Source and Antenna Development

**Highly repetitive light sources**
- Driver for PCSS
- Modulated UV narrowband light source with high power (~ 100 W) at rf frequencies

**Challenges**
- Optimize tradeoff between antenna efficiency/size/tunability
- Improve PCSS photonic efficiency
- Increase output power of light source

**PCSS – Photoconductive Semiconductor Switching**
- Achieved 700 kV/cm switching field
- Demonstrated repetition rates of up to 65 MHz at 20 kV switching amplitude
- Direct rf drive approach

**ESA – Electrically Small Antenna** to interface with UMD 50 Ohm impedance rf source.
- Factor of 5 to 10 smaller than dipole
- Frequency tunability demonstrated

**Direct Drive Concept**

**1 MHz light pulse train**

**PCSS die for size comparison**
Photoconductive Solid State Switches

Radial PCSS
Photoconductive Solid State Switch
(50 kV device)

20 kV 65 MHz burst mode switching into a 52 Ω load
(6 MW peak electrical power)

400 MHz RF waveform (laser modulated)

Laser signal
MHz Repetitive UV/VUV Light Source

Experimental Conditions
- Ar:H₂ (99.7:0.3%), 50 Torr
- Microhollow cathode discharge (MHCD)

Results
- Ar:H₂ Lyman-α can be achieved under very high input power
  - For 80 ns, pulses at 1 MHz
    - 3.4 W/42.8 W (avg/peak) VUV power
    - 0.63 % efficiency
  - For 50 ns pulses at 100 kHz
    - 310 mW/62 W (avg/peak) VUV power
    - 1.1% efficiency
- Overall 2 to 3 orders of magnitude higher instantaneous power over DC case.
- About 30 x increased efficiency

Tunable Electrically Small Antenna

Scaled to 10 MHz:
CST simulated peak power capabilities:
- 20 to 30 kV/cm limit (assumed dielectric strength of air)
  - ~ 2.5 MW max power limited by field in capacitive region
  - Power limit extends with use of dielectric

Experimentally demonstrated tunability via progressive insertion of dielectric slab.
(ESA antenna size: ~ 1/5th in size compared to dipole)
Project Objective
Development of a compact, high voltage (10-25 kV) photoconductive switch capable of operation at ~10 MHz at ~1-2 MW.

Accomplishments
- Demonstrated switching of 26.39 MW single shot
- Demonstrated 4.61 MW switching at 65 MHz burst
- 3x Increase in photocurrent efficiency
- Development and evaluation of alternative optical sources
- Publication of four peer-reviewed journal papers and seven conference papers.
PCSS Geometry

Lateral

- Relatively insensitive to wavelength

Vertical

- Very sensitive to wavelength
Scaling of Trap Parameters and Voltage Hold-Off

Space charge limited currents
- Trap
- Trap Energy (sets current)
- Trap Density (sets voltage)

Trap Limited Current:
\[ N_T > n_c + \Delta n_{\text{injected}} \]
Scaling of Trap Parameters and Voltage Hold-Off – Electron Irradiation

**Electron Irradiation**

- Energy: 1 MeV
- Si and C atom displaced from normal lattice site
- Additional defects (traps) added (EH 6/7 & Z 1/2)

**Graph:**

- X-axis: 1 MeV Electron Fluence (cm⁻²)
- Y-axis: 1 μA Crossover Voltage (kV)
- Legend:
  - No irradiation
  - 5.8x10¹⁵
  - 2.5x10¹⁶
  - 1.2x10¹⁷
  - 5.8x10¹⁷

**Additional notes:**

- Pre Irradiation
- Post Irradiation

- (Si)licon (C)arbon
- V_{Si}
Scaling of Trap Parameters and Voltage Hold-Off – Quenching

**Quenching**

- Heat sample to 1,800 C
- Control rate of cooling
  - -10 C / min → Eliminates traps
  - -100 C / min → Introduces traps
- 2x decrease in carrier lifetime (5 ns → 2-3 ns)
Vertical PCSS

- 3.175 mm x 3.175 mm x 0.361 mm
- Top contact: Grid - 51 μm line width & 54% optical transparency
- Bottom contact: Solid 4 mm²

$\Phi = 19.05$ mm
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
Lateral - Radial PCSS: MW Switching

4.61 MW at 65 MHz
- Switched 300 A at 65 MHz into 50 Ω (4.61 MW)
- \( \frac{di}{dt} = 205 \text{ kA/µs (20/80)} \) Rise Time: 1.3 ns (20/80)

26.39 MW Single Shot
- Switched 938 A into 30 Ω load (26.39 MW)

Laser limited
Common Laser Wavelength Optimization

In-Line Lateral - Back-side illumination
- Optimize PCSS thickness (balance absorption and penetration depth)
- Front-side illumination → Naturally efficient at 355 nm

Radial Lateral - Front-side illumination

Photocurrent Efficiency (a.u.)

- 350 μm
- ~250 μm
- ~100 μm

Decreasing Thickness

3x Nd:YAG
Lateral In-Line PCSS: Structure and Material Limitations

Device Cross Sections

- **Version 1**
  - Anode
  - Cathode
  - Incident Light
  - 1.63 mm
  - 1.83 mm
  - 360 μm
  - 1 μm Au
  - 300 nm Ni
  - 150 nm n⁺ SiC

- **Version 2**
  - Anode
  - Cathode
  - 0.61 mm
  - 0.81 mm
  - 360 μm
  - 5 μm Au
  - 50 nm NiCr
  - 150 nm n⁺ SiC

- **Version 3**
  - Anode
  - Cathode
  - 0.61 mm
  - 0.81 mm
  - 360 μm
  - 5 μm Au
  - 50 nm NiCr
  - 1 μm n⁺ SiC

1.5 in
2.7 in

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

Material Limitations – Device Lifetime

- Cracks observed near metal / SiC interface
- Cause: transient high electric fields and high current densities

4H-SiC

Anode  High Current Density Regions  Cathode
Material Limitations - Device Lifetime

- 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
Material Limitations - Device Lifetime

2D Finite Difference Implementation

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

\[ R_{\text{Load}} = 50 \ \Omega \quad V_{\text{an}} = 1 \ \text{kV} \]
Device Lifetime - Modeling

E-Field vs Time

- Transient spikes in electric field ~6x DC electric field
- 2 processes contributing to switch degradation
  1) Joule Heating
  2) Dielectric Failure

E-Field vs Position

- E-fields + high current density leads to significant joule heating (~1000 °K)
- E-fields scaled to experimental voltage (10 kV → ~5 MV/cm) on the order of theoretical breakdown strength of SiC
Scaling of Optical Parameters

- Vary optical trigger energy
  - Constant wavelength and area
  - Variable energy / density
- Vary the area illuminated
  - Constant wavelength and density
  - Variable area
- Vary the wavelength
  - Constant area and density

3x: Nd:YAG
5 ns FWHM
0-300 mJ
OPO
200-750 nm
5 ns FWHM
Variation of Energy Density
Constant Wavelength and Area

- Conclusions: More efficient to operate at lower density and parallel devices
  - 57 µJ $\rightarrow$ 64 Ω
  - 10 devices $\parallel$ $\rightarrow$ 6.4 Ω
  - 570 µJ $\rightarrow$ 20 Ω
- Increased recombination rate due to Bimolecular and Auger recombination

355 nm
5 ns FWHM
Variation of E-Density - 1st Order Model

- 2D Finite Difference Implementation
- 1st order estimate of carrier populations

\[ I = \text{Optical Power} \]
\[ n = \text{index of refraction} \]
\[ n_c = \text{carrier concentration} \]
\[ \alpha = \text{absorption coefficient} \]

\[ \frac{\delta I}{\delta t} = \frac{c}{n} \left( \frac{\delta I}{\delta x} - \alpha I \right) \]

\[ \frac{\delta n_c(t)}{\delta t} = \frac{\delta I}{\delta x} \frac{1}{E_{\text{photon}}} - \frac{n_c(t)}{\tau_{\text{Bulk}}} - B n_c(t) - C n_c(t) \]

Rate of change in carrier population = Photo-absorption - Bulk Recomb - Bimolecular Recomb. - Auger Recomb.

\[ \tau_{\text{Bulk}} = 8 \text{ ns} \quad \alpha = 310 \text{ cm}^{-1} \]
\[ B = 4.0 \times 10^{-11} \text{ cm}^3\text{s}^{-1} \]
\[ C = 1.2 \times 10^{-30} \text{ cm}^3\text{s}^{-1} \]
Simulation and Experimental Comparison

- Bimolecular and Auger recombination plausible explanations
- Epoxy non-linear absorption ruled out as possible explanation
- More efficient optically to operate at lower energy densities
Variation of Area
Constant Wavelength and Density

18.5 J/m²

- Confirms trend in the density sweep curve
- Entire illuminated area contributes to conduction

181.0 J/m²

- Optimal to illuminate as much of the A/K gap as possible
Variation of Wavelength Constant Area and Density

- 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
Focus on small, practical devices

- Solid State Sources
  - Laser diodes
  - LEDs

- Plasma Sources
  - Pulsed Microhollow Cathode Discharge
  - Dielectric Barrier Discharge
Light Sources for PCSS Switching

- Commercially available 365 nm LED
  - LED Engin: LZ4-00U61 (4-die)

- Evaluated Parameters
  - Forward Voltage
  - Optical Output Power
  - Efficiency
  - Spectral Output

- Scaled Parameters
  - Pulse-width
  - Pulsed current
  - Temperature

![Graph showing optical power as a function of current (DC vs. Pulsed 10 µs)]

![Graph showing center wavelength and FWHM as a function of time]
Light Sources for PCSS Switching

![Circuit Diagram]

![Graph]

- 200 μs LED Pulse (AU)
- 1 kV Charge
- 2 kV Charge
- 3 kV Charge
- 4 kV Charge
- 5 kV Charge
- 6 kV Charge
- High power microdischarge (MD) geometry (MHCD)
  – Direct bonded copper, Cu-Al$_2$O$_3$-Cu
  – 400 μm hole diameter
Experimental Results: MD-VUV

Experimental Conditions
- Ar:H₂ (98:2%), 100 Torr
  - 121.6 nm H I emission
  - 1.6 ns radiation time constant
- 250 μm Al₂O₃ substrate

Results
- Over 1% efficiency
  (100 kHz, 50-250 ns)
- Over 60 watt peak power
  (100 kHz, 50 ns)
- 3 watt average power
  (5 MHz, 150 ns)
  - Strong impurities
Spectral impurity increases with increasing power input

Experimental spectra well represented by SpectraPlot$^2$
(N I, O I, H I, C I, C II, C III)

---

**Stark Broadening**

- Peak electron density, \( n_e \sim 5.6 \times 10^{15} \) cm\(^{-3}\)
  - From Stark broadening of H\(_\beta\)
- Electron temperature, \( T_e \sim 3.5 \) eV
  - Estimated using the ionization rate
- Electron density and temperature are in agreement with simple, zero-dimensional model

\[
\frac{dn_e}{dt} = \nu_{iz} - \nu_r. \\
\frac{d(n_e e_e)}{dt} = en_e \mu_e |E|^2 - \Delta E_{ex} \nu_{ex} - \Delta E_{iz} \nu_{iz} - 3 \frac{m_e}{m_N} (T_e - T_N) \nu_{ela}.
\]

- See also;

Exciplex sources

- XeCl* (308 nm) and XeF* (351 nm) excimers
  - Higher pressure $\rightarrow$ higher intensity
  - Nickel plated MD electrodes
- DC experiments
  - Excimer emission present
- Pulsed experiments (50 ns, 100 kHz)
  - XeCl* excimer emission only achieved with specific conditions
    - High pressure (760 Torr)
    - High gas flow (approx. 1+ slm)
    - 1 – 1.5 % energy efficiency
    - 10.5 W/84 mW (avg./peak) power
  - XeF* emission not achieved
**Exciplex sources**

- XeCl* (308 nm) and XeF* (351 nm)
- Energy and efficiency
  - XeCl* (1,200 Torr)
    - 80 – 100 μJ radiated energy
    - 2.3 – 2.9 % energy efficiency
    - Non-negligible shot-to-shot fluctuations (30%)
  - XeF* (1,200 Torr)
    - 20 – 40 μJ radiated energy
    - 0.3 – 0.5 % energy efficiency
    - Non-negligible shot-to-shot fluctuations (30%)
- Problem
  - Electrode shielding dielectric inhibits power delivery from the electrical source
Initial Switching Result

Opposing Electrode Structure

- XeF* (351 nm)
- High parasitic capacitance causes diagnostic issue when PCSS impedance is high
  - $R_{PCSS} \cdot C_{parasitic}$ time constant while under illumination
  - $R_{load} \cdot C_{parasitic}$ time constant following illumination
- ~100-300 kΩ PCSS impedance
- Anticipate much better results with focusing optics and XeCl*
- Goal:
  Switch on-state impedance below 377 Ω
Conclusion

Accomplishments
• 26.4 MW switching single shot
• 4.6 MW Switching at 65 MHz
• Root cause of lifetime limitations identified
• 3x increase in photo-efficiency
• Publication of four peer reviewed journal papers
• Development and evaluation of alternative optical trigger sources

Future Work
• Embedded Contacts to minimize field transients
• Junction Devices
• Further investigate scaling of optical parameters (increasing efficiency with decreasing wavelength)
• Selective elimination of traps with annealing and implantation
• Increase efficiency to drive PCSS with laser diode or MHCD
Publications

Peer – Reviewed Journal Publications

Conference Publications / Presentations