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Plasma molding over surface topography: measurement of energy and angular distributions of ions extracted through a large hole

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Abstract

Interaction of a plasma with a hole on a solid wall bounding that plasma was investigated by measuring the energy and angular distribution of ions extracted through a hole in contact with a high density deuterium plasma. Experiments were conducted by varying the ratio of the hole diameter to the sheath thickness (d/l) and the hole aspect ratio. In contrast to reported studies, holes with diameter larger than as well as smaller than the local sheath thickness were used. At one extreme, when $d/l \ll 1$, the plasma was not perturbed by the presence of the hole. The ion energy distribution (IED) had multiple peaks and the ion angular distribution (IAD) was Gaussian, peaking at zero angle with respect to the surface normal. At the other extreme, when $d/l \gg 1$, the plasma "leaked" through the hole. The IED had a single peak with a shoulder and the IAD was quite broad extending up to 30° off normal. The IAD was not affected by varying power and pressure suggesting that the plasma leaked completely out of the hole. When $d/l \approx 1$, the shape of the IED and IAD was in-between the two extremes mentioned above.

Keywords: Plasma molding; Sheath; Ion energy distribution; Ion angular distribution

1. Introduction

Understanding interaction of a plasma with a hole on a solid wall bounding that plasma finds applications in plasma "molding" over surface topography (for coating of curved objects, etching of surfaces of complex form, plasma immersion ion implantation, etc.) and ion extraction from a plasma by electrically biased grids (for use in neutron generators, ion beam assisted growth and etching of thin films, neutral beam etching, ion thrusters, neutron generators, etc.) [1,2]. The flux, energy and angular distributions of ions incident on the target are of primary importance in these applications. These quantities depend critically on the shape of the meniscus (plasma–sheath boundary) formed over the topography.

For plasma–grid hole interaction, the important length scales are the plasma–sheath thickness (l) and the diameter of the holes (d). The plasma–sheath meniscus is shaped differently according to the ratio of the hole diameter to the sheath thickness (d/l). Fig. 1 shows three cases of plasma meniscus over holes. In case (a), $d/l \ll 1$ so that the presence of holes does not disturb the plasma. The plasma–sheath boundary remains nearly planar as if the hole were a solid wall. In case (b), $d/l \gg 1$ so that the plasma–sheath interface follows the surface contour. Plasma leaks through and under the holes. Case (c) is the intermediate situation where $d/l \approx 1$ and there is significant disturbance of the plasma–sheath meniscus due to the presence of the holes.

Cases (a)–(c) in Fig. 1 will produce drastically different angular distributions of ions extracted from the plasma. Case (a) will result in a rather collimated ion beam (assuming no ion collisions in the sheath), while cases (b) and (c) will produce a divergent beam. The hole thickness can also affect the beam divergence. Thicker holes will produce less divergent beams, since the diverged ions will strike the sidewalls and vanish (turn into neutrals). Finally, the ion energy can be controlled by the magnitude of the bias applied to the hole. The required ion beam quality

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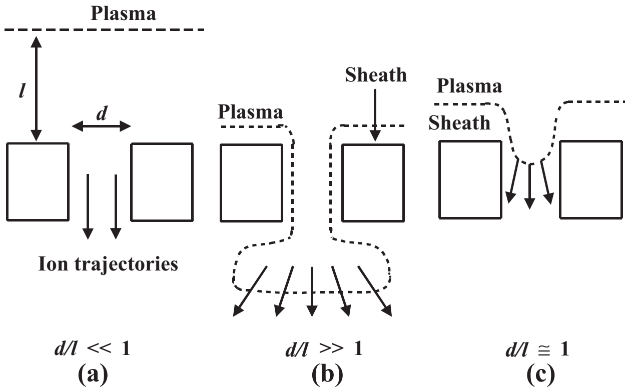

Fig. 1. Schematic of plasma–sheath meniscus over holes. (a) Sheath thickness, l, is larger than hole diameter, d, (b) l is smaller than d, and (c) l comparable to d.

(energy and divergence) depends on the application. For example, neutral beam sources for anisotropic etching applications require a collimated beam, while coating the sidewalls of microscopic features in ion beam assisted deposition or surface cleaning of sidewalls is facilitated with divergent beams.

In this work, interaction of a deuterium plasma with a hole was investigated. Deuterium was chosen because of its long mean free path, which made the sheath collisionless. In addition, it has been reported that the etch rate of silicon is enhanced by a deuterium plasma instead of a hydrogen plasma [3]. Holes were selected to represent the three possible cases of plasma–sheath meniscus depicted in Fig. 1: hole diameter is less than, larger than, and comparable to the sheath thickness. Holes with the same diameter, but with different thickness were also used to investigate the effect of the hole aspect ratio.

2. Experiment

Fig. 2 shows a schematic of a plasma source equipped with a gridded retarding field ion analyzer. An inductively coupled high-density plasma was used based on an earlier design by Chen [4]. The plasma source was described in detail in Ref. [5]. The plasma was ignited in a ceramic tube ($\mathrm{Al_2O_3}$) with 1.25 in. in inner diameter and 3.25 in. in length, by applying 13.56 MHz rf power to a three-turn coil through a matching network. The plasma source was also equipped with a Langmuir probe to measure bulk plasma parameters such as plasma density and electron temperature. The pressure and the power ranged 10–50 mTorr and 200–600 W, respectively. The source was mounted on an ultrahigh vacuum (UHV) chamber. During experiments (with a gas flowing into the plasma), a pressure of about 1×10^{-5} Torr was routinely achieved in the UHV chamber.

A gridded retarding field ion analyzer was located behind a hole electrode (grounded) to measure the flux, energy and angular distribution of ions striking the hole electrode. The ion analyzer consists of three screens and 11 annular current collecting electrodes. All screens and collecting electrodes are shaped as part of concentric hemispheres centered at the hole. Thus, this ion analyzer enables us to measure the ion angular distribution as well as the ion energy distribution.

The hole on the grounded stainless steel electrode was thought to be a well-defined single grid hole. Experiments were conducted for holes with various diameters. A 10-μm diameter hole was achieved by laser drilling of a 2.5-μm-thick nickel foil attached on the stainless steel electrode; 508-μm and 1270-μm diameter holes were directly drilled on a 254-μm-thick stainless steel electrode. These holes represent three cases mentioned earlier: $d/l \ll 1$ (d=10 μm), $d/l \gg 1$ (d=1270 μm), or $d/l \approx 1$ (d=508 μm). Experiments were also conducted with holes having the same diameter of 127 μm, but with different thickness (25.4 and 254 μm) to investigate the effect of the hole aspect ratio.

3. Results and discussion

3.1. Plasma parameters

The bulk plasma parameters such as electron temperature and bulk plasma density were obtained by Langmuir probe measurements. Fig. 3 shows the electron temperature in a deuterium plasma as a function of power at various discharge gas pressures. The electron temperature is nearly independent of power, and increases with decreasing gas pressure. Using the experimentally determined values of electron temperature, the ion density in the bulk plasma (i.e.,

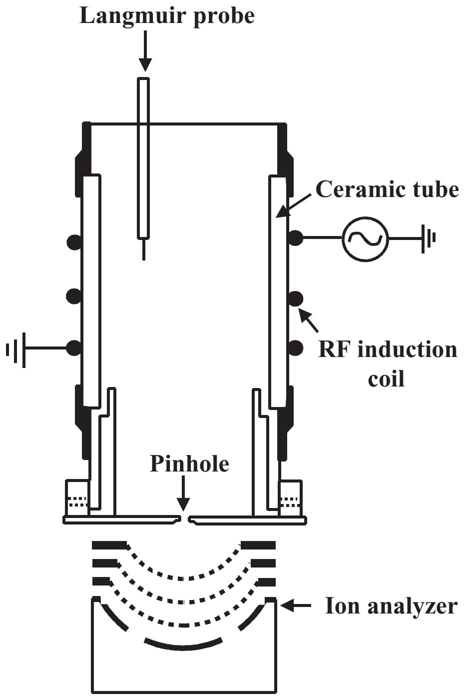

Fig. 2. Schematic of the plasma source equipped with a gridded retarding field ion analyzer.