Project Objectives

Development of a compact, high voltage (10-25 kV) photoconductive switch capable of operation at ~5-10 MHz freq, ~1-2 MW power

Background

- Switch geometry
- Material parameters and modification
  - Electron irradiation
  - Annealing
  - Laser enhanced diffusion
- Triggering Wavelengths
- Other switch design parameters

Demonstrated Performance

- Blocking of DC electric fields up to 705 kV/cm
- Maximum switched current of 1 kA at 30 kV
- Switched 250 A at 20 kV at a burst repetition frequency of 65 MHz
What is a PCSS?

Optically controlled semiconductor switch ($G\Omega \rightarrow \Omega$ ns)
Linear mode (1 photon = 1EHP) and avalanche mode (carrier multiplication)

Advantages
• Compact geometry
• Optical isolation
• Highly controllable
  – Jitter, timing

Applications
• Laser systems
• Particle accelerators
• Trigger generators
• Directed energy sys.
## Why SiC?

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>GaAs</th>
<th>GaN</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap (eV)</td>
<td>1.11</td>
<td>1.42</td>
<td>3.39</td>
<td>3.23</td>
</tr>
<tr>
<td>Breakdown Field ($10^6 \frac{V}{cm}$)</td>
<td>0.3</td>
<td>0.4</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Electron</td>
<td>Hole Mobility ($\frac{cm^2}{V \cdot s}$)</td>
<td>1400</td>
<td>8500</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal Conductivity ($\frac{W}{cm \cdot ^\circ C}$)</td>
<td>1.3</td>
<td>0.455</td>
<td>1.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Band Structure</td>
<td>Indirect</td>
<td>Direct</td>
<td>Direct</td>
<td>Indirect</td>
</tr>
</tbody>
</table>

### High breakdown field
- 10x blocking capability of Si
- Shorter gap distance → lower $R_{on}$

### High thermal conductivity
- High current switching
- Low Defect Material Available
- Commercial 6” wafers
• Growth impurities unavoidable (B, Al, N, P) 
  \(N_D\) and \(N_A\) both \(\sim 10^{15}-10^{16} \text{ cm}^{-3}\)
• Add traps \((N_T > N_D-N_A)\)

• Vanadium Compensation
  • Amphoteric defect (donor or acceptor)
  • Added during growth
  • Max density: \(3 \cdot 10^{17} \text{ cm}^{-3}\) (solubility limit)
  • Unable to be altered after growth

• High Purity Semi-Insulating (HPSI)
  • Intentional introduction of crystal defects during growth process
  • Defect (trap) concentration able to be altered after growth through various processes (quenching, irradiation, annealing)
Pros:
- Insensitive to triggering $\lambda$ ($\lambda > E_g$)
- Mechanical thinning not necessary for operation at common laser $\lambda$
- Insensitive to micropipes
- Gap width / voltage hold-off variable

Cons:
- High current densities near semiconductor/metal interface

Pros:
- Uniform current densities

Cons:
- Semi-transparent contacts
- Substrate thickness $\rightarrow \lambda$ dependent
- Susceptible to micropipes
Voltage Hold-off

Critical Parameters

- Gap Distance
- Trap Density
- Trap Energy

Traps reduce mobility, limit current
\( N_T > n_c + \Delta n_{\text{inj}} \)

![Graph showing current vs. voltage for different trap energies](image1)

![Graph showing current vs. voltage for different trap densities](image2)

Unoccupied traps, \( p_{\text{tr}} \):
- 1x10^{12} cm^{-3}
- 1x10^{11} cm^{-3}
- 1x10^{10} cm^{-3}
• Trap Filling
  \[ N_T = (N_D - N_A) + p_{t,0} \]
  where \( p_{t,0} \) is the unoccupied trap conc.
• First unoccupied trap sets \( F_0 \)
• \( E_{\text{Fermi}} \) increases once trap is filled

\[
I_{\text{ohmic}} = q \cdot n_0 \cdot \mu \cdot \frac{V_{ap}}{l} \cdot A \quad \quad \quad \quad V_{TFL} = \frac{q \cdot l^2}{2 \cdot \varepsilon} \cdot p_{t,0}
\]

\[
I_{\text{TFSL}} = \frac{9}{8} \cdot \varepsilon \cdot \mu \cdot \frac{V_{ap}^2}{l^3} \cdot A \quad \quad \quad \quad p_{t,0} = \frac{N_T}{g} \cdot \exp \left( \frac{E_T - F_0}{k_B \cdot T} \right)
\]

\( E_T \) & \( F_0 \) referenced from \( E_v \)

\( F_0 \): fermi level \quad \( l \): gap distance \quad V_{ap} \): voltage \quad q: charge
\( \varepsilon \): permittivity \quad g: degeneracy \quad k_B: \text{Boltzmann} \quad T: \text{temperature}

<table>
<thead>
<tr>
<th>Trap</th>
<th>Energy ((E_C - E_T)) (eV)</th>
<th>Silvaco Conc. ((N_D - N_A) + 1.6 \cdot 10^{13})</th>
<th>Calculated Conc. (1.4 \cdot 10^{13})</th>
<th>Likely Trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap 1</td>
<td>1.17</td>
<td>(1.6 \cdot 10^{13})</td>
<td>(1.4 \cdot 10^{13})</td>
<td>EH5</td>
</tr>
<tr>
<td>Trap 2</td>
<td>0.65</td>
<td>(1.6 \cdot 10^{13})</td>
<td>--</td>
<td>Z_{1/2}</td>
</tr>
</tbody>
</table>

\( E_T \) & \( F_0 \) referenced from \( E_v \)
Recombination Lifetime - Efficiency

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

- Dominated by shortest lifetime
- SiC is indirect → Radiative negligible
- Auger requires \( n_{\text{carrier}} > \sim 1 \times 10^{18} \text{ cm}^{-3} \) → minimal
- Recombination dominated by Shockley-Read-Hall (SRH) recombination

\[ \frac{1}{\tau_{\text{SRH eff}}} = \frac{1}{\tau_{\text{SRH 1}}} + \frac{1}{\tau_{\text{SRH 2}}} + \frac{1}{\tau_{\text{SRH 3}}} + \ldots \]

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

\( N_{\text{SRH 1}} \): density (cm\(^{-3}\))  \( \sigma \): capture cross sect. (cm\(^2\))  \( v_{\text{Th}} \): thermal velocity (cm/s)

100 kW, 355 nm input

![Graph showing resistance over time with different lifetimes](image)
Design Parameters and Trade-offs

\[ R_{on} \propto \frac{L^2}{\tau_{eff}} \]

- Minimize \( L \): Introduction of traps allows for minimization of \( L \)
  - Only deeper traps contribute to voltage blocking

- Introduction of traps decreases recombination lifetime
  - All traps contribute to reduction of recombination lifetime
  - Especially traps with larger capture cross sections

![Various Trap Energy Levels](image)
Means of Increasing Voltage Hold-Off

Electron Beam Irradiation
- Energy: 1 MeV
- Fluences: $4.8 \cdot 10^{15}$ cm$^{-2}$ to $2 \cdot 10^{18}$ cm$^{-2}$
- 3.175 mm x 3.175 mm x 0.361 mm
- $1 \cdot 10^{18}$ cm$^{-2}$ @ 1 MeV
- 7x increase after irradiation

![Pre Irradiation](image1)
![Post Irradiation](image2)
**Quenching**

- Heat sample to 1800 C
- Control rate of cooling
  - -10 C / min → Eliminates traps
  - -100 C / min → Introduces traps
- 2x improvement increase in trap filled voltage
- 2x decrease in carrier lifetime (5 ns → 2-3 ns)

![Graph showing current vs voltage for Cree Quenched and Cree Unannealed samples](image1)

![Graph showing detector response time for different cooling rates](image2)

\[\tau_{r} = \begin{cases} 13 \text{ ns} \\
5 \text{ ns} \\
2 \text{ ns} \end{cases} \]
Current State – PCSS Performance

Radial Lateral Switch
- 4 μA at 50 kV
- 1 kA at 30 kV into 30 Ω
- 250 A at 20 kV at 65 MHz burst
- Requires mechanical thinning for operation at 355 nm due to back-side illumination
- \( 5.56 \cdot 10^{-6} \text{ A} \cdot \mu \text{J}^{-1} \text{V}^{-1} \)

*In-Line Lateral Switch
- 200 nA leakage at 10 kV
- 182 A at 10 kV into 50 Ω
- \( 1.071 \cdot 10^{-5} \text{ A} \cdot \mu \text{J}^{-1} \cdot \text{V}^{-1} \)
- Does not require mechanical thinning for operation at 355 nm
Challenges

**Efficiency**

- **1.071 \times 10^{-5} \text{ A} \cdot \mu\text{J}^{-1} \cdot \text{V}^{-1} 170 \text{ kW optical power (for } \sim 1 \text{ Ohm } R_{on})**
  - Contact resistance
  - *Shallow defects*
  - Surface Recombination

- Parallel multiple devices → allow for higher $R_{on}$ and lower optical power

**Lifetime**

- Current density at metal/semiconductor interface
- Space charge effects

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![Graph showing minimum on-state resistance vs pulse energy](image)

![Image showing cracks and anode/cathode with 200 µm scale](image)
Efficiency

- Goal – Eliminate/reduce defects not contributing to voltage hold-off and defects with large capture cross sections
  - Annealing, Implantation
- PCSSs fabricated on samples with epi demonstrated means of shifting \( \tau \) vs leakage-current curve
  - Epi layer grown at \( \sim 1500 \) C

[Graph showing 1 \( \mu \)A crossover point vs bulk lifetime]

[Graph showing various trap energy levels]
Efficiency – Defect Identification

• Substantial literature regarding defects in doped 4H-SiC, little regarding HPSI 4H-SiC
  – Limited due to range of exp. data
  – Limited by reliability of Silvaco

• To date – defects have been identified primarily through fitting experimental IV curves with Silvaco

  Thermally Stimulated Current (TSC)
  – Chill to ~70 K → measure current while heating at controlled rate
  – Not consistent with Silvaco

  Solutions
  – Extend experimental data and continue to fit with Silvaco
  – Develop means of directly measuring characteristics of defects

<table>
<thead>
<tr>
<th>PCSS</th>
<th>ID</th>
<th>Silvaco Trap Energy (eV)</th>
<th>Silvaco Conc. (cm⁻³)</th>
<th>TSC Trap Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Received</td>
<td>Trap 1</td>
<td>1.19</td>
<td>(N_D-N_A) + 1.6·10¹³</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Trap 2</td>
<td>0.65</td>
<td>&gt;1.6·10¹³</td>
<td>0.66</td>
</tr>
<tr>
<td>Annealed 1·10¹⁸ cm⁻³</td>
<td>Trap 1</td>
<td>1.3</td>
<td>(N_D-N_A) + 3.6·10¹³</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Trap 2</td>
<td>1.01</td>
<td>2.7·10¹³</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Trap 3</td>
<td>0.81</td>
<td>&gt;3.0·10¹³</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Extend Experimental Data

• IV characteristics at higher voltages and currents correspond with shallower traps
  → Extend IV data to fit with Silvaco

• Custom HV-curve tracer used for IV characterization
  – 0.3 V to 45 kV
  – 9 pA to 4 mA (100 fA resolution)
  – Limit: DC power dissipation in PCSS (sweeps take ~2 min)

• Rapid IV System
  – Rapidly apply voltage and measure current decay
  → Limits time of power dissipation in PCSS to ~ 5 s
  – Fit with Silvaco
Rapid IV System

- Early Results
  - DC measurements align with HV curve tracer
  - Transient current much higher than DC data

![Rapid IV Discharge Graph](graph.png)

![Circuit Diagram](circuit.png)
Rapid IV System Cont.

- Transient trap filling
  - Initial spike in current followed by relaxation to DC leakage current
Three lateral PCSSs fabricated
• F1 : ~50 nm subcontact doping
• F2 : 1 μm subcontact doping
• F3 : 1 μm subcontact doping
Virtually identical contact pattern
• F1 : Cracks visible in < 50 shots at 2 kV into 52 Ω (~35 A)
• F2 & F3 no cracks after ~ 50 shots at 2 kV into 52 Ω (~35 A)
• F2 cracks visible after 3 shots at 10 kV into 52 Ω (~200 A)
• F3 no cracks visible after > 150 shots at 10 kV into 1.2 kΩ (~8 A)

Damage occurs preferentially on cathode

AFM and SEM analysis to be conducted on a failed device in near future
Device Lifetime – Space Charge/Field

- Tested PCSS F3 with modified test circuit
- Collapse electric field before end of laser pulse
Device Lifetime Cont.

Transmission Line Results

• 2 kV – 16 kV voltage sweep in 2 kV steps (1 kV – 8 kV effective) into 52 Ω load
• > 100 shots at 16 kV (8 kV effective) into a 52 Ω load
• Substantially less number of cracks, and cracks were smaller in size

Lifetime Conclusions

• Cracking appears to be related to both current density, and electric field during turn-off.
Future Work – GaN Sub-contact Layer

  - 0.148 A·μJ⁻¹·V⁻¹ at 900 V, $R_{on} = 62.5 \, \Omega$ and 0.06 uJ (1.073 x 10¹¹ photons)
  - Substantial performance difference between wet and dry etching methods
  - Elimination of cracking of bulk material
  - 0.067 A·μJ⁻¹·V⁻¹ at 4.5 kV
  - Passivation improved voltage hold-off
  - Photocurrent saturation > 2 µJ
- TTU Lateral
  - 1.071 x 10⁻⁵ A·μJ⁻¹·V⁻¹ at 10 kV, $R_{on}$~1 Ω and 1.7 mJ (3 x 10¹⁵ photons)

Possible reasons contributing to increased efficiency and crack reduction
- Lower carrier density
- 2D electron gas formed at SiC/GaN interface
- Higher hole mobility in GaN (200 cm²V⁻¹s⁻¹ vs 120 cm²V⁻¹s⁻¹)
Future Work
Current Density and “Turn Off”

- Previous investigation was not able to directly observe/compare development of cracks with capacitor source and transmission line source
- Plan to construct several devices and document development of cracks until failure
- Learn at which current densities the cracks begin to form
- Confirm “turn-off” plays a significant role in crack formation
Future Work – Defect Characterization

Photoemission Spectroscopy

• Chill to cryogenic temperatures
• Fill traps and then excite traps
• Measure emitted spectrum as electrons relax to trap states

• Defect Energy levels: 0.05 eV - 1.6 eV (0.5 µm - 20 µm)
• Goal: Find defect energy level and density
**Project Objectives**

Development of a compact, high voltage (10-25 kV) photoconductive switch capable of operation at ~5.. 10 MHz freq, ~1-2 MW power.

**Demonstrated Performance**

- Blocking of DC electric fields up to 700 kV/cm
- Maximum switched current of 1 kA at 30 kV
- Switched 250 A at 20 kV at a burst repetition frequency of 65 MHz

**Future Plans**

- Characterize / Eliminate defects
- Determine switch failure modes
- Increase switch efficiency
- Evaluate pulsed light sources (e.g. XeF MD, pulsed LEDs)
- Improve switch model parameters