High Temperature Operation of SiC Power Devices

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Cree Inc.

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Workshop on Extreme Environments Technologies for Space Exploration

Outline

- SiC Bulk Material
- 600 -1200 V Schottky Diodes
- Systems Benefits
- 1200 V SiC BJTs
- SiC Power MOSFETs
- SiC PiN Diodes
- Highlights

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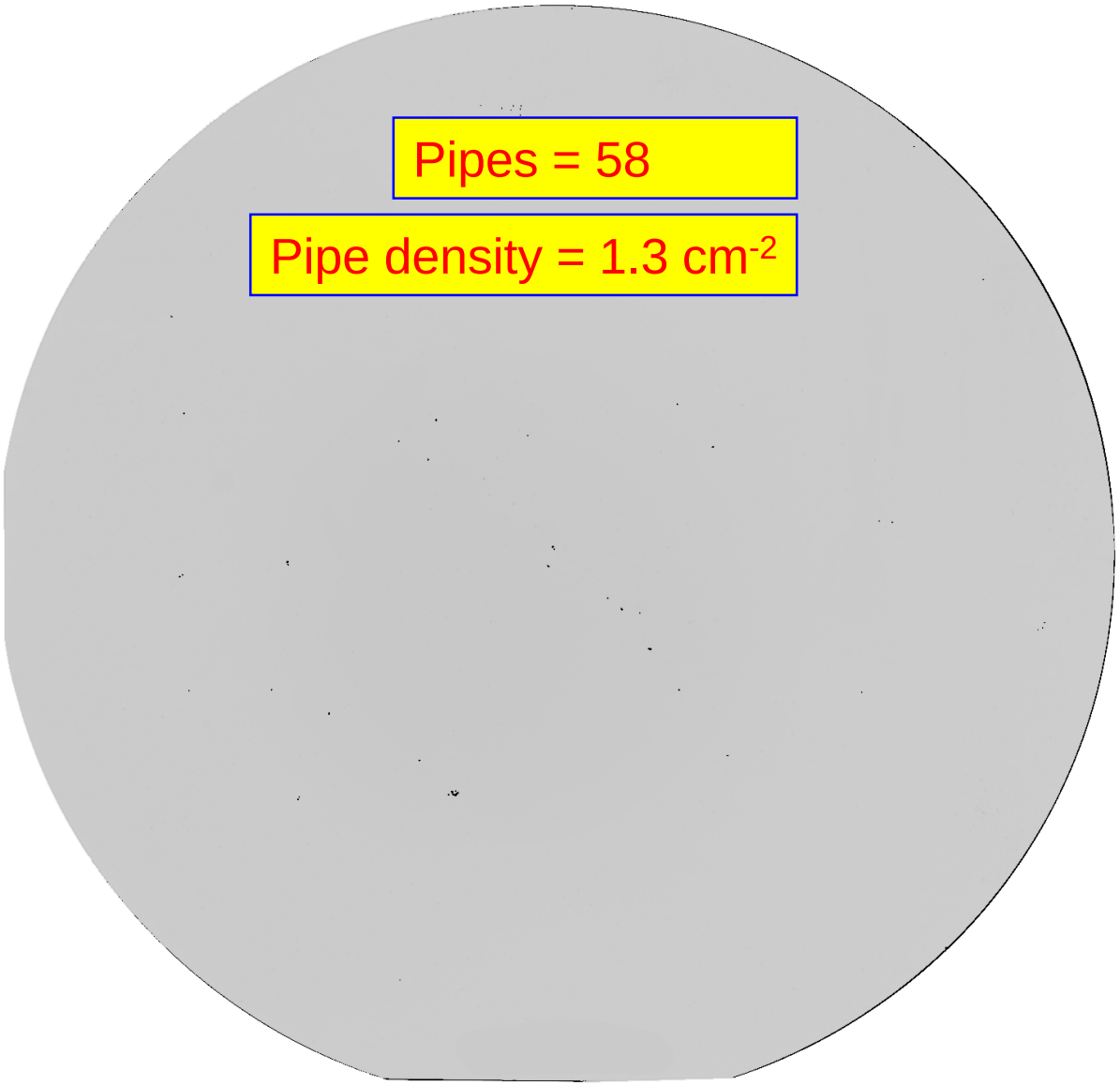
SiC Bulk Material

3” 4H-N SiC Substrate



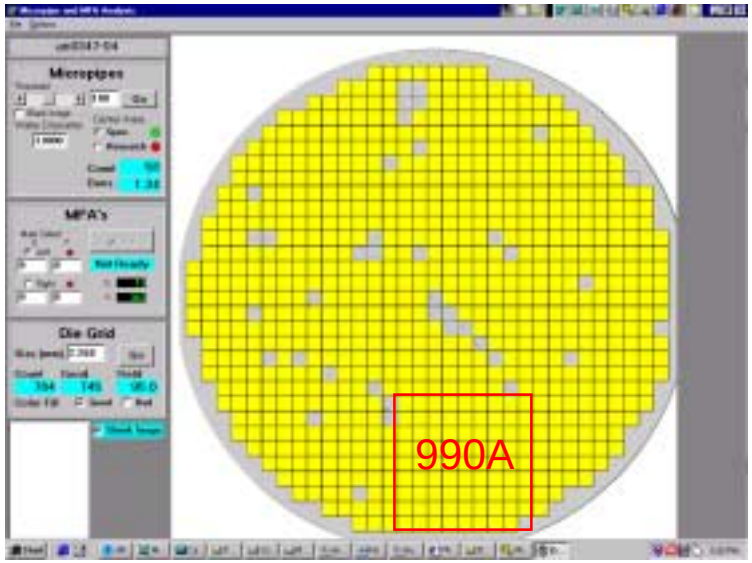
Pipes = 58

Pipe density = 1.3 cm^{-2}

Expected Yield for Current High Quality Substrate

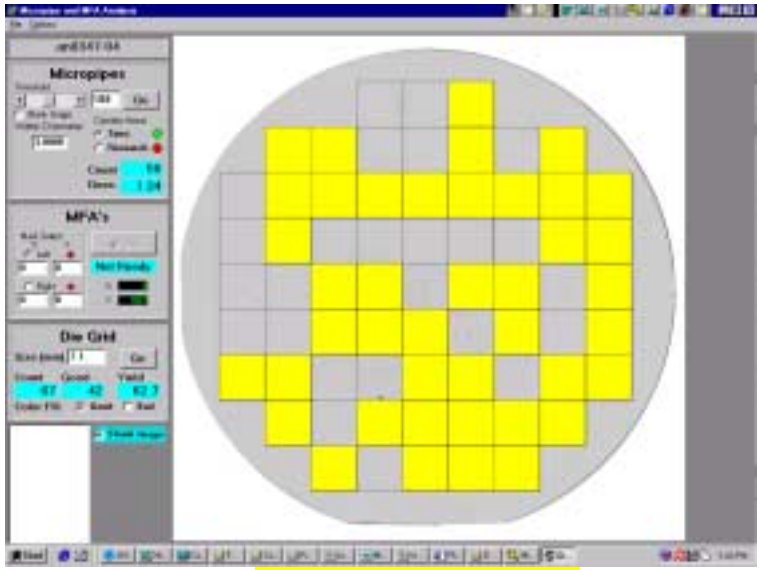
For our current “good” wafers the expected yield of 10 and 100 A devices is shown below (Loss due to pipes only)

600 V/10 A SBD



Yield = 95%

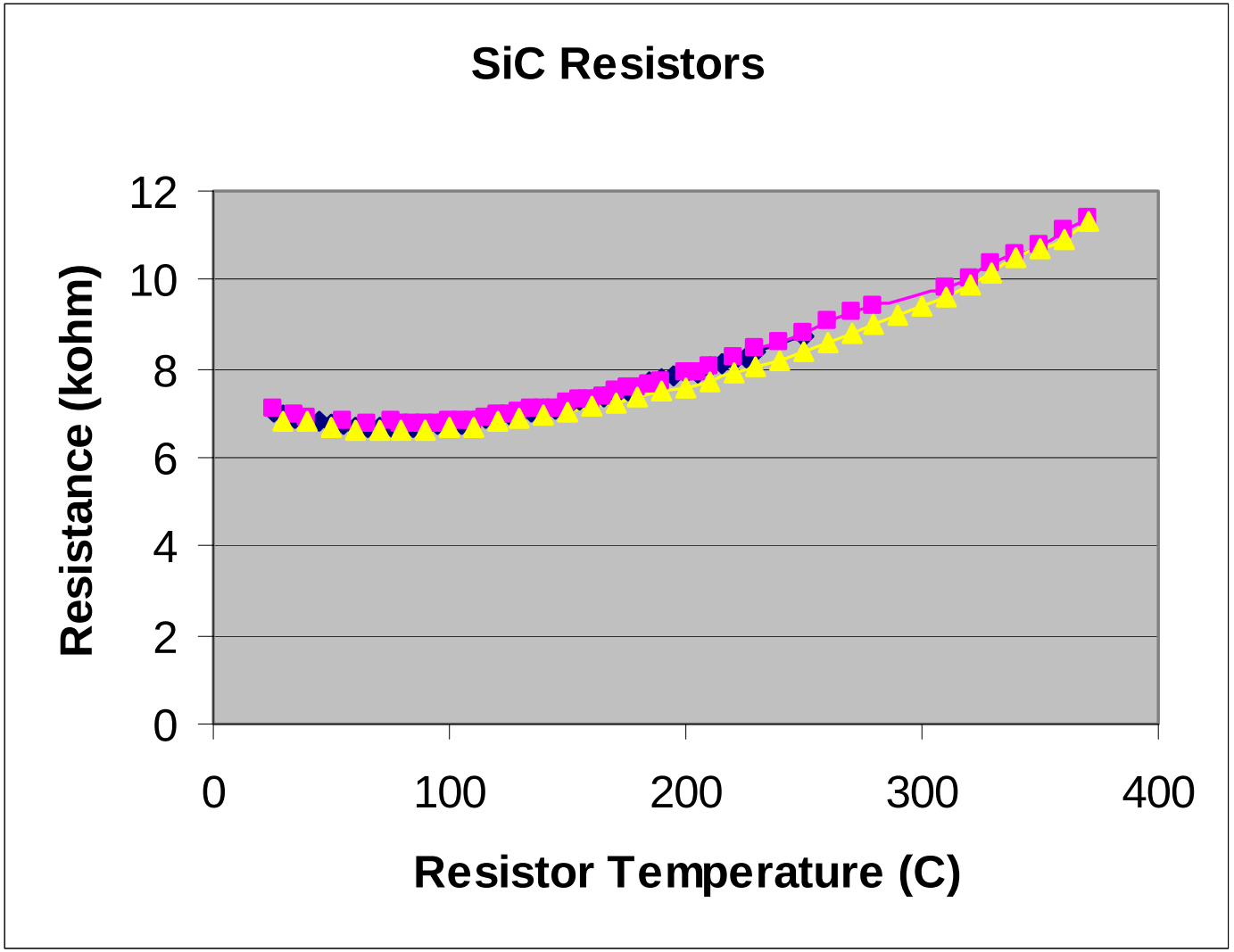
600 V/100 A SBD



Yield = 62%

Pipe density = 1.3 cm^{-2}

N, 4H-SiC Resistors are Relatively Temperature Insensitive



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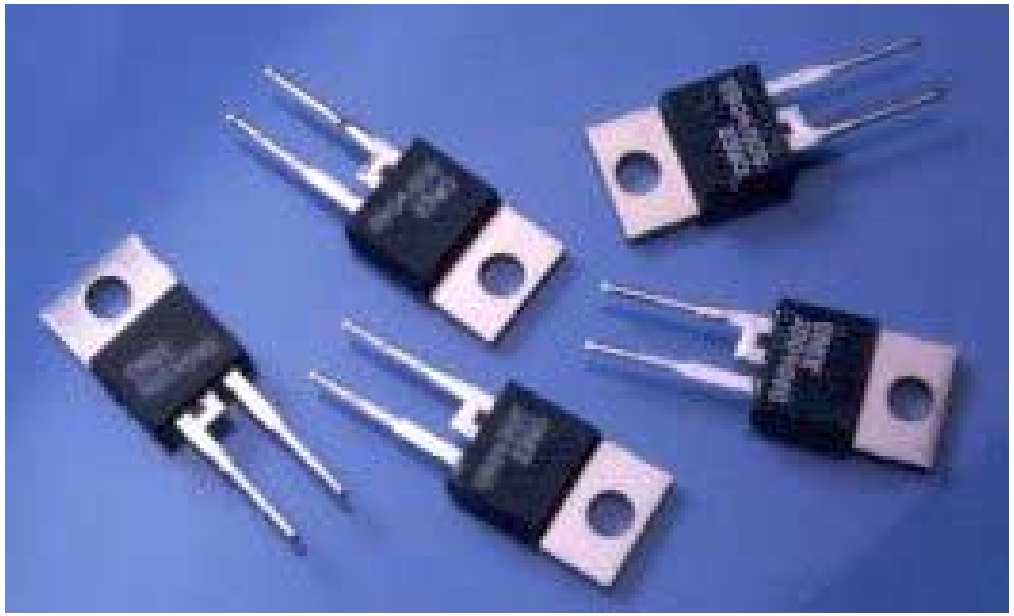
Boeing

SiC Schottky Barrier Diodes

SiC Schottky Diodes are Commercially Available from Cree

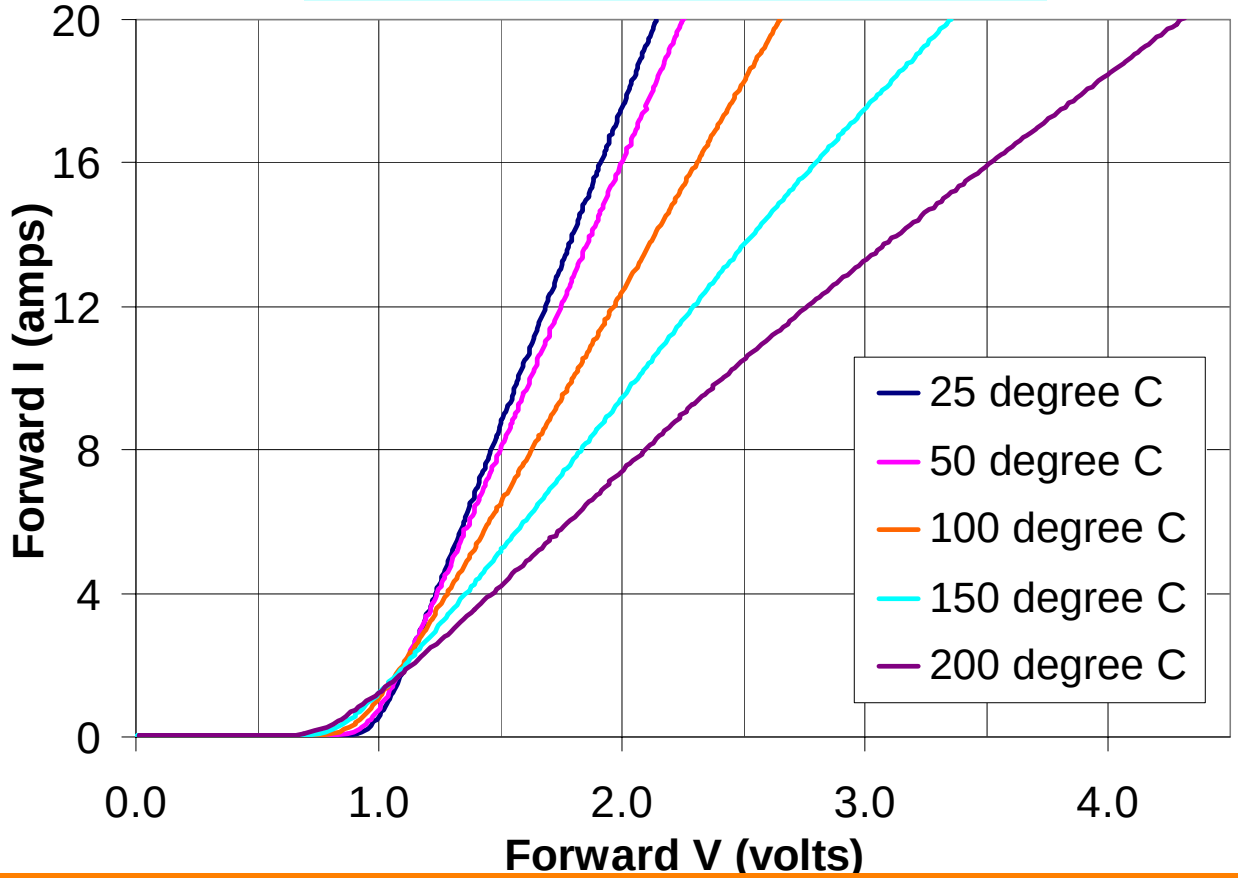


Zero Recovery Rectifiers™

Parts commercially released
600 V - 1, 4, 6, 10 & 20 A
1200 V - 5, 10 A

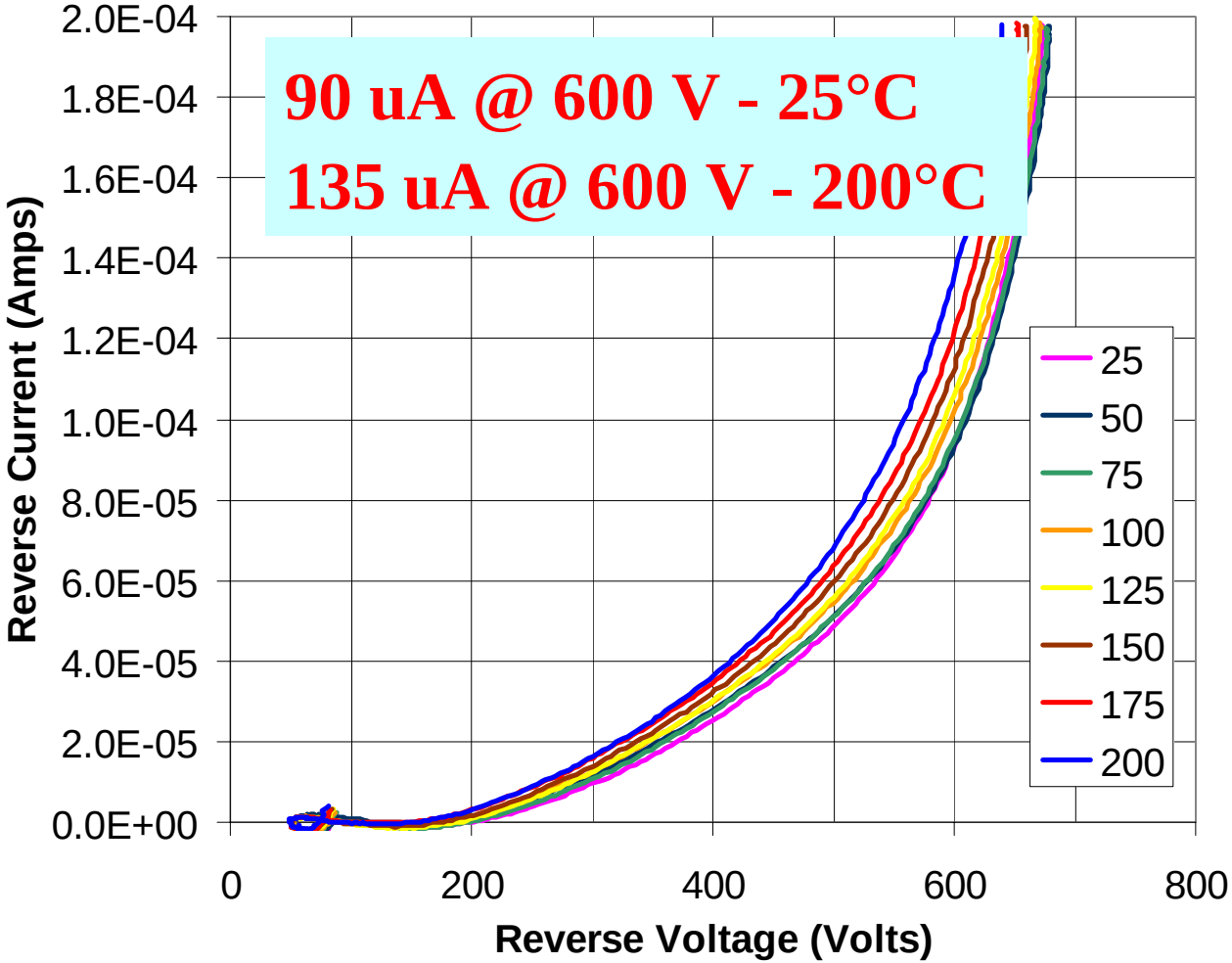
10 A, 600 V Schottky Diode

10 A @ 1.6 V - 25°C
5 A @ 1.6 V - 200°C

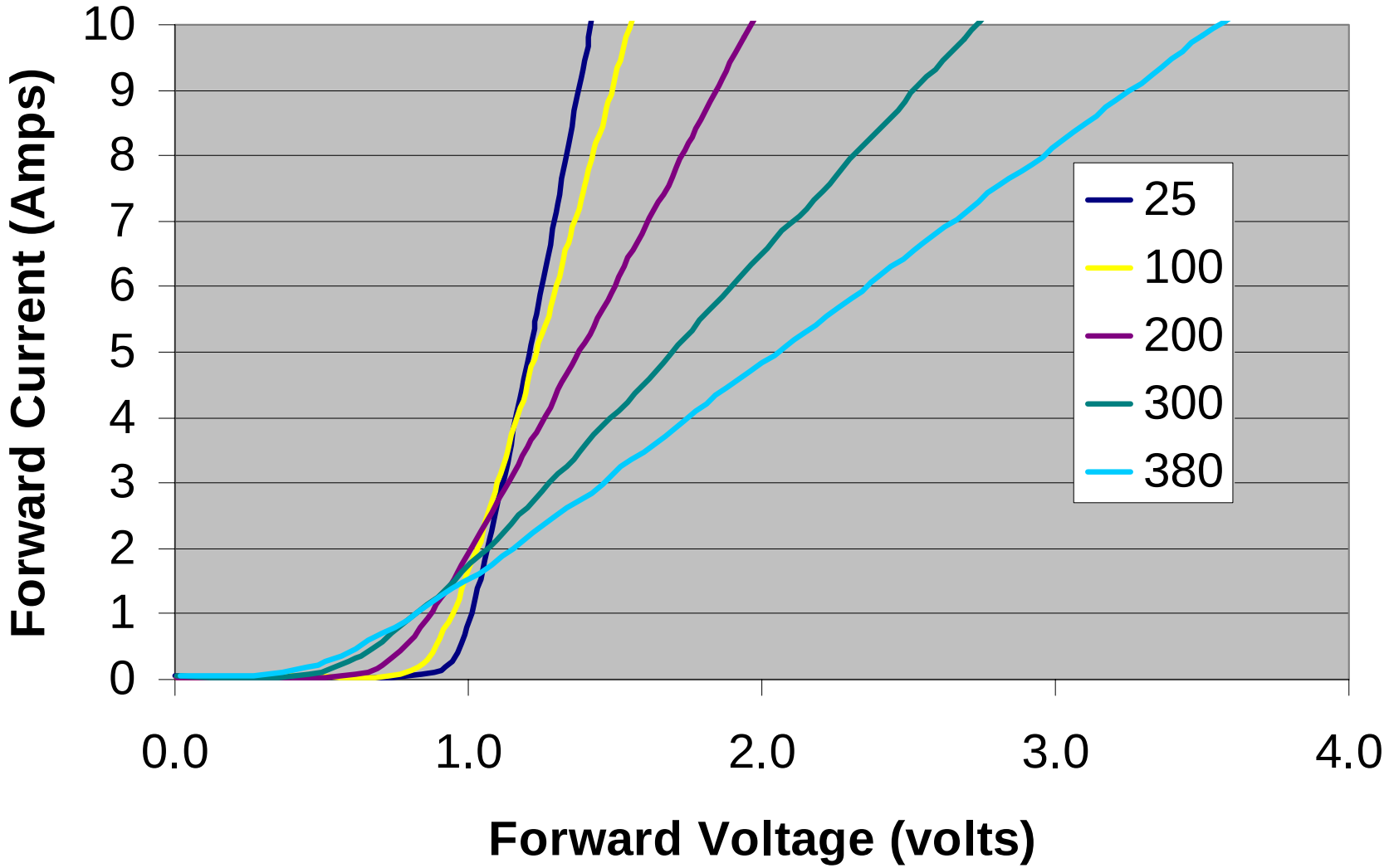


Positive Temp. Coefficient is good for paralleling

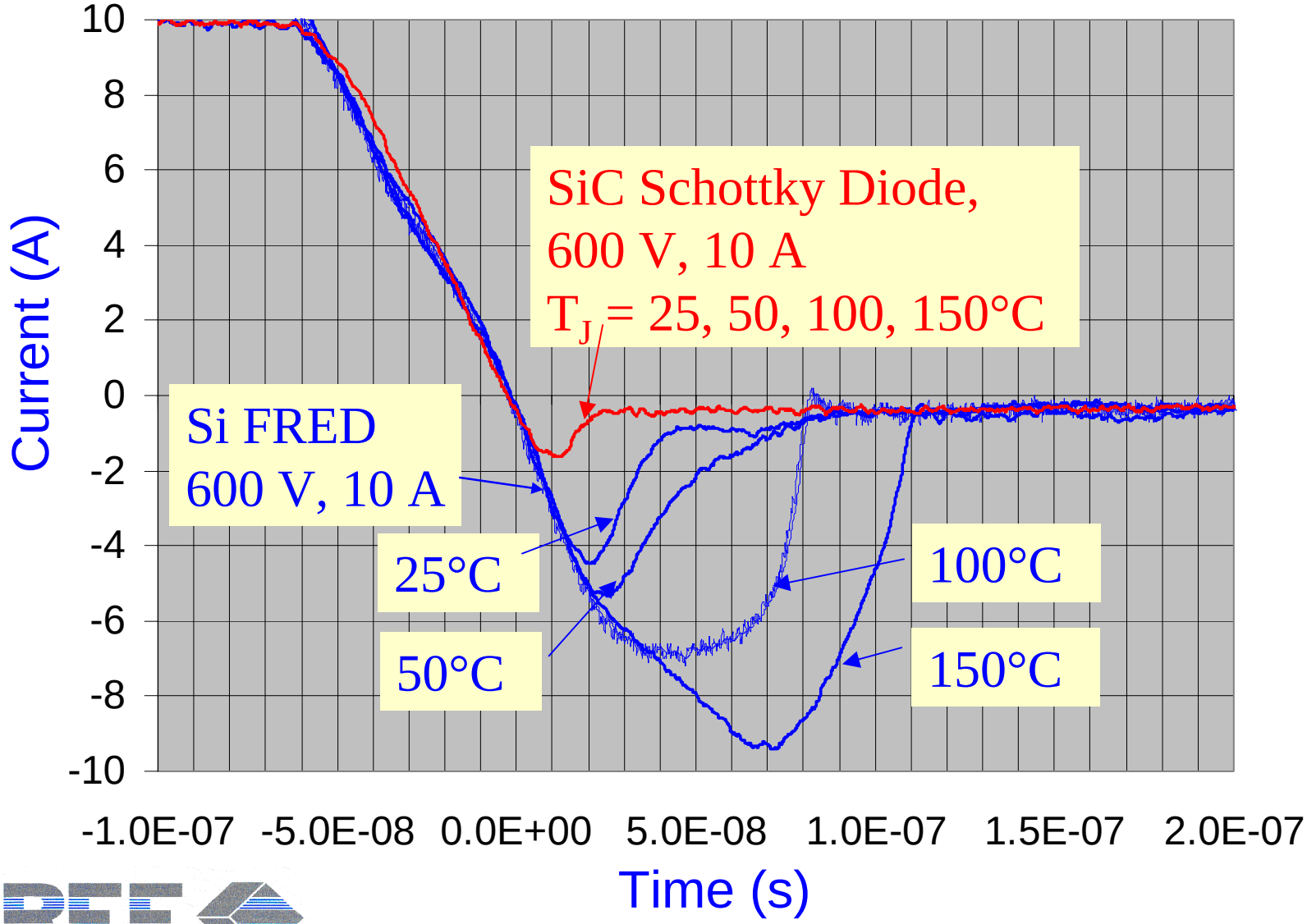
Reverse I - V vs. Temp. - 600 Volt, 10 Amp Device



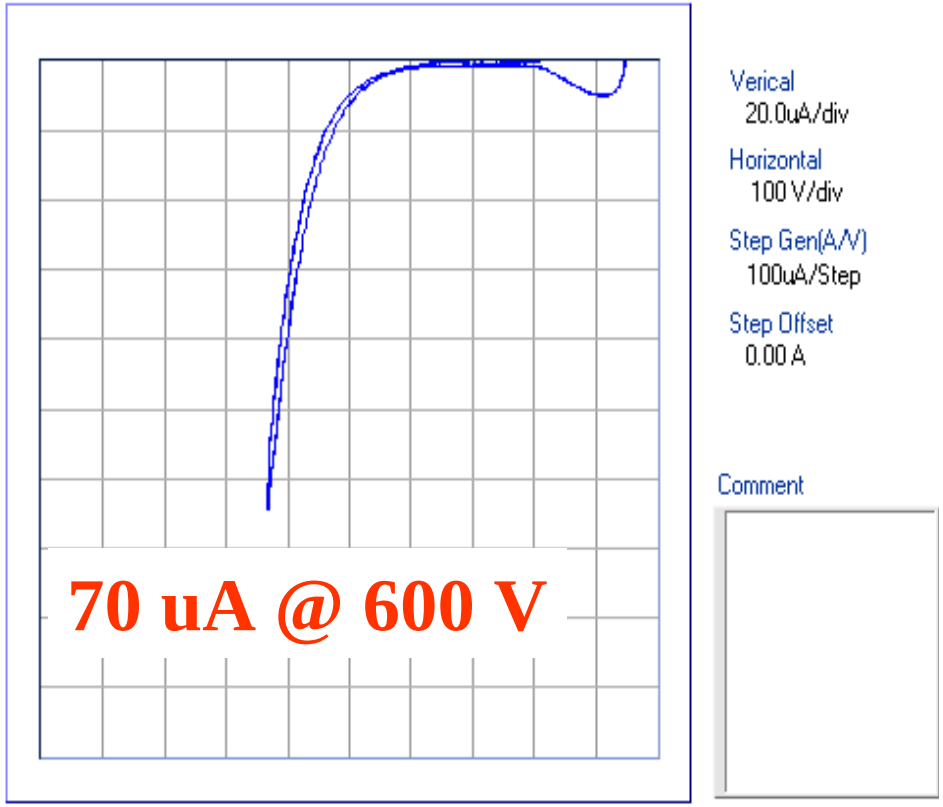
10 Amp SiC Schottky Diode

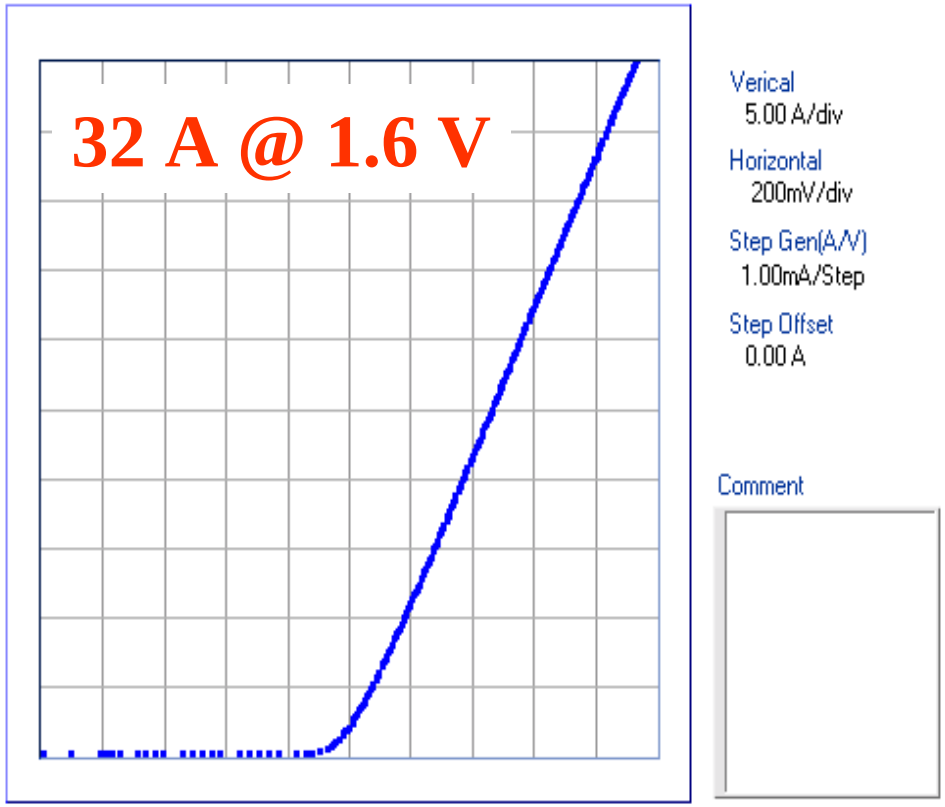


Reverse Recovery of SiC Schottky Rectifier vs. Si FRED

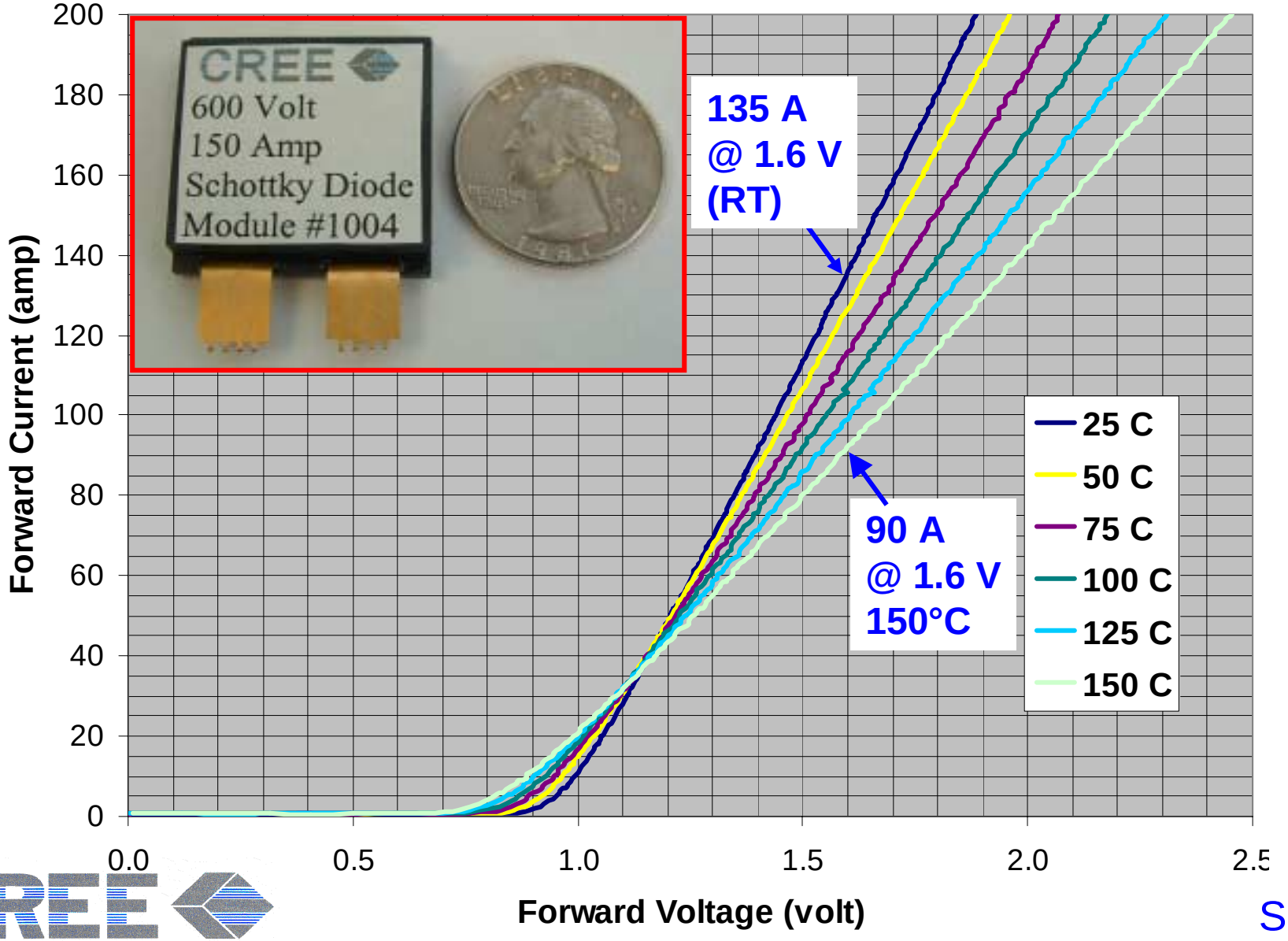


Large Area Schottky Diodes





600 V, 135 A SiC Schottky Rectifier Module



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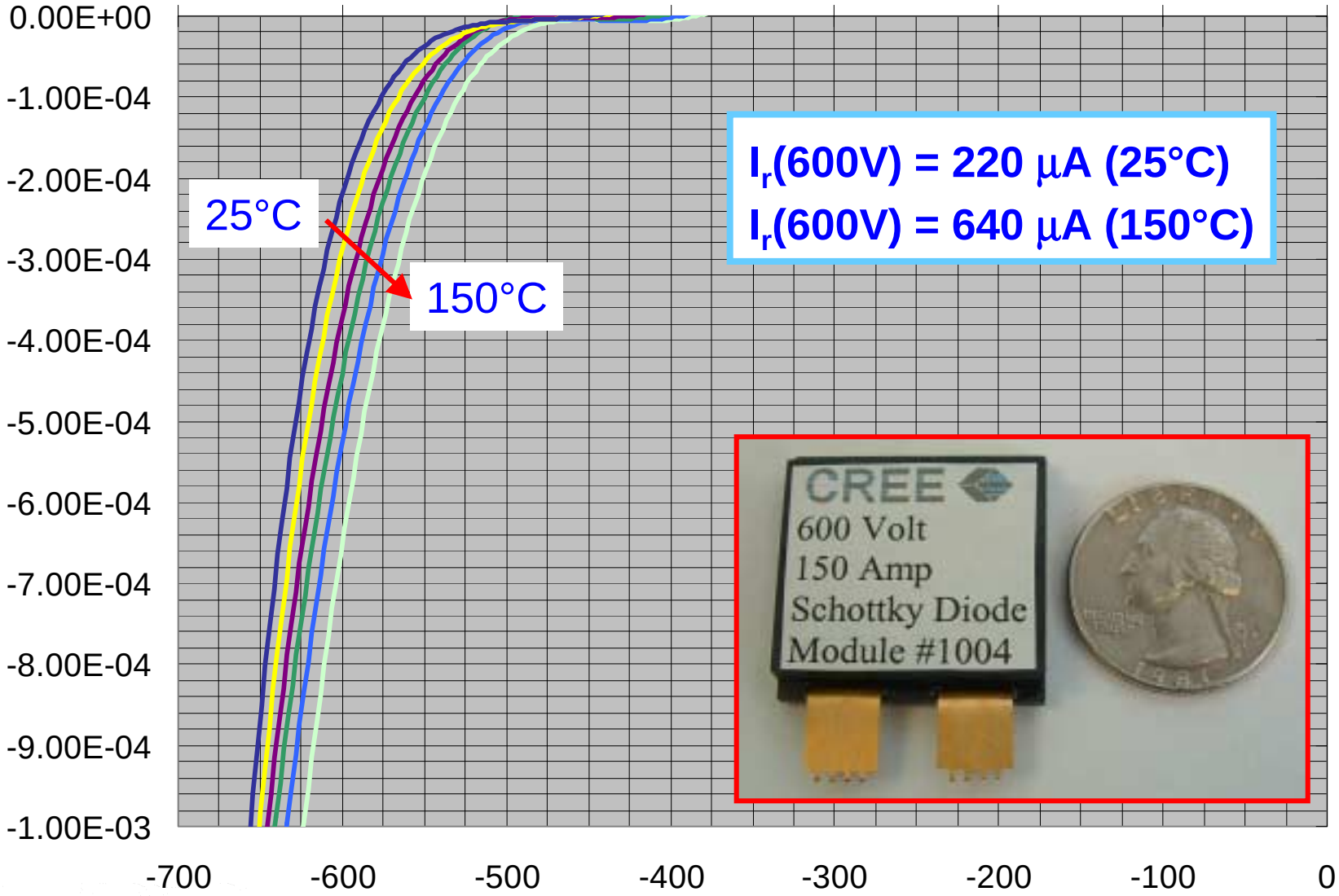
SatCon

600 V, 135 A SiC Schottky Rectifier Module



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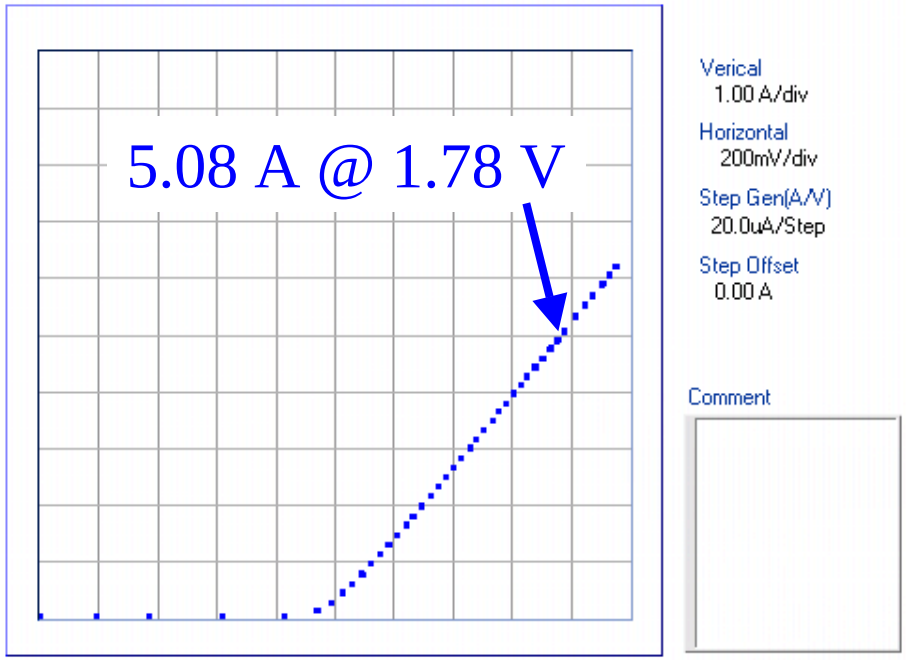
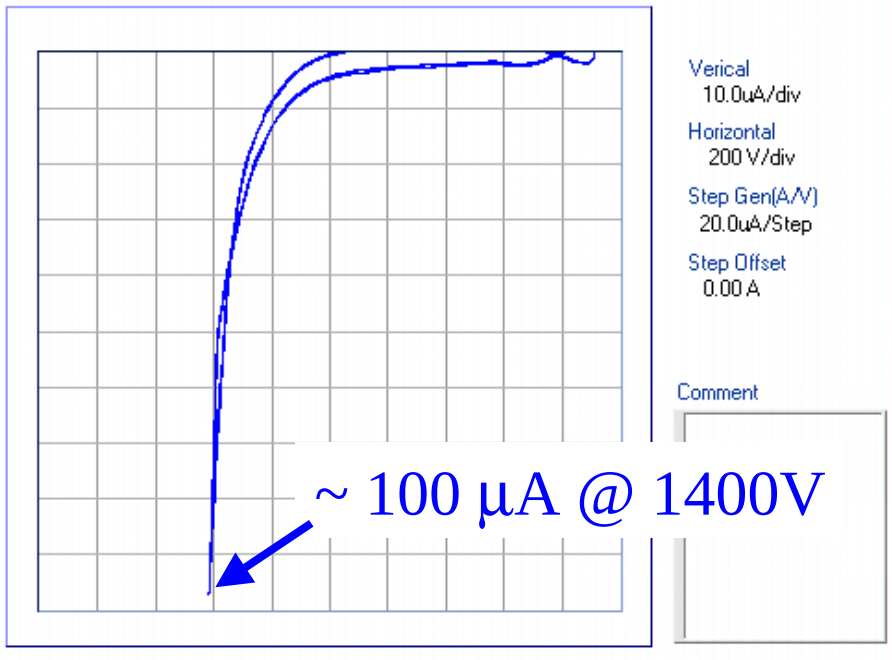
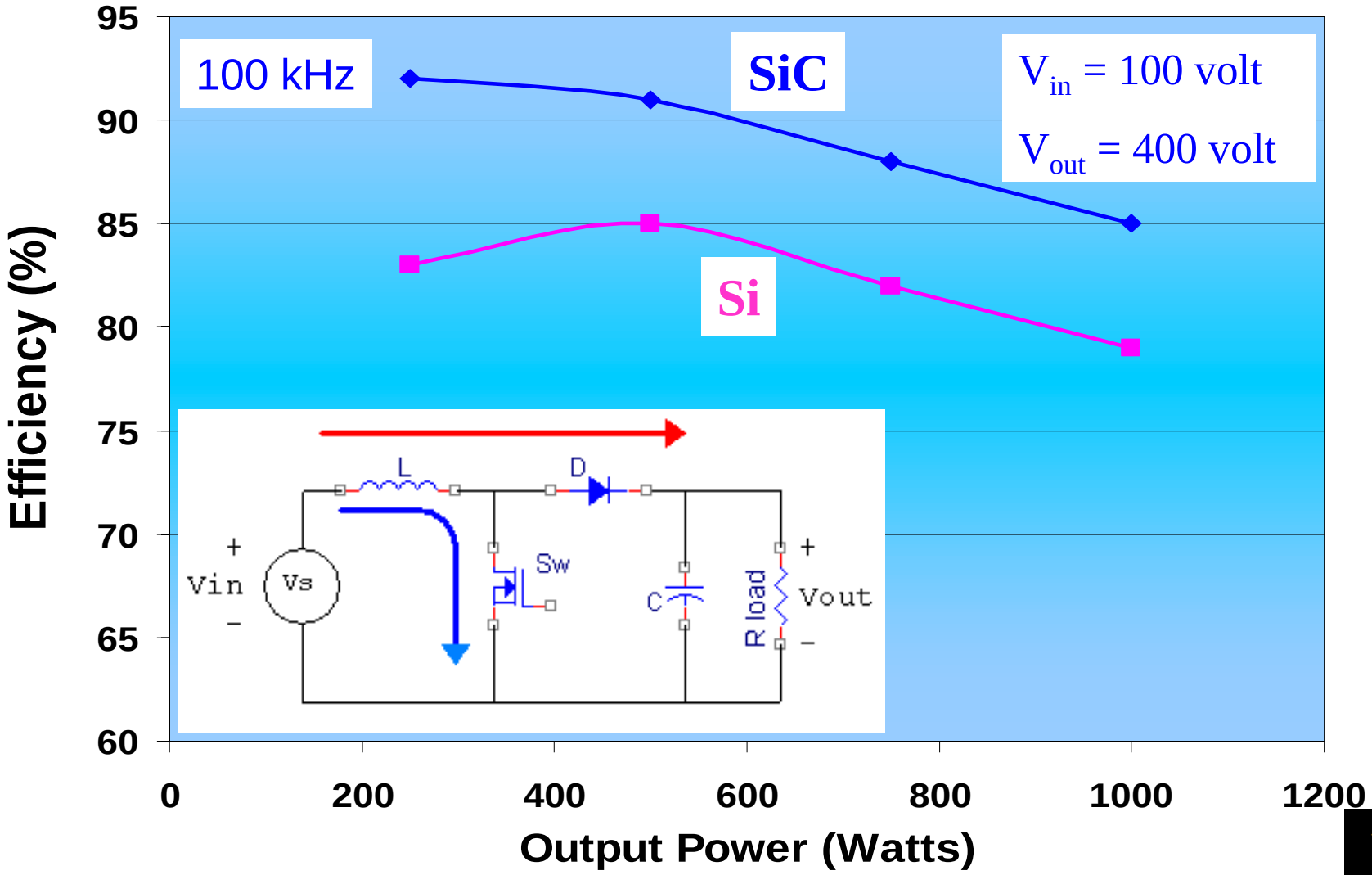
SatCon

I-V characteristics of 1200 V, 5 A SBDs



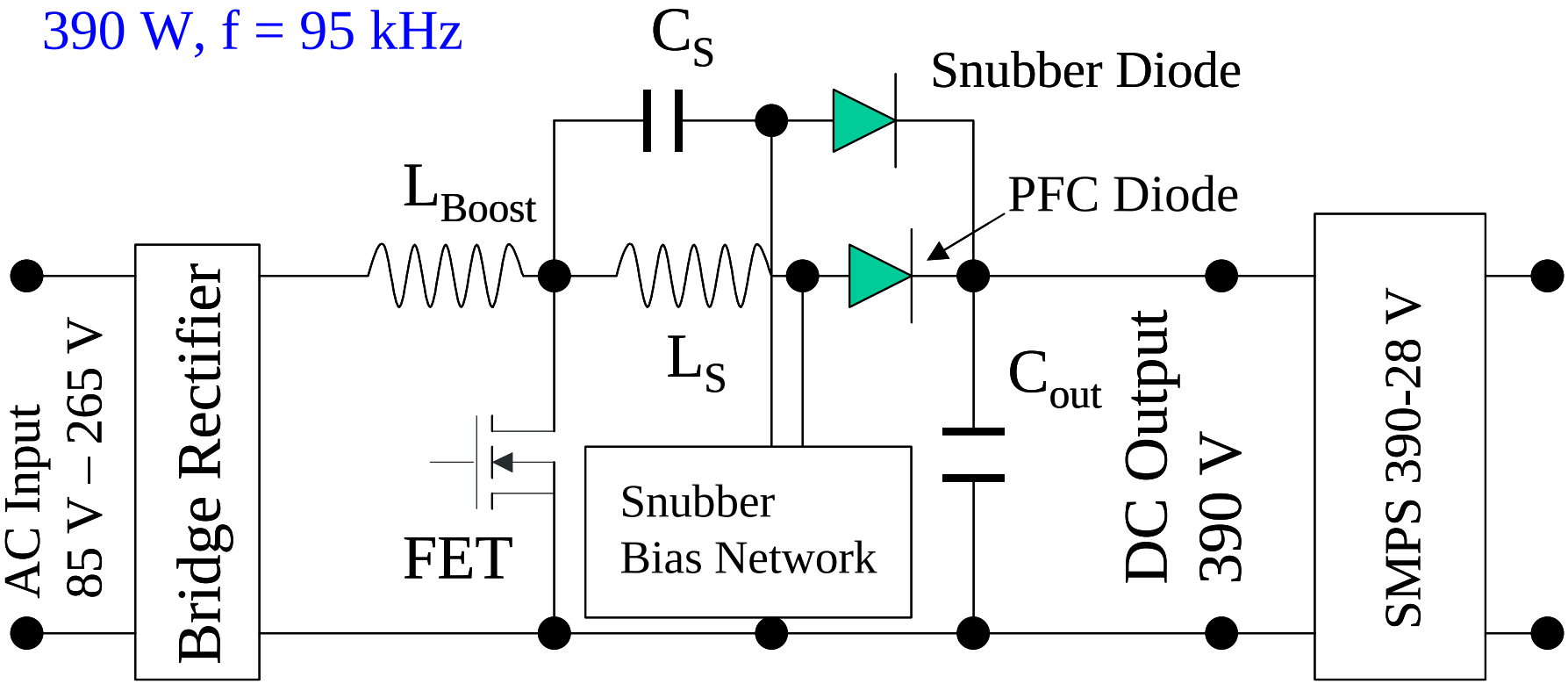


10 A SiC SBD *vs.* 15 A Si PiN Diode in a 1000 Watt Boost Converter



High Power PFC Circuit using Snubbers

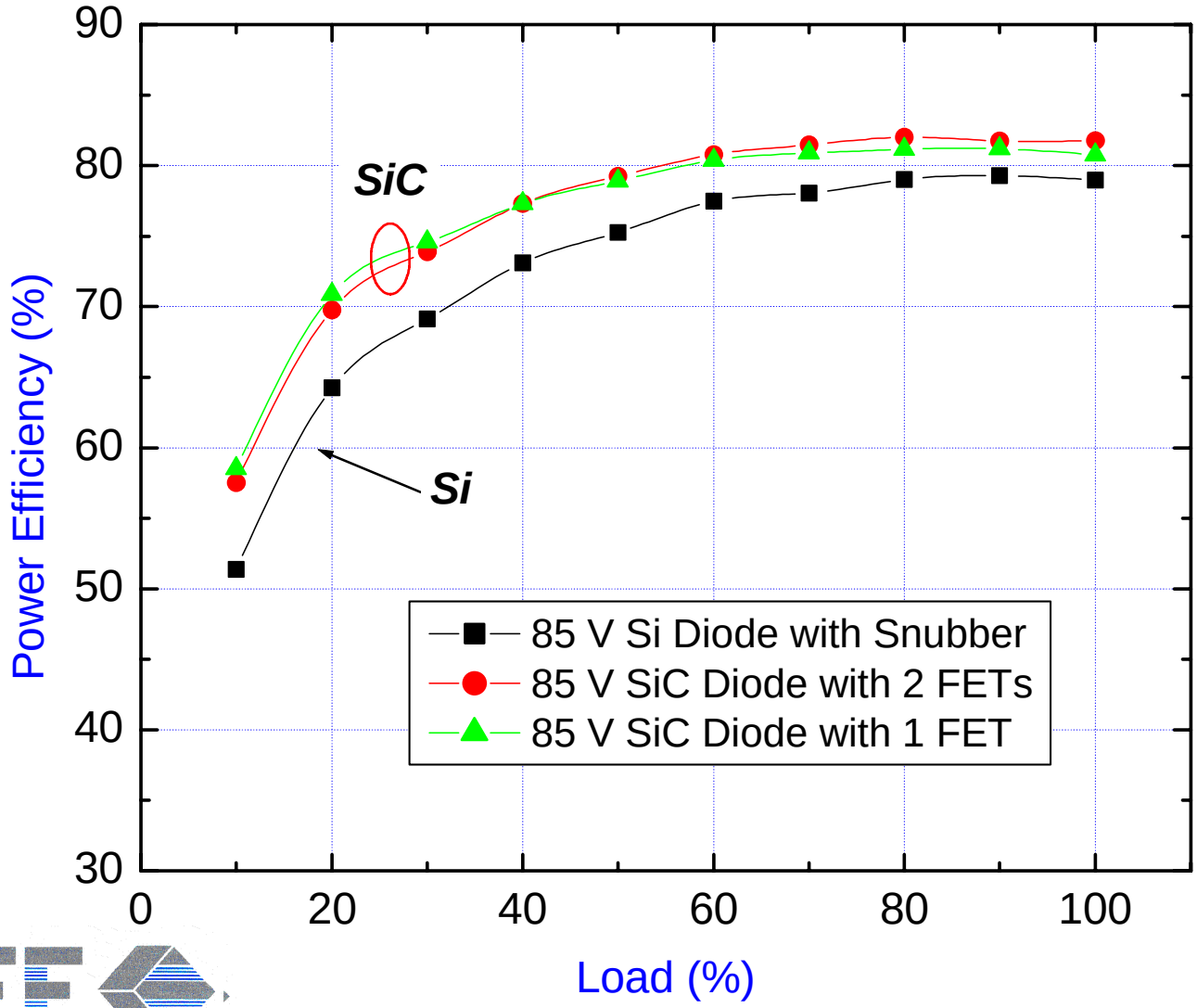
390 W, f = 95 kHz



2 MOSFETs (500 V, 14 A), IRFP450

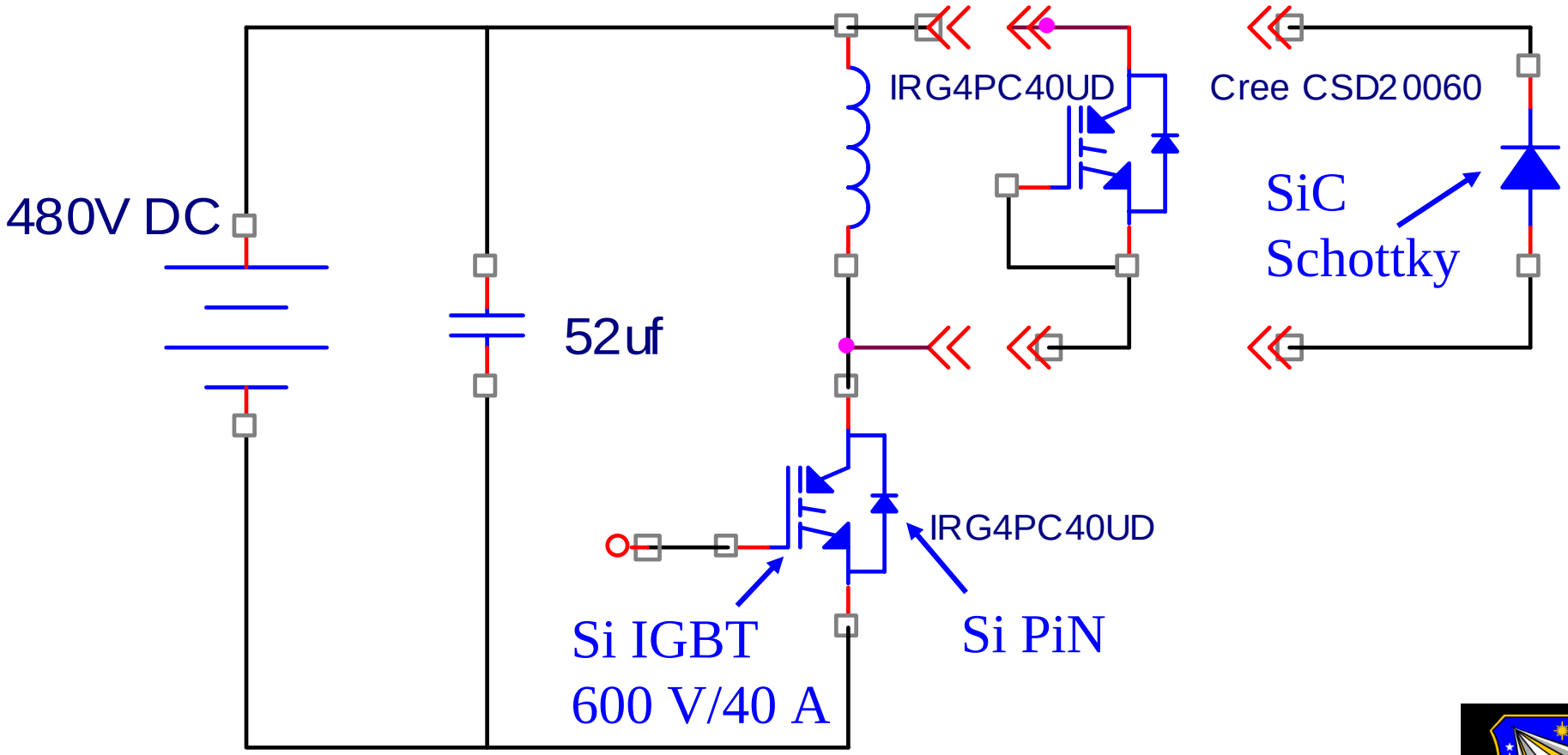
Dual Si PiN Diodes (600 V, 4 A), MURH860CT

SiC Schottky Diode Improves the PFC Efficiency by ~ 5% and Eliminates the Snubber



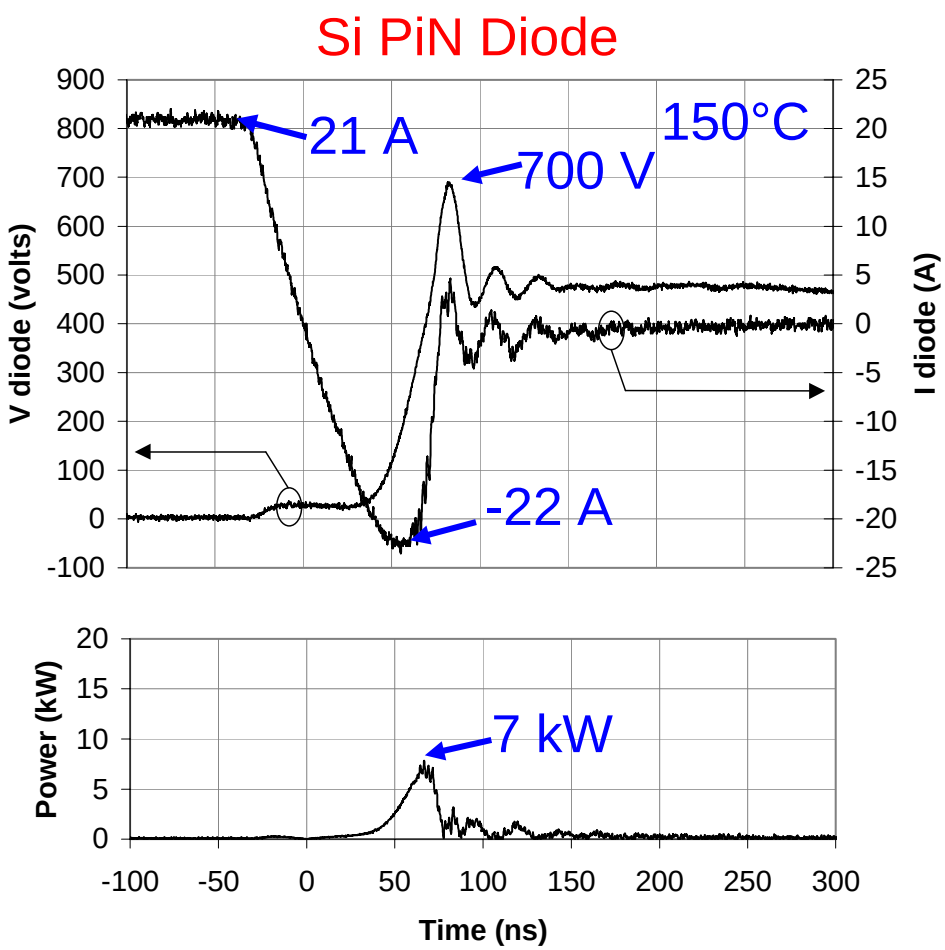
Motor Control Applications

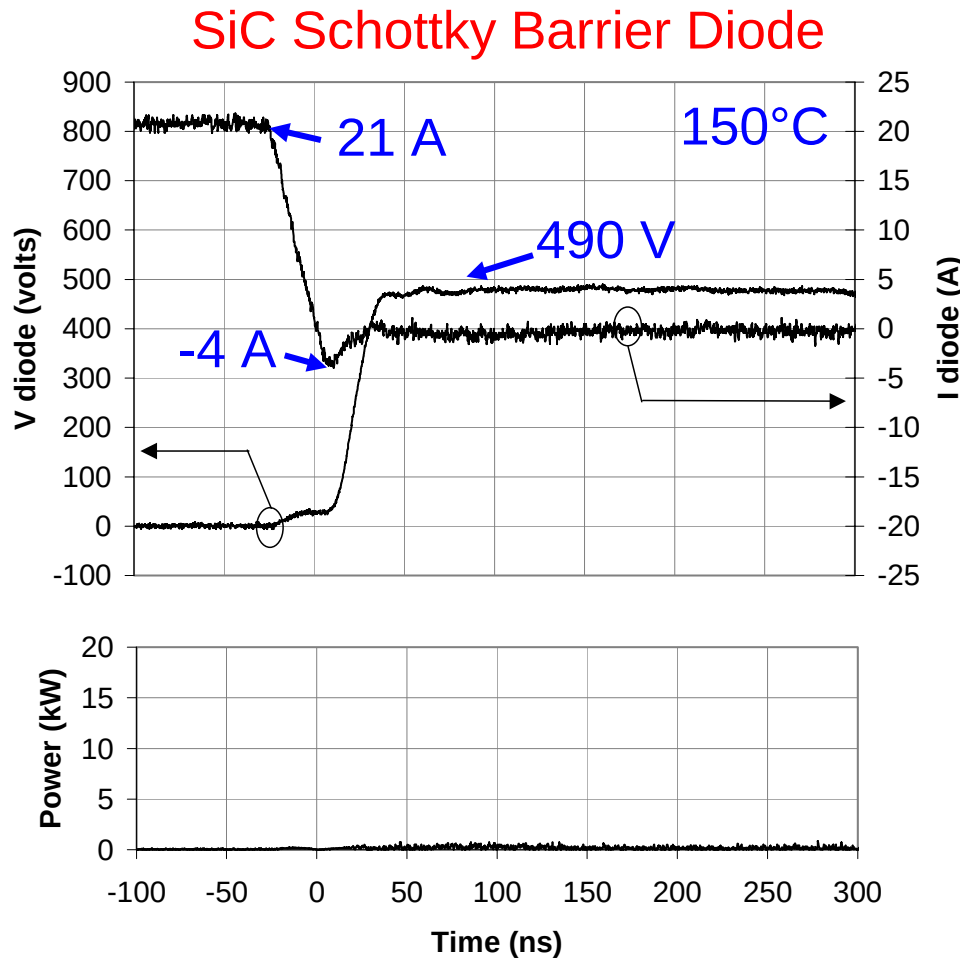
Si IGBT + Si PiN → Si IGBT + SiC SBD



Hard Switched Silicon IGBT's

Diode Waveforms

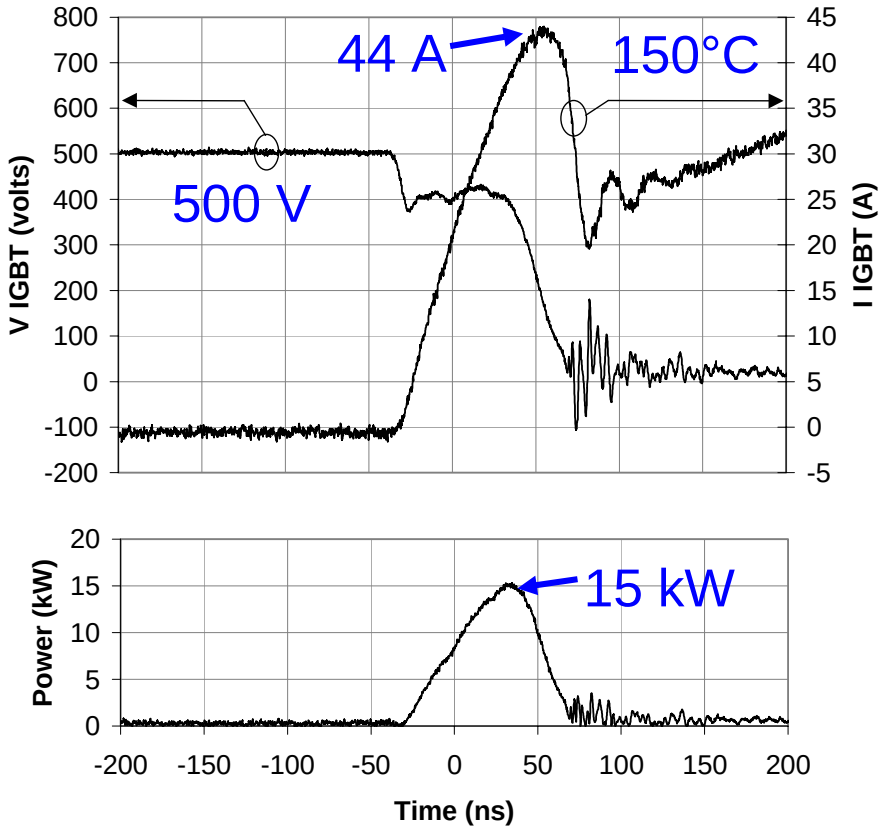




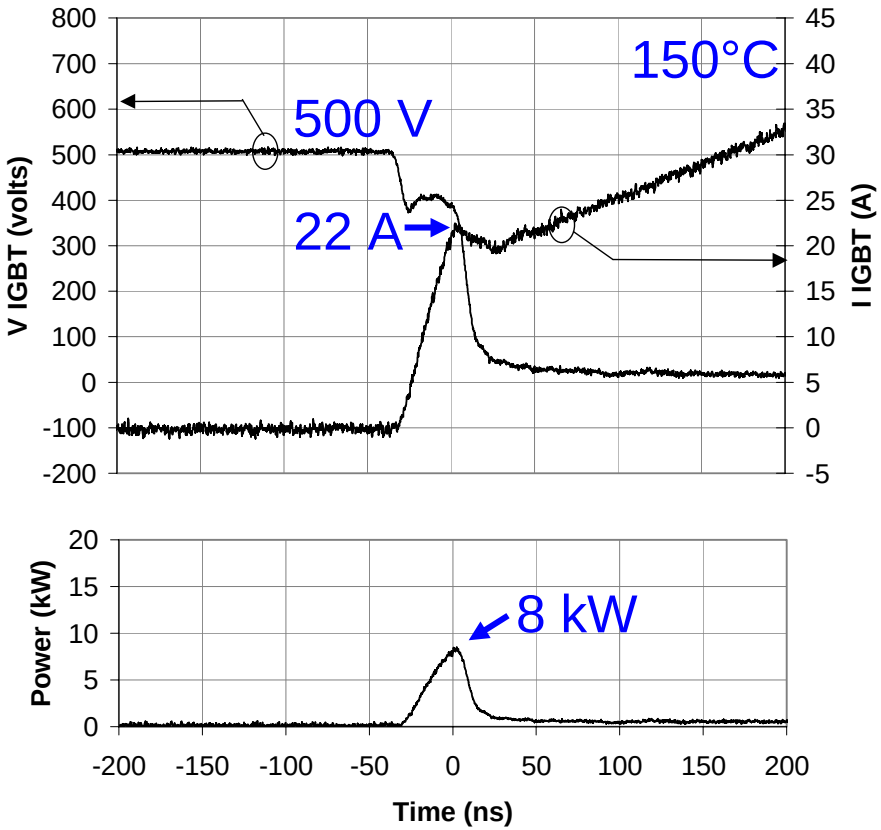
Hard Switched Silicon IGBT's

IGBT Waveforms

Si PiN Diode

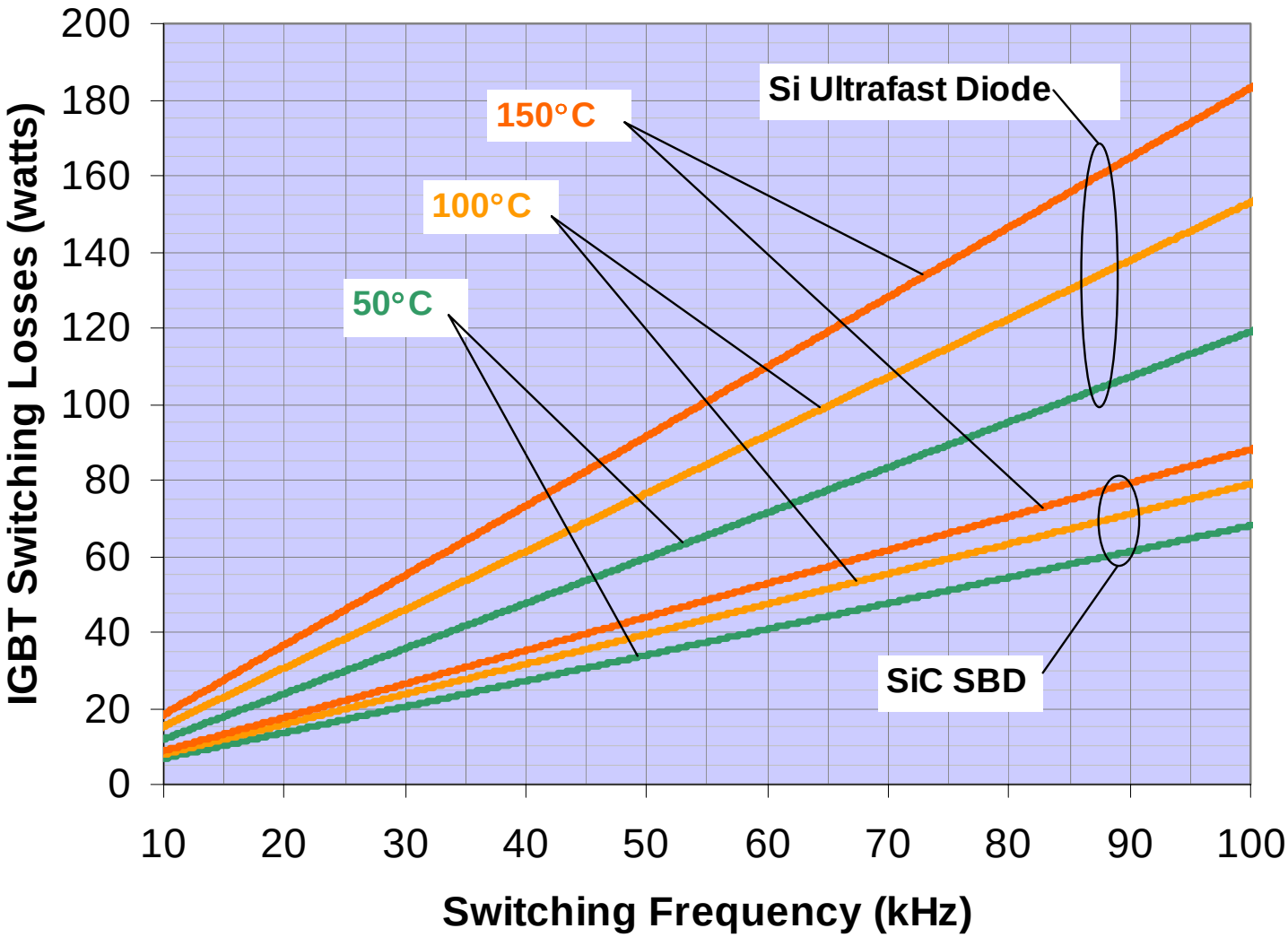


SiC Schottky Barrier Diode



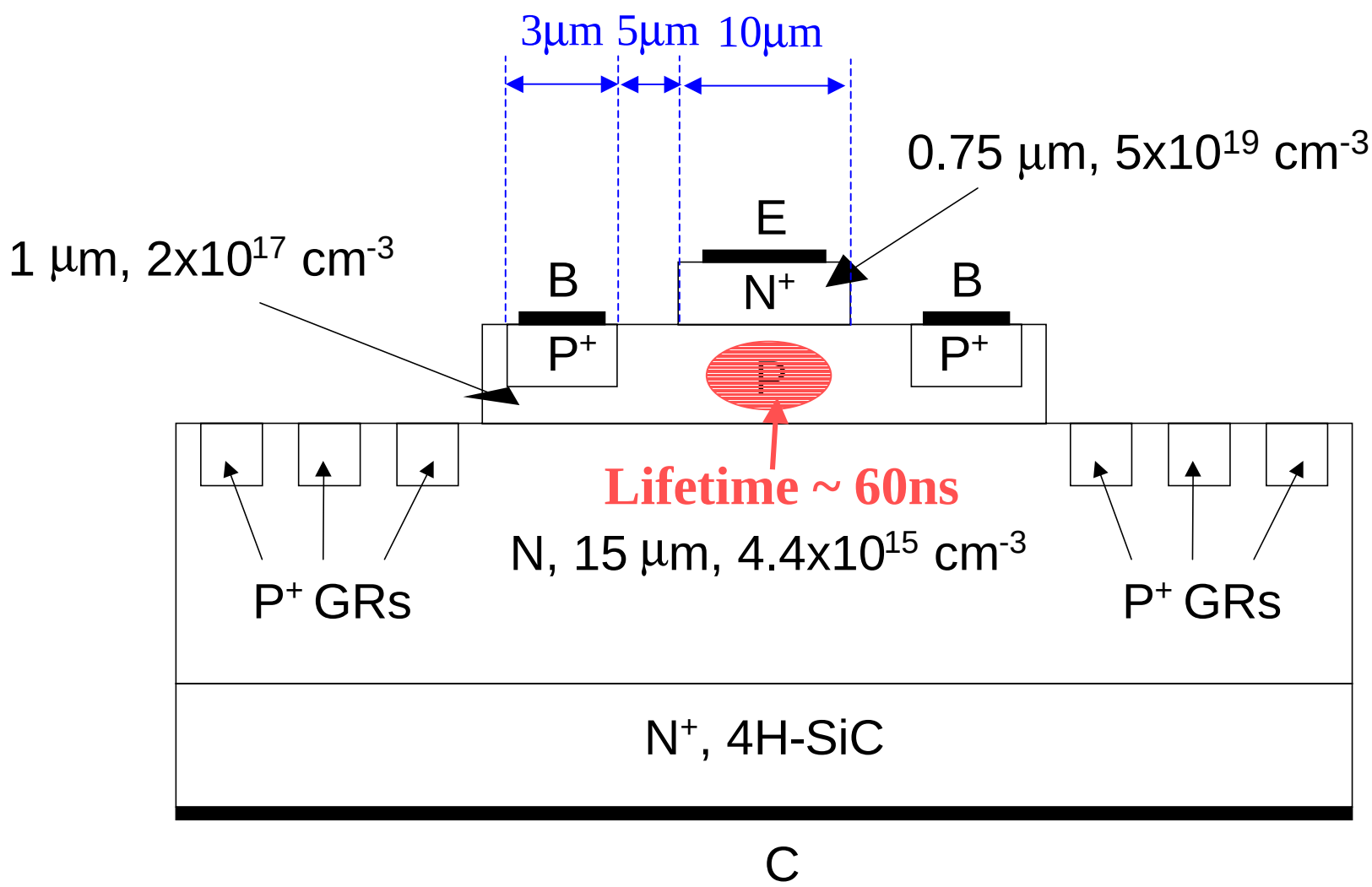
Hard Switched Silicon IGBT's

Cut Switching Losses by 50% with SiC SBD

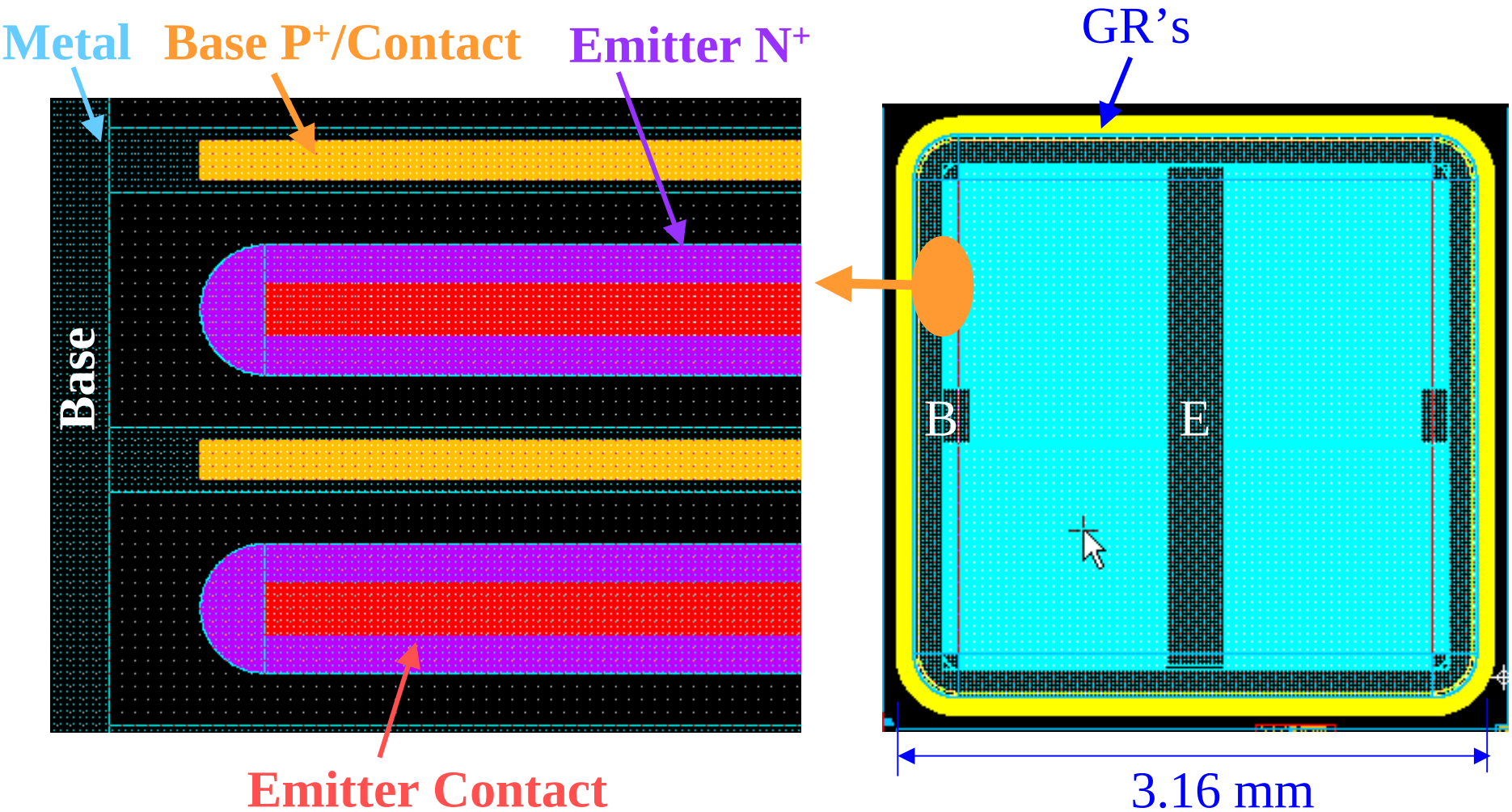


SiC Bipolar Junction Transistors

1200 V, 4H-SiC BJT Structure

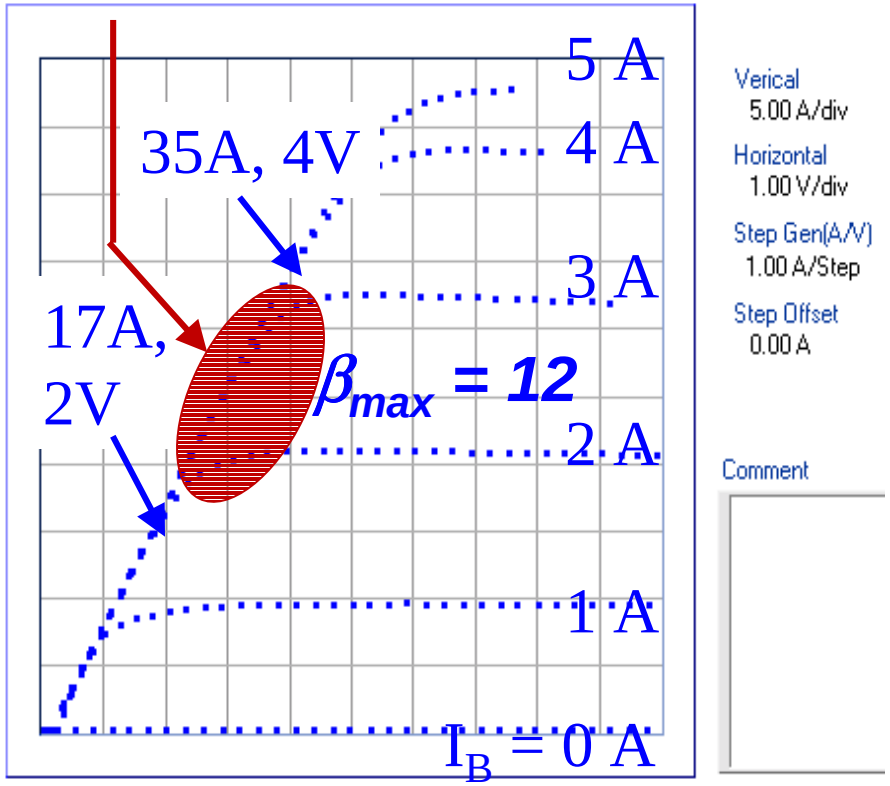


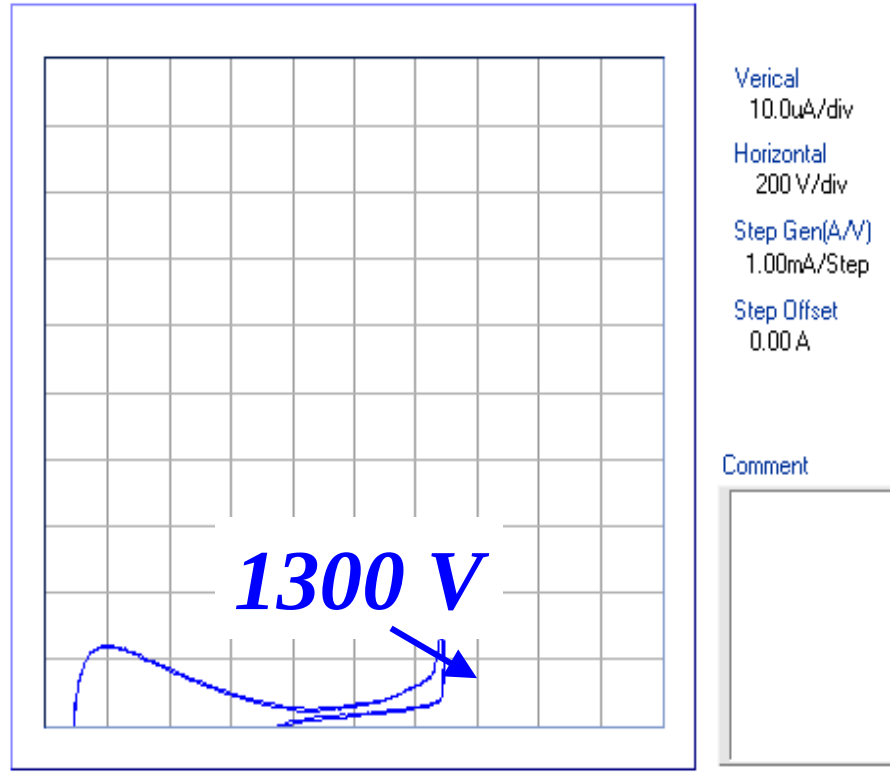
CAD Layout of the 3 mm x 3 mm BJT



3 mm, 1200 V, 4H-SiC BJT

Poor conductivity modulation in the collector





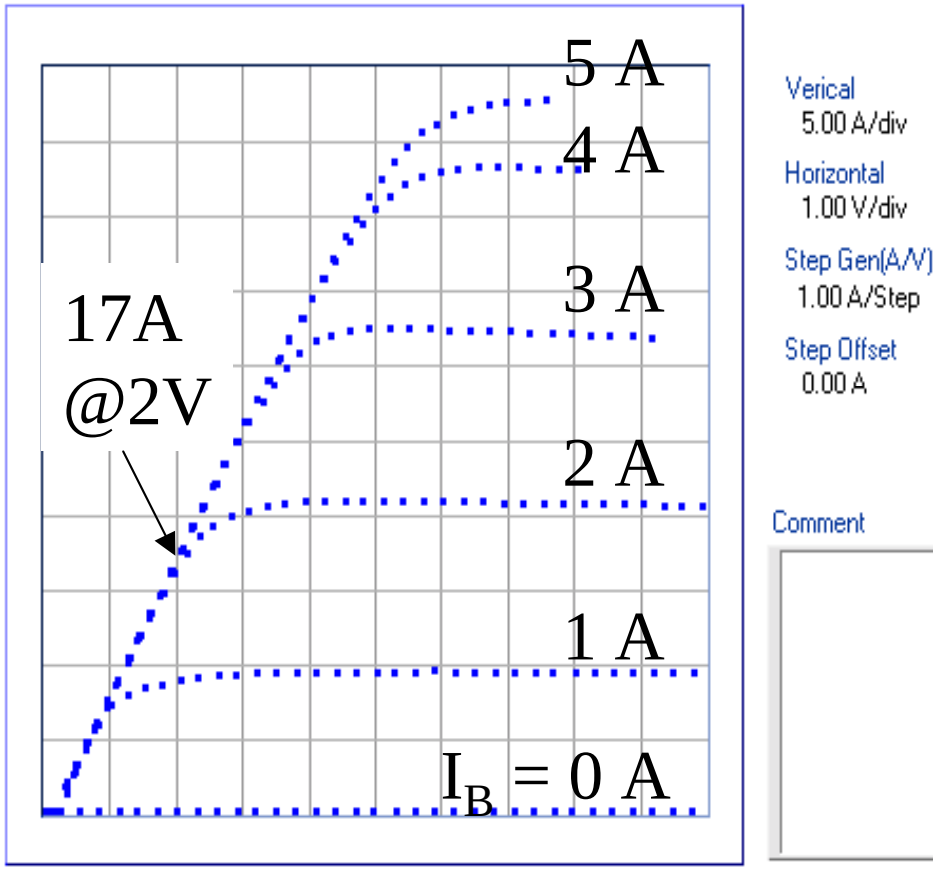
On-Resistance = 8 mohm-cm²

Equivalent SiC MOSFET ~ 24-30 mohm-cm²

Temperature Dependence

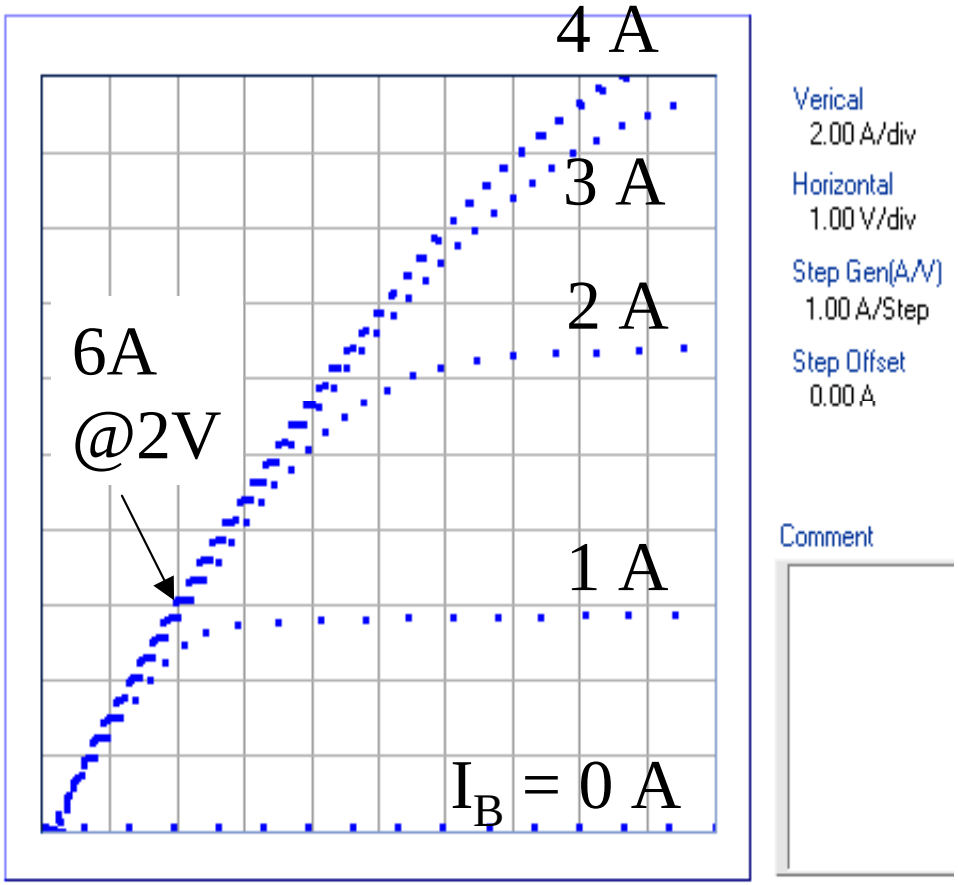
Good for paralleling

T = 25°C



β = 12, R_{on} = 8 mohm-cm^2

T = 250°C



β = 6, R_{on} = 23 mohm-cm^2

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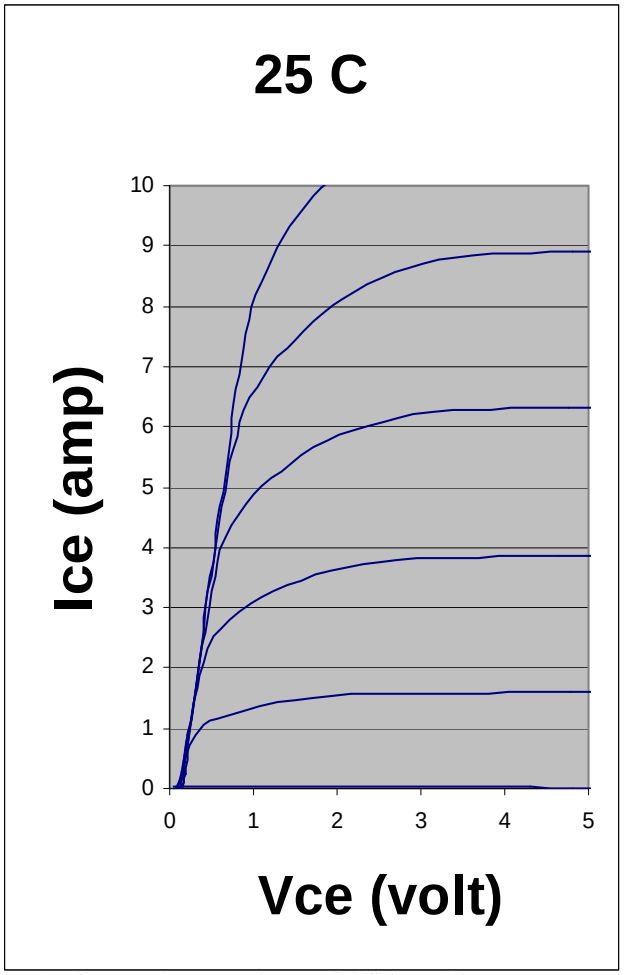
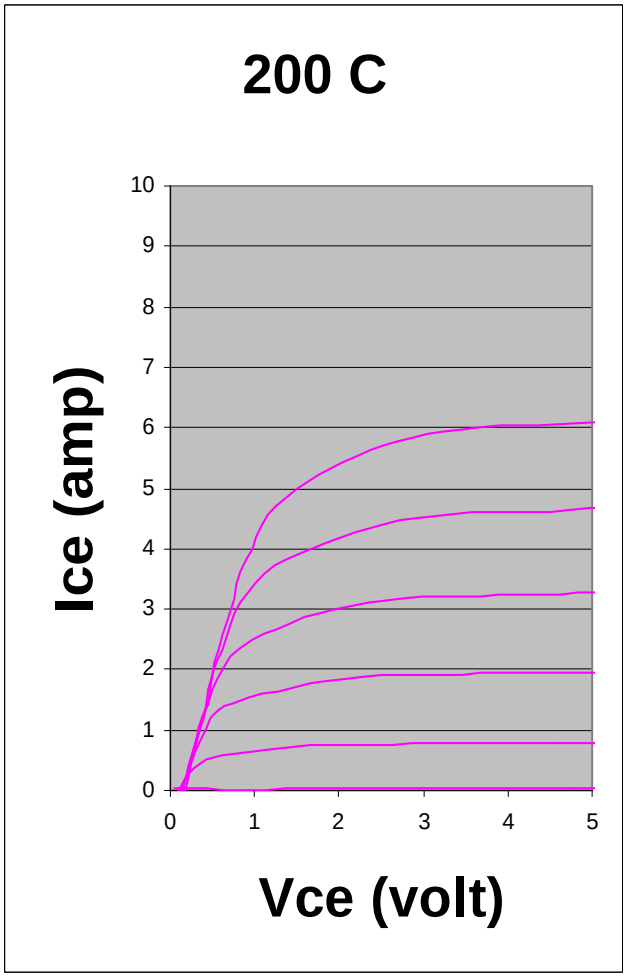
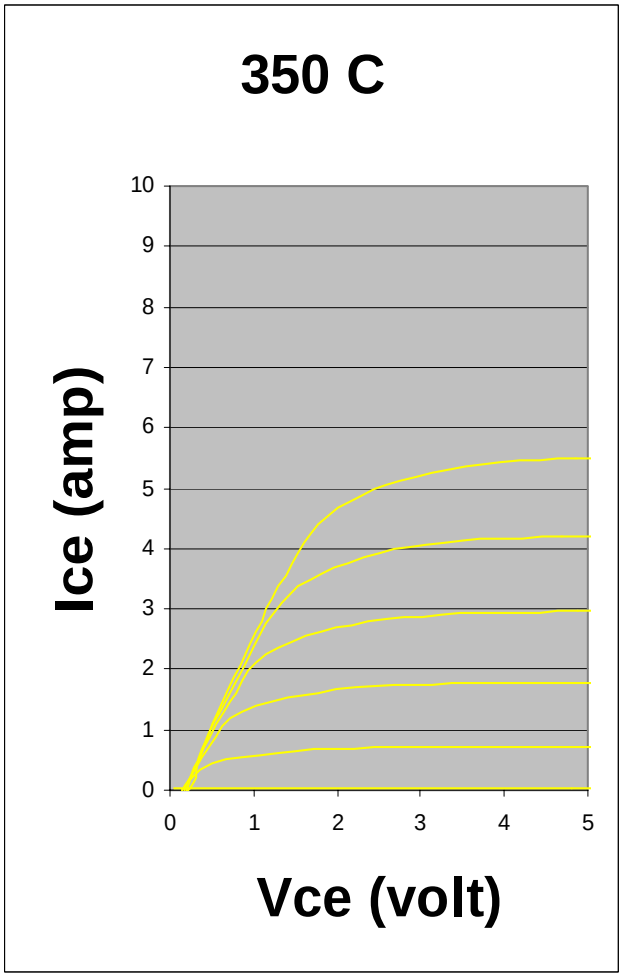
3 mm x 3 mm, 600 V SiC BJT

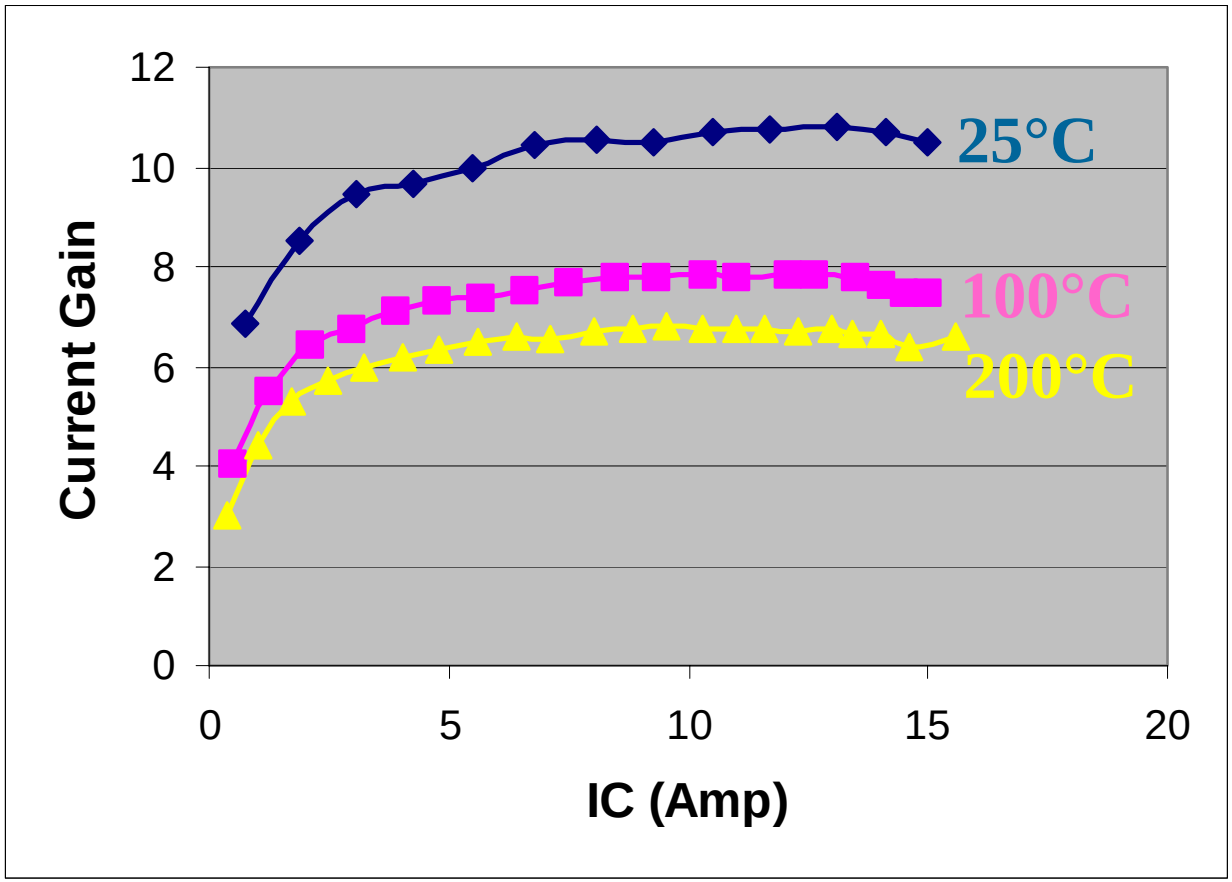
Base Current = 200 ma per step







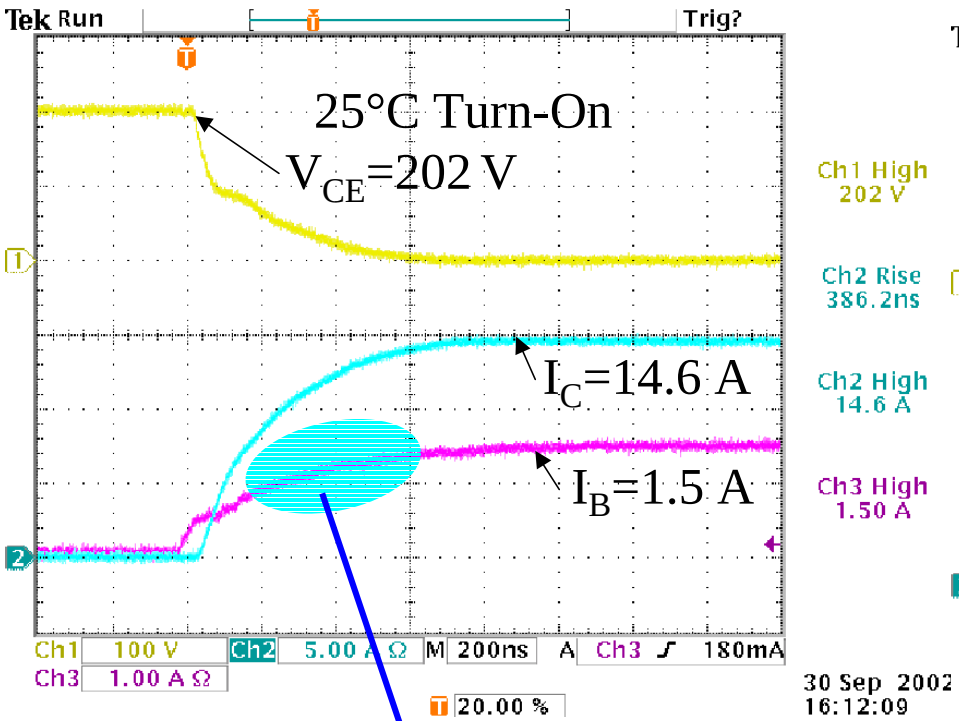
Negative Temperature Coefficient of β Helps Paralleling



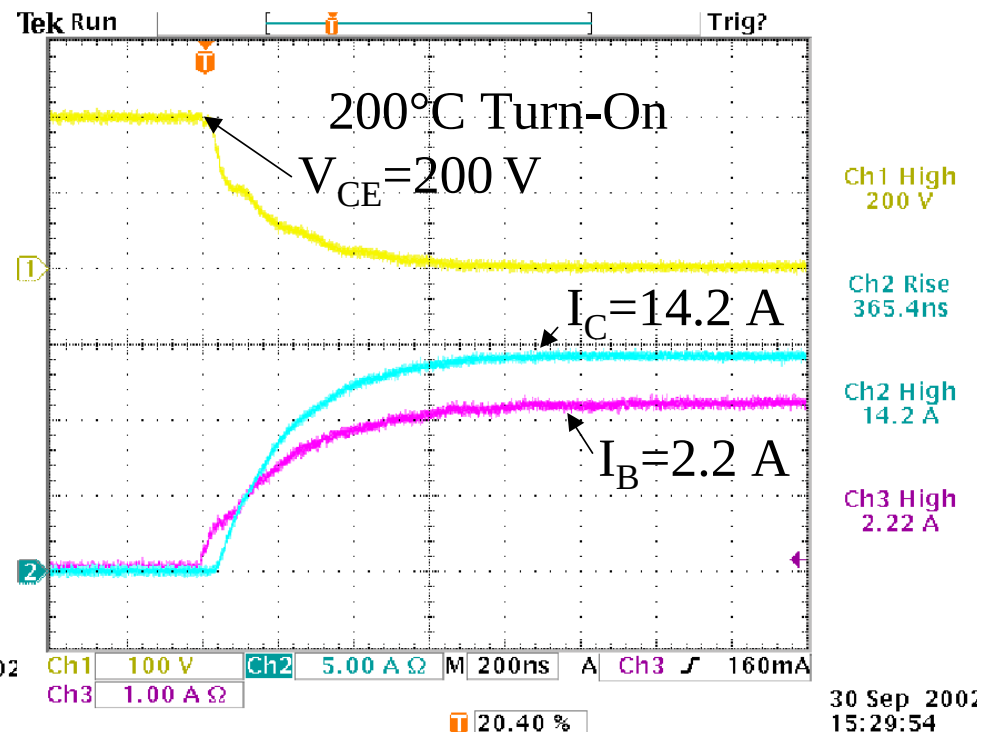
Enhanced ionization of the acceptors in the base

Turn-On Transient of the 4H-SiC BJT

t_r = 386 ns



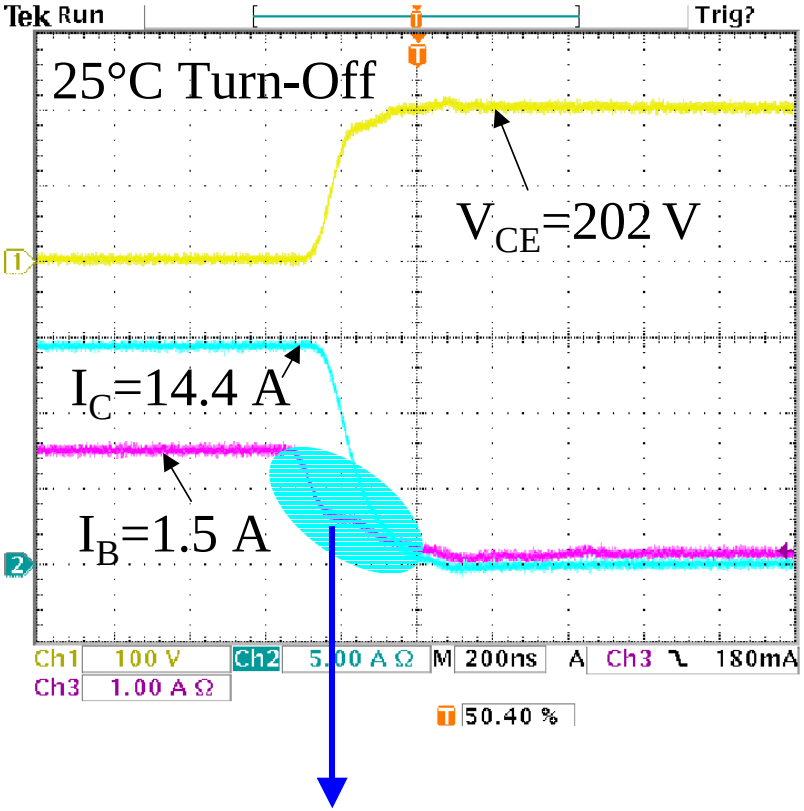
t_r = 365 ns



Turn-on time can be reduced by reducing the base resistance

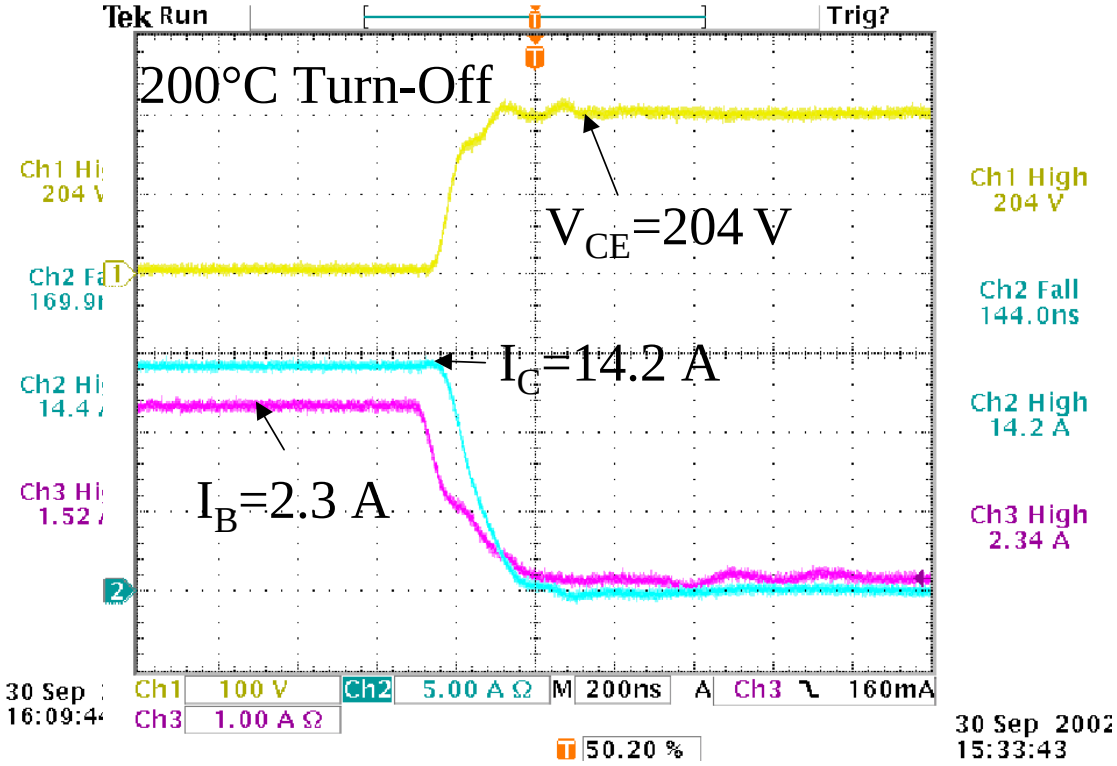
Turn-Off Transient of the 4H-SiC BJT

t_f= 170 ns



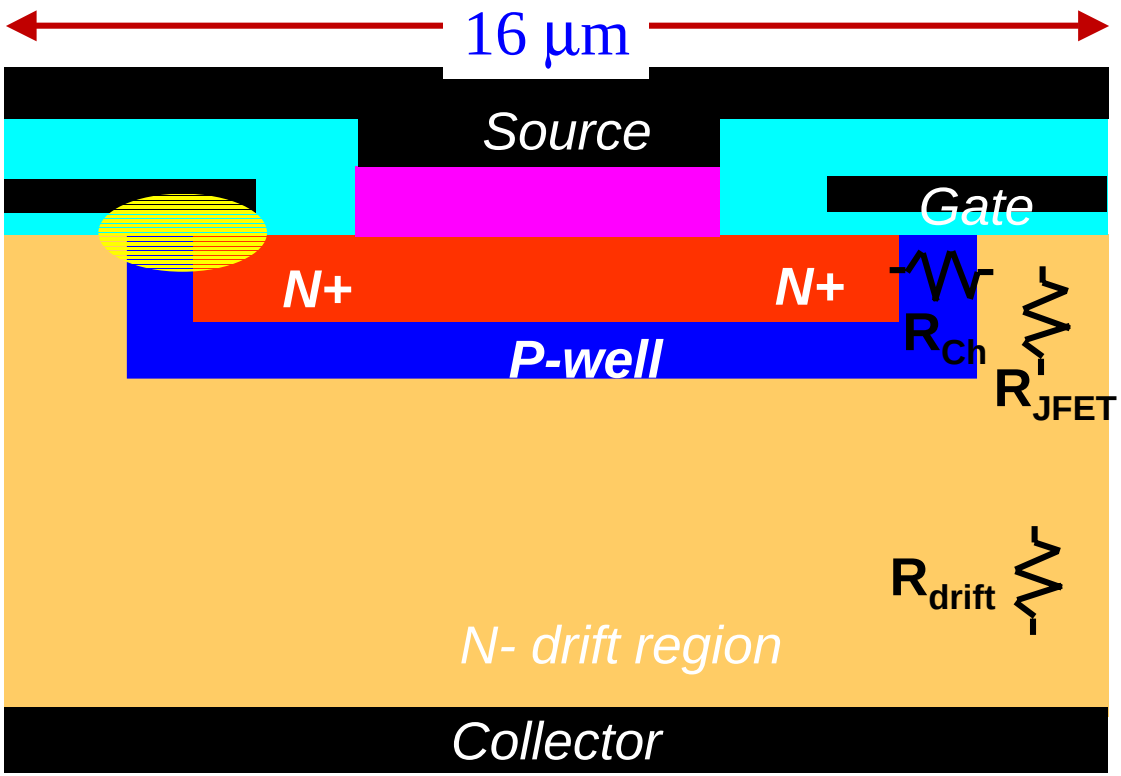
High Base Resistance

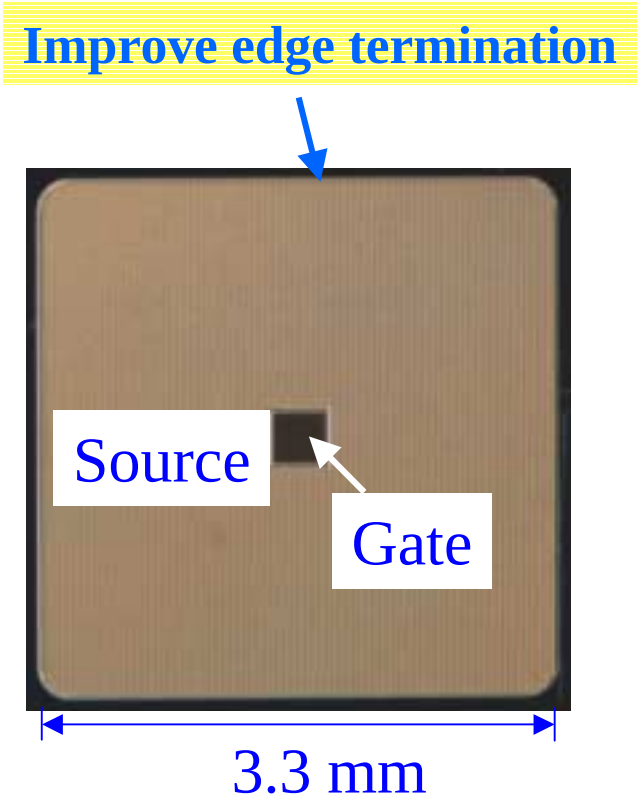
t_f= 144 ns



4H-SiC Power MOSFET Development

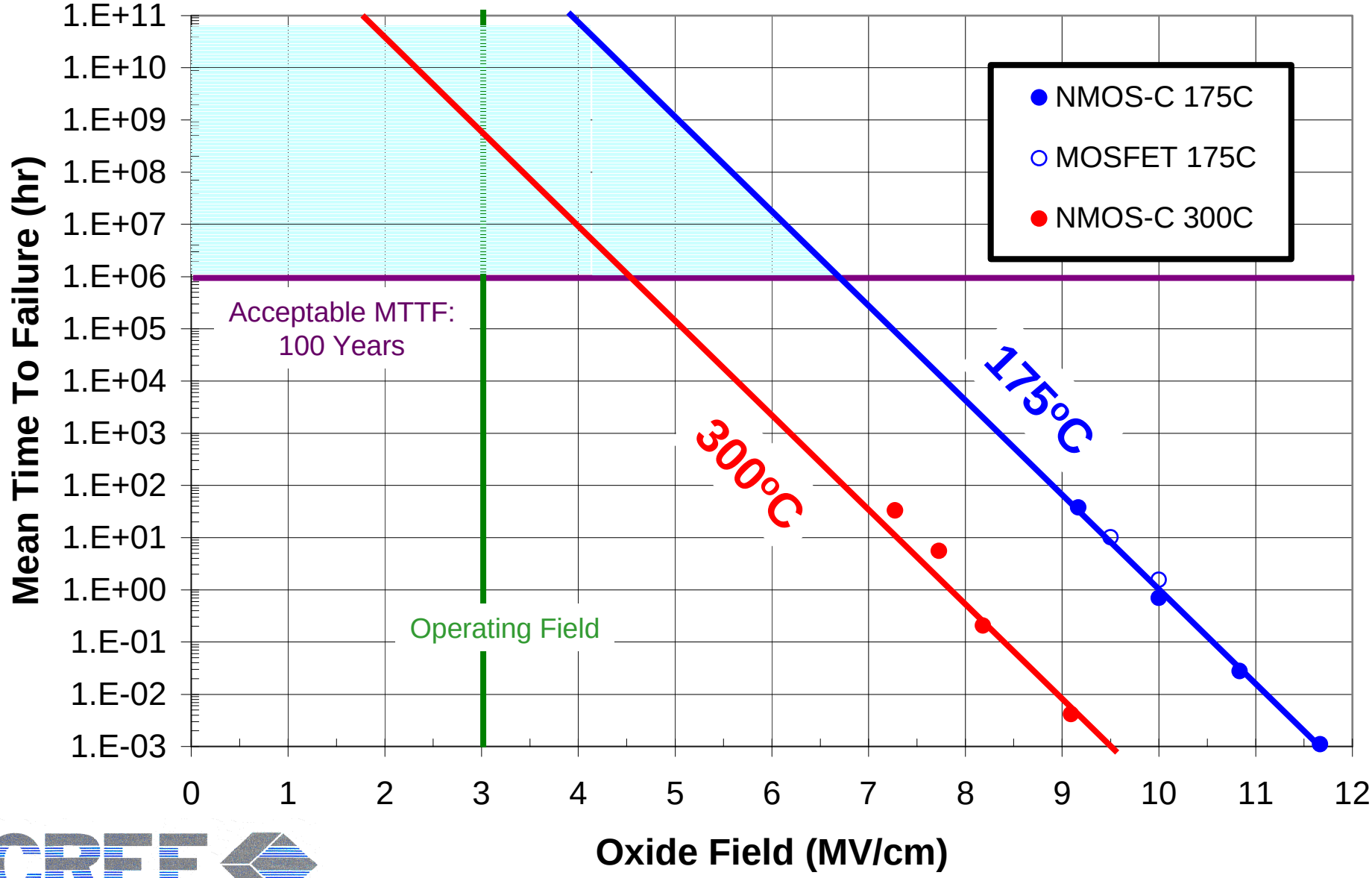
SiC DMOSFET



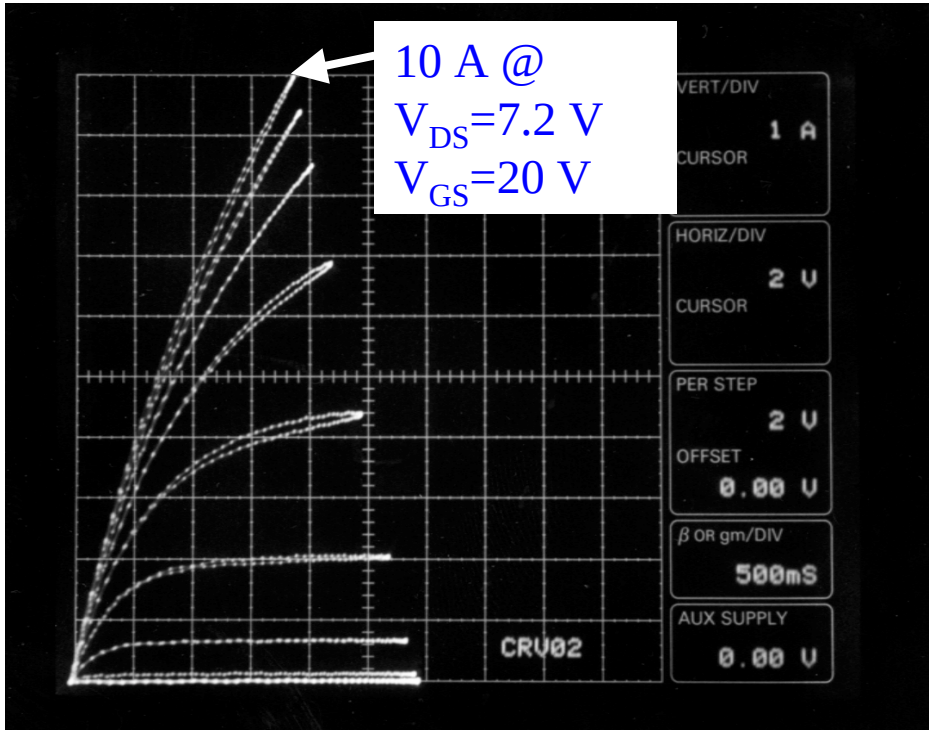


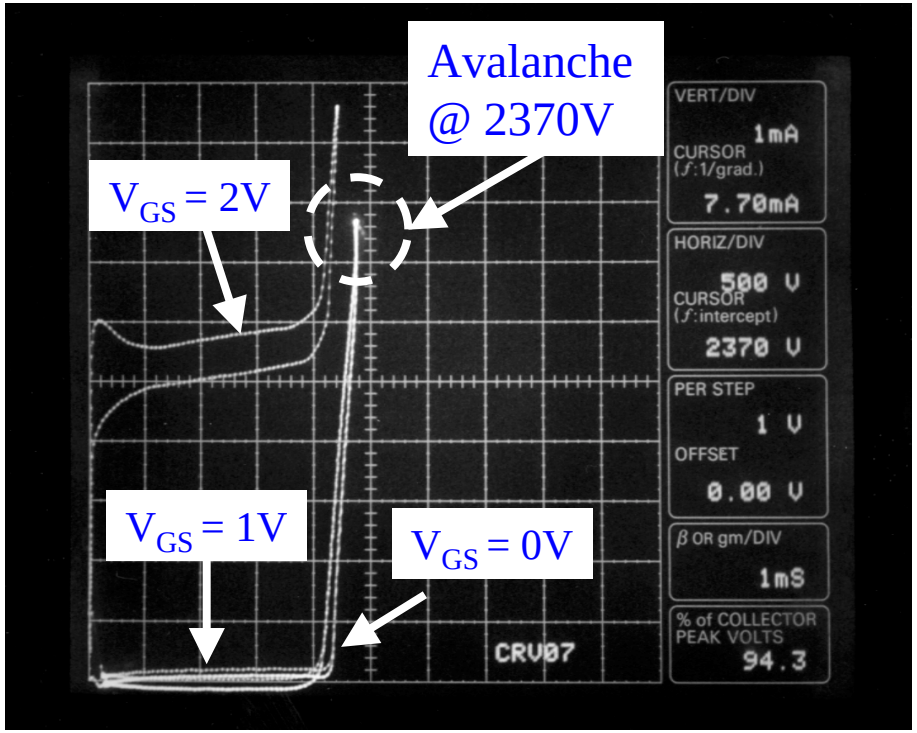
- **Improve Inversion layer electron mobility**
- **Improve gate oxide reliability**

4H-SiC MOS Yields
High Reliability at 300°C!!



3.3 mm x 3.3 mm (0.103 cm^2 active area) 4H-SiC DMOSFET 10 A on-current and 2.4 kV blocking!



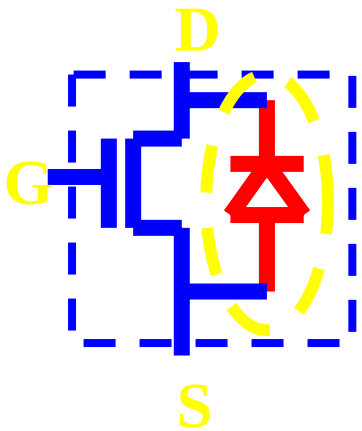


$R_{on,sp}$ = 42 mΩ-cm^2

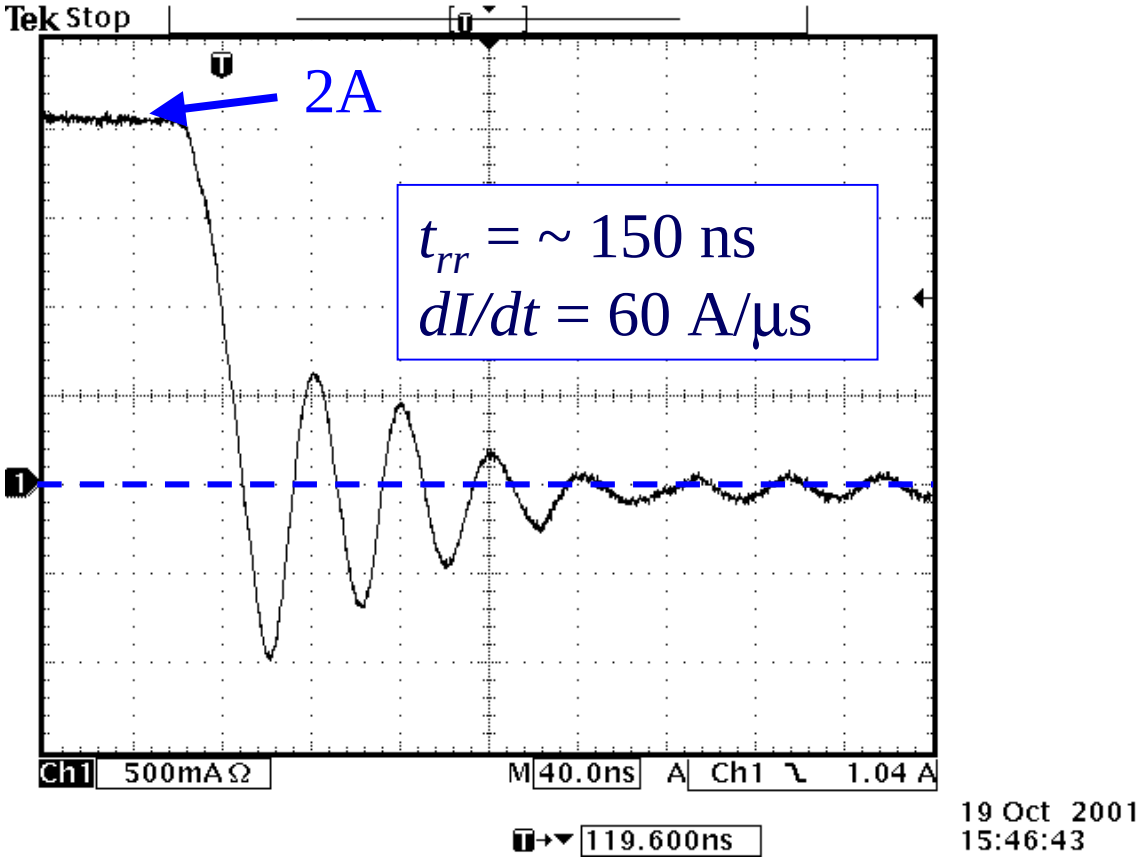
BV = 2370 V

Inversion Layer Electron Mobility =20 cm^2/V-s

Reverse Recovery of the Body Diode of a 0.0387cm^2 4H-SiC DiMOSFET



International Rectifier IRFPG50
(1000 V, 2.0 Ω Si MOSFET)
t_{rr}(body diode) = 630 ns



Comparison of a 0.0387 cm^2 4H-SiC DiMOSFET and a commercially available Si MOSFET*

	0.0387cm^2 4H-SiC DiMOSFET	IRFPG50* Silicon HEXFET
Blocking Voltage	2400 V	1000 V
Current Rating @ 27°C	2 A	6.1 A
$R_{DS(on)}$ @ 27°C	1.08 Ω[1)]	2.0 Ω
C_{iss} (Input Capacitance)[2)]	1080 pF	2800 pF
C_{oss} (Output Capacitance)[2)]	92.5 pF	250 pF
C_{rss} (Reverse Transfer Capacitance)[2)]	1.66 pF	84 pF
t_{rr} (body diode reverse recovery time)	150 ns	630 ns

[1)] measured at V_{GS} = 20 V, V_{DS} = 1 V

[2)] V_{GS} = 0 V, V_{DS} = 25 V, f = 1.0 MHz

* IRFPG50, from International Rectifier. From http://www.irf.com

1200 V, 10 mΩ-cm^2 Power MOSFET Proposal

Reduction of Channel Resistance

- **Reduction of Pitch from 16 μm to 10 μm**
- **Inversion Layer Electron Mobility to ~75 cm^2/V-s**
- **Reduction of Gate length from 2 μm to 0.75 μm**

Reduction of JFET Resistance by JFET Implant

Improved Oxide Reliability

1200 V, 100 A SiC Power MOSFET in 7 mm x 7 mm Die
Area of SiC chip ~ 1/20th of an equivalent Si Chip

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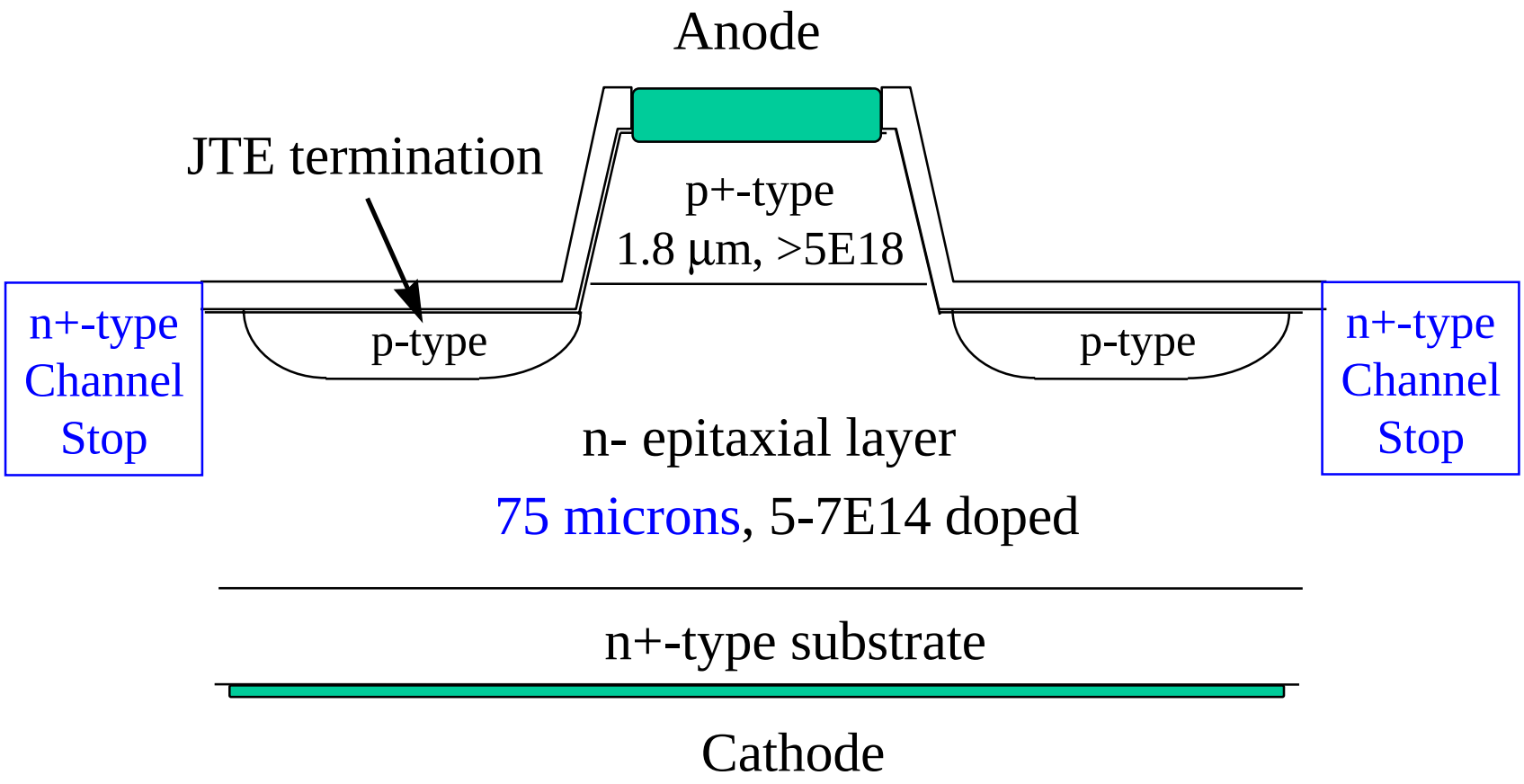
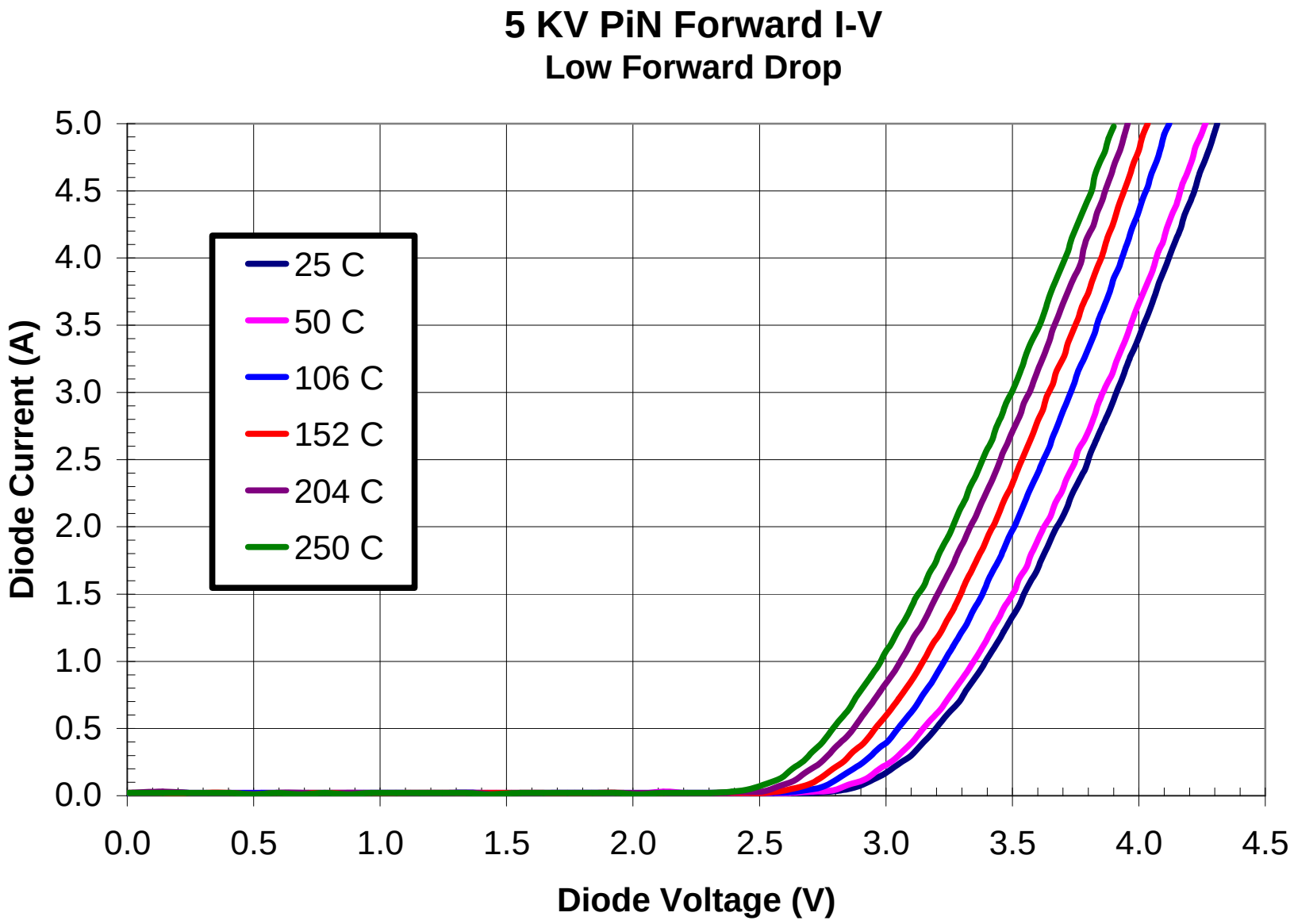
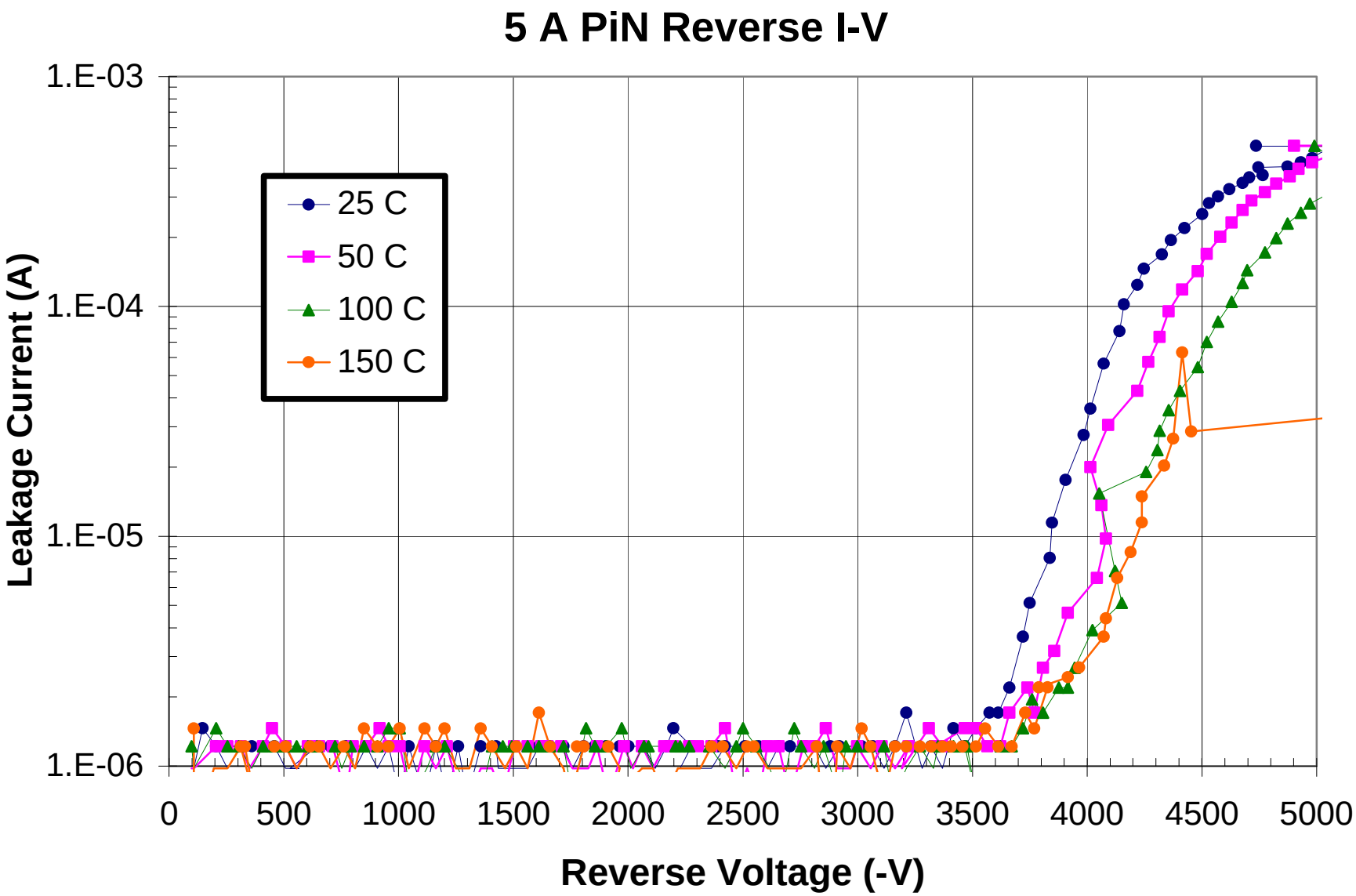
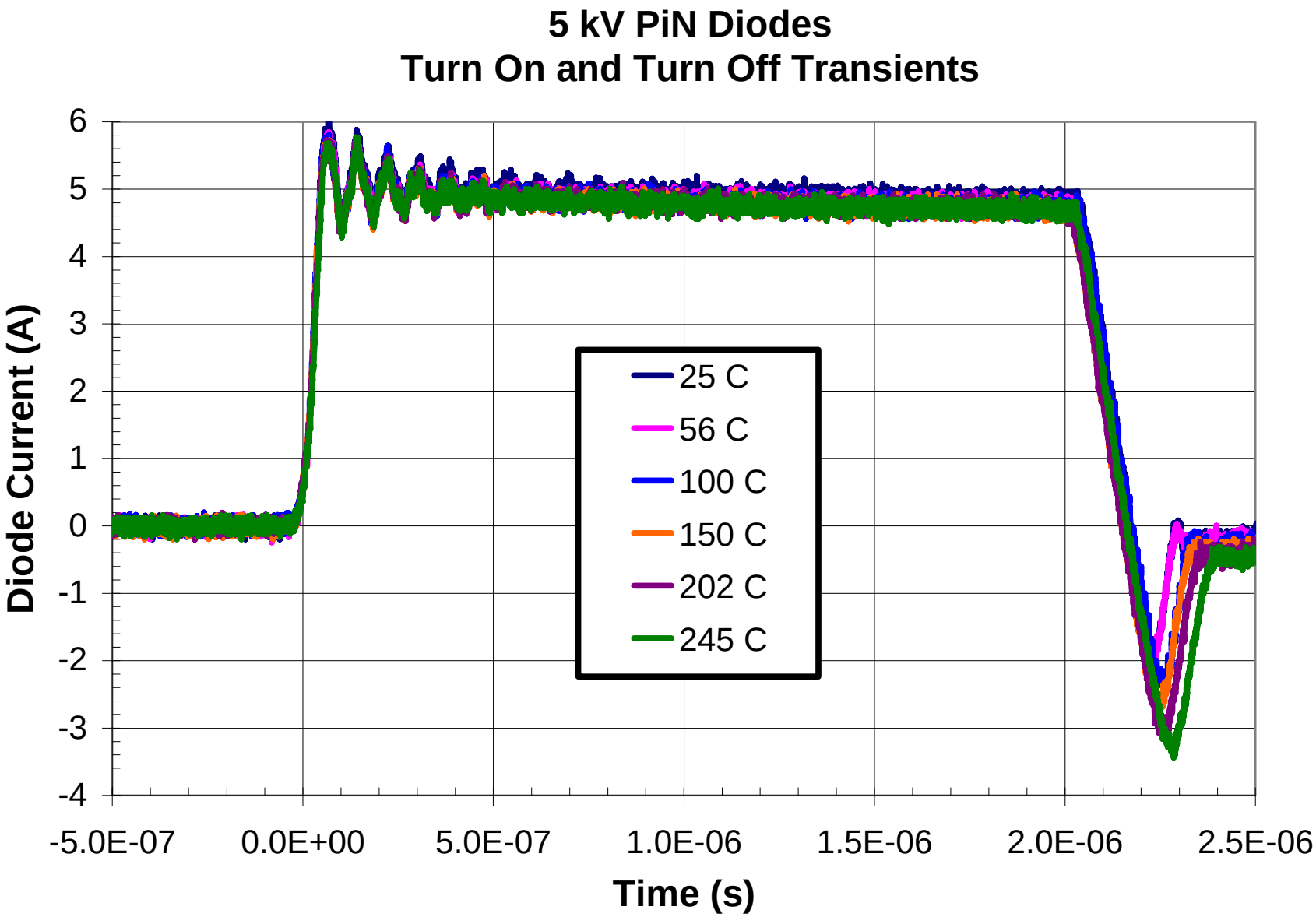
10 kV, 4H-SiC PiN Diode Development

PiN Cross Section

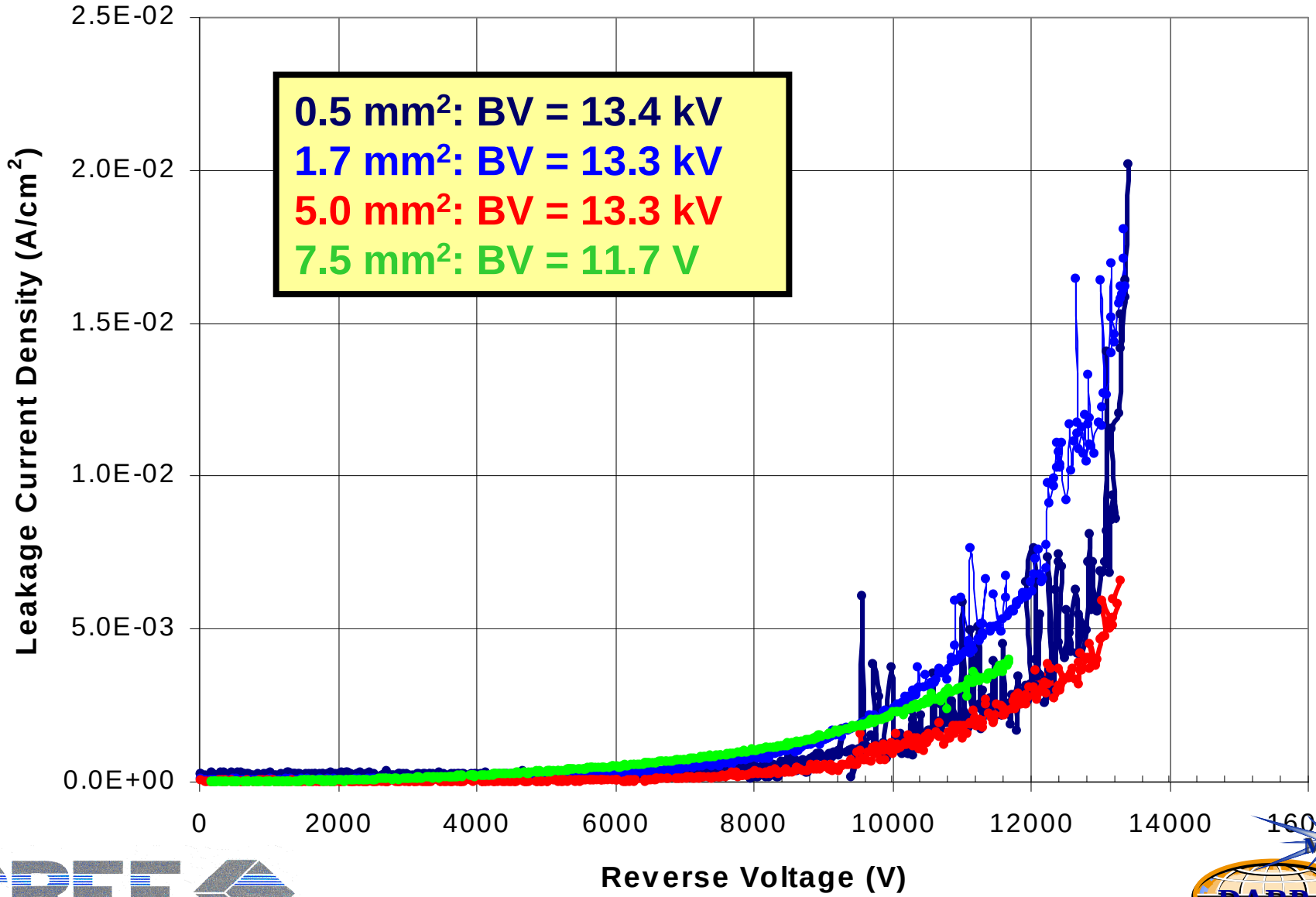



5 KV PiN Forward I-V
Low Forward Drop
Diode Current (A)
Diode Voltage (V)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
25 C
50 C
106 C
152 C
204 C
250 C

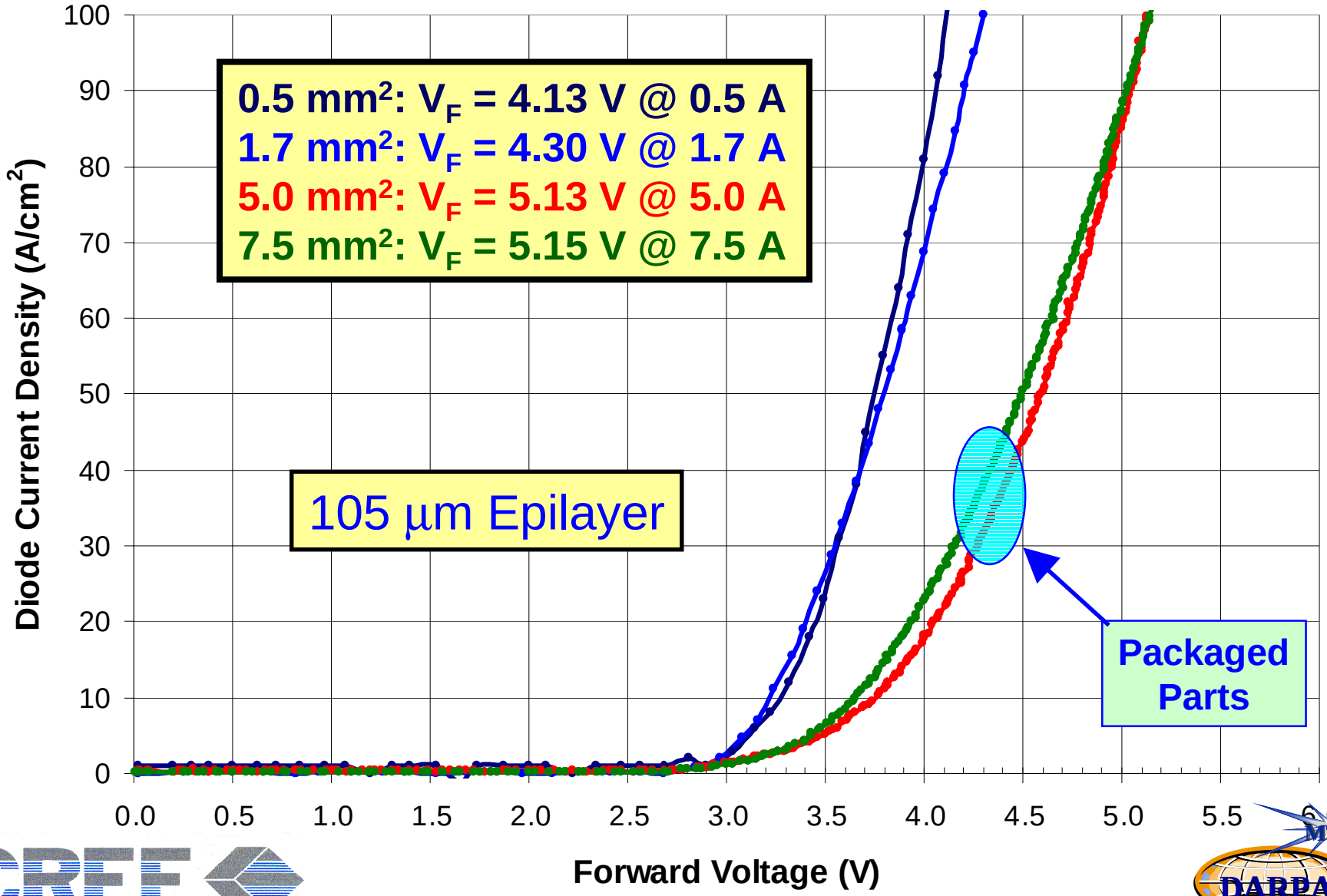

5 A PiN Reverse I-V
Leakage Current (A)
1.E-03
1.E-04
1.E-05
1.E-06
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Reverse Voltage (-V)
25 C
50 C
100 C
150 C


5 kV PiN Diodes
Turn On and Turn Off Transients
Diode Current (A)
6
5
4
3
2
1
0
-1
-2
-3
-4
-5.0E-07
0.0E+00
5.0E-07
1.0E-06
1.5E-06
2.0E-06
2.5E-06
Time (s)
25 C
56 C
100 C
150 C
202 C
245 C

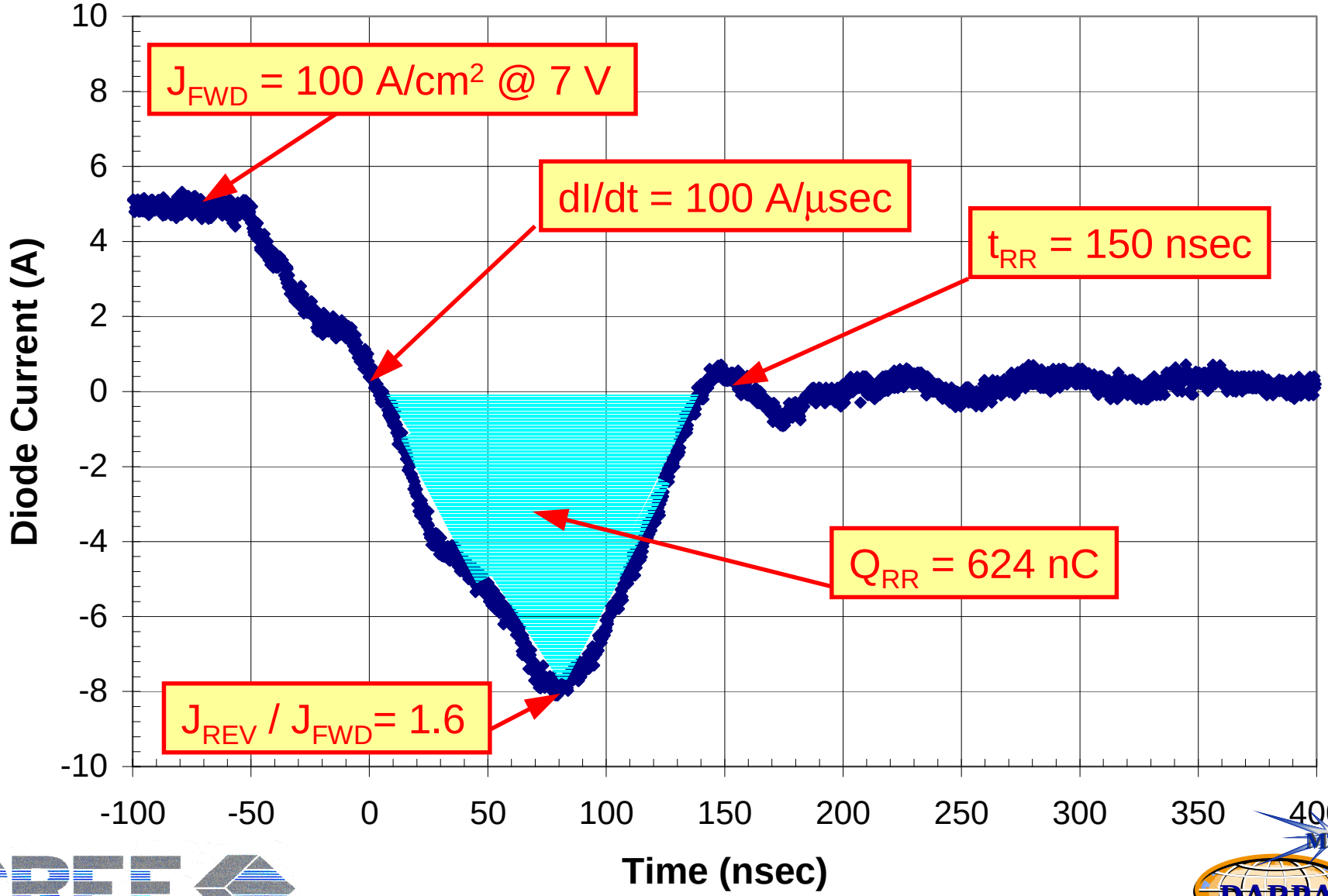
Blocking Characteristics



Forward Characteristics



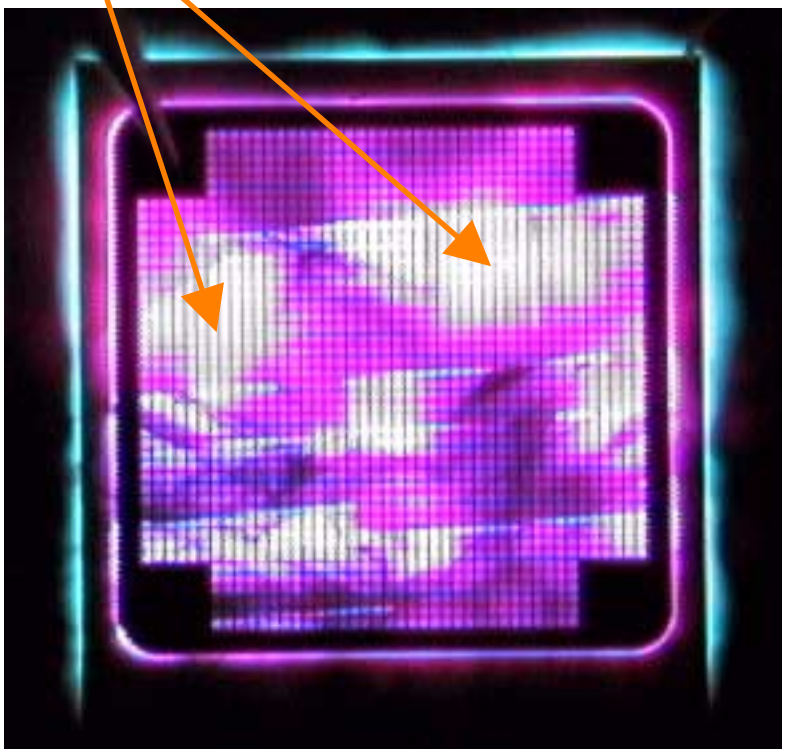
Room Temperature Reverse Recovery of 5 mm², 10 kV PiN Diode on 150 μm Drift Layer



Gridded PiN Diode Measurements in thick Epilayers

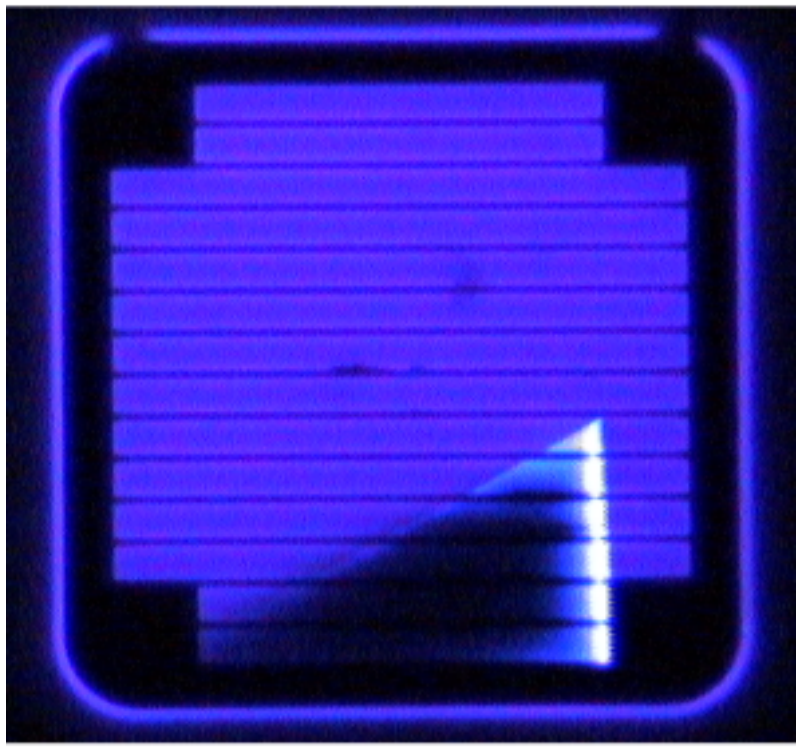
Stacking Faults

0.8 A for 1 min



150 µm epilayer

150 A/cm^2 for 100 hrs



100 µm epilayer

Highlights

- Average Micro-pipe density of 1.3 pipes/cm^2 in 3” 4H-SiC
- 600 V and 1200 V SBDs have been commercialized
- 600 V/ 135 A SiC Schottky Rectifier Modules demonstrated
- 50% reduction in Si IGBT switching losses with a SiC SBD
- 1200 V, 17 A BJTs demonstrated. Current gain and base resistance need to be improved.
- 1200 V, 25-100 A power MOSFETs are possible within two years with active area 1/10th to 1/20th of the silicon devices
- PiN Diodes: BV= 13.3 kV, V_F = 4.3 V @ 100 A/cm^2,
- Progress on Stacking Faults in thick epilayers

CREE