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Semiconductor Power Electronics Technology

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CEM Industry Advisory Panel Meeting

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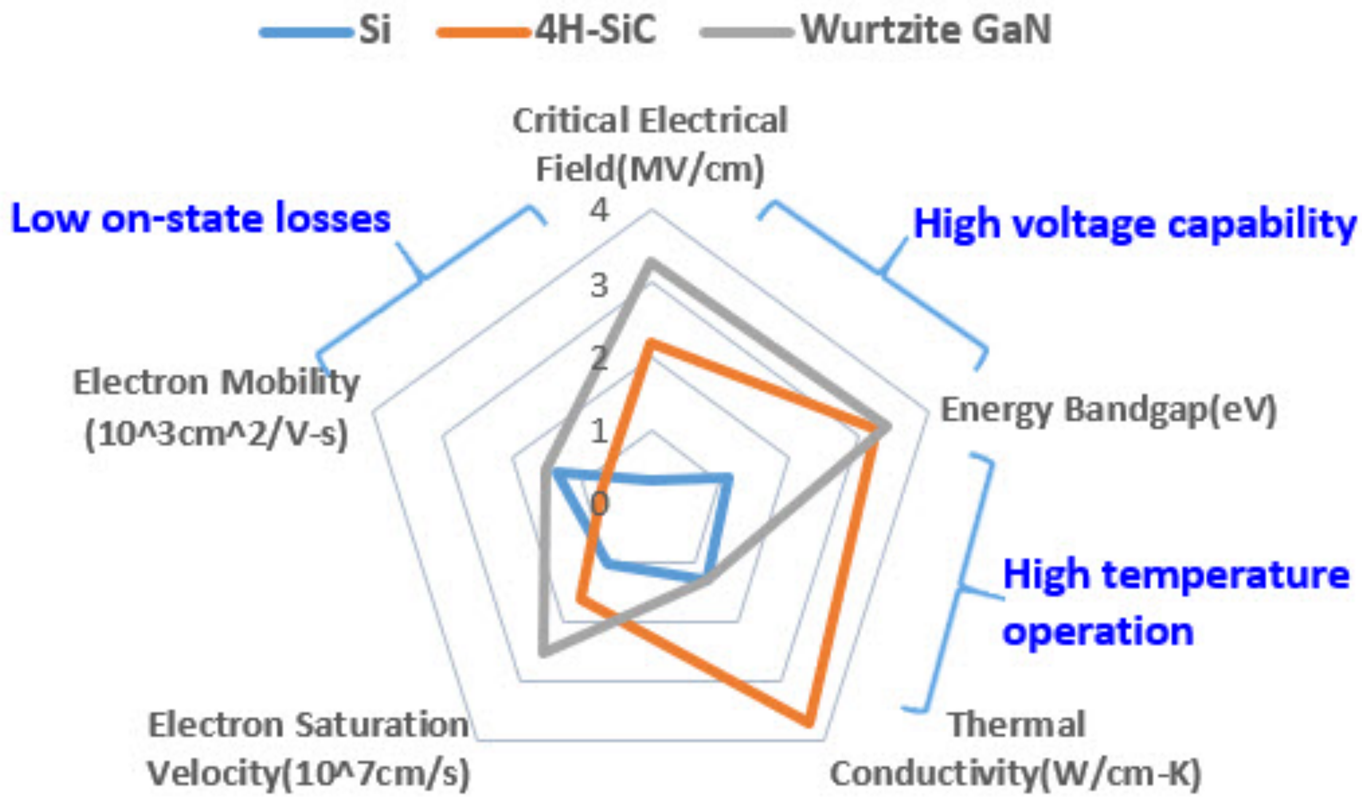
WBG Material Advantages



Data source: www.ioffe.ru/SVA/NSM/Semicond/

There are other WBG materials being actively researched, including AIN, GaO, Diamond

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Power Semiconductor Milestones
Decades of innovations

- First BJT was made in **1948** [3]
- Fairchild BJT [3]
- MOSFET was patented in **1959** [4]

- Power MOSFET was commercialized in **1980s** [5]
- First IGBT was reported and commercialized in **1983** [6]

- First IGCT was reported in **1996** in [17]
- First ETO was reported in **1998** [23]
- First CoolMOS commercialized in **1998** [8]

- 1.2 kV SiC JFET was commercialized in **2008**
- 12 kV SiC IGBT reported in **2008** [11]
- First 4.5 kV SiC ETO reported in **2009** [19]

- EPC GaN device was commercialized in **2009[21]**
- First 600 V GaN device reported in **2013 [22]**

1960 | **1980** | **1990** | **2000** | **2010**

- Thyristor/SCR commercialized in **1958** [17]
- First GTO was reported in **1962** [17]

- SiC Diodes were reported in **1992** [7]
- First SiC GTO was reported in **1997** [18]

- SiC diode was commercialized in **2001**[9]
- Si IGBT + SiC SBD hybrid module reported in **2003** [15]
- 10 kV SiC MOSFET reported in **2003** [10]

- 1.2 kV SiC MOSFET commercialized in **2011**
- 1.2 kV SiC MOSFET module released in **2012** [16]
- Si IGBT + SiC SBD hybrid module commercialized in **2012**

- 15-22 kV SiC GTO was reported in **2013** [12,13]
- 22 kV SiC IGBT was reported in **2014** [14]
- 22 kV SiC ETO was reported in **2015** [20]

Device concepts are more or less settled on several well established concepts

thyristor (symmetric and asymmetric, forced turn-off or line commutated)
IGBT
MOSFET (or other FET variations)
Schottky diode
PN junction diode

Next major trend: move from Si to WBG

1st wave: Si MOSFET/IGBT
2nd superjunction device
3rd moving to WBG:MOSFET as the dominant device concept

Power Device and Me

(1979-1983)

Power MOSFET

(1983-1986)

IGBT

(1989-1992)

Power integrated circuits

(1994-2004)

SiC/IPEM/PEBB

(2004-2017)

WBG in the grid

WBG cost reduction

Power Electronics Research @ UT

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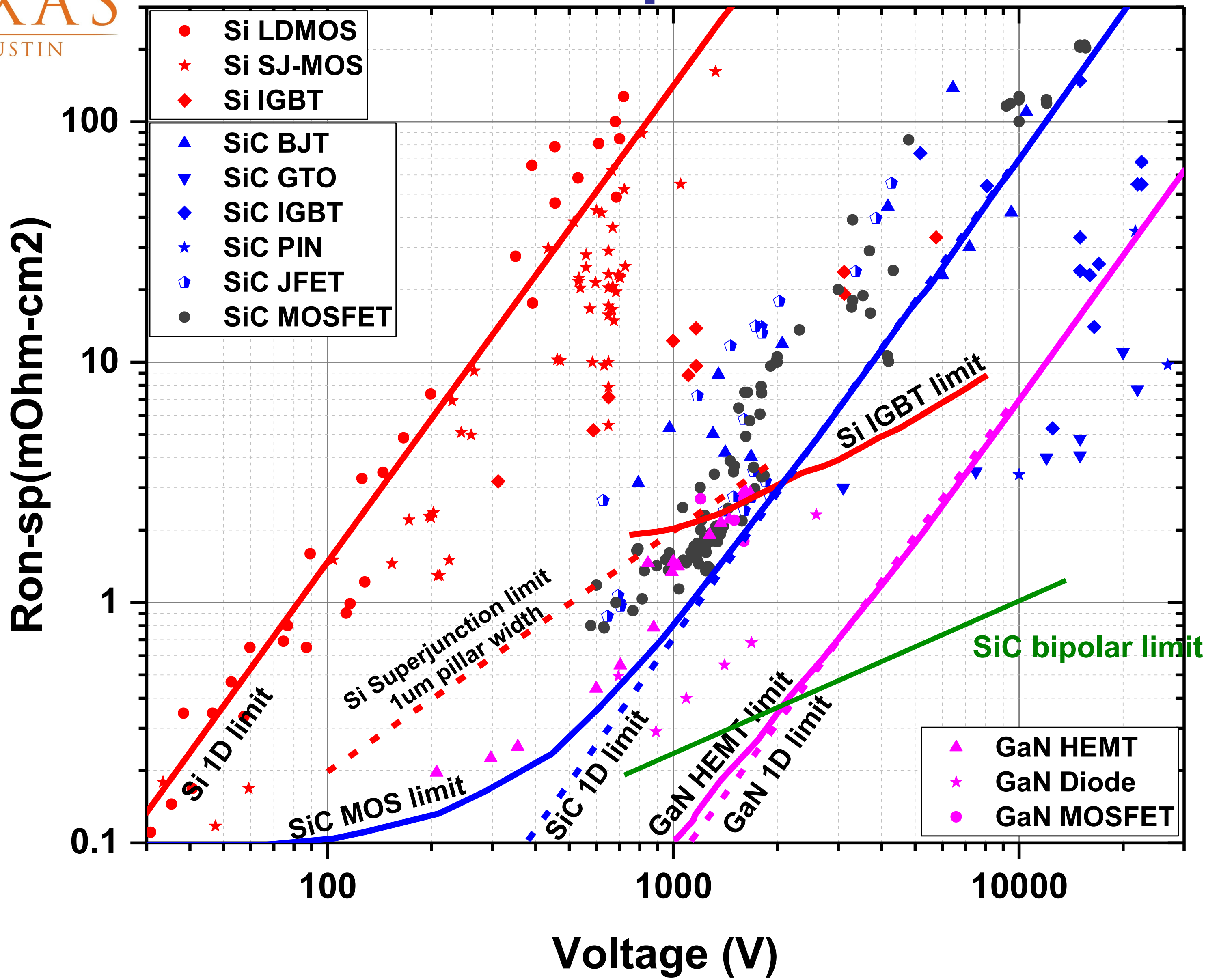
- Power Management IC (PMIC)
  - Power system on chip design; High voltage integrated circuit; GaN HVIC
- Power Semiconductor Devices (PSD)
  - Si, GaN, SiC, GaO power devices
  - Power electronics packaging
- High Density Power Electronics (HDPE)
  - GaN/SiC High density power electronics; Driving, thermal and packaging techniques
  - Magnetic materials and devices
- High Power Electronics (HPE)
  - High power electronics based on Si solution (IGBT, ETO)
  - Ultra high voltage SiC power electronics
  - Solid State Transformer; Solid State Circuit Breaker, Hybrid breaker
- Renewable Energy System, Microgrid and Smart Grid (RMS)
  - Solar/Wind/EV Systems/Wireless Power Transfer/Storage Systems
  - 380V DC Microgrid; Medium Voltage DC (MVDC); High Voltage DC (HVDC)
- Energy Internet (EI)
  - Blockchain/Communication/Energy router

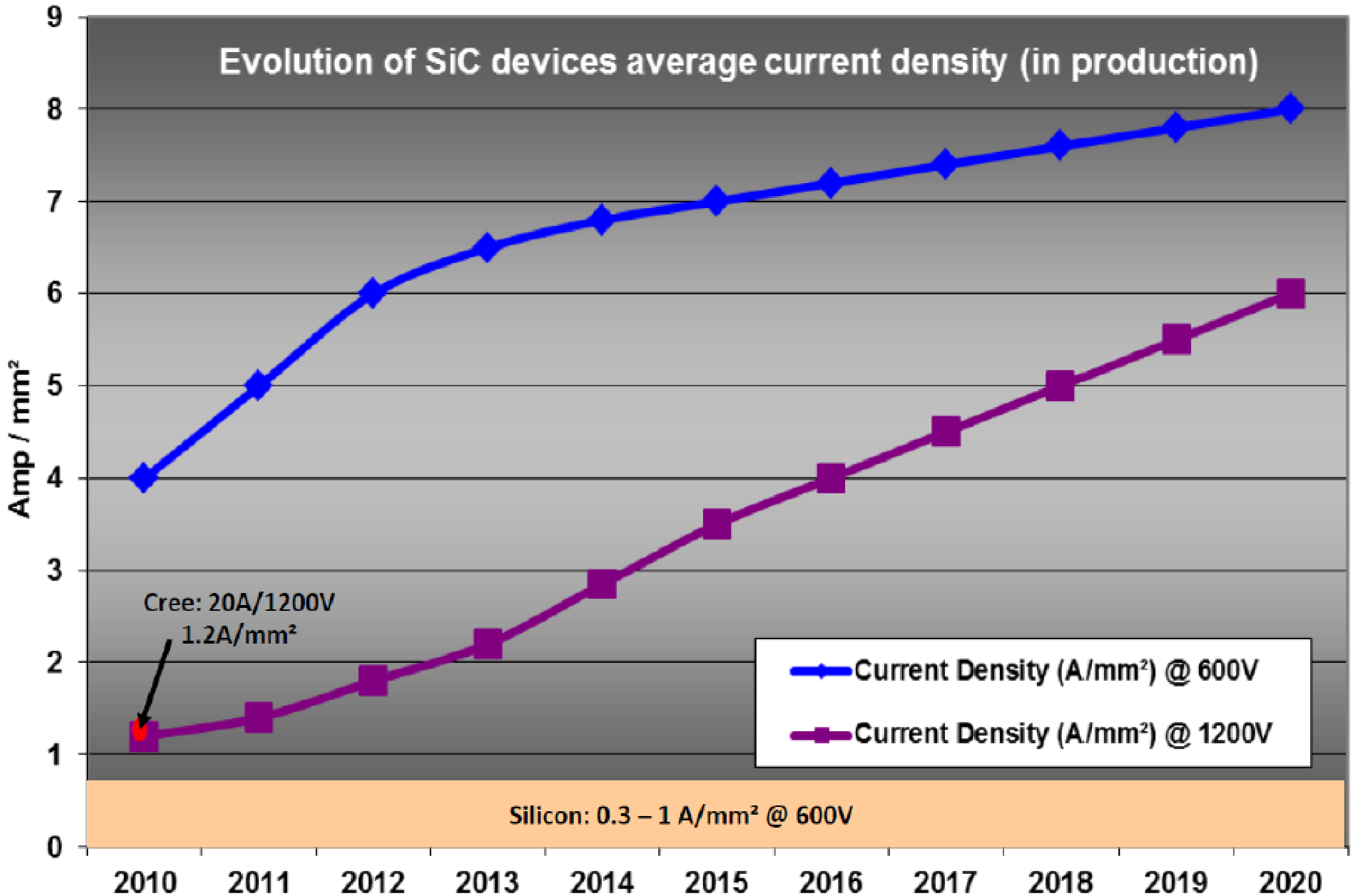
Ron FOM Competition: Current Status



SiC MOSFET: Achieved 100X reduction over Si and 10X over Si SJ
Not much improvement over Si IGBT

Direct Impact: Current Density Increase & Chip Size Reduction

$$J = \sqrt{\frac{VT}{R_{jc-sp} * R_{on-sp}}}$$



Yole Developpement, 2012

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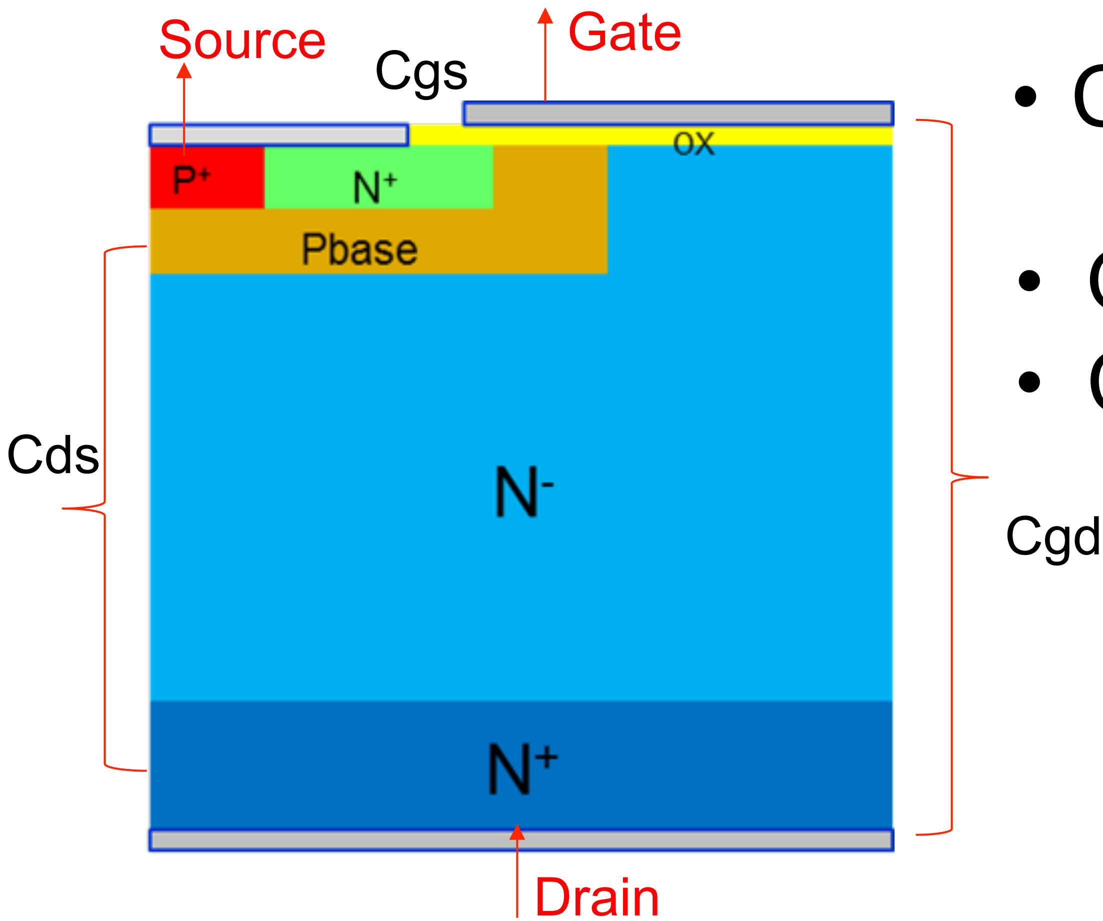
Si/SiC: Vertical Power Devices

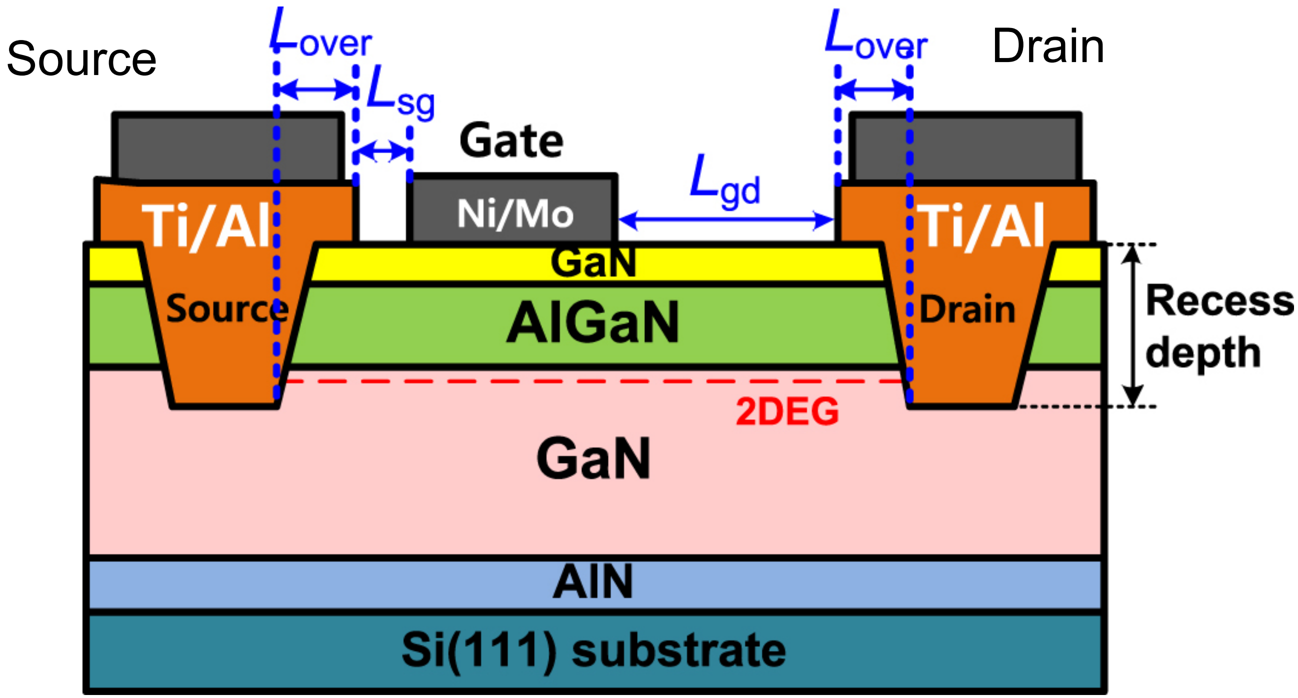


- Cgs ~ Cox*Achip
- Qoss ~ Ɛ*Ec*Achip
- Coss ~Ec

$$dV/dt = \frac{J}{C_{sp}}$$

Since capacitance also increased by 10X
so dV/dt will be similar unless J(WBG) >10X J(Si)

GaN: Lateral Device Construction



Bottomline:

- On Ron, not as good as vertical SiC, still much better than Si
- But even lower capacitance due to the lateral structure!

  C not simply scale with Achip

A Closer Look at Ron, Capacitance, Qrr

600V Devices Compared

600V FETs	Ron (mohm)	Ciss (nF)	FOM 1 (Ron*Ciss)	Coss (nF)@400V	FOM2 (Ron*Coss)	Qrr(uC)	FOM3 (Ron*Qrr)
Si SJ	37	7.24	267	0.38	14	36	1332
SiC MOS	120	1.2	144	0.09	10.8	0.053	6.3
GaN HFET	25	.52	13	0.13	3.25	0.113	2.8

Si SJ: Infineon IPW65R037C6. SiC MOSFET: Rohm SCT2120AF GaN HFET: GaNSystem GS66516T

- Gate loop is getting faster & faster

Drain loop
dV/dt increase?
$dV/dt \sim I/C=J/C_{sp}$

Reverse recovery charge/loss
Basically eliminated in WBG devices

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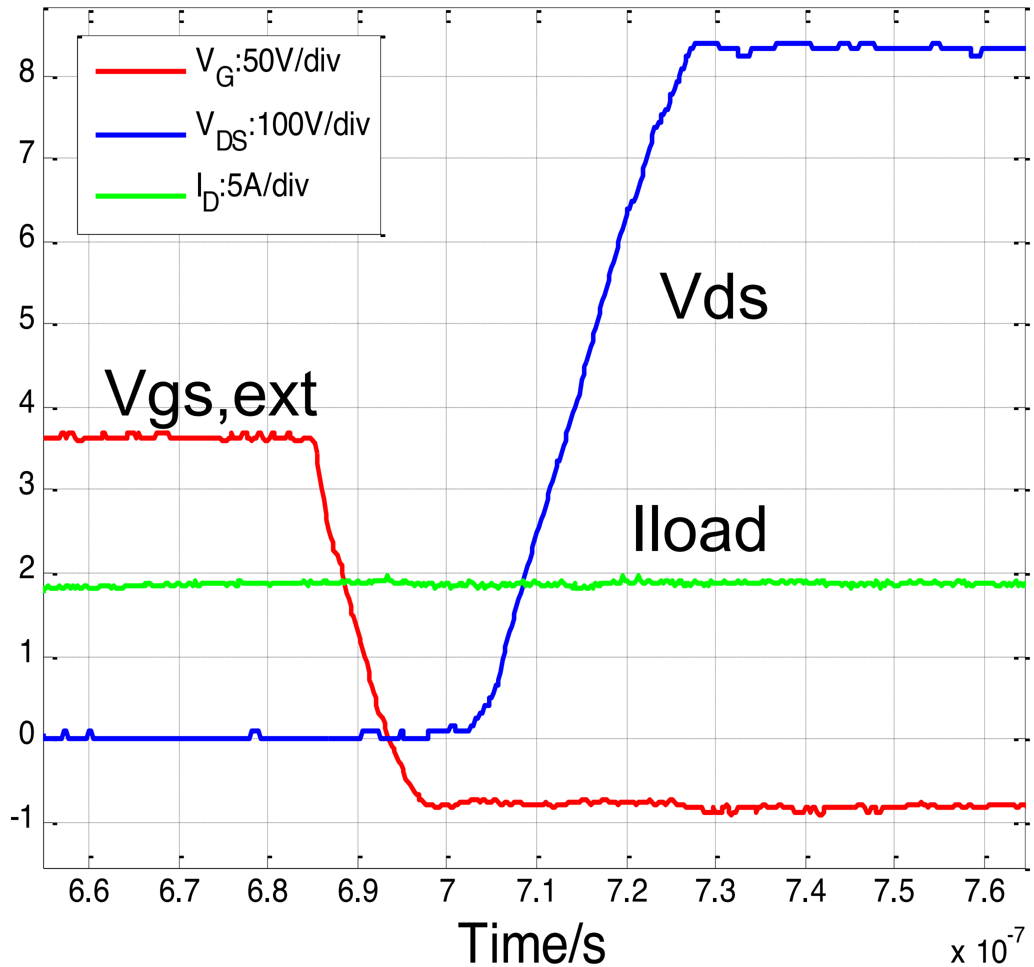
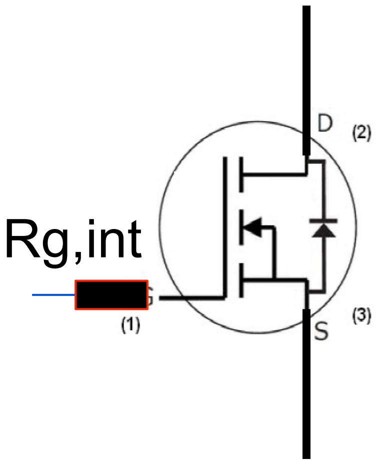
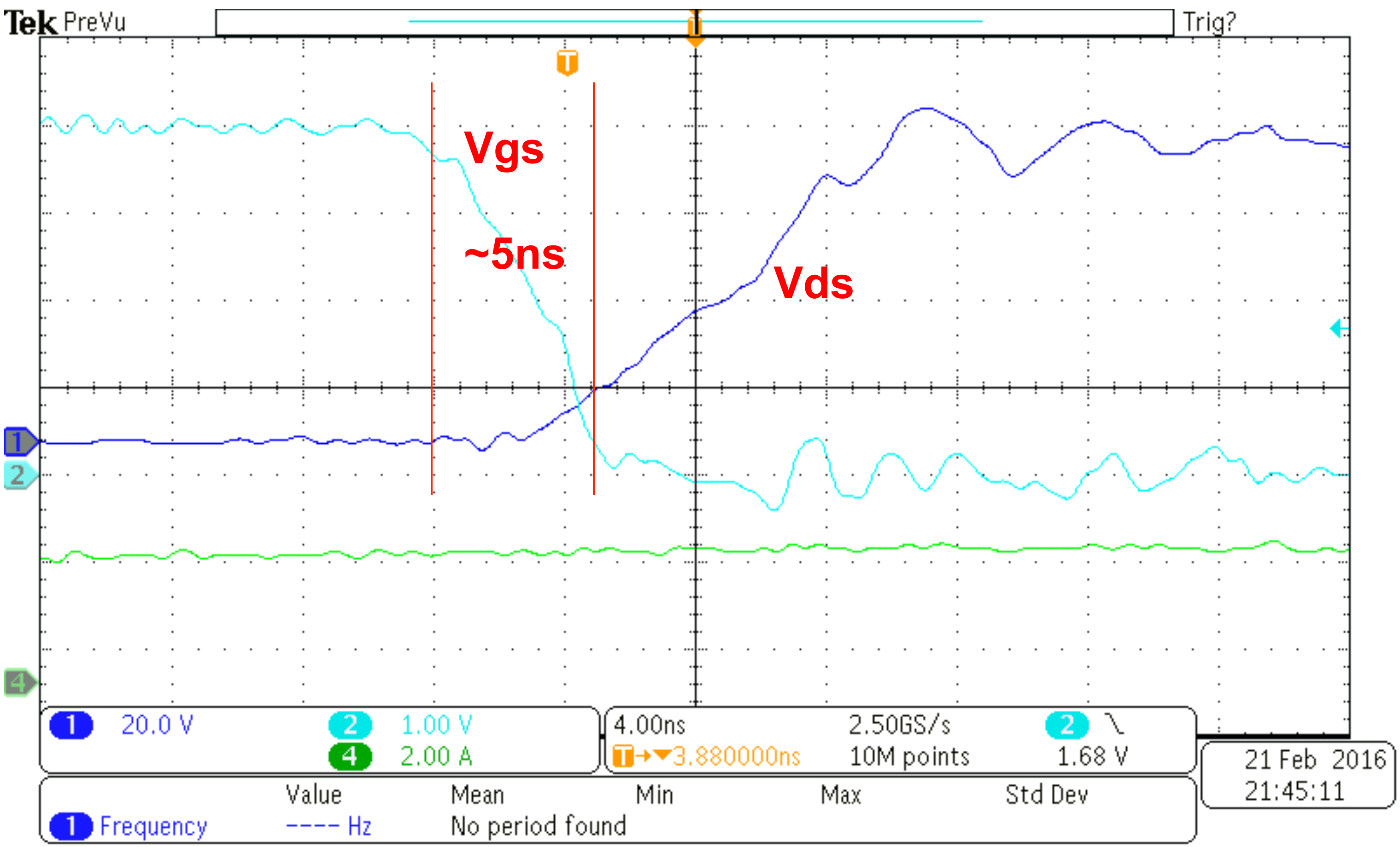
Zero Turn-off Loss (Hard Driven MOSFET)

80 mohm 1200VC SiC MOSFET, Rg,ext=0, V=800V, I=10A





650V GaN turn-off waveform



Zero turn-off loss is also achieved in hard-driven GaN

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Achieving Zero Switching Loss

- Hard switching application

  E_{on} =E_{on}(measured)+ E_{oss} + Eoss (diode + load cap)
  E_{off} =E_{off}(measured) –E_{oss} ~ 0 within ZTL region
  E_{total}=E_{on}+E_{off}=E_{on}(measured) + E_{off}(measured)
  Gate drive loss ~ fs*Vg*Qg

- ZVS soft switching application
  E_{on} ~ =0
  E_{off} = E_{off} (measured) –E_{oss} ~0 within ZTL region
  E_{total}=E_{on}+E_{off} = 0
  Gate drive loss ~ fs*Vg*Qg

- **Switching frequency no longer a constraint**
- **Ron keeps going down so RMS current less a concern**

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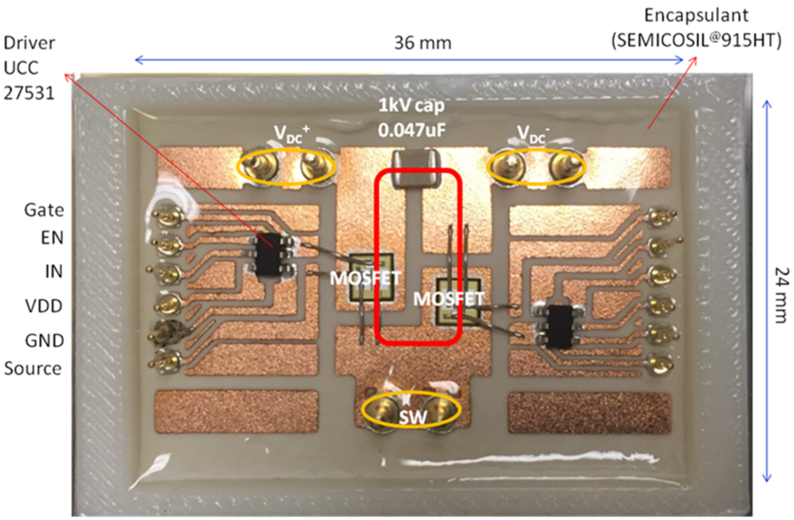
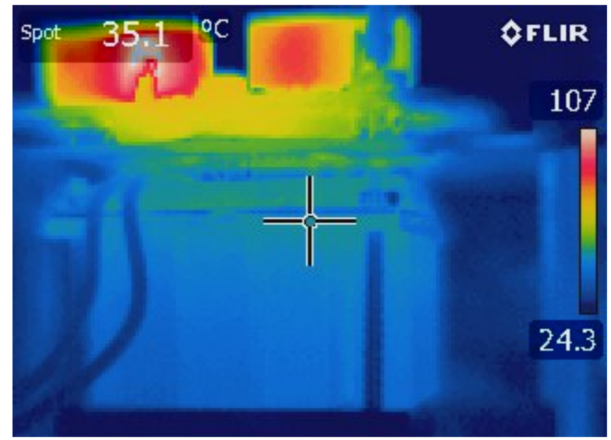
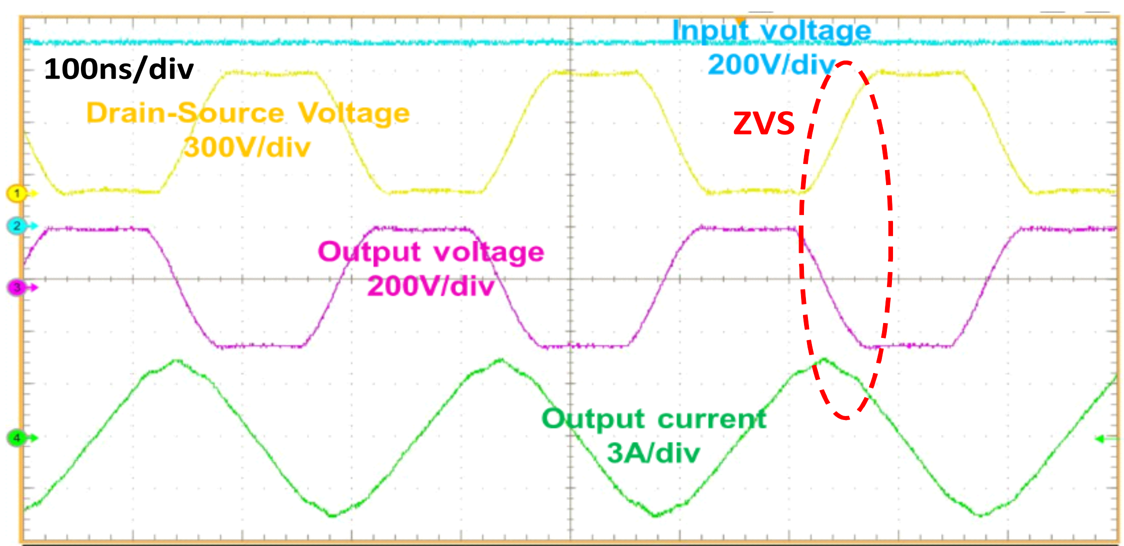
3.38 MHz operation of 1200V SiC MOSFET (with ZVS turn-on)



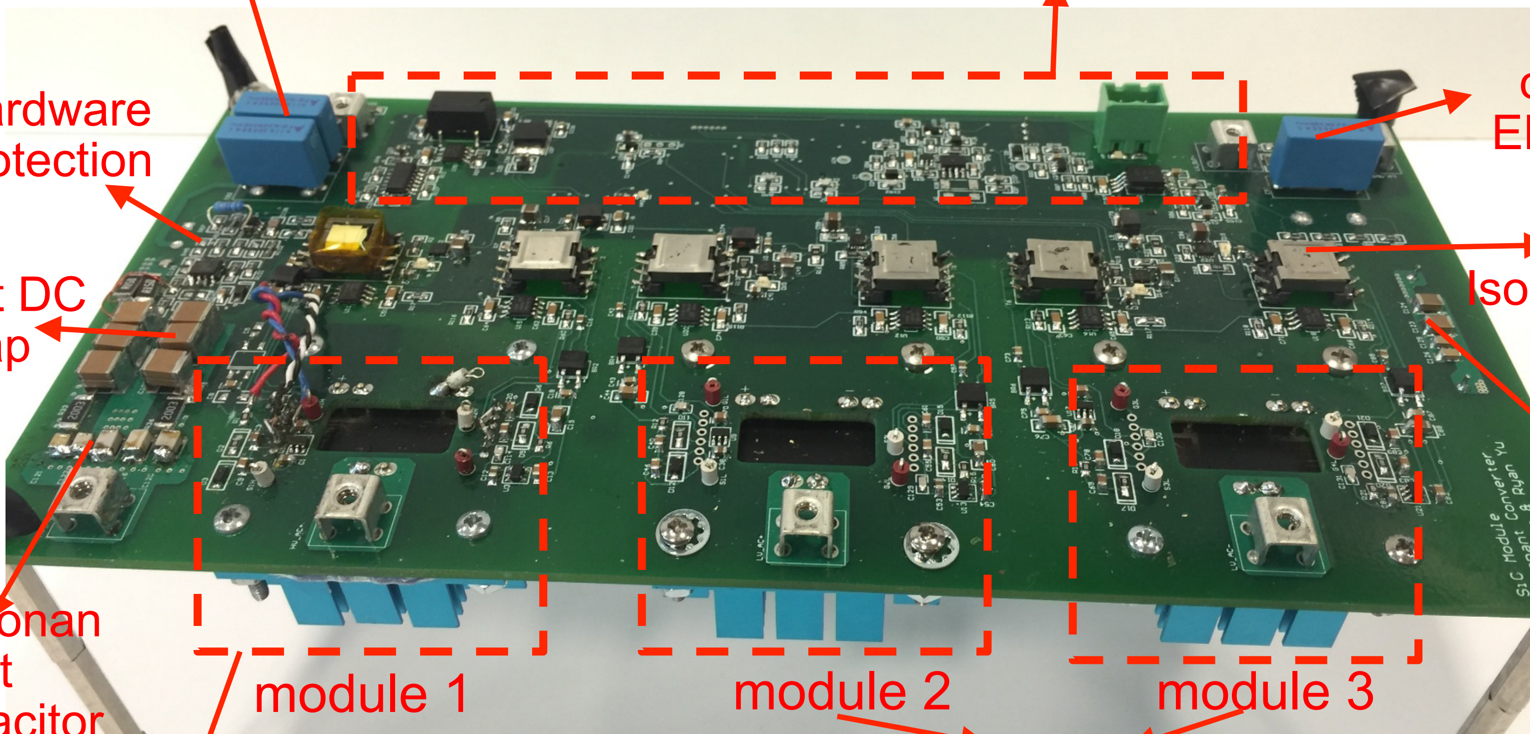


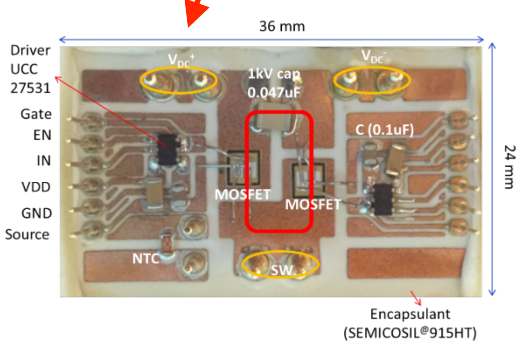


*Guo and Huang at WIPDA 2015

Demonstrated zero switching loss

1 MHz LLC Resonant Converter Prototype





Input voltage Vin	800 V
Output voltage Vout	400 V
Rated Power Pr	4.5 kW
Transformer turns ratio	1 : 1
Leakage inductance, Llk	2 uH
Magnetizing inductance, Lm	11 uH
Switching frequency fsw	1.2 MHz

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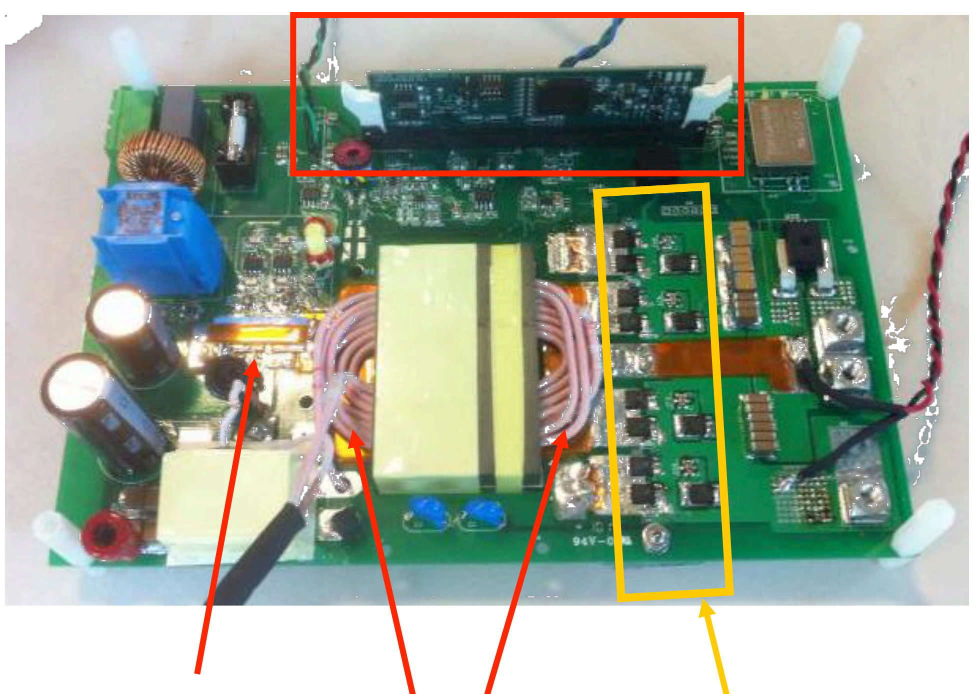
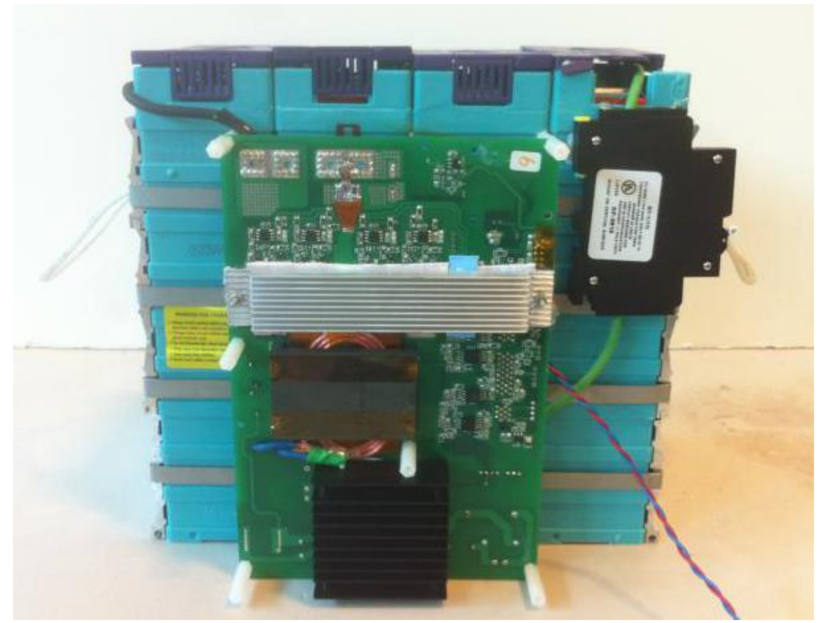
1kW Isolated Bidirectional DC/DC

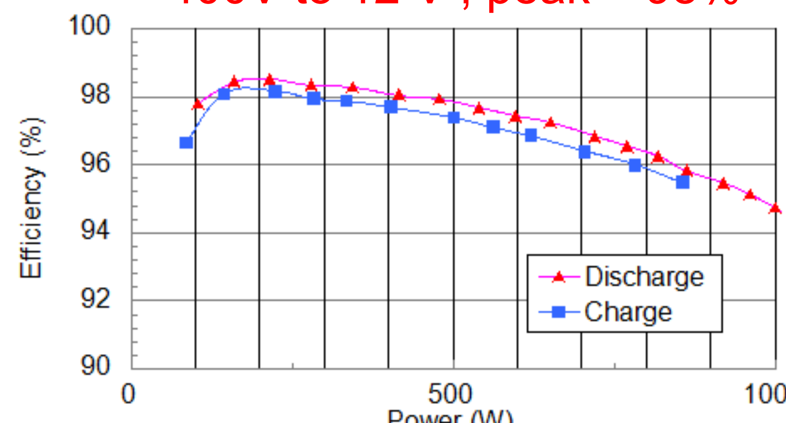


Picture with 1 kWH battery



Storage capacity	1 kWh
Charge/discharge power	1 kW
LV side voltage (V_{LV})	(10.8~14.4)V
HV side voltage (V_{HV})	(350~410)V

400V to 12 V , peak > 98%



*Xue and Huang, at IEEE PEDG 2015

Project Highlight 3: 3.2kW AC/DC PFC

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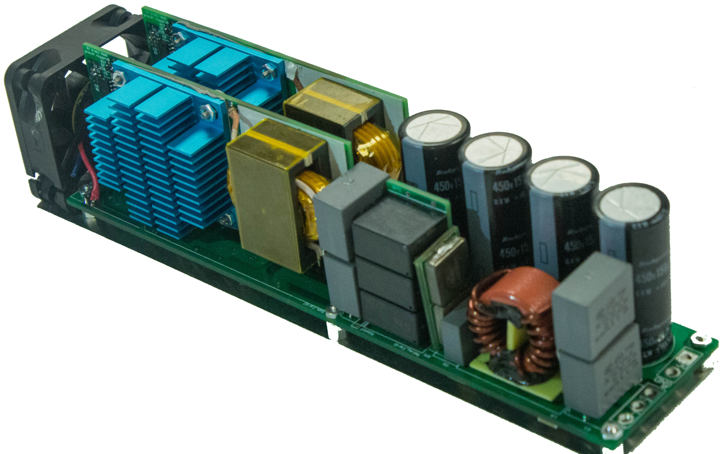
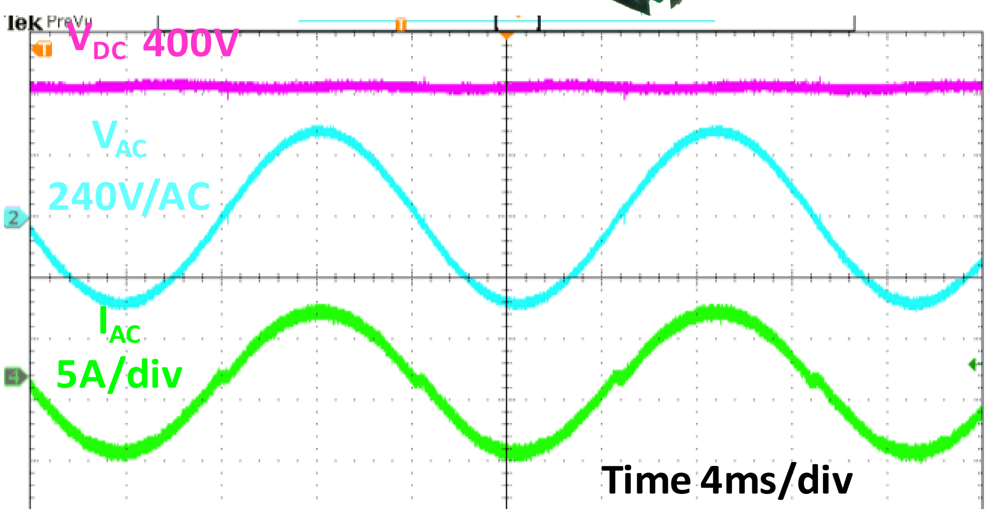
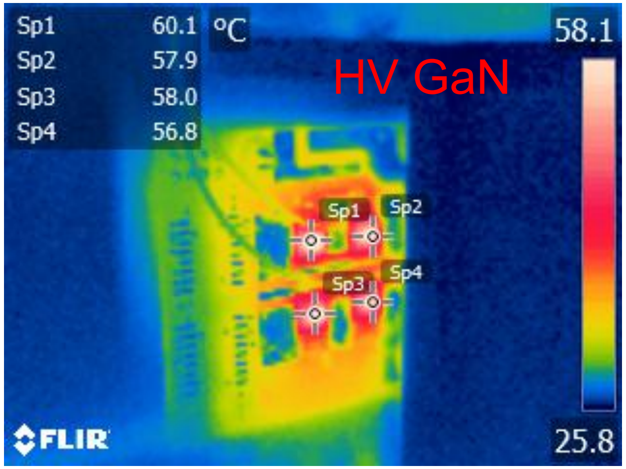
- Two Phase Totem-Pole true bridgeless PFC with full ZVS operation
- HV 650V GaN daughter-boards
- Extreme power density
- Excellent thermal design



Power	3.2 kW
Topology	Two phase Totem-Pole PFC (300k-2 Mhz)
Input	Universal input AC
HV side voltage (V_{HV})	400V
Tested efficiency	>99%
Power density	130 W/inch^3

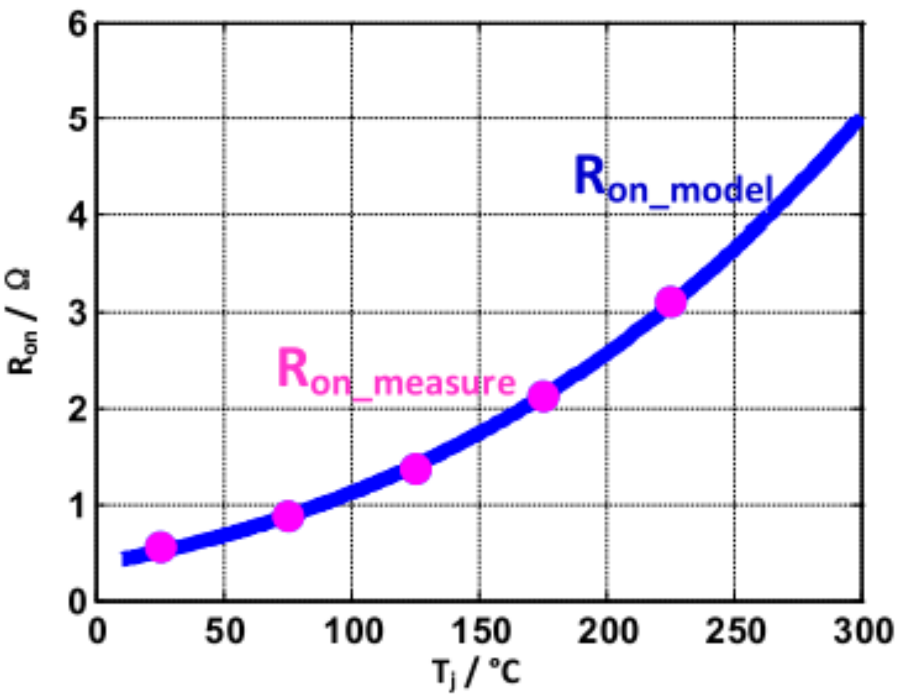


One phase test result at 1.6kW



Only 35°C rise at full power

15 kV SiC MOSFET: 10-20X Increase in BV

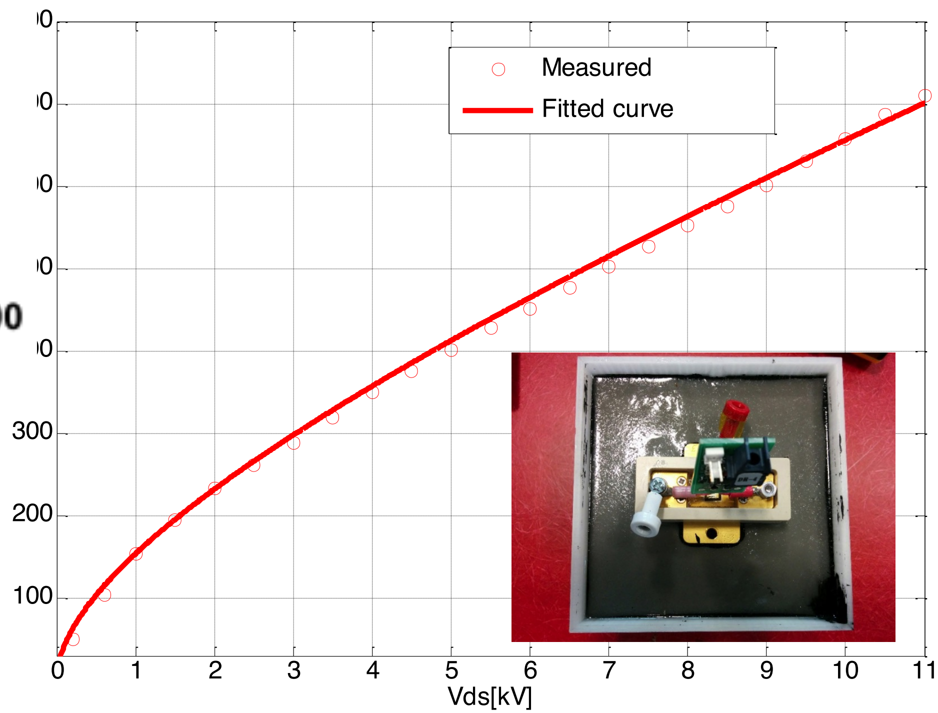


$$R_{on} = R_0 \left(T_j / T_0\right)^2$$

$$R_0 = 0.875\Omega \quad T_0 = 348.16K$$

$$Q_{loss} = 4.08\cdot10^{-9}\sqrt{V_{ds}} + 24.8\cdot10^{-12} V_{ds}$$

Output Charge of 15kV SiC MOSFET & JBS



Li Wang, Qianlai Zhu, Wensong Yu, Alex Q. Huang ,"A Study of Dynamic High Voltage Output Charge Measurement for 15 kV SiC MOSFET," ECCE2016

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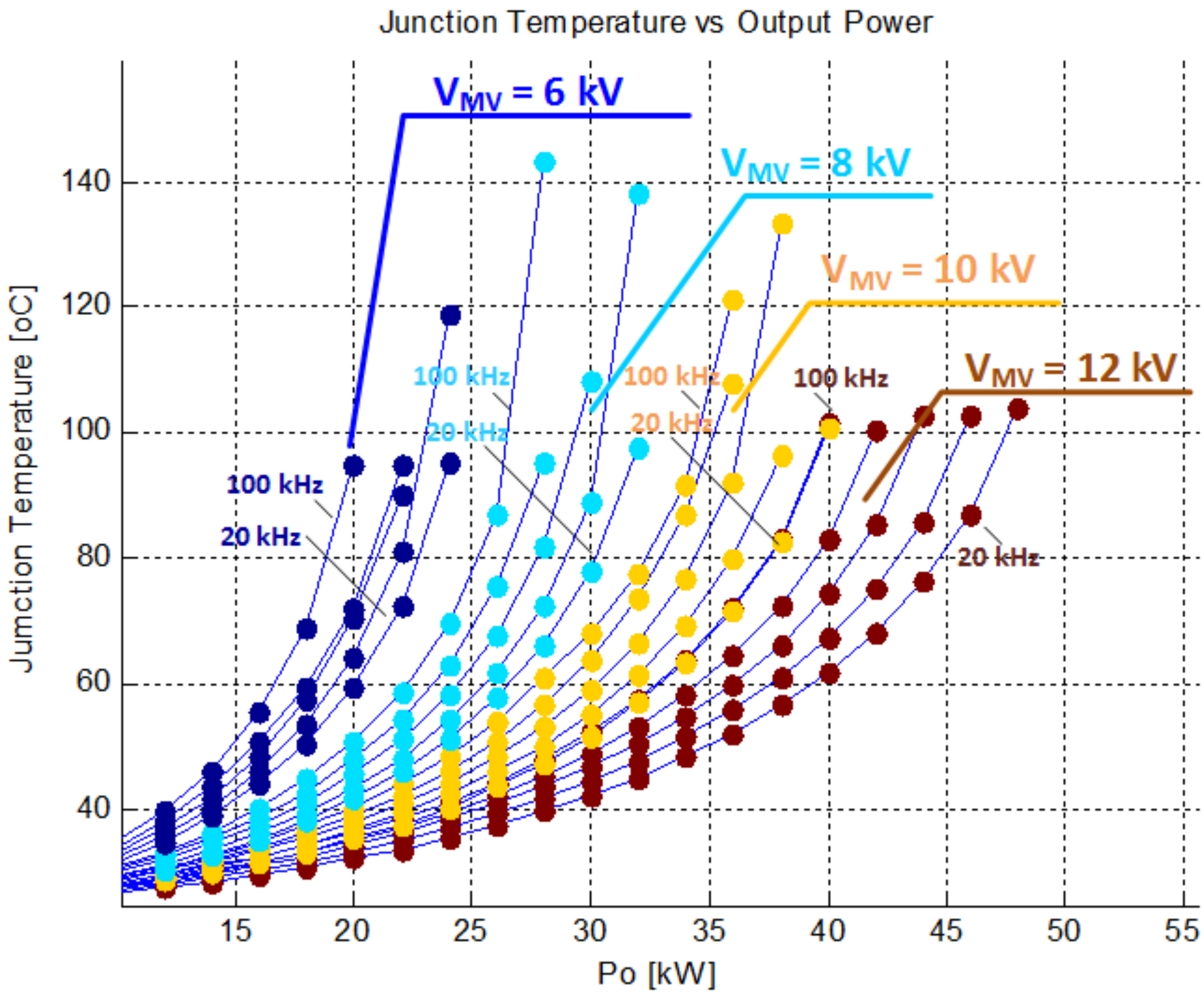
15 kV SiC MOSFET Capability: 100 kHz

Higher DC link voltage, Better device utilization



Only two 15 kV MOSFET used

Total SiC die size=2 cm^2

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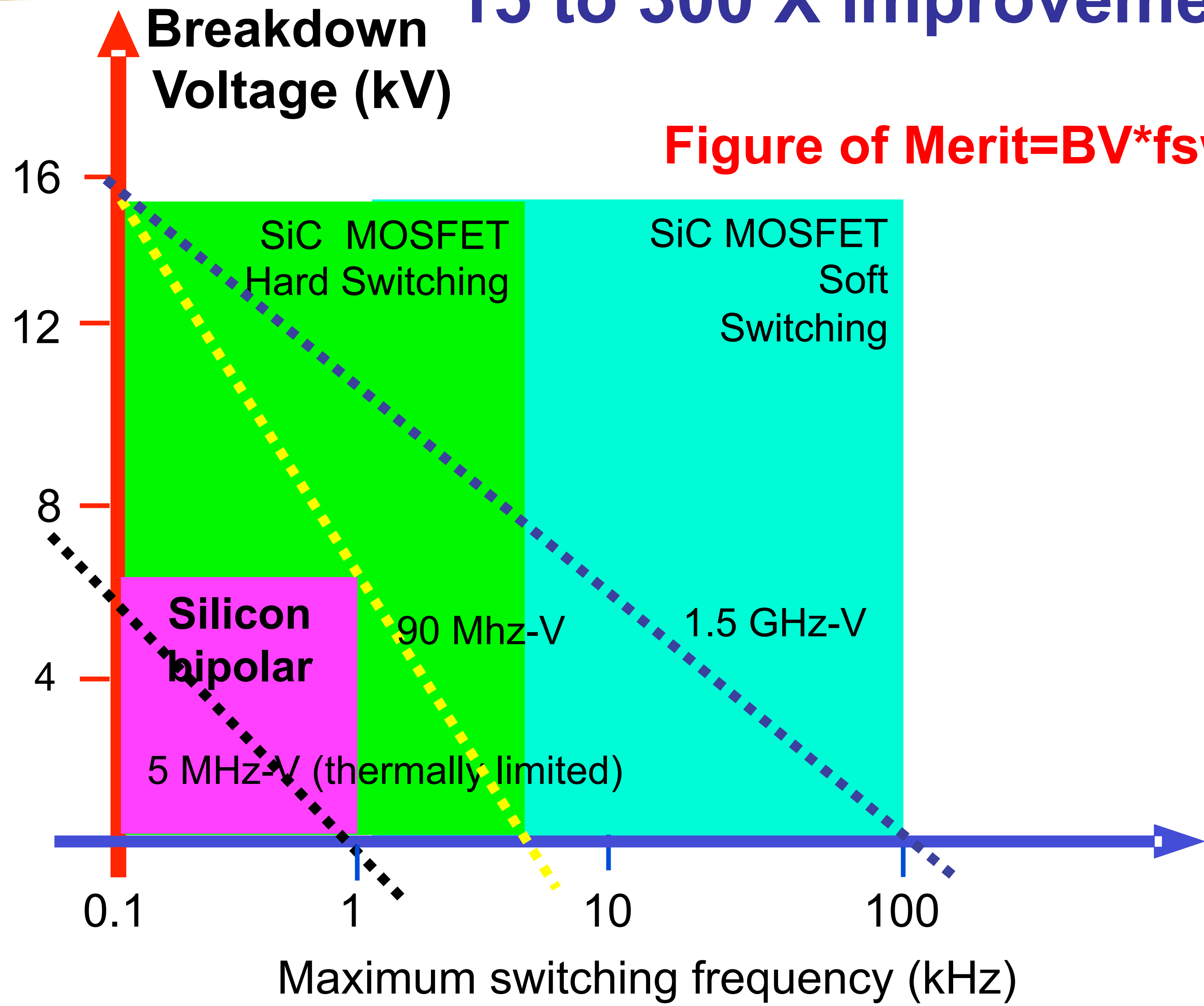
With SiC MOSFET: 15 to 300 X improvements



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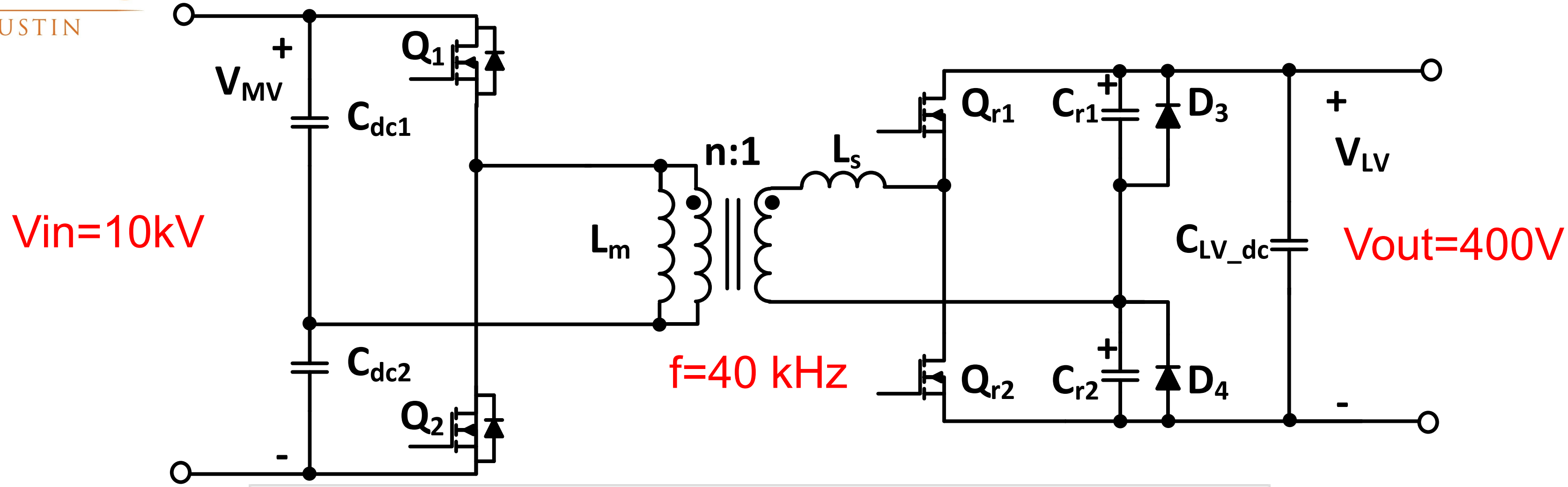
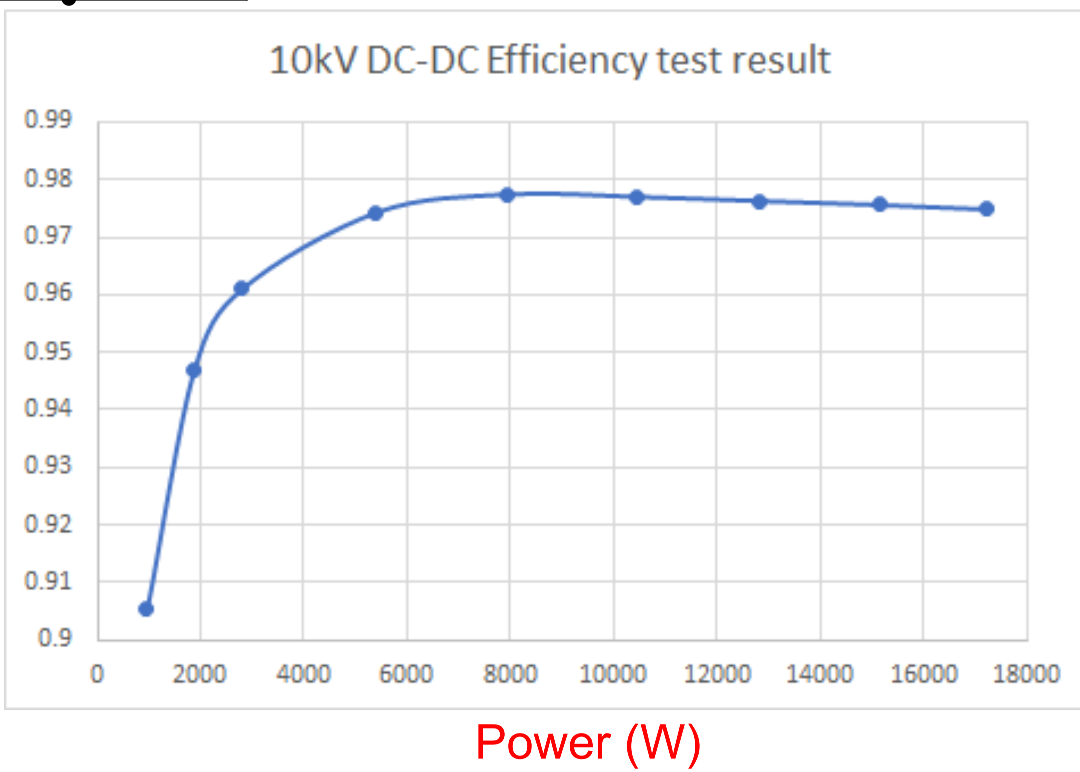
10 kV DCX: Two 15 kV SiC MOSFETs





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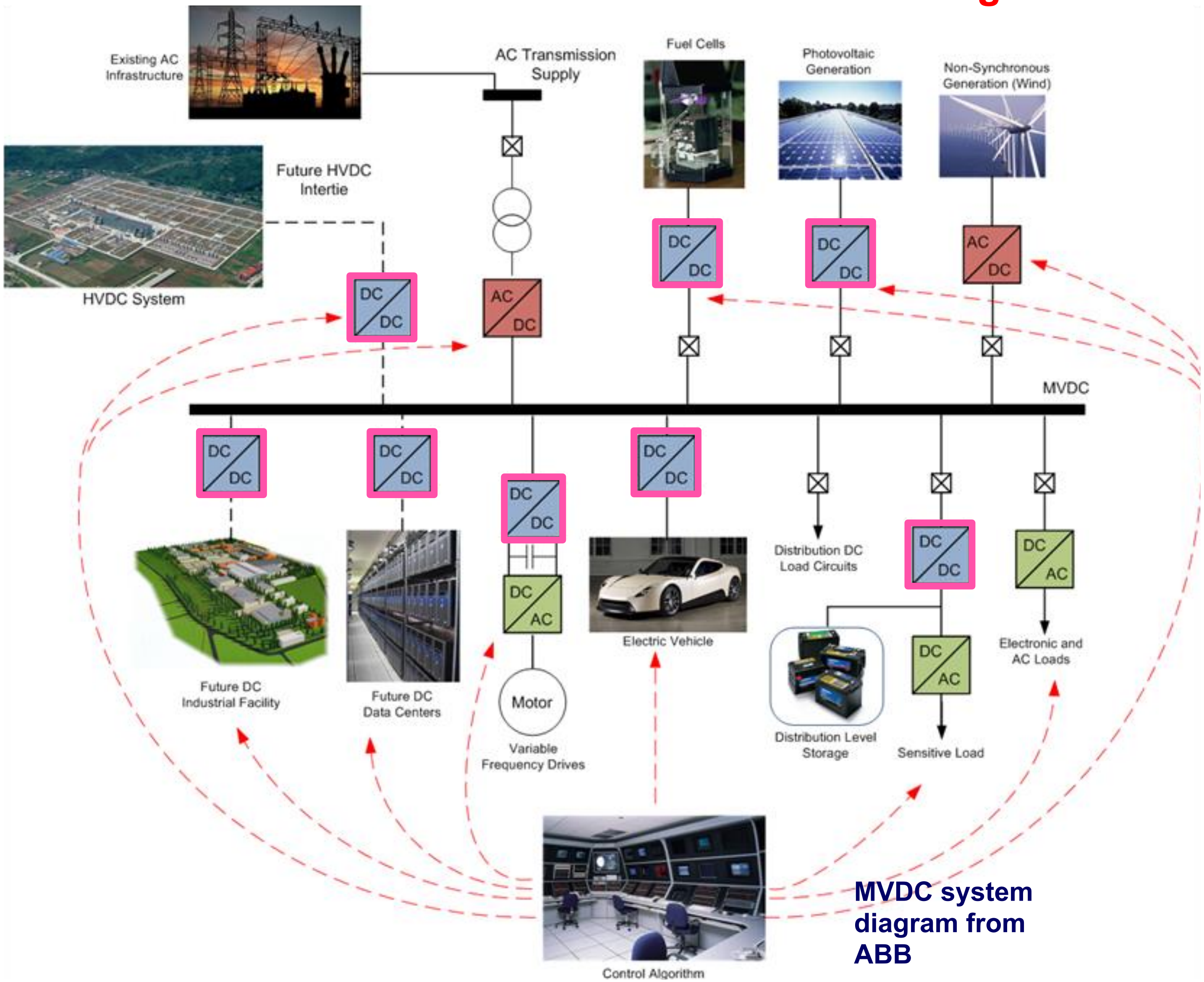
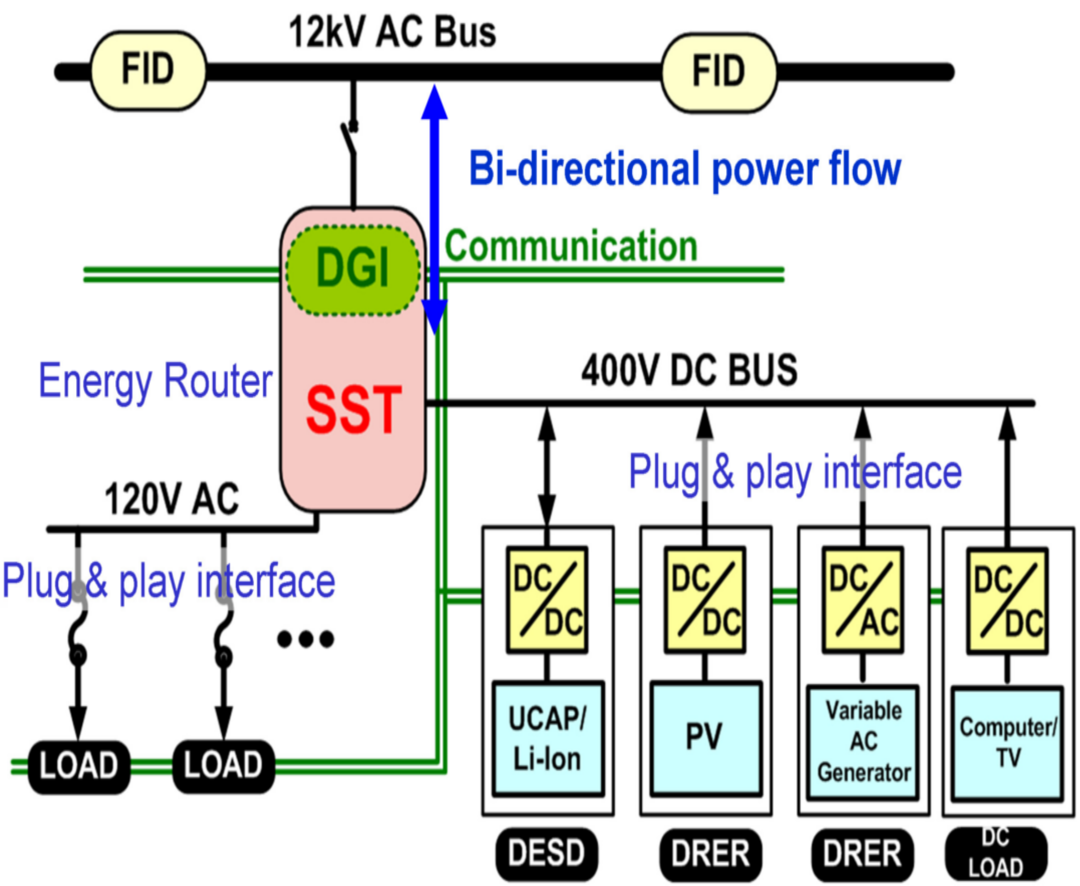
MVDC Application

MVDC Voltage: 10 to 20 kV

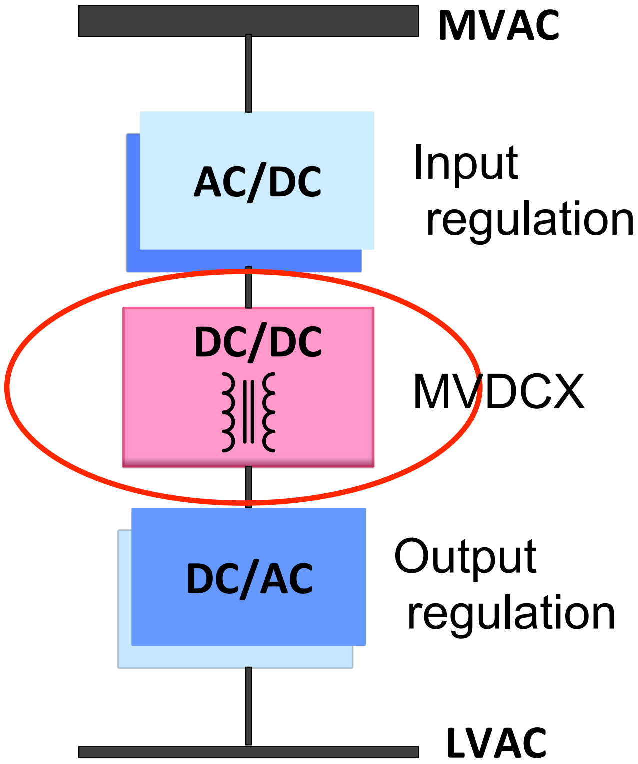


MVDC system diagram from ABB

Solid State Transformer (Smart Transformer, Digital Transformer)



Role of Solid State Transformer (SST) in FREEDM Systems



Three Stage SST

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The impact we can make

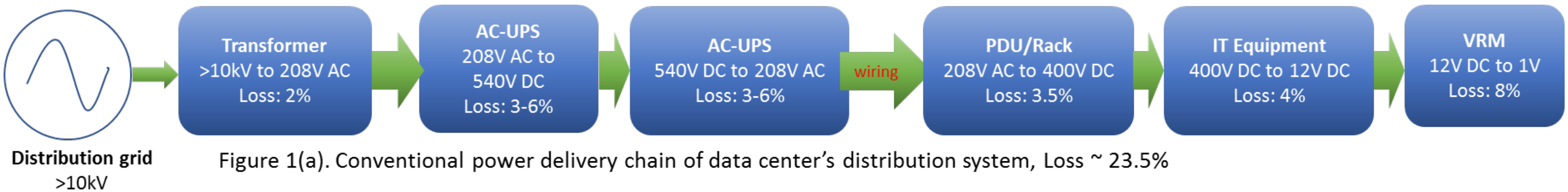


Figure 1(a). Conventional power delivery chain of data center's distribution system, Loss ~ 23.5%

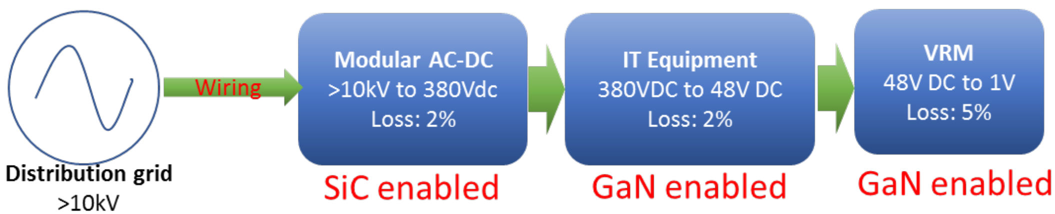
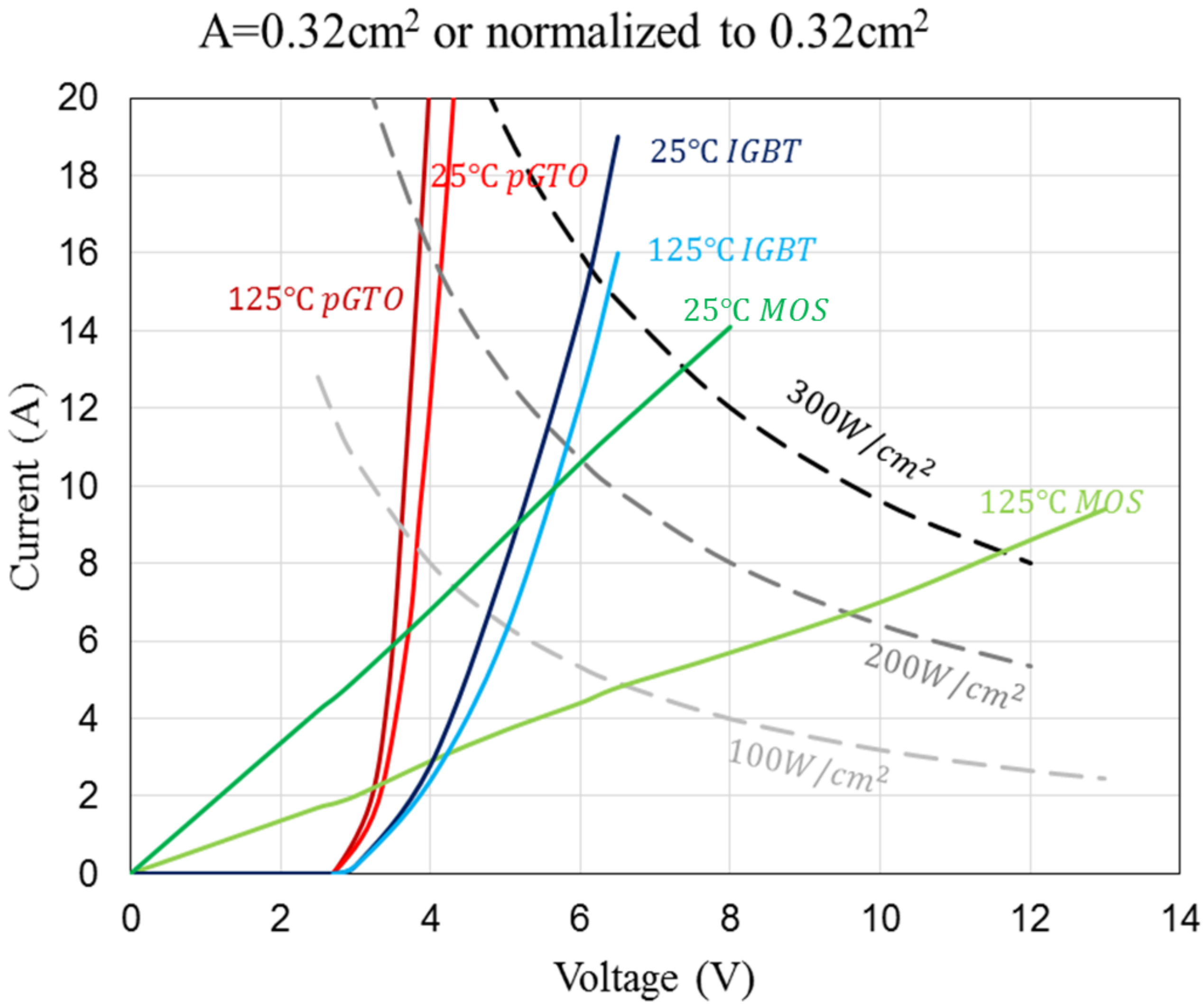


Figure 1(b). Proposed Direct-DC architecture for data center's distribution system. Loss ~ 9%

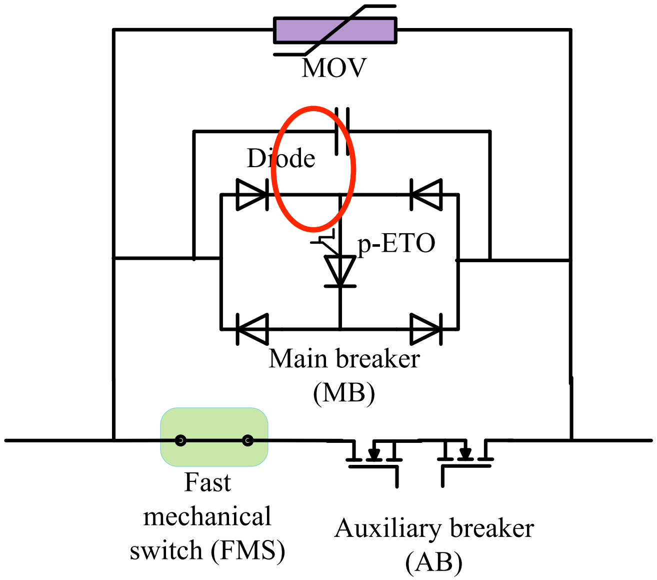
14.5% loss reduction could mean 10 billion kWH of energy saving in US data center along

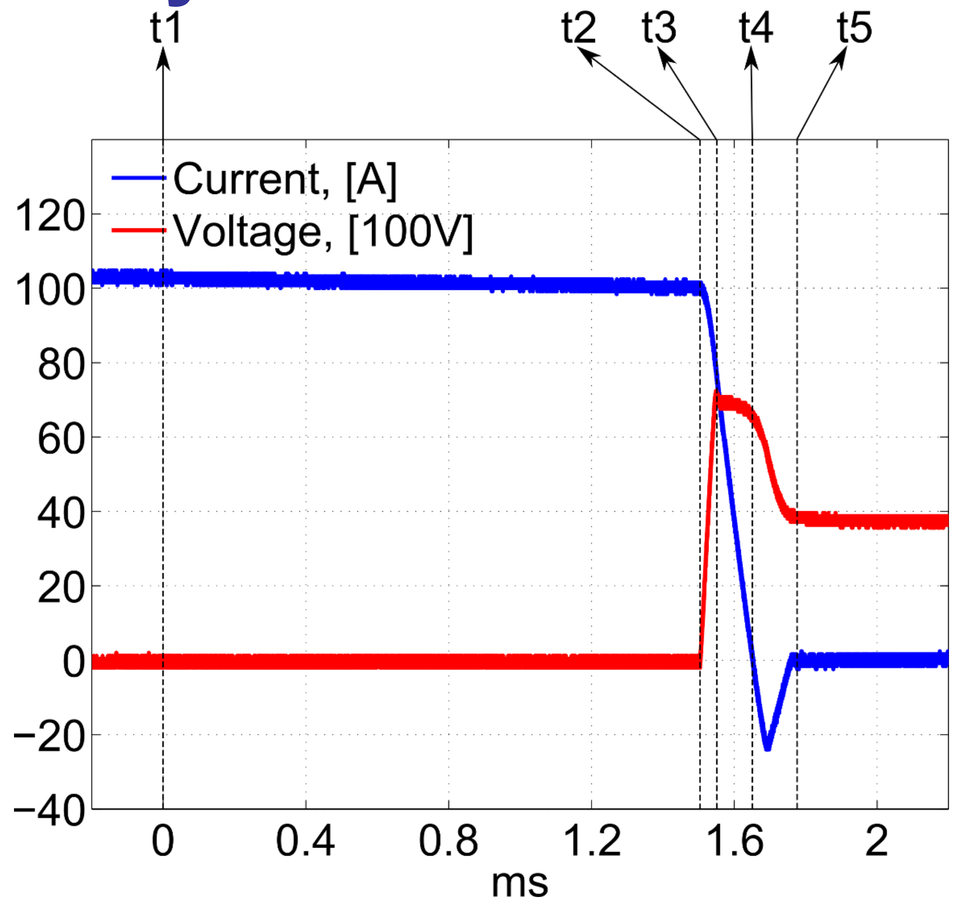
15kV SiC GTO, n-IGBT and MOSFET



SiC bipolar devices are more suitable for high power and high temperature operation

Solid state or hybrid DC circuit breaker





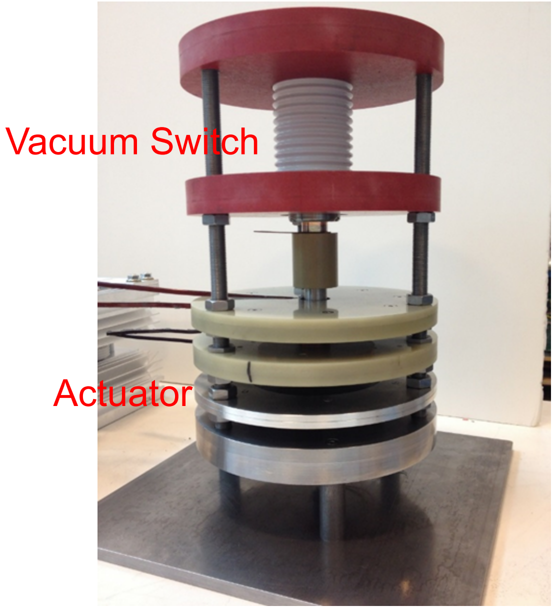
<2 ms interruption time

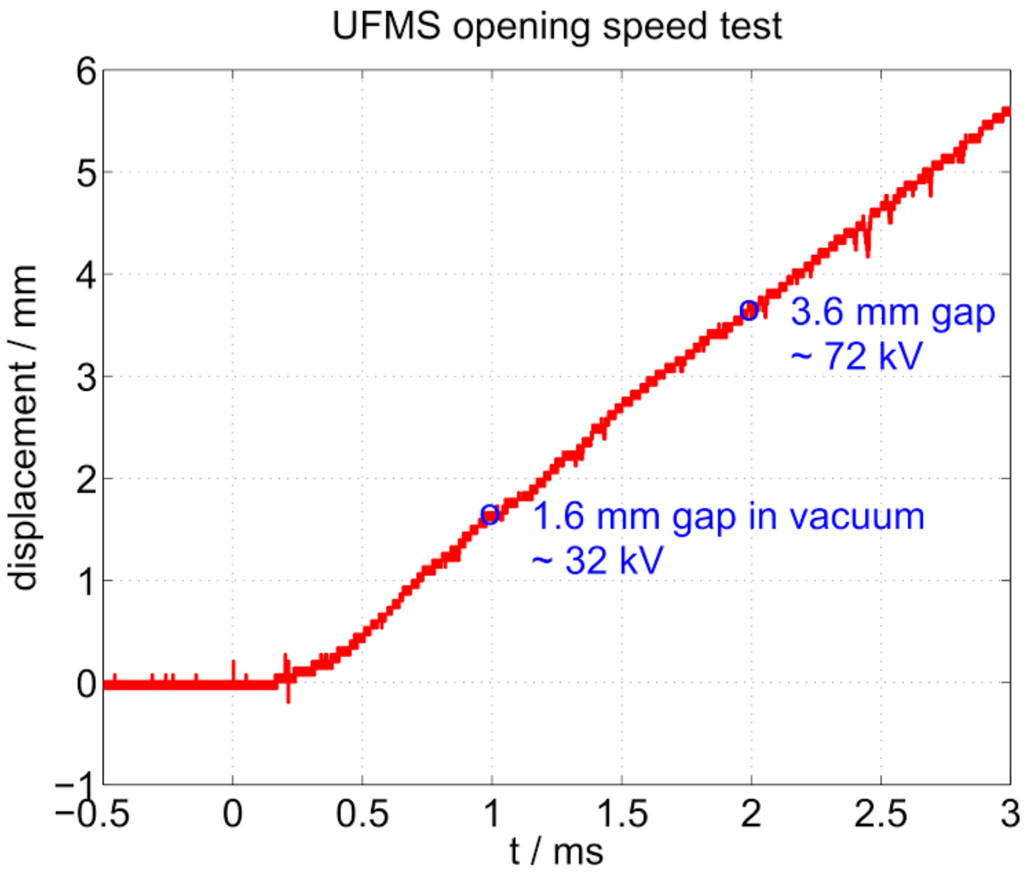
- t1 – t2: mechanical switch delay: 1.5 ms;
- t2 – t3: cap limited dv/dt (100A/0.5 uF~200V/us) rise b/c, ~40 us;
- t3 – t4: MOV clamped at 7 kV, drives current to zero, ~105 us:
- t4 – t5: diode reverse recovery and oscillation, ~100 us.

FMS Based on Thomson Coil

1ms opening speed demonstrated and tested

15 kV/630A FMS based on Thomson coil actuator





*Supported by an associated project. Results published @APEC2015

* Invention disclosure filed at NCSU

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Conclusions

WBG power devices scale the Voltage and Frequency capability well above and beyond Si capability

- **Frequency** scaling in LV power system will substantially improve the power density while maintaining high efficiency
- **Voltage*Frequency** scaling of SiC MOSFET can transformer the MV and HV power delivery system into a smart AC or DC power delivery system
- **Voltage** scaling of SiC Bipolar device can enable future generation of AC and DC circuit breakers

We look forward to the new partnerships