SiC Power Diode Characterization, Modeling, and Circuit Evaluation

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Outline

- Introduction
- 1500 V Silicon-Carbide MPS Diode
  - Device design
  - Characterization
  - Power supply performance
  - Circuit simulator model
- 5000 V Silicon-Carbide PiN Diode
  - Device design
  - Characterization
  - Performance comparison
  - Circuit simulator model
- Conclusion

Introduction

- Superior power devices expected from SiC
- Order of magnitude higher breakdown field
  - 10 times higher blocking layer dopant density
  - 1/10th blocking layer thickness
  - 100 times lower resistance for majority carrier device
  - 100 times faster for minority carrier device $L = \sqrt{D \cdot t}$
- Larger band gap gives high temperature capability
  - improve failure mechanisms for fault conditions
  - higher power with future high temperature packages

Selection of SiC Technologies

- **There are three classes of SiC power rectifiers:**
  - **PiN diodes:** **low leakage current in off-state**
    BUT stored charge and high built-in voltage
  - **Schottky diodes:** **high switching speed**
    BUT high leakage current, high resistance
  - **Merged PiN Schottky:** **Schottky-like on-state and switching**
    AND PiN-like low leakage current
- **1500 V SiC MPS is superior to 600 – 1500 V Si**
- **5000 V SiC PiN is superior to 2kV-5kV Si**

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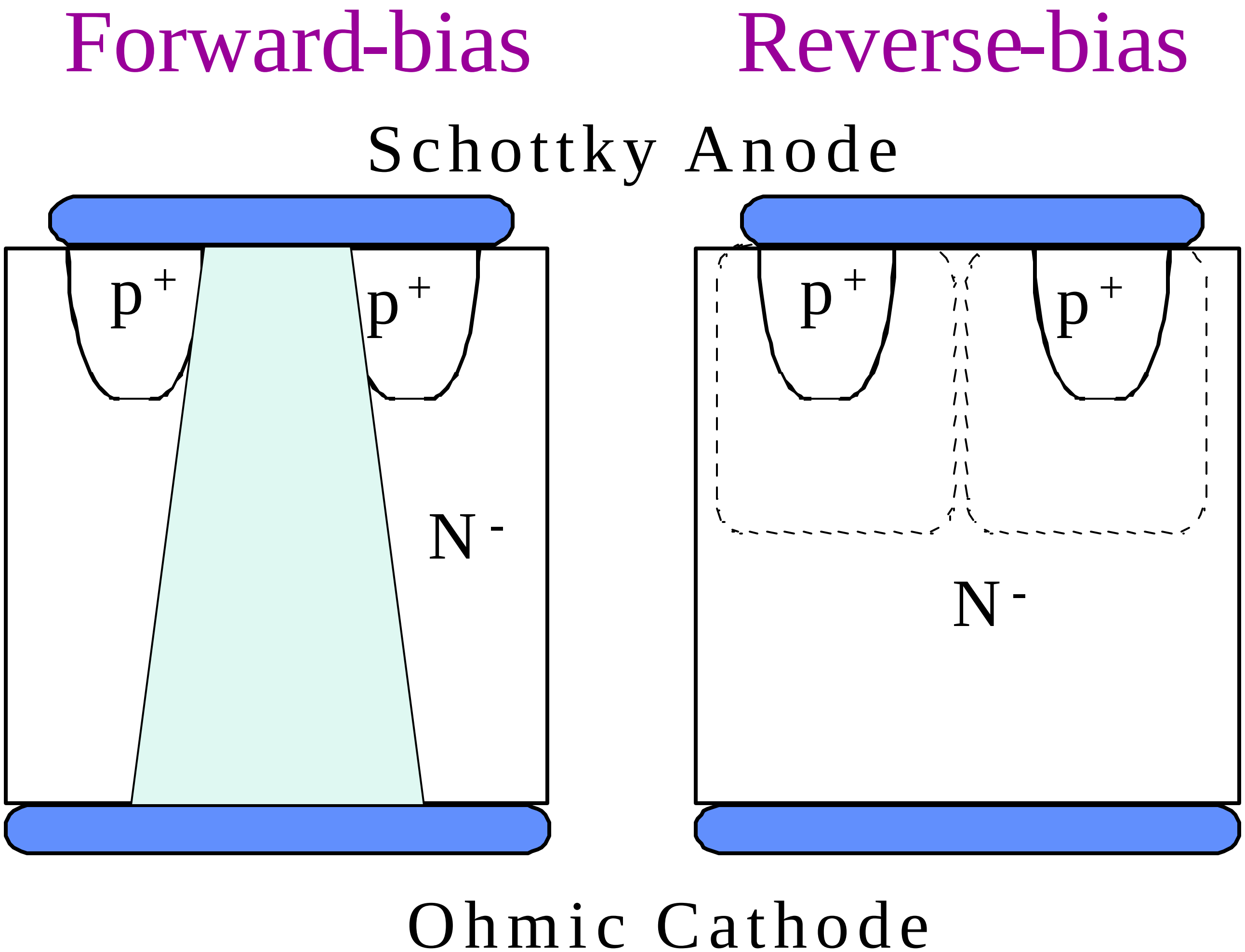
1500 V SiC Merged PiN Schottky

- Combine advantages of Schottky and PiN diodes
  - low voltage drop in the on-state like the Schottky
  - low leakage in the off-state like the PiN
  - fast switching characteristics like the Schottky

- Interdigitated Schottky and p^+-implanted areas
  - only Schottky regions conduct because on-state < 3 V
  - for reverse bias the depletion regions from p^+ regions pinch off the leakage current

Diagram of MPS Diode Operation



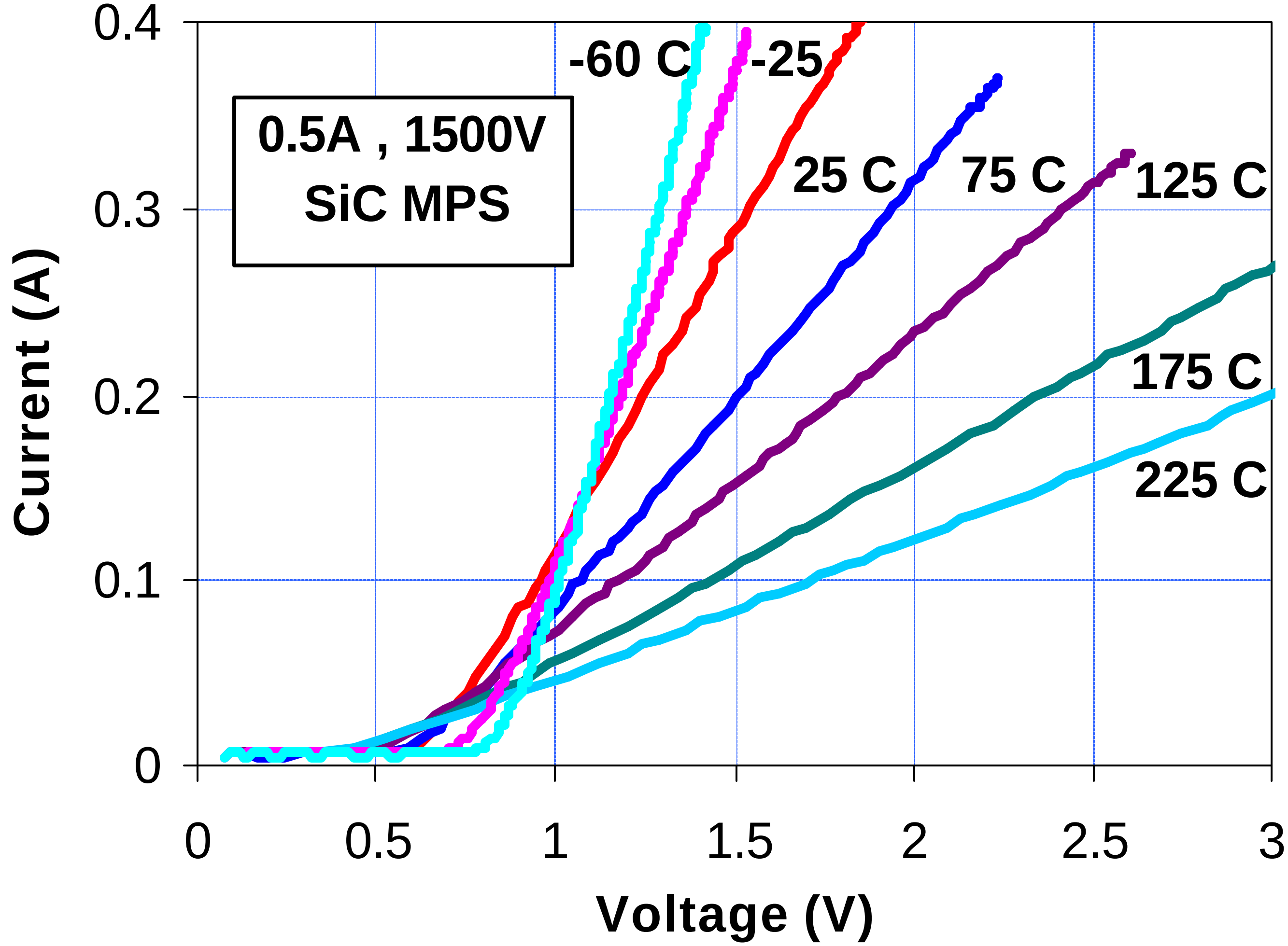
1500 V On-State Characteristics

- SiC PiN diode has large built-in junction voltage
  - due to the wide band gap of 4H-SiC (> 3 V)
  - less desirable for 1500 V applications

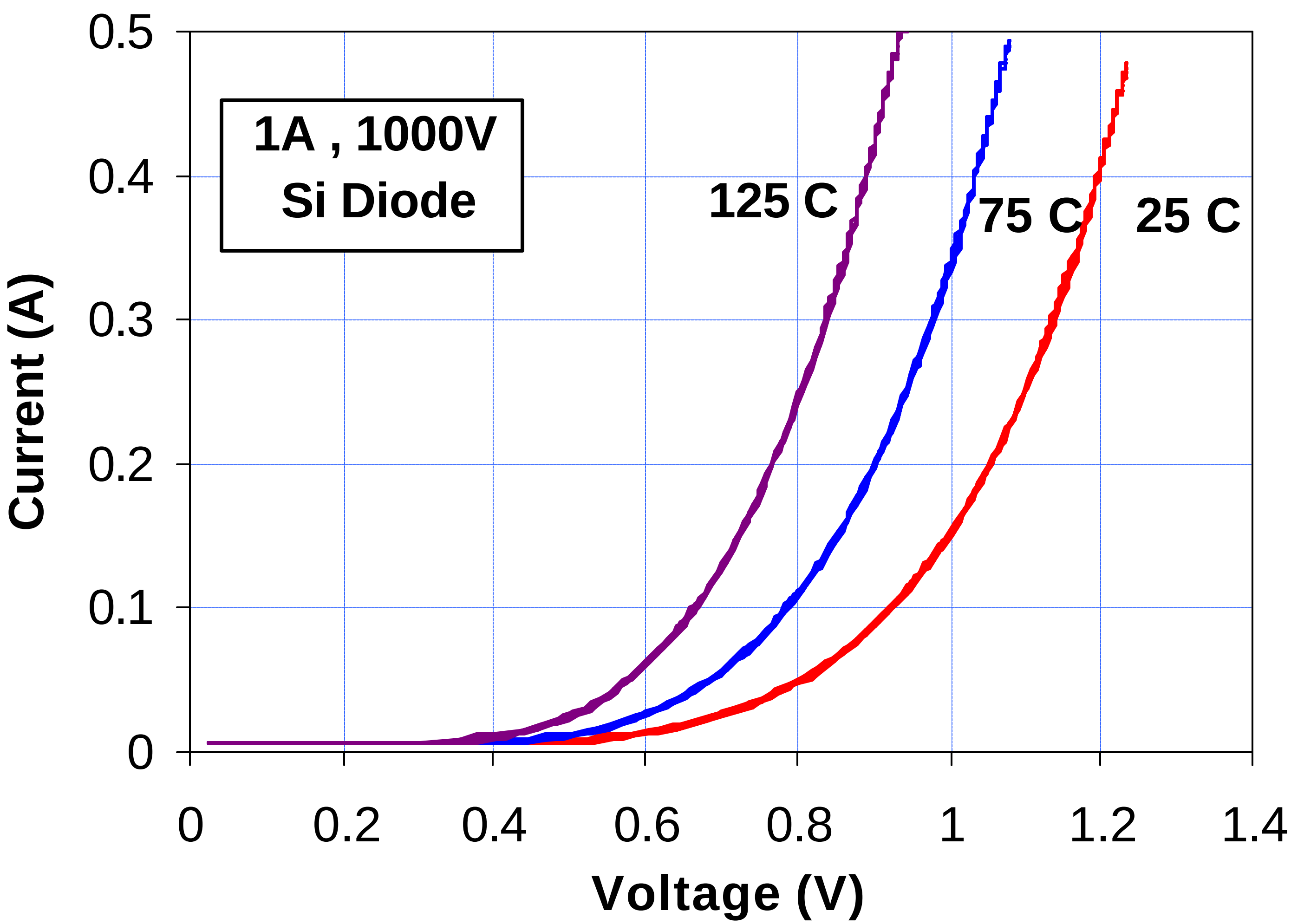
- SiC MPS diode has low built-in voltage of Schottky
  - positive temperature coefficient majority carrier device
  - beneficial for paralleling and large area current sharing

- Si PiN diode has minority carrier injection
  - negative temperature coefficient
  - difficult to parallel

SiC MPS On-state Characteristics



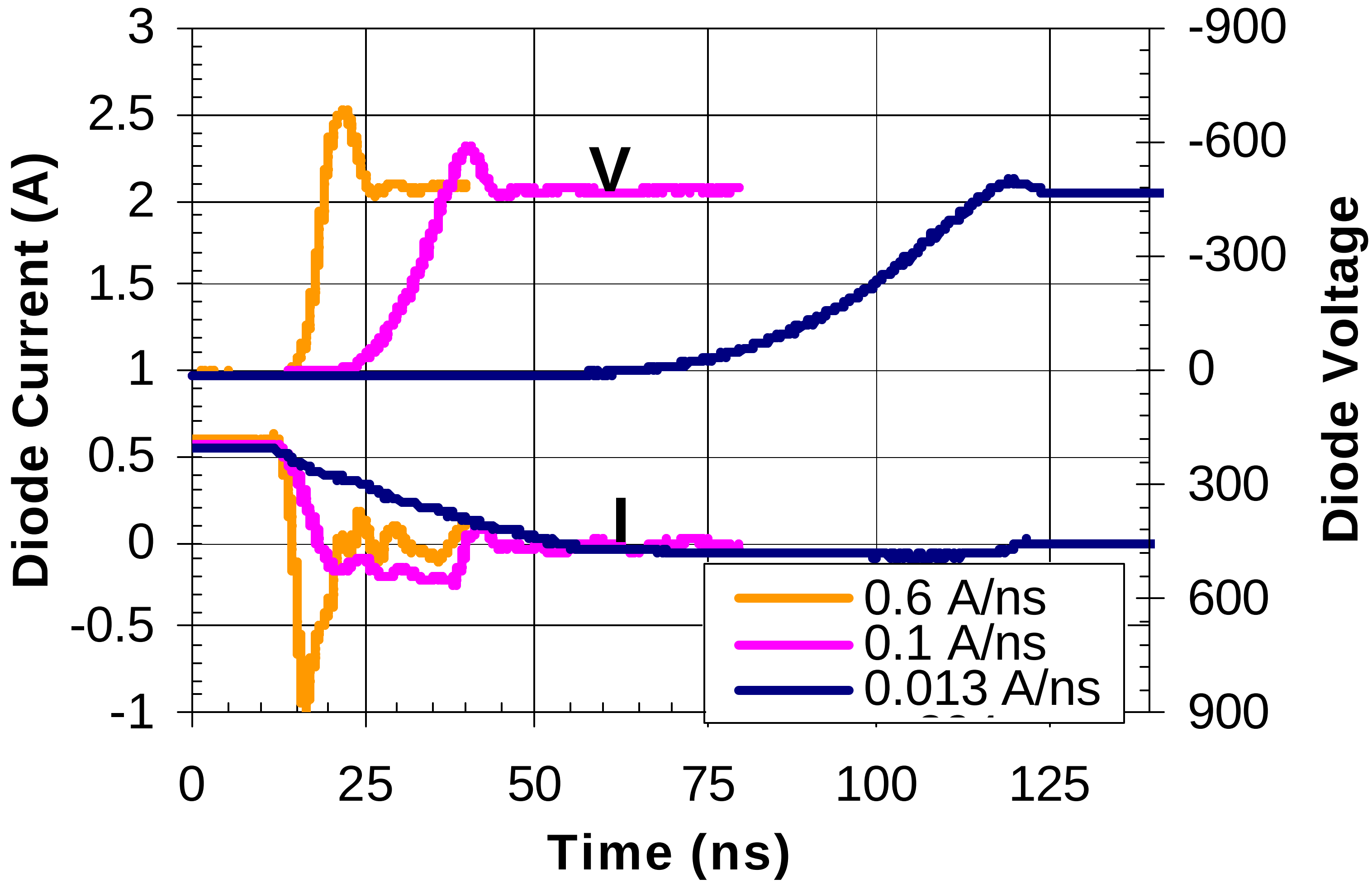
Si PiN On-state Characteristics



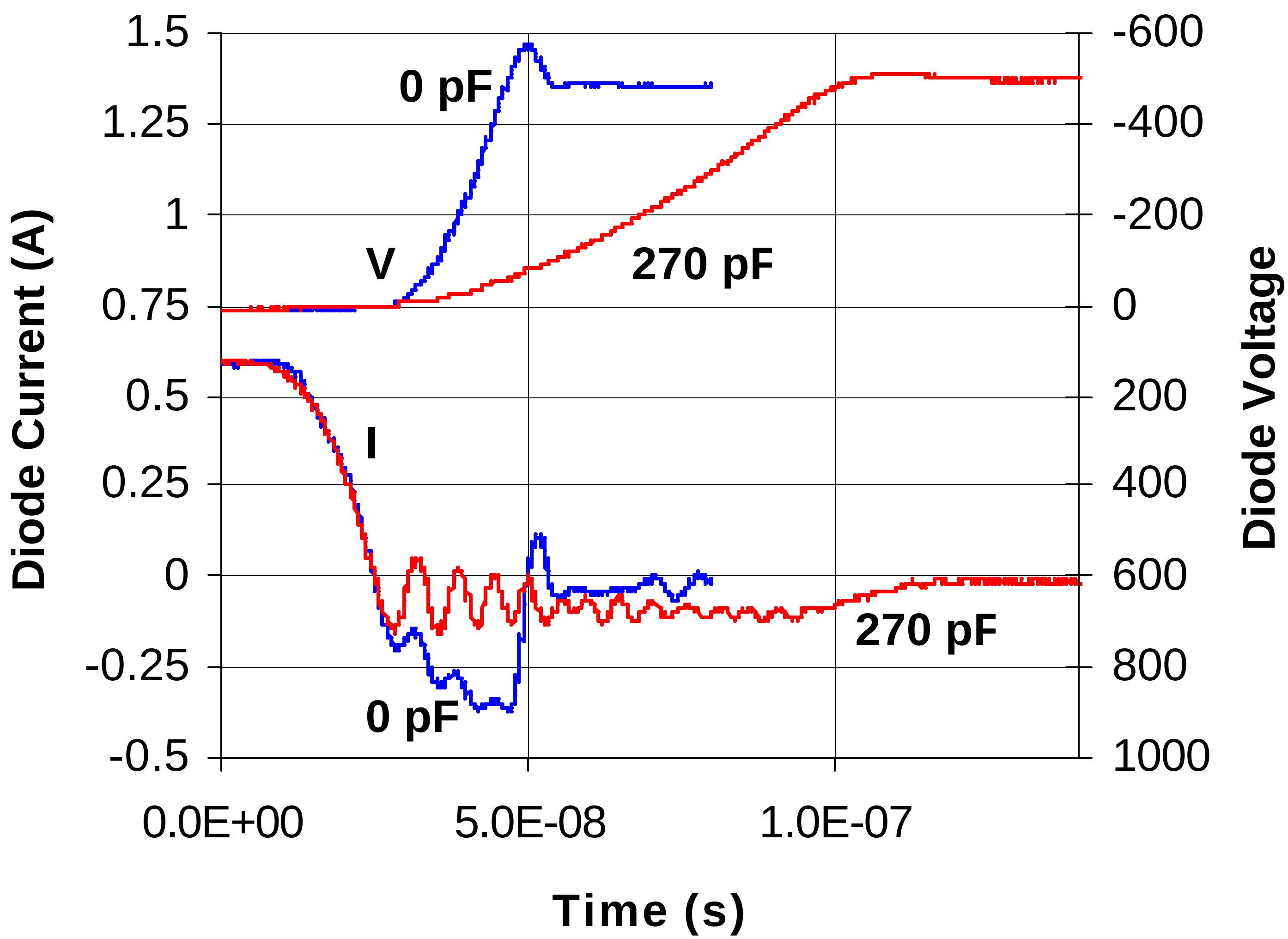
Diode Reverse Recovery Tests

- Test system uses 6LF6 vacuum tube
  - achieve low parasitic capacitance
  - extremely fast switching speed
  - 9 A, 2000 V capability
- Diodes tested for full range of application conditions
  - di/dt controlled by tube screen drive circuit
  - dv/dt controlled by placing capacitors across tube output
- Adding different capacitance values to tube output
  - emulates switching devices of different output capacitance
  - distinguishes charge storage and device capacitance effects

MPS Diode dI/dt Dependence



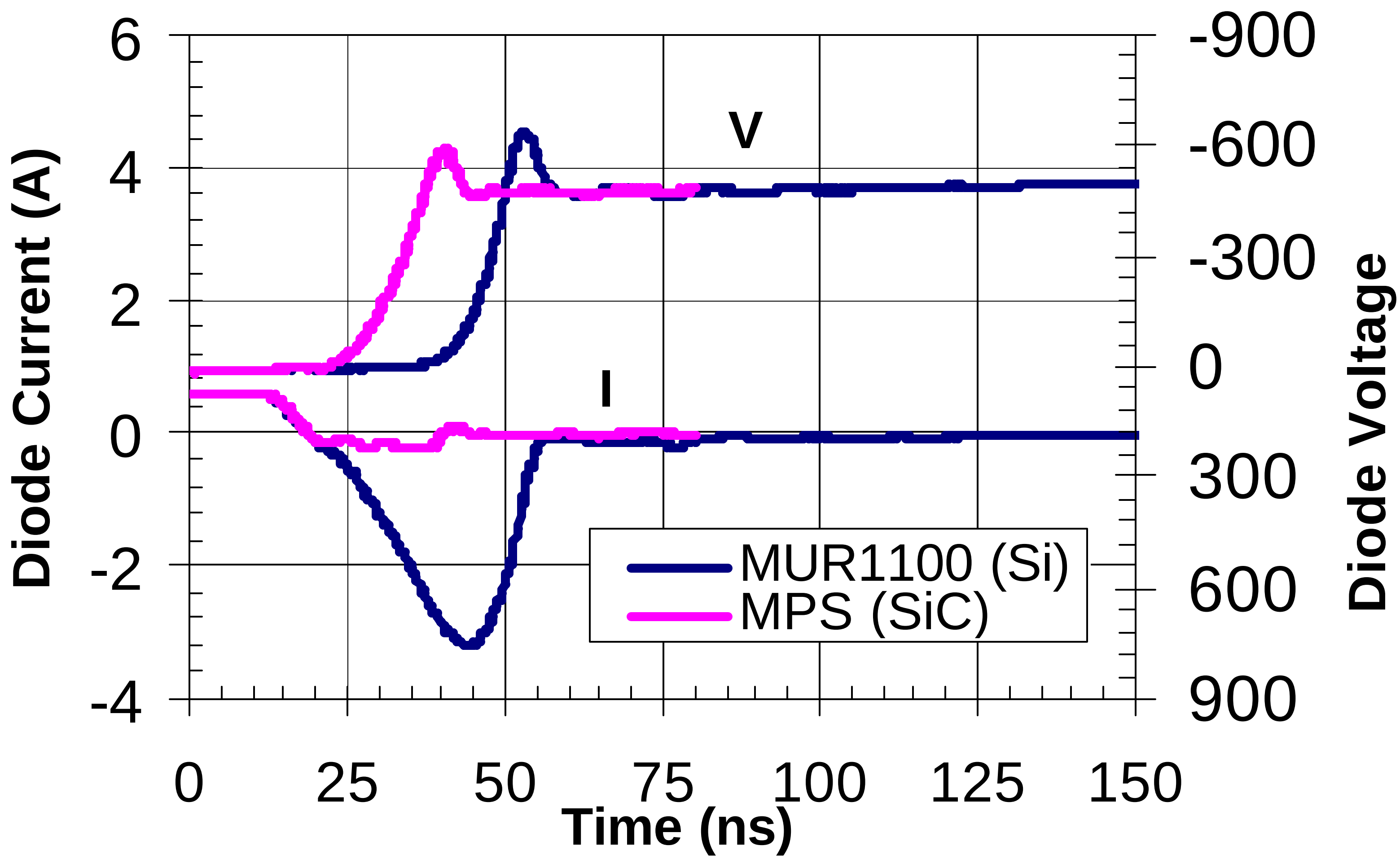
MPS Diode dV/dt Dependence



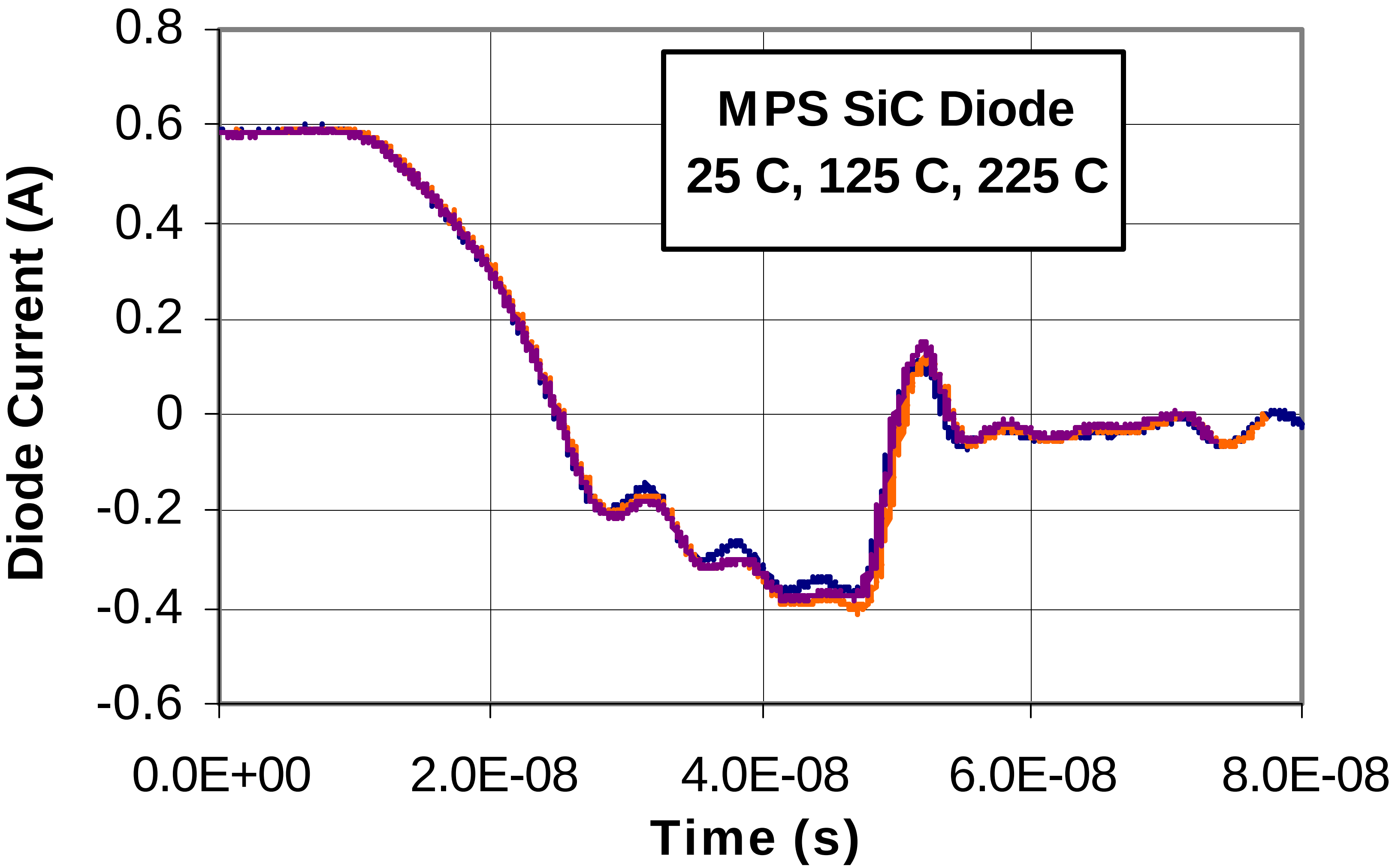
Comparison of Si PiN and SiC MPS

- SiC MPS has no minority carrier charge recovery
  - current waveform dominated by junction capacitance
  - much lower energy loss than Si PiN diode
  - voltage rise not delayed as in Si PiN diode
  - reduced loss and stress on complementary switches
- Reverse recovery temperature dependence
  - Si PiN reverse recovery charge increases with temperature because lifetime increases
  - SiC MPS recovery has no temperature dependence

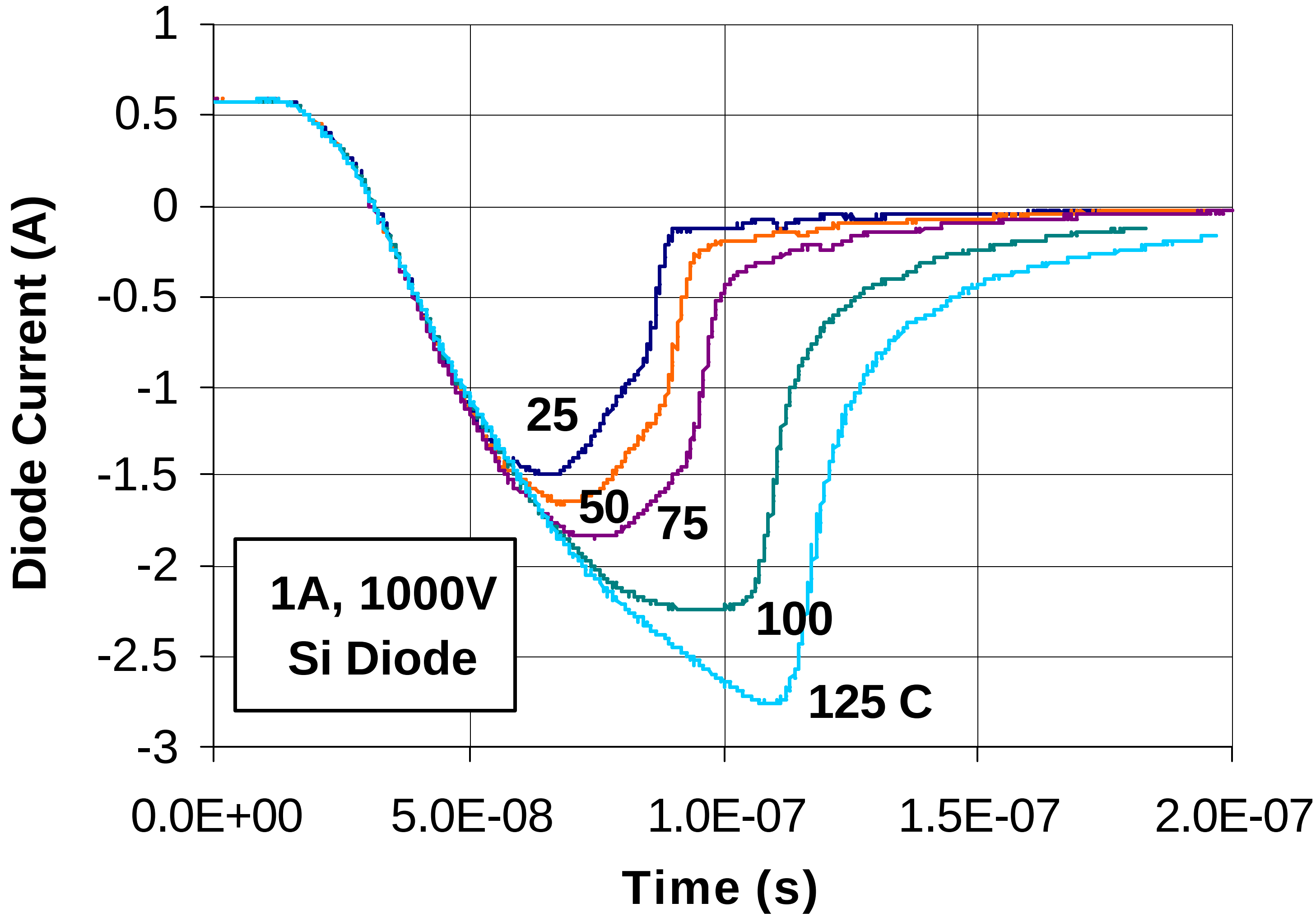
Recovery of Si PiN versus SiC MPS



Temperature Effect for SiC MPS



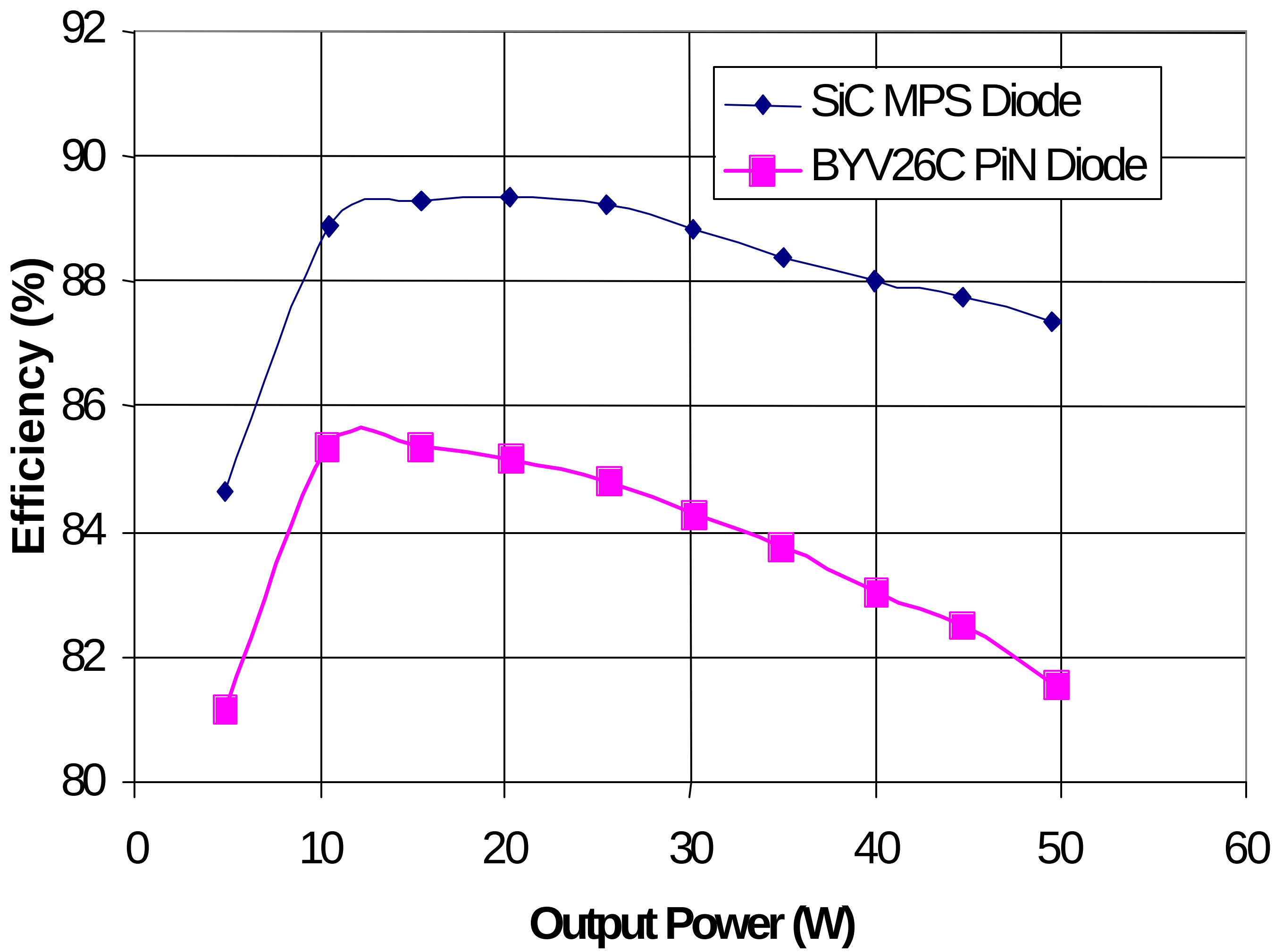
Temperature Effect for Si PiN



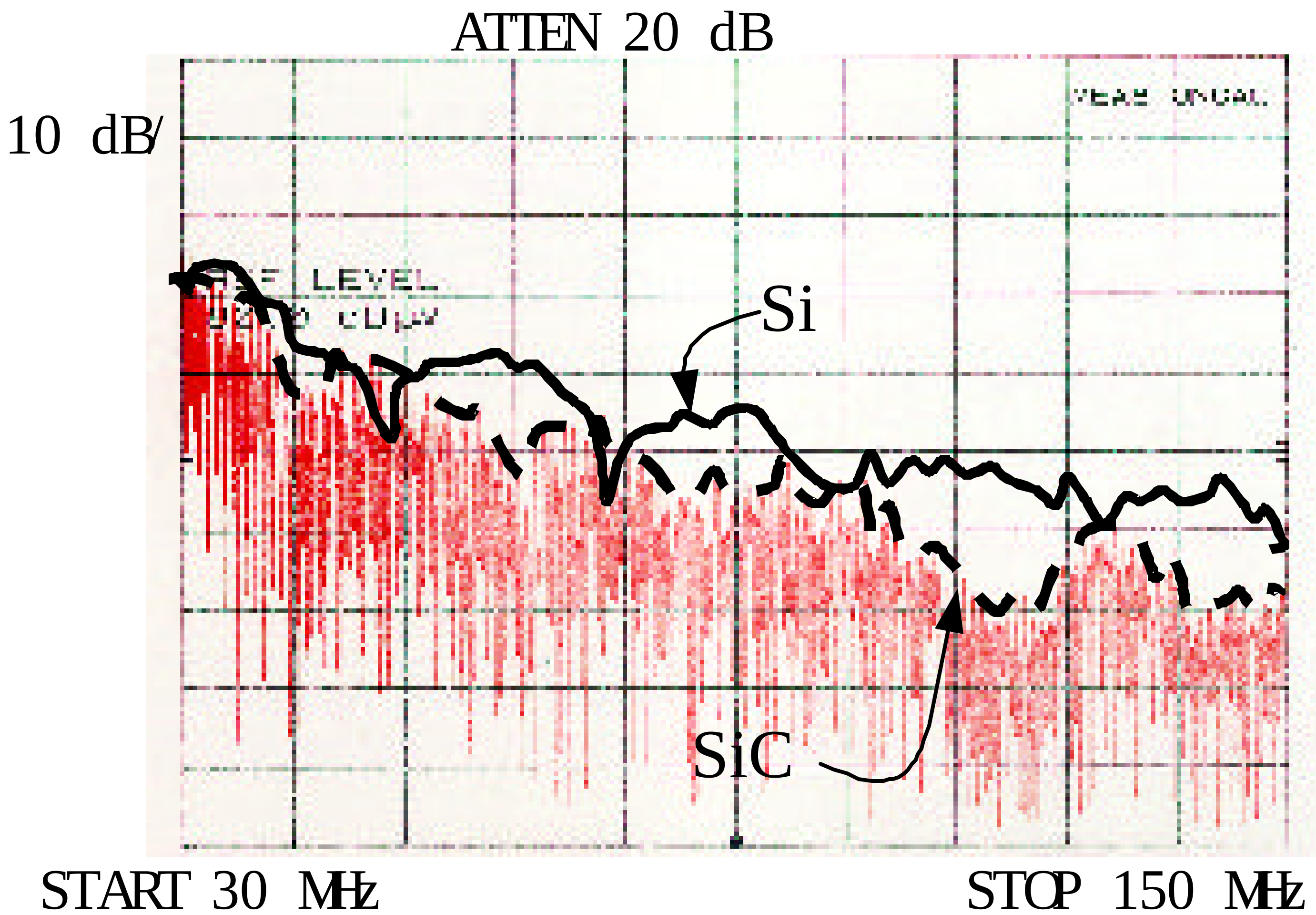
Power Supply Performance

- Test case 500-V to 100-V step-down power supply
  - Cool MOS™ transistor for the switch
  - switching at 100 kHz and 186 kHz
- Loss comparison made between different diodes
  - 1000 V ultra-fast Si diode overheats and fails at 100 kHz
  - 600 V ultra-fast Si diode has high loss, low voltage margin
  - 1500 V SiC MPS diode has low loss, wide voltage margin
- SiC MPS has lower EMI emissions than Si diode

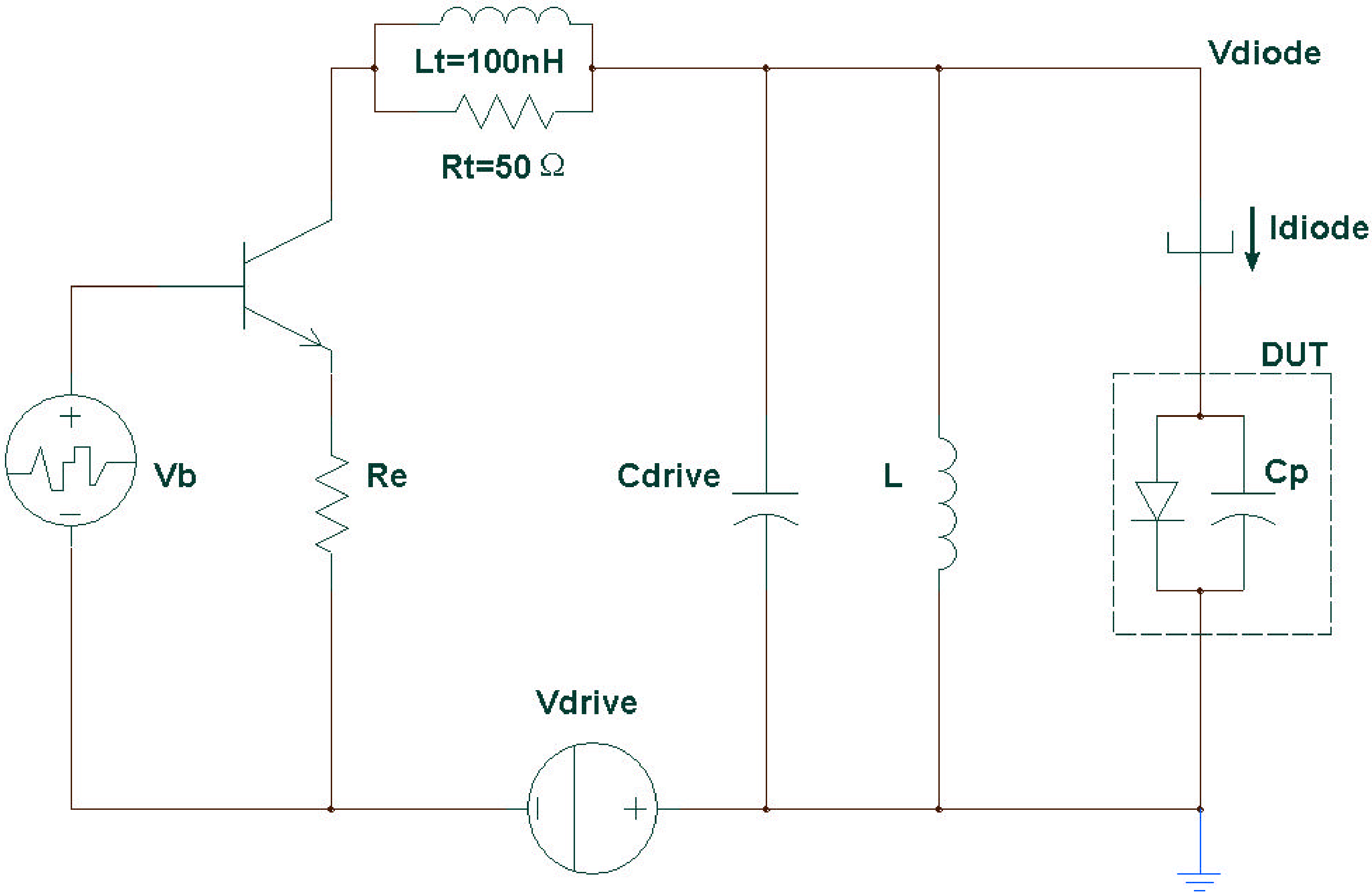
Power Supply Efficiency



Electromagnetic Interference



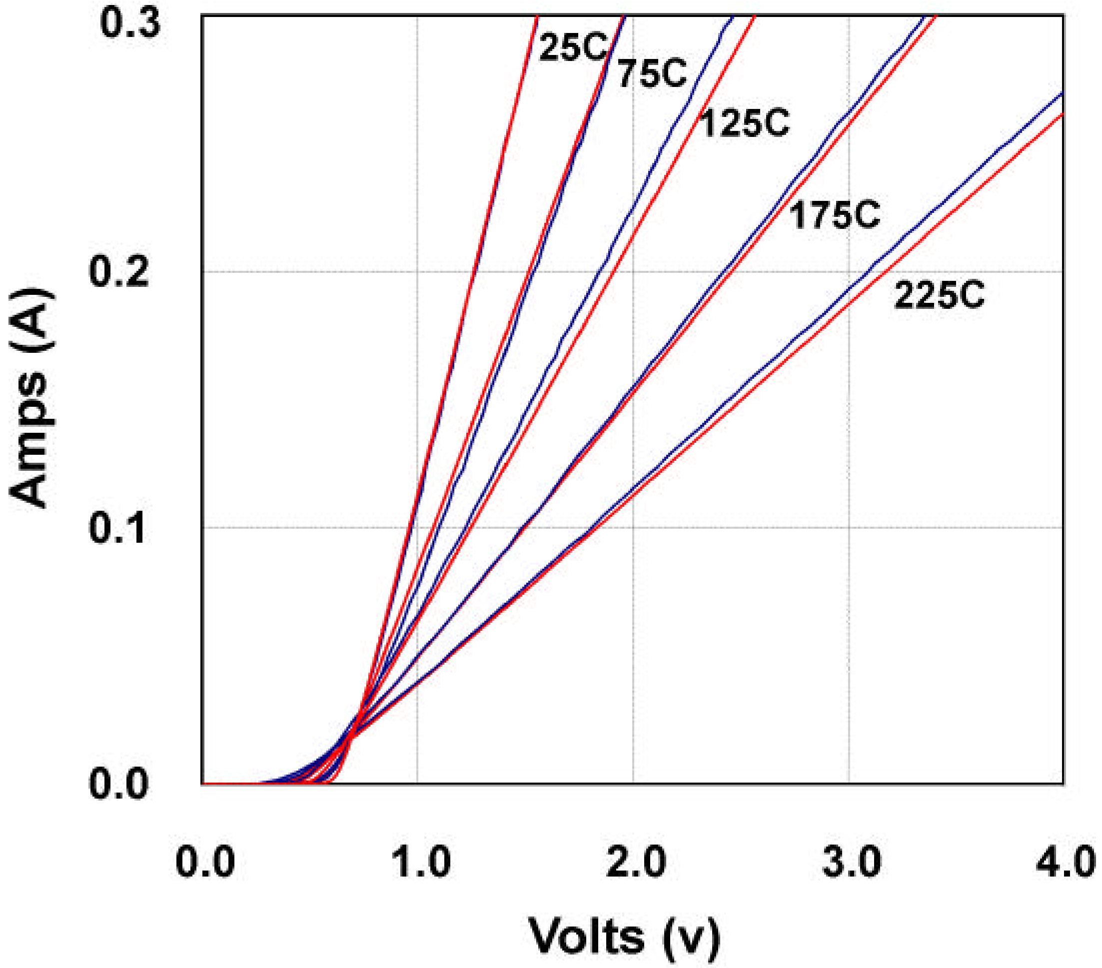
Behavioral Model of Test System



SiC MPS On-State

--- Experiment

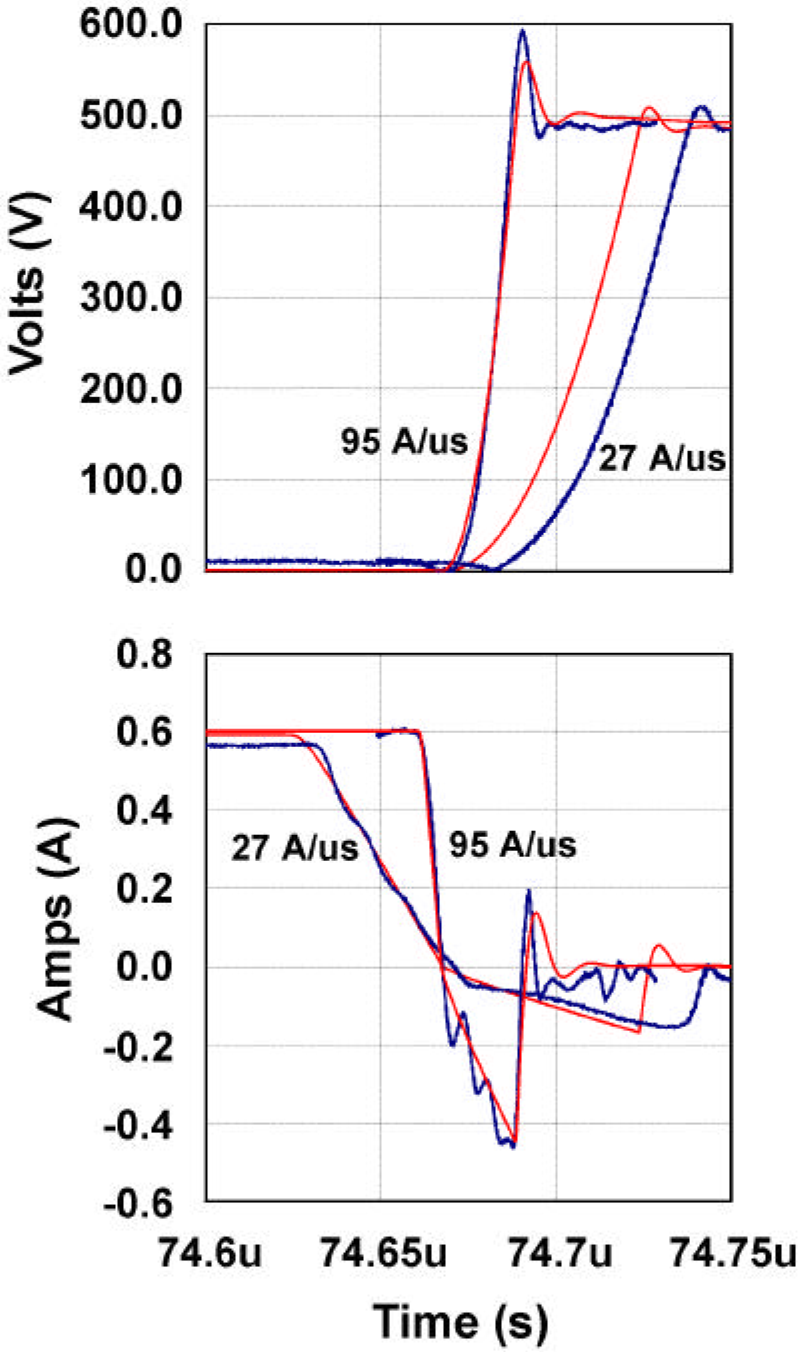
--- Model



SiC MPS di/dt Dependence

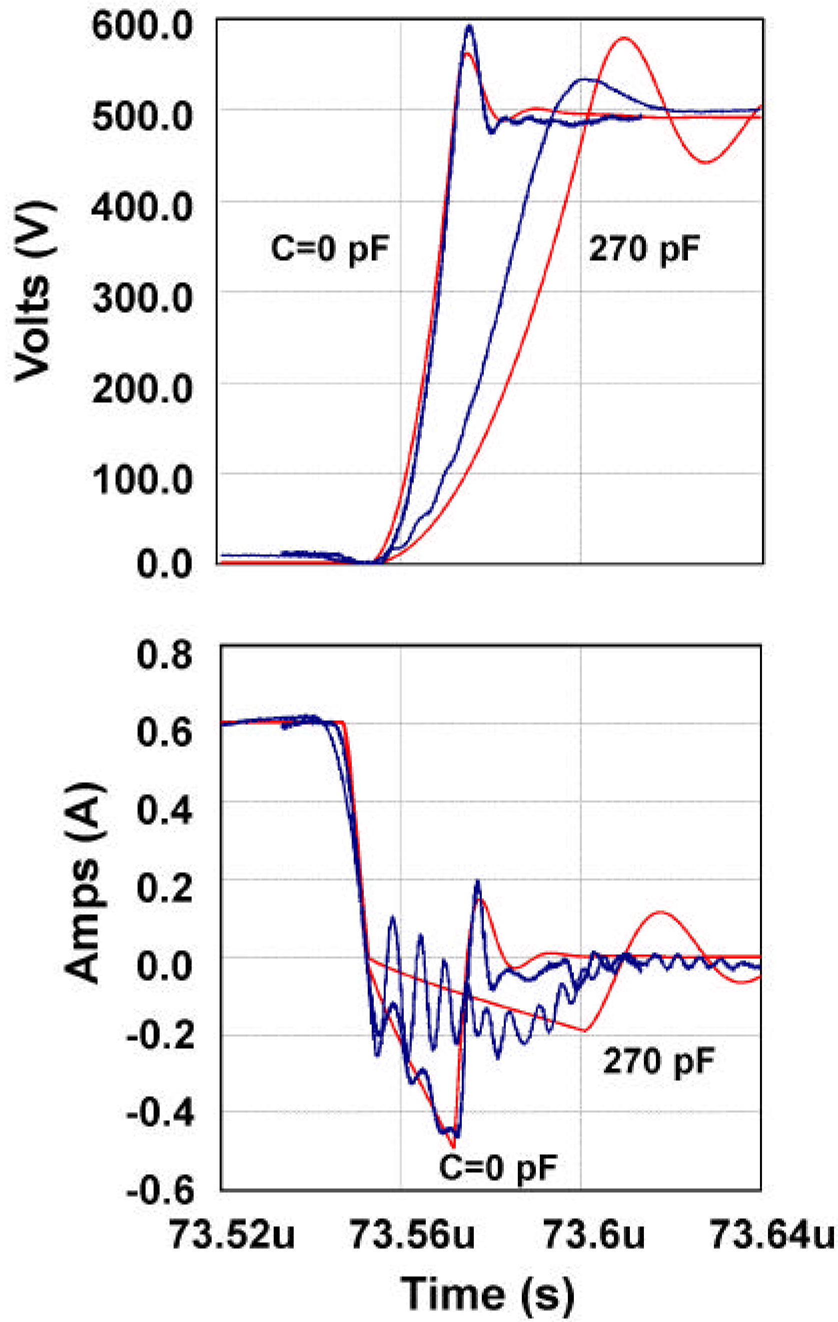
--- Experiment

--- Model



SiC MPS Capacitance Dependence

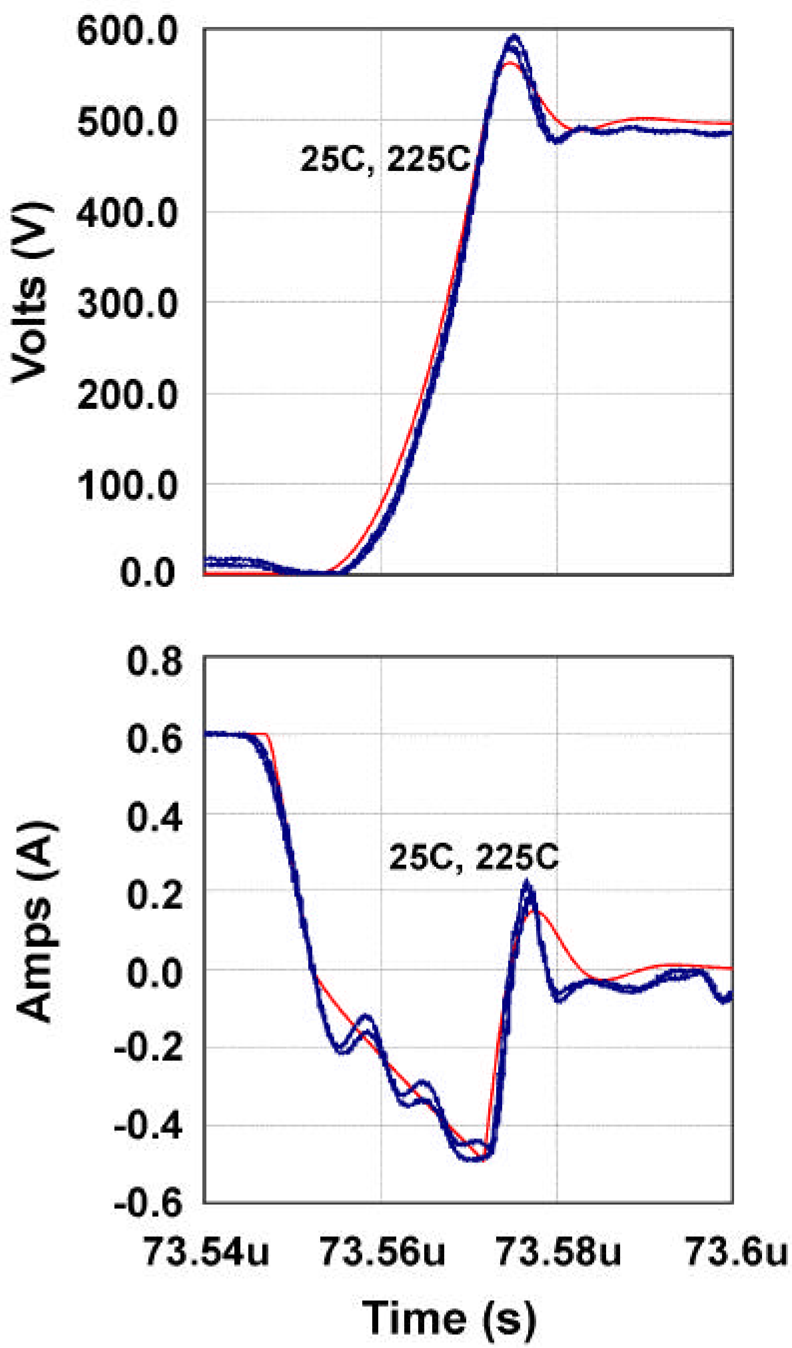
--- Experiment
--- Model



SiC MPS Temperature Dependence

--- Experiment

--- Model



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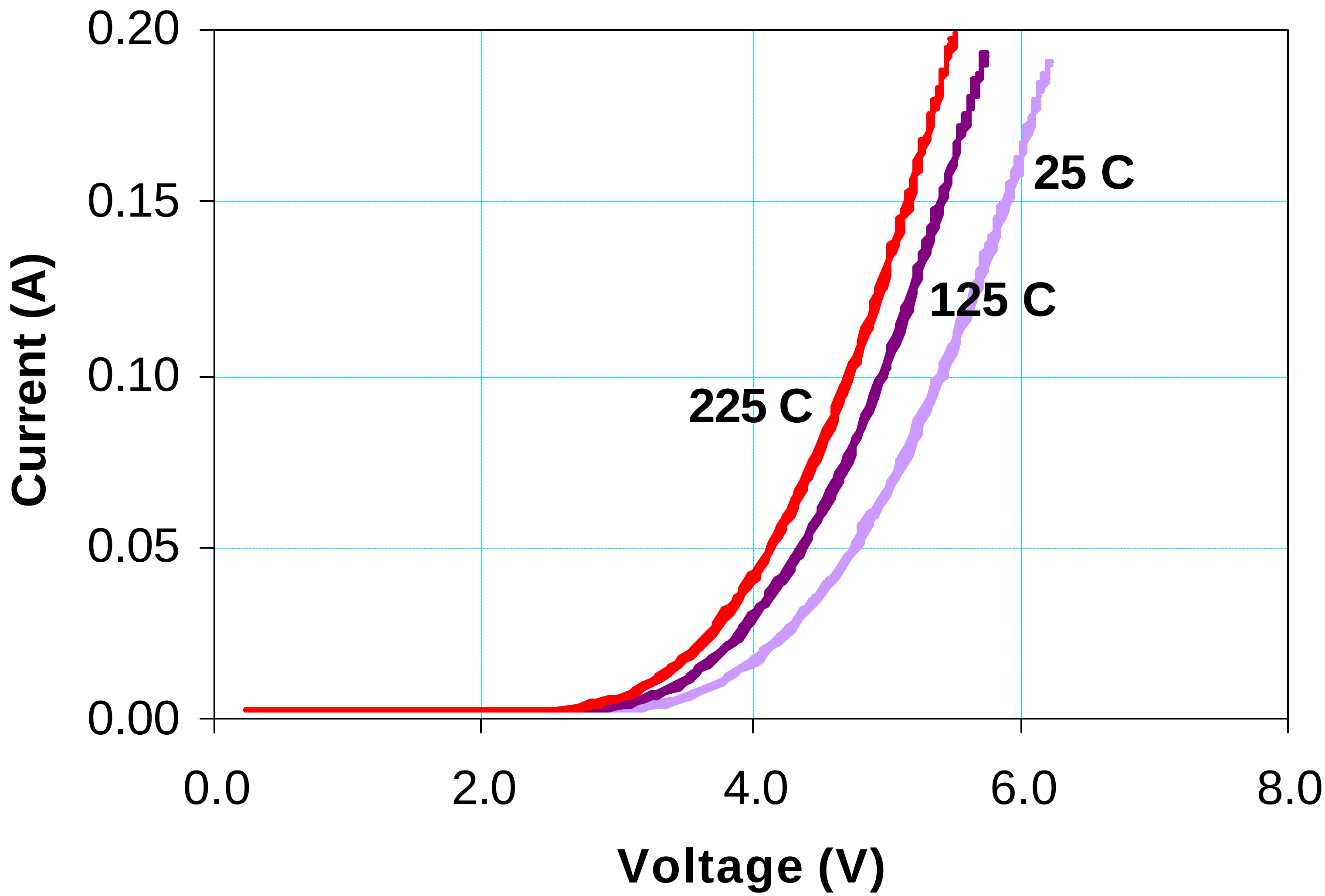
5000 V SiC PiN Diode

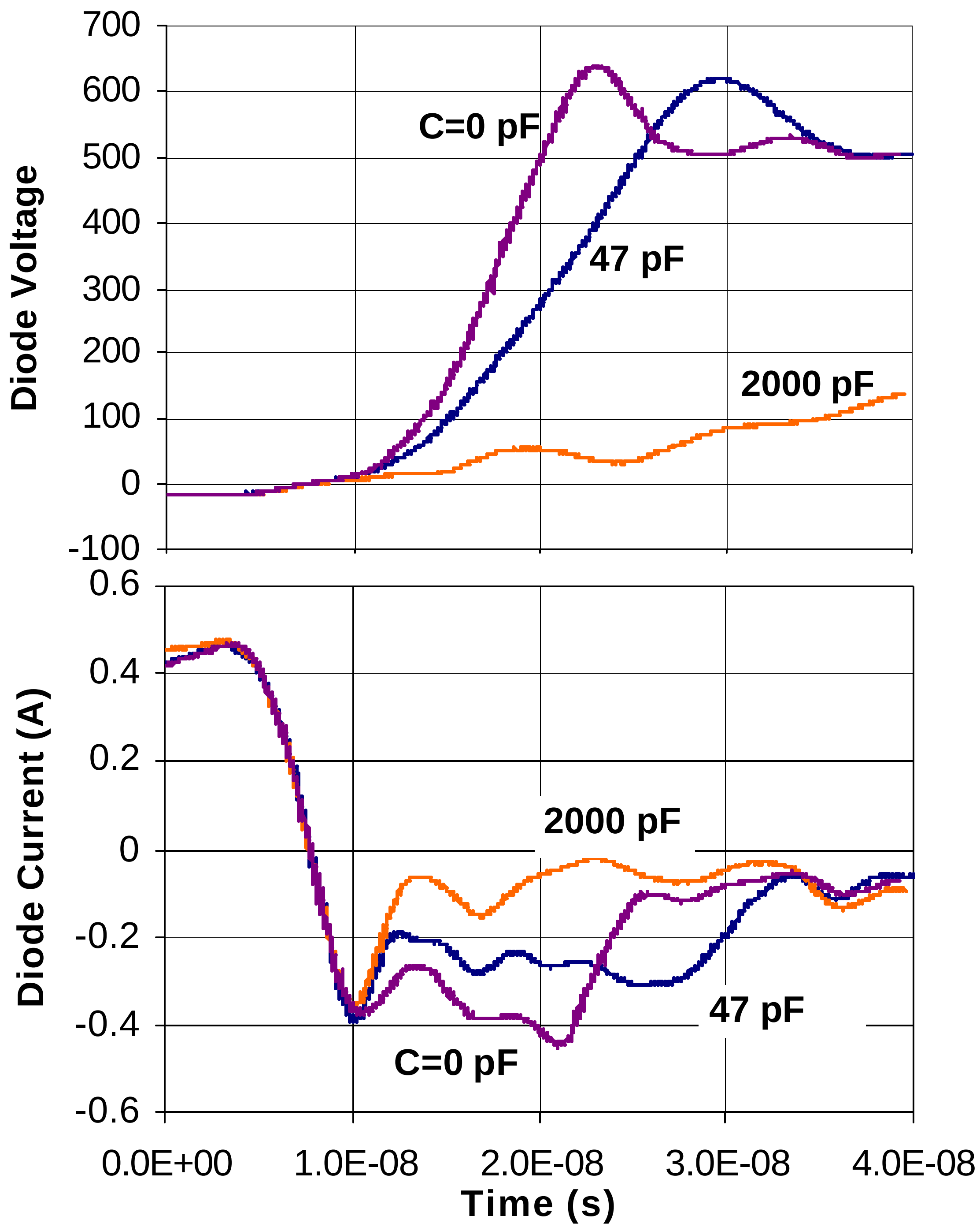
- SiC PIN diode more desirable for 5000 V application
  - MPS voltage blocking layer has no conductivity modulation
  - PiN diode reduces resistance by high-level injection
- 5000 V SiC PiN power diodes fabricated
  - 4H-SiC n^- layer with a thickness of 50 μm and N=8E14
  - Junction Termination Extension (JTE) used at edges
- 5000 V SiC better trade-off than 2000 V - 5000 V Si
  - voltage drop in on-state comparable to stacked Si diodes
  - speed much faster than Si PiN because lower lifetime

5000 V SiC On-state Voltage



5000 V SiC Capacitance Dependence

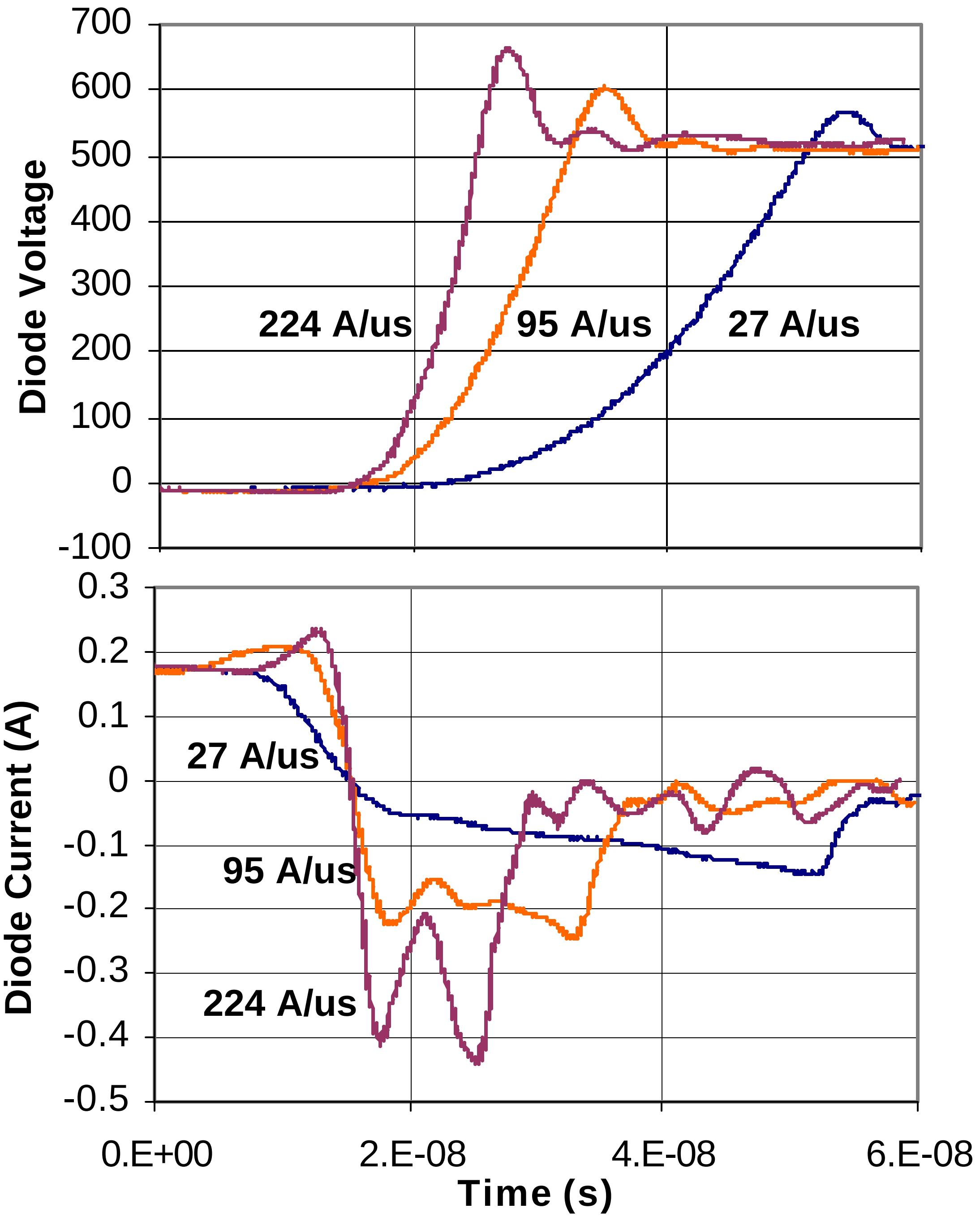
- SiC diode recovery: stored charge and junction capacitance
- Capacitor decreases voltage rise rate and separates mechanisms
- C_j = 4 pF
- t_{rr} = 6 ns



5000 V SiC dI/dt Dependence

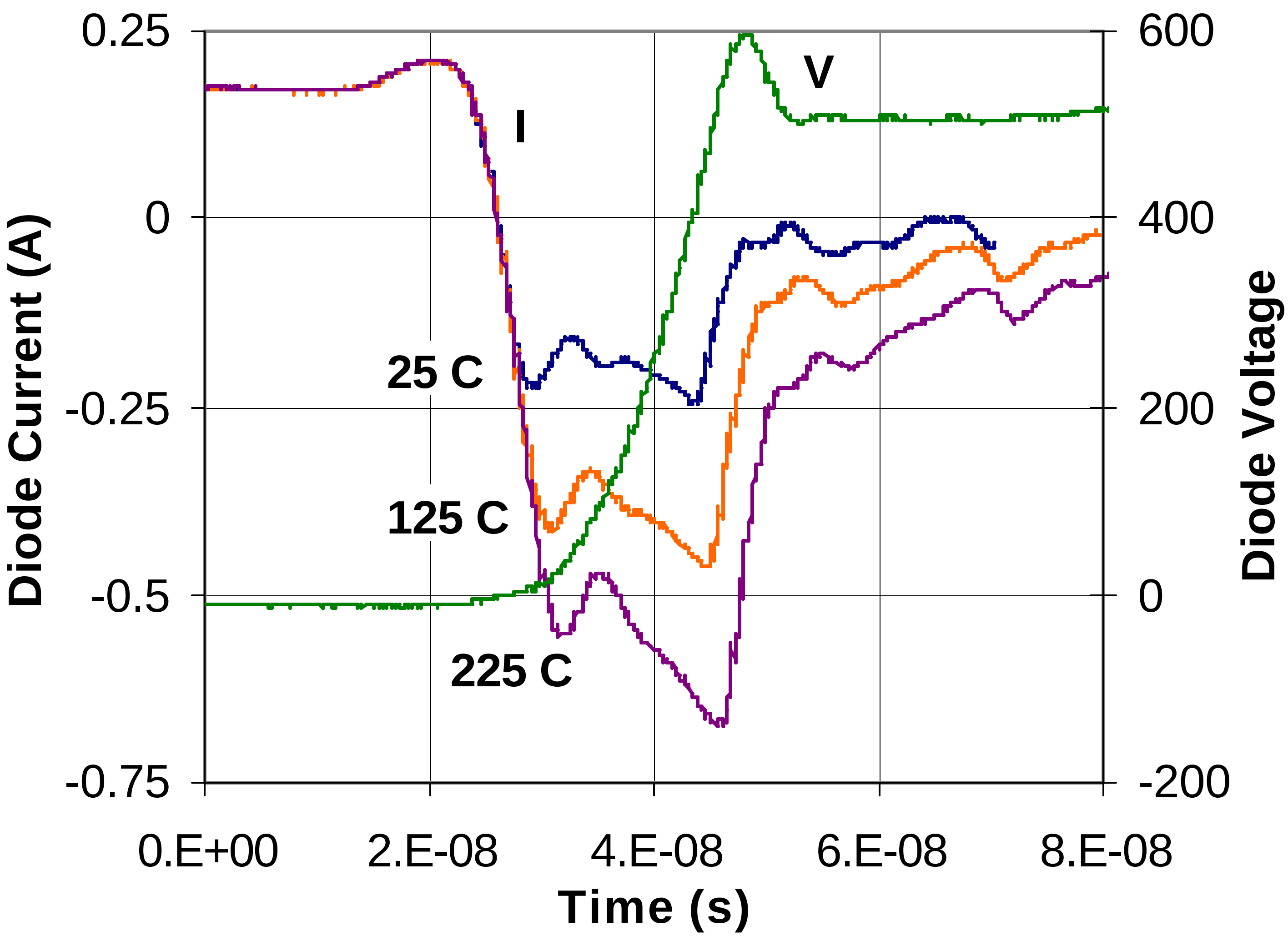
C=0 nF

- Low dI/dt: junction capacitance only
- High dI/dt: both stored charge and junction capacitance



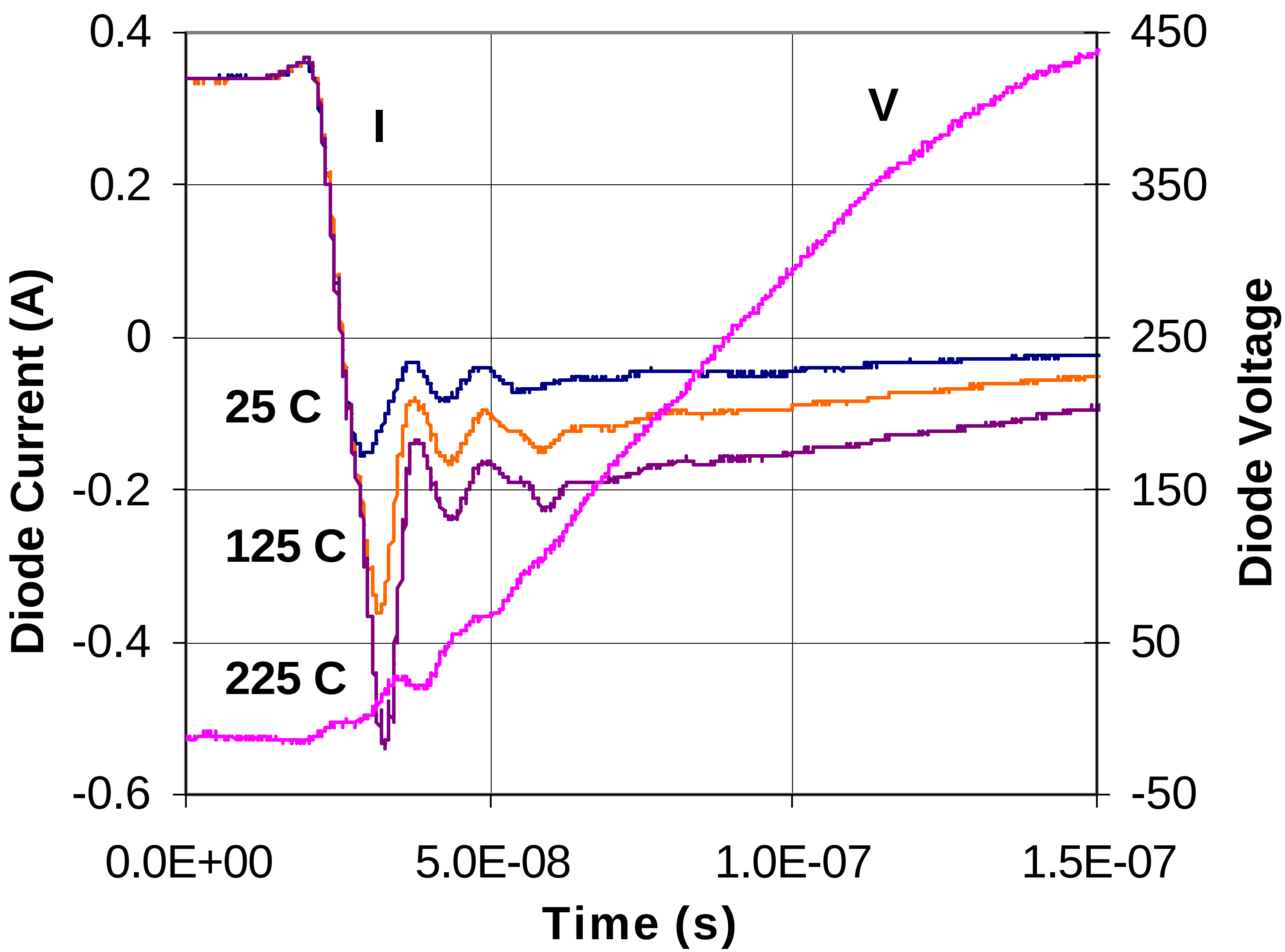
5000 V SiC Temperature Dependence

C=0 nF



5000 V SiC Temperature Dependence

C=2 nF



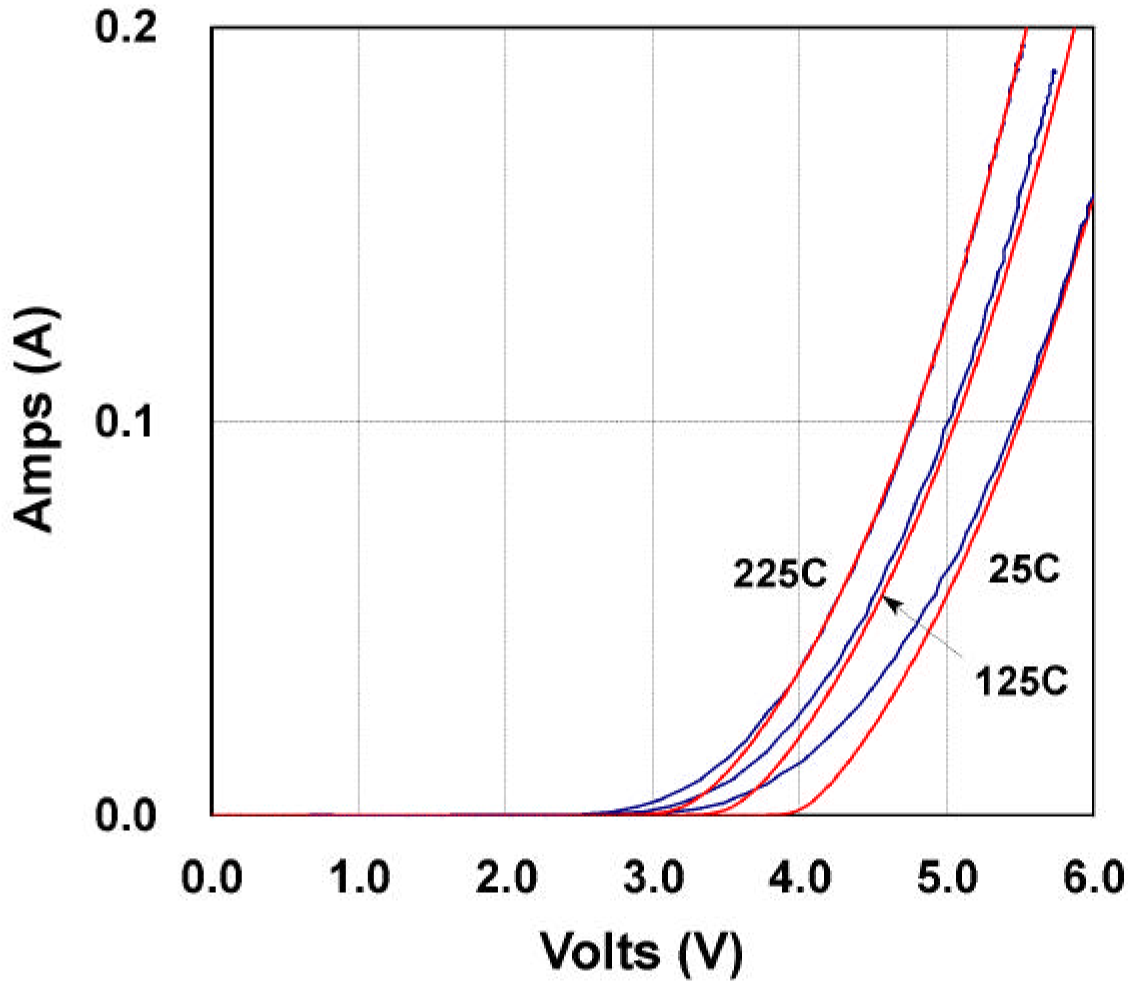
Comparison of High Voltage Diodes

	Repetitive Peak Reverse Voltage V_{RRM} (V)	Forward Voltage Drop V_f (V)	Reverse Recovery Time t_{rr} (ns)
SiC PiN	5000	5.7	6
VMI X50FF3	5000	12.5	30
VMI X20FF3	2000	7.5	30
VMI 1N6523	3000	5.0	70
VMI 1N6524	4000	7.0	70
Philips BYX105G	5000	10.9	600
Philips BYX106G	5000	12.7	350
Philips BYX107G	5000	15.8	175
Philips BYX108G	5000	27.7	50

SiC PiN On-State

--- **Experiment**

--- **Model**



SiC PiN di/dt Dependence

--- Experiment

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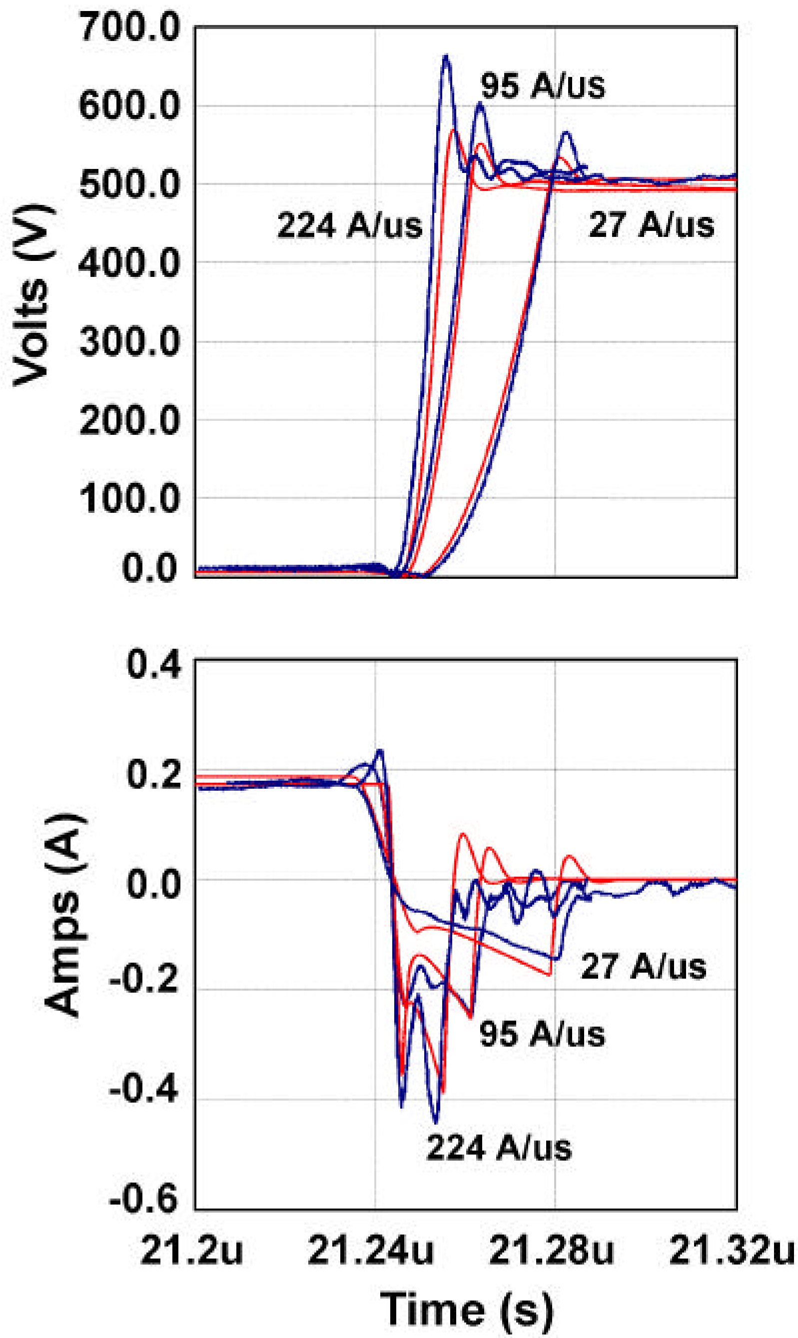

SiC PiN Capacitance Dependence

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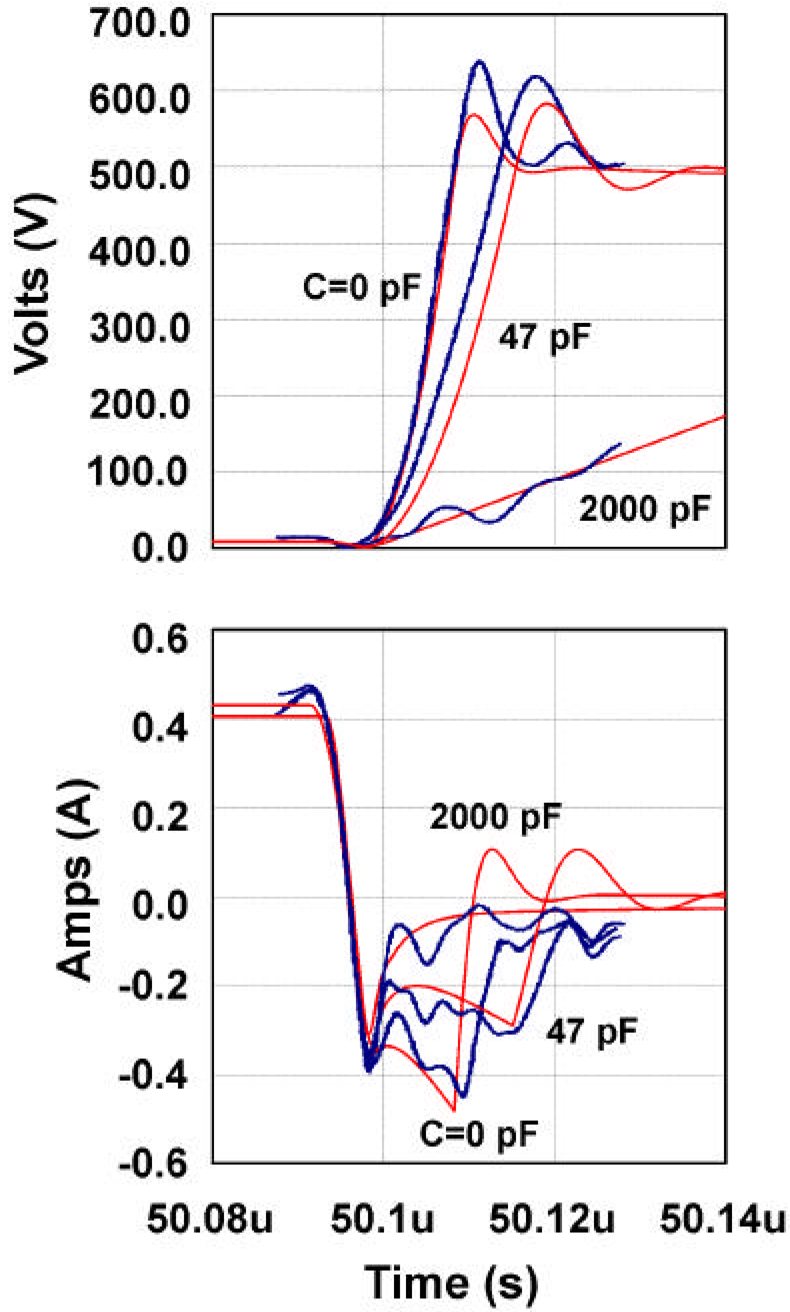

Conclusion

- **1500-V SiC Merged PiN Schottky (MPS) diode**
  - virtually no reverse recovery current
  - forward voltage drop comparable to silicon devices
  - more efficient than Si PiN optimized for 600 – 1500 V
- **Si PiN diodes designated: fast, very fast, and ultra fast**
  - trade-off between forward drop and speed
  - trade-off gets worse with higher blocking voltage
- **5000 V SiC PiN outperforms each 2000 V - 5000 V Si**
  - on-state voltage comparable to stacked Si diodes
  - stored charge recovery time an order of magnitude faster
  - junction capacitance comparable for all devices (3 – 5 pF)
- **SiC power diode models in Saber circuit simulator**