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Laser-induced fluorescence measurements for plasma processing

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Abstract

Laser-induced fluorescence (LIF) has been used in plasmas for over 20 years and in plasma processing for about 10 years. Complexity and expense of this non-invasive diagnostic have limited it to laboratories although diode lasers offer hope for real-time processing metrology. LIF offers time- and space-resolved ion distribution functions, allowing study of plasma thermodynamics and transport and calibration of energy analyzers and mass flow probes. LIF was applied to an RF ion beam source (Veeco/Ion Tech). Ion distributions are compared with energy analyzer results and manufacturer's estimates. LIF distributions show narrower beam velocity spread, and better resolution, than energy analyzers. Beam ion energy can be measured rather than relying on manufacturer's estimate. Spatial resolution of LIF has permitted measurement of multidimensional ion velocity distributions in the bulk, and entering the sheath, near a conducting boundary wall.

Keywords: Plasma processing and deposition; Fluorescence

1. Introduction

Laser-induced fluorescence (LIF) developed in research laboratories beginning as early as 1975 [1–3]. Through scanning a single-frequency laser through a Doppler-broadened electronic resonance, ion velocity distribution functions in the direction of the laser beam could be determined (among other plasma properties). Subsequently, optical tomography was developed [4], and refined [5], giving multidimensional velocity distributions. Ion velocity components normal and parallel (and full velocity distributions) to surfaces can be measured non-intrusively with LIF.

Process plasmas began using LIF in the early 1990s such as with electron cyclotron resonance (ECR) [6–10], magnetron [11], and ion cyclotron sources [12]. LIF applications to plasma processing in glow discharges were reviewed in 1992 [13]. Helicon sources received LIF attention as well [14–17]. Transformer-coupled plasma (TCP) and reactive ion etch (RIE) sources have been studied with LIF [18,19] as have inductively coupled plasmas (ICP) [20] and micro-wave-driven chemical vapor deposition (CVD) sources [21]. Ion energy analyzers have been used to examine one-dimensional ion distributions in the output of ion beam etching and deposition sources [22] and multidimensional energy distributions in helicon sources [23,24]. Ion distribution functions found inside ion beam etching and deposition sources have been studied with LIF [25].

Ion velocity distribution measurements [26,27] in plasma sheaths and presheaths generally have involved plasma densities lower than those in plasma processing. This is due partly to reduction of sheath size (and debye length) with increasing plasma density. LIF resolves spatial scales of 1 mm easily but obtaining detectable signal as the sheath scale gets less than a millimeter is difficult.

2. Diagnostic arrangement

For experiments reported here, dye [3] and diode laser [28] systems were utilized for LIF work. Single species argon plasmas were produced and a metastable argon ion level was interrogated for LIF ion distributions and total signal. The dye laser system excited a 611.6 nm transition

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(observing 461.0 nm LIF) and the diode laser system excited 668.6 nm (observing 442.6 nm). Importantly, metastable states excited in these two cases reside about 19.2 eV and 17.5 eV above the ground state for argon and benefit from electron impact excitation for sufficient state population to be visible when LIF is applied.

3. Ion beams for etching and deposition

Commercial ion beams are used for many purposes in surface modification such as ion beam assist or deposition in optical coatings processes. Neutralized ion beams can be made with Kaufmann-type sources (or similar evolutions in design) using filament, hollow cathode, or rf sources. Some sources produce ion beams in the range of 100–1200 eV. Beams are characterized by beam density, energy, profile, species, etc. Beam energy is a function of combined accelerating/decelerating grid structures, environment into which the beam is launched (e.g., into plasma or no plasma), and plasma potential within the ion beam source. As a rule of thumb, many ion beam sources assume total beam energy to be of order 25 eV more than accelerating grids provide. As surface features require finer control over dimensions, ion beam energy and direction becomes more important. Perpendicular spread in ion energy may effect trenching capabilities, particularly processed aspect ratios via anisotropic etch. Ion beam energy variations may affect deposition product structure by varying the structural molecular content of the product etched by the beam for deposition. In the experiment described here, we studied ion beam output from a Veeco/Ion Tech 3 cm rf ion source with plasma bridge neutralizer.

LIF has been somewhat restricted to laboratory experiments because of difficulty of implementation with dye lasers and processing parameter issues reducing the range of its utility [29]. One concern slowing use of LIF for real-time metrology in processing has been difficulty getting detectable signals at higher pressures. Much LIF can be done with pressures below 1 mTorr but above that pressure metastable states are increasingly depleted via charge exchange and decreasingly produced due to a reduction in electrons with sufficient energy to excite the metastable population. For example, Fig. 1 shows how LIF signal diminishes with increasing pressure about 1 cm in front of the Veeco/Ion Tech rf ion source. Neutral gas is fed into the source (see [25] for source geometry) and the gas not released as ions comes out the accelerating grid along with the ion beam. A neutral gas cloud exists in front of the ion beam source, this gas cloud is available for charge exchange with the ion beam and produces a low density cold, non-drifting background plasma [25]. Inside the source, as pressure is raised, the tail population electrons needed for metastable excitation probably are reduced in density and charge exchange distances become sub-centimeter so metastable ions which may be diagnosed in the visible by LIF become scarce. The result may be seen in Fig. 1. We see the magnitude of the LIF signal goes roughly as the inverse of pressure. For the system utilized, the signal became undetectable at about 1 mTorr of argon in the main vacuum chamber, corresponding to a few SCCM of neutral argon put into the source. Many processing operations desire the fastest possible production and therefore benefit from maximizing gas flow. While the Veeco/Ion Tech source used for Fig. 1 data was being operated within the normal recommended SCCM range, other sources need to operate at higher pressures where LIF may not be feasible. At the same time, we wish to note that LIF can succeed in some cases at higher pressure [30].

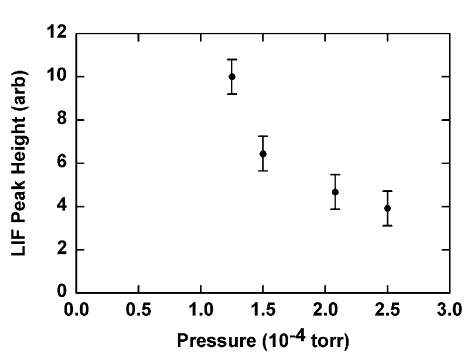

Fig. 1. LIF pressure dependence in front of beam source.

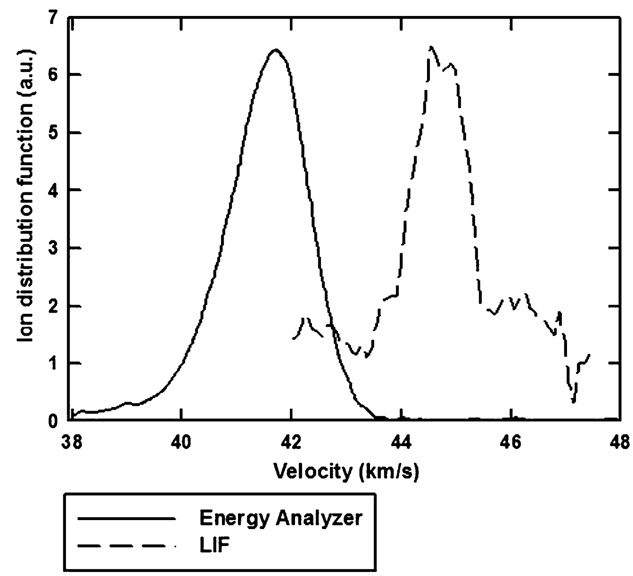

Fig. 2. Beam velocity distribution from energy analyzer and LIF, normalized to equal peak heights. LIF data are not corrected for Zeeman splitting (distribution appears wider than reality by factor of 6/5).

When this 3 cm rf ion beam source was operated in the range of 0.2–1.1 keV, ion beam energy was seen to be equal to acceleration potential plus an offset varying from 35 to 130 eV which appears due mostly to plasma potential within the ion beam source [31]. The plasma potential in the source may vary with source operating conditions which probably alter the electron temperature in the source plasma. Ion beam energies from similar sources have been measured in the past via energy analyzers [22,23] (beam width of

FWHM about 23 eV) and with pulsed LIF [32] (lacking precise energy resolution, FWHM of 137 eV). In comparison, our current setup of the ion beam source and CW laser system yielded beam widths of FWHM around 29 eV via energy analyzer and as low as FWHM of 12 eV via LIF. Fig. 2 shows representative ion distributions from the energy analyzer data and raw LIF scan (uncompensated for Zeeman splitting which broadens the apparent signal compared to actual velocity distribution). It can be seen that the LIF scan has greater resolution than the energy analyzer. Another factor uncovered with LIF here was drifting of the ion beam energy. With the greater resolution of LIF, the ion beam was observed to drift with time in tens of minutes over a range of about ±10 eV. We speculate this was due to changes in plasma potential within the source (accelerating grid power supplies were seen to stay within a ±2.5 V range).

4. Plasma sheaths and presheaths near conducting surfaces

Process plasmas often occur near surfaces. Ions in presheaths may be those leaving the bulk plasma, accelerating up to near sound speeds in the presheath [26,27] and increasing beyond that as they enter the sheath [27] or they may be at lower speeds if they were created by ionization in the presheath region. These measurements have shown the component of the ion speed normal to the surface. Energy analyzers have seen the angular dependence of velocity distributions in at least one circumstance at the plasma edge [24]. Collisions play a role in ion speeds and spreads in speeds as well.

In the present experiments, we arranged an argon plasma made by 18.62 MHz applied to a multi-turn coil similar (3.8 cm diameter with 6 turns extending 5.6 cm axially surrounded by a 7.4 cm diameter metal shell) to that in the Veeco/Ion Tech rf ion beam source but standing free with no dielectric chamber or accelerating grid structure. The rf coil was placed at the center of the 3 m long, 30 cm diameter vacuum vessel. We define the z-direction as along the axis of the vacuum vessel and the x-direction as perpendicular to the axis. A flat conducting wall surface

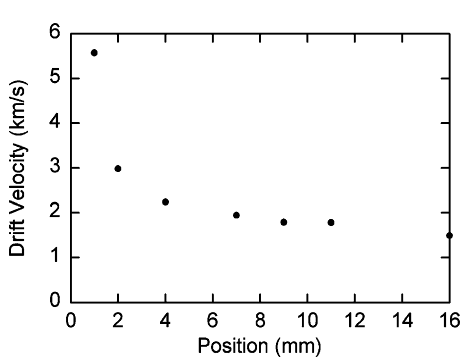

Fig. 3. Ion drift velocity normal to plate. Each data point is peak of velocity distribution at specified distance from plate.

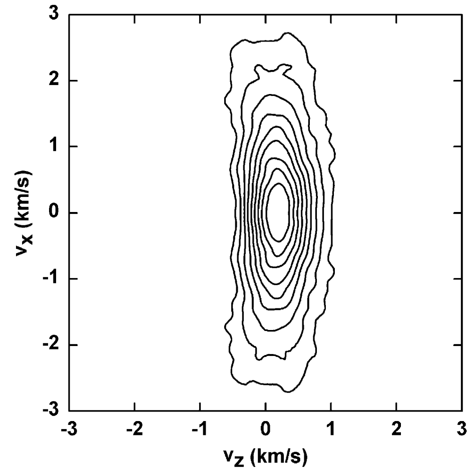

Fig. 4. Bulk plasma multidimensional ion velocity distribution function made by 18.62 MHz rf coil source in argon.

was placed 45 cm away from the source along, and perpendicular to, the axis of the vacuum vessel and ion velocity distributions were measured via LIF near the conducting surface. Hence, ion speeds in the positive z-direction are towards, and normal to, the conducting surface and x-direction speeds are parallel to the surface. Fig. 3 shows ion drift speeds at distribution peaks, in the z-direction, as a function of distance away from the conducting surface. The x-direction drift speed was approximately 0 m/s in the region where measurements were taken. Ions moved towards the conducting surface at about the ion sound speed in the presheath until they entered the sheath at about 1–2 mm from the surface. These results are consistent with those of Gulick et al. [26] and Severn et al. [27].

We applied optical tomography techniques [4,5] to get more than just the velocity distribution normal to the conducting surface. Fig. 4 shows the multidimensional ion distribution in the bulk plasma. Here we see undrifting ions

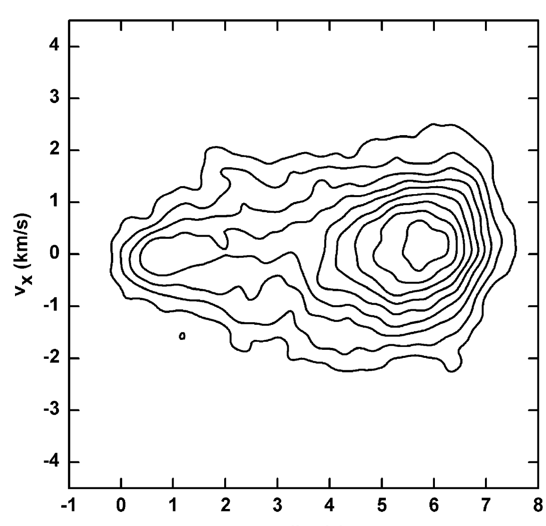

Fig. 5. Multidimensional ion velocity distribution function entering sheath near conducting surface for 18.62 MHz rf coil source argon plasma.

have substantial velocity spread in the x-direction of exciting rf electric fields.

When ions just reached the sheath, as shown in Fig. 5, the situation became more complex. Here we see many ions were accelerated to speeds near 6 km/s towards the surface and retained the perpendicular spread in velocities but additionally there were ions moving much slower towards the surface. Note although contours of equal phase space density initially appear closer together for slower ions (which therefore might be thought of as having colder perpendicular temperatures), in fact slower ions have comparable perpendicular temperatures to faster z-directed ions. These slower ions may be due to ionization in the sheath, or presheath, and subsequent metastable state filling so LIF may detect them. Ions do not approach the surface with uniform normal speeds and variation in angle of approach to the surface can be considerable. Surface processes which require uniformly energetic, normally directed ions may not be provided for suitably in this kind of rf plasma source and surface geometry. Ion distributions in sheaths and presheaths are not simply represented by a normal-drifting single velocity model.

Acknowledgements

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