Performance Comparison of Semi-Insulating SiC Materials for Photoconductive Switches

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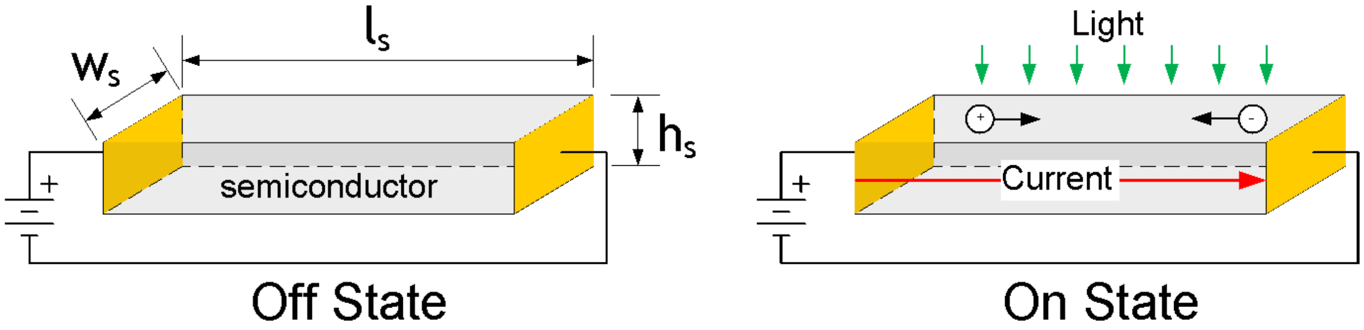
Background

- Bulk photoconductive switches
  - High voltage, short pulse (> 20 kV, < 10 ns rise time)



- High resistivity semiconductor (SiC) modulated by light source (laser)
  - Ideal Case: Linear Mode Ohmic Photoresistor

C. Hettler, “Investigation and evaluation of high voltage silicon carbide photoconductive semiconductor switches,” M. S. thesis, Texas Tech University, Lubbock, TX, USA, August 2009.

Important Parameters

1. Blocking Voltage
    - ➢ Impact Ionization ↔ Breakdown Field
    - ➢ Edge termination
2. Illuminated (On-state) Resistance
    - ➢ Conduction Path Length
    - ➢ Mobility
    - ➢ Carrier Recombination Lifetime

Silicon Carbide Polytypes

- Two Commercially Available Polytypes:
  - 4H-SiC: (1 hex, 1 cubic, 0.8 anisotropic ratio)
  - 6H-SiC: (2 hex, 1 cubic, 0.2 anisotropic ratio)

- Important Performance Parameters

	4H-SiC	6H-SiC
Bandgap (eV)	3.23	3.02
Electron Mobility (cm^2/V-s)	900 *	80 *
Critical Field (MV/cm)	3.4 *	2.8 *

*** - Properties parallel to c-axis (Vertical device on c-plane material).**

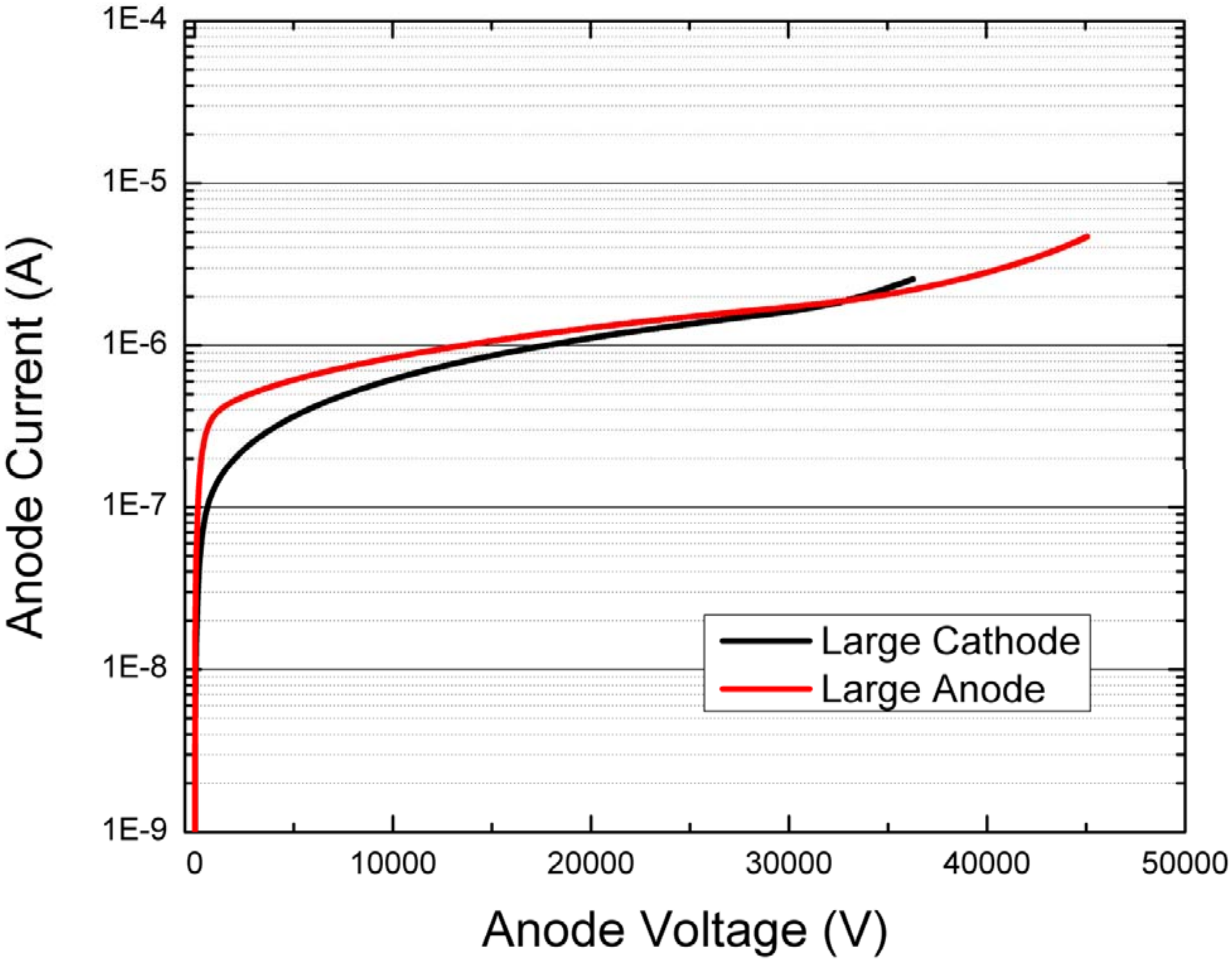
B. Rhagathan, J. Baliga, Impact Ionization coefficients of 4H-SiC, 1997.

Blocking Voltage

<u>Breakdown Simulation:</u>

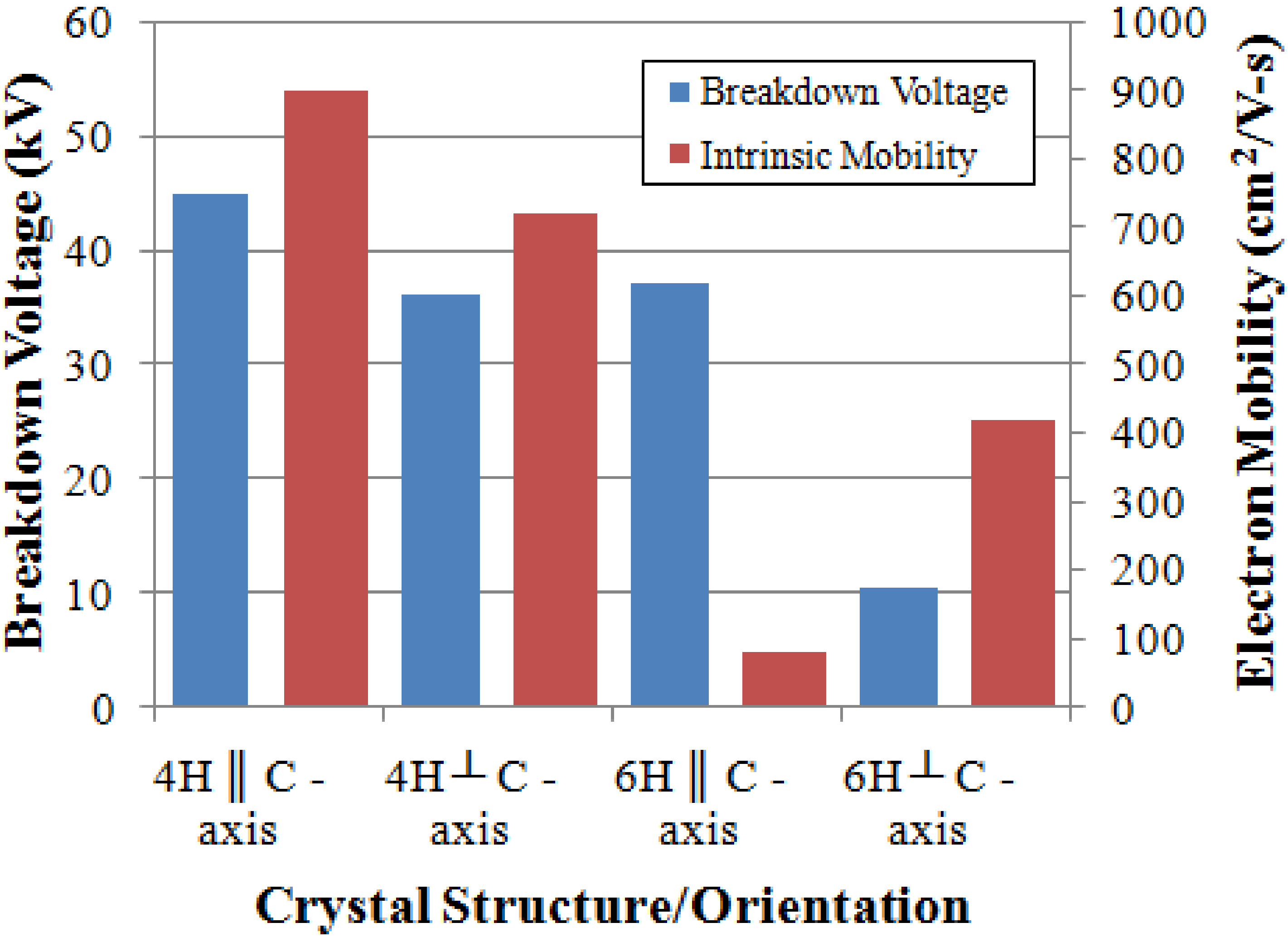
- Vertical 4H switch on c-plane material
- 335 μm thickness
- Two electrode geometries, large cathode, anode
- Varies over 10 kV

- Voltage depends on termination, geometry



C. James, High Purity Semi-Insulating 4H-SiC as a Photoconductive Switch Material, PhD Dissertation, 2010.

Breakdown Voltage



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On State Resistance

- Illuminated Resistance Model:

$$n_c(t) := e^{\frac{-t}{\tau_e}} \cdot \int_0^t e^{\frac{\tau}{\tau_e}} \cdot \left[\frac{I_o(\tau) \cdot \lambda \cdot \left(1 - R_\lambda\right) \cdot \left(1 - e^{-\alpha \cdot l_s}\right)}{h \cdot c \cdot l_s \cdot A_{active}} \right] d\tau$$

$$R_{ON}(t) := \frac{l_s}{q_e \cdot \mu_n \cdot n_c(t) \cdot A_{active}}$$

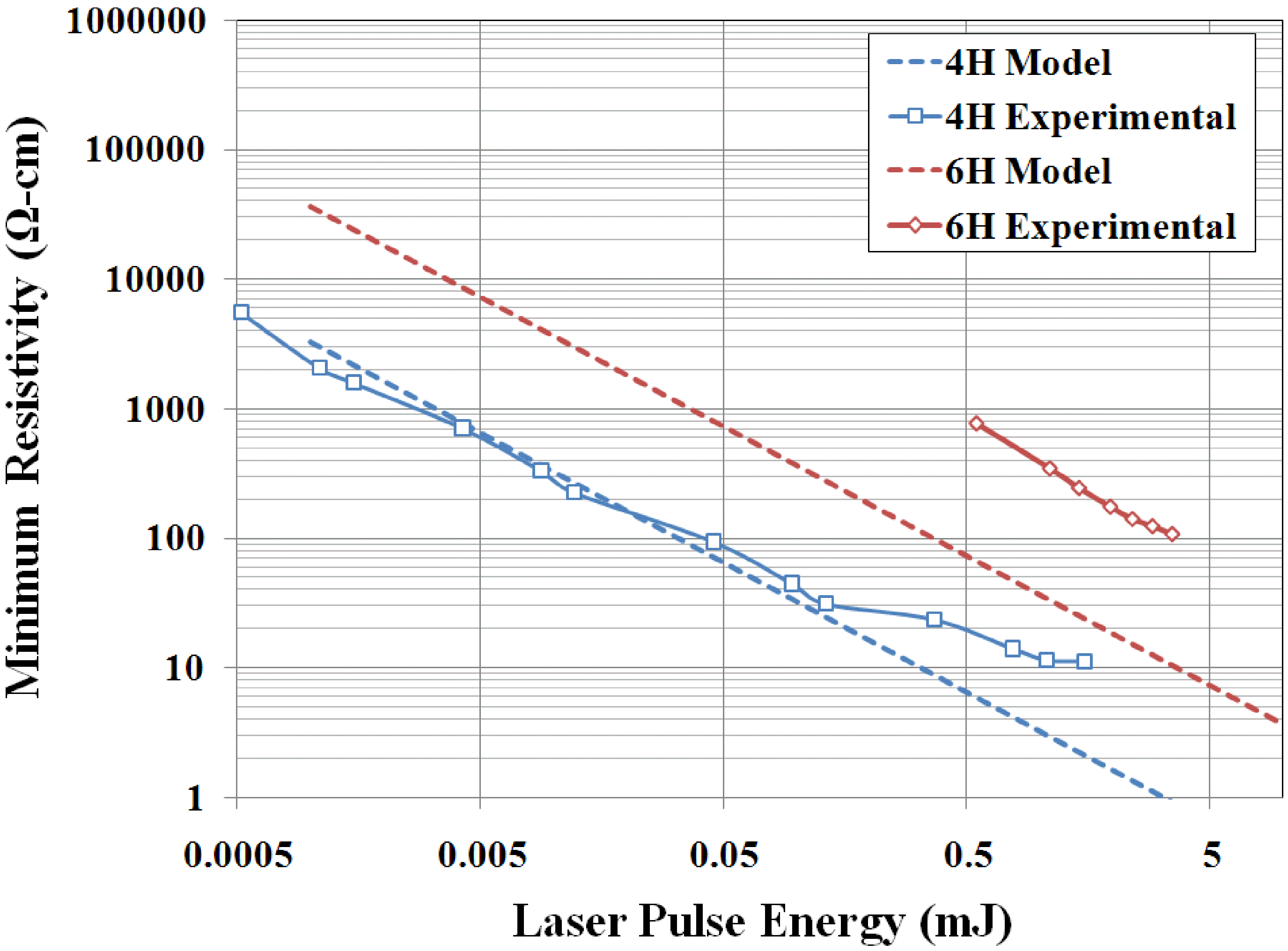
- Resistivity vs. Pulse Energy
  - 4H vertical switch and 6H lateral switch comparison

On State Resistance

<u>Experimental Data:</u>
HPSI 4H-SiC vertical switches

V-doped 6H-SiC lateral switches

Comparing resistivity to account for geometry differences



C. James, High Purity Semi-Insulating 4H-SiC as a Photoconductive Switch Material, PhD Dissertation, 2010.
C. Hettler, "Investigation and Evaluation of Vanadium-doped 6H-SiC Photoconductive Semiconductor Switches, 2009.

On State Resistance

- Moderate correlation between 4H model and experiment
- Poor correlation for 6H model and experiment

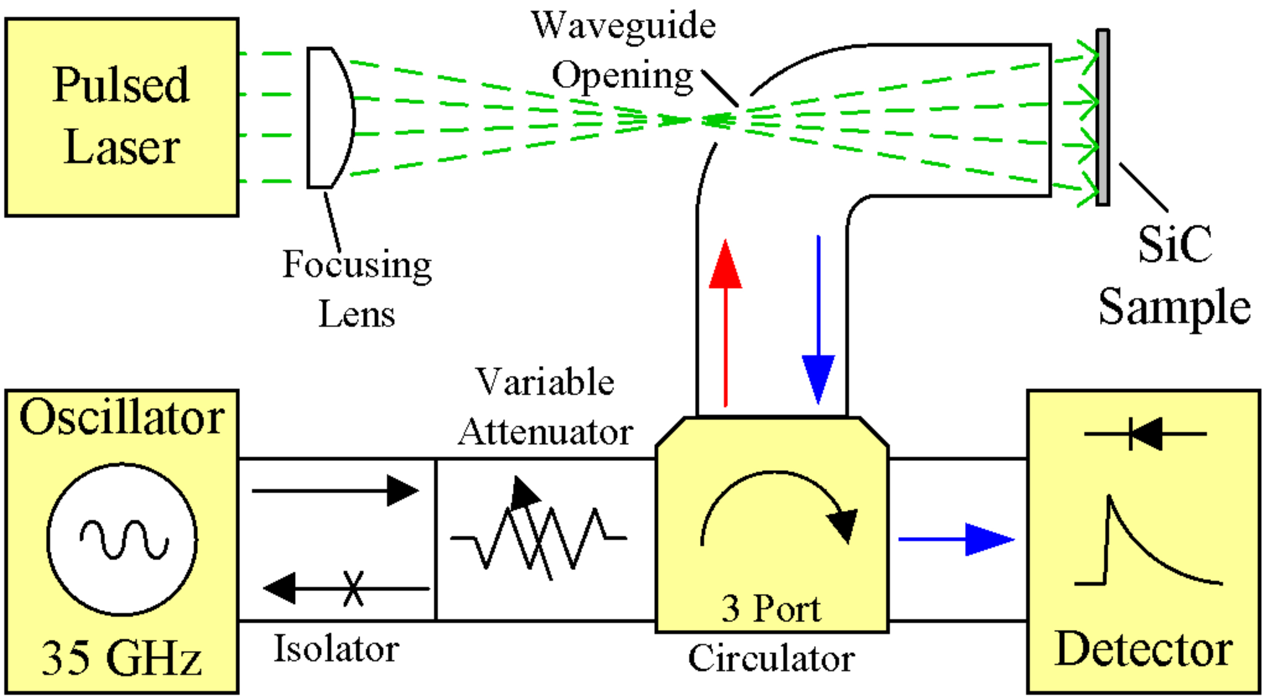
Which model parameter is incorrect?

$$R_{ON} \propto \frac{1}{\tau_r}$$

(Previous assumption: carrier recombination lifetime of 1 ns)

- Directly measure carrier recombination lifetime to improve model→Microwave Photoconductance Decay (MPCD)

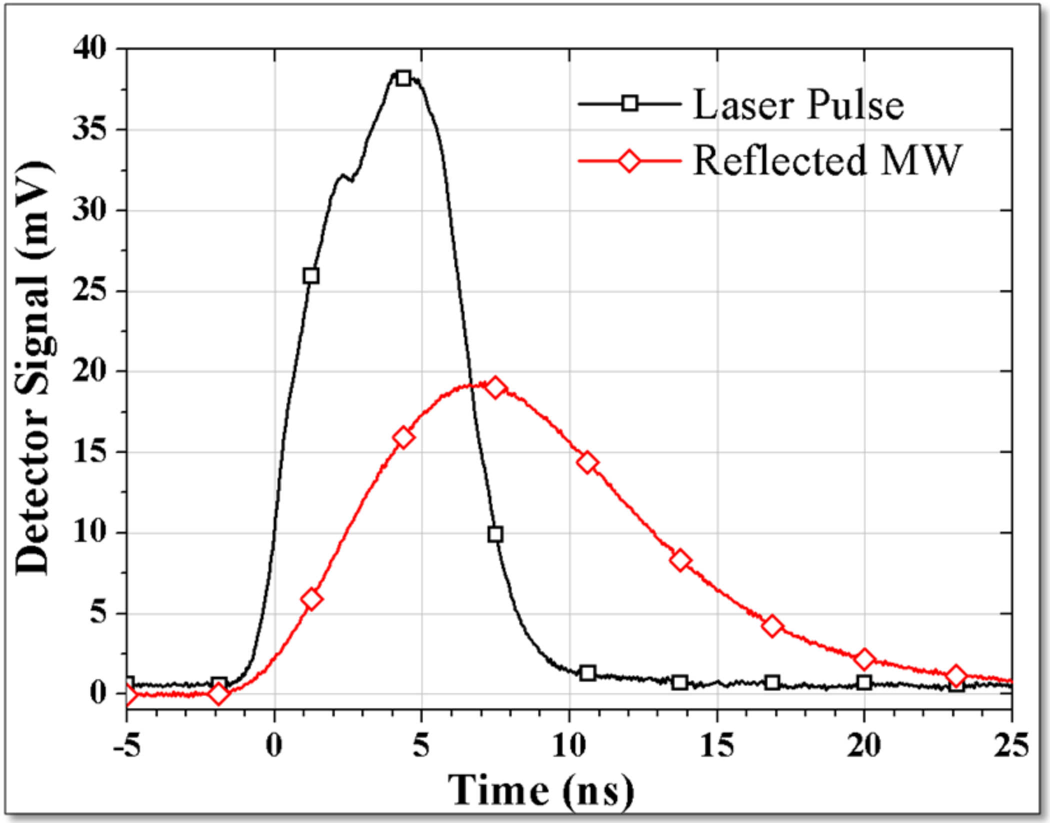
MWPCD Setup



- Laser illuminates sample, increasing conductivity
- CW incident microwaves reflected to detector
- Records transient conductivity of SiC sample

C. Hettler, C. James, J. Dickens, A. Neuber, “Carrier Lifetimes studies of semi-insulating silicon carbide for photoconductive switch applications, Power Modulator conference, 2010.

MPCD Experiment



Typical MPCD Result

- Photodiode records laser
- RF detector monitor reflected MW power

Detector voltage directly proportional to conductivity

Use MATLAB fit to find recombination lifetime with laser pulse as input

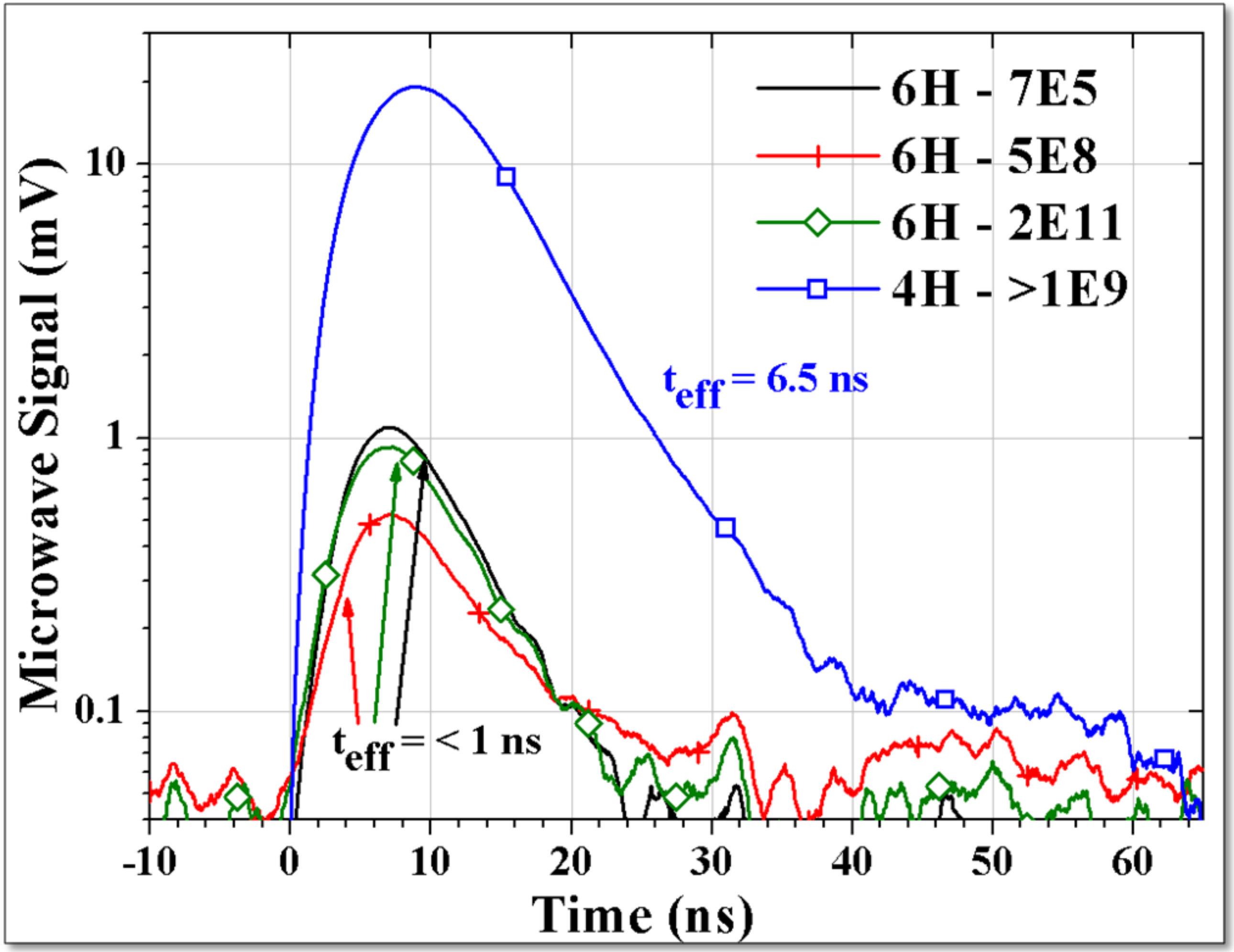
C. Hettler, C. James, J. Dickens, A. Neuber, “Carrier Lifetimes studies of semi-insulating silicon carbide for photoconductive switch applications, Power Modulator conference, 2010.

Above-Band MPCD Results

- 4 samples
- 355 nm
- 10 µJ/pulse

- 4H HP-SI
  - lifetime 6.5 ns
  - 20x conductive

- 6H V-doped
  - lifetime < 1ns



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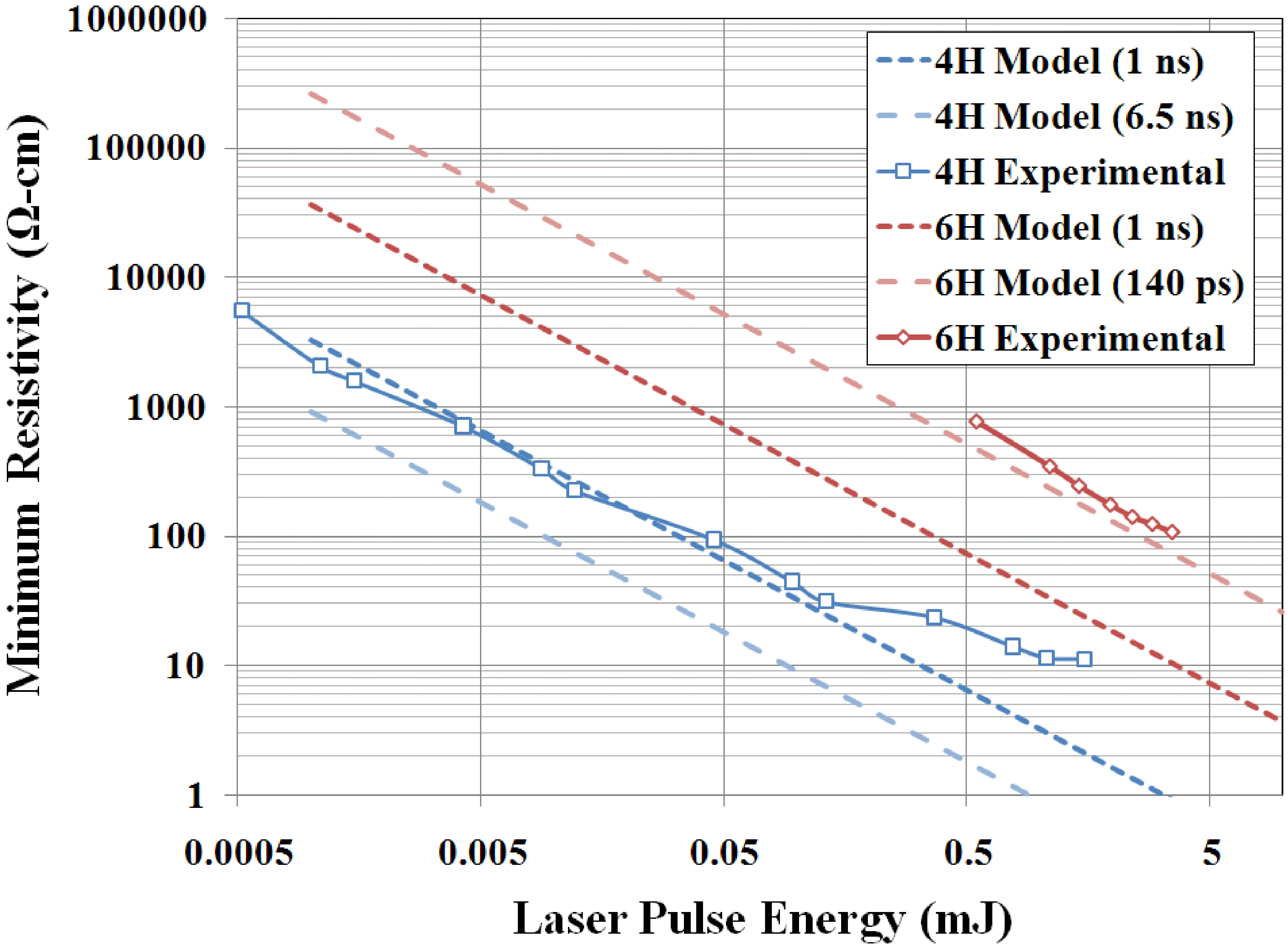
On State Resistance



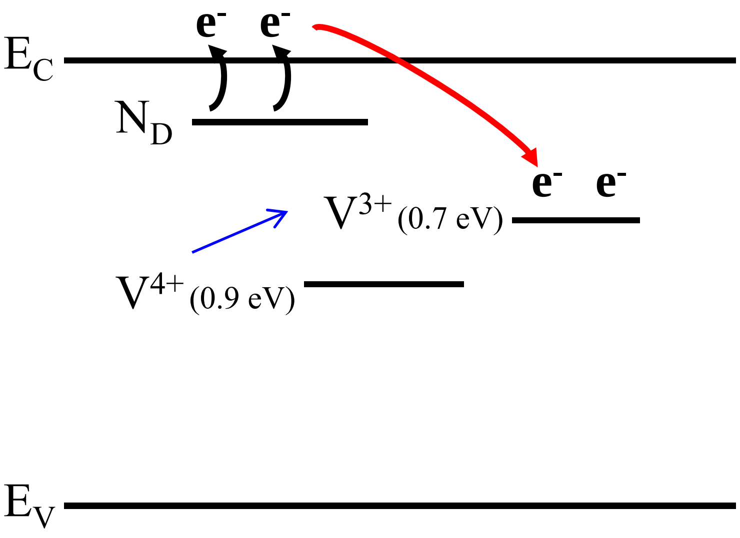
Carrier Lifetime Analysis

- Why the large difference in carrier lifetime?
  - Compensation methods – additional processes/doping used to form semi-insulating material

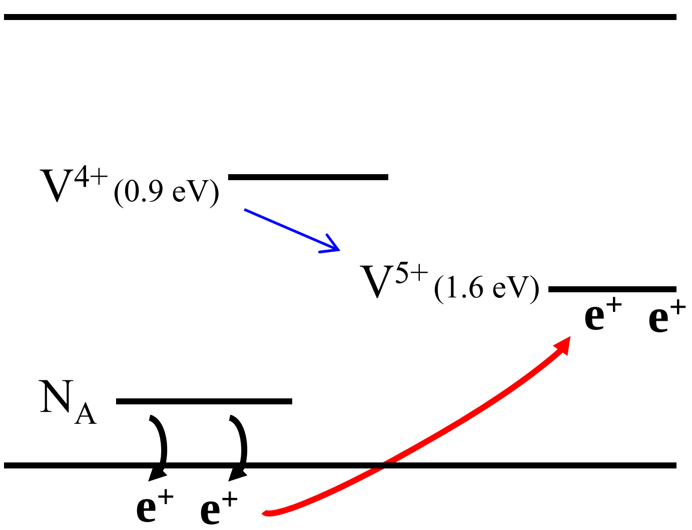
- Nitrogen (donor), Boron (acceptor) are uncontrollable background impurities which must be trapped (interband) to have semi-insulating material.
  - Vanadium Doped
  - Defect Compensation (High Purity Semi-insulating)

Semi-Insulating SiC

1. Doping with Vanadium
   - ➢ Amphoteric, multiple stable oxidation states (+3,+4,+5)



Shallow Donor (Nitrogen)
Deep Acceptor Compensation

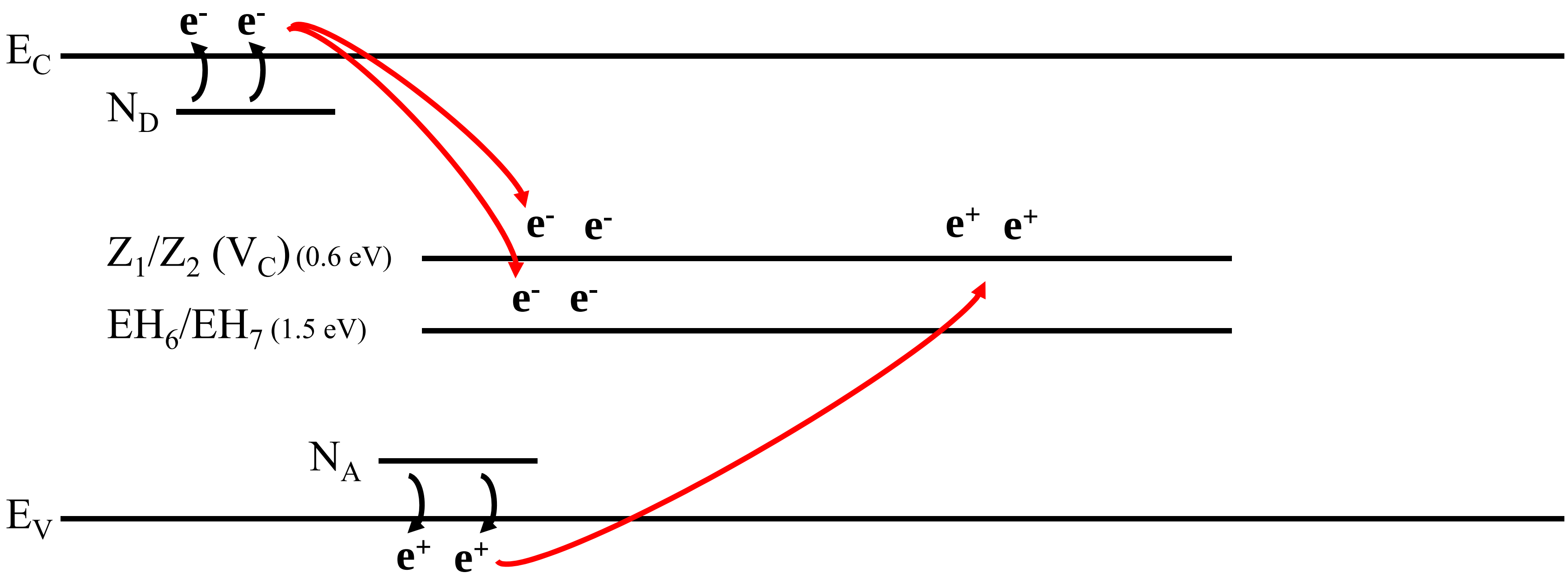


Shallow Acceptor (Boron)
Deep Donor Compensation

Semi-Insulating SiC

2. Native Defect Compensation (HPSI)

- Vacancies, anti-site pairs, divacancies



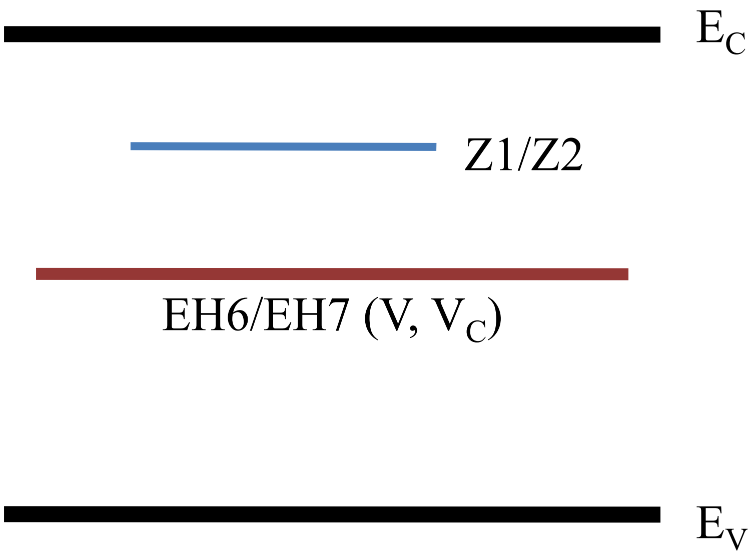
Controlled Process: Encouraging moderate defect growth by ratio Si/C > 1

Compensation Overview

1. Vanadium doping
   - Substitutional Compensation
   - Highly effective, stable → Large Capture cross sections
   - Resistivity: 10^{10}- 10^{15} Ω-cm
   - Short Carrier Lifetimes (< 200 ps)

2. Native Defect Compensation
   - Holes/Electrons in deep defects
   - Smaller capture cross sections, instable at $T > 2100$ K
   - Resistivity: 10^{8}- 10^{11} Ω-cm
   - Carrier Lifetimes (~7 ns)

HPSI Annealing Experiments



- Shallow traps
  - Decrease carrier lifetime as a SRH recombination center
  - Do not play major role in overall material resistivity

- Anneal 4H & 6H samples to reduce shallow trap levels
- 1800 ˚C for 120 minutes in Argon

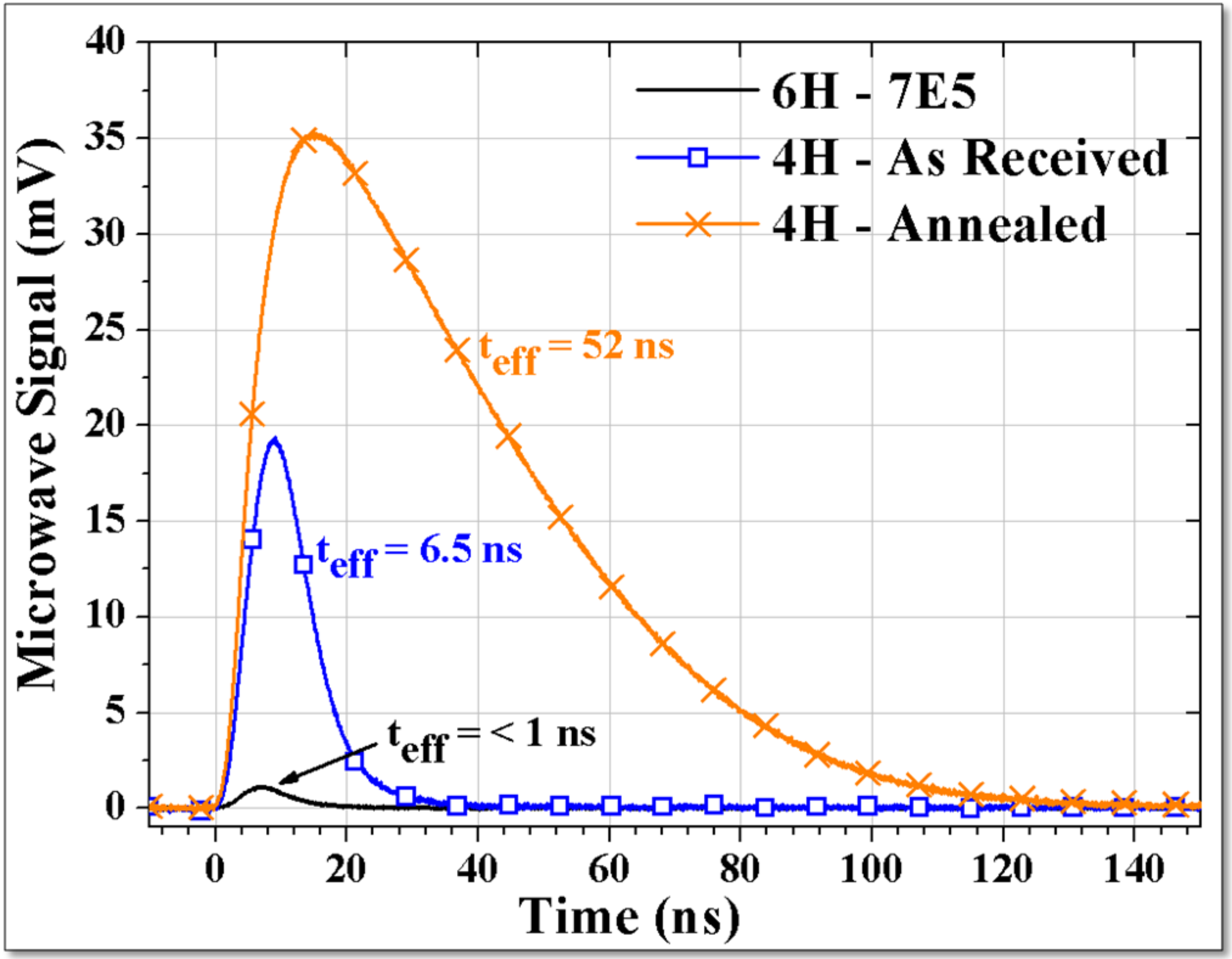
- No changes in 6H material
- 4H material, carrier lifetime increased

R. J. Kumar, et al, "Microwave photoconductivity decay characterization of high-purity 4H-SiC substrates," J. of App. Physics, vol. 102, 013704 pp. 1-8, July 2007.

Above-Band MPCD Comparison

- 355 nm
- 10 µJ /pulse

- 4H Annealed
  - 2x Conductivity
  - 8x Lifetime

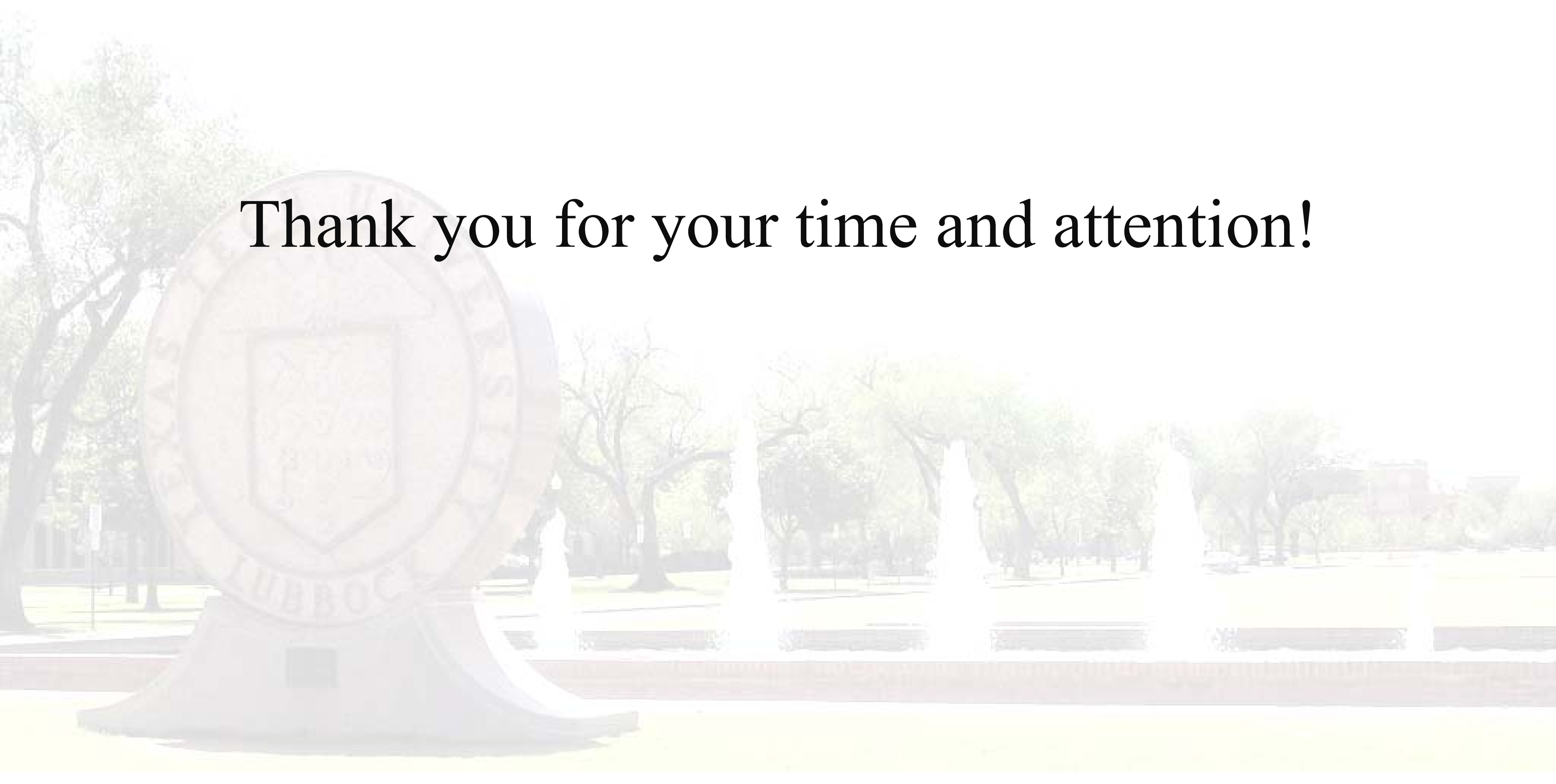


Summary

- Combination of Numerical and Experimental methods to investigate performance of semi-insulating SiC materials

- Breakdown Voltage:
  - 4H slightly higher breakdown voltage compared to 6H materials

- Illuminated Resistance
  - 4H material superior due to higher mobility
  - HPSI compensation superior due to longer carrier lifetimes
    - Demonstrated method to alter lifetime of HPSI materials



Thank you for your time and attention!