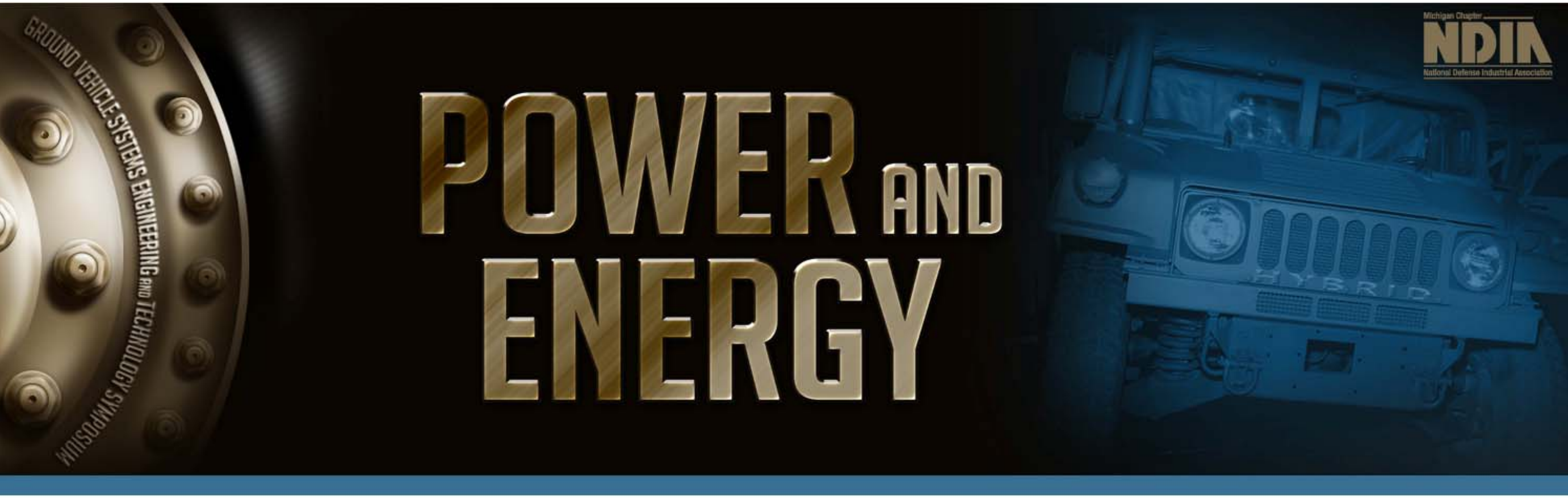

SILICON CARBIDE FOR NEXT GENERATION VEHICULAR POWER CONVERTERS

John Kajs – SAIC

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Why SiC?

POWER AND ENERGY

- Higher Temperature Capability than High Power Silicon
  - 175 ºC for silicon (Si) IGBT & diode junction temperature
  - >250 ºC for SiC DMOSFET & diode junction temperature
- Faster Switching Characteristics
  - Lowers switching losses for hard switched converters
  - Reduces size of passive components
- Improved Thermal Conductivity of SiC compared to Si
  - Thermal performance becomes limited by packaging which is typically a modified silicon package

Overview

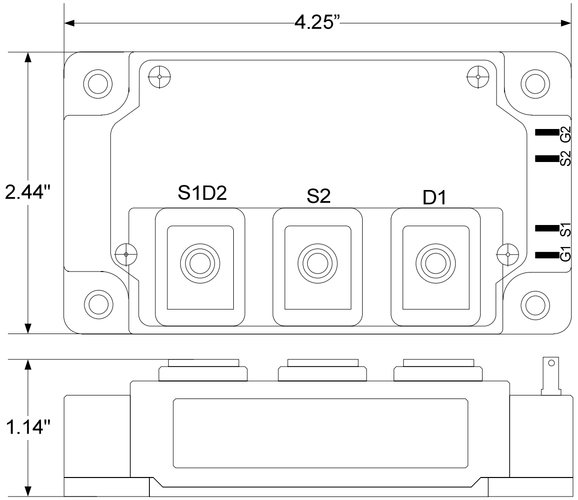
- Benefits of SiC
- Status of commercially available SiC at this time
- Converters being developed
- Data measured
  - DC
  - AC
  - Thermal
- Conclusions

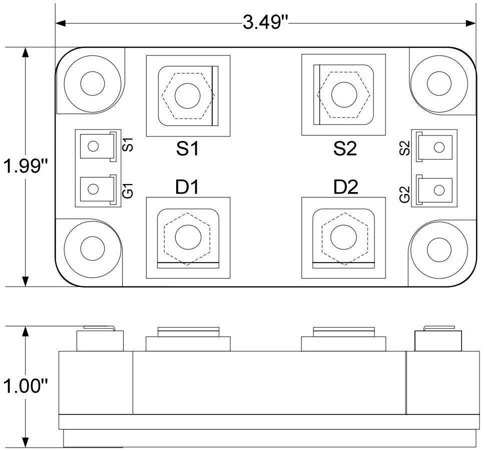
Status of High Power SiC

- Devices available from multiple vendors
  - Modules tested used 1200 Volt/20 Amp DMOSFET and 1200 Volt/10 Amp JBS Diodes per location from Cree
  - Significant data available from device testing
- Modules tested are commercially available from Powerex & MS Kennedy in half H-bridge modules
  - ½ H-Bridge modules similar to IGBT modules available from both vendors
  - 5 parallel devices (DMOSFETS & diodes) per location
  - **<u>Limited or incomplete datasheets for modules presently available</u>**
- Purpose of testing was to obtain adequate data to enable initial design of converters using available SiC modules

Modules Tested

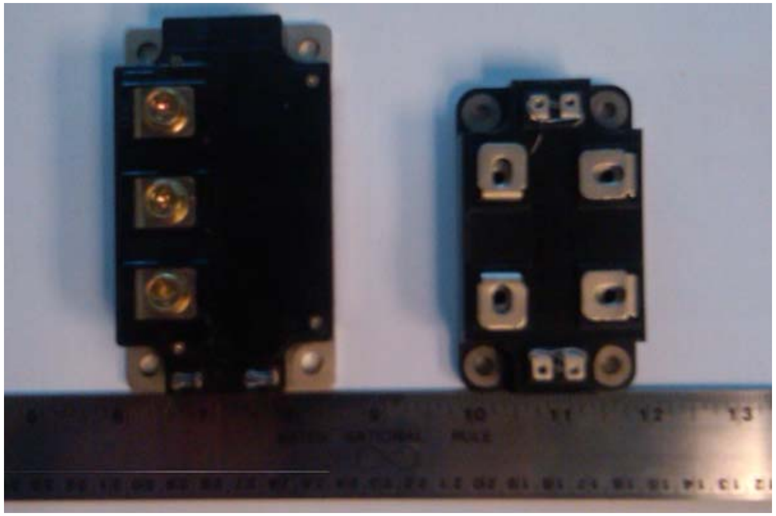
- Mass
  - Powerex: 400 g
  - MSK: 200 g





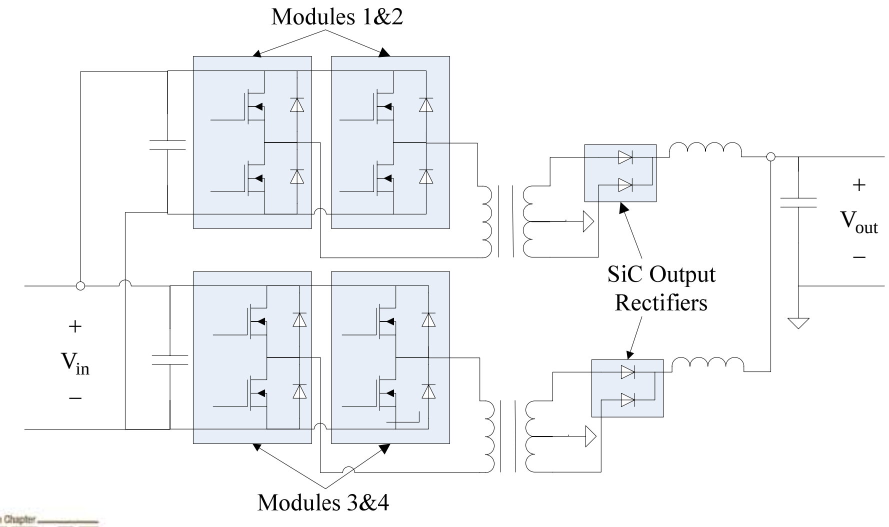
Powerex (left), MSK (right)

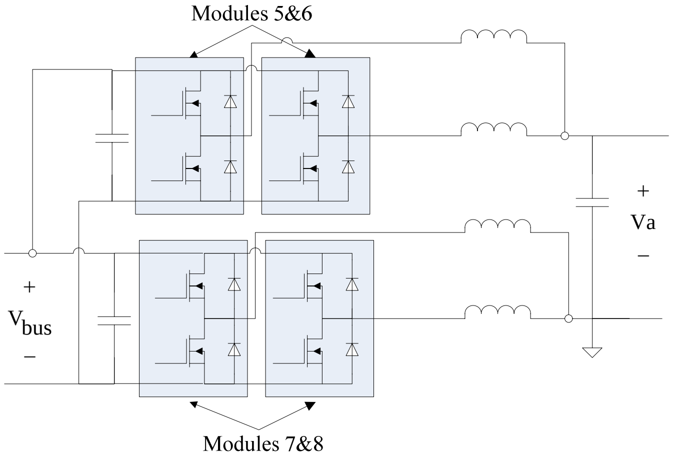
Powerex (left), MSK (right)



Converters Being Developed

- DC-DC Converter
  - 300 Volt DC to 28 Volt DC
  - 30 kW Power Level
- DC-AC Converter
  - 300 Volt DC to 50/60 Hz Output
  - 30 kW Power Level
  - Utilizes DC-DC converter as isolation stage
    - 300 to 400 Volt DC-DC
    - Full bridge rectified rather than ½ bridge





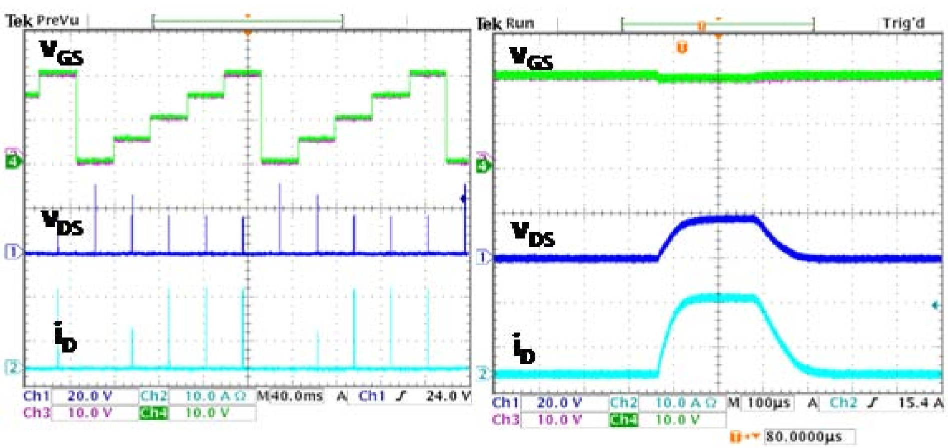
Data Measured

- DC Characteristics (JBS Diodes & DMOSFETS)
  - Primarily verification of scaling of parallel devices or datasheet values
- AC Characteristics
  - Turn-on & Turn-off losses
    - Typically given as curves for silicon IGBT & MOSFET modules
    - Some data available for SiC devices
    - Little or no data presently available for SiC modules
  - Gate Circuitry
    - Combination of voltages & resistances
  - Packaging differences (ie stray impedances) can become dominant factor as a result of higher speed switching of SiC devices
- Thermal Characteristics
  - Limited or no data presently on available datasheets
- Reliability data for module design choices not evaluated due to limited funding & time (will eventually be needed for long-term converter reliability)

Rds On Measurements

POWER AND ENERGY

- Measured with Sony/Tektronix 371b in short pulses over range of operation
- All measured values (both Powerex & MSK) at 25 ºC & 175 ºC were within range of values given in Powerex datasheet



Rds Measurement Waveforms

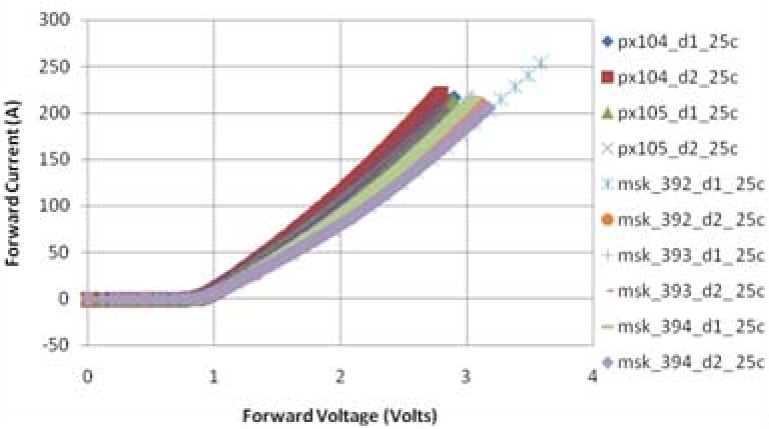
Rds Measured at 100 Amps & Vgs=20 V

		25 C	100 C	175 C
		Ron (m-Ω)	Ron (m-Ω)	Ron (m-Ω)
PX104	Device 1	18.81	20.00	24.06
	Device 2	17.89	18.81	23.56
PX105	Device 1	19.23	19.23	23.71
	Device 2	18.72	19.70	25.00
Powerex Ave		18.66	19.44	24.08
MSK 392	Device 1	20.71	22.45	31.58
	Device 2	19.40	22.45	29.72
MSK 393	Device 1	20.19	21.74	29.47
	Device 2	19.81	21.26	29.63
MSK 394	Device 1	21.15	23.27	30.98
	Device 2	20.69	21.78	29.57
MSK Ave		20.33	22.16	30.16
MSK/Powerex		109%	114%	125%

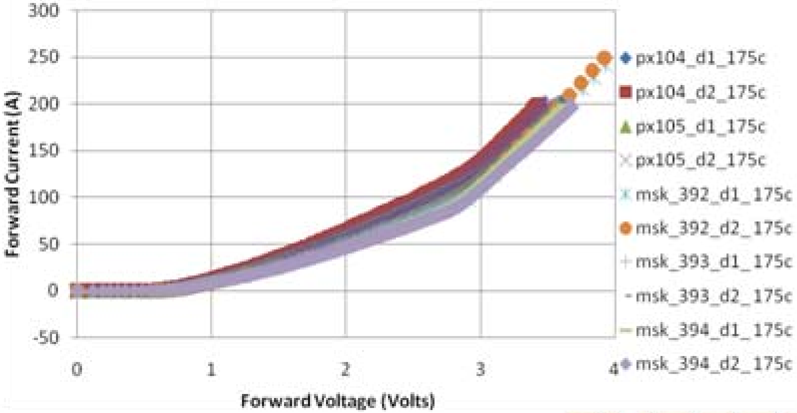
Diode Measurements

- Voltage measurements at 25 ºC consistent with Powerex datasheet
- Voltage measurements at 175 ºC lower (less lossy) than Powerex datasheet indicated
- Upon closer examination Powerex datasheet is only indicating voltages for external SB diodes
  - Actual measurements include effect of both SB diodes & intrinsic PN diodes (part of DMOSFETS)

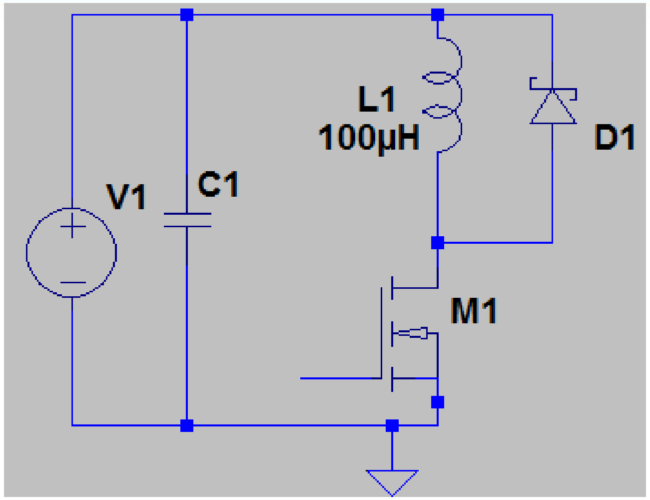
Measurements at 25 ºC

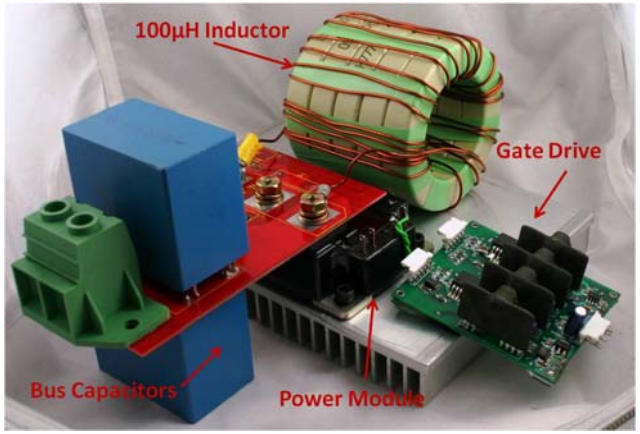


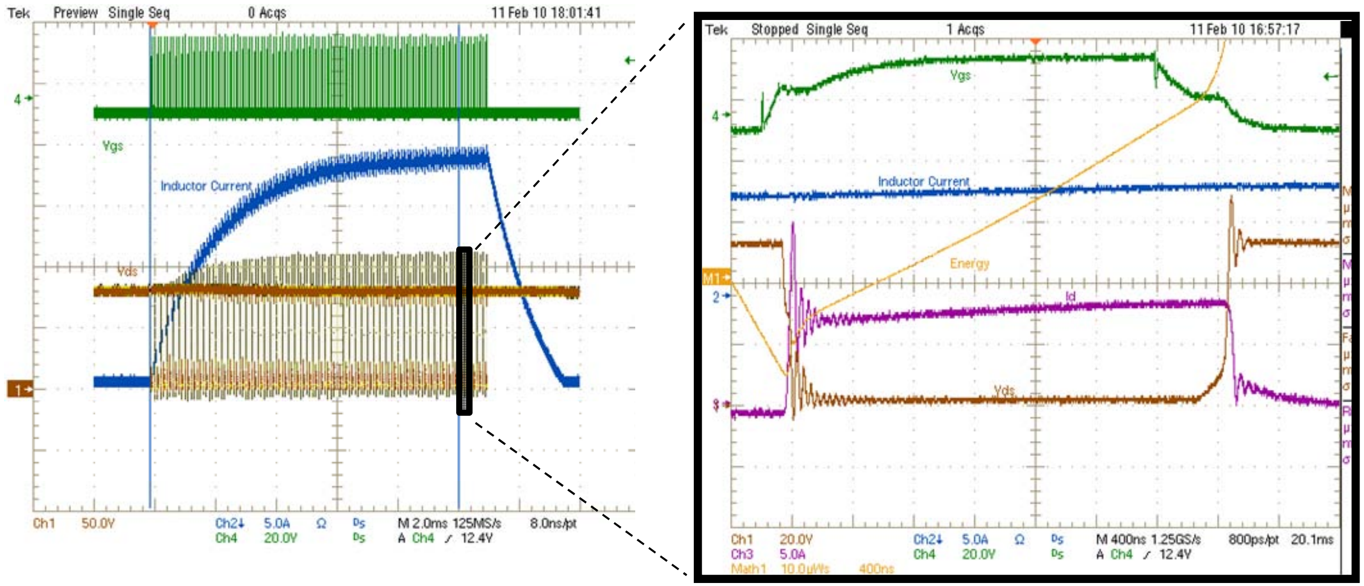
Measurements at 175 ºC



Switching Loss Setup





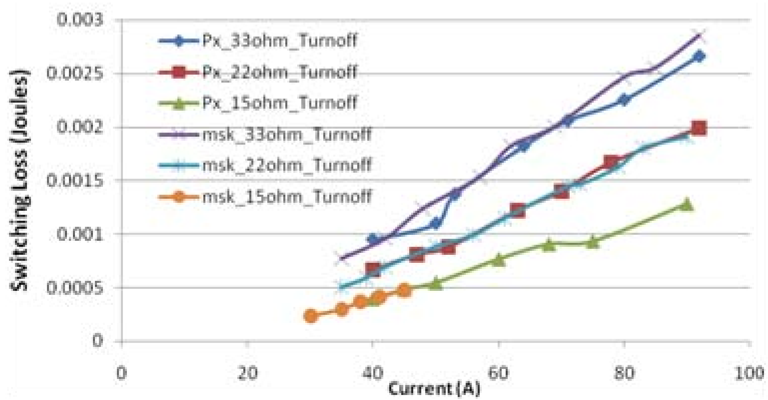


Switching Loss Measurements

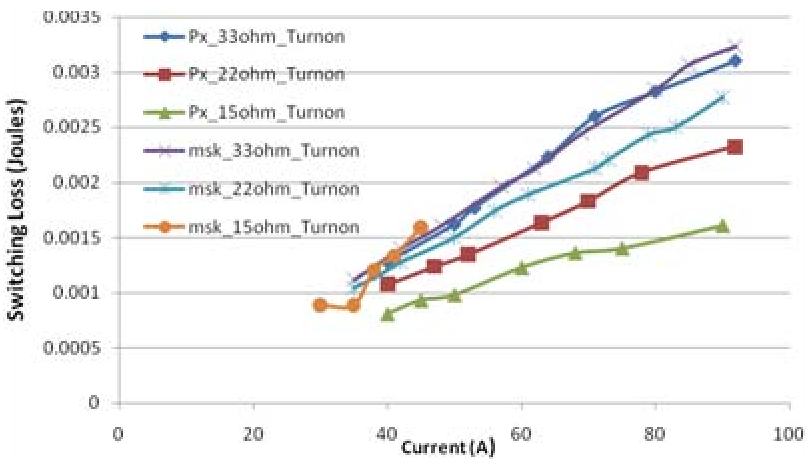
POWER AND ENERGY

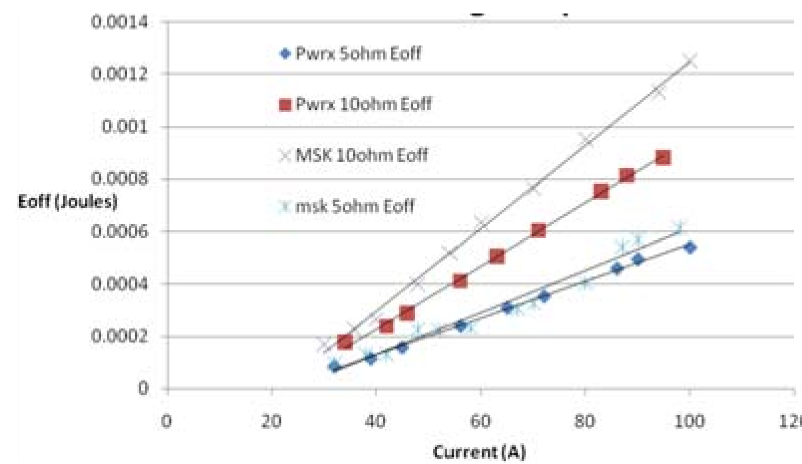
- Losses were similar between 2 types of modules
- Powerex modules had lower ringing than MSK modules
  - Powerex modules appear to have lower internal inductance than MSK modules
  - Lower ringing allows safe operation at higher switching speeds

Turn-Off Losses



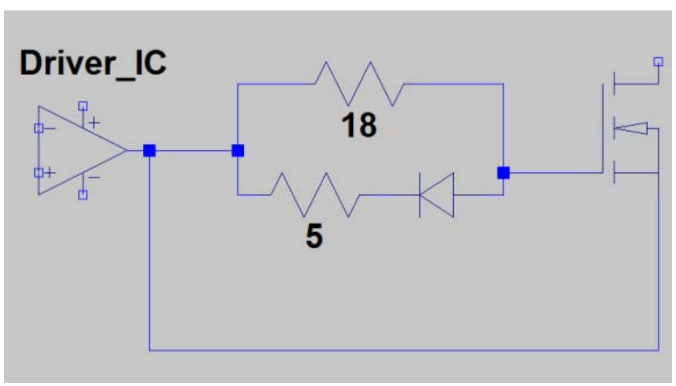
Turn-On Losses



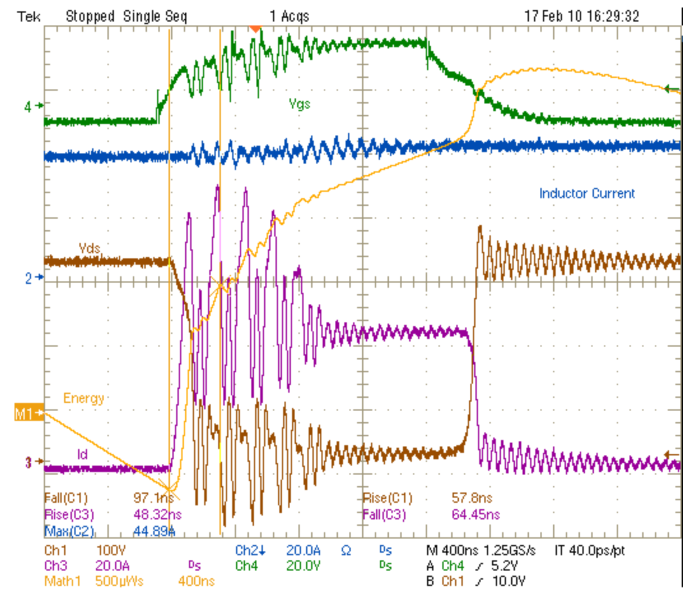


Gating Modifications

- Recommendation was for operation at Vgs,on=20 V & Vgs,off=-5 V & Rg=5Ω
- Operation with Rg,on~18Ω used to avoid excessive ringing, Rg,off=5Ω used



Gate Drive Circuit to allow different Turn-on & Turn-off resistor



Test Example at Rg=Ω for MSK Module

Thermal Measurements

POWER AND ENERGY

Powerex DMOSFET Thermal Measurements

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
75	3.304	247	0.0442	62	107	0.18	49	0.24
60	2.855	171	0.0476	50	78	0.16	42	0.21
50	2.51	126	0.0502	43	64	0.16	37	0.21
40	2.08	83	0.0520	38	50	0.15	33	0.20

Powerex Diode Thermal Measurements

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
75	1.854	139	0.0248	48	71	0.17	39	0.23
60	1.635	98	0.0272	41	51	0.10	35	0.16
50	1.496	75	0.0299	38	44	0.09	33	0.15
40	1.365	55	0.0341	34	34	0.01	31	0.07

- Powerex Datasheet
  - DMOSFET
    - Rth,j-c=0.17 ºC/W
    - Rth,j-h=0.21 ºC/W
  - Diode
    - Rth,j-c=0.28 ºC/W
    - Rth,j-h=0.32 ºC/W

MSK DMOSFET Thermal Measurements

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
60	3.05	183	0.0509	76	117	0.22	47	0.38
50	2.77	139	0.0555	65	98	0.24	43	0.40
40	2.45	98	0.0614	53	75	0.23	36	0.39
30	2.06	62	0.0685	43	55	0.19	32	0.37

MSK Diode Thermal Measurements

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
75	2.29	171	0.0306	72	122	0.29	45	0.45
60	1.98	119	0.0330	59	99	0.33	40	0.49
50	1.77	88	0.0353	51	81	0.33	35	0.52
40	1.56	62	0.0389	44	61	0.27	32	0.46
30	1.37	41	0.0456	37	40	0.07	29	0.26

- No MSK datasheet provided
- Measured MSK thermal peformance (junction to heat-sink) ~60% worse than Powerex Modules

Overall Comparison

- DC Losses
  - Measured Powerex module losses lower than measured MSK module losses
  - All modules (Powerex & MSK) within range provided by Powerex indicating possibility that variation could be device lot dependent
- AC Losses
  - Powerex modules have less ringing allowing operation at higher frequency than MSK modules
  - Indication primarily of lower module inductances
  - Next generation MSK modules likely different than tested modules
- Thermal Properties
  - Measured MSK module performance worse than Powerex module performance
- Physical
  - MSK module is smaller & lighter than Powerex module

Conclusions

- Module measurements completed to allow initial designs for fabrication of converters to demonstrate of SiC converters using Commercially available SiC modules