



Welcome to the Post-Silicon World: Wide Bandgap Powers Ahead

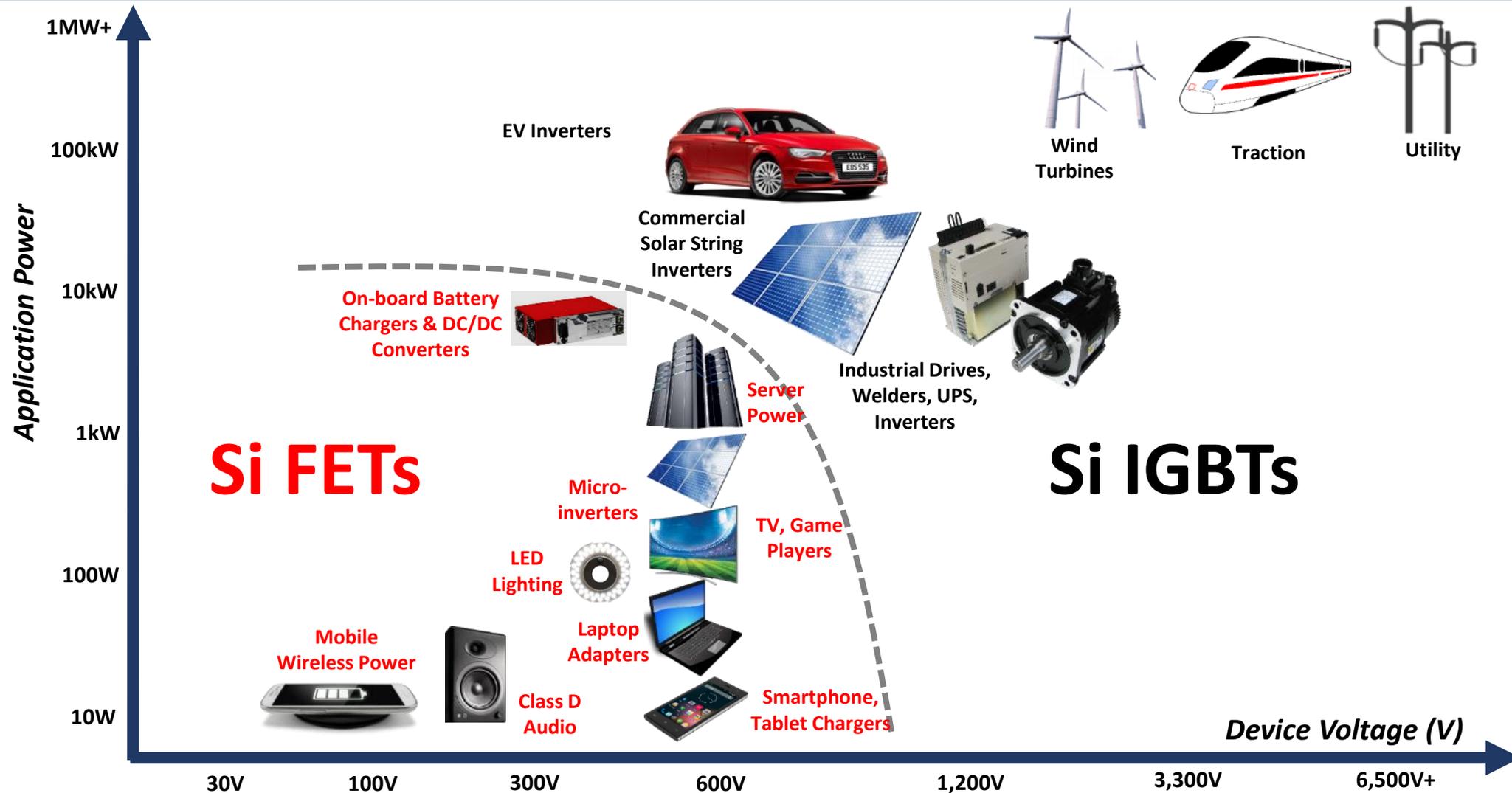
May 10, 2016

Nuremberg, Germany

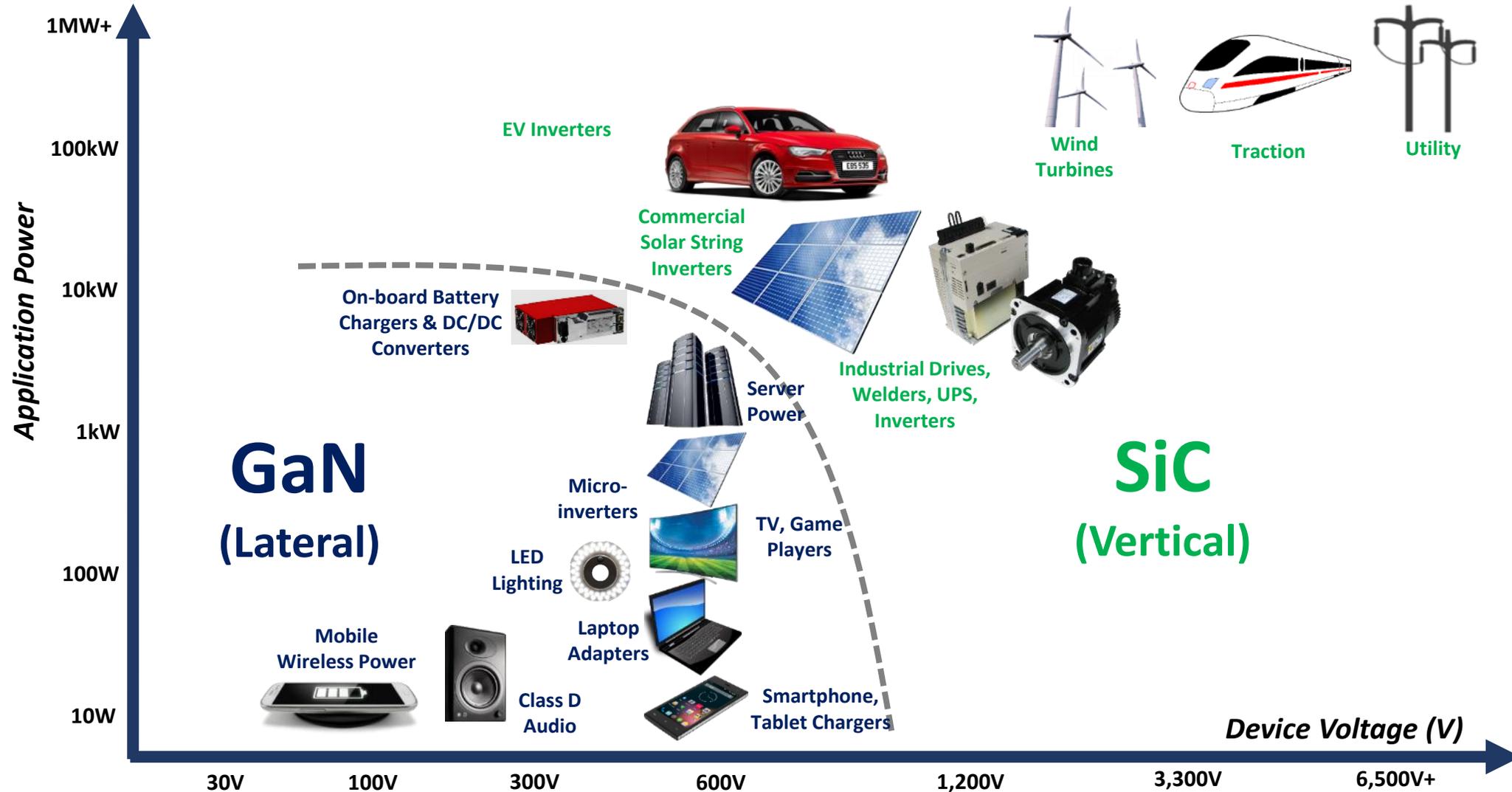
Dan Kinzer, COO/CTO

dan.kinzer@navitassemi.com

The Si Landscape



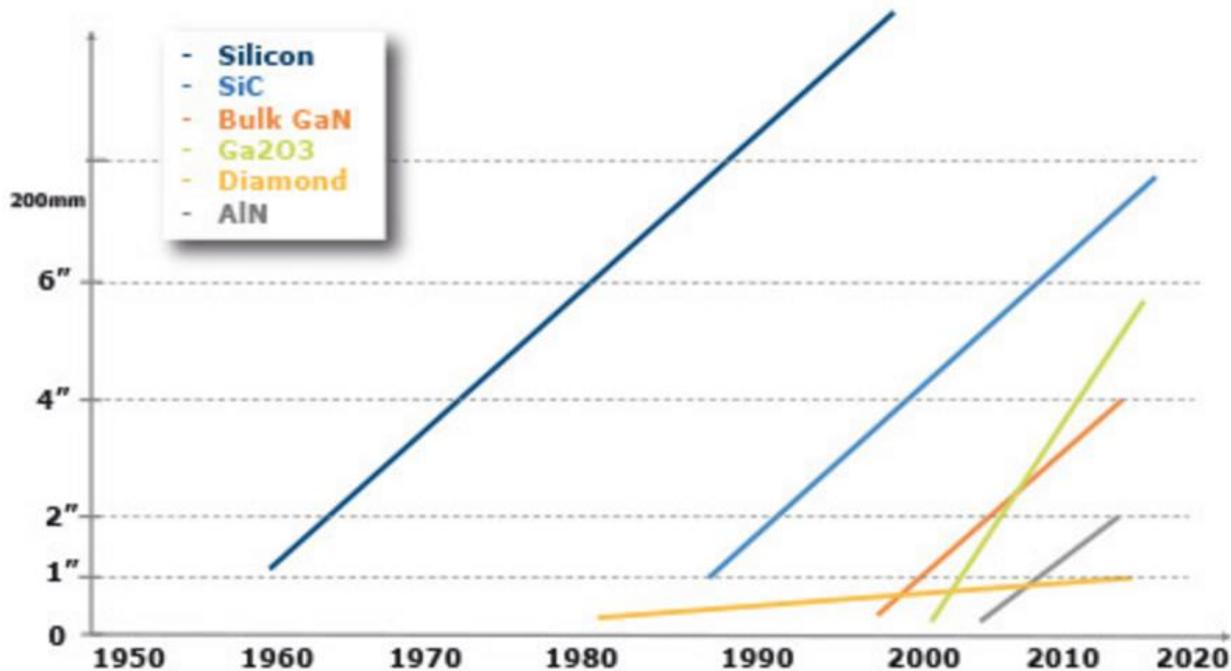
The WBG Landscape



Timeline of Bulk Semiconductor Development

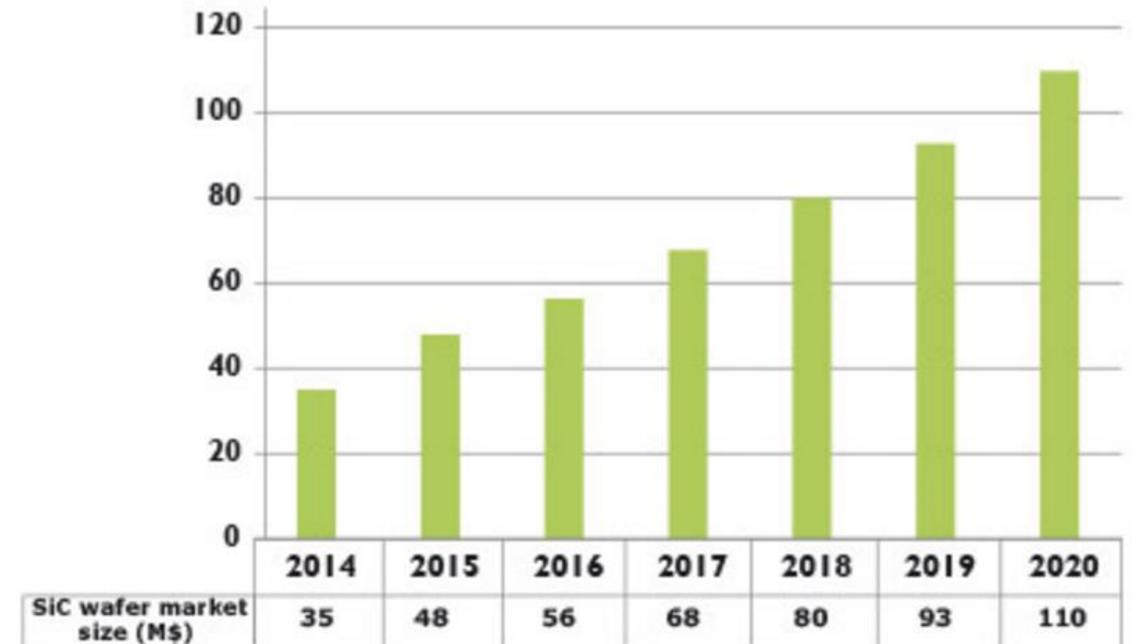
Different crystal diameter expansion

(Source: SiC, GaN, and other Wide Band Gap (WBG) materials for power electronics applications, October 2015)

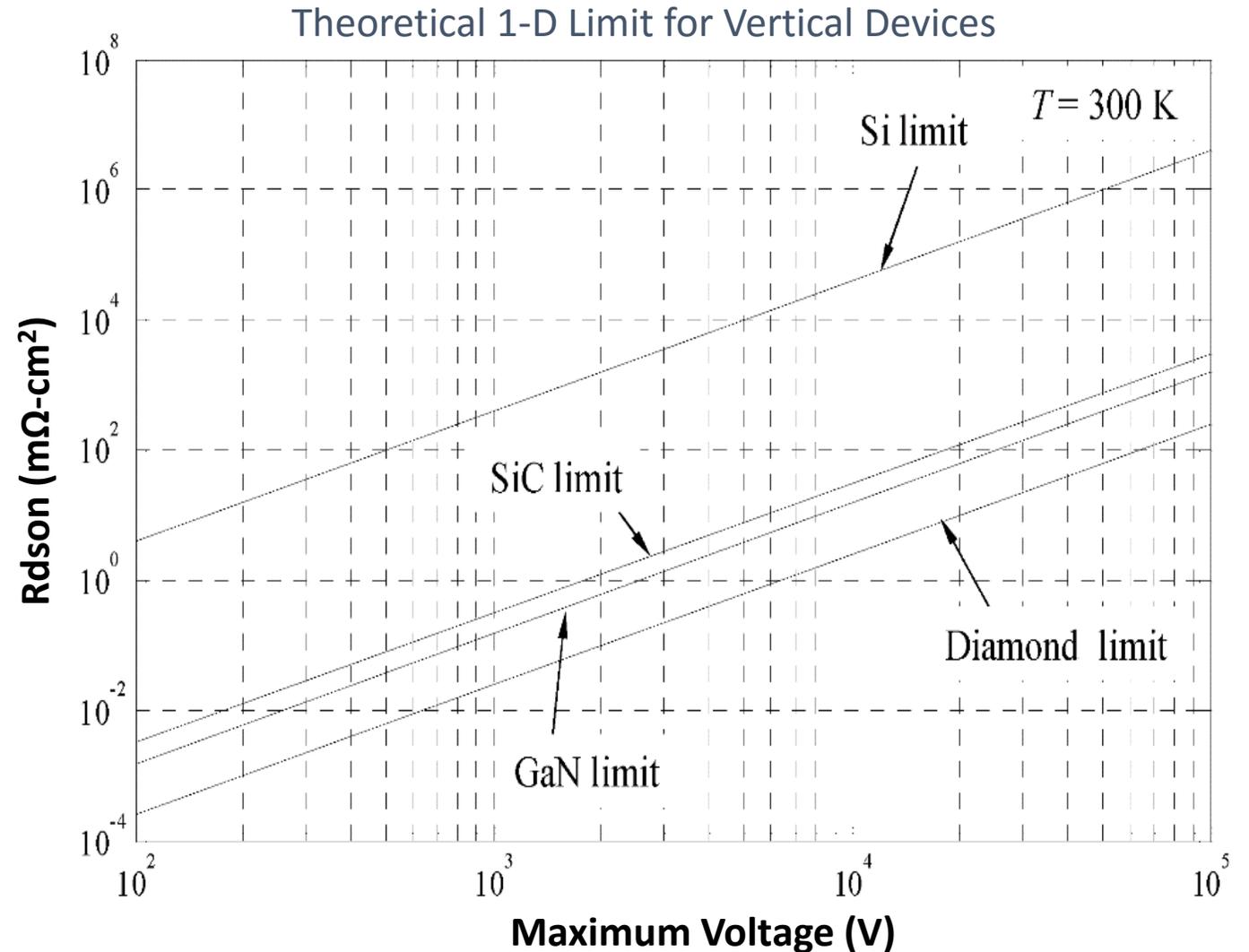
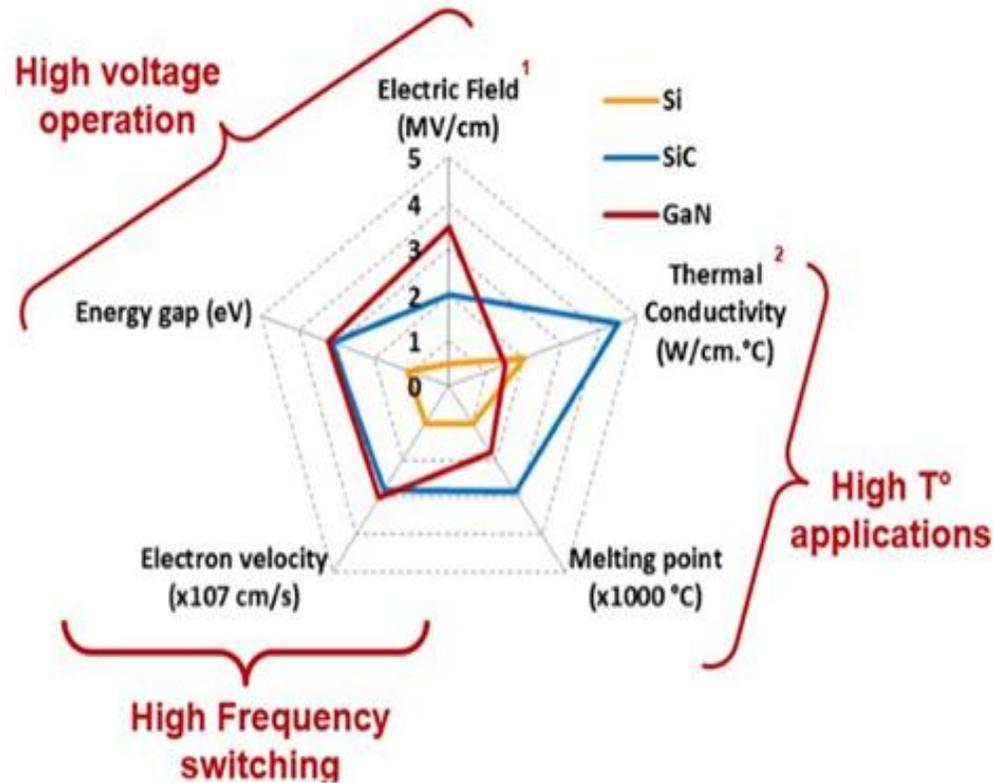


Projected SiC n-type substrate market size (\$M) through 2020

(Source: SiC, GaN, and other Wide Band Gap (WBG) materials for power electronics applications, October 2015)

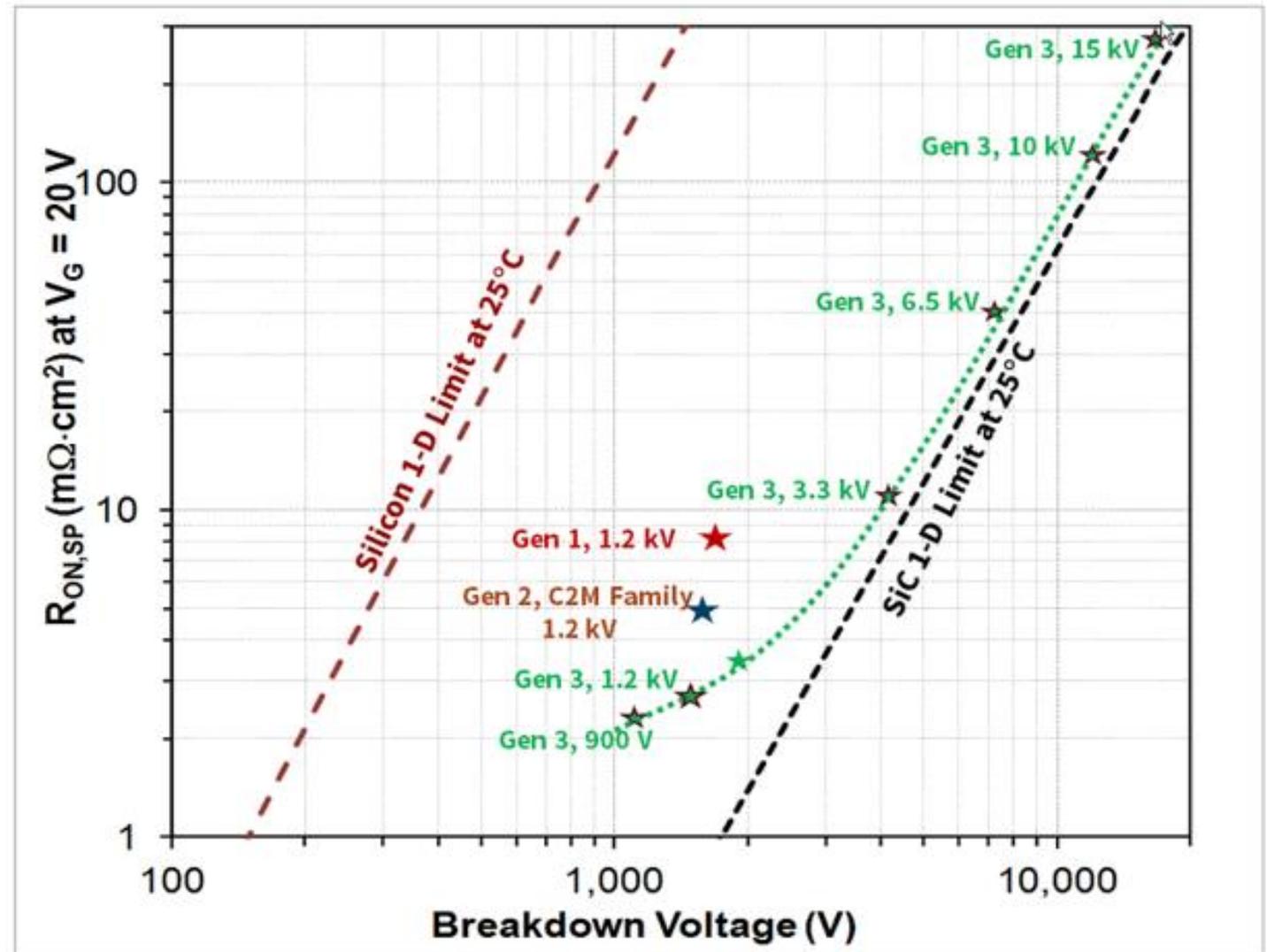


Performance Limits of WBG Materials



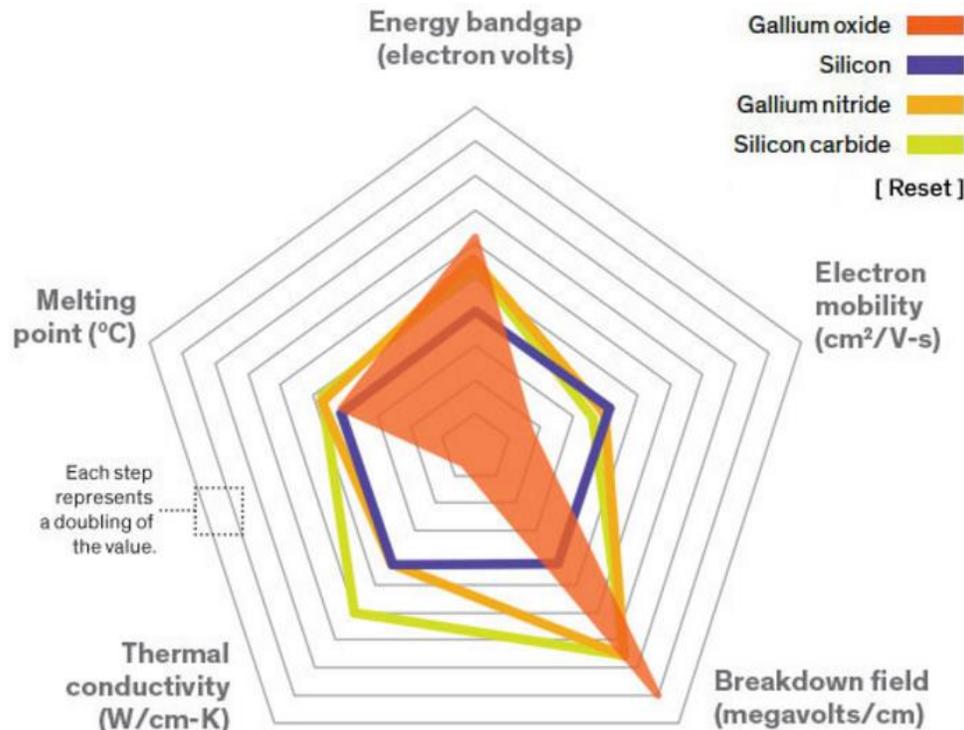
SiC MOSFETs Approach 1-D Theoretical Limit

- Latest SiC devices are approaching the 1-D limit across a wide range, even up to 30kV
- At lower voltages like 900V, the gap widens due to channel and substrate resistance
- System cost advantage is possible across the range
- At 900V, SiC MOSFET is reaching cost parity with Superjunction silicon

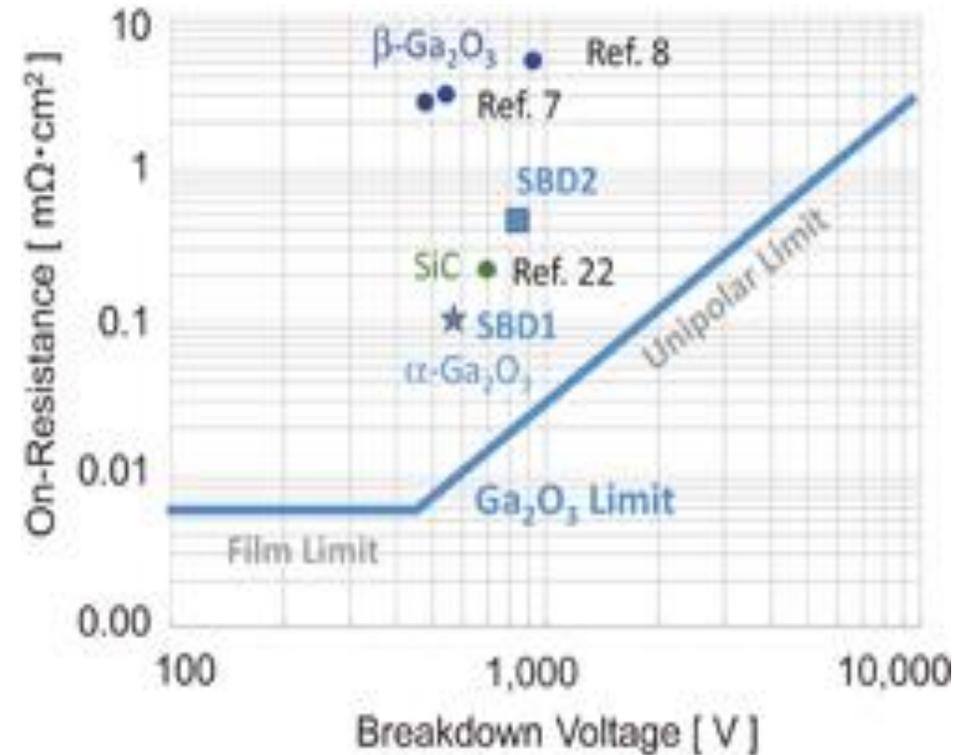


A Future HV Alternative to GaN and SiC: Ga₂O₃?

- Flosfia (Kyoto startup), is working to show that Gallium Oxide can be the next big thing in WBG
- Incumbents, and aluminum nitride and diamond players, may not agree!



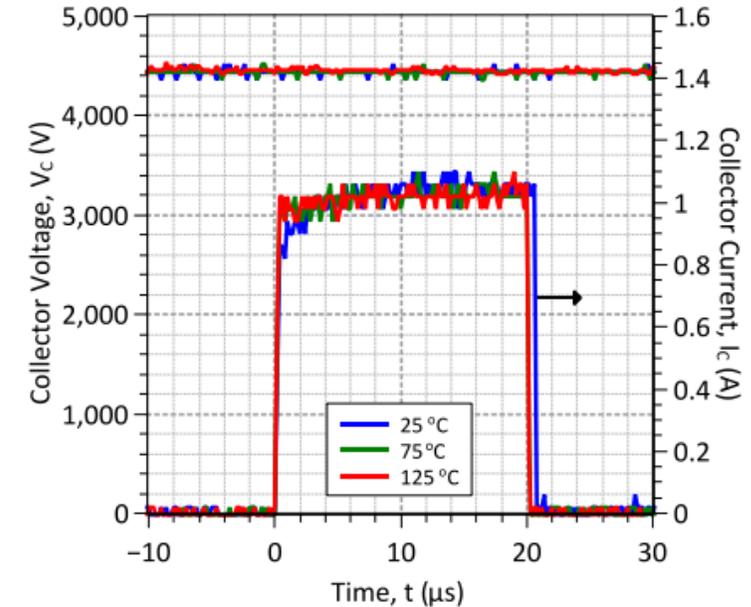
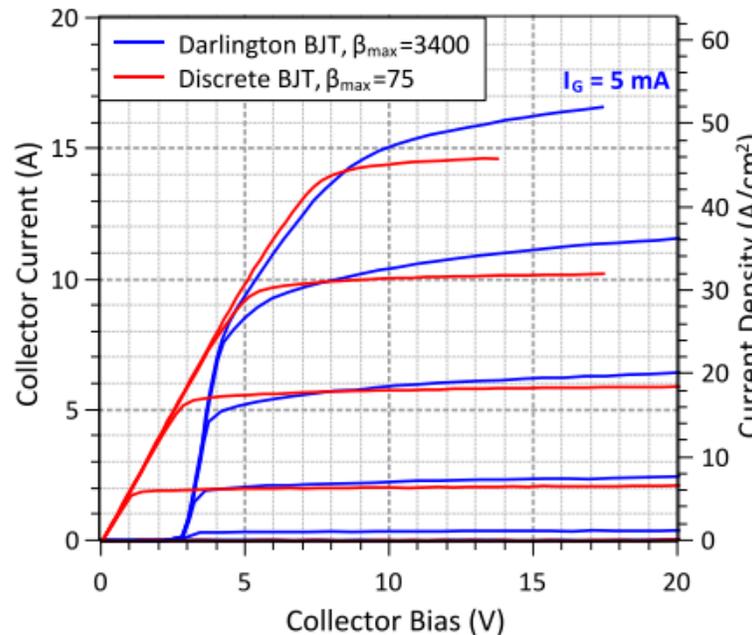
Source: Yole Développement, Lyon, France



10kV SiC BJT vs. Si IGBT

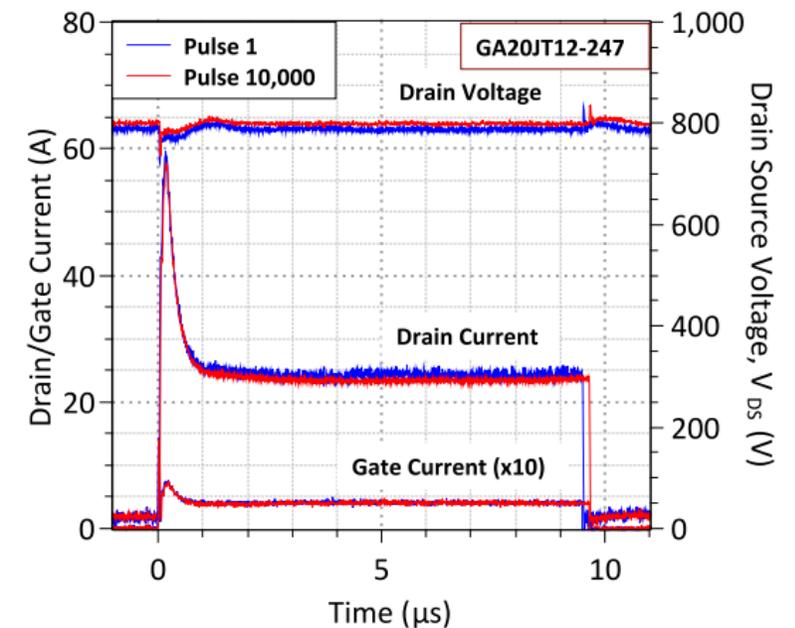
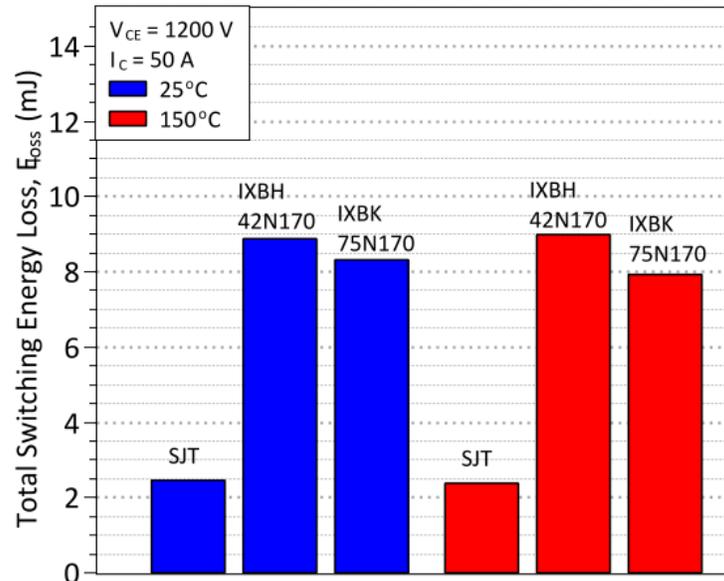
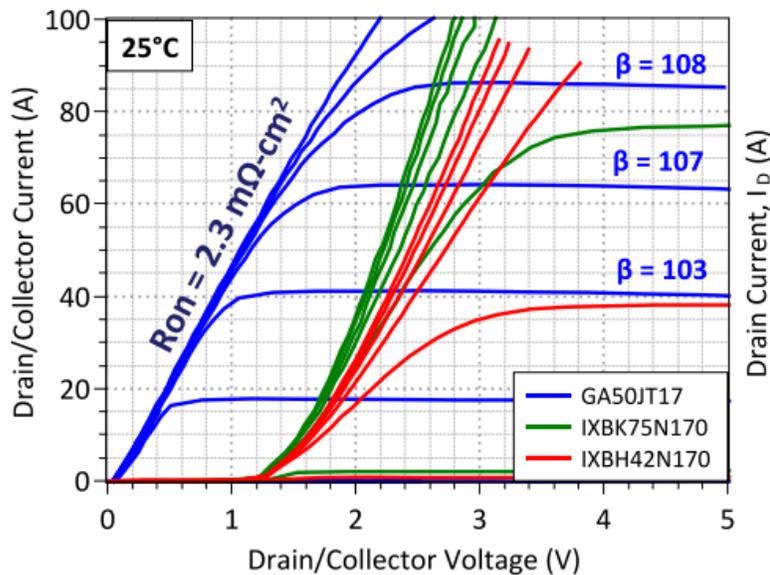
- SiC 50% more blocking capability
- On-state voltage higher relative to BV
- 20x faster switching
- With Beta of 75, drive current will be 200mA
- With the Darlington, only 5mA achieves the same voltage drop at maximum load
- Short circuit capability at 4.5kV is greater than 20us, and temperature independent

Device	BV	I _C	Temp.(C)	V _{CE,sat} (V)	E _{on} (mJ)	E _{off} (mJ)
SiC BJT	10 kV	8 A	150°C	6.4	4.2	1.6
Si IGBT	6.5 kV	10 A	125°C	4	80	40
				↑ 1.6 x	19 x ↓	25 x ↓



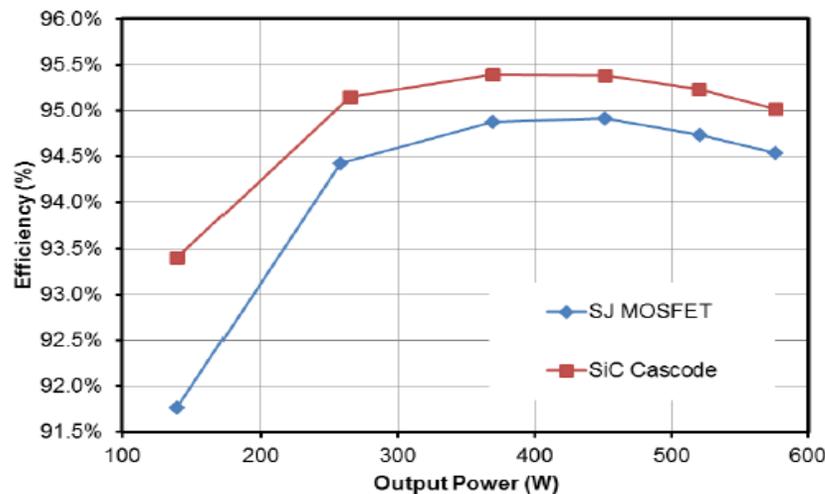
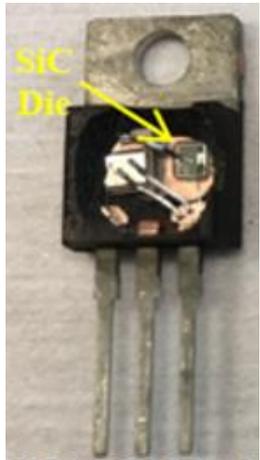
1,700V SiC Junction Transistor vs IGBT

- Best-in-class SiC devices clearly outperform Si IGBTs in all major metrics:
 - Conduction loss down by >50% across temperature range
 - Switching loss down by 75% at full operating voltage with clamped inductive load
 - SOA capability is robust to industry standards, even demonstrated to 10K pulses
 - Hot leakage reduced by 3-4 orders of magnitude (1k -10k x better)



A 650V SiC Cascode Approach

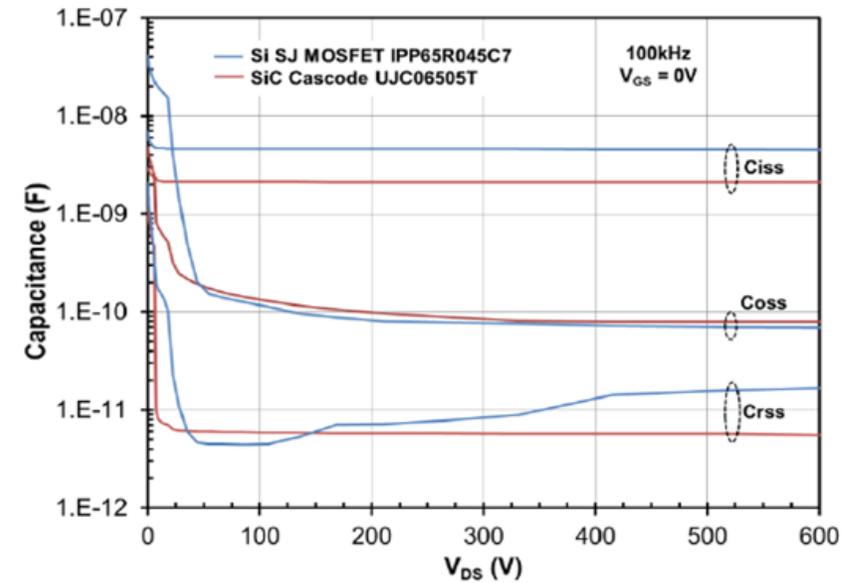
- “Ultra-low R_{dsA} of 0.75mohm-cm^2 compared to 10mohm-cm^2 for Si SJ leads to 7.3X smaller die”
- “The die cost of the 6inch SiC solution will reach parity with Silicon”
- “Lower $R_{ds} \cdot Q_g$, $R_{ds} \cdot E_{oss}$, excellent body diode recovery, adequate avalanche capability is compelling for high power applications”



Efficiency vs. output power for phase shifted full bridge with SiC cascode and Si superjunction MOSFET, 400V in, 24V out, $f=75\text{kHz}$

KEY DATASHEET PARAMETERS OF USCi's 650V CASCODE SWITCH COMPARED TO SUPERJUNCTION MOSFET

Device	R_{DS}	Q_G	Q_{GS}	Q_{GD}	Q_{TR}	E_{OSS}	V_{TH}	TCR	Gate Drive	Die Area
	$m\Omega$	nC	nC	nC	μC	μJ	V	@ 150C		
SiC Cascode UJC06505T	34	58	15	15	0.15	8	5	1.8	0 to 12V	1
Si Superjunction IPP65R045C7	40	93	23	30	13	11.7	3.5	2.4	0 to 12V	7.3x

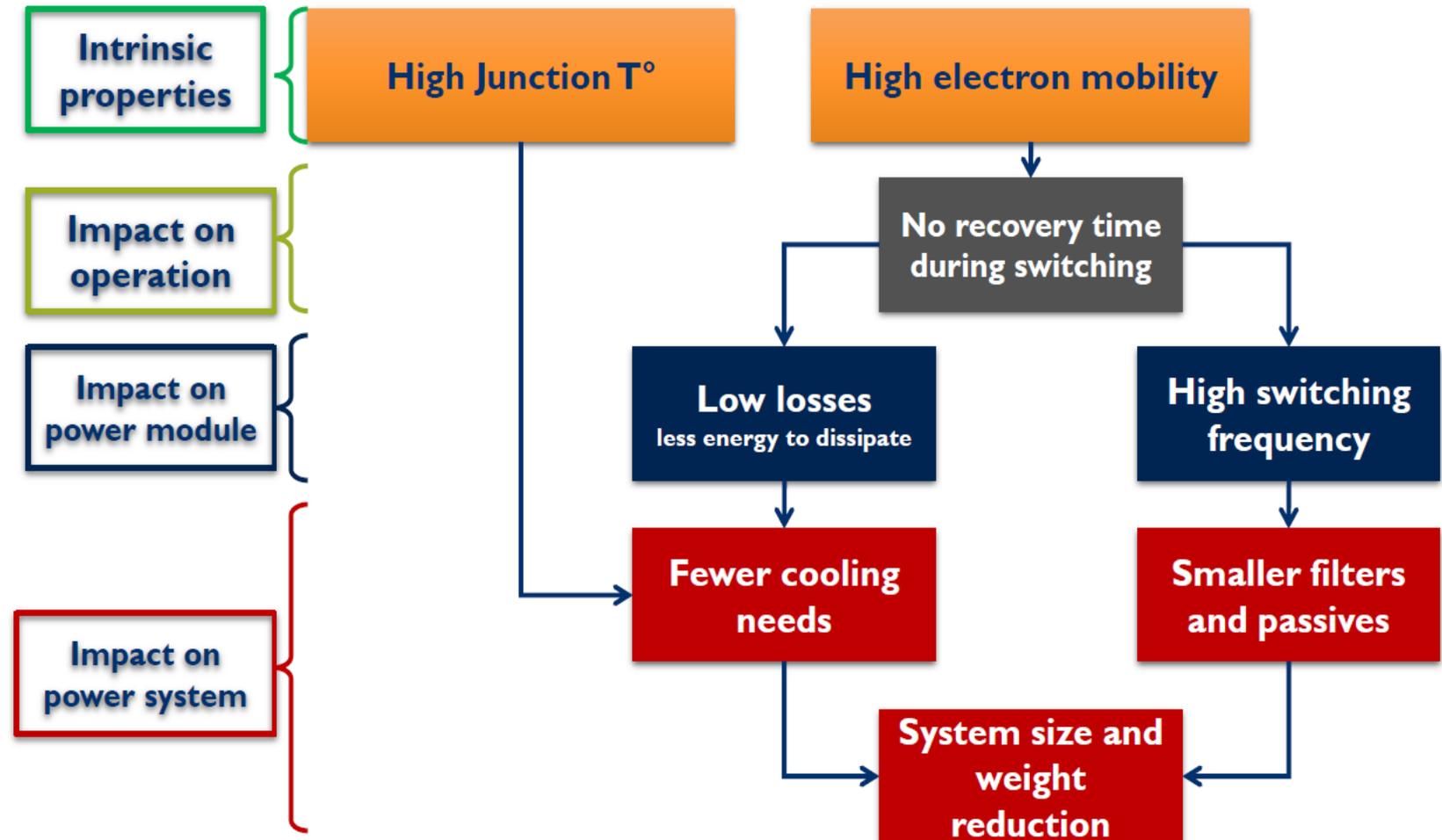


Capacitance curves comparison between SiC Cascode UJC06505T and superjunction MOSFET IPP65R045C7

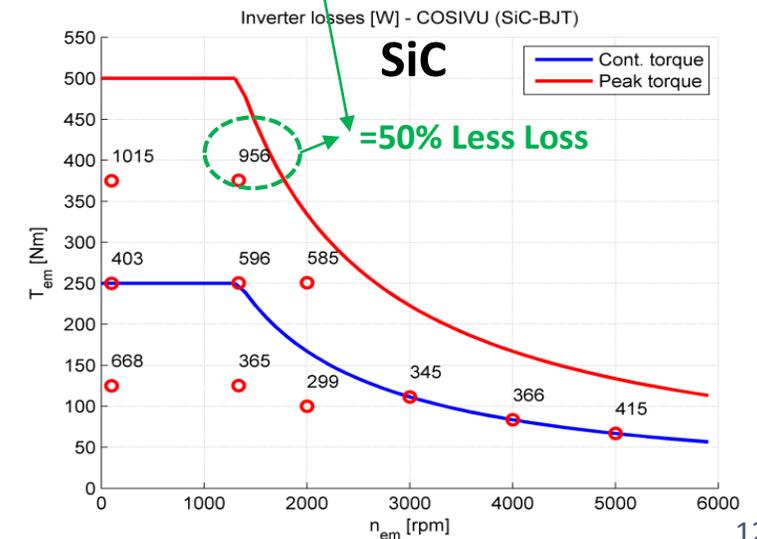
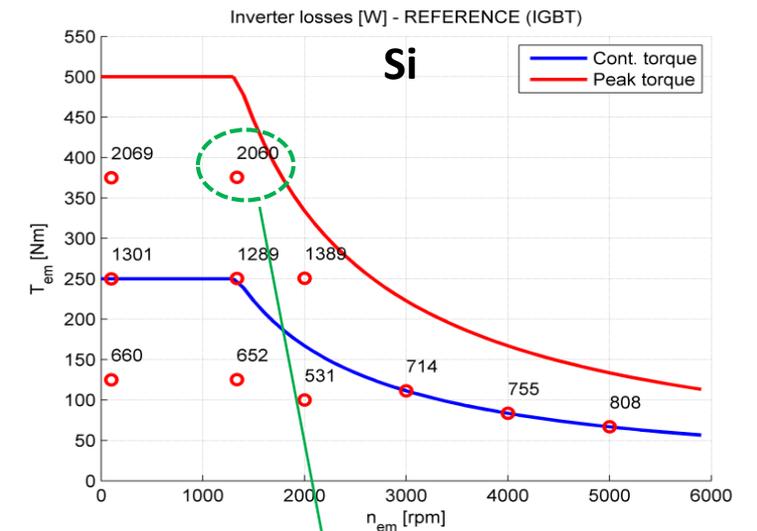
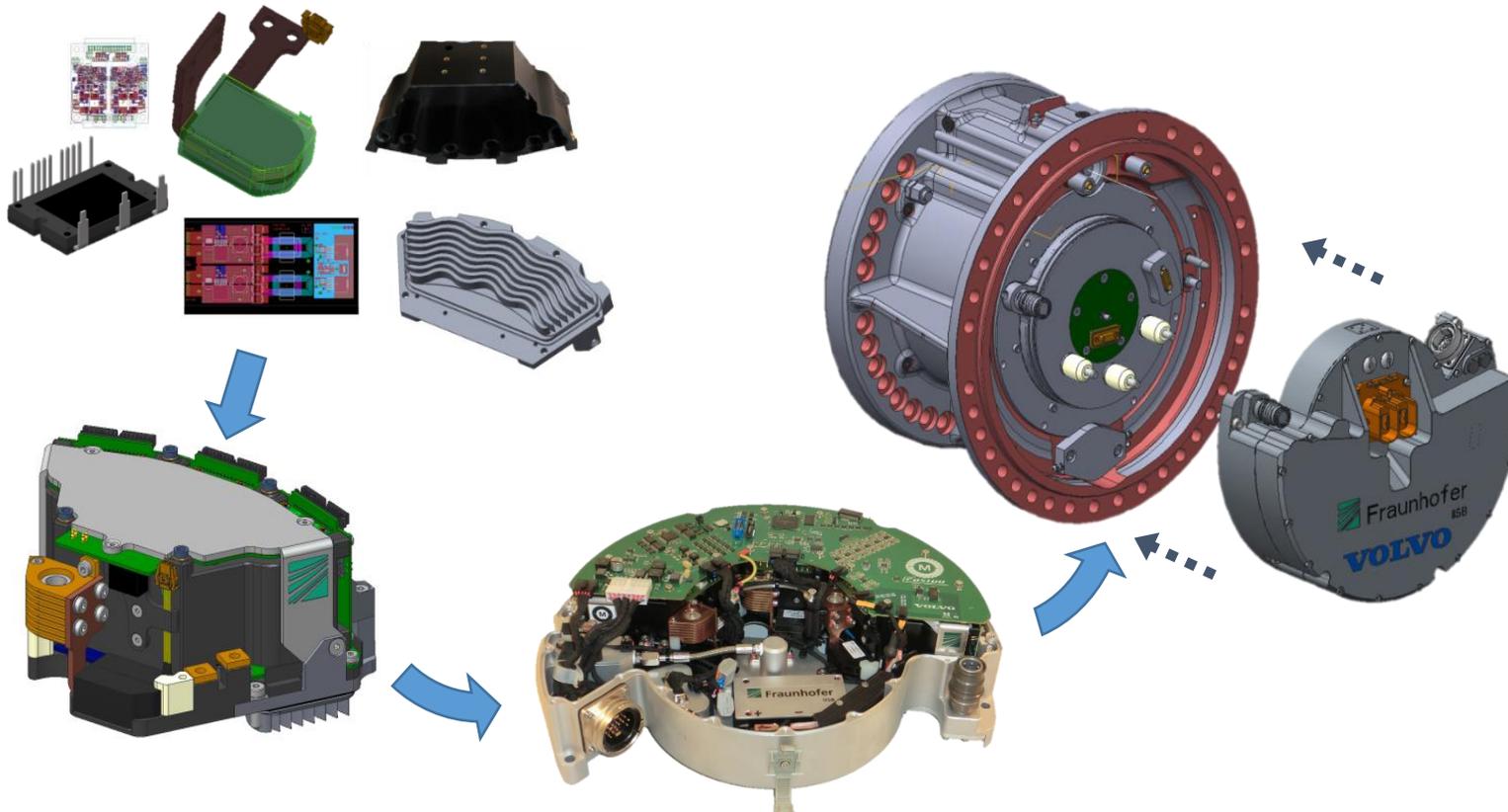
WBG Enables Small Size, Low Weight

WBG means:

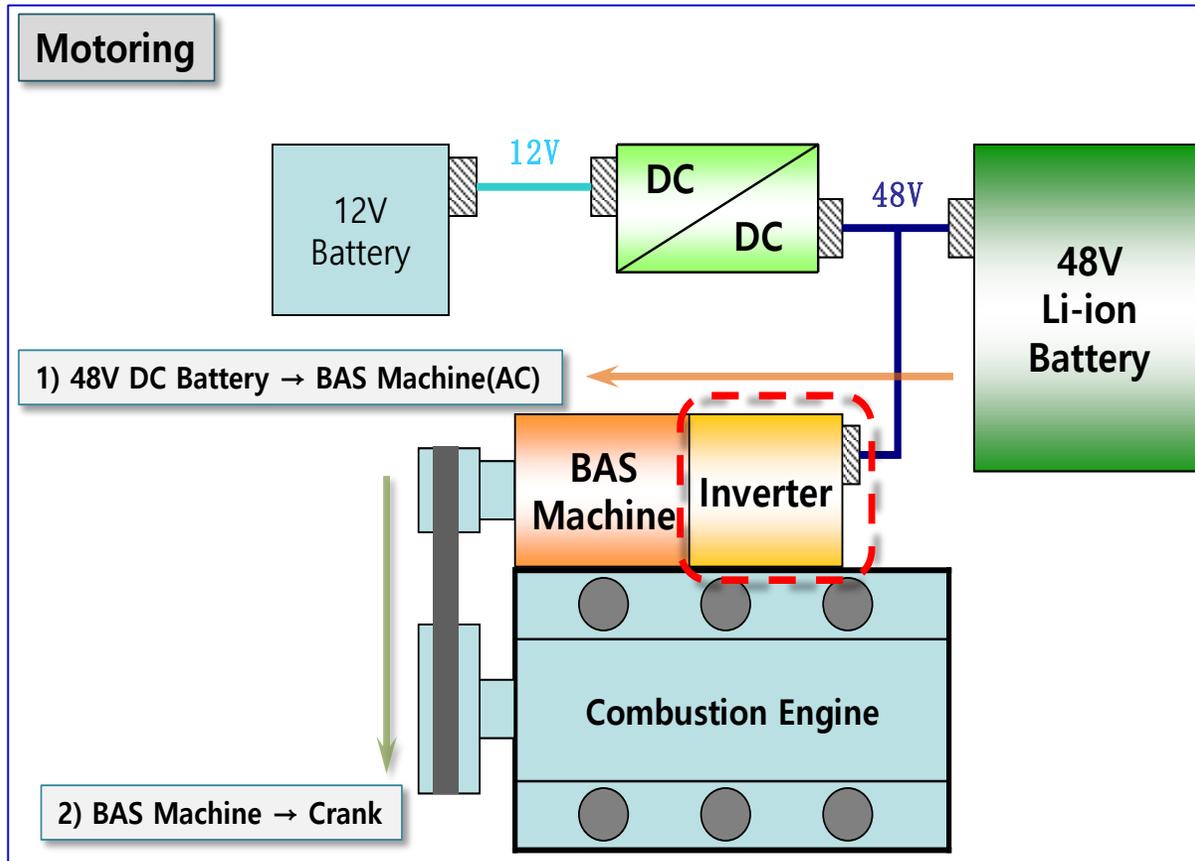
- High Electric Field
- Reduced Dimensions
- Reduced Chip Size
- Low Input Capacitance
- Low Output Capacitance
- Low Conduction Loss
- Low Junction Leakage
- High Thermal Conductivity
- High Efficiency
- High Power Density



EV Drive: 50% Less Loss Across Torque Range



Mild Hybrid – 80% Smaller with 100V GaN



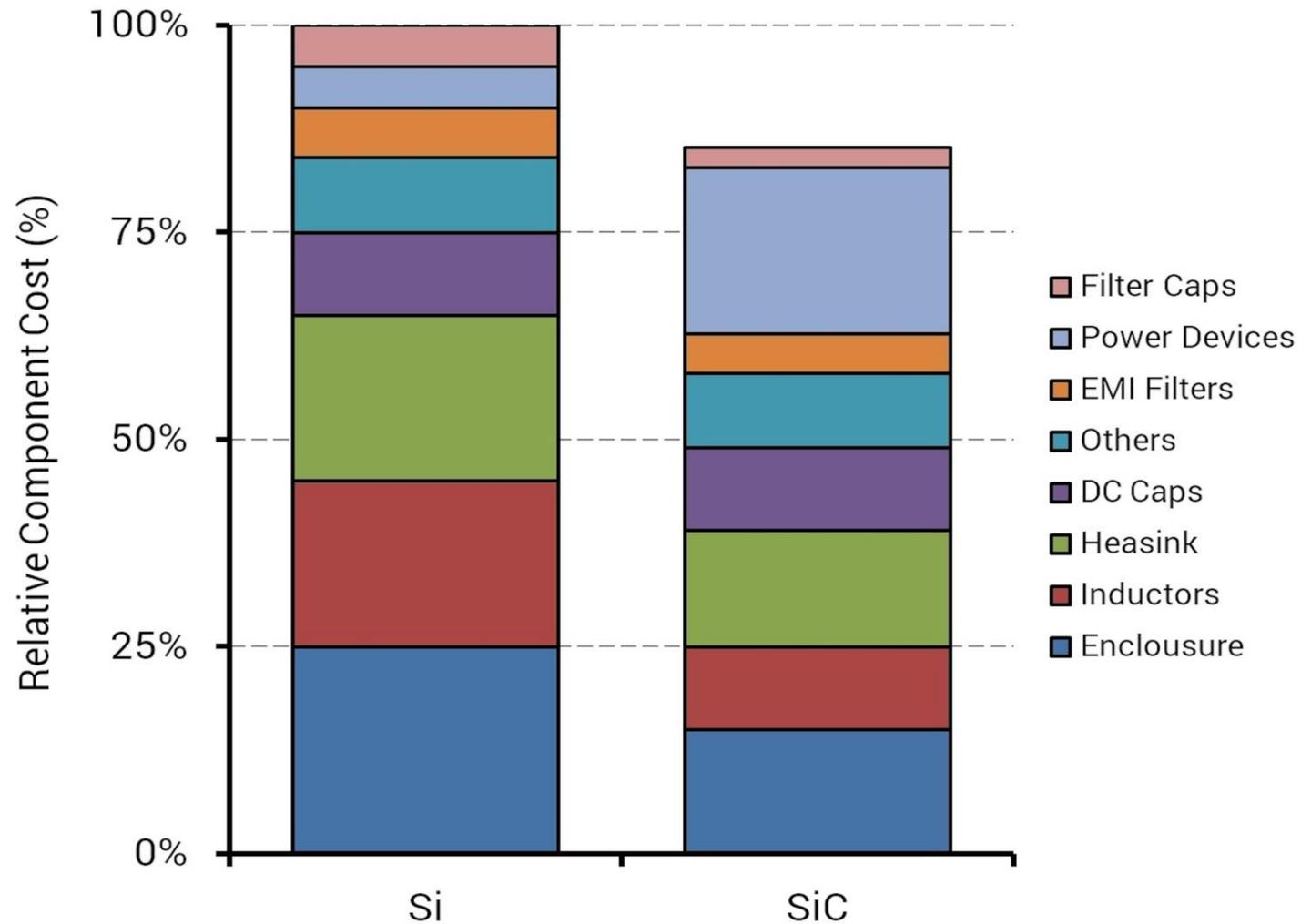
- 48V bi-directional inverter
- 12kW (motor drive) / 10kW (generating)
- 80% smaller
- 70% lighter
- +12% efficiency

50kW Inverter: 75% Smaller, 80% Lighter with SiC



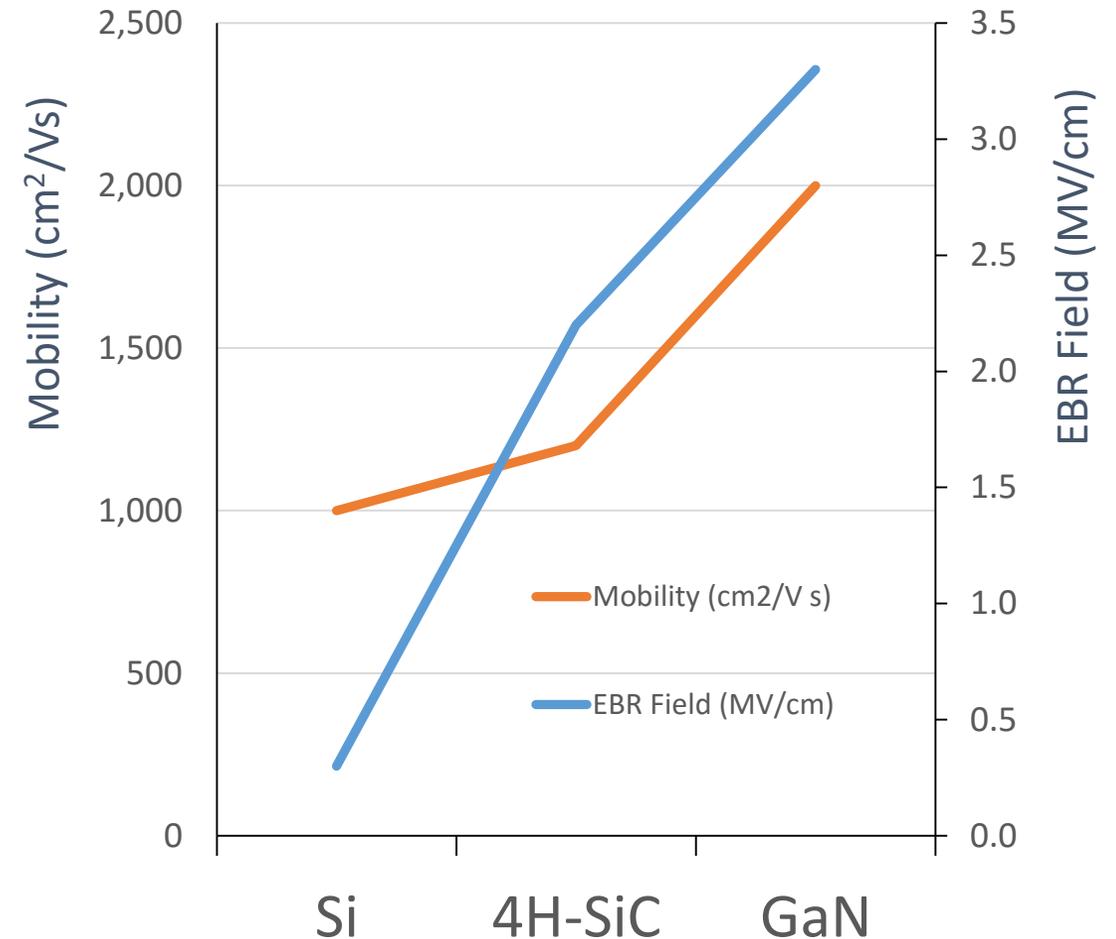
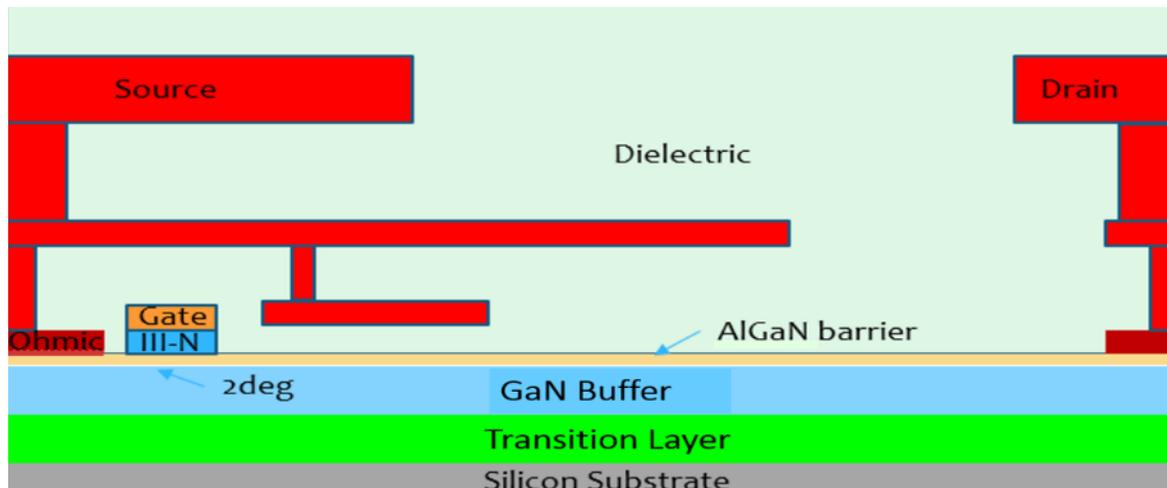
Year	2013		2014	2015
Powertrain	Si Module		SiC Discrete	SiC Module
Efficiency (peak)	98.3%	50% less loss		99.1%
Size (m ³)	0.41	50%-75% smaller	0.21	0.09
Weight (kg)	173	70%-80% lighter	50	33

50kW Inverter: 15% Lower Cost with SiC



Lateral GaN Advantage for Off-line Applications

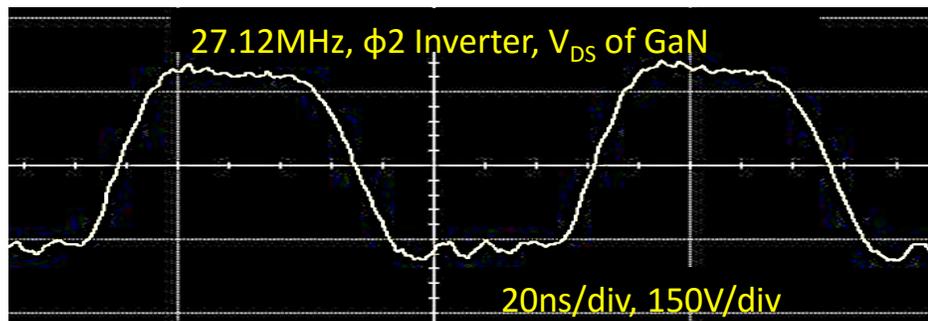
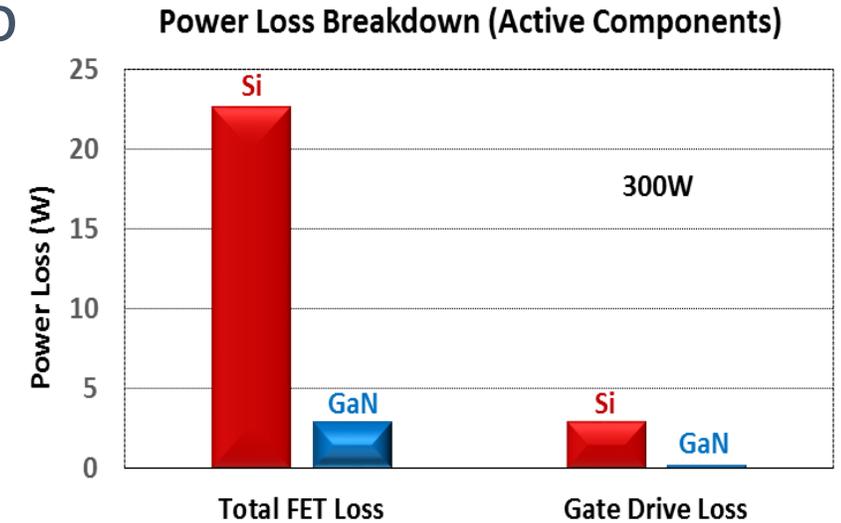
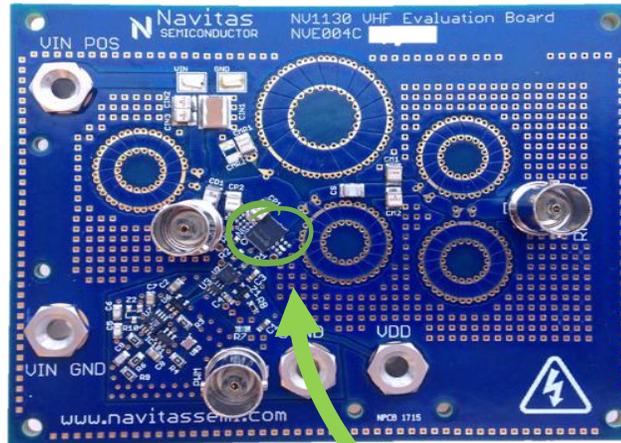
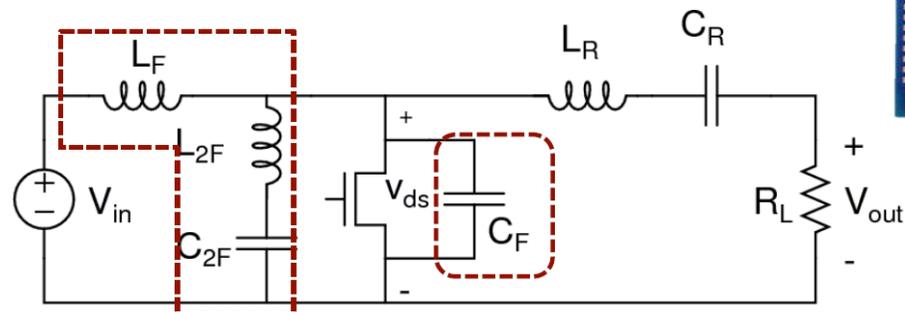
- WBG GaN material allows high electric fields so high carrier density can be achieved
- Two-dimensional electron gas with AlGaN/GaN heteroepitaxy structure gives very high mobility in the channel and drain drift region
- Lateral device structure achieves extremely low Q_g and Q_{OSS} and allows integration
- Integration on silicon substrates means mature low cost wafer fabrication is available



650V Navitas eMode GaN at 27MHz & 40MHz

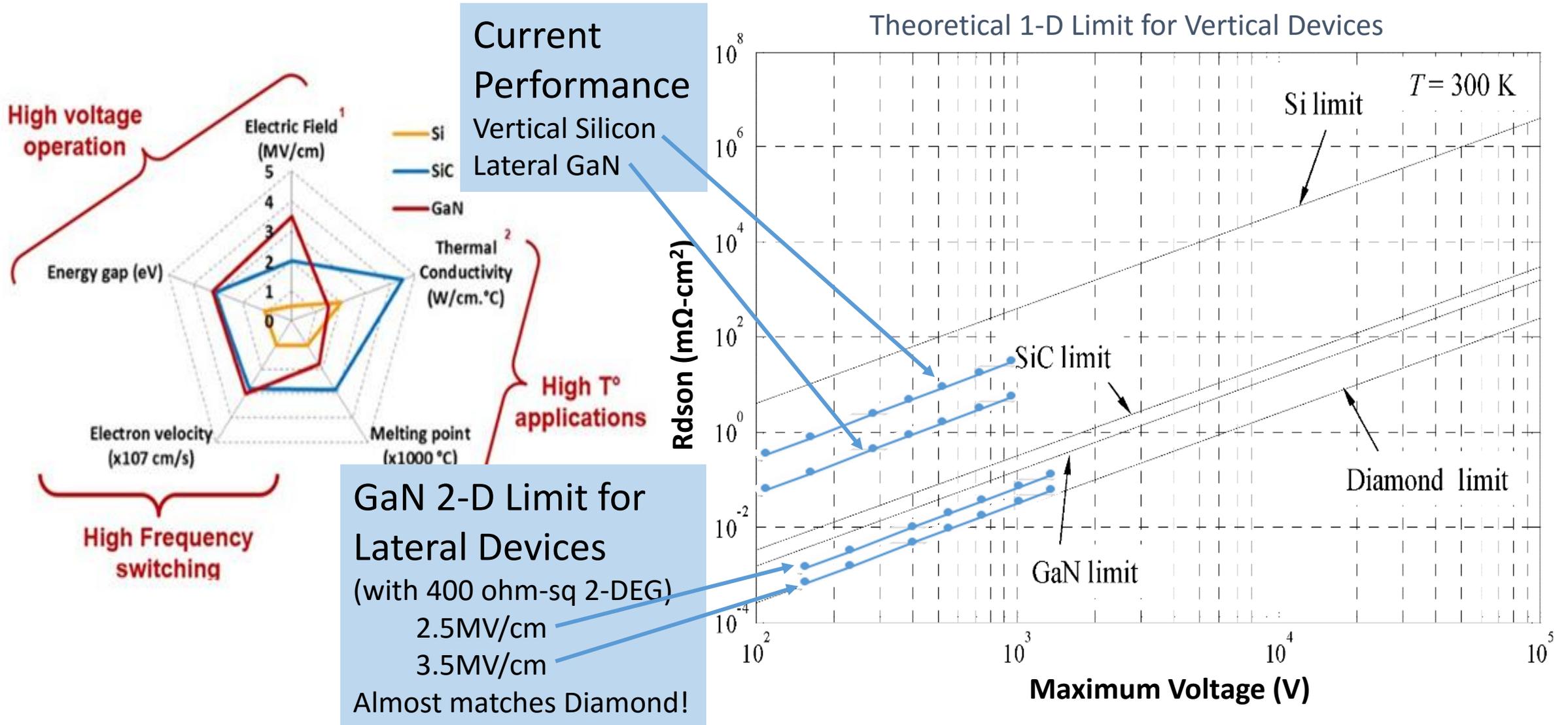
Class Phi-2 DC/AC converter: Stanford / Navitas demo

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



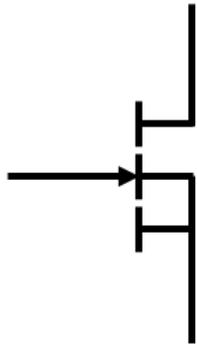
Technology	V	Pack (mm)	F_{sw} (MHz)	Eff. (%)	Power (W)
RF Si (ARF521) 	500	M174 22x22 	27.12	91%	150
eMode GaN 	650	QFN 5x6 	27.12	96%	150
			40.00	93%	115

Performance Limits of WBG Materials

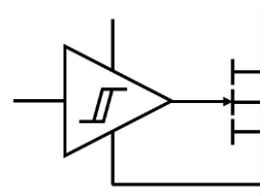


Creating the World's First AllGaN™ Power ICs

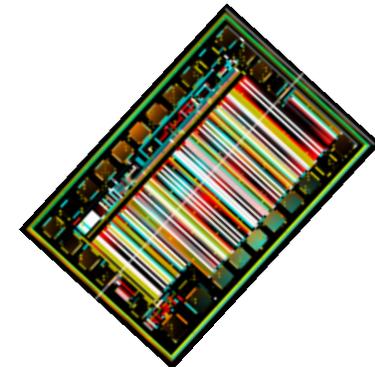
Fastest, most efficient
GaN Power FETs



First & Fastest
Integrated GaN Gate Driver



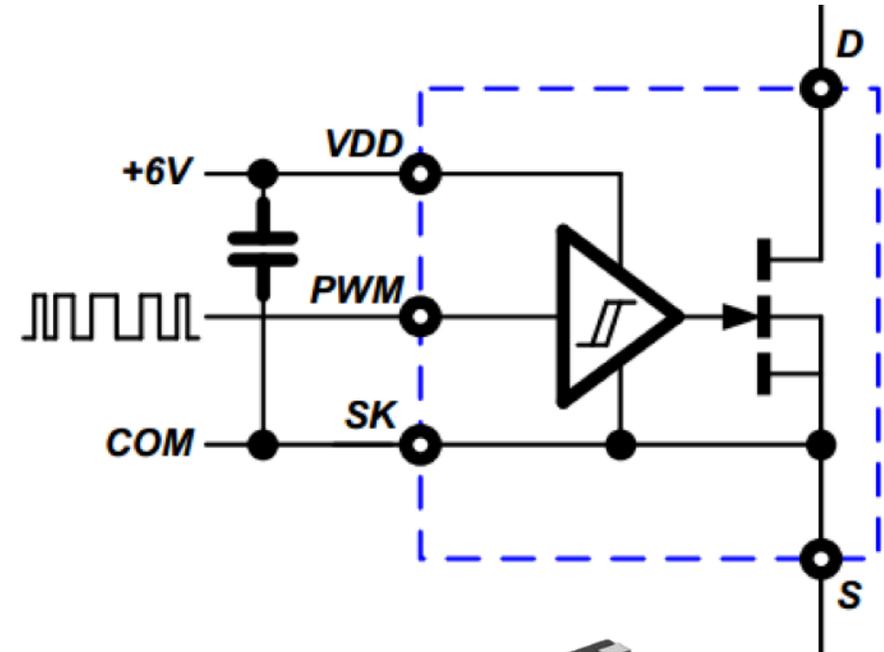
World's First
AllGaN™ Power IC



Up to 40MHz switching, 4x higher density & 20% lower system cost

Navitas GaN Power IC

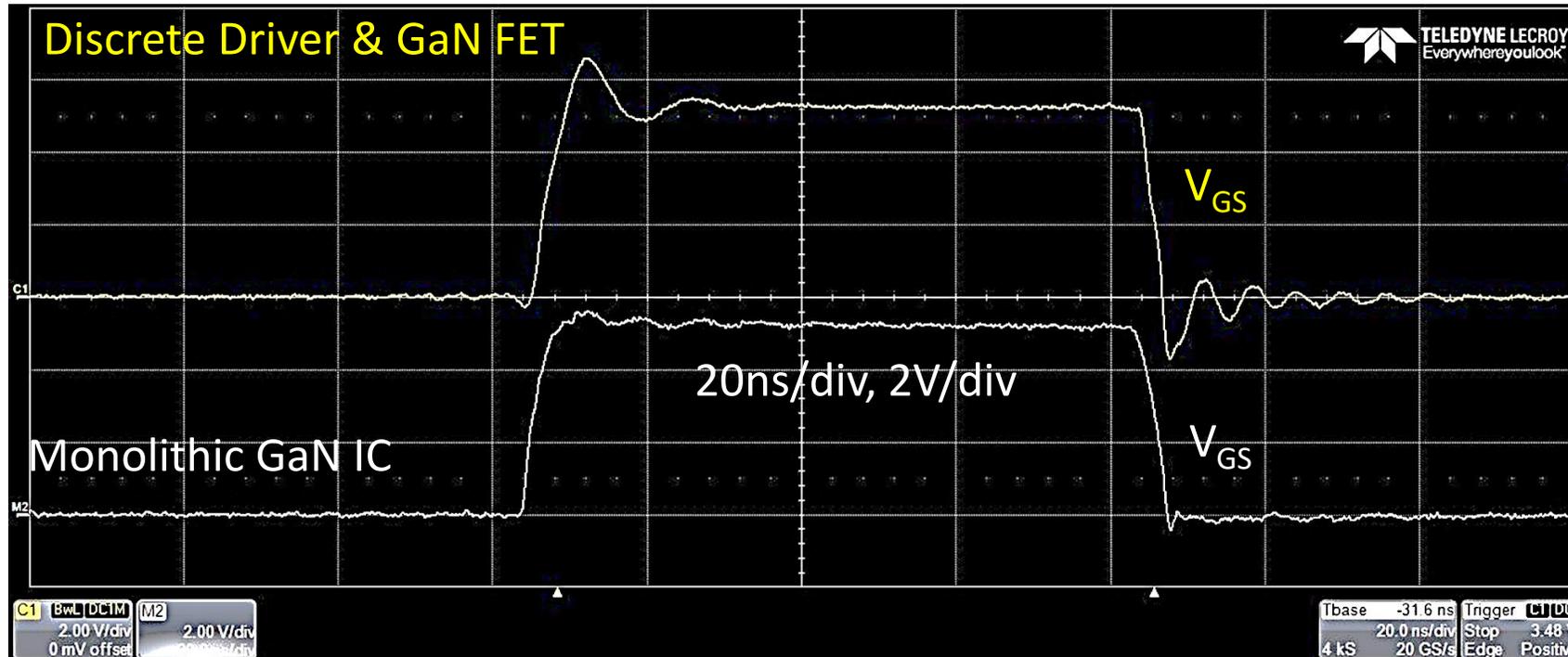
- Monolithic integration
- 20x lower drive loss than silicon
- Driver impedance matched to power device
- Shorter prop delay than silicon (10ns)
- Zero inductance turn-off loop
- Digital input (hysteretic)
- Rail-rail drive output
- Layout insensitive
- Industry-standard 5x6mm PQFN
 - High volume, reliable, low cost
 - Low profile (0.85mm), low inductance (0.2nH), low thermal resistance (<math><2^{\circ}\text{C}/\text{W}</math>)



QFN 5x6mm

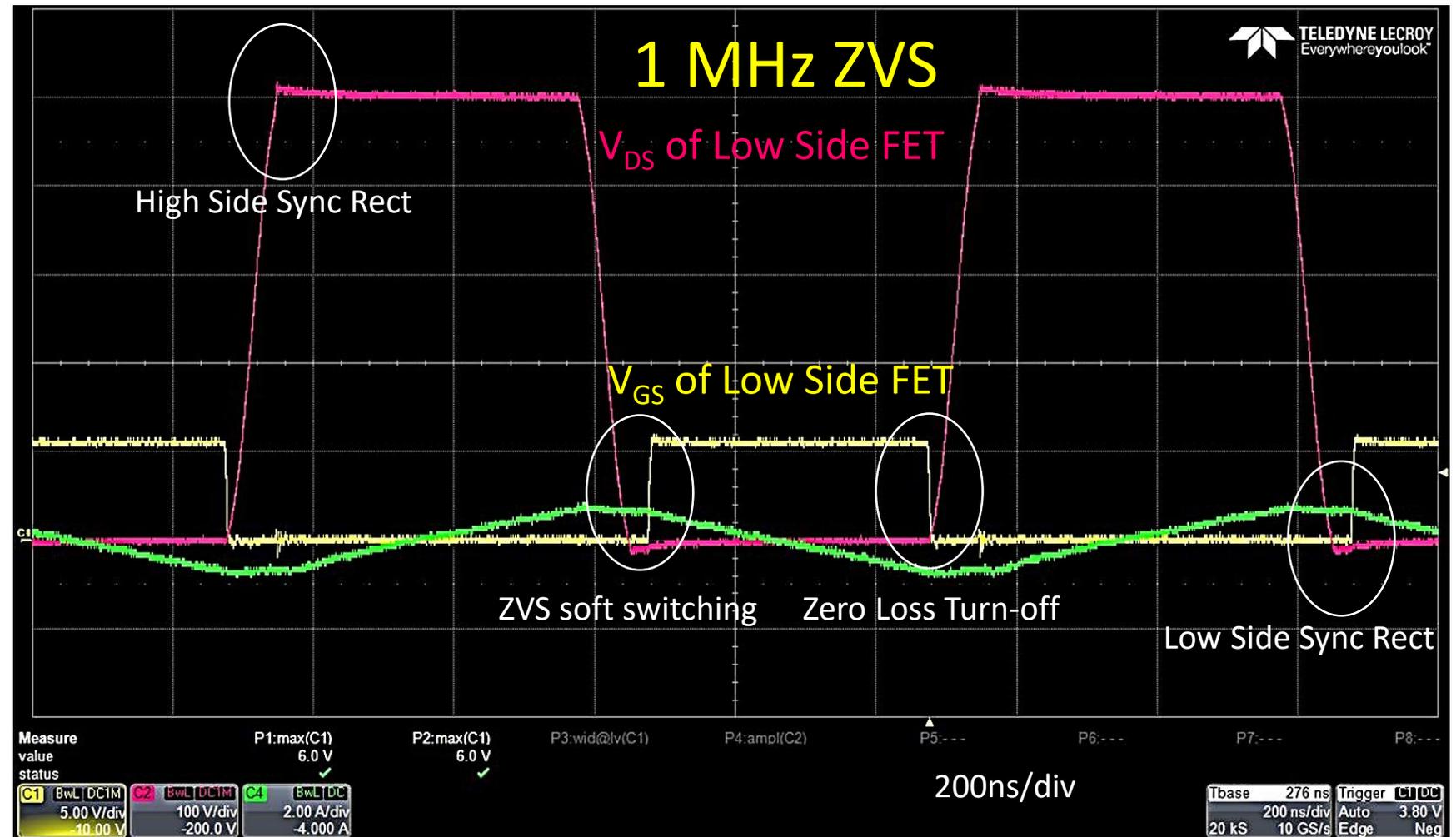
Crisp & Efficient Gate Control

- Monolithic Drive:
 - Eliminates gate overshoot and undershoot
 - Zero inductance on chip insures no turn-off loss



Smooth, clean, controlled waveforms

- 500V Switching
- No overshoot / spike
- No oscillations
- 'S-curve' transitions
- ZVS Turn-on
- Zero loss turn-off
- Sync rectification
- High frequency
- Small, low cost filter



Hard-Switch → Soft-Switch with GaN Power IC

Primary Switch Power Loss:

$$P_{FET} = P_{COND} \overset{\text{Minimized}}{\circledast k} + \overset{\text{Minimized}}{\circledast} P_{DIODE} + P_{T-ON}^{\times} + P_{T-OFF}^{\times} + P_{DR}^{\times} + P_{QRR}^{\times} + P_{QOSS}^{\times}$$

- k-factor >1 due to increased circulating current, duty cycle loss
- P_{T-On} = 0 (soft-switch)
- P_{Qoss} ↓ 10x ~~2-3x~~ (GaN C_{OSS} charging/discharging loss negligible up to 2MHz)
- P_{DRIVER} ↓ 10x (GaN P_{DR} negligible up to 2MHz)
- P_{QRR} = 0
- P_{DIODE} ↓ 3x ~~2x~~ (synchronous rectification with improved dead-time control)
- P_{T-OFF} = 0 ~~Reduced~~ (near-zero drive loop impedance with integration)

>10x frequency increase possible with higher efficiencies

The MHz Eco-System

-  **Navitas** GaN Power ICs plus...

- High-frequency controllers (PFC, PWM, DSP, LLC, SR)



- High-frequency magnetics



- High-frequency SR FETs

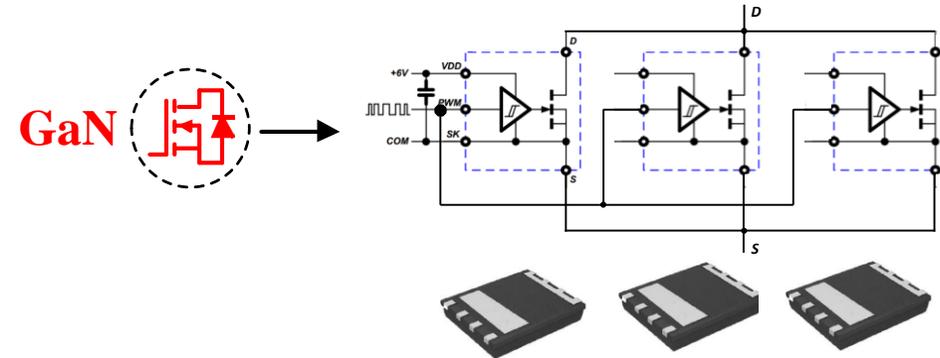
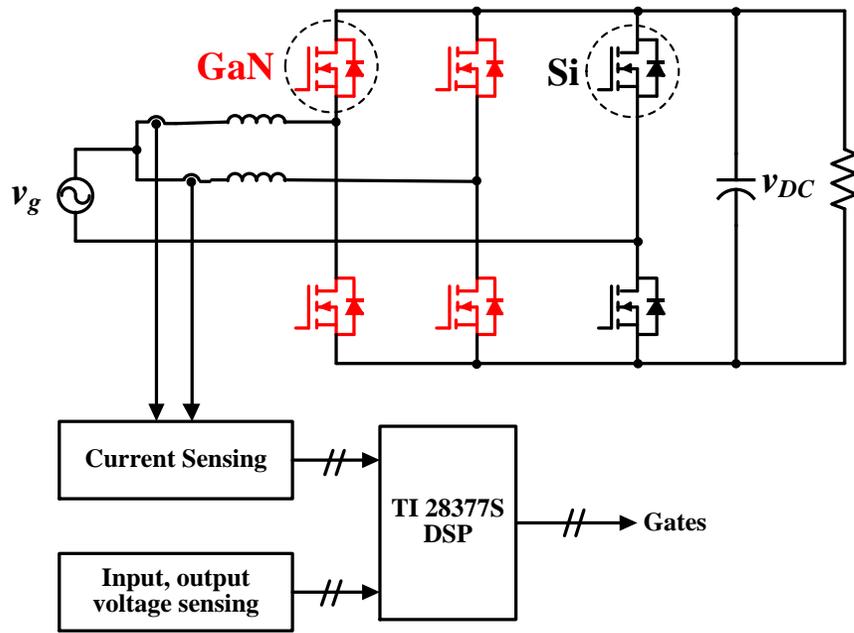
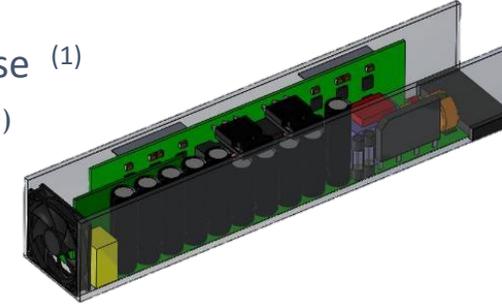


3kW PFC (2-phase Totem-Pole CrCM)

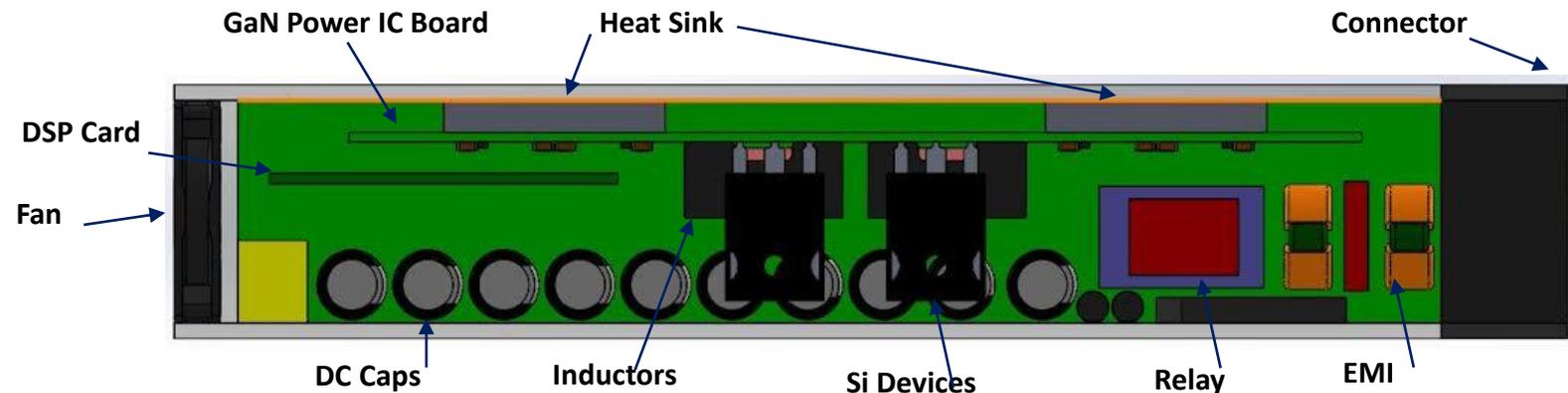
- Input : 220V_{AC} (47-63Hz)
- Output : 400V, 3,000W
- Frequency* : 1MHz each phase

*Dual phase variable frequency interleaving (500kHz – 1.5MHz range)

- Efficiency : >99% @ 800kHz, 200-1200W/phase ⁽¹⁾
>98.8 @ 500kHz, 1800W /phase ⁽¹⁾
- Power Factor : >0.995 ⁽¹⁾
- Power Density : 135W/in³ ⁽²⁾
- Size : 220 x 35mm x 1U ⁽²⁾

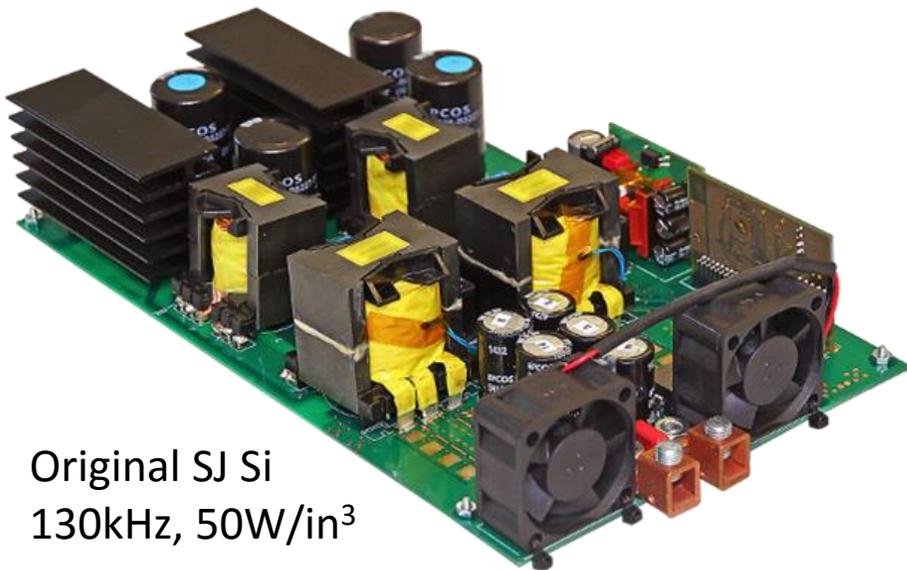


(1) Achieved on Alpha prototype
(2) Target for Beta prototype



3kW LLC: 2x–3x Smaller with GaN

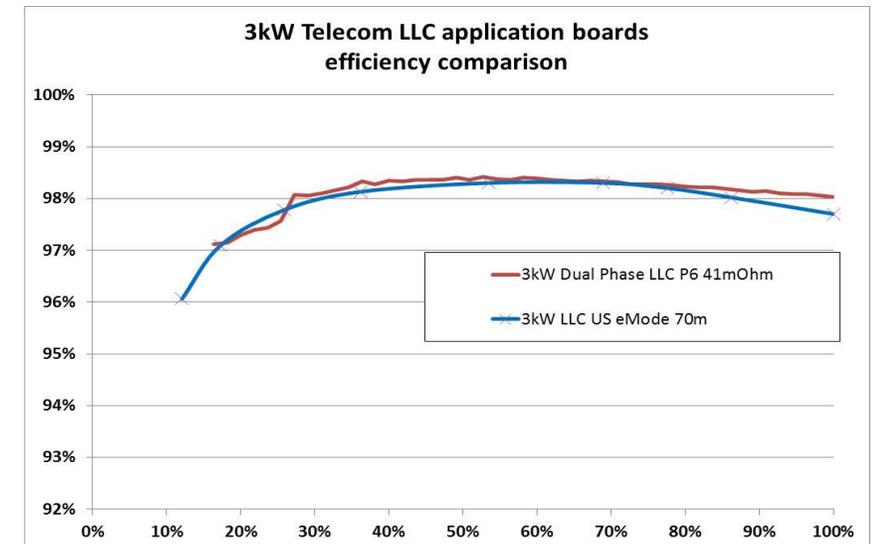
- Input : 380V_{DC}
- Output : 52V, 3,000W
- Frequency : 350kHz
- Efficiency : 98.4% peak
- Power Density : 140W/in³ (2)
- Size : 152 x 91 x 32mm



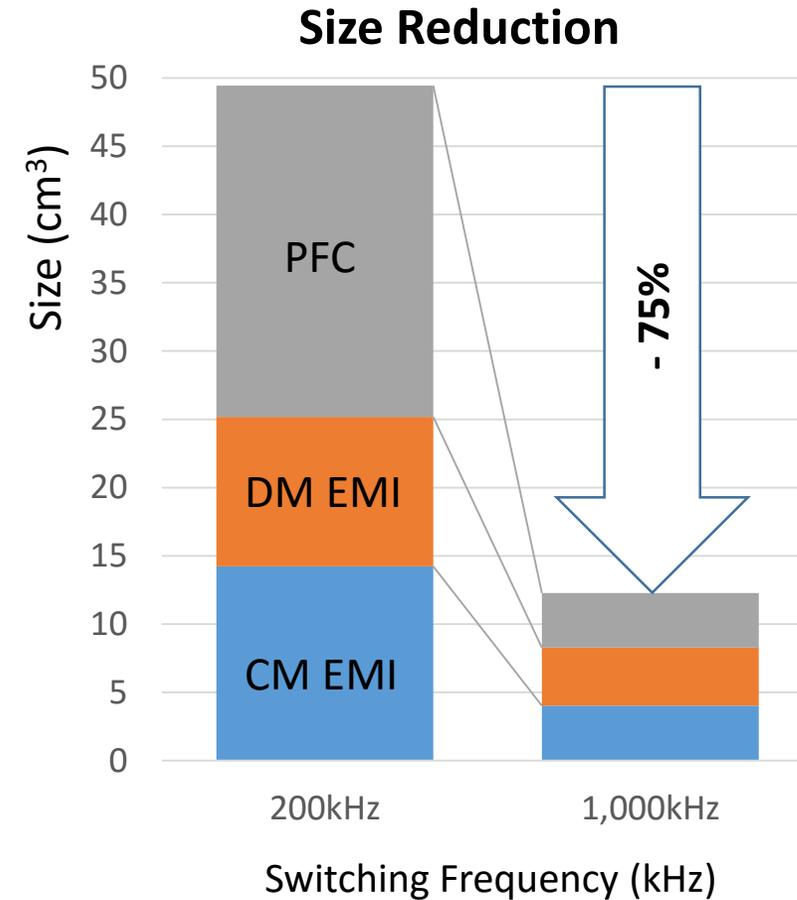
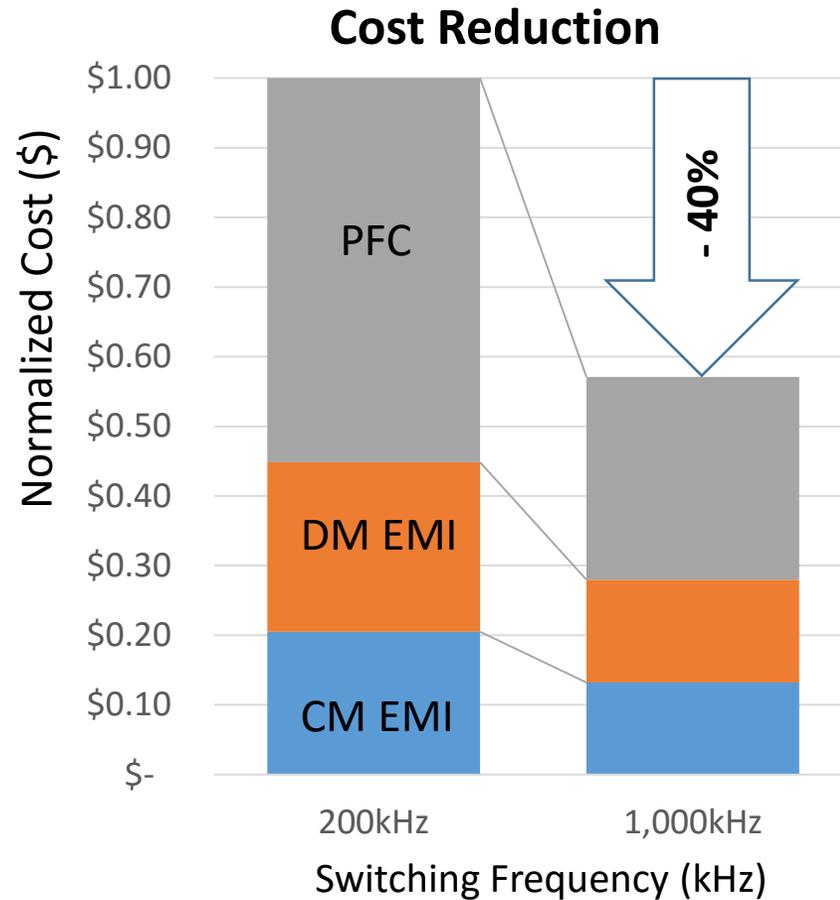
Original SJ Si
130kHz, 50W/in³



New CoolGaN™
350kHz, 140W/in³



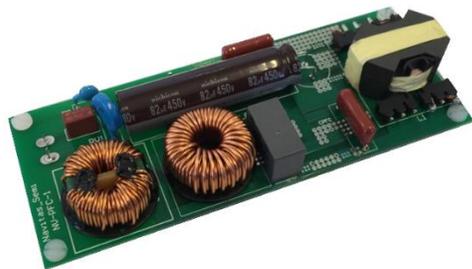
Higher Frequency = Smaller, Cheaper



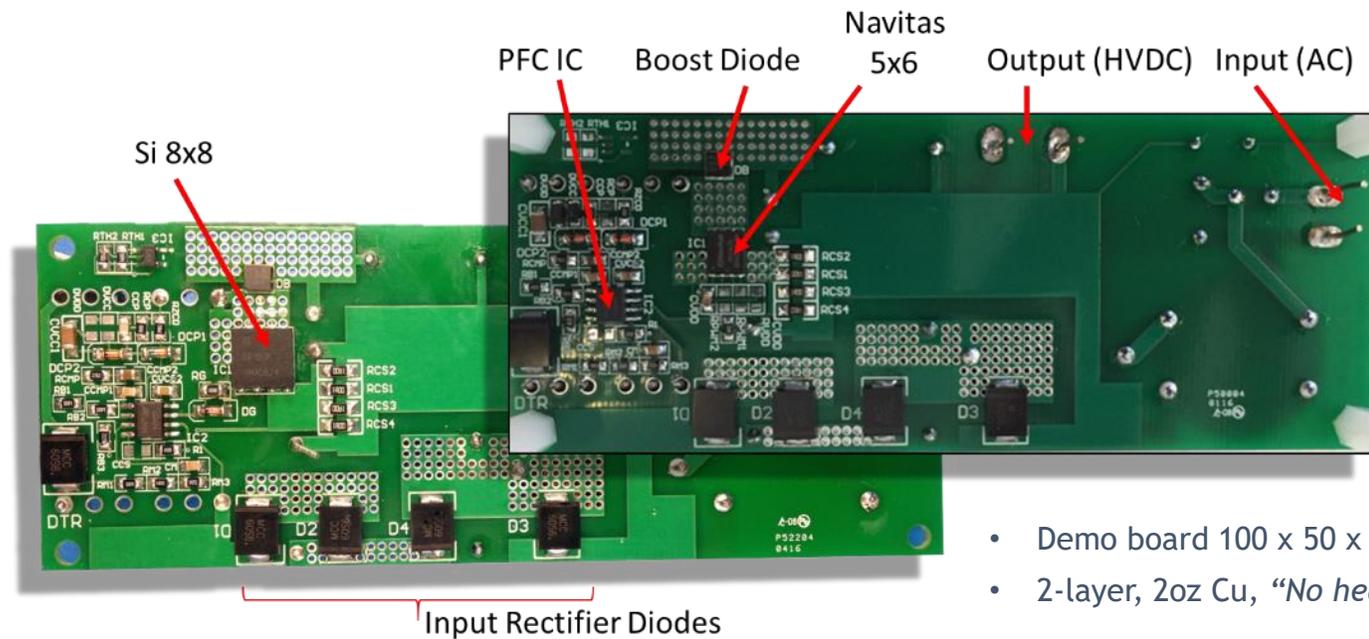
EMI & PFC Magnetics

SJ Si vs. GaN Power IC (CrCM PFC 150W)

	Pack	$R_{DS(ON)}$ m Ω	Q_G nC	$C_{OSS(er)}$ pF	$C_{OSS(tr)}$ pF	$R * Q_G$ m Ω .nC	$R * C_{OSS(tr)}$ m Ω .pF	$R * C_{OSS(er)}$ m Ω .pF
Navitas	5x6	160	2.5	30	50	400	8,000	4,800
IPL65R199CP	8x8	180	32	69	180	5,760	32,400	12,400
IPL60R130C7	8x8	115	35	53	579	4,025	66,600	6,100
GaN Benefits	>50%	n/a	>10x	>2x	>10x	>10x	>7x	>2.5x

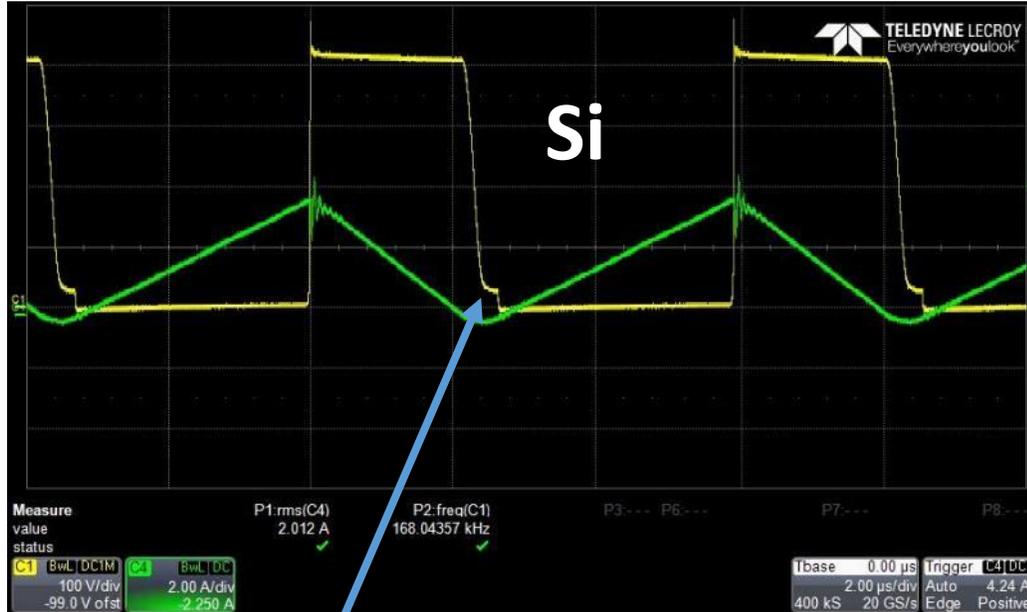


- AC to 400V_{DC}, 150W
- 120V = 167-230kHz
- 220V = 230-500kHz
- 265V = 1MHz (limited by PFC IC (L6562A))



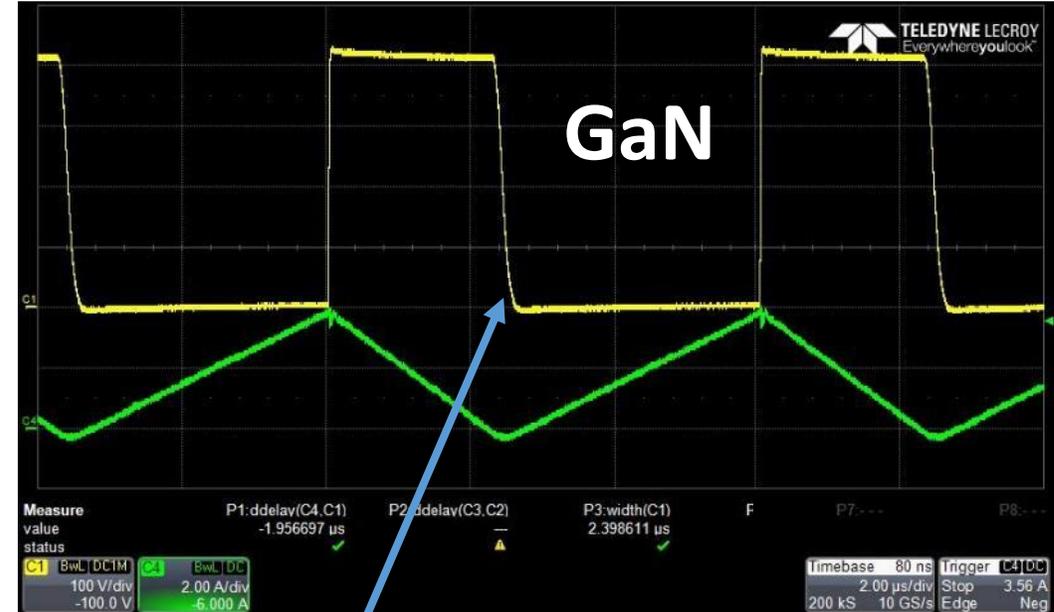
- Demo board 100 x 50 x 20mm
- 2-layer, 2oz Cu, "No heatsink" design

Si Starts Hard Switching as Frequency Increases



120V_{AC}, Si CP partial hard-switching (~200kHz)

- Voltage spikes
- Partial hard-switching (loss)

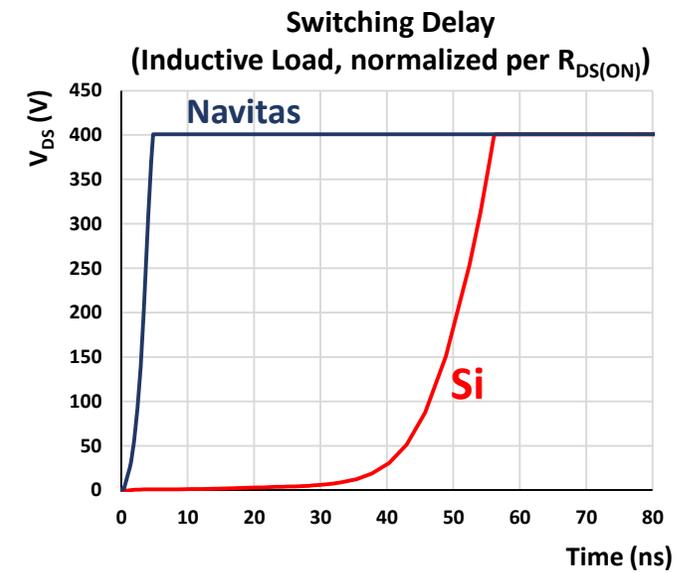
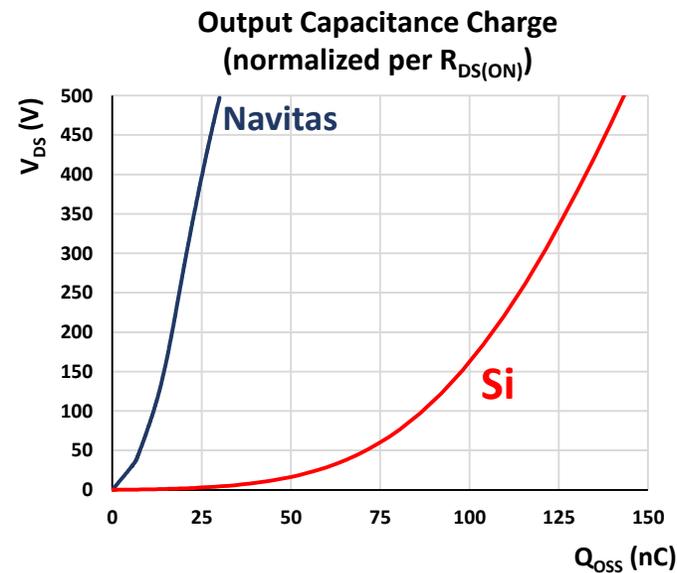
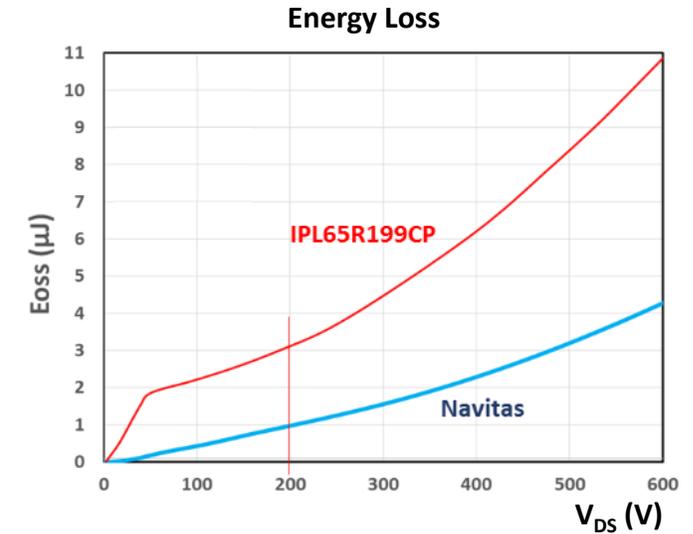
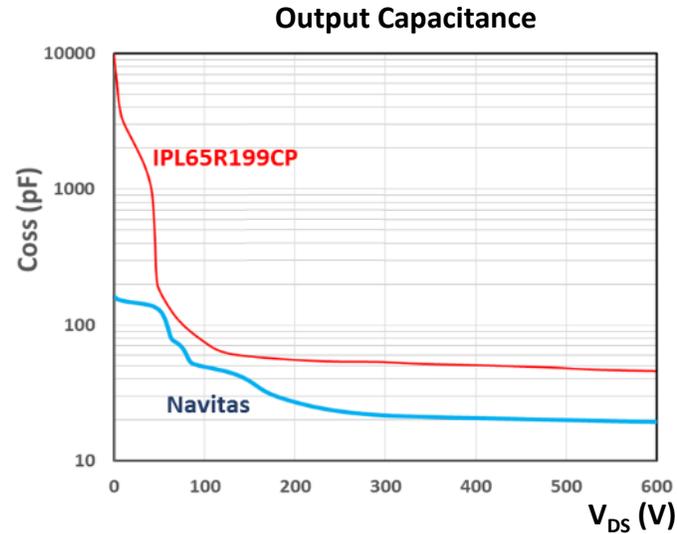


120V_{AC}, GaN clean ZVS waveforms (~200kHz)

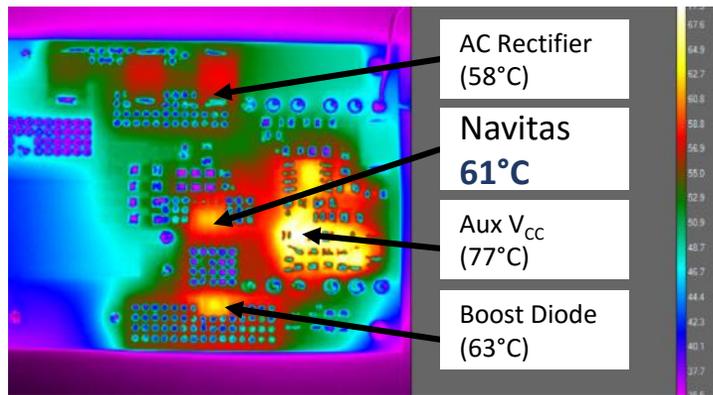
- No voltage spikes / overshoot
- Clean ZVS turn-on transition
- Minimize deadtime for low reverse conduction loss

Si: High C_{OSS} = Long ZVS Transition = Trapped Energy

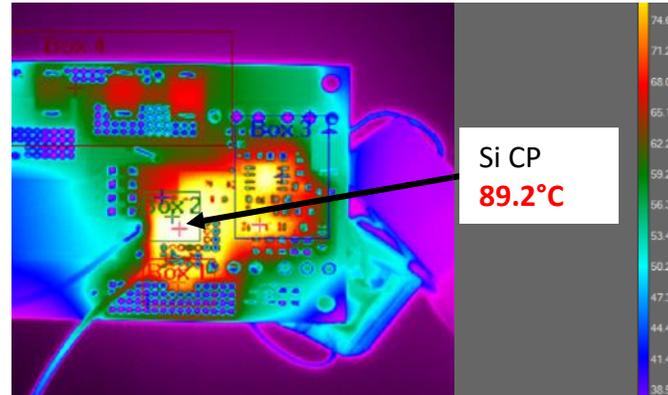
- Switching loss:
 $P_{LOSS} = E_{OSS} (V_{DS}) * F_{SW}$
- $C_{OSS} \rightarrow$ Delay (limits F_{SW})
- Too slow \rightarrow partial ZVS $\rightarrow E_{OSS}$ loss
- Si C_{OSS} is 50x-100x higher than GaN at $V_{DS} < 30V$
- Si P_{LOSS} is 3x higher than GaN at 200V (partial ZVS)
- Big effect at full or light load condition
- Further information: “ C_{OSS} Hysteresis in Advanced Superjunction MOSFETs”, Harrison, APEC 2016



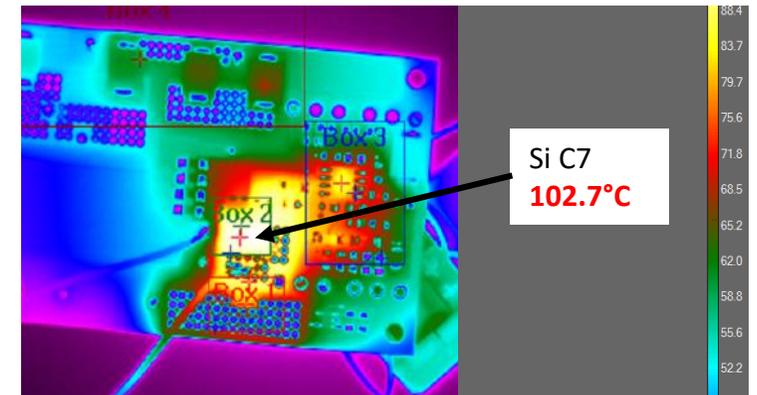
Full Load Performance



220V_{AC}, 150W



220V_{AC}, 150W



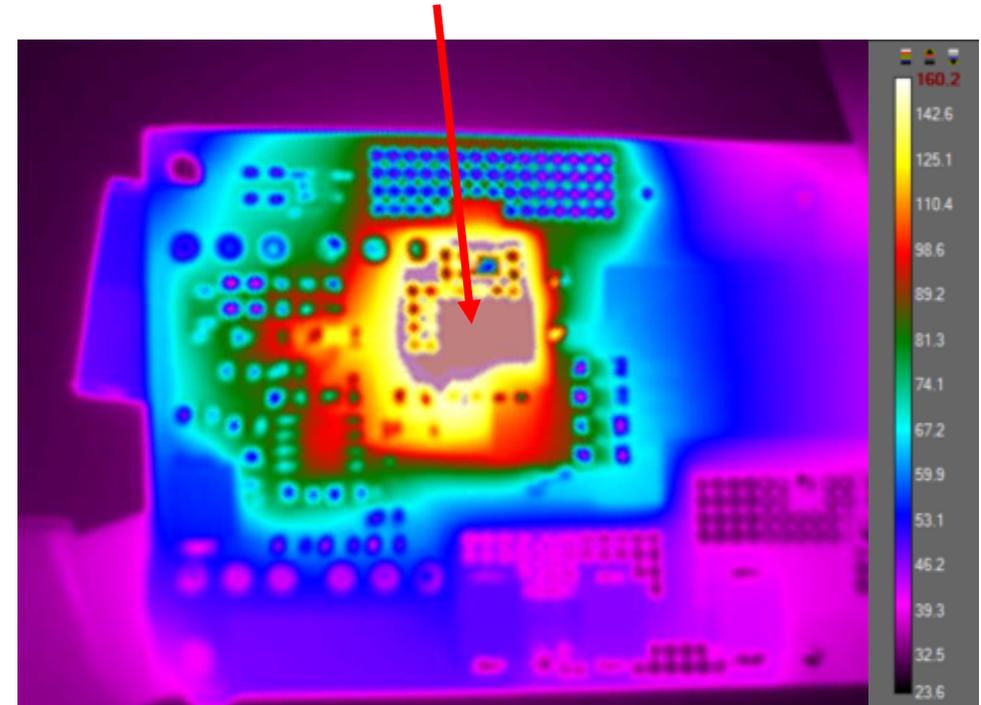
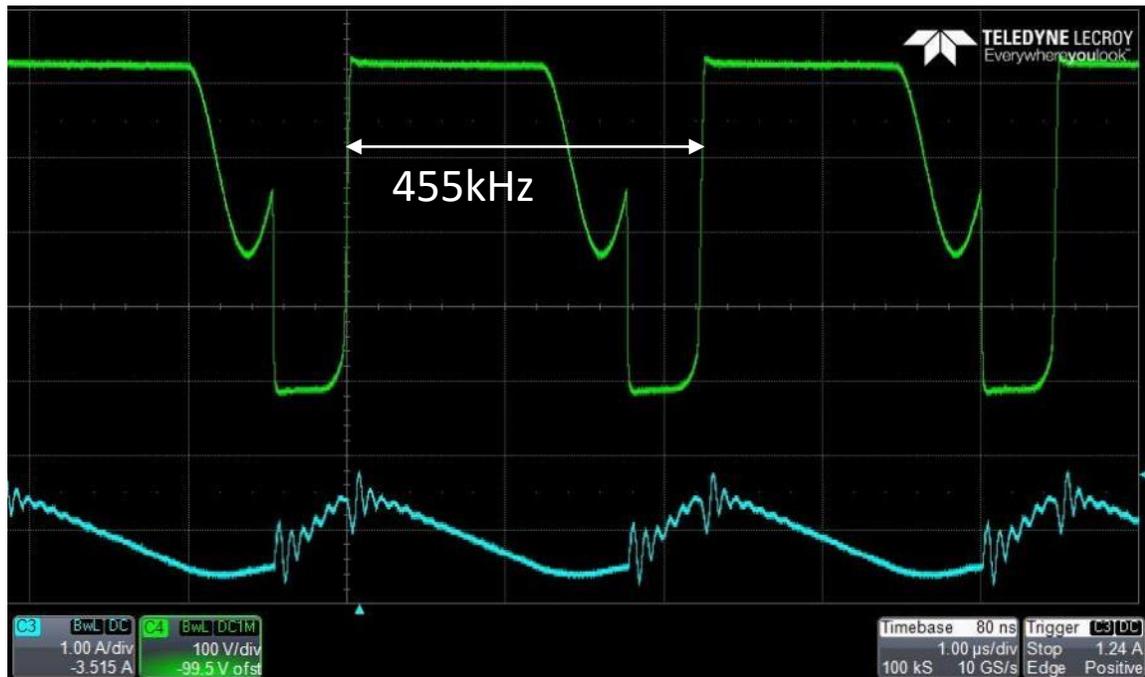
180V_{AC}, 150W

- GaN runs cool (61°C)

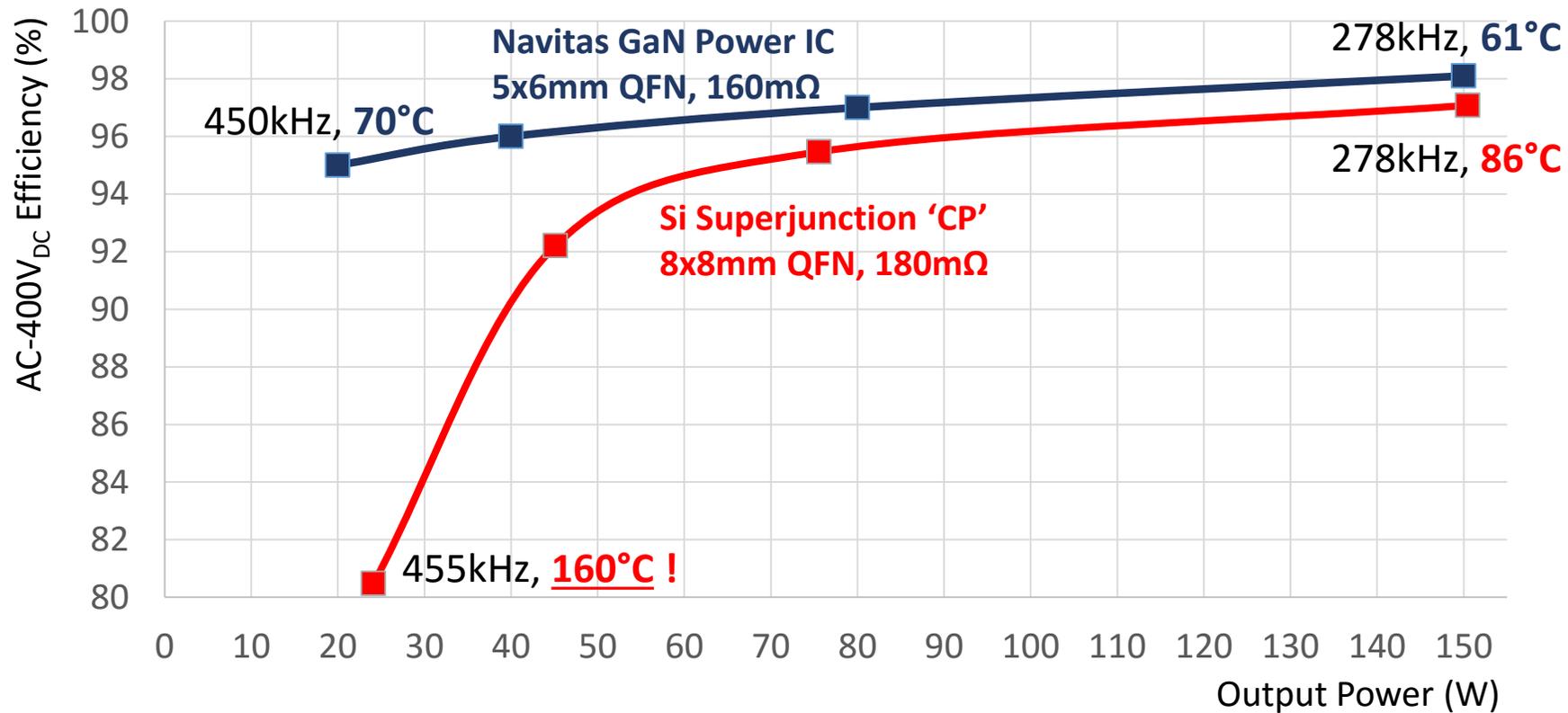
- CP Si running >90°C
- C7 Si too hot to run at 220V_{AC}

Light Load = High Frequency = High Loss for Si

Si switching loss: $P_{LOSS} = E_{OSS} (V_{DS}) * \text{frequency (at 20W)}$
 $= 3.5\mu\text{J} * 455\text{kHz}$
 $= 1.59\text{W} \longrightarrow = 160^{\circ}\text{C} !$

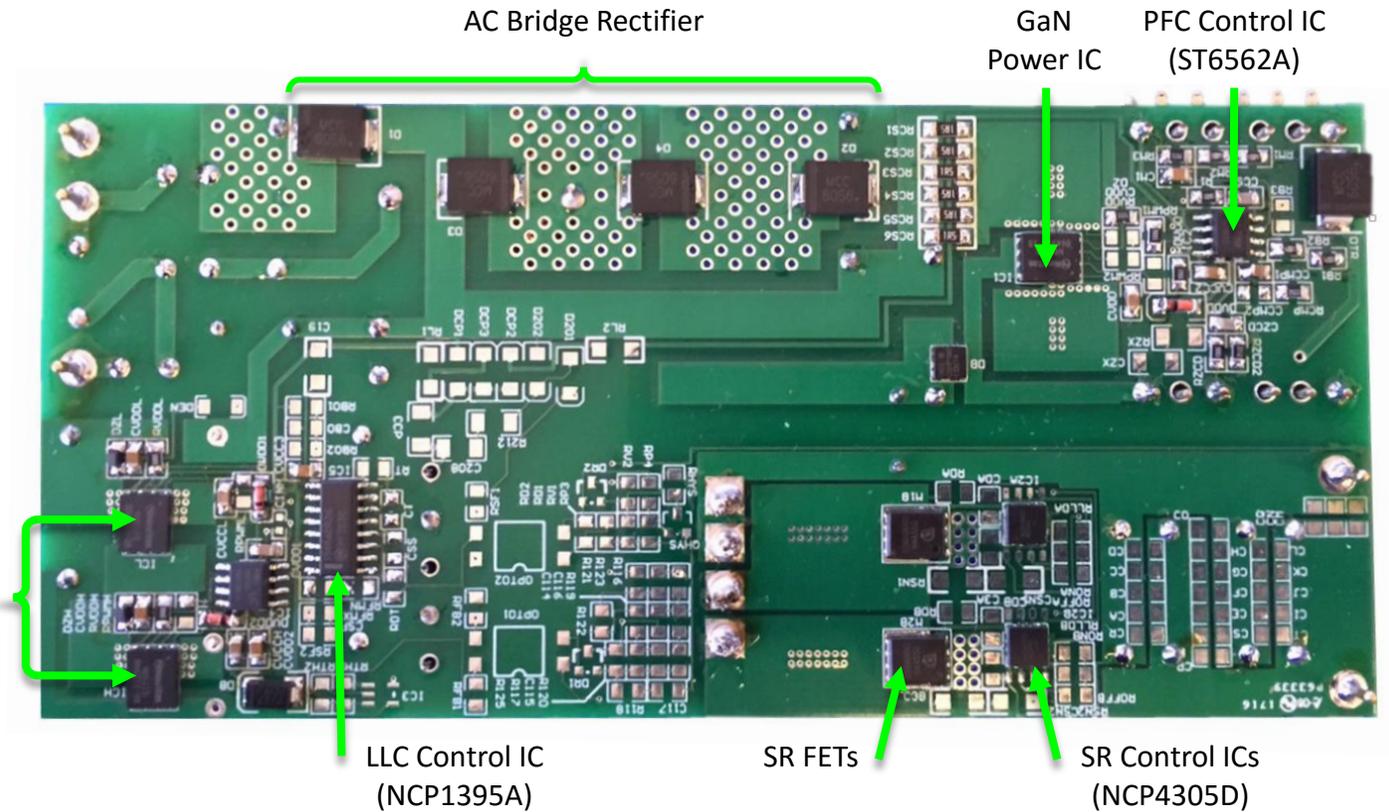
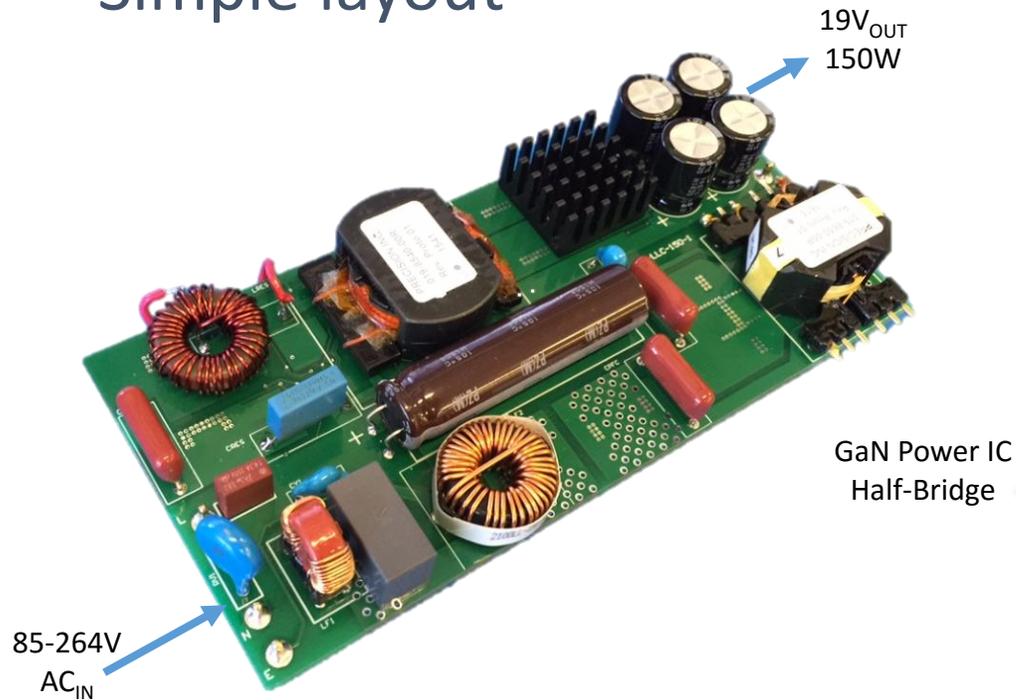


Hot Si, Cool GaN



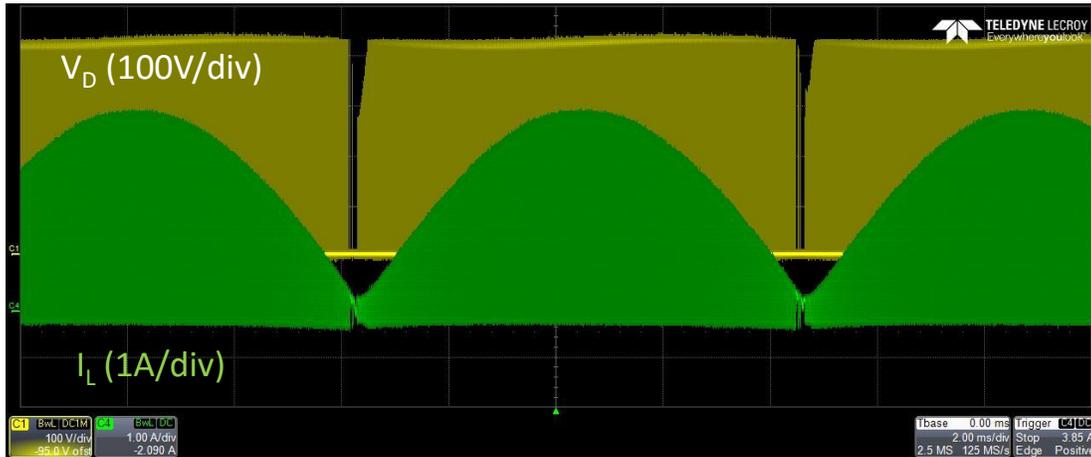
AC-19V: GaN Power ICs in PFC, LLC

- Simple schematic
- Simple layout

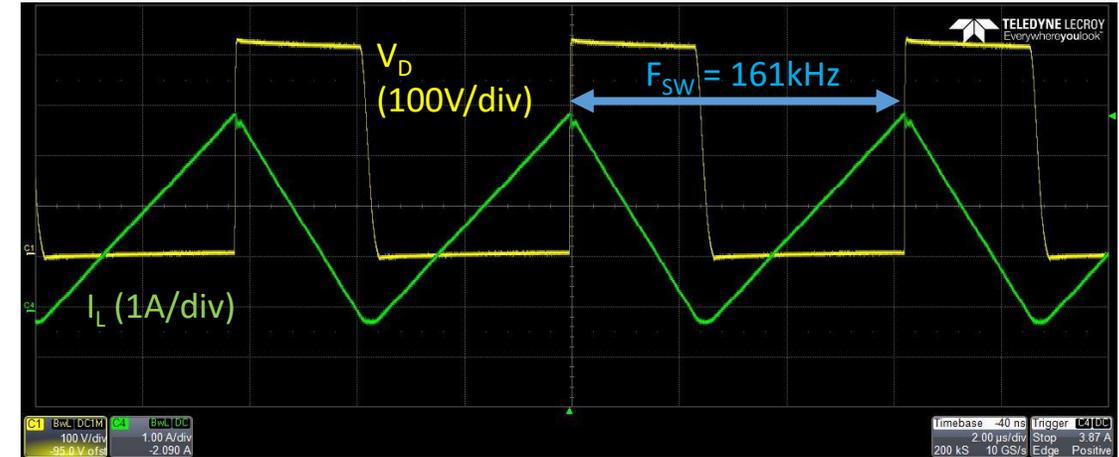


CrCM PFC: High-Frequency, High Performance

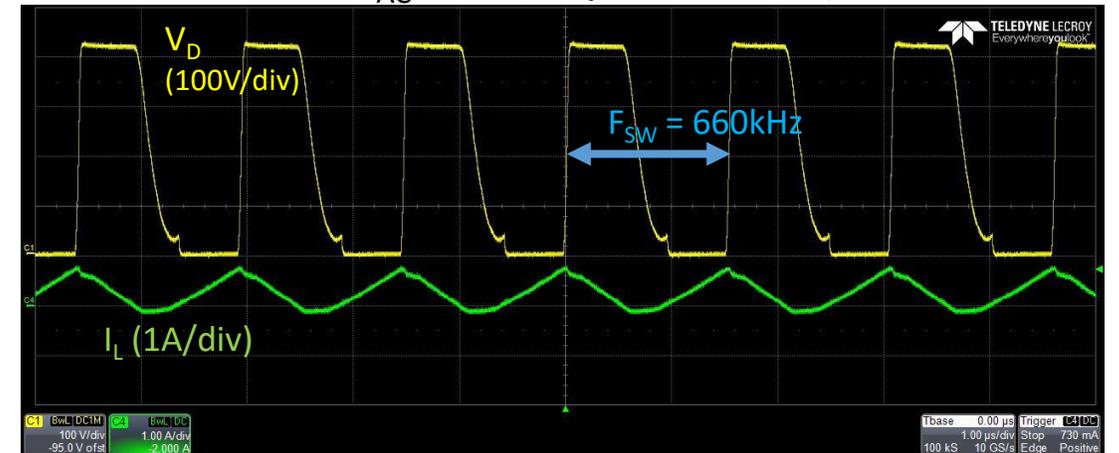
120V_{AC}, 150W



120V_{AC}, 150W, @peak AC line)

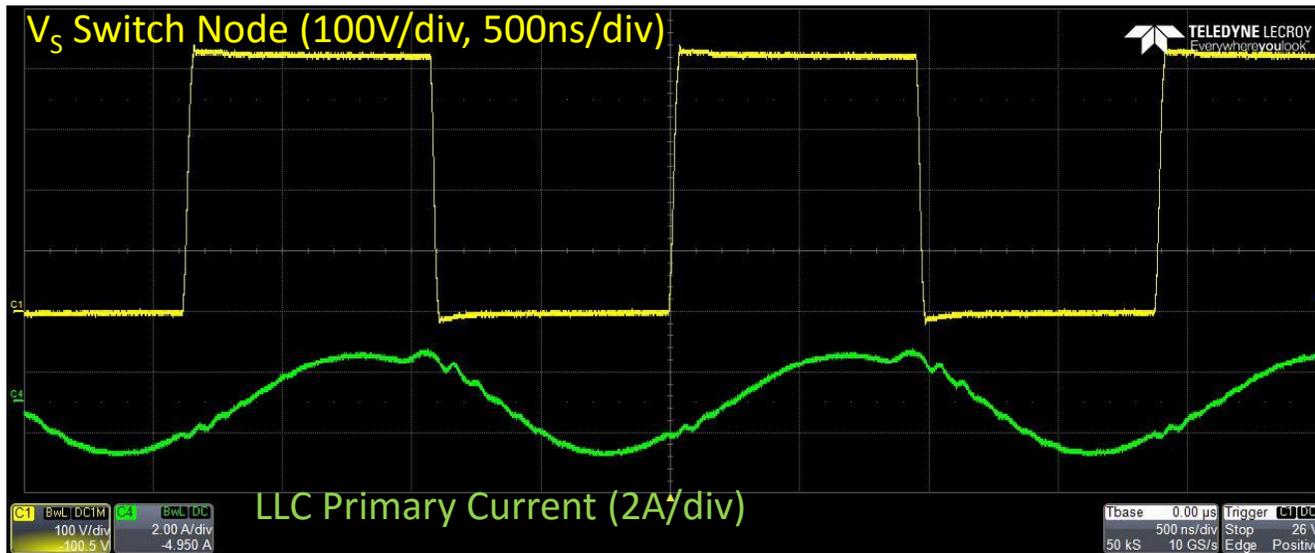


220V_{AC}, 85W, @peak AC line)

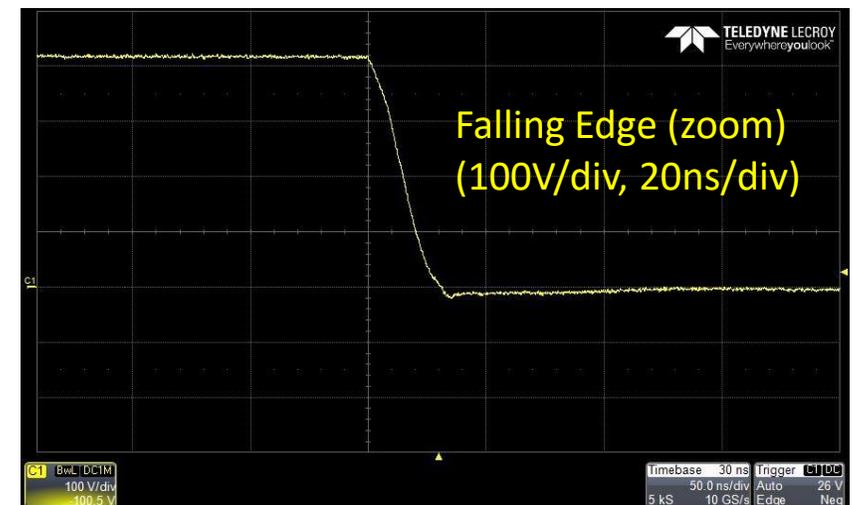
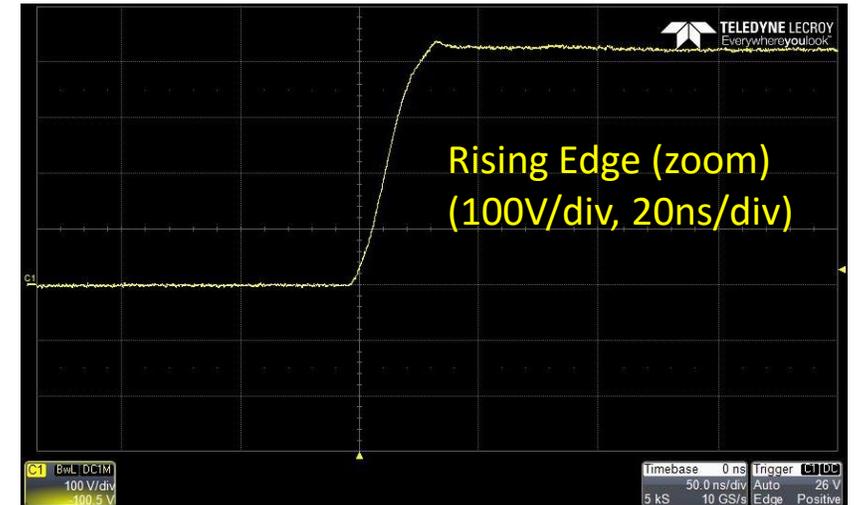


- PF >99.5%
- Efficiency 97.1% (120V_{AC}), 98.1% (220V_{AC})

LLC: Smooth, Fast, Quiet



- No spikes, overshoot
- Smooth ‘S-curves’ with fast $\sim 40\text{V/ns}$ slope
- Low EMI signature

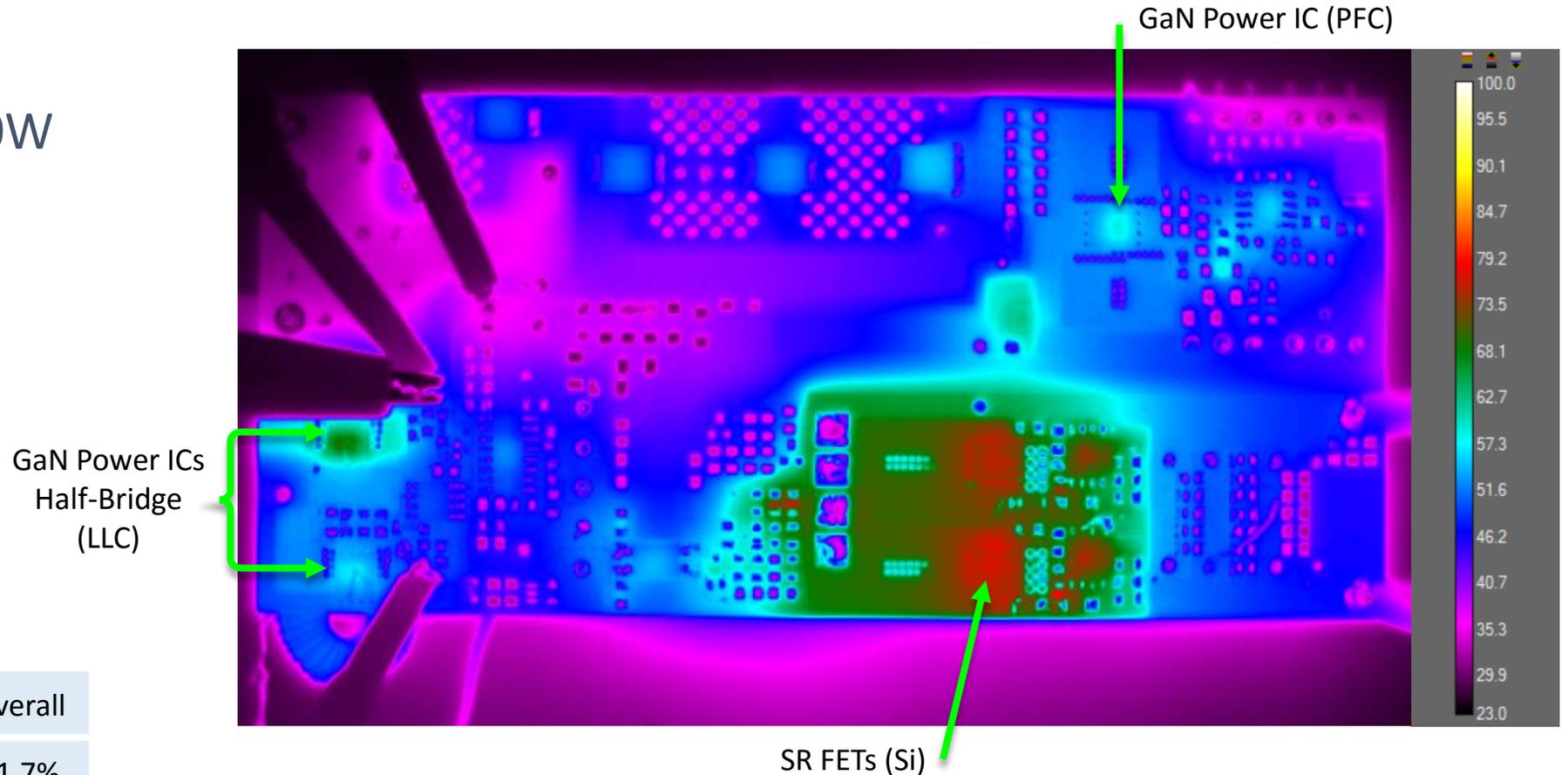


GaN Power ICs: Cool at Full Load

- 120V AC_{IN}, P_{OUT} = 150W
- PFC at ~500 kHz
- LLC at ~600 kHz
- GaN Power ICs ~65°C
- Si SR FETs ~75°C

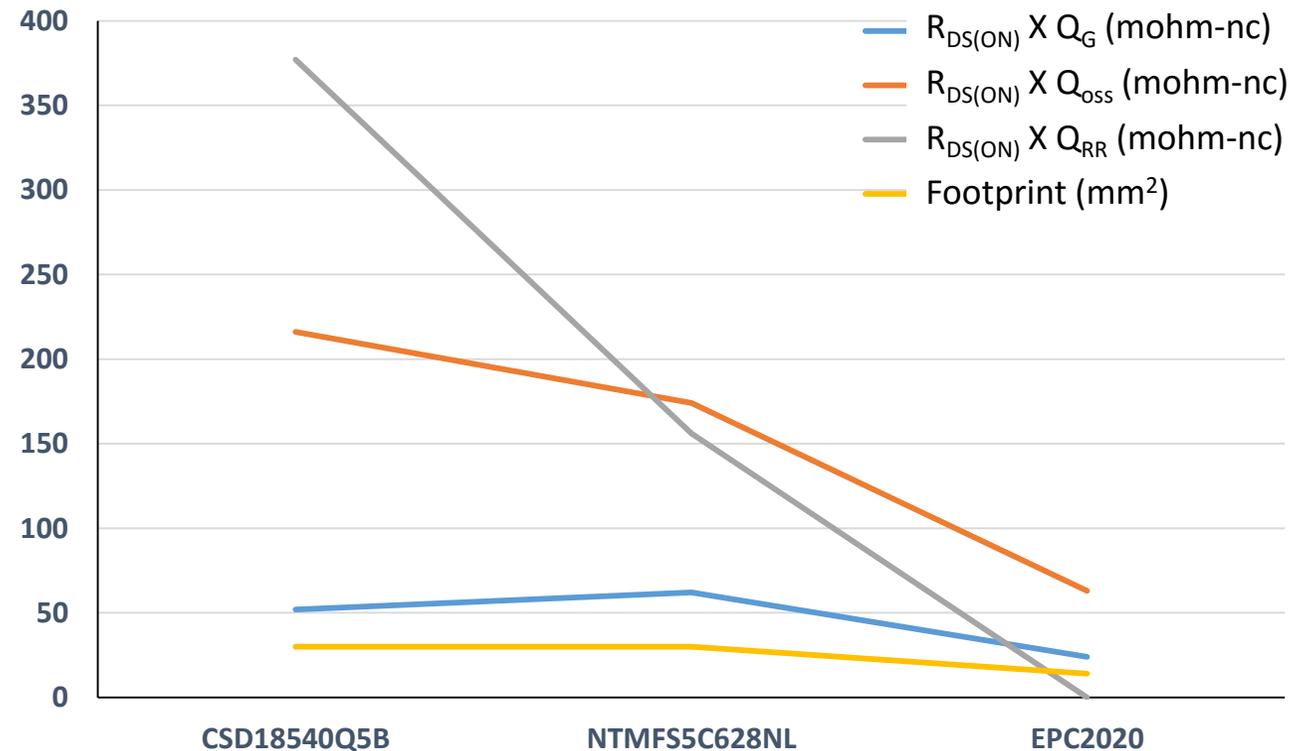
- Efficiency:

	PFC	LLC	Overall
120VAC	97.1%	94.4%	91.7%
220VAC	98.1%	94.8%	93.0%



Comparing 60V SR FETs: Better with GaN

- All relevant FOMs favor GaN at 60V
 - $R_{DS(ON)} \times Q_G$ reflects drive losses
 - $R_{DS(ON)} \times Q_{OSS}$ reflects turn-off losses with non-resonant rectification
 - $R_{DS(ON)} \times Q_{RR}$ reflects stored minority carrier turn-off losses (minimized with dead-time control)
- Si in QFN 5x6mm, GaN is Chip-Scale BGA



Note: Datasheet typicals at 4.5/5V gate drive and capacitance curves

Frequency drives 2x-4x Power Density

- Typical adapters (65-150kHz) = 5-12W/in³
- Navitas demo (500kHz) = 13.5W/in³
- Navitas customer estimate = 20-25W/in³



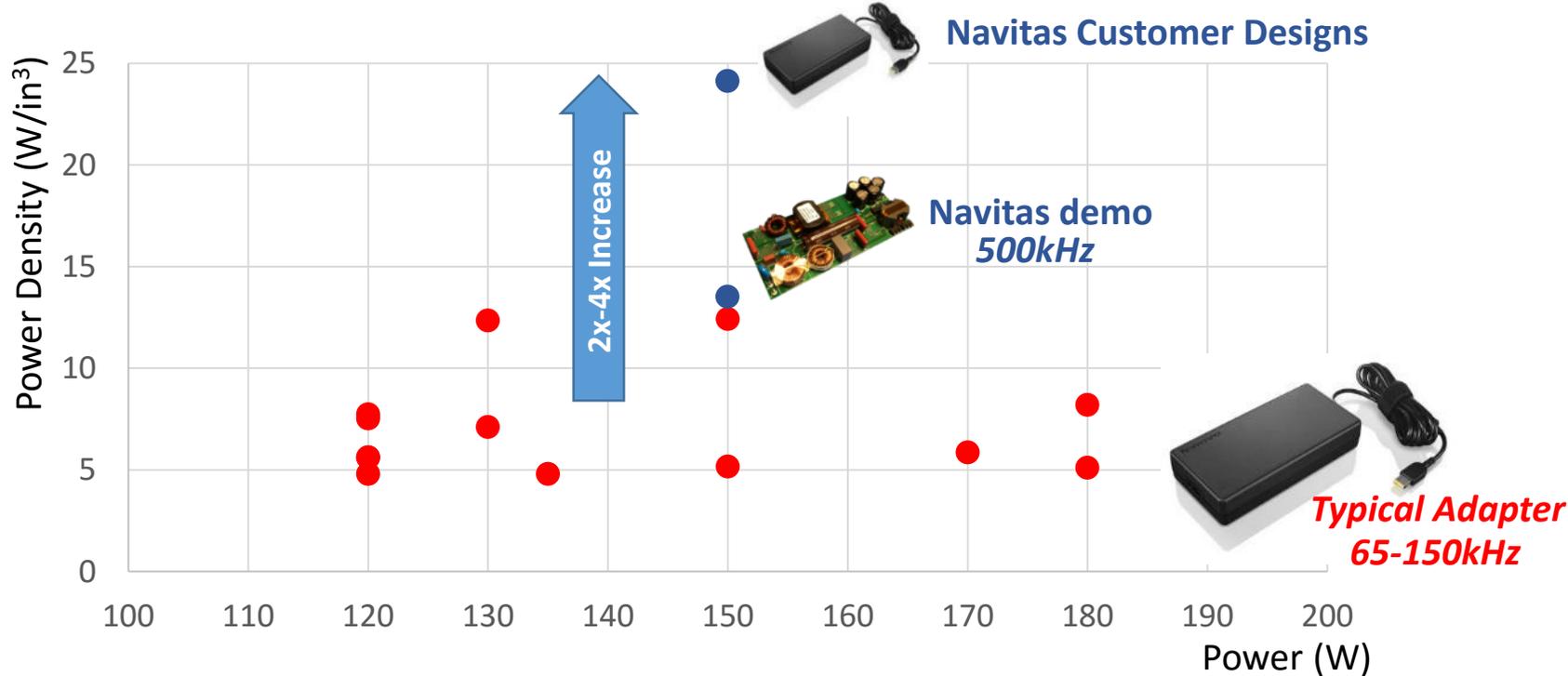
Gamer Laptops (100-150W)



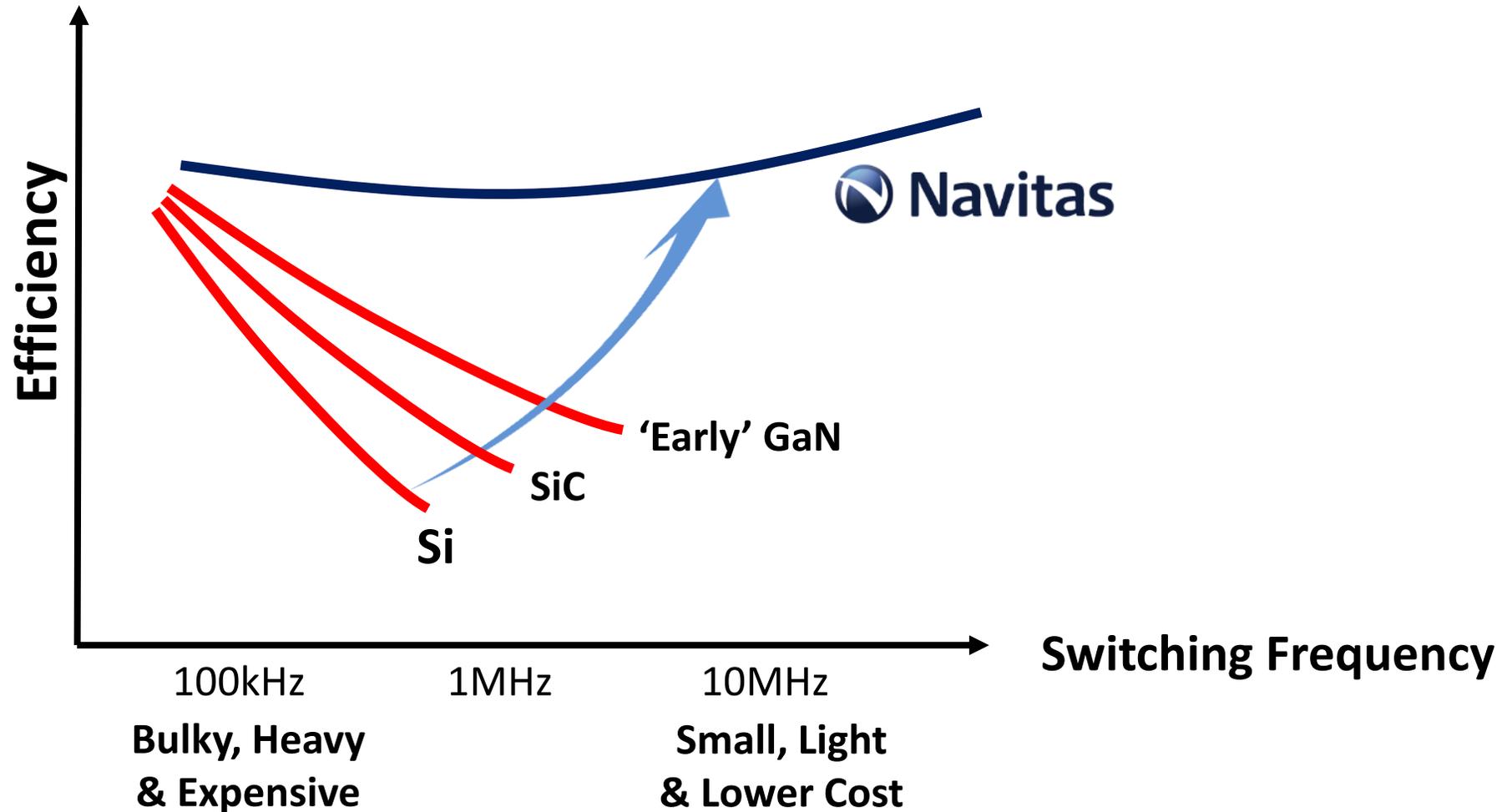
All-in-One PCs (150-200W)



38"-52" TVs (100-200W)



GaN Power IC's Enable High Frequency & Efficiency



The New World...



The New World...



Questions?