Fundamental Study of Interactions Between High-Density Pulsed Plasmas and Materials for Space Propulsion

University of Texas at Austin

University of Illinois at Urbana-Champaign

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Project Overview

Team:

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Ian McNab, Institute of Advanced Technology (The Univ. of Texas-Austin)
Graeme Henkelman, Dept. of Chemistry (The Univ. of Texas-Austin)
Roger Bengtson, Dept. of Physics (The Univ. of Texas-Austin)
Waltraud Kriven, Dept. of Materials Sci. and Eng. (Univ. of Illinois, Urbana-Champaign)
Additionally: **2** post doctoral fellows, **3**PhD students, and **2**undergraduate students.

Objective: Study at the fundamental level interactions between pulsed, high-pressure, thermal plasmas and materials such as those encountered in space propulsion devices including Pulsed Plasma Thrusters (PPT), Magneto-Plasma Dynamic (MPD) thrusters and capillary plasma-based thrusters. The ongoing research work brings together a team of researchers from the University of Texas at Austin (UT) and the University of Illinois at Urbana-Champaign (UIUC) with diverse backgrounds in experimental and computational plasma physics, pulsed power engineering, materials science and atomistic-scale materials modeling.

Interactions, Accomplishments, and Findings

Developed techniques to expose samples to known fluxes from a plasma of known composition. We have identified the shortcomings of pulsed *ablative* capillary plasma sources for plasma-materials interactions studies (plasma too cold and too "dirty.") We have built and tested a new, gas-fed, non-ablative, rep-rated capillary plasma source for our studies.

Developed methods to prepare samples and measure ablation. We have created arrays of trenches in silicon samples using nanofabrication techniques, and have applied material characterization techniques such as SEM, GA-XRD, surface profilometry, and EDXS to study exposed samples.

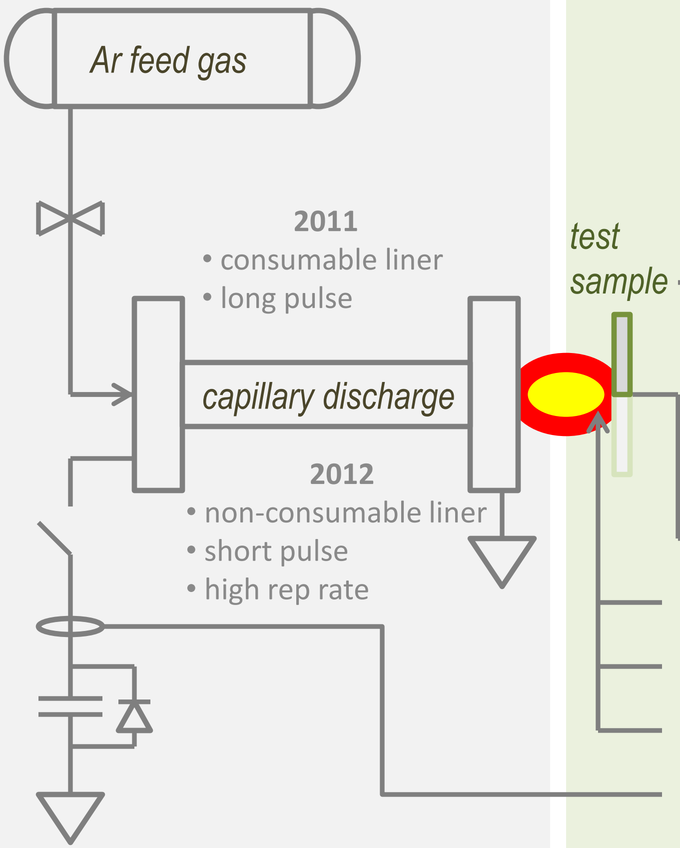
Used plasma models to simulate the capillary source jet and the interactions of jets with the exposed materials. These models have provided insights into the dynamics of the transient plasma jet and are in agreement with experimental measurements.

Used an MD atomistic modeling technique to simulate physical sputtering (ablation) of several materials exposed to inert particle impact, to mimic the plasma-materials interaction experiments we have studied. The MD simulations predicted the low ablation yields we achieved under the high-pressure pulsed capillary plasma conditions, consistent with the findings from the materials characterizations. A new approach is being developed that will assist in the MD modeling of very low-yield ablation processes.

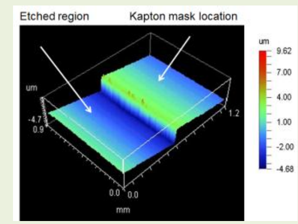
All team members interact on a regular basis, which has been critical to realizing the goals of the project. The entire team meets every Friday to discuss progress and exchange information/insights into the research problem at hand. Regular conference calls are held between a subgroup at UT-Austin with the UIUC team to discuss materials issues. The entire team has benefitted from these interactions.

Overview of Experiment

Apparatus



Measurements



- Profilometry
- Pressure
- Temperature
- Relative intensity I(λ)
- Total intensity
- High speed video
- Current and Voltage

Outputs

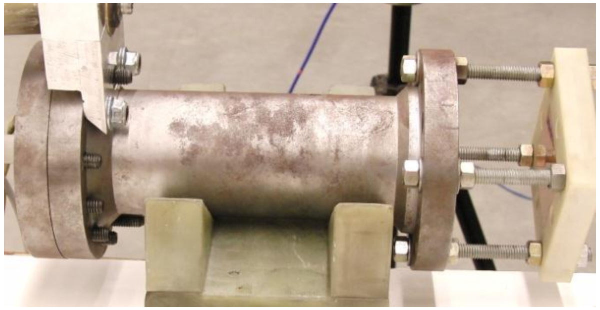
- *Atomic layers removed per exposure*
- *Plasma composition*
- *Particle flux*
- *Radiative flux*
- *Surface temperature*

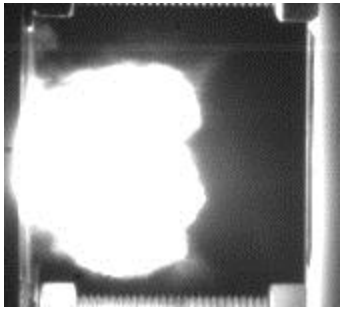
Summary of Experiments

2011: Capillary with $(C_2H_4)_nH_2$ liner

Charge Voltage	Peak Current	Peak Power	Plasma Energy	Plasma Pressure At 60 cm
3 kV	13 kA	25 MW	3.5 kJ	0.75 MPa
4 kV	18 kA	40 MW	6.3 kJ	0.5 MPa

Plasma Temperature: 1 ± 0.3 eV
Flux $(\Gamma \bullet \tau) = 10^{28}$ argon atoms/m^2/test
Electron density $n_e = 5 \times 10^{16}$ cm^{-3}
Ionization fraction: $n_e/n = 0.02$



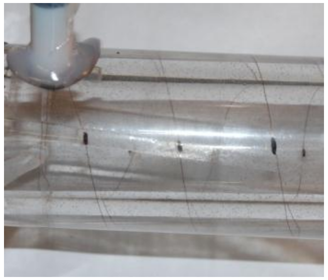


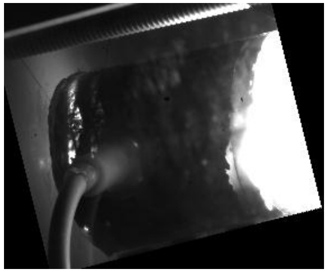
Consumable liner capillary (old) with pressure transducer (left). High speed image of plume (right)

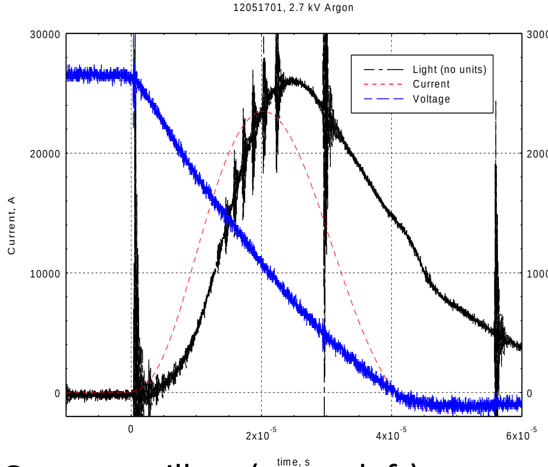
Multiple tests conducted on $Al_2 0_3$ and silicon
Problems: -plasma too cold to ablate samples
-plasma produces too much soot.

2012: Capillary with quartz liner

- flash-lamp and triggered spark gap approaches used initiate breakdown (3-50 kV)
- Argon plasma w/ 2% H_2 for diagnostics
- survives pressure and thermal shock
- designed for high power and temperature
- compensates for reduced energy by exposing samples to multiple (~100) pulses.





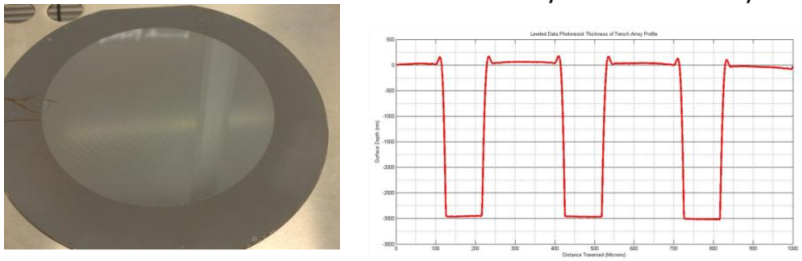


Quartz capillary (upper left)
High speed image of plasma (lower left)
Current and voltage at low power (right)

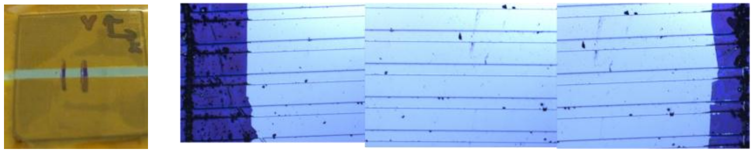
Ablation Testing of Silicon

- Purchased mechanical grade silicon wafers.
- Designated (100), ∅=6”, 650 μm thick.
- Performed photolithography and plasma etching to produce reference features for characterizing ablation.
- Test region profiled and photographed under microscope prior to exposure.
- Test region masked to provide an un-exposed control region.
- samples exposed to ablative capillary:
    - 20 – 30 tests
    - two energies: 3 kV and 4 kV
    - distance from muzzle ranged from 30 mm to 60 mm
- Post test characterization conducted by UT and UIUC, both found little evidence of ablation, and presence of soot on samples.

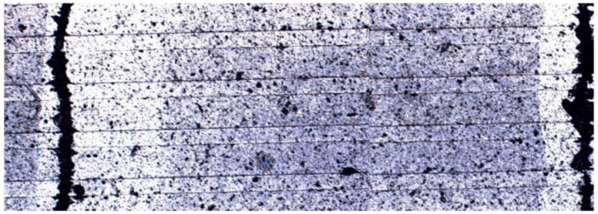
Profilometry Of Trench Array



Fabrication and characterization of 5 μm deep trench array: 200 μm wide mesas; 100 μm wide valleys



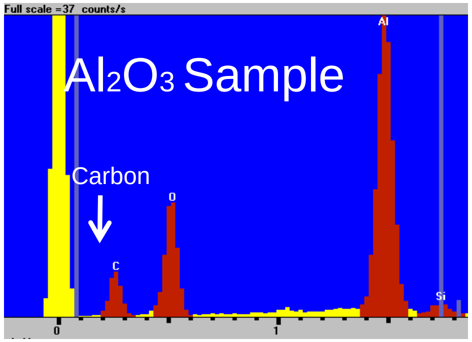
Pre exposure: Kapton mask and test region (left), magnified view of test region (right)



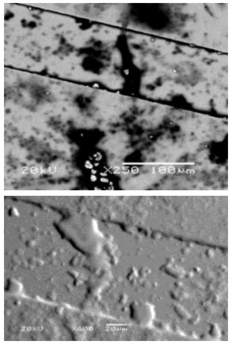
Post exposure with ablating lining capillary. Black lines delimit test region. Black speckles are soot.

UIUC Analyses of exposed silicon and $Al_2 0_3$

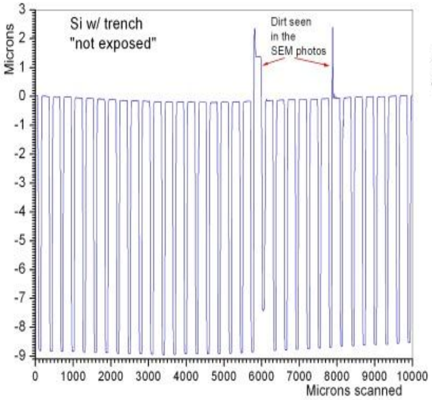
- Evidence of contamination by carbon of all exposed samples was confirmed by analyses at UIUC.
  - An SEM-EDXS image of an alumina $Al_2 0_3$ tile exposed to thermal plasma showed carbon deposition.
  - Back Scattered Electron (BSE) images of exposed silicon, an accumulation of carbon in topographical image and prevalence of black, indicative of carbon.
- Profilometry of exposed silicon confirmed carbon deposition seen in BSE.
- GA-XRD of Silicon showed poly-crystalline structure rather than (100) as listed by manufacturer.



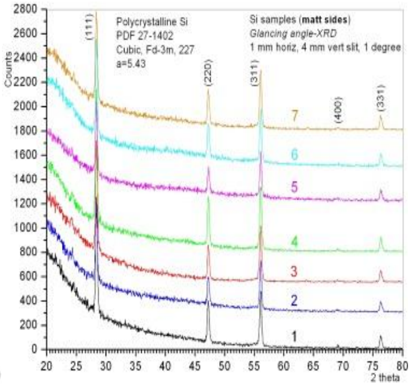
Al2O3 SEM-EDXS



Silicon BSE



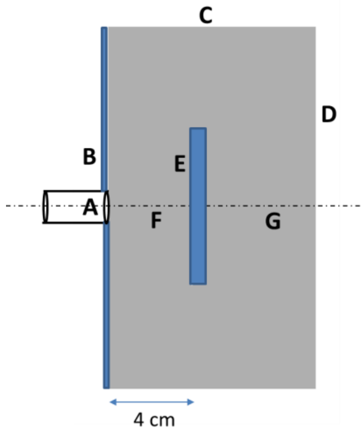
Profilometry of Silicon



GA-XRD of Silicon

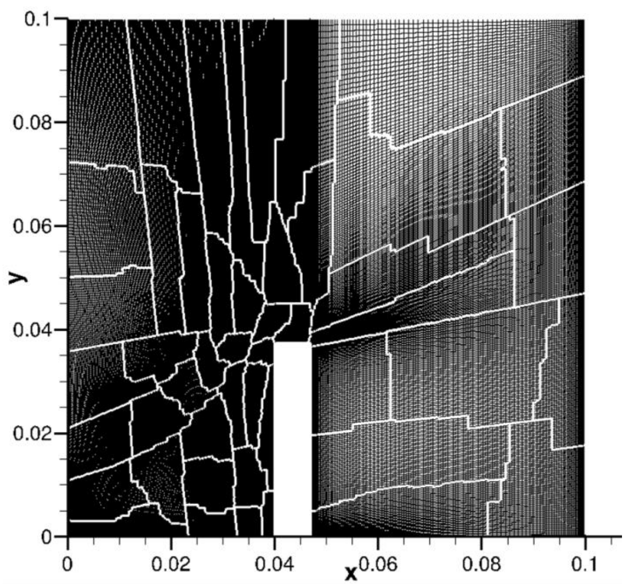
Capillary discharge simulations

Boundary	type	attributes
A	Inflow total	$P_0 =$ P(t) ; $T_0 =$ T(t)
B,E	Viscous wall fixed temp.	$\vec{V} = 0$ $T_B = 300\ K$ $T_E = 1000\ K$
C,D	Outflow	P = 100 kPa
F,G	Axis	Zero flux

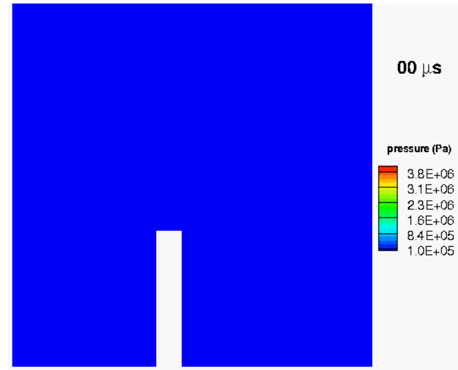


- Plate thickness = 7 mm
- Exit diameter = 2.5 cm

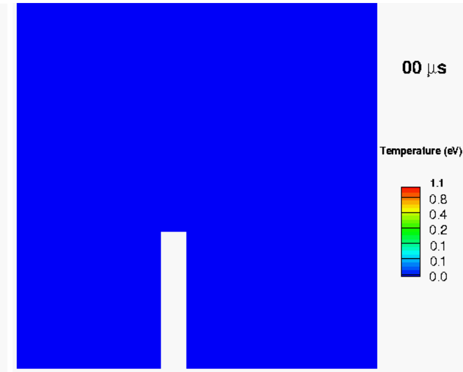
- Computation details
  - axi-symmetric
  - Viscous with radiation effects
  - Time accurate calculation with implicit scheme
  - Done on 48 cores
  - No: of cells = 112,500



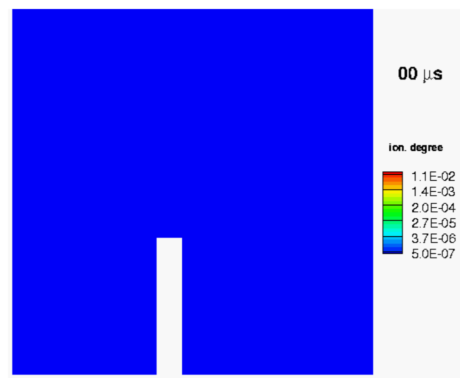
Domain decomposition of mesh on 48 processors (only top half)



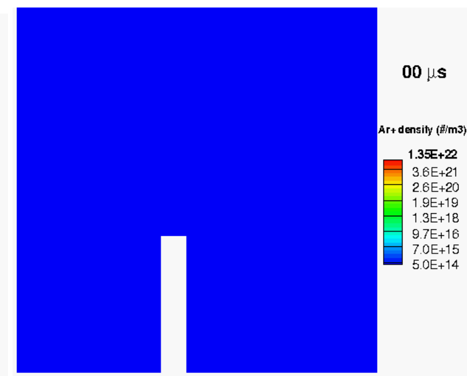
Pressure (Pa)



Temperature (eV)



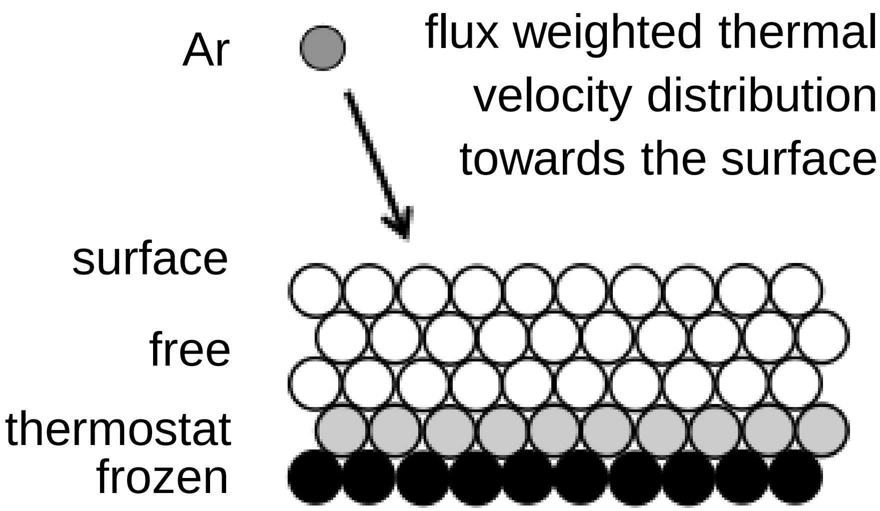
Degree of ionization

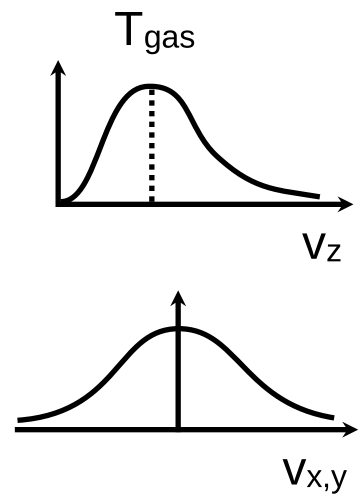


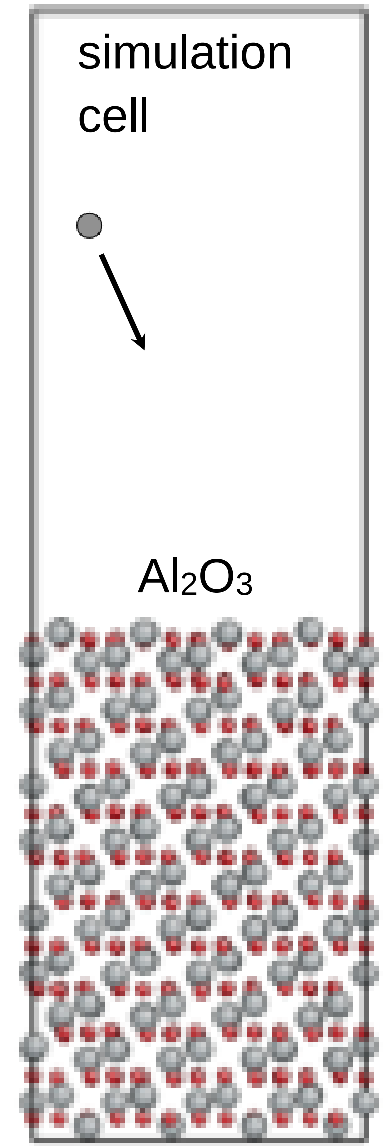
Electron density (#/m^3)

- Electron densities computed using Saha equilibrium ~ 10^{16} #/cm^3
- Higher degree of ionization seen downstream of the shock due to higher temperatures

Molecular dynamics simulations



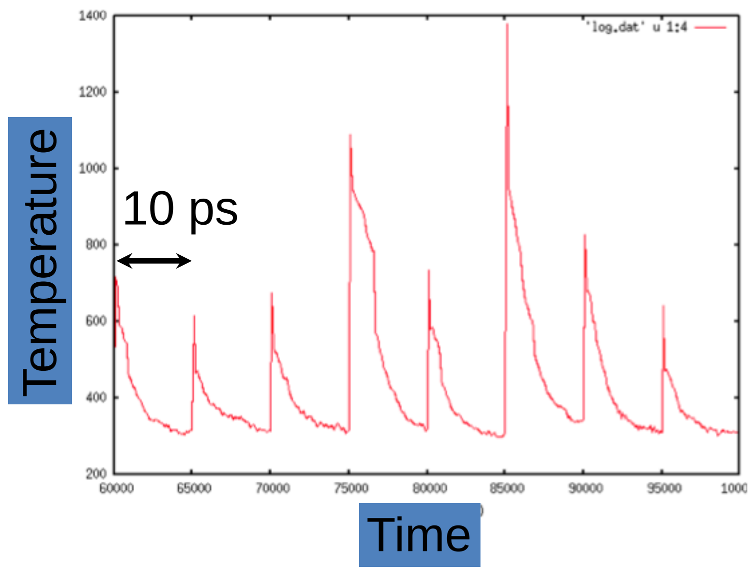




Collision events

kinetic energy of collision is dissipated in a few picoseconds

time between collisions is longer: ns - ms



Quantification of damage: Ablation of Al_2O_3