Downstream Plasma Delivery From a Remote VHF Source

Created by

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Abstract

A new remote plasma source (RPS) driven by capacitively coupled VHF power is investigated and compared with alternative technologies. The generation of plasma by high frequency capacitive coupling, opposed to inductive coupling, results in noticeable differences in plasma behaviors. Plasma densities near the output of the source are high as expected from both approaches. Uniquely, with the VHF source, significant plasma can be delivered downstream to a remote chamber at densities far exceeding what is demonstrated from the more confined ICP alternatives. This paper describes this plasma projection behavior of a VHF CCP source and presents plasma parameters including density, current and ion energy measured at the output and downstream into both confined and expanded chamber volumes. The behaviors of different gases including argon, nitrogen and hydrogen are contrasted to show the influence from chemistry on the projected plasma behaviors.

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Introduction

Remote plasmas are commonly used in CVD and PECVD chamber cleaning [1, 2] where optimized plasma generators can dissociate reactive gases at efficiencies superior to in-situ sources while providing an added benefit of less wear and tear on critical chamber components.

In semiconductor and related fields, device and film stack scaling and increasingly exotic materials have driven plasma chambers and associated process flows to unprecedented complexity and sensitivity. As these trends continue there is increasing awareness of the need for broader operating space and process flexibility to accommodate a growing set of challenges. Incorporation of remote plasma generation, to either augment or replace in-situ plasma sources is, as a result, gaining interest for processes demanding wider operating space and finer control of parameters like radical density and ion/ neutral ratios than in-situ sources alone can offer.

As a result, remote plasmas are beginning to find use in a growing list of applications including low-k dielectric etch [3, 4], PEALD [5 ,6], TCO deposition [7], surface modification [8, 9], amorphous silicon deposition [10] and MOCVD processing [11, 12].

A primary objective in any plasma application, remote or direct, is the ability to deliver a desired stream of energized particles (ions and neutrals) from the plasma to the surface being processed. The segregation of high energy species away from delicate layers is often a goal of remote plasma processing, but an unfavorable consequence can be the loss of potentially desirable species, resulting from wall and volumetric interaction associated with delivery through some distance to the processing chamber [13, 14].

Installing the remote source physically closer to the primary chamber can minimize the impact of some loss mechanisms, but practical, mechanical constraints often pose a limit to the proximal installation of a remote device. A new class of RPS source [15], capacitively driven at VHF frequencies, has shown potential to remedy, at least in part, this limitation. By virtue of its capacitively coupled design the VHF RPS reviewed here exhibits a characteristic ability to project significant plasma density well beyond the immediate exit of the device.

The first measurements of plasma projection from a VHF CCP source were presented in this previous study showing rather high plasma densities as far as 15 cm downstream. While observations showed visible plasma well beyond this point, these original measurements were limited to argon projection and taken in a relatively confined volume; thus the utility of the behavior for industrial applications has remained unclear.

Here, density, current and energy measurements in nitrogen and hydrogen, in addition to argon were taken both in confined and expanded volumes in order to more thoroughly evaluate projection to the downstream. As a reference, a commercial ICP source was also evaluated in a similar manner. The object of the investigation was to quantify and characterize plasma projection from the two sources in a more practical arrangement and determine whether the glow in the downstream can be of a usable density and what process and chamber parameters are important in promoting or manipulating the downstream discharge.

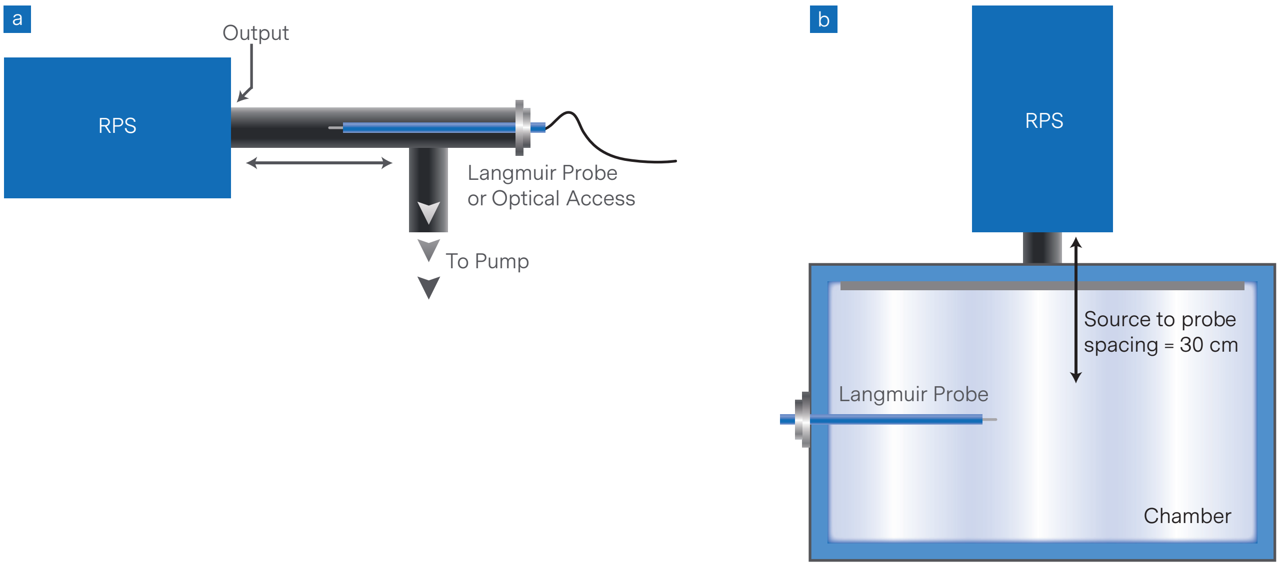

Figure 1. Configurations used for testing a) downstream projection into a confined space and b) projection into open-volume downstream chamber.

Experimental

The VHF RPS (described previously) was mounted to an open-volume downstream vacuum chamber in one of two configurations (Figure 1). The downstream chamber has a total volume of approximately 30 liters. Pumping was provided by an Edwards QDP80 dry mechanical pump equipped with an Edwards QMB500 blower.

In the first orientation (Figure 1a) the RPS was mounted on a perpendicular axis with respect to the chamber port made with 50 mm ID flange. A 200 mm long, 50 mm ID tubulation was connected to a "T" which led to the downstream chamber. This orientation allowed the plasma to be sampled with a Langmuir probe near to the output of the source and directly downstream within the confined volume of the 200 mm tube. In this configuration the probe (Scientific Systems Smart Probe®) was inserted into the 50 mm tube and positioned at discrete points downstream from the RPS output. Plasma density was measured in what we deem a "confined space" for this orientation.

In the alternate mounting (Figure 1b), the RPS was attached to the downstream chamber on-axis through a similar 50 mm ID tube. The distance from the output of the source to the opening in the chamber ceiling was approximately 150 mm. In this orientation, plasma parameters were measured in what we call the "expanded volume" of the downstream chamber. Langmuir probe measurements were supplemented with ion energy and ion current density measured using an Impedans Semion® Retarding Field Ion Energy Analyzer which was placed on a translatable stage enabling measurements from multiple vertical positions.

Argon, nitrogen and hydrogen were each tested in the range of 300 mT to 5 Torr. The test chamber used lacks active throttling so pressures are regulated using gas flow. Flows used to achieve the stated pressure range varied from 500 sccm to 5 slm.

Results

Projection into confined space

Measurements of plasma density out to 15 cm downstream were made and reported previously for argon in the range of 1 to 10 Torr and 200 to 1000 watts [15]. These measurements showed densities from the high 10^{11} to the mid $10^{12}/cm^3$ range with a peak in density approximately 6 cm downstream at 1 Torr and 1000 watts. The ability to go higher in power was limited due to probe heating.

Here we extended the testing beyond the output region and at 1 Torr source pressure the projected plasma was allowed to expand into the larger volume downstream chamber. Measurements taken at the chamber center showed an expected drop in density but values remained in the $10^{10}/cm^3$ range at 200 watts and $4x10^{11}/cm^3$ at 1000 watts. Figure 2 shows argon plasma densities measured at different positions downstream from the source. Positions 0, 7 cm and 15 cm were within the confined space, while data at the 30 cm position represents a location near the center of the open volume downstream chamber. The chamber wall was located approximately 22 cm from the output of the source.

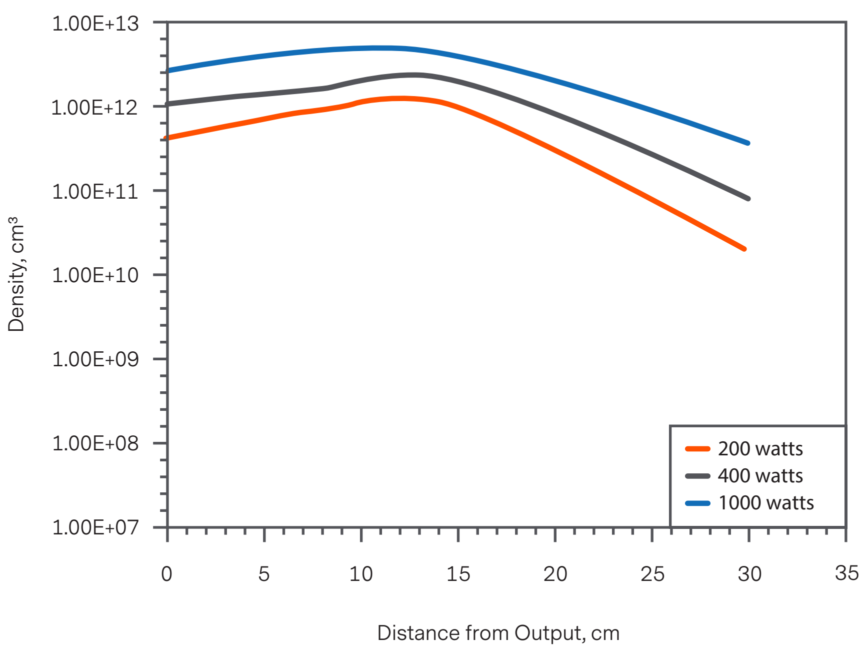

Figure 2. Plasma density for argon measured in the confined space downstream from the VFH RPS source.

While argon data are valuable to show the potential for distributing plasma to the downstream, the utility of argon alone is rather limited. Of greater interest for practical applications are reactive chemistries such as hydrogen and nitrogen. Not surprisingly, densities were generally lower for these gases compared to argon. Figure 3 shows plasma density versus power at various pressures in the confined space for hydrogen and nitrogen 15 cm downstream. Nitrogen densities were higher compared to hydrogen and both were strongly dependent on power and only weakly dependent on pressure, more so at low power. Density was detectable only above a threshold power in the 500 to 1500 watt range. Below this power level, little or no plasma current was measured by the probe. This threshold appears to indicate a point where the confined volume beyond the exit of the RPS begins to fill with plasma. The threshold power needed to achieve this tended to be higher with increasing pressure.

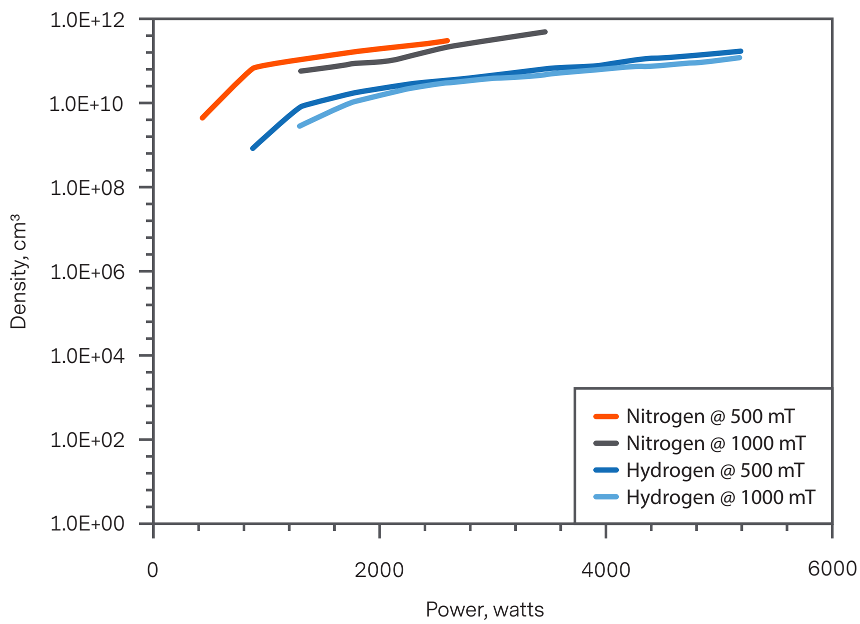

Figure 3. Nitrogen and hydrogen density at 15 cm downstream within confined volume.

Figure 4 has density in nitrogen versus power at three different positions downstream from the output of the source. Once the "projection" threshold was reached, plasma appeared to fill the volume of the confined space, out to the 22.5 cm point, the limit of the probe's translation. The relationship between density and power appeared consistent at each position tested. Densities were highest nearest the output and then fell off with increasing distance. At 2.5 kW, density remained in the 1011 $/cm^3$ range out to 15 cm. Beyond 15 cm density fell more rapidly but remained above 1 x 1010 $/cm^3$ at and above 2.5 kW out to the translation limit. Data collection for hydrogen at less than 15 cm proved problematic due to probe overheating during close-in sampling attempts. Hydrogen data at 15 and 23 cm showed good repeatability and less probe heating. In general, hydrogen required more power and somewhat lower pressure to reach densities comparable to nitrogen.

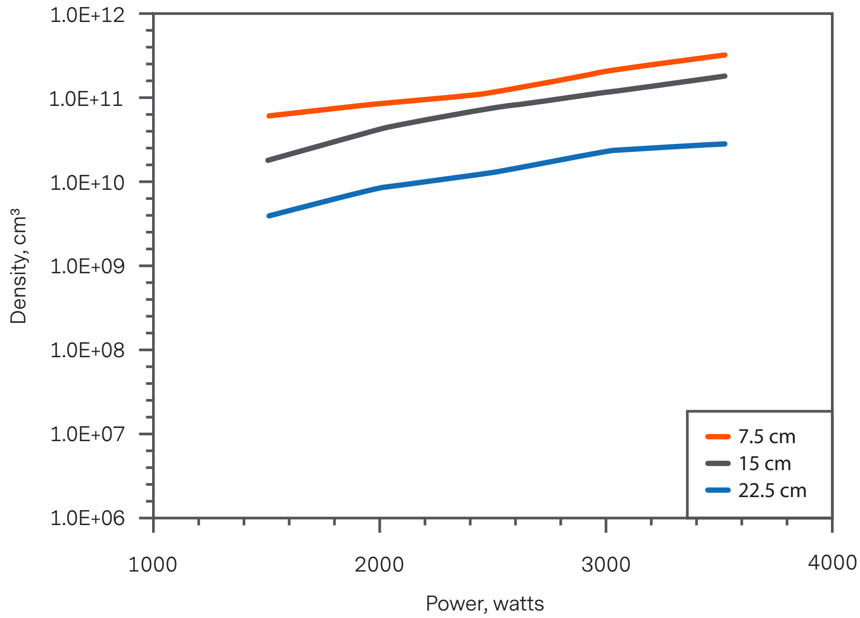

Figure 4. Nitrogen density versus power at various positions downstream.

Projection into open-volume chamber

The existence of a projection threshold has implications on the ability to deliver plasma into a larger volume downstream. If conditions are such that the projection fails to fill the confined space immediate to the output of the device, then projection into a larger volume, farther removed, would not be expected. For the open-volume projection tests here, the chamber interface was positioned approximately 22 cm downstream from the output of the RPS. As an example, for this arrangement, based on the results above, projection of nitrogen plasma into an expanded volume would be possible at 500 mT beginning at 500 watts and above and at 1 Torr for powers 1500 watts and higher.

Figure 5 shows actual densities for nitrogen and hydrogen projected into the open-volume chamber. For these tests the probe was located in the center of the chamber approximately 30 cm from the output, and as mentioned, the chamber interface was at a position approximately 22 cm downstream from the source. Not surprisingly, lower pressure and higher power resulted in higher density, and similar to the confined space measurements, nitrogen produced higher densities compared to hydrogen.

Density downstream was enhanced by decreasing the distance between the source and the chamber interface. For hydrogen at 0.5 Torr, Figure 5b shows the impact of reducing the source to chamber interface distance from 22 cm to 12 cm (and the total distance from the source output to the probe from 30 cm to 22 cm).

IEDF measurements were made with the retarding field analyzer positioned on a movable chuck. The chuck was translatable in the vertical axis giving the ability to spatially profile the energy distribution from the ceiling (at the opening to the expanded volume) down through the volume of the chamber. The Langmuir probe was not translatable in this manner so densities were inferred using ion currents taken from the ion energy probe. Ion energy distributions measured at all locations and all conditions were Gaussian in shape with a narrow, peaked profile, all similar to the sample distribution from hydrogen at 300 mT and 3 kW shown in Figure 6.

The spatial profile of ion current and energy through the downstream chamber is shown in Figure 7. A plume of bright plasma was observed at the entry point to the chamber that quickly became diffuse through the remaining volume of the vessel. The ion current measured by the IEDF probe corroborated this observation (Figure 7a) indicating high plasma current at the ceiling of the chamber that fell off over a few centimeters then, at higher powers, largely leveled off as the probe was translated deeper into the chamber. At lower power, 2 kW, the plasma current continued to fall off almost linearly with distance. Ion energy was also highest near the ceiling of the chamber and in this region strongly affected by power averaging 12 eV at 2 kW increasing to 20 eV at 4 kW. Moving away from the ceiling, energy dropped to a nearly constant value through the remainder of the chamber (Figure 7b).

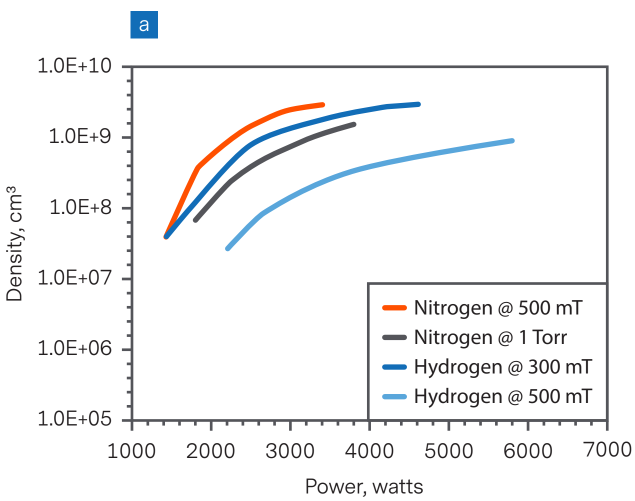

Figure 5. a) Projected density to the center of an open-volume chamber for nitrogen and hydrogen for source to probe spacing of 30 cm; b) projected density for hydrogen at 0.5 Torr showing the impact of reduced source to chamber/probe spacing.

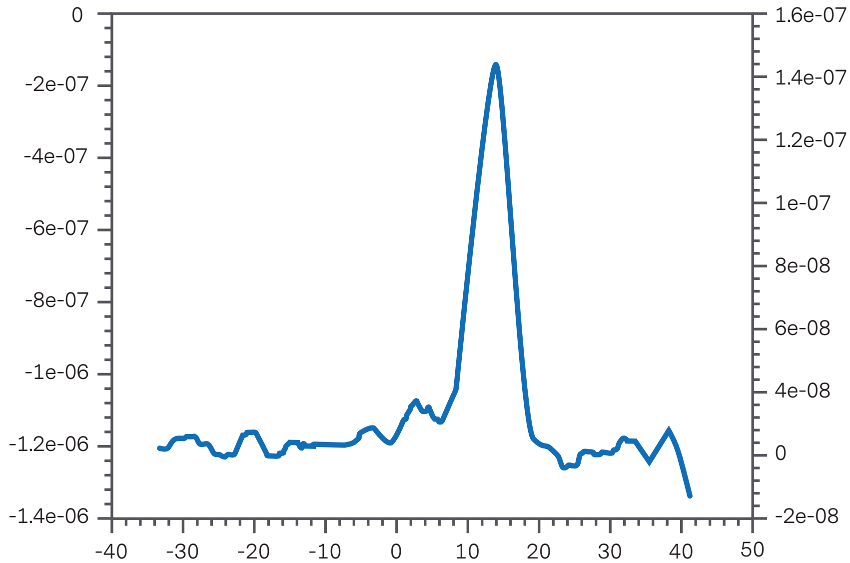

Figure 6. IEDF for hydrogen plasma projected to downstream chamber operated at 500 sccm, 300 mT and 3000 watts.

The effects of power on ion current and energy at each position are shown in more detail in Figure 8. Again, density (current) is shown to be much higher in the plume immediately below the entry point to the chamber. In this region, increasing power led to rapidly increasing density, and outside the plume, currents were lower and not as strongly influenced by power. Similarly, energy was more strongly influenced by power within the plume, and in the diffuse region through the bulk of the volume, was nearly constant, and largely independent of power.

While ion currents and plasma densities measured in the open, downstream chamber were decidedly less than those measured in the confined space, the ability to deliver even moderate densities into a large volume of this type appeared to be unique for the VHF RPS remote source. Table 1 compares downstream density measurements made using a toroidal ICP source compared to those made using the VHF RPS. Densities for all three gases tested were at least two orders greater for the VHF RPS. While operating the toroidal source, no ion current was registered at any power for nitrogen.

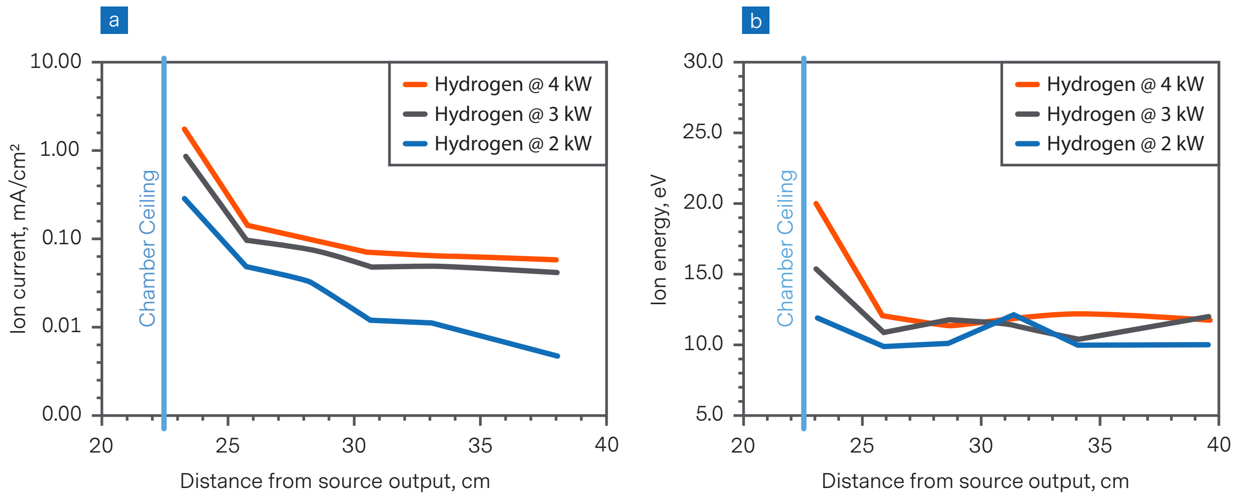

Figure 7. a) Ion current and b) ion energy projected from remote plasma source into large volume downstream chamber.

Table 1.

	Plasma density at chamber center	
Gas type	**VHF RPS**	**Toroidal ICP**
Argon (1 kW)*	3.8 x 10^{11} /cm^3	7.9 x 107 /cm^3
Hydrogen (3 kW)	1.8 x 10^9 /cm^3	1.2 x 107 /cm^3
Nitrogen (3 kW)	2.9 x 10^9 /cm^3	none registered

* Toroidal required 2 kW to operate, data shown for toroidal was taken at 2 kW.

Summary and Conclusions

A VHF capacitively coupled remote plasma source shows the interesting characteristic of supporting rather high plasma densities well beyond the immediate output of the device. Densities measured in a 50 mm ID confined space, 15 cm downstream from the device exceeded 10^{11} /cm³ at 1 Torr for all gases tested. Argon registered the highest density readings with hydrogen values slightly less than those for nitrogen. A threshold power for hydrogen and nitrogen in the 500 to 1500 watt range was required to expand the plasma into the confined space downstream from the chamber. Above this threshold power, plasma was detected throughout the entire length of the confined space. Beyond the confined space, plasma was seen to expand into a larger volume chamber with densities highest at the entry point. A higher density, higher energy plume of plasma appears to form at the ceiling of the reactor that quickly moderates in both density and energy into a more diffuse plasma that appears to fill the remainder of the chamber. Outside the bright plume within this diffuse glow energy remained nearly constant through the remainder of the chamber. Ion energies within this bulk region of the chamber for hydrogen were found to be quite low with a narrow single peak distribution averaging between 10 to 12 eV. Energies were largely independent of both power in addition to position, with the exception of the bright region in close proximity to the chamber ceiling.

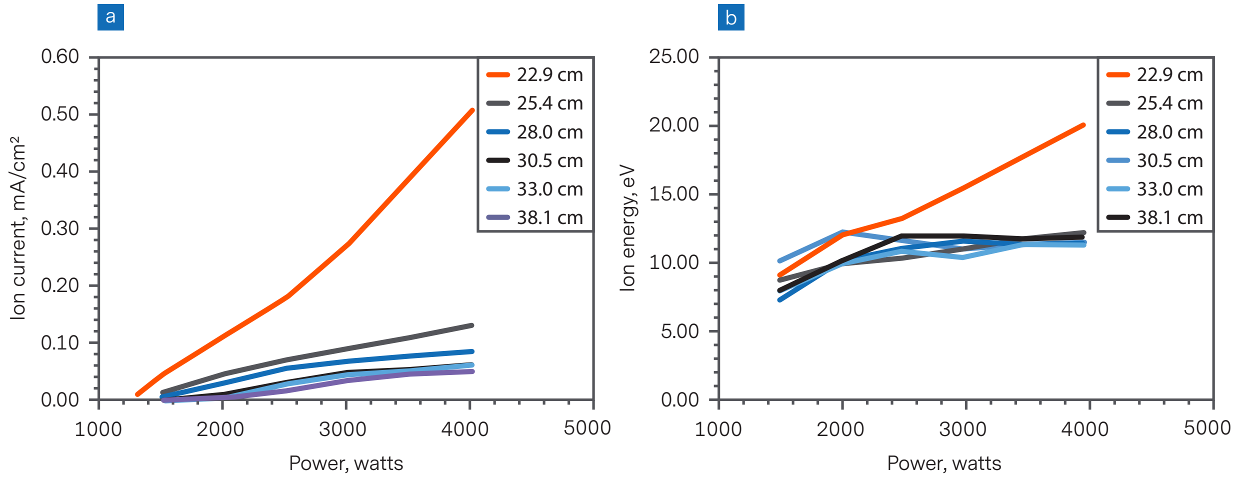

Figure 8. a) Ion current and b) energy projected to the downstream chamber as a function of VHF RPS power.

The projection of plasma into an expanded volume of this type appears to be a unique attribute of this type of plasma source. Compared to a toroidal ICP operated under the same conditions, densities measured in the downstream chamber were well over 100 times higher for the VHF capacitive source. This ability to project significant, low energy plasma well beyond the confines of the RPS itself may prove valuable especially for processes needing finer control over radicals and ions and for those involving sensitive or delicate structures that may be damaged by higher energy particles generated by in-situ sources.

Acknowledgements

The authors wish to thank Victor Brouk and Bill Hattel for their assistance in defining and refining the match circuitry used in the testing conducted in this review.

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