GaN in a Silicon world: competition or coexistence?

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Abstract

Significant development resources have been expended and Gallium Nitride (GaN) based power conversion devices are now being introduced to the market on the heels of much hype. It remains to be seen how widely GaN power transistors will be adopted. Will GaN devices eventually replace all Silicon power transistors? Or will there be peaceful coexistence with complementary performance? Where will GaN succeed and where will Silicon still thrive? This presentation will attempt to answer these questions by considering historical precedence, by considering relative strengths and weaknesses of each technology, by examining initial applications for GaN devices, and by peering into the crystal ball and projecting GaN vs Silicon adoption trends.

Outline

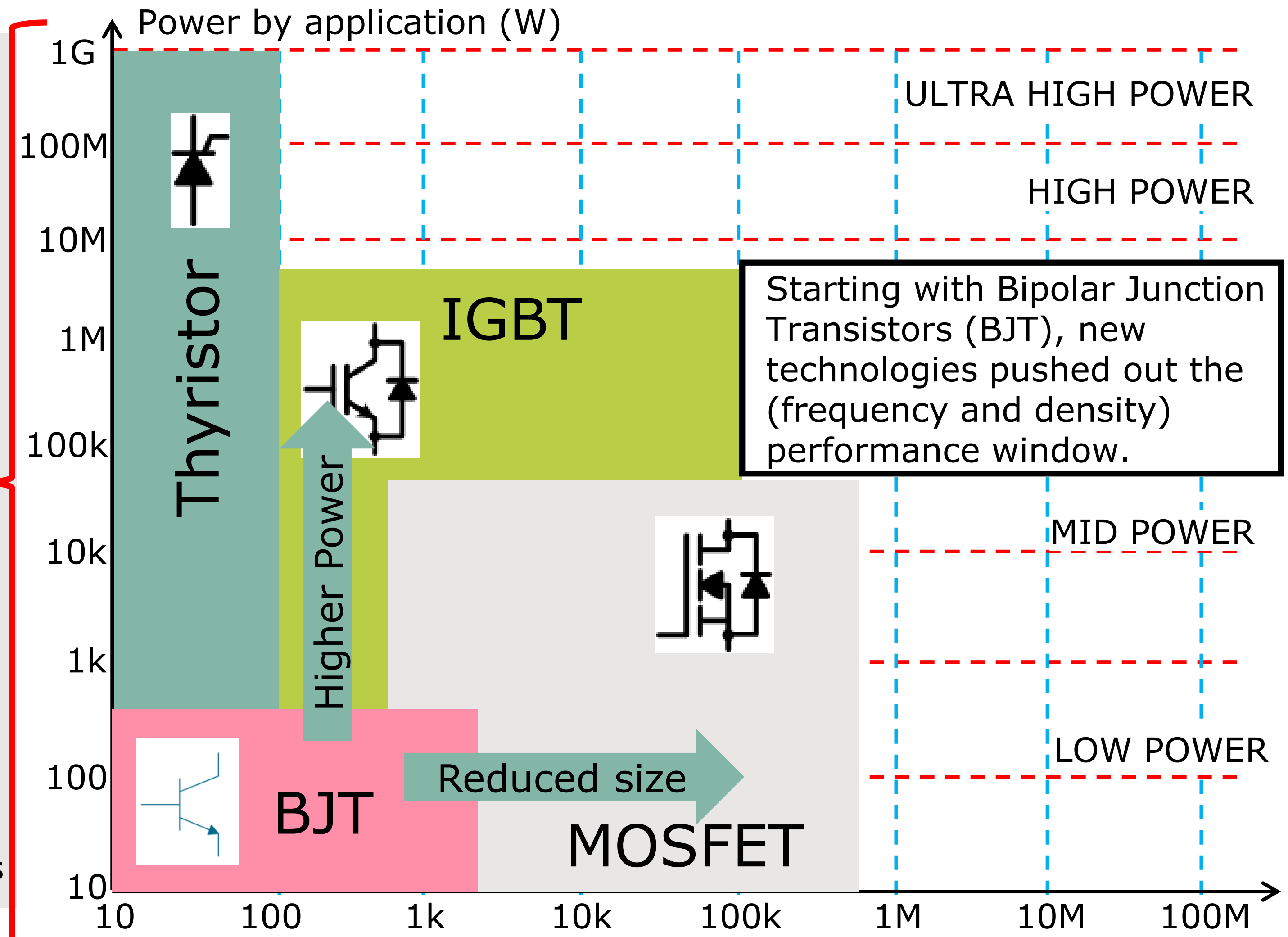
1. Historical Perspective for new power switch technology
2. GaN vs. Silicon Technology
3. First uses of GaN
4. Crystal gazing: where will silicon thrive and where will GaN be adopted over time?
5. Concluding comments

1a

Today‘s switch technology use by power and frequency

Application	Future scenario power electronics

- HVDC
- HC-supplier
- Large drives
- Ships
- Locomotives
- Large solar plants
- Trams, buses
- Electric cars
- On-roof PV
- Small drives
- Air conditioner
- Robotics
- Washing machine
- SMPS
- Chargers/Adapters



Degree of adoption depends strongly on cost

1b

Historical perspective: “conversion” from power bipolar transistor to power MOSFET

Power Transistor Market Size ($M)		
Technology	**1984 (HTE, 1991)**	**2015(IHS)**
Bipolar Junction Transistor	$957	$881
MOSFET	$115	$6,034
Superjunction MOSFET	$0	$895
IGBT	$0	$4,946
Total (Less SJ MOSFET)	$1,072	$11,861

- **After 30 years of “conversion” the bipolar market is basically unchanged in size (not accounting for inflation)**
- **New power transistor technologies nibbled at the edge of predecessor technologies but basically established new markets enabled by higher performance (frequency, power)**
- **Incumbent technologies are not easily “replaced”; rather a new technology is adopted in new designs and new applications where it offers higher overall efficiency , density or cost benefits (which vary greatly by market segment)**

2a

Technology comparison: GaN vs Silicon*

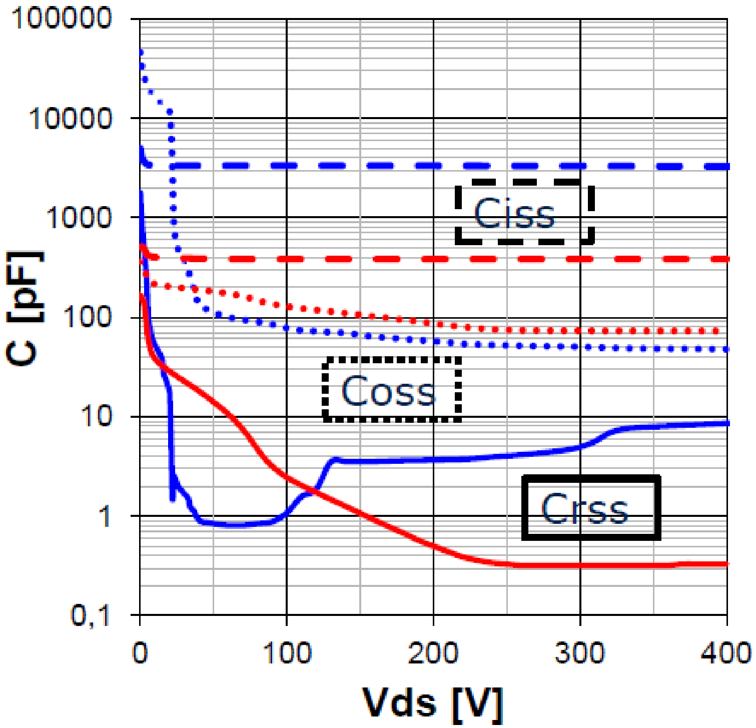
Parameter	E-mode GaN	Equivalent Super junction FET	Comments
V_{dss}	600 V	600 V	
R_{DSon} typ 25°C	52 mΩ	52 mΩ	
E_{oss}	7 uJ	8 uJ	Near parity for hard switching performance
$T_k, R_{DS(on)}$ (150°C/25°C)	1.8	2.37	$R_{DS(on)}$ Tempco
Q_g (10 V V_{gs}, 400 V V_{ds})	6 nC	68 nC	GaN >10x lower than Superjunction FET
Q_{rr} (100 A/µs, 25°C)	1 nC (Q_{oss}: 44 nC)	6,000 nC	GaN >100X lower than SJ (including Q_{oss})
$C_{o(tr)}$ (400 V)	110 pF	1,050 pF	GaN ~10x lower
Rθ J-C (°C/W)	1.0	0.77	Consistent with package

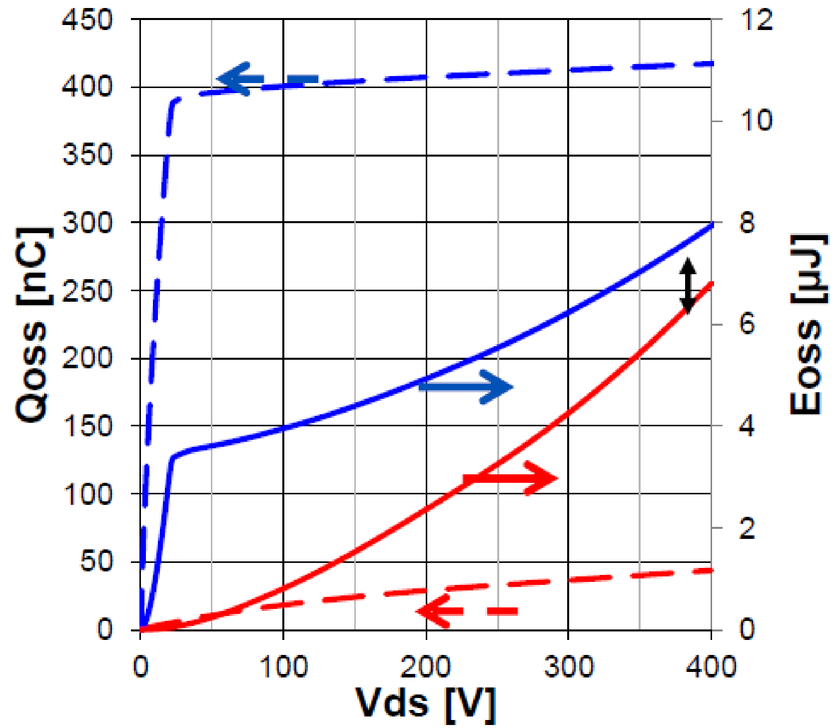
* GaN values are for prototype devices

2b

Superjunction vs GaN: why no large difference is seen in hard switching losses

Blue = superjunction
Red = e-mode HEMT
Both ~70 mΩ max $R_{DS(on)}$

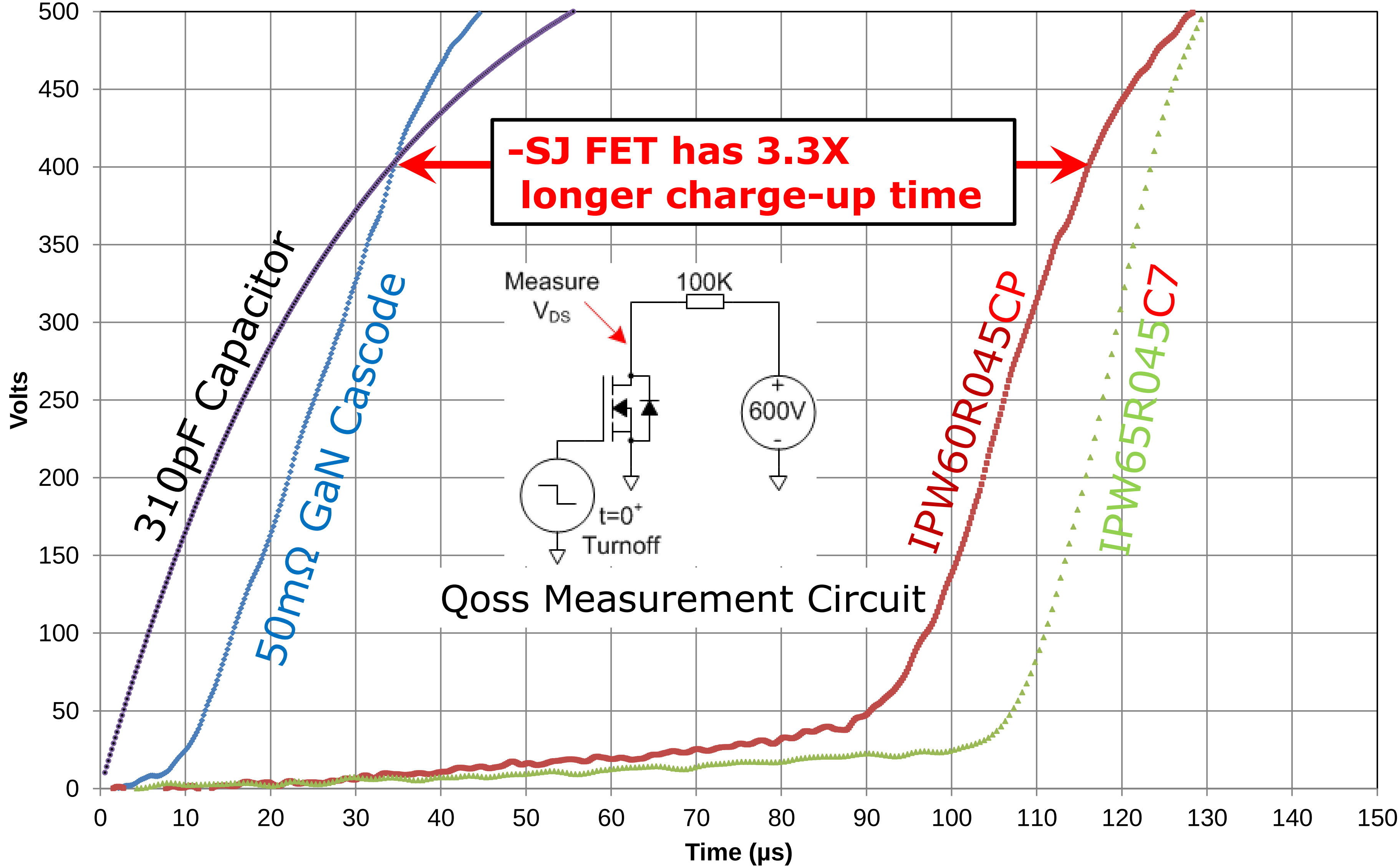




- Superjunction capacitances are much higher when compared to GaN
- Superjunction C_{oss} and C_{rss} behave very nonlinearly with voltage

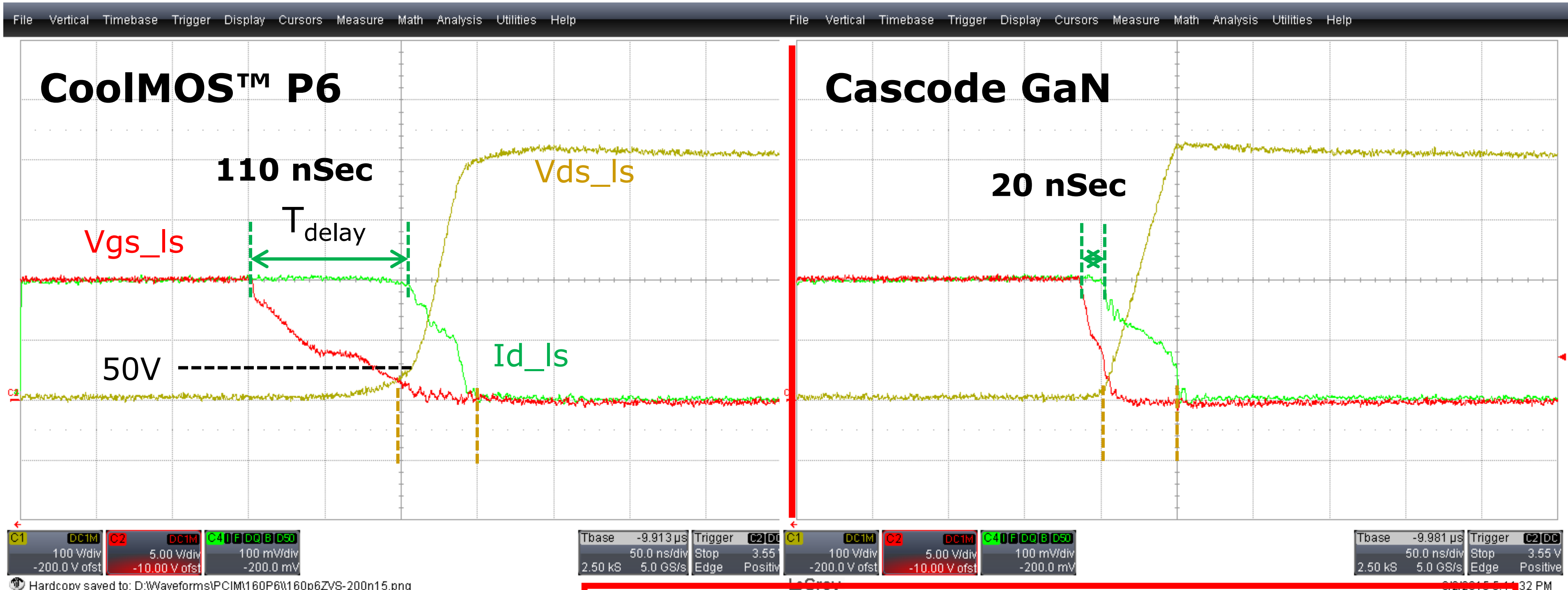
- Output charge difference is very large (up to 10x at 100 V) between superjunction and GaN
- But gap in E_{oss} is much smaller (eg: 20% at 400 V)

Nonlinear Q_{oss} charge affects deadtime



Non linearity of C_{oss} results in longer minimum dead time for SJ FET in ZVS

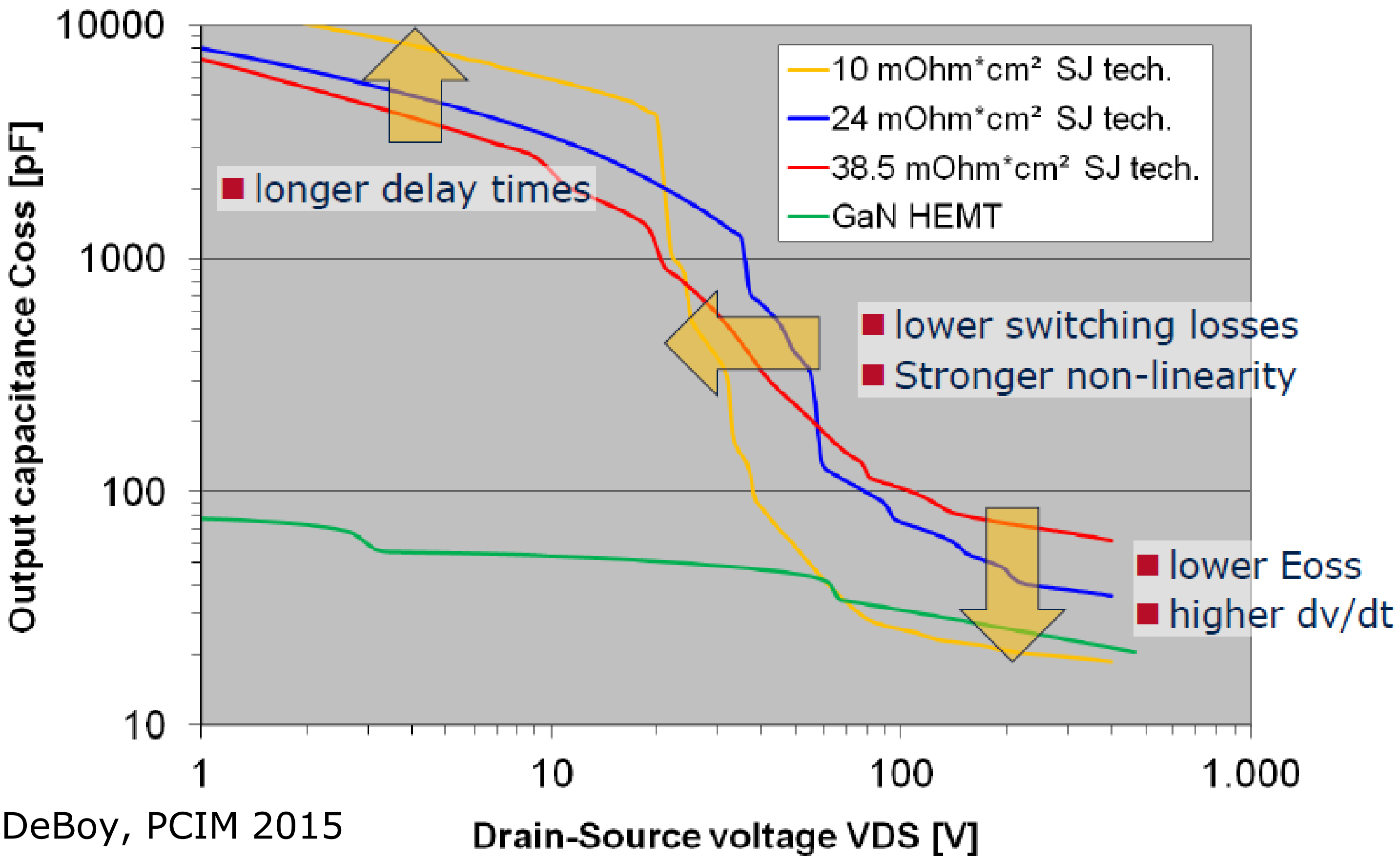
2d



- V_{gs}=10 V, I_d=2 A, R_g=10 ohm

SJ FET High capacitance at low voltage results in 5-6x longer delay time (110 nsec vs 20 nsec)and therefore longer required deadtime which increases RMS current and therefore conduction losses. The higher the frequency the more the losses

2e Superjunction devices continue to improve

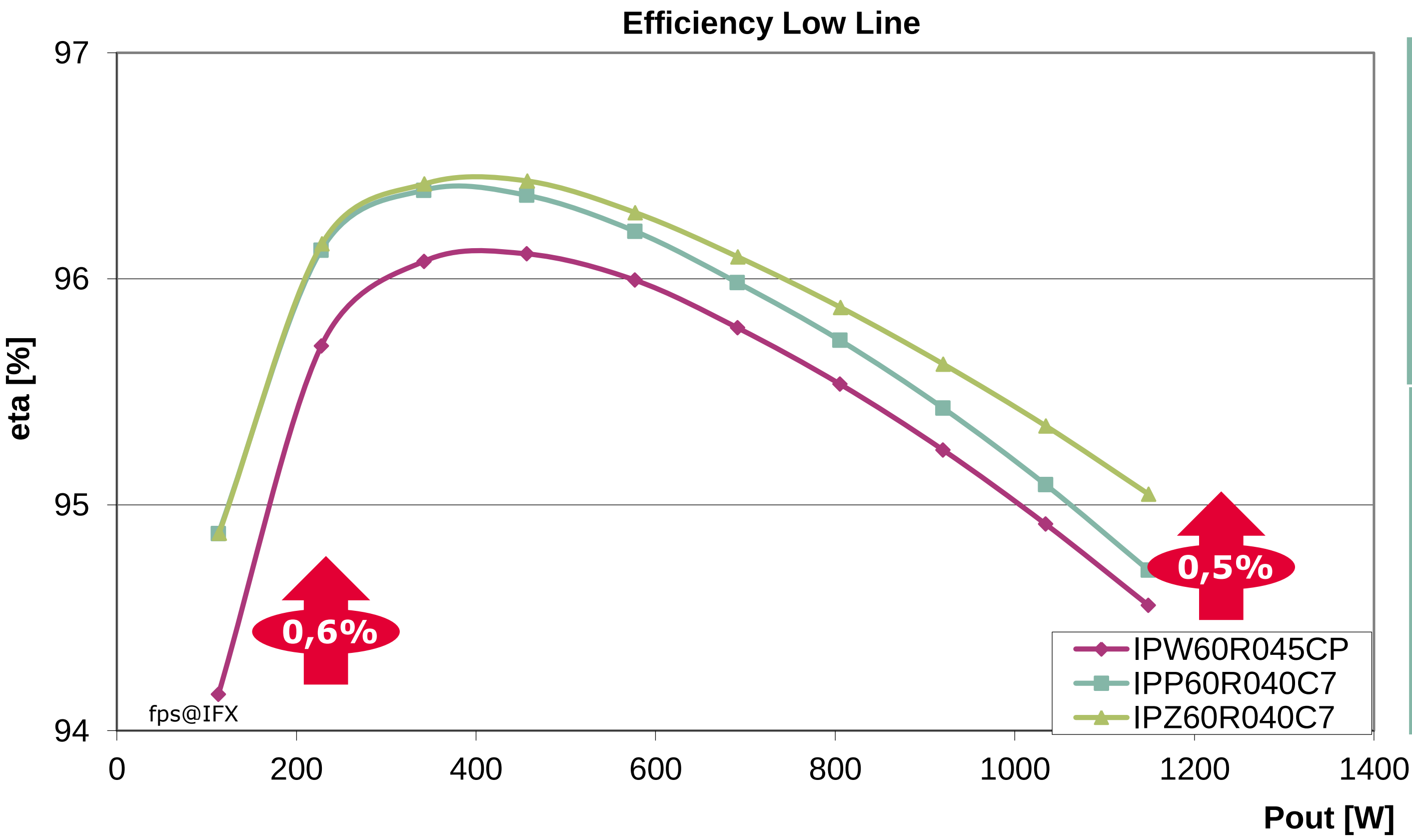


Reference: G. DeBoy, PCIM 2015

Yet the more the improvement in hard switching figure of merit the longer the delay times (limits performance in ZVS applications at higher frequency)

Significant efficiency gains in superjunction – C7 600 V with ≥0,5% improvement across load

PFC efficiency difference for 90 V_{ac} (PFC CCM, 1150 W @ 65 kHz)



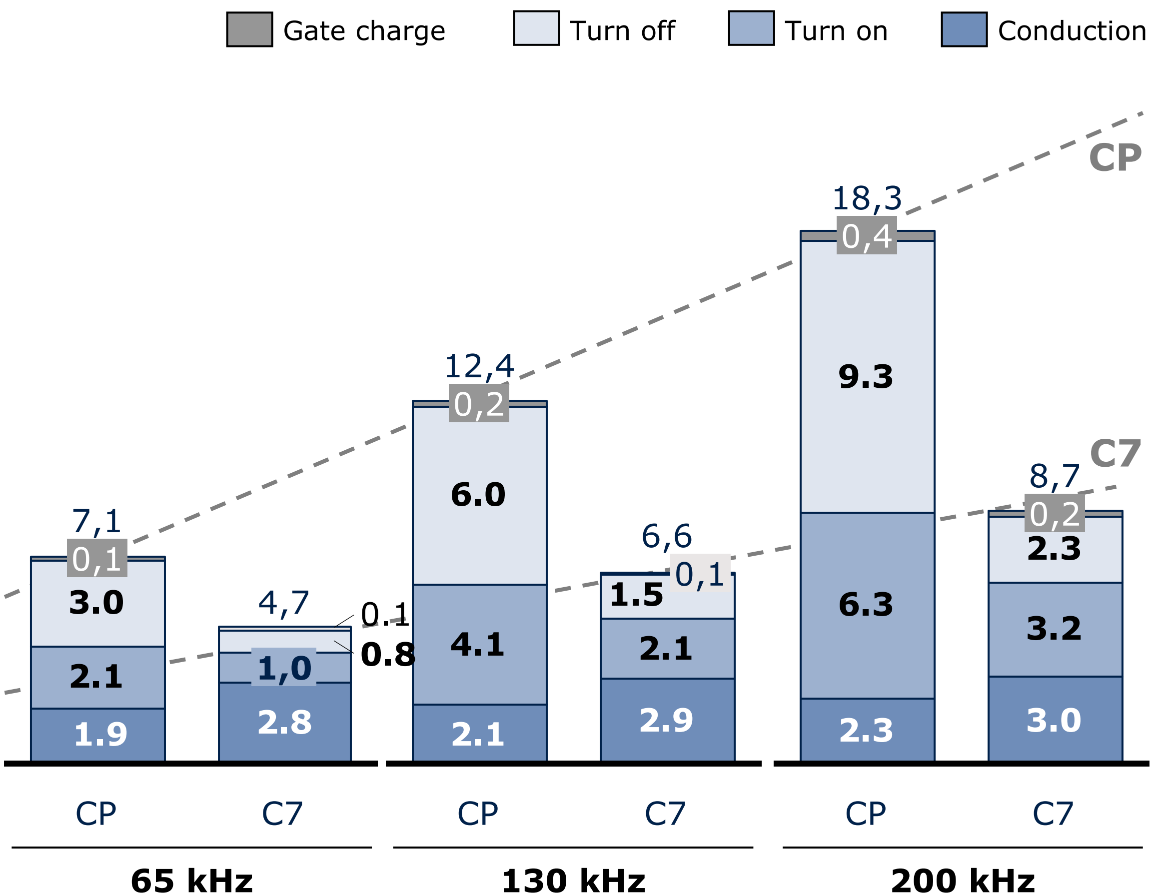
Superjunction FET performance continues to improve in hard switching PFC applications

≥ 0,5% efficiency increase across entire load range with CoolMOS™ C7 4-pin vs. CP

Benefits of C7 CoolMOS™ enables operation at higher (hard) switching frequencies

2g

Total simulated MOSFET losses [W]
IPW60R045CP vs IPZ60R060C7, highline 2.5 kW



- > Smaller MOSFET losses for C7 @ 130 kHz than CP @ 65 kHz
- > Increasing relative advantage of C7 with growing frequencies

C7 opens a path to higher frequencies in proven silicon technology

2h

Technology comparison summary

- Superjunction C_{oss} and C_{rss} behave very nonlinearly with voltage and frequency
- Comparable $R_{DS(on)}$ GaN devices have much lower capacitance than their SJ FET counterparts when measured at low voltage; this difference greatly diminishes at higher voltages; there is not a large difference in E_{oss} at 400 V
- **$C_{o(tr)}$ of GaN device is ~10x lower than SJ FET** and this difference is sustainable; this benefit can be leveraged in ZVS applications where it can result in lower power losses
- This benefit grows with frequency (as a fixed deadtime grows in percentage of total switching cycle time)
- **Q_{rr} >100x lower for GaN devices**: this can be leveraged in choice of topology and application

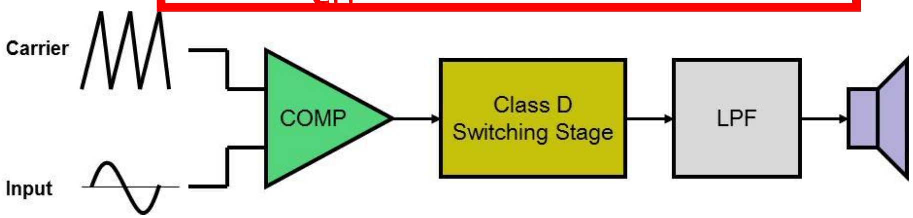
3a First uses for GaN

- Initial Applications for GaN Devices:
  - Leverage Q_{rr}: Class D Audio Amplification for lowest distortion
  - Leverage Q_{rr} and switching: high efficiency AC:DC power conversion for operational cost sensitive applications such as datacenters
  - Leverage $C_{o(tr)}$: high density power conversion applications from servers to consumer electronics
- The list above is just the start! The study of other applications (to leverage GaN FOM's vs Silicon) is an ongoing effort

3b

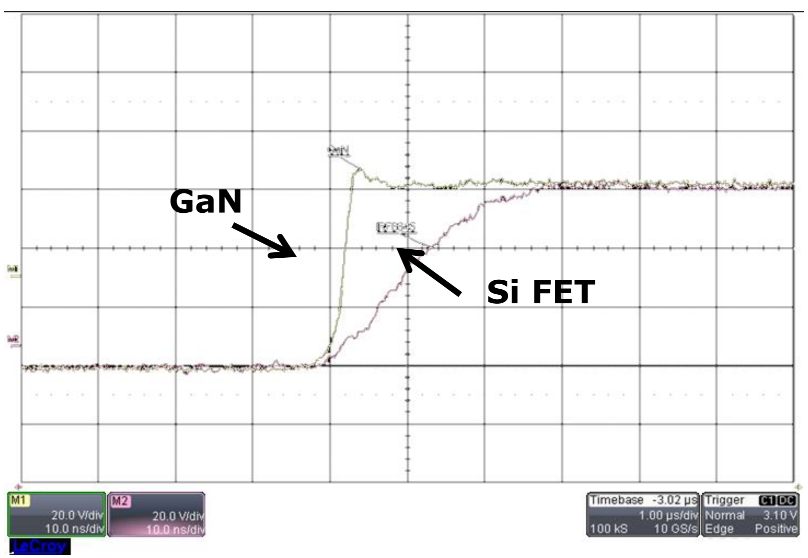
First use of GaN: 100 V cascode device for class D audio amplifier

Leverages extremely low Q_{rr}



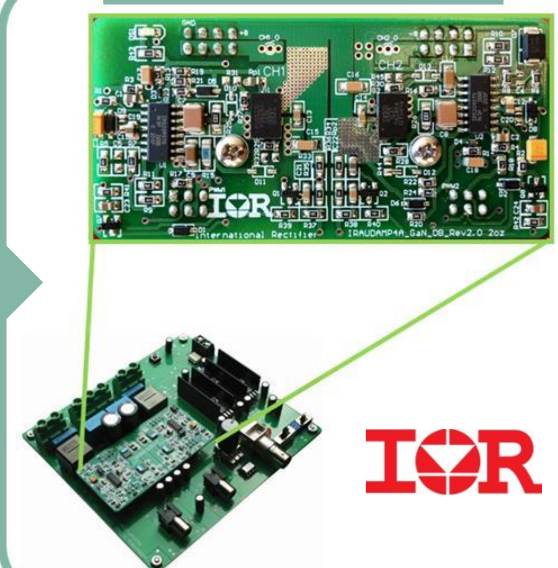
Key values	GaN benefit vs Silicon
Audio Quality	Lower - THD improves from faster/cleaner switching characteristics
Efficiency	Higher - from lower resistance
More channels, smaller size	Smaller – Full SMD w/o heatsink, high frequency for smaller LPF

Fast switching

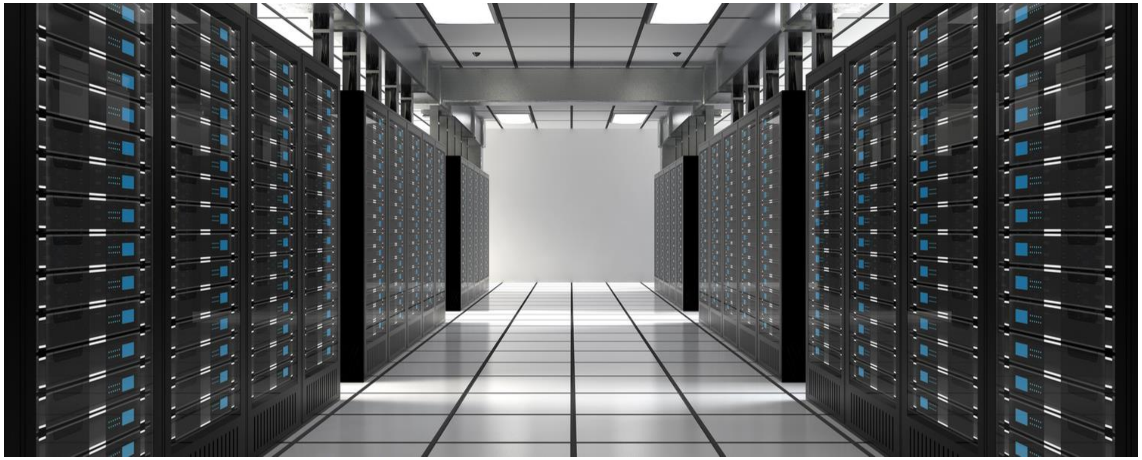


MP: 2013

166W GaN Class D



First Uses of GaN:
GaN value proposition for data centers



- **Total Cost of Ownership (TCO) matters**: hardware/software + operational costs really matters
- **Electricity costs** is ranked in TOP 5 costs
- Efficiency of electricity usage can lead to significant **system cost savings**

Effect of higher efficiency on electricity costs

Stage	Efficiency increase	Savings per server per year
PFC	0.5%	4.5$
DCDC (LLC)	0.5%	4.5$
Total	1.0%	9.0$

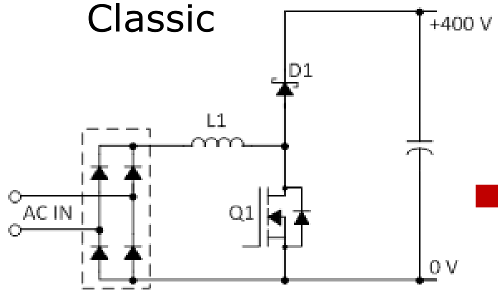
Based on energy cost: 0.06USD/kWh, 1.5kW average power consumption per server, 80% yearly utilization

3d

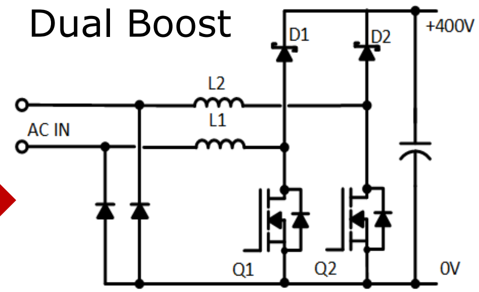
High Power SMPS in datacenters:
Evolution of high efficiency topologies for PFC

TODAY´S BEST

Classic

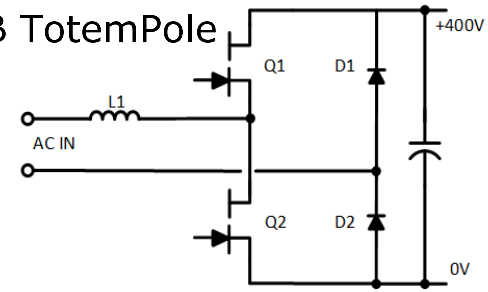


Dual Boost



› Higher efficiency (>98%)

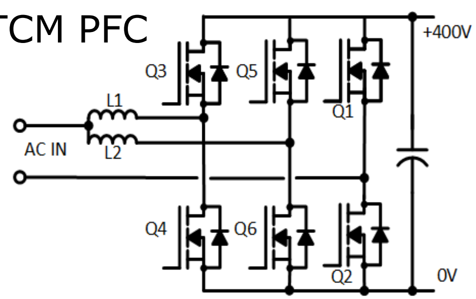
HB TotemPole



› Highest efficiency (>98%)
› Simpler
› Reduced part cont

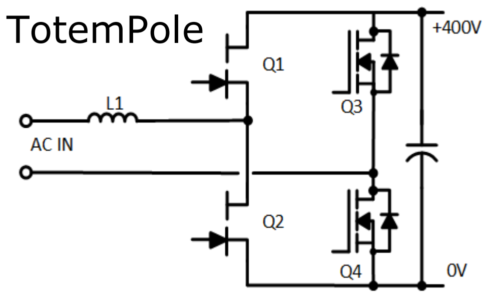
TODAY/ TOMORROW

TCM PFC



› Higher efficiency (99%)
› 2-phases (high part count)
› Complex control
› 100 kHz+ operation

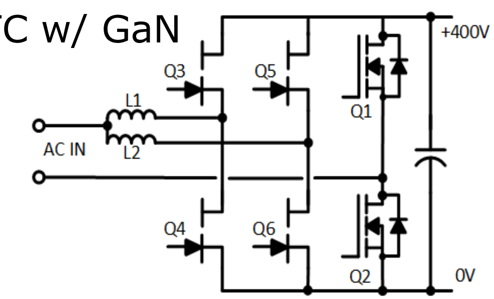
FB TotemPole



› Higher efficiency (>99%)

TOMORROW´S BEST

TCM PFC w/ GaN

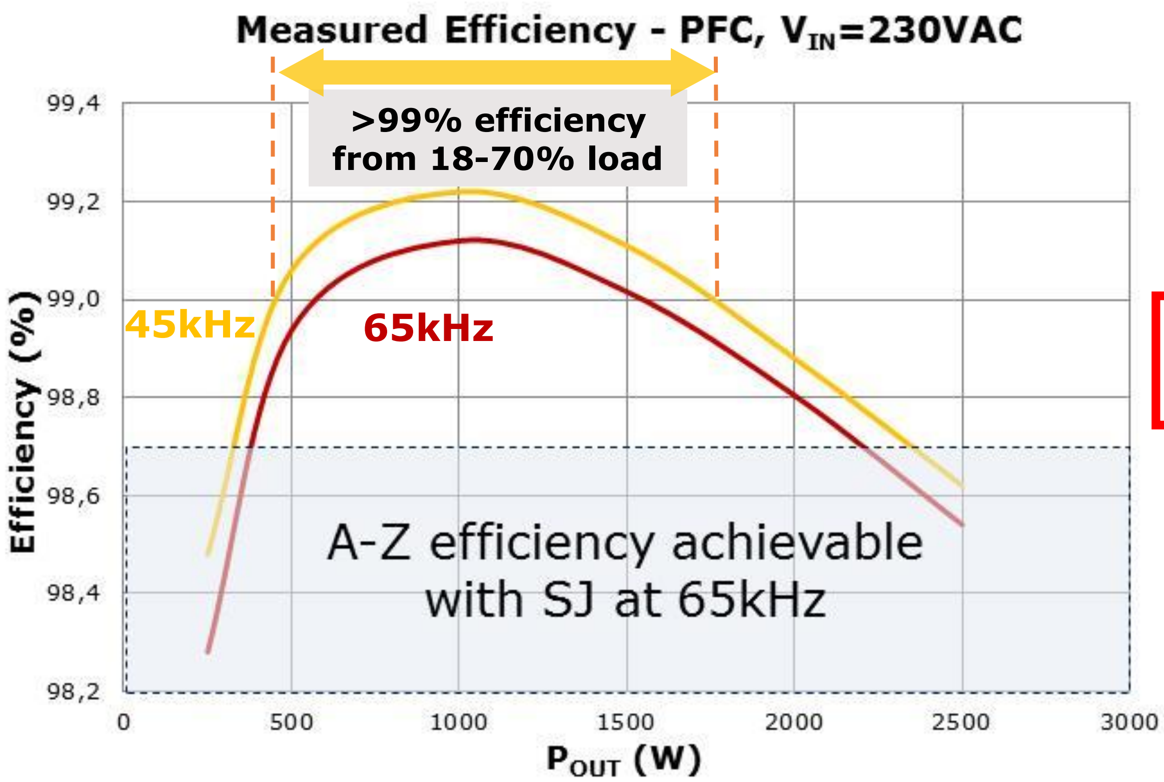


› Highest efficiency (99.5%)
› Suitable for 1 MHz+ operation
› Coupled with HF LLC for extreme power density (>>100 W/in^3)

Targeting 99% A-Z

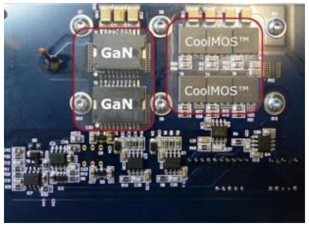
3e

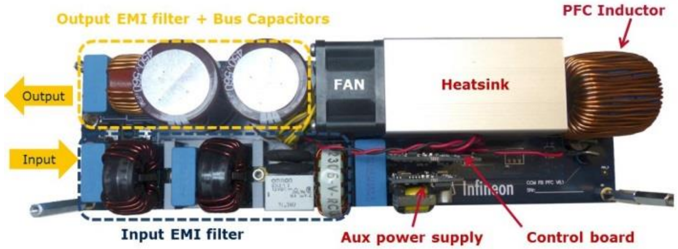
GaN enables >99% PFC efficiency



Leverages:
extremely low Q_{rr}

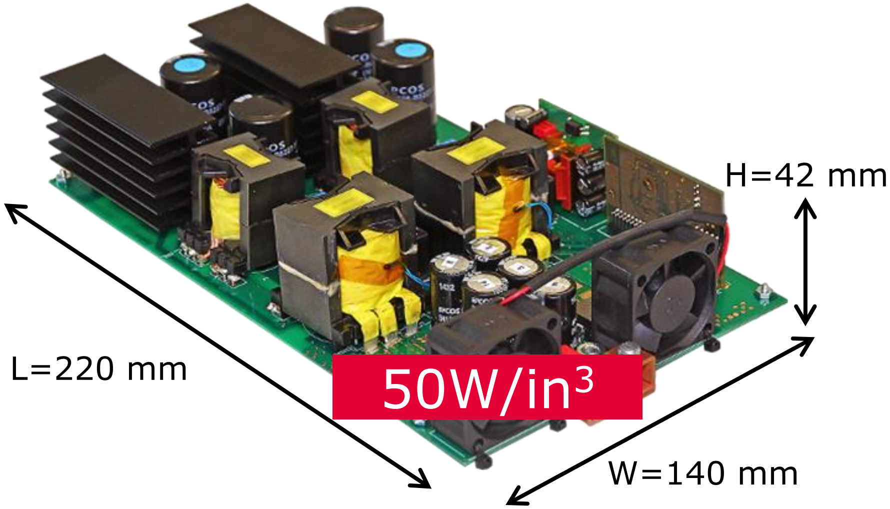
- Measurements: Infineon 2015
- Complete Power Stage. 2.5 kW, V_{in}=230 V, T_{amb}=25° C
- Full SMD solution



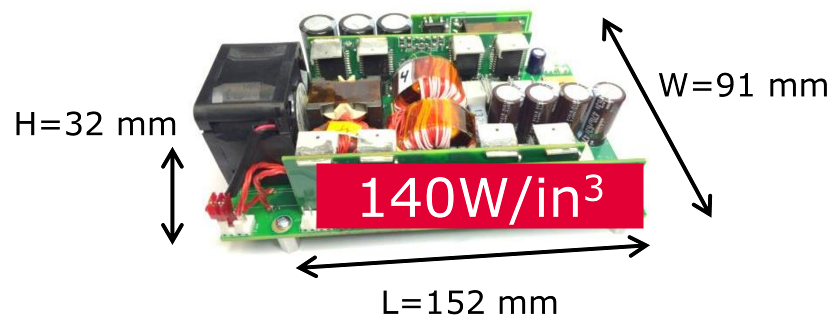


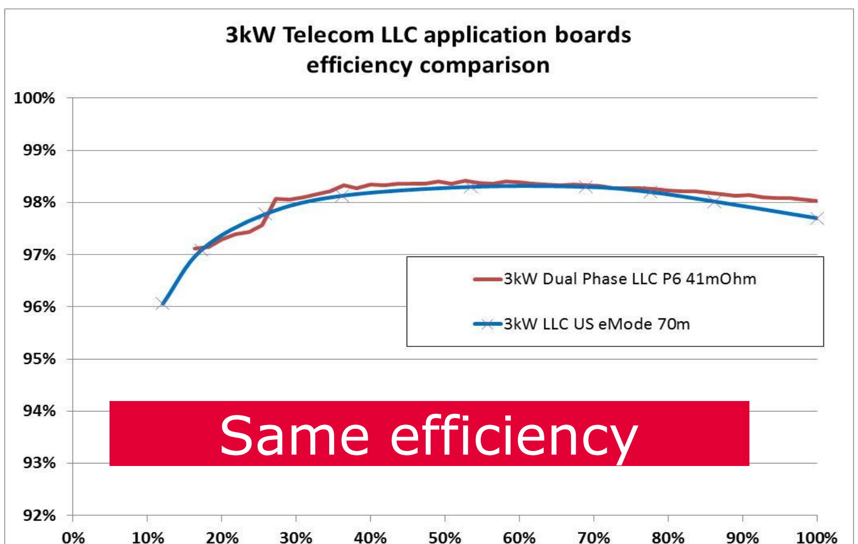
1. 600 V CoolGaN™ for density: 3 kW LLC PD~140 W/in³

SJ based 130 kHz design



GaN based 350 kHz design



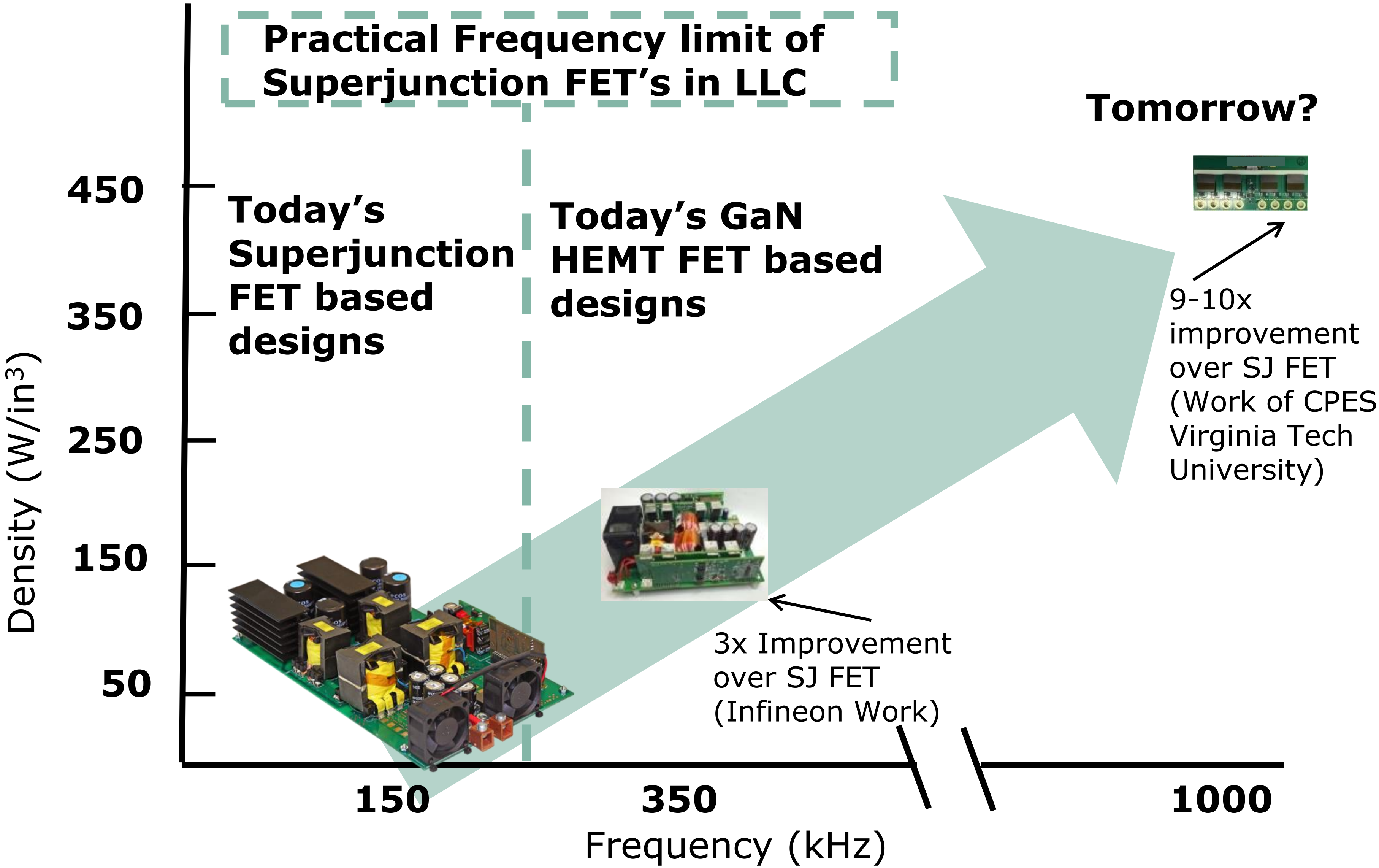


KEY MESSAGES

- LLC w/ CoolMOS™ (380 V-54.3 V): >98% peak efficiency at 50 W/in³ density (res freq: 130 kHz)
- LLC w/ CoolGaN™ (380 V-52 V): same efficiency at 140 W/in³ density (res freq: 350 kHz)
- **GaN enables ~3x increase in power density. When size/weight matters GaN is the choice**
- **All this is achievable with full SMD solution, either with DSO-20 or TOLL**
- Similar results have been demonstrated for low power and different ZVS topologies (e.g. PSFB)

3g

CoolGaN™ enables dramatic increase in power conversion density using ZVS in LLC

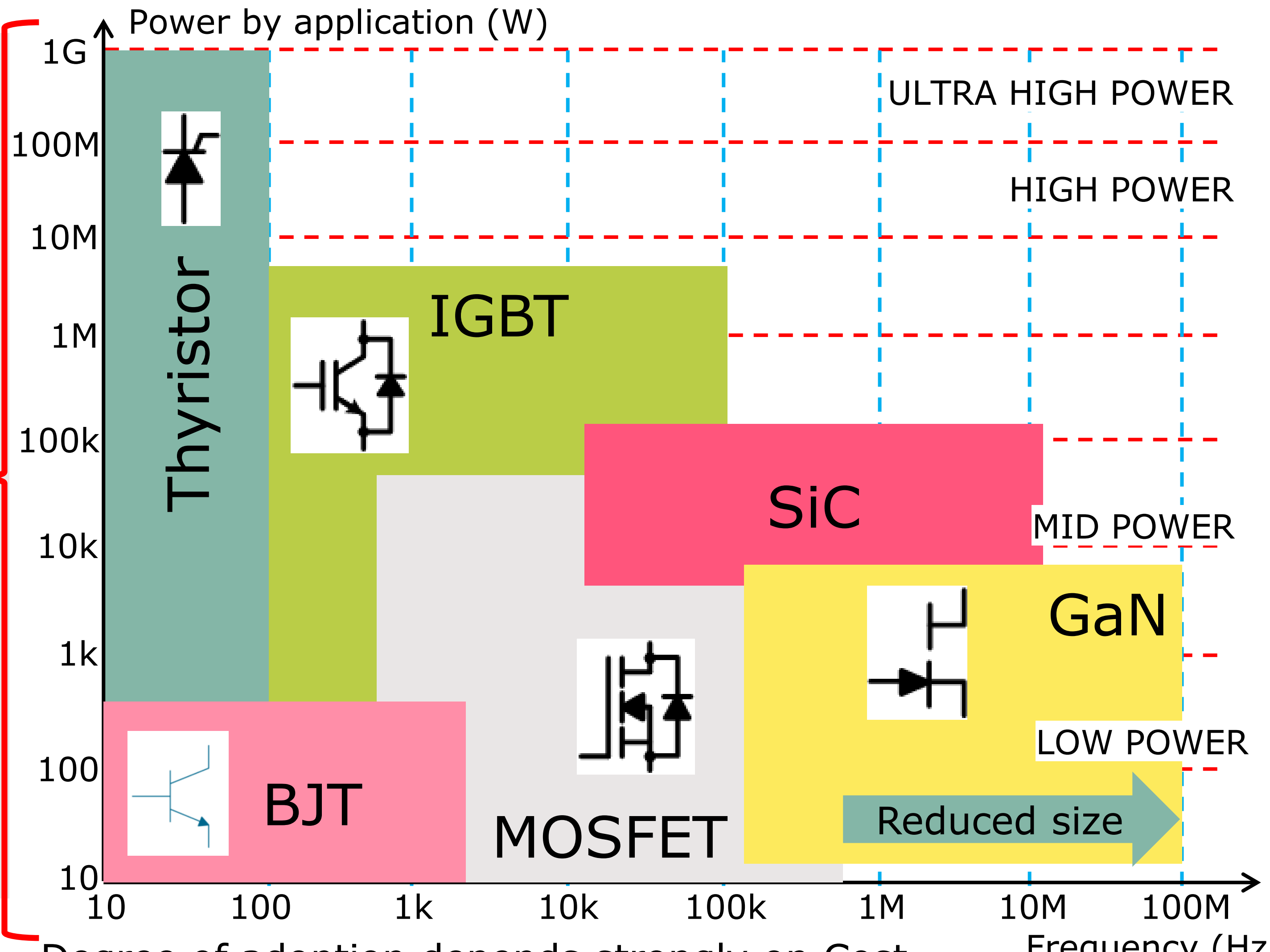


In which power and frequency domain might GaN be used?

4

Application	Future Scenario Power Electronics

- HVDC
- HC-supplier
- Large drives
- Ships
- Locomotives
- Large solar plants
- Trams, buses
- Electric cars
- On-roof PV
- Small drives
- Air conditioner
- Robotics
- Washing machine
- SMPS
- Chargers/Adapters



Degree of adoption depends strongly on Cost

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Concluding comments

- The historical record shows new switch technologies are adopted and grow new market segments where they push the performance window

- KEY GaN device FOM‘s are demonstrated with 10-100x improvement over silicon (C_{oss} TR, Q_{rr})
  - It is clear this can be leveraged for higher density power conversion solutions using ZVS and LLC topology
  - Early applications identified but more will follow as cost of GaN device lowers and investment continues in new topology and application infrastructure

- LV and HV MOSFET‘s continue with fast pace of improvement in market segments that are still growing: Silicon is not at the end of the road!
  - Silicon Market size not shrinking any time soon

- **Ultimately the size of new market segments which adopt GaN will depend strongly on system cost**

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