VISUALIZATION OF POWDER TRAPPING IN RF SILANE PLASMAS BY 2-D POLARIZATION-SENSITIVE LASER SCATTERING

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Abstract - Powder studies in plasmas are motivated by the need to reduce contamination during plasma processing. Understanding particle dynamics requires comparison of spatially-resolved measurements with 2-D simulations. In this work, a cross-section of a capacitive discharge is illuminated with a polarized expanded laser beam and global scattered light is recorded by a CCD camera. For steady-state conditions with many particles, spatial size segregation is demonstrated by fringes which reverse with the light polarization. Plasma equipotentials near the potential maximum are visualized using the scattered intensity from a small amount of particles trapped in an argon plasma. Good agreement is found with 2-D fluid simulations.

Contamination by particles in plasma processing [1] has motivated extensive theoretical and experimental studies [2]. Theoretical studies of particle transport [3] and the effect of reactor geometry, [4] require experimental input from diagnostics of the particle dynamics. Particles are usually detected by *in-situ* laser scattering, where spatial resolution is obtained by displacing the reactor or the laser beam. In this work, we use a polarized expanded laser beam and visualize the global scattered intensity with a CCD camera [5]. Although the scattered intensity is a complex convolution of particle size, refractive index and number density [6], combinations of the 2-D scattered intensity images for particular polarizations can provide direct visualization of constant-size contours if particle size segregation exists [5].

The experiment and theory are described in detail elsewhere [5]. The capacitive reactor comprises two 130 mm-diam. electrodes: The lower, rf electrode has a concentric grounded guard ring and is capacitively-coupled to a rf source (10-30 MHz). The gases were pure silane, argon-diluted silane, or pure argon, at a total pressure of 0.1-0.2 mbar. The polarized, vertically-expanded beam of a 488 nm wavelength argon ion laser illuminates a diametrical cross-section of the electrode gap. A CCD camera records the 2-D scattering images at 90° with both source and detector polarizers in the vertical (W_v) and horizontal (W_h) directions consecutively, with equal incident intensities. We define $P = (W_v - W_h) / (W_v + W_h)$, which would be equivalent to the degree of linear polarization for the case of unpolarized incident light.

Figure 1 represents pseudocolor images of the 2-D scattered intensity for both polarizations (W_h and W_v) and the corresponding degree of polarization (P) for three different steady-state plasma conditions. Also shown are contours of the zones for which $W_h = 0$ and $W_v \neq 0$ (Rayleigh scattering [6]), which contain particles of radius < 20 nm. The first two plasmas are in a dynamic equilibrium where the powder structure is frozen even though particles continually form and escape from the plasma volume. The third is obtained from the second plasma by stopping the reactive silane flow leaving the powder trapped in the remaining argon plasma. The powder structure changes gradually during 2 min. from two layers to an annular structure. If the silane flow is restored, the band-like structure reappears within 0.5 s. This indicates that the trapping topography depends not only on reactor geometry but also on plasma composition. In addition, well-defined spatial fringes are observed within the layers or annulus of the scattering images in Fig. 1. This fine structure is not simply due to zones alternately with or without powder because the bright/dark regions are reversed for both polarizations. The degree of polarization P enhances fringe contrast and eliminates the dependence on number density. Moreover since P is a sensitive function of particle size [5], isochromes in pseudocolor represent contours of constant size. However, a unique determination of the size profiles is not possible since P is a multi-valued function of particle size [5].

For the experiments described above the particle number density was estimated to be at least 10^6 cm^{-3} [5], and strong particle coupling is expected [7]. Clearly, such a large amount of trapped particles strongly modifies the plasma: In order to provide useful data for comparison

with models of pristine plasmas, experiments have been performed with a small amount of particles trapped in an argon discharge to visualize the time-averaged plasma potential contours. This was achieved by partially exhausting the particles towards the pumps with a higher gas flux and brief interruptions of the rf power. The particles are expected to be trapped near the maximum of plasma potential if the electrostatic force is dominant. Thermophoretic [8] and gas drag forces [3] were minimized respectively by working at ambient temperature and with a low, diffused gas flow.

Figure 2 shows two comparisons between measurements and calculations using a 2-D fluid model [4] with the same reactor geometry, gas pressure, rf voltage and frequency. The DC self-bias and power dissipated in the discharge, calculated self-consistently in the fluid model, agree to within 30%. In Fig. 2 a) we compare the measured local plasma emission and an image produced from the calculated ionization rate [9] in pseudocolor. The former is obtained by Abel inversion of the chord-integrated total emission from a pristine argon plasma measured with the CCD camera. The agreement in Fig. 2 a) also shows that the model provides an adequate spatial description of complex plasma phenomena. In Fig. 2 b), the scattered intensity from trapped particles gives an image similar to calculations of the plasma potential contours. From the calculated potential contours it follows that the remaining particles are confined to within about 0.8 V below the 30.8 V maximum. If the number of particles is further reduced, the remainder concentrate on a thinner ring closer to the calculated potential maximum. Their local number density is fixed by the balance between Coulomb repulsion and electrostatic forces due to potential gradients. Systematic comparison of the measured and calculated data shown in Fig. 2 were performed for various geometries. Good agreement is found in all cases for electrode voltages less than 50 V amplitude. For voltages above 75 V a vertical splitting of the annulus, attributed to ion drag [3], begins to occur.

In summary, this technique provides direct visualization of particle size gradients, and reveals the importance of both plasma chemistry and particle content in determining the trapping topography. Mapping of the plasma potential contours by means of particle trapping, and imaging of the local plasma emission both provide experimental input to test 2-D simulations.

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FIGURE CAPTIONS

FIG 1: Pseudo-color images of the measured 2-D scattering intensities W_h, W_v and the corresponding image constructions of the degree of polarization P, for 3 steady-state plasmas. Rayleigh scattering zones in which particle radius < 20 nm are outlined in blue. Plasma conditions: pure silane 30 sccm; silane/argon at 5/20 sccm; and powder trapped in 20 sccm of argon, all at 0.1 mbar, 5W, 30MHz.

FIG 2: Pseudo-color images and contour plot comparisons of measured and calculated data using a 2-D fluid model. Plasma conditions: 10 sccm argon at 0.2 mbar and 25 V amplitude, 13.56 MHz. (a) Abel-inverted plasma emission and an image produced from the calculated ionisation rate; (b) dust particle location by scattered intensity measurement and calculated plasma potential contours (only four 0.4 V-spaced equipotentials below the 30.8 V maximum are represented).
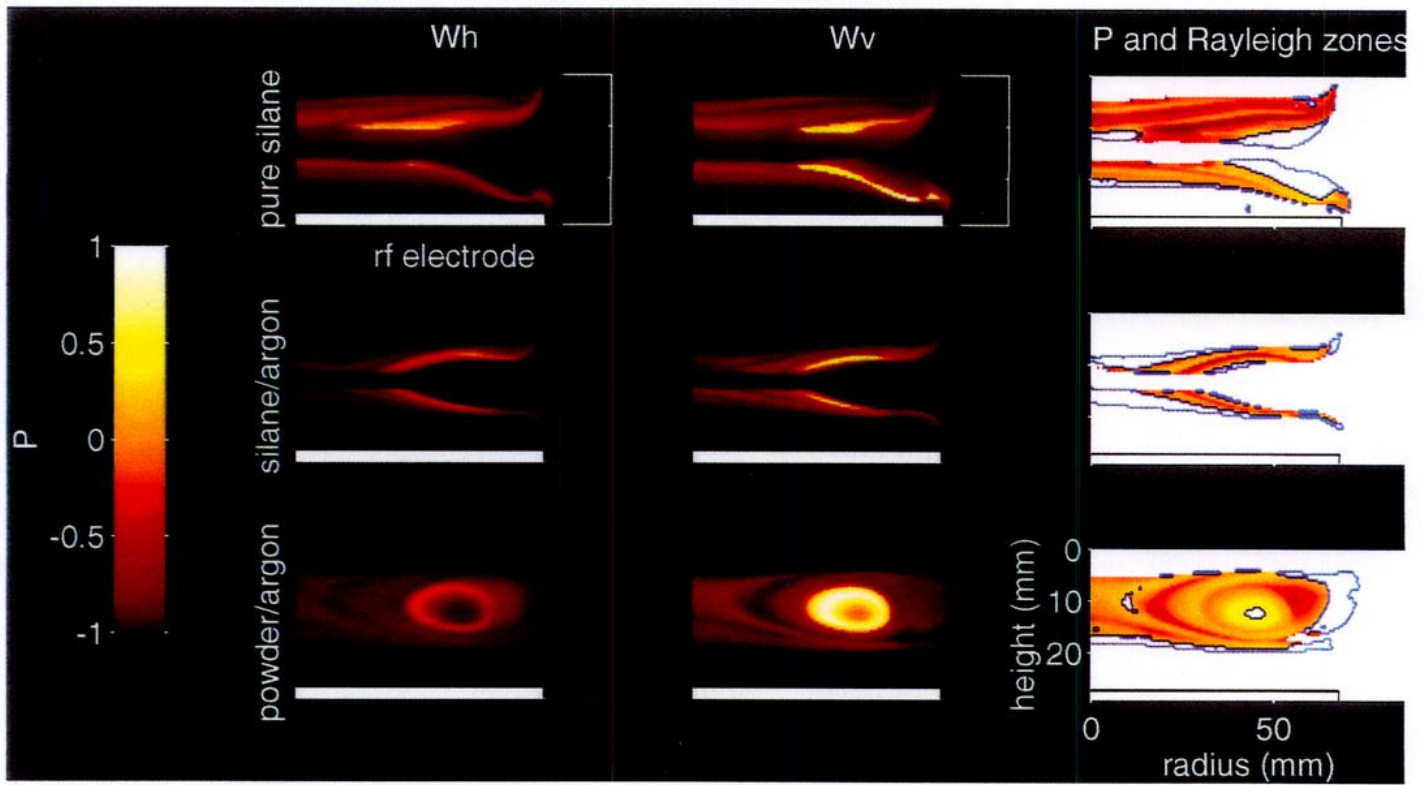
Wh

Wv

P and Rayleigh zones

pure silane

rf electrode

silane/argon

powder/argon

P

1

0.5

0

-0.5

-1

height (mm)

0

10

20

0

50

radius (mm)

FIG 1

a) Abel-inverted emission

ionisation rate (cm-3.s-1)

x 10^{13}

2