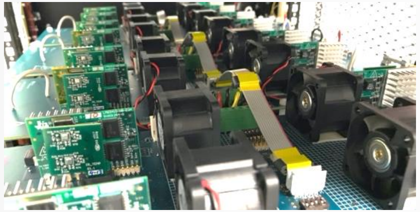


- Smaller and cheaper magnetic components
- Integrated magnetics (eg, inductor + transformer)
- Lower BoM with highly integrated devices

Faster to market

- Solutions that easily scale from 3.3-22 kW and address both 400-V and 800-V battery systems, while delivering on performance metrics.

Reliability



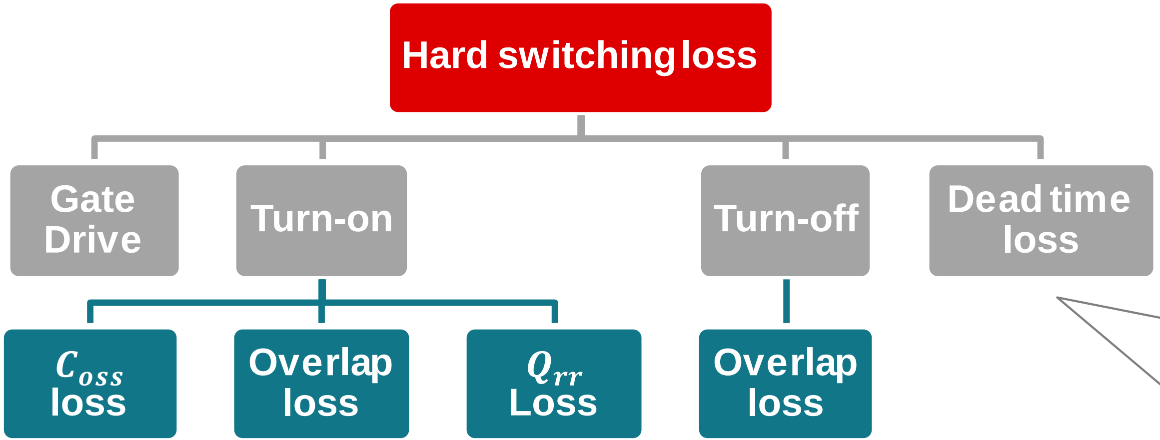
- Component level and application level reliability
- Confidence for adopting new technologies or design approaches

Outline

- TI GaN: engineered for high-frequency operation
- Applications driving for higher efficiency and density
  - Information technology power supplies
  - Automotive onboard chargers
- TI GaN for power factor correction (PFC) design
- TI GaN for DC/DC converter design
- TI GaN reference design and tools

Hard-switching loss breakdown: TI GaN solution

- Hard-switching loss occurs in CCM Totem Pole PFC.



Low C_{OSS} output capacitance in TI GaN given its better Figure of Merit (FOM).

Ideal Diode Mode enables automatic synchronous FET operation, and adapts to load current.

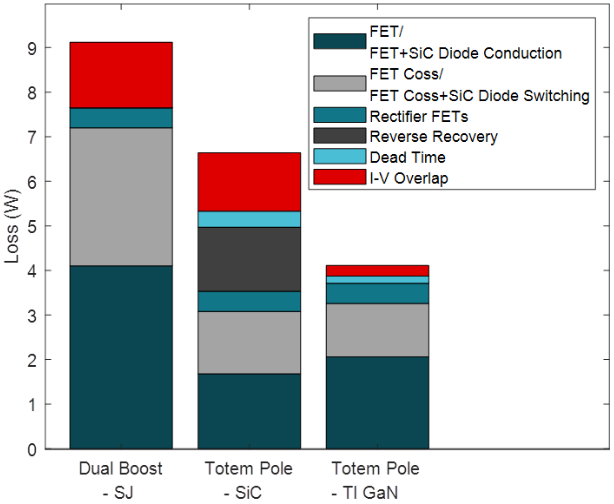
Integrated gate drive that is capable of providing **>150 V/ns** switching speed for TI GaN.

No body diode conduction and there is no Reverse Recovery loss in TI GaN device.

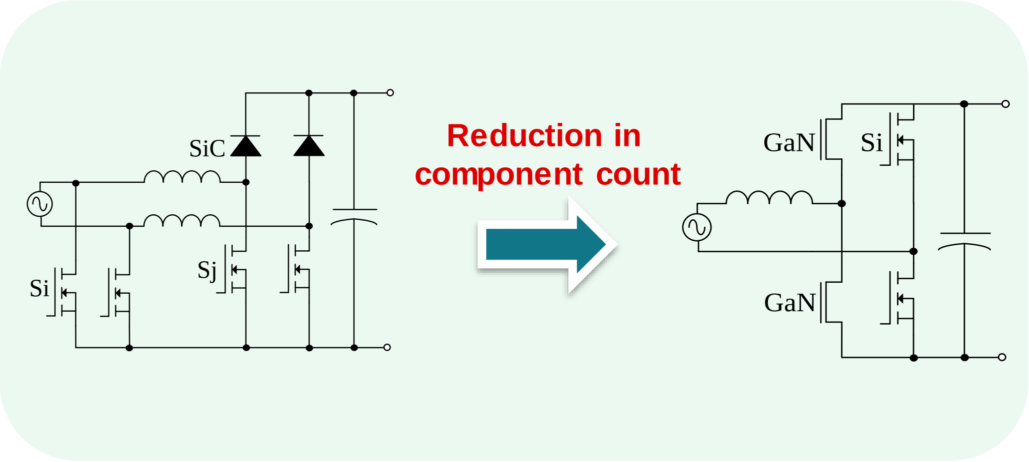
Integrated gate drive that provides a strong gate drive to turn-off.

Bridgeless PFC comparison: Si vs. SiC vs. TI GaN

- **Dual-boost bridgeless PFC with Si MOSFET + SiC Schottky diode:** Si MOSFET has high C_{oss} loss and overlap loss, while SiC diode has high conduction loss
- **SiC MOSFET totem-pole (TP) bridgeless PFC (w/o anti-parallel Schottky diode):** SiC MOSFET still has reverse recovery loss and high dead time loss
- **TI GaN totem-pole (TP) bridgeless PFC:** lowest loss, zero reverse recovery, minimal overlap

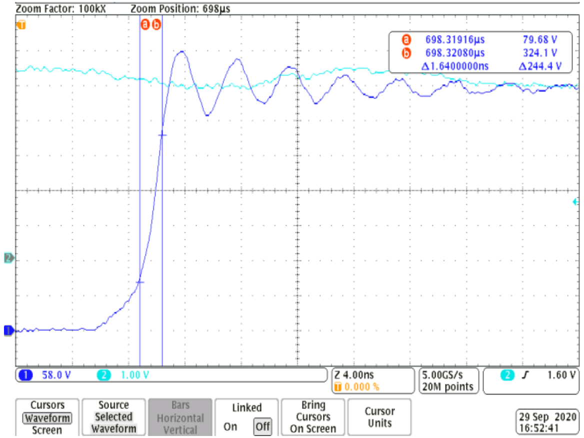


Loss comparison at 1 kW, 100 kHz

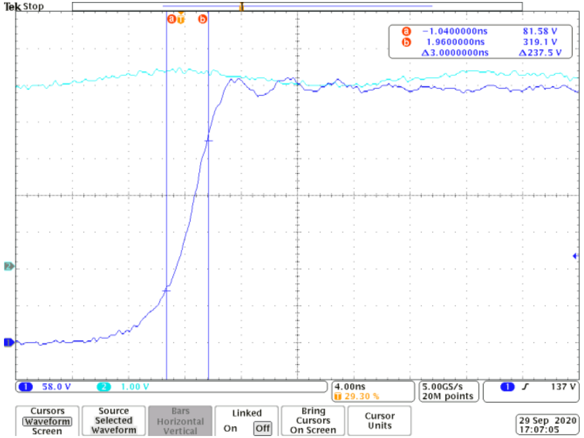


Technical article: [Wide-bandgap semiconductors: Performance and benefits of GaN versus SiC]

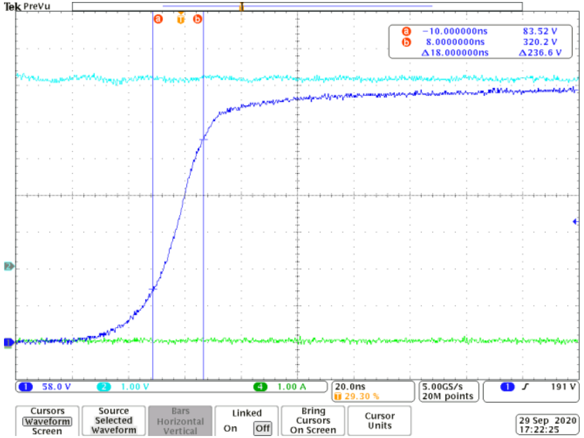
Adjustable slew rate



149 V/ns



80-85 V/ns

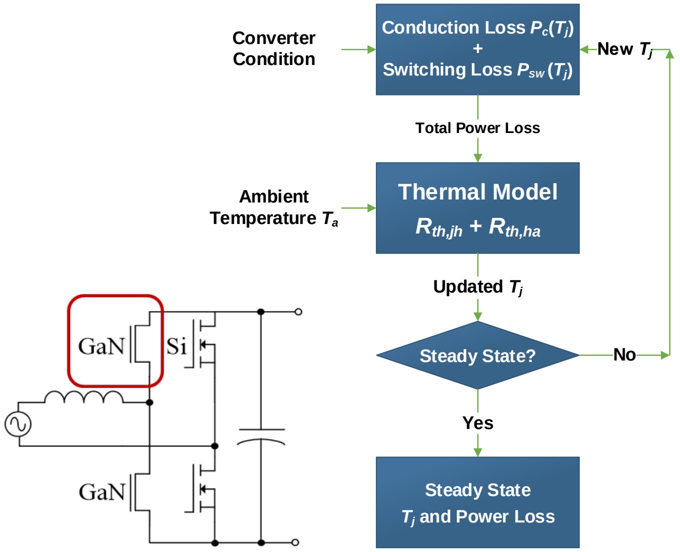


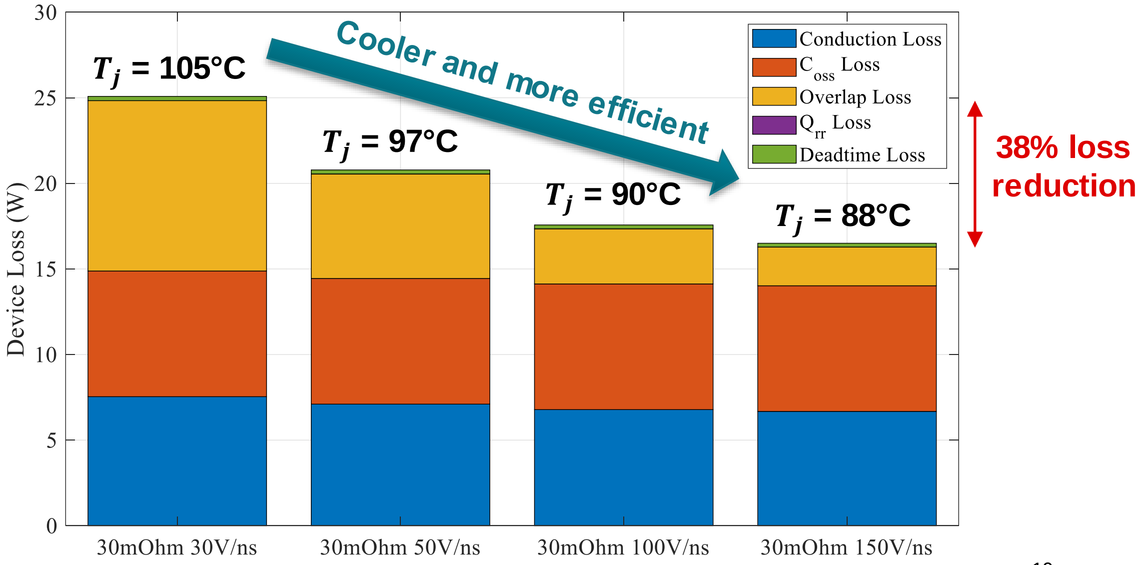
13 V/ns

- High slew-rates with minimal ringing and voltage overshoot
- Tested in Buck converter at 400 V, and the turn-on *dv/dt* can be adjusted according to different R_{drv} resistances.
- The slew rate is defined from 20% to 80% at a bus voltage of 400 V.

Impact of slew rate on device loss

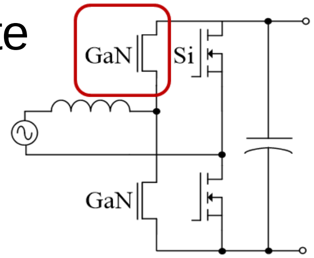
- Analysis at 4 kW, 230 V V_{ac_RMS}, 400 V bus, 55°C ambient and f_{sw} = 200 kHz
  - Full load (4 kW) is considered for thermal design, and the steady-state loss is obtained.
  - With TI GaN's 150 V/ns slew rate, the device is cooler and the system is more efficient.

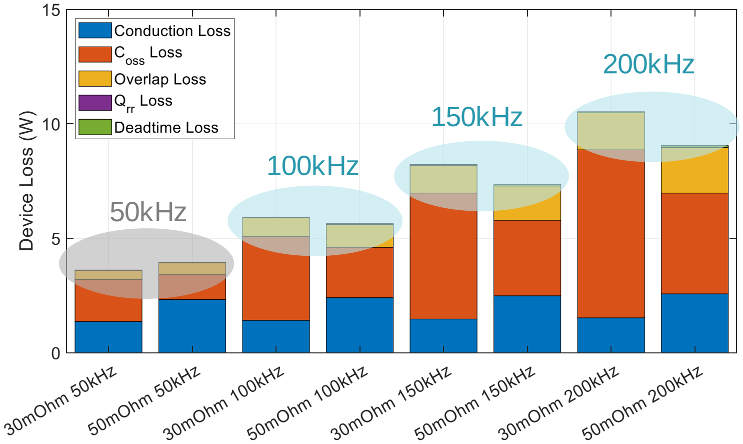




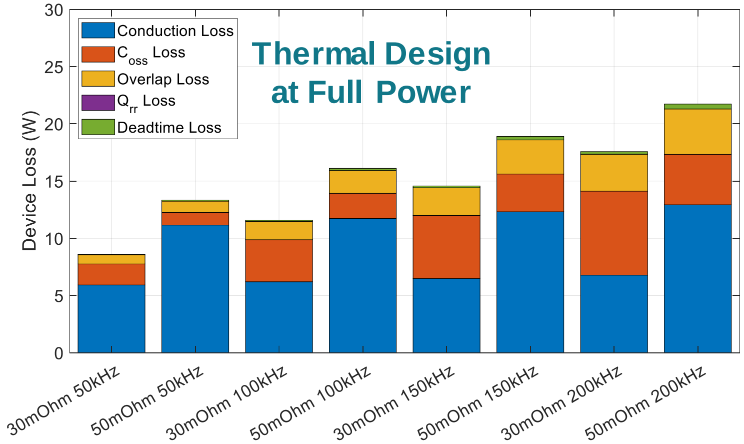
Case study: CCM TP PFC $R_{ds,on}$ v.s C_{oss} trade-off

- 30 mΩ and 50 mΩ comparison at different f_{sw} with 100 V/ns slew rate
  - 230 V V_{ac_RMS} and 400 V bus. Ambient temperature is 55°C.
  - 30-mΩ device shows lower loss at full power (4 kW).
  - At 50% load, the 50-mΩ device indicate lower loss when the switching frequency is beyond 100 kHz.



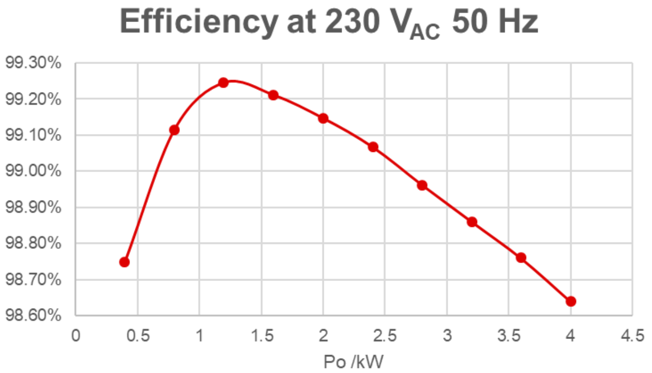


Loss Comparison at 50% Load: 2kW

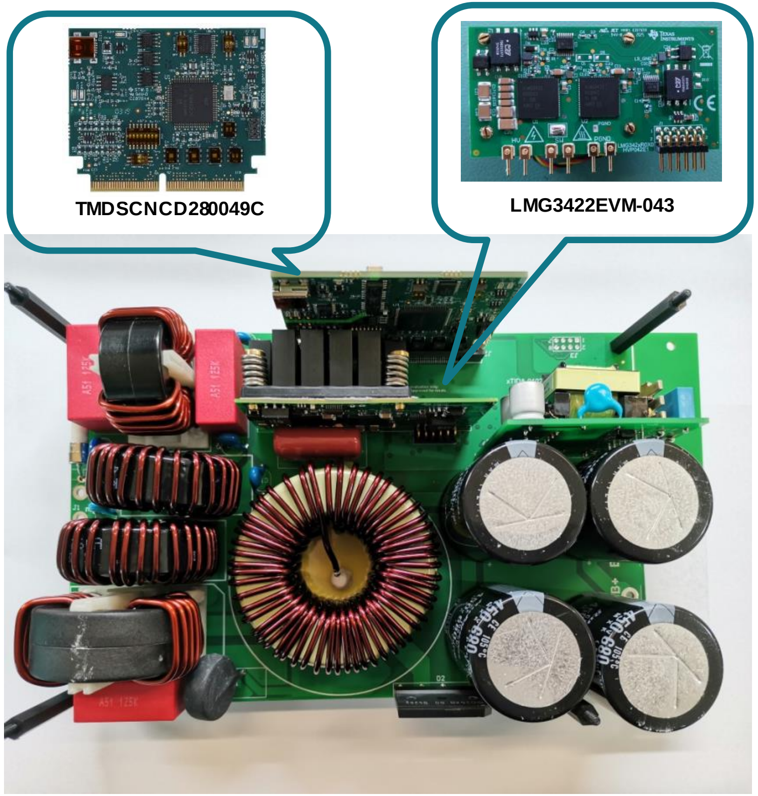


Loss Comparison at Full Load: 4kW

4-kW single-phase CCM totem-pole PFC



Key parameters	Key specification
Input range	200 V_{AC}-277 V_{AC}
Nominal input	230 V_{AC}
DC link voltage	400 V_{DC}
GaN HEMT (Q1/Q2)	LMG342xR030
Switching frequency	50 kHz

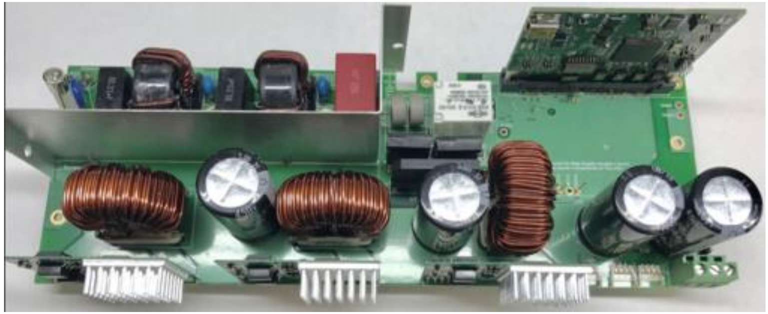


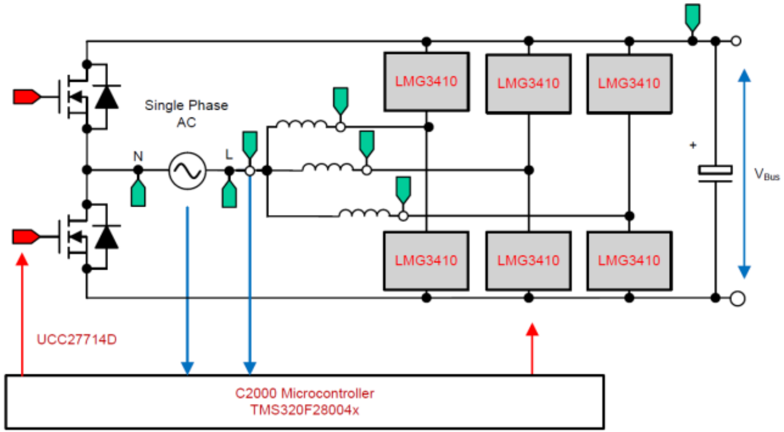
Phase shedding for higher light load efficiency

Features

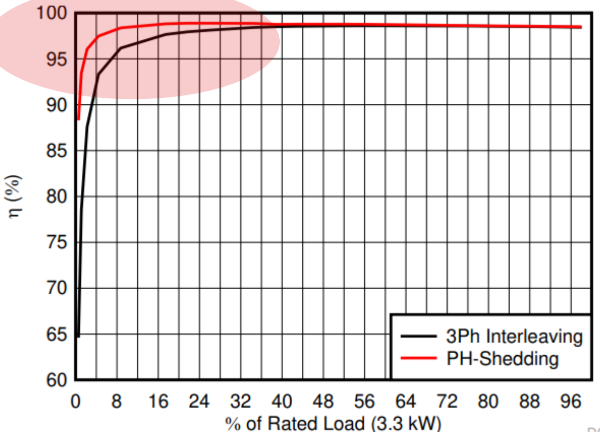
- **TI GaN-based** 3-phase interleaved totem pole bidirectional PFC
- Rated Power : 3.3 kW (at 230 V_{rms})
- Peak efficiency : 98.7 % (at 230 V_{rms})
- Total Harmonic Distortion (THD) < 2% (at low line)
- PWM switching frequency : 100 kHz
- Phase shedding control for higher efficiency

Bidirectional 3.3kW CCM Totem Pole PFC



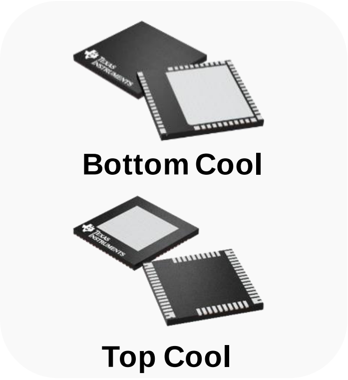


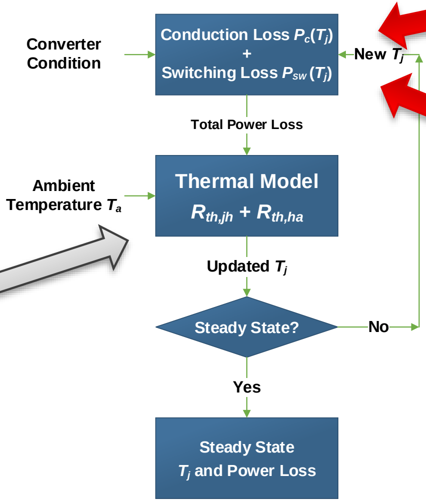
Phase shedding control for higher efficiency at light load



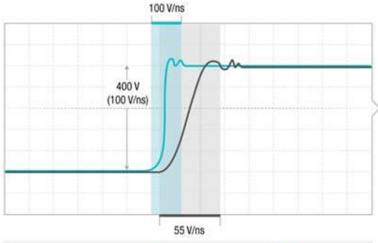
Summary: CCM TP PFC Design with TI GaN

- TI GaN provides different QFN package variants for optimized thermal design at full power and max T_a.
- TI GaN's 30 V/ns to 150 V/ns adjustable slew rate provides a design flexibility to optimize the system efficiency and help on thermal design.
- TI GaN provides a variety of on-resistance to optimize the system design at different switching frequency.





TI GaN with Different $R_{ds,on}$



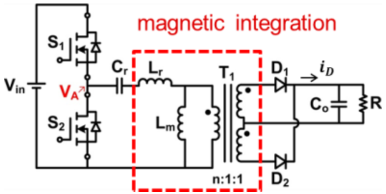
Up to 150 V/ns Slew Rate

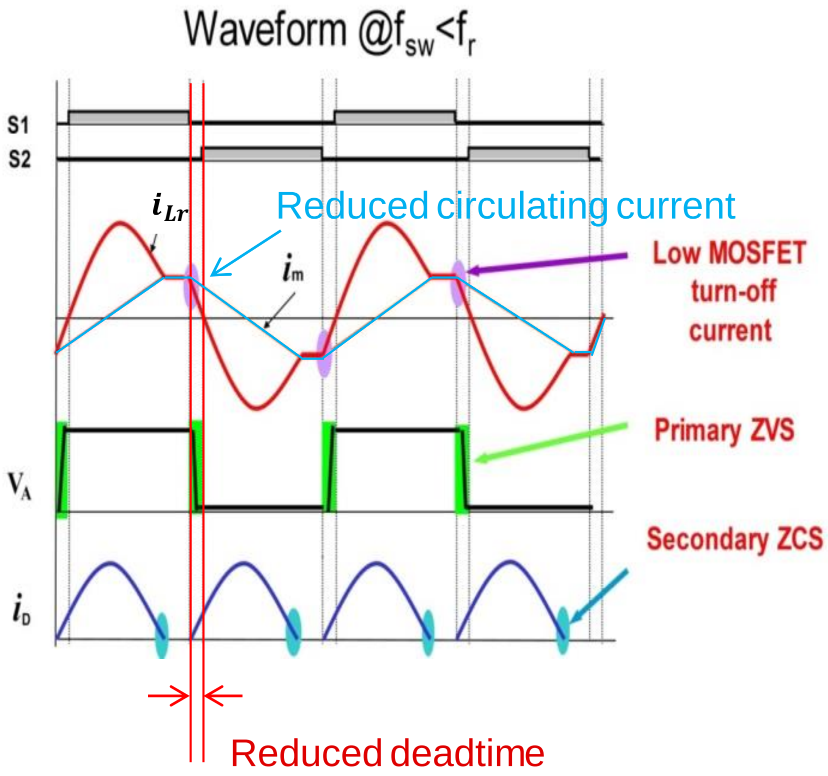
Outline

- TI GaN: Integrated for high-frequency operation
- Applications driving for higher efficiency and density
  - Information technology power supplies
  - Automotive onboard chargers
- TI GaN for power factor correction (PFC) design
- TI GaN for DC/DC converter design
- TI GaN reference design and tools

TI GaN: superior solution for soft-switching DC/DC

- **Reduced output capacitance C_{OSS}**
  - Reduces dead-time, increasing the time when current delivered to the output
  - Low transformer magnetizing current to minimize circulating current loss & eddy loss.
- **Reduced gate driver losses**
- **High power density in system**
  - GaN enables higher switching frequency to reduce magnetic components, and enables further magnetic integration.





1-MHz Isolated LLC DC/DC converter with TI GaN

	Design target
Input voltage (V)	380 ~ 400 V
Output voltage (V)	48 V Nom unregulated
Power (W)	1000 W
Integrated Transformer size (mm)	33 x 53 x 43
Power density	140 W/in3 (8.5 W/cm3) High power density
Efficiency	>97.5% High Efficiency
Switching frequency	1 MHz High Frequency

[Link to PMP20637]

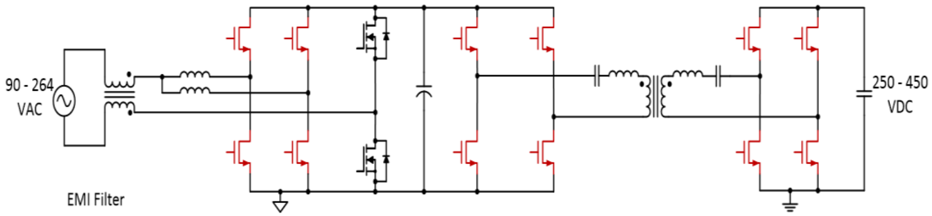
Compared with 100-kHz LLC design, the 1 kW transformer is **6X smaller**

6.6 kW Bidirectional On-Board Charger with TI-GaN

Design Features

- Single TI **C2000** used for control (TMS320F28388D)
- Two phase Interleaved CCM totem-pole bridgeless PFC converter (125kHz)
- CLLLC DC-DC Converter (**200-800 kHz**), <100ns dead-time
- 250 to 450V output (battery voltage range)
- Liquid cooled heatsink
- Integrated active EMI filter circuit
- Total Size ~ 113mm (w) x 271mm (l) x 58.4mm (h)

CCM Totem Pole PFC **Resonant CLLLC**



Design Benefits

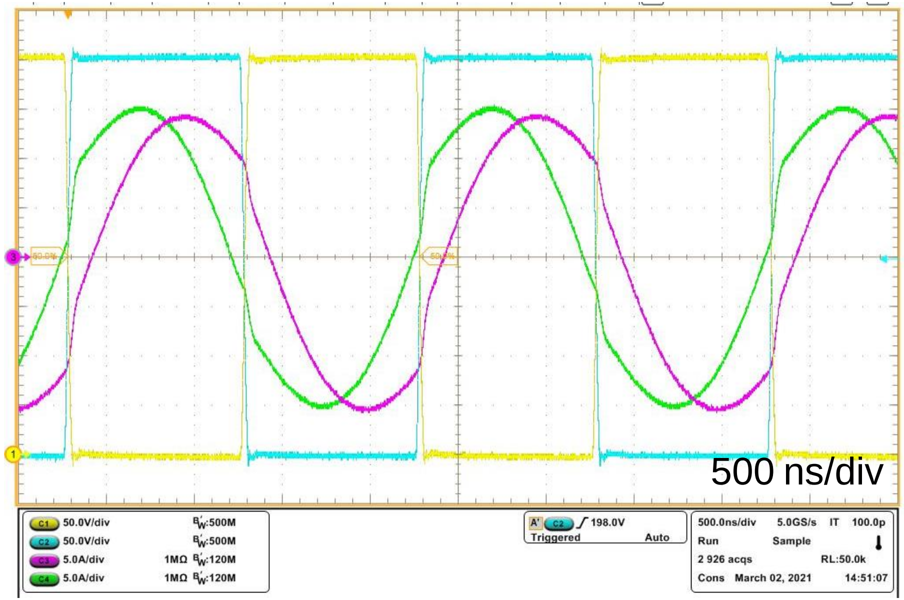
- Higher power density and lower solution cost **than SiC**.
- **59% smaller DC/DC magnetics** offering lower cost.

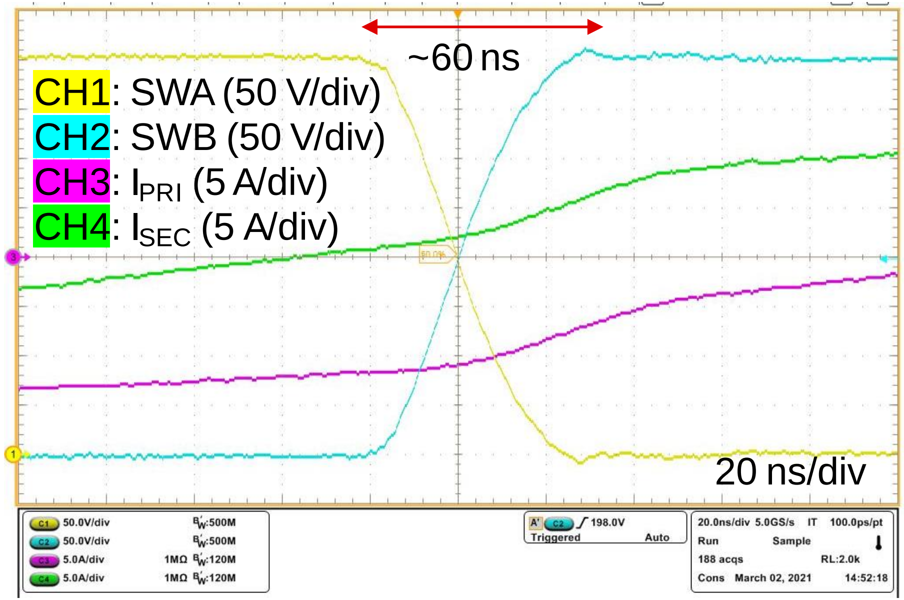
Typical Operating conditions		SiC	TI-GaN
PFC Switching Frequency (kHz)		67	**125**
DC-DC Switching Frequency (kHz)		<300	**~500**
Open frame Power Density	(W/in³)	54	**62.5**
	(kW/liter)	3.3	**3.8**
Efficiency (%)		96.5	**97+**

	65kHz Totem Pole PFC	120kHz Totem Pole PFC	150-300kHz CLLLC	200-800kHz CLLLC
Magnetic volume	149 cm^3	119 cm^3 (~25 % smaller)	166 cm^3	69 cm^3 (~60 % smaller)

Soft switching waveforms in CLLLC

- Conditions: V_{in} = 400 V, V_{out} = 354 V, I_{out} = 10 A, f_{sw} = 500kHz.

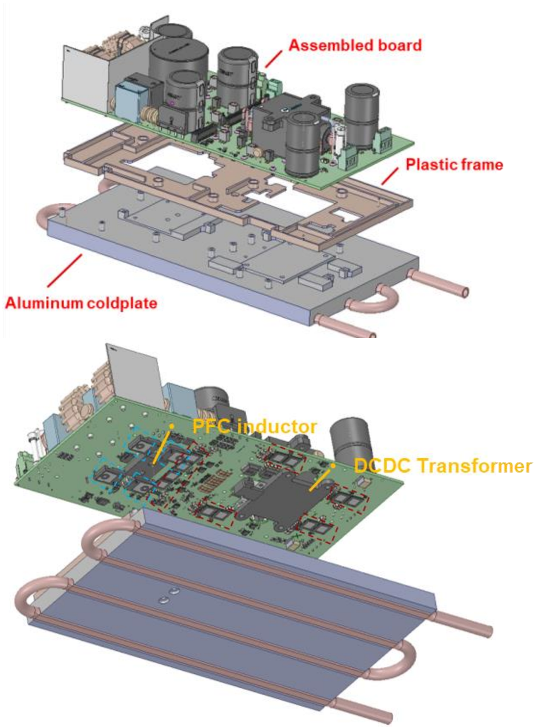


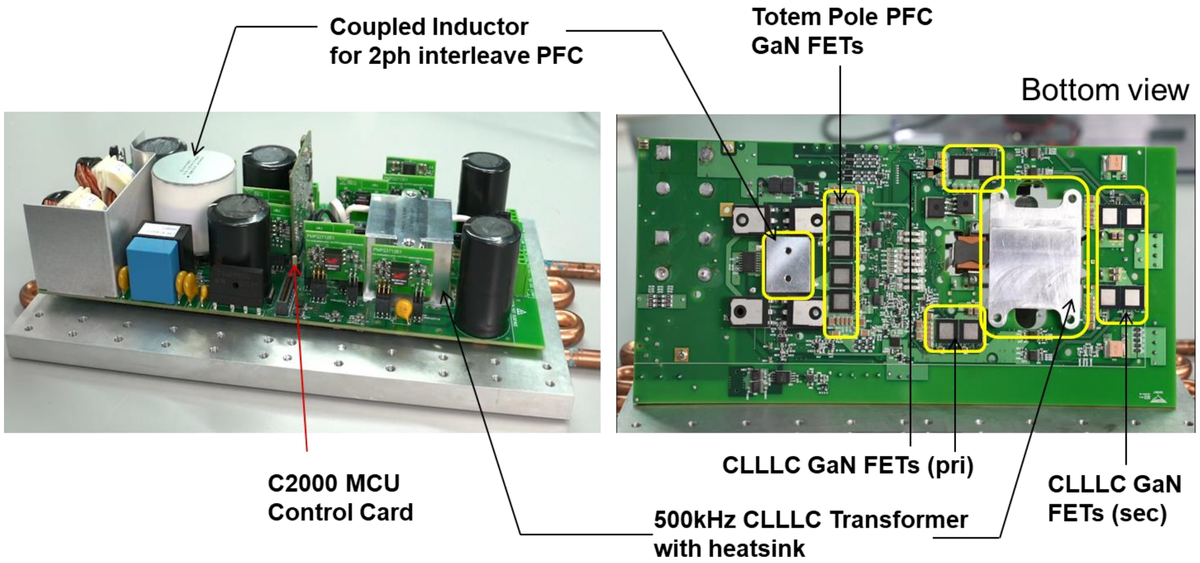


Low $C_{OSS(tr)}$ of TI GaN enables ZVS with ~60 ns deadtime

Cooling design for top-cooled device: 6.6kW OBC

- 12 GaN FETs (tsQFN12x12), 4 Si FET (TO-247), PFC inductor and DC/DC transformer are cooled by one aluminum coldplate.

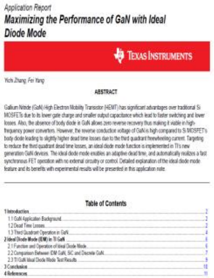




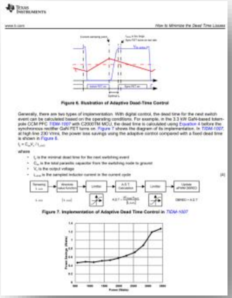
Additional resources and tools

App notes

TI GaN Ideal Diode Mode [Link]

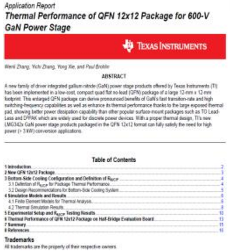


TI GaN 3rd Quadrant Operation [Link]



TI GaN Direct Drive [Link]

Thermal Design [Link]

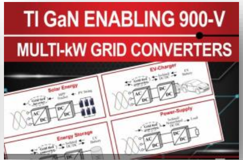


Training videos

[Link]

[Link]

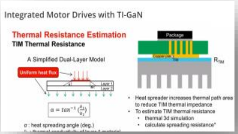
[Link]



[Link]

[Link]

Motor Drive Training



[Link]

Design tools

GaN reference designs

99% efficient 3-phase inverter

1MHz 1.6kW CrM Totem Pole PFC

Bidirectional 3.3kW CCM Totem Pole PFC

GaN plug-in daughter cards

LMG3411R050 Daughter Card

LMG3422R030 Daughter Card

LMG3522R030 Daughter Card

GaN Buck-Boost Motherboard

ti.com/gan