White Paper for *Frontiers of Plasma Science Panel*

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• Plasma Atomic physics and the interface with chemistry and biology	P
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	"X"
Oral	
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Will not attend	x

Title:	A Shared Research Infrastructure for the Study of The Science of Near-Threshold Plasma Surface Interactions
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Corresponding author cannot attend the Town Hall meeting because of travel, and plans to attend via Adobeconnect and also would like/would be available to participate in future planned workshops.

<u>The Science Frontier of Near-Threshold Plasma Surface Interactions</u>

The scientific understanding of plasma-surface interactions is a prerequisite for the rational design and control of systems that use plasmas for processing of materials or for maintaining control of plasmas, ranging from burning plasma in a fusion device [1] to plasma medicine [2]. One important science frontier is the understanding of *near-threshold plasma surface interactions*. This topic encompasses diverse situations that can be characterized in different ways. For instance, it may refer to conditions where the kinetic energies of ions impinging on surfaces become comparable to or smaller than the potential energy carried by the ions to the surface [3], or where the energy carried by impinging energetic atom fluxes produced in the plasma becomes significant relative to the energy of electrons, photons or ions striking surfaces. For these "mild" plasma-surface interaction conditions, the conventional techniques for high-energy PSI do not apply. For example, high energy ions incident onto a surface primarily sputter or implant. They typically do not chemically alter the surface without producing physical damage. However, particles with near-threshold energies are more likely to chemically interact with the surface without dramatically altering the macroscopic character of the surface. The plasma therefore responds to the altered chemical character of that surface. Under these conditions, a range of physical and chemical phenomena that are not well-understood at this time [2,4], become important. An

example is the observation of photo-assisted etching of silicon in chlorine- and bromine-containing plasmas for very low ion bombardment energies [5], the mechanistic origin of which is unclear.

Near-threshold plasma surface interaction phenomena are important for plasmas ranging from low (mTorr) [6,7] to high pressure (1 atm) discharges [8,9,10,11]. In particular, our understanding how the plasma particle or energy fluxes incident on a surface affect the state of the surface, stimulate physical and chemical processes, or in turn how the surface state affects the plasma itself, is very incomplete. Specific scientific questions include: How is the kinetic and potential energy of low energy ions dissipated at a surface, and what is the spatial extent of the surface over which this takes place? What are the chemical reactions induced by low energy ions, electrons or photons, and which pathways do they follow? How is the energy released by bond formation dissipated? How do these processes change with energy of the incident particles and/or substrate temperature [12]? What is the influence of the kinetic and internal energy distributions of the interacting atoms, the effects of multiple collisions, and competition between parallel reactions? What is the impact of the sputtered or volatilized fluxes of surface species on the plasma? How do electrons enter the surface? What is the magnitude of the surface charge, how does it vary with space and time and how does it affect plasma properties [13,14]. How is secondary electron emission affected? What is the role of electric fields, e.g. plasma sheath fields? What is the role of photons (especially UV/VUV) produced in the plasma? Additionally, the consequences of the interactions of multiple plasma particle fluxes with a surface at energies below the physical sputtering thresholds change dramatically when chemically reactive precursors strike simultaneously or are present on the surface. Such synergistic effects are essential for the success of many plasma processes at the atomic scale [2,4,15].

Approaches to Advancing The Frontier of Near-Threshold Plasma Surface Interactions

Significant scientific progress on the above issues for prototypical plasma sources operating at both low and higher pressures requires the combination of plasma characterization, with the measurement/decomposition of particle fluxes incident on a surface or leaving the surface, their energy and angular distributions, along with in-situ surface characterization. The results of the experimental investigations need to be coupled with existing and developing computational techniques to describe and understand the observed phenomena.

For large-scale plasma devices, e.g., a fusion reactor, a centralized facility may be the most effective approach. However, these large facilities do not map onto the needs of laboratory-scale investigations of plasma surface interaction of interest to the large community of low temperature plasma researchers performing interdisciplinary research/applications. These investigations would benefit most from a two-fold approach to characterize and understand near threshold plasma surface interactions:

First, availability of a suite of portable diagnostics that are designed for travel to the laboratories of different researchers where specialized plasma devices have been established can significantly advance our understanding of near threshold plasma-surface interactions under a wide range of situations. Increasingly, plasma characterization equipment, e.g. electrical probes, optical emission spectroscopy systems, IR laser absorption measurements, high-speed cameras, etc., are portable, ready to plug into computers and enable highly effective measurement campaigns at the collaborators laboratory. These diagnostics could be maintained either by the user facilities below, or selected users, who also would provide the necessary expertise and training of the collaborating partners.

Second, a network of user facilities having a number of different instruments which would permit plasma researchers to access diverse capabilities at low cost by enabling them to visit and perform critical measurements. These facilities would accept different plasma sources of other users, and provide a spectrum of plasma measurements, incident particle flux characterizations, and surface preparation/characterizations for in-situ surface spectroscopic, morphological and other information. For instance, ultra-short pulse laser diagnostics, sophisticated mass spectrometers, optical surface diagnostics along with UHV surface science tools, etc. could be available at different facilities.

This kind of shared infrastructure could be supported and coordinated by DoE and would enable a maximum amount of collaboration and also leverage existing equipment installations. It would strengthen

ongoing interdisciplinary research and collaborations where plasma physicists work with/share facilities with colleagues from other disciplines by allowing this community to collectively use capabilities that exist or could be established in a cost-effective fashion and reduce duplication. The use of standard diagnostics and experimental procedures would result in high quality data, enhance the ability to compare results of researchers using different sources and configurations, and increase their usefulness for computational model validation and development of scientific models.

Impact of This Research

Near-threshold plasma-surface interactions are important for many situations where plasma is bounded by external surfaces. The proposed research infrastructure would provide the necessary data and means to do experiments that will sharpen our scientific understanding of near-energy threshold phenomena by enabling their study in highly diverse situations. This ultimately will enable improved control of plasma surface interactions for a wide range of uses for societal benefits ranging from materials processing, e.g. formation or etching of ultra-thin layers by plasma-enhanced atomic layer deposition and etching to make sophisticated and ultra-small electronic and optoelectronic devices, to interaction of plasma with soft materials and biological matter, e.g. the emerging field of plasma medicine, and others. This scientific understanding will impact the semiconductor, healthcare, energy and other industries, and, thus, will have far-reaching societal benefits.

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