A 2-D scalable, VHF/UHF compatible, capacitively coupled plasma source for large-area applicaiton

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Abstract

A novel plasma source topology is described. The design is similar to a traditional capacitive diode, except the powered electrode is divided into a 2-dimensional tile array. Neighbouring tiles are powered 180-degree out of phase. Current coupled to the plasma through one tile is canceled by the neighboring tile, resulting in zero net current into the plasma and substrate. In this way, wavelength-effects causing center-to-edge voltage non-uniformities are avoided. This breaks the relationship between substrate size and rf frequency, enabling high-VHF to UHF frequency capacitive plasma sources for application to large area substrates. Plasma density profiles for a 300mm size system have good uniformity at 400 MHz, where the plasma loaded wavelength is about 50mm. The electromagnetic coupling in this configuration is considered. A 600x720 mm^2 multi-tile plasma source operated at 162 MHz is used to deposit PECVD Silicon with a narrow plasma gap (as low as 6mm) giving good uniformity films, without the 1/4-wavelength voltage non-uniformity effects.

Introduction

A recent trend in plasma etch and CVD has been the increase in rf frequency used to sustain the plasma. These higher frequencies offer at least two advantages. For capacitively coupled plasma sources, increasing the rf frequency increases the fraction of power coupled into the electrons and reduces ion energy gained in the sheath. Second, in systems operated at hundreds of Megahertz, Samukawa, et al.[1] presented evidence of changed electron kinetics which supports the idea of "high-frequency chemistry". However, the present trend of increasing rf frequency is incompatible with increases in wafer size to 450mm and beyond. The economic imperative to overcome these two opposing phenomena is presently being driven by PECVD of amorphous and microcrystalline silicon for the photo-active layer in thin-film photovoltaic devices (TFSiPV). At higher rf frequencies it has been shown that increased deposition rates and superior film properties can be achieved simultaneously.[2] However, for conventional plasma diode topology, substrate sizes exceeding 1m put substantial limits on the use of frequency as a control vector to increase deposition rate.

Power Coupling

Consider the two tiles on the left in Figure 1. At the rf-phase shown, current flows around the outside of tile 1 and into the wire connection at the top of the tile, and into the transmission line; Current flows into tile 2 from the wire connection at the top, which is fed from the transmission line (dV_{tile}/dt is negative in tile 1, and positive in tile 2.) First, consider the electrostatic coupling (ES) in the plasma. The dV/dt at the tile face results in displacement current, represented by the three vertical ($\hat{z}$) arrows in front of each tile. Real current is driven through the plasma, with displacement current between the plasma and substrate. The direction of the currents into the substrate are opposite (-/+$\hat{z}$ below the first/second tile) resulting in zero net current into the substrate. The impedance along this current path results in a voltage oscillation in the plasma potential (V_p), and thus a gradient in $V_p(y)$ [4]. Depending on the density, collisionality, and height of the plasma some, or indeed all, of this current between the two tiles can connect via the plasma, $I_p \hat{-y}$. Second, consider the electromagnetic coupling (EM) in the plasma. The dI_y/dt causes, from Faraday's law, a magnetic field, dB_x/dt. For sufficiently dense plasma, currents in the plasma limit the penetration of the magnetic field. The scale-length for the image currents is the skin-depth, $\lambda = c/\omega_{pe}$. For the density range of $n_e = 10^{10} - 10^{12}$ the skin depth is $50 - 5$ mm, respectively, comparable to typical plasma heights.

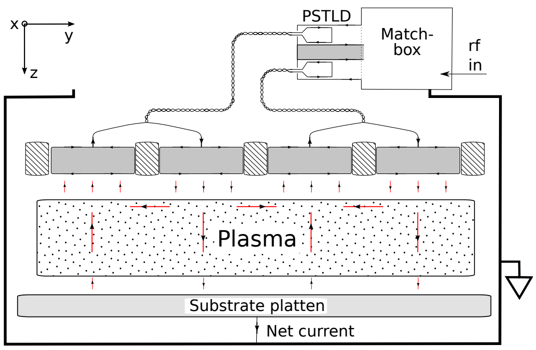

Figure 1: Cross-section of the PASTIS plasma source. rf currents at one phase are shown with arrows.

The total power deposited in the plasma is the combined effects of the ES and EM coupling between the tiles and the plasma.

Scaling to Large Area and High Frequency

The Hawaii plasma source is built onto a ISO-400 vacuum flange. A ground-ring, 300 mm diameter extends 40 mm into the vacuum region, with a 300 mm diameter quartz disk, 1.25 mm thick, closing the top of the re-entrant volume which is pumped with a TMP to high vacuum providing a 'vacuum dielectric'. Eight high-current, ceramic-insulated feed-thrus are situated across the ISO-400 flange, providing contact to the 8 tiles that comprise the source. The 8 tiles, each 55 mm wide and 65 mm tall, are arranged in the high-vacuum environment in 3 rows with 2x, 4x, and 2x tiles, respectively, with a 10 mm gap between tiles and approximately 1 mm spacing from the quartz disk. The source-flange is mounted on a 220 mm long, 400 mm long cylinder with multiple ports for gas-feed, pumping, diagnostics, etc. Figure 1 gives a reasonable impression of the cross-section of the source through the 4x central tiles, but in HAWAII the inter-tile dielectric is vacuum and the quartz-disk separates the plasma volume from the tiles.

Figure 2 shows ion saturation current (in Volts across a 10 kOhm sense resistor, -25V bias, 4 mm diameter single-sided planar probe, 35 mm from tiles) versus position across the chamber. Experimental conditions are: 1000 Watts at 13.56 MHz, 50 mTorr Nitrogen. Peaks in density associated with individual tiles are seen. The central area, approximately 180 mm diameter, is smaller than the width of the array. The edge of the plateau is 35 mm inside the tile edges; This is indicative of plasma formation at the face of the tiles, and 2-D diffusion away from the tiles.

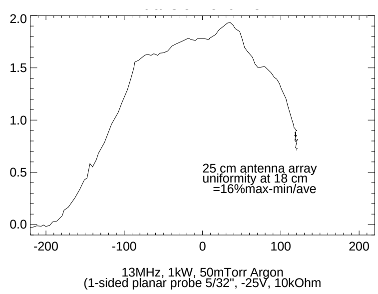

Figure 2: Ion saturation current vs position in HAWAII, 13 MHz.

In contrast, Figure 3 shows ion saturation current at identical operational conditions (same probe, same probe location, etc.) but powered with 200 Watts at 400 MHz. Multiple probe traces are shown, both from the front of the chamber and back of the chamber. The plasma density is twice as high, and the diameter over which the tile array couples power has increased by 50%. The increase in efficiency is due to the low drive voltages associated with the UHF sheath impedance and/or EM coupling which has an electric field parallel to the sheath and therefore does not couple power into the ions transiting the sheath. The greater plasma width supports the EM coupling description, as the radial electric field extends beyond the tile edges into the gap between the tiles and the radial ground-boundary of the source, located at 290 mm diameter. As the EM coupling occurs over a skin-depth penetration of 1-2 cm, the position of the probe is substantially closer to the volume with EM driven electron heating and ionization.

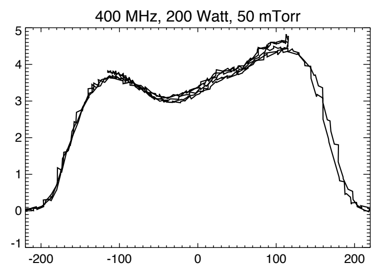

Figure 3: Ion saturation current versus position in HAWAII, 400 MHz

The MAMELUK system is a 600 mm x 720 mm tile array designed to demonstrate scalability of the multi-tile plasma source. The is functionally twice the extent of the PASTIS system in both width and height.

Figure 4: 600 mm x 720 mm PECVD μcSi:H layer from MAMELUK at 162 MHz.

Figure 4 shows a 600 mm x 720 mm substrate with a μcSi:H layer, grown in the MAMELUK system in the high-pressure-depletion process regime [6] at 162 MHz. The material properties of these films is given elsewhere [5]. The observable fringes show interference patterns from the camera flash; note that the expected 130 mm 1/4-wavelength patterns are not seen. Thickness measurements along the orthogonal scribe-lines seen in the photo give uniformity (max-min/average) of 10% in the 600 mm direction and 30% in the 720 mm direction. Ignoring the edge effects which are expected for substrate the same size as the source array, the uniformity is quite good. In particular, the EM coupling across the tile-gaps enables uniform deposition across the gaps, even in this HPD case with only 8 mm plasma gap.

Conclusions

The multi-tile plasma source operated in push-pull mode enables size scaling of the capacitive-couple plasma source beyond the 1/4-wavelength voltage non-uniformities limitations. Uniform plasma ion flux and μcSi:H deposition have been demonstrated on such systems.

Acknowledgements

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