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Evaluation of SiC Diodes for SMPS Applications

Prof. K Shenai

Commercial Power Converters

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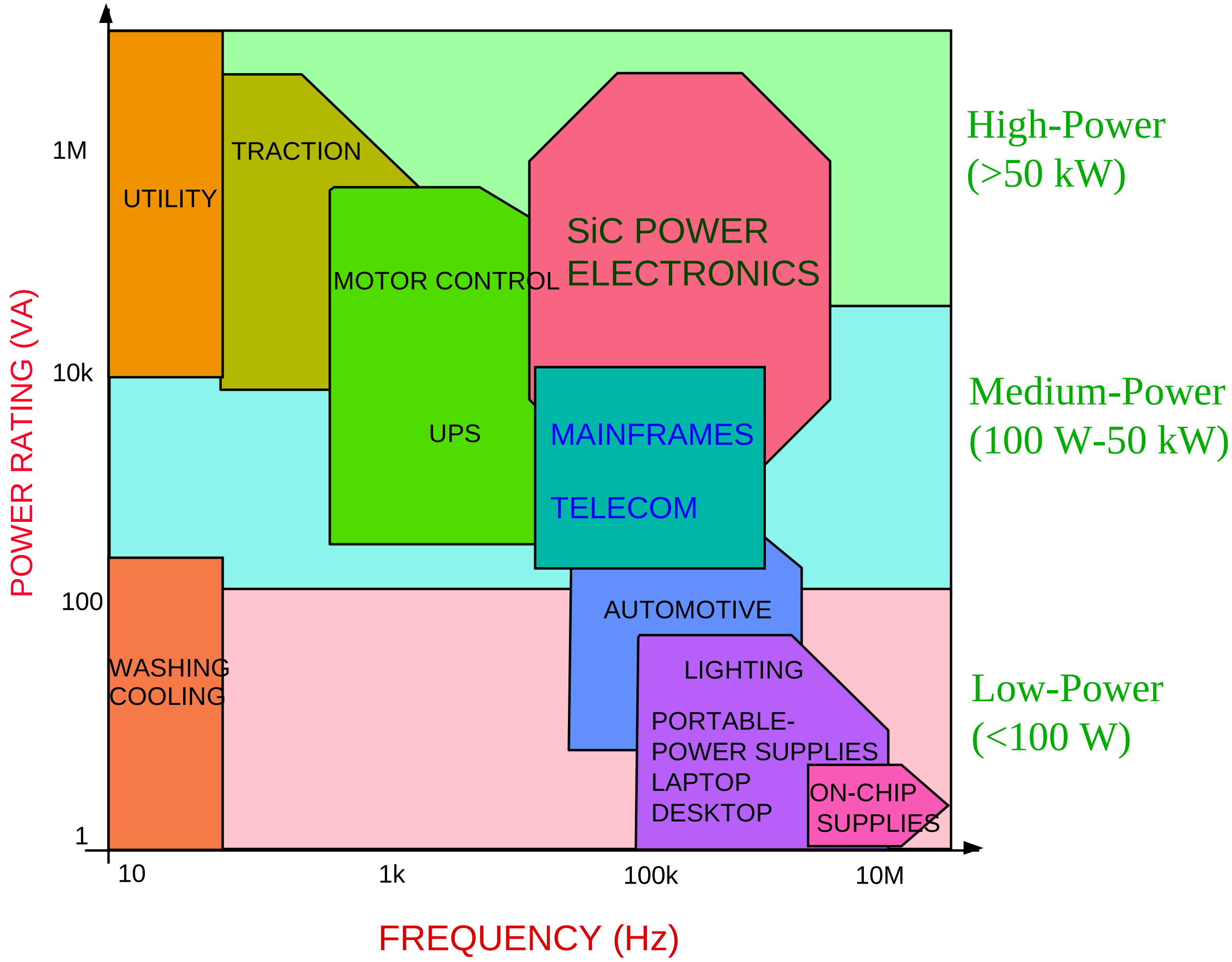

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250V/ 0.1A SiC Schottky Diode

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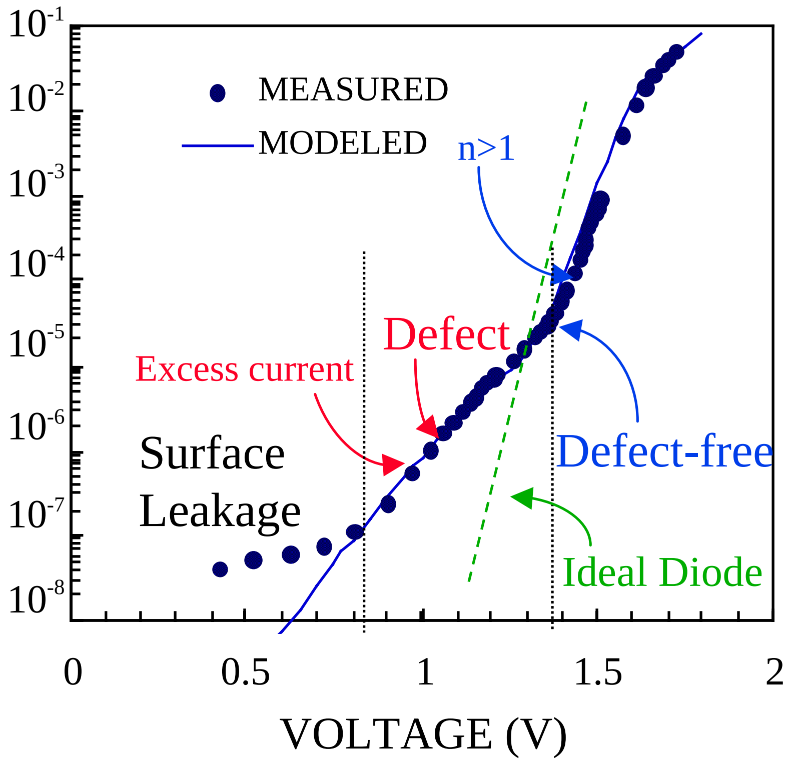
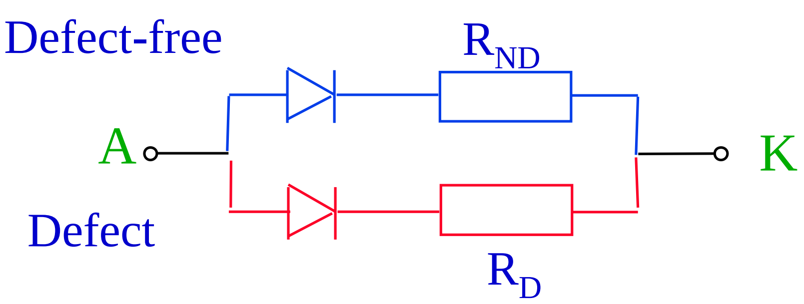
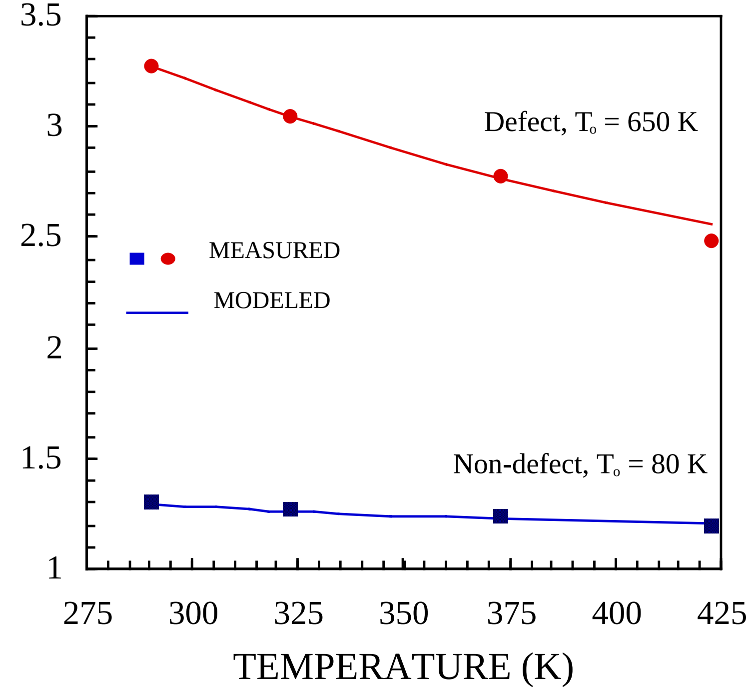
Static Characteristics





Ideality Factor



- Anomalies in forward conduction
- Material parameters vary at defect sites
- Ideality factor (n) represents quality of the diode
- A good diode has n ~1

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Forward I-V Characteristics

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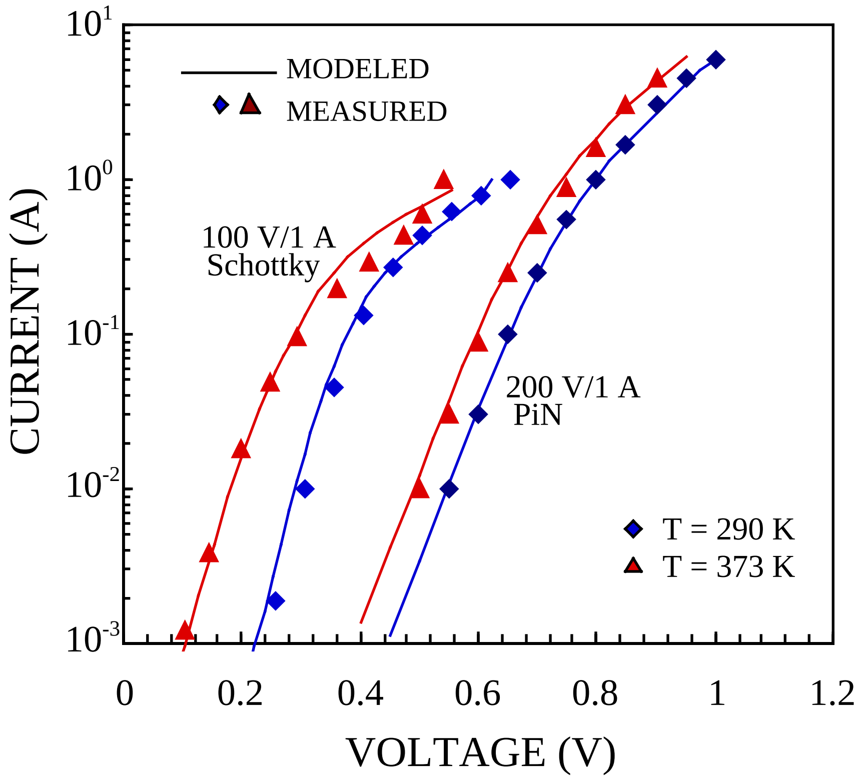
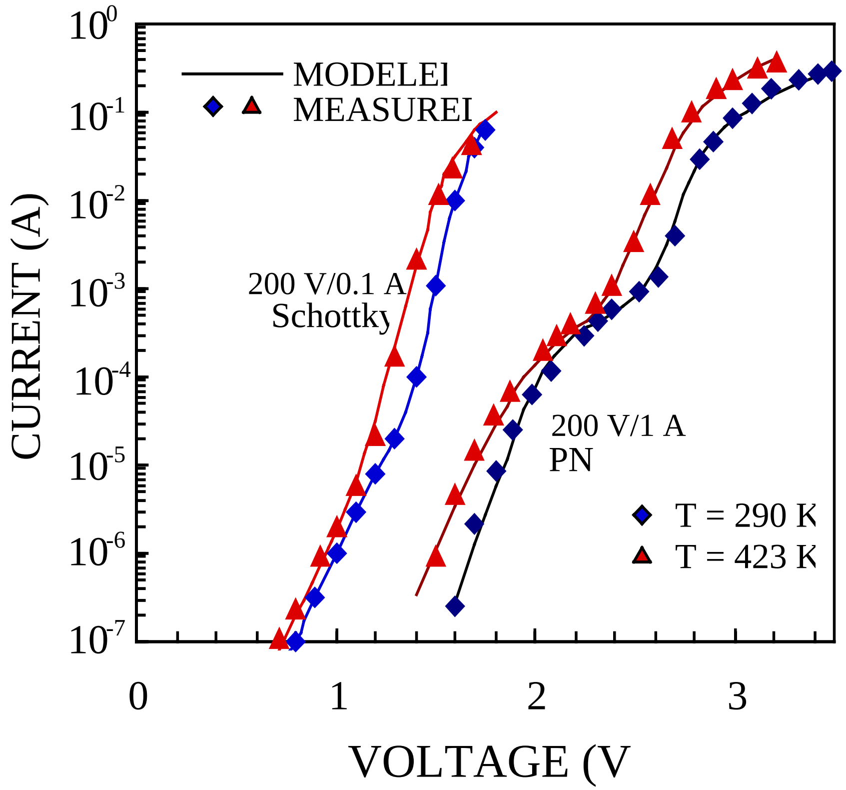
Si Diode



4H-SiC Diode



Si diodes have much lower on-state voltage than SiC diodes

Defect-induced excess current in SiC Schottky and PN diodes at low forward bias

Reverse Recovery Test Circuit

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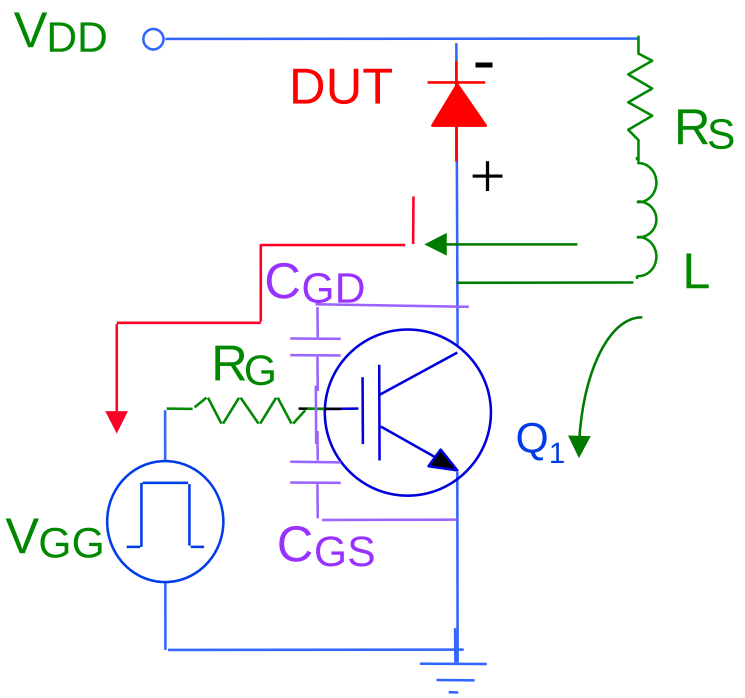
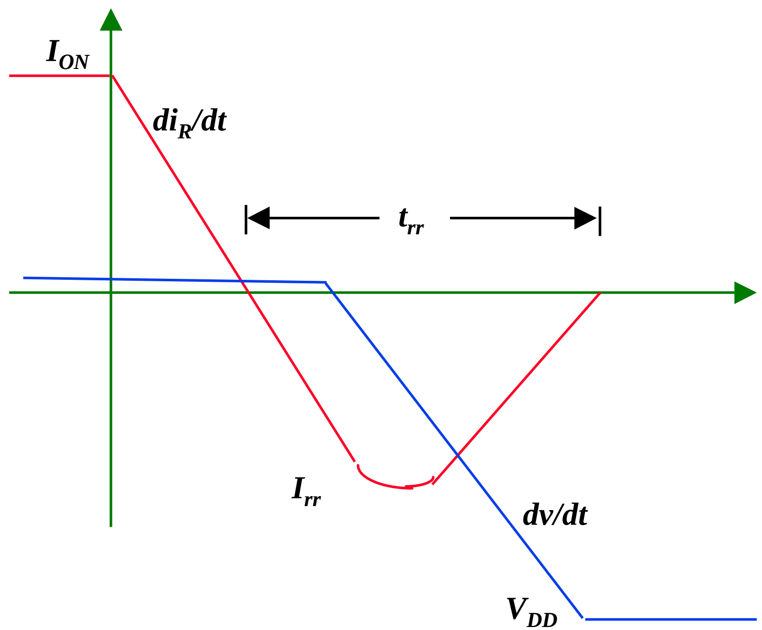
Test Circuit



- Forward current adjusted with pulse width of Q_1 gate pulse
- Gate pulse is applied to Q1 to intiate reverse recovery of diode
- Turn-off dI/dt is controlled by R_G
- Reverse recovery performance under various conditions of V_{DD}, I_{ON}, di_R/dt

Reverse Recovery



I_{ON}: Forward Current
di_R/dt: Turn-off di/dt
dv/dt: Recovery dv/dt
I_{rr} : Peak Reverse Recovery Current
t_{rr} : Reverse Recovery Time

Reverse Recovery Performance

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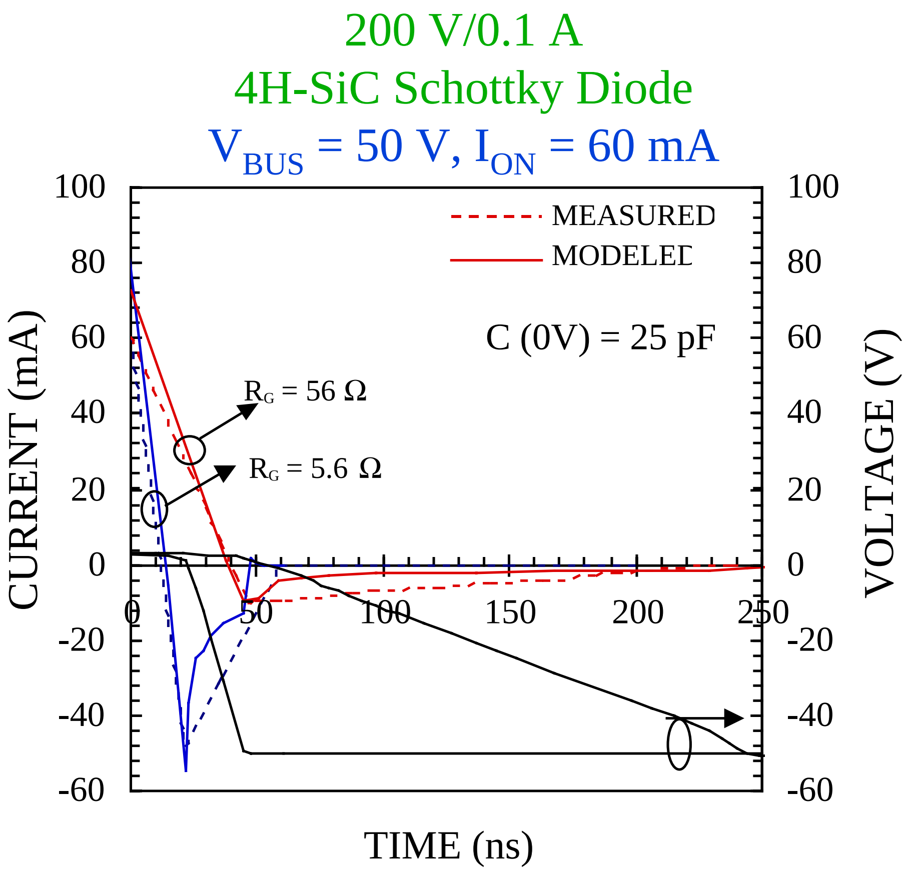

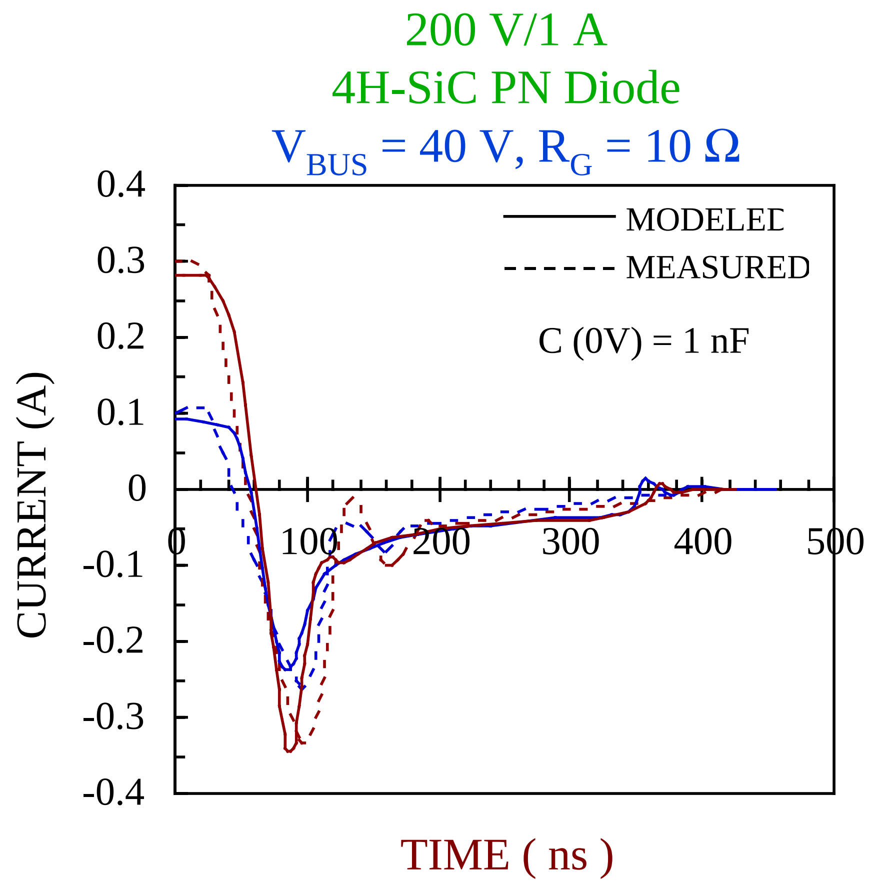

Tail in turn-off current appears because of junction capacitance
Schottky diode reverse recovery independent of temperature
PN diode reverse recovery weakly dependent on on-state current

DC-DC Buck Converter for Diode Testing

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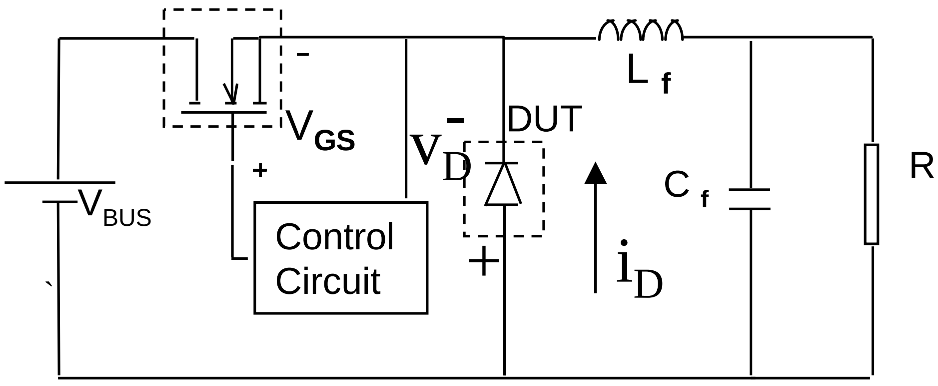
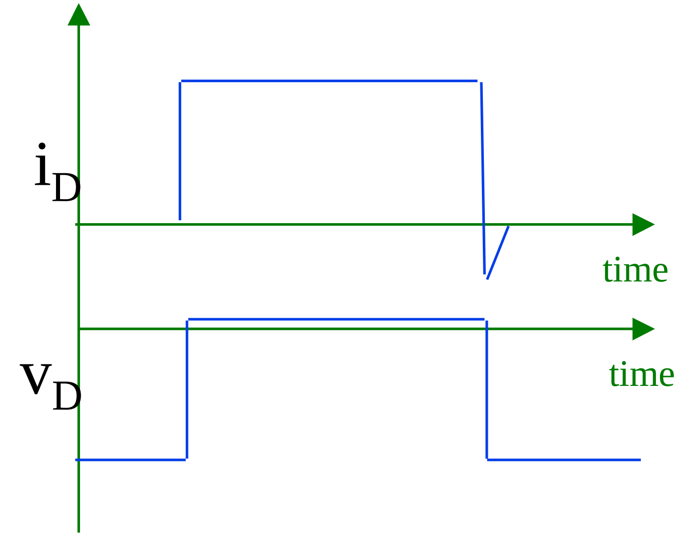
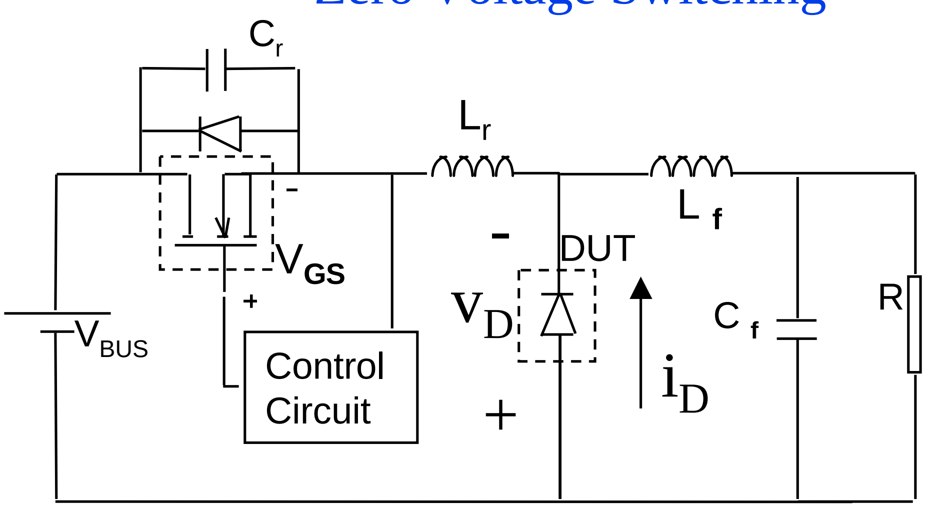
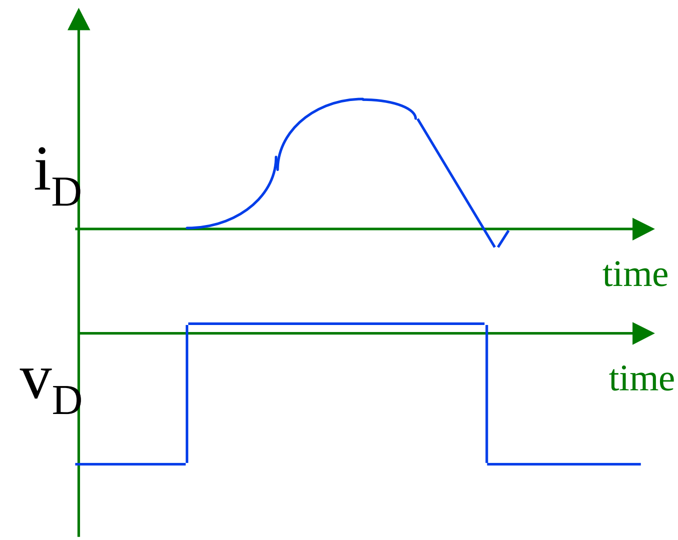
Hard Switching





Zero Voltage Switching





DC-DC Buck Converter Performance

SiC Schottky, SiC PN and Si PiN diodes

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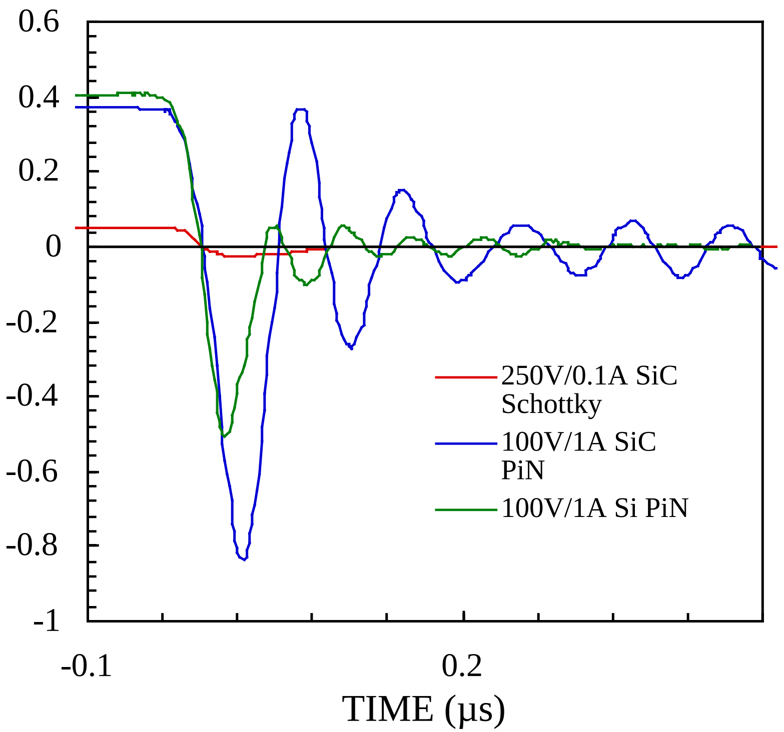
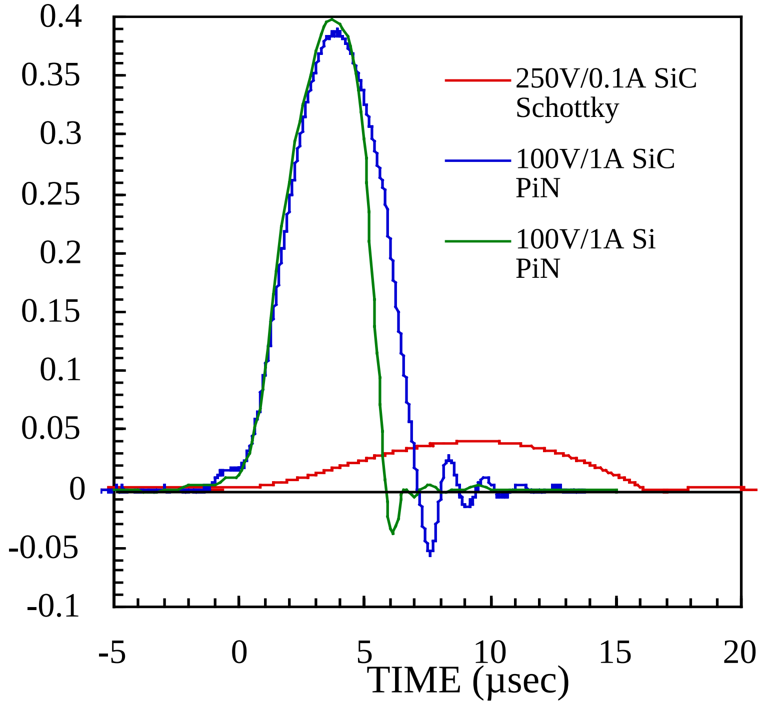
Hard Switching



Zero Voltage Switching



- Comparable switching performance of low-voltage SiC and Si PiN Diodes
- Negligible switching transient in zero voltage switching configuration
- Low voltage SiC devices only offer advantage of high-temperature operation

Hard-Switching Buck Converter Performance

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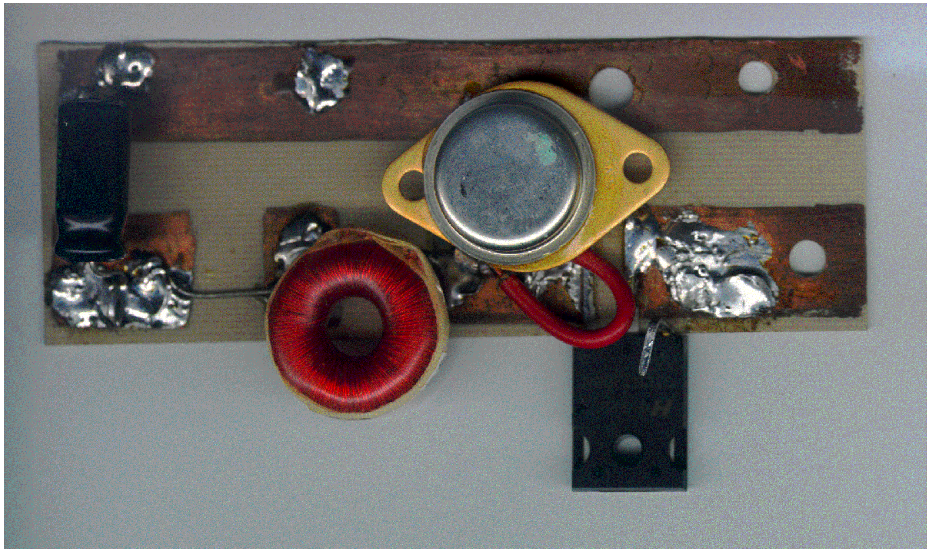

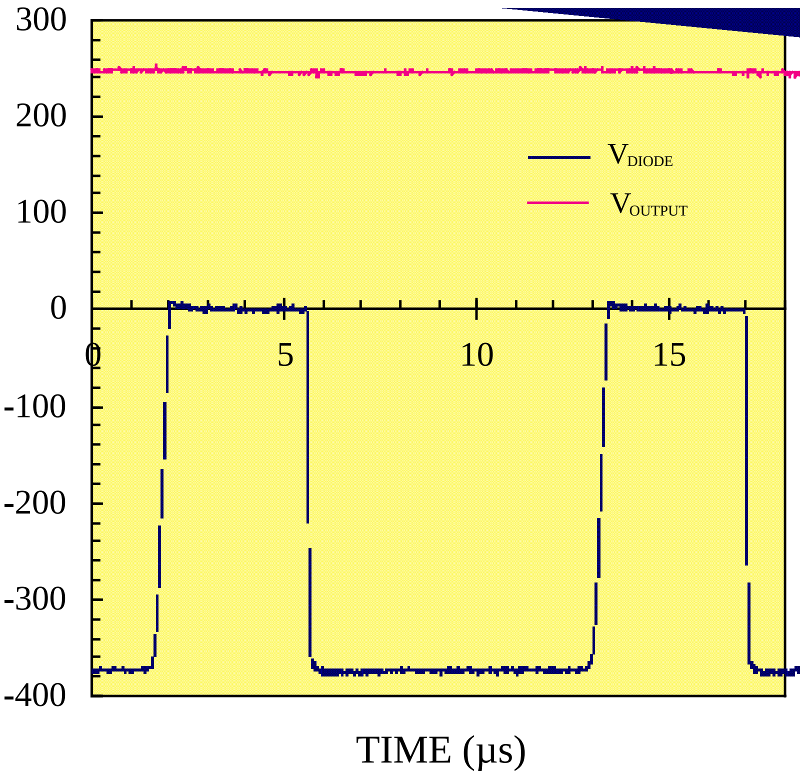

Converter Parameters

Switch : 600 V/ 5 A Si MOSFET
Inductor : 5 mH
Capacitor : 1 μF
Frequency : 90 kHz
I/O Voltage : 400 V/ 250 V
Output Power : 150 W

Si diode converter failed at 90 W, 30 kHz, 290 K

Simulation of Diode Performance
Hard-Switching of PiN Diodes

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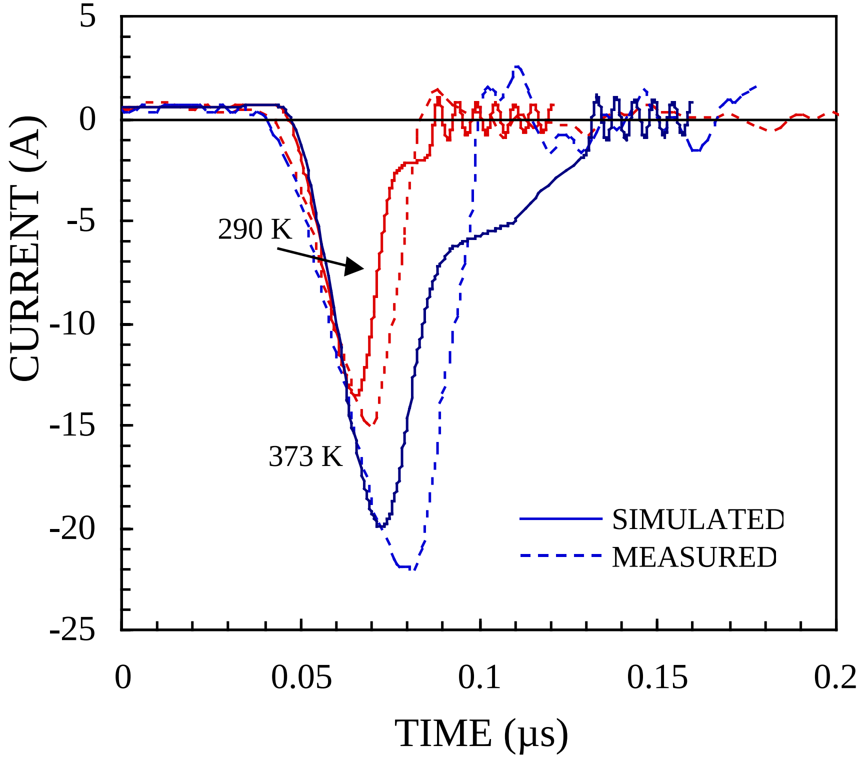
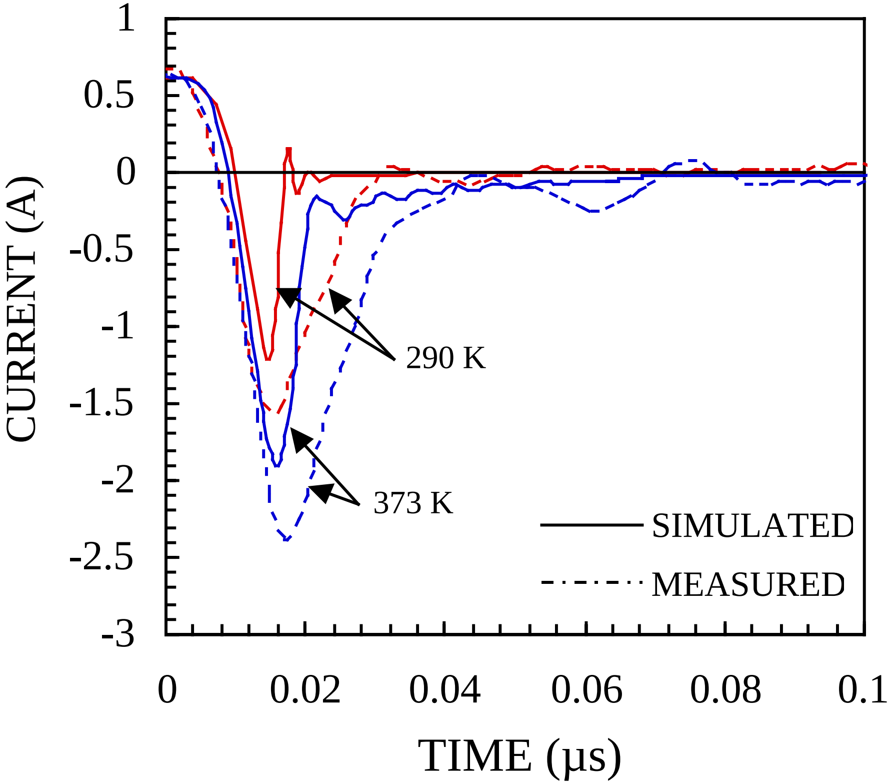
1.5 kV/10 A Si



3 kV/1 A 4H-SiC



Reasonable match between static and switching simulations and measurement
4H-SiC material parameters from recent published reports

ZVS Buck Converter Performance
PiN Diodes

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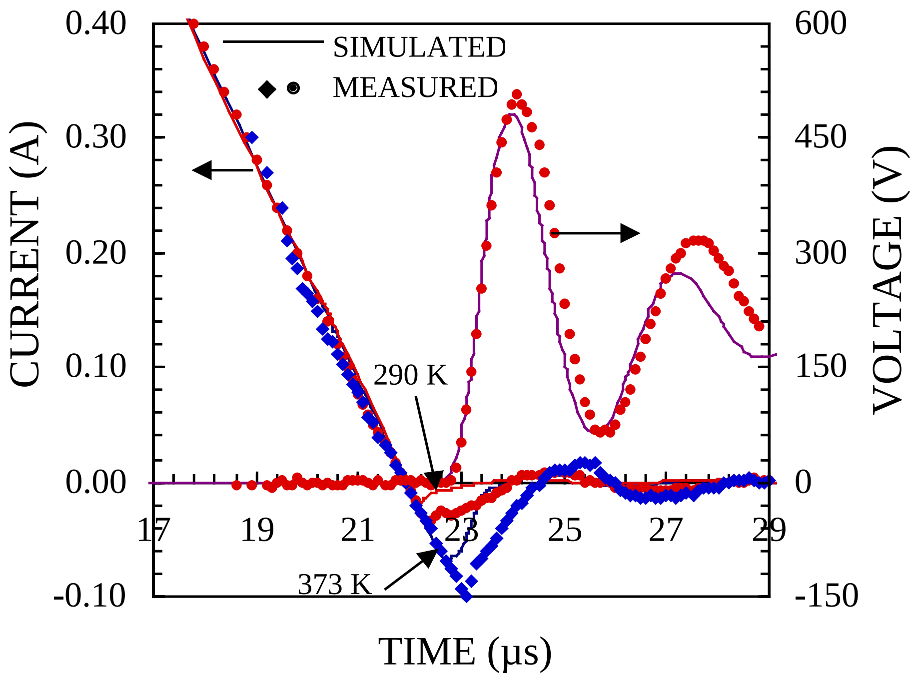
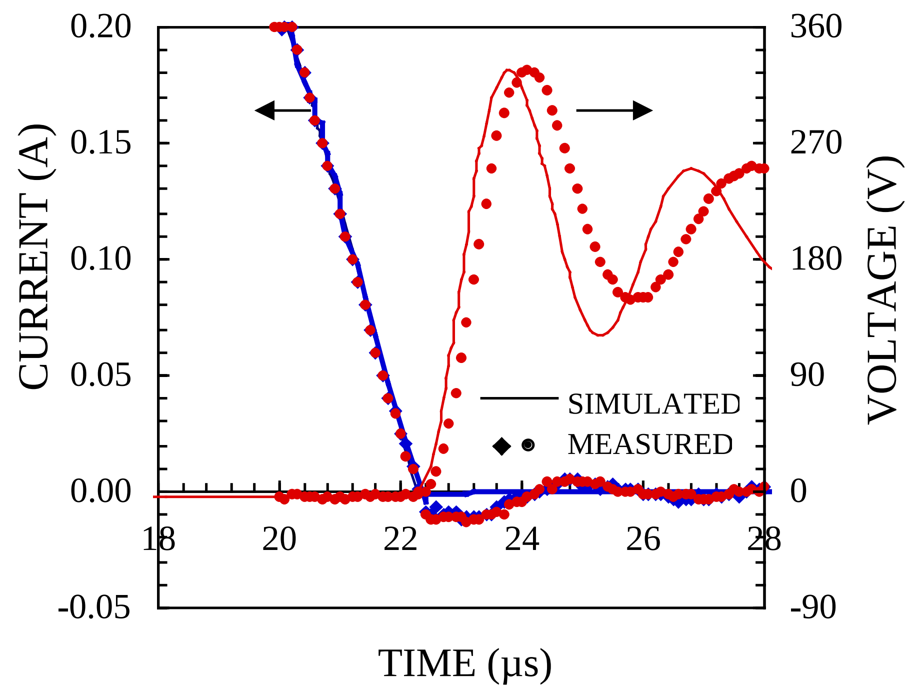
V_{BUS} = 200 V, I_{MAX} = 0.6 A

1.5 kV/10 A Si



3 kV/1 A 4H-SiC



Reasonable match between static and switching simulations and measurement
4H-SiC material parameters from recent published reports

Comparison of Si and 4H-SiC High-Voltage PiN Diodes

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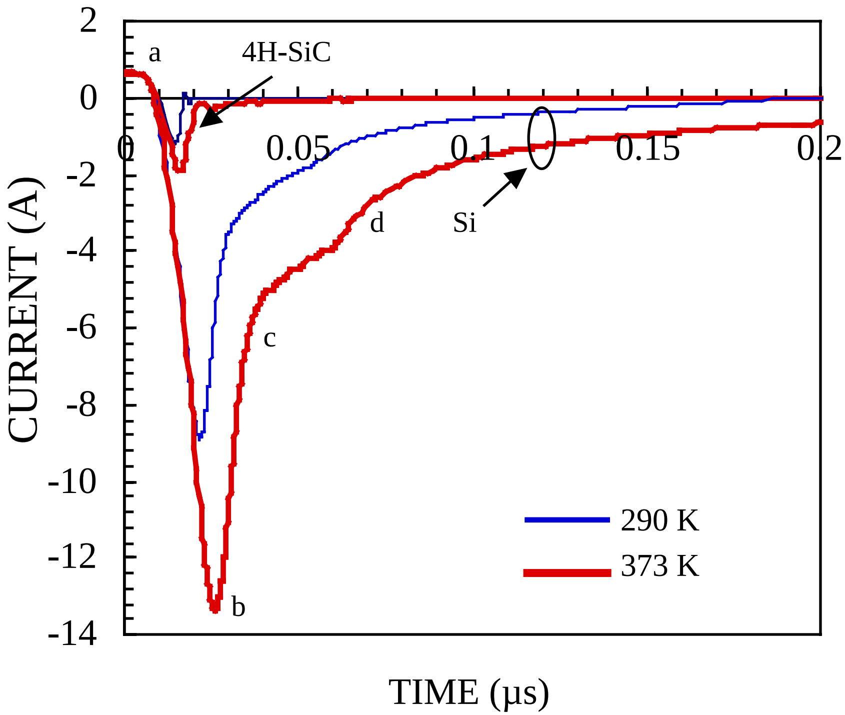
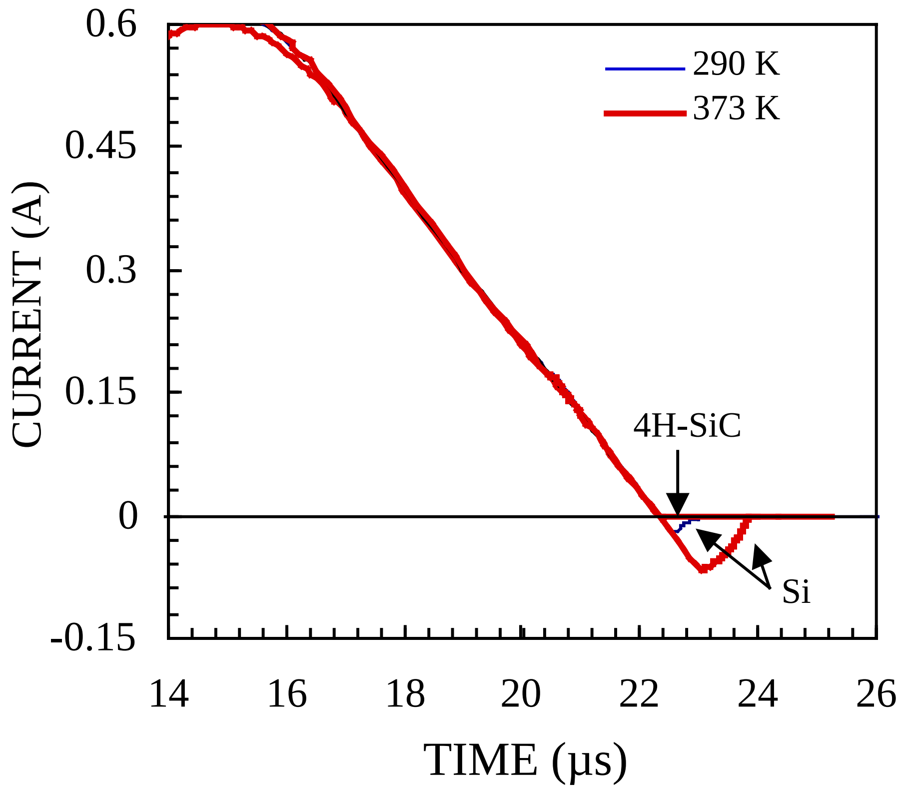
Hard-Switching

$V_{BUS} = 300$ V, $J_F = 100$ A/cm^2



Soft-Switching

$V_{BUS} = 200$ V, $J_F = 100$ A/cm^2



SiC has negligible reverse recovery compared to Si under identical switching conditions

Considerable performance improvement in Si diode with soft-switching (lower *di/dt*)

Charge Decay During Reverse Recovery (PiN Diode 2-D Simulations)

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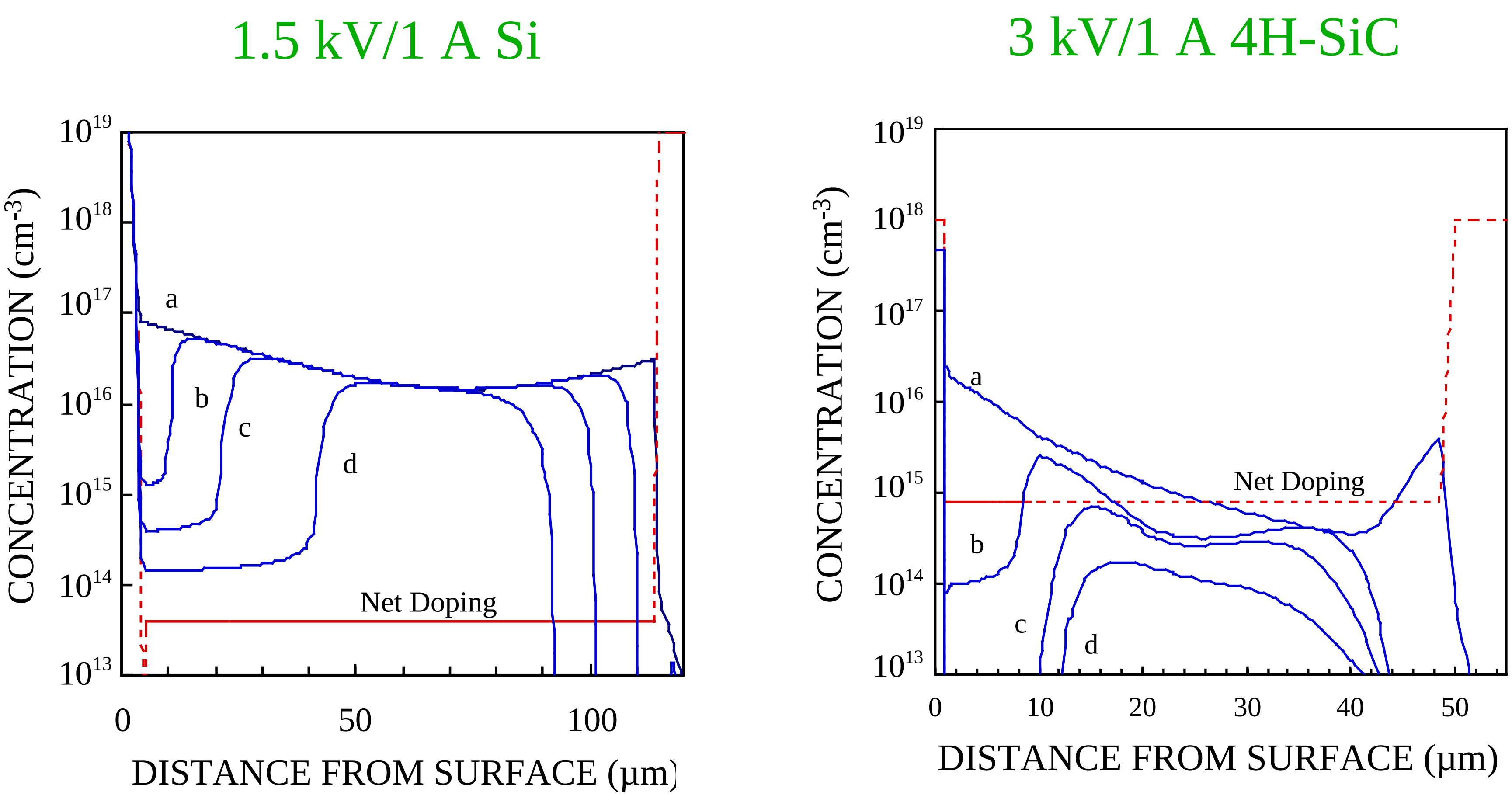

Si diode has very high excess charge in drift region

Rapid charge decay in SiC diode because of low carrier lifetime

Current tail because of excess charge trapped in quasi-neutral drift region

Simulated PiN Diode Buck Converter Performance Trend

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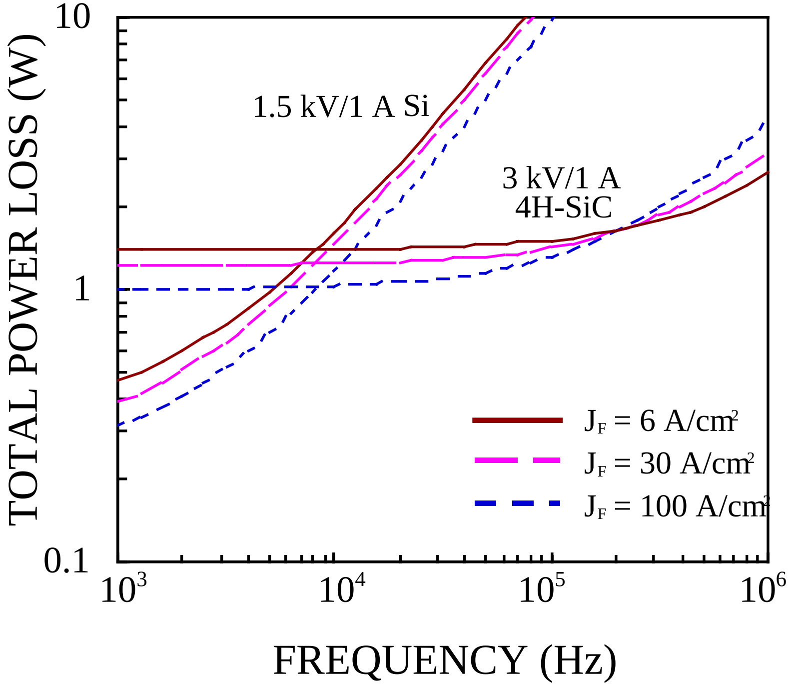
300 V/150 V, 90 W, 373 K



$$P_D = DV_{ON} I_{ON} + E_{sw} f_{sw}$$

- Total power loss in Si diode is very sensitive to switching frequency
- Frequency dependence of SiC diode above 300 kHz
- Total loss in SiC diode dominated by conduction loss
- Switching loss in Si diode appears because of excess charge removal
- Switching loss in SiC diode appears because of junction capacitance

Reliability Testing of Diodes

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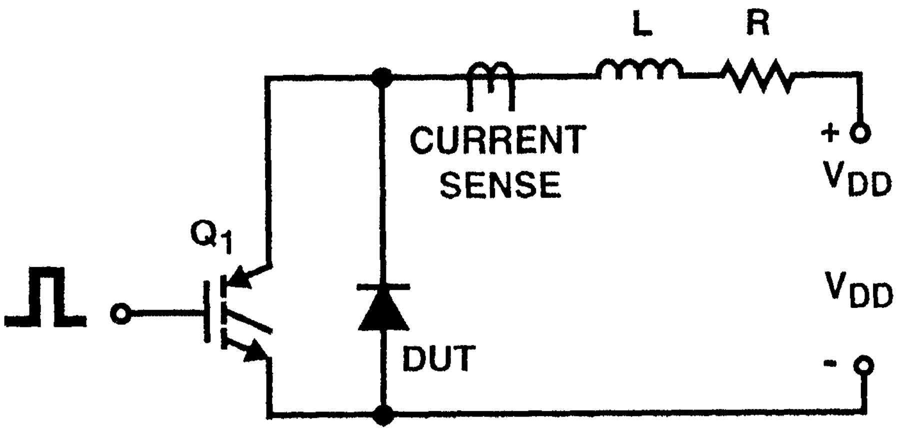
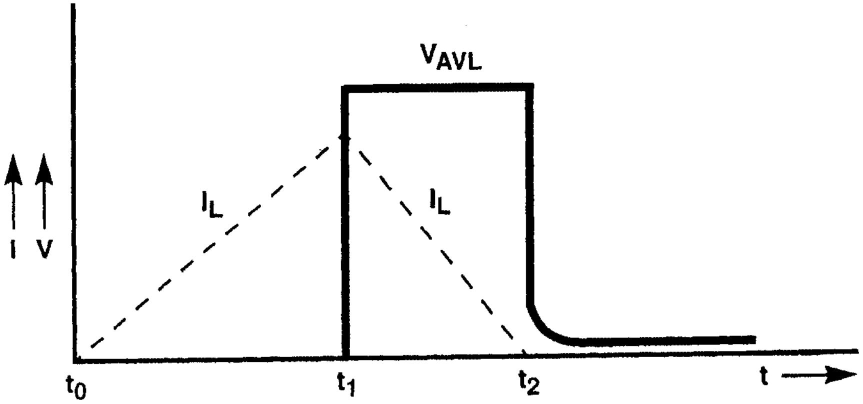
TEST CIRCUIT



TYPICAL WAVEFORMS



- Performance evaluation was conducted at voltage and current levels much lower than rated values
- Fragile SiC devices

- Assessment of device reliability is crucial
- Dynamic stress testing to determine avalanche rating of SiC diodes

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High-Density SiC Power Converters

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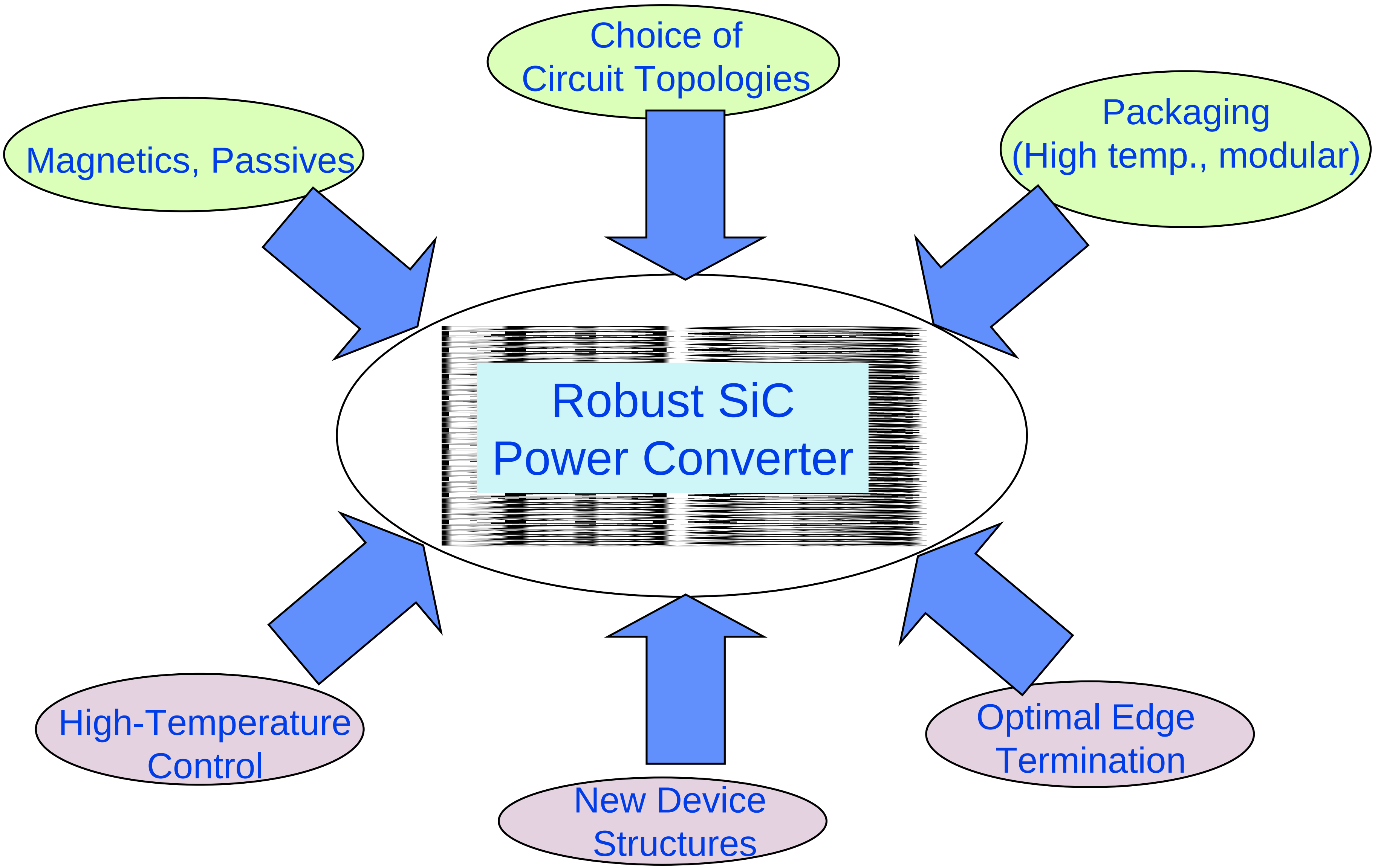
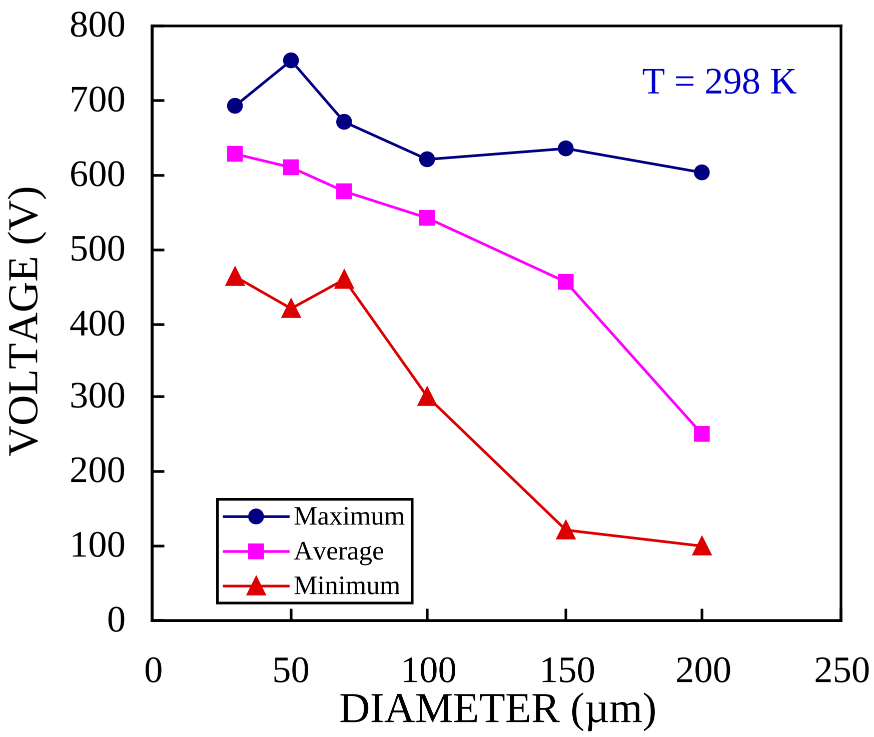


NASA Schottky Diodes

- Performance evaluation of 4H-SiC schottky diodes was conducted
- Comparative study of diodes with different perimeters and areas was conducted
- Tests were conducted to evaluate the dv/dt withstanding capability of the diodes
- 5 identical samples of each device were tested for consistency in results
- All devices were rated at I kV

Breakdown Performance

MEASURED RESULTS



- Strong area dependence of breakdown voltage was observed
- Highest breakdown voltage of 750 V was measured on a 50 µm device
- Lowest breakdown voltage of 100 V was measured on a 200 µm device
- High temperature breakdown measurements were not performed

Forward I-V Characteristics

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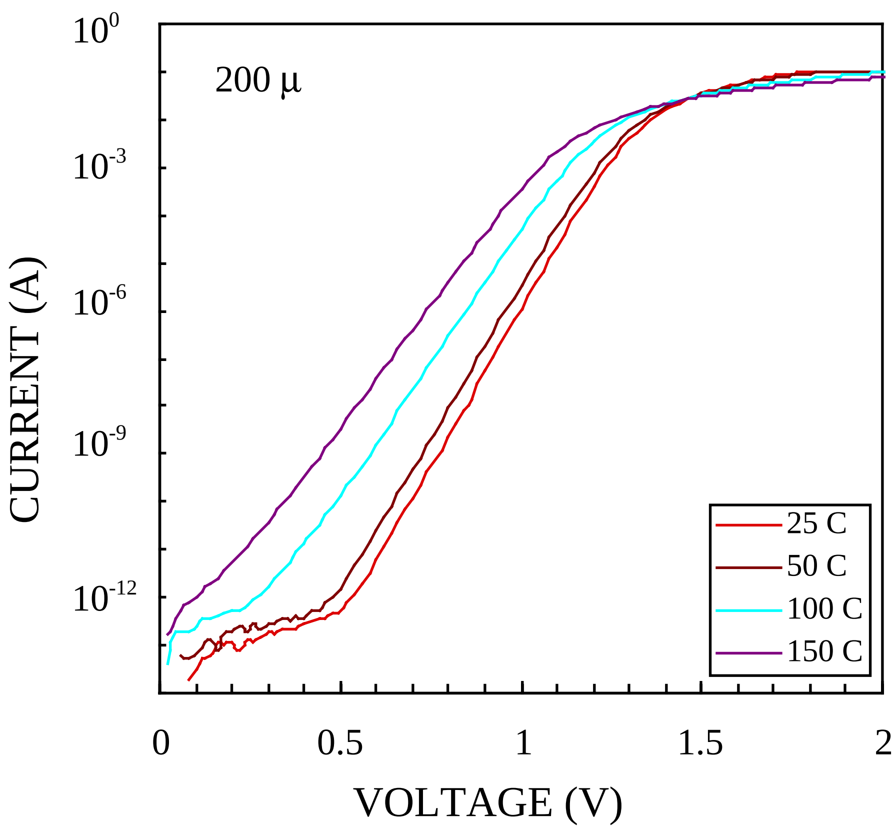
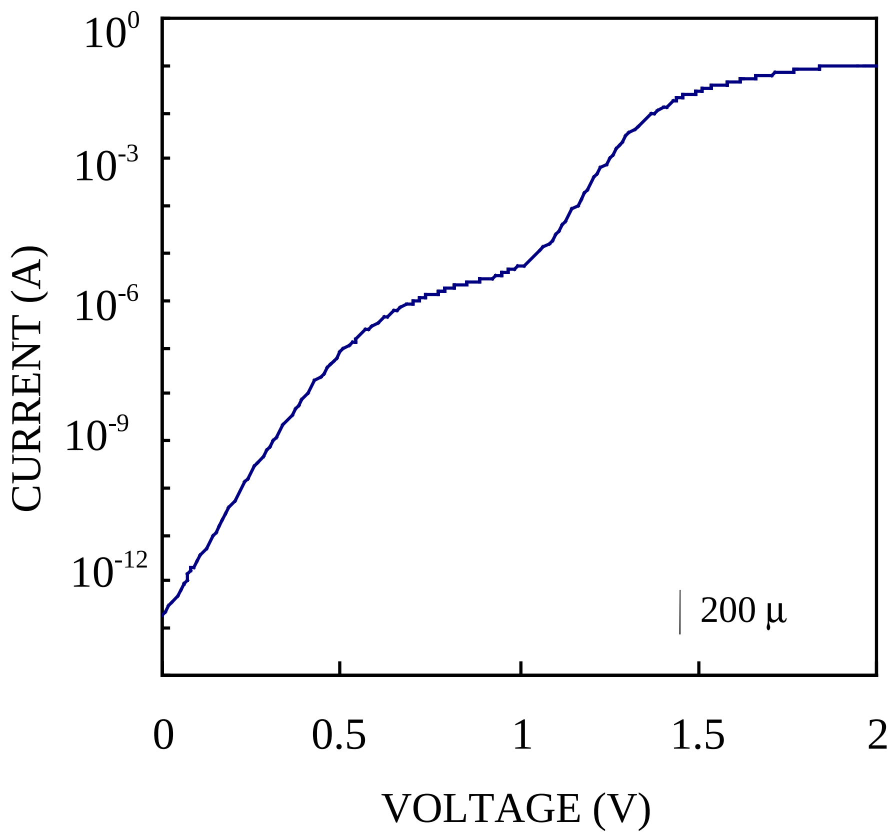
NON - DEFECTIVE DIODE I-V



DEFECTIVE DIODE I-V



- Leakage current increases with temperature
- Defective diode current starts rising rapidly at very low bias voltages

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Forward J-V Characteristics

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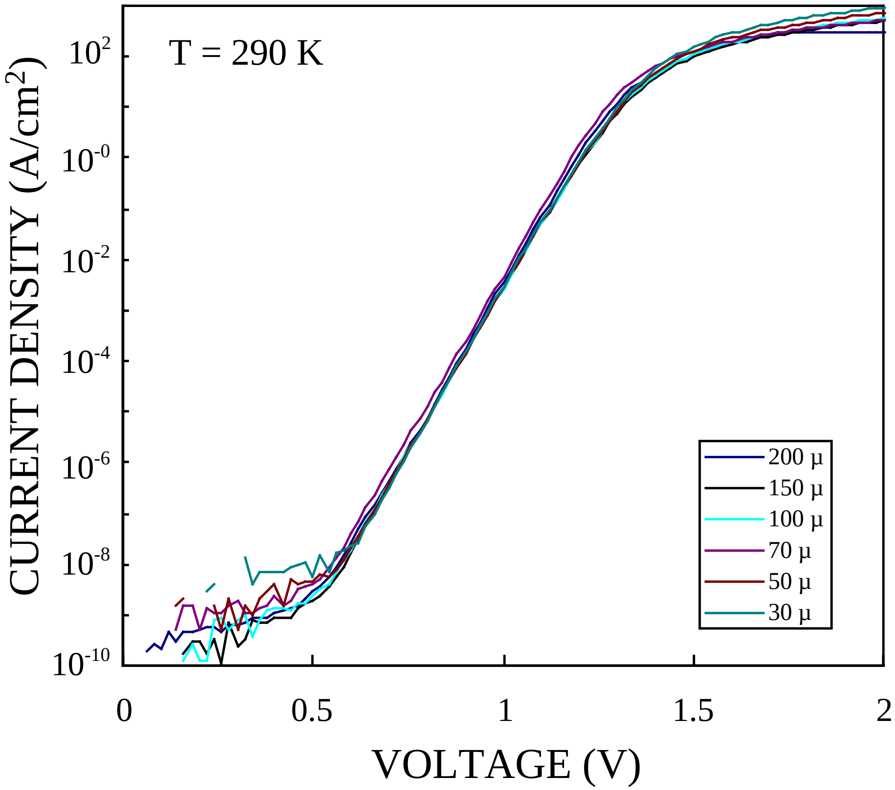
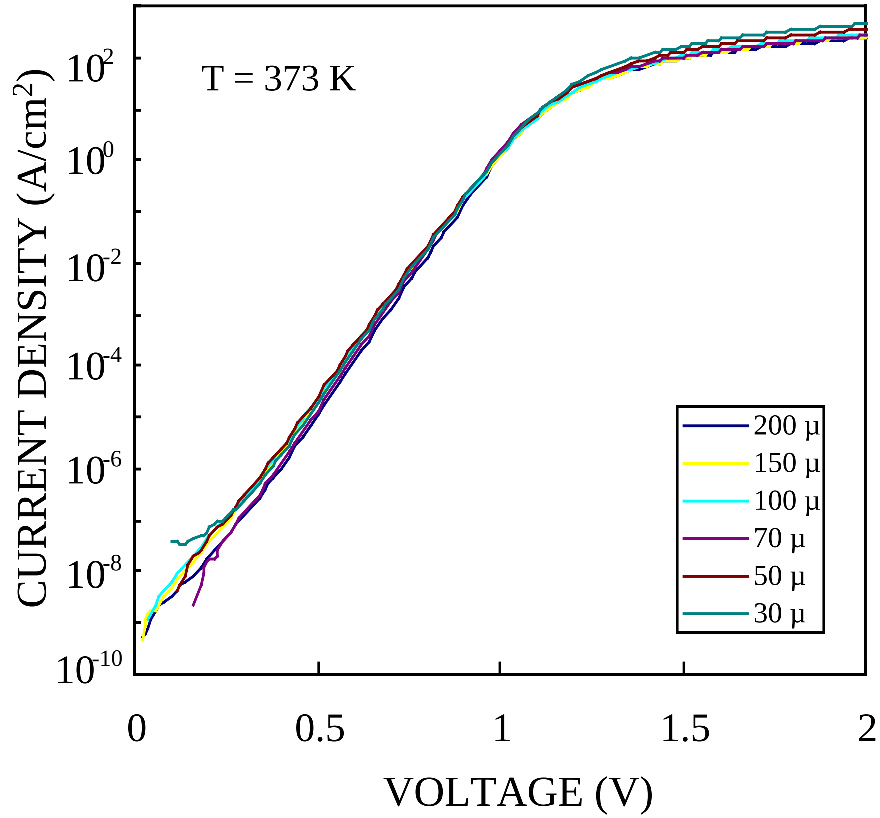
MEASURED WAVEFORMS





- Influence of perimeter on leakage current density is negligible

Perimeter/Area Dependence

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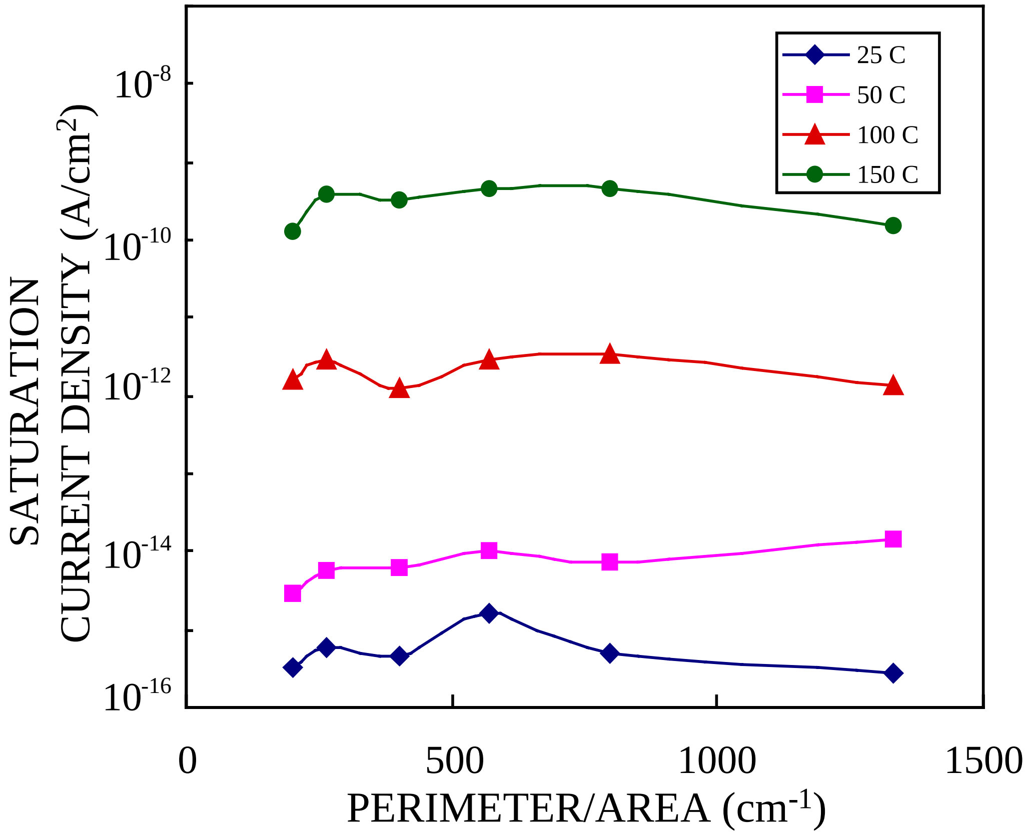

- Saturation current densities were extracted from the J-V characteristics
- Saturation current density is independent of P/A ratio
- No perimeter recombination current along the periphery because of absence of a junction

Ideality Factor Extraction

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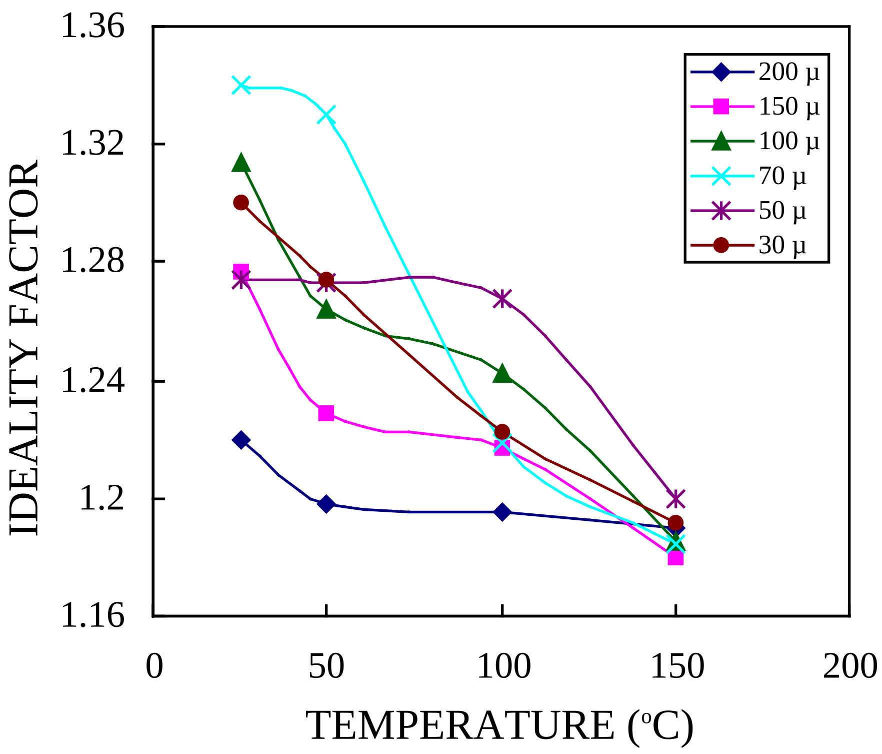


- Ideality factor was extracted from forward I-V characteristics

$$n = \frac{1}{\frac{\partial(\ln I_F)}{\partial V_F} V_T}$$

- Room temperature ideality factor ranged from 1.22 - 1.33

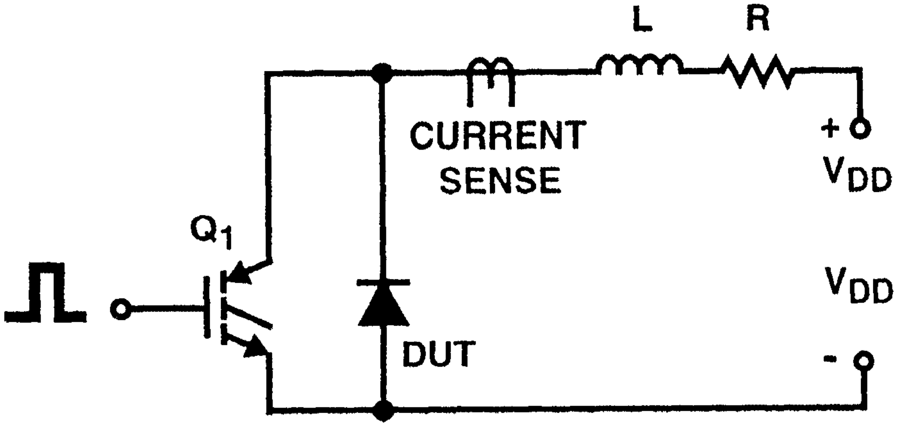
- Ideality factor decreases with temperature

- Thermionic emission current contribution is more at higher temperatures.

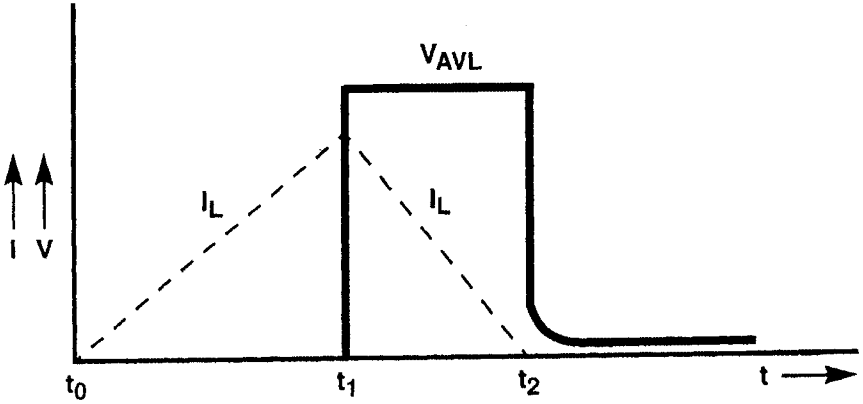
- Therefore the ideality factor approaches unity

Reliability Testing of Diodes

TEST CIRCUIT



TYPICAL WAVEFORMS



- Performance evaluation was conducted at voltage and current levels much lower than rated values
- Fragile SiC devices

- Assessment of device reliability is crucial
- Dynamic stress testing to determine dv/dt rating of SiC diodes

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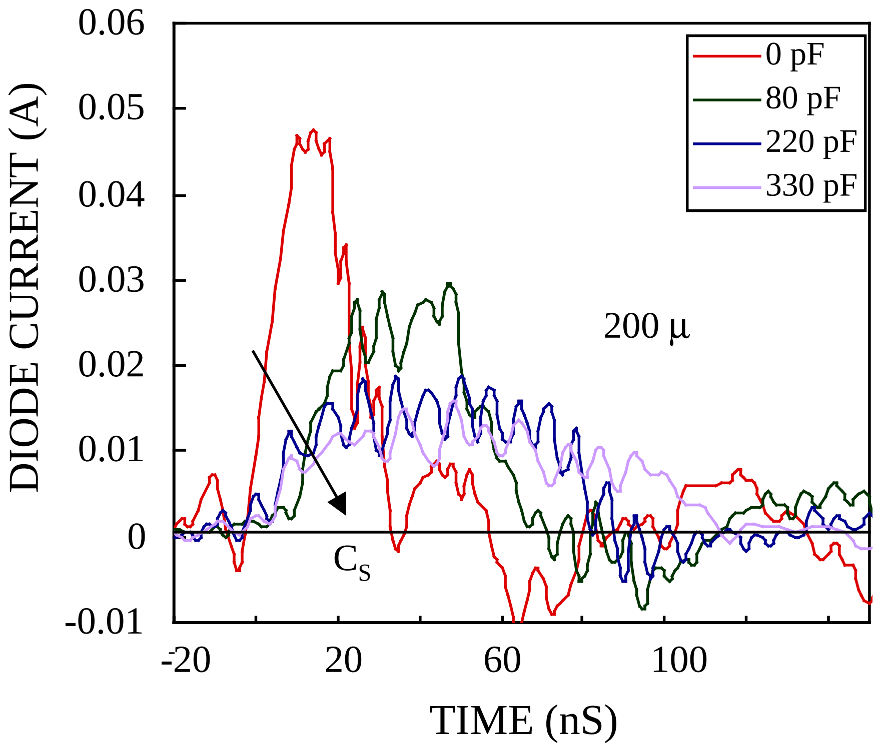
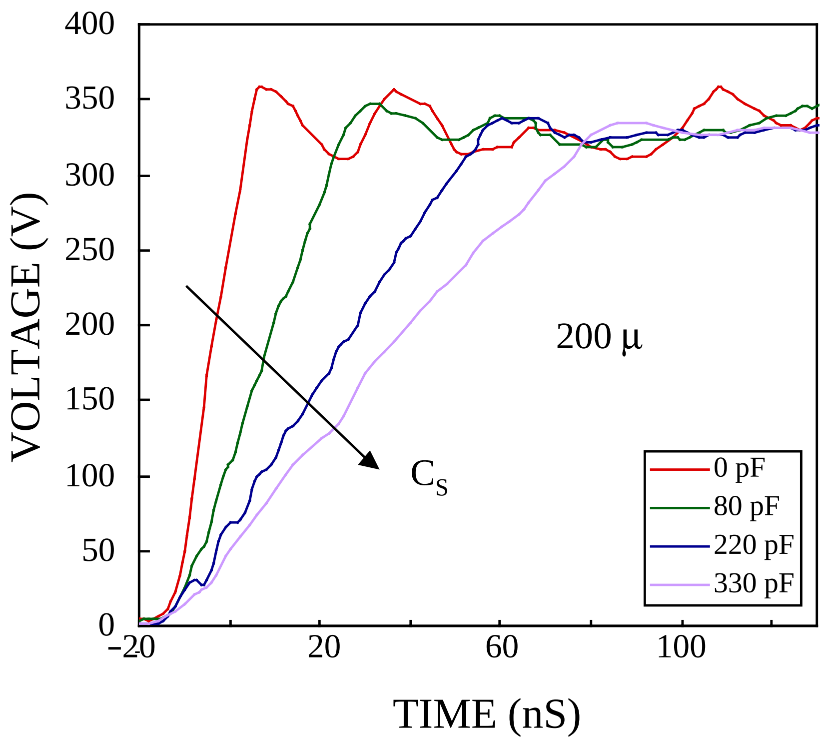
dv/dt Characterization

DIODE WAVEFORMS





- Diode current increased at higher dv/dt
- dv/dt varied from 4V/ns to 30 V/ns
- With a 250 V switch the DUT survived the highest applied dv/dt
- With a 500 V switch the device failed even for the lowest dv/dt
- Failure was voltage dependent rather than dv/dt

SiC Diodes
for
SMPS applications

Forward I-V Characteristics

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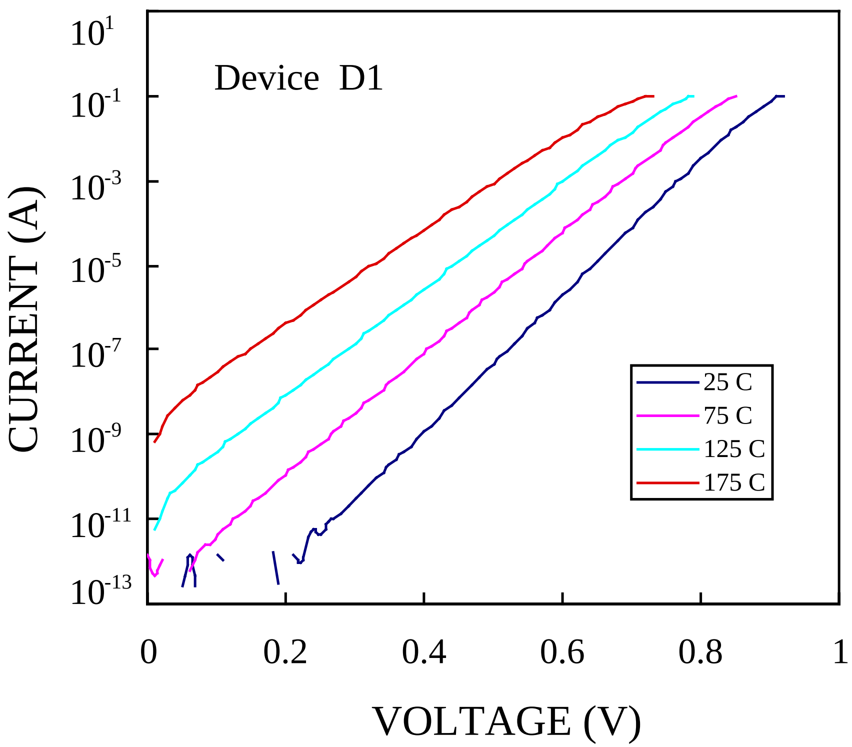
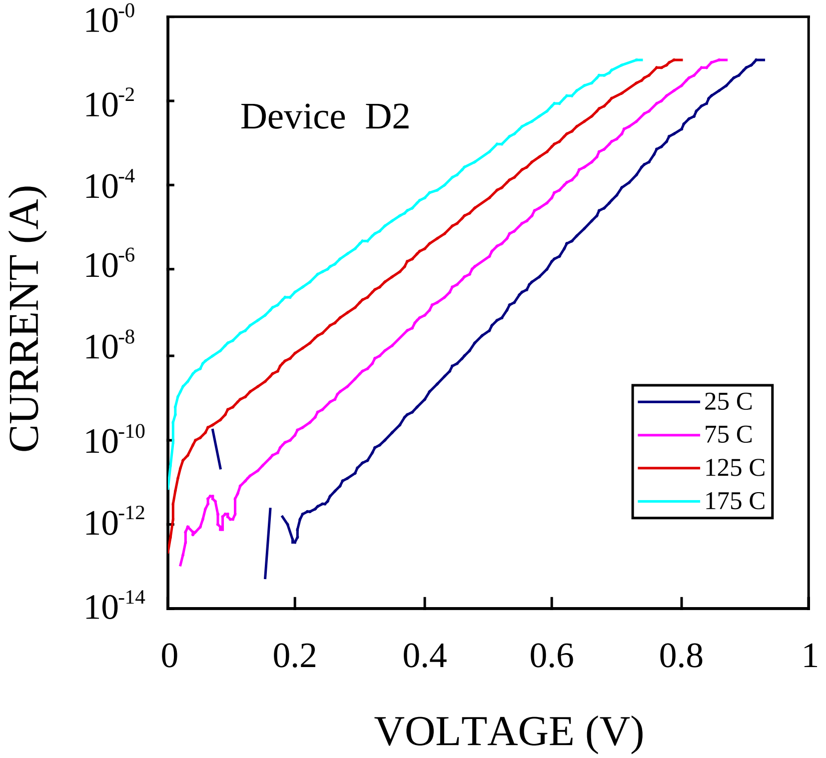
MEASURED WAVEFORMS





- 5 samples of each device were tested for consistency
- Leakage current increases with temperature

Breakdown Performance

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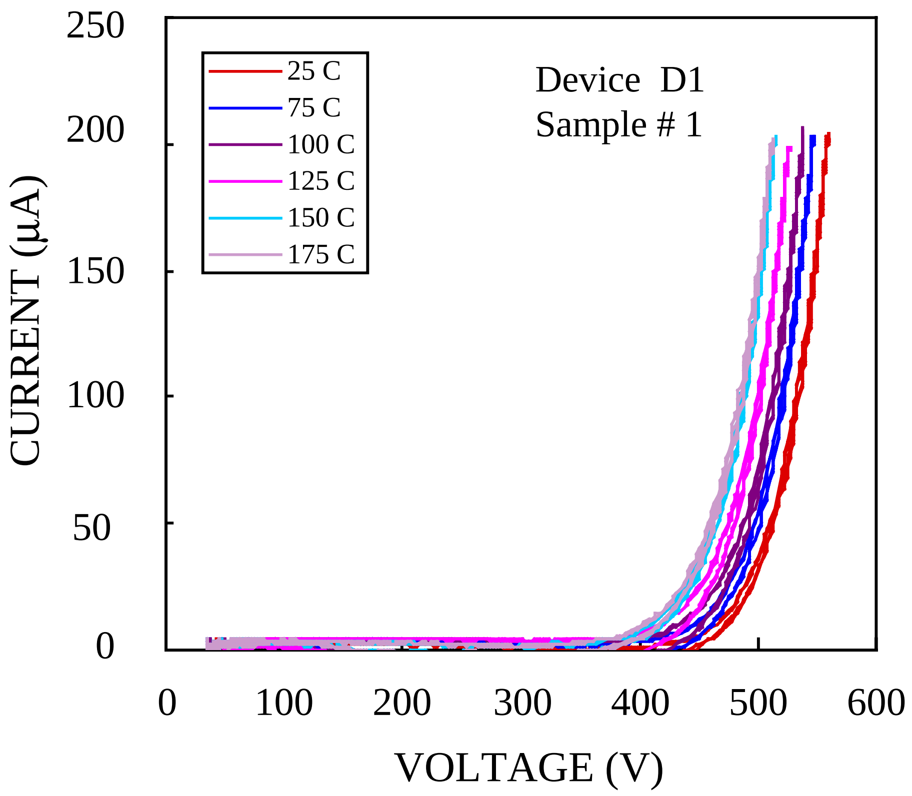
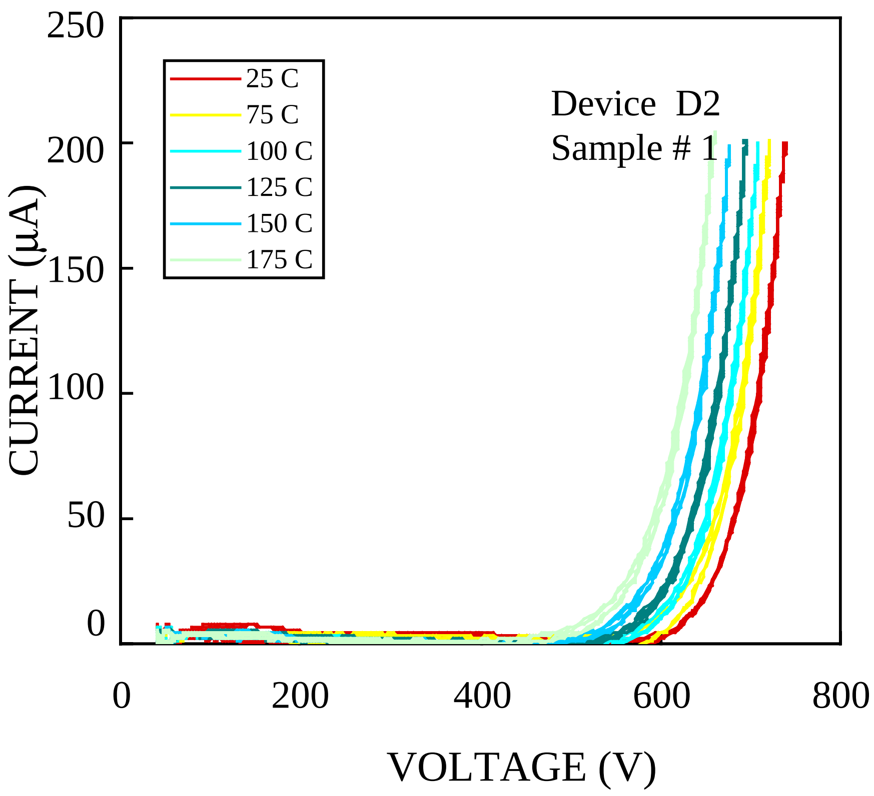
MEASURED WAVEFORMS





- Breakdown voltage decreases with increase in temperature

Breakdown Performance

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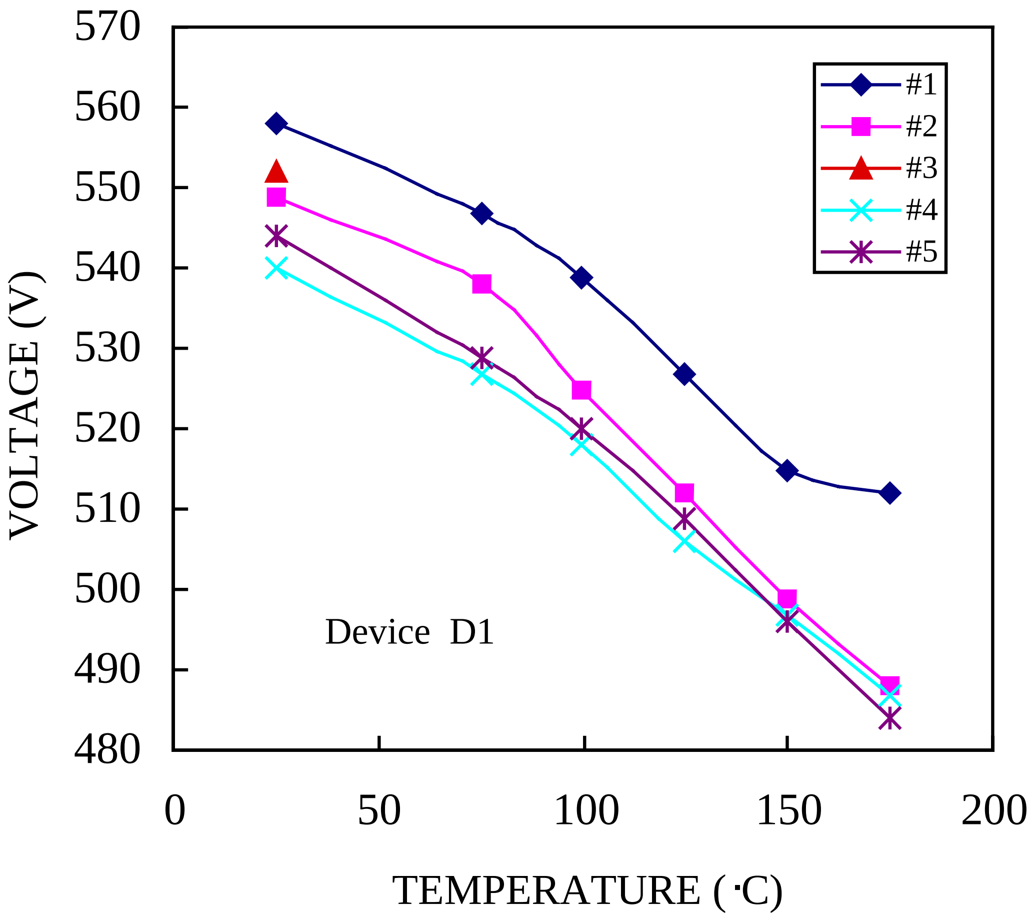
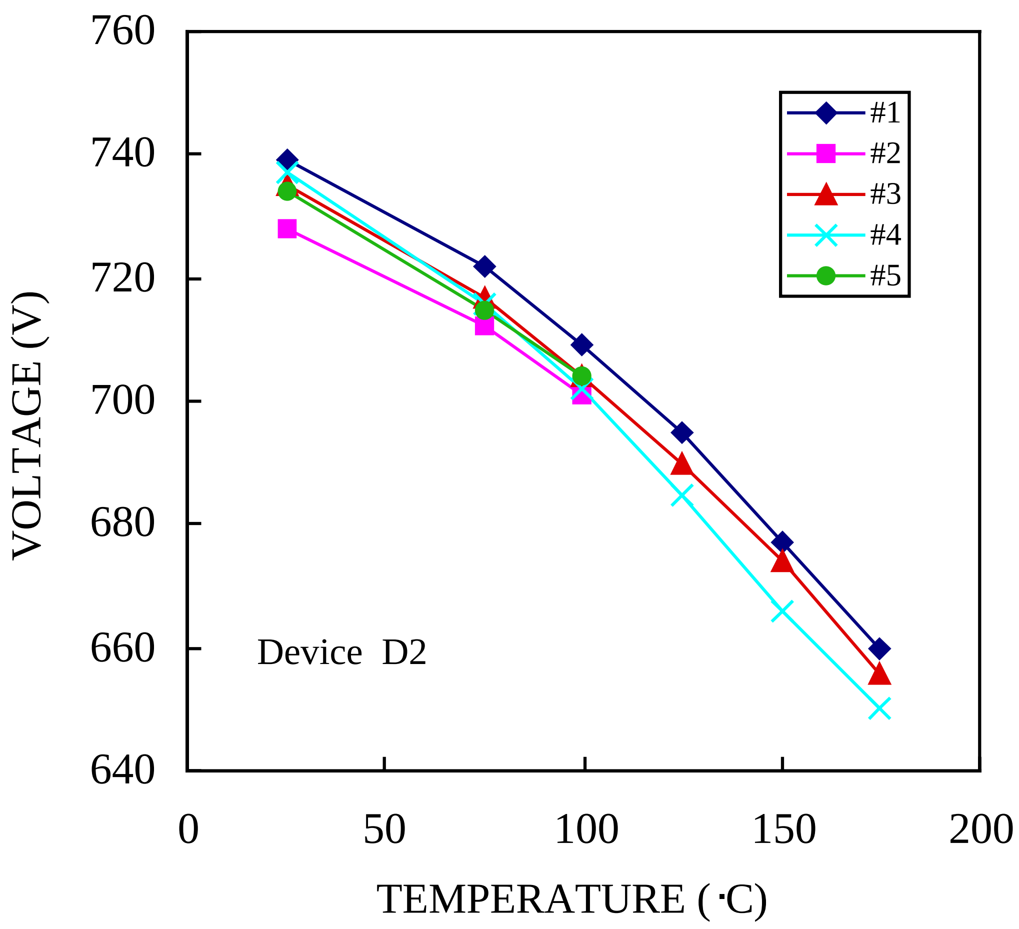


- 5 samples of device D1 were characterized
- Sample # 2 failed during testing
- For every **1·C** rise in temperature the voltage drops by **0.5** V approximately

Breakdown Performance



- 5 samples of device D2 were characterized.
- Sample # 2 and 5 failed during testing.
- For every **1·C** rise in temperature the voltage drops by **0.6** V approximately.

Ideality Factor Extraction

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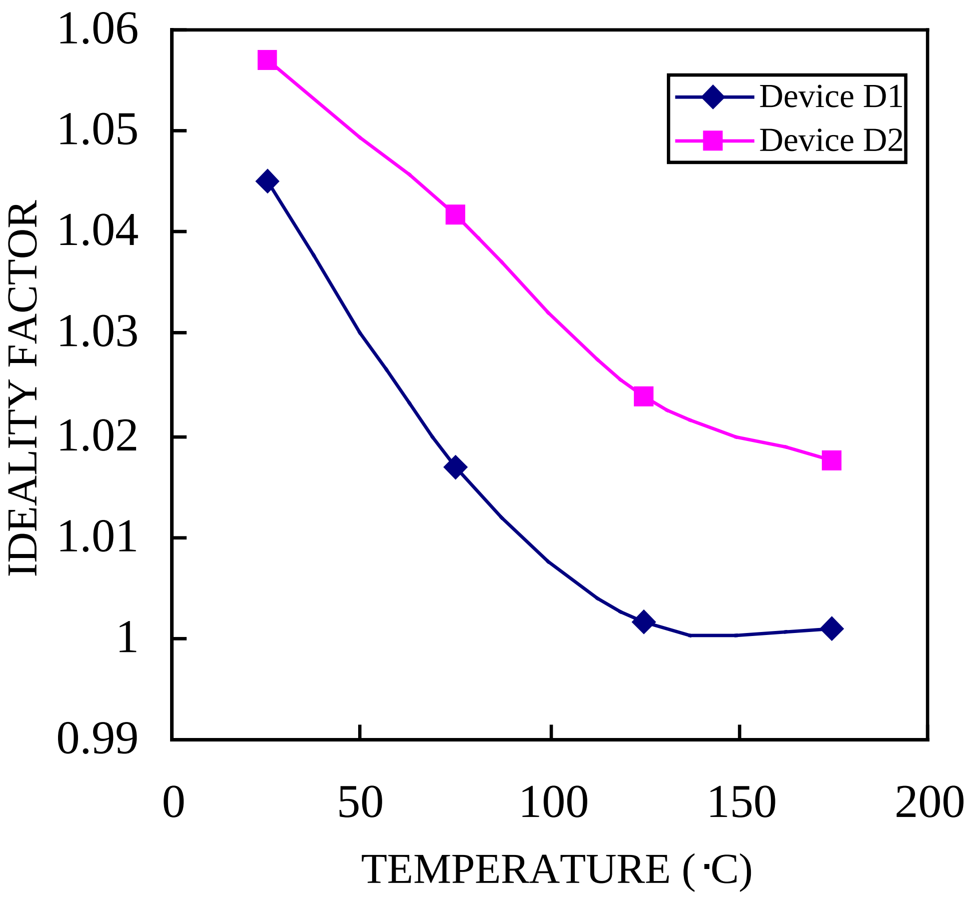


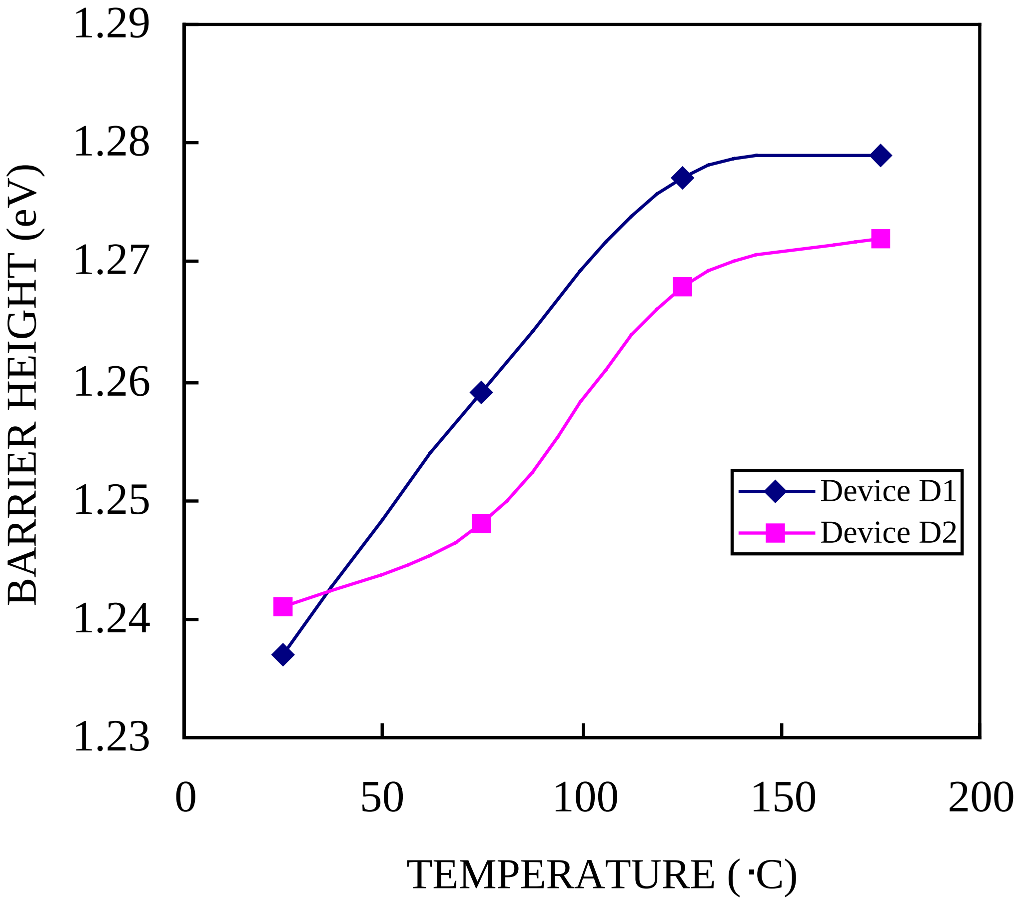
Ideality factor was extracted from the expression for diode forward current

$$n = \frac{1}{\dfrac{\partial(\ln I_F)}{\partial V_F} V_T}$$

Ideality factor approaches unity with increase in temperature.

- Thermionic emission current contribution is more at higher temperatures

Barrier Height from forward IV



Since **n ≡ 1** the barrier height was extracted using the simplified expression for J_S

$$\phi_B = V_T \ln\left(\frac{A^{**}T^2}{J_S}\right)$$

Where

A^{**} is Richardson's constant

V_T is the Thermal Voltage

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Barrier Height from C-V Characteristics

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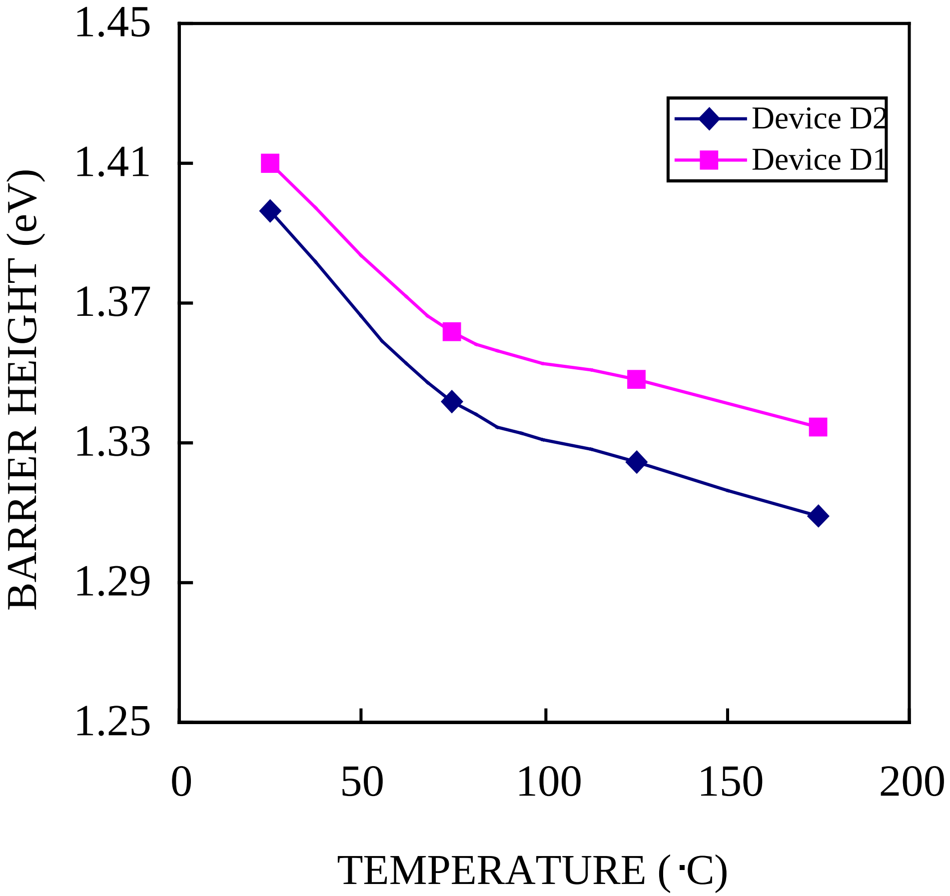

- Doping concentration and device Area were provided.
- Using the device area and the slope of the $(1/C^2)$-V plot the doping was extracted from the expression for Capacitance.

$$C = A\sqrt{\frac{q\varepsilon_S N_D}{2(V_R + V_{bi} - \frac{kT}{q})}}$$

- Extracted value of doping was then used to estimate the barrier height

$$\phi_B = V_i + \frac{kT}{q} + \frac{E_G}{2q} - \frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right)$$

V_i is voltage intercept $(1/C^2)$-V plot
V_{bi} is the built in voltage

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Reverse Recovery Measurement Procedure

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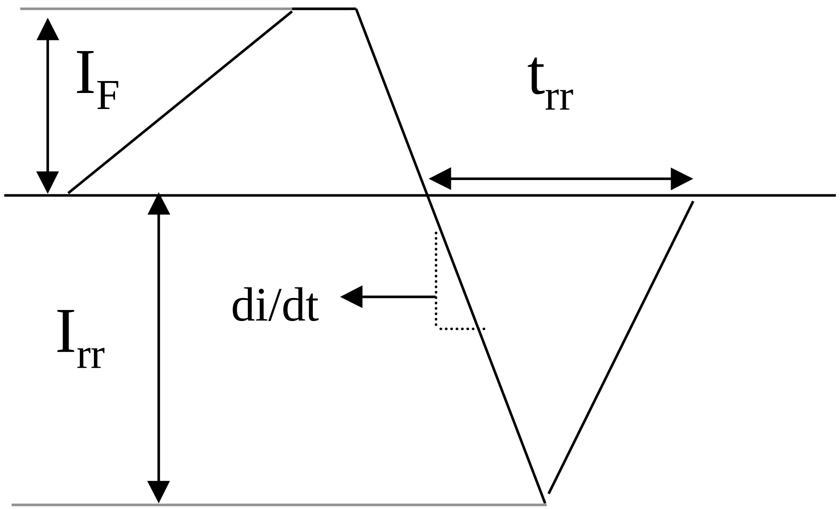

- Devices Under Test (DUT)
  - D1
  - D2

- Measurements were performed at:
  - Three different forward currents (2A, 4A and 6A)
  - Three different temperatures (25 ·C, 75 ·C, 125 ·C)
  - Three different bus voltages (200V, 250V,300V)

Test Circuit

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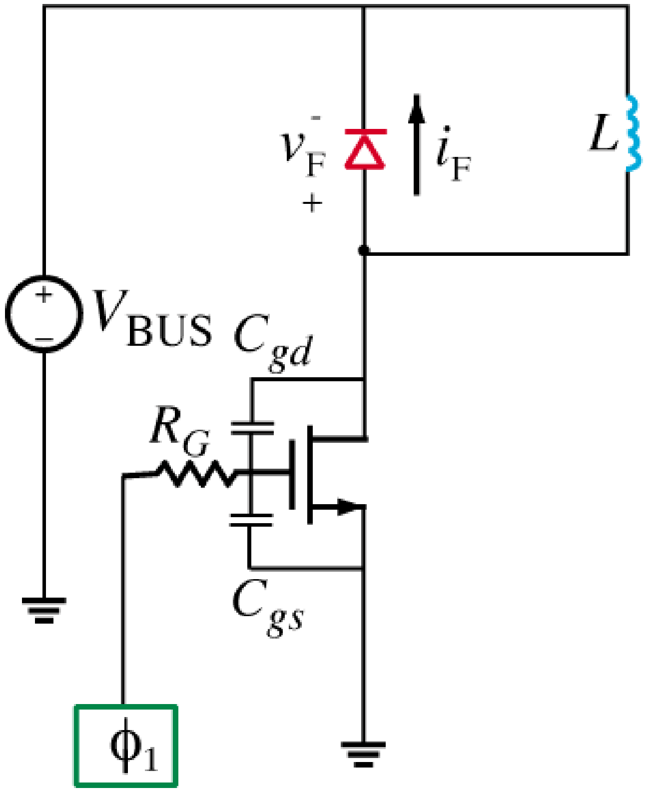
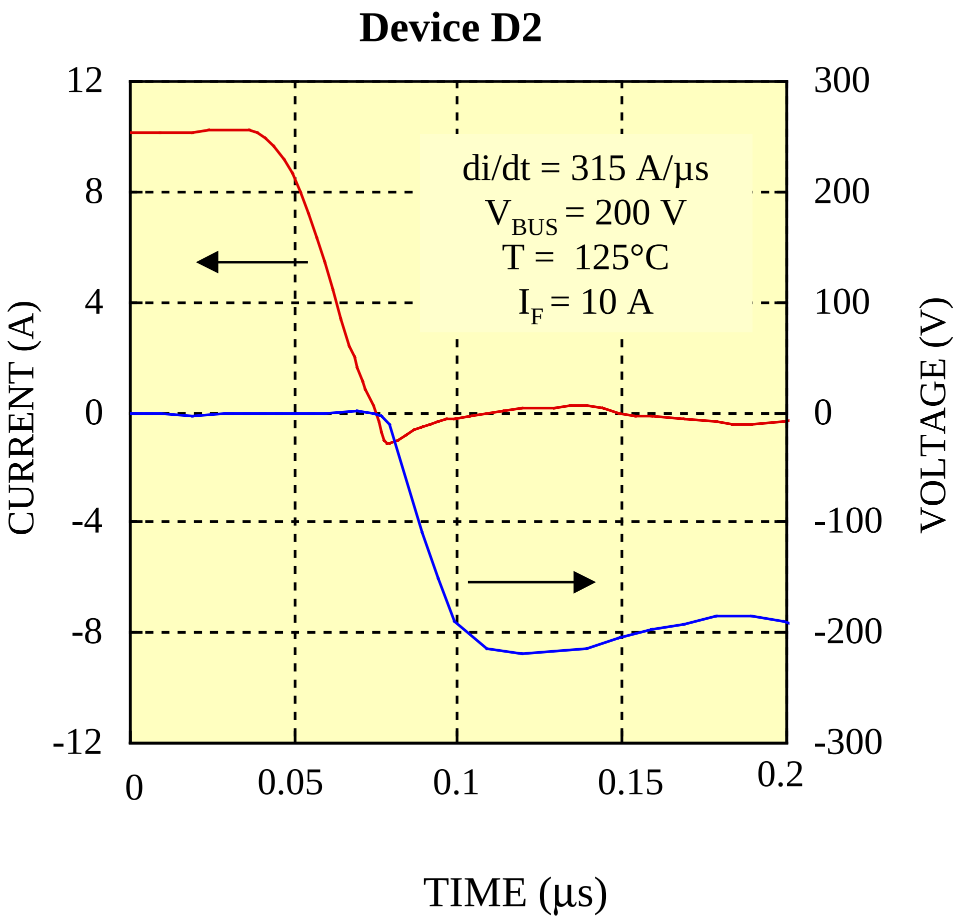
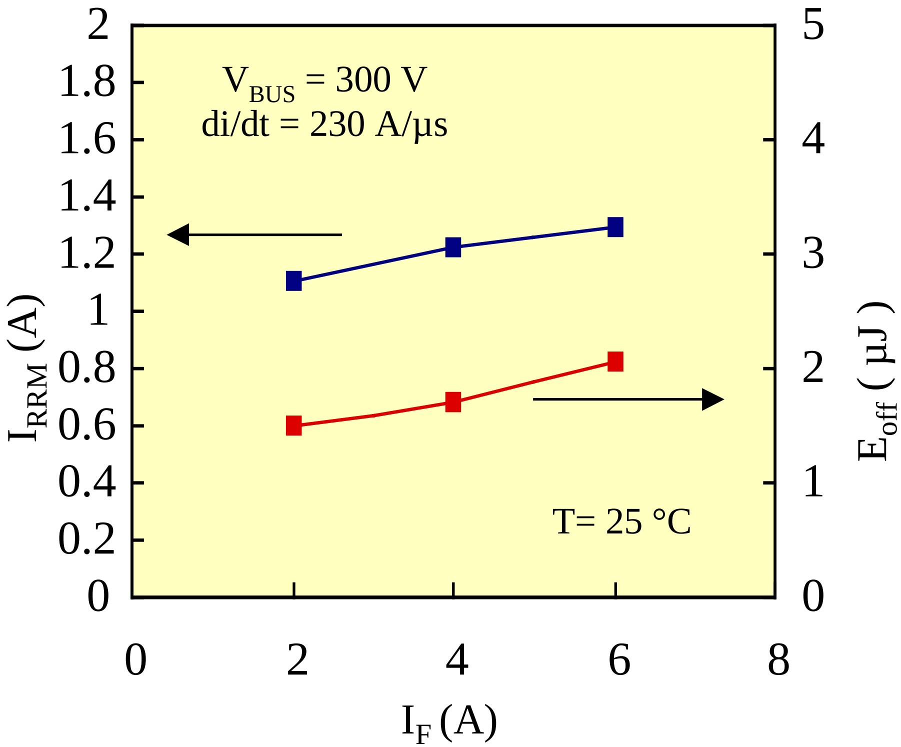
at Chicago**

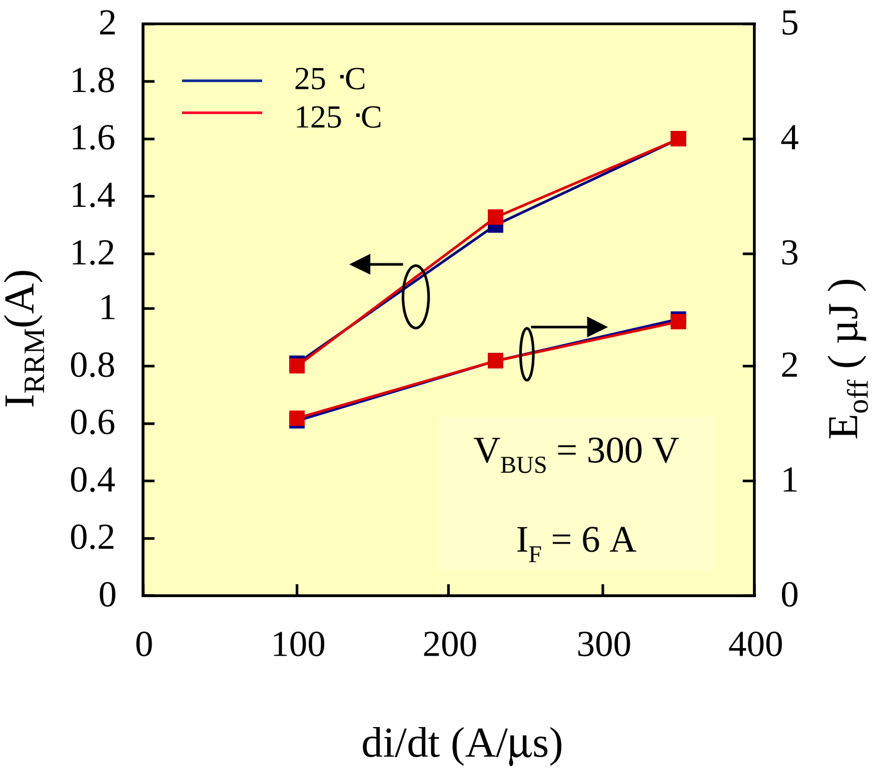




Measured Results

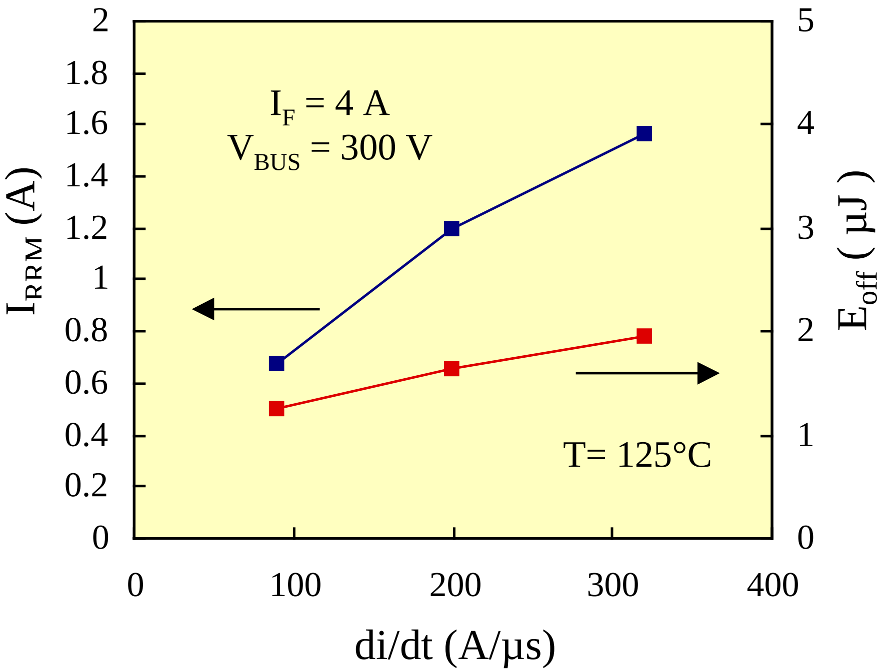
Device D1

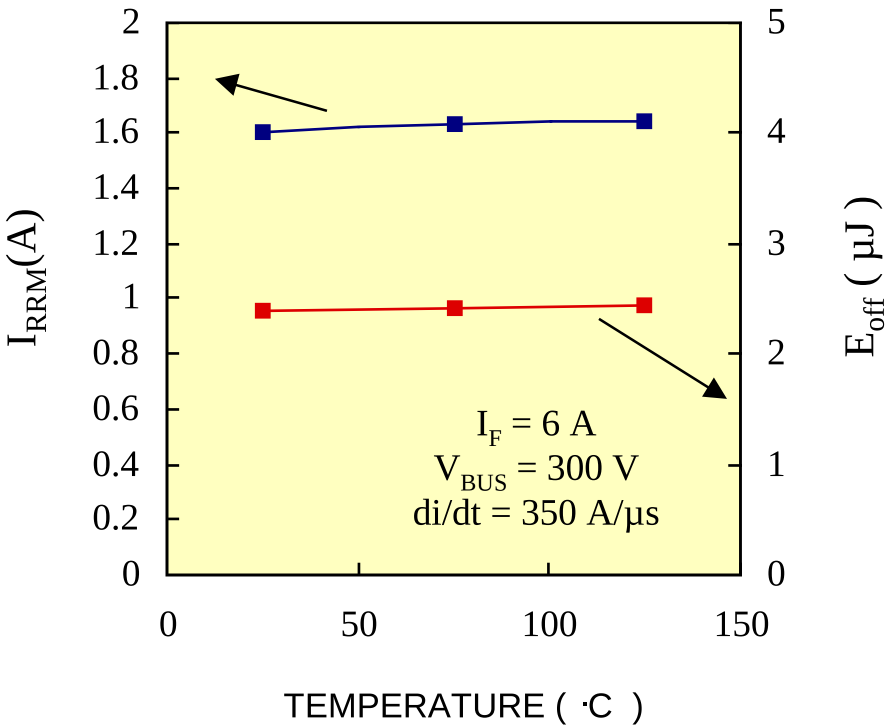




Measured Results

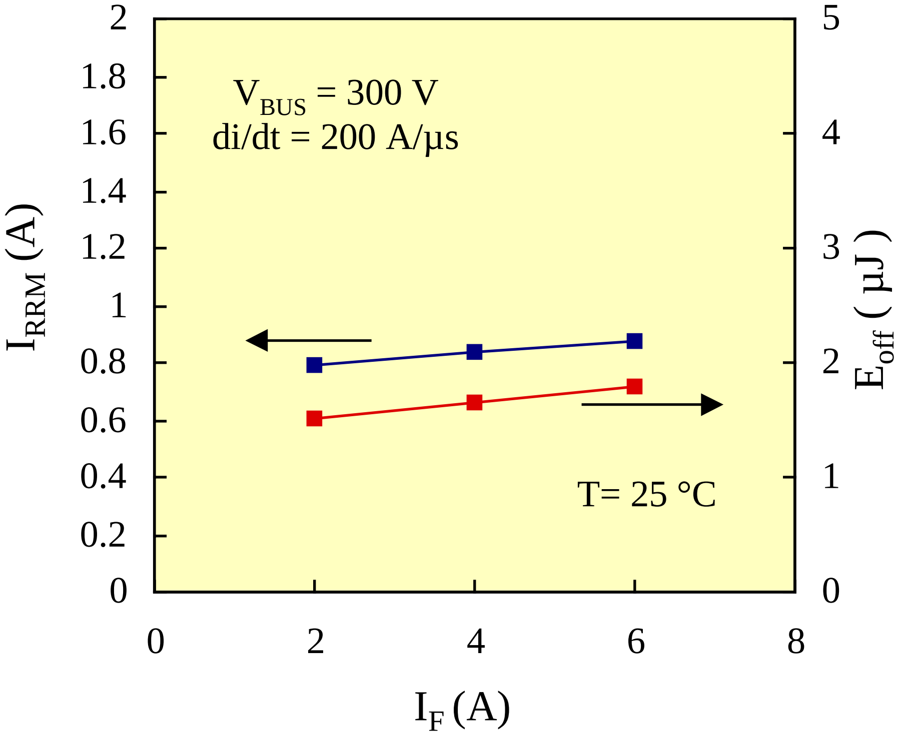
Device D1

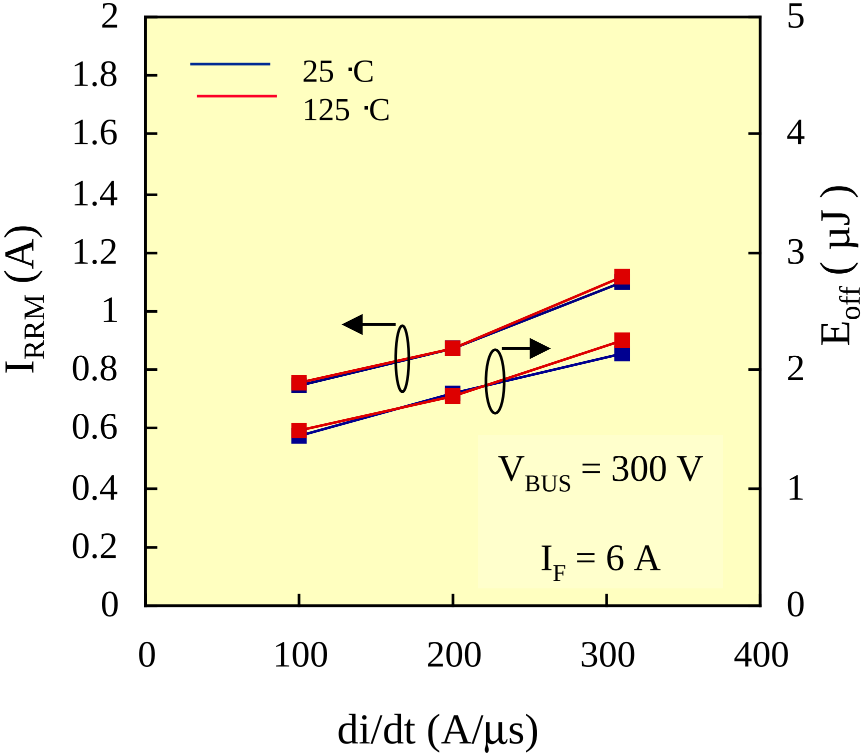




Measured Results

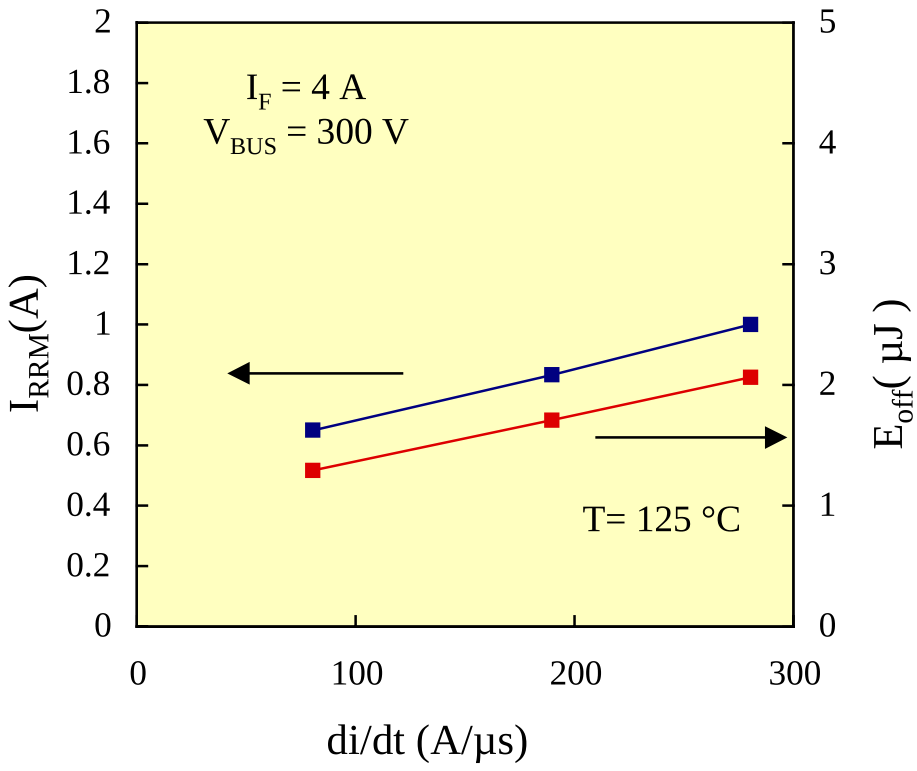
Device D2

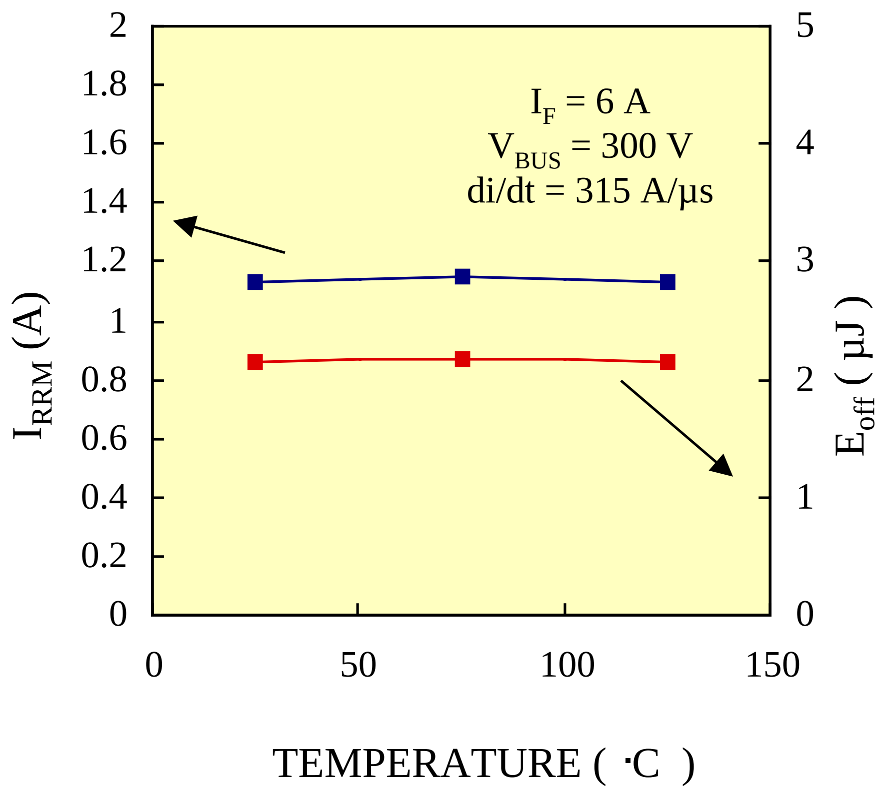




Measured Results

Device D2





Conclusion

- SiC Schottky diodes show promise for SMPS applications.
- Needs further investigation in key SMPS circuits
- SiC device reliability needs to be investigated in detail.