IS2.3-6 Wide Bandgap (WBG) Power Devices for High-Density Power Converters - Excitement and Reality

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APEC 2014, Fort Worth, TX

Industry Session Paper – IS2.3-6

Wednesday , March19, 2014

2:00 pm – 5:30 pm

Implications of WBG Materials on Transportation Power Electronics

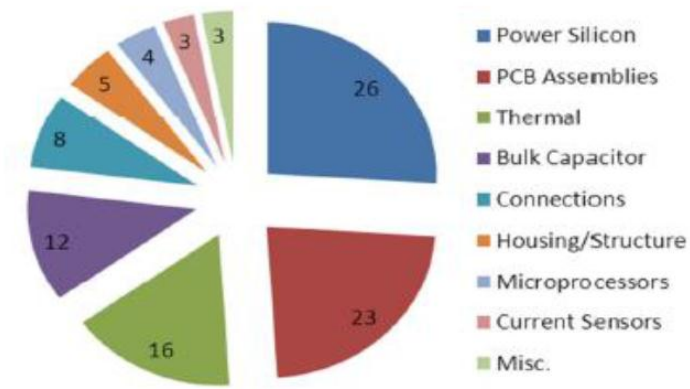
Current state of a traction drive rated at 55 kW peak for 18 sec., 30 kW continuous and 15 years lifetime

Traction Drive System				
Impacts →	Reduce Cost	Reduce Weight	Reduce Volume	Reduce Energy Storage Requirements
Year	Cost ($/kW)	Specific Power (kW/kg)	Power Density (kW/l)	Efficiency
2010*	19	1.08	2.60	>90%
2013	14.8	1.14	3.16	>92%
2015	12	1.17	3.53	>93%
2020	8	1.44	4.00	>94%

Power Electronics		
($/kW)	(kW/kg)	(kW/l)
7.9	10.8	8.7
6.16	11.5	10.7
5	12	12
3.3	14.1	13.4

Electric Motors		
($/kW)	(kW/kg)	(kW/l)
11.1	1.2	3.7
8.64	1.26	4.48
7	1.3	5
4.7	1.6	5.7

Source: DOE VTO



An example of traction inverter cost breakdown

G. Cameron et al, *Proc. EVS26, 2012*

Compact energy-efficient power train and EV charging systems

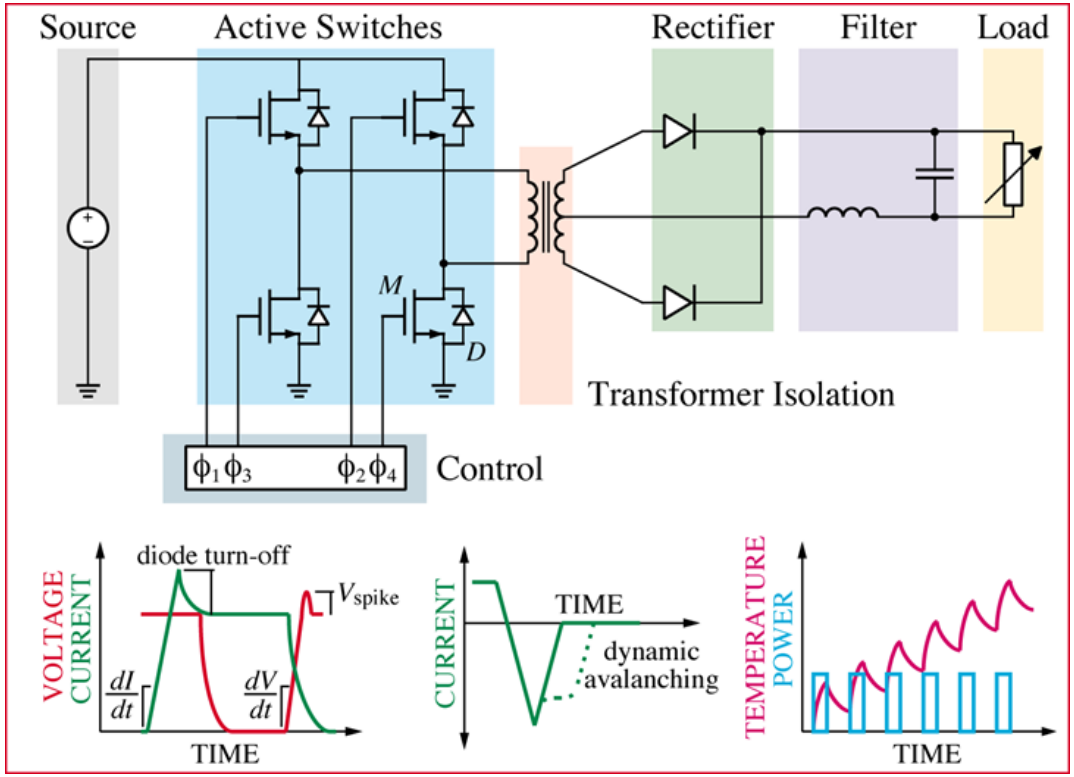
Design for Reliability

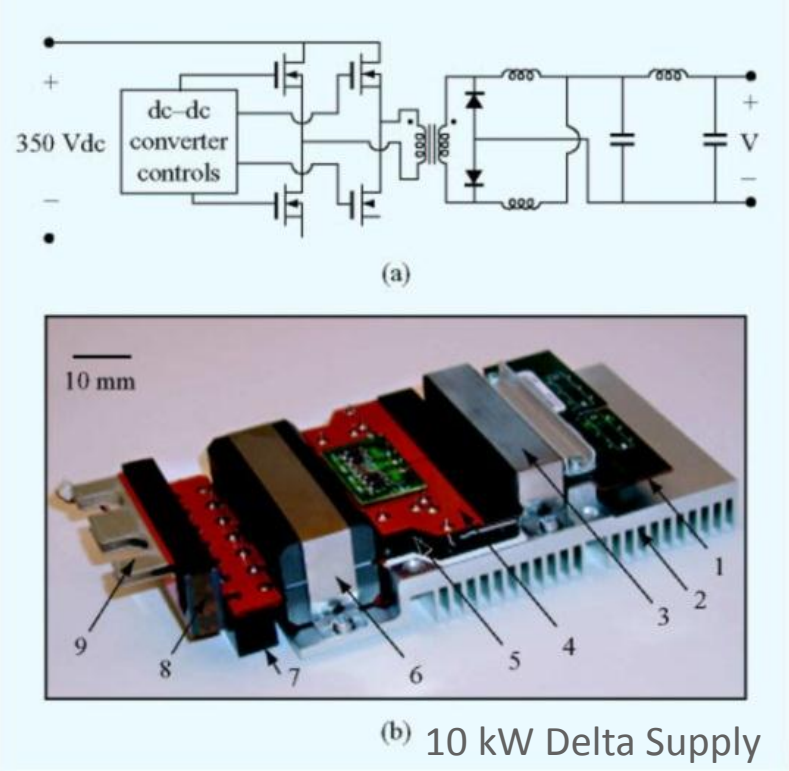
Power Electronics Systems Should be Built-to-Last Under Appropriate Field-Operating Conditions.

WBG data sheet statement:

"This product has not been designed or tested for use in, and is not intended for use in, applications implanted into the human body nor in applications in which the failure of the product could lead to death, personal injury or property damage, including but not limited to equipment used in the operation of nuclear facilities, life-support machines, cardiac defibrillators or similar emergency equipment, aircraft navigation or communication or control systems, air traffic control systems, or weapons systems."

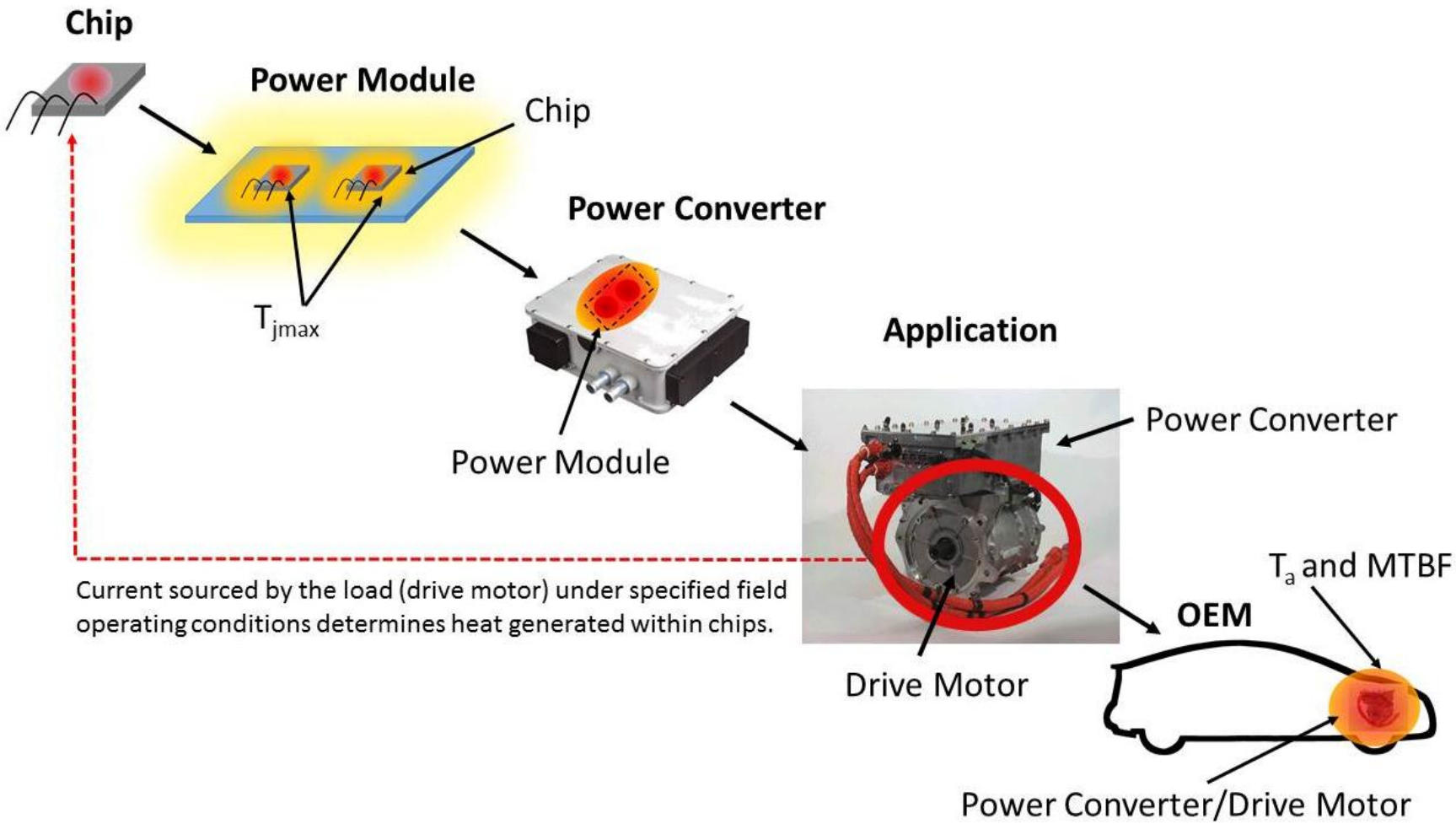
What does this mean?





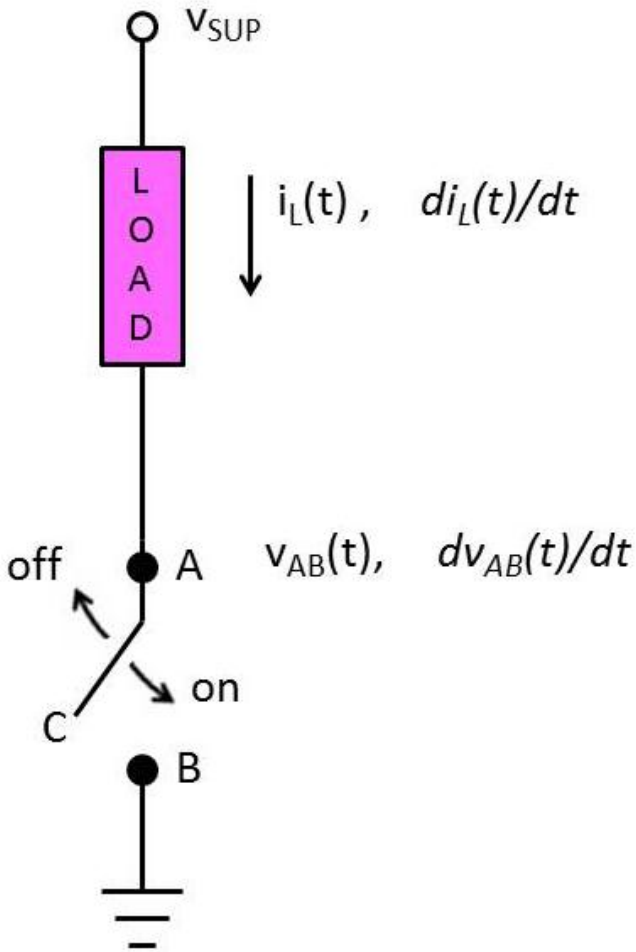
High-end computer server power supplies demand an MTBF ~ 1,000,000 hours

How are today's power converters designed?

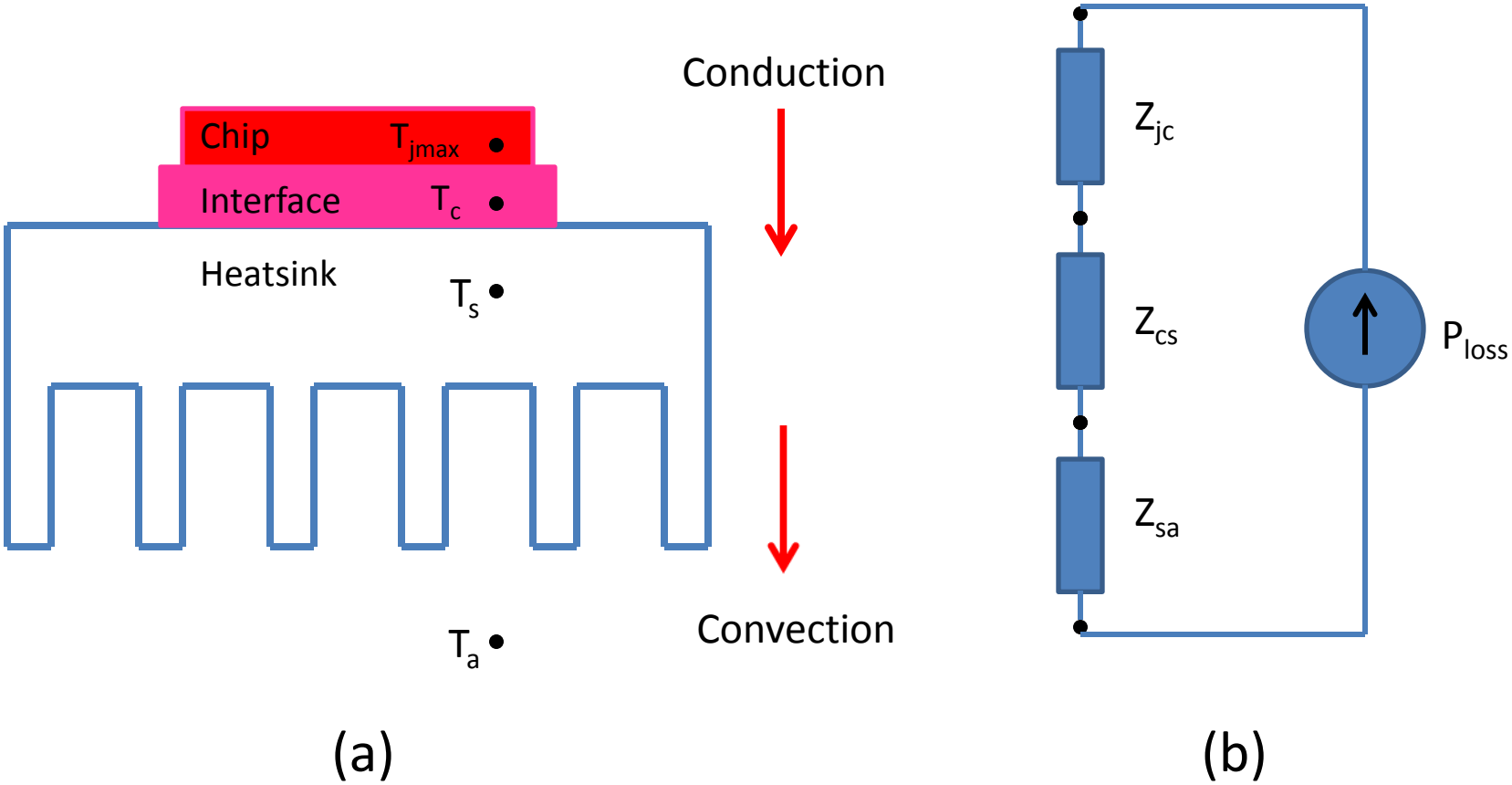


Automotive traction inverters and battery chargers demand MTBF > 500,000 hours

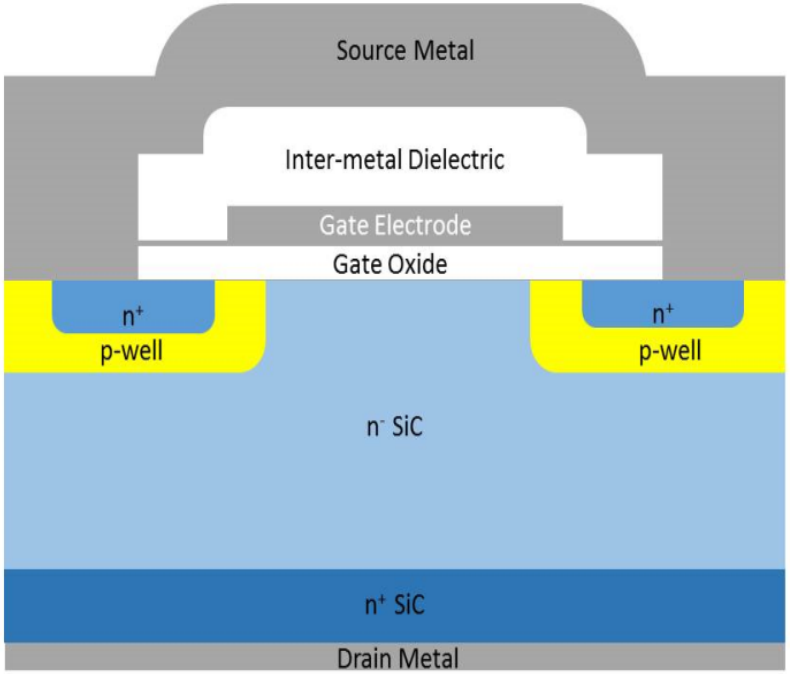
Power Semiconductor Switching Stresses

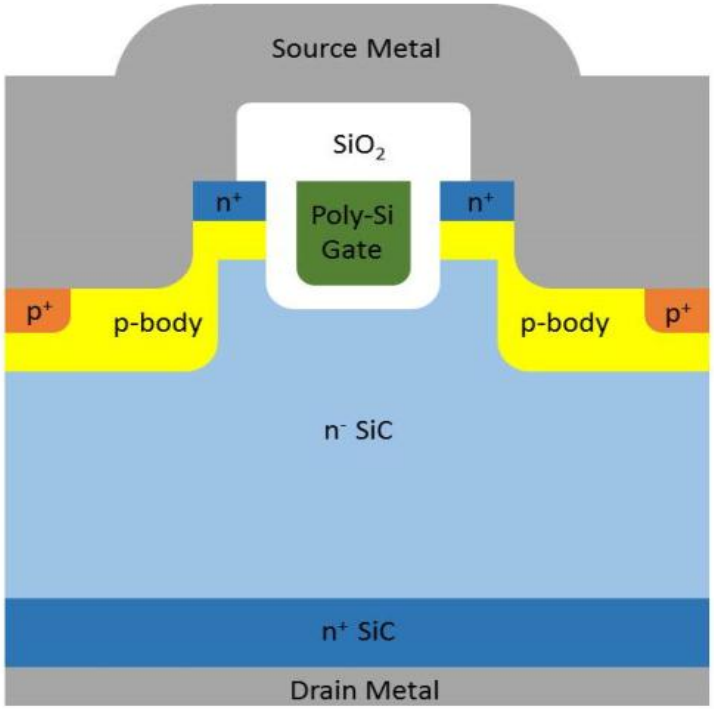


Power Semiconductor Switch Module



“Industry-Best” SiC Power MOSFETs

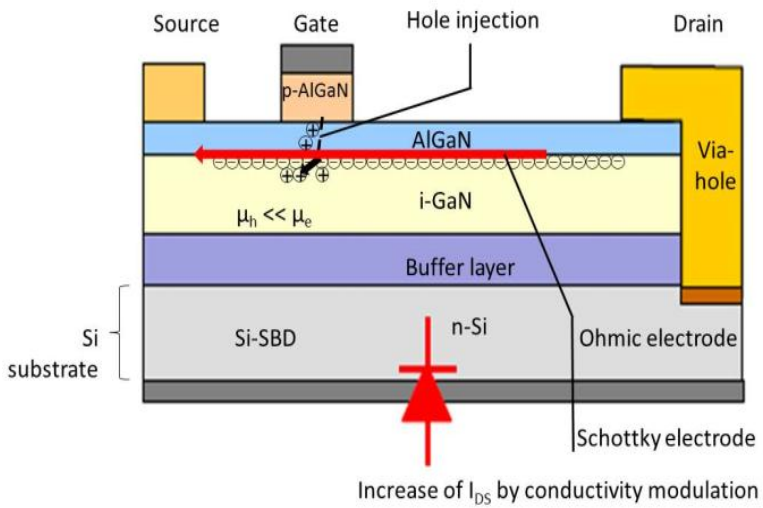


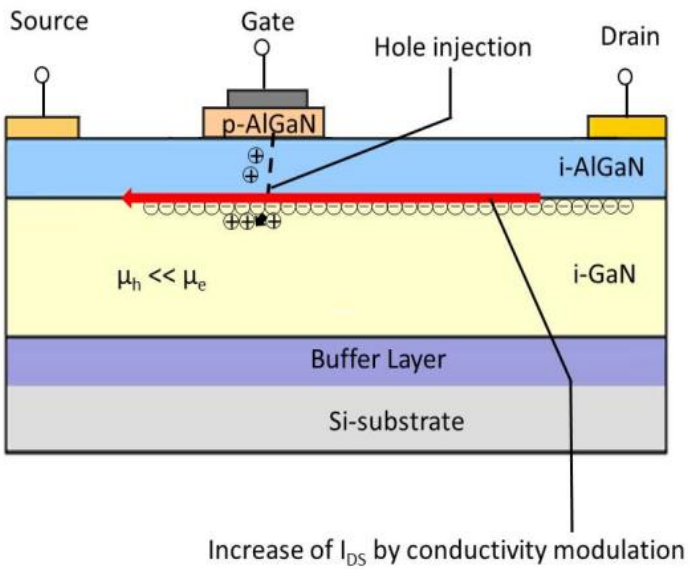


1,200V Cree MOSFET
R_{sp} = 3.7 mΩ.cm^2

1,200V Rohm MOSFET
R_{sp} = 2.6 mΩ.cm^2

“Industry-Best” GaN Power Switches

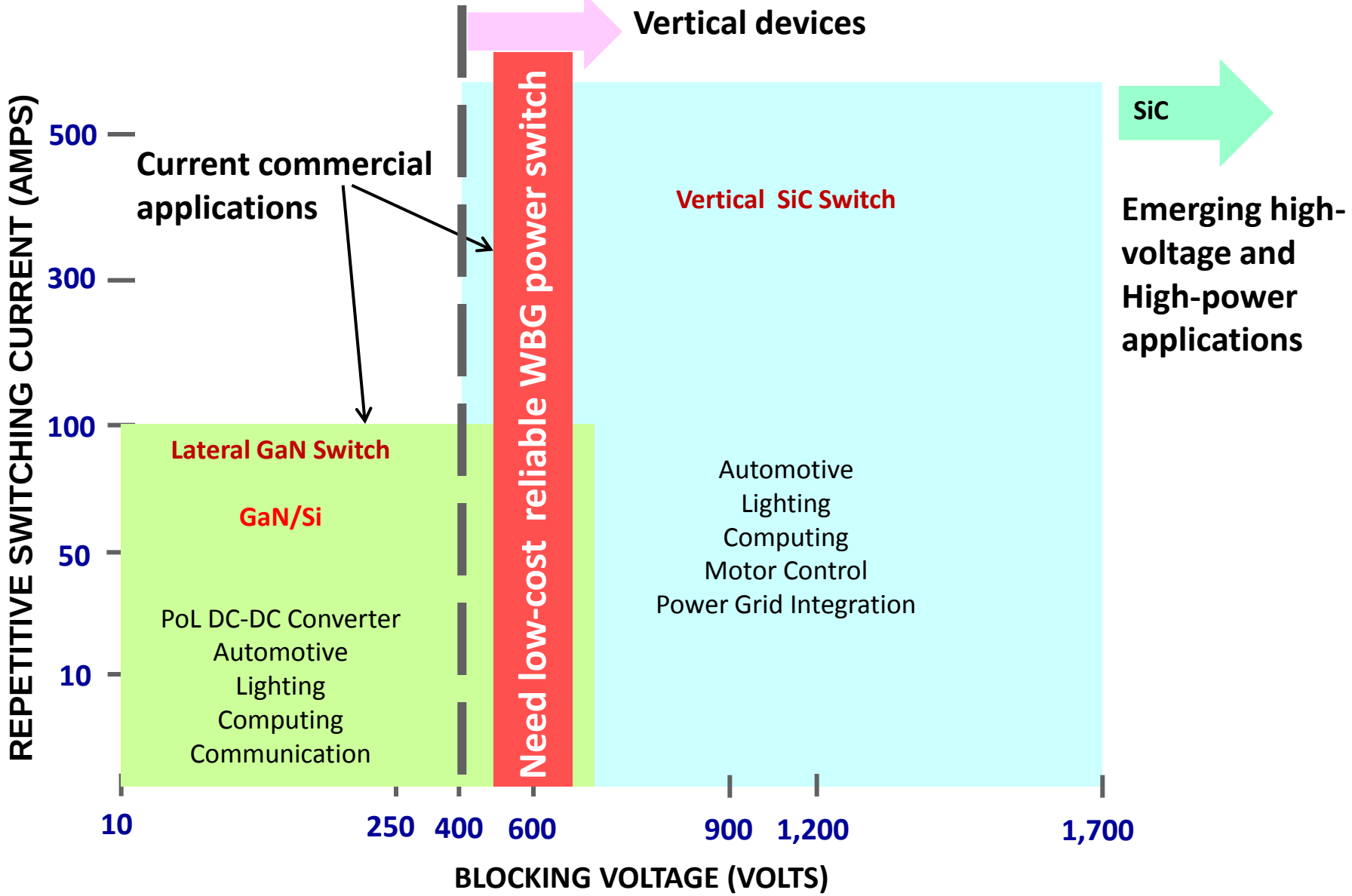




600V Panasonic GIT

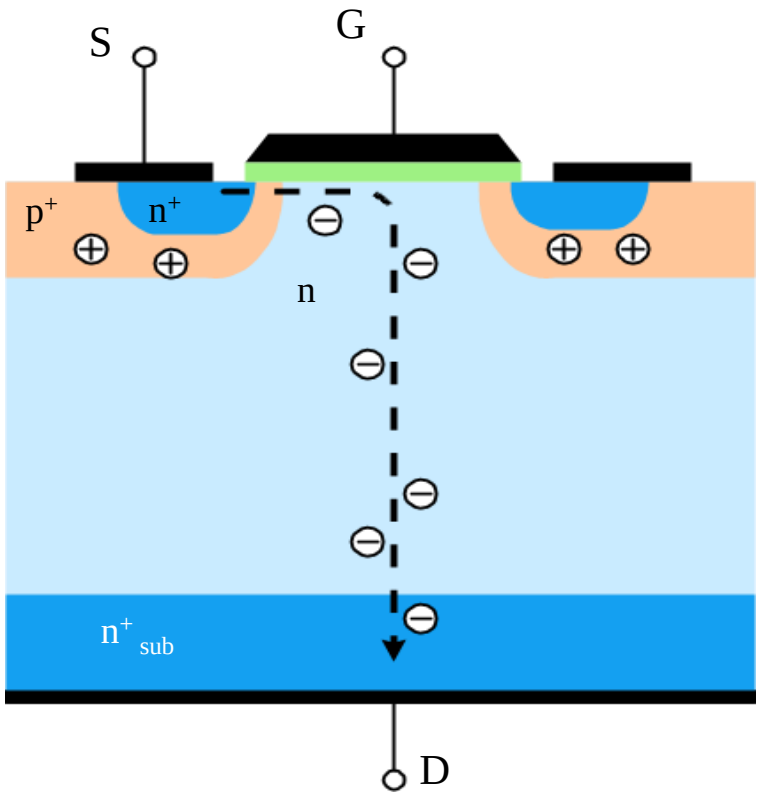
R_{sp} = 2.5 mΩ.cm²

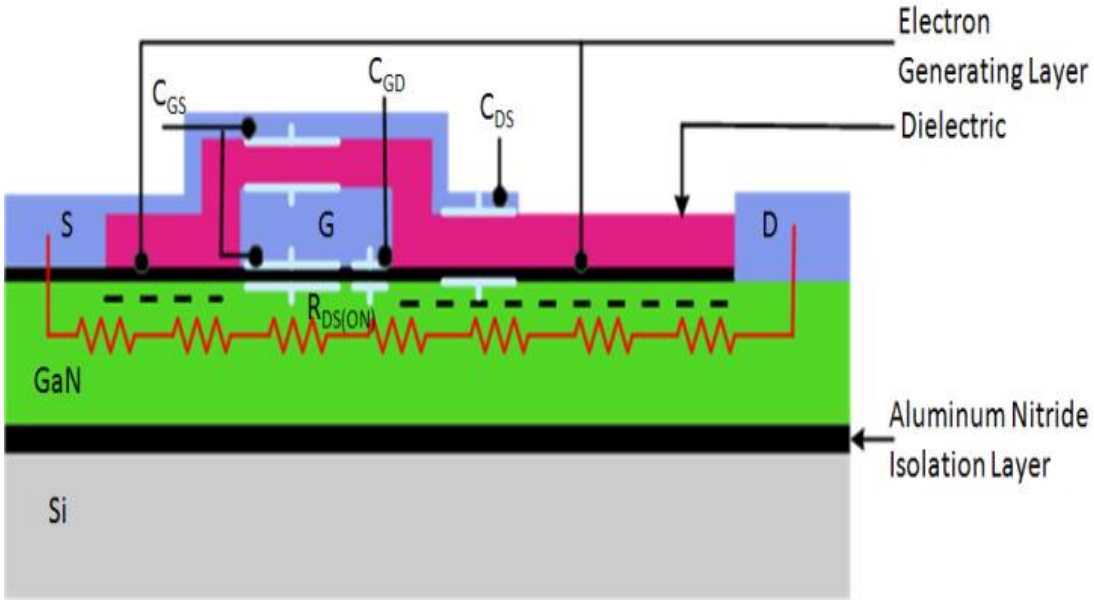
WBG Power Technology Roadmap



SiC and GaN power devices will make converters more compact and energy-efficient, and will enable new applications

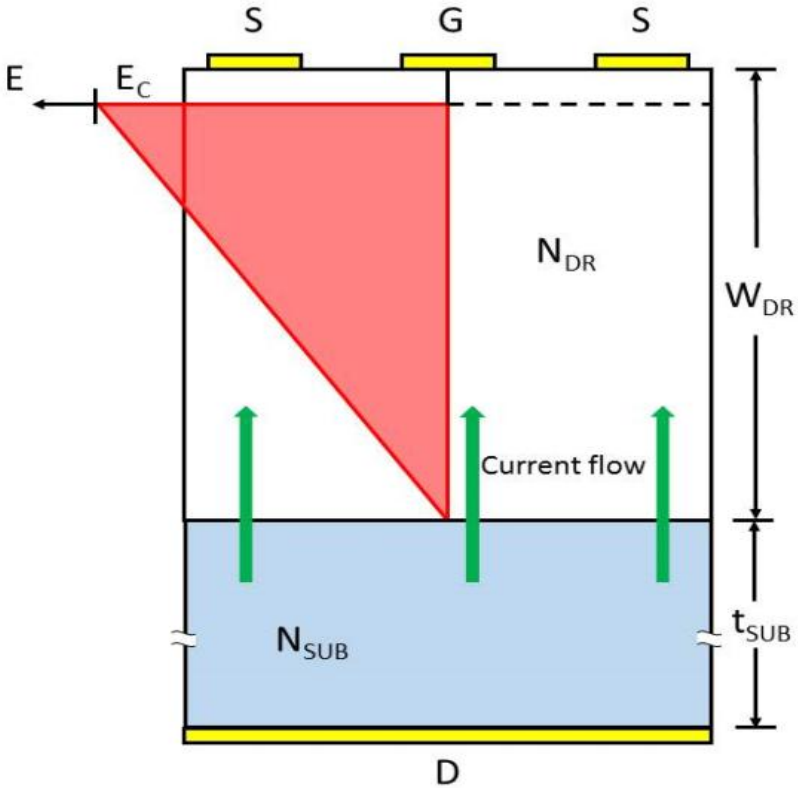
Vertical vs. Lateral Power Switches

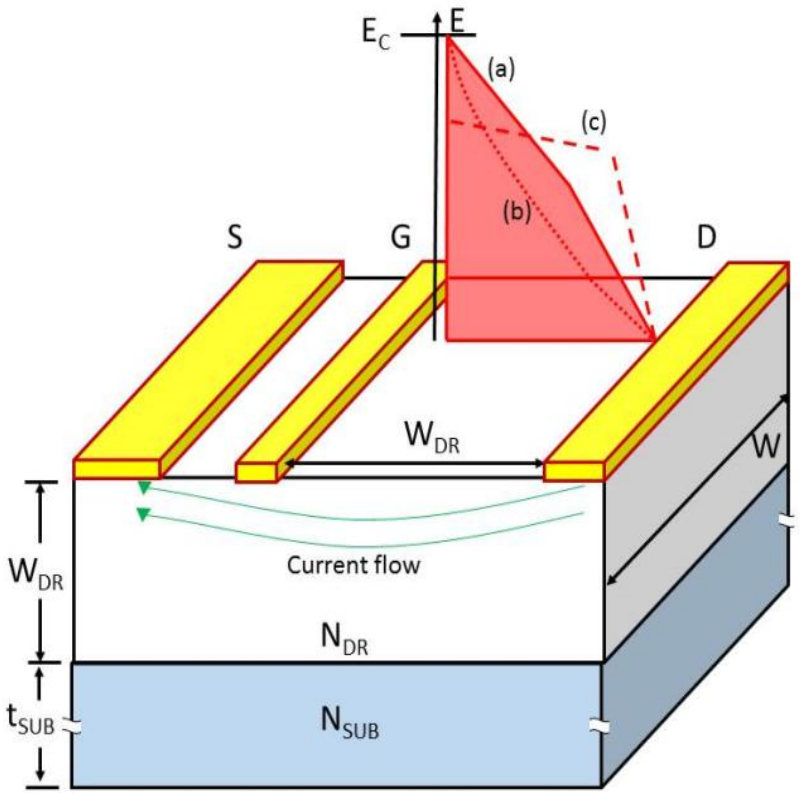




Vertical **Lateral**

Unipolar Power Switch





Vertical **Lateral**

“Industry Standard”

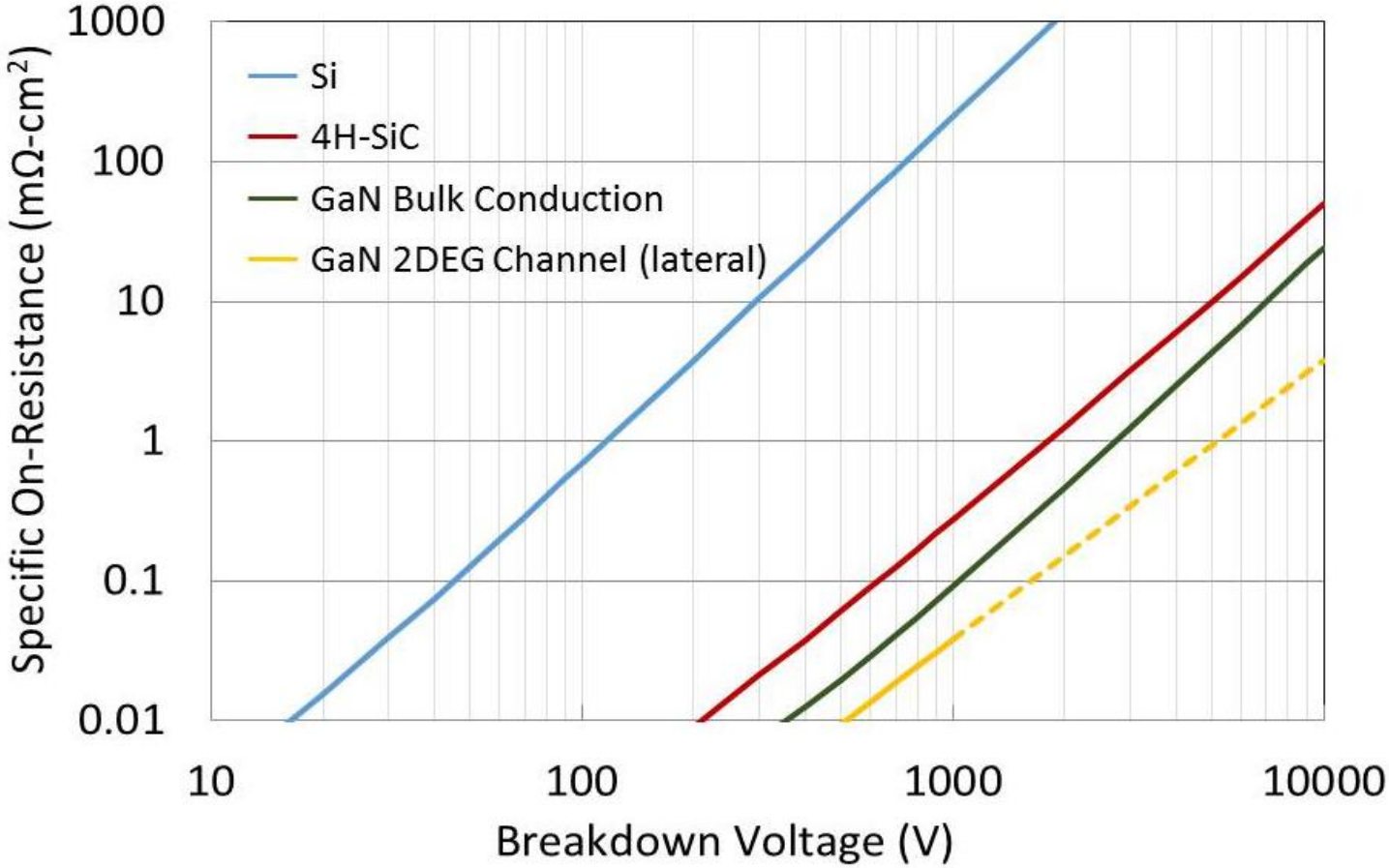
$$R_{sp} = \frac{4V_B^2}{\varepsilon_s \mu E_c^3} \qquad (1a)$$

$$Q_g = C_{iss} V_{gs} \qquad (1b)$$

$$R_{spl} = \frac{V_B^2}{q\mu_s n_s E_c^2} \qquad (3)$$

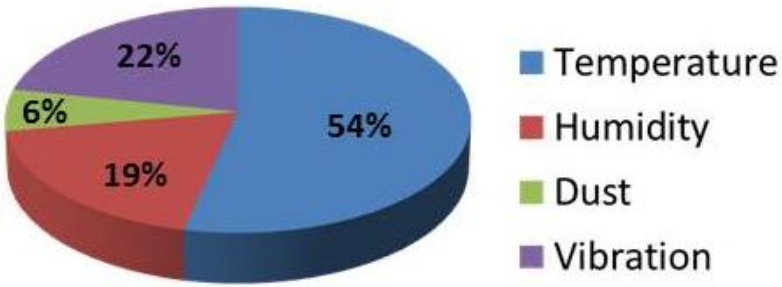
K. Shenai et al, *IEEE Electron Device Letters,* vol. 35, no. 12, p. 2459, Dec. 1988

Specific On-State Resistance

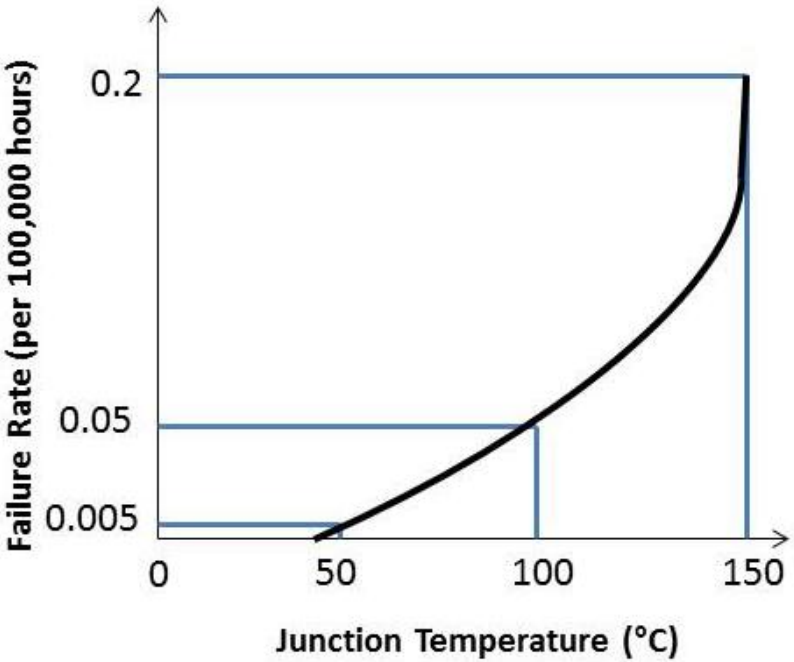


K. Shenai et al, *IEEE Trans. Electron Devices,* vol. 36, no. 9, pp. 1811-1823, Sep. 1989

Thermal Failures in Electronics



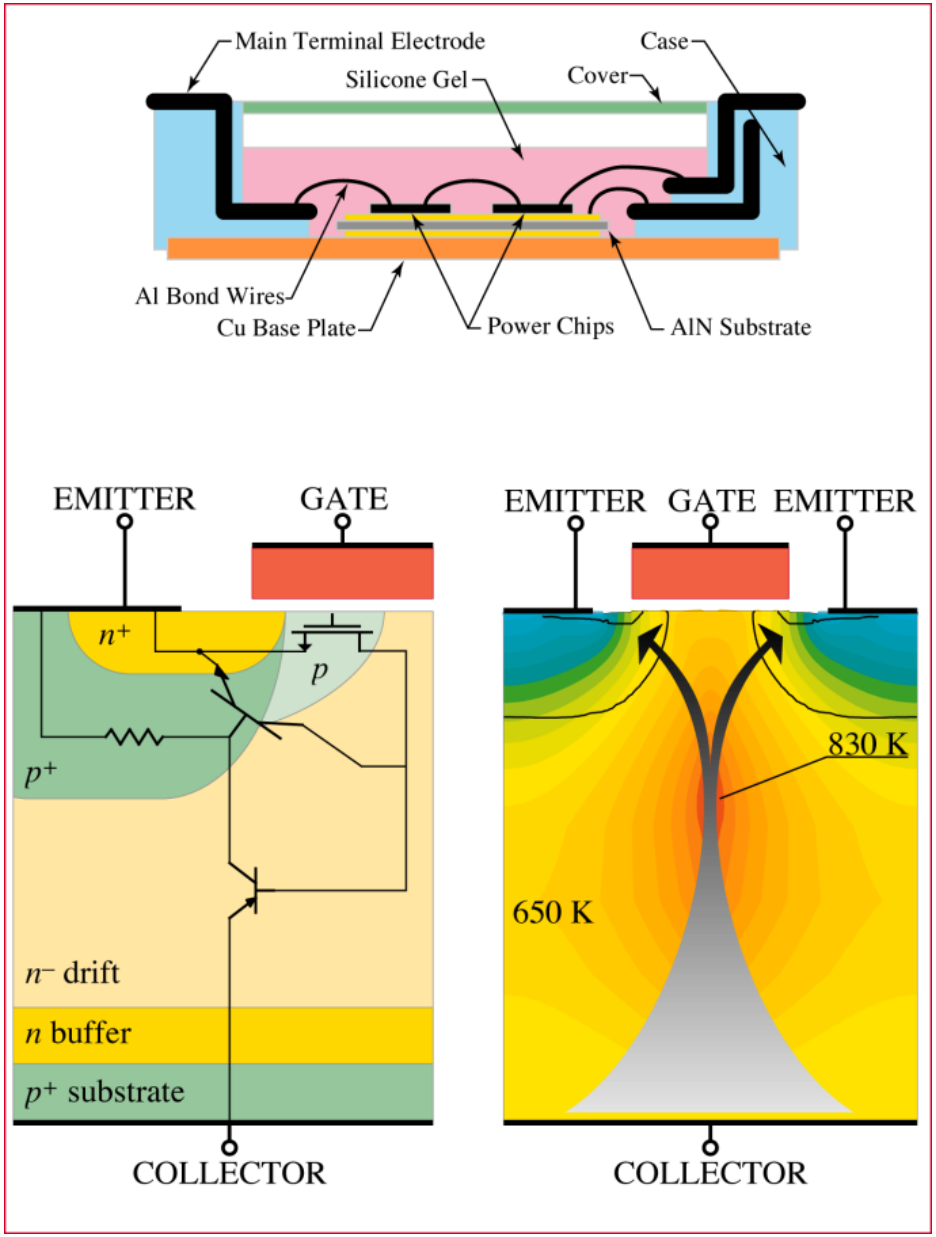
(a)



(b)

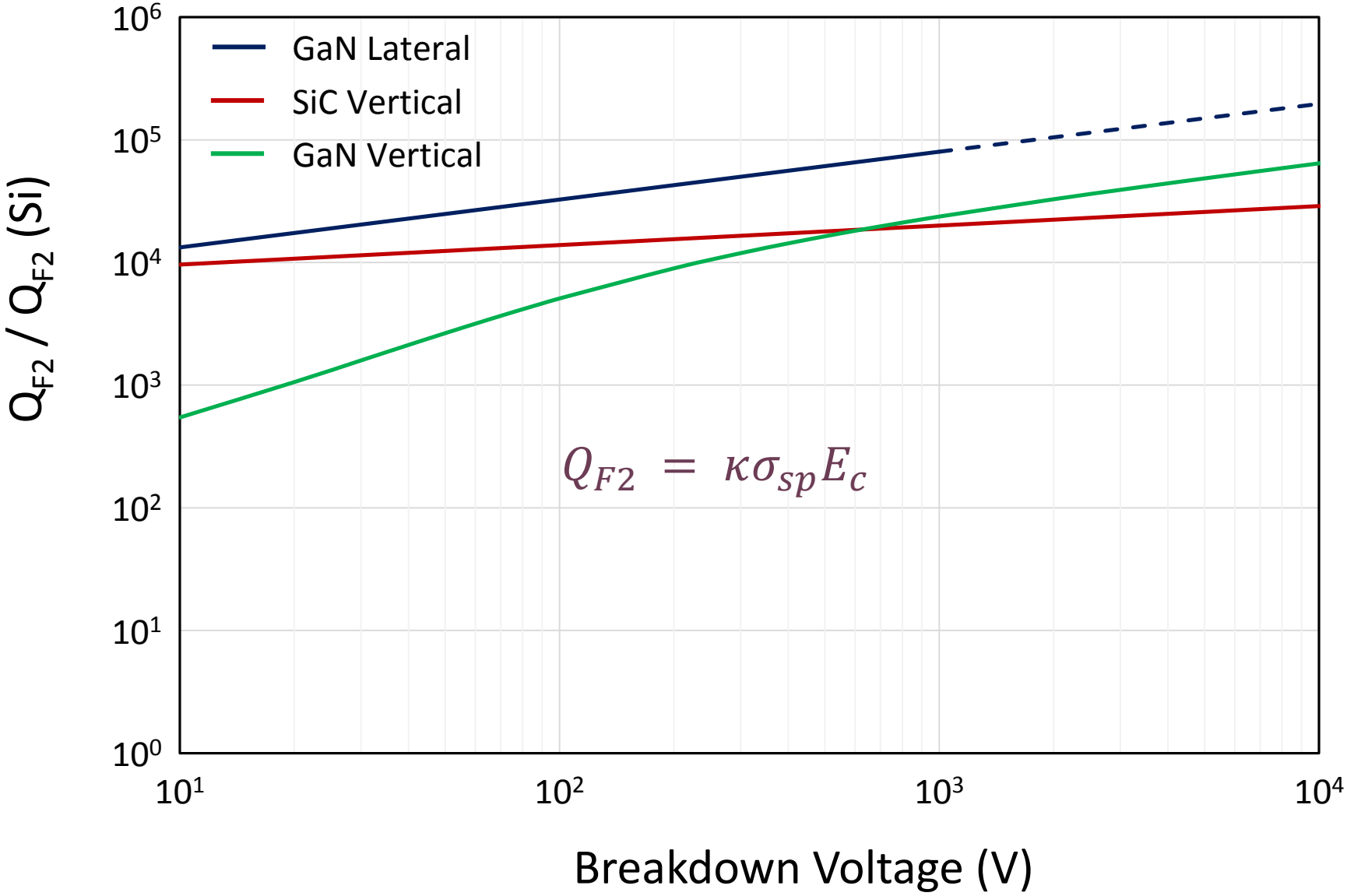
Avionics Integrity Program (AVIP), MIL-STD-1796A (USAF), October 13, 2011

Localized Failure in Power Semiconductors



M. Trivedi and K. Shenai, *IEEE Trans. PELS,* vol. 14, no. 1, pp. 108-116, Jan. 1999

Thermal "Figure of Merit"



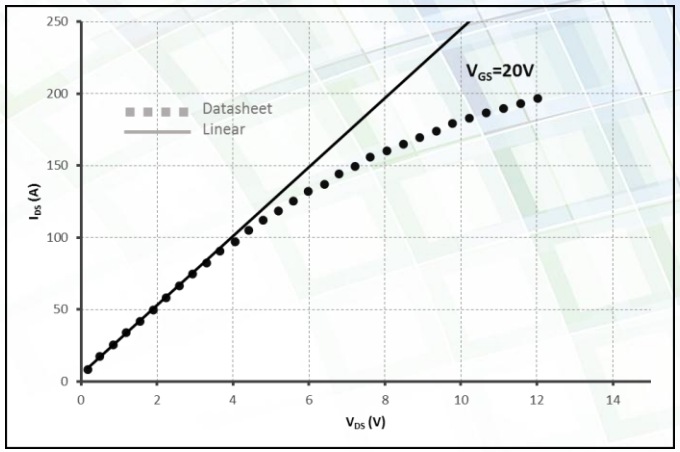
K. Shenai et al, *ECS J. Solid State Sci. & Technol.*, vol. 2, no. 8, pp. N3055-N3063, Jul. 2013

Why WBG Power Semiconductors are not in the Transportation Sector?

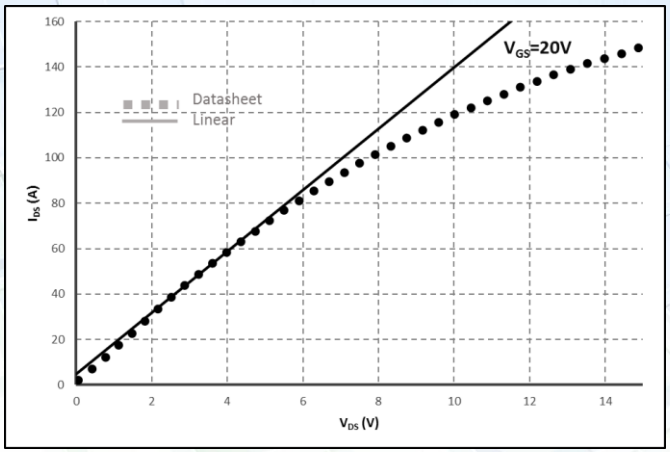
- Reality !

On-State Resistance

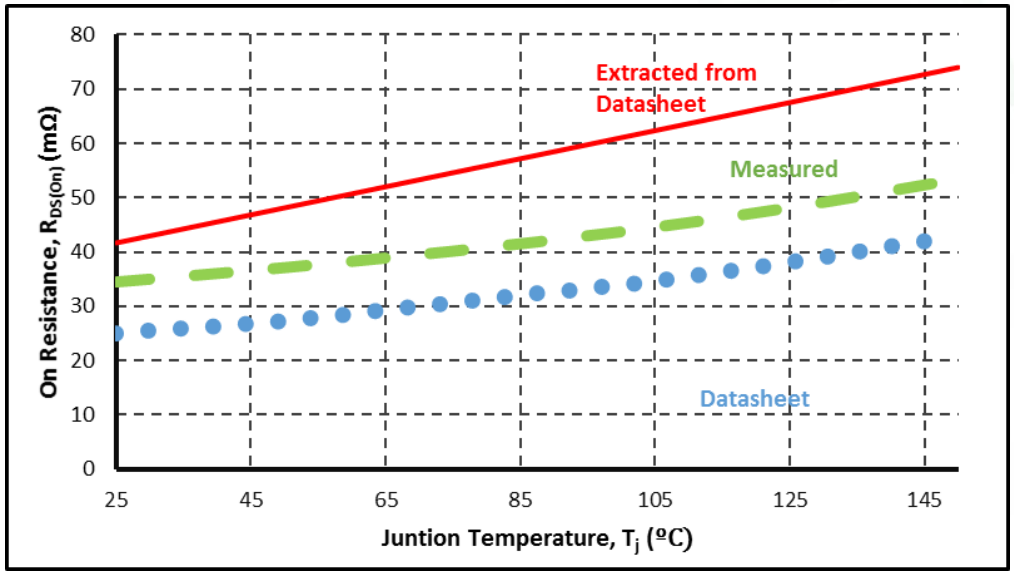
C2M0080120D



Typical Output Characteristic (T_j = 25° C)



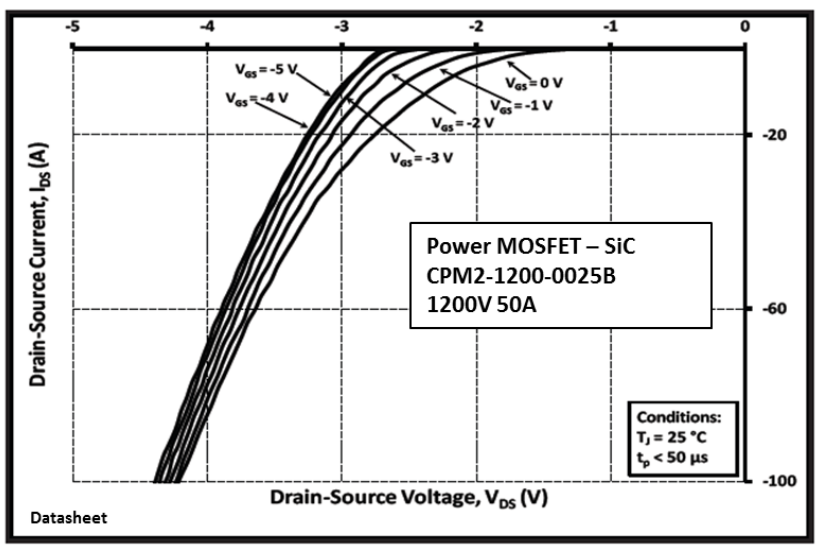
Typical Output Characteristic (T_j = 150° C)

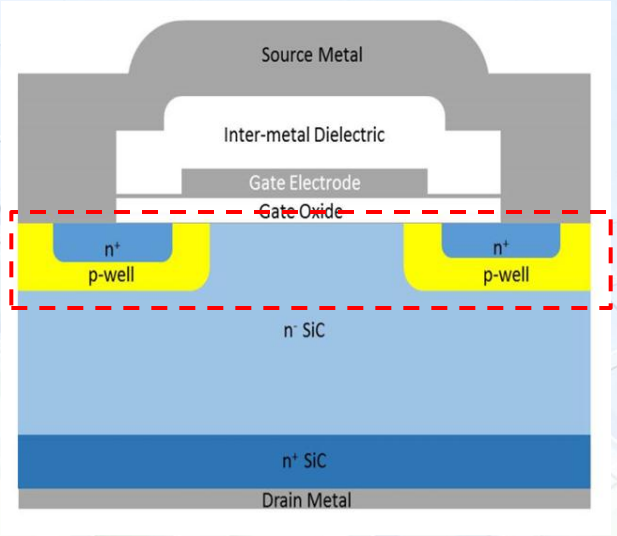


On Resistance vs. Temperature (V_{GS} = 20 V)

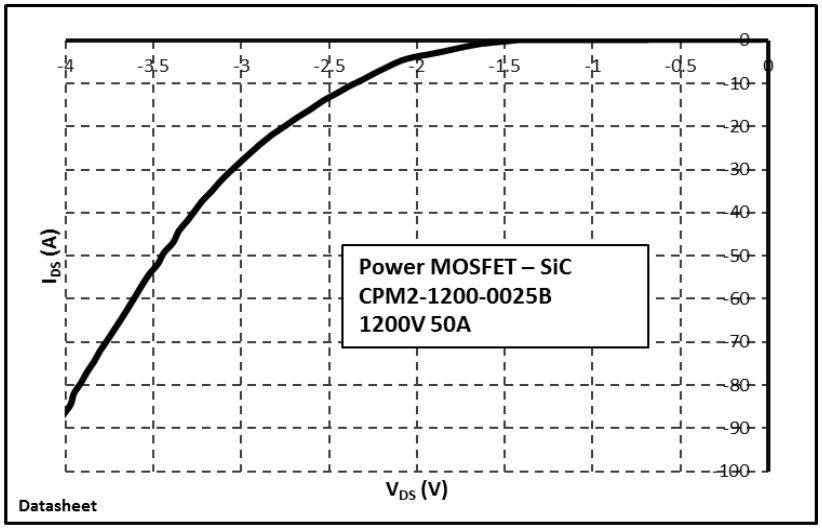
On-resistance data is inconsistent with I-V data

Body Diode Characteristics

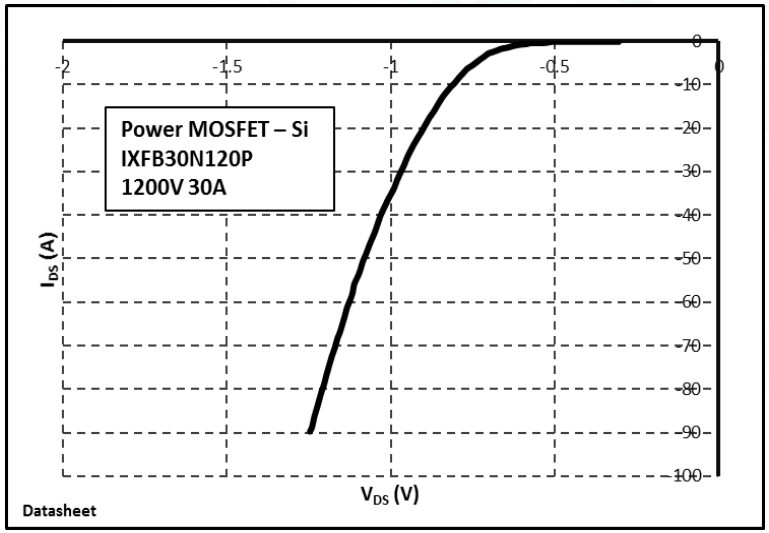




Strong indication of the Influence of gate oxide charge

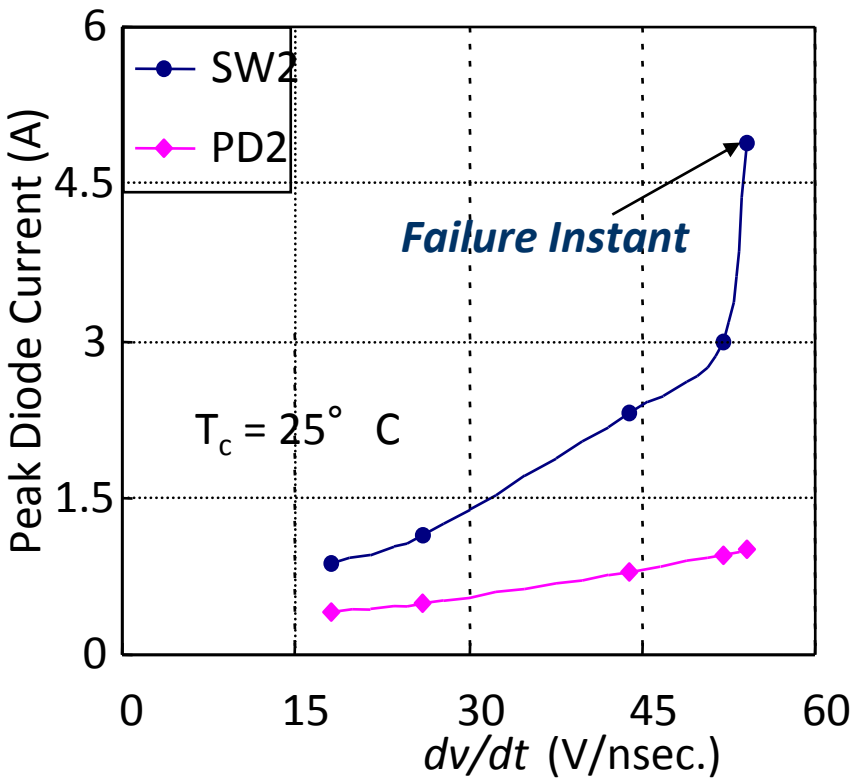


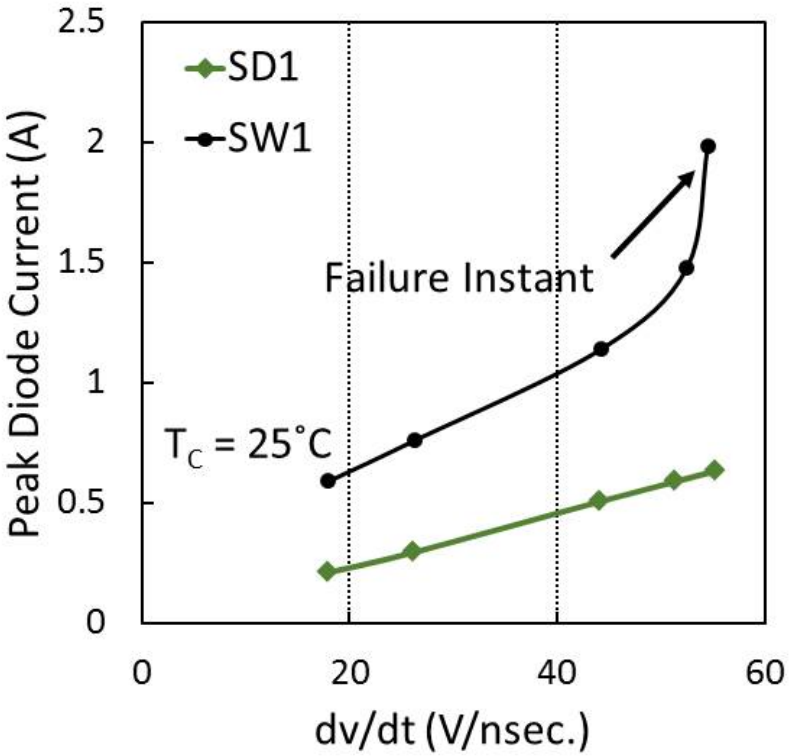
Typical Body Diode Characteristic (T_j = 25° C)



Typical Body Diode Characteristic (T_j = 25° C)

Measured *dv/dt* of SiC Power Diodes





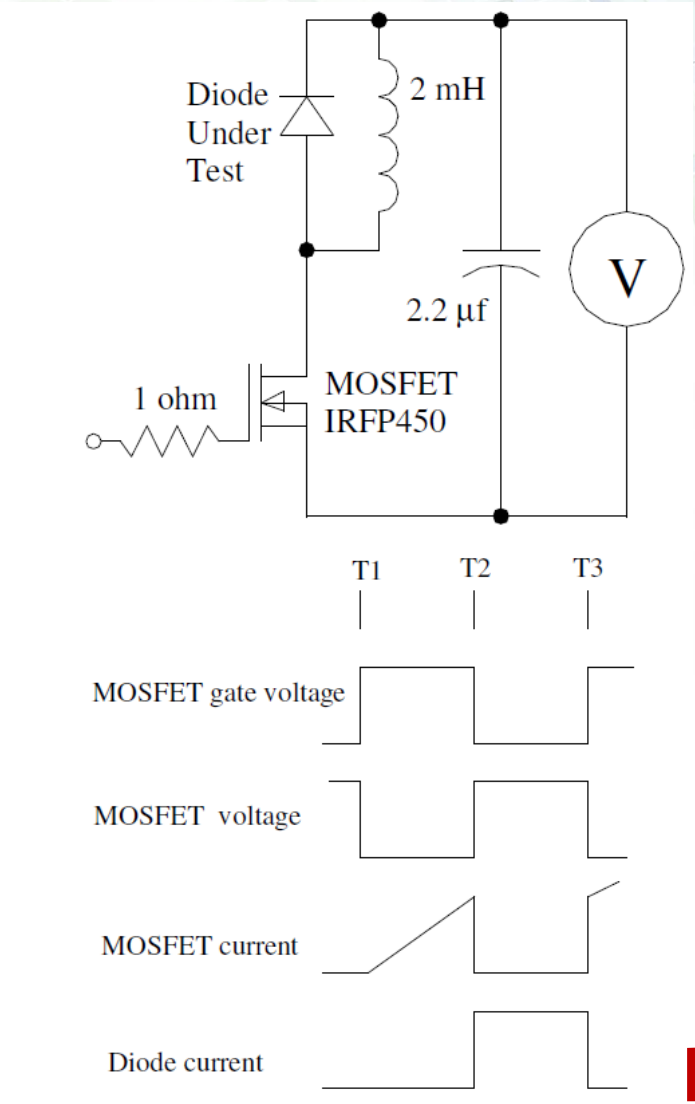
SW2: 600V/6A 4H-SiC JBS diode
PD2: 600V/8A silicon MPS diode

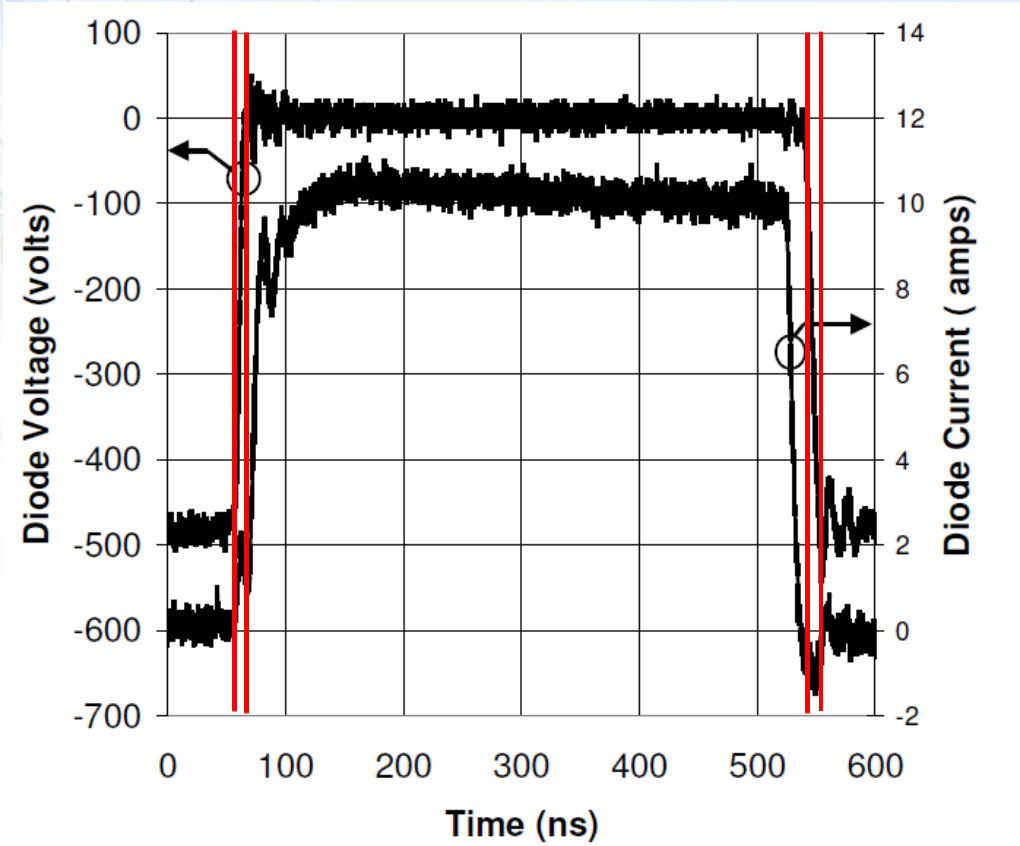
SD1: 300V/10A 4H-SiC JBS diode
SW1: 200V/12A silicon MPS diode

WBG data sheets do not provide *dv/dt* ratings

K. Acharya and K. Shenai, *Power Electronics Technology,* pp. 672-677, Oct. 2002

Manufacturer Report on *dv/dt*

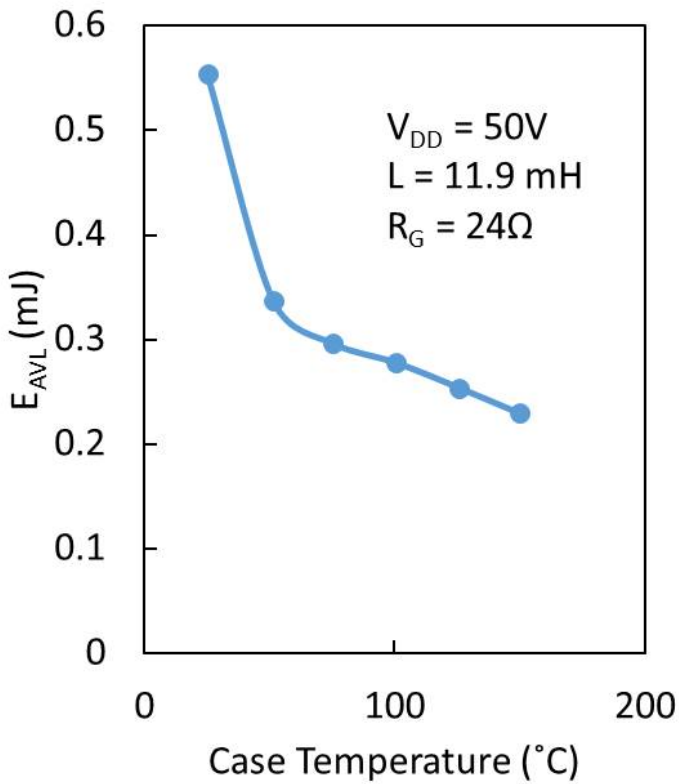




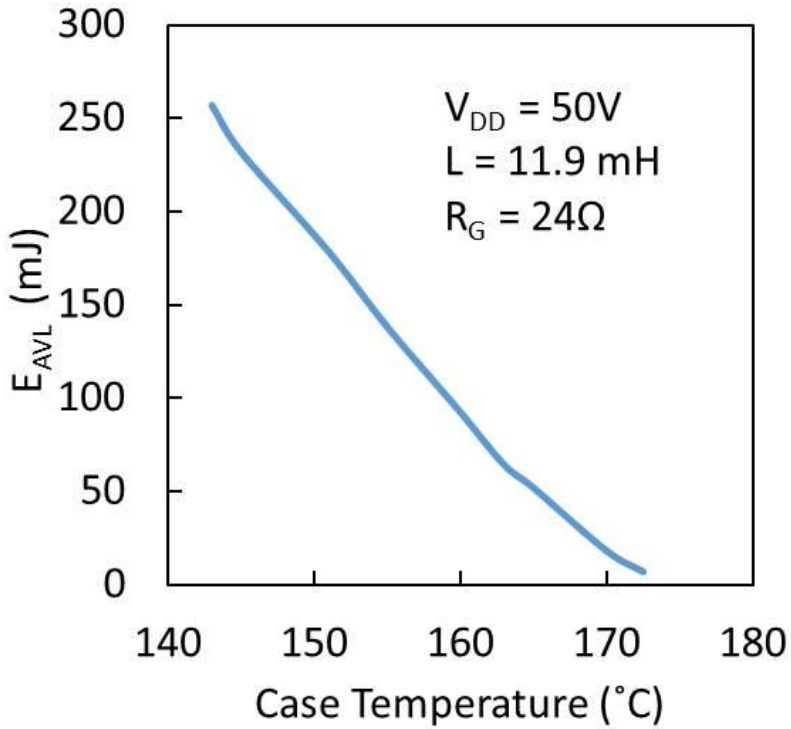
Turn-on *dv/dt* = 75 V/ns
Turn-off *dv/dt* = 100 V/ns
Cree Report # CPWR-RS01, Rev A

Does not make any sense!

Measured Avalanche Energy of Diodes



600V/8A 4H-SiC JBS diode



600V/6A silicon MPS diode

WBG data sheets do not provide *avalanche energy* ratings

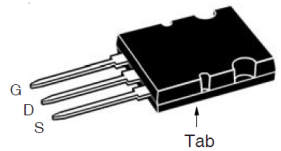
K. Shenai et al, *Proc. IEEE*, Jan. 2014

Safe Operating Area (SOA)

IXFB30N120P

V_{DSS} = 1200V
I_{D25} = 30A
$R_{DS(on)}$ ≤ 350mΩ
t_{rr} ≤ 300ns

PLUS264™

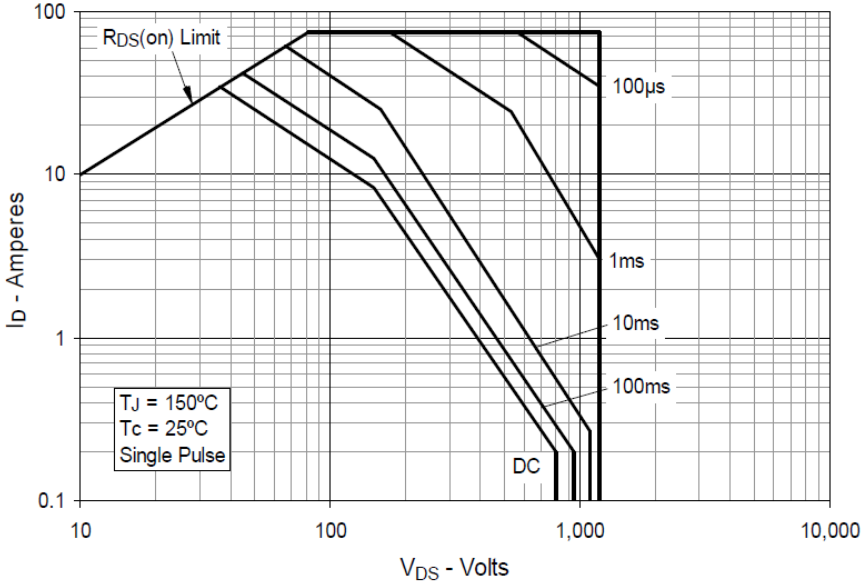


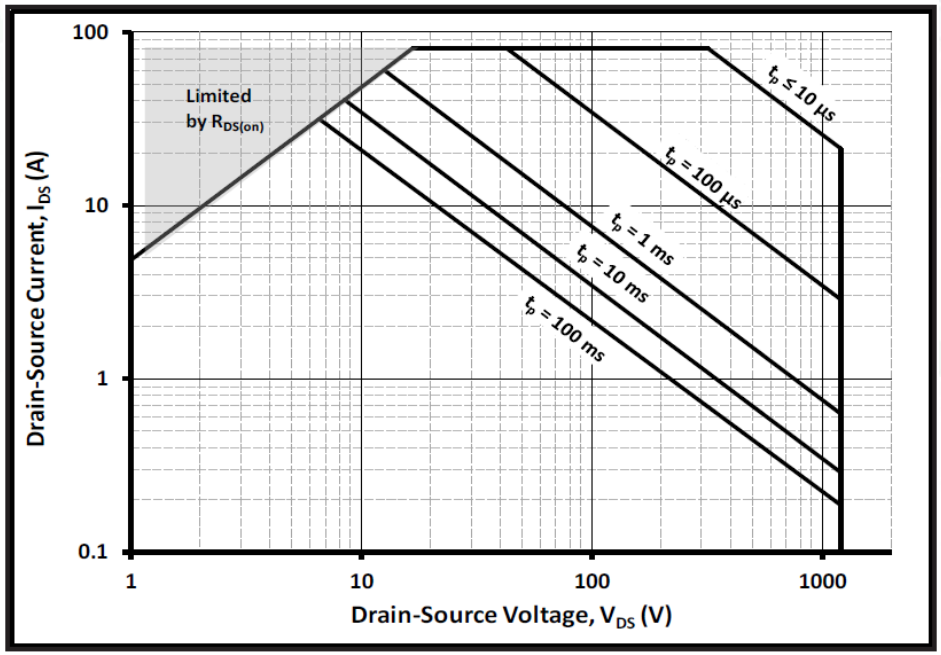
C2M0080120D

V_{DS}	1200 V
I_D @ 25°C	31.6 A
$R_{DS(on)}$	80 mΩ

TO-247-3

Why SiC SOA is smaller than silicon?





Silicon Carbide MOSFET Gate Oxide Failures

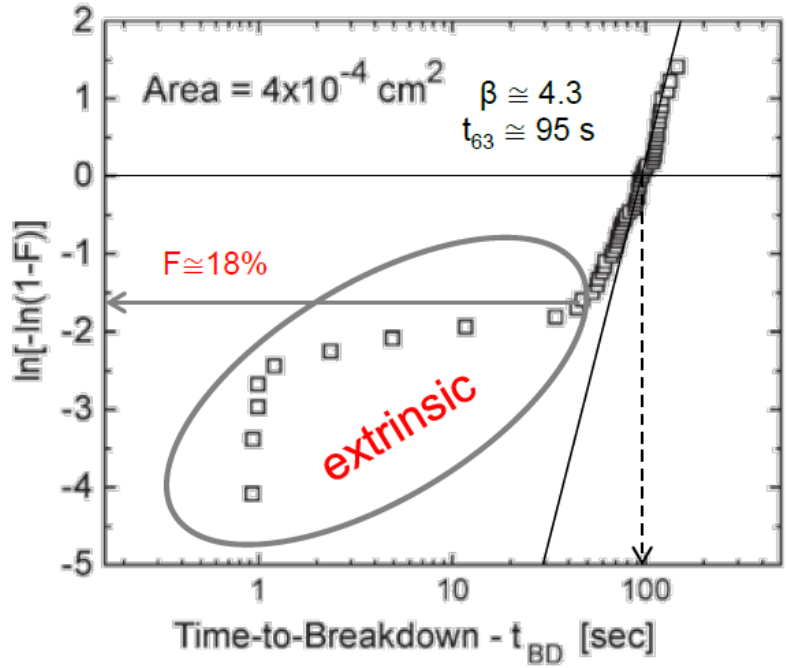
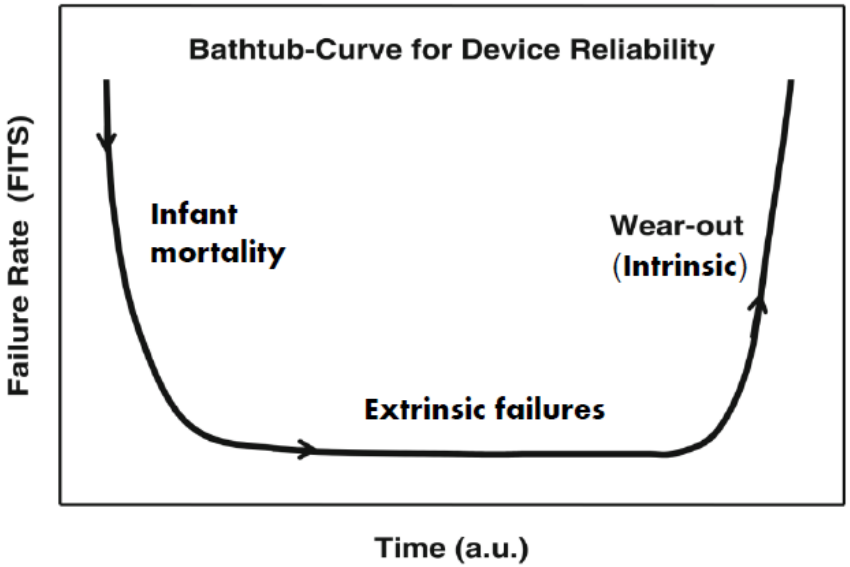


Fig. 9. Uncensored Weibull distribution of 4×10^{-4}-cm^2 4H-SiC capacitors at a temperature of 230 °C and under electric field of 8.9 MV/cm.

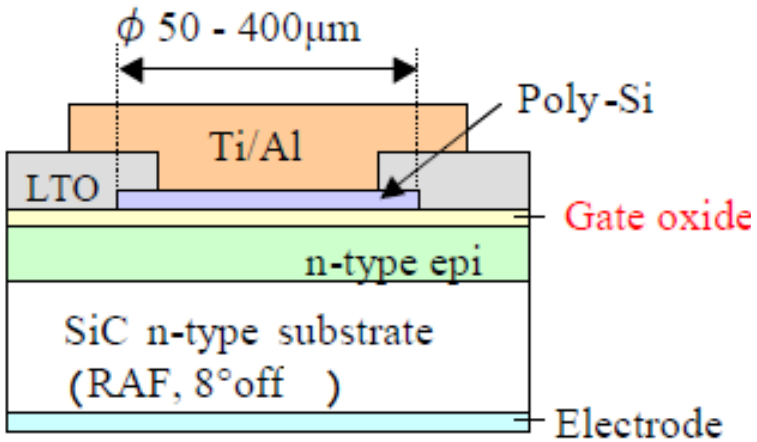
M. Gurfinkel et al., "Time-Dependent Dielectric Breakdown of 4H-SiC/SiO2 MOS Capacitors," Device and Materials Reliability, IEEE Transactions on, 2008, vol. 8, pp. 635-641.

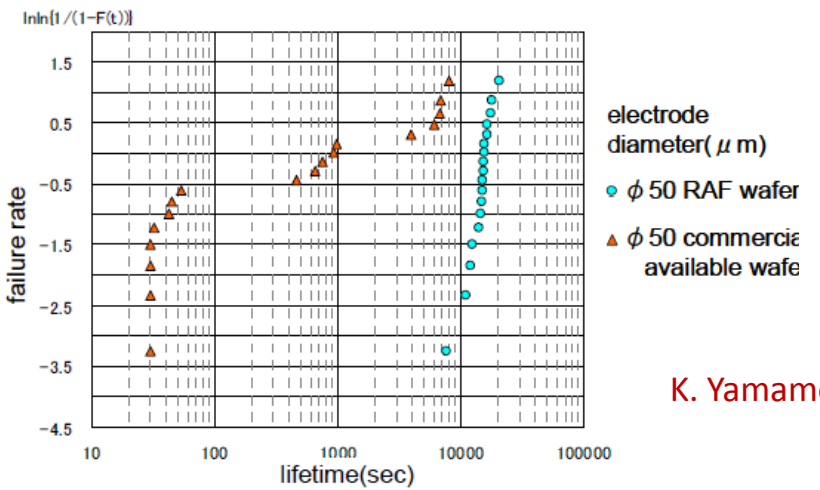
- Pre-screening or burn-in difficult
  - Extrinsic population is Poisson-distributed in area
  - Can't predict next failure during useful life of device
- Critical reliability issue

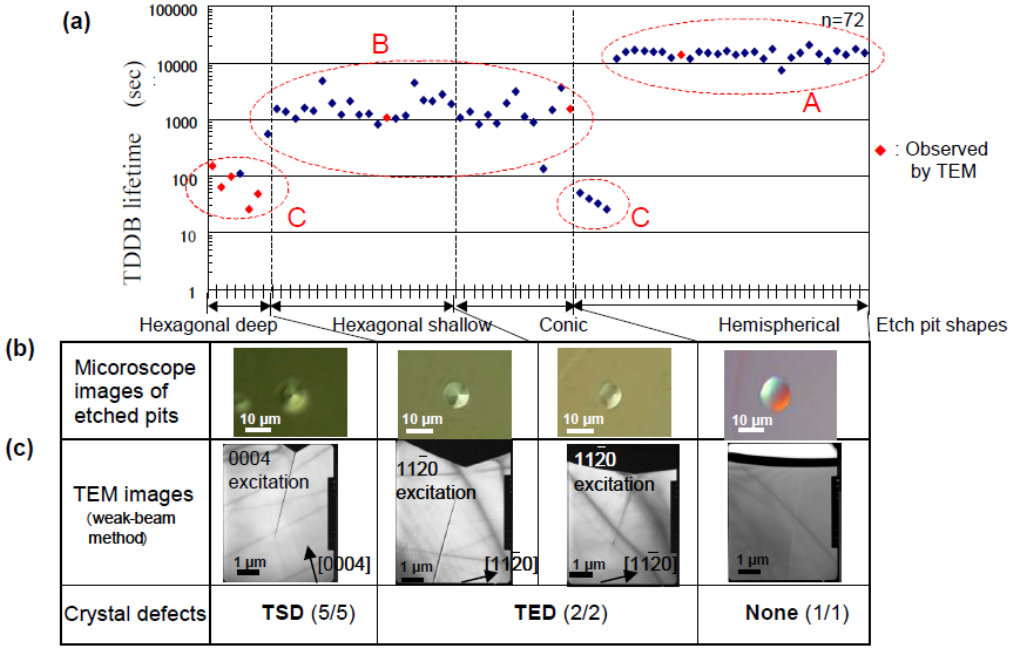


J. W. McPherson, Reliability Physics Engineering. Boston, MA: Springer U 2010.

4H-SiC Material Defects and MOS Gate Oxide Reliability



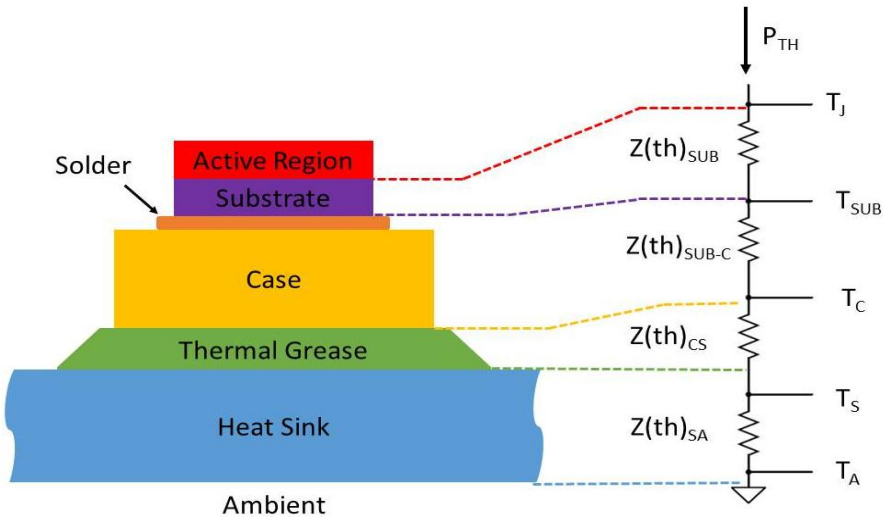


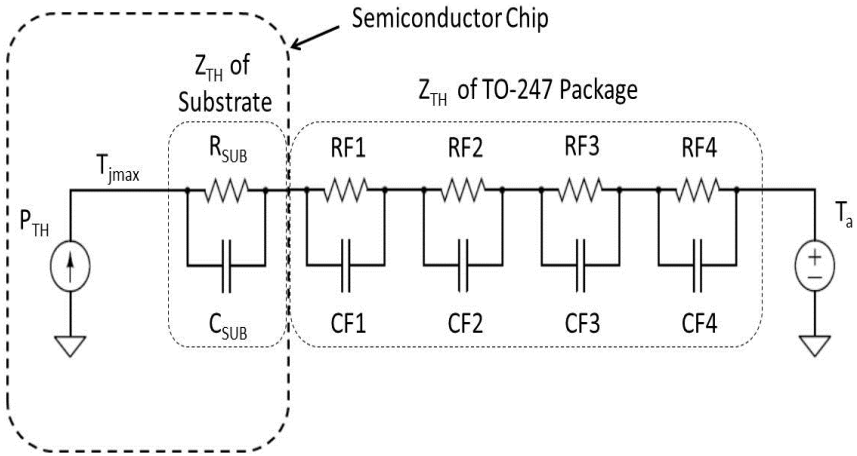


K. Yamamoto et al, *Mat. Sci. Forum,* vols. 717-720 (2012), pp. 477-480.

SiC MOS gate oxide charge and poor reliability originate from material defects in the epitaxial region

Substrate Effect on Heat Removal

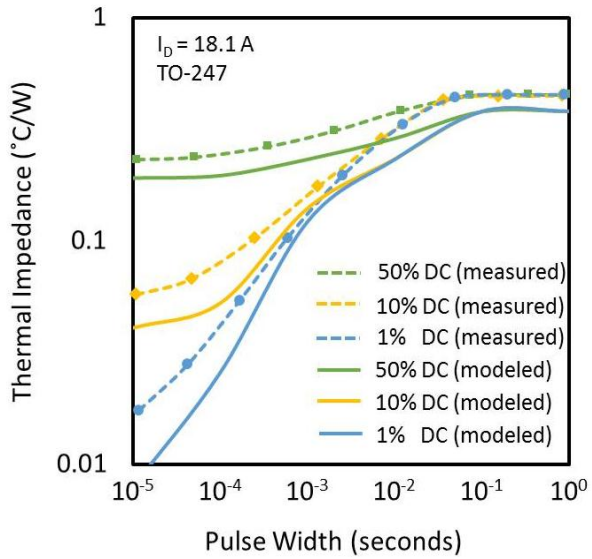




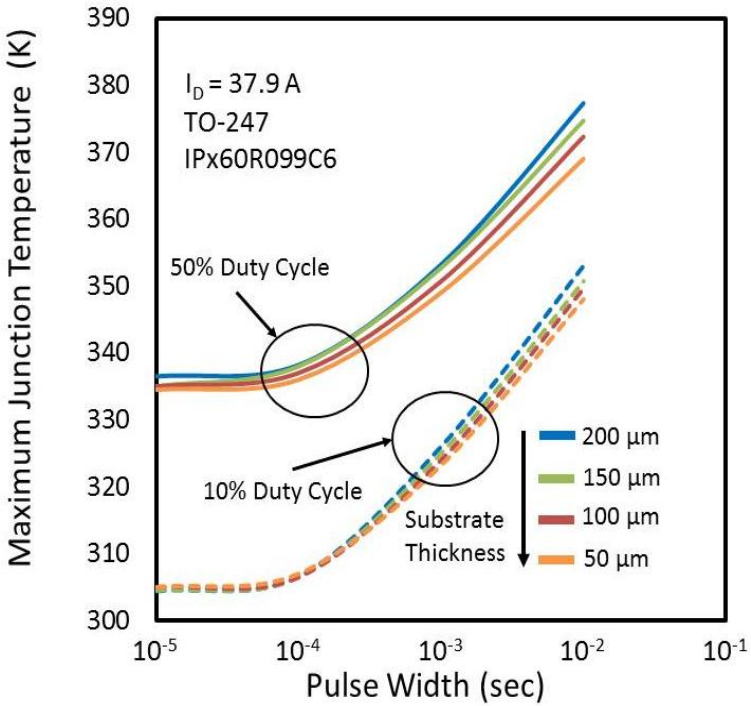
Package Layout

Thermal Model

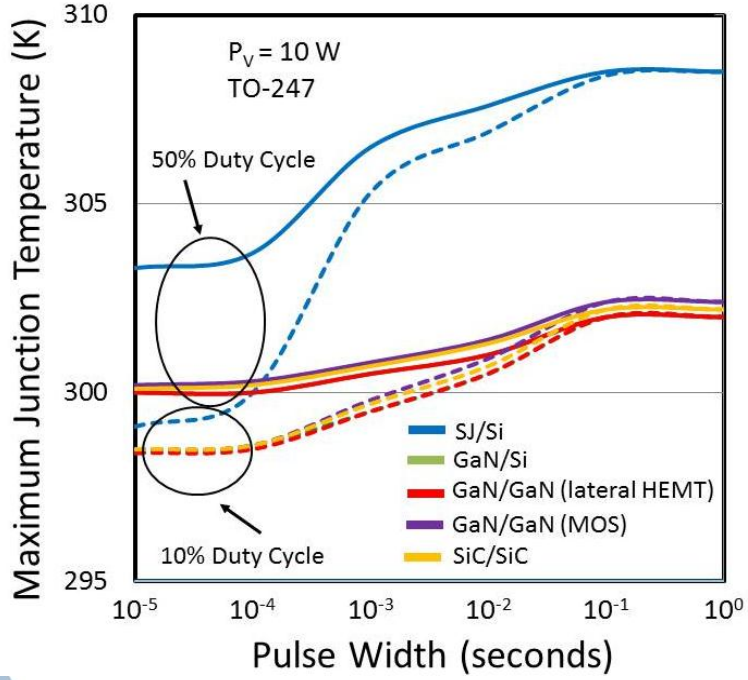
Preliminary Results



(a)



(b)



(c)

(a) Thermal impedance and (b) T_{jmax} vs. substrate thickness for 600V/24A silicon SJT, and (c) estimated T_{jmax} for 1,200V power transistors fabricated on various substrate materials when dissipating 10W power in the on-state.

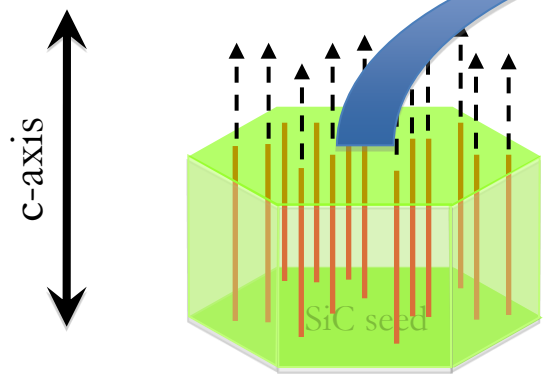
K. Shenai, to appear in *Proc. GOMACTECH Conference*, Mar. 2014

Where do we go from here?

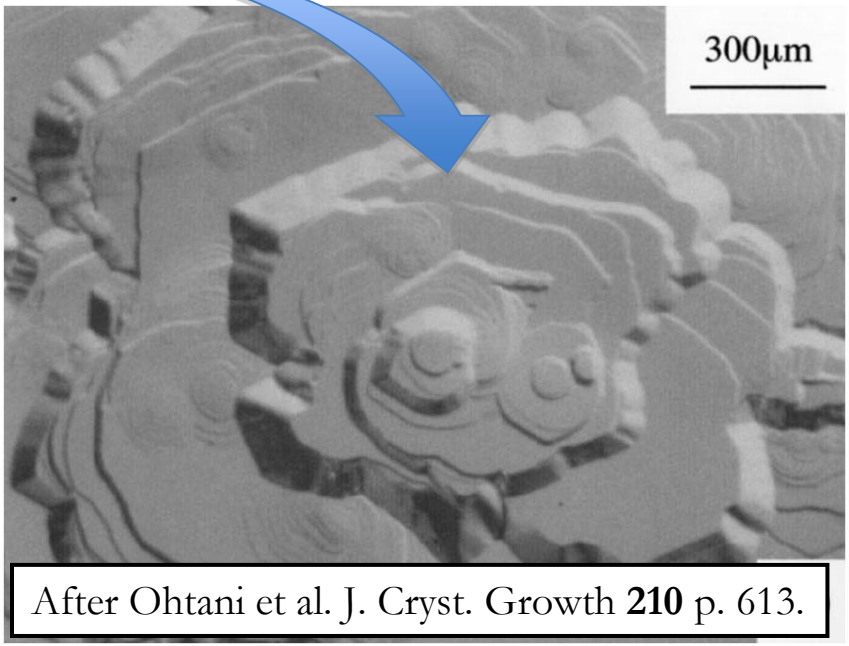
- Need a New Approach !

Present PVT SiC Crystal Growth Process

Growth in the c-axis direction, enabled by screw-dislocations providing steps!



Vertical (c-axis) 4H-SiC boule growth proceeds from top surface of large-area seed via hundreds to thousands of threading screw dislocations (TSDs).



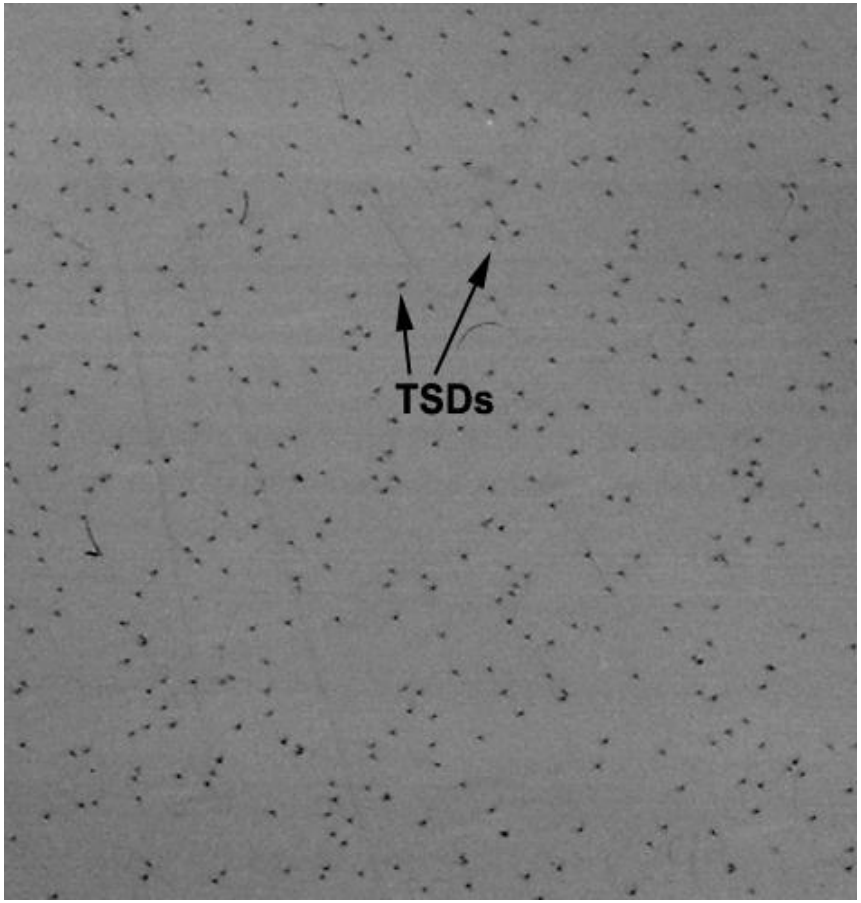
After Ohtani et al. J. Cryst. Growth **210** p. 613.

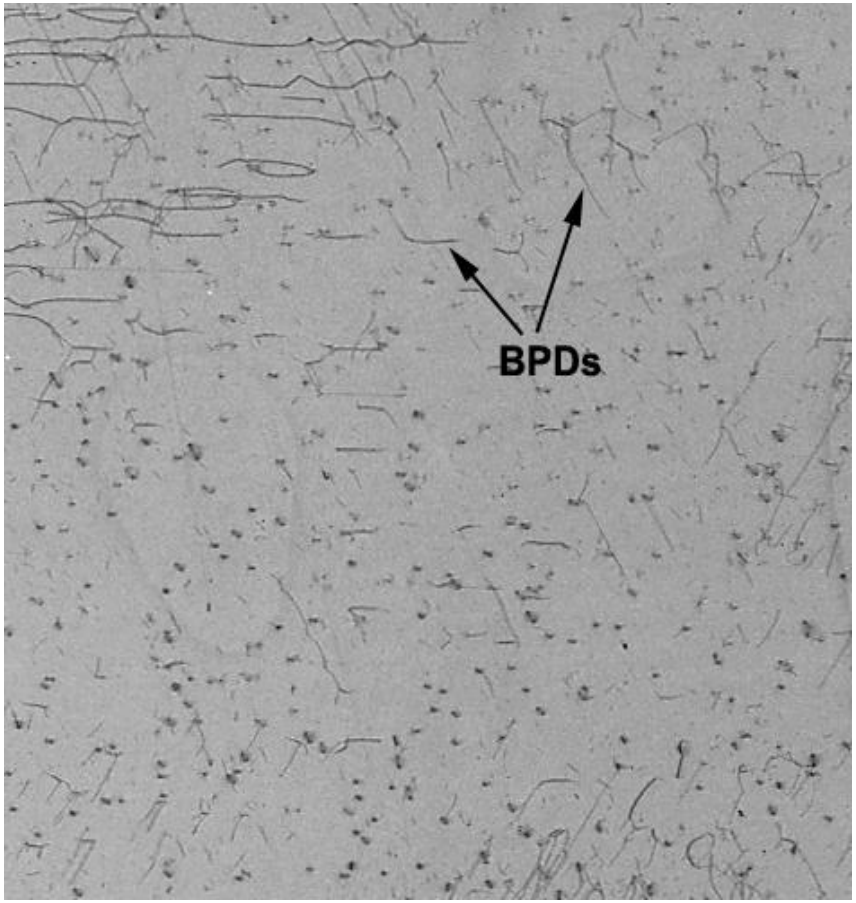
Threading screw dislocation growth spirals (THE sources of steps for c-axis growth) found at top of grown 4H-SiC boule.

Contention: Elimination of screw dislocations from power devices not possible while maintaining commercially viable crystal quality and growth rate and via this approach.

Crystal grown at T > 2200 ° C --> High thermal gradient & stress --> More dislocations

Defects in SiC Material

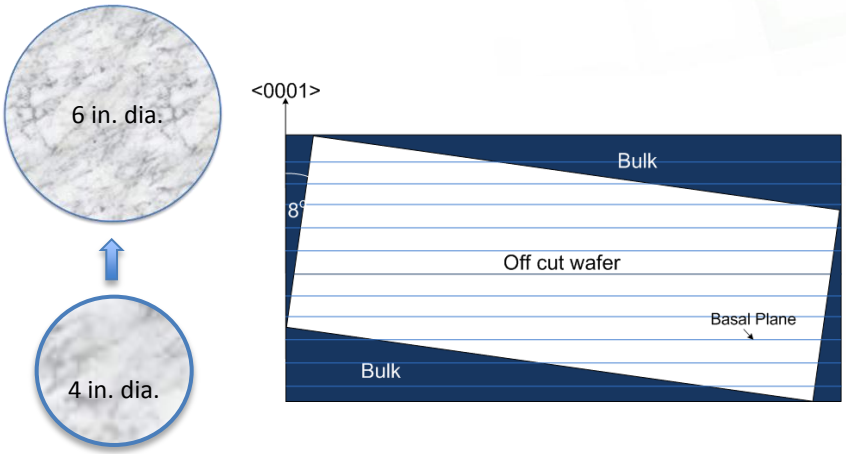




Joint OSD/Army/Navy SiC HEPS ManTech

M. Loboda, DOW CORNING, ICSCRM 2011 Industry Session

100 mm wafers
Micropipe Density ~ 0 cm^{-2}
Threading Screw Dislocation Density < 1,000 cm^{-2}
Basal Plane Dislocation Density < 1,000 cm^{-2}



TED and TSD densities are higher for 6 in. dia. wafers

Key Objectives:

- Increase wafer dia. from 4" to 6"
- Increase voltage ratings by 2-3X of Si rating
- Bring down die cost to within 2-2.5X of Si cost
- Reliable operation up to T_C = 150°C (vs. 70°C for Si)

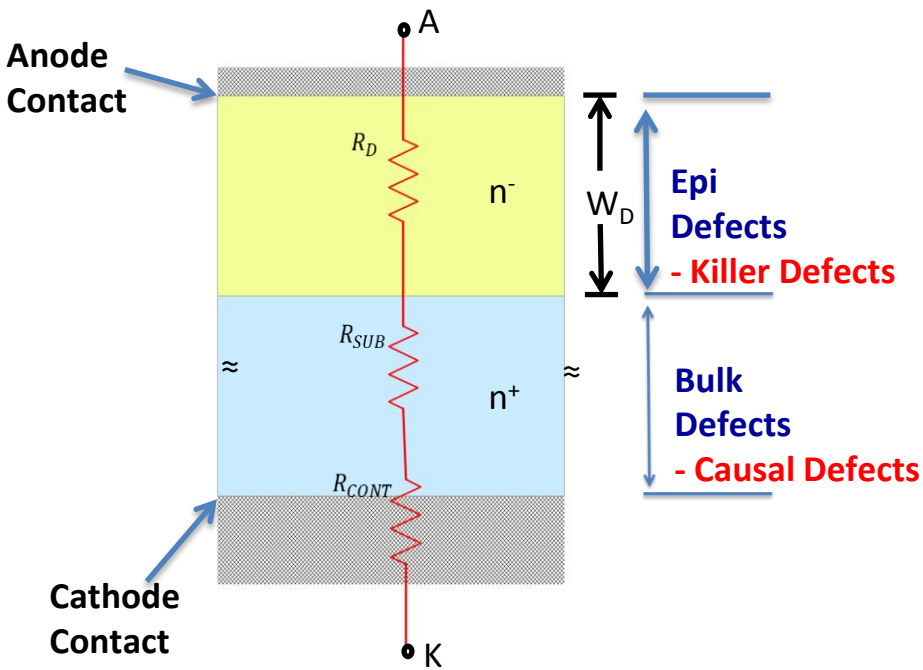
Si and SiC IGBTs

Parameter	Baseline (4" dia. median)	Best R&D in FY13 (6" dia.)	Commercial (6" dia. median)
Micro-pipes (cm^{-2})	< 0.8	< 0.8	< 0.2
TEDs and TSDs (cm^{-2})	**275**	**2,000**	**800**
BPDs in epi (cm^{-2})	< 2 (50 µm)	< 50 (75 µm)	< 1 (160 µm)
Epi thickness/doping uniformity/thickness	2%/5%/75 µm	2%/20%/75 µm	1%/6%/160 µm

- **Role of TEDs and TSDs not investigated**
- **Radically new bulk and epi crystal growth processes may be needed in order to further reduce and/or eliminate TEDs and TSDs**

- **Yield and cost metrics are not well-defined**
- **Not directly applicable to commercial power devices**

Key Device Challenge

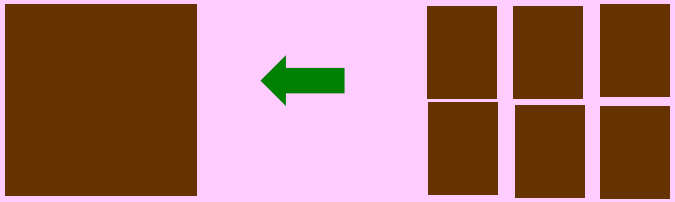


There are other challenges

High starting Wafer Cost
Epi Uniformity
Gate Dielectrics
Contacts
HV Passivation
Carreer Lifetime Control
…….

Consequences:

- Voltage De-Rating
- Limited Die Size
- Poor Wafer Yield
- High Cost
- Less Than Optimal Performance
- Field-Reliability Unknown
- Bipolar power switch questionable

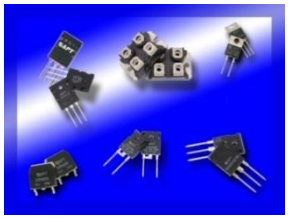


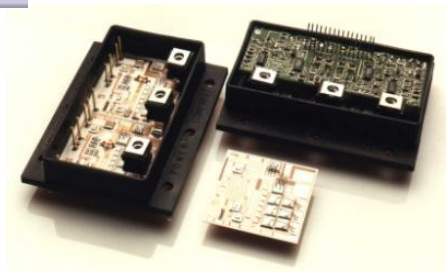
300 amps

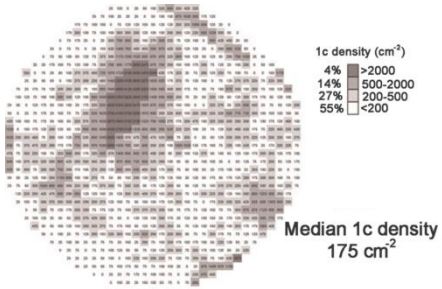
Six 50 amp dice

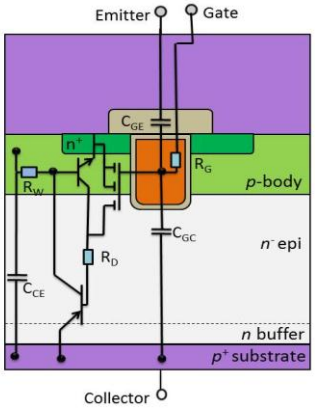
K. Shenai, *Interface*, Electrochemical Society, vol. 22, no. 1, pp. 47-53, Spring 2013 (**invited paper**).

Material – Device – Module – Converter Interaction

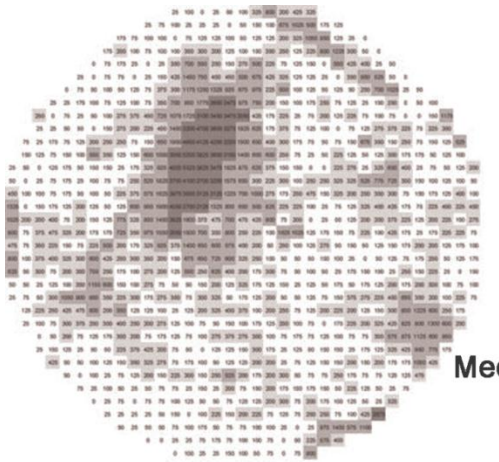




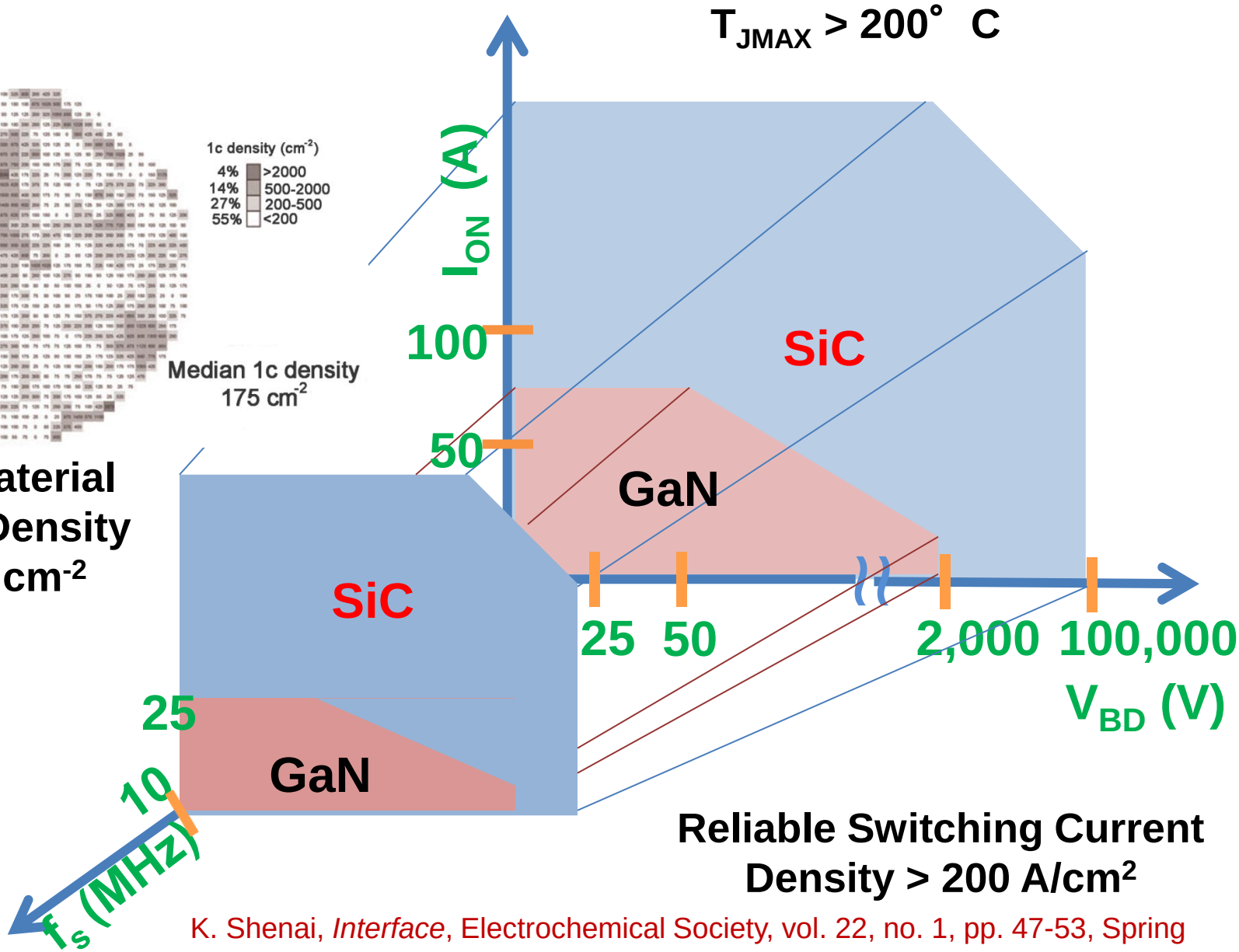




Key Material Challenge



Bulk Material Defect Density < 100 cm^{-2}



Reliable Switching Current Density > 200 A/cm^2

K. Shenai, *Interface*, Electrochemical Society, vol. 22, no. 1, pp. 47-53, Spring 2013 (**invited paper**).

Summary and Recommendations

- WBG power devices have the potential for transformative advances in transportation sector.
- Progress is severely hampered by a high density of crystal defects in WBG semiconductors.
- Need reliability-driven application engineering with improved data sheets in order to infuse WBG power electronics into the transportation sector.
- This is a challenge especially since the power electronics industry supply chain is highly fragmented.