Successful High-Frequency Applications with SiC

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Contents

- Background
- Challenges of SiC Devices for High Frequency Application
- Comparative Analysis Based on Buck Circuit
- GaN+SiC Based 500kHz 6.6kW Bi-DC/DC Development
- Summary

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EV OBC Development Trend

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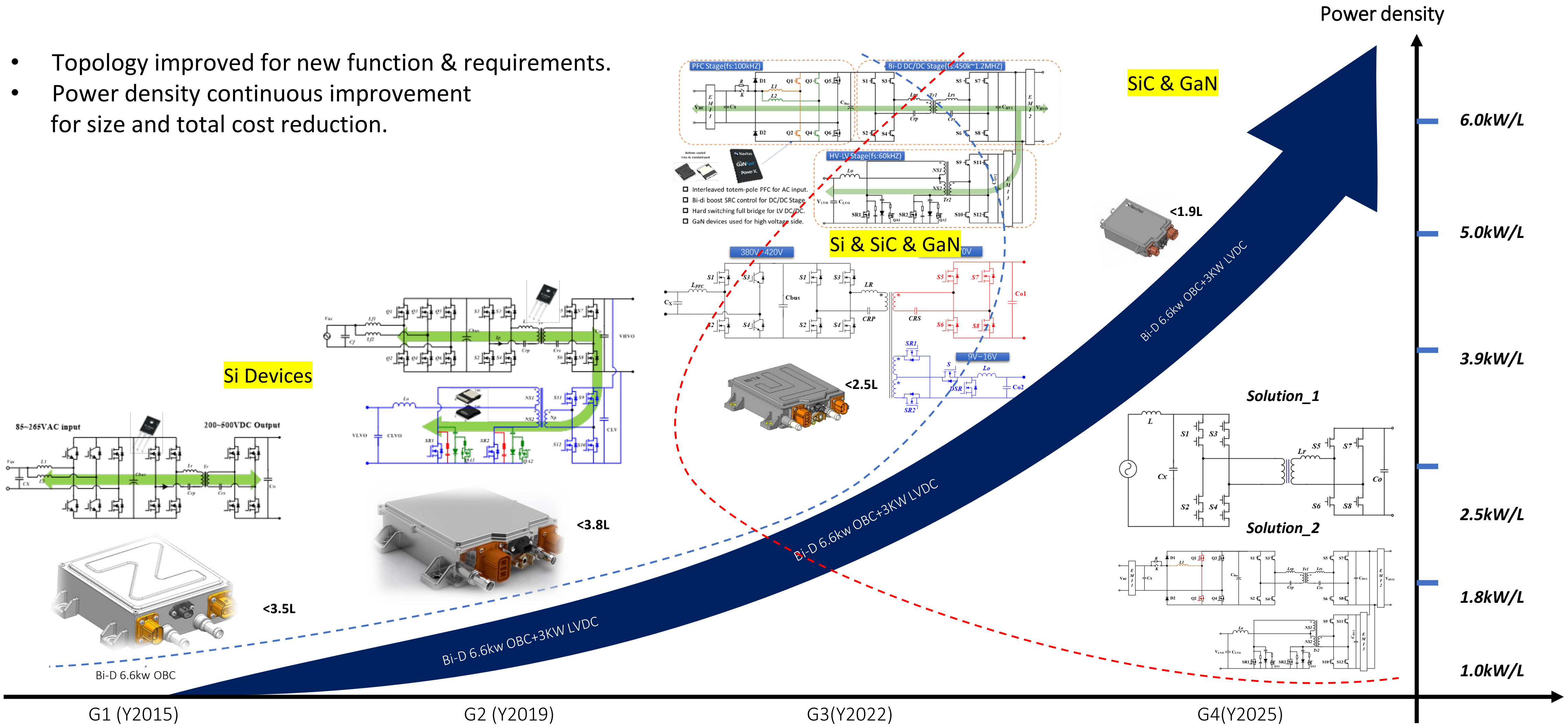
- Topology improved for new function & requirements.
- Power density continuous improvement for size and total cost reduction.



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Comparisons of Si, GaN and SiC

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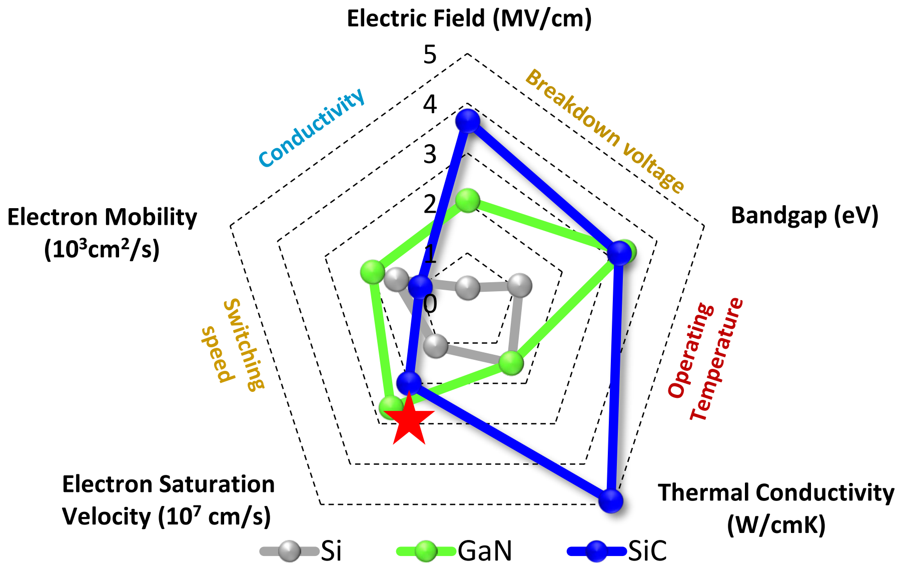
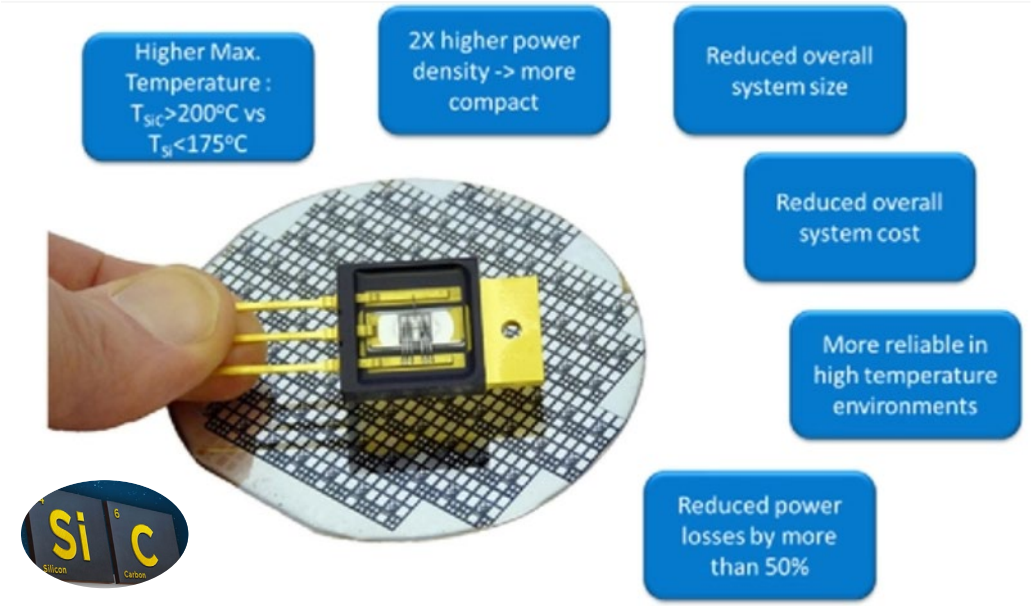
- Si vs GaN vs SiC



	Si	GaN	SiC
Band gap energy (eV)	1.12	3.45	3.26
Melting point (×1000°C)	0.15	0.8	0.76
Thermal conductivity (W/m.K)	1.5	1.3	4.9
Ctritical electric field (MV/cm)	0.3	3.5	3.2
Electron saturation velocity (10^7cm/s)	1	2.5	2
Electron mobility (×1000 cm^2/Vs)	1.4	1.8	0.9

- Characters of SiC



- 3rd WBG device had a huge advantage in switching speed, FOM, and thermal capability
- SiC has a slightly lower ***Electron Saturation Velocity*** than GaN, but it is still 2 times higher than traditional Si

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SiC Trench Technologies

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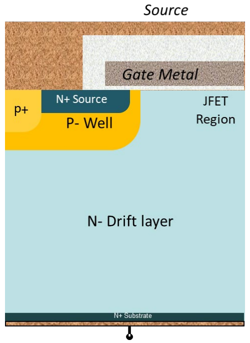

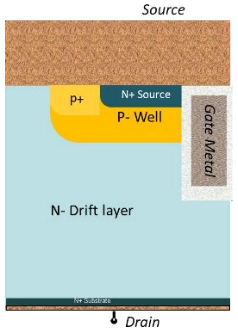

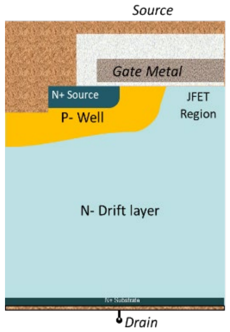

Trench-Assist Planar Gate SiC MOSFET

	SiC Planar	*SiC Trench*	*GeneSiC SiC MOSFET*
Manufacturability	➢ Repeatable ➢ High yield ➢ Low cost	➢ Inconsistent trench-etch profile ➢ Lower yields ➢ High cost	✓ Repeatable ✓ High yield ✓ Low cost
Performance	➢ High $R_{DS(ON)}$ / area ➢ Slower switching FoM	➢ Lower $R_{DS(ON)}$ / area ➢ Faster switching FoM ➢ High $R_{DS(ON)}$ / Δ temp	✓ Lower $R_{DS(ON)}$ / area ✓ Fastest switching FoM ✓ Lowest $R_{DS(ON)}$ / Δ temp
Reliability	➢ Rugged gate oxide (stable V_{TH})	➢ Non-uniform gate oxide	✓ Rugged Gate oxide (stable V_{TH}) ✓ Highest 100% tested avalanche ✓ Long short-circuit withstand time

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SPEC. Comparisons of the SiC Devices

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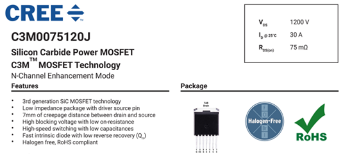

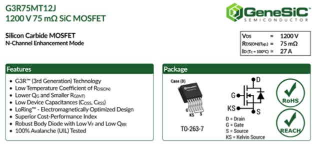

	CREE（1200 SiC) (C3M0075120J)	IFX (1200v SiC）(IMBG120R060M1H)	Genesic (1200v SiC）(G3R75MT12J)
I_{DS}	30A@25°C, 19.7A@100°C , Vgs=15V	36A@25°C, 26A@100°C ,Vgs=18V	38A@25°C, 27A@100°C , Vgs=18V
V_{GS}	-8V ~ +19V （-4V ~15V）	-7V ~ +23V （-5V ~18V）	-10V ~ +22V（-5V ~18V）
$V_{GS(th)}$	1.8V<Vth=2.5V<3.6V	3.5V<Vth=4.5V< 5.7V	1.8V<Vth_Typ=2.7V
$R_{DS(ON)}$	75mΩ(MAX=90mΩ)@25°C, 100mΩ@150°C /Vgs=15V and ID=20A	60mΩ(MAX=83mΩ)@25°C, 113mΩ@175°C /Vgs=18V and ID=13A	64mΩ(MAX=85mΩ)@25°C, 92mΩ@175°C /Vgs=18V and I_D=20A
Ciss	1390pF	1145pF	1545pF
Coss	58pF	22pF	47pF
Qg	48nC	34nC	47nC
Qrr	109nC Vgs=-4V , Isd=20A,Vr=800V, dIS/dt=1925A/us, Tj=25°C	165nC Vgs=-5V , Isd=13A,Vr=800V, dIS/dt=1000A/us, Tj=25°C	64nc @Vgs=-5V, Isd=20A,Vr=800V, dIS/dt=1200A/us, Tj=25°C
Vsd	4.5V (Typ.) ,4.0V(175°C)	4.1V(25°C), 3.9V(175°C)	4.9V (25°C), 4.4V(175°C)
Eoss	33uJ	22uJ	18uJ
Rg (int)	9 Ω	6 Ω	1.3 Ω
Rjc	Max=1.1°C/W	Max=0.83°C/W (typ=0.62 °C/W)	Max=0.77°C/W

扩散焊接芯片贴装工艺（.XT工艺）

- The same parameter, different manufacturers show different performance

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E_{ON}, E_{OFF} and $R_{DS(ON)}$ Comparison

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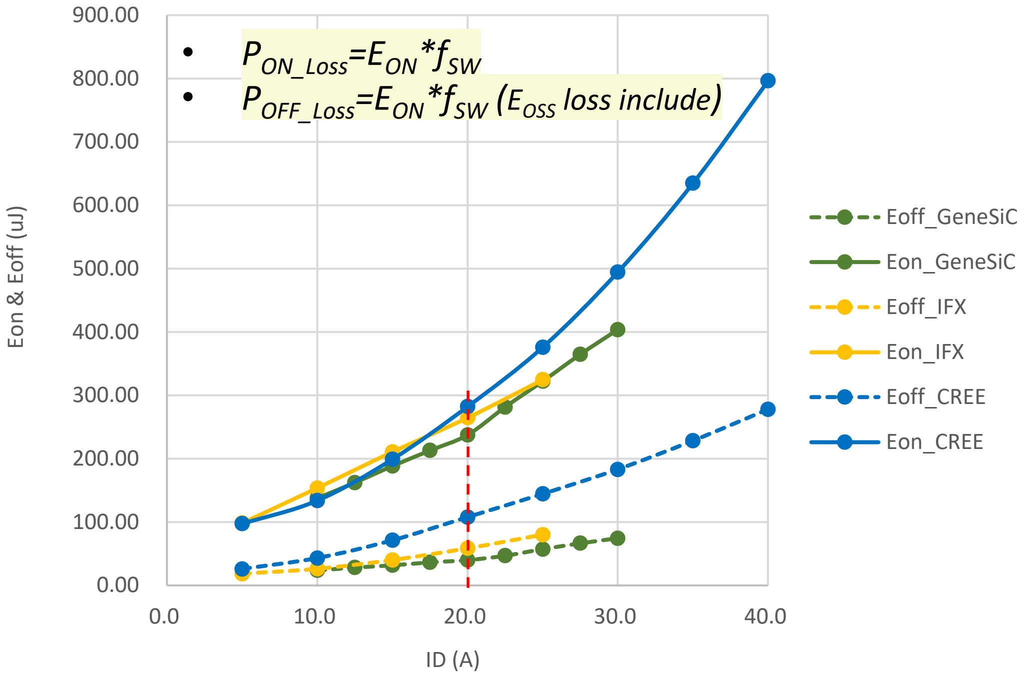
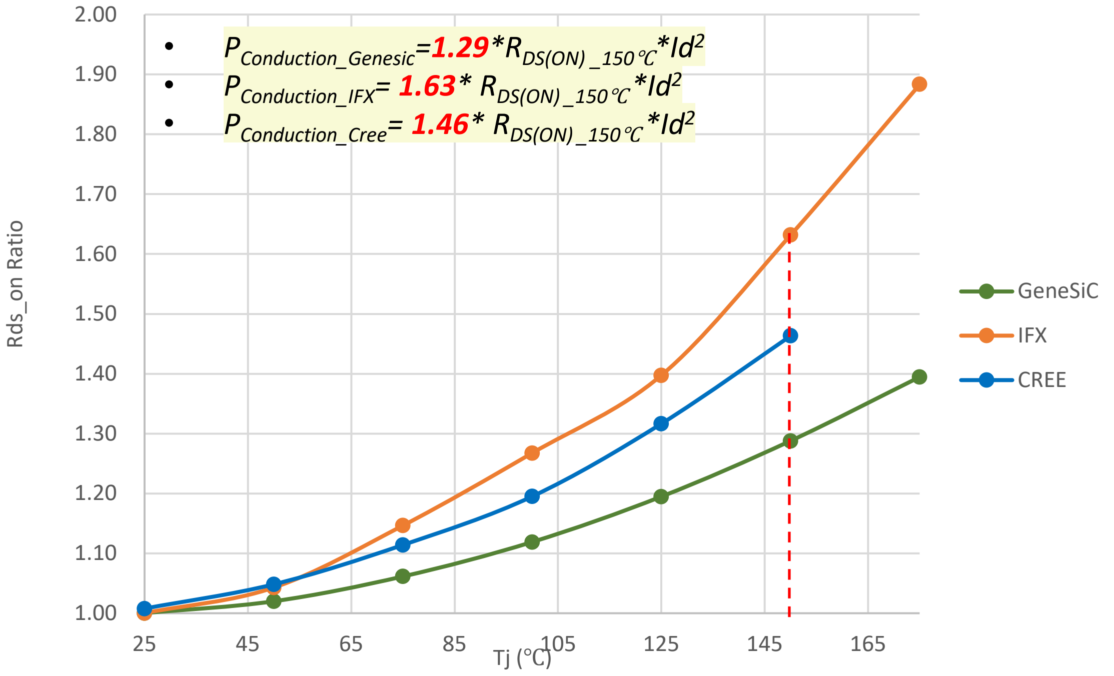
- 800V, Rg_ext=2Ω,Vg=-5V/18V, Tj=150℃





	GeneSiC		IFX		CREE	
	100kHz	600kHz	100kHz	600kHz	100kHz	600kHz
Eon@20A	183.5uJ		264.7uJ		282.2uJ	
Eoff@20A	25.5uJ		58.5uJ		107.7uJ	
P_on_loss	18.35W	***110.1W***	26.47W	***158.82W***	28.22W	***169.3W***
P_off_loss	2.55W	15.3W	5.85W	35.1W	10.7W	64.6W

- SiC devices of similar specifications from different venders show different characteristics in E_{ON}, E_{OFF} and $R_{DS(ON)}$ characteristics.

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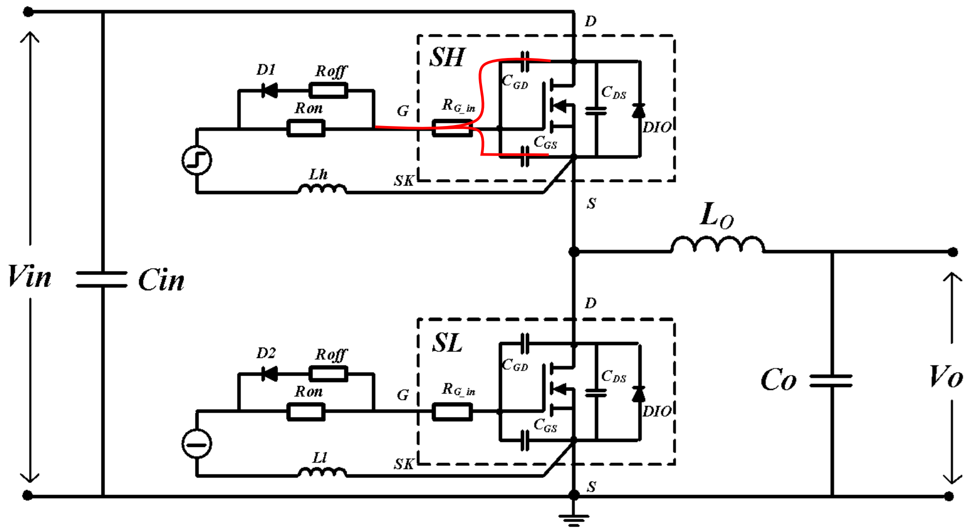
Drive Circuit Design

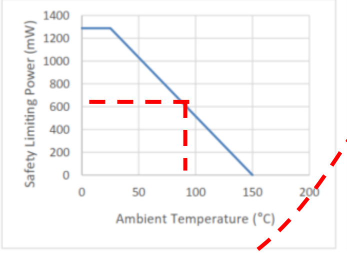


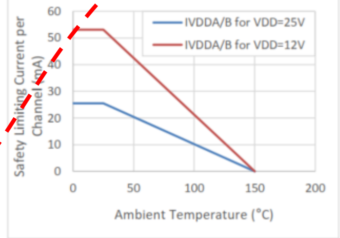
Reinforced isolation safety-limiting values as outlined in VDE-0884-11 of NSI6602x-xSWxR (SOW16/SOW14)

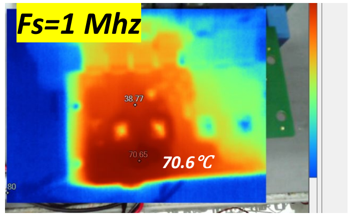
Description	Test Condition	Side	Value	Unit
Safety Supply Power	$R_{\theta JA}$ = 97 °C/W[1], T_J = 150 °C, T_A = 25 °C	Input	12	mW
		Driver A, Driver B	638	mW
		Total	1288	mW
Safety Supply Current	$R_{\theta JA}$ = 97 °C/ W[1], VDDA/B = 12V, T_J = 150 °C, T_A = 25 °C	Driver A, Driver B	53.1	mA
	$R_{\theta JA}$ = 97 °C/ W[1], VDDA/B = 25V, T_J = 150 °C, T_A = 25 °C	Driver A, Driver B	25.5	mA
Safety Temperature[2]			150	°C

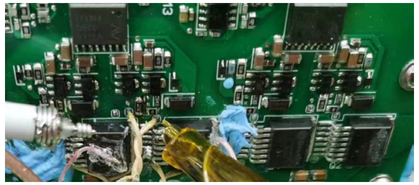
1) Calculate with the junction-to-air thermal resistance, $R_{\theta JA}$, of SOW16/SOW14 package (*Thermal Information Table*) which is that of a device installed on a low effective thermal conductivity test board (1s) according to JESD51-3.

2) The maximum safety temperature has the same value as the maximum junction temperature (T_J) specified for the device.





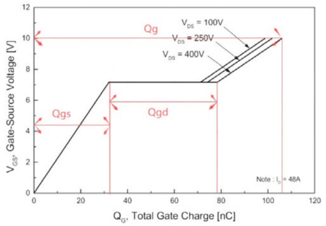




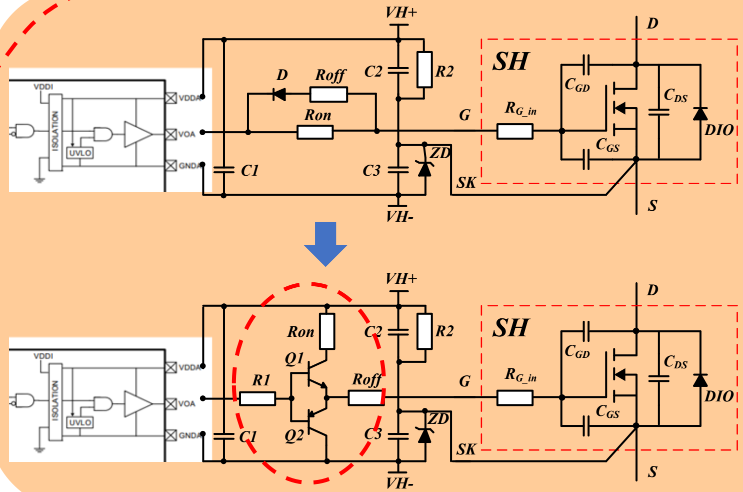
$$P_{Dmax} \le \frac{T_{jmax} - T_A}{\Theta ja}$$

- The driving loss mainly comes from the charge and discharge of *Cgd* and *Cgs,* and satisfies the following formular:

$$P_{loss\_dr} = V_{dr} * Q_g * f_s$$



P_{loss_dr} @ Qg=47nC,	Vgs=18V
100kHz	0.085W*2=0.17W
500kHz	0.423W*2=0.846W
1 Mhz	0.846W*2=1.692W



- High temp. of driver IC for high fs amplicons.
- Heat dissipation measures must be taken for the driver IC
- Low temp. of driver IC for high fs amplicons.

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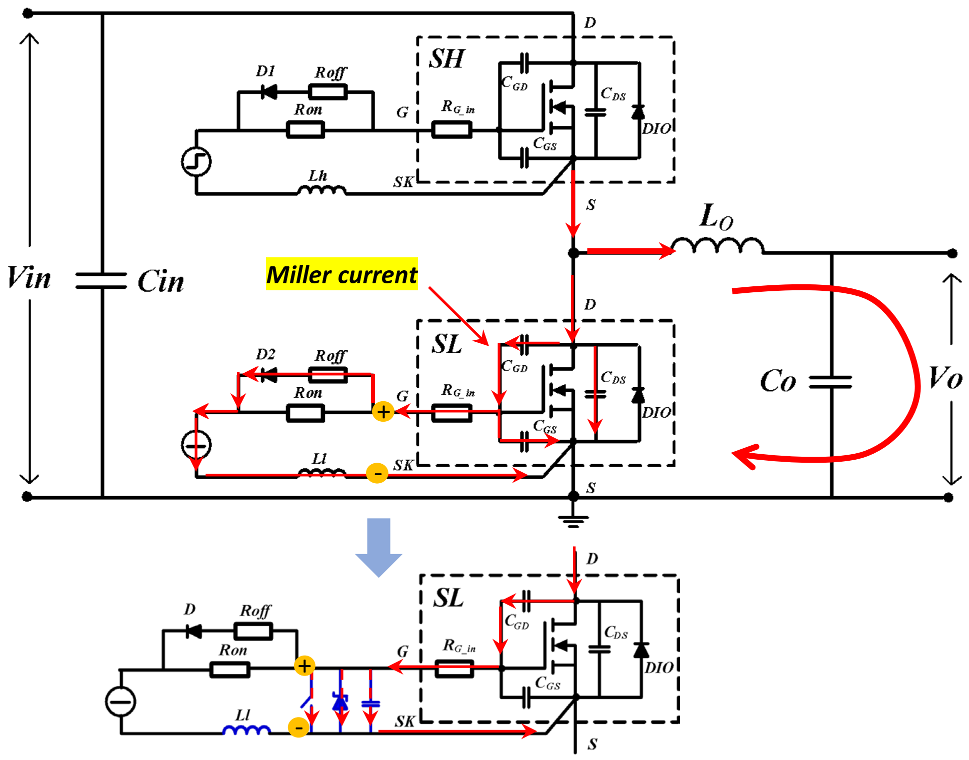
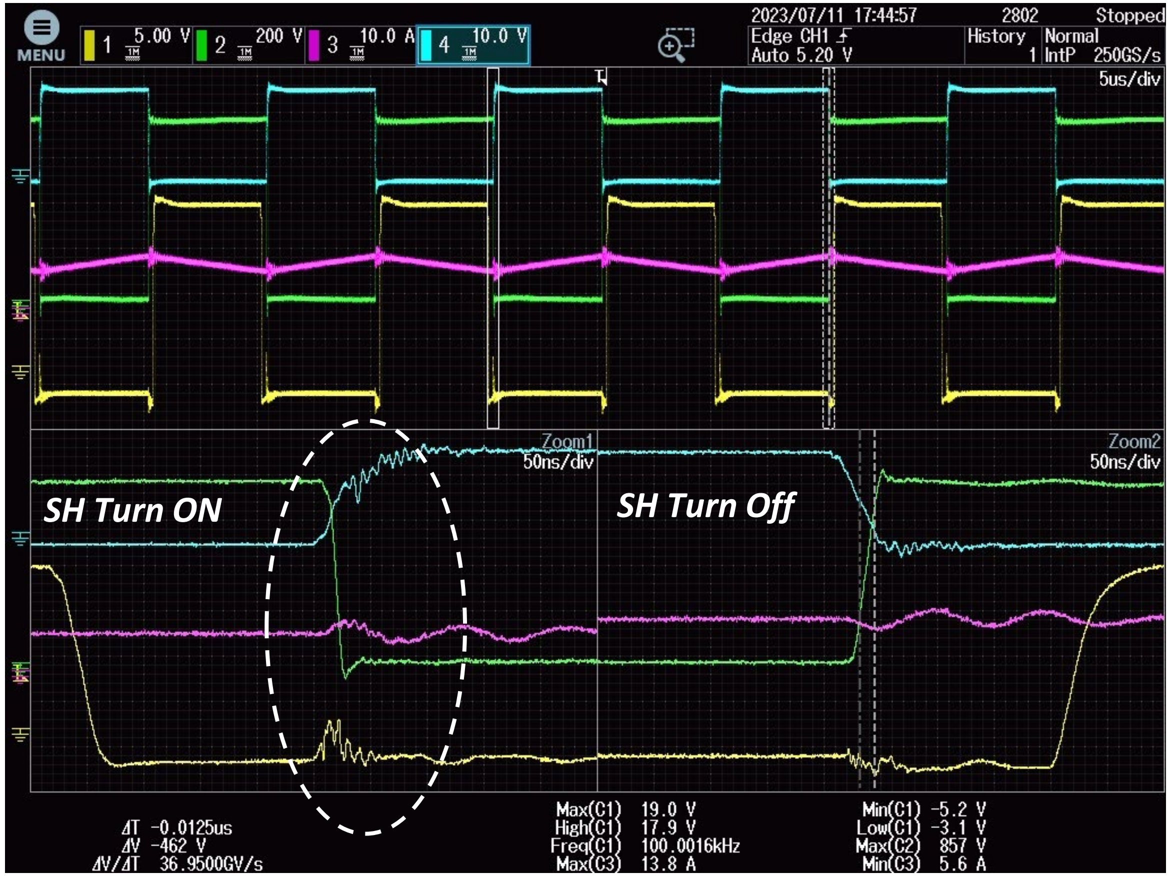
Turn-on Crosstalk and Suppression Methods

- High side device turn-on





Ch1:Vgs_SL, Ch2:Vds_SH, Ch3: IL_O, Ch4: Vgs_SH

- Reduce drive loop inductance
- The value of Ron increase and Roff decrease
- Add clamp switch or ZD diode
- Add absorption Cap. @G-SK
- Use negative voltage power supply

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Turn-off Crosstalk and Suppression Methods

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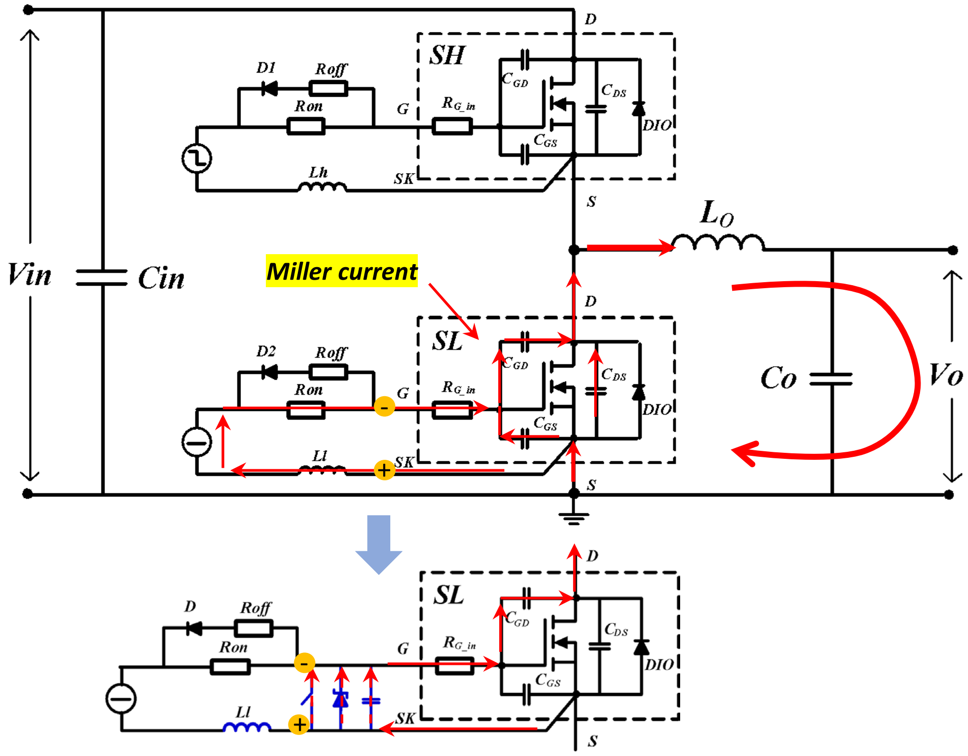
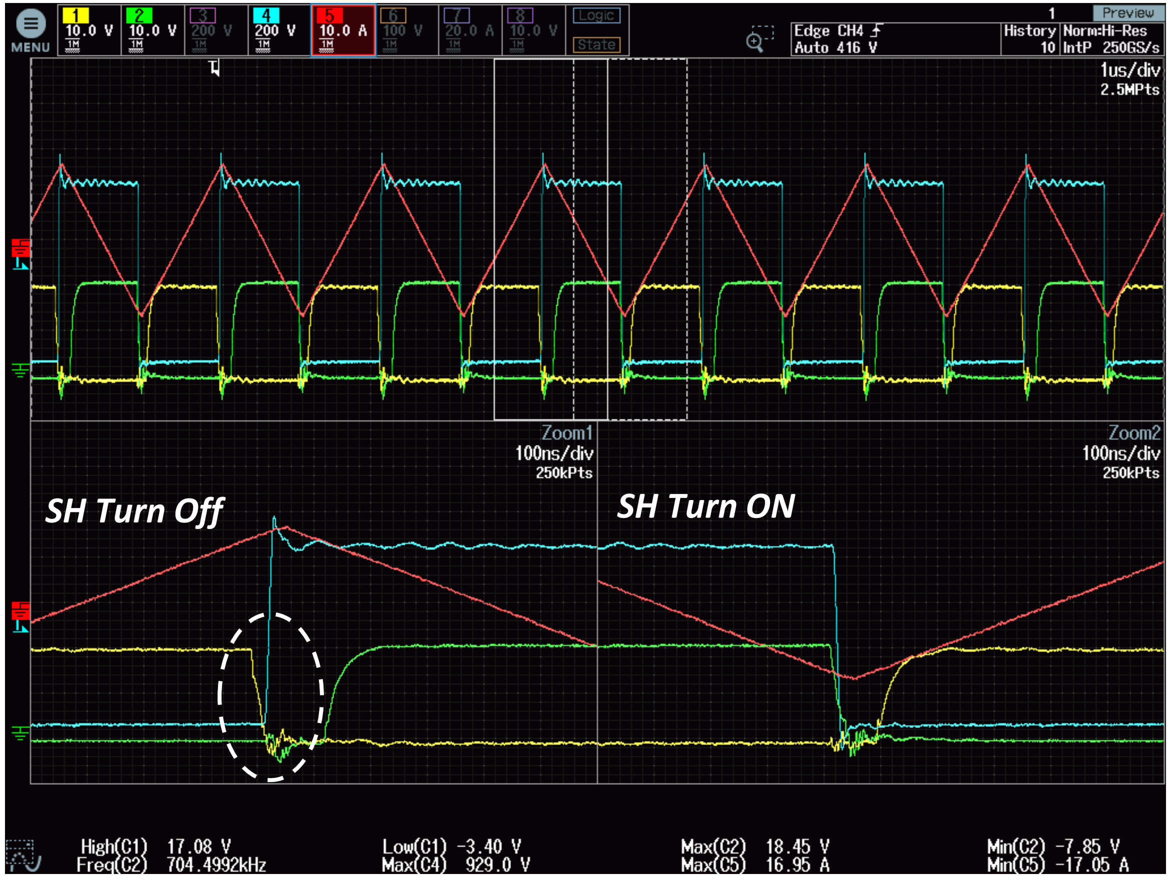
- High side device turn-off



- Reduce drive loop inductance
- The value of Ron increase and Roff decrease
- Add clamp switch
- Add clamp diode
- Add absorption Cap. @G-SK



*Ch1:*Vgs_SH, *Ch2:*Vds_SL, *Ch4:* Vgs_SH, *Ch5:*IL_O

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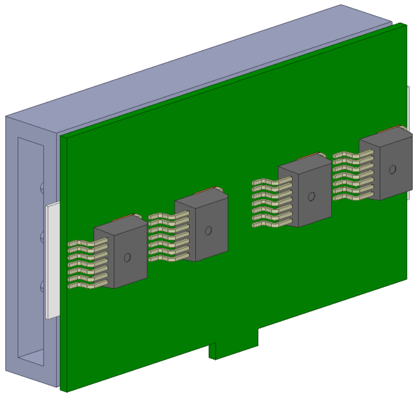
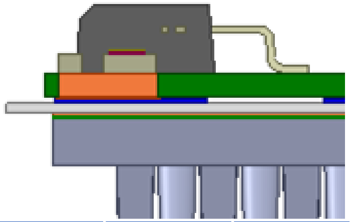
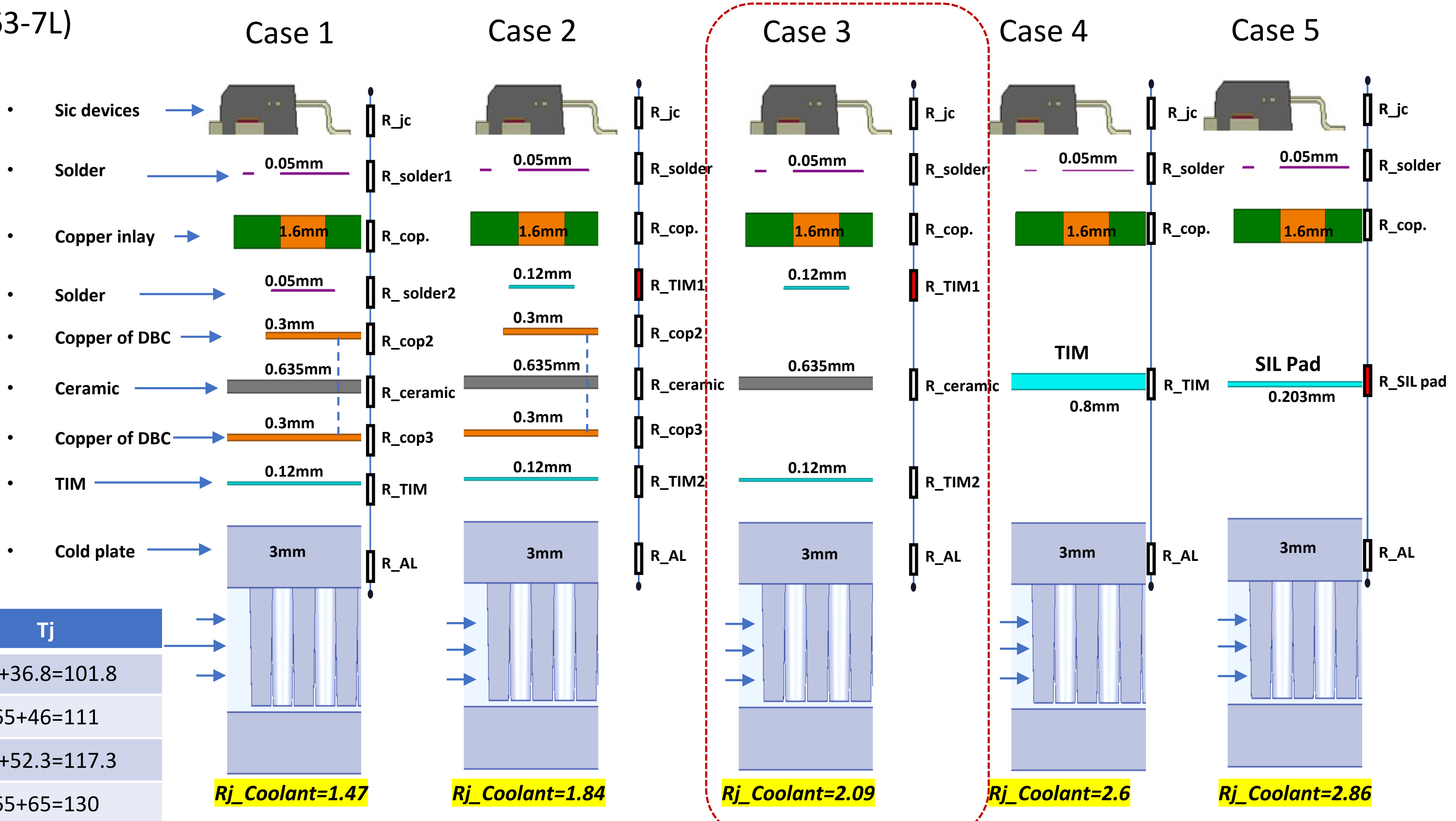
Thermal Solution

- Simulation Mode (To263-7L)







	Ploss	ΔT	Tj
Case1	25W	36.8	65+36.8=101.8
Case2	25W	46	65+46=111
Case3	25W	52.3	65+52.3=117.3
Case4	25W	65	65+65=130
Case5	25W	71.5	65+71.5=136.5

- Thermal design is important for SiC devices application.

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Buck circuit Design

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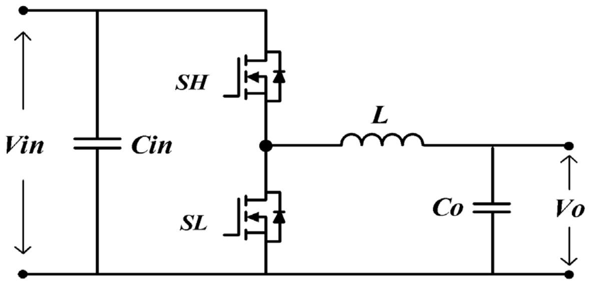
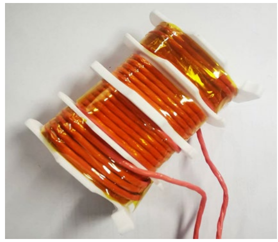
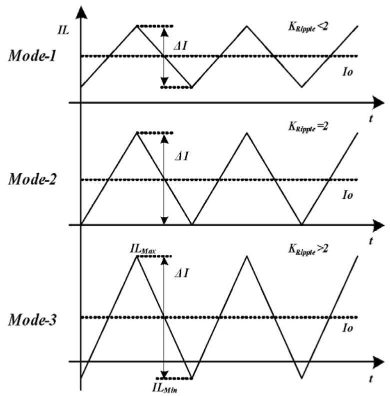
- Vin=800V
- Vo=400V
- Po=3.6kW







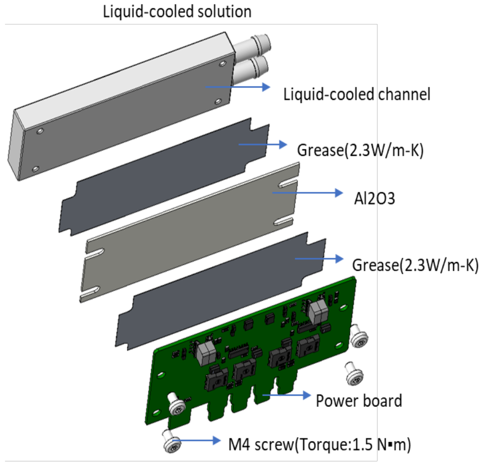
- Current ripple coefficient：

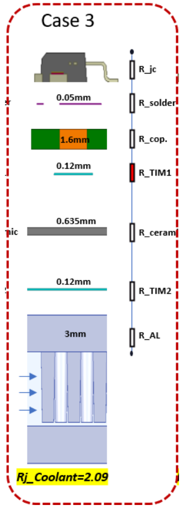
$$K_{ripple} = \frac{\Delta T}{I_o}$$

- CCM Mode：

$$L_{CCM} = \frac{(V_{in} - V_o)\ \Delta T}{K_{ripple} * I_o}$$

K_{RIPPLE}	f_{SW}	Inductor
<2(0.45)	100kHz	500uH
>2 (2.6)	300kHz	29uH
>2 (2.6)	600kHz	14uH
>2 (2.6)	800kHz	10uH





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Simulation and Loss Breakdown

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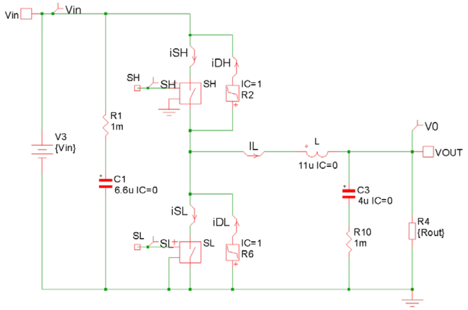
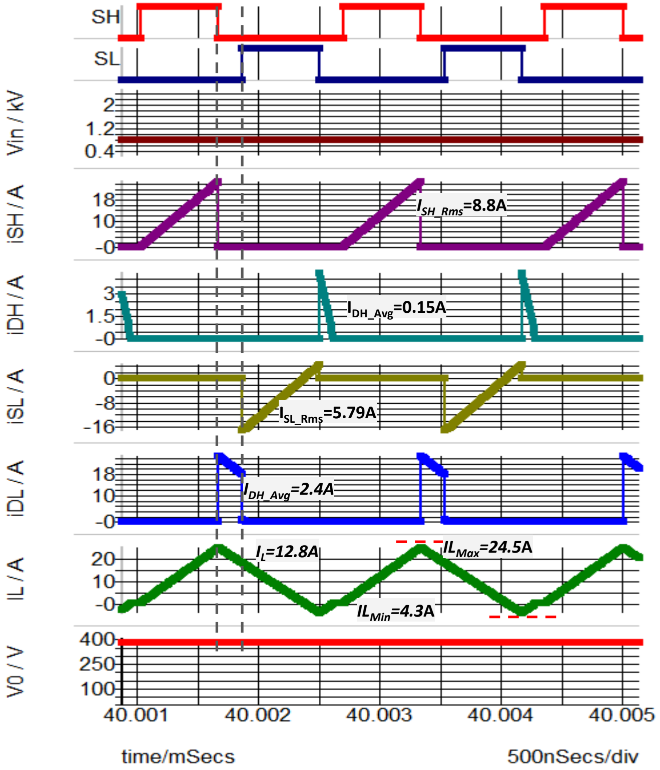
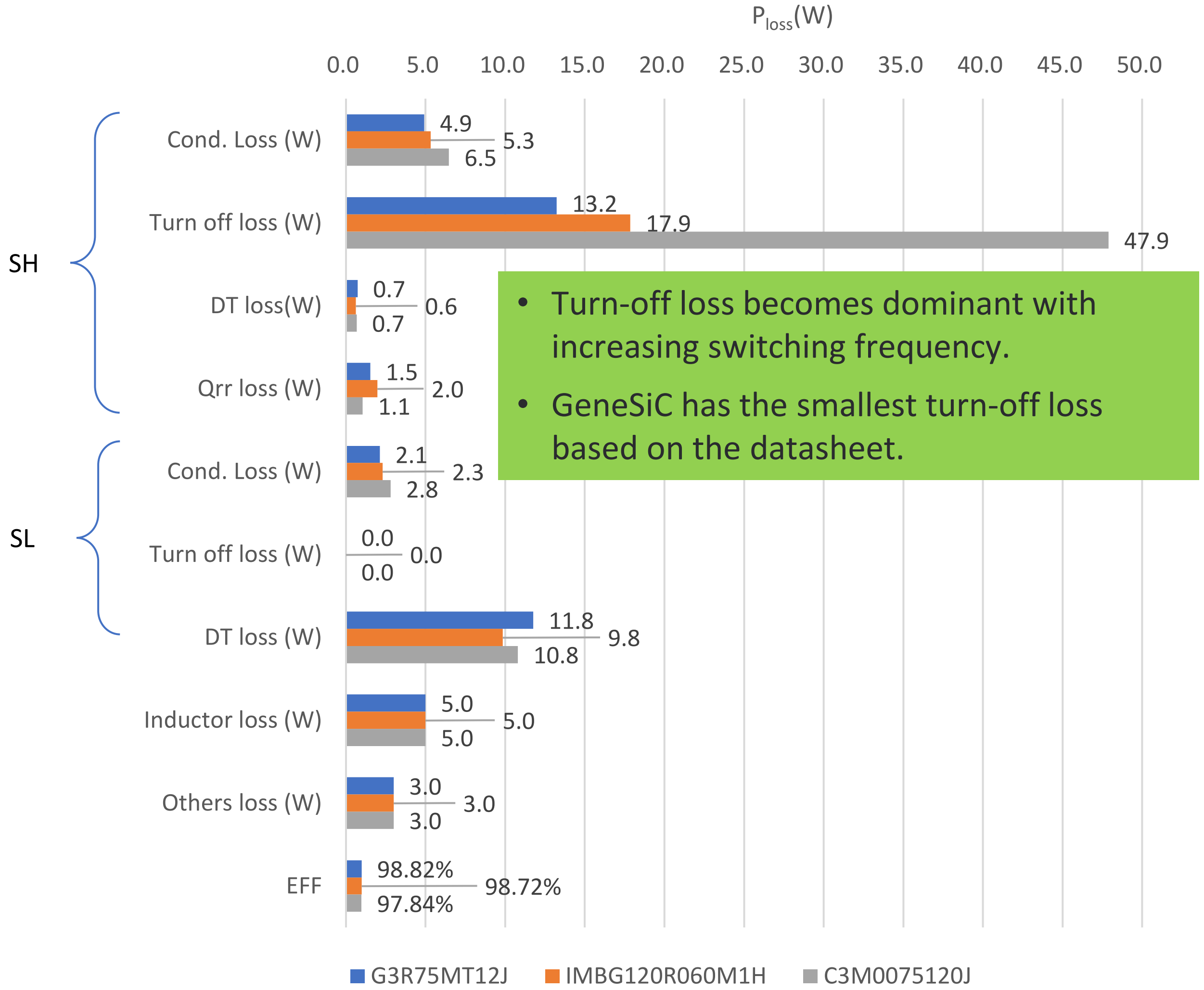
- Vin=800V
- Vo=380v
- Po=3.6kW
- L=11uH
- Dead time=120ns







- Turn-off loss becomes dominant with increasing switching frequency.
- GeneSiC has the smallest turn-off loss based on the datasheet.

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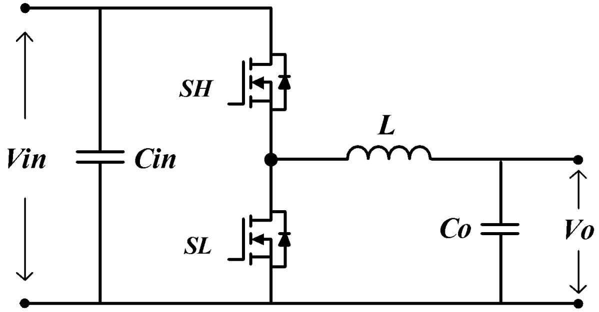
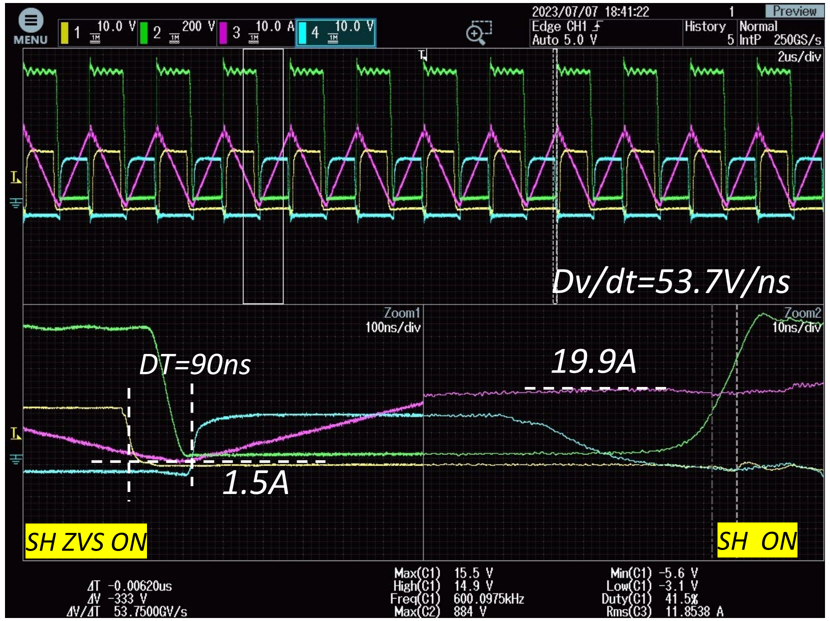
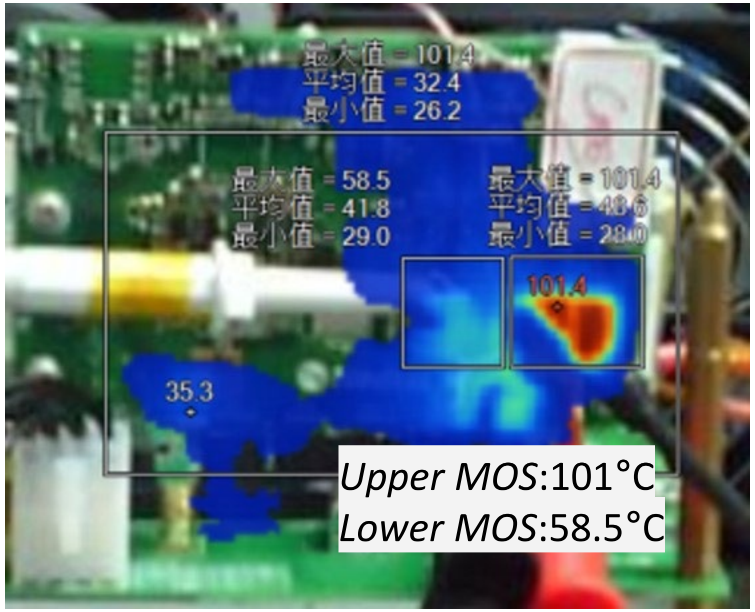
ZVS CCM Waveforms @600kHz CREE

- C3M0075120J-CREE *L*=11.35μH

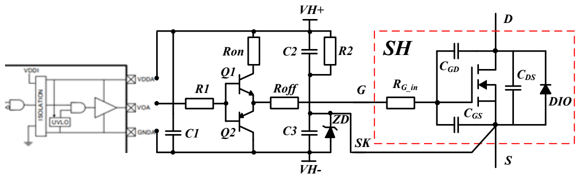




CH1:Vgs_SL, CH2:Vds_SH, Ch3: IL, Ch4:Vgs_SH



- Ron=2Ω, Roff=1 Ω



- ***Ion=1.5A***
- ***Ioff=19.9A***
- ***Off dv/dt=53.7V/ns***

	Iin	Pin	Vout	Iout	Pout	Eff
399.76	2.3321	932.2803	191.39	4.7806	914.959	0.981421
499.71	2.9375	1467.898	240.08	5.9972	1439.808	0.980864
599.6	3.5446	2125.342	288.69	7.21	2081.455	0.97935
699.5	4.1749	2920.343	338.02	8.441	2853.227	0.977018

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ZVS CCM Waveforms @600kHz Infineon

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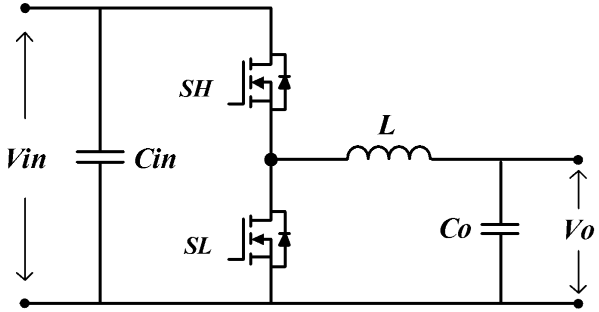
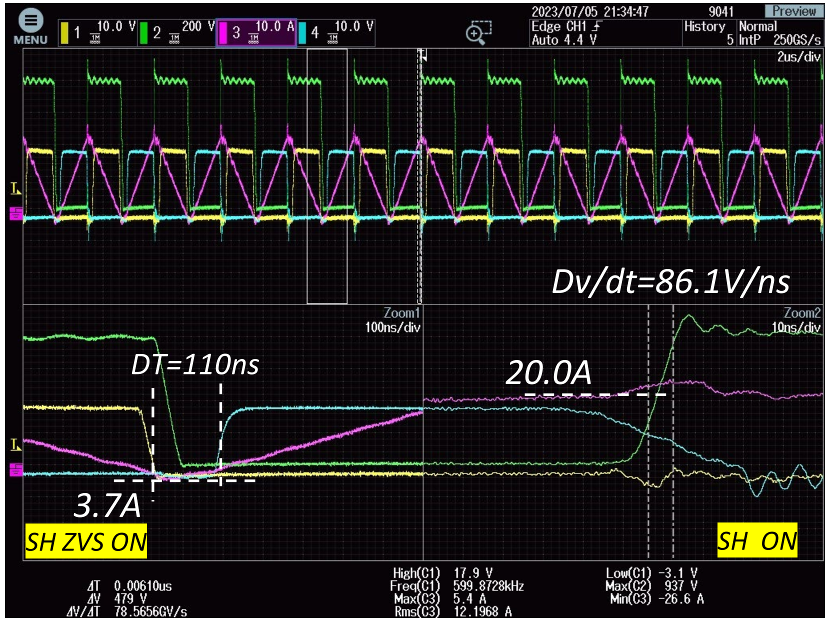
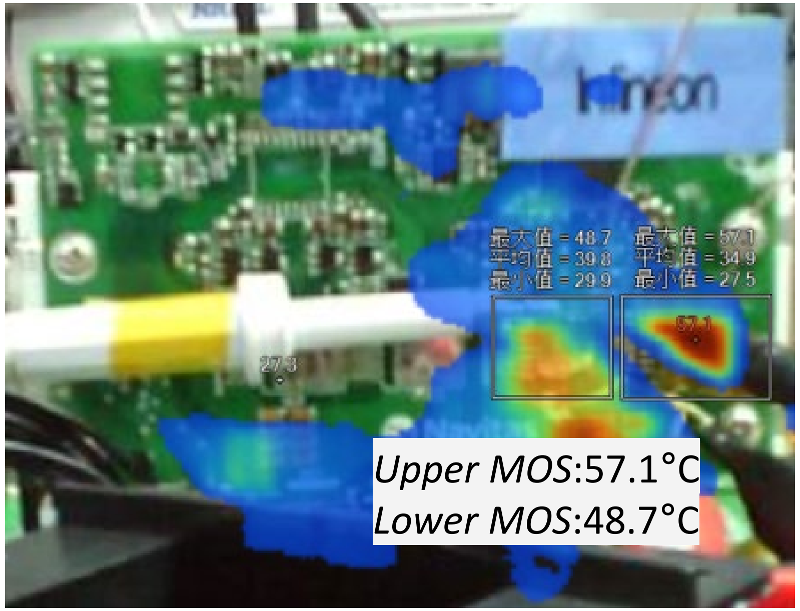
- IMBG120R060M1H-Infineon *L*=11.35µH

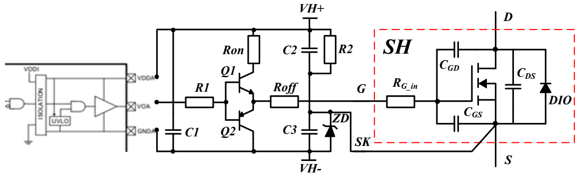






CH1:Vgs_SL, CH2:Vds_SH, Ch3: IL, Ch4:Vgs_SH

- Ron=3Ω, Roff=1 Ω



- ***Ion=3.7A***
- ***Ioff=20.0A***
- ***Off dv/dt=86.1V/ns***

Vin	Iin	Pin	Vout	Iout	Pout	Eff
399.77	2.3062	921.9496	190.55	4.763	907.5897	0.984424
499.71	2.9087	1453.506	239.12	5.9791	1429.722	0.983637
599.6	3.5072	2102.917	287.8	7.192	2069.858	0.984279
699.5	4.1225	2883.689	336.89	8.425	2838.298	0.98426
799.4	4.7364	3786.278	386.1	9.661	3730.112	0.985166

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ZVS CCM Waveforms @600kHz GeneSiC

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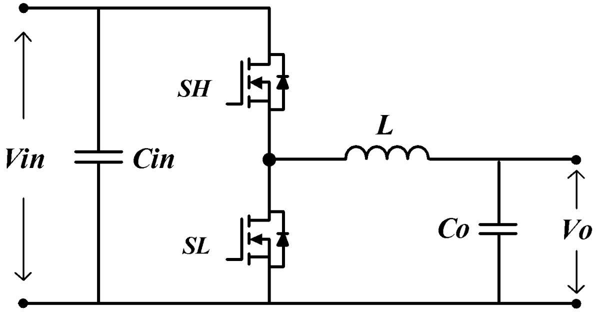
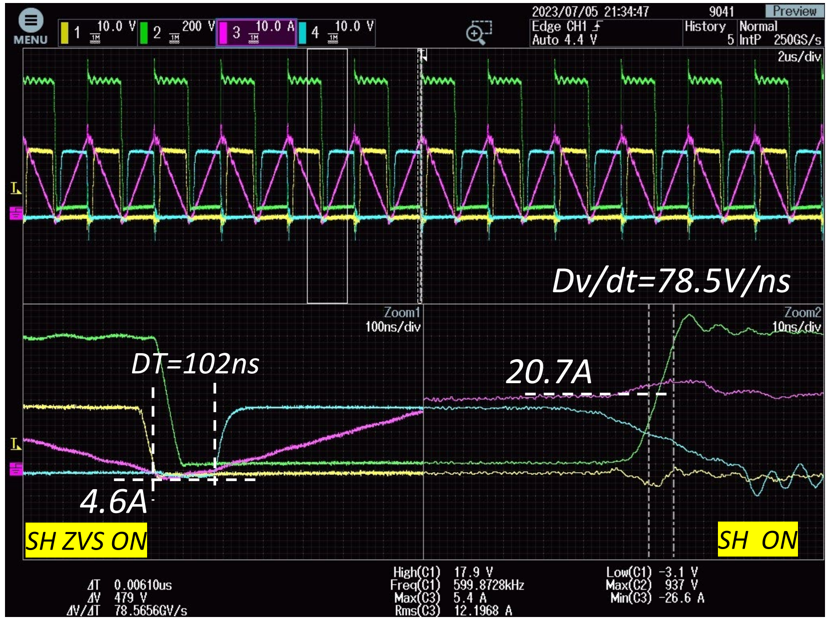
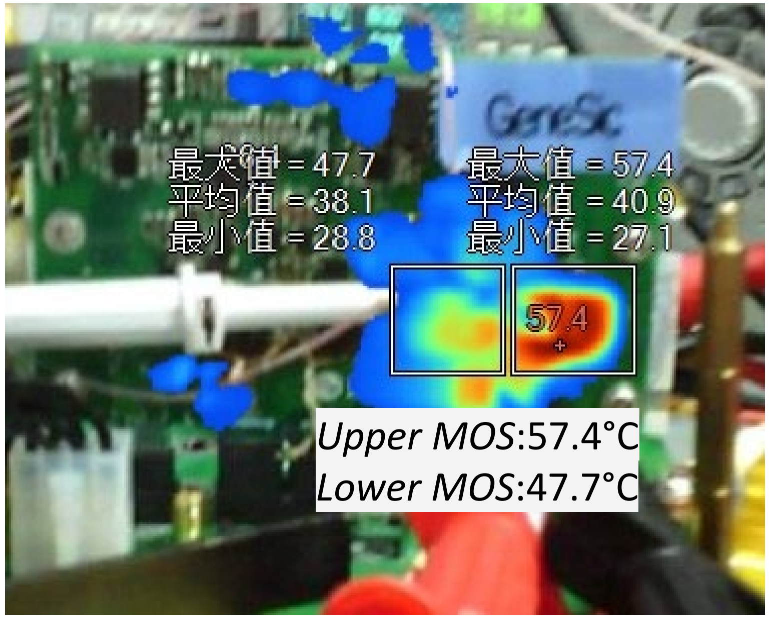
- G3R75MT2J-GeneSiC L=11.35μH

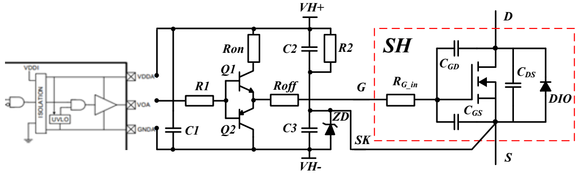




CH1:Vgs_SL, CH2:Vds_SH, Ch3: IL, Ch4:Vgs_SH



- Ron=6.9Ω, Roff=2.2 Ω



- ***I_{on}=4.6A***
- ***I_{off}=20.7A***
- ***Off dv/dt=78.5V/ns***

Vin	*Iin*	*Pin*	*Vout*	*Iout*	*Pout*	*Eff*
399.79	2.2761	909.962	189.36	4.7295	895.5781	0.984193
499.74	2.8691	1433.804	237.75	5.94	1412.235	0.984957
599.6	3.4541	2071.078	285.81	7.142	2041.255	0.9856
699.5	4.0499	2832.905	334.27	8.355	2792.826	0.985852
799.4	4.643	3711.614	382.57	9.565	3659.282	0.9859

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Test Results Analysis of ZVS CCM Buck

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300 kHz	G3R75MT2J-GeneSiC	IMBG120R060M1H-Infineon	C3M0075120J-CREE
I_{ON} (A)	5.7	6.0	5.3
I_{OFF} (A)	24.1	24.4	24.1
Turn-Off dV/dt (V/ns)	83.1	95.0	62.6
Efficiency	98.64%	98.70%	98.17%
Temperature (°C) (Up/Down Devices)	38.9/40.5	43.2/40.6	69.4/51.2

600 kHz	G3R75MT2J-GeneSiC	IMBG120R060M1H-Infineon	C3M0075120J-CREE
I_{ON} (A)	4.6A	3.7A	1.5A
I_{OFF} (A)	20.7A	20.0A	19.9A
Turn-Off dV/dt (V/ns)	78.56	86.09V	53.75
Efficiency	98.59%	98.39%	97.7%
Temperature (°C) (Up/Down Devices)	57.4/47.7	57.1/48.7	101.4/58.5

800 kHz	G3R75MT2J-GeneSiC	IMBG120R060M1H-Infineon	C3M0075120J-CREE
I_{ON} (A)	2.6A	3.7A	/
I_{OFF} (A)	20.9A	20.0A	/
Turn-Off dV/dt (V/ns)	77.80	86.094	/
Efficiency	98.42%	98.29%	/
Temperature (°C) (Up/Down Devices)	45.1/47.1	48.8/49.3	/

- High dv/dt means fast switching speed， small turn-off loss and high efficiency.
- Infineon's SiC has the fastest turn-off speed, followed by Genesic, but due to Genesic's flat groove & Trench-assisted planar gate technology, Rjc is small,$R_{DS(ON)}$ is low and efficiency is the highest.
- Cree has the slowest turn-off speed, the largest turn-off loss and the worst efficiency at high frequency.

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Hard Switching CCM Buck converter

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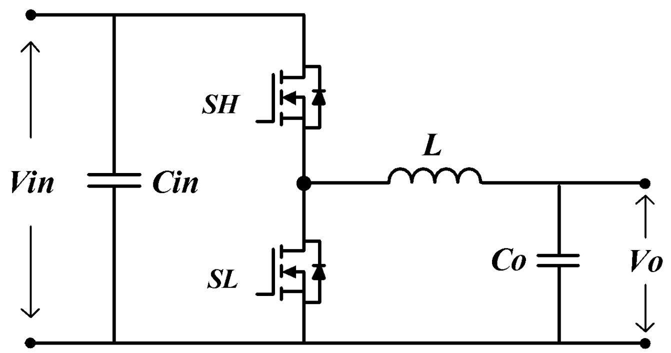
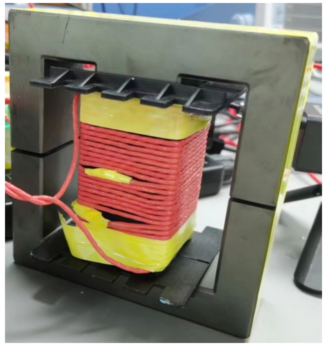
- Vin=800V
- Vo=400V
- Po=3.6kW





ferrite with air gap
L=553.47uH

Cin
MKP1848520924K2 2uF

Cout
B32672P6105 1uF

Item	Parameters
HS&LS SiC	G3R75MT2J-GeneSiC/IMBG120R060M1H-Infineon /C3M0075120J-CREE
Rated Operating Condition	800Vin-400Vout 4kW Pout
Switching Frequency	150kHz&200kHz
Inductor	ferrite with air gap 553.47
C_{in}	MKP1848520924K2 2uF*3
C_{out}	B32672P6105 1uF*4
Cooling method	Water coolant

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CCM Buck Waveforms @200kHz GREE

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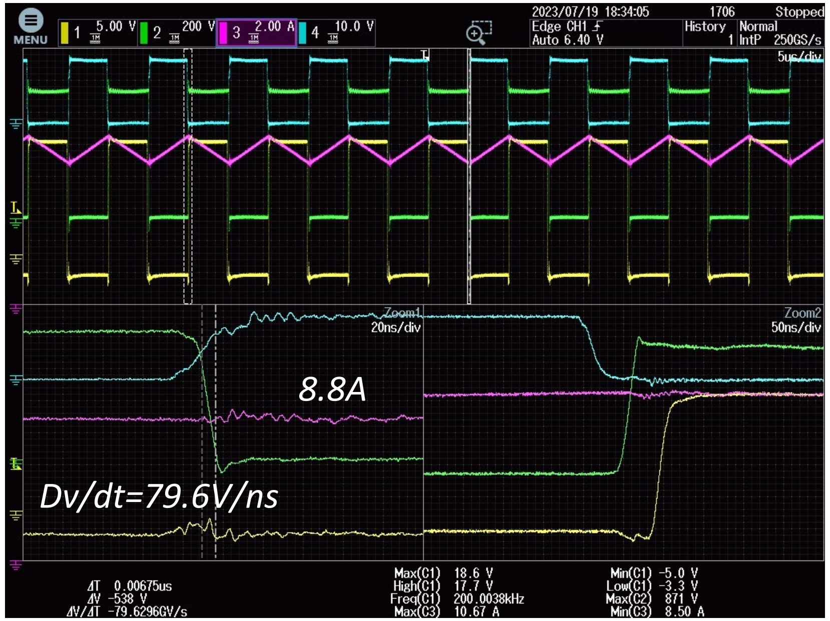
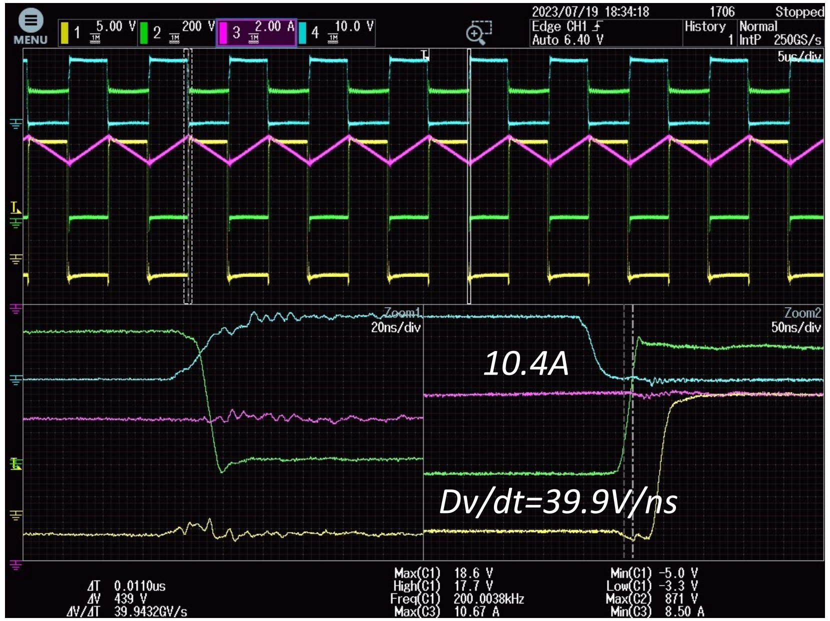
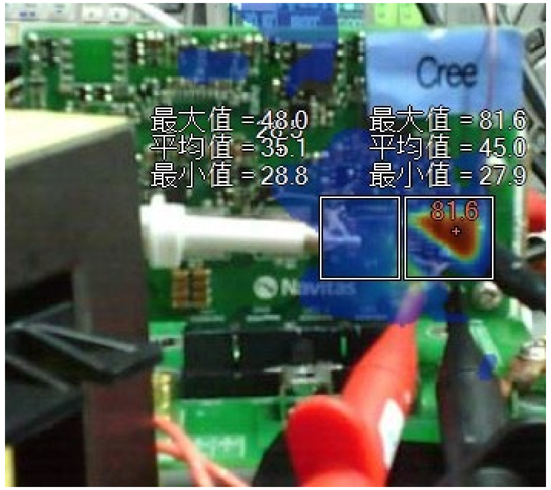
- **C3M0075120J-CREE Ron=2Ω, Roff=1Ω**







Upper MOS:81.6°C
Lower MOS:48.0°C

CH1:Vgs_SL, CH2:Vds_SH, Ch3: IL, Ch4:Vgs_SH

- **I_{on}=8.84A**
- **I_{off}=10.40A**
- **Turn On dv/dt=79.6V/ns**
- **Turn Off dv/dt=39.9V/ns**

Vin	*Iin*	*Pin*	*Vout*	*Iout*	*Pout*	*Eff*
399.78	2.4036	960.9112	194.53	4.8598	945.3769	0.983834
499.73	3.0005	1499.44	243.05	6.0711	1475.581	0.984088
599.6	3.5986	2157.721	291.63	7.283	2123.941	0.984345
699.5	4.1997	2937.69	340.27	8.498	2891.614	0.984316
799.4	4.8042	3840.477	389.03	9.715	3779.426	0.984103

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CCM Buck Waveforms @200kHz Infineon

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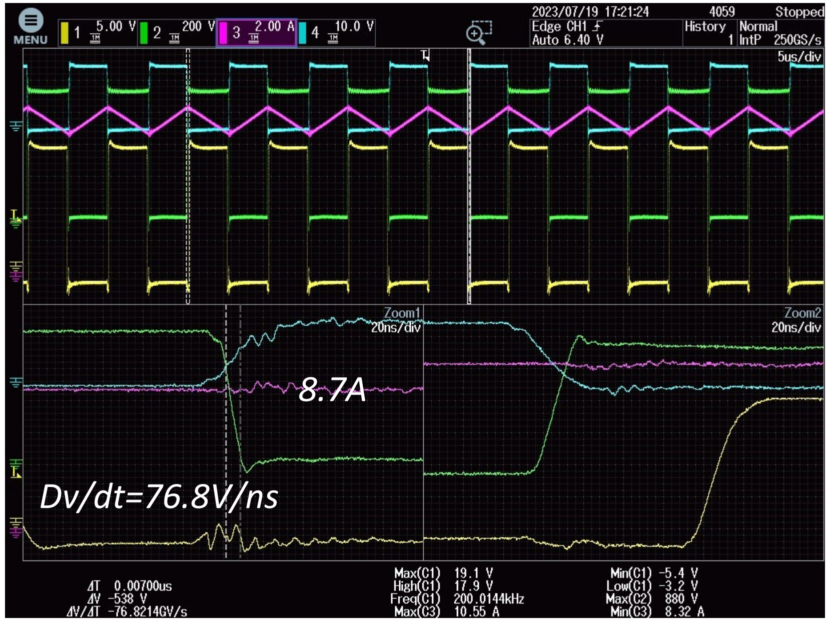
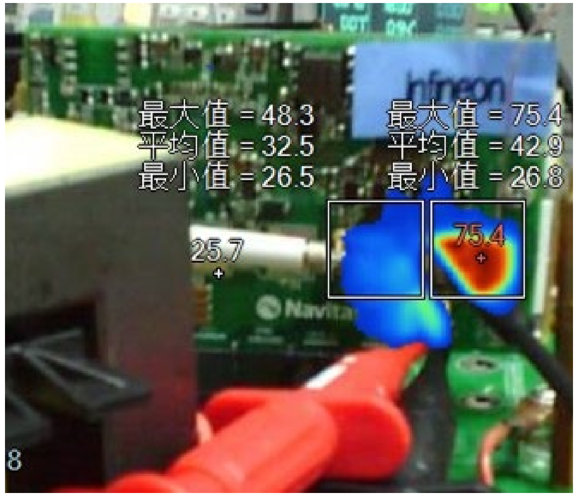
- **IMBG120R060M1H-Infineon Ron=3Ω, Roff=1Ω**





Upper MOS:75.4°C
Lower MOS:48.3°C

CH1:Vgs_SL, CH2:Vds_SH, Ch3: IL, Ch4:Vgs_SH

- **I_{on}=8.7A**
- **I_{off}=10.3A**
- **Turn On dv/dt=76.8V/ns**
- **Turn Off dv/dt=43.3V/ns**

Vin	Iin	Pin	Vout	Iout	Pout	Eff
399.79	2.3344	933.2698	191.72	4.7891	918.1663	0.983817
599.6	3.4947	2095.422	287.42	7.179	2063.388	0.984712
699.5	4.0746	2850.183	335.25	8.373	2807.048	0.984866
799.4	4.6546	3720.887	383.06	9.567	3664.735	0.984909

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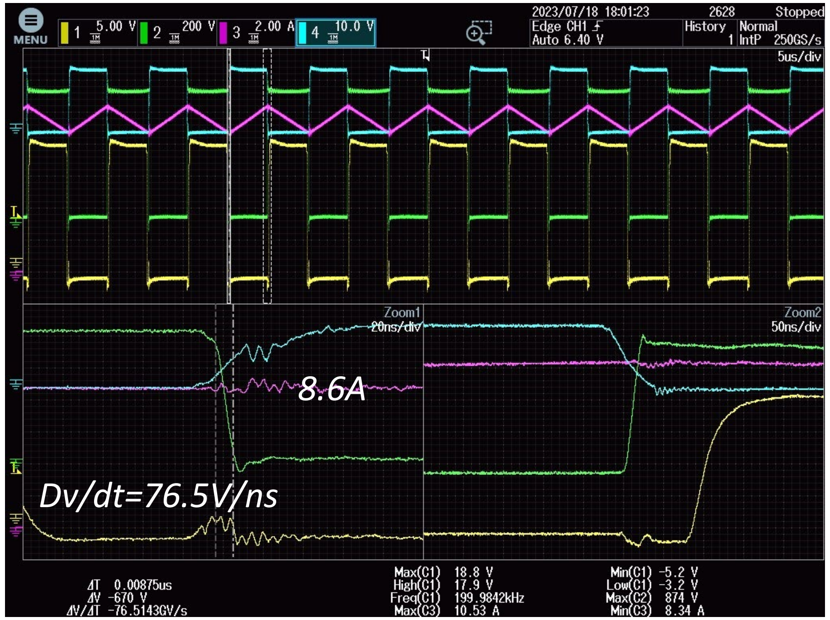
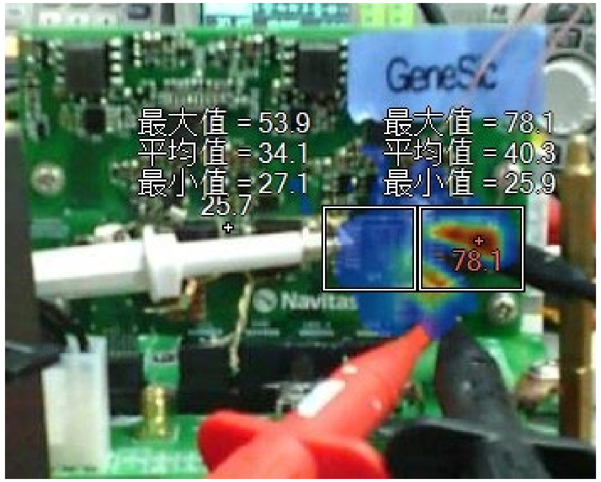
CCM Buck Waveforms @200kHz GeneSiC

- **G3R75MT2J-GeneSiC R_{on}=6.9Ω, R_{off}=2.2Ω**





Upper MOS:78.1°C
Lower MOS:53.9°C

CH1:Vgs_SL, CH2:Vds_SH, Ch3: IL, Ch4:Vgs_SH

- **I_{on}=8.6A**
- **I_{off}=10.2A**
- **Turn On dv/dt=76.5V/ns**
- **Turn Off dv/dt=43.8V/ns**

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	Eff (%)
399.8	2.3	932	191.6	4.8	917	98.39
499.7	2.9	1,454	239.4	6.0	1,432	98.44
599.6	3.5	2,093	287.3	7.2	2,061	98.45
699.5	4.1	2,848	335.2	8.4	2,805	98.49
799.4	4.7	3,721	383.0	9.6	3,663	98.44

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Test Results Analysis of Hard Switching Buck

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150kHz	G3R75MT2J-GeneSiC	IMBG120R060M1H-Infineon	C3M0075120J-CREE
Ion (A)	8.46A	8.4A	8.56A
Ioff (A)	10.58A	10.5A	10.8A
Turn on dv/dt （V/ns）	78.3	75.8	76.6
Turn off dv/dt （V/ns）	46.4	45.5	42.4
Efficiency	98.75%	98.76%	98.72%
Temperature (Up/Down Devices °C)	67.2/47.6	63.2/41.1	67.6/44.3

200kHz	G3R75MT2J-GeneSiC	IMBG120R060M1H-Infineon	C3M0075120J-CREE
Ion (A)	8.64A	8.7A	8.84A
Ioff (A)	10.24A	10.3A	10.4A
Turn on dv/dt （V/ns）	76.5	75.8	79.6
Turn off dv/dt （V/ns）	43.8	43.3	39.9
Efficiency	98.44%	98.38%	98.41%
Temperature (Up/Down Devices °C)	78.1/53.9	75.4/48.3	81.6/48.0

- GeneSiC ,Infineon and Cree have similar turn-on and turn-off speeds at same setup, so similar efficiency and thermal conditions.
- At present, due to the small turn-on current, the difference in turn-on loss is not large.

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Contents

Navitas

- Background
- Challenges of SiC Devices for High Frequency Application
- Comparative Analysis Based on Buck Circuit
- GaN+SiC Based 500kHz 6.6kW Bi-DC/DC Development
- Summary

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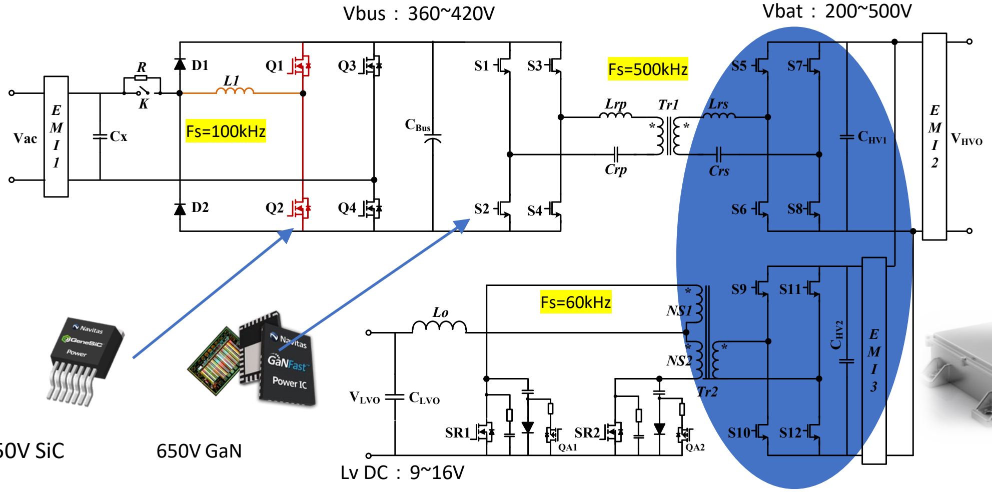
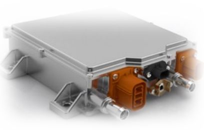
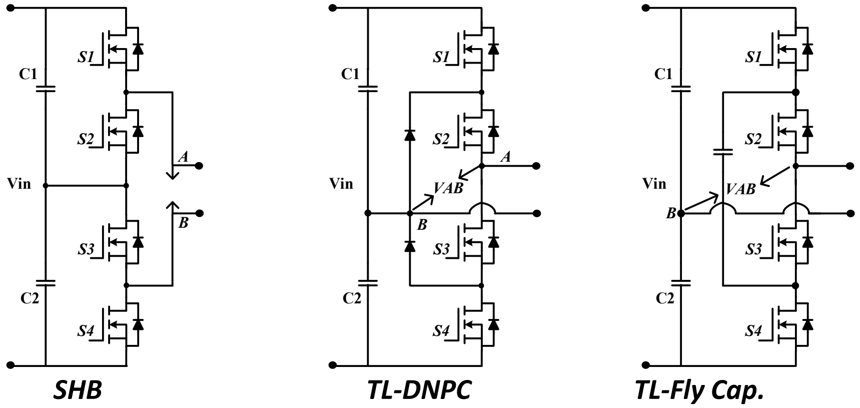
GaN + SiC Solution for OBC

- GaN+SiC Solution for 400Vbat system

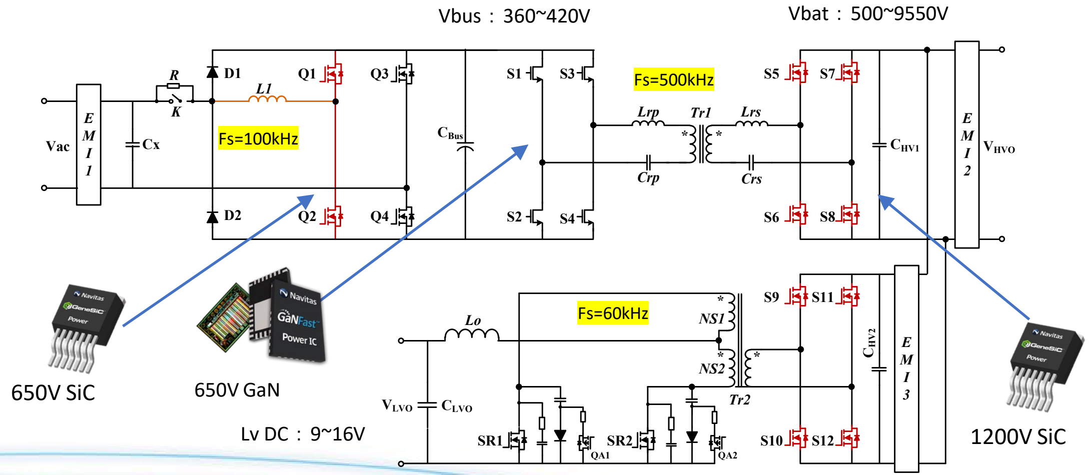




- GaN based TL solution for 800Vbat system



- GaN+SiC Solution for 800Vbat System



- GaN+SiC 400V solution, NVTS has been designed, power density up to 3.9kw/L.
- The 800V solution based on GaN is complex in control and its reliability needs to be tested.
- GaN+SiC 800V solution, simple and reliable, the device's own characteristics have special requirements for 500khz application.

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Experimental platform 500 kHz Bi-DC/DC

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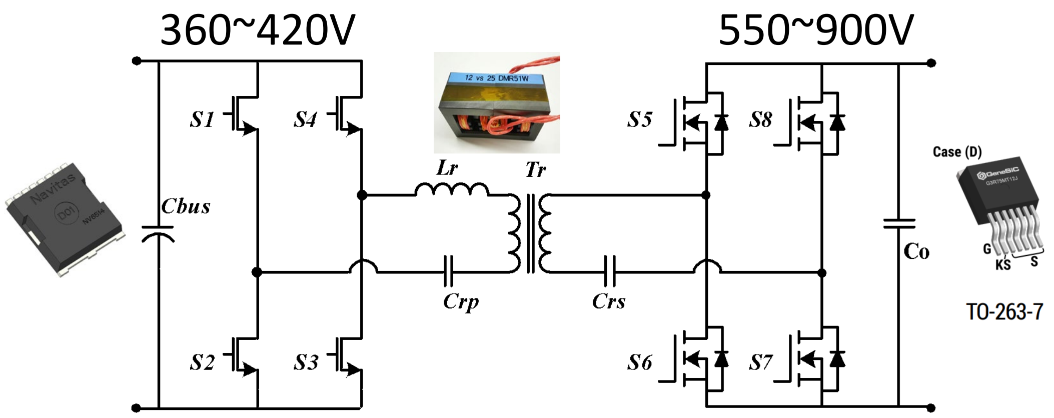
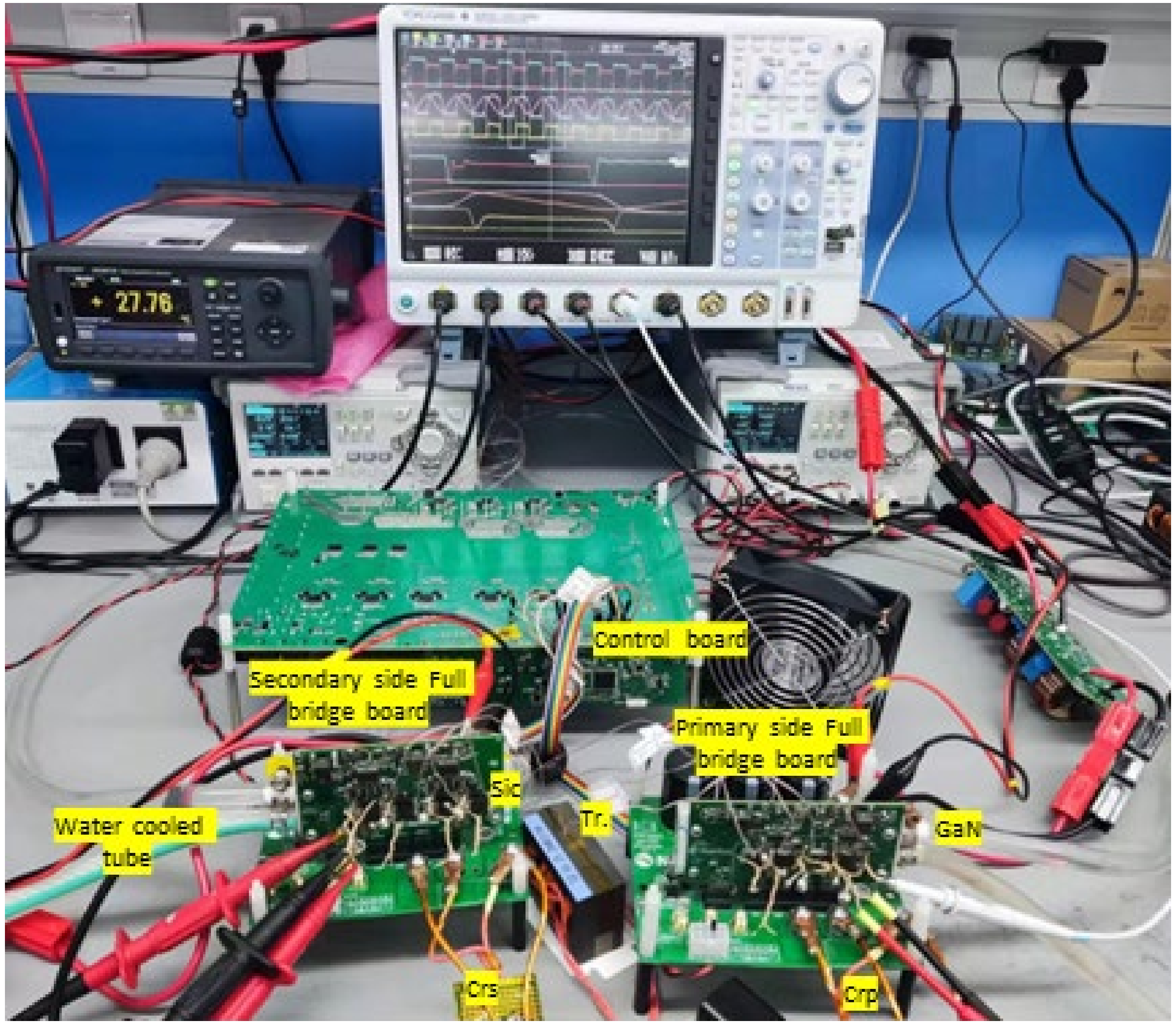


NV6514 (650V)

G3R75MT12J (1200V)

	Parameters
Lr	6uH
Cr	50nF
f_{SW}	290 kHz
Turns ratio	12 : 25 (S9-P6-S7-P6-S9)
Magnetic	DMR51W



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6.6kW Bi-DC/DC Charging Mode

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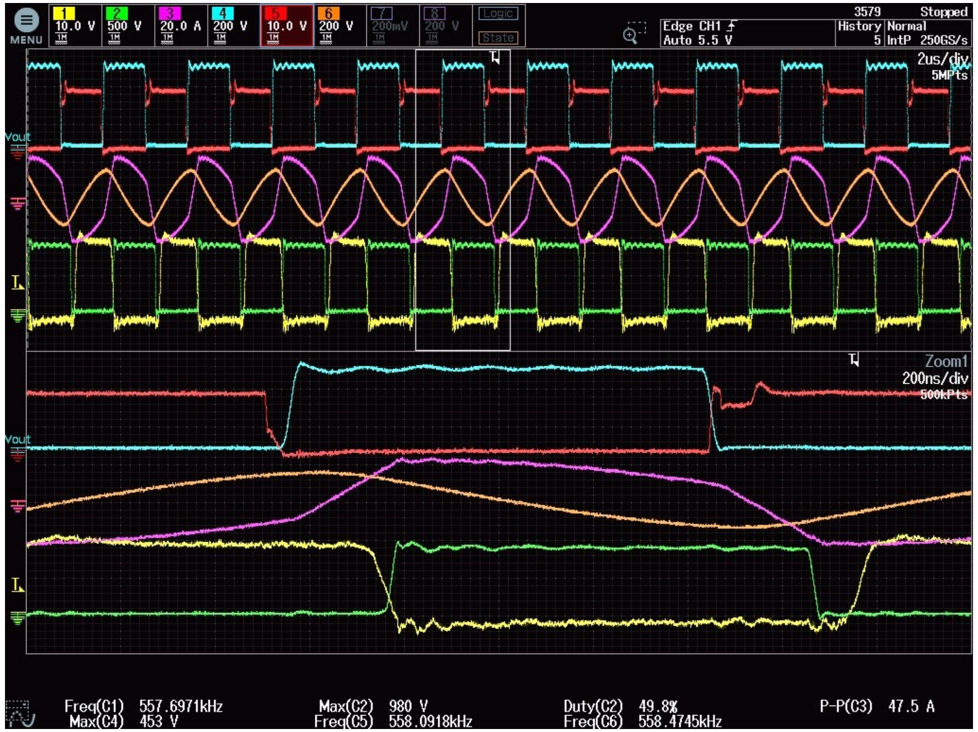
- V_{Bus}=360V; V_{Bat}=550V; P_o=6.6kW; D_{ps}=0.085

CH1:Vgs,S7 CH2:Vds,S7 CH3:ILrp CH4:Vds,S2 CH5:Vgs,S2 CH6:VCrp

f_{sw}=394kHz; I_{off_GaN}=20.5A; I_{off_SiC}=6.9A

- V_{Bus}=420V; V_{Bat}=890V; P_o=6.6kW; D_{ps}=0.105



CH1:Vgs,S7 CH2:Vds,S7 CH3:ILrp CH4:Vds,S2 CH5:Vgs,S2 CH6:VCrp

f_{sw}=561kHz; I_{off_GaN} =8.7A; I_{off_SiC} =12.7A

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6.6kW Bi-DC/DC Discharging Mode

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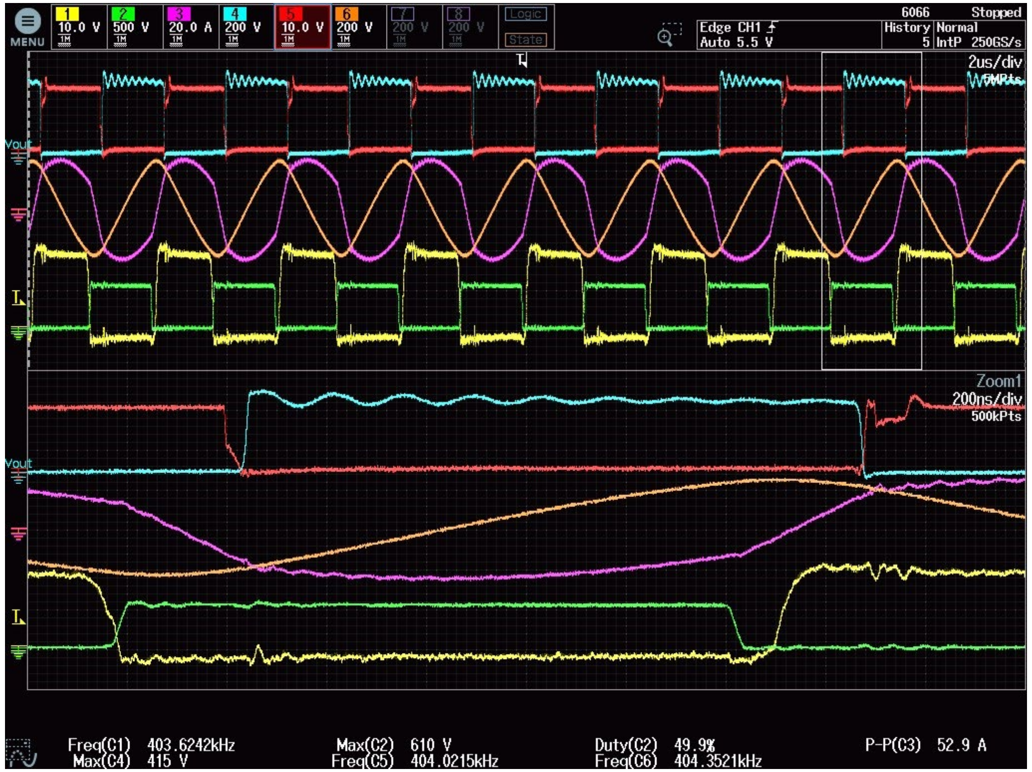
- V_{Bus}=360V; V_{Bat}=550V; P_o=6kW



CH1:Vgs,S7 CH2:Vds,S7 CH3:ILrp CH4:Vds,S2 CH5:Vgs,S2 CH6:VCrp

f_{sw}=405kHz; I_{off_GaN}=17.4A; I_{off_SiC}=7.5A

- V_{Bus}=420V; V_{Bat}=905V; P_o=6kW

CH1:Vgs,S7 CH2:Vds,S7 CH3:ILrp CH4:Vds,S2 CH5:Vgs,S2 CH6:VCrp

f_{sw}=568kHz; I_{off_GaN} =3.5A; I_{off_SiC} =12.0A;

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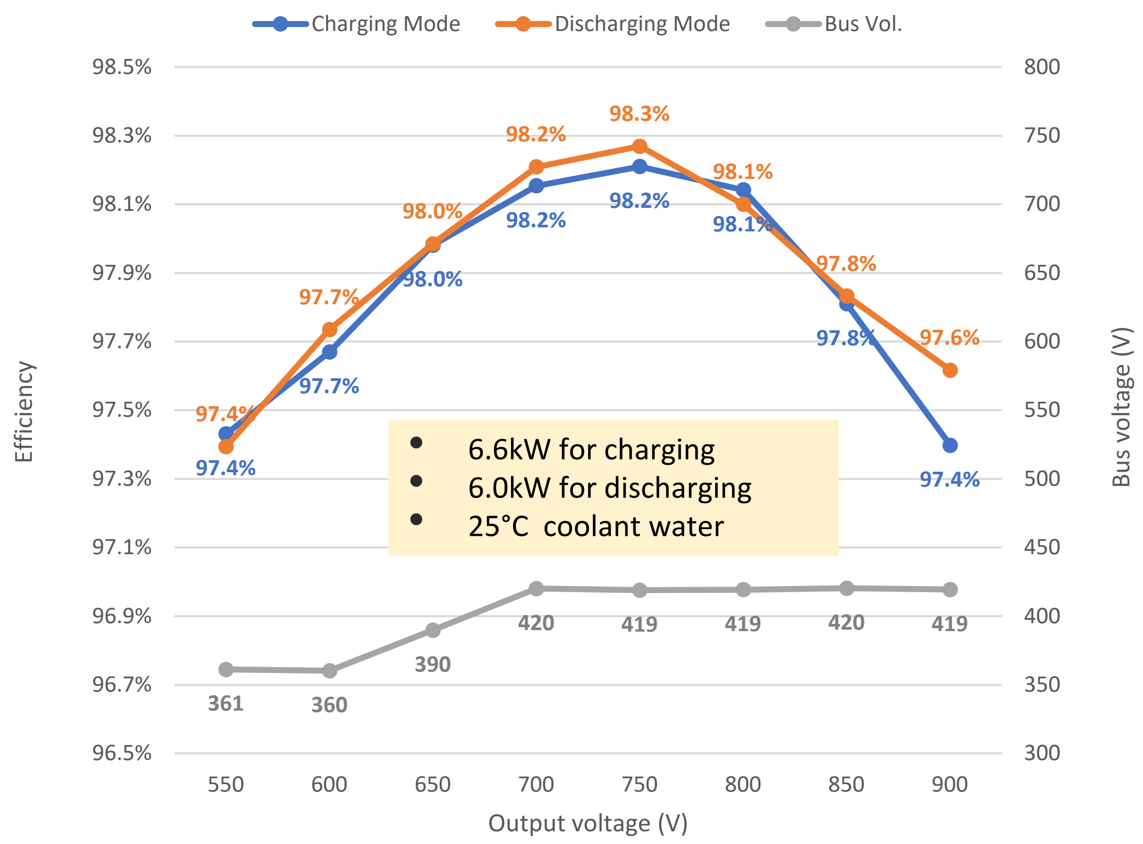
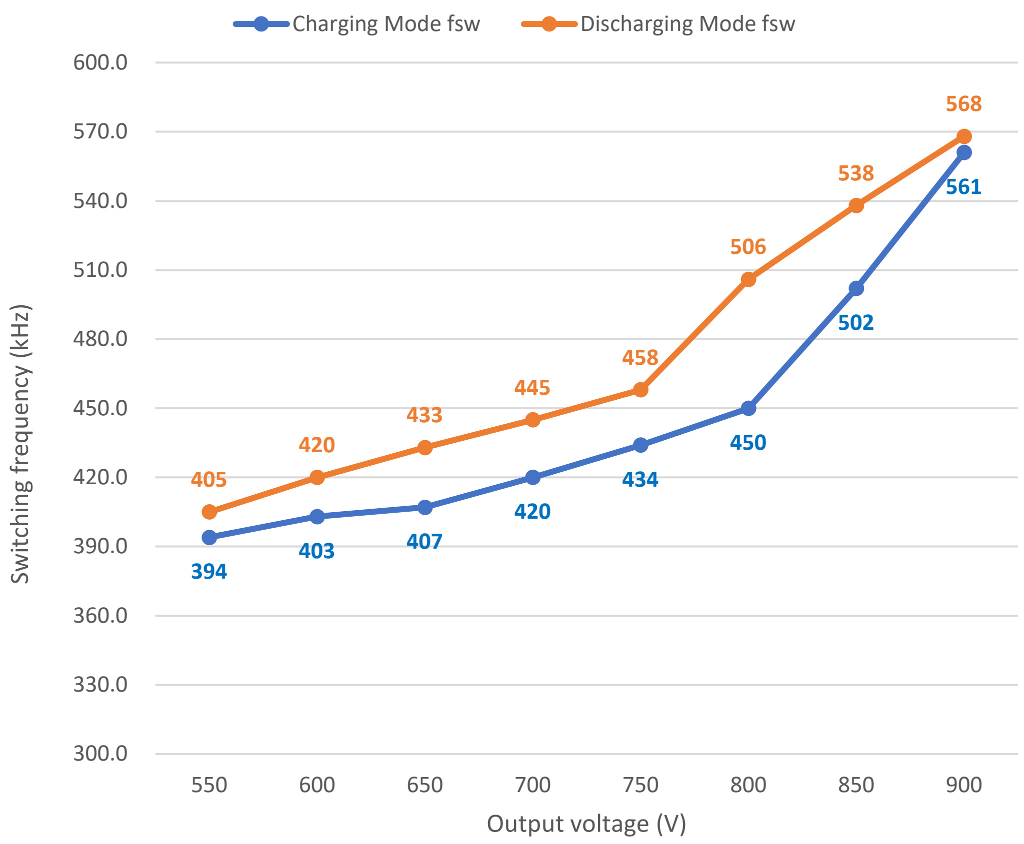
6.6kW Bi-DC/DC Test Efficiency





- Peak Efficiency is 98.3% @charging mode.
- Output voltage 550V to 900V supports full load operation.

- Switching frequency range is from 400kHz to 570kHz.

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Summary

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- Since the gate capacitance of SiC is still relatively large, the drive capacity of the chip should be considered for applications above 500khz.
- The design of DBC insulation heat dissipation is an effective heat treatment method for SiC devices.
- Comparative test results show that low switching loss and low system thermal resistance should be considered, which is helpful for high frequencies design.
- Bi-DC/DC based on NVTS GaN and SiC for 500 kHz 6.6 kW 800V applications was evaluated. the results show that GeneSiC SiC delivers high efficiency and high power in high frequency (up to 600kHz), Thus for 800V charging applications, to provide customers with a simple and effective solution.

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