Plasma-Aided Manufacturing
at CPMI
Should more of these plasmas go into LAM?

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Department of Nuclear, Plasma, and Radiological Engineering
College of Engineering
University of Illinois at Urbana-Champaign
My Biodata

- BS in Physics and Applied Math, Purdue, 1979
- PhD in Physics, Princeton, Jan. 1984
  - Did thesis at PPPL under Dr. Sam Cohen on a energetic neutral particle detector for the PLT tokamak, measuring cross-sections
- Joined the UIUC Faculty, Department of Nuclear Engineering, in July 1984
- Promoted, and received tenure in 1989
- Convinced Department to change name to “Nuclear, Plasma and Radiological Engineering”
- Promoted to full professor in 1994
- Served as part-time Assistant Dean, and Associate Vice President for the UI system at various times
- Industrial funded Center began in 2002
- Fellow of American Nuclear Society, 2004
- Named “Micron Professor” in 2005
- Wrote AVS Monograph on “Electric Probes for Low-Temperature Plasmas”
- Created and teach “Plasma Engineering” and “Plasma Laboratory” courses to senior undergraduates and graduate students.
- Numerous patents, 100+ publications, expert witness, etc.
First research at UIUC was related to fusion edge
- Sputtering of first wall
- Ionization of ejected wall materials
- Chemical sputtering (ie etching) reactions in low-temperature, neutral-dominated plasma.

Natural transition to microelectronics research:

“We make the machines that make the chips”

Long history with INTEL. Director of components research at INTEL founds Center for Plasma Material Interactions at Illinois in 2002. Funding increased significantly.

<table>
<thead>
<tr>
<th>Year</th>
<th>Industrial $</th>
<th>Government. $</th>
<th>Total $</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>625,000</td>
<td>296,000</td>
<td>921,000</td>
</tr>
<tr>
<td>2004</td>
<td>1,302,000</td>
<td>328,000</td>
<td>1,630,000</td>
</tr>
<tr>
<td>2005</td>
<td>864,000</td>
<td>315,000</td>
<td>1,179,000</td>
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<td>2006</td>
<td>802,000</td>
<td>265,000</td>
<td>1,067,000</td>
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<tr>
<td>2007</td>
<td>935,000</td>
<td>240,000</td>
<td>1,175,000</td>
</tr>
</tbody>
</table>

Alumni from the group now work at many of the companies in this business. Every graduate who wants to work in industry has multiple job offers well before graduation.

Current stats: 3 post docs, 12 grad students (incl. 1 PhD/MBA student, 1 MD/PhD student), 25 undergrad students in variety of disciplines, 1 technician.
Research Partners and Sponsors

ASML
Energetiq
Micron
Cymer
Novellus
Sematech
SRC
Starfire Industries
USHIO
P R I S M
Argonne National Laboratory

Center for Plasma Material Interactions
http://starfire.ne.uiuc.edu
Current Research Focus Areas

- Manufacturing of Microelectronics
  - EUV Lithography --- 8 projects
  - Particle Removal --- 1 project
  - Plasma Sources for Etching and Deposition --- 3 projects

- Fusion Technology
  - Plasma Facing Components --- 4 projects

- Desire to rekindle work in macro-plasma-material interactions. A tremendous infrastructure has been accumulated at CPMI that can be put to use for a number of other research processes.
Xtreme Technologies, XTS 13-35:

---- 100 ns 5J Z-pinch operating at 1.5kHz
---- puts 35 W of 13.5 +/- 0.2 nm EUV light into 4 pi
XTREME Technologies XTS 13-35
Commercial pulsed z-pinch EUV source (only three in US, others at INTEL and Sematech)
Operable with gaseous Xe or SnCl₄ fuels
Mounts for sample exposures
Diagnostics:
- ICE Energy analyzer
  - Ion and Neutral particle flux measurement
- EUV photodiode detector
- In-situ photodetector for exposing samples
  - Can measure time-evolution of EUV reflectivity

Debris Mitigation Tool
Debris Mitigation Region

Funding provided by

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XCEED: Results

- Measurement of Ion flux – Xe vs. Sn fuels
- Flux measurement of neutral particles
- Mixed fuel experiment [INERT technique]
- In-situ reflectivity of Gibbsian segregated alloys
- Secondary RF plasma for debris mitigation
- Mixed fuels for ion debris energy reduction
- Cross-section measurements of heavy ions

**Relevant Publications**

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**Ion Spectra of Xe-fueled XTS with no buffer gas at 20° - 1.57m from the pinch**

**Ion Spectra of Sn-fueled XTS with no buffer gas at 20° and 1.57m from the pinch**

**Neutral particle flux at the neutral detector no buffer gas**

**Xe+ Ion Spectra**

**Mixed Fuels**
ICE machines

**Illinois Calibrated Energy Sector Analyzer**

- Spherical Sector energy analyzer calibrated to true units
- Capable of measuring individual ions up to 15 keV
- Mobile – entire system combined in two racks
- Systems “sold” to Xtreme, UCD and Sematech

\[
\frac{E}{q} = \frac{\Delta V}{r_1 - r_2}
\]

Top and bottom spherical sectors charged to a voltage difference ($\Delta V$) governed by:

**Relevant Publications**


**Funding provided by**

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Plasma Modeling

Given the XTS 13-35 waveform, initial gas pressure and size, Helios will give the electron and ion temperature, density and the mean charge state, PrismSpect will give the population distribution for the charge states.

EUV Spectra produced by HELIOS-CR Code

EUV Spectra measured experimentally using an IRD SXUV HS5 EUV Photodiode

Relevant Publications

Gibbsian Segregated (GS) Alloy Optics

- **System components**
  - Solid solution film was produced using two 2" DC magnetrons using a co-sputtering system.
  - The substrate is rotated during deposition to obtain an uniform layers thickness.
  - System has a low base pressure (< 10^-8 Torr) and uses ultra high purity argon to prevent contamination of the films.
  - The substrate and samples can be biased to better control the ion bombardment and film quality.
  - There is an array of halogen heating lamps to pre-heat the substrate and bake out the chamber.
  - Sputtering targets used were 99.95% Mo and 99.99% Au.

**Funding provided by**

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http://starfire.ne.uiuc.edu
Gibbsian Segregated (GS) Alloy Optics: Results

SEM Erosion Measurements

<table>
<thead>
<tr>
<th>Virgin Film</th>
<th>1.30M Shots</th>
<th>3.36M Shots</th>
<th>5.26M Shots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion [nm]</td>
<td>1.2</td>
<td>2.0</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Compare to 25.5nm erosion for pure Mo.

AES Depth Profile


Ruthenium Control Sample

<table>
<thead>
<tr>
<th>RM3</th>
<th>∆RM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.86</td>
<td>-</td>
</tr>
<tr>
<td>0.63</td>
<td>0.73X</td>
</tr>
<tr>
<td>0.89</td>
<td>1.03X</td>
</tr>
<tr>
<td>0.61</td>
<td>0.71X</td>
</tr>
</tbody>
</table>

Notice reflectivity close to predicted model.
Cleaning Sn debris from EUV source by plasma etching

- Reactive Ion Etching (RIE) method is used to clean Sn debris on EUV collector mirror. Sn can be removed under a certain condition through volatile product between Sn and Cl (SnCl$_4$).
- GALAXY system designed for Ar/Cl$_2$ plasma is equipped with:
  - An internal ICP coil to generate RF plasma
  - Computerized mass flow control system
  - Pumping system with a dry pump, a cryogenic pump and a turbo pump
- 3nm-thick Sn samples prepared by EUV source exposure were mounted on the collector shell mock-up.
- A variety of surface analysis technique is being used to study how cleaning works and interacts with surface.

Funded provided by Intel and USHIO

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GALAXY: Results

AES results after 20 sec. plasma cleaning

- AES profile shows that Sn can be cleaned off of collector optics in situ
- Ru capping layer is not removed
- SiO₂ is not etched either
- Good selectivity

Relevant Publications

- “Selective etching of Sn from Si- or Ru-capped EUV multilayer mirrors with Ar/Cl₂ plasma”, H. Shin, D. N. Ruzic, 5th International Symposium on EUVL, Barcelona, Spain, October 2006
**SCOPE**

Surface Cleaning of Optics by Plasma Exposure

- **Multifunctional device that is capable of:**
  - Creating low energy Li neutral debris
  - Measuring Li evaporation rates from collector optic.
  - Measuring Li sputter rates from collector optics.
  - Modeling in situ cleaning recipes for collector optics

- **System components**
  - Lithium magnetron
  - Lithium ion gun, 0-3 keV
  - Multi-use E-beam evaporator
  - Helicon plasma source
  - Heated and biasable sample holder and transfer system.
  - RF Compensated Langmuir probe

Funding provided by

Center for Plasma Material Interactions

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SCOPE: Results

Innovative results show the functionality and ability for in situ cleaning of collector optics with a helium secondary plasma due to temperature enhanced sputtering.

Deposition with Magnetron

Secondary He plasma alone

Heating to 400° C Alone

Heating and secondary He plasma

Relevant Publications

SHADE – created the GS alloys

Sputtering and Hhigh-purity Atomic Ddeposition Eexperiment

- Dual magnetron deposition and sputtering system. 10⁻⁹ Torr base pres.
- Magnetrons can be run simultaneously or separately.
- System Info:
  - Quartz Crystal Microbalance (QCM)
  - Quadrupole RGA
  - Loadlock / Magnetic transfer arm
  - Cryopump (1e⁻⁹ Torr base press)
  - Substrate heater
  - Substrate bias
  - Rotatable substrate stage
  - Low mass RGA (to be installed)
  - Multiple targets in possession (Sn, Mo, Cu, Ru, C, Ti, Au, Ta, W, Al, etc.)
  - Atomic hydrogen source (to be installed)
- Work in conjunction with Prof. Angus Rockett, UIUC MATSE Dept.

Funding provided by Cymer®
SHADE: Progress

- Sputtering and deposition of materials commonly found in Extreme UltraViolet Lithography (EUVL) systems
- Use of dual magnetrons to allow concurrent or consecutive deposition of materials onto a substrate without breaking vacuum
- Current focus: Removal of Sn debris using atomic hydrogen
  - Deposition of various materials found in EUVL systems onto Si substrates
  - Measurement of removal rates and effectiveness of atomic hydrogen
  - Determination of preferential removal of Sn and not Mo or Ru
  - Effectiveness of removal of SnO₂
- Use of surface measurement techniques (Profilometry, AFM, SEM, AES, etc.) to characterize deposition

High purity Sn deposition source
As feature sizes approach the 45 nm node, the imperfections left from the removal process become important.

Process developed in conjunction with Intel to expose sample wafers.

Process still confidential at this point.

Actually doing experiments on 45 nm lines and spaces made by XTS 13-35 sourced, EUV microexposure tool in Intel's fab.

Exposed samples are examined using a Hitachi S-4700 Scanning Electron Microscope (SEM) and compared to unexposed samples to determine roughness reduction.

Images are examined by Intel to obtain quantitative values for LER.

Funding provided by Intel.
LER: Results

- Initial results (shown below) appeared to be promising.
- Intel was able to obtain quantitative LER measurements on exposed and unexposed samples
  - Exposed: 3.8±0.3 nm
  - Unexposed: less than that
- From these preliminary tests, the process was shown to have enough potential to be tested with a more intensive and dedicated experimental set-up.
Particle Removal --- PACE

**Plasma-Assisted Cleaning by Electrostatics**

- A new process to remove nanometer scale contamination from surfaces:
  - Contamination on the Mask will print defects on every wafer
  - Current cleaning technology (wet cleaning) may not be 100% effective in particle removal

- **How does PACE work?**
  - Apply a pulsed DC bias to the substrate
  - Use a plasma to charge the particle up more negative
  - Use the modification of the sheath potential to create a larger electric field in the sheath region
  - Particles are removed by $F=qE$

Funding provided by [ASML](http://www.asml.com) [Intel](http://www.intel.com)
PACE: Results

- The PACE technique can remove contamination with a high degree of success
- Surface damage is not seen in roughness or sample material removal
- PACE is a quick/low cost solution to particle removal, eliminating large chemical use and disposal as well as long cleaning times.

Relevant Publications

Charging in Aspect Ratio Dependent Etching

### Background and Mission:
- Next generation DRAM chips see a new type of defect – twisting – that occurs in features with aspect ratios greater than 15.
- Defects caused by charging inside the microscopic features.
- Elimination of charging will improve chip construction reliability.

### System components:
- Donated commercial etch chamber capable of high aspect etching:
  - Three frequencies, inductively coupled.
- 12 kW RF power system.
- Hazardous gas scrubber system.

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Funding provided by **Micron**
CARDE: Progress

- In order to study charging in features, project is constructing an in-situ diagnostic that can measure charging along a feature profile.

- Diagnostic composed of alternating layers of conducting and insulating thin films with thousands of vias with different diameters.

- Voltage measurements taken on conducting layers when exposed to plasma.

- Several arrays of holes on each diagnostic corresponding to a different aspect ratio.

- Diagnostic will measure charging and allow us to determine if charge-reduction techniques are successful.

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Pulsed Hollow Cathode Magnetron

- **High Ionization Metal Magnetron Sputtering**
  - Uses conventional magnetron techniques to trap electrons and enhance sputtering efficiency.
  - Electron confinement by EM bucking magnet, such that a magnetic mirror at opening of HCM prevent electron loss, achieving higher density plasmas.
  - High ionization due to magnetic and electrostatic confinement.

- **System components**
  - Hollow Cathode Magnetron Plasma Source
  - 36kW DC power supply
  - Electrostatic pedestal for HV wafer handling
  - Cryo and Turbo pumps
  - Scannable RF Compensated Langmuir probe
  - Soon to be upgraded to pulsed operation

Funding provided by
Pulsed Hollow Cathode Magnetron: Progress

- High level of ionization of sputtered atoms at moderate power density.
- Higher deposition rate than conventional DC magnetron.
- Higher rate of reactive sputtering than conventional DC magnetron.
- Applicable for large area sputtering. ††

Current Advantages of HCM Cu Seed Technology (Novellus)

- Resputter bottom coverage to sidewall
- Remove overhang

- Improve deposition sidewall coverage without overhang
- Improve morphology

DC HCM Operation with grounded stage. Ti, 6 kW, 6 mTorr. Courtesy of Novellus Systems.

Inverted Helicon Plasma Source

- **Extension of a helicon plasma source**
  - Helicon plasmas are wave-heated, not CCP or ICP
  - Antenna wrapped around dielectric cylinder
  - Requires parallel magnetic field for wave-coupling
  - Highly efficient, high $T_e$ and $n_e$ for low magnetic field
  - Coil and geometry requirements limit applications – no metal walls

- **Inverted source employs an antenna within vacuum chamber, covered in dielectric material**
  - Attempts to launch a helicon wave and characterize inside and outside antenna region
Inverted Helicon Plasma Source: Progress

- Helicon plasmas are believed to be heated by Trivelpiece-Gould (TG) modes, a surface wave
  - Dielectric cylinder inhibits plasma measurements near plasma surface
  - If antenna is inside, and covered in dielectric, measurements can be made arbitrarily close to antenna radius
- Measurements made through several diagnostics used in parallel
  - **Langmuir probe**: $V_f, V_p, T_e, n_e$
  - **3 Orthogonal B-dot probes**: $B_r, B_\theta, B_z$
  - Spectroscopy: $T_e, n_e$
  - Diagnostics on linear feedthrough to determine radial and axial profiles
- Objectives
  - Determine plasma heating method
  - Develop more efficient source for plasma processing
- Relevant Publications
  - B.C. Masters and D.N. Ruzic "Characterization of an Inverted Geometry Helicon Plasma Source" ICOPS June 2006, Traverse City, MI
  - B.C. Masters and D.N. Ruzic "Characterization of an Inverted Geometry Helicon Plasma Source" 48th APS DPP 2006, Philadelphia, PA
**Fusion Technology --- IIAX**

**Ion-InterAction eXperiment**

- **IIAX defined:**
  - Uses a low-energy velocity and mass–filtered ion beam to bombard samples.
  - Uses direct measurement of ion current and collection of ejected mass onto quartz-crystal microbalances to determine sputtering yields of solid or liquid surfaces.
  - Uses direct measurement of ion current and collection of ejected mass onto quartz-crystal microbalances to determine sputtering yields of solid or liquid surfaces.

- **System Specifications:**
  - Gas or vapor plasma monoenergetic ion source: Recent species: D₂, He, Ne, Ar, Li (from LiCl), Sn (from vaporization into Ar plasma).
  - Low energy regime: 100 - 3000 eV
  - 100 - 1000 nA (for > 500 eV)
  - Well focused: > 90% of beam current within 2-mm diameter Faraday cup aperture – flux ~ 10¹⁴ cm⁻²s⁻¹.
  - Very stable for gaseous ion source: Successful data runs for up to 60+ hrs recorded.

**Funding provided by**

[ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN]

[Center for Plasma Material Interactions](http://starfire.ne.uiuc.edu)
**IIAX: Results**

- Work has been done in liquid metal erosion studies, particularly erosion of lithium from various surface conditions (i.e. deuterium coverage, variation in temperature).

![Graph showing liquid Li sputtering yield vs. liquid lithium target temperature](image)

- Recent work focused on temperature-dependent low energy ion sputtering of liquid Sn for advanced Tokamak divertor surfaces (EUV connection too).

![Graph showing sputtering yield vs. ion energy](image)

- Confirmed that temperature enhancement exists only for low energy, light ion bombardment.

![Graph showing Deuterium coverage studies](image)
IIAX: Current Work

- Current work involves measuring overall erosion rates of plain, lithium coated and boron-plasma-treated ATJ graphite under light ion bombardment.
- This work is being done in conjunction with Argonne National Laboratory, to help explain NSTX experimental results.

Will ultimately vary Li film thickness, sample temperature, ion energy.

Relevant Publications

DEVeX

**Divertor Edge and Vapor shielding eXperiment**

- **Designed and currently being built in CPMI**
  - Study material interactions during disruptions relevant to fusion reactors
  - Quantify the ability of vapor shielding to protect divertor materials from these disruptions

- **Conical θ-pincha plasma source**
  - Used to create dense \(10^{21}/m^3\), hot (~1 keV) plasmas relevant to fusion-material interactions

- **System components**
  - θ-pincha
  - Main Capacitor bank
    - 36 μF, 60 kV (32.4 kJ stored energy)
  - Pre-ionization Plasma (PiP) source
    - Pulsed, annular discharge
    - Creates high density (~10¹⁹/m³), low temperature plasmas to be compressed
  - Guide magnetic field coils
    - Pulsed (< 1 ms) to achieve high, ITER relevant magnetic fields
    - Required to guide plasma from θ-pincha plasma to target materials
  - Diagnostics
    - Plasma: Triple Langmuir probe, spectroscopy
    - Material: QCM, IR temperature sensors, witness plates, etc

*Funding provided by* [U.S. Department of Energy](http://starfire.ne.uiuc.edu)
DEVeX: Theoretical Results

- Using a 1-D snow plow model, the performance of the DEVeX facility can be estimated.

- Plasma density scales quadratically with $I_\theta$.
- Densities of $10^{21}/m^3$ can be achieved with modest currents.
- Ion heating from joule and shock heating.
- Increases linearly with $I_\theta$.
- Initial gas pressure, $P_0$, decreases ion temperature.

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SLiDE

Solid-Liquid Lithium Divertor Experiment

Facility for studying surface tension driven flows with MHD effects

- Temperature gradients induce passive flowing of liquid metal
- Effectively redistributes heat away from local heating
- May enable lithium to redistribute larger power fluxes before evaporating into a fusion machine

Experimental capabilities

- 15 kW beam power for local heating of lithium
- Adjustable beam shape to explore power flux profile effects
- Magnetic fields up to 0.2T (0 < Ha < 400)
- Transient and steady state measurement of operation

Funding provided by
**SLiDE: Progress**

Initial analysis and design developed for experimental construction and planning

- Electron beam being designed for operation with and without magnetic field

Expected behavior of velocity with increasing magnetic field

\[ u_{\text{max}} = \frac{\gamma b L}{\mu H a} \tanh(\mu H a) \]

Temperature distribution through tray and liquid lithium modeled to determine optimal thermocouple placement

Expected behavior of flow velocity for Li in the tray, heated at top left point

Time = 2, 5, 15, 44s
SPARCS

Surface Plasma Arcs by RF Control Study

Capabilities of the device:
- High $10^{-8}$ Torr ultimate pressure.
- Experimenting with multiple gases and liquid chemicals.
- DC and RF glow discharge.
- Gap controllable reproducibly to $\pm 2\mu m$.
- Tip electric high temperature annealing.

System components:
- Residual Gas Analyzer
- DC power source, +15 to -33kV
- RF power source, 3kW
- Micrometer linear motion feedthrough
- Rogowski Coil Current Transducers
- Pyrometer

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U.S. DEPARTMENT OF ENERGY
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
SPARCS: Results

The effect of conditioning, as well as different halogen compounds on field emission from the surface were studied.

Effects of the chemicals on the electrode surfaces: CCl₄ to the right and XeF₂ on the bottom

Relevant Publications

Other Research and Analysis Facilities On Campus used by CPMI

- **Center for Microanalysis of Materials**
  - Emphasizes the microstructural and microchemical composition of materials, chemistry and electronics of surfaces, crystal structures, phase transitions and defect structures of materials.
  - Access to 30 major instruments in the areas of ellipsometry, FTIR, SEM, FIB, AFM, AES, SIMS, TOF-SIMS, XPS, Rutherford Backscattering, TEM, STEM, XRD, LEEM, and Profilometry.

- **Micro and Nanotechnology Laboratory**
  - Multidisciplinary research facility that houses advanced equipment to support research in photonics, microelectronics, nanotechnology, and biotechnology.
  - Access to major instruments in the areas of e-beam lithography, Optical Lithography, SEM, RIE, Ashers, Etchers, Sputter deposition, CVD, PVD, iPVD, PECVD, Furnaces, Ellipsometry, FIB, SEM, AFM, and packaging.
Prior (Relevant) Research Areas

- Hard Coatings – PECVD Alumina for tool bits etc.
- Atmospheric Plasmas for coating 2-liter soda bottles
- Plasma treatment of plastics for biological implants
- Plasma-created bio-mimetic structures for repelling water
- Diamond-like carbon films
- Plasma treatment of graphite for densification and gas removal
- MD and Monte-Carlo modeling of plasma-material interactions, particularly hydrogen and hydrocarbon interactions with graphite
- Amorphous silicon solar cell development
Conclusion

- We do plasma-aided manufacturing for microelectronics
- We have had research in the past on more macroscopic plasma-material interactions.
- Wide ranging industrial contacts
- A desire to reach out and work with other Universities in the NSF Center framework.
- Should CMPI join LAM and add a little more plasma to the mix?
Acknowledgements

- MD/PhD proto-postdoc: Martin Neumann -- for gathering the material from all the students and making it all look good.
- Our research sponsors.
- The NSF and LAM for inviting me.

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