Single-stage Power Converter Enabled by GaN Bidirectional Switches

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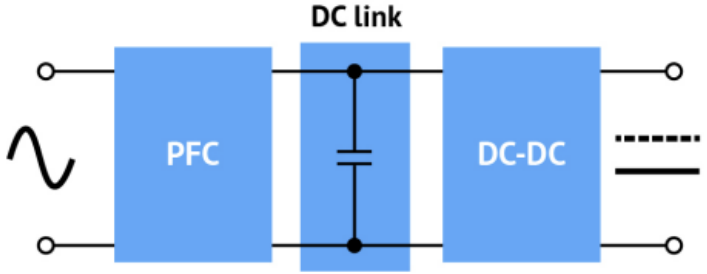
Navitas

Presentation Number IS027.4 from APEC Program

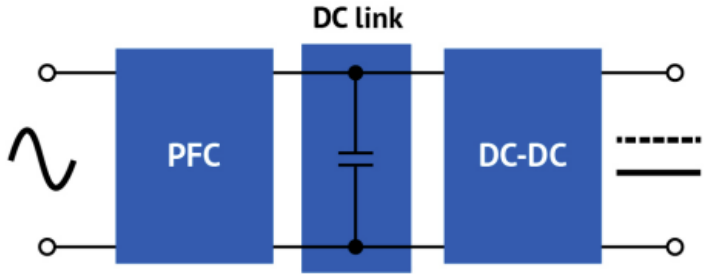
Single-stage Topology Advantage

Traditional Two-Stage with Si Uni-Directional Devices



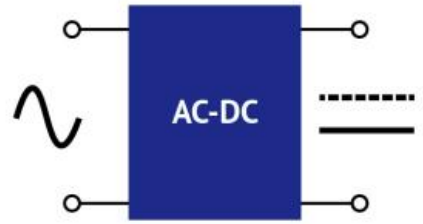
- Inefficient
- Low power density
- Higher costs
- Low frequency

Latest Two-Stage with GaN/SiC Uni-Directional Devices



- Medium frequencies
- 20-30% energy savings
- 20-30% higher density
- 0-20% more expensive

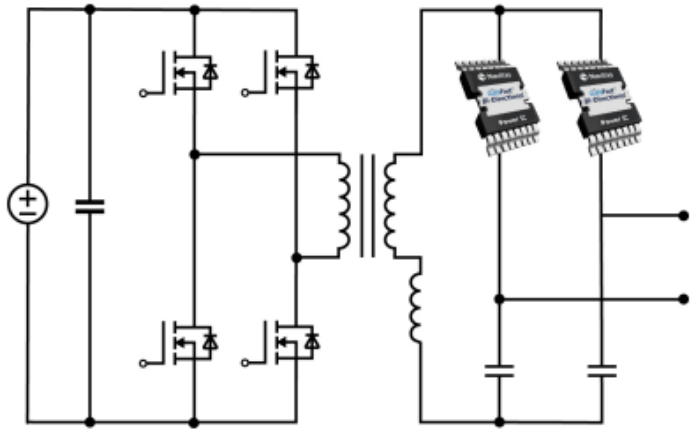
New Single-Stage with Bi-Directional GaN/SiC



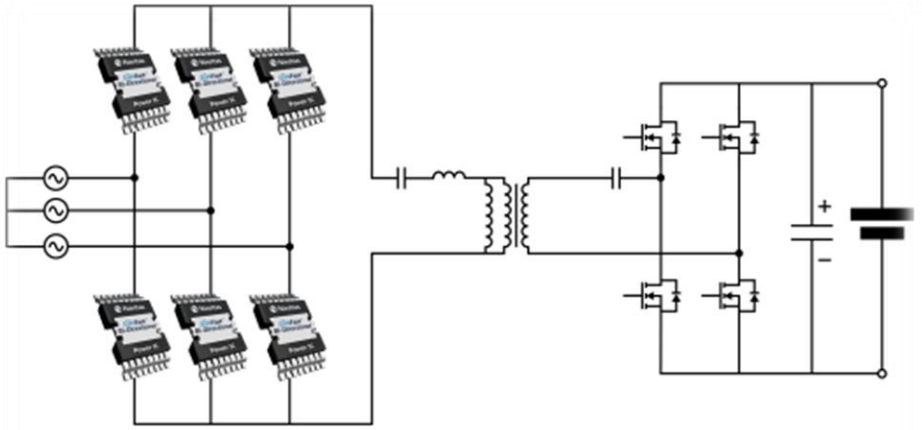
- Inherently bi-directional
- Eliminates PFC stage
- Eliminates DC Link capacitors
- Enables ultra-high frequencies
- 30% density, size, weight
- 10% energy savings
- 10% system cost savings

- 70% of AC-DC converters use a ‘two-stage’ topology.
  - PFC stage & DC-DC stage with ‘DC-link’ capacitors – Large, lossy, expensive
- Bi-directional GaN consolidates 2-stages into a single, high-speed, high-efficiency stage
  - eliminates bulky capacitors & input inductors

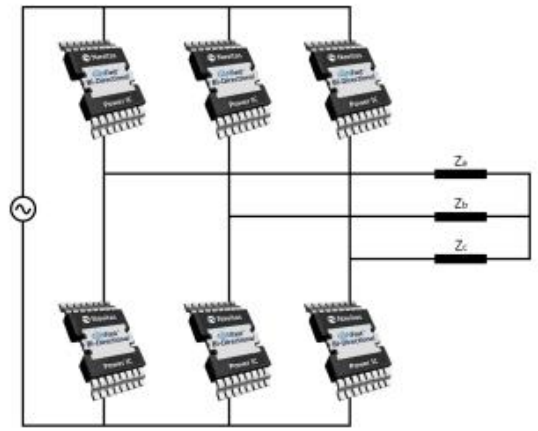
Single-stage Converters



Solar Microinverter



EV On-Board Charger (OBC)

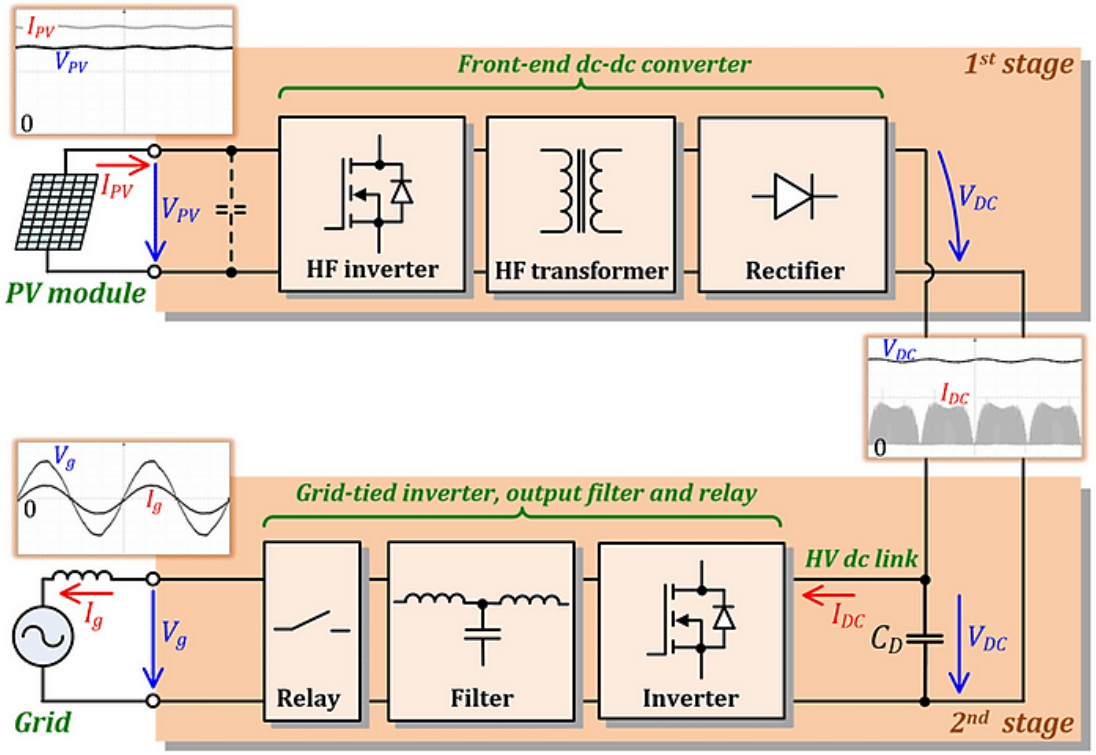


Motor Drives

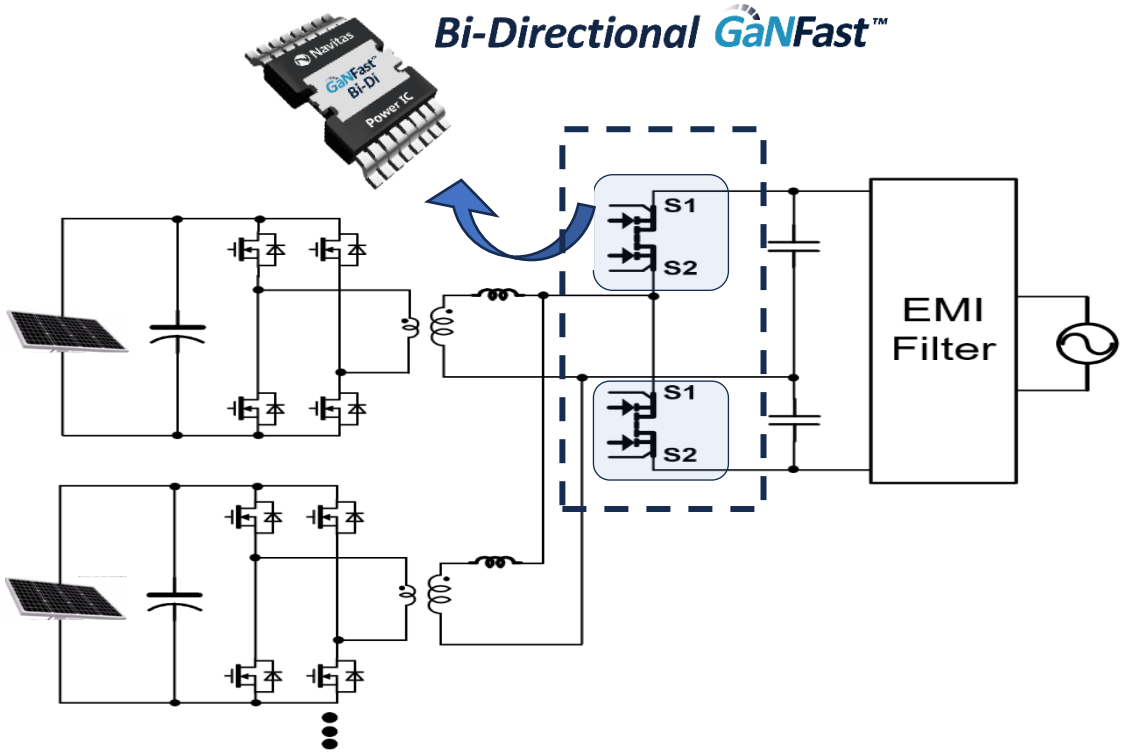
- ***Bi-Directional GaNFast directly converts AC input voltage into a highly-efficient, corrected & controlled AC or DC output voltage.***

Single-stage Converters

Traditional Two-Stage



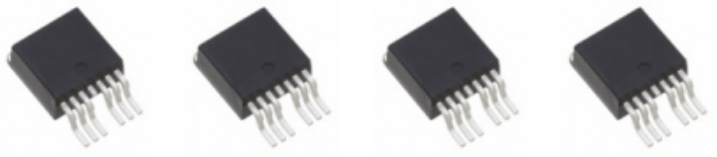
Single-Stage BDS Converter

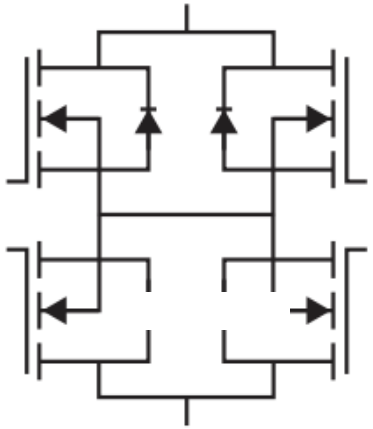


- *30% smaller, lighter & higher density*
- *10% more energy efficient*
- *10% lower system cost*
- *30% higher GaN content*

GaNFast™ Bi-Directional Replaces up to 4 Power Switches

4x Si MOSFETs





- Simplified circuit design
- Reduced component cost
- Reduced PCB area

4 to 1 component reduction

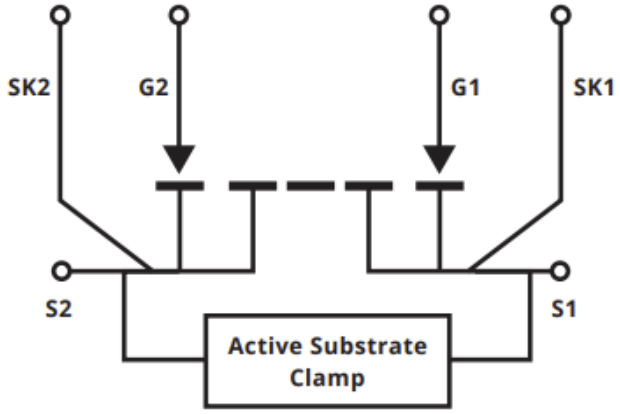
Over 50% footprint reduction

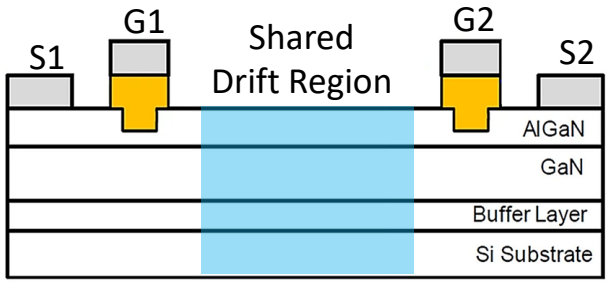
Over 20x lower Q_G & 10x lower C_{oss}

Proprietary integrated substrate clamp

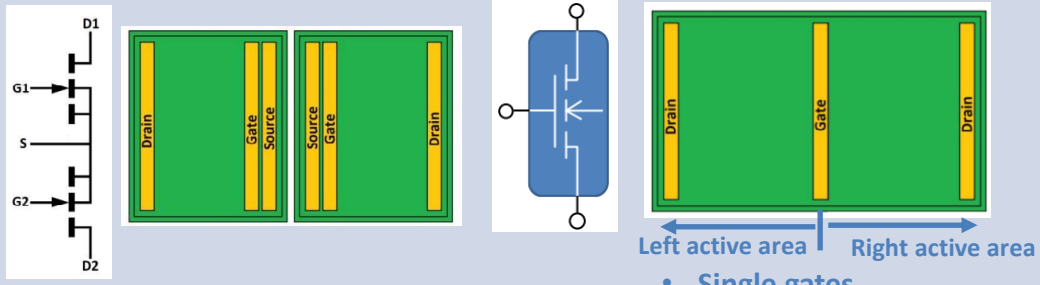
- Higher system efficiency
- MHz switching frequency
- Improves reliability

1x Bi-Directional GaNFast™

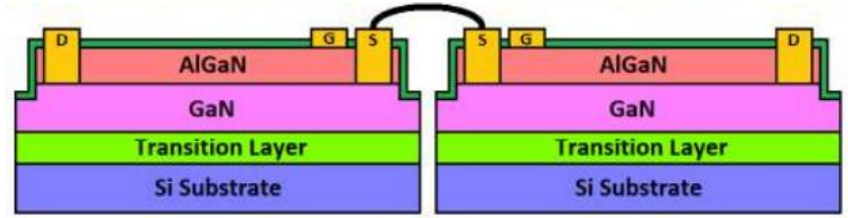




Common Source vs Common Drain

4QS Device	Common Source	Common Drain
Internal structure	 • Single gates	 • Sharing drift region • Two gates
Advantage	✓ Simple Aux power supply ✓ Simple gate driver control	✓ Smaller die size ✓ Almost equal Rdson to single device with bi-directional ✓ Lower switching loss
Disadvantage	× Large die size, two dies × Almost double Rdson to single device with bi-directional	× Complicate Aux power supply × Complicate gate driver control × Substrate termination design

2 x Uni-directional GaN HEMT

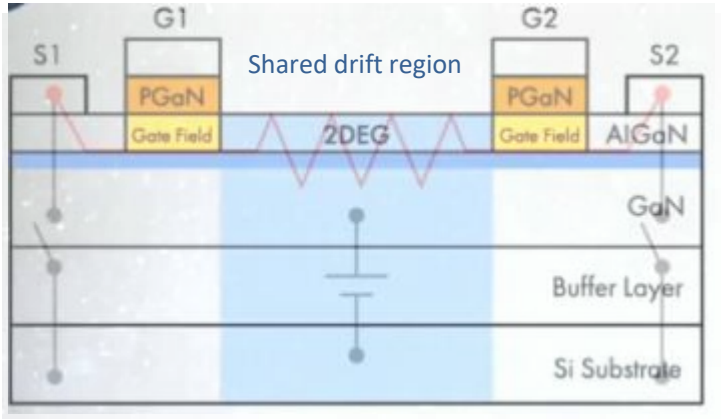


Bi-directional GaN HEMT

- *3x smaller than two Uni-directional GaN*

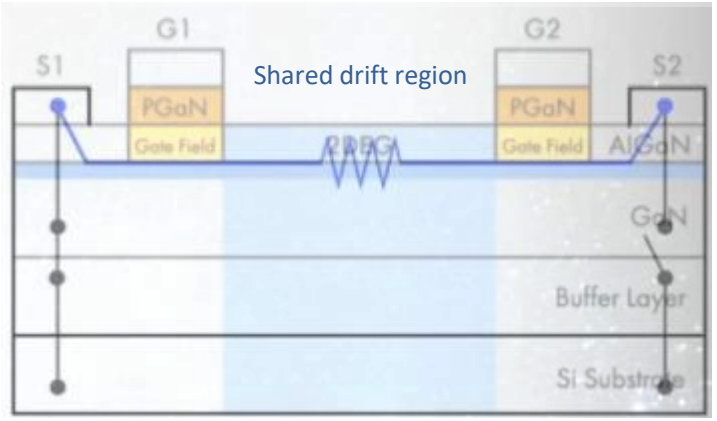
Integrated Active Substrate Clamp

- Navitas patented integrated active substrate clamp
- Automatically connects each Source to the common substrate
- Eliminates a ‘back-gating’ effect, which prevents an undesired increase in RSS(ON) when the substrate potential is uncontrolled.
- This results in a stable RSS(ON) for highest performance, efficiency, & reliability



$R_{DS(ON)}$ 3 x$R_{SS(ON)}$

Negative voltage at Si substrate increases resistance

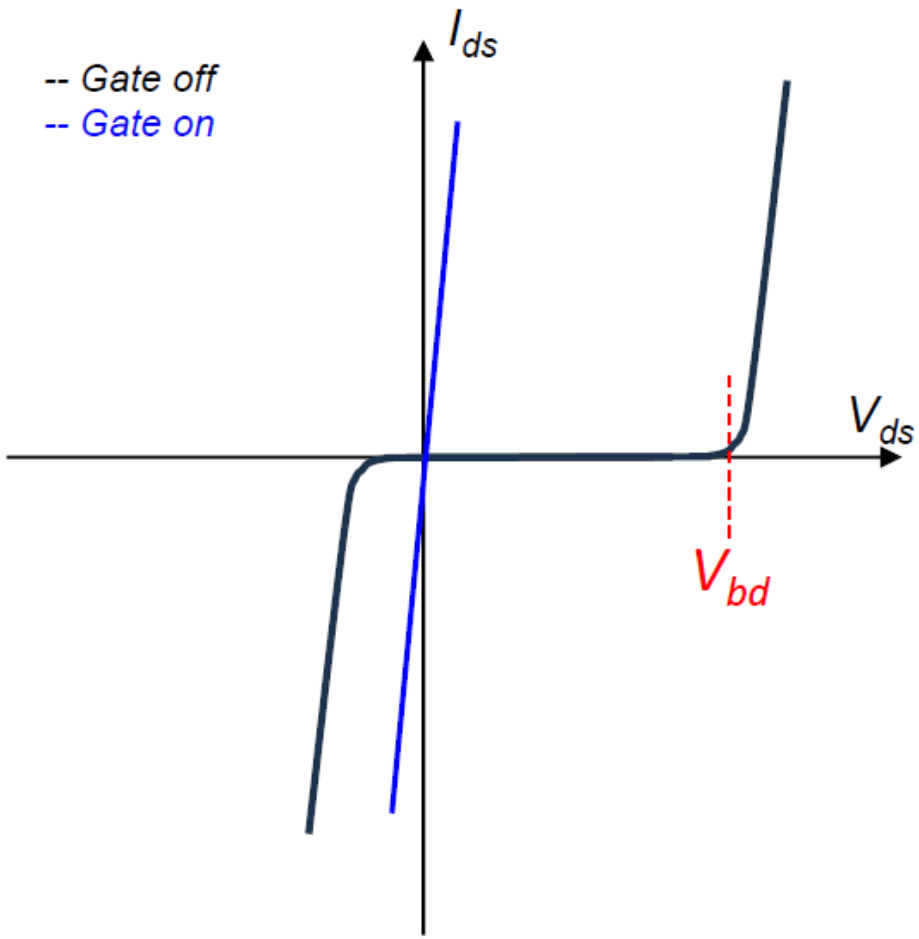


$R_{DS(ON)}$ 1 x$R_{SS(ON)}$

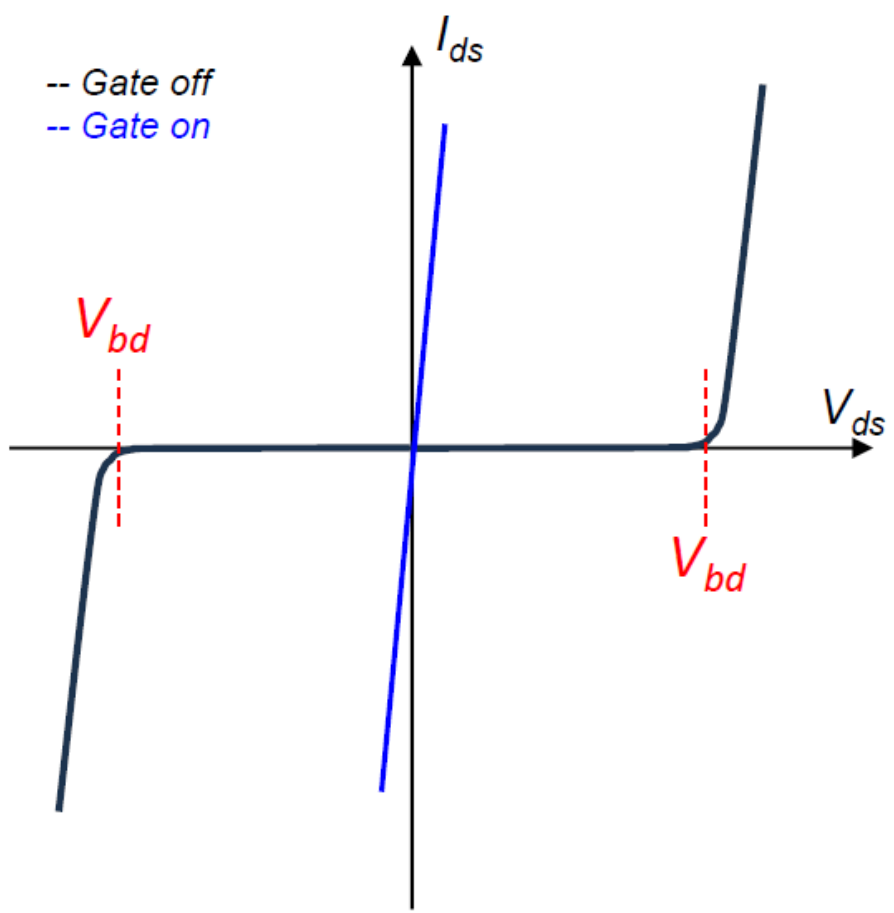
Clamped substrate has no effect on resistance

3x lower R_{DSON} = 15°C cooler!

Characteristic Comparison

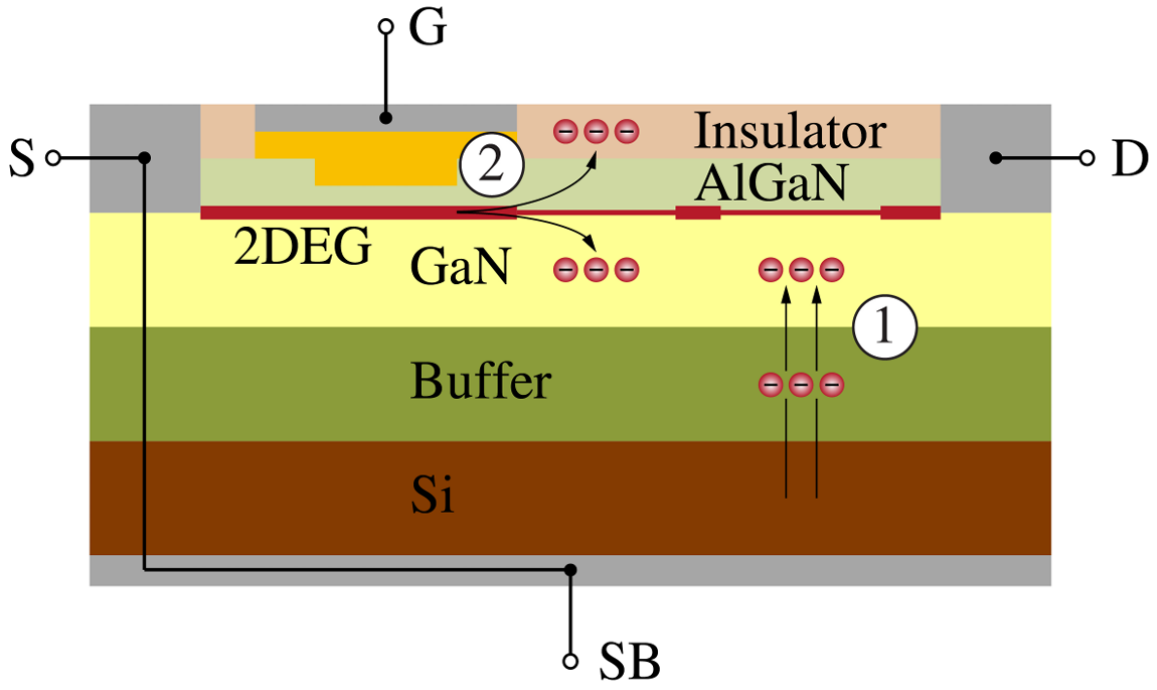


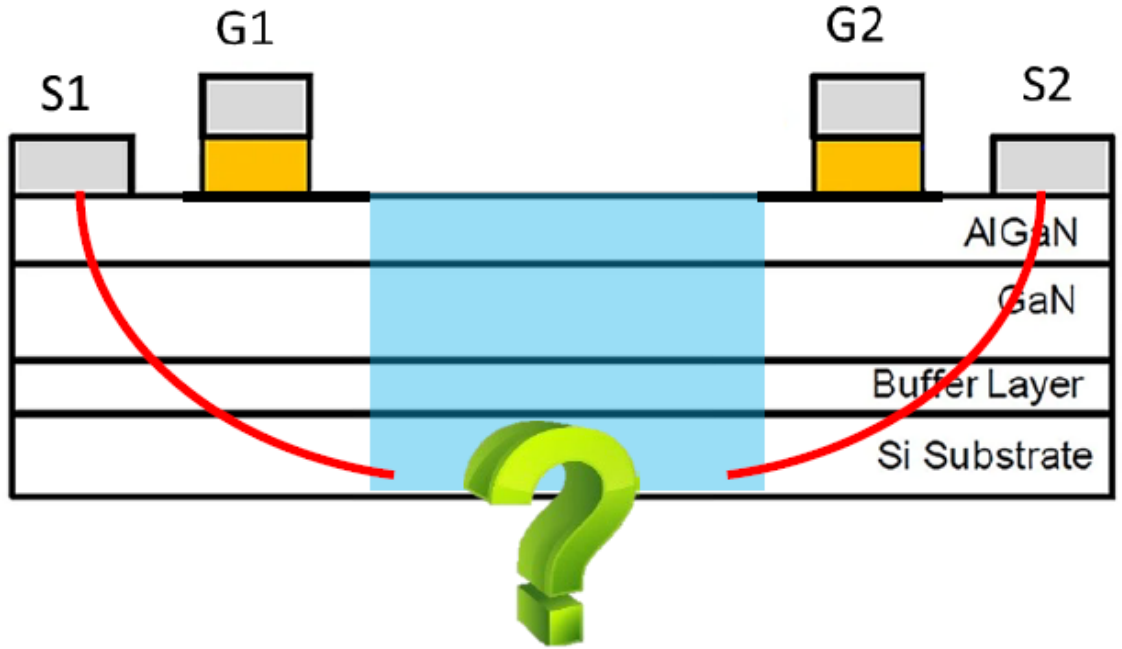
Uni-directional device



Bi-directional device

Substrate Clamp



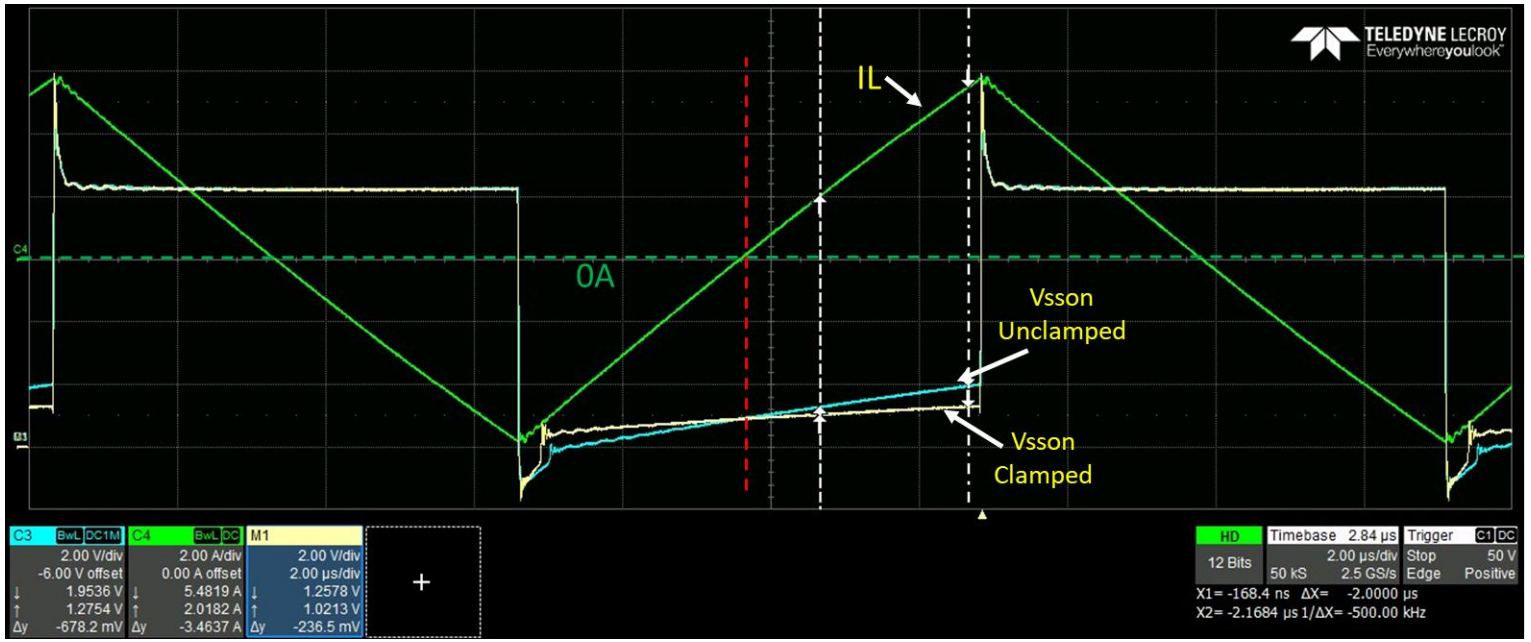


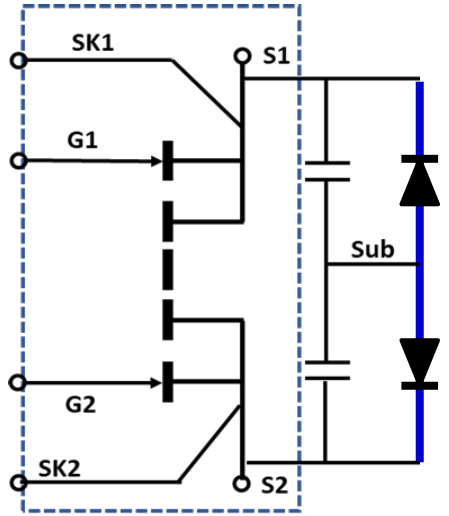
1. Off state trapping
2. Hot-electron trapping[1]

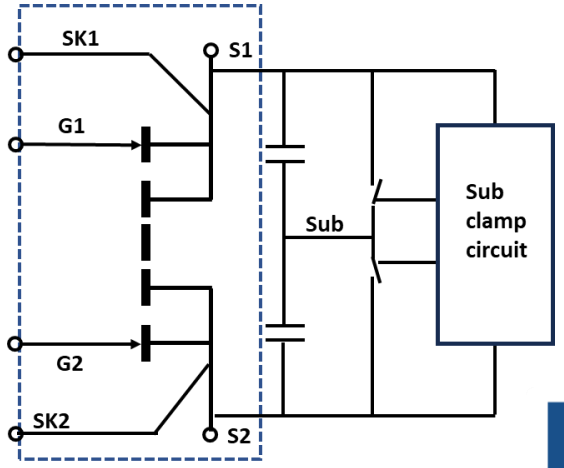
Where should the substrate go?

[1] G. Zulauf, M. Guacci, and J. W. Kolar, "Dynamic on-Resistance in GaN-on-Si HEMTs: Origins, Dependencies, and Future Characterization Frameworks," *IEEE Transactions on Power Electronics*, vol. 35, no. 6, pp. 5581–5588, Jun. 2020.

Active Substrate Management Stabilizes $R_{DS(ON)}$







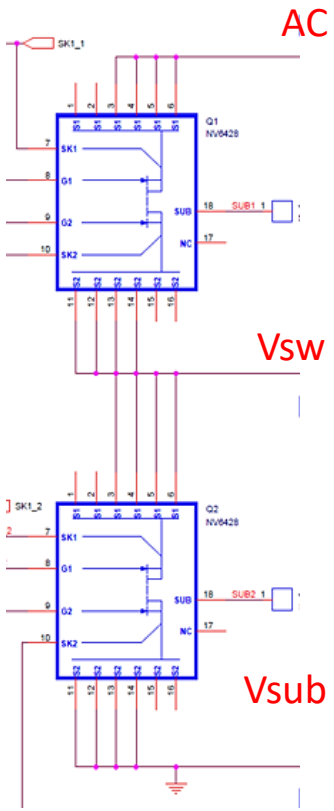
$R_{SS(ON)}$ comparison:

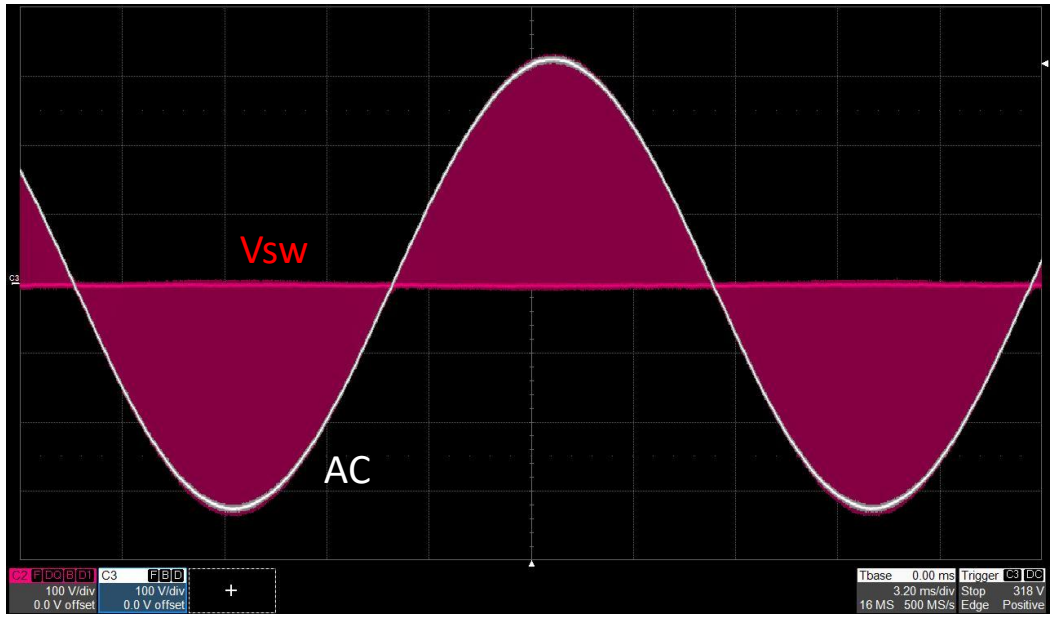
- Unclamped: 196mΩ
- Clamped: 68mΩ

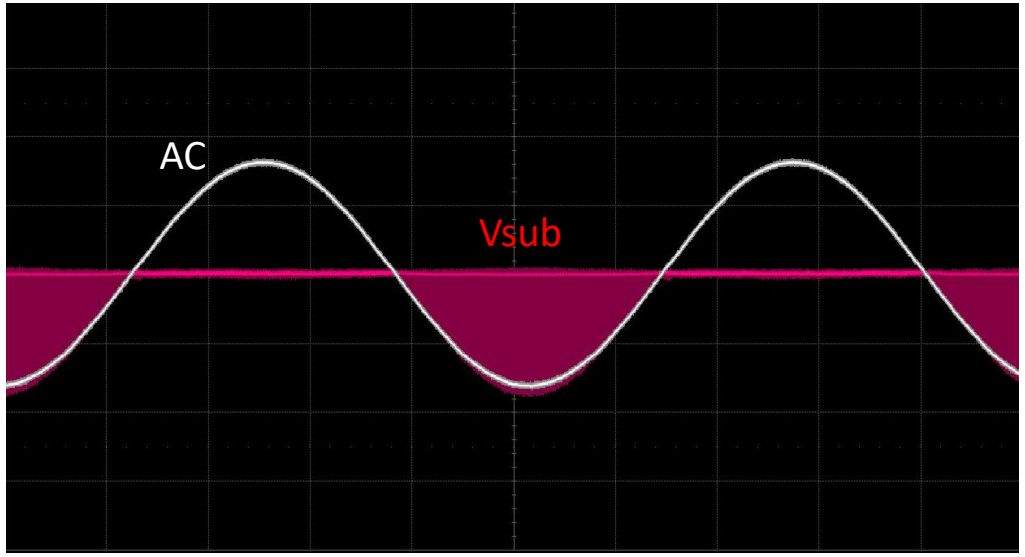
T_{CASE} comparison:

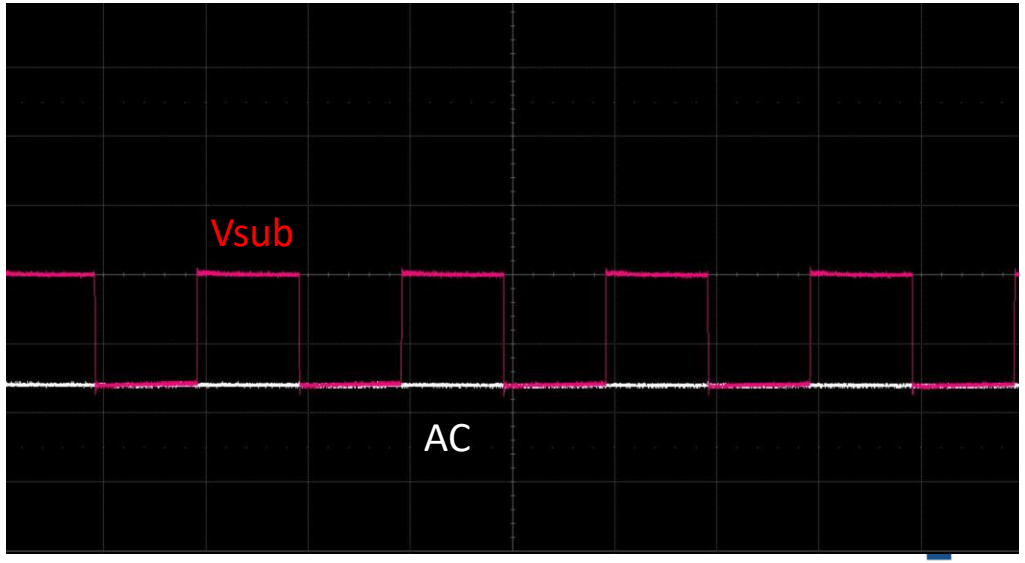
- Unclamped: 76 ^{0}C
- Clamped: 61 ^{0}C

Integrated Substrate Clamp



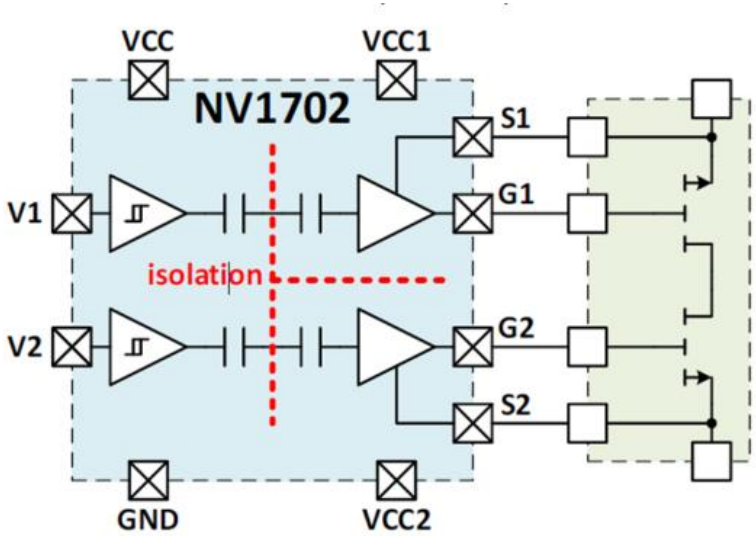


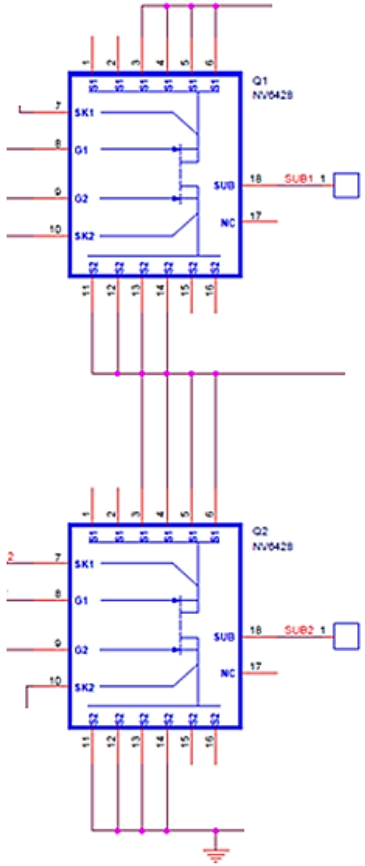




- Substrate connects to the lower source terminal
- Works under all conditions (incl. DC bias)

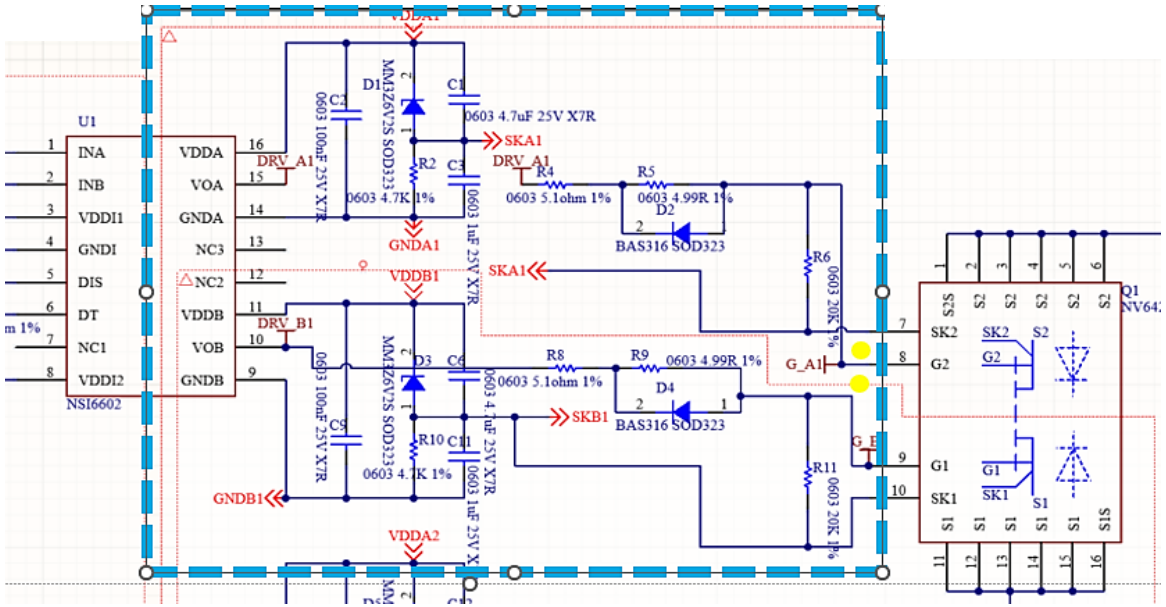
GaN BDS Half Bridge Test Board

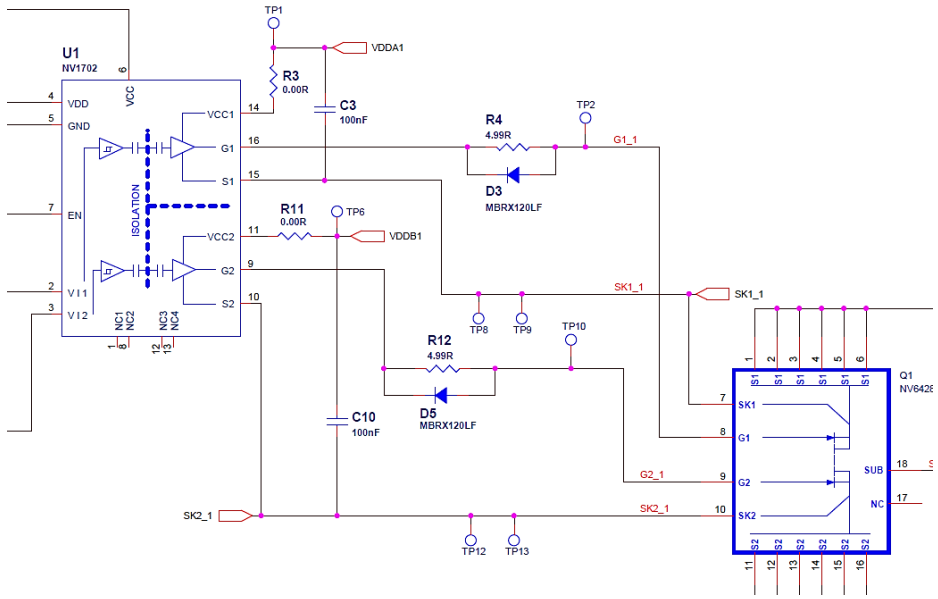




- Four independent gate signals
- 2 channel isolated GaN drivers with regulated gate voltage

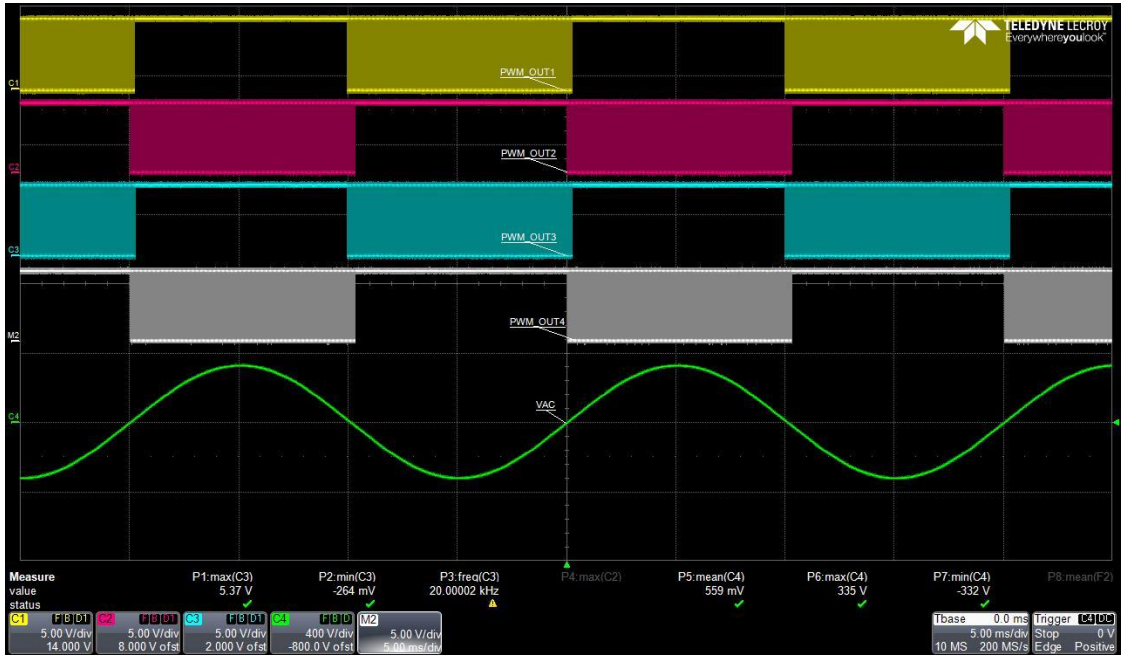
Dedicated Dual Channel Isolator Simplifies GaN Drive

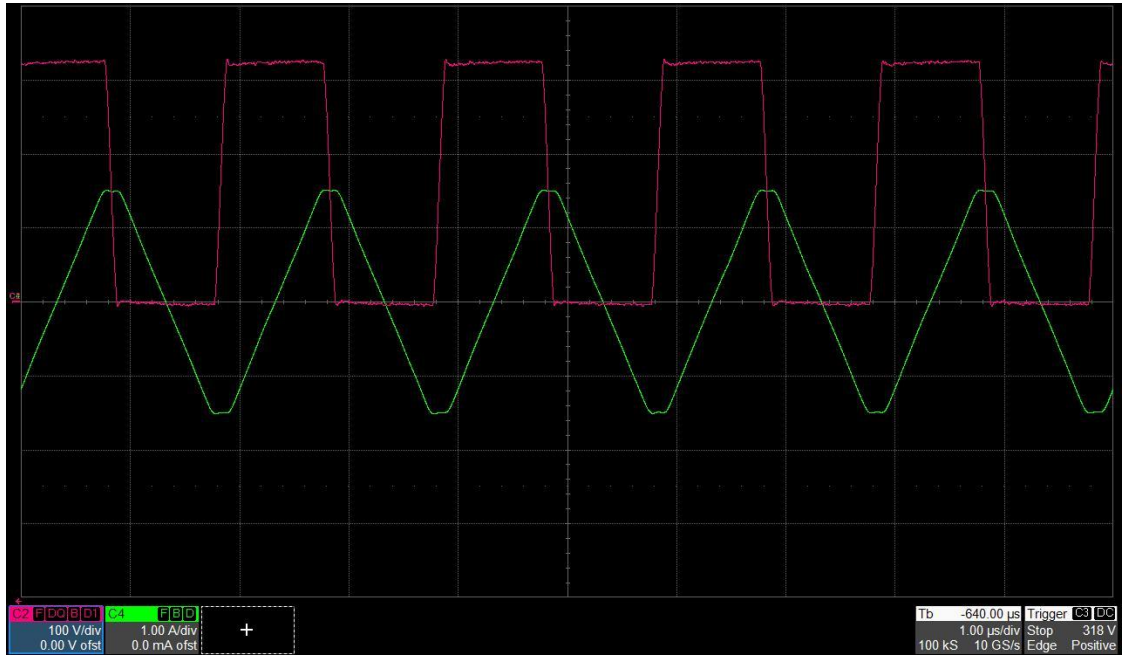




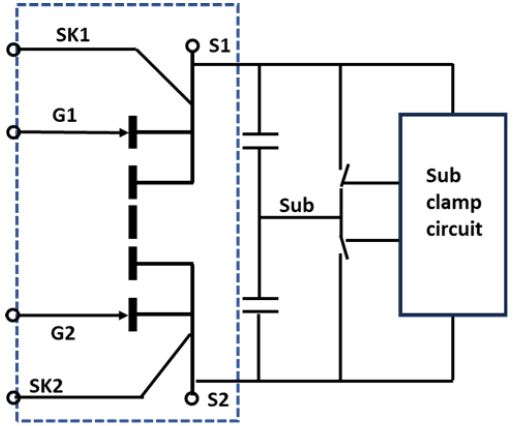
- Regulated 6V gate drive with a wide range of Vcc.
- No need for negative drive. Bootstrap solution possible.

GaN BDS Half Bridge at 500kHz



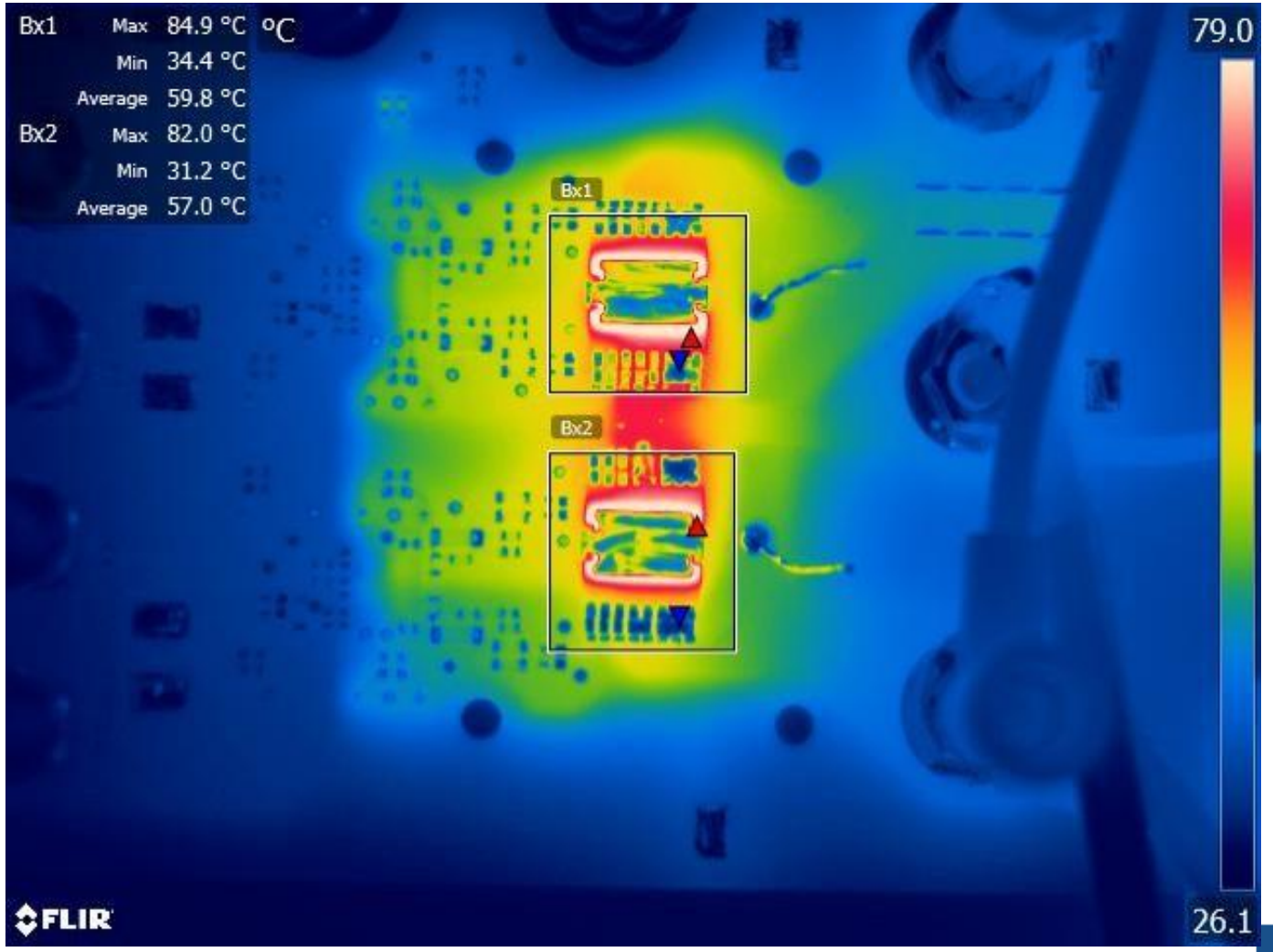


- Clean ZVS switching
- Sync gates stay on during half AC cycles to allow ZVS



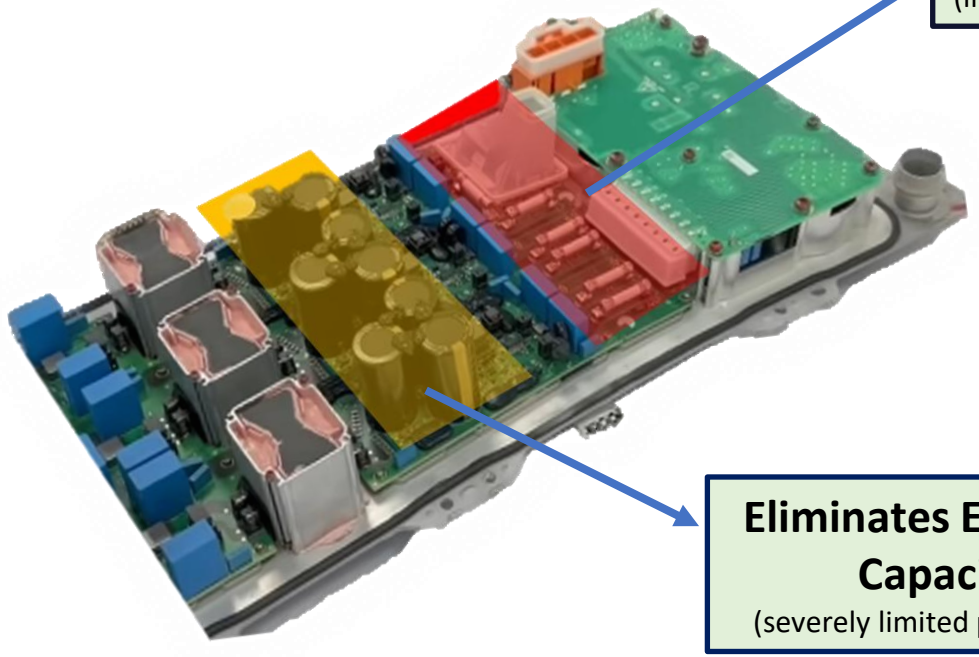
500W GaN BDS Inverter Thermal

- Low T_{CASE} without any heatsink
- Input: 230 Vac
- Fsw: 500 kHz
- Full ZVS, 500 W power stage



Single-stage Bi-Directional Switch (BDS) Converter

Traditional Two-Stage with GaN / SiC



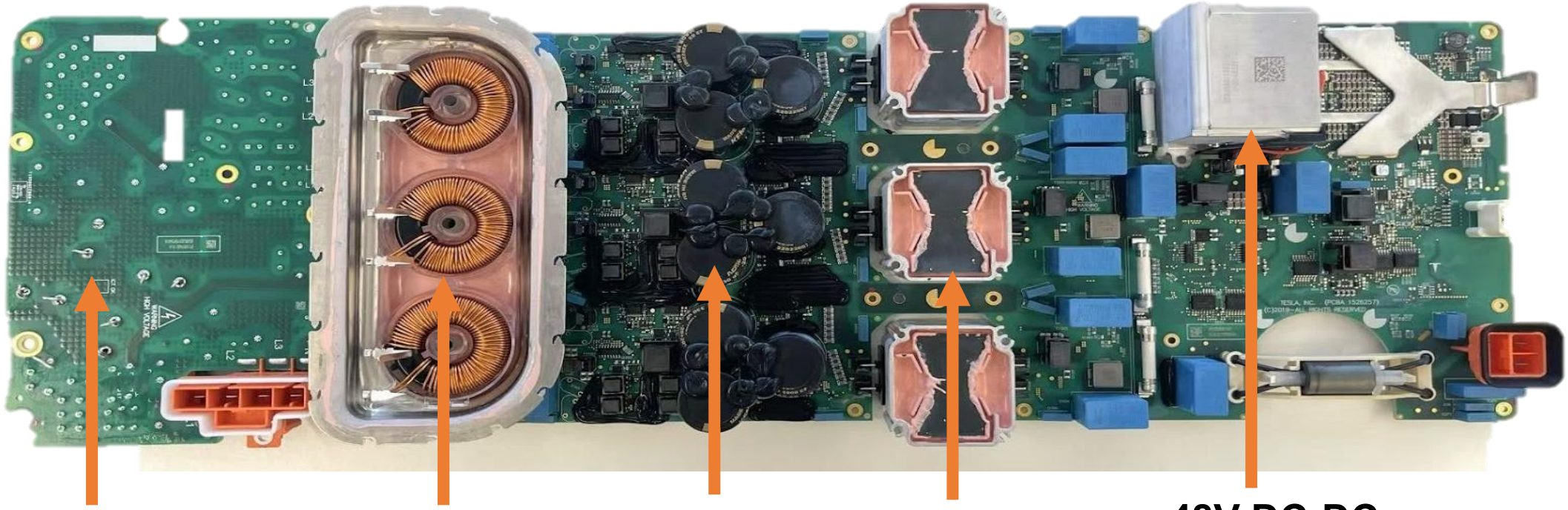
Eliminates PFC Stage
(limited frequency, bulky inductor)

Eliminates Electrolytic Capacitors
(severely limited power density)

Single-Stage Converter with Bi-Directional GaN / SiC

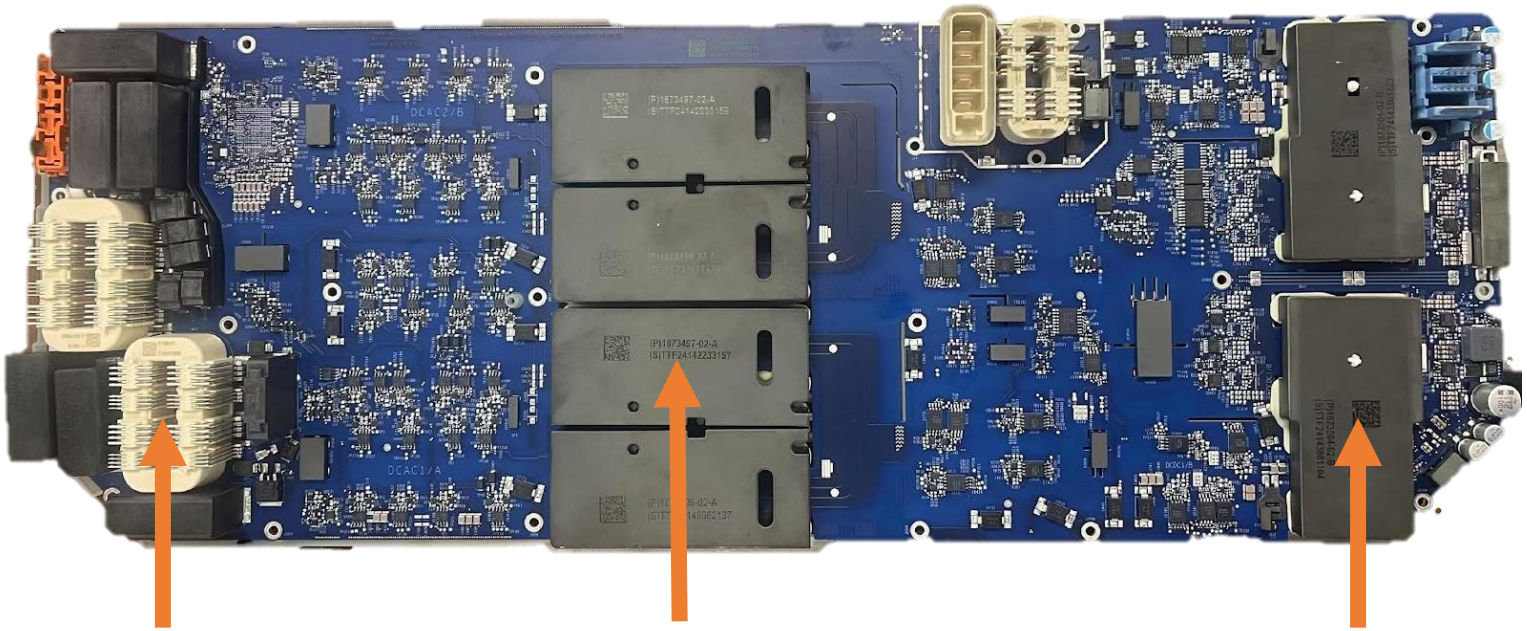
- ***30% smaller, lighter & higher density***
- ***10% more energy efficient***
- ***10% lower system cost***
- ***30% higher GaN/SiC content***

2-stage Converter (11.5 kW OBC)



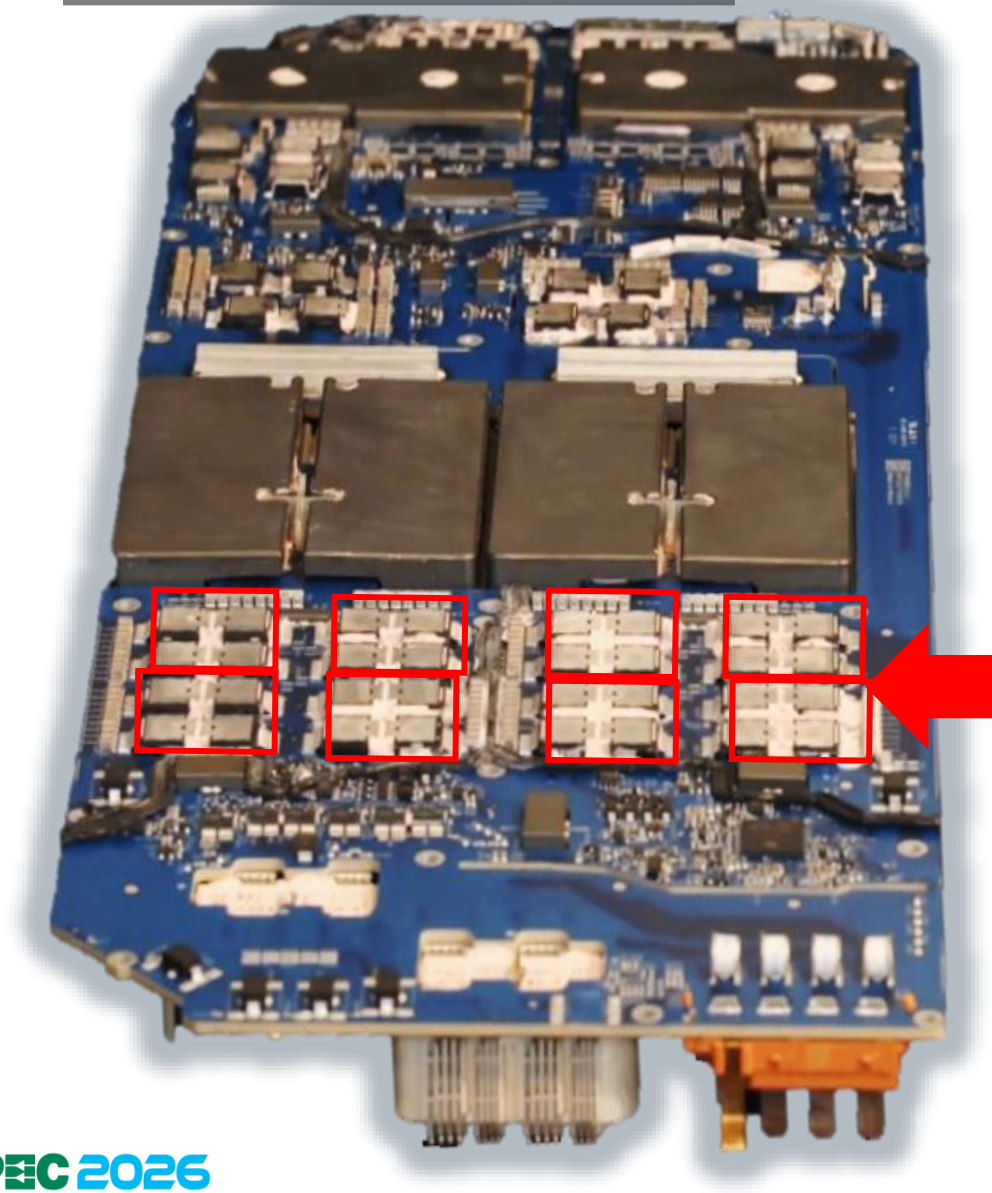
- *Traditional PFC + LLC two stage design*
- *Bulky inductors & capacitors*
- *Many through-hole high profile components*
- *Difficult to heatsink passive components*

Single-stage BDS Converter (11.5 kW OBC)

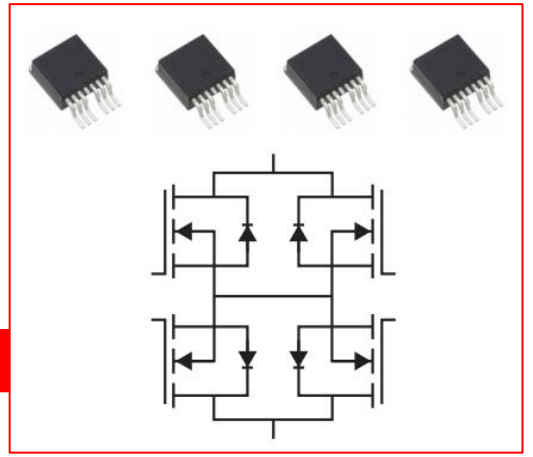


- *High frequency ZVS, planar transformers*
- *No PFC, no bulk inductors and capacitors*
- *100% SMD to reduce assembly cost and profile*
- *Simple thermal management*

Implementing Bi-Directional GaNFast will further reduce system size & cost by 20%



32 x Power switches



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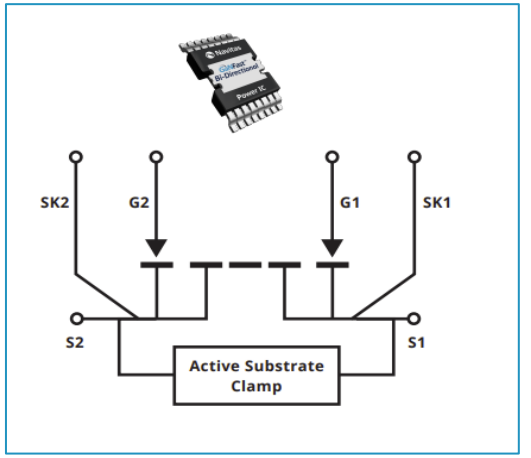
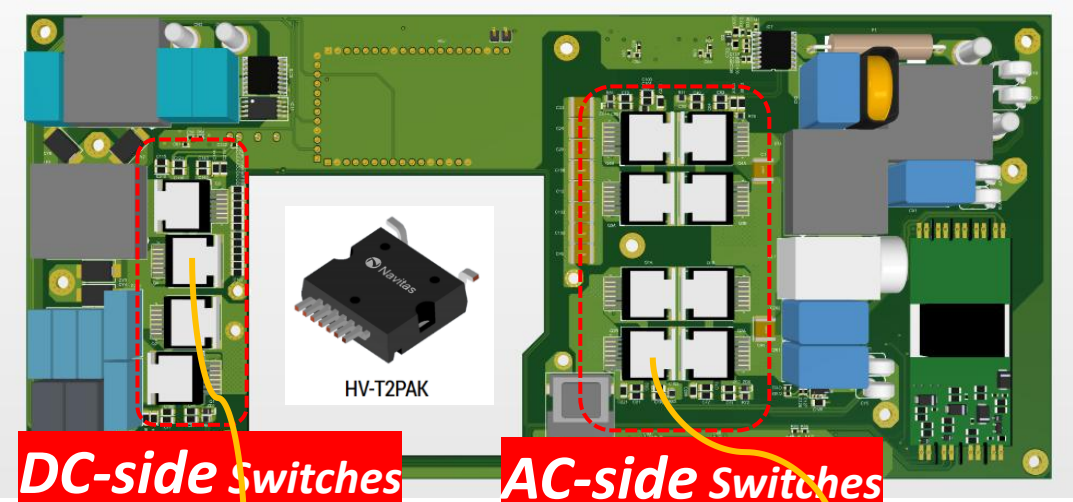
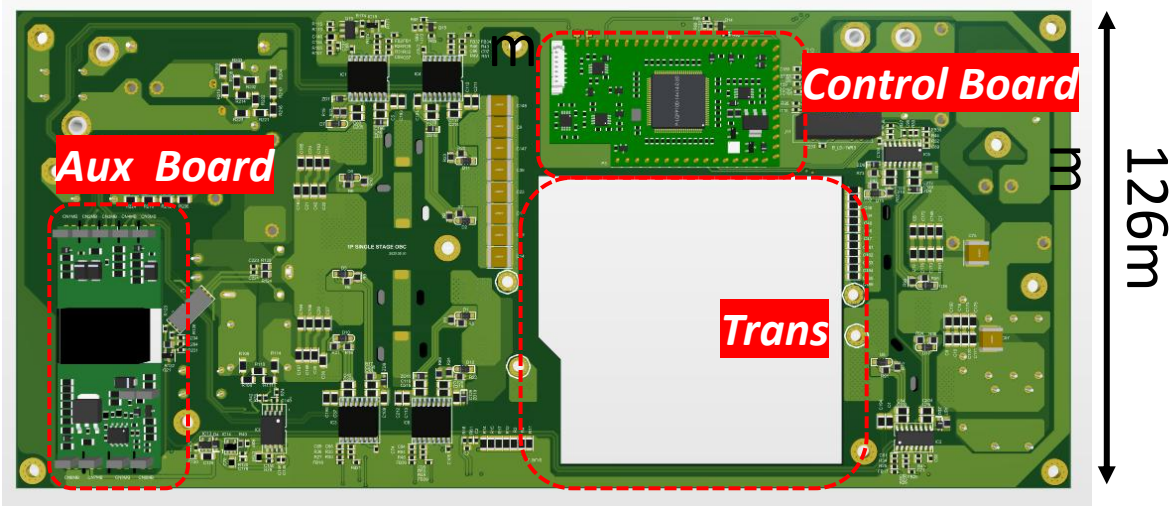
8 x Bi-Directional switches

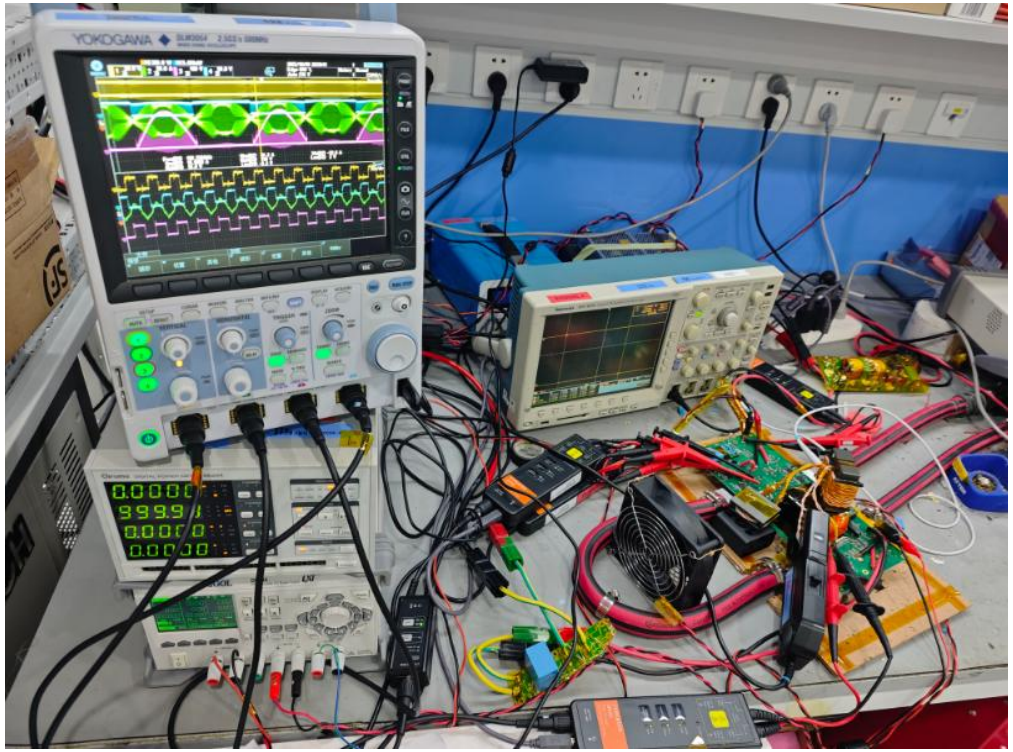


- ***3x higher fsw = 200kHz > 600kHz***
  - *(thinner & smaller magnetics)*
- ***4x lower component power switch count***

6.6kW Single Stage AC/DC





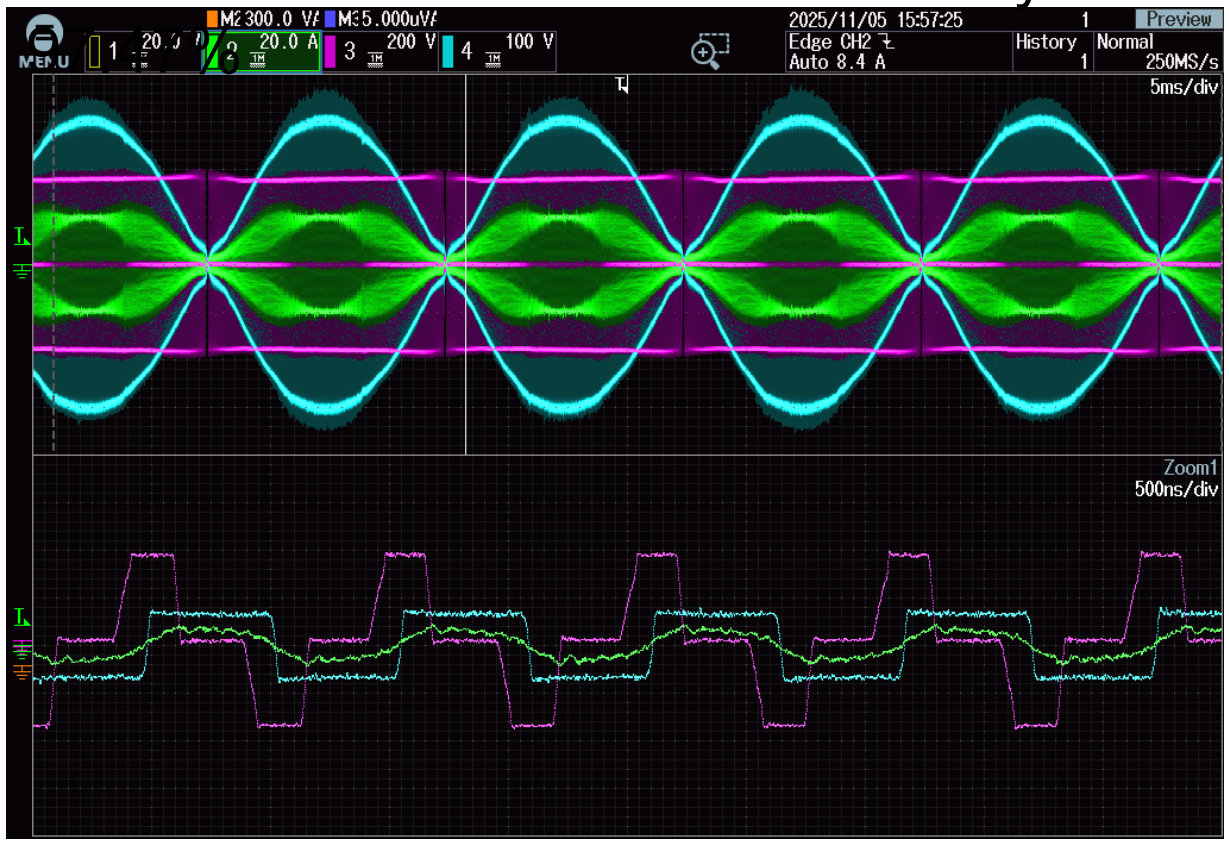


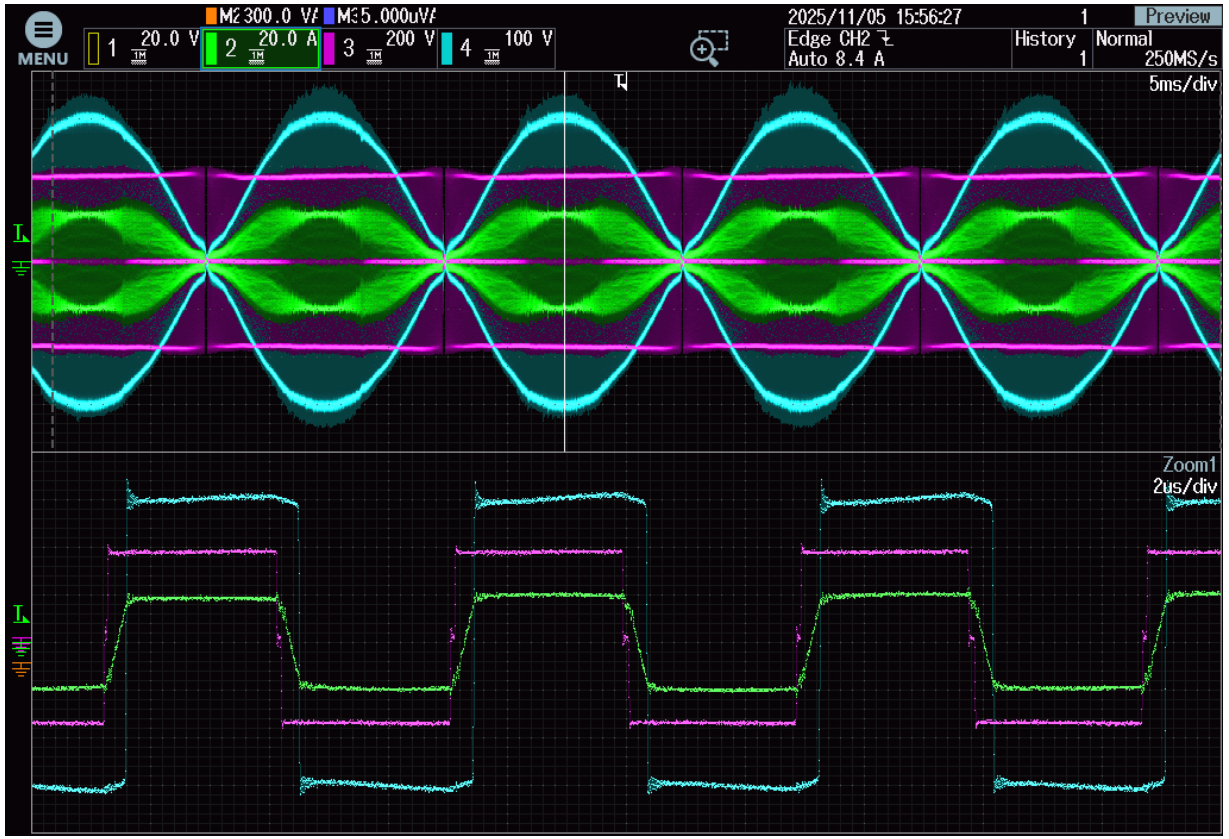
- T2PAK package SiC device
- DSP：TMS320F280039
- Power density：7.5kW/L (Target)
- Peak Efficiency：97%
- Switch Frequency：100k~1Mhz

*The initial workbench uses discrete inductors and transformers.

6.6kW Single Stage AC/DC Waveform

Half Load（3.3kw）： Efficiency





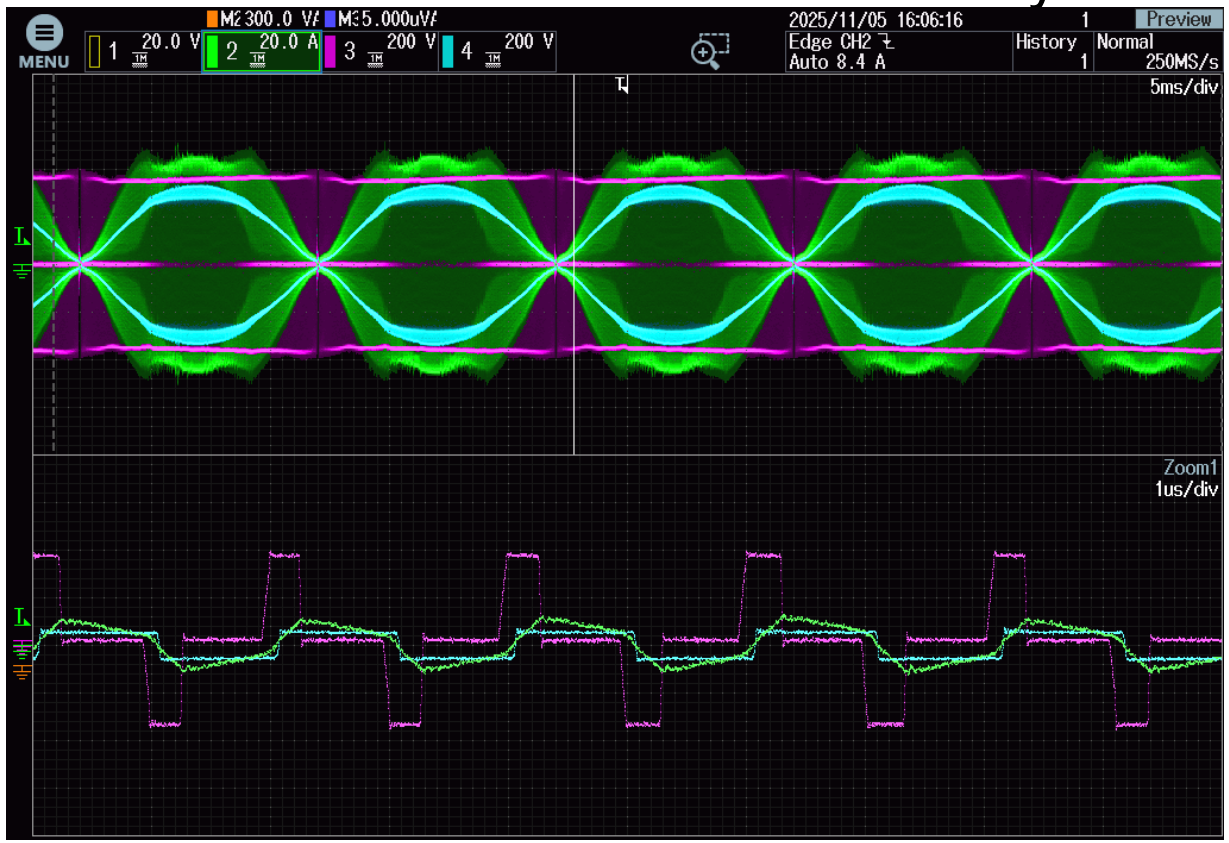
Is(20A/DIV) VtransDC(200V/DIV) VtransAC(100V/DIV)

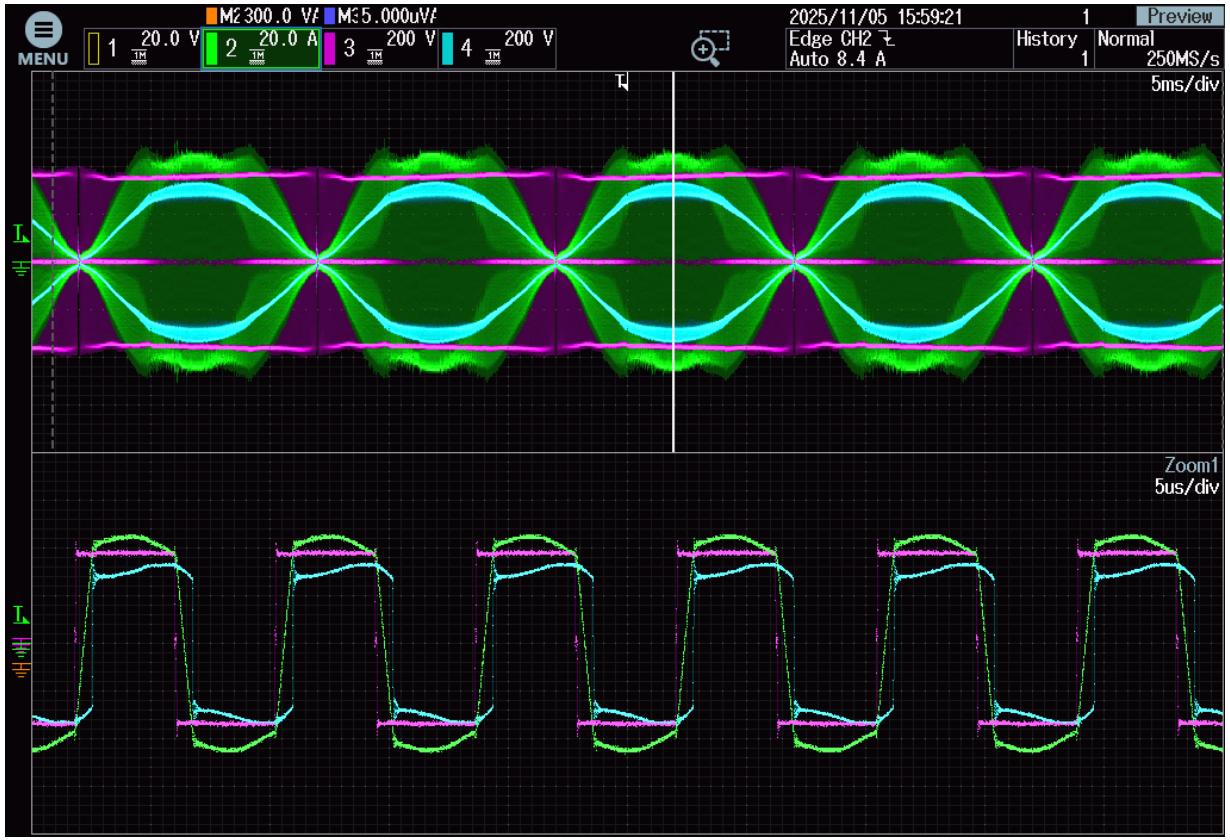
Around Zero Cross

At the AC Peak

6.6kW Single Stage AC/DC Waveform

Full Load（6.6kw）： Efficiency



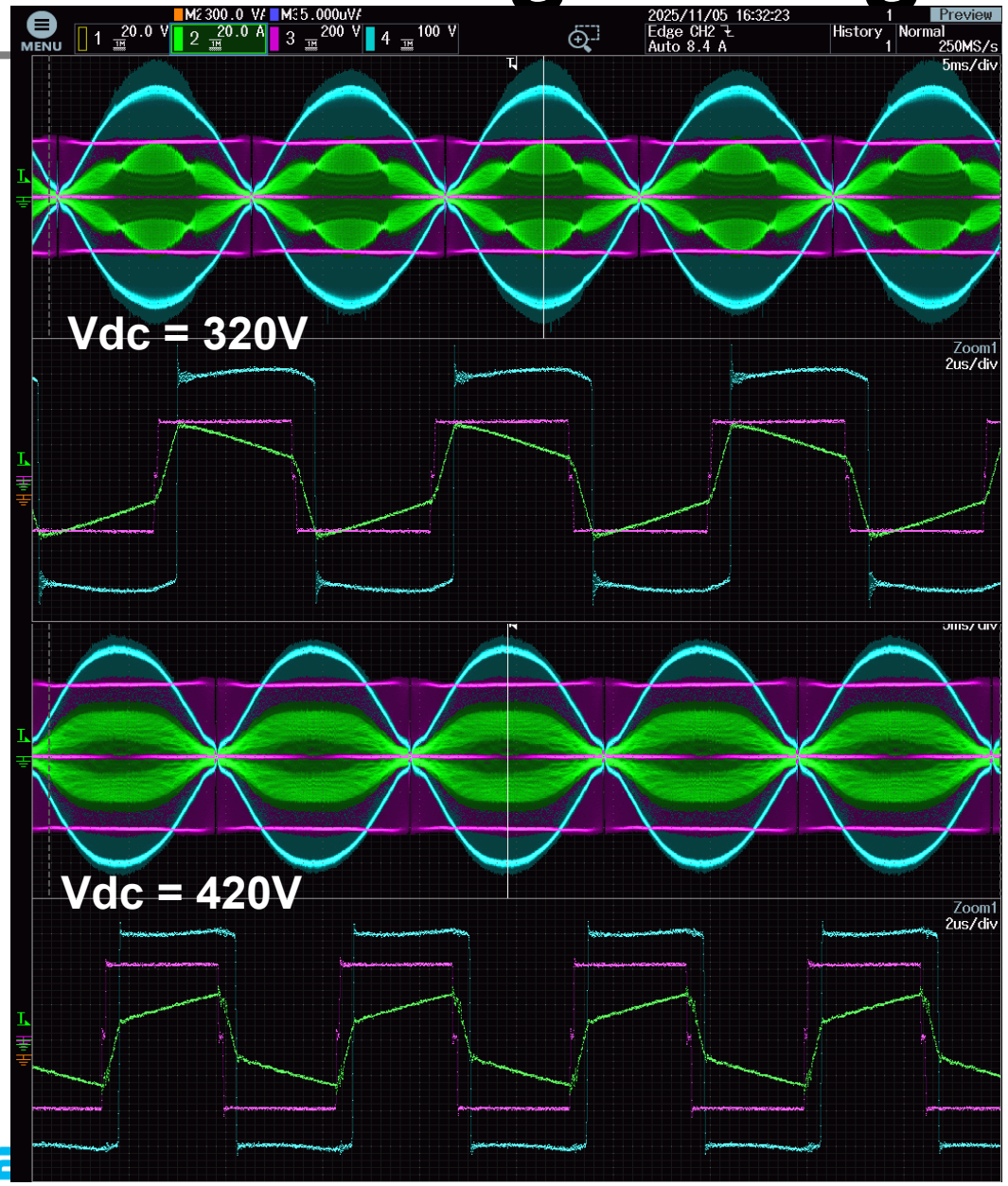


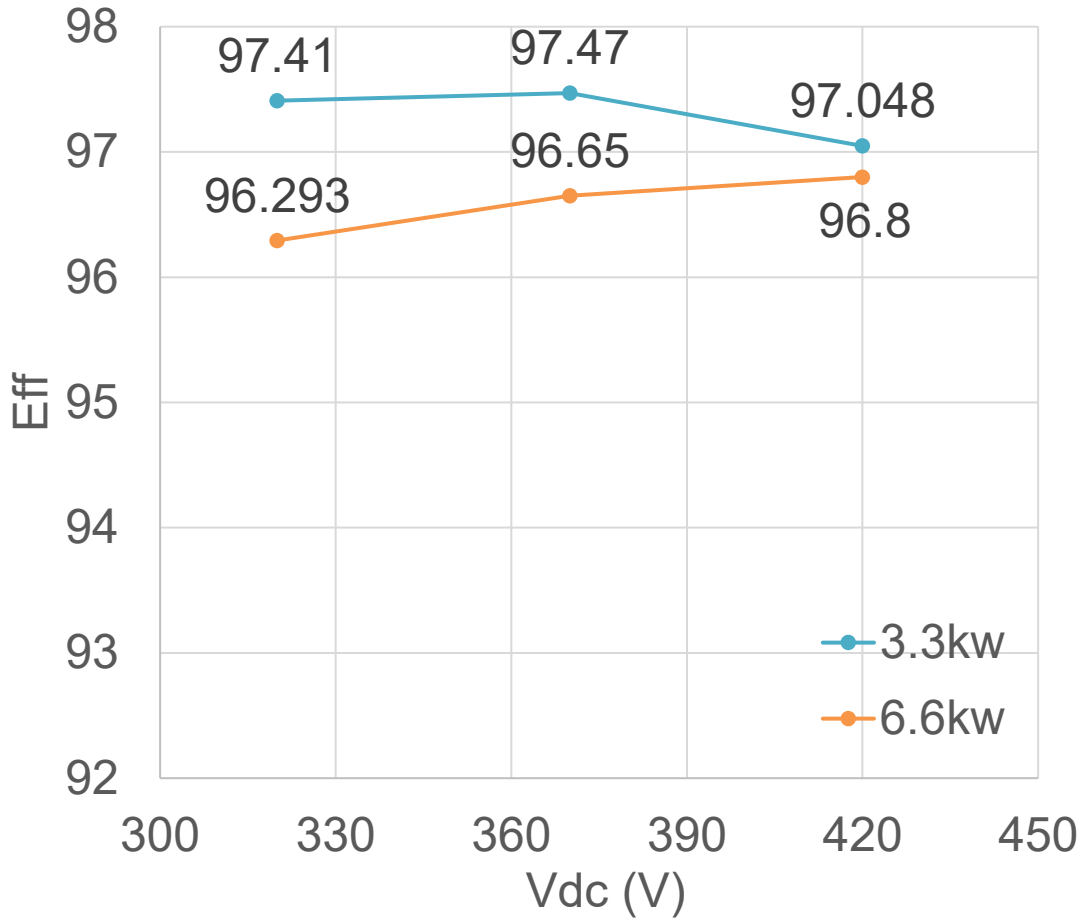
Is(20A/DIV) VtransDC(200V/DIV) VtransAC(100V/DIV)

Around Zero Cross

At the AC Peak

6.6kW Single Stage AC/DC Waveform

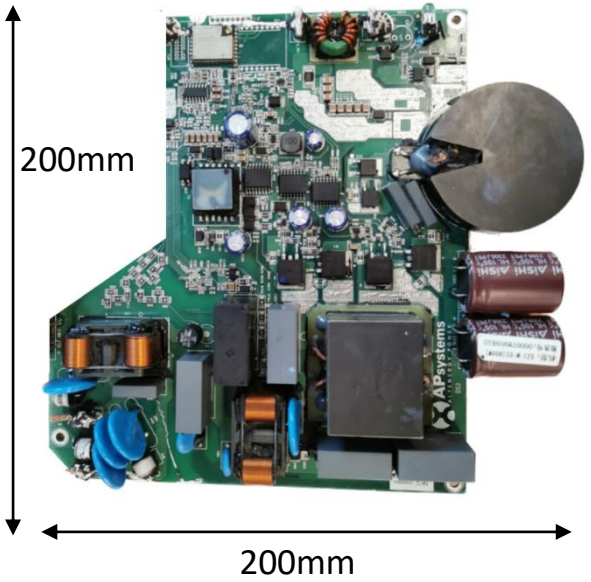




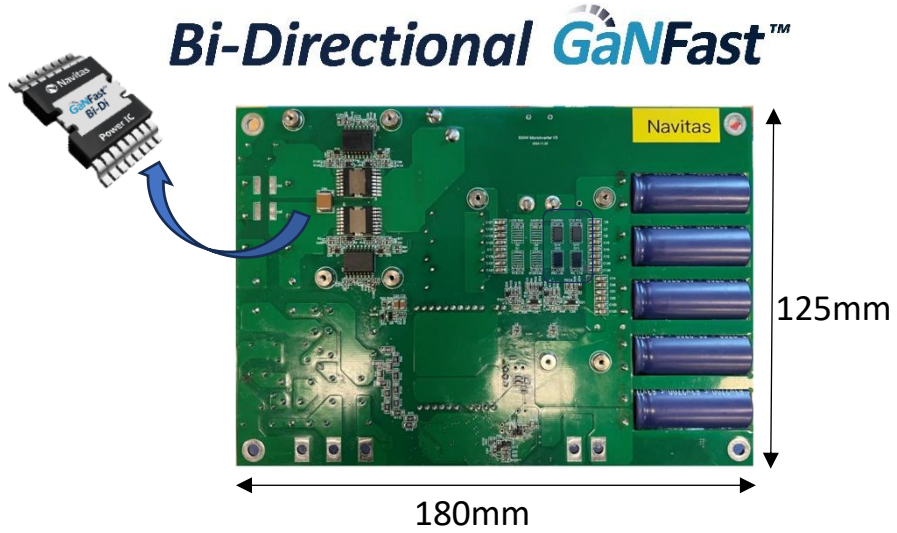
- Flat efficiency (>96%) across 300V-420V；
- Peak Efficiency up to 97.5%.

Single-stage BDS Converter (Solar)

Traditional Two-Stage



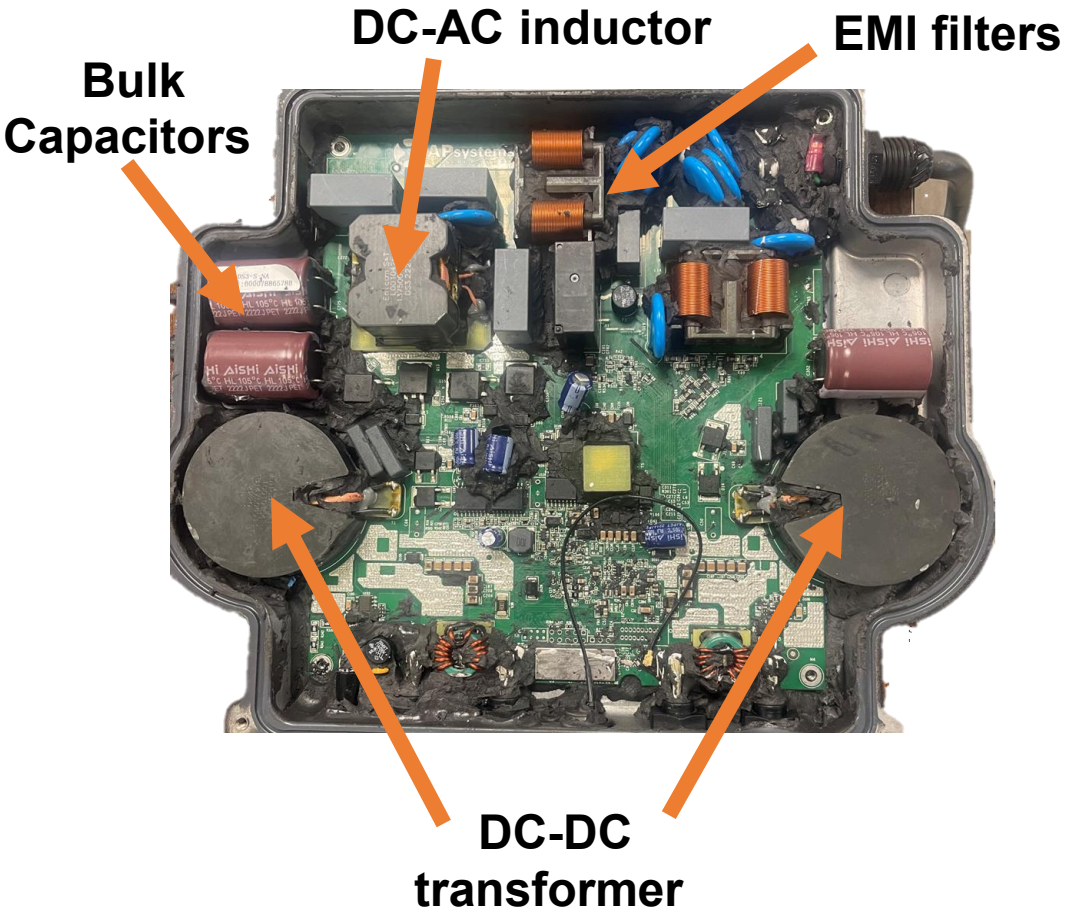
Single-Stage BDS Converter



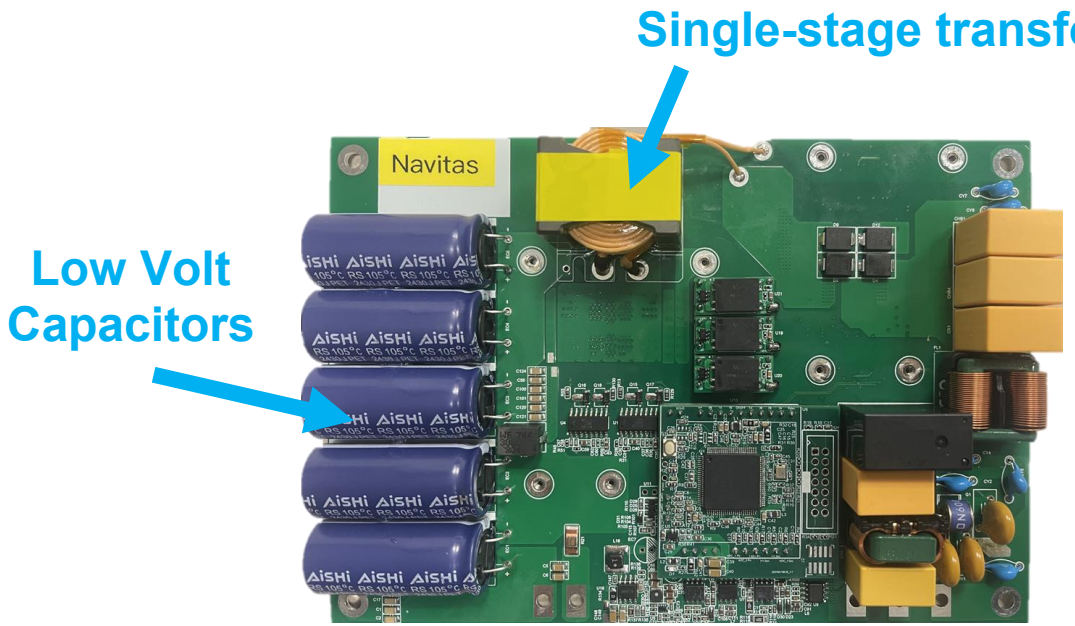
	Competitor	Navitas	Benefit
Topology	LLC + Full-bridge Inverter	Cyclon Single Stage DC/AC	**Simple design, 40% smaller size**
Peak Efficiency	95.5%	97.5%	**2% higher efficiency**
Power Magnetics (pcs)	2 pcs	1 pc	**Reduced by 50%**
High Voltage Switches (pcs)	4 pcs	2 pcs (BDS GaN)	**GaN BDS reduces part count by 50%**
High Voltage Diodes (pcs)	2 pcs	0 pcs	**No high voltage Diodes**
E-Cap Voltage Rating	High (500 V)	Low (63 V)	**No high voltage Caps**
Other Features	PFC/Inverter (Hard-switching)	ZVS (Soft-switching)	**High-speed soft-switching**

Single-stage BDS Converter (Solar)

Traditional Two-Stage



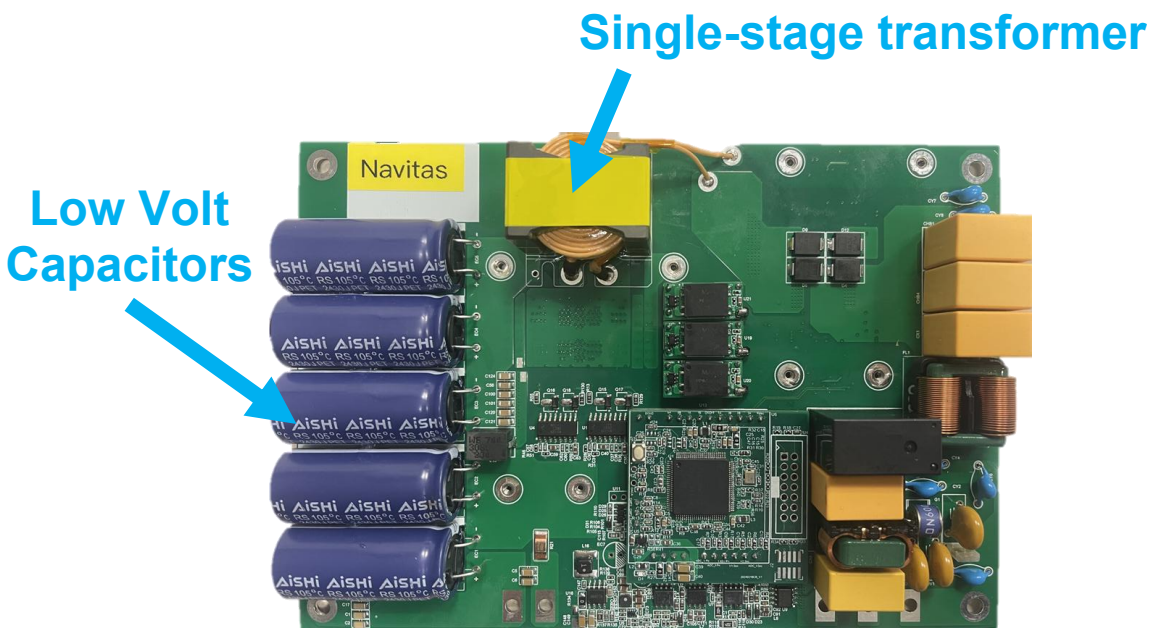
Single-Stage BDS Converter



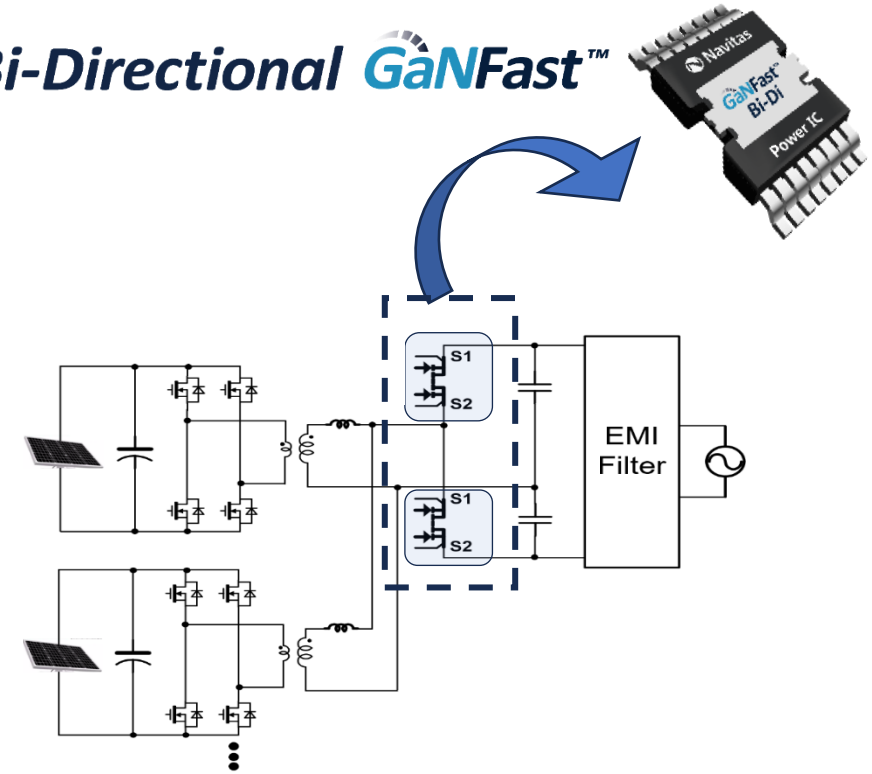
- *50% smaller size*
- *25% less loss*
- *30% lower system cost*

- *Less switches*
- *Higher reliability*
- *Below 7 c$/Watt*

500W Single Stage BDS Solar Microinverter



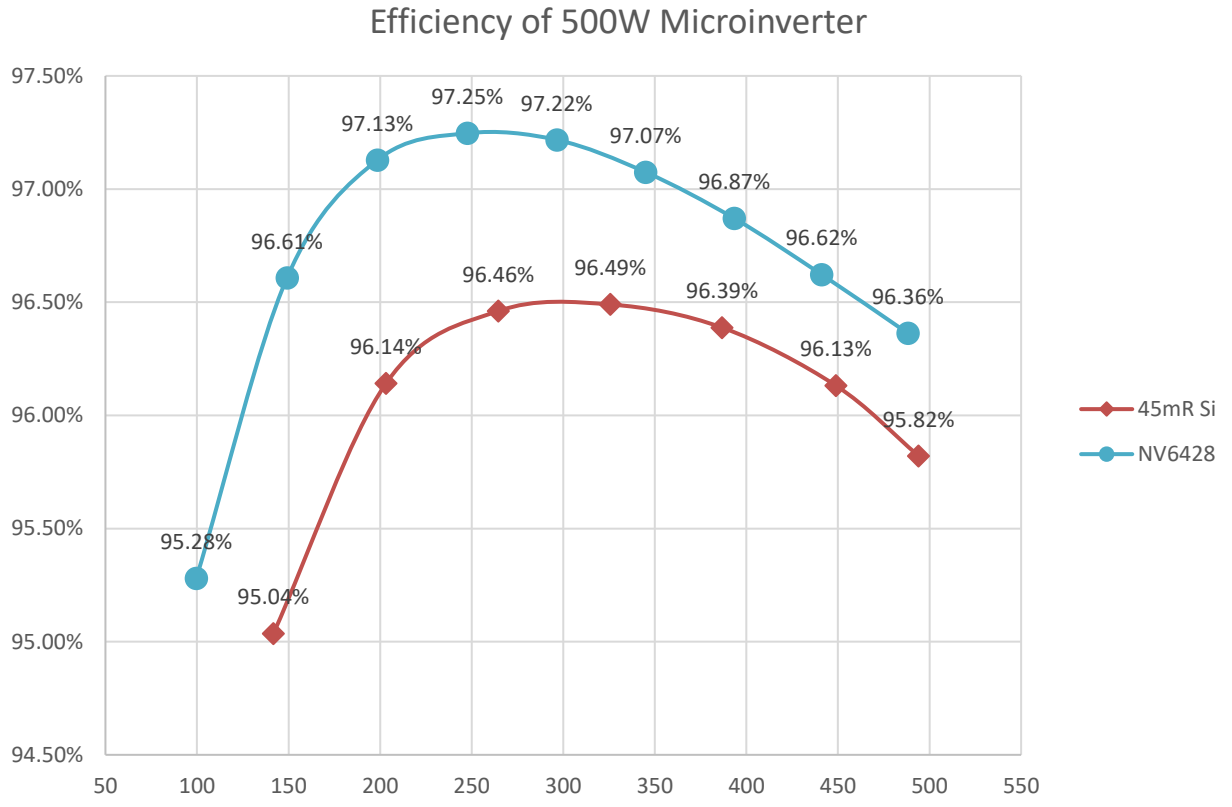
Bi-Directional GaNFast™



AC Voltage	220V RMS Nom.
MPPT voltage	30 - 45 V
Operating DC voltage	20 – 58 V
fsw	fixed 100kHz

- ***97.25% efficiency***
- ***Only 1 transformer***
- ***No HV Caps***
- ***2x less power switches***
- ***High-speed ZVS switching***
- ***No HV Diodes***

500W Microinverter Efficiency Boosted by GaN BDS



Load		20%	30%	50%	70%	100%
Weight factor		0.13	0.15	0.29	0.33	0.1
CEC Eff.	45mR Si	96.01%				
	BDS	96.65%				

Summary

- BDS enables single stage converters in EV OBC, Solar, ESS, MatrixGaN
- Single stage has large benefits in efficiency, weight, density and cost
- Matching drivers and bias supplies are important
- ‘Back-gating’ effect has been solved and production ready
- GaN BDS has lower cost and better FOM
- GaN allows high frequency switching
- Visit www.navitas.com for datasheets, Eval board, etc.

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Llew Vaughan-Edmunds, GaN VP & GM