Wide Band Gap Devices and its related EMC issues in power electronics

Wenjie Chen

School of Electrical Engineering

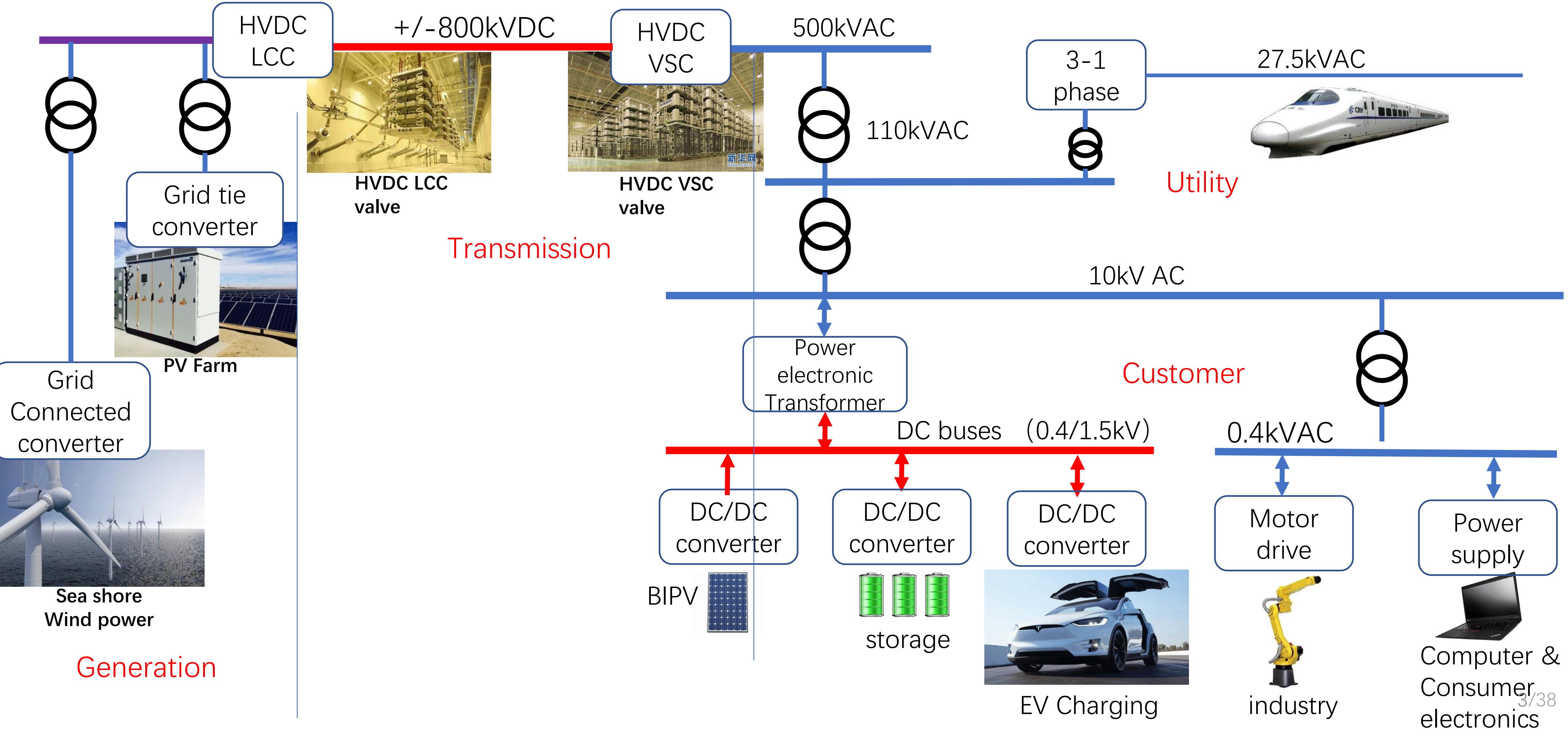
Xi'an Jiaotong University

西安交通大學 電氣工程學院
School Of Electrical Engineering Xi'an Jiaotong University

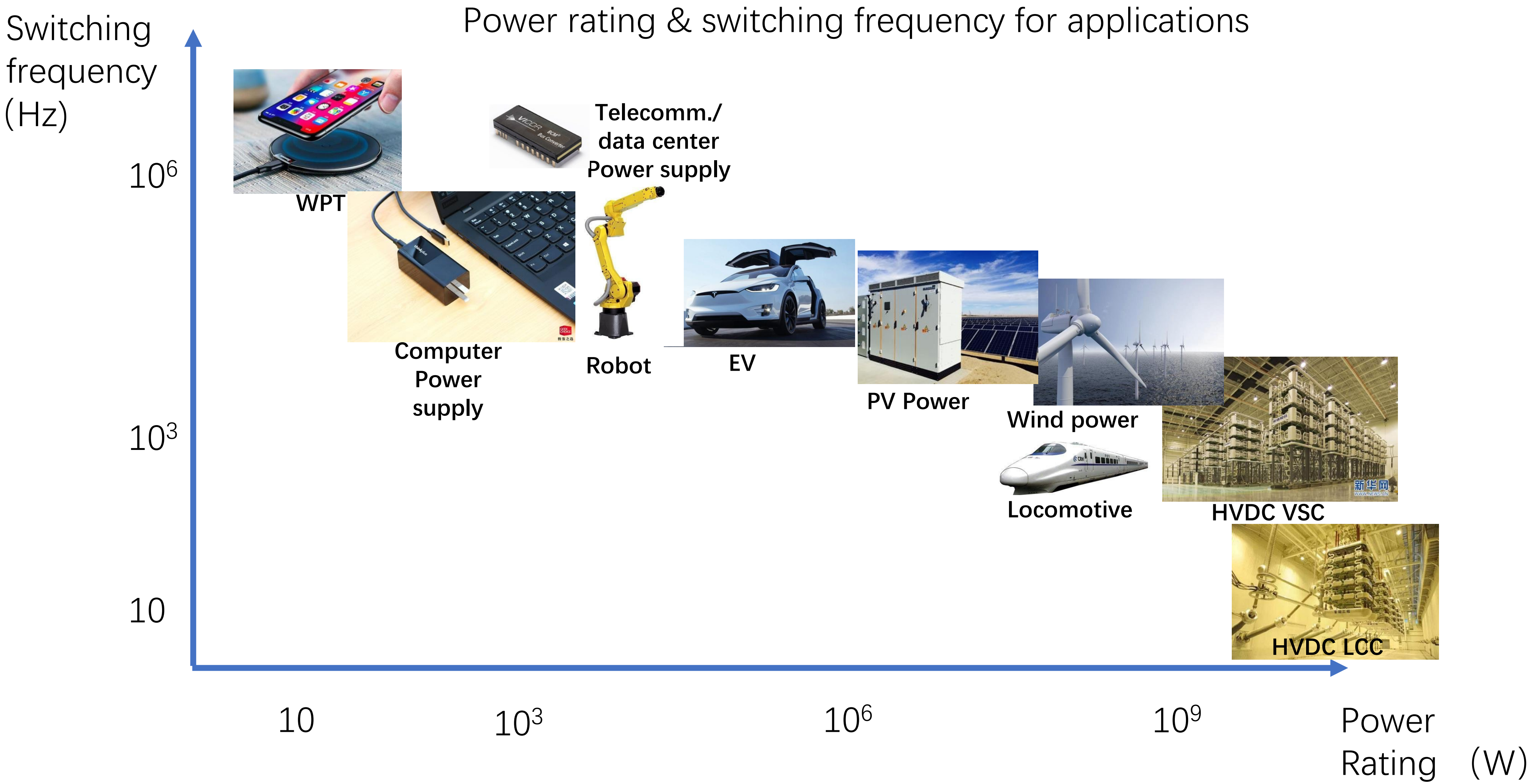
Catalogue

- Wide Band Gap devices is changing power electronics
- Impacts on EMC for WBG devices

Applications for power electronics



Applications for power electronics

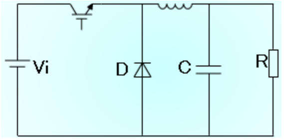


Demands for power electronics

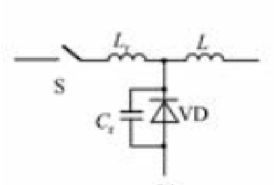
- High power
- High efficiency
- High power density
  - High switching frequency
  - Low switching loss
- High precision

Motive factors for improvements

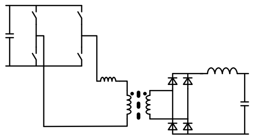
Improvements in topologies：



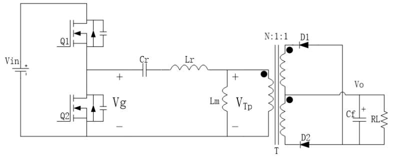
PWM circuits



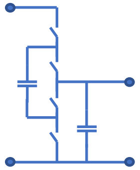
ZCS QRC



FB ZVS



LLC



SC

60-70s

Soft switching circuits
80-90s

~2000s

~2005

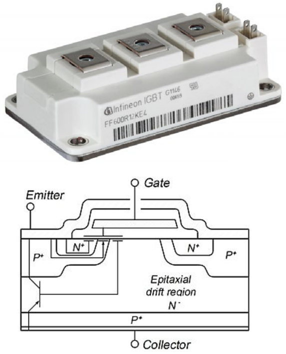
Improvement from devices:

1947
Bipolar
transistors

1950s
Power
diode

1956
thyristor

1976
Power
MOSFET



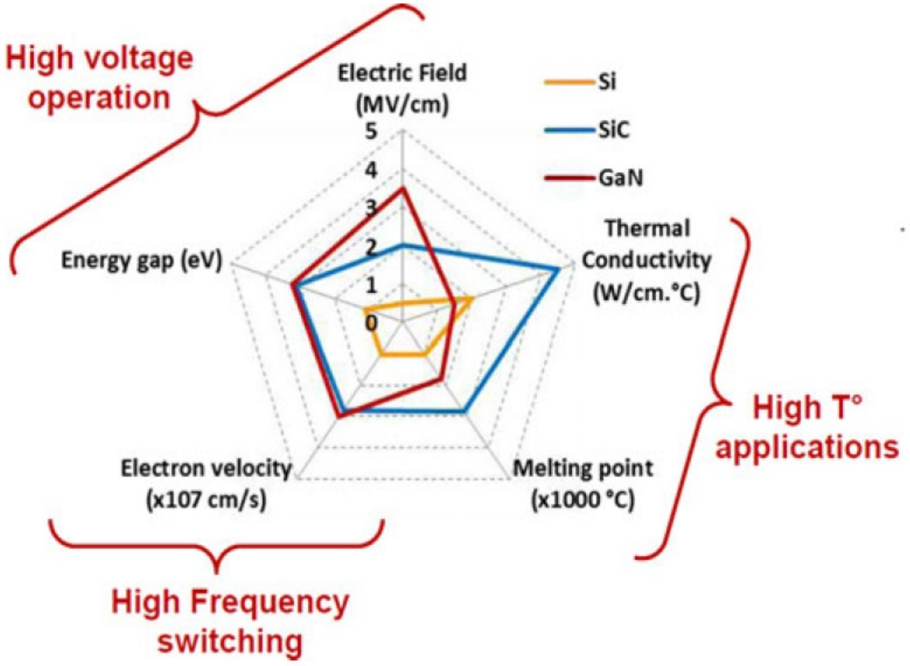
1982
IGBT

2010
eGaN

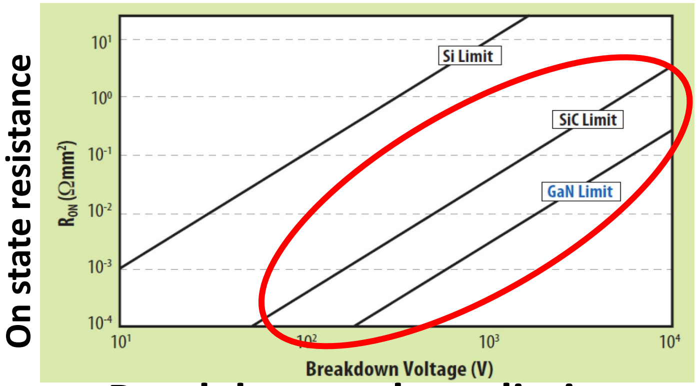
2011
SiC
MOSFET

Wide band gap materials and devices

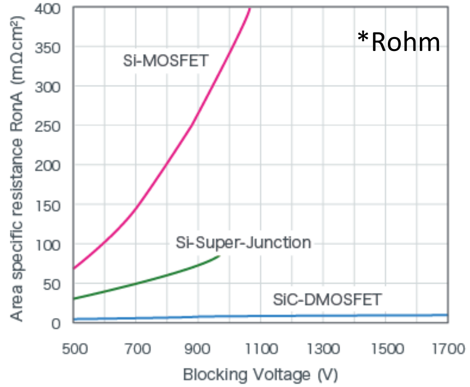
- **Advantage for WBG materials**
  - High breakdown voltage
  - High electron mobility velocity



- **Advantage for WBG devices**
  - **Much lower on-state resistance @ high voltage**



Breakdown voltage limits



Example for SiC

  - **Much faster switching**

*GaNSystem

Device	Vds	Rds(on)	Qg	FOM
GaNSystems GS66516T	650V	32mΩ	12nC	384
GaNSystems GS66508P	650V	63mΩ	5.8nC	365
Si CoolMos IPB65R045C7	650V	45mΩ	93nC	4185
Si CoolMos IPW65R019C7	650V	19mΩ	215nC	4085

Jose Millan, Philippe Godignon, Xavier Perpin`a, Amador Perez-Tomas, and Jose Rebollo. A Survey of Wide Bandgap Power Semiconductor Devices. IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 29, NO. 5, MAY 2014

Impacts on power electronics

Laptop PD charger

	Si	eGaN
Eff.	88-90%	95-97%
f_{sw}	100-200kHz	300-500kHz
Size	100%	30-50%

Motion Control

	Si	SiC
Eff.	95-97%	99%
f_{sw}	9-11kHz	10-20kHz
Size	100%	60-80%

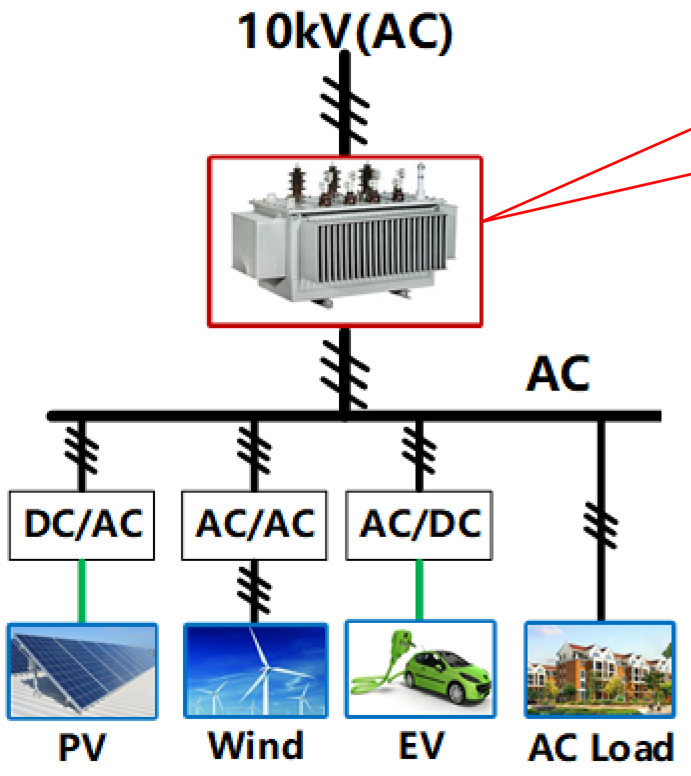
Renewable power generation to grid connection

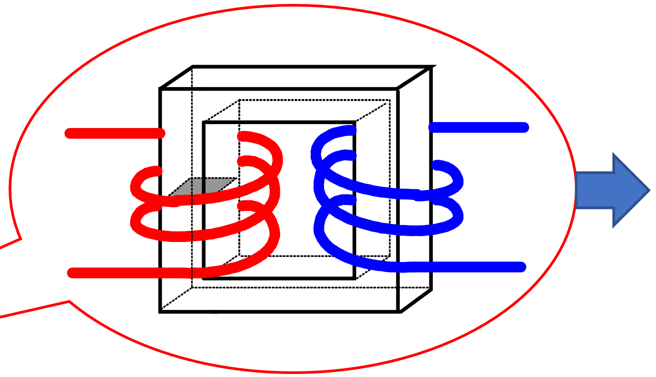
	Si	SiC
Eff.	97-98%	99.5%
f_{sw}	5-15kHz	10-20kHz
Size	100%	60-80%

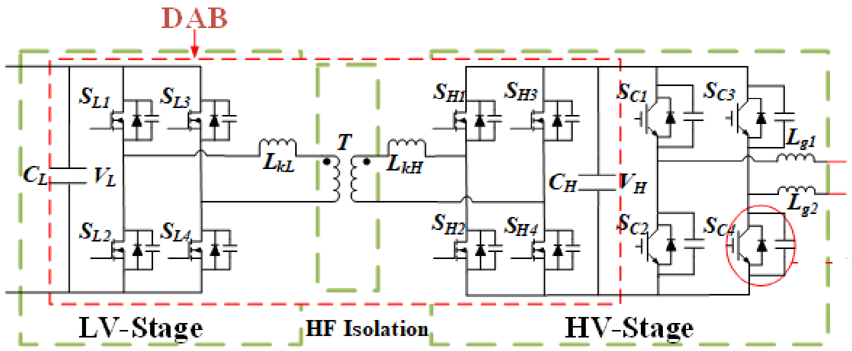
Much higher eff. , Much higher switching frequency, much smaller size.

Example 1: SiC device in power system application

Power electronic transformer – a coming technology in utility grid







Conventional transformer
Coil & Core

- ✓ Low cost
- ✓ Reliable
- X Not for DC
- X Uncontrollable
- X Power quality issues

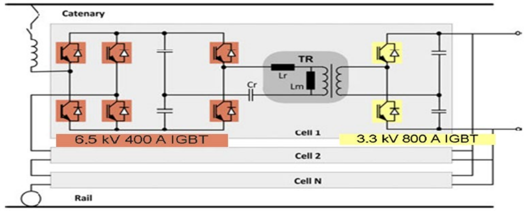
Power electronic transformer
Switching circuit & high frequency transformer

- ✓ DC conversion available
- ✓ Highly controllable
- ✓ Eliminate power quality issues
- X Higher cost (now)
- X Poor over load

Example 1: SiC device in power system application

ABB

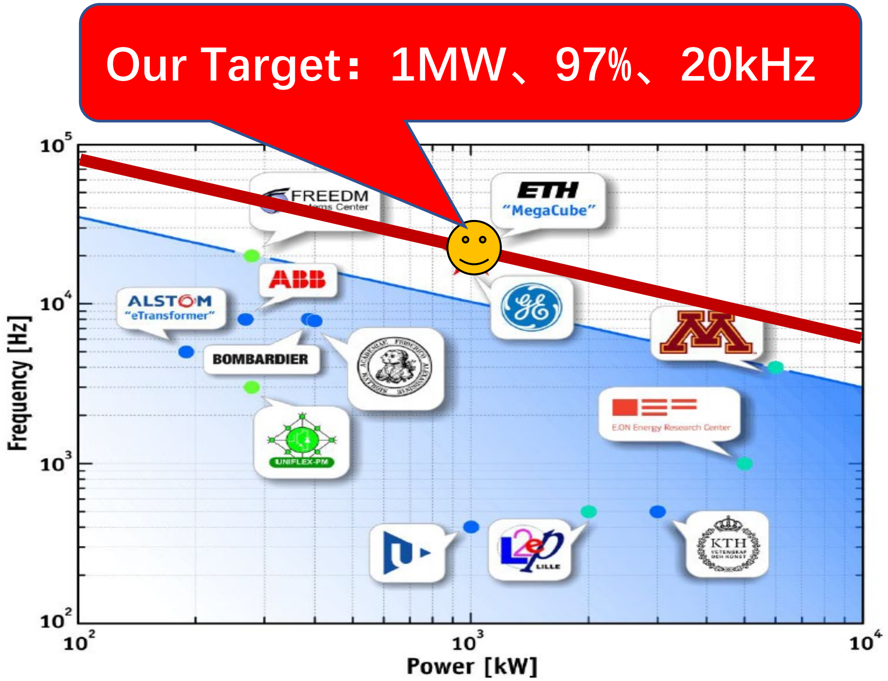
PET System



Power（MVA）	1.2
Input Voltage（kV）	15
Numbers of SM（N+1）	8+1
IGBT（kV）	6.5/3.3
HV-side DC Voltage(kV)	3.6
LV-side DC Voltage(kV)	1.5
Switching Frequency of AFE(Hz)	357X8
Frequency of Transformer(kHz)	1.8
Efficiency	95%

GE

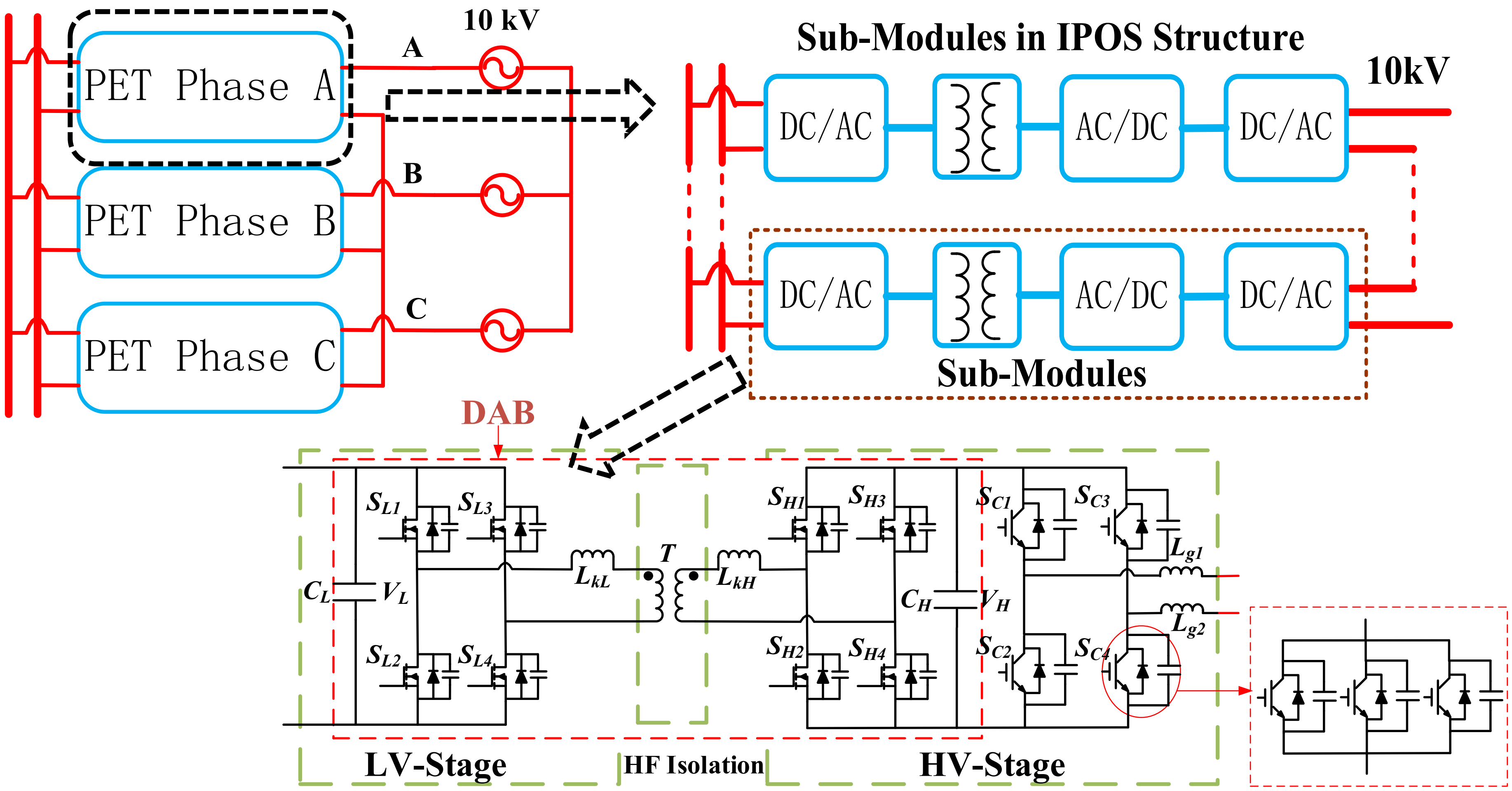
Power（MVA）	1.0
Input Voltage（kV）	13.8
SiC（kV）	10
HV-side DC Voltage(kV)	5
LV-side DC Voltage(kV)	$465/\sqrt{3}$
Frequency of Transformer(kHz)	20
Efficiency	97%



Spec.	
Input	10kV AC 3phases
Output	820V DC
Power	1MVA
Switching Frequency	20kHz
Target Efficiency	97%

*In cooperative with **TBEA China**

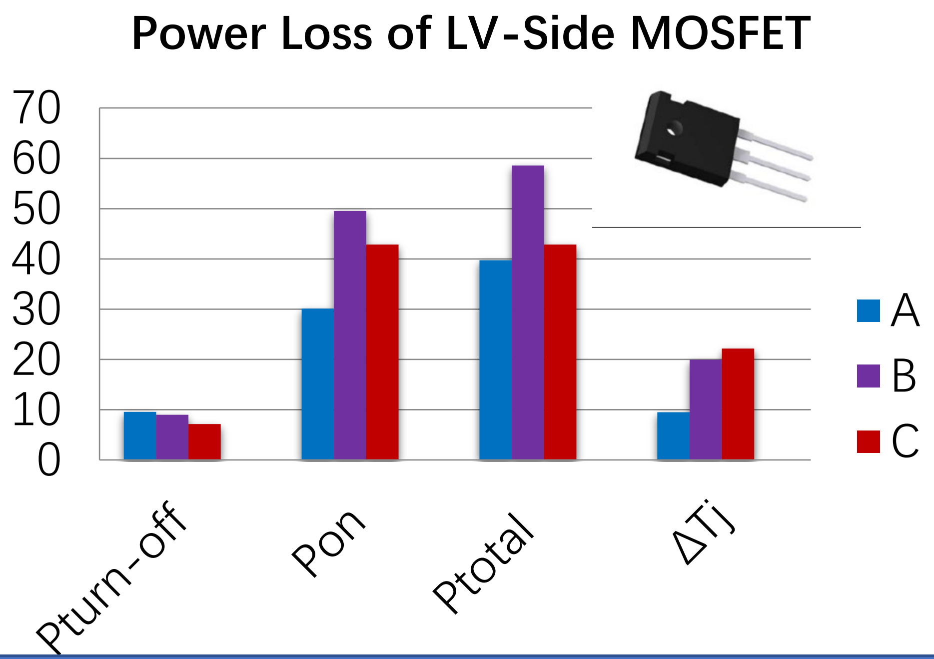
Example 1: SiC device in power system application

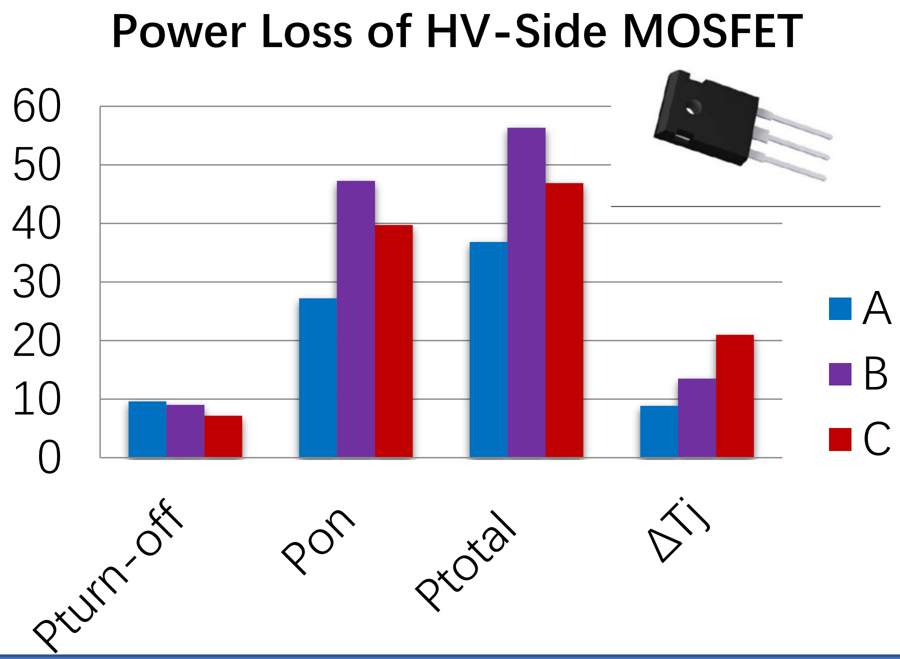


Example 1: SiC device in power system application

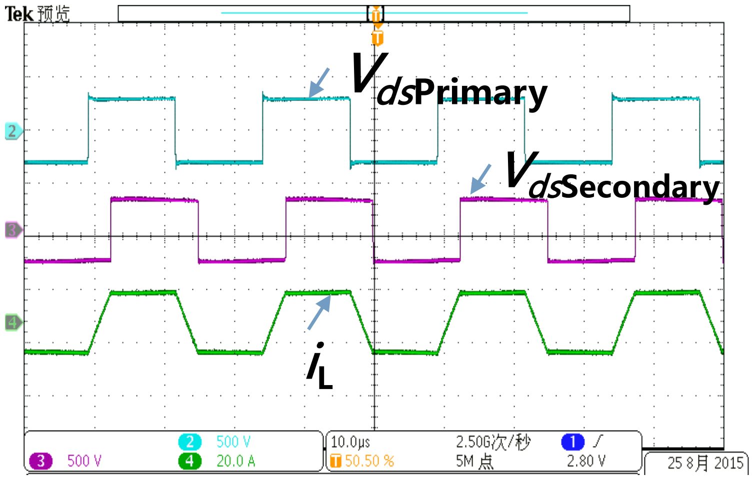
Power	Voltage	Peak Current	Frequency	Inductor	Capacitor
P_{SM}	V_L	$I_{L,peak}$	f_s	L_k	C_L
30kW	820V	37A	20kHz	48μH	50nF

A--C2M0025120D B--C2M0040120D C--SCH2080KE(Paralleled)

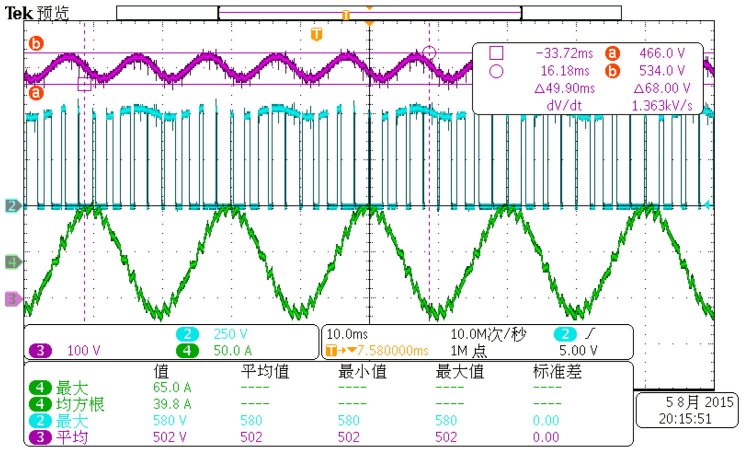




Example 1: SiC device in power system application



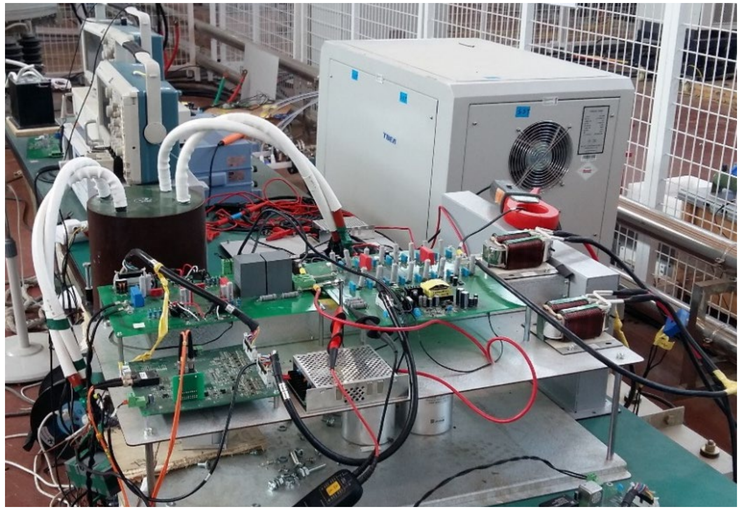
Test waveforms in DAB



Test waveforms in inverter

*In cooperative with TBEA

Module Parameters	Specs.
Bus Voltage	820V DC
Power Rating	30kW
Switching frequency	20kHz
Tested Efficiency	98%



Module under testing

Example 1: SiC device in power system application

Demonstration

TBEA 特变电工

The PE transformer is installed to connect 1MW PV roof to 10kV utility grid.

The PE transformer installed in TBEA Park

Demonstration project in Tangjiawan, Zhuhai,
(珠海唐家湾示范工程)

Example 2:　GaN in high density DC/DC converters

Typical application

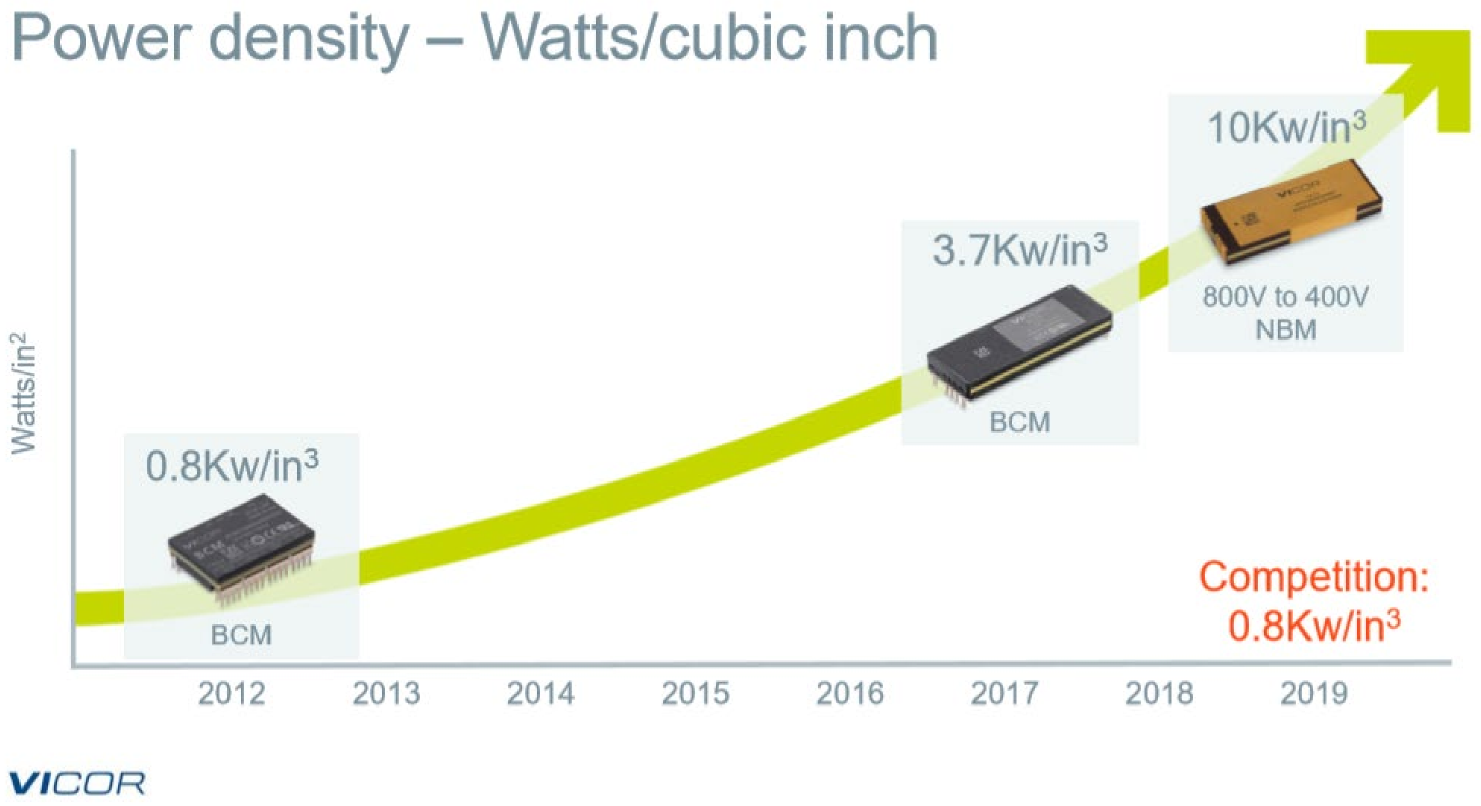
DC/DC converter

aircraft

space

Telecomm.

Data center



*from manufacture's website

Example 2: GaN in high density DC/DC converters

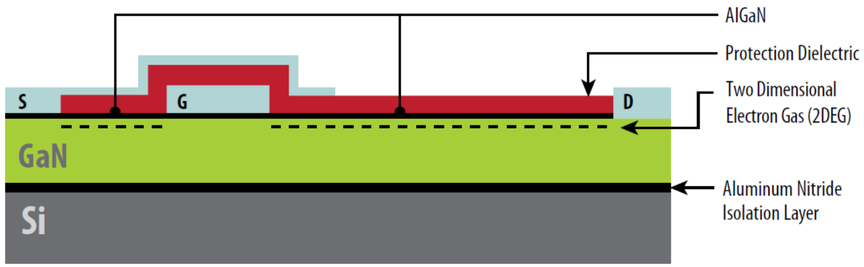


Figure 1: GaN on silicon devices have a very simple structure similar to a lateral DMOS device and can be built in a standard CMOS foundry

eGaN HEMT on Si substrate (EPC)

*Table 1: Characteristics of the Silicon and eGaN FETs

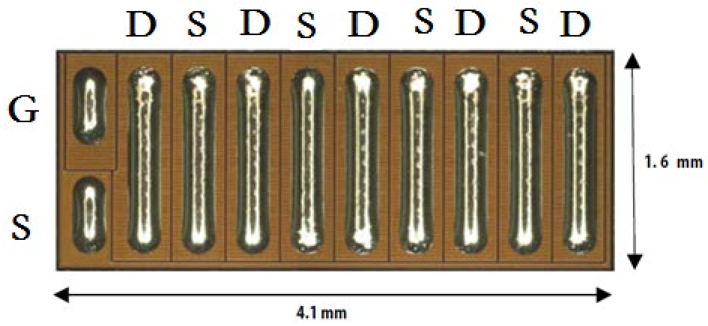
	Part Number	V_{DS} (V)	I_{DS} (A)	$R_{DS(ON)}$ (mΩ)	Q_G (nC)	Figure of Merit (mΩ.nC)	Package Type	PCB Area (mm^2)
Silicon Control FET	Si7850	60	6.2	25	18	450	PowerSO-8	31.7
Silicon Sync FET	RJK0652	60	35	6.5	29	189	LFPAK	29.8
eGaN Control FET	EPC1007	100	6	24	2.7	65	Flip Chip	1.8
eGaN Sync FET	EPC1001	100	25	5.6	10.5	59	Flip Chip	6.7

Lower on-state

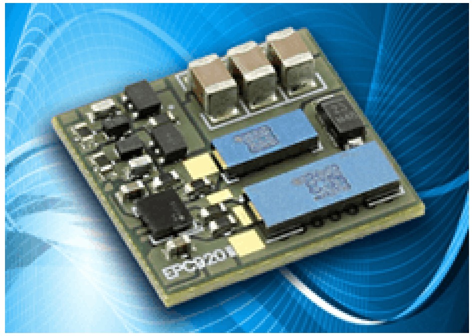
Faster switching

Smaller footprint

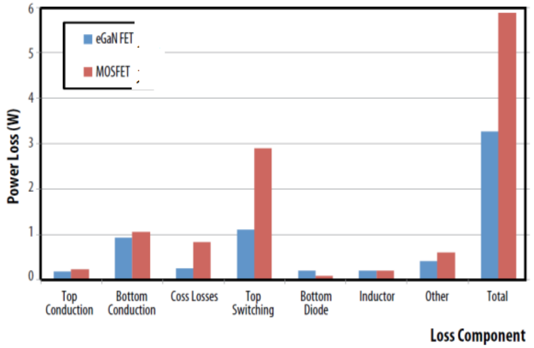
*Driving eGaN® FETs in High Performance Power Conversion Systems.
Alexander Lidow, Johan Strydom, and Michael de Rooij, Efficient Power Conversion Corporation,Andrew Ferencz, Consultant for Efficient Power Conversion Corporation, Robert V. White, Embedded Power Labs



Pinout for eGaN device



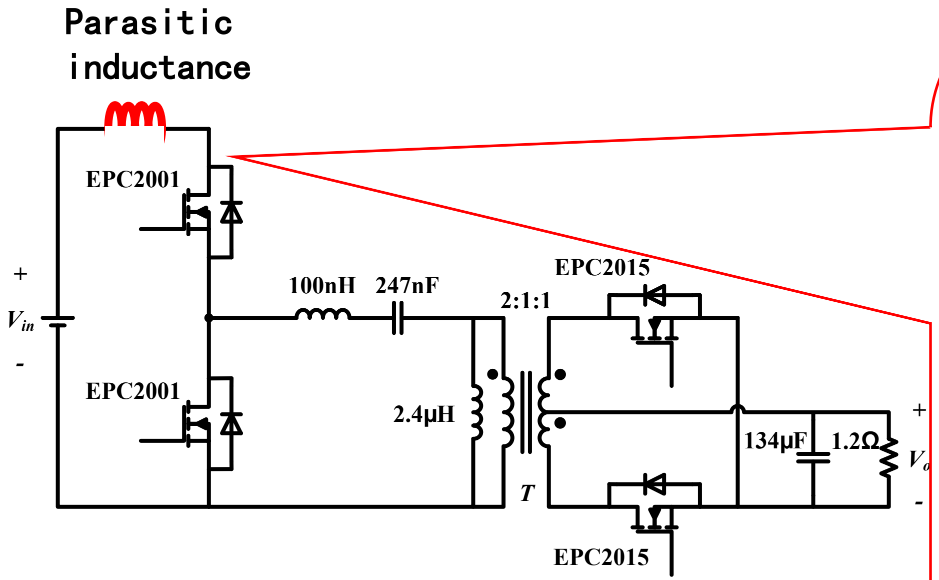
DC/DC w/t eGaN



Much lower losses

Issues for Wide band gap devices

- High voltage/current slew rate
- High ringing voltage / current due to parasitic inductance



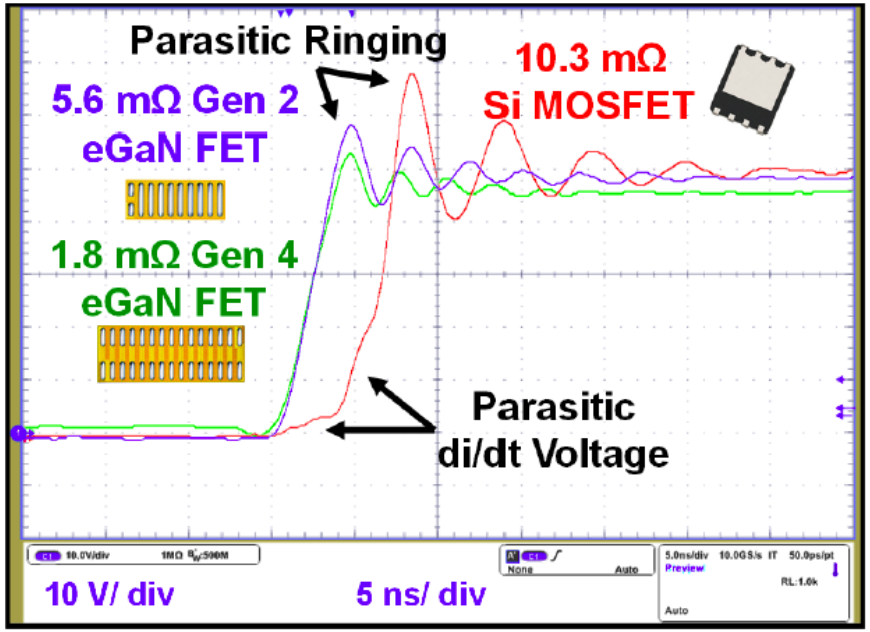
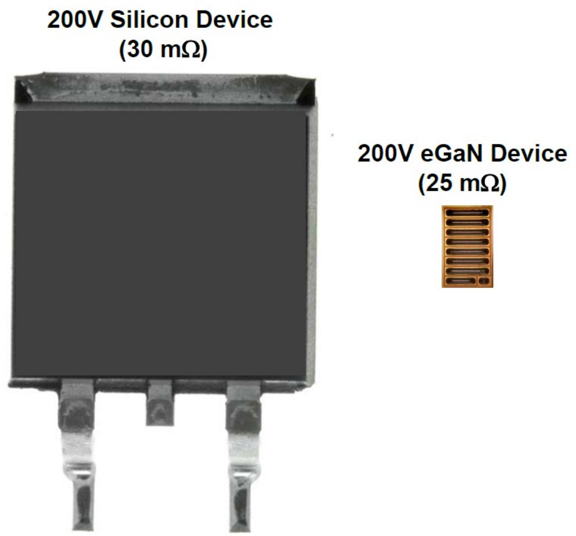


Fig. 5: switching node waveforms of eGaN FET and MOSFET designs (V_{IN}=48 V, I_{OUT}=10 A, f_{sw}=300 kHz, Gen 4 GaN transistors: EPC2021, Gen 2 GaN transistors: EPC2001, MOSFETs: BSZ123N08NS3G)

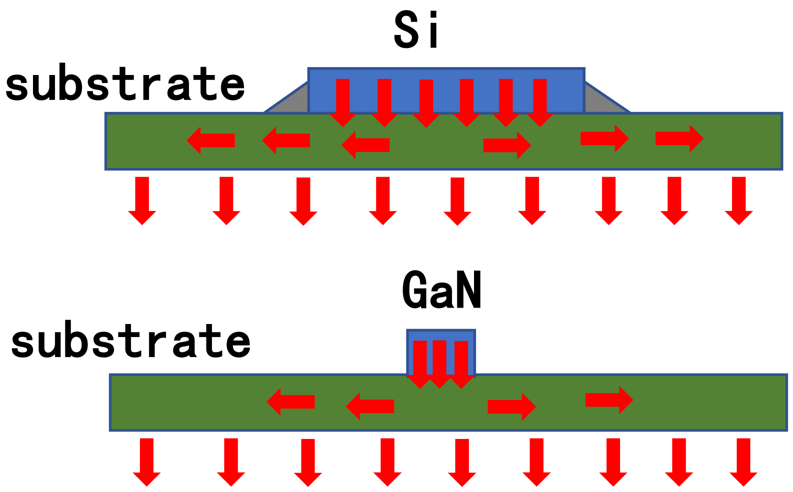
Issues for Wide band gap devices

- Thermal management issue for GaN

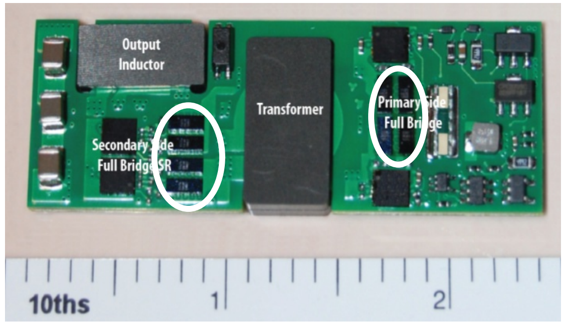


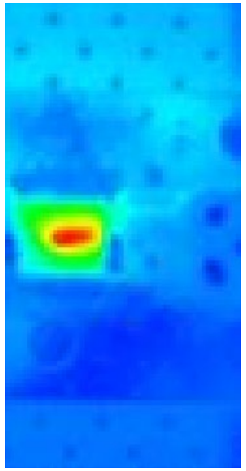
GaN device has

much smaller footprint



Heat flow density is much higher

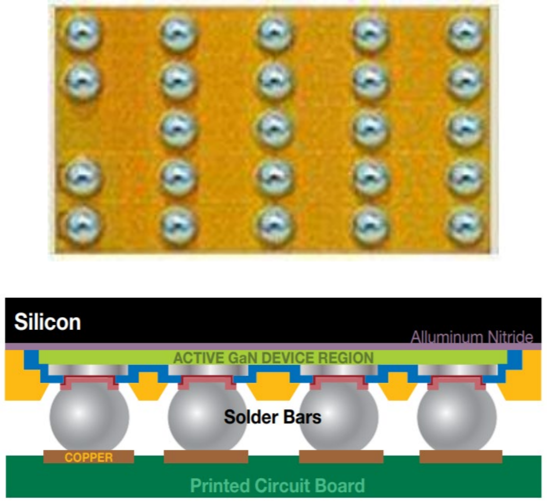




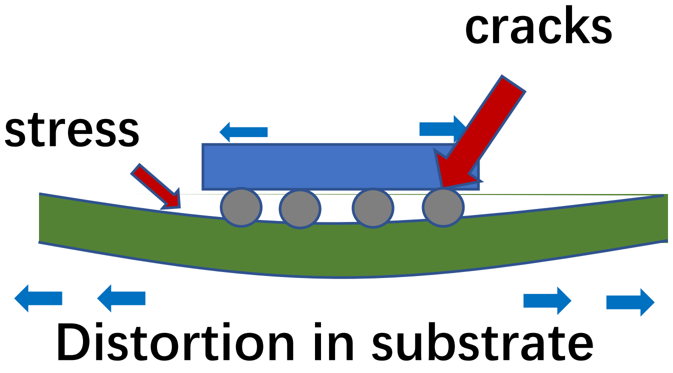
Junction temperature is high

Issues for Wide band gap devices

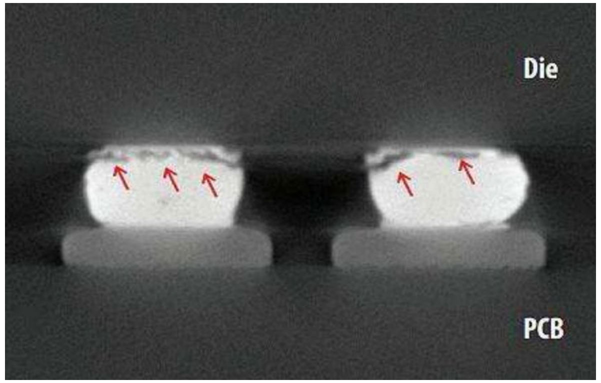
- Reliability issue



GaN uses Chip Scale Package-CSP



Thermal expansion mismatch leads to distortion and stresses



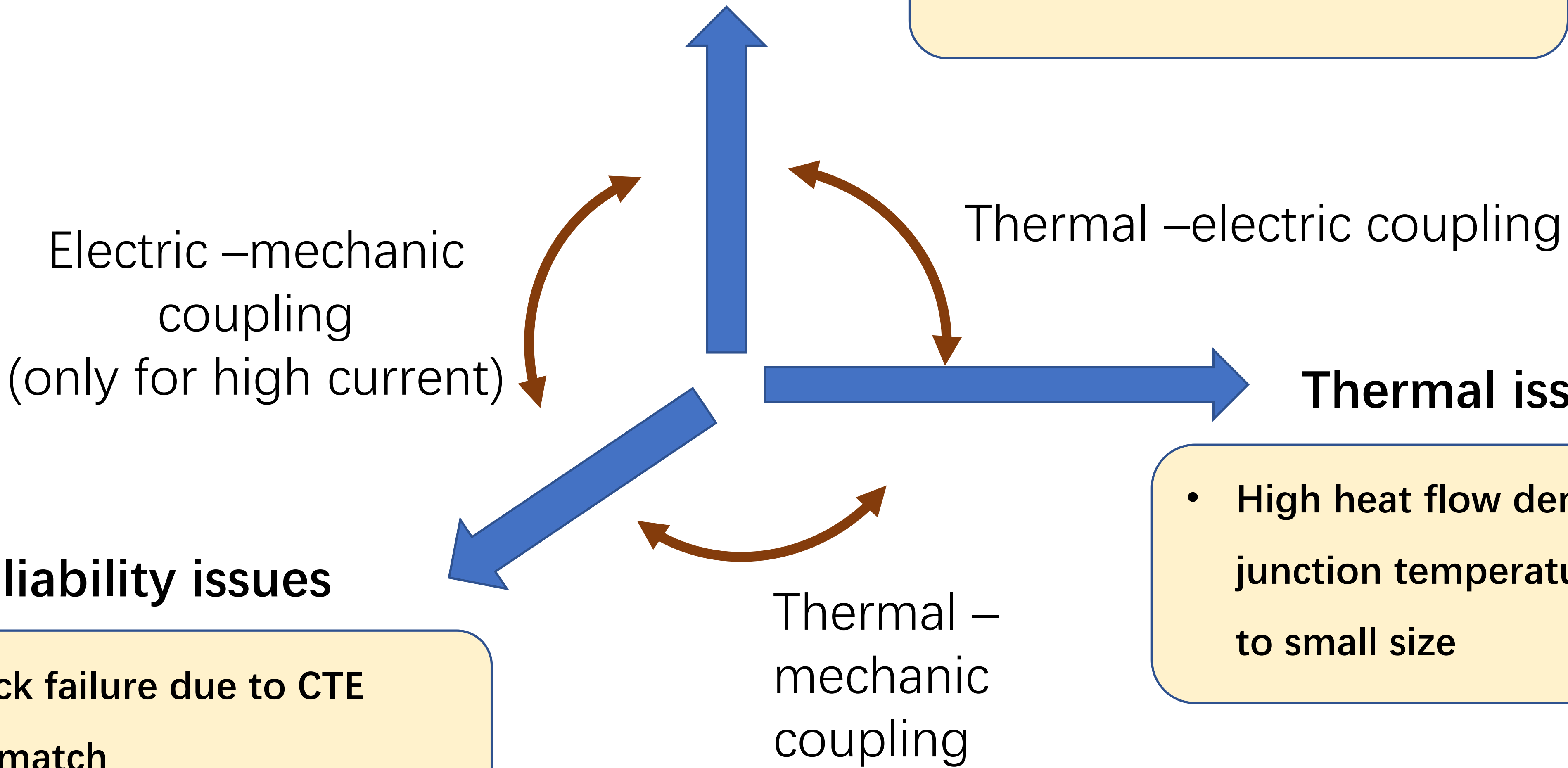
Failure cracks after temperature cycles

https://www.planetanalog.com/egan-technology-reliability-and-physics-of-failure-blog-4/

Issues for Wide band gap devices

Electric issues

- **Overshoot voltage and ringing dur to parasitic inductance**



Thermal issues

- **High heat flow density & junction temperature due to small size**

Reliability issues

- **Crack failure due to CTE mismatch**

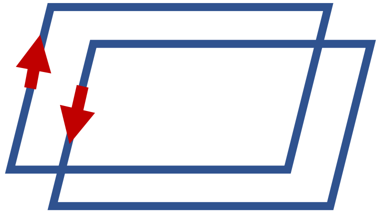
Design for GaN devices

To minimize inductance in power loop:

$$L = \frac{\psi}{I}$$

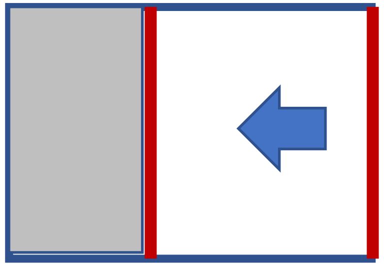
$$\psi = N \iint_S B ds$$

Number of turns



Reduce No. of turns or coupling

Loop area



Reduce loop area

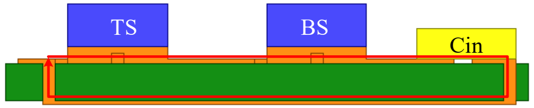
Magnetic field

Shielding

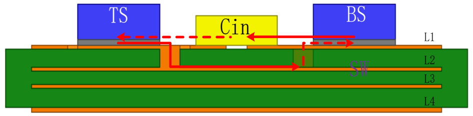
Reduce magnetic field strength

Design for GaN devices

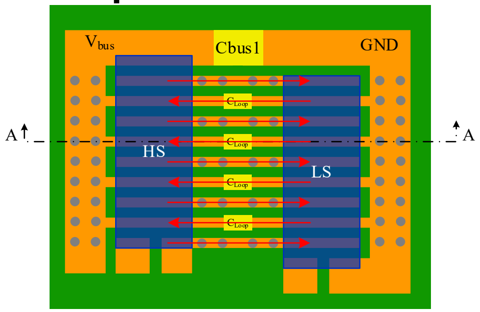
To minimize inductance in power loop:



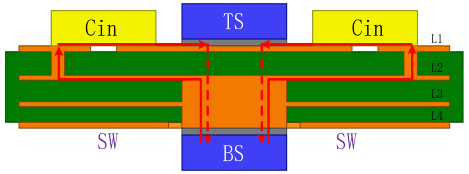
Minimized loop



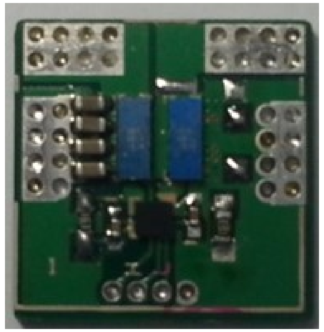
Shielding layer



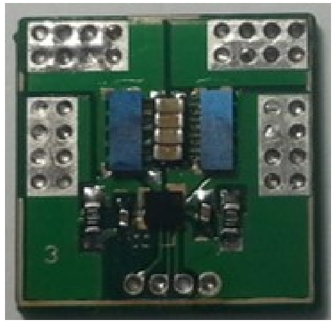
Decoupled loops



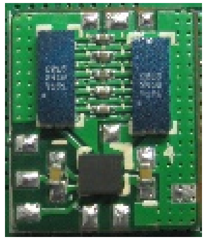
Shielding +Minimized loops



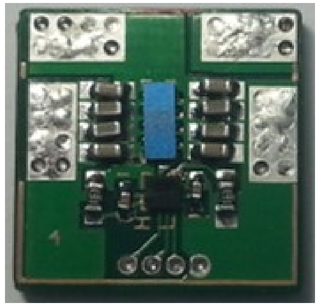
Bench mark**(1nH)**
15mm*15mm



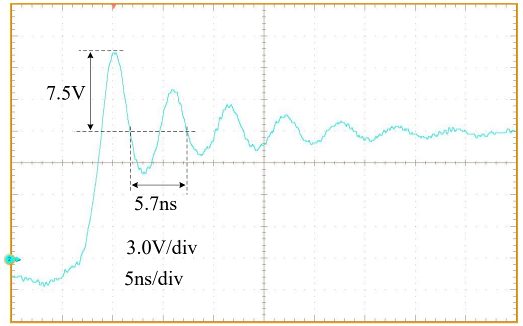
Parallel loop 1(**0.22nH**)
15mm*15mm



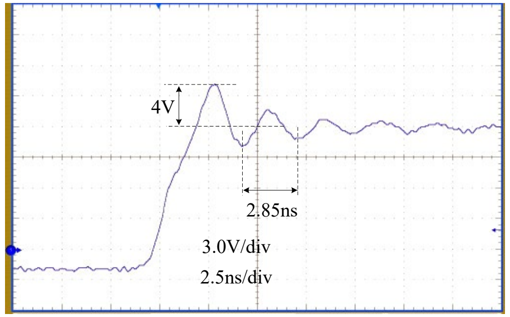
Parallel loop 2 （**0.2nH**）
9mm*9mm



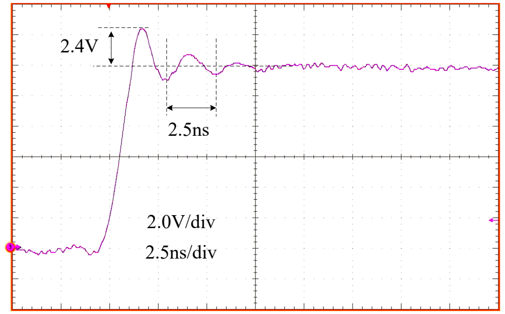
Double side**(0.1nH)**
15mm*15mm



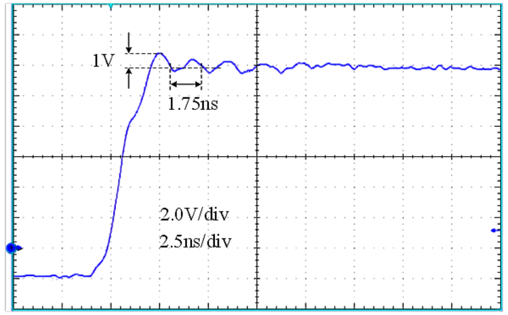
Overshoot 7.5V



Overshoot 4V

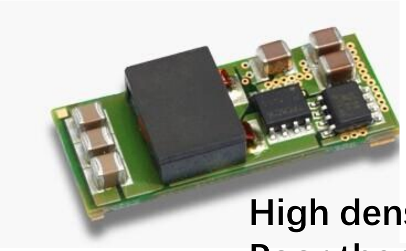


Overshoot 2.4V



Overshoot 1V

Design for GaN devices

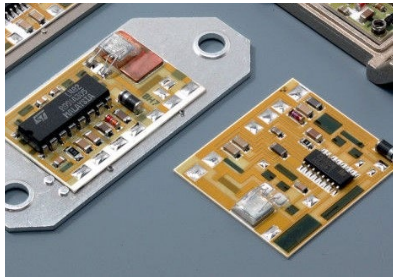


FR4 PCB

High density
Poor thermal

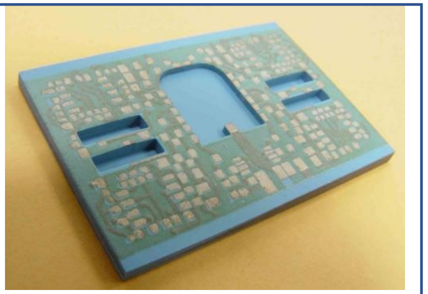
IMS

Low density
Fair thermal



Thick film

Low density
Good thermal

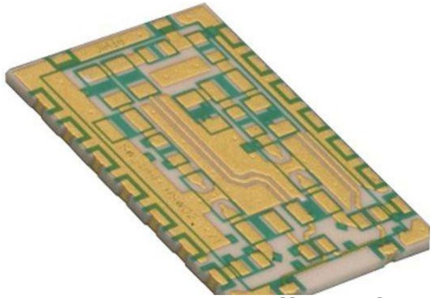


LTCC

High density
Fair thermal

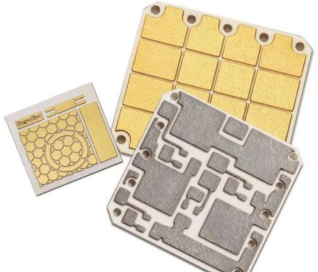
Hi k PCB

High density
Fare thermal



DPC

medium density
Good thermal



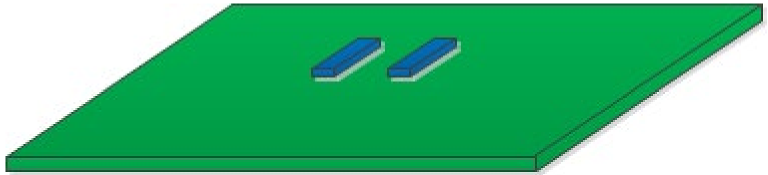
DBC

Low density
Very good thermal

Materials	Si	GaN	SiC	Cu	FR4	LTCC	Al_2O_3 DBC	AlN DBC
Thermal conductivity W/m/K	150	50	490	400	0.3	3.3	25	180
CTE (10^{-6}/K)	2.6	3.2	6.6	17	200	4	6	4

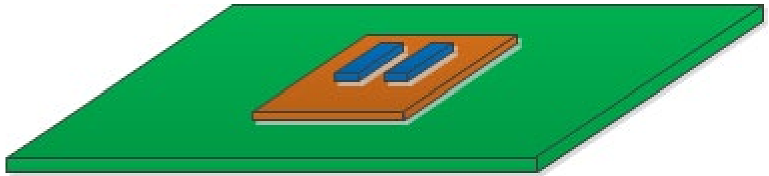
Design for GaN devices

Trade off between density and thermal



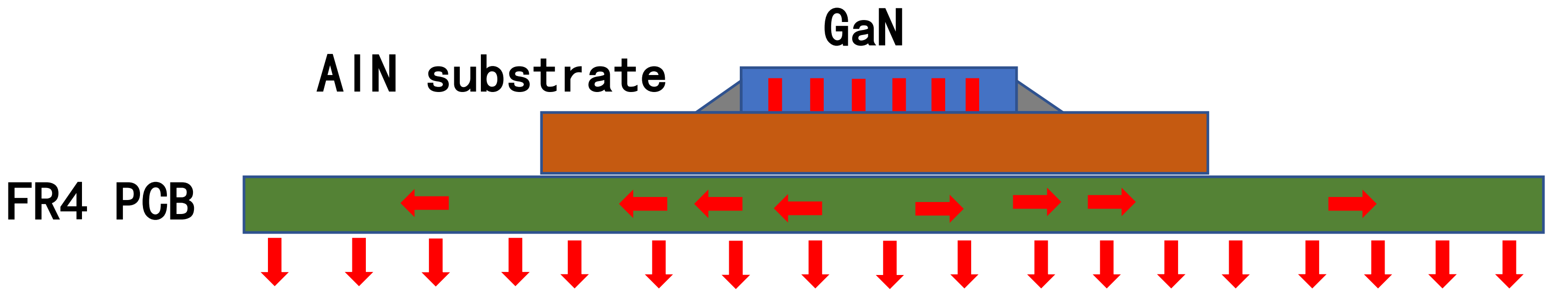
GaN device mounted on PCB

- Poor thermal performance
- More conductor layers for high density layout
- Low cost



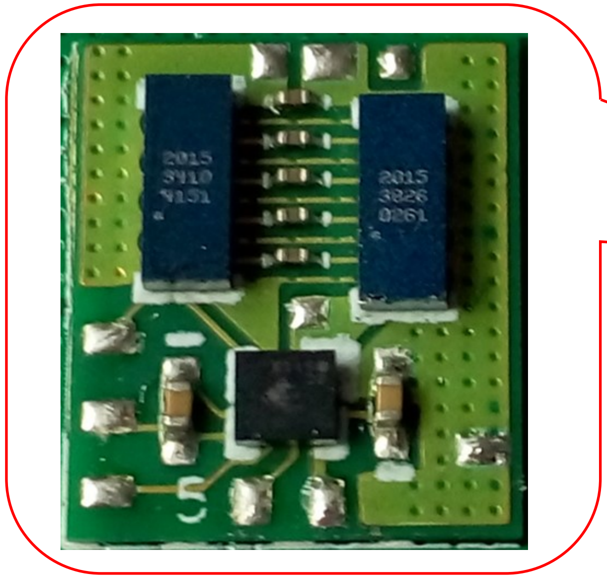
GaN mounted on AlN substrate

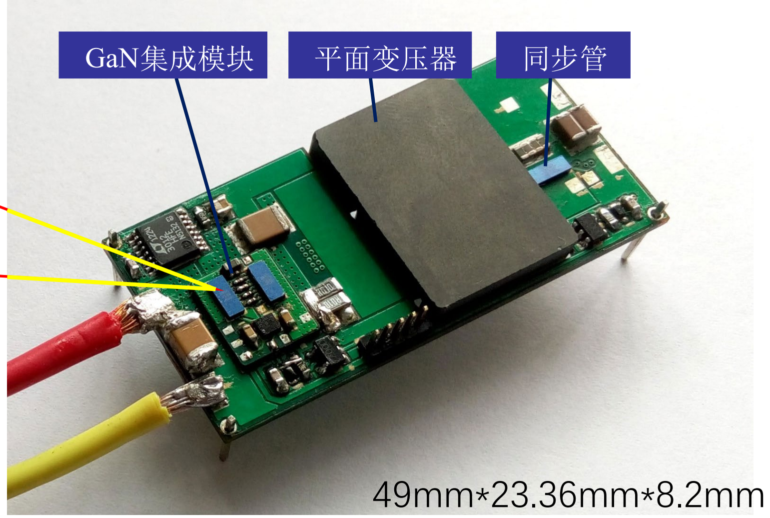
- Much better thermal performance
- Less conductor layers for layout
- Higher cost



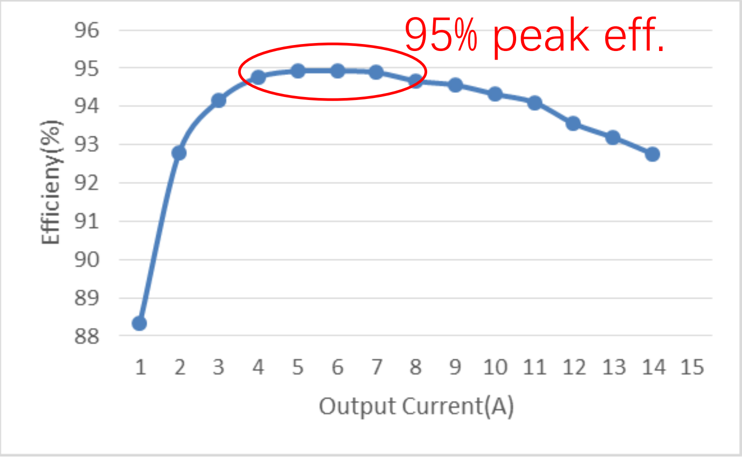
- High density
- Improved thermal performance

Design for GaN devices

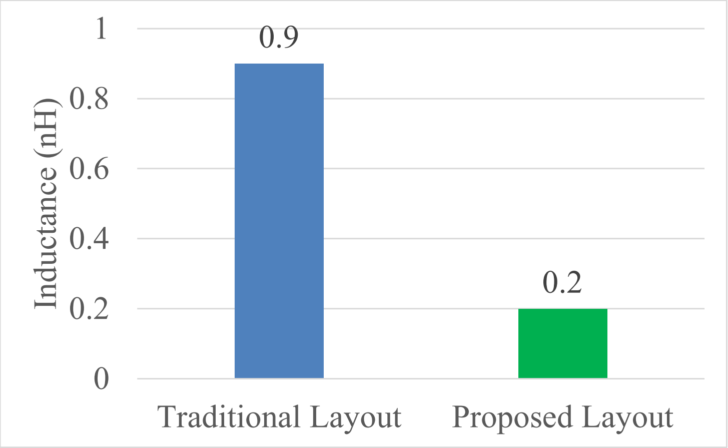




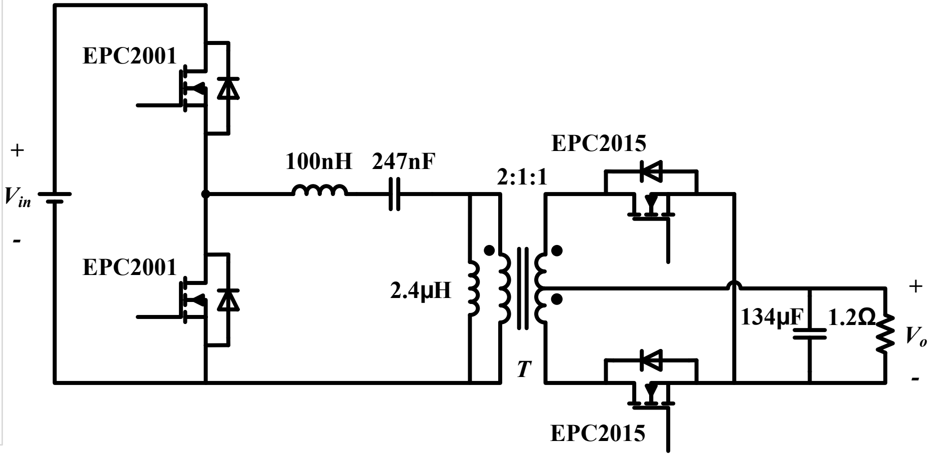
LLC converter prototype



efficiency



Parasitic inductance comparison

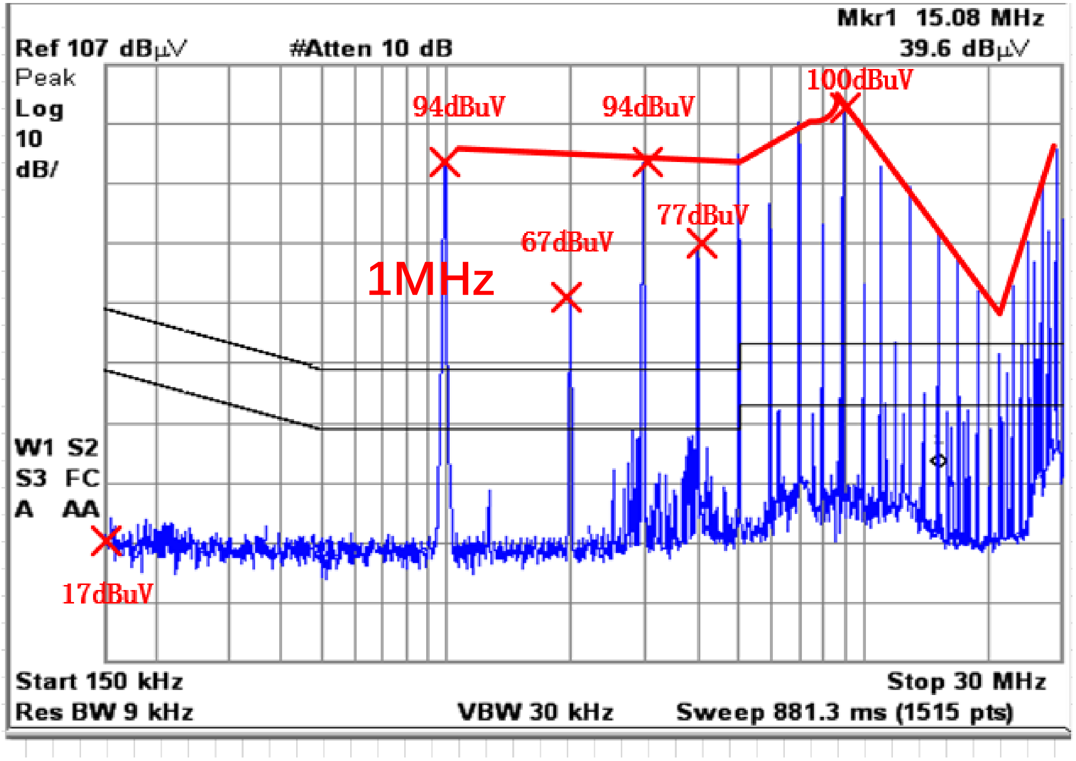


LLC topology

Input voltage	48V
Output voltage	12V
Output power	200W
Switching frequ.	1MHz
Device	EPC2001 (100V, 25A)

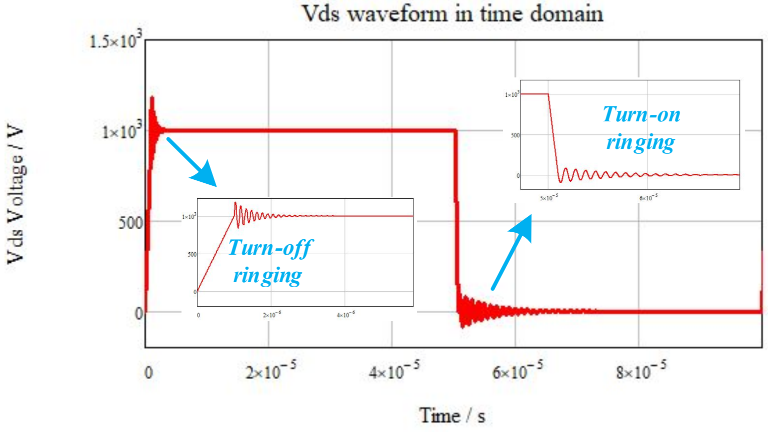
EMC issues for wide band gap devices

- **High switching frequency**
  - Switching frequency moves into standard range
  - Resulting in high peak in low band

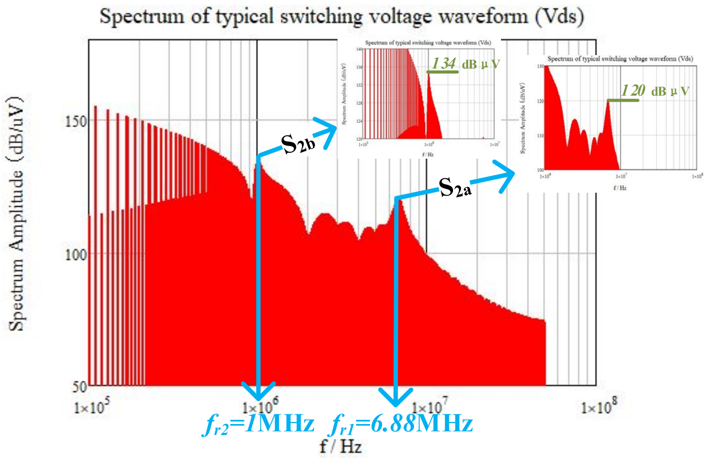


CM noise spectrum for 1MHz GaN converter

- **High slew rate during switching**
  - 10 times fast than Si devices
  - Resulting in peaks at high band



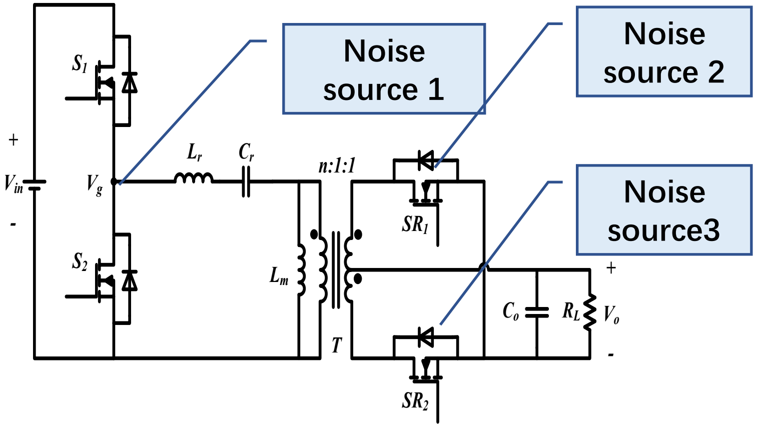
Switching waveform for GaN device shows high slew rate



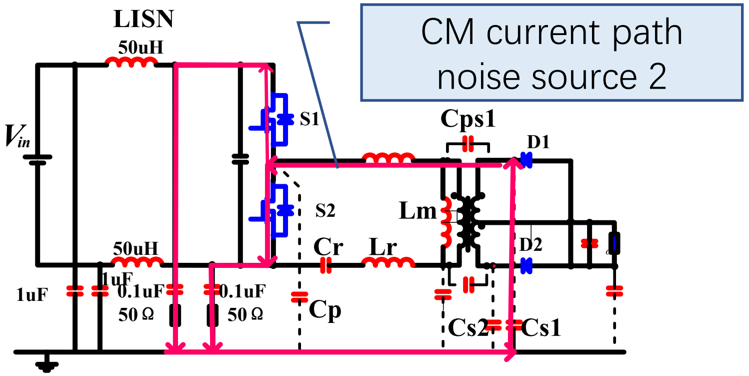
Noise peak shown in high band in spectrum

EMC issues for wide band gap devices

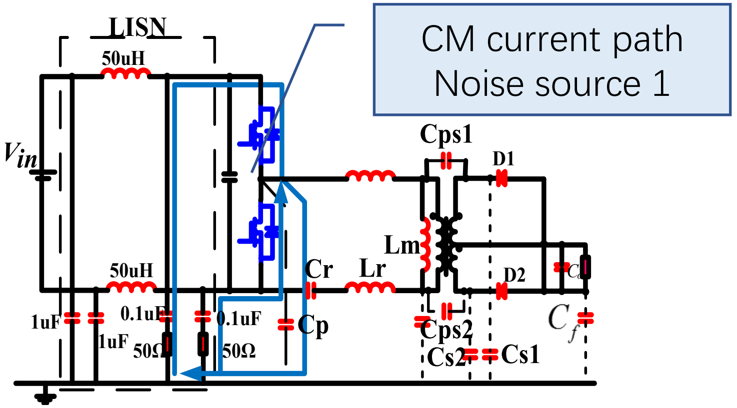
- **CM equivalent circuits for switching circuit**
  - Both primary & secondary side switches are noise source
  - Their noise feature can be modeled independently



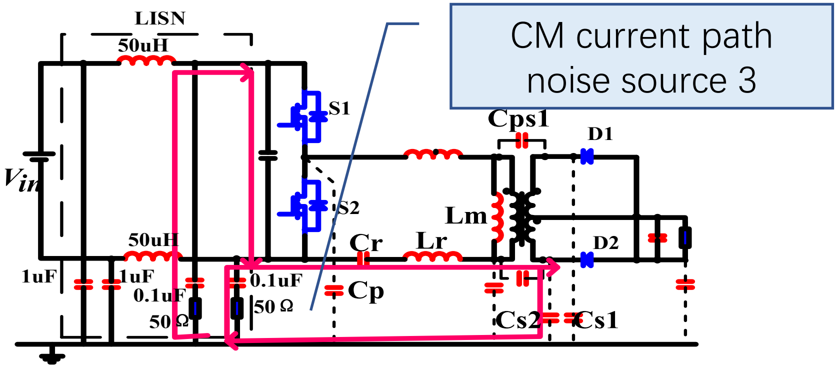
Switches in converter circuit



Noise model for source 2



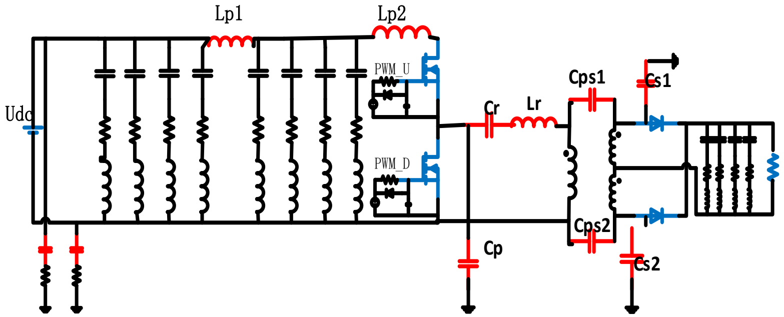
Noise model for source 1



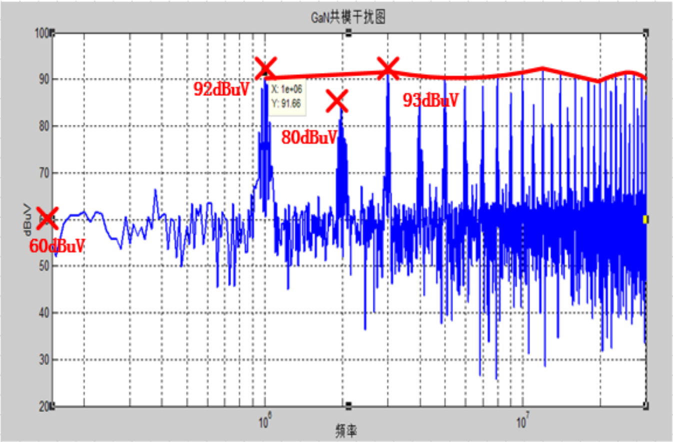
Noise model for source 3

EMC issues for wide band gap devices

- **Simplified CM noise model**
  - Switch is modeled as noise voltage source
  - Equivalent circuit is simplified

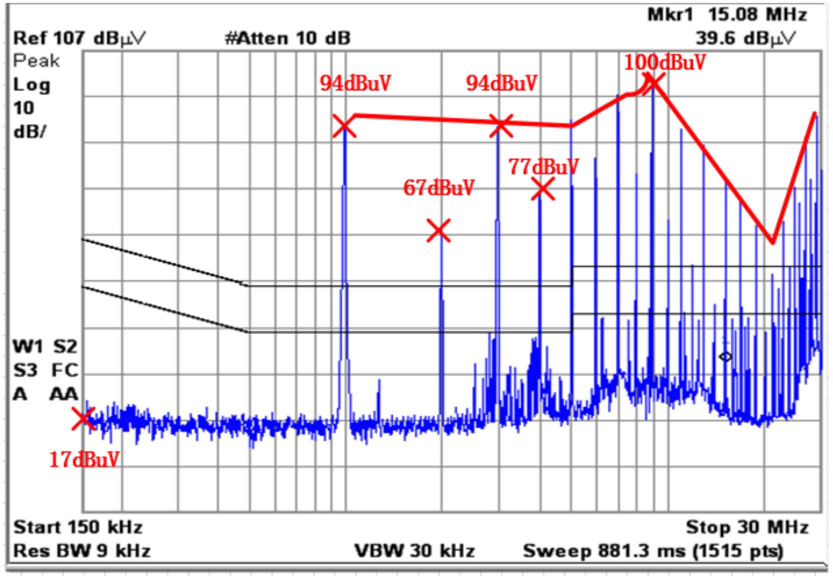


Noise model with Switches
(Massive calculation needed)

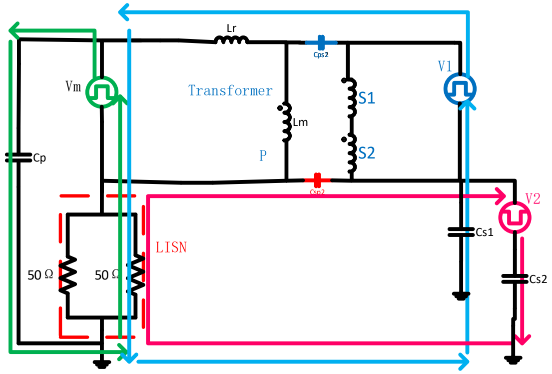


Noise spectrum calculated

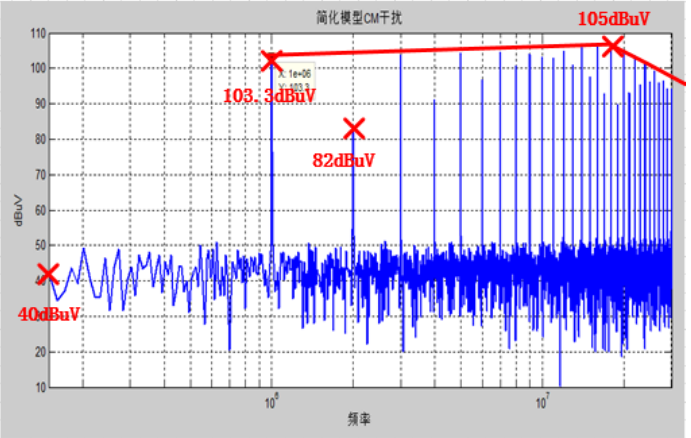
Difference : 2-5dB



Noise spectrum tested



Simplified Noise model
(much faster calculation)

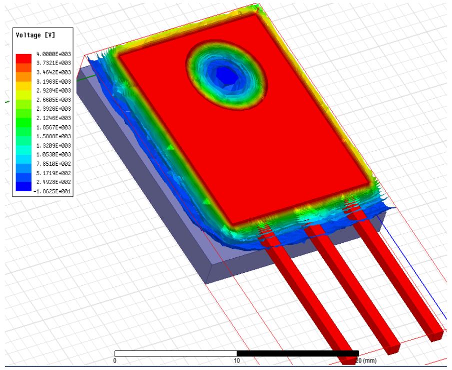


Noise spectrum calculated

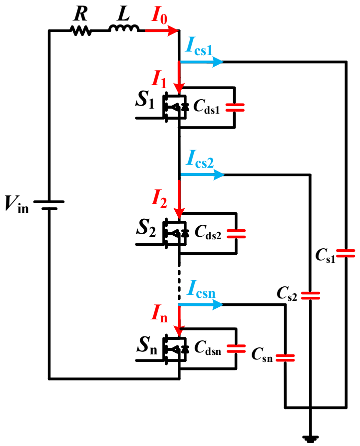
Difference : 5-8dB

EMC issues for wide band gap devices

- **Modelling the parasitic capacitance for WGP devices**
  - Parasitic capacitance between device & heat sink is calculated
  - Impact for slew rate & Vds on noise spectrum is analyzed

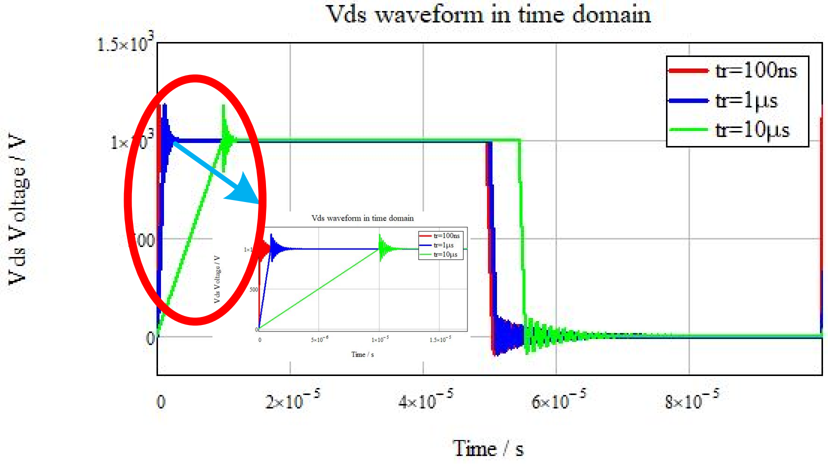


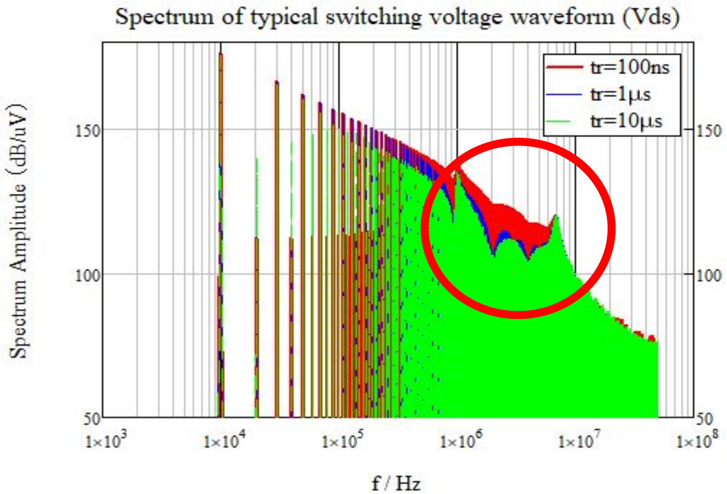
3D model to extract parasitic



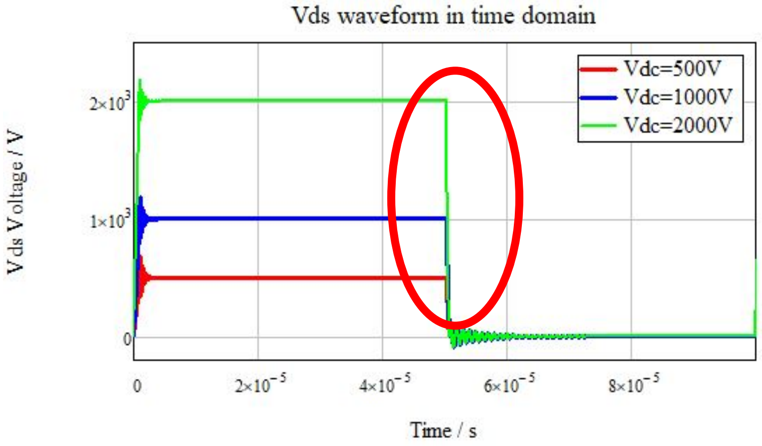
Equivalent circuit for parasitic between device & heat sink

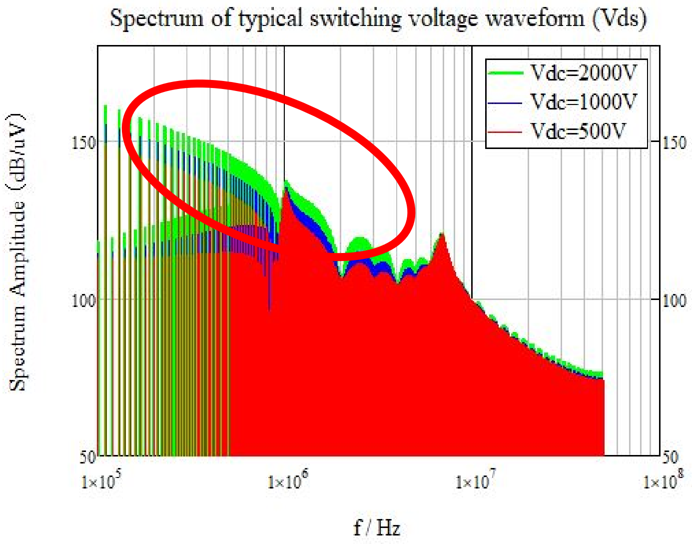
Impact of slew rate





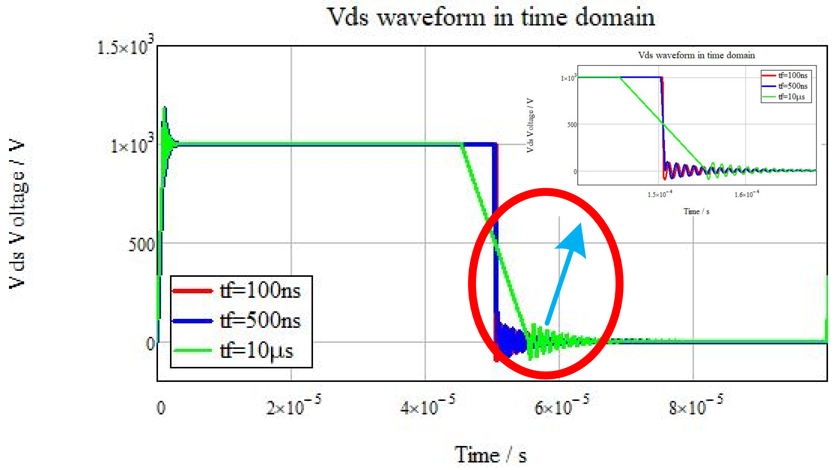
Impact of Vds



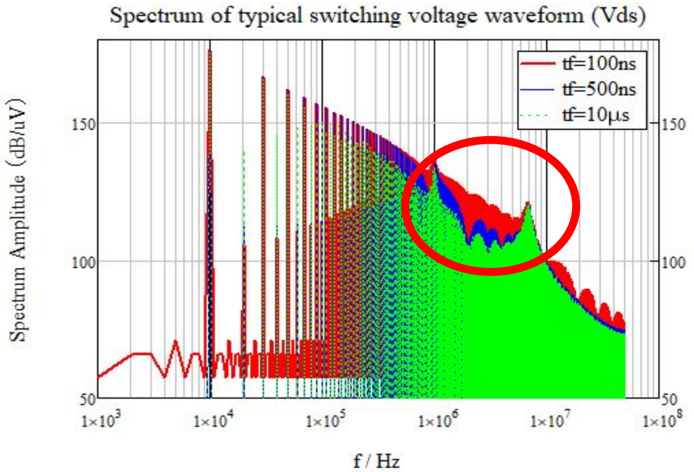


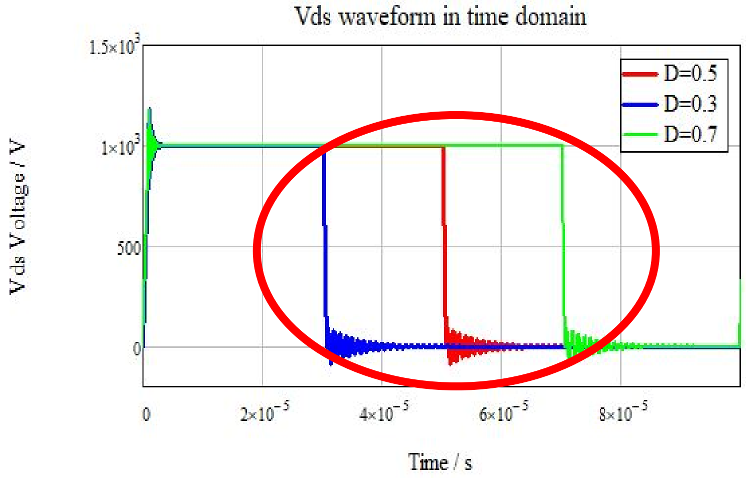
EMC issues for wide band gap devices

- **Modelling the lagging edge and duty cycle on WGP devices**
  - Lagging edge with different time are analyzed
  - Duty cycle with different value are analyzed

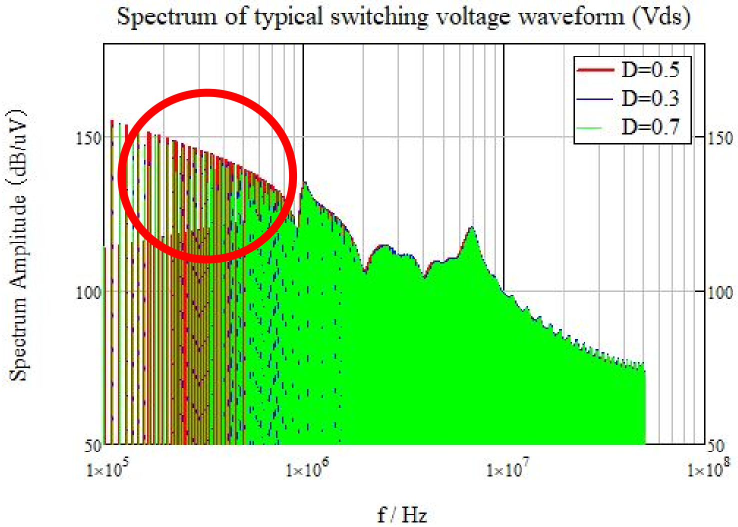


Lagging edge





Varying duty cycle

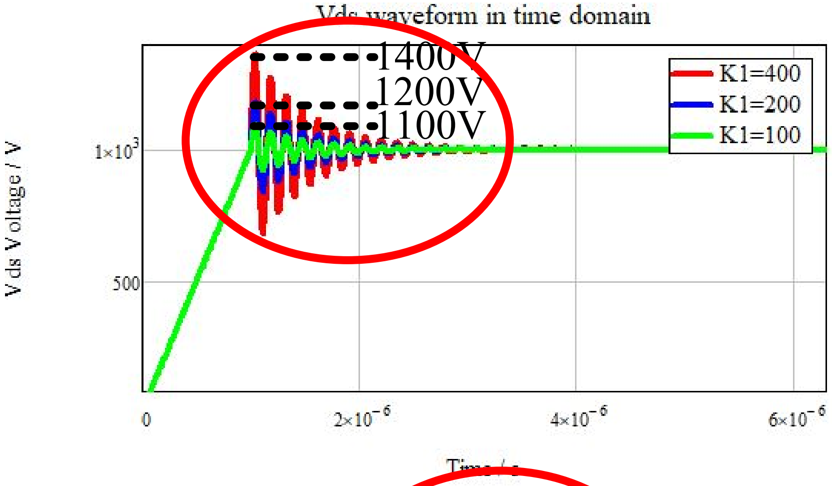


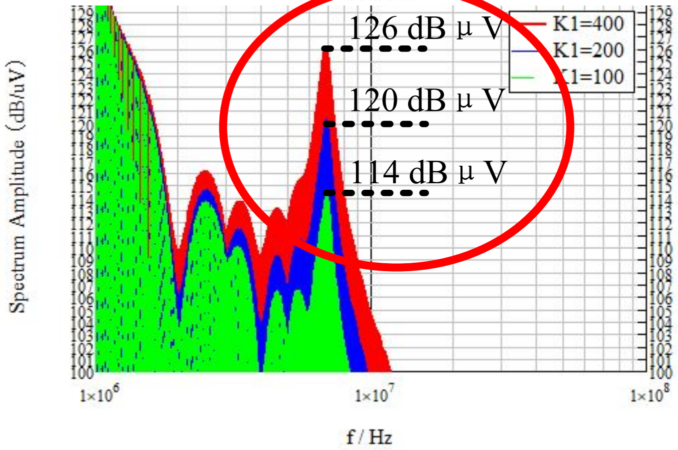
Impact on spectrum

EMC issues for wide band gap devices

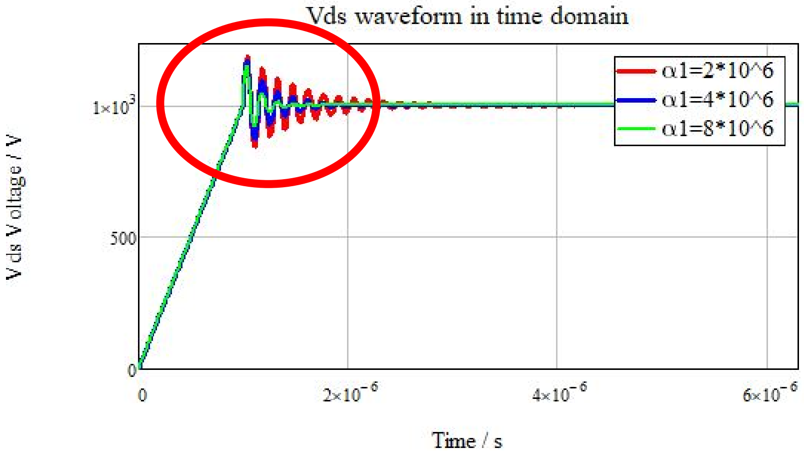
- **Modelling the parasitic ringing on WGP devices**
  - Ringing with different magnitude & damping are analyzed
  - Spectrums are compared

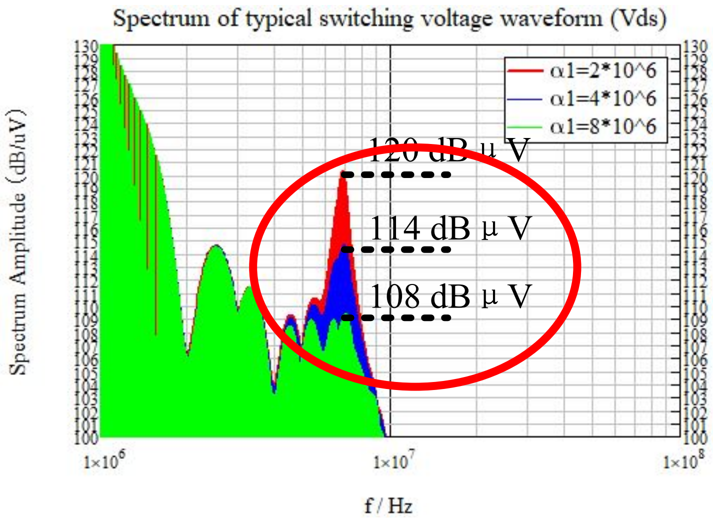
Ringing with different magnitude





Ringing with different damping

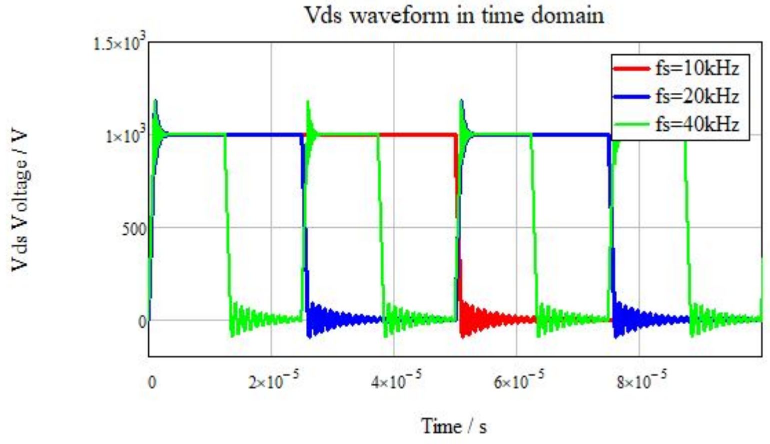


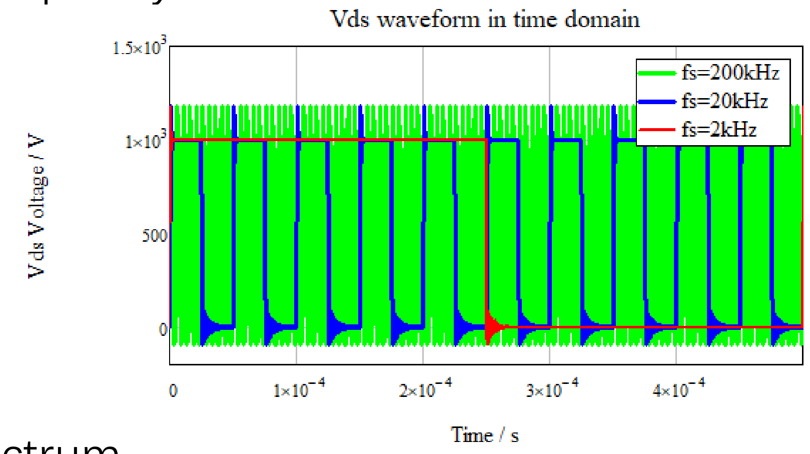


EMC issues for wide band gap devices

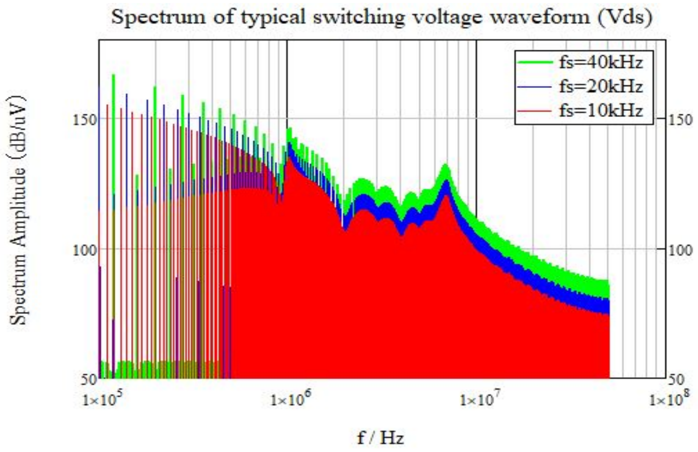
- **Modelling the Switching frequency on WGP devices**
  - Devices with different switching frequency are analyzed
  - Spectrums are compared

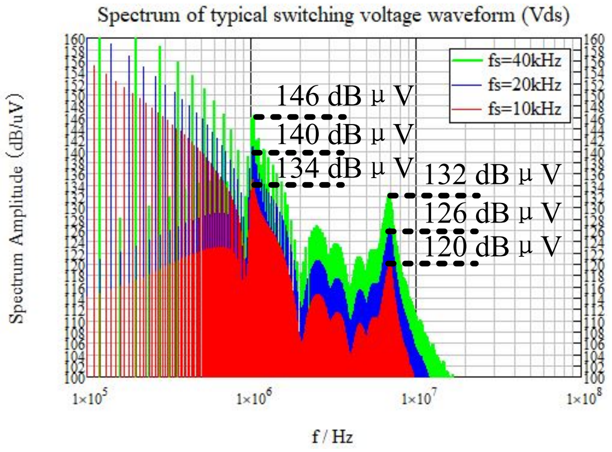
Devices with different switching frequency

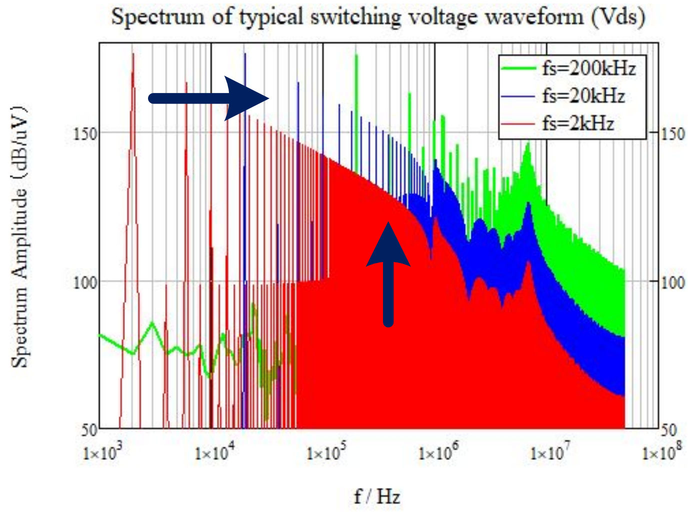




Impact on spectrum

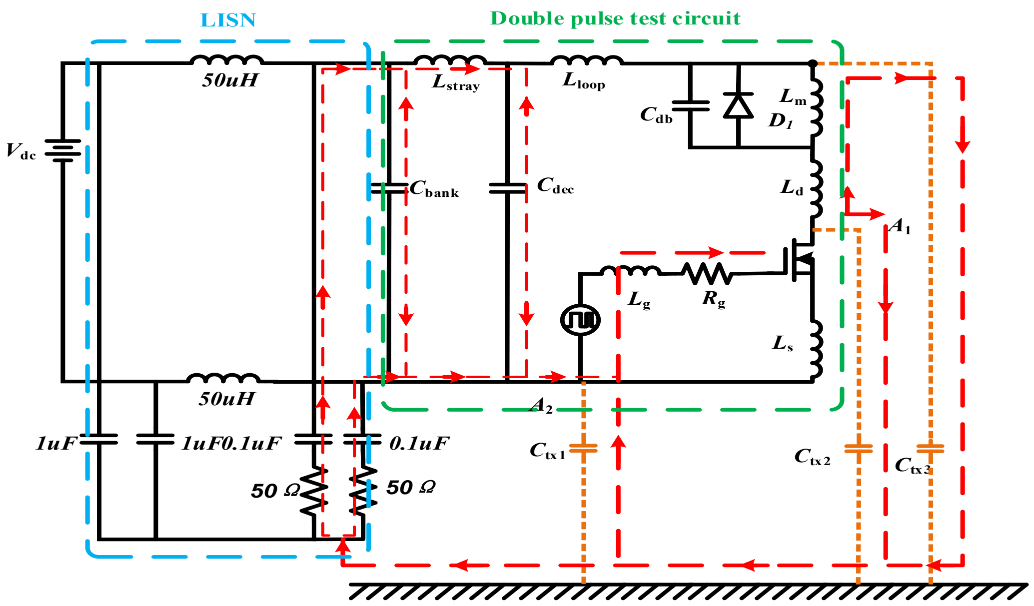


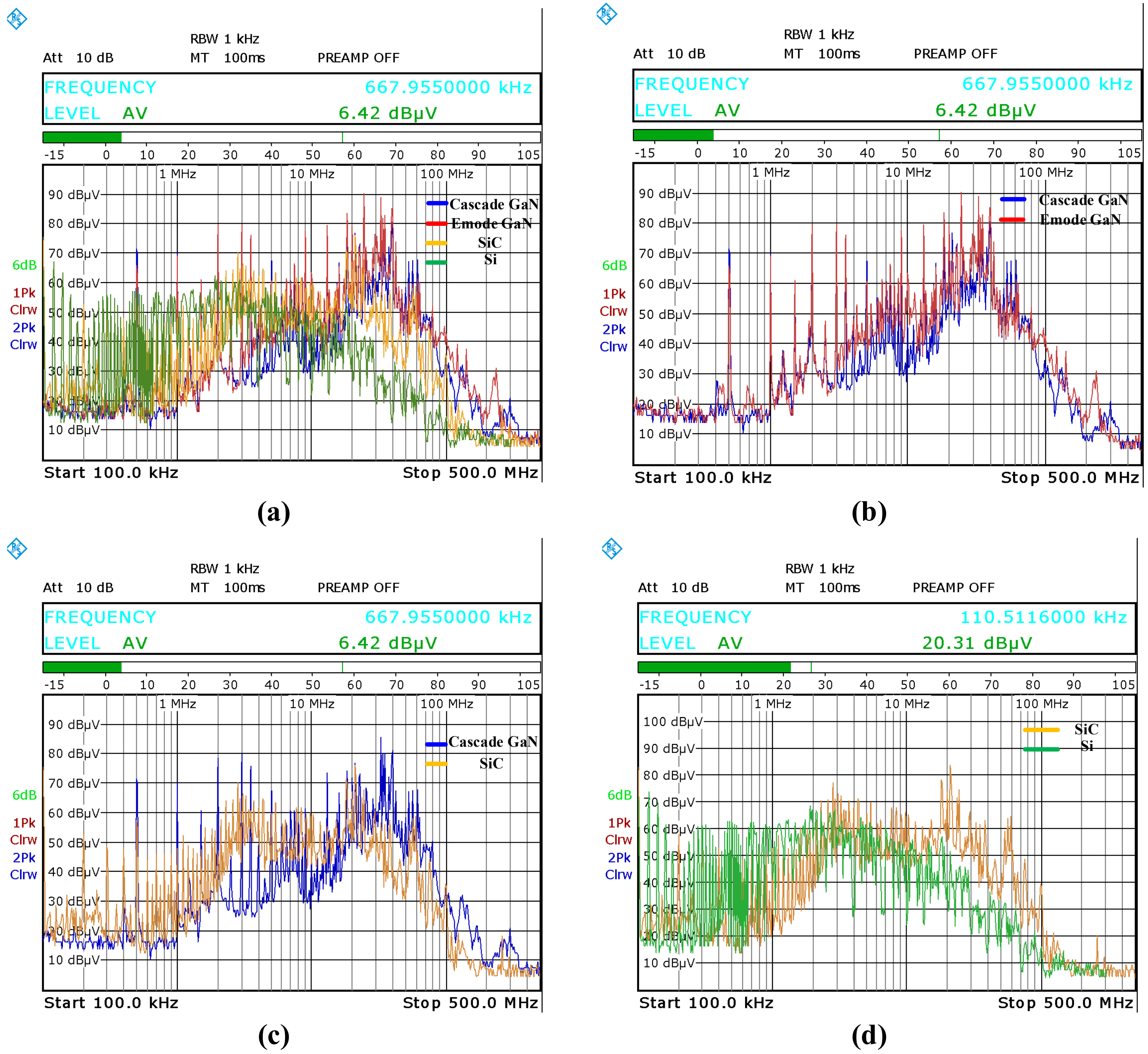




EMC issues for wide band gap devices

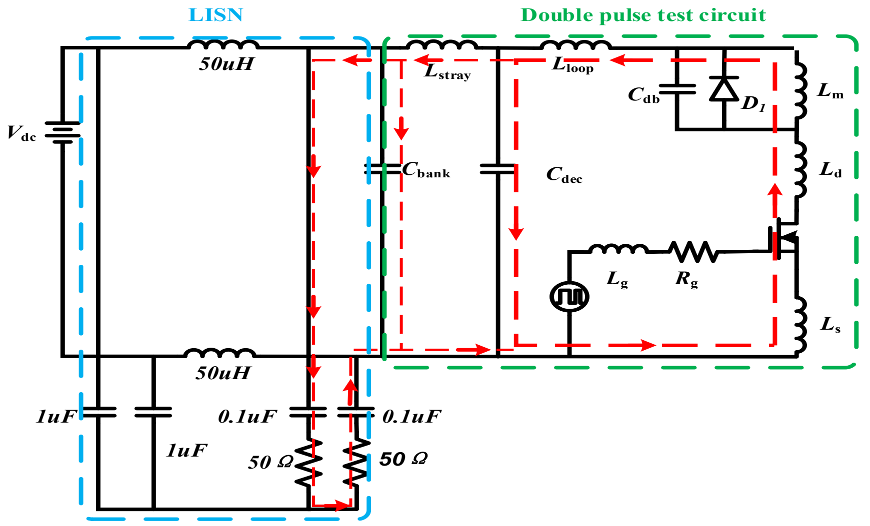
- CM tested results with Si, SiC, Cascade GaN and Emode GaN

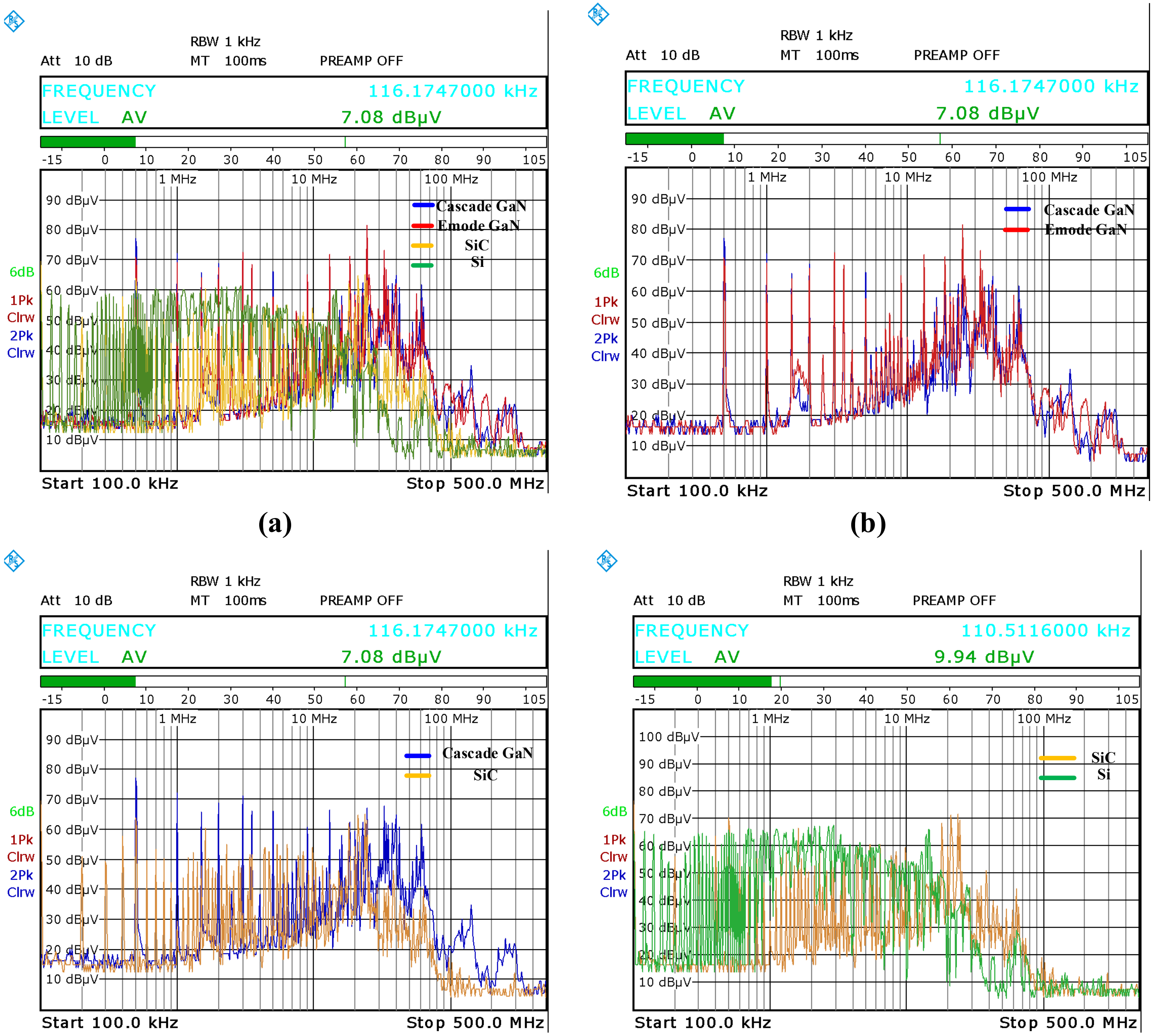




EMC issues for wide band gap devices

- DM tested results with Si, SiC, Cascade GaN and Emode GaN

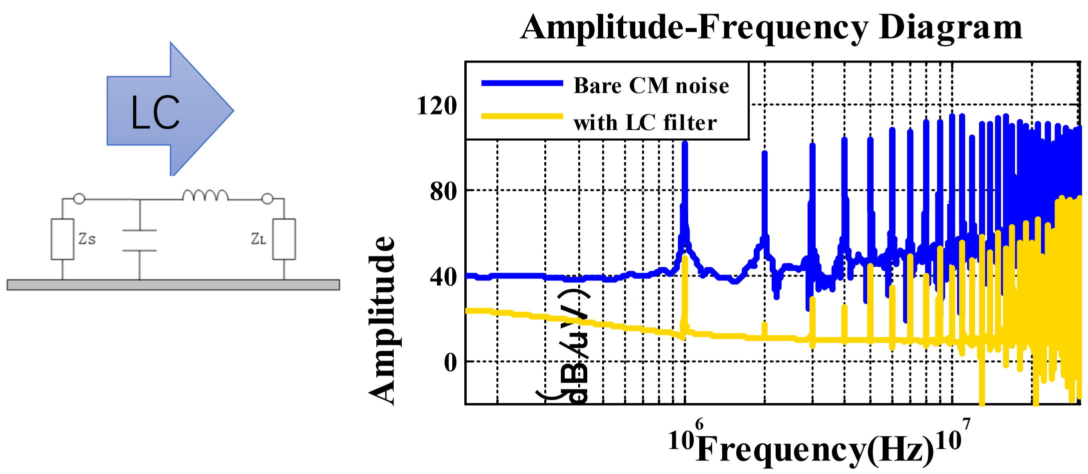


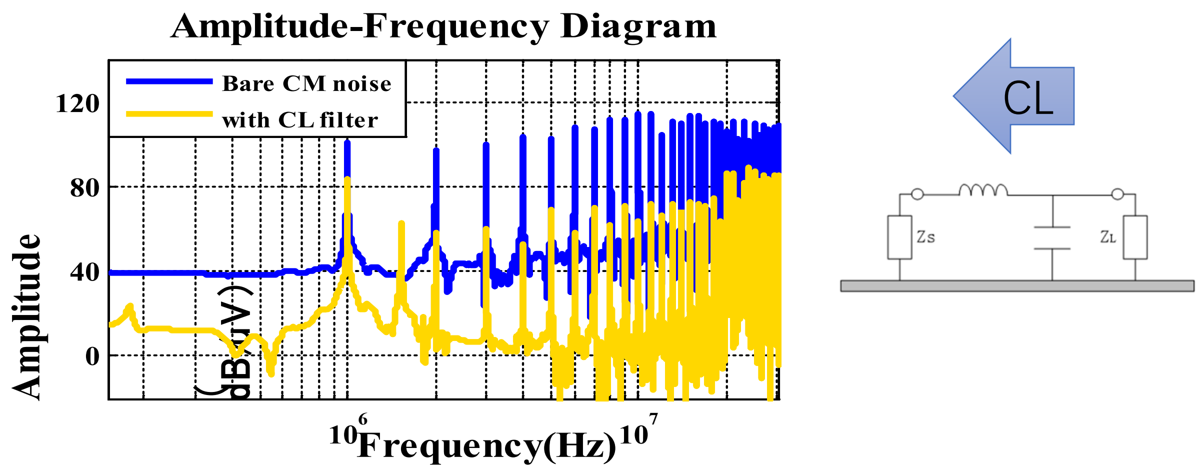


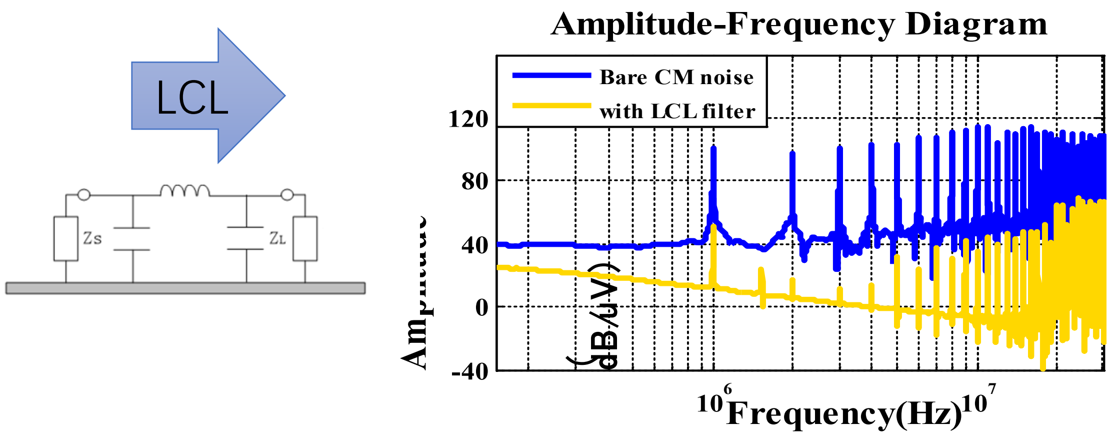
(a)
(b)
(c)
(d)

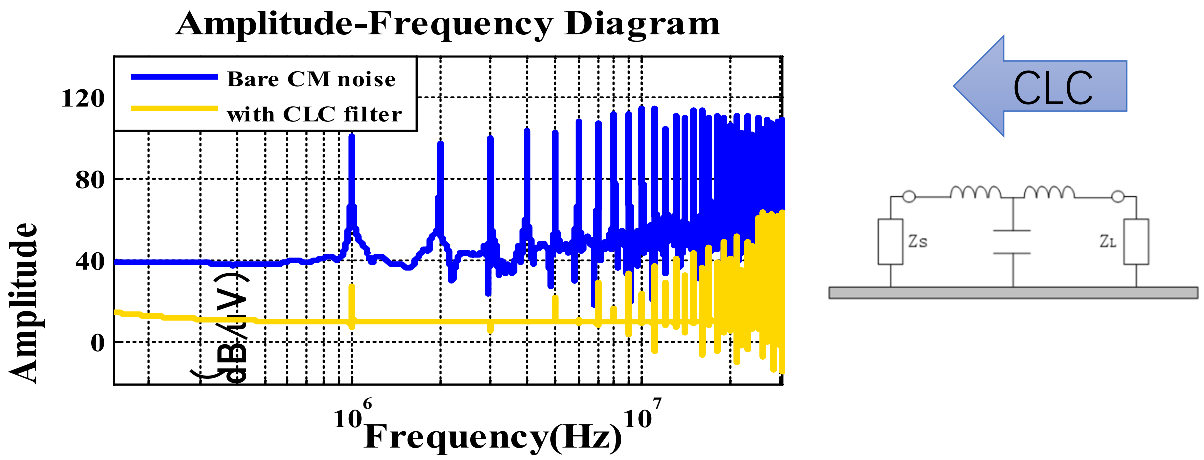
EMC issues for wide band gap devices

- **Passive filter designed**
  - Second and third order filters are compared



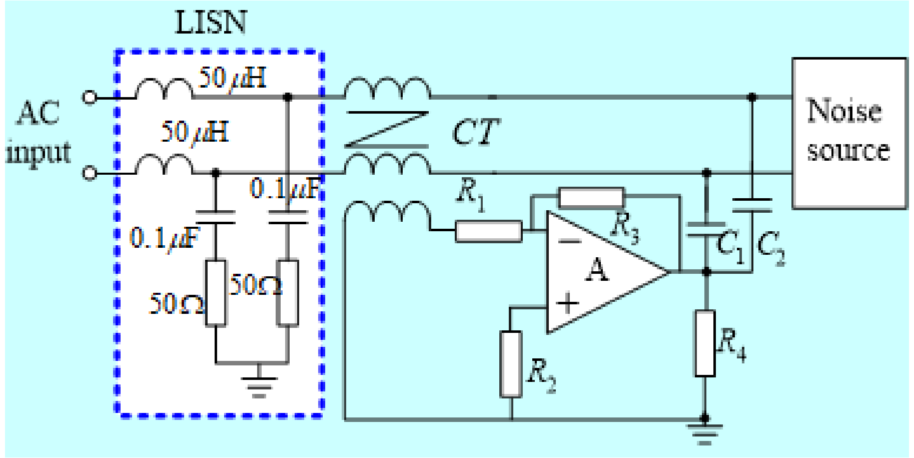


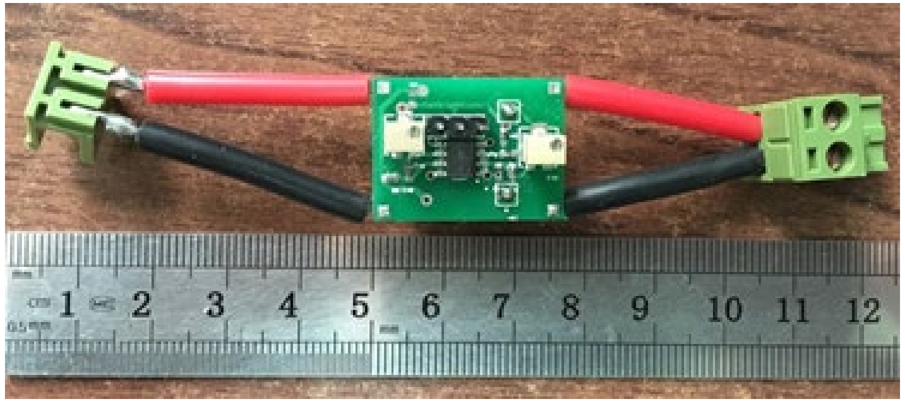




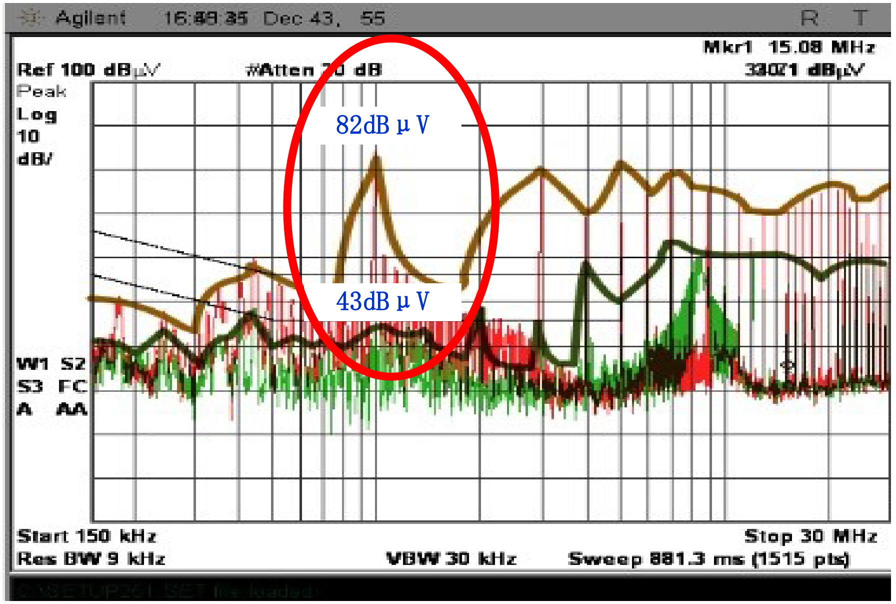
EMC issues for wide band gap devices

- **Active filter is designed**
  - High bandwidth Op-Amp is used
  - Low band insertion loss is greatly improved





Active filter built with op-amp



Insertion loss achieves 39dB @ 1MHz

Summary

- **Wide band gap devices are coming into application and greatly improves the performance for power electronic converters in both power system and customer applications**
- **High speed switching feature for WBG devices result in many issues in EMC performance in power electronic converters**
- **Passive and active filters can be designed to overcome the EMS issues and pushing the application for WBG device for wider applications.**

Thank you for your attention!