Project Objective
Development of a compact, high power photoconductive switch capable of operation at ~10 MHz at ~1-2 MW.

Accomplishments / Progress
• Experimental demonstration of high power switching single shot and burst rep-rate (26.4 MW single / 4.6 MW at 65 MHz burst)
• Continuing development and evaluation of alternative optical sources (gas discharge and solid state)
• Characterization of PCSS in previously untested parameter space
• Understanding of underlying physics pertinent to voltage blocking, device failure, and device efficiency
• Present / Future focus on PIN PCSS
Presentation Overview

• **Introduction / Overview**

• **Linear Bulk PCSS**
  – Blocking physics
  – Conduction physics
  – Performance
  – Failure Mechanisms
  – Limitations

• **PIN PCSS**
  – Fundamentally different than “linear bulk” PCSS
  – Fabrication
  – Challenges
  – Simulation Results
- Empirically found that by irradiating SiC, hold-off voltage could be increased significantly
- Irradiation known to add additional deep level traps to the material.
- Likely space charge limited currents


- Silvaco ATLAS Simulator
- Qualitatively matched trends of experimental data
- Trap energy sets the magnitude of the leakage current
- Trap density sets the hold-off voltage

- Incorrectly estimated magnitude of current
- Neglected multiple physics related to traps
  - Trap to band impact ionization
  - Band to trap impact ionization
  - Field dependent trap cross section
  - Field dependent capture trap capture coeff.
Custom 1D Simulation
- Steady State – constant current density
- Band to trap impact ionization
- Trap to band impact ionization
- Field dependent trapping and emission
- Trap assisted tunneling

Non-Irradiated:
*Trap 1: \( N_T = 4.5 \times 10^{13} \text{ cm}^{-3} \) \( E_T = 0.263 \text{ eV} \)
Trap 2: \( N_T = 6.5 \times 10^{14} \text{ cm}^{-3} \) \( E_T = 0.333 \text{ eV} \)
*Trap 3: \( N_T = 4.5 \times 10^{12} \text{ cm}^{-3} \) \( E_T = 0.383 \text{ eV} \)

Irradiated
Trap 1: \( N_T = 2.55 \times 10^{13} \text{ cm}^{-3} \) \( E_T = 1.07 \text{ eV} \)
Trap 2: \( N_T = 2.55 \times 10^{13} \text{ cm}^{-3} \) \( E_T = 1.09 \text{ eV} \)
Features of Bulk PCSS Model

- Drift-diffusion with self-consistent Poisson.
- 1D, time-dependent analysis. Electrons only, no holes included.
- Multiple (3) traps with different energies and densities below conduction band
- Trap assisted tunneling from cathode necessary to match low-field currents
- Field-dependent rates include processes: Poole-Frenkel, Barrier-lowering, Tunneling
- Trap to band impact ionization, Coulombic & repulsive trapping potentials included.
- Field-dependent emission $e_{ni}(E,t)$, capture $c_{ni}(E,t)$ & band-to-trap ionization $R_i(E,t)$:
  $$dn(x,t)/dt = e_{ni}(E,t)N_{Ti}^{-}(x,t) - c_{ni}(E,t)n(x,t)[N_{Ti}(x,t) - N_{Ti}^{-}(x,t)] + R_i(E,t)n(x,t) N_{Ti}^{-}(x,t)$$
- Trap to band impact ionization, and attractive trapping potentials included.

Electron emission processes:
- Poole-Frenkel
- Poole-Assisted Tunneling
- Direct Tunneling

Field dependencies
- $e_{ni}(E,t) = e_{ni0} \exp(a|E|)$
- $c_{ni}(E,t) = c_{ni0} [\exp(b|E|)-1]$  
- $R_i(E,t) = R_{i0} \exp(c|E|)$
Key Model Predictions

- Electric field dependence of rate coefficients necessary
- Trap-assisted electron tunneling injection responsible for low field currents
- Trap-to-band impact ionization important at high fields
- Hole injection from anode contact negligible → no bipolar transport

* Higher E-field towards anode → larger charge
  → more trap filling → repulsive barrier

* At higher current (hence higher E), trap-to-band ionization kicks in → further trap filling curtailed → knee in E-field
Linear Bulk PCSS Conduction

• Does the entire illuminated region contribute to conduction?
• What is the optimum wavelength of light to use to illuminate the PCSS?
• Does the PCSS photocurrent efficiency vary with optical fluence?
• Does “bleaching” occur?
Linear Bulk PCSS Conduction

\[ R \propto \frac{1}{E \left( \frac{1}{r} \right)} \]

- Emulates increasing // resistance
- Entire illuminated area contributes to conduction

Energy \((E) \propto \) Area
- Sylgard 184 Encapsulated PCSS (EFI epoxy degrades)
- Wavelength varied from 305 nm to 380 nm – 5 ns FWHM
- Constant Energy: 25 µJ (+/- 5%)
- Constant Area: 0.9 mm² (16 J / m²)

- Wavelengths < 350 nm optimal *
- Bimolecular / Auger recombination at lower wavelengths (higher density)
- Conclusions limited due to high on-state resistance of PCSS ~ 40-50 Ω
**Linear Bulk PCSS Conduction**

- Energy Density (J/m²)
  - $V_{ch} = 2 \text{ kV}$
  - $R_L = 50 \Omega$
- 2 Decades of previously untested parameter space
- Possible Causes:
  - Auger / Bimolecular
  - Collapsing E-Field
- Conclusions limited due to collapsing E-Field
**Linear Bulk PCSS Conduction**

*Sample Thickness: 490 µm*

**Graphs:***
- **Left Graph:**
  - Title: SiC Measured at 355 nm
  - X-axis: Energy Density (J/m^2)
  - Y-axis: Transmittance (%)
  - Data points showing increase in transmittance with energy density.

- **Right Graph:**
  - X-axis: Energy Density (J/m^2)
  - Y-axis: \(\alpha\) (cm\(^{-1}\))
  - Data points showing variation in \(\alpha\) with energy density.

**Diagram:***
- **OPO**
- **Aperture**
- **ND Filter**
- **Photodiode**
- **Energy Meter**
- **Sample at 15°**
- **ND Filter**

**Notes:**
- [3/4/2016]
- COLLABORATIVE RESEARCH ON NOVEL HIGH POWER SOURCES FOR AND PHYSICS OF IONOSPHERIC MODIFICATION
Radial PCSS

Rear-illuminated coaxial structure
- 12.7 mm x 12.7 mm area (1.62 cm²)
- 2.75 mm gap spacing
- Optimized for 355 nm (3x Nd:YAG)
- Blocked > 50 kV
- Switched 300 A at 65 MHz into 50 Ω (4.61 MW)
- Switched 938 A into 30 Ω load (26.39 MW)
- \( \text{di/dt} = 205 \text{ kA/µs (20/80) Rise Time: 1.3 ns (20/80)} \)
Linear Bulk PCSS Performance

**HV Blocking**

- Version 3
  - 0.81 mm Gap
  - 272 kV/cm

- Version 2
  - 0.81 mm Gap
  - 376 kV/cm

- Version 1
  - 1.63 mm Gap
  - 231 kV/cm

<table>
<thead>
<tr>
<th>Leakage Current (A)</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E-3</td>
<td></td>
</tr>
<tr>
<td>1E-4</td>
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<tr>
<td>1E-5</td>
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<td>1E-6</td>
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<td>1E-7</td>
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<td>1E-8</td>
<td></td>
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<td>1E-9</td>
<td></td>
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<td>1E-10</td>
<td></td>
</tr>
<tr>
<td>1E-11</td>
<td></td>
</tr>
<tr>
<td>1E-12</td>
<td></td>
</tr>
</tbody>
</table>

**MW Switching**

- Blocked fields up to 376 kV/cm with < 10 µA leakage
- Switched 1.6 MW into 50 Ω
- $di/dt$: 85kA/µs  Risetime: 1.49 ns (20/80)

Anode  | 4H-SiC  | Cathode

3/4/2016
Linear Bulk PCSS Failure Modes

Device Cross Sections

Version 1
4H-SiC

Anode

1.63 mm
1.83 mm

Cathode

Incident Light

360 µm

1 µm Au
300 nm Ni

150 nm n⁺ SiC

Version 2
4H-SiC

Anode

0.61 mm
0.81 mm

Cathode

5 µm Au
50 nm NiCr

150 nm n⁺ SiC

Version 3
4H-SiC

Anode

0.61 mm
0.81 mm

Cathode

5 µm Au
50 nm NiCr

1 µm n⁺ SiC

Cracks
Linear Bulk PCSS Failure Modes

Cracks observed near metal / SiC interface - Cause: transient high electric fields and high current densities.
• Device 3-1 tested with original test circuit (capacitor)
• Device 3-2 tested with modified test circuit (transmission line)
• Collapse the electric field before the end of the laser pulse
• Substantially less number of cracks, and cracks were smaller in size
2D Finite Difference Implementation

$$dx = dy = 2.5 \ \mu m \quad dt = 5 \ \text{fs}$$

$$R_{\text{Load}} = 50 \ \Omega \quad V_{\text{an}} = 1 \ \text{kV}$$
- Transient E-Field ~ 6x DC E-Field
- 2 Degradation Processes
  1) Joule Heating    2) Dielectric Failure
- E-fields + high current density leads to significant joule heating (~1000 °K)

- E-fields scaled to experimental voltage (10 kV $\rightarrow$ ~5 MV/cm) on the order of theoretical breakdown strength of SiC

Ideal assuming only photo-generated current - \(~100\times\) less than ideal
Ideal assuming no recombination - Contributing causes:
- \(~1\) ns recombination
- Collapsing electric field

\[ \mu \approx 25 \text{ cm}^2/\text{V s} \quad L_{\text{PCSS}} = 0.6 \text{ mm} \]

\[ E = 33 \text{ kV/cm} \]

\[ \text{time}(s) = \frac{L_{\text{PCSS}}(m)}{\mu \left(\frac{cm^2}{Vs}\right) E \frac{V}{m}} \]

\[ t \approx 70 \text{ ns} \quad \tau_r \approx 0.9 \text{ ns} \]
- Recombination lifetime decreases with increasing irradiation

\[
\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{SRH}_{\text{eff}}}} + \frac{1}{\tau_{\text{Aug}}} + \frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{surf}}}
\]

\[
\frac{1}{\tau_{\text{SRH}_{\text{eff}}}} = \frac{1}{\tau_{\text{SRH}_1}} + \frac{1}{\tau_{\text{SRH}_2}} + \frac{1}{\tau_{\text{SRH}_3}} + \ldots
\]

\[
\tau_{\text{SRH}_1} = \frac{1}{N_{\text{SRH}_1} \cdot \sigma_{\text{SRH}_1} \cdot v_{\text{Th}}}
\]

\(N_{\text{SRH}_1}\): density (cm\(^{-3}\)) \(\sigma\): capture cross sect. (cm\(^2\)) \(v_{\text{Th}}\): thermal velocity (cm/s)

\(\tau_r \propto N_T\) - Traps near middle of bandgap most effective recombination centers

- Need deep traps for hold-off

- Traps reduce recombination lifetime \(\rightarrow\) decrease efficiency
- High voltage, reverse biased PIN photodiode
- Fundamentally different blocking physics
  - Junction based vs. space charge limited currents
  - Decouples recombination lifetime and voltage hold-off
- Successfully demonstrated previously with Si and GaAs
- SiC technology sufficiently mature to create device


PIN PCSS Operation

- Reverse biased PIN structure
- Photons absorbed in depletion region (minimize absorption in other regions) $(1-2 \alpha^{-1})$
- Electron/hole pairs generated by absorption of photons
  - Separated by electric field
  - Cause current in external circuit if electrodes reached
- Efficiencies near 100%

$$\eta = \frac{\text{Carriers Extracted}}{\text{Incident Photons}}$$
PIN PCSS Fabrication

- **N⁺ SiC substrate**
  - commercially available from Cree Inc.

- **N⁻ layer grown epitaxially**
  - commercial service offered by Cree Inc.

- **P⁺ regions - Ion implantation**
  - commercially available service
  - used commercially and reported extensively in literature

- **Electrode deposition**
  - Thermal evaporation / sputtering / electro-plating

- **Commercially available service offered by Cree Inc.**
  - N⁺ SiC substrate
  - N⁻ SiC
  - N⁻ SiC (epitaxial growth)
  - P⁺ regions (ion implantation)
  - Electrode deposition (thermal evaporation, sputtering, electro-plating)
PIN PCSS Fabrication

**SiC**
- Deposit SiO₂
- Pattern w/ Resist
- Etch SiO₂ w/ HF
- Deposit Nickel
- Pattern w/ Resist
- Liftoff Resist
- Aluminum Implant
- Etch mask w/ HF

SiO₂: light blue  P⁺SiC: pink  Photoresist: red  Ni: gray
PIN PCSS Fabrication

-Aluminum Implant Schedule
[Dose (cm\(^{-2}\)) / Energy (keV)]

<table>
<thead>
<tr>
<th>Dose (cm(^{-2}))</th>
<th>Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 x 10(^{14})</td>
<td>380</td>
</tr>
<tr>
<td>2.0 x 10(^{14})</td>
<td>280</td>
</tr>
<tr>
<td>1.5 x 10(^{14})</td>
<td>200</td>
</tr>
<tr>
<td>1.0 x 10(^{14})</td>
<td>120</td>
</tr>
<tr>
<td>8.0 x 10(^{13})</td>
<td>80</td>
</tr>
<tr>
<td>6.0 x 10(^{13})</td>
<td>40</td>
</tr>
<tr>
<td>4.0 x 10(^{13})</td>
<td>20</td>
</tr>
<tr>
<td>2.0 x 10(^{13})</td>
<td>10</td>
</tr>
<tr>
<td>1.0 x 10(^{13})</td>
<td>2.5</td>
</tr>
</tbody>
</table>

ION RANGES

- Ion Range = 2436 A
- Skewness = 0.3105
- Straggles = 546 A
- Kurtosis = 2.7456

Net Doping (/cm\(^3\))

Doping Concentration (/cm\(^3\)) vs Depth (um)
PIN PCSS Challenges: Junction Termination

- Voltage hold-off reduction due to junction curvature
- Minimized with field rings


**Simulation Results**

**P⁺ SiC**: 1 µm : $1 \times 10^{19} \text{ cm}^{-3}$

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Doping Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>N⁻ SiC</td>
<td>50 µm</td>
<td>$1 \times 10^{14} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>N⁺ SiC</td>
<td>25 µm</td>
<td>$1 \times 10^{19} \text{ cm}^{-3}$</td>
</tr>
</tbody>
</table>

- **Expected Breakdown**: 9 kV
- **Simulated Breakdown**: 9.4 kV

**Graphs**

- 50 µm, $10^{14} \text{ cm}^{-3}$
- Expected Breakdown: 9 kV
- Simulated Breakdown: 9.4 kV

TCAD – SILVACO - ATLAS

Simulation Results

P⁺ SiC : 1 µm : 1x10¹⁹ cm⁻³

N⁻ SiC : 50 µm : 1x10¹⁴ cm⁻³

N⁺ SiC : 25 µm : 1x10¹⁹ cm⁻³

- 50 µm, 10¹⁴ cm⁻³
- Parallel Breakdown : 9.4 kV
- Realistic Structure: 1.86 kV
- 5x reduction in hold-off
Projected Performance

Spectra Physics Quasar
- 355 nm
- UV Fiber Laser + Power Amp + harmonic generator
- CW operation at 0Hz – 3.5 MHz
- 2 ns – 100 ns FWHM
- Peak Power (optical): 6.5 kW
- Power consumption (electrical): 1.9 kW

Maximum Current: \[
\frac{11.4 \ \mu J}{3.49 \ eV} \ \frac{q}{40 \ ns} \ QE = 74.5 \ A
\]
- Assuming ~90 % photon conversion
Projected Performance

- **RF Generation / Antenna Direct Drive**
  - 95 dBW (Ionosphere Mod) $\rightarrow$ 20 kV / 500 A $\rightarrow$ 24 lasers
  - 80 dBW (ELF) $\rightarrow$ 3.35 kV / 83.9 A $\rightarrow$ 3 lasers (repetition frequency)
  - 70 dBW (ELF) $\rightarrow$ 1.06 kV / 26.55 A $\rightarrow$ 1 laser (modified)

- **IOT Grid Modulation**
  - Drive $\sim$ 40pF // 10 kΩ
  - 12 W Average / 3 ns
  - Small fiber laser
Conclusion

• Linear Bulk PCSS (years 1-3)
  – Thorough understanding of blocking and conduction processes
  – Ideal for high power, low jitter closing and opening switch applications
    single shot and burst rep-rate
    • > 26 MW Single shot
    • > 4 MW at 65 MHz burst
  – Understanding of damage mechanisms
  – Limited presently by photocurrent efficiency (~250 kW optical power necessary for ~1 Ω)

• PIN PCSS (focus of years 4-5)
  – Decouples recombination lifetime and blocking voltage
  – Clear path forward in development based on current technology
  – Orders of magnitude increase in photocurrent efficiency expected
    (10-25 kW optical power necessary)
Thank You
Concludes PCSS Portion
-Objective: Investigate enhanced optical power output from a commercial UV LED under pulsed conditions (LZ4-00U610 - 365 nm – Gen 1 – 630 mW DC).

-LED output spectrum closely matches optimum wavelength for un-thinned radial PCSS

-Investigated optical power, wavelength, and forward voltage over varying pulse-width, and forward current
### Alternative Light Sources – UV LED

<table>
<thead>
<tr>
<th>Property (at 0.5 A)</th>
<th>DC</th>
<th>Pulsed (10 µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Output</td>
<td>0.55 W</td>
<td>1.0 W</td>
</tr>
<tr>
<td>Forward Voltage</td>
<td>16.5 V</td>
<td>17 V</td>
</tr>
<tr>
<td>Optical Efficiency</td>
<td>6.75 %</td>
<td>11.5 %</td>
</tr>
</tbody>
</table>

![Graph showing Optical Power (W) vs. Current (W) and Center Wavelength (nm) vs. Time (s)]

- **Optical Power (W) vs. Current (W):**
  - **DC**
  - **Pulsed (10 µs)**

- **Center Wavelength (nm) vs. Time (s):**
  - **FWHM**

![Graph showing Optical Efficiency (%) vs. Current (W)]

- **Optical Efficiency (%):**
  - **DC**
  - **Pulsed (10 µs)**

-Achieved ≈ 6x peak pulsed optical power (4.04 W) relative to peak DC optical power (0.658 W).
-Successfully switched PCSS into a high impedance load.
Thank You
PIN PCSS Fabrication

• P+ Ion implantation and thermal activation

• Ohmic contacts to P+ SiC

• Ohmic contacts to N+ SiC