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Ion Dynamics in a Single and Dual Radio Frequency Sheath
Measured by Laser-Induced Fluorescence

A dissertation submitted in partial satisfaction of the
requirements for the degree of Doctor of Philosophy
in Physics

by

Nathaniel Breckenridge Moore

2015

ABSTRACT OF THE DISSERTATION

Ion Dynamics in a Single and Dual Radio Frequency Sheath

Measured by Laser-Induced Fluorescence

by

Nathaniel Breckenridge Moore

Doctor of Philosophy in Physics

University of California, Los Angeles, 2015

Professor Walter Gekelman, Chair

Ion dynamics are investigated in a single and dual radio frequency sheath as a function of radius above a 30 cm diameter biased silicon wafer for the first time in an industrial inductively coupled (440 kHz, 500 W) plasma etch tool. Ion velocity distribution (IVD) function measurements in the argon plasma are taken using laser induced fluorescence (LIF). Planar sheets of laser light enter the chamber both parallel and perpendicular to the surface of the wafer in order to measure both parallel and perpendicular IVDs at thousands of spatial positions. A fast (30 ns exposure) CCD camera measures the resulting fluorescence with a spatial resolution of 0.4 mm. The dual-frequency bias on the wafer is comprised of a 2 MHz low frequency (LF) bias and a 19 MHz high frequency (HF) bias. The laser is phase locked to the LF bias and IVD measurements are taken at several different LF phases. Ion energy distribution (IED) function measurements and calculated moments are compared for several cases. For the LF case (no HF), the IEDs were found

to be highly phase dependent and were varied radially up to 10%. Calculated mean velocity vectors showed large impact angles near the surface of the wafer with the largest angles observed near the wafer edge. The LF experimental results are compared with simulations designed specifically for this particular plasma tool and showed good qualitative agreement. For the dual frequency case, IEDs were measured at two disparate phases of the phase-locked LF bias. IEDs were found to be multi-peaked and were well-approximated by a sum of Maxwellian distributions. The calculated fluxes in the dual frequency case were found to be substantially more radially uniform than the single frequency bias case. For industrial applications, this radially uniform ion flux is evidently a trade off with the undesirable multi-peaked structure in the IEDs.

The dissertation of Nathaniel Breckenridge Moore is approved.

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University of California, Los Angeles

2015

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LIST OF SYMBOLS AND ABBREVIATIONS

$A_{G(T)}$	area of grounded (target) electrode
CCD	charge-coupled device
CCP	capacitively coupled plasma
c_s	ion sound speed
E	energy, electric field
e	elementary charge
EETM	Electron Energy Transport Module
EMM	Electron Magnetic Module
$f(\epsilon), f(v)$	ion energy (velocity) distribution function
FKM	Fluid Kinetic Module
HF	high frequency
HPEM	Hybrid Plasma Equipment Model
$i(v_z)$	image function
ICP	inductively coupled plasma
IEAD	ion energy angular distribution function
IED	ion energy distribution function
IVD	ion velocity distribution function
J_0	current density
$\mathbf{k}, k_{\parallel}$	wavevector, parallel wavevector
LF	low frequency
LIF	laser-induced fluorescence

m	electron mass
M	ion mass
$n(x)$	density
$o(v_z)$	object function
PCMCM	Plasma Chemistry Monte Carlo Module
P_{rf}	rf power
r	radial position across wafer
s	sheath, sheath width
$s(v_z)$	source function
S_{stoc}	stochastic heating
T_e	electron temperature
$u(x)$	velocity
u_B	Bohm velocity
v	velocity
V_0, V_{rf}	applied bias
$v_{th,e}$	electron thermal velocity
x	position
z	height above wafer
$\Gamma_{i(e)}$	ion (electron) flux
ΔE_i	energy peak separation
ϵ_0	permittivity of free space
λ	wavelength
λ_{ce}	charge exchange mean free path

λ_D	Debye length
ν	frequency
ρ	charge density
τ	period
Φ	potential, bias phase
Φ_f	floating potential
ω	frequency

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PUBLICATIONS AND PRESENTATIONS

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Chapter 1

Introduction

Plasmas are critical in the fabrication of integrated circuits for microelectronics. In particular, plasmas are used extensively during the etching and deposition processes. After depositing a photoresist layer onto the wafer and selectively exposing the photoresist to ultraviolet (UV) light using an overlay of the desired pattern, the exposed film is removed via an etching process [1]. This etching is performed by biasing the wafer to enable ions in the plasma to bombard the exposed portion of the wafer and chemically react with the silicon, leaving the desired integrated circuit pattern.

In plasma etch tools, substrates are biased with radio frequency (rf) power in order to enhance ion impact energy incident upon the substrate. The energy and angle of impact of ions on the surface of wafers and dielectrics during plasma etching processes are critical parameters for the fabrication of microelectronic devices [1]. As narrow ion energy and flux ranges are required for both the selectivity of the chemical reactions used in etching and the prevention of physical damage due to unwanted physical sputtering, control of these parameters allows for finer control in etch rate and etch anisotropy [1, 2]. The region of the plasma where ions experience the majority of their acceleration – the sheath – is difficult to investigate due to it being thin, typically less than a few mm, and being transient due to the radio frequency biasing that is typically used. Electrical probes are difficult to use in the sheath as the probe and sheath are comparable in size. A probe creates its own sheath which could perturb the characteristics that are being measured. In addition, the physics describing ion dynamics in the sheath are highly nonlinear and thus difficult to study

analytically. In industry, etching optimization has thus been largely empirically driven by changing input parameters, such as the rf bias frequency, power, and duty cycle and observing the resulting product. Computer models [3-10] and analytic investigations [11-18] have also provided insights to the dynamics of ions while being accelerated through sheaths.

Control of ion energy distributions (IEDs) [or ion velocity distributions (IVDs)] in the context of plasma etching in microelectronics fabrication has made impressive progress. A variety of techniques have been developed which utilize multiple rf frequencies [6-8, 19], non-sinusoidal waveforms [9] and pulsed power [10, 20]. Control of IEDs in many of these techniques is based on based on the time for ions to cross the sheath, τ_{ion} , compared to the rf period, τ_{rf} . Defining $\omega_{rf} = 2\pi/\tau_{rf}$ and $\omega_{ion} = 2\pi/\tau_{ion}$, the ratio of these two frequencies, ω_{rf}/ω_{ion} , is an important parameter controlling ion dynamics in the sheath. For low frequency biases ($\omega_{rf}/\omega_{ion} \ll 1$), the transit of ions across the sheath during the rf period appears to be an ensemble of DC sheaths – the ion dynamics are essentially determined by the rf phase and voltage at which the ions enter the sheath [10]. In this regime, the time-averaged IED is bimodal [3]. As the rf bias frequency is increased, the separation between peaks of the bimodal distribution, ΔE_i , decreases. At high frequencies ($\omega_{rf}/\omega_{ion} \gg 1$) $\Delta E_i \rightarrow 0$ and the IED converges to a single peak at V_s , corresponding to the average sheath potential [10, 14]. The intermediate regime ($\omega_{rf}/\omega_{ion} \approx 1$) has been more difficult to analytically model as the ion dynamics heavily depend on both the rf phase at which the ions enter the sheath and how many RF periods the ion experiences in crossing the sheath [13-16]. As a result, most models addressing this regime have been numerical [3-10, 14, 15].

IEDs striking the substrate in plasma processing reactors are typically measured using energy resolved mass spectrometers or gridded ion energy analyzers. The first of these experiments measured the ion energy distribution function at a grounded electrode with a small sampling hole

[21, 22]. Subsequent experiments were able to take similar measurements at an rf-powered electrode [23-28]. The time-averaged, single position energy distribution function measurements from all of these experiments tended to confirm the predicted feature of two peaks separated in energy.

The measurements of IEDs and IVDs to date have typically emphasized the characteristics of the ions striking the substrate. Several studies have investigated IVDs in the presheath. These have been done over unbiased surfaces [29-32], dc biased surfaces [33, 34], and in rf sheaths [35]. Claire *et al.* [31] measured both longitudinal and transverse IVDs in both the presheath and sheath above a floating plate in a multipolar dc discharge. Measurements along a line extending from the presheath to the sheath above an rf biased silicon wafer were done by Jacobs *et al.* [35] The work presented in this dissertation is an extension of this experiment. In this work, measurements of IVDs using planar laser-induced-fluorescence (LIF) in a commercial inductively coupled plasma (ICP) sustained in an Ar/O₂ gas mixtures of a few mTorr pressure with both a single lower frequency (2.2 MHz) and dual frequency (2.2 MHz and 19 MHz) rf bias on the substrate are described. IVDs are measured from the bulk plasma, into the presheath and through the sheath. The biases used in this experiment place this experiment in the intermediate regime. For the single frequency experiment, $\omega_{2\text{ MHz}}/\omega_{ion} = 0.5$. For the dual frequency experiment, $\omega_{2\text{ MHz}}/\omega_{ion} = 0.76$ and $\omega_{19\text{ MHz}}/\omega_{ion} = 5.5$. The transit time for the 2.2 MHz bias in the dual frequency case increased from the single frequency case as the bias voltage was increased for the dual frequency experiment.

Chapter 2

Sheath Physics

DC Sheaths

Sheaths form at the boundary between a plasma and any finite physical surface (such as a chamber wall, a probe, silicon wafer, etc.) with which the plasma comes into contact [36, 37]. In the absence of applied fields, ions and electrons will both strike the surface and recombine. Electrons, however, will be lost to the wall at a faster rate due to their larger thermal velocities. This disparity in species depletion leads to a net positive space charge in the plasma near the surface boundary. In addition, the charging of the physical surface due to the electron loss rate will result in a potential difference between the negative surface and the neutral plasma bulk. This region of positive space charge, called the sheath, acts as a potential barrier in order to keep the more mobile electrons in electrostatic equilibrium [36]. Namely, the height of the barrier is such that the electron flux that can cross the barrier remains equal to the ion flux to the wall. A qualitative depiction of the sheath is shown in Fig. 2.1 [1].

In a 1D geometry, following Lieberman [1], the height of this barrier can be solved for by beginning with the conservation equations for the ion energy and flux from the edge of the sheath to the surface. Letting $x=0$ be the sheath edge, $u(x)$ be the ion velocity, $u_s = u(0)$, and setting $\Phi(0)=0$, we have by conservation of energy

$$\frac{1}{2}Mu_s^2 = \frac{1}{2}M(x)^2 + e\Phi(x),$$

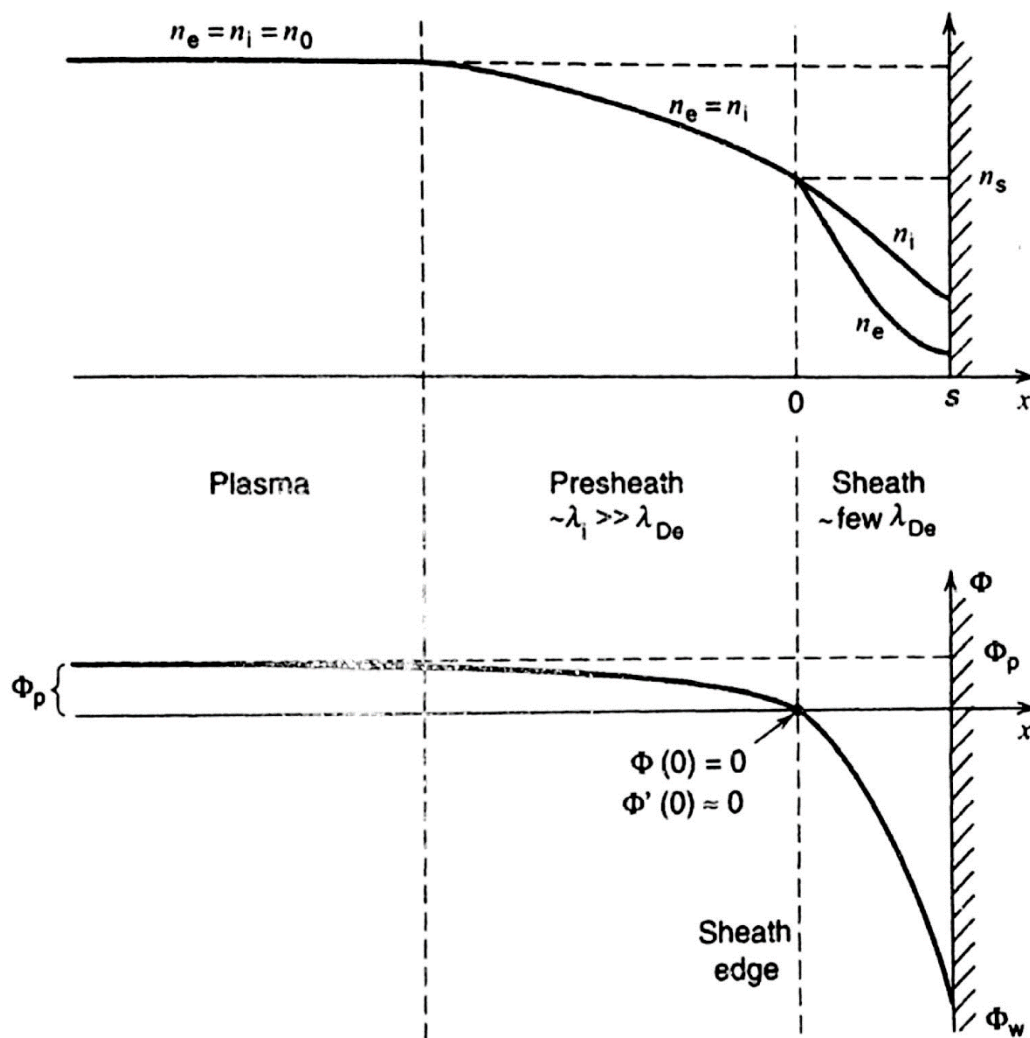


Figure 2.1. The qualitative dependence of the ion and electron density and the plasma potential from the bulk plasma, through the presheath, and in the sheath near a boundary surface as depicted in Ref. 1 by Lieberman. Reprinted with permission. Copyright © 2005 by John Wiley & Sons, Inc. All rights reserved.

or equivalently,

$$\frac{1}{2}Mu(x)^2 = \frac{1}{2}Mu_s^2 - e\Phi(x). \quad (2.1)$$

Assuming no ionization in the sheath, from the conservation of ion flux, where $n_i(x)$ is the ion density and $n_i(0)=n_i$, the density at the sheath edge, we have

$$n_s u_s = n_i(x)u(x).$$

Solving for $u(x)$ and inserting into eq. 2.1 yields

$$\frac{1}{2}M \left(\frac{n_s u_s}{n_i(x)} \right)^2 = \frac{1}{2}M u_s^2 - e\Phi(x),$$

where we can obtain a relationship for the ion density:

$$n_i(x) = n_s \left[1 - \frac{2e\Phi(x)}{Mu_s^2} \right] - \frac{1}{2} \quad (2.2)$$

We assume that the electron density, $n_e(x)$, is given by the Boltzmann relation:

$$n_e(x) = n_s e^{\frac{e\Phi(x)}{kT_e}} \quad (2.3)$$

From eqs. 2.2 and 2.3, we can use Poisson's equation and the charge densities to obtain a non-linear differential equation for the potential:

$$\frac{d^2\Phi}{dx^2} = -\frac{\rho}{\epsilon_0} = \frac{en_s}{\epsilon_0} \left[e^{\frac{e\Phi(x)}{kT_e}} - \left(1 - \frac{2e\Phi(x)}{Mu_s^2} \right)^{-1/2} \right]$$

Making a variable substitution of $\epsilon_s = \frac{Mu_s^2}{2e}$, where $e\epsilon_s$ is the ion energy at the sheath edge, we obtain

$$\frac{d^2\Phi}{dx^2} = \frac{en_s}{\epsilon_0} \left[e^{\frac{e\Phi(x)}{kT_e}} - \left(1 - \frac{\Phi(x)}{\epsilon_s} \right)^{-1/2} \right] \quad (2.4)$$

To solve for $\Phi(x)$, we first define the quantity $\Psi \equiv \frac{d\Phi}{dx}$. Next, multiply each side by Ψ and integrate. The left hand side yields:

$$\int_0^x \frac{d\Phi}{dx} \frac{d^2\Phi}{dx^2} dx = \int_0^x \Psi \frac{d\Psi}{dx} dx = \frac{1}{2} \Psi^2 = \frac{1}{2} \left(\frac{d\Phi}{dx} \right)^2. \quad (2.5)$$

The right hand side gives

$$\frac{en_s}{\epsilon_0} \int_0^x \frac{d\Phi}{dx} \left[\frac{e^{e\Phi}}{kT_e} - \left(1 - \frac{\Phi}{\epsilon_s}\right)^{-1/2} \right] dx,$$

or, canceling the dx 's and integrating over Φ :

$$\begin{aligned} & \frac{en_s}{\epsilon_0} \int_0^\Phi \left[\frac{e^{e\Phi}}{kT_e} - \left(1 - \frac{\Phi}{\epsilon_s}\right)^{-1/2} \right] d\Phi \\ &= \frac{en_s}{\epsilon_0} \left[\frac{T_e}{e} e^{\frac{e\Phi}{kT_e}} - \frac{kT_e}{e} - 2\epsilon_s + 2\epsilon_s \left(1 - \frac{\Phi}{\epsilon_s}\right)^{1/2} \right] \end{aligned} \quad (2.6)$$

From eq 2.5, the result from eq. 2.6 must be greater than or equal to 0. Since this would only be an issue for small Φ , we Taylor expand eq. 2.6. To second order,

$$\frac{kT_e}{e} e^{\frac{e\Phi}{kT_e}} = \frac{kT_e}{e} + \Phi + \frac{e\Phi^2}{2kT_e} + \dots$$

and

$$\left(1 - \frac{\Phi}{\epsilon_s}\right)^{1/2} = 1 - \frac{\Phi}{2\epsilon_s} - \frac{\Phi^2}{8\epsilon_s^2} + \dots$$

In other words,

$$\frac{1}{2} \frac{e\Phi^2}{kT_e} - \frac{1}{4} \frac{\Phi^2}{\varepsilon_s} \geq 0 \Rightarrow \varepsilon_s \geq \frac{1}{2} \frac{kT_e}{e}$$

or:

$$u_s \geq \sqrt{\frac{kT_e}{M}} = c_s \quad (2.7)$$

which is the Bohm sheath criterion. It states that an ion that enters the sheath must have a velocity greater than or equal to the ion sound speed in the plasma.

To calculate the potential drop between the sheath edge and the floating surface, we can compare and equate the electron and ion fluxes at the surface [1]. Assuming a Bohm flux for the ion throughout the sheath ($\Gamma_i = n_s u_B$, where n_s is the ion density at the sheath edge and u_B is the Bohm velocity from eq. 2.7) and an electron thermal speed of $v_{th,e} = \sqrt{\frac{kT_e}{2\pi m}}$, where m is the electron mass, we have

$$\Gamma_e = n_e v_{th,e} = n_s e^{\frac{e\Phi_f}{kT_e}} \sqrt{\frac{kT_e}{2\pi m}}.$$

Equating the fluxes of the two species yields

$$n_s \left(\frac{kT_e}{M} \right)^{1/2} = n_s \sqrt{\frac{kT_e}{2\pi m}} e^{\frac{e\Phi_f}{kT_e}},$$

or, solving for Φ_f ,

$$\Phi_f = -\frac{kT_e}{e} \ln \left(\frac{M}{2\pi m} \right)^{1/2} \quad (2.8)$$

In other words, the floating potential of the surface is proportional to the electron temperature, with a proportionality constant of $\ln \left(\frac{M}{2\pi m} \right)^{1/2}$. For argon, the gas used in the following experiment, this constant is approximately 4.7. At the sheath edge, ions at the Bohm velocity will have energy $\frac{1}{2}Mu_B^2 = \frac{kT_e}{2}$. Hence, for an unbiased surface, singly ionized argon ions will bombard the surface with energy $\frac{kT_e}{2} - e\Phi_f = 5.2kT_e$.

A direct current (dc) bias can be applied to the surface of a metal in order to further enhance the ion impact energy. When applying a high-voltage bias $-V_0$, where $V_0 \gg kT_e/e$, ion current to the surface will follow the Child-Langmuir Law. In order to show this, we first assume that the ion kinetic energy at the sheath boundary is much smaller than the kinetic energy gained traversing the sheath (namely, $\frac{1}{2}Mu(x)^2 \gg \frac{1}{2}Mu_B^2$). Furthermore, a large bias on the surface will repel all but the most energetic electrons. Since $V_0 \gg kT_e/e$, we will assume that there are no electrons

energetic enough to traverse the sheath; namely, we assume $n_e=0$. Starting from these assumptions, we can obtain an approximate solution for the potential, density, and sheath width. Starting with the energy conservation equation (eq. 2.1) and the stated assumptions, we obtain

$$\frac{1}{2}Mu(x)^2 = -e\Phi(x). \quad (2.9)$$

Once again, assuming no ionization within the sheath, ion current is conserved throughout:

$$en(x)u(x) = J_0.$$

As before, solving for $u(x)$ and substituting into eq. 2.9, we obtain a relationship for $n(x)$:

$$\frac{J_0^2}{e^2n^2} = -\frac{2e\Phi}{M} \Rightarrow n(x) = \frac{J_0}{e} \left(-\frac{2e\Phi(x)}{M} \right)^{-1/2}. \quad (2.10)$$

Taking $n_e=0$, we use eq. 2.10 and Poisson's equation to obtain a differential equation for the potential across the sheath:

$$\frac{d^2\Phi}{dx^2} = -\frac{J_0}{\epsilon_0} \left(-\frac{2e\Phi}{M} \right)^{-1/2} \quad (2.11)$$

As before, we solve eq. 2.11 by multiplying each side by d/dx and integrate from $x=0$ to x . From

eq. 2.5, the left hand side equals $\frac{1}{2} \left(\frac{d\Phi}{dx} \right)^2$. The right hand side equals

$$-\int_0^\Phi \frac{J_0}{\epsilon_0} \left(-\frac{2e\Phi}{M} \right)^{-1/2} d\Phi = -\frac{2J_0}{\epsilon_0} \left(\frac{2e}{M} \right)^{-1/2} (-\Phi)^{1/2}. \quad (2.12)$$

Setting eq. 2.12 equal to the left hand side, $\frac{1}{2} \left(\frac{d\Phi}{dx} \right)^2$, we take the square root of both sides and separate the differential:

$$\frac{d\Phi}{dx} = 2 \left(\frac{J_0}{\epsilon_0} \right)^{1/2} \left(\frac{2e}{M} \right)^{-1/4} (-\Phi)^{1/4} \Rightarrow d\Phi (-\Phi)^{-1/4} = 2 \left(\frac{J_0}{\epsilon_0} \right)^{1/2} \left(\frac{2e}{M} \right)^{-1/4} dx$$

Integrating both sides, we obtain an expression for the potential in the sheath,

$$-\Phi^{3/4} = \frac{3}{2} \left(\frac{J_0}{\epsilon_0} \right)^{1/2} \left(\frac{2e}{M} \right)^{-1/4} x \quad (2.13)$$

From the applied bias, we know that $\Phi(s) = -V_0$. Inserting this into eq. 2.13, we can obtain a relationship between the applied bias and the ion current:

$$\left(\frac{J_0}{\epsilon_0}\right)^{1/2} = \frac{2}{3} \frac{V_0^{3/4}}{s} \left(\frac{2e}{M}\right)^{3/4},$$

or, solving for J_0 :

$$J_0 = \frac{4}{9} \epsilon \left(\frac{2e}{M}\right)^{1/2} \frac{V_0^{3/2}}{s^2}, \quad (2.14)$$

which is the Child-Langmuir Law for space-charge limited current [1, 38].

From eq. 2.13, we note that we can obtain an expression for the width of the sheath, s . Using the Bohm velocity (eq. 2.7), the current at the sheath edge is $en_s u_B$. Hence, from ion current conservation, $J_0 = en_s u_B$. Using this, we solve eq. 2.14 for s and obtain

$$s = \frac{\sqrt{2}}{3} \lambda_{Ds} \left(\frac{2eV_0}{kT_e}\right)^{3/4}, \quad (2.15)$$

where we have used $\lambda_{Ds}^2 = \frac{\epsilon_0 kT_e}{e^2 n_s}$.

Of particular interest to plasma etching are the ion dynamics within the sheath. The sheath is the region where the ions experience the majority of their acceleration, so the evolution of the velocity distribution function from the plasma bulk through the presheath and sheath is critical to ion bombardment of the surface of the silicon wafer and hence the quality of the resulting etch. For DC sheaths, assuming a negative bias $-V_0$ with respect to the plasma potential, positive ions

at the wafer surface will have a monoenergetic distribution with $E=eV_0$, where E is the ion energy and e is the charge of the ion.

Several experiments have been performed to measure ion dynamics in unbiased [29-32] and DC biased sheaths [33, 34, 39]. Sadeghi et al. [29] used laser-induced fluorescence to measure the ion velocity distribution functions both parallel and perpendicular to a glass plate surface in an inductively coupled plasma device. The ions were shown to accelerate perpendicular to the surface as the ions moved from the plasma bulk closer to the surface, indicating the presheath region. Claire et al. [31] performed similar LIF measurements in the presheath and sheath near a floating plate in a multipolar dc discharge.

Goeckner et al. [39] also used laser-induced fluorescence to measure ion velocity distribution functions and ion densities near a $V_0=-100$ V DC biased electrode in a multidipole chamber. The authors confirmed that, as expected, ion velocities increased in the sheath as the ion density correspondingly decreased. These measurements were in agreement with flux conservation. The authors also found that while the Child-Langmuir description of the sheath approximately predicted correct ion densities near the surface of the electrode, the model fails to predict ion densities closer to the boundary between the bulk plasma and the sheath.

RF Sheaths

For the purpose of plasma processing, a high voltage dc bias is not sufficient for control of ion energies. As the biased surface is typically a semiconductor or dielectric, a dc discharge current cannot be sustained across the sheath due to charging of the surface from bombarding ions. One solution to this problem is to instead use a radio frequency (rf) bias. During phases where the bias

is 0 or positive, electrons can once again be lost to the surface. With such a bias, there can be a large ion current during negative potential phases while still maintaining 0 net current throughout an rf cycle.

Due to the high degree of non-linearity and transient nature of rf sheaths, these regions are extremely difficult to study analytically. Most analysis and simulations have focused on sinusoidal waveforms and specific frequency regimes defined by the parameter ω_{rf}/ω_{ion} , where $\omega_{rf} = 2\pi f_{rf}$ is the rf bias frequency and ion is related to the ion transit time across the sheath by $\tau_{ion} = 2\pi/\omega_{ion}$. To obtain an expression for the ion transit time, we start with a collisionless dc Child sheath [1]. We have from eqs. 2.13 and 2.14 that

$$\Phi = -V_0 \left(\frac{x}{s}\right)^{4/3}. \quad (2.16)$$

Assuming a small initial ion energy as compared to the potential (i.e., $-e\Phi \gg \frac{1}{2}Mu_B^2$) as before, inserting eq. 2.16 into eq. 2.9 yields

$$u(x) = \left(\frac{2eV_0}{M}\right)^{1/2} \left(\frac{x}{2}\right)^{2/3} = \frac{dx}{dt}.$$

By separating the differential, we can integrate both sides of the expression and obtain the following relation for $x(t)$:

$$\frac{x(t)}{s} = \left(\frac{t}{3s}\right)^3 \left(\frac{2eV_0}{M}\right)^{3/2}.$$

Setting $x(\tau_{ion}) = s$ and solving for τ_{ion} , we find that

$$\tau_{ion} = 3s \left(\frac{M}{2eV_0}\right)^{1/2}. \quad (2.17)$$

For rf sheaths, if we take τ_{ion} to be the average transit time across all cycles, then by averaging the right side of eq. 2.17 we arrive at an expression for the critical parameter ω_{rf}/ω_{ion} [14]:

$$\frac{\omega_{rf}}{\omega_{ion}} = \frac{\tau_{ion}}{\tau_{rf}} = \frac{3\bar{s}\omega_{rf}}{2\pi} \left(\frac{M}{se\bar{V}_s}\right)^{1/2}, \quad (2.18)$$

where $\bar{V}_s$ is the average bias potential and $\bar{s} = \frac{\sqrt{2}}{3}\lambda_{Ds} \left(\frac{2e\bar{V}_s}{kT_e}\right)^{3/4}$ (eq. 2.15) is the average sheath width.

For the low frequency regime, $\omega_{rf}/\omega_{ion} \ll 1$. The ions traverse the sheath must faster than the time it takes the bias phase to change appreciably. The ion response to the sheath potential is thus extremely dependent on the bias phase at which the ion enters the sheath [14]. Ions will only respond to the potential the of the bias at which the ion enters the sheath and the problem essentially reduces to an ensemble of high voltage dc sheaths, which can be modeled with Child's Law and was discussed in the previous section.

Conversely, for the high frequency regime, $\omega_{rf}/\omega_{ion} \gg 1$. For these sufficiently high frequencies, ions will experience many phases of the rf bias as they fall through the sheath and will no longer respond to the instantaneous sheath potential [14]. The phase at which the ions enter the sheath does not greatly affect the dynamics within the sheath and hence the ions will effectively only experience the time-average of the rf bias.

The time-average of the ion energy distribution function at the rf biased surface is well known to be bimodal (Fig. 2.2) [1, 14]. For low frequency sheaths, these peaks correspond to phases in the rf bias where ions are the most likely to enter the sheath. Namely, this corresponds to times where the sheath potential is varying the least, i.e., where $dV_s/d(\omega t_0) \approx 0$, where V_s is the potential at the sheath edge, and t_0 is the time at which the ion enters the sheath. For a sinusoidal waveform of the form

$$V_s(t) = \bar{V}_s + V_{rf} \sin(\omega t), \quad (2.19)$$

this would correspond to the minimum and maximum of the bias potential. Hence, for a bias of this form, this would correspond to a peaks in the distribution function corresponding to the minimum and maximum sheath potentials and the peak separation, ΔE_i , being equal to V_{rf} , the amplitude of the sinusoidal bias.

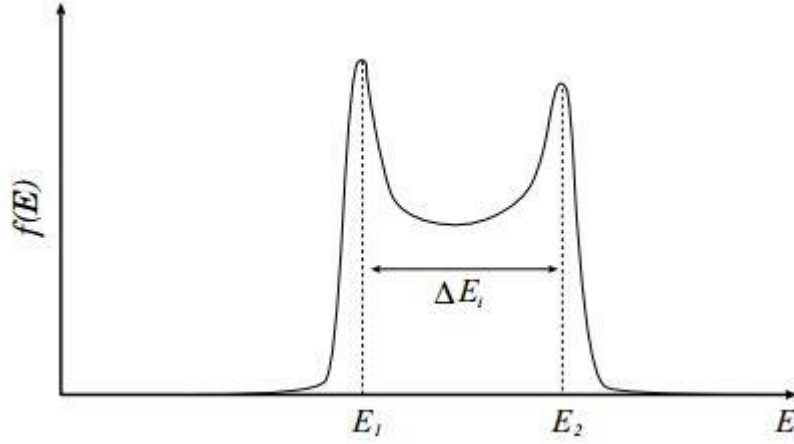


Figure 2.2. A typical time-average bimodal ion energy distribution function from Ref. 14 (DOI:10.1088/0963-0252/8/3/202). © IOP Publishing. Reproduced with permission. All rights reserved.

As the driving frequency is increased, the separation between peaks in the ion energy distribution function decreases (Fig. 2.3) [1, 14]. At high frequencies, the peaks eventually converge to a monoenergetic value corresponding to the time average potential. Benoit-Cattin and Bernard [11] used a Child-Langmuir model to estimate the separation between the peaks in the ion energy distribution function and found that

$$\Delta E_i = \frac{4e\bar{V}_s}{\pi}(\omega/\omega_{rf}). \quad (2.20)$$

As ω_{rf}/ω_{ion} increases, eq. 2.20 shows that the peak separation ΔE_i will approach 0 and the distribution function will become monotonic, as expected.

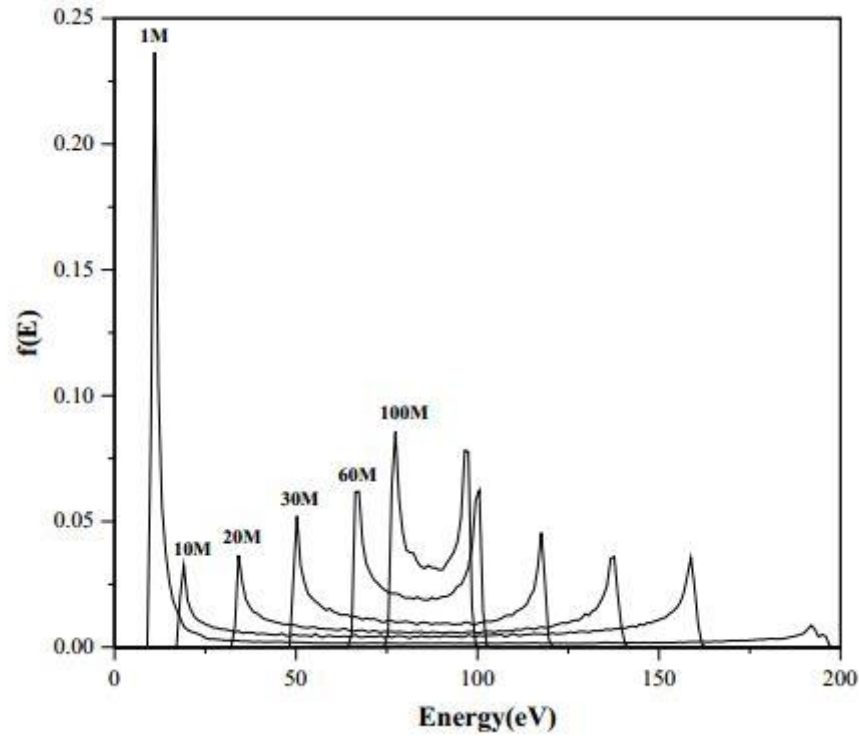


Figure 2.3. Ion energy distribution functions at various bias frequencies calculated from a PIC simulation from Kawamura *et al.* (DOI:10.1088/0963-0252/8/3/202) [14]. The energy separation between peaks of the bimodal IEDs decreases as the bias frequency is increased. © IOP Publishing. Reproduced with permission. All rights reserved.

Additional peaks can occur in the ion energy distribution function for plasmas where the ion transit time is larger than the bias period and charge exchange collisions between ions and neutrals are significant (Fig. 2.4) [40]. In these conditions, Wild and Koidl found that stationary ions will be created in the sheath due to charge exchange collisions and will tend to accumulate during phases when the rf sheath is collapsed. Each additional time that the sheath front passes these accumulated ions, an additional peak will arise in the time-averaged energy distribution function as these stationary ions now accelerate towards the surface. PIC simulations by Lee et. al

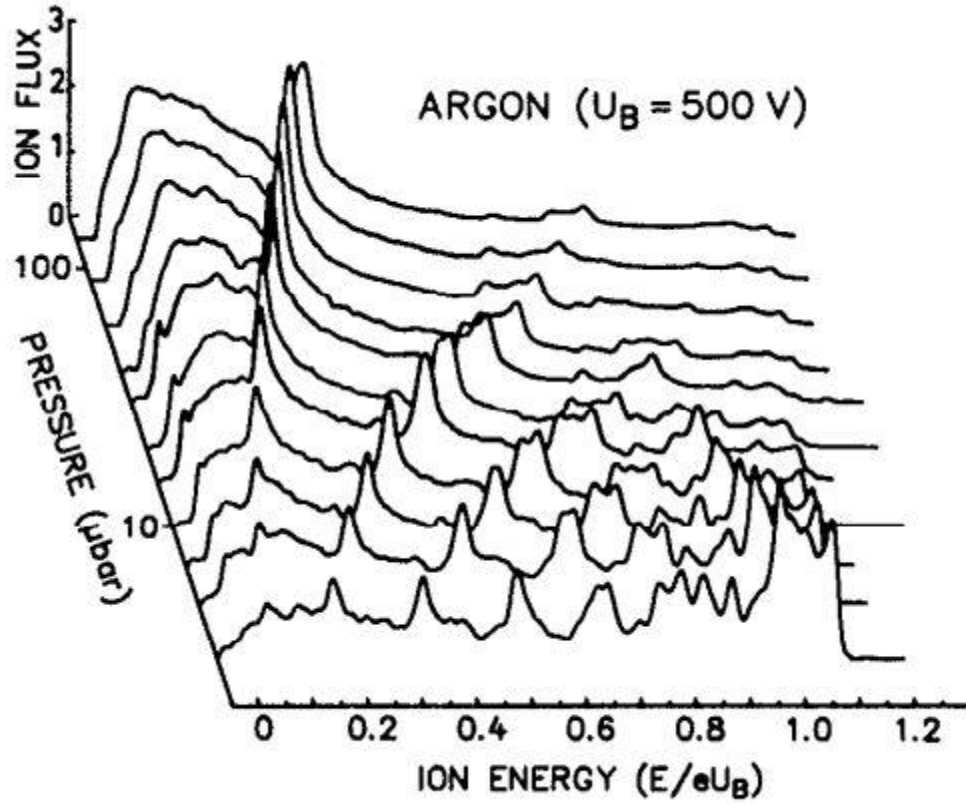


Figure 2.4. Ion energy distribution functions measured by Wild and Koidl [40] in a high frequency sheath at several chamber fill pressures. Additional peaks arise in the distribution due to modulation from the rf sheath and ionization within the sheath due to charge exchange collisions. Reprinted with permission from C. Wild and P. Koidl, J. Appl. Phys. **69**, 2909 (1991). Copyright 1991, AIP Publishing LLC.

[7] showed similar peaks in the distribution function for both single and dual frequency rf sheaths at various bias powers.

For either the low frequency or high frequency case, for a sinusoidal bias of the form given by eq. 2.19 the peaks in the time-averaged distribution function will be shifted by an amount corresponding to the dc offset $\bar{V}_s$. Most capacitively coupled discharges used in industry are highly asymmetric (i.e., the driven surface has an area much smaller than the grounded surface) with a blocking capacitor which prevents any net dc current. For such a configuration with $V_{rf} < 0$, a dc offset $\bar{V}_s$ builds between the driven and grounded surface - often referred to as the self-bias - and can be estimated by equating the electron current collected by the driven and grounded surfaces [14]. Doing so, Kawamura *et. al* calculated the self-bias as

$$\bar{V}_s = V_{rf} \sin\left(\frac{\pi A_G - A_T}{2 A_G + A_T}\right), \quad (2.21)$$

where A_G and A_T are the areas of the grounded and target (driven) surfaces, respectively. When $A_G \gg A_T$, as is the case for highly asymmetric capacitive discharges such as the experiment described in this dissertation, eq. 2.21 reduces to $\bar{V}_s = V_{rf}$. Using this result, the assumed bias from eq. 2.19 becomes

$$V_s(t) = V_{rf}[1 + \sin(\omega t)],$$

such that the maximum value of the sheath potential is $2V_{rf}$.

The intermediate frequency regime ($\omega_{rf}/\omega_{ion} \approx 1$) is not as well understood as the other two regimes. In this case, the ion dynamics are extremely dependent on the phase which the ion entered the sheath. In addition, the ions will experience several phases of the bias as they traverse the sheath. Sobolewski [41] developed a fluid model for all ω_{rf}/ω_{ion} ranges to predict currents, potentials, and power deposition within the sheath. Predictions from this model compared favorably to experimental results. However, most attempts to describe the evolution of the ion energy distribution functions have been numerical rather than analytical [3-10, 14, 15].

Experiments measuring the ion energy distribution functions in rf sheaths to date have typically used energy resolved mass spectrometers or gridded ion energy analyzers at either grounded [21, 22] or rf powered electrodes [23-28, 42] to measure the surface ion bombarding energy. Few experiments have measured the distribution function directly within an rf sheath. Using laser-induced fluorescence, Jacobs et. al [35] measured the phase-resolved ion velocity distribution function in a rf presheath and sheath in the intermediate frequency ($\omega_{rf}/\omega_{ion} = 0.3$) regime. The calculated time-averaged distribution function exhibited the characteristic bimodal distribution and the phase-resolved measurements were extremely phase-dependent, as expected.

Dual Frequency Sheaths

For finer control of the etching process in the fabrication of microelectronic circuits, control of the ion energy distribution functions and the ion flux bombarding the surface of the substrate is crucial. For low frequency sheaths, it was previously shown that there will be a peak in the distribution corresponding to the maximum negative voltage. Control of the ion density (and hence, the flux) cannot be performed with this single frequency, however, as changing input power

to accommodate the desired flux would cause the distribution function shift correspondingly. For high frequency sheaths the peak separation, ΔE_i , of the time-averaged ion energy distribution approaches a monoenergetic distribution. Thus, by using a sufficiently high frequency with a fixed voltage and variable input power, a monoenergetic ion energy distribution could possibly be achieved with a chosen flux based dependent on the input power. However, at these high frequencies, electromagnetic effects from standing waves will occur and negatively affect the plasma uniformity [43, 44].

Many novel bias configurations have been investigated in order to solve this issue and achieve greater control of the ion energy and angular distribution functions. One such technique is to use non-sinusoidal waveforms to bias the substrate [2]. Wang and Wendt [45] proposed a bias consisting of a short voltage spike with a slow ramp and simulated the resulting IEDs. They found that this bias resulted in a much narrower IED compared to a sinusoidal bias and was nearly monoenergetic. In practice, the authors noted that this configuration might be difficult to implement in practice as no matching network could be used as the bias consists of frequencies of multiple harmonics. Barnat and Lu [46] measured IEDs using an ion energy analyzer on the surface of an electrode powered using pulsed dc bursts. The authors found that the IED width decreased with increasing pulse frequency and the relative heights of the low and high energy peaks could be controlled with the pulse duty cycle. Agarwal and Kushner [9] investigated the use of non-sinusoidal tailored waveforms through computational techniques. They found that the width and energy of the IEDs could be adjusted using this configuration.

Pulsed plasmas have also been investigated as a method of controlling ion energy distribution functions [2]. In such a configuration, the source generating the plasma is pulsed and the bias applied to the substrate is pulsed on during the plasma afterglow. During the afterglow,

the electron temperature will decay significantly within a few microseconds of the plasma shutoff. The lower electron temperature will result in a more narrow distribution of ions entering the sheath, and hence a narrow IED at the surface of the biased substrate [2]. In addition, the angular distribution will also be narrower, resulting in a more directional surface bombardment. Xu *et. al* [47] pulsed a dc bias in the afterglow of a pulsed capacitively coupled plasma. The bias was applied to an accelerating ring which surrounded the plasma near the grounded surface of the CCP. IEDs were measured at the grounded surface using a gridded ion energy analyzer. IEDs measured during the afterglow were found to be significantly narrower than those measured during the plasma discharge. The monoenergetic peak could also be controlled by varying the dc bias on the accelerating ring.

The most widely used method to attempt to control the ion energy distribution function in the sheath is to use a dual frequency bias. By using both a low frequency and high frequency bias together, it can be possible to achieve independent control of the ion energy and flux [48-50]. In such a configuration, the low frequency (lf) power controls the ion energy while the high frequency (hf) controls the ion density, and hence the ion flux bombarding the surface of the wafer or substrate [1].

Many models describing ion dynamics within dual frequency sheaths make the simplifying assumptions $|V_{lf}|/|V_{hf}| \gg 1$ and $\omega_{hf}/\omega_{lf} \gg 1$ [1, 51]. In such a configuration, the mean potential drop across the sheath (and hence the ion energy) can be approximated by $\bar{V}_s = |V_{lf} + V_{hf}|$ and will be predominantly controlled by the low frequency bias. Using a Child sheath approximation from eq. 2.15, we also have that $\bar{s} \propto V_{rf}^{3/4}$, where $\bar{s}$ is the average sheath width. Hence, the sheath can be thought of primarily as a low frequency sheath with modulations from the high frequency

bias [51]. The ion energy distribution will thus be primarily bimodal from the low frequency bias with peaks due to modulations from the high frequency bias.

The primary role of the high frequency bias is to control the plasma density. For low pressure discharges, the main mechanism for power deposition into the plasma is stochastic heating, also known as collisionless heating [1, 51]. This heating arises from power transfer between the moving sheath front and mobile electrons, akin to the energy gained by a ball bouncing off of a moving wall. In these conditions, $n \propto \bar{S}_{stoc}$ and $\bar{S}_{stoc} \propto \omega^2 V_{rf}$, where $\bar{S}_{stoc}$ is the mean power transfer due to stochastic heating [1]. In other words, as $n \propto \omega^2 V_{rf}$, the density will primarily depend on the high frequency bias power.

Most investigations into dual frequency sheaths have been computational [49-53]. Kim *et al.* [49] developed an analytic model for dual frequency sheaths using an effective frequency and compared the results to PIC simulations. Using an effective frequency, the authors obtained several other effective plasma parameters, such as plasma density, plasma potential, and particle currents. The authors also found that the reduction of the size of the bulk plasma due to expansion of the sheath can be significant and needs to be taken into consideration. Boyle *et al.* [50] used a PIC simulation to show that is possible to achieve independent control of the ion energy and flux in a CCP reactor by using two frequencies that are sufficiently different. The authors note that for their simulations, in order for this independent control to be achieved the sheath size must be comparable to the size of the bulk plasma. Kim and Lee [54] confirmed this assertion as they found that with a larger bulk plasma size (~20 times larger than the sheath), the plasma density increases with low frequency power rather than decrease.

Investigations of the ion energy distribution in a dual frequency sheath have also been performed using computational techniques [52, 53]. Lee *et al.* [52] performed PIC simulations to

calculate IEDs, plasma potential, self-bias, and densities in a CCP reactor. The authors found the IED to be multi-peaked. With increasing low frequency voltage, the shape of the IEDs changed such that the peaks in the distribution smoothed out. The sheath width, plasma potential, and self-bias also increased with increased low frequency voltage while the plasma density decreased. Zhang *et al.* [53] used a hybrid model to calculate ion energy and angular distributions in a CCP reactor. The authors found the IEDs to be bimodal and multi-peaked in between. The relative heights of the bimodal peaks, and hence the ion flux, could be controlled by changing the input high frequency power. The authors also investigated effects from changing the relative phases between the low and high frequency powers. They found that by alternating between disparate phases in the high frequency power, the smaller peaks between the broad bimodal peaks were smoothed out.

Several experimental investigations into dual frequency sheaths have also been performed [19, 55-58]. Booth *et al.* [19] measured electron density and ion flux in a 50 mTorr Ar/O₂ CCP using a hairpin resonator probe and ion flux probe, respectively. Measurements were taken in the bulk plasma at several combinations of 2 MHz and 27 MHz bias powers (Fig. 2.5). The investigators found that both electron density and ion flux increased with both increasing low and high frequency power and the ratio of the two to be relatively constant. This demonstrated that the plasma density and flux can still be strongly coupled to the low frequency bias in a dual frequency bias configuration. The authors also noted that the effect from the low frequency power could be caused by enhanced ionization caused by secondary electron emission from the oxidized silicon wafer. As there is oxygen present in the plasma, the surface of the silicon wafer will oxidize to SiO₂, which has a much larger (16 times) secondary electron yield [59].

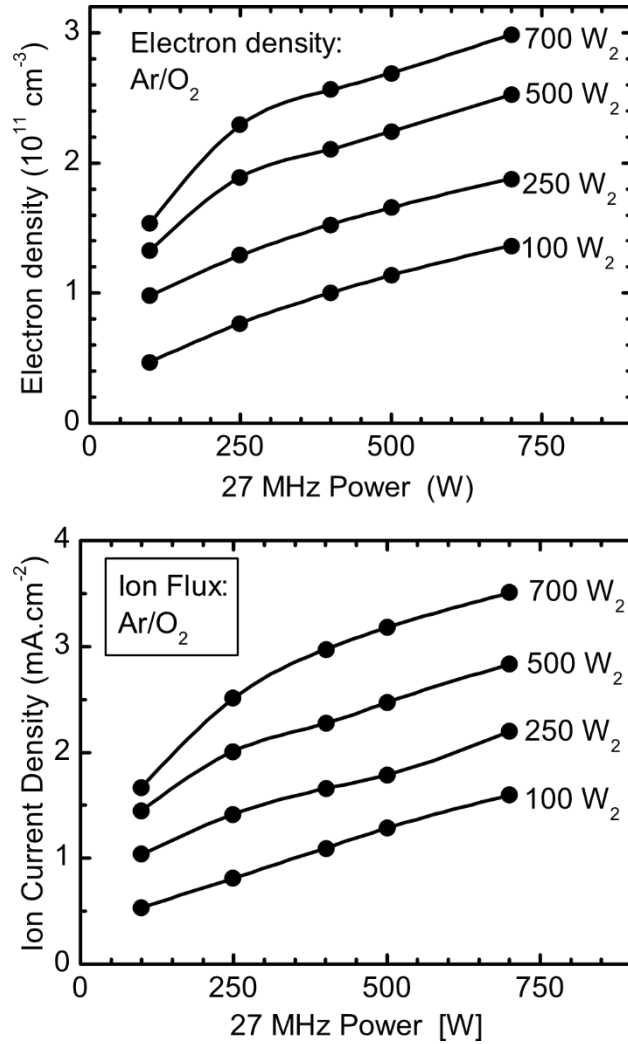


Figure 2.5. Electron densities and ion fluxes measured by Booth et al. [19] in a dual frequency CCP at several low frequency powers (DOI:10.1088/0963-0252/19/1/015005). Measurements show an increase in the electron density and ion flux with increasing low frequency power, indicating the continued presence of coupling between the low and high frequency biases. © IOP Publishing. Reproduced with permission. All rights reserved.

Electron density measurements have been performed in the plasma bulk in dual frequency CCP reactors by using rf compensated Langmuir probes [58, 60]. Yuan *et al.* [60] found in a plasma driven with 60/13.56 MHz biases, at lower pressures (10 mTorr) the electron density did not change appreciably with varying low frequency power, suggesting independent control of the ion energy and flux can be achieved in these conditions. At higher pressures (30 mTorr - 100 mTorr) this was not the case increasing the low frequency increased the plasma density. Measurements performed by Ahn and Chang [58] in a 2/27.12 MHz dual frequency capacitive discharge were consistent with these results as at higher pressures (50 and 300 mTorr) increasing the 2 MHz power simultaneously increased the electron density.

Liu *et al.* [55] measured argon and oxygen ion energy distribution functions on a grounded electrode in a dual frequency CCP using an energy resolved mass spectrometer. The authors investigated the dependence of the bimodal shape of the IED on low frequency bias frequency and power (Fig. 2.6). Measurements showed a strong dependence on the high energy peak with frequency and power. As the frequency of the low frequency bias increased, the separation between the two peaks of the distribution decreased as the high energy peak approached the lower energy peak. The low energy peak remained at relatively the same energy, corresponding to approximately the floating potential, at all frequencies. The size of the peak increased with frequency, suggesting that the sheath remains collapsed for a longer time. The opposite dependence was observed with increasing bias power.

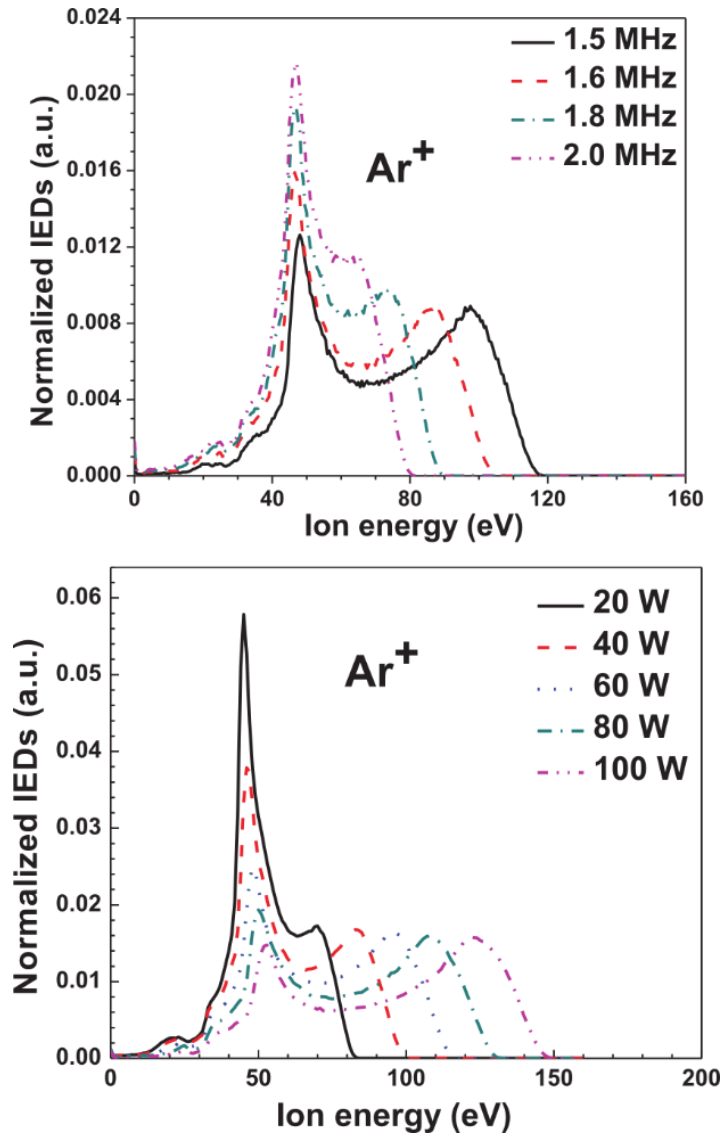


Figure 2.6. Ion energy distribution functions measured by Liu et al. [55] at the grounded electrode in a dual frequency Ar/O₂ CCP reactor at several low frequency bias frequencies and powers at a fixed high frequency bias (DOI:10.1088/0022-3727/46/23/235202). Measurements showed a relatively stationary lower energy peak and a high energy peak the decreased with increased frequency and increased with increased power. © IOP Publishing. Reproduced with permission. All rights reserved.

Summary

The properties of the sheath near a biased silicon wafer are critical to the dynamics of the bombarding ions used for etching processes. Radio frequency biasing is typically used in industry in order to control the ion energies and fluxes. For independent control of both of these ion properties, a dual frequency bias is often implemented such that the low frequency bias controls the ion energies and the high frequency bias controls the ion flux. Due to the small size and transient nature of the sheath region, direct measurements of the ion properties are difficult and investigations into these regions have focused on modeling and simulations. Laser-induced fluorescence, a non-invasive diagnostic, has been used to measure ion velocity distribution functions above unbiased, dc bias, and single frequency bias surfaces, but not in industry-relevant dual frequency sheaths.

Chapter 3

Laser-Induced Fluorescence

Laser-induced fluorescence (LIF) is a non-invasive plasma diagnostic that has been used to measure various ion and plasma properties [61-63]. The technique allows for multiple spatial positions to be simultaneously probed with a temporal resolution determined by the width of the laser pulse (typically on the order 10 ns) and the lifetime of the excited state. In the context of low pressure plasmas for materials processing, the technique has been used to measure ion densities, drift velocities, and energy distribution functions in dc and rf sheaths [29-35, 64-67]. The electric field inside an rf sheath has also been measured by using a two-step process called LIF-dip in which the field is calculated from the Stark shifted fluorescence from ions [68, 69].

The implementation of the LIF technique used in this experiment uses the $3d\ ^2G_{9/2} - 4p\ ^2F_{7/2}$ transition in argon (Fig. 3.1). A metastable ion state (State 1, $3d\ ^2G_{9/2}$) absorbs a laser photon with an energy matching a specific transition to a short-lived excited state (State 2, $4p\ ^2F_{7/2}$). Depending on the metastable state being probed, this excited state can radiatively relax to the original state or to a different state (State 3, $4s\ ^2D_{5/2}$). This second transition will then emit a fluorescent photon at a different energy from the pump photon whose frequency can be detected, for example, with a photomultiplier tube or CCD camera. This is the LIF signal. The strength of the LIF signal is proportional to the density of State 1, which is representative of the ground state density [39]. This method can be used to obtain IVDs in the plasma. The frequency of the incident photon in the frame of reference of the metastable atom in the State 1 $\rightarrow$ State 2 transition will

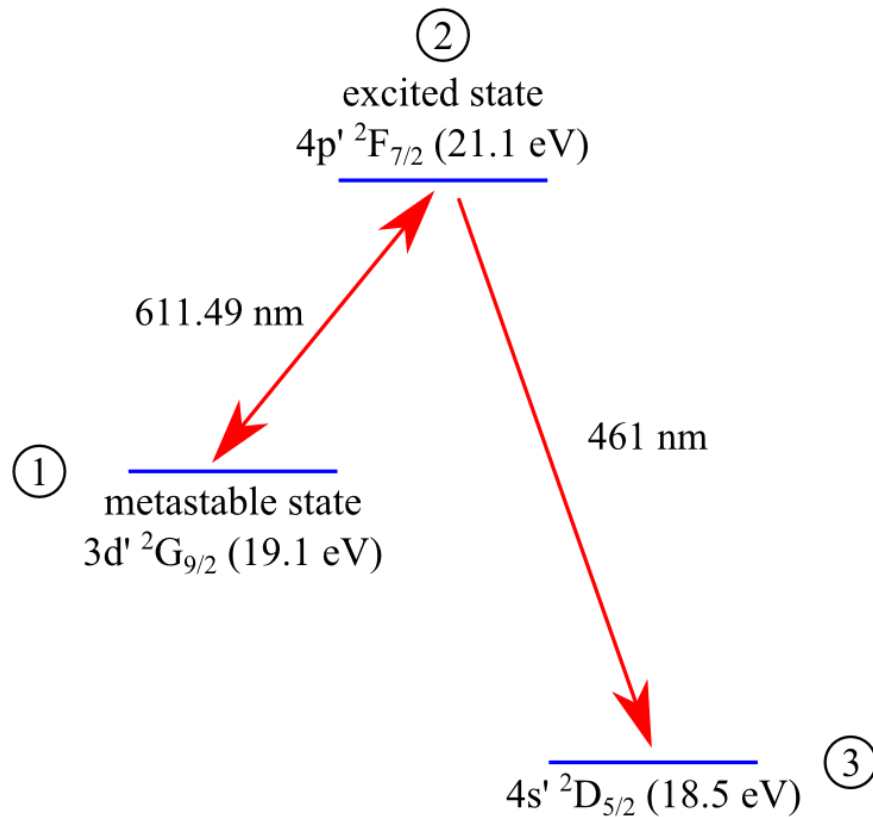


Figure 3.1. The Grotrian diagram of the LIF scheme used for this experiment. Argon ions in the metastable state $3d' \ ^2G_{9/2}$ are pumped to an excited state $4p' \ ^2F_{7/2}$ by using a tunable dye laser. The excited state will either radiatively relax to the original state or to a new state, $4s' \ ^2D_{5/2}$. This relaxation will result in a fluorescing photon which can be detected by, for example, a CCD camera.

depend on the relative velocity of the atom with respect to the direction of the laser beam due to Doppler shifting. By probing the plasma with a range of wavelengths (such as from a tunable dye laser), one can obtain the ion velocity distribution functions from the LIF signal,

$$2\pi\Delta\nu = 2\pi(\nu_L - \nu_0) = \vec{v} \cdot \vec{k} = v_{\parallel}k \quad (3.1)$$

where ν_L is the laser probing frequency, ν_0 is the center line frequency of the Doppler shifted transition, $\mathbf{v}$ is the ion velocity, and $\mathbf{k}$ is the laser wavevector. The State 1 $\rightarrow$ State 2 transition in this implementation is pumped by a 611.492 nm photon and the measured State 2 $\rightarrow$ State 3 transition emits a 461 nm photon. A narrow band-pass filter is used to mask out the pump beam as well as other plasma line radiation. This is necessary because the 461 nm light is a much lower intensity.

The Doppler shift is not the only mechanism contributing to the broadening the LIF signal under these conditions. The lineshape is also subject to power broadening [66]. As there are only a finite number of metastable states with velocities corresponding to the center of the beam profile, all of the metastable ions will be excited from State 1 $\rightarrow$ State 2 when a threshold laser power is exceeded. The LIF signal then saturates and increasing power does not result in an increased signal from these ions. However, the incident laser radiation is not strictly monoenergetic as even a narrow banded laser has a finite spectral width. Photons from the wings of the incident beam induce fluorescence from a population of ions moving at increasingly differing velocities. As a result, the apparent velocity distribution can be broadened depending on the incident power.

Power broadening can be avoided by using a lower laser power, but in the case of this experiment doing so significantly reduces the signal-to-noise ratio of the measurement. The amount of averaging that would be needed to reduce the noise to a reasonable level would unacceptably increase the time for taking a complete data set. For this reason, except for calibration, a relatively high laser power was intentionally used ($\approx 1 \text{ kW/cm}^2$ entering the reactor per laser pulse). The measured LIF signal must then be deconvolved to extract the unbroadened IVD. In general, the measured signal is a convolution of the true signal with the broadening mechanism,

$$i(v_z) = (s \otimes o)(v_z) = \int_{-\infty}^{\infty} s(v_z - v'_z) o(v'_z) dv'_z \quad (3.2)$$

where $i(v_z)$ is the image function (the measured data, in this case), $s(v_z)$ is the spread function (from power broadening), and $o(v_z)$ is the object function (the true IVD). To obtain the true IVD, the measured signal must be deconvolved with the spread function.

A maximum entropy algorithm was used for deconvolution [70]. To obtain the spread function, first a low intensity scan was performed to measure an unbroadened IVD in the bulk of the plasma where the average velocity is approximately zero. A spread function is computed by deconvolving a broadened distribution function from a high intensity scan with the unbroadened distribution function. This spread function is then used in all subsequent scans to obtain the true IVDs. This technique will ultimately overestimate the temperature of the cold, background ions, but not the high energy tail that is of interest in plasma processing.

Summary

Laser-induced fluorescence is a non-invasive plasma diagnostic based on using the Doppler shift equation with a tunable laser source in order to directly measure ion velocity distribution functions. Distribution functions can be artificially broadened if the laser power is sufficiently high, but this can be mitigated by deconvolving the data with a spread function corresponding to the broadening mechanism. The work described in this dissertation uses this technique (along with cylindrical optics in order to create a sheet of laser light) as the primary diagnostic in measuring ion dynamics in both a single and dual radio frequency sheath.

Chapter 4

Experimental Setup

Inductively Coupled Plasma Source

The ICP reactor used in the experiment, schematically shown in Fig. 4.1, is a modified commercial plasma etch tool provided by the Intevac Corp. The chamber is approximately cylindrical with a diameter of 50 cm and height of 40 cm. Ports were added to the sides and top of the chamber to allow access for diagnostics. The ICP is produced by a 500 W, 440 kHz solenoidal antenna surrounding a ceramic cap to the plasma chamber. The ceramic cap sits on the aluminum chamber. For this experiment gas entered the chamber through six symmetrically spaced feed nozzles in an aluminum plate on the top of the chamber and was exhausted by a turbomolecular pump at the bottom of the chamber. This plate included a window and replaced the original showerhead. The feedstock gas was $\text{Ar}/\text{O}_2 = 80/20$ at a pressure of 0.5 mTorr. The fill pressure was necessarily lower than that typically used in semiconductor processing (10-100 mTorr) as collisions with neutrals would begin quenching the metastable ions used in the LIF diagnostic at pressures as low as a few mTorr. Since operation of the plasma tool required a silicon wafer on the substrate, the small rate of sputtering Si atoms in pure argon plasmas eventually deposited on and covered the windows of the chamber, which would have required frequent cleaning of the chamber on times shorter than a typical diagnostic run. Oxygen was added to enable in situ cleaning of the windows. In addition, the Ar/O_2 combination mimics the gas combinations used in processing where electronegative atoms such as fluorine are present.

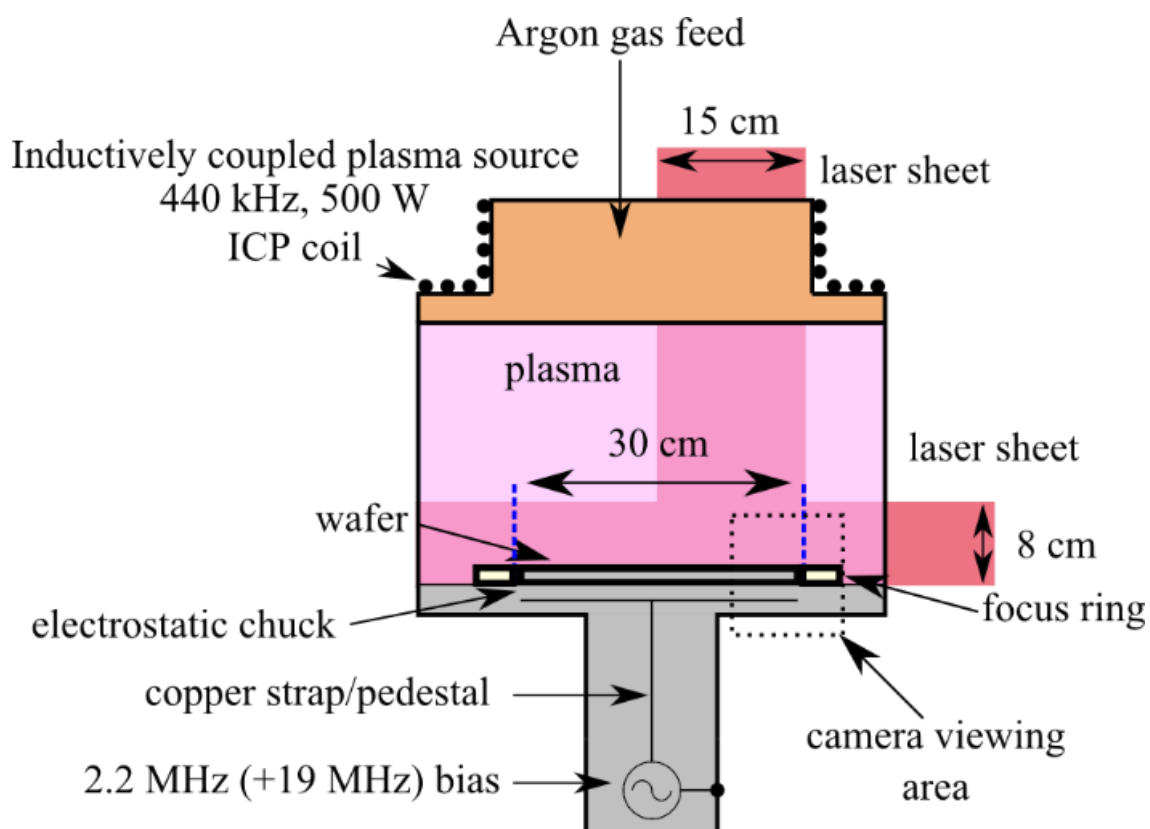


Figure 4.1. Schematic of the ICP chamber used for the experiment. The ICP coils were situated on the top of the machine in a “top hat” configuration and the wafer was on an electrostatic chuck at the bottom of the chamber. Planar laser sheets entered the chamber from the top and sides of the chamber via quartz windows.

Bulk plasma parameters were measured at 317 spatial locations in a plane 2 cm above the wafer using a Langmuir probe connected to an automated drive mechanism capable of positioning the probe in a 2D plane. For these probe measurements, the ICP source was pulsed and measurements were taken 50 μs and later following the shutdown of the ICP source. This significantly reduced rf noise introduced from the ICP source and obviated the need for an rf compensated probe. The electron temperature, T_e , and ion density, n_i , were calculated at 100 μs intervals from the I-V traces. At 100 μs , in the middle of the wafer, T_e was measured to be ≈ 1.7 eV and $n_i \approx 2 \times 10^{10} \text{ cm}^{-3}$. (See Fig. 4.2.) Although T_e may be somewhat lower (approximately a factor of 2) than during the ICP power on stage, n_i likely closely approximates that during the ICP power on stage.

RF Bias Setup

The 30 cm diameter silicon wafer was electrostatically clamped to the chuck at the bottom of the chamber and surrounded by a dielectric focus ring. The volume above the wafer in which measurements were taken is shown in Fig. 4.3. For the single frequency experiment, the 2.2 MHz rf bias was run with an 11% duty-cycle and pulsed frequency of 10 Hz delivered from the source to the electrode underneath the wafer via a copper strap after a fixed match network. This results in the rf bias being on for 11 ms with a 10 Hz repetition rate, with LIF measurements being made in the last 1 ms of the pulsed bias. This rf pulse length is sufficiently long that the IVDs at all frequencies of interest are in a quasi-steady state at the time that the LIF measurements are made. The bias current and voltage were measured at the current strap using a Faraday coil and voltage

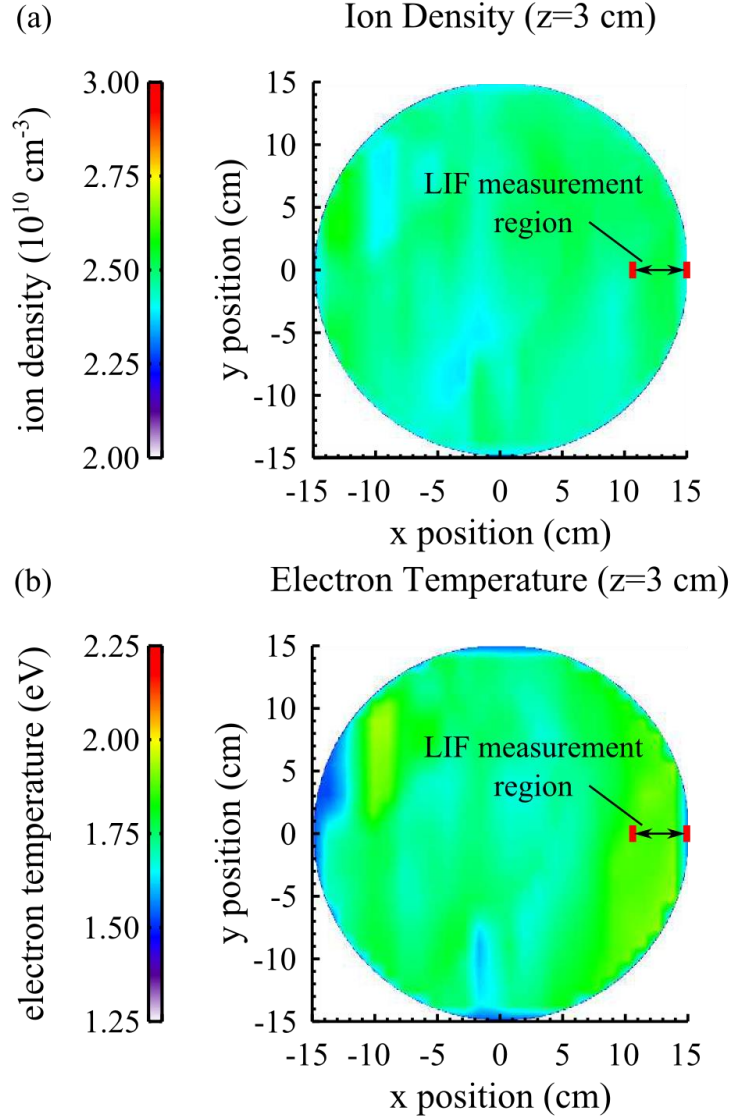


Figure 4.2. Bulk plasma parameters 3 cm above the wafer ($100 \mu\text{s}$ after ICP shutoff) measured using a Langmuir probe. (a) Electron temperature calculated from the exponential region of the measured I-V curve ($\delta T_e/T_e \sim 0.3$). (b) Ion density calculated from the ion saturation current and T_e ($\delta n/n \sim 0.35$). Both sets of measurements show minimal variation across the LIF measurement region.

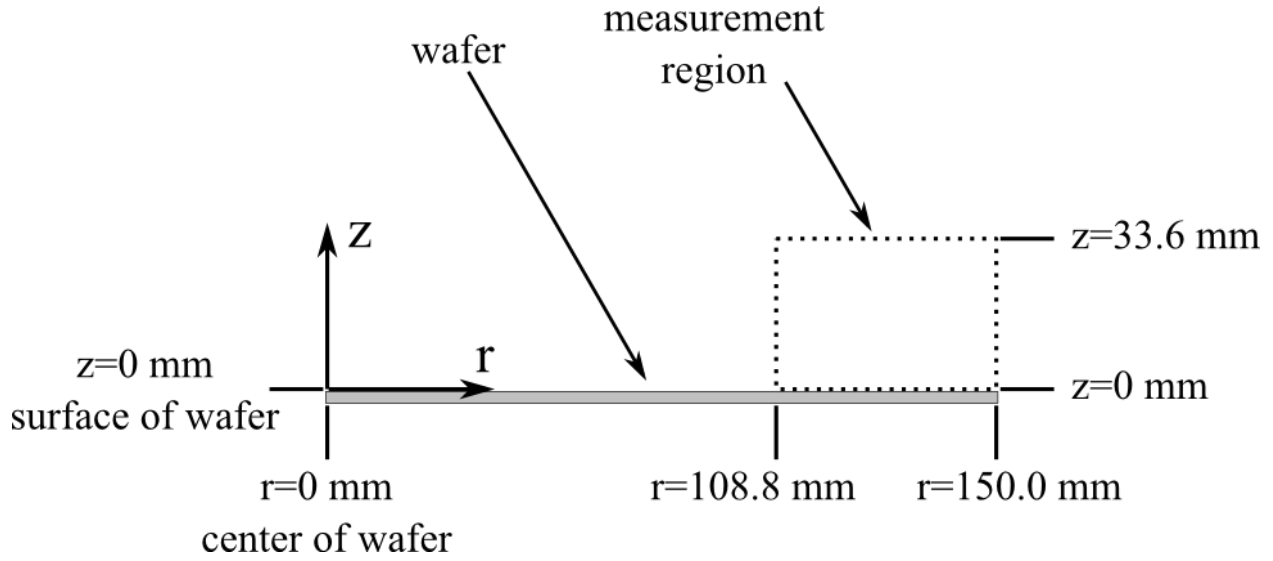


Figure 4.3. The region over the outer edge of the wafer where data were taken. Included is the coordinate system used for the analysis.

divider, respectively. Impedance of the strap, wafer, and plasma were then used to estimate the applied rf voltage both at the chuck and at the surface of the wafer. The latter was approximately 600 V peak-to-peak. Taking into account the plasma potential and uncertainty in the voltage measurement, the maximum sheath potential drop was approximately 650 V.

For the dual frequency experiment, the copper strap leading to the electrostatic chuck was replaced with a more secure, lower inductance (~ 10 nH) copper tube. The 2.2 MHz tank circuit was modified to account for the change in impedance and was then secured via screws onto the outer surface of the copper tube. The duty cycle was also changed from 11% to 10%. These changes resulted in an increase in peak power to 1960 W and 2500 V peak to peak voltage.

A tunable high frequency (10-20 MHz) source was added to the existing setup for the dual frequency bias experiment (Fig. 4.4). A function generator was set to output sinusoidal voltage waveforms at 19 MHz with the total pulse duration equal to 10 ms (10% of the experiment repetition rate). This output was amplified in three stages by separate rf amplifiers. A tank circuit for the high frequency source was constructed and attached to the copper cylinder for optimal power transmission to the electrostatic chuck and wafer. The tank circuit was composed of a 3 turn inductor (~ 50 nH) constructed out of wound copper tubing and a variable capacitor (7-1000 pF). Using a directional coupler, maximum power transfer to the copper pedestal was found to occur at 19 MHz driving frequency. Peak to peak voltage at maximum power (1930 W) was measured to be 600 V.

Laser and Optical Setup

A tunable dye laser probed the 611.49 nm range needed for the LIF scheme used here (Fig. 4.5). The dye laser was pumped by a Spectra Physics Quanta-Ray Nd:YAG laser that was frequency-doubled to 532 nm. The pump laser was pulsed at 10 Hz with each pulse having 10 ns duration and an energy of 450 mJ. The dye laser was a Sirah Cobra-Stretch with a Rhodamine B and Rhodamine 101 dye mixture which in turn generated 85 mJ pulses at wavelengths ranging from 611.350 nm to 611.650 nm. The laser wavelength was stepped at increments of 1 pm. The wavelength was calibrated using a HighFinesse meter, accurate to 0.5 pm (or, in units of ion velocity, to within approximately 0.3 km/s, or 3×10^2 m/s). A pair of Glan-Thompson polarizers were placed after the dye laser in order to control the beam energy, and the beam was delivered to

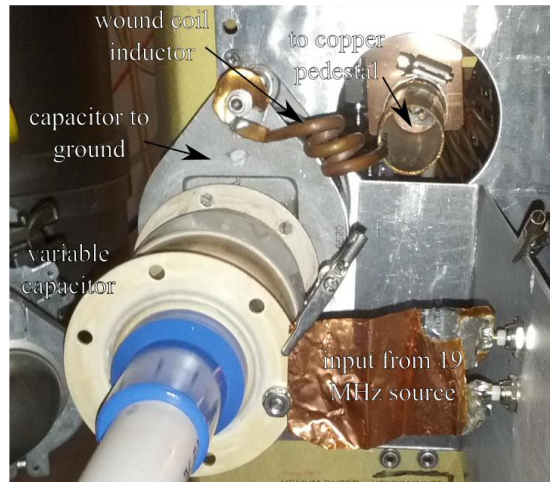
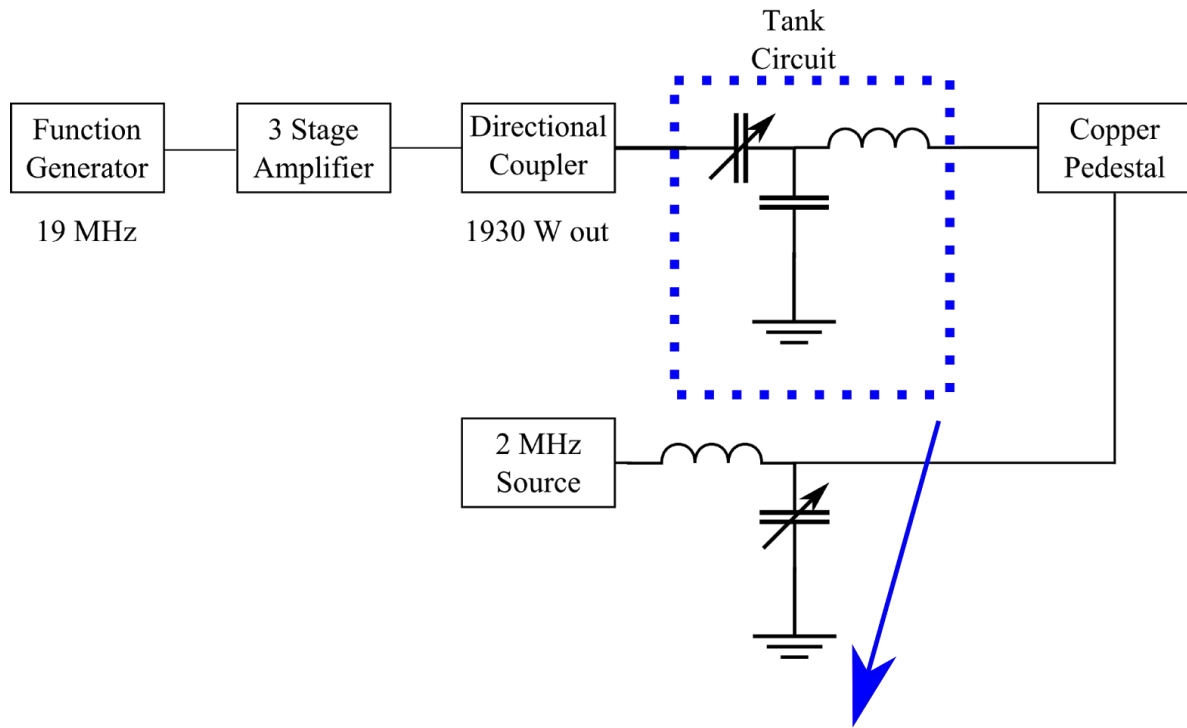


Figure 4.4. Schematic of the bias setup for the dual frequency bias experiment. For the additional high frequency bias, a 19 MHz sinusoidal waveform was amplified by a three stage amplifier and passed through a resonant tank circuit. The existing 2 MHz setup remained unchanged other than replacing the inductor with a larger inductor in order to accommodate the smaller capacitance of the copper pedestal as compared to the copper straps previously used for power transfer to the electrostatic chuck.

Laser Room

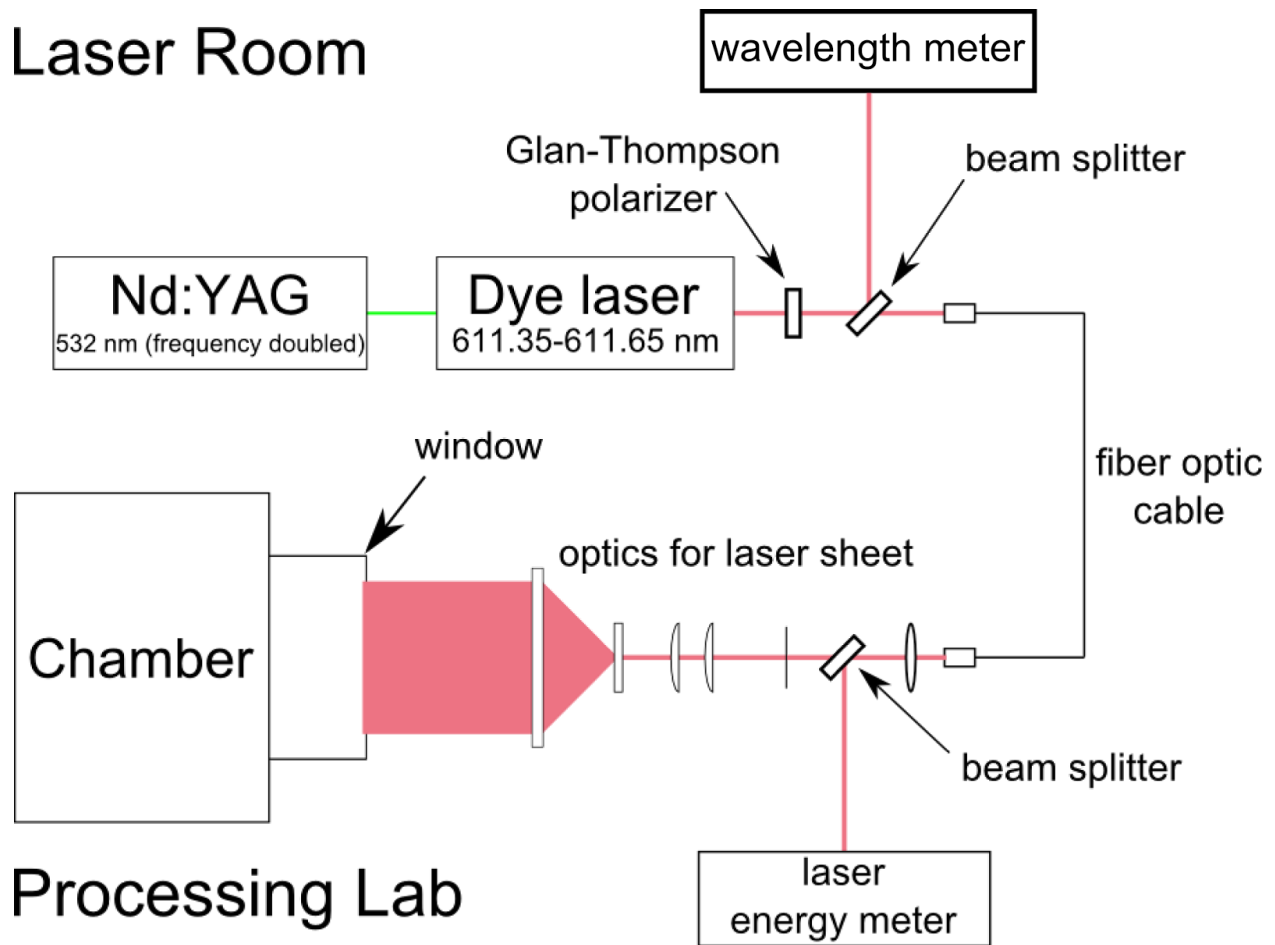


Figure 4.5. The laser delivery system used for the laser-induced fluorescence diagnostic. Output from a tunable dye laser was coupled into a fiber optic cable leading to the etch tool in the processing lab. The light was collimated using an aspherical lens and focused onto a pair of cylindrical lenses in order to create a planar sheet of light.

the reactor through a 1 mm fiber optic cable. The energy on the reactor side of the fiber was set to 250 μJ per pulse for each experimental run.

Light exiting the fiber was collimated onto a plano-convex converging lens by an aspherical lens. The beam was passed through two cylindrical lenses to create a sheet of laser light. For IVD measurements perpendicular to the surface of the wafer, the planar laser sheet entered the chamber through a rectangular window located on top of the chamber. For IVD measurements parallel to the wafer's surface, the laser sheet entered through a circular window on the side of the chamber, centered on the surface of the wafer. Parallel IVDs were measured only for the single frequency (2.2 MHz) bias case.

The LIF signal was calibrated to account for spatial variation in the laser power in the planar laser sheet in order to measure absolute ion velocity distribution functions. The calibration was performed by comparing parallel and perpendicular LIF data for an unbiased case. For example, the radial variation of the density calculated from the parallel IVD is a true representation of the density as the intensity of each parallel subsection of the planar sheet does not vary radially across the plasma. The calibration was obtained by comparing this radial density variation to the radial variation measured from the perpendicular IVD. Likewise, the vertical density variation was obtained by comparing the true representation from the perpendicular IVDs to the transverse IVDs.

The LIF signal was recorded using a fast (30 ns exposure), 12 bit DiCam-Pro Intensified CCD camera. The axis of the camera was centered vertically along the top edge of the wafer and aligned to record images of the fluorescence above the outer 10 cm of the diameter of the wafer. The images were 1280 pixels wide by 1056 pixels tall and were averaged over 1000 shots. These images were then averaged over 2×2 pixel bins twice, once by the data acquisition software and once again before analysis, to give a final resolution of 320×256 pixels. An absolute spatial

calibration was performed by imaging a $1\text{ cm} \times 1\text{ cm}$ gridded aluminum plate placed in the laser path inside the plasma chamber. After the pixel averaging, the final resolution was $0.4\text{ mm} \times 0.4\text{ mm}$ per pixel.

Timings

The timing sequence used for the single frequency experiment is schematically shown in Fig. 4.6. Specific trigger settings are shown in Table 4.1. A photo-diode was used to measure laser light immediately before entering the plasma chamber. The signal from the photo-diode, along with adjustments to the delay between the phase lock and the Q-switch of the laser, were compared with the voltage waveform to calibrate the phase measurements. The pulse width of the laser and timing jitter combined were approximately 40 ns. This spread in time corresponds to a maximum uncertainty in the sampled bias voltage of 60 V. The base repetition rate of the entire experiment was set by the laser, which ran at 10 Hz. An average run which provided either a parallel or perpendicular component of the IVD at one phase and 82,000 spatial locations consisted of 1000 camera shot averages at 300 wavelength points, and required upwards of 10 hours to complete. A typical complete run for all phases and both laser orientations required up to two weeks of continuous data acquisition.

For the dual frequency experiment, the timings were modified to account for the additional rf source as shown in Fig. 4.7. The specific trigger values are shown in Table 4.2. Each source was set to a 10% duty cycle (10 ms on, 10 Hz repetition rate) and initialized simultaneously. The laser was again phase locked to the 2 MHz bias waveform and measurements were taken at 2 different phases, corresponding to the expanded and collapsed sheath.

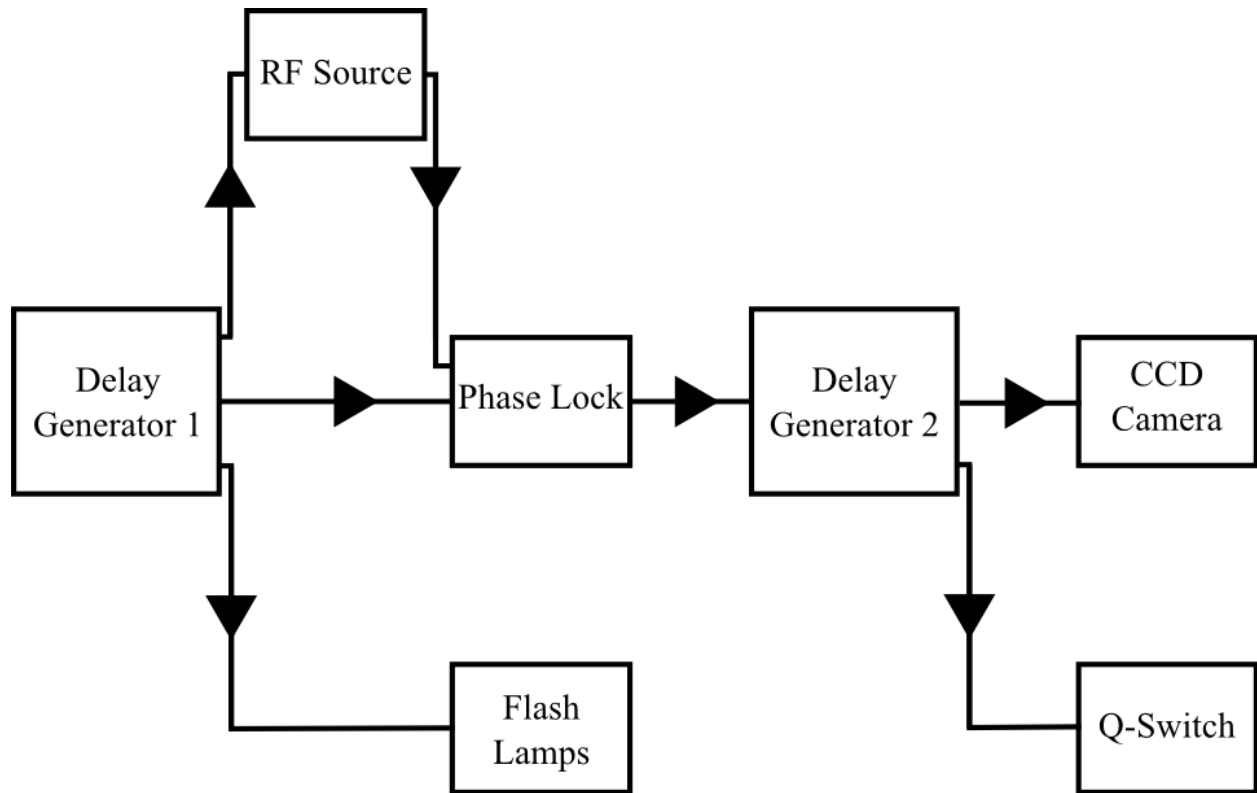


Figure 4.6. Schematics of the timings for the single frequency bias experiment. Two delay generators are used in the experiment. The first triggers first the RF source (11 ms pulse width) and then the phase lock and laser flash lamps after 10 ms (to allow the plasma response to the applied RF to stabilize). The phase lock receives a signal from a voltage divider on the copper strap leading up to the chuck and outputs a trigger for a second delay generator once the voltage waveform crosses zero. The second delay generator then triggers the CCD camera and the laser Q-switch. The Q-switch timing varies depending on the desired RF phase for LIF measurements.

Single Frequency Bias Timings

Stanford Delay Generator 1			
Internal trigger, 10 Hz repetition rate			
Device Triggered	Trigger Source	Delay	Gate Width
2 MHz bias source	Trig	0	11 ms
Laser flash lamps	Trig	10 ms	
Phase lock	Flash lamps ON	170 μ s	100 μ s
Stanford Delay Generator 2			
External trigger from 2 MHz phase lock			
Device Triggered	Trigger Source	Delay	Gate Width
Laser Q-switch	Trig	variable (<470 ns)	-
CCD camera	Laser Q-switch ON	500 ns	30 ns, set by software

Table 4.1. Delay generator timings for the single frequency bias experiment. In addition to the trigger received from the first Stanford generator, the phase lock received an input voltage signal from a resistive voltage divider measuring the 2 MHz voltage output at the copper straps.

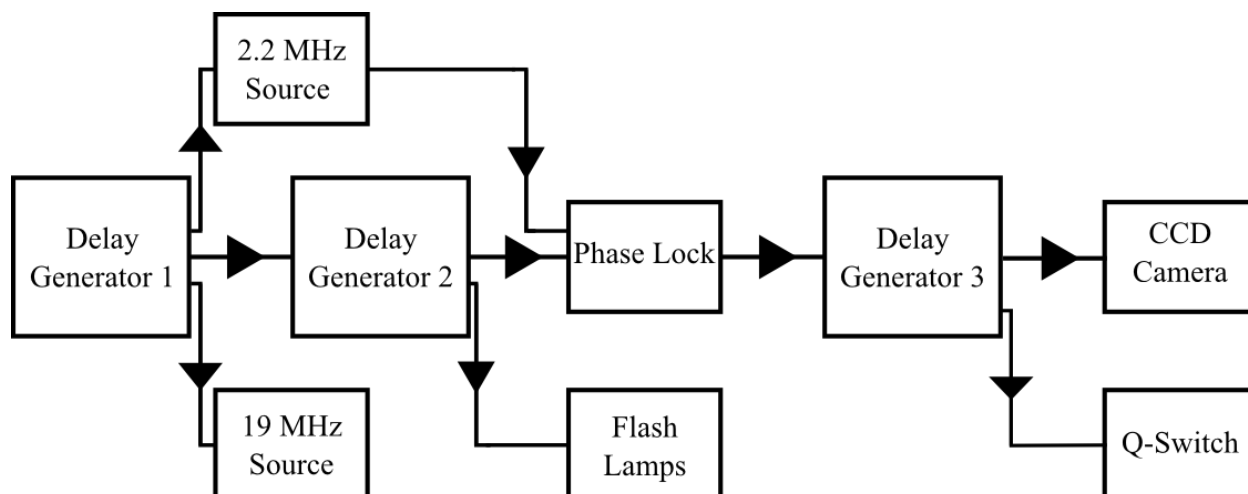


Figure 4.7. Schematics of the timings for the dual frequency bias experiment. A third delay generator is added in order to accommodate the additional channels needed to trigger the 19 MHz source. Both of the rf sources and second delay generator are triggered simultaneously. The two rf sources receive the same gate pulse width (10 ms). The timings following the second delay generator remain the same as for the single frequency bias case (Fig. 4.6).

Dual Frequency Bias Timings

Stanford Delay Generator 1			
Internal trigger, 10 Hz repetition rate			
Device Triggered	Trigger Source	Delay	Gate Width
2 MHz bias source	Trig	0	10 ms
19 MHz bias source	Trig	0	10 ms
Stanford Delay 2	Trig	0	-
Stanford Delay Generator 2			
External trigger from Stanford Delay Generator 2			
Device Triggered	Trigger Source	Delay	Gate Width
Laser flash lamps	Trig	10 ms	
Phase lock	Flash lamps ON	170 μ s	100 μ s
Stanford Delay Generator 3			
External trigger from 2 MHz phase lock			
Device Triggered	Trigger Source	Delay	Gate Width
Laser Q-switch	Trig	variable (<470 ns)	-
CCD camera	Laser Q-switch ON	500 ns	30 ns, set by software

Table 4.2. Delay generator timings for the dual frequency bias experiment. In addition to the trigger received from the second Stanford generator, the phase lock received an input voltage signal from a resistive voltage divider measuring the dual frequency voltage output at the copper pedestal.

Chapter 5

2D Ion Velocity Distribution Functions in a Single Frequency

Sheath

Bias and Plasma Parameters

f_{rf}	2.2 MHz
ω_{rf}	1.38×10^7 rad/s
V_{rf} (peak-to-peak)	650 V
P_{rf}	1960 W
T_e	1.5 eV
n_0	$3 \times 10^{10} \text{ cm}^{-3}$
s	3.0 mm
ω_{ion}	2.75×10^7 rad/s
ω_{rf}/ω_{ion}	0.5
Fill pressure	0.5 mTorr
λ_{ce}	6.7 cm

Table 5.1. A list of parameters for the 2.2 MHz bias and plasma for the single frequency bias experiment.

In industrial etching during microelectronic fabrication, the silicon wafers used are typically biased with rf voltages in order to control the energies and fluxes of the reactive ions. Due to the difficulty of directly investigating the sheath, the region of the plasma where the ions experience the majority of their acceleration, relatively few measurements of ion dynamics have been taken in settings closely mimicking those used in industry. For this experiment, planar laser induced fluorescence is used to measure the ion velocity distribution functions both parallel and perpendicular to the surface of a single radio frequency biased wafer. The goal of the experiment is to extend the work done by Jacobs *et al.* [35] in order to measure the radial dependence of ion dynamics and angular energy distributions within the sheath. The shape of the measured distribution functions and the separation between peaks in the time-averaged distribution function are consistent with previous measurements in the same device [35].

Experimental Results

LIF data were taken at eight different phases of the 2.2 MHz rf cycle, as shown by the dashed red lines in Fig. 5.1. The phases shown were calibrated to account for phase shifts due to the impedance of the copper straps and electrostatic chuck. The coordinate system used for the analysis is shown in Fig. 4.3. Data were taken over the outer 4 cm of the wafer ($10.88 \text{ cm} < r < 15.0 \text{ cm}$) and up to 3.36 cm above the wafer ($0 \text{ cm} < z < 3.36 \text{ cm}$).

A typical deconvolved vertical IED measured at various heights above the wafer when the rf phase of the bias is most negative ($\Phi = \pi$) is shown in Fig. 5.2. Data corresponding to particles moving upward were ignored as it was not possible to distinguish between the LIF signal from actual particles moving in this direction and the signal from light reflected off the surface of the wafer. Data for heights less than 1.2 mm were also ignored as the signal was too small to be reliable

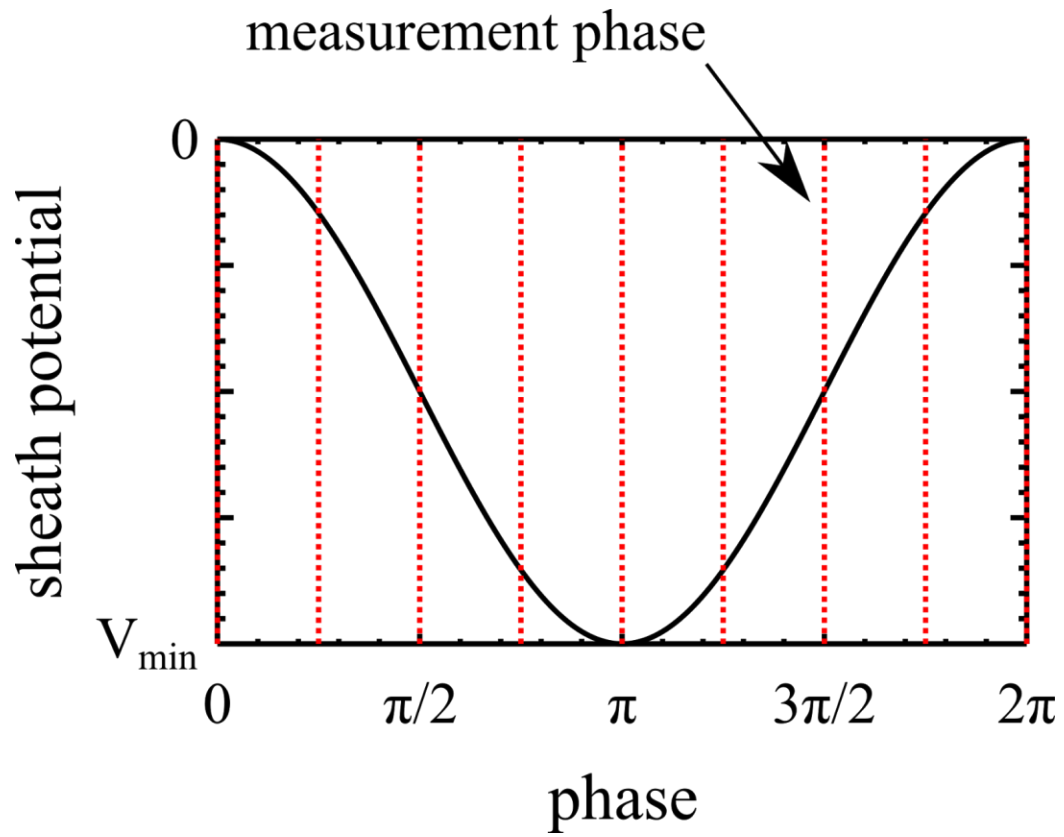


Figure 5.1. Phase reference diagram for the 2.2 MHz bias. The vertical lines represent phases at which measurements were taken.

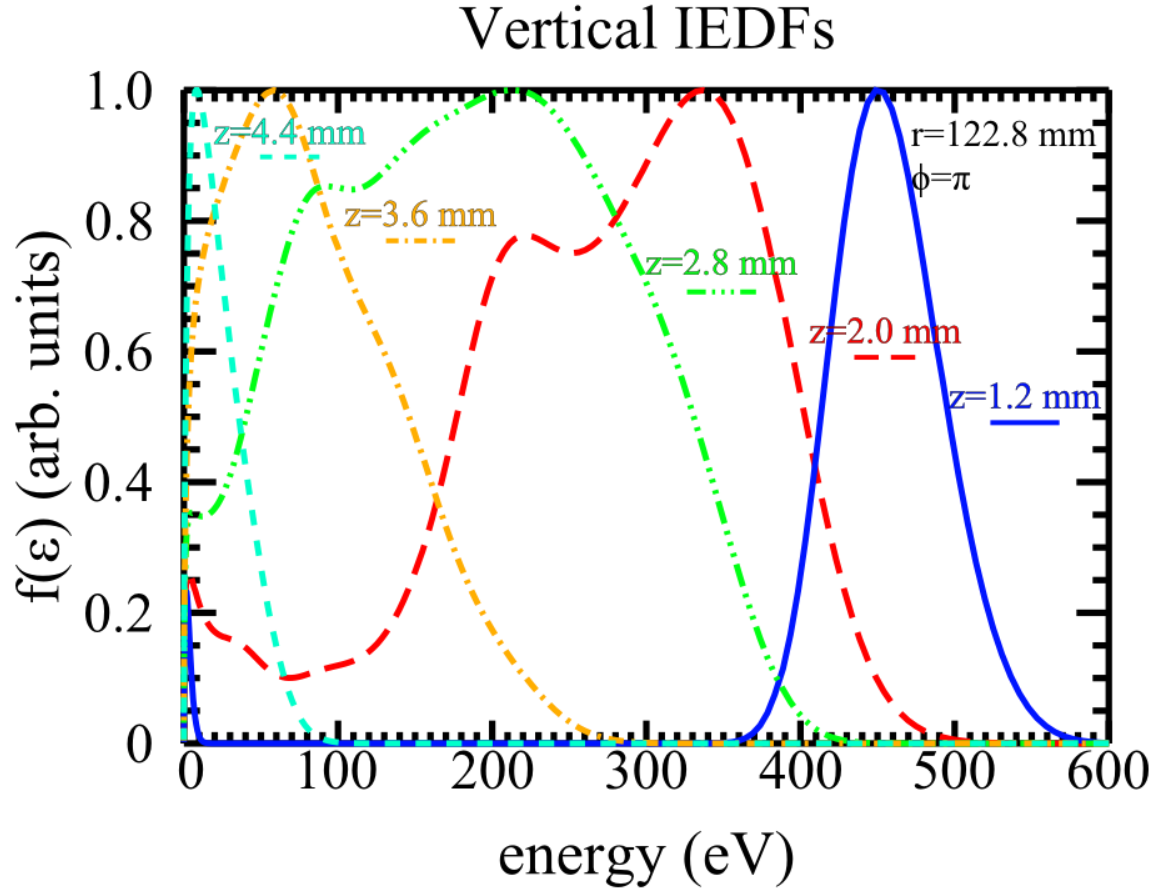


Figure 5.2. Example vertical ion energy distribution function at multiple heights for the most negatively biased phase. IED widths larger than what would be expected from the bulk ion temperature can be attributed to a combination of the deconvolution algorithm and an uncertainty in the sampled bias voltage due to timing jitters and the laser pulse width.

due primarily to the decrease in ion density. Since the total ion flux is conserved, the ion density decreases as the velocity increases approaching the wafer surface. The deconvolved IED has a width larger than what would be expected from the bulk ion temperature. The width can be attributed in part to the deconvolution algorithm and in part to the aforementioned 60 V uncertainty in the sampled bias voltage.

For an unbiased wafer, the thickness of the sheath is estimated to be $s \approx 10\lambda_D = 0.5$ mm. The measured sheath thickness for the biased case was $s \approx 4.0$ mm at a radius on the wafer for $r = 105$ mm compared with a predicted value of 3.0 mm [10]. The measured sheath thickness did not change significantly towards the edge of the wafer.

These sampled vertical IEDs show the emergence of high energy ions as the particles enter the sheath region. The distribution function in the plasma bulk is essentially Maxwellian, with the peak centered at $v_z = 0$. At 4 mm above the wafer, near the edge of the sheath, the peak begins to shift and widen. Close to the surface of the wafer at this phase, high energy (400-500 eV) ions dominate. However a small Maxwellian peak corresponding to stationary ions remains. This would need to result from ionization or charge exchange within the sheath. While the mean free path for collisions exceeds the sheath width, a small number of collisions are still possible. At a distance of $r = 13$ cm, the density 4 mm above the wafer was observed to be 15.6 (6.4%) times smaller than the plasma bulk. Using the measured sheath width of 4 mm and the ion charge exchange mean free path $\lambda_{ce} = 6.7$ cm, we can estimate the proportion of collided ion flux by $\Gamma/\Gamma_0 = 1 - e^{-s/\lambda_{ce}} = 5.7\%$ [1]. This is consistent with the observed density.

The horizontal IED is shown in Fig. 5.3 at the same positions and phase. There is little variation in the horizontal IED at different heights other than the change in magnitude due to the

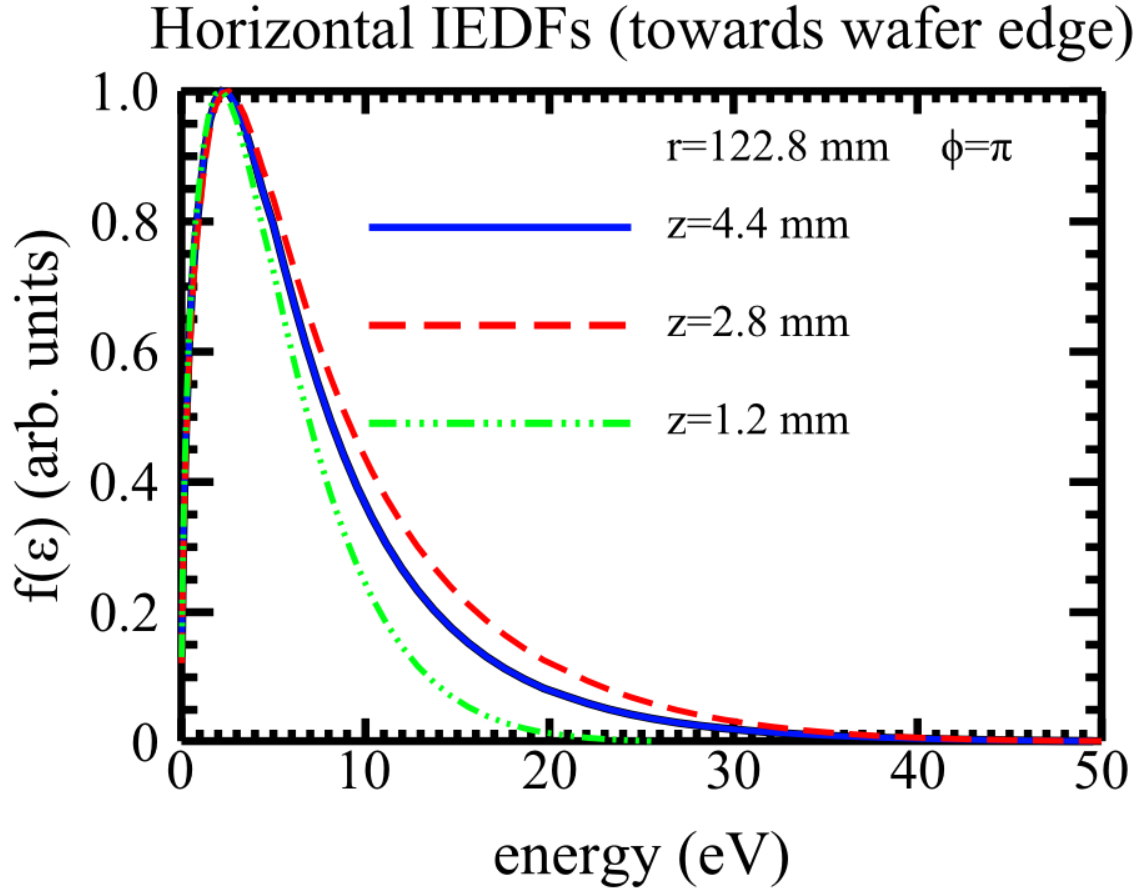


Figure 5.3. Horizontal ion energy distribution function at multiple heights above the wafer for $\phi=\pi$. Ions exhibit minimal transverse acceleration.

decrease in ion density. The distribution function remains primarily Maxwellian with little acceleration of ions to large velocities parallel to the surface of the wafer.

Planar laser illumination allows comparison of distribution functions at multiple horizontal positions across the surface of the wafer. Vertical IEDs between mid-wafer and the wafer edge for two phases are shown in Figs. 5.4 and 5.5. For the phase when the bias is most negative ($\Phi = \pi$), ions ($E > 10$ eV) are accelerated from the zero-net velocity distribution at a height of about 4 mm where the sheath starts. At mid-wafer (4 cm from the edge), the ions accelerate to an average energy of 450 eV with a maximum extent of roughly 500 eV about 1.2 mm above the surface of the wafer, which is the extent of the measurement. If the IED is linearly extrapolated to zero height (at the wafer surface), the estimated average energy is 600 eV and the maximum energy is about 650 eV. Ions at the edge of the wafer accelerate to slightly lower energies. For the phase having the least negative bias ($\Phi = \pi$), there was little variation between mid-wafer and the edge of the wafer as few fast ions were observed in either case. The radial dependence of the vertical IED at all heights is shown in Fig. 5.6.

Taking the average over all measured phases yields the time-averaged IEDs shown in Fig. 5.7 at a height of 2 mm. Averages both at the edge of the wafer and at the middle of the wafer give the expected two-peak structure. While the overall shape and relative heights of the two peaks change with radial position, the energy separation ΔE_i at the edge and mid-wafer is the same, roughly 150 eV. This measurement is consistent with previous work performed in this reactor [35].

Calculated mean ion velocities were compared at multiple phases of the rf bias and are shown in Fig. 5.8. These plots have the horizontal component of the velocity vector increased by a factor of 10 to emphasize the radial velocity. For $\Phi = \pi$ (most negative bias), ions near the surface of the wafer have a highly directed velocity downward towards the wafer, with a maximum

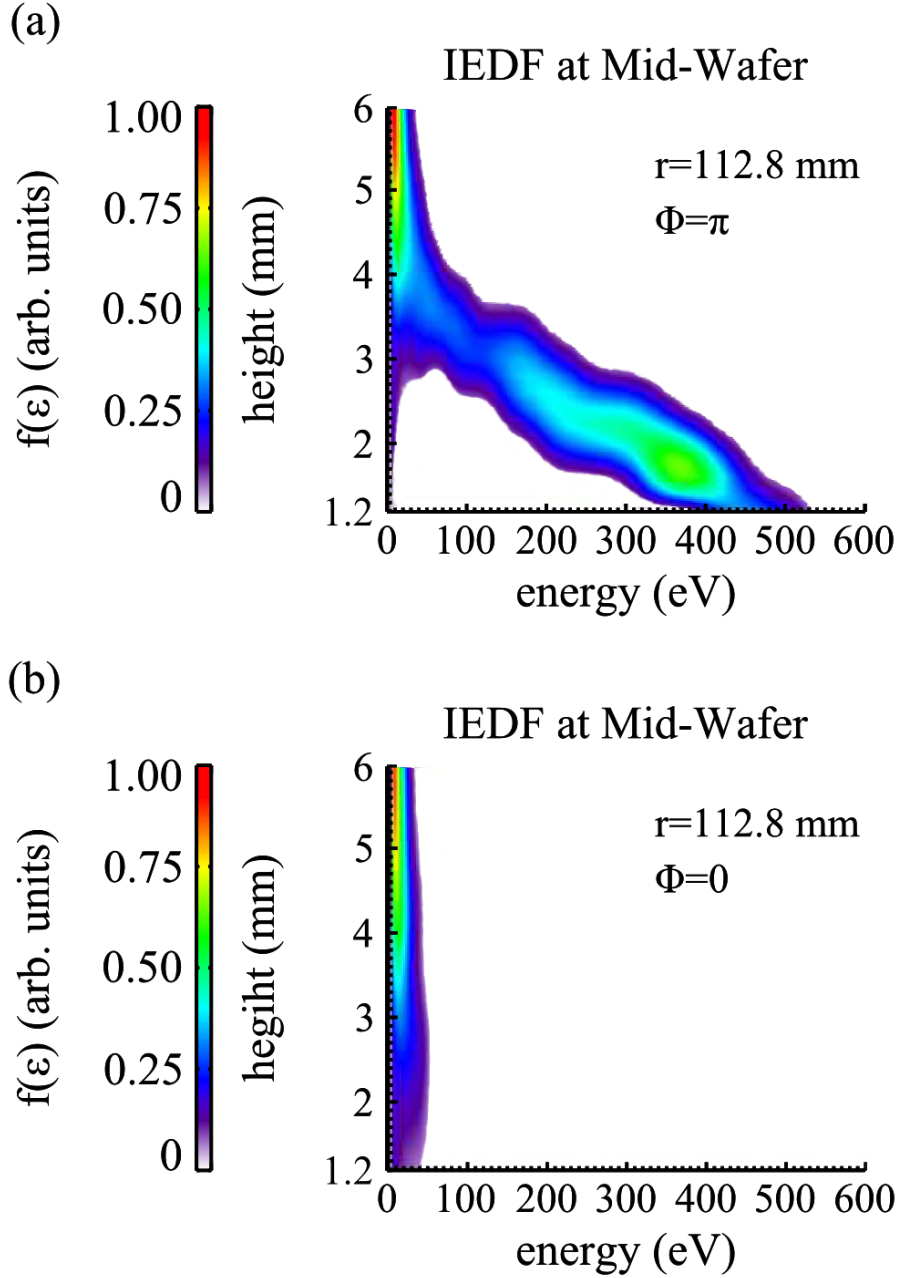


Figure 5.4. Vertical IEDs at mid-wafer ($r=112.8$ mm) for two different phases. (a) IED for $\Phi = \pi$. Ions are accelerated from the thermal distribution prior to the presheath as the ions enter the sheath. The maximum energy reached by these ions at 1.2 mm, the lowest observation height, is approximately 500 eV. (b) IED for $\Phi = 0$. For this phase, the distribution remain primarily Maxwellian as the ion transit time is short compared to the rf cycle.

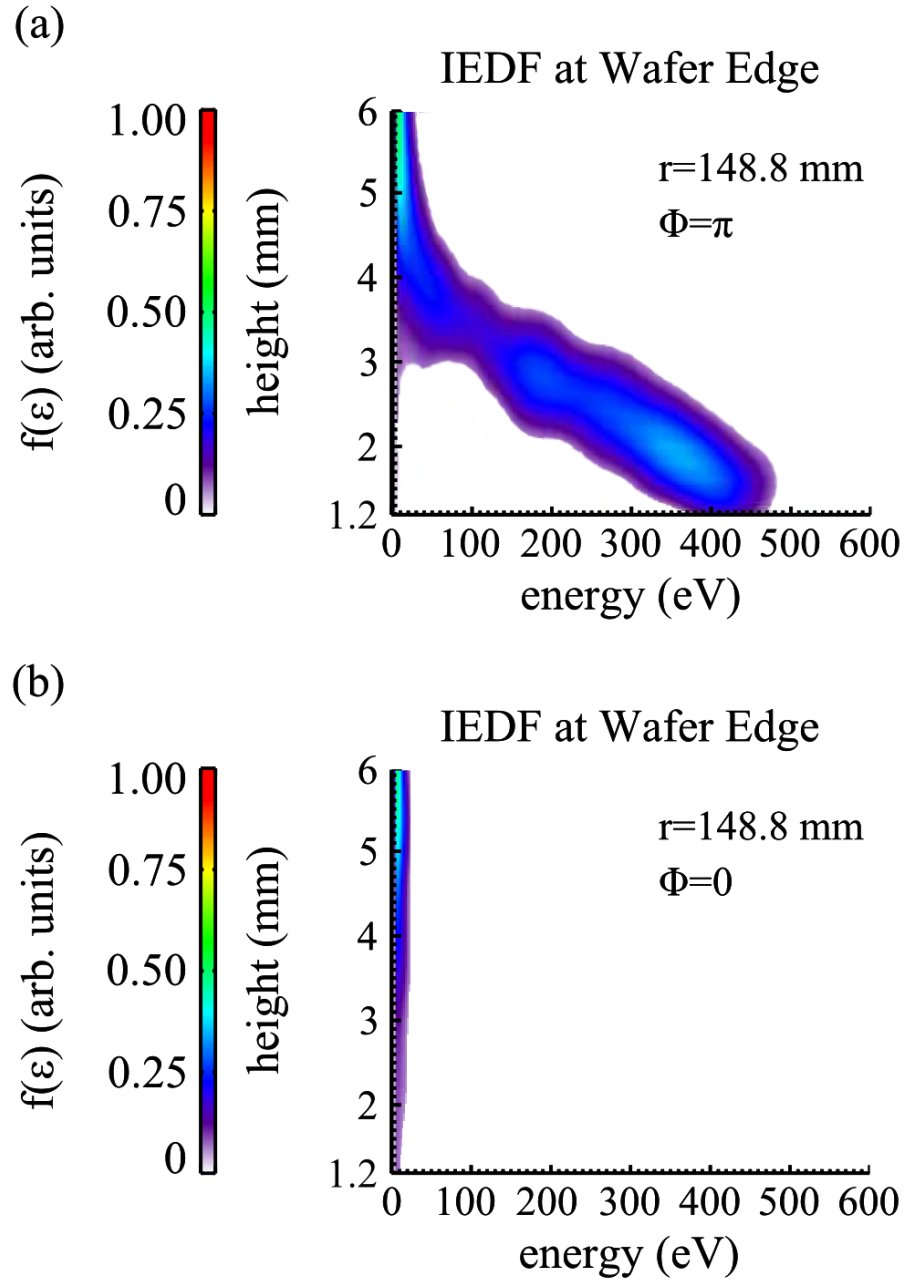


Figure 5.5. Vertical IEDs at the edge of the wafer ($r=148.8 \text{ mm}$) for two different phases. (a) IED for $\Phi = \pi$. Ions accelerate to energies comparable to those reached at mid-wafer. (b) IED for $\Phi = 0$. The distribution remains essentially Maxwellian through the sheath.

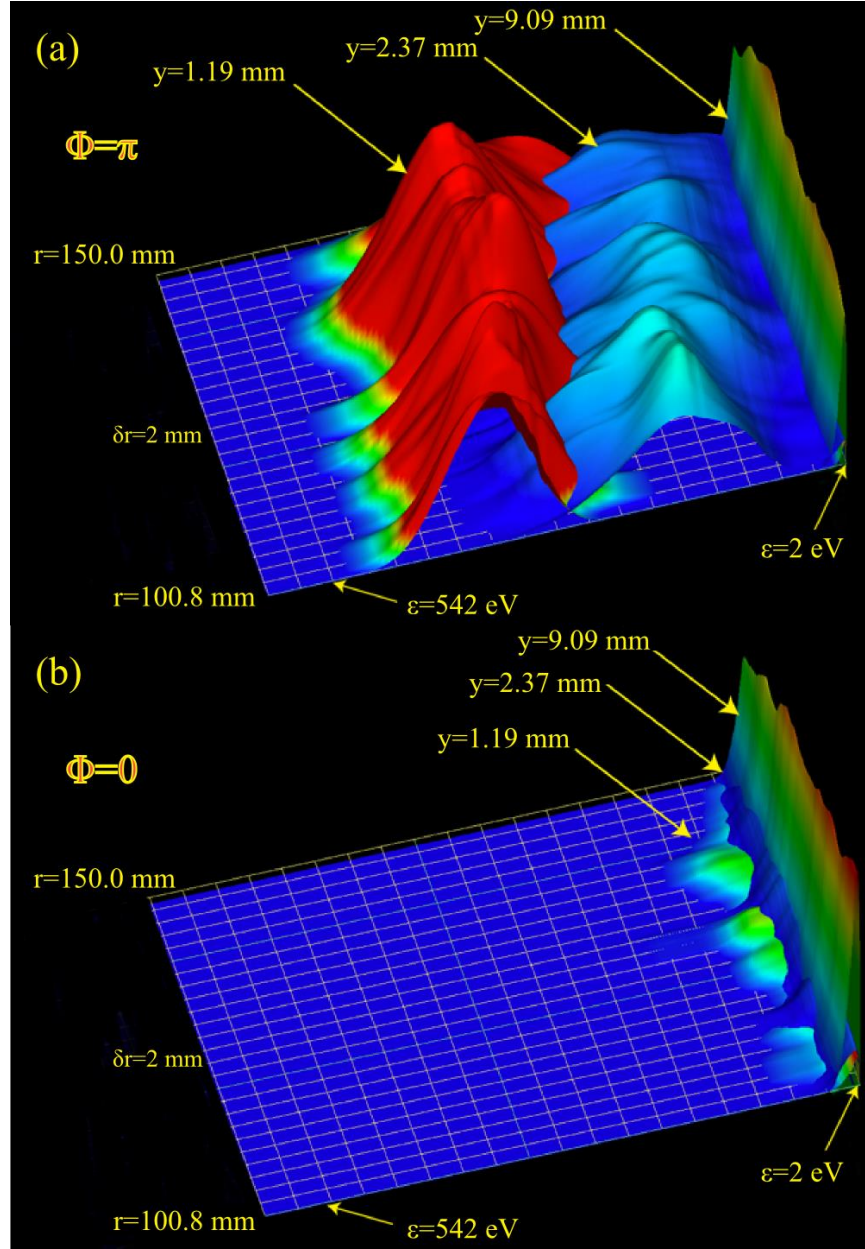


Figure 5.6. The ion distribution function as a function of energy and radial position at three heights above the wafer. (a) IED at $\Phi = \pi$. At $z=1.2$ mm, the IED peaks at approximately 500 eV. This peak remains relatively unchanged across several radial positions. (b) IED for $\Phi = 0$. Few high energy ions are present at any height or radial position.

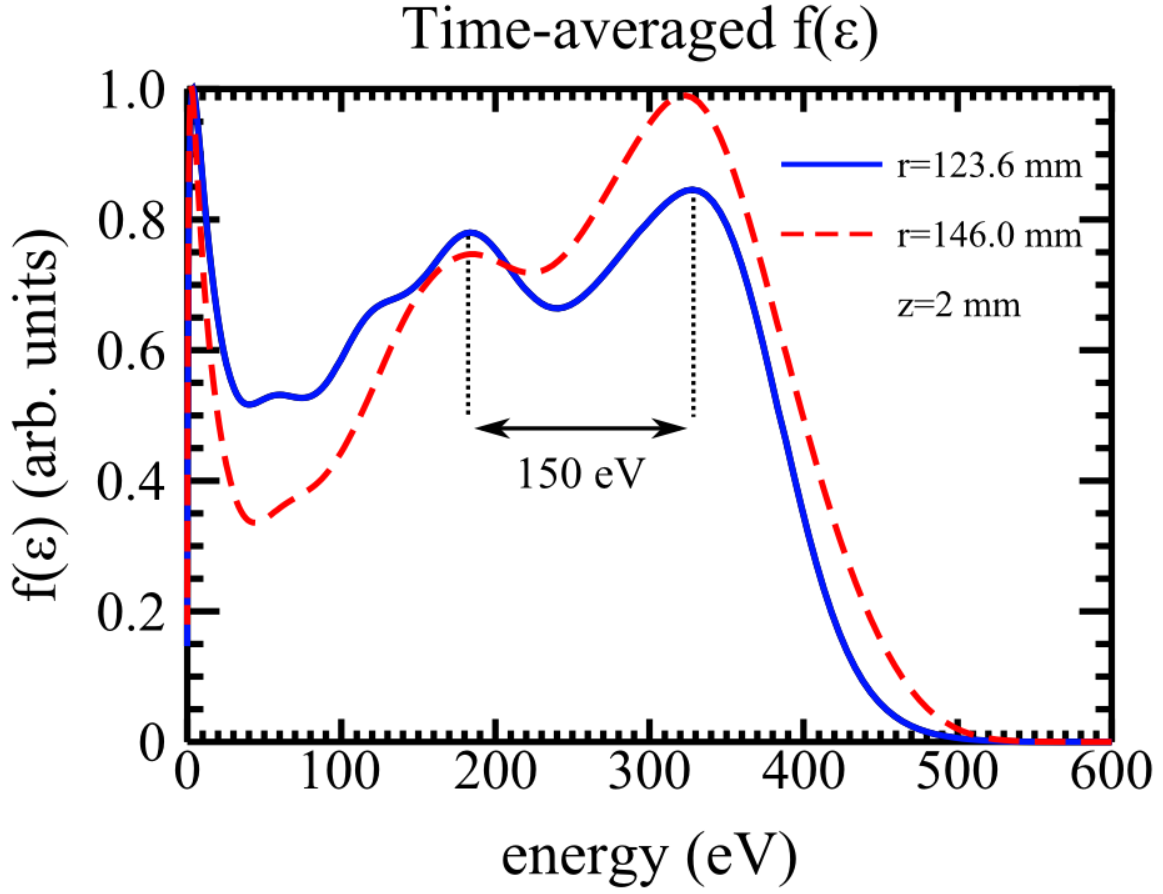


Figure 5.7. Time-averaged ion energy distribution functions at the edge of the wafer and towards the center of the wafer. The distribution function is bimodal, as expected. The energy peak separation is approximately 150 eV for both cases.

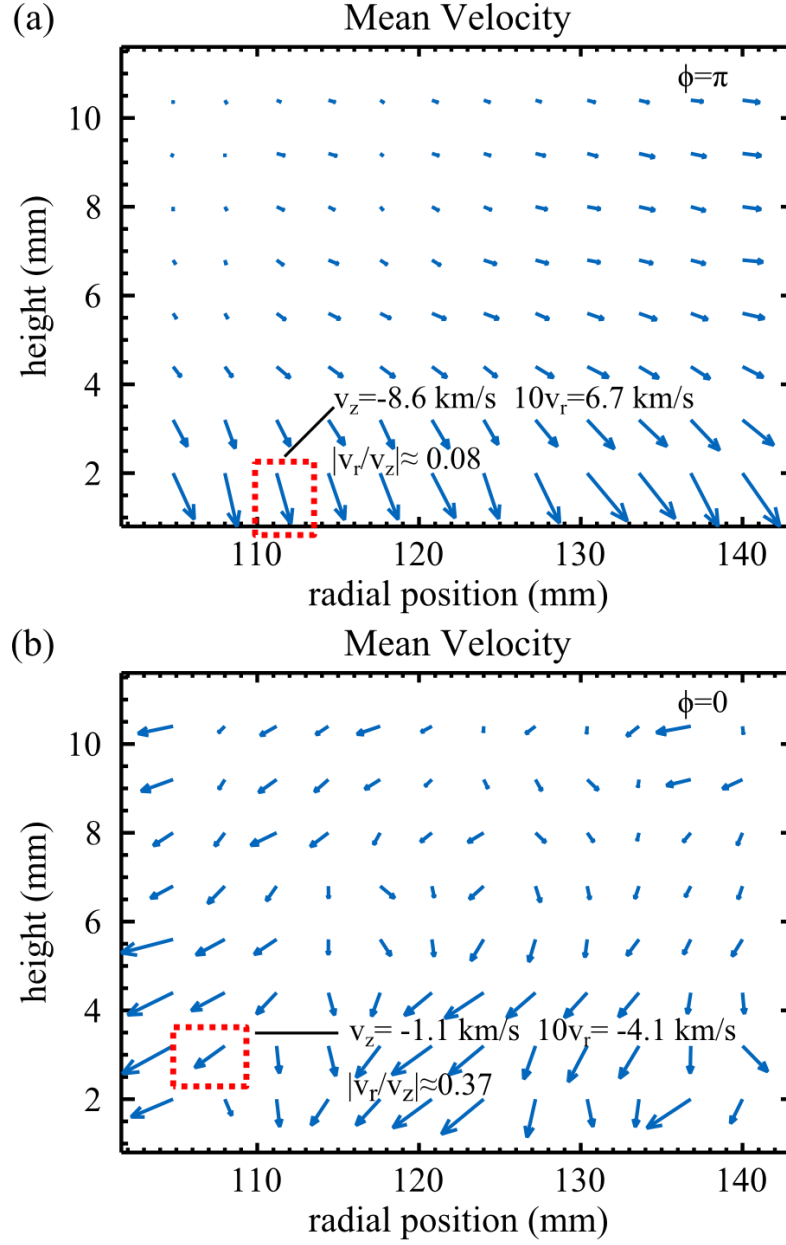


Figure 5.8. Mean velocity vectors for two disparate phases. The radial component of velocity is multiplied by 10 to emphasize radial variations in the velocities. (a) Phase $\Phi = \pi$. Towards the middle of the wafer, the velocities are dominantly downward towards the wafer. Closer to the edge of the wafer, the mean velocities have a larger radial contribution directed away from the center of the wafer. This effect persists into the main bulk of the plasma, several mm above the sheath.

(b) Phase $\Phi = 0$. For this phase, the radial component is a more significant part of the mean velocity.

of $v_z = 1.2 \times 10^4$ m/s reached at $r = 110$ mm and $z = 2.0$ mm. Closer to the radial edge of the wafer, $r = 150$ mm, and higher above the surface of the wafer ($z > s$, the sheath thickness), the velocities have a larger perpendicular component. For the least negative bias, $\Phi = 0$, the horizontal component of the velocity is much more significant compared to the strongly biased case, though the maximum velocity reached is much less ($v = 2.3 \times 10^3$ m/s).

Using both the time-averaged distributions and the transverse velocity distribution functions, it is possible to calculate the ion angular energy distribution (IAED). The transverse IVDs were fit to Gaussians as the distributions were shown to be Maxwellian (Fig. 5.3). To account for power broadening, these fits were then scaled such that a distribution in the plasma bulk had a width consistent with 0.2 eV ions. Angles are calculated with respect to a velocity vector directed towards the wafer with a magnitude equal to the mean velocity at the particular point. Negative angles are directed toward the center of the wafer and positive angles towards the wafer edge.

IAEDs at several heights above the wafer are shown in Fig. 5.9 at a radial position of $r=124$ mm. In the plasma bulk, the IEADs are centered around 0 degrees and broad, ranging from -40 degrees to 40 degrees. As ions traverse the presheath and sheath, the IAEDs narrow considerably, ranging from -20 to 20 degrees at $z=2$ mm. There is a skew towards the wafer edge present in the IAED, which is less pronounced closer to the wafer surface. This is consistent with the velocities presented in Fig. 5.8.

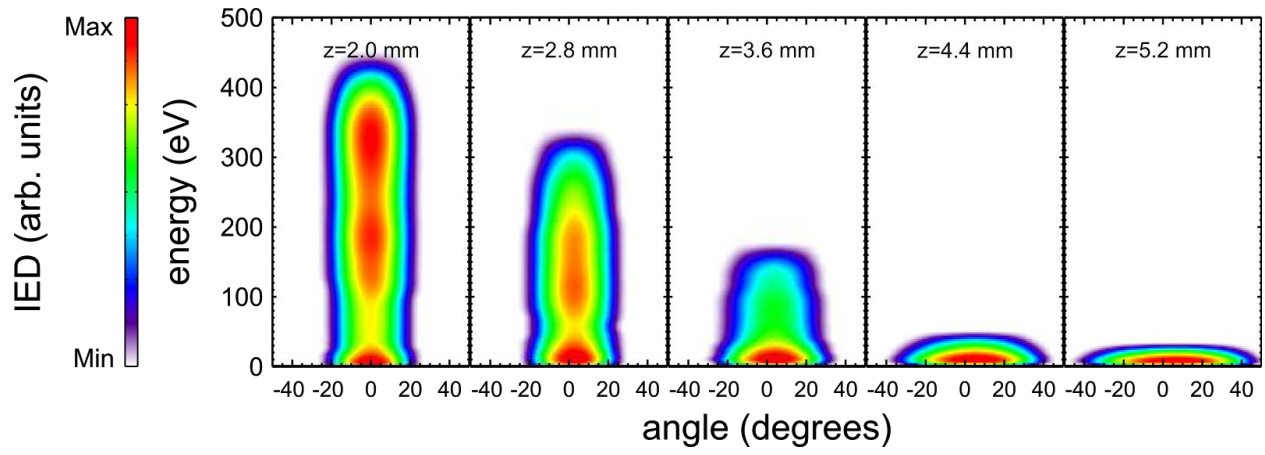


Figure 5.9. IEADs measured at a radius of 124 mm. The IEADs are shown at heights above the wafer from 2 to 5.2 mm (left to right). The narrowing of the IEADs is shown as the ions traverse the presheath and sheath. Contours are on a log scale.

The heat flux calculated from the IVDs varied significantly across the eight measured phases and horizontally across the wafer surface. Away from the edge of the wafer ($r = 112.8$ mm), the peak heat flux was 5.2 kW/m^2 at $\phi = \pi$, 2 mm above the surface, as shown in Fig. 5.10. At the edge of the wafer ($r = 146$ mm), the heat flux for this phase drops to 3.9 kW/m^2 . For the intermediate phases, the drop in heat flux from mid-wafer to the wafer edge is also present. For example, at $\Phi = 3\pi/2$, the heat flux decreases from 3.1 kW/m^2 to 1.9 kW/m^2 . Heat fluxes for phases near the least negative bias were (expectedly) much less than the peak heat flux at all horizontal positions. This strong spatial and temporal dependence on the heat flux is demonstrated in Fig. 5.11 in which the heat flux is plotted as a function of radial position of rf bias phase at a fixed height of 2 mm above the wafer. The heat fluxes shown are interpolated across the 8 measured rf phases. Here it is clearly shown that the most negative phases contribute the majority of the heat flux produced throughout the rf cycle. Fig. 5.11 further illustrates that the strongest heat flux is seen towards mid wafer and falls off towards the edge of the wafer. If we extrapolate these powers to the surface of the wafer and average over the cycle, the heat flux due to ion transport is approximately 300 W. The average power deposition at 2 MHz for the bias is 400 W, which confirms that the majority of the power deposited into the sheath is used in ion acceleration.

Comparison with Simulation

The corroborating simulations were performed at the University of Michigan by Kushner and Zhang using the Hybrid Plasma Equipment Model (HPEM), described in detail in Refs. [71, 72] and briefly discussed here. As a hybrid model, the HPEM has a hierarchical structure in which different modules address different physical processes. For this study, the Electron Magnetic

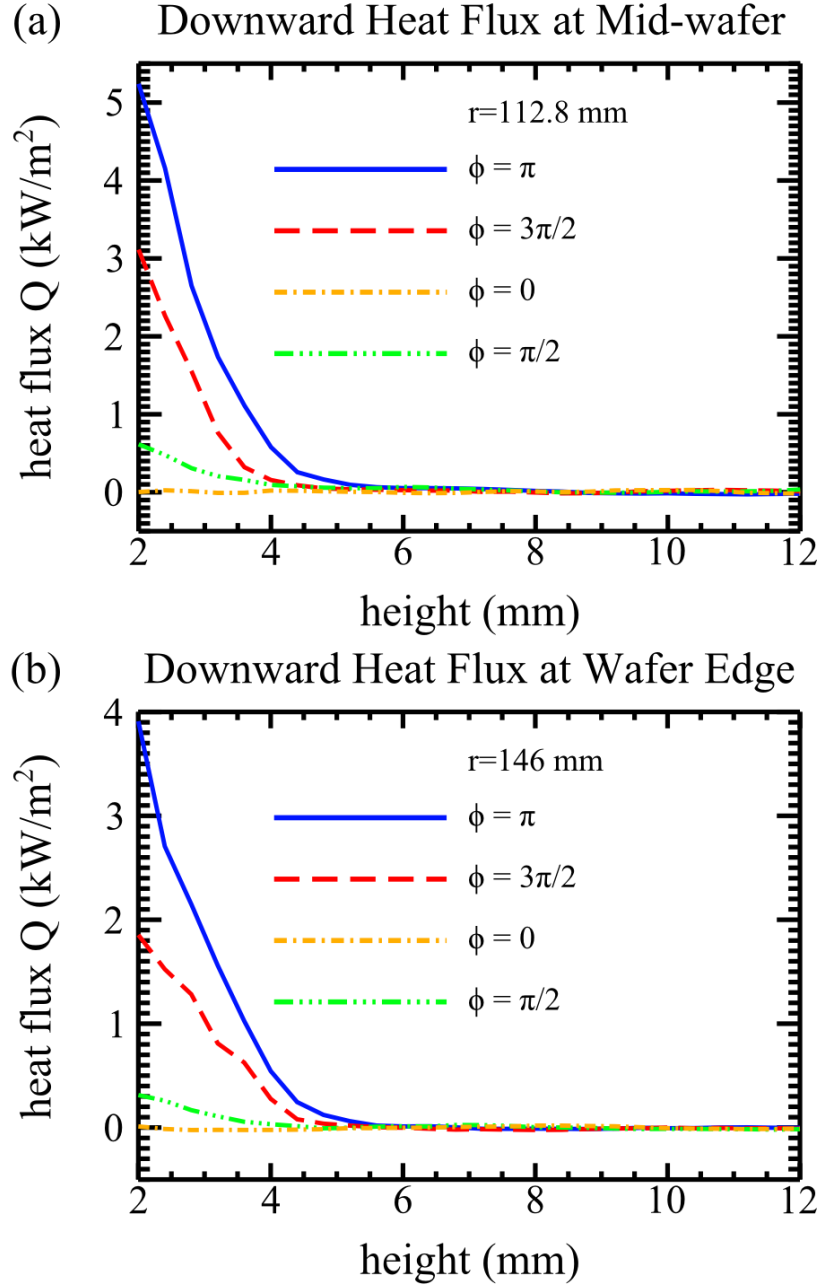


Figure 5.10. Calculated downward heat flux at four different bias phases at two different radii: (a) $r=112.8$ mm and (b) $r=146$ mm. Larger heat flux is observed towards the center of the wafer as compared to the edge.

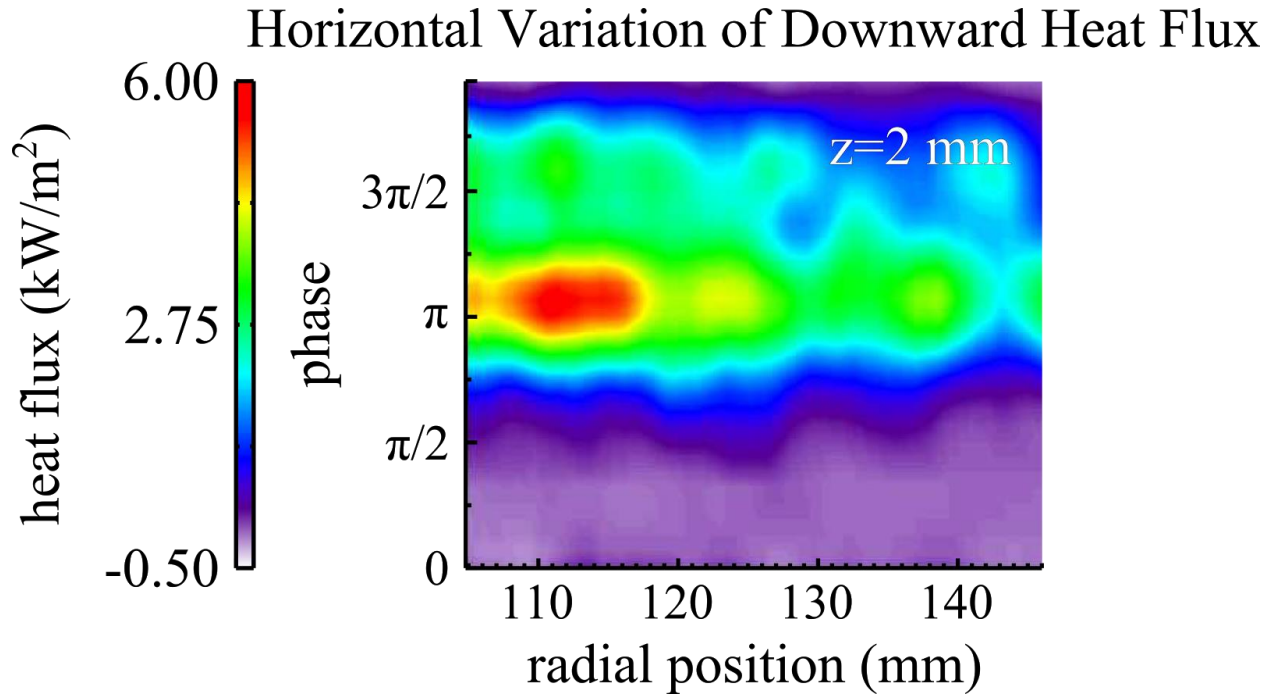


Figure 5.11. Temporal and radial dependence of the ion heat flux at a fixed height of $z = 2 \text{ mm}$. The majority of the ion heat flux is produced during the most negative portions of the rf bias and these peak values fall off from the middle of the wafer towards the edge.

Module (EMM), Electron Energy Transport Module (EETM), Fluid Kinetics Module (FKM) and Plasma Chemistry Monte Carlo Module (PCMCM) were employed. The computational structure is shown schematically in Fig. 5.12. The EMM solves the frequency domain form of the wave equation for the inductively coupled fields. In the EETM, the electron Monte Carlo simulation provides electron energy distributions of bulk electrons. A separate Monte Carlo simulation is used for secondary, sheath accelerated electrons. The FKM solves heavy particle and electron continuity, momentum, energy and Poisson's equation for the electric potential. These three modules transfer parameters to the other modules using time-slicing techniques. When a quasi-steady state is reached, the PCMCM is used to obtain ion energy (or velocity) and angular distributions in the bulk plasma, pre-sheath, sheath and wafer. Pseudo-particles representing ions are launched from the site of their formation and their trajectories are integrated as function of time using electric fields from the FKM recorded as a function of phase. Collisions are accounted for using Monte Carlo techniques. As improvements to the previously described PCMCM, a finer sub-mesh is used within the HPEM in order to resolve ion transport from the bulk, through the presheath and sheath, and onto the wafer. Statistics on the velocity components of the ion trajectories are recorded as function of position (radius and height above the wafer) and phase during the rf cycle. The position of the sub-mesh was chosen to match with LIF measured area (100 to 148 mm in radius and 0.2 to 6 mm above the wafer).

The reactor for the simulation is essentially the same as in the experiment as shown in Fig. 4.1 – an inductively coupled plasma with a 2 MHz bias on the substrate. The gas pressure was 0.5 mTorr and gas mixture $\text{Ar}/\text{O}_2 = 80/20$ with a total flow rate of 50 sccm. The reaction mechanism for the Ar/O_2 plasma is discussed in Ref. [73]. The ICP power deposition was 500 W and the substrate bias was 400 V. The self-generated dc bias is around -360 Volt. This voltage amplitude

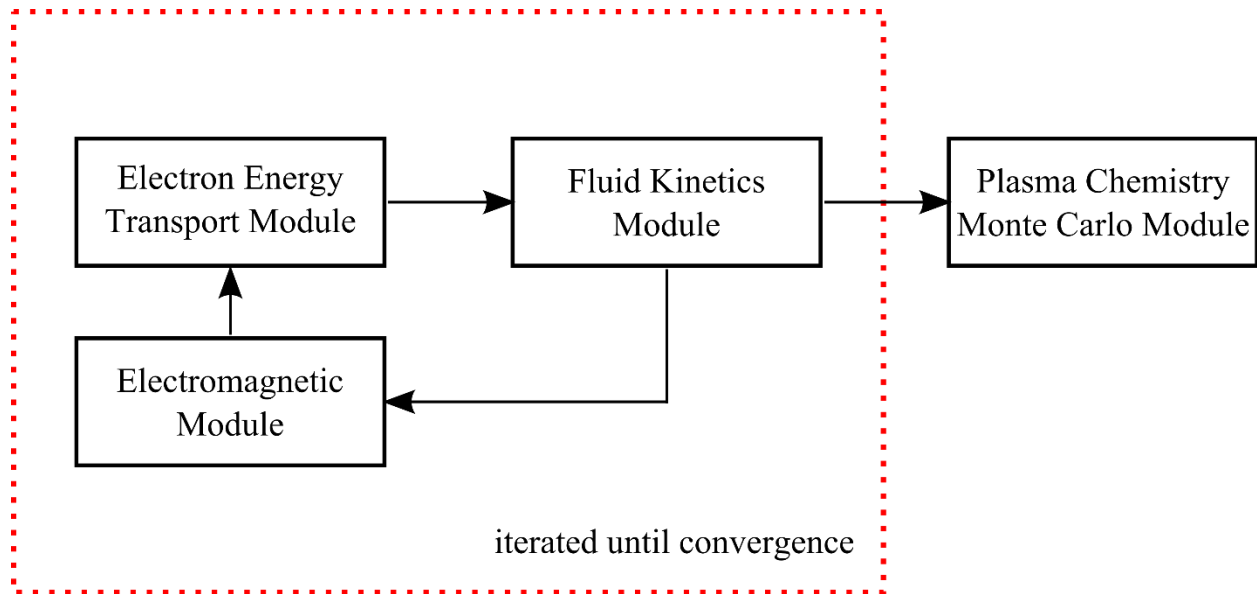


Figure 5.12. A schematic of the computational modules employed for the simulation of the experiment. The electromagnetic module solves the wave equations for the inductively coupled fields and the electron energy transport module solves for the electron energy distribution functions. These modules feed the fluid kinetics module which solves the conservation equations and Poisson's equation for the electric potential. These modules iterate until they converge, at which point the plasma chemistry Monte Carlo module uses the output to solve for the ion energy distribution functions.

was chosen so that the predicted maximum energy of the IEDs within the spatial region accessible to measurements matched the experiments. The sub-mesh resolution was 4 mm in radius and 0.4 mm in height. The phase resolution was 62.5 ns (8 phases within 2 MHz).

Predictions for the IEDs extend from the bulk plasma through the sheath to the wafer at phases of $\Phi = \pi$ (most cathodic) and $\Phi = 0$ (most anodic) are shown in Figs. 5.13 and 5.14 for an inner radius (112 mm) and at the wafer edge (148 mm). Comparing to the experimental results (Figs 5.4 and 5.5), the model predicts a similar range of energies (350-400 eV) at 1.2 mm above the wafer at phase $\Phi = \pi$. For the least negative bias, $\Phi = 0$, the maximum energy is about 50 eV at 1.2 mm above and reach the wafer at 50-100 eV. The double-peaked nature of the IED begins at the sheath edge at about 4 mm. At this low frequency of 2 MHz, there is clear separation with phase of the low and high energy components of the IEDs regardless of radial position above the wafer. We have found that the details of IEDs near the edge of the wafer are sensitive to the charging of the focus ring, its dielectric constant and subtleties of its geometrical relationship to the edge of the wafer. The simulation predicts an edge effect of only 10 eV difference in the maximum of the IED since the sheath is fairly uniform in this reactor. The experimental results (Figs 5.4 and 5.5) confirmed this trend. The maximum energy at the surface of the wafer extends to 720-730 eV at the inner radius and 690-700 eV at the edge of the wafer, somewhat higher than seen in the experiments, 650 eV. Computed IEDs at a radius of 112 mm for a phase of $\Phi = \pi$ at different heights above the wafer are shown in Fig. 5.15. For $\Phi = \pi$ (most cathodic portion of the cycle), the low energy portion of the IED is nearly absent as the ions are essentially collisionlessly accelerated through the sheath. Comparison to the experimental results confirm this separation in phase.

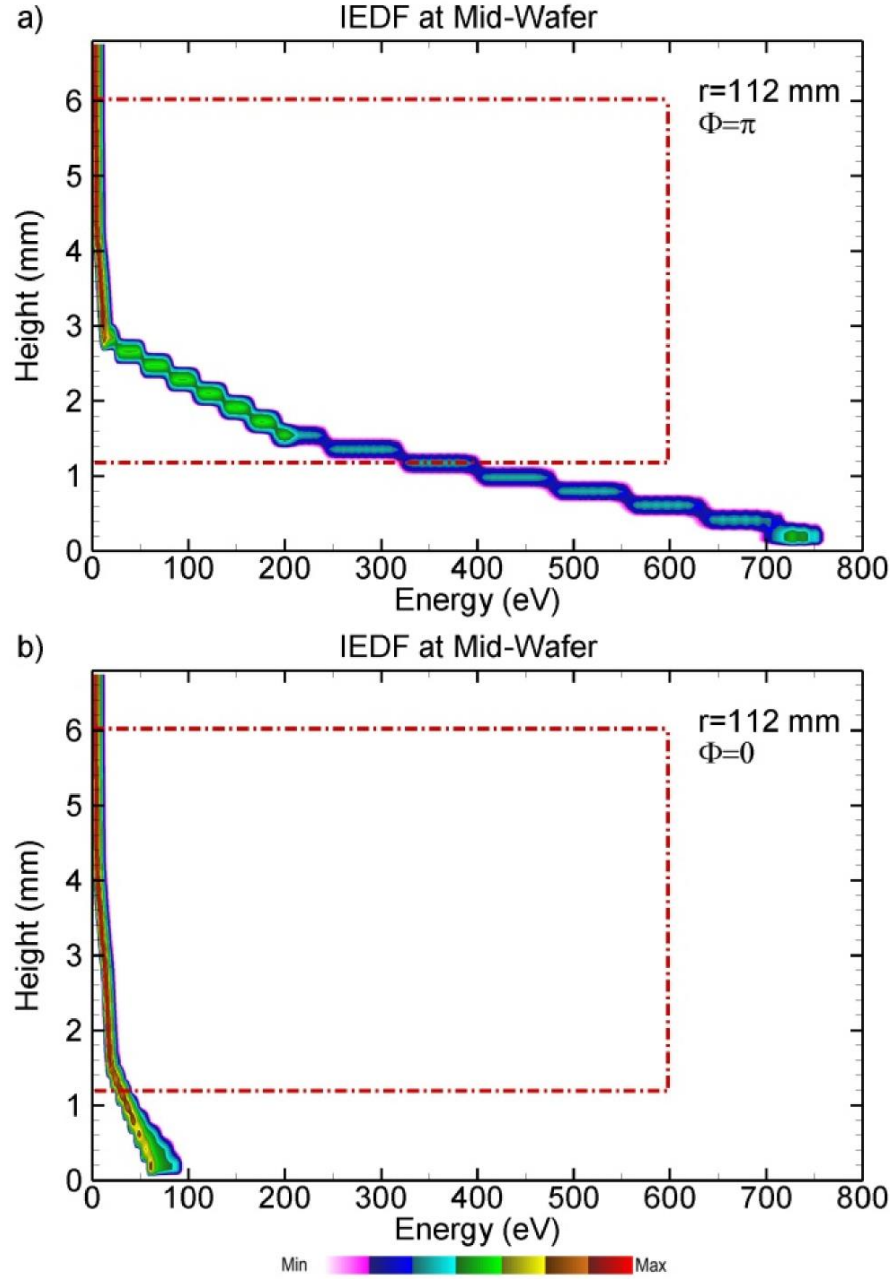


Figure 5.13. Computed IEDs from bulk plasma through the sheath to the wafer at $r = 112$ mm for $\text{Ar}/\text{O}_2 = 80/20$, 0.5 mTorr for 2 MHz rf, 400 Volt amplitude and dc bias of -360 Volt. (a) Phase $\Phi = \pi$ and (b) Phase $\Phi = 0$. The stair-step appearance is due to the discreteness of the mesh upon which the IEDs are collected. The plot is in log scale.

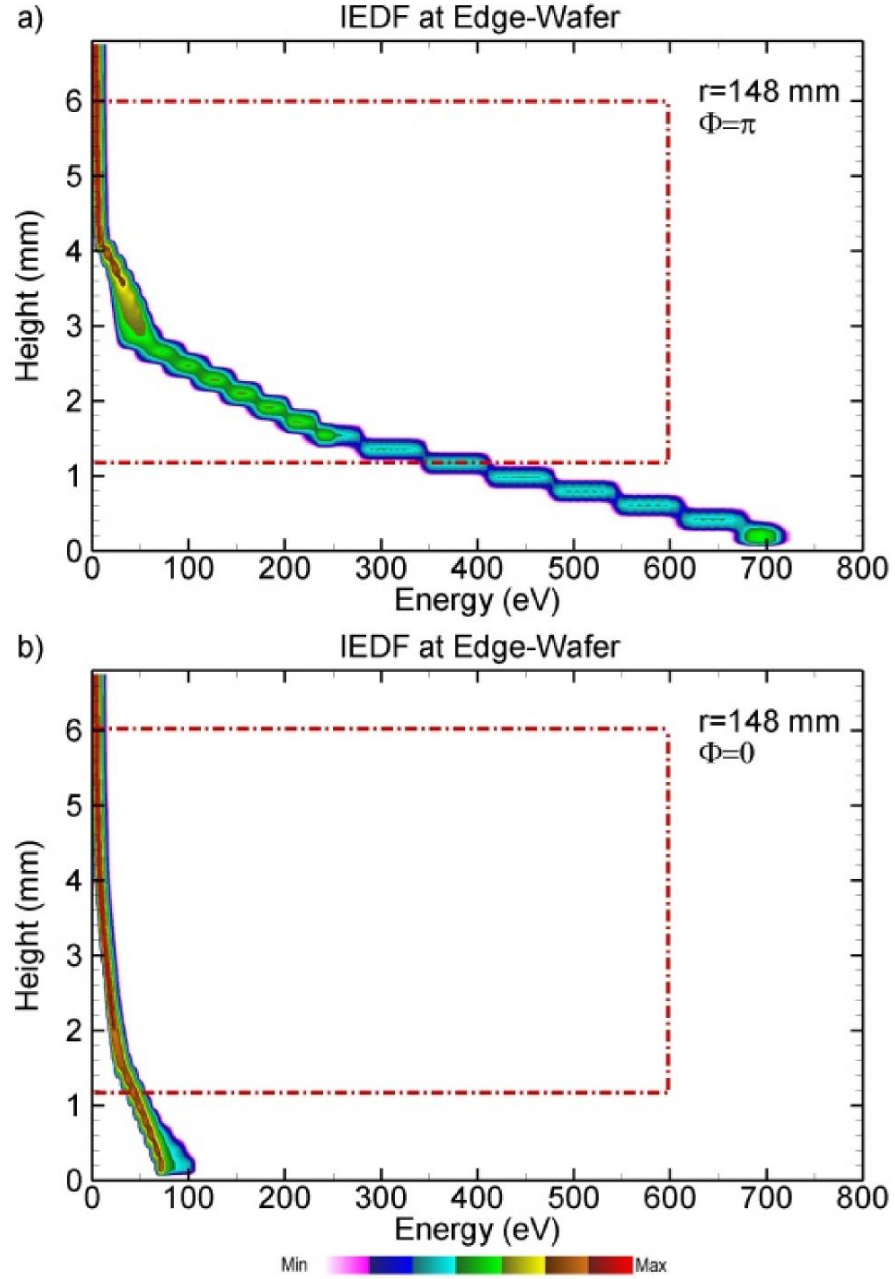


Figure 5.14. Computed IEDs from bulk plasma through the sheath to the wafer at $r = 148$ mm for $\text{Ar}/\text{O}_2=80/20$, 0.5 mTorr for 2 MHz rf bias, 400 Volt amplitude and dc bias of -360 Volt. (a) Phase $\Phi = \pi$ and (b) phase $\Phi = 0$. The stair-step appearance is due to the discreteness of the mesh upon which the IEDs are collected. The plot is in log scale.

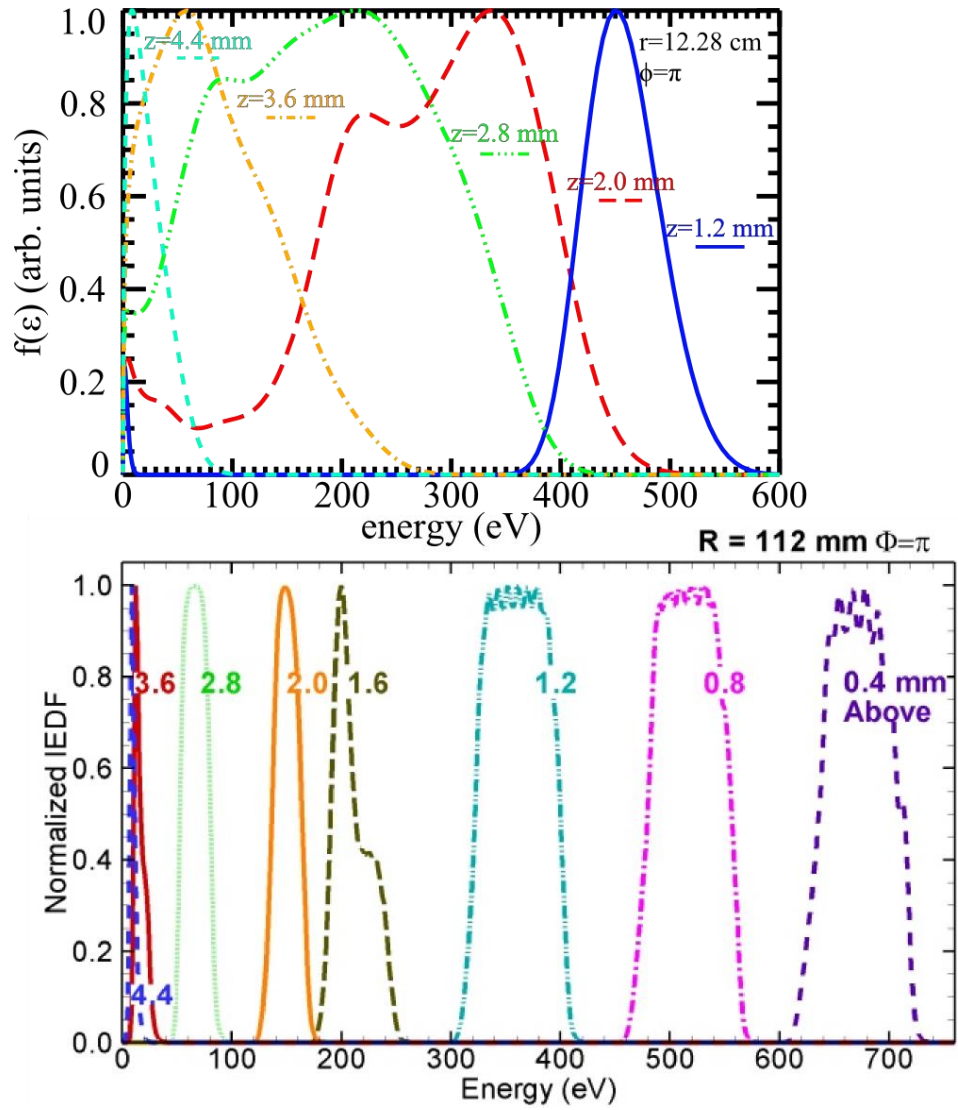


Figure 5.15. A comparison of measured (top) and computer (bottom) IEDs at a radius of 112 mm for a phase of $\phi = \pi$ for different heights above the wafer. Higher energies were consistently observed in the measured results as compared to the simulation. The reason for this discrepancy is not well understood.

Summary

Planar laser-induced fluorescence was used to measure for the first time both the perpendicular and parallel component of the velocity distribution function of ions in a single rf sheath as a function of radius and height above a biased wafer. Results for individual radial positions are consistent with measurements performed by Jacobs *et al.* [35]. Measurements were extremely phase dependent and both the energy distribution functions and mean velocity vectors were found to vary radially across the wafer. In particular, lower energies and larger impact angles were observed near the wafer edge. Both of these traits would be undesirable for etching. This could help explain the relatively inferior etch quality typically observed at the edge of the wafer.

The experimental results showed good qualitative agreement with simulations specifically designed for this tool. Ion energy measurements, however, were consistently larger than results from the simulations. The exact reason for this is not well understood. One possible explanation could be charging near the surface of the wafer which is not taken into account in the model used for the simulations. Such charging would increase the electric field near the wafer and thus increase ion bombarding energies.

Chapter 6

Ion Velocity Distribution Functions in a Dual Frequency Sheath

Bias and Plasma Parameters

f_{LF}	2.2 MHz
ω_{LF}	1.38×10^7 rad/s
V_{LF} (peak-to-peak)	1900 V
P_{LF}	2500 W
f_{HF}	19 MHz
ω_{HF}	1.19×10^8 rad/s
V_{HF} (peak-to-peak)	900 V
P_{HF}	1930 W
T_e	1.5 eV
n_0	$2 \times 10^{10} \text{ cm}^{-3}$
S_{LF}	7.8 mm
S_{HF}	4.5 mm
$\frac{2\pi}{\tau_{ion,LF}} = \omega_{ion,LF}$	1.8×10^7 rad/s
$\omega_{rf}/\omega_{ion,LF}$	0.76
$\frac{2\pi}{\tau_{ion,HF}} = \omega_{ion,HF}$	2.2×10^7 rad/s

$\omega_{rf}/\omega_{ion,HF}$	5.5
Fill pressure	0.5 mTorr
λ_{in}	6.7 cm

Table 6.1. A list of parameters for the 2.2 MHz bias and plasma for the single frequency bias experiment.

In addition to a single low frequency bias, a second higher frequency bias is typically applied to the wafer in industrial settings in order to independently control both the ion energy and flux. In order to more closely emulate the dual frequency setups used in industry, a 19 MHz bias was added to the existing experimental setup outlined in Chapter 5. Planar LIF was used once again to investigate the height, radial, and phase dependence of the ion velocity distribution function and associated calculated moments. The investigation focuses on how the IEDs and the radial uniformity of the densities, velocities, and fluxes change with the addition of a second bias frequency and how this might impact industrial ion etching.

Experimental Results

The voltage delivered to the wafer was measured at the base of the copper pedestal using a resistive voltage divider. A network analyzer was used to measure the frequency response of the voltage divider to ensure voltage measurements in the desired 2-19 MHz frequency range were correct. These results showed the response to be comparable to a DC signal, as desired. During

separate single frequency operation, the calibrated peak-to-peak voltage measurements of the 2 MHz bias was measured to be 2500 V and the 19 MHz to be 900 V. During dual frequency operation, the high frequency voltage remained at 900 V while the 2 MHz component of the measured voltage dropped to 1900 V.

The 2 MHz bias was phase-locked to the laser Q-switch as was the case in the single frequency bias experiment. The pedestal voltage measurement was filtered and the resulting 2 MHz signal is shown in Fig. 6.1. Phase-locking the experiment to the 2 MHz bias resulted in a time-averaged 19 MHz voltage added to the low frequency bias, the upper and lower bounds of which are shown along with the filtered 2 MHz. LIF measurements were taken at two disparate phases of the low frequency rf cycle, denoted by $\Phi_{LF} = \pi$ and $\Phi_{LF} = 0$, corresponding to the most negative ($\Phi_{LF} = \pi$) and least negative ($\Phi_{LF} = 0$) phases. As with the single frequency case, due to the highly asymmetric geometry of the capacitive discharge and the blocking capacitor, the dc self-bias across the sheath is approximately half of the applied peak-to-peak voltage. In other words, the maximum potential drop across the sheath would be approximately 2800 V with a dc bias of -1400 V.

Using the Child sheath approximation from eq. 2.15, the calculated sheath widths of the low and high frequency sheath separately are $s_{LF}=7.8$ mm $s_{HF}=4.5$ mm, where s_{LF} is the low frequency sheath width and s_{HF} is the high frequency sheath width. The sheath width is thus controlled primarily by the low frequency bias. As the low frequency bias is phase-locked in this experiment, the sheath front during data acquisition can be thought of as slowly moving low frequency sheath with oscillations due to the high frequency time-averaged sheath.

From eq. 2.18, the ion transit parameters for the two biases are $\omega_{2MHz}/\omega_{ion} = 0.76$ for the low frequency bias and $\omega_{19MHz}/\omega_{ion} = 5.5$. This places the lower frequency sheath in the

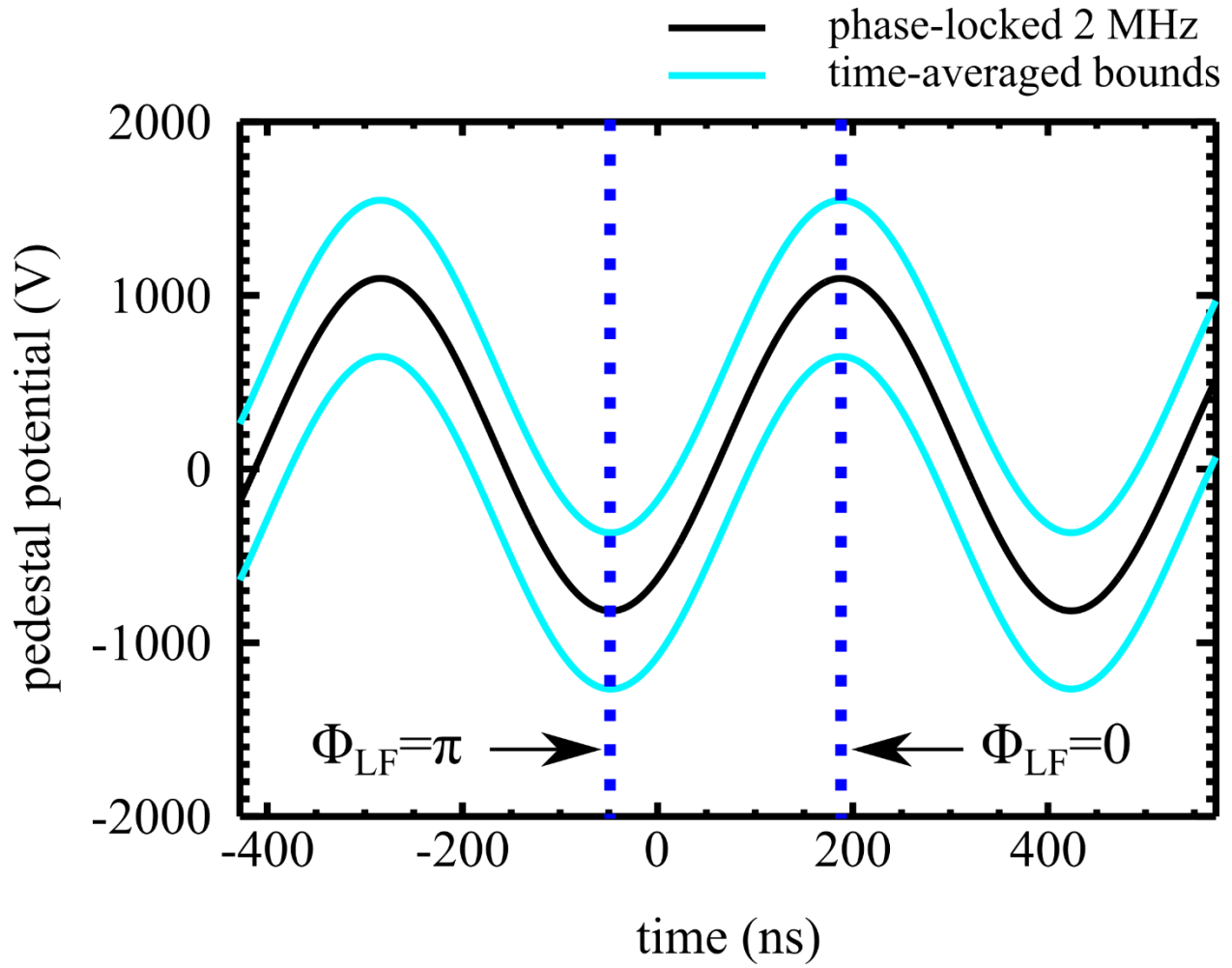


Figure 6.1. The phase-locked 2 MHz component of the applied bias voltage. Also shown are the maxima and minima of the time-averaged high frequency component of the bias. The peak-to-peak voltage of the 2 MHz component was approximately 1900 V and the high-frequency component was approximately 900 V. Measurements were taken at two phases of the phase-locked 2 MHz bias, as shown in the figure.

intermediate frequency ($\omega_{rf}/\omega_{ion} \approx 1$) regime, meaning the sheath will change substantially as the ion traverses the region. The 19 MHz sheath is closer to the high frequency approximation ($\omega_{rf}/\omega_{ion} \gg 1$) as described in Chapter 2, but still low enough that the phase at which the ion enters the sheath is important to the evolution of the ion energies through the sheath.

The deconvolution algorithm used for the single frequency experiment was not used in this dual frequency experiment. The LIF signal corresponding to the high energy ions was sufficiently small such that the deconvolution algorithm would suppress the high energy peaks and leave only the central peak corresponding to the cold ions. The decrease in LIF signal from this experiment as compared to the single frequency bias experiment can be explained by a lower bulk plasma density (26% lower than in the single frequency experiment) and lower densities of high energy ions within the sheath due to the substantially larger bias voltages. From flux conservation, larger ion velocities will result in a corresponding drop in the ion density. This lower density will in turn result in a lower LIF signal at higher velocities. Without the deconvolutions, the widths of the distribution functions presented will be artificially broadened by mechanisms discussed previously.

Ion energy distribution functions at several heights above the wafer (4, 2.4, and 0.8 mm) for the phase $\Phi_{LF} = \pi$ are shown in Fig. 6.2. Measurements are shown only up to 2000 eV as the LIF signal was unreliable above this point due to the aforementioned decrease in ion densities. The energy distribution functions shown are normalized to the maximum of each distribution. A large central peak is once again observed in the ion energy distributions well into the sheath, as was the case with the single frequency bias. As discussed in the previous chapter, while the charge exchange mean free path is larger than the sheath width, a small fraction of ions could still undergo collisions and could cause such a large central peak. Booth *et al.* have also observed enhanced

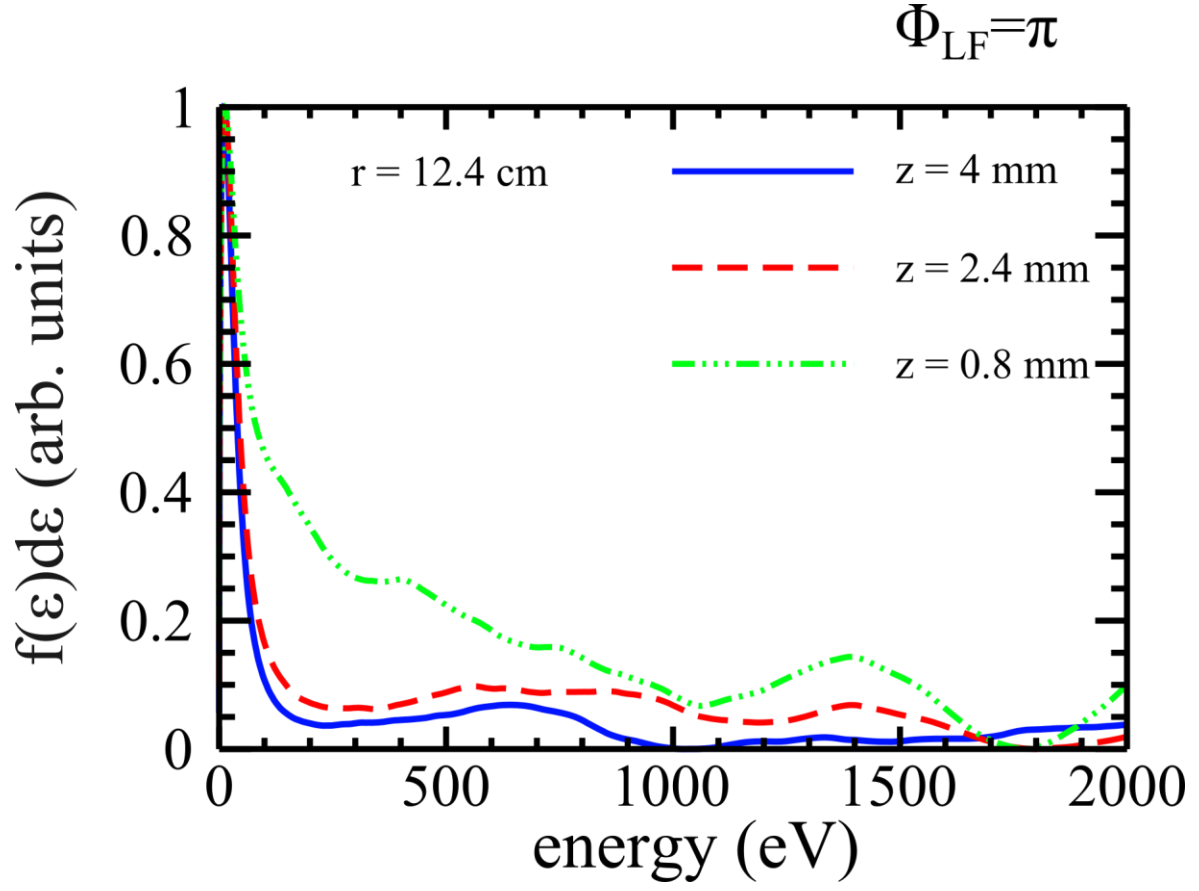


Figure 6.2. Normalized ion energy distribution functions towards mid wafer at several heights for the most negative biased phase. Observed IEDs were multi-peaked. Lower energy peaks were more difficult to resolve. This could be due to power broadening and the lack of the deconvolution algorithm.

ionization near a silicon wafer in a 50 mTorr Ar/O₂ plasma, possibly due to SiO₂ secondary electron emission from oxygen ions bombarding the wafer [59]. This is not likely significant in this experiment, however, as the fill pressure is much lower. As such, the electron ionization mean free path is ~ 1 m. Contributions from charge exchange are on the order of 10 times larger than the contributions from second electron ionization collisions. Towards the edge of the sheath, the distribution function is comparatively flat and higher energy peaks emerge as the ions approach the wafer surface. The observed peaks are rather broad, which can be attributed to the broadening of the LIF measurement. Notably, the ion energy distribution functions close to the surface of the wafer are multi-peaked. If there is ionization within the sheath, these peaks would arise due to the rf modulation of the high frequency bias, as described in Wild and Koidl [40]. The number of high frequency periods that an ion would experience as it traverses the sheath is given by the ratio of the ion transit time across the expanded low frequency sheath to the period of the high frequency bias. From eq. 2.18, this ratio is 6.6, meaning that we would expect to see up to six peaks in the distribution function.

Ion energy distribution function measurements in the same conditions at a radial position closer to the edge of the wafer ($r=14.6$ cm) are shown in Fig. 6.3. Similar peaks as those seen closer to the mid-wafer are observed in the distribution function at the wafer edge, including the multi-peaked structure. The location of the peaks are similar to those observed at the smaller radial position.

Removal of the peak in the distribution function corresponding to the cold ions further emphasizes the high energy ions that perform the etching. Fig. 6.4 shows two such distribution functions as a comparison between IEDs at the wafer edge and mid wafer at a height of 0.8 mm. The remaining peaks in the distribution functions can be approximated by the sum of several

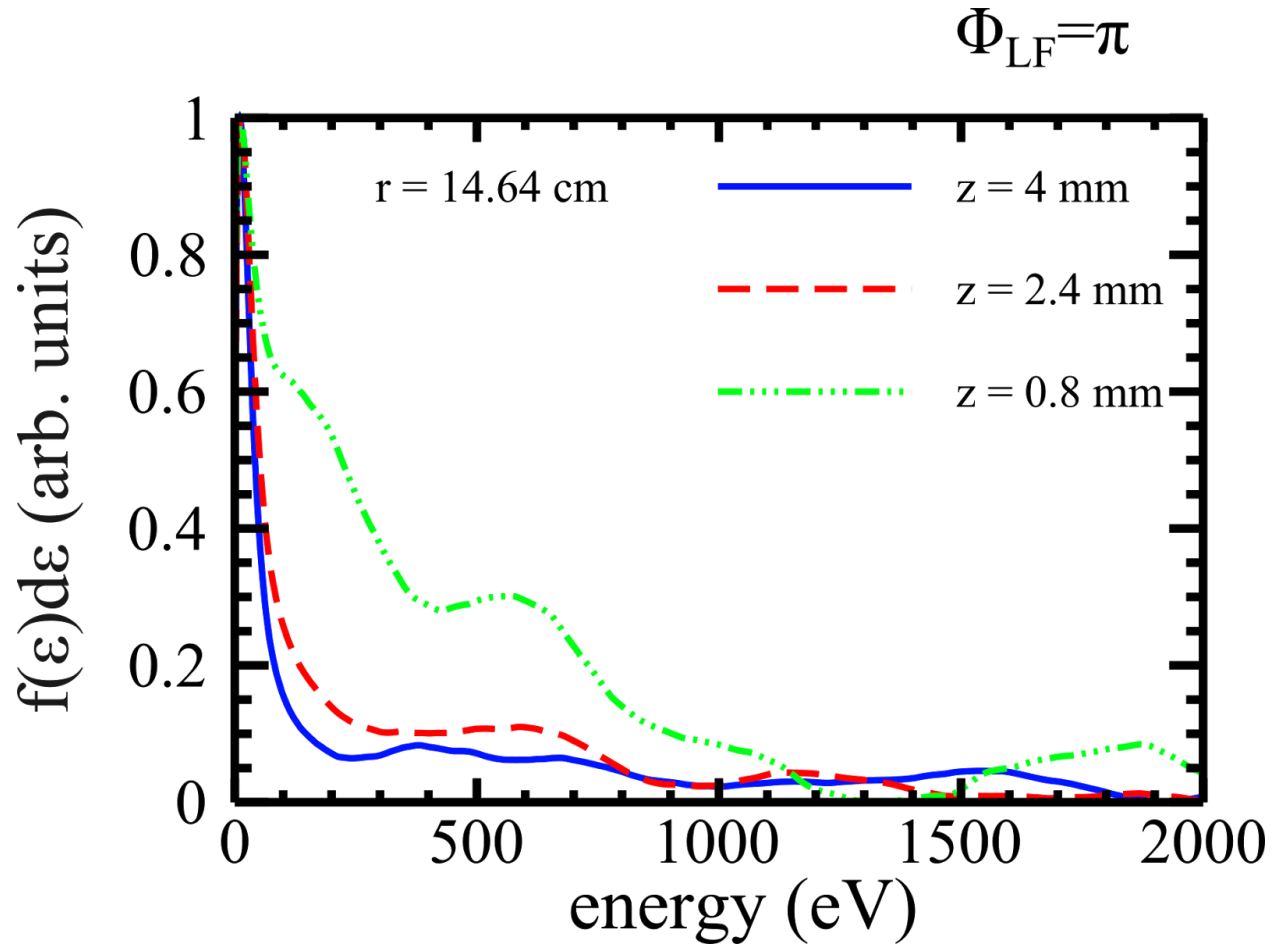


Figure 6.3. Normalized ion energy distribution functions at the wafer edge at several heights for the most negative biased phase. IEDs were again observed to be multi-peaked.

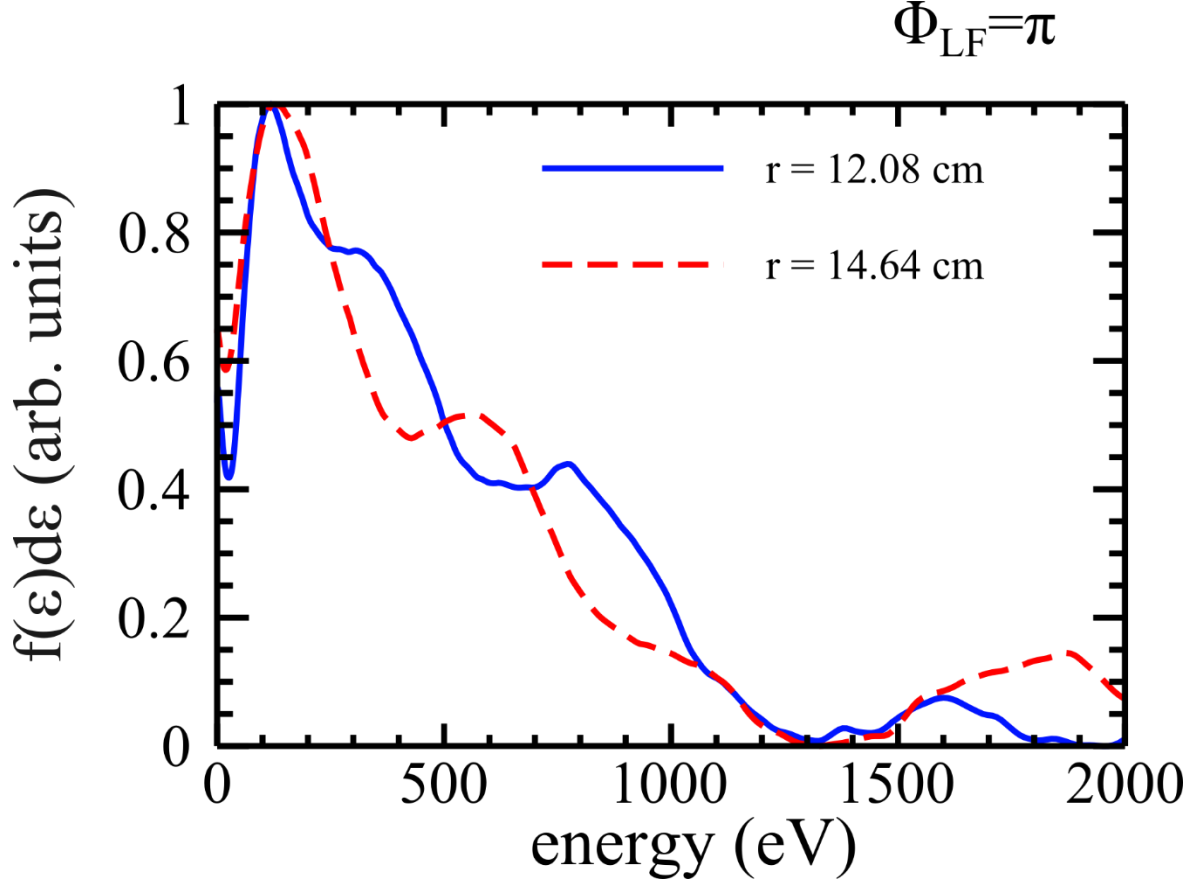


Figure 6.4. A comparison of distribution functions at a height of 0.8 mm for two different radial positions for the $\Phi_{LF} = \pi$ phase. The peak corresponding to the cold ions was fit to a Maxwellian and subtracted out to emphasize the remaining fast ions.

Maxwellian distributions centered around different velocities. The ion velocity distribution function for both the mid-wafer and wafer edge case presented in Fig. 6.4 were each fit to a sum of four Maxwellian distribution functions. The resulting ion energy distributions are shown in Figs. 6.5 and 6.6. In the top half of the figures, the sum of the Maxwellian fits are shown to compare favorably with the measured data. The IEDs corresponding to the four separate ion energies are shown in the bottom half of the figures along with the overall sum. For the mid-wafer case (Fig. 6.5), the four peaks were centered at 110, 370, 780, and 1600 eV. Energies at the wafer edge were larger (Fig. 6.6), with peaks centered at 130, 610, 1030, and 1800 eV.

Distribution function measurements for the collapsed sheath phase ($\Phi_{LF} = 0$) for several heights are shown for radial positions 12.6 cm and 14.6 cm in Figs. 6.7 and 6.8, respectively. For this less negatively biased phase, fewer high energy ions are observed as compared to the $\Phi_{LF} = \pi$ phase. The multi-peak structure observed in the expanded sheath case is also not present for this case. If the peaks are caused by rf modulation from the higher frequency source, fewer peaks would be expected in this phase. A smaller sheath width would result in a shorter ion transit time across the sheath and thus an ion would experience fewer cycles of the high frequency bias. This would result in few peaks in the energy distribution function. A comparison of the distribution functions near the wafer edge and towards the middle of the wafer for this phase are shown in Fig. 6.9. The cold peak was once again removed.

For a purely high frequency sheath, one would expect to see a single peak in the distribution function corresponding to the time-averaged potential drop across the sheath. In this experiment, that would correspond to a peak around 450 eV. Closer to the intermediate frequency regime a bimodal structure would be expected. Broadening of the LIF signal, however, might prevent resolution of the peak separation. As low frequency bias is also present, the value of the peak will

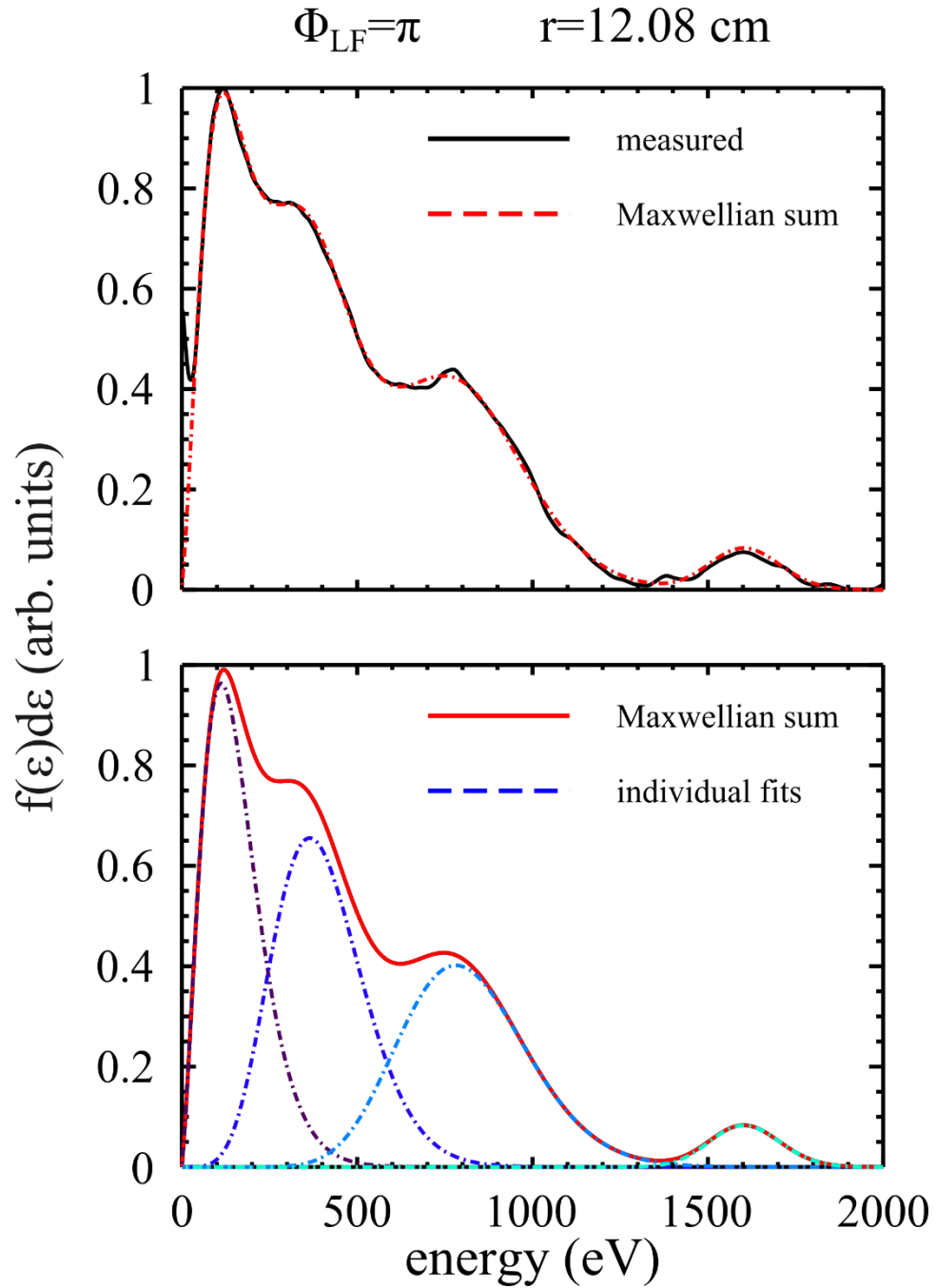


Figure 6.5. A comparison of the measured IED at height of 0.8 mm at mid-wafer to a fit comprised of the sum of four Maxwellian distributions at 110, 370, 780, and 1600 eV. The bottom half of the figure shows the individual Maxwellian fits.

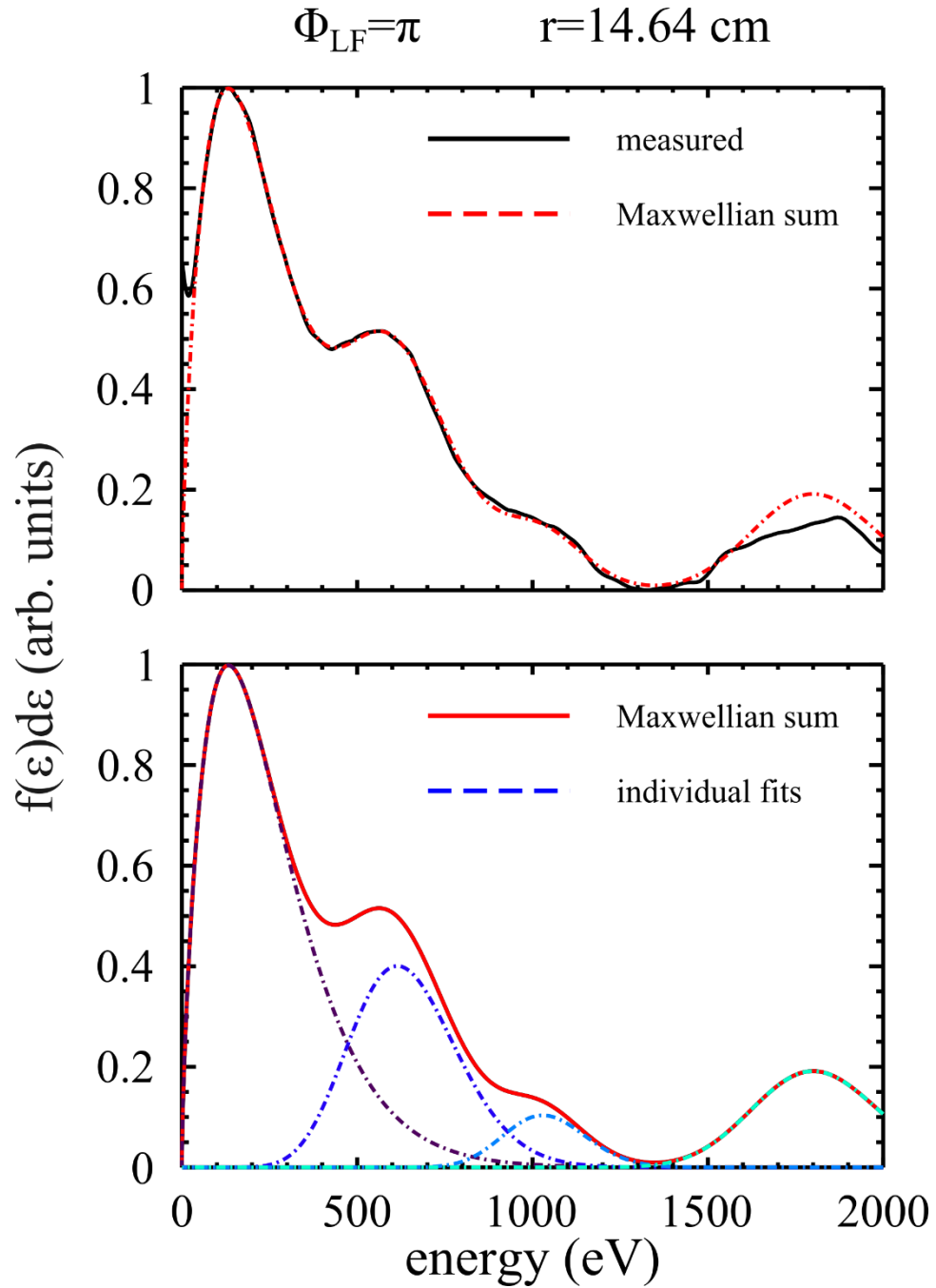


Figure 6.6. A comparison of the measured IED at height of 0.8 mm at the wafer edge to a fit comprised of the sum of four Maxwellian distributions at 130, 610, 1030, and 1800 eV. The bottom half of the figure shows the individual Maxwellian fits.

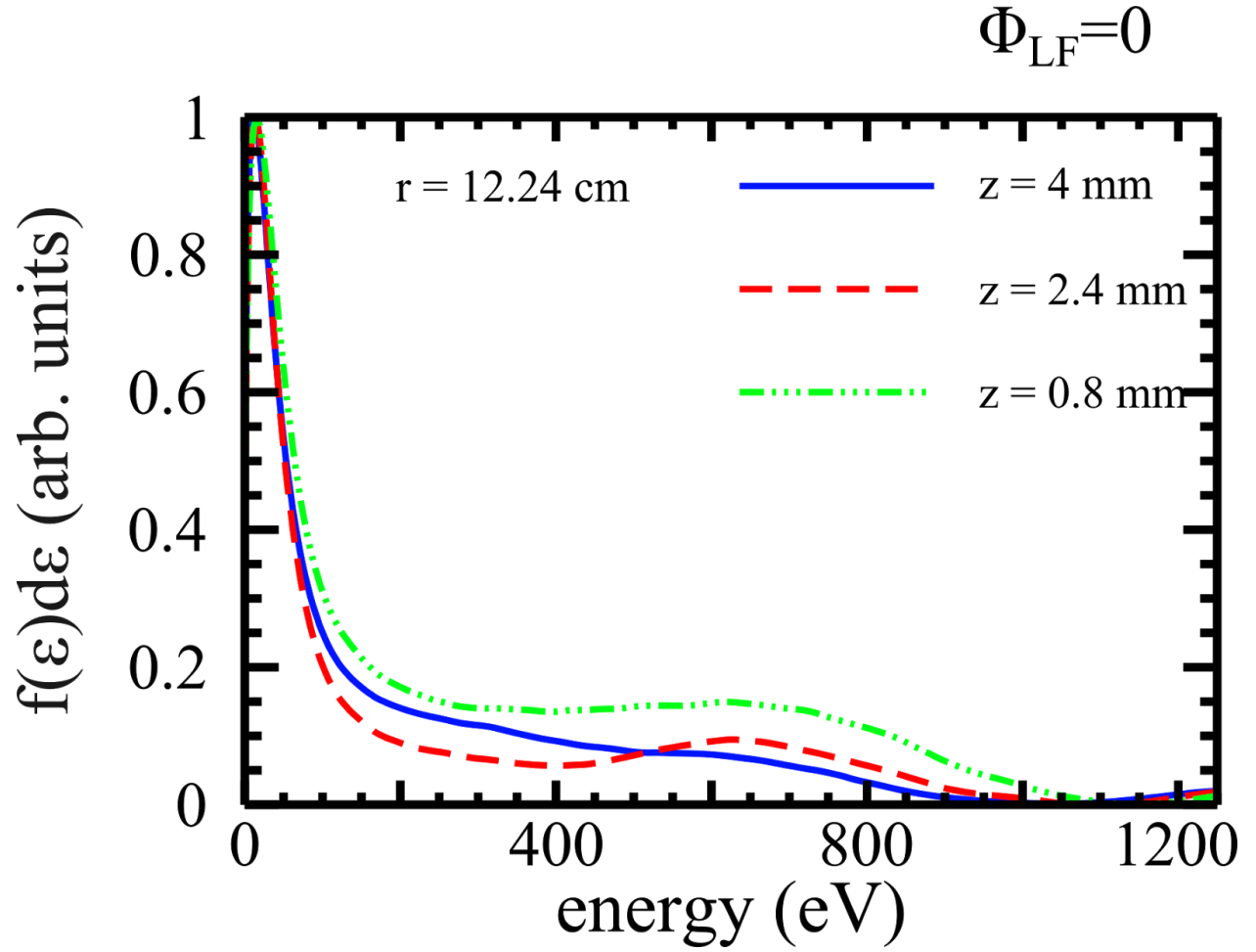


Figure 6.7. Normalized ion energy distribution functions towards mid wafer at several heights for the least negative bias phase. Observed peaks for this case are lower energy than those observed in Figs. 6.2 and 6.3.

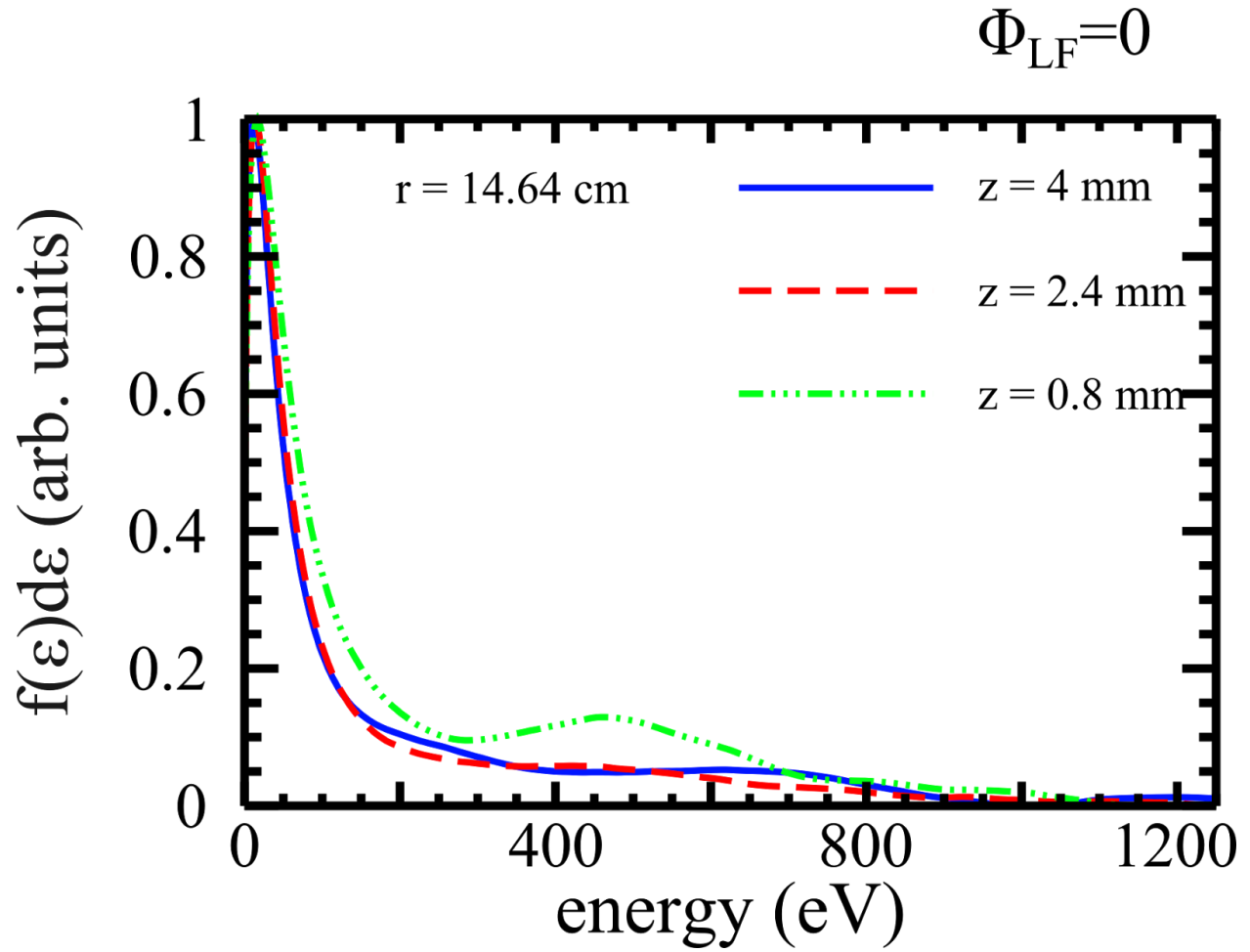


Figure 6.8. Normalized ion energy distribution functions at the wafer edge at several heights for the least negative bias phase. Only peaks towards lower energies are observed.

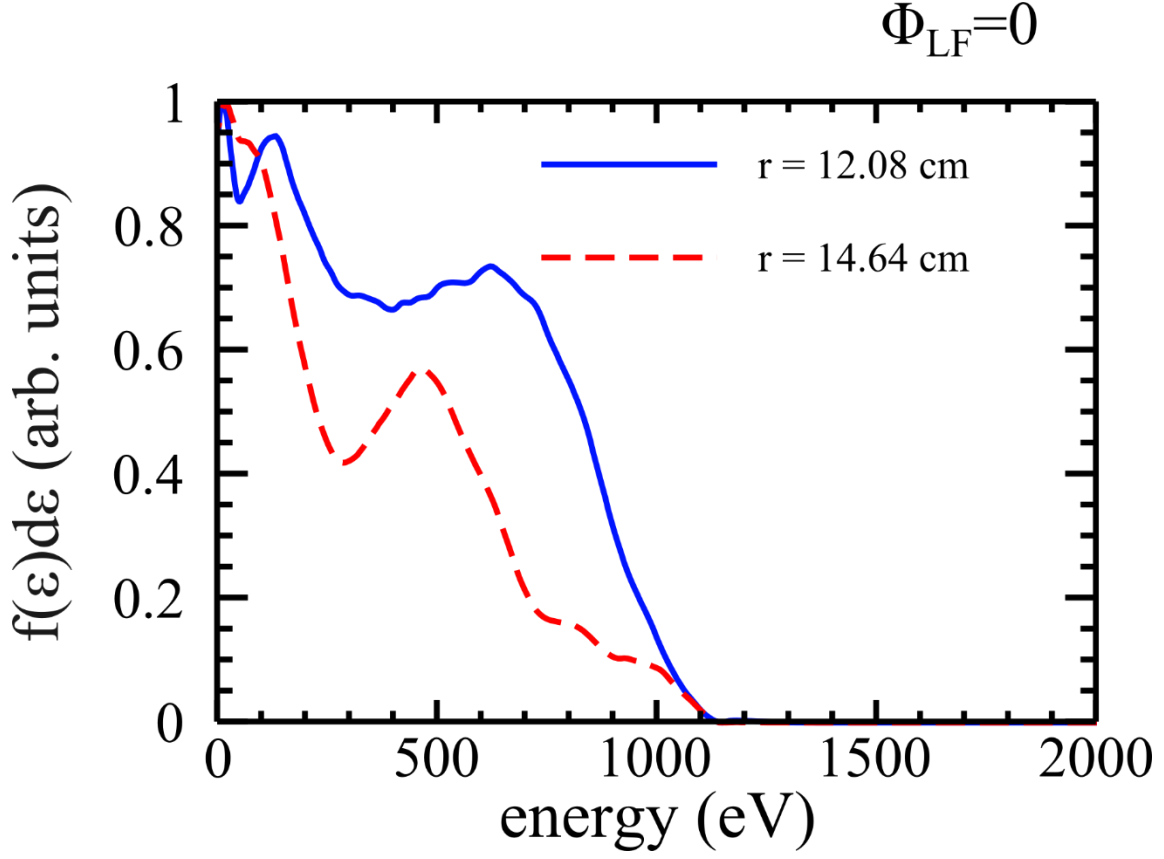


Figure 6.9. A comparison of distribution functions at a height of 0.8 mm for two different radial positions for the $\Phi_{LF} = 0$ phase. The peak corresponding to the cold ions was fit to a Maxwellian and subtracted out to emphasize the remaining fast ions.

change depending on the sheath potential for this particular phase. It is difficult to determine the exact effect from the low frequency bias in this experiment, however, as the sheath is changing substantially as the ion traverses the sheath. Single peaks are observed in the distribution function at 450 eV at the wafer edge and approximately 600 eV more towards mid wafer. These values agree with the expectation of a peak near the time-averaged value of the 19 MHz bias. The larger energy towards the mid wafer suggests a more significant contribution from the changing sheath width and potential as compared to larger radial positions.

Integrating the velocity distribution functions over all measured velocities will yield the spatial dependence of the ion density ($n(r, z, t) = \int f(r, z, v_z, t) dv_z$), as shown in Figs. 6.10 and 6.11. For these calculations, data corresponding to ions moving away from the wafer surface were once again ignored as it was not possible to distinguish between ion moving upwards and fluorescence resulting from reflected light off the surface of the wafer. The data presented is normalized to maximum density of the three separate cases ($\Phi_{LF} = \pi$, $\Phi_{LF} = 0$, and unbiased), approximately $2 \times 10^{10} \text{ cm}^{-3}$. The bulk plasma density was the same for each case. For the $\Phi_{LF} = \pi$ phase shown in Fig. 6.10, the density is shown to be highly radially non-uniform. At the wafer edge, densities are a factor of two lower than those seen towards the middle of the wafer. This trend continues even several cm above the wafer, well outside the sheath region. Densities for the $\Phi_{LF} = 0$ case are shown in Fig. 6.11 and compared with measurements from an unbiased case. The densities for the two cases are essentially the same and are much more radially uniform than the expanded sheath case. This discrepancy in radial uniformity could possibly be due to effects from ponderomotive forces. By approximating the amplitude of the electric field from the sheath potential drop, the ponderomotive potential from the 1900 V 2 MHz bias was approximately 180 V. This is substantially larger than the effects from the high frequency bias (a few volts) and

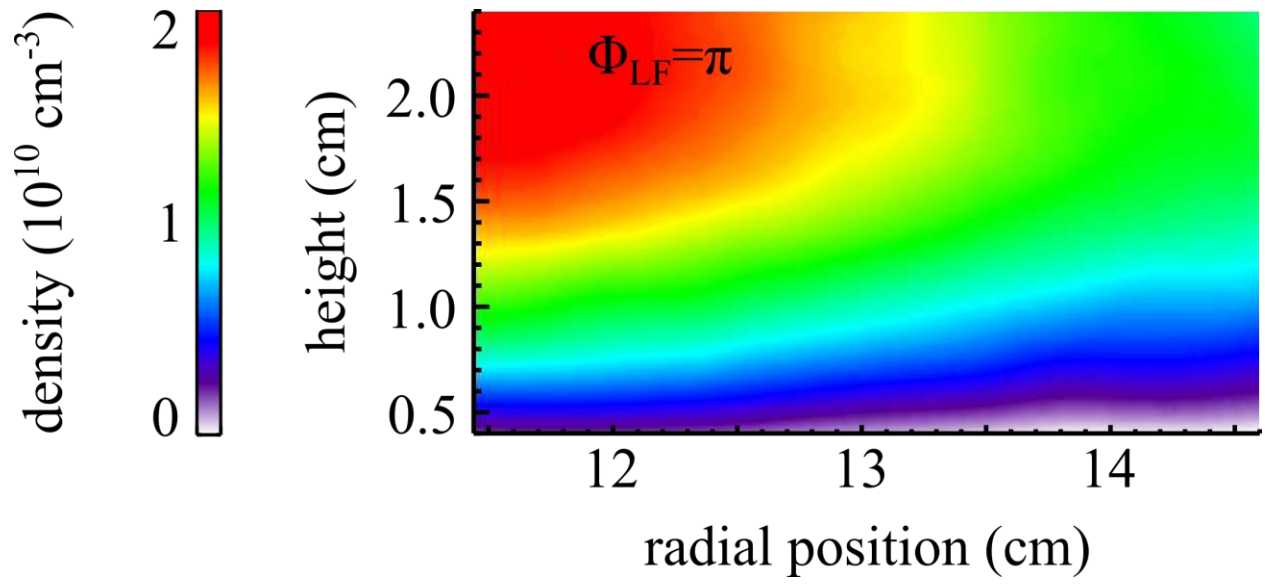


Figure 6.10. Densities for the $\Phi_{LF} = \pi$ case calculated from the ion velocity distribution functions (linear scale). The calculated densities were found to be radially non-uniform with lower densities observed towards the wafer edge.

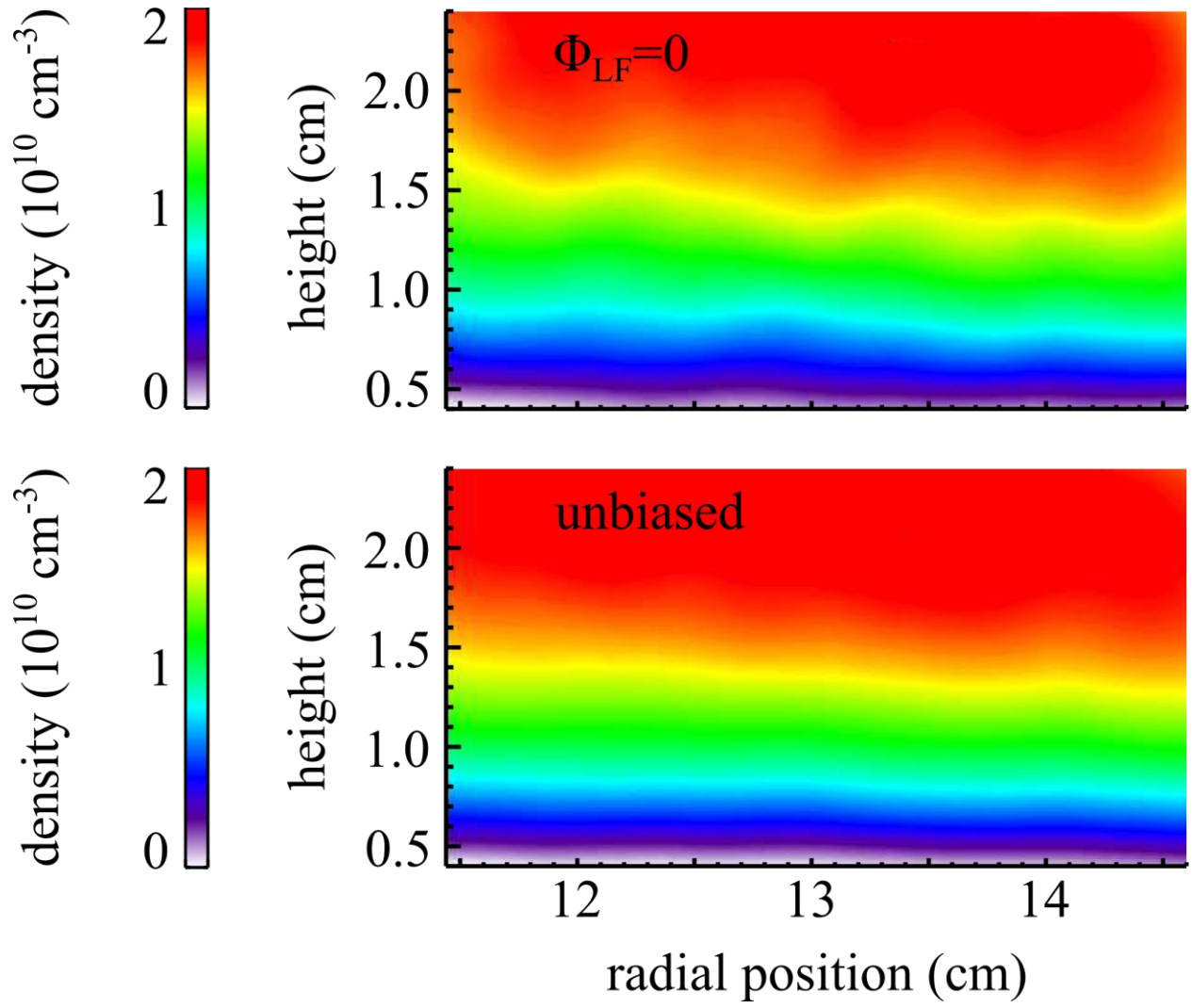


Figure 6.11. Calculated densities for the $\Phi_{LF} = 0$ and unbiased cases (linear scale). The calculated densities for the $\Phi_{LF} = 0$ bias case were found to be much more radially uniform as compared to the $\Phi_{LF} = \pi$ case. The calculated densities were extremely similar to those found in the unbiased case.

approximately twice as large as the potential from the single frequency case where a 650 V bias was used. The gradient of the electric field would also be most pronounced near the edge of the wafer, which is consistent with the shape of the density profile. Zhang *et al.* [53] have reported similar measured and computed density radial profiles in a capacitively coupled device. Densities were radially uniform with a single high frequency (60 MHz) bias, but the addition of a low frequency bias resulted in a decreased plasma density towards the wafer edge.

Mean velocities are calculated from the distribution function in a similar fashion to the densities ($\bar{v}_z(r, z, t) = \frac{1}{n} \int v_z f(r, z, v_z, t) dv_z$). Velocities presented in Figs. 6.12-6.15 are normalized to the maximum velocity across all cases. A comparison of the mean velocity at the edge of the wafer (14.2 cm) and towards mid-wafer (12.0 cm) is given in Fig. 6.12 for the $\Phi_{LF} = \pi$ phase as a function of height above the wafer. The velocities at the edge and mid-wafer both increase at roughly the same rate towards the wafer. Closest to the surface of the wafer, the ion velocity at the edge of the wafer is slightly (20%) larger than that observed towards the mid-wafer. The radial variation shown in Fig. 6.13 confirm this trend as the means velocities are radially uniform down close to the surface of the wafer, at which point ion towards the wafer edge accelerate to slightly larger mean velocity.

Similar measurements for the low bias phase are presented in Figs. 6.14 and 6.15. Velocities for this phase are much lower (approximately 2.4 times) than for the $\Phi_{LF} = \pi$ phase, as expected. This factor of 2.4 is in line with estimations made by comparing the sheath potential drop for each phase. The maximum sheath potential drop for the $\Phi_{LF} = \pi$ phase can be approximated as a the sum of the 1900 V low frequency bias and 450 V time-averaged high frequency bias, or 2350 V. Likewise, the sheath potential drop for the $\Phi_{LF} = 0$ phase can be approximated by the 450 V time-averaged high frequency bias. Assuming 2350 eV and 450 eV

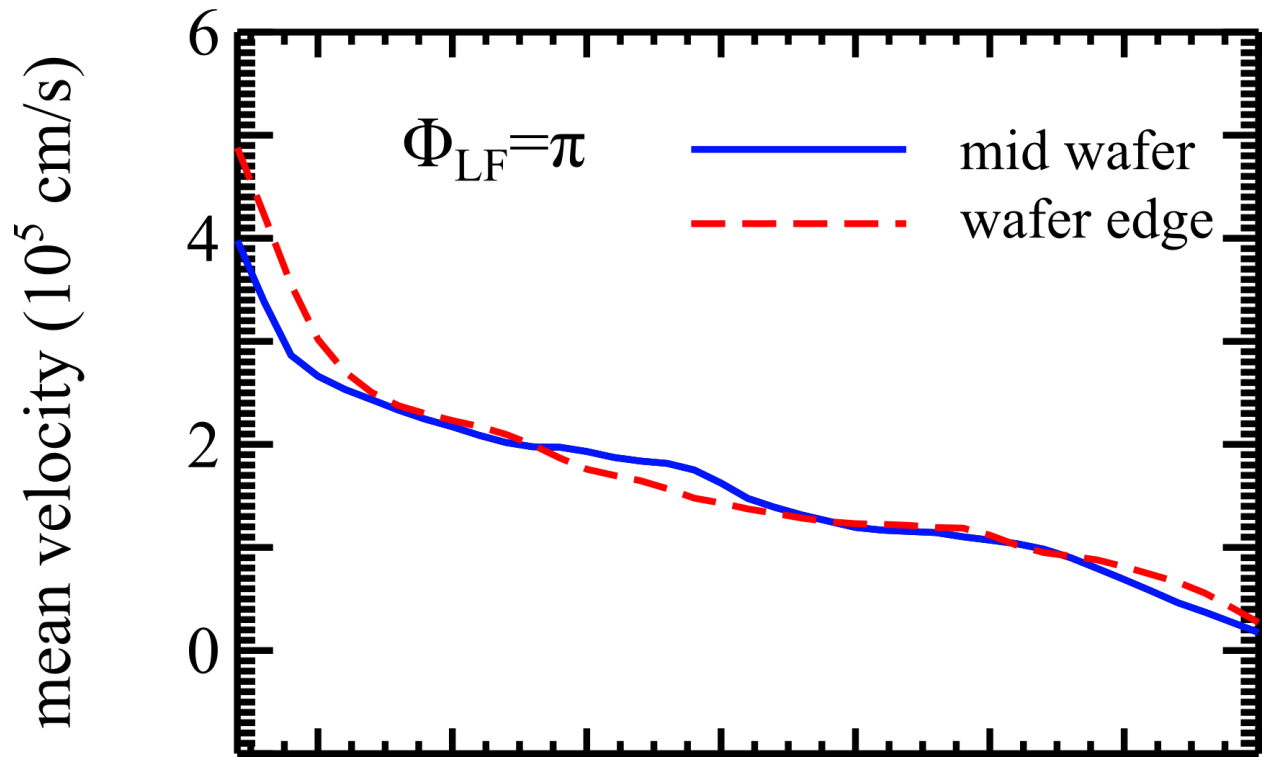


Figure 6.12. A comparison of the mean velocities at the edge of the wafer to velocities at mid wafer as a function of height above the surface of the wafer for the most negative bias phase. The velocities are very comparable, with velocities at the wafer edge being slightly higher directly above the surface of the wafer.

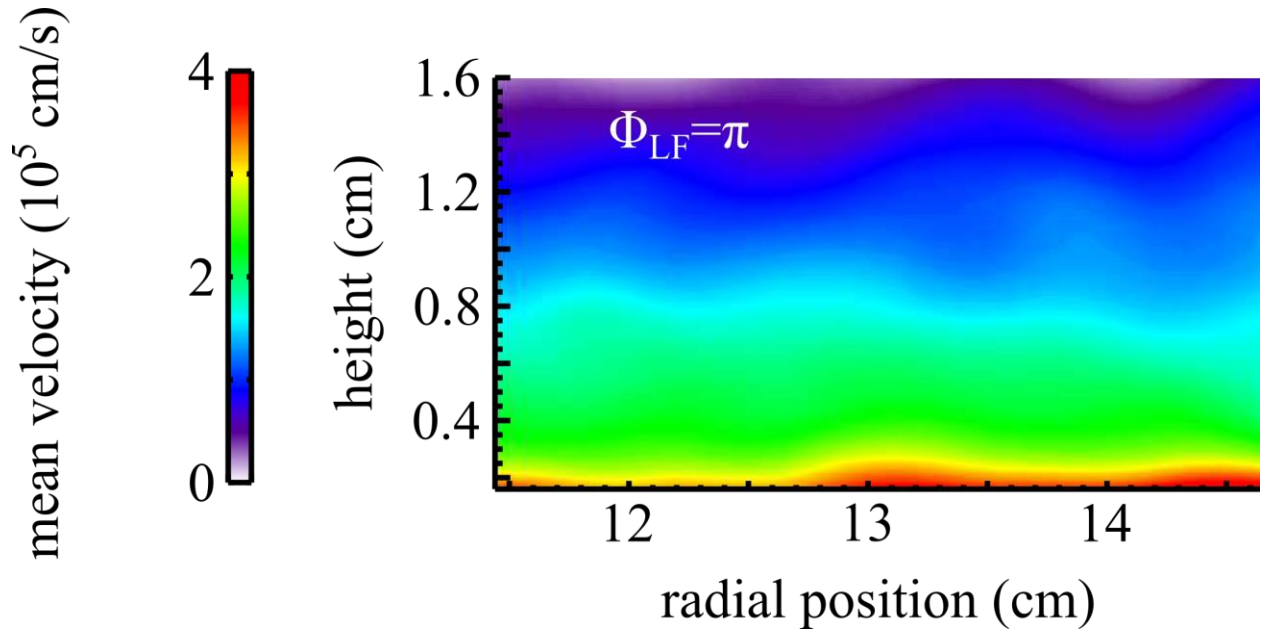


Figure 6.13. The spatial variation of the mean velocities for the most negatively biased phase. Higher velocities are seen towards the edge of the wafer, in contrast to the results from the single frequency bias case.

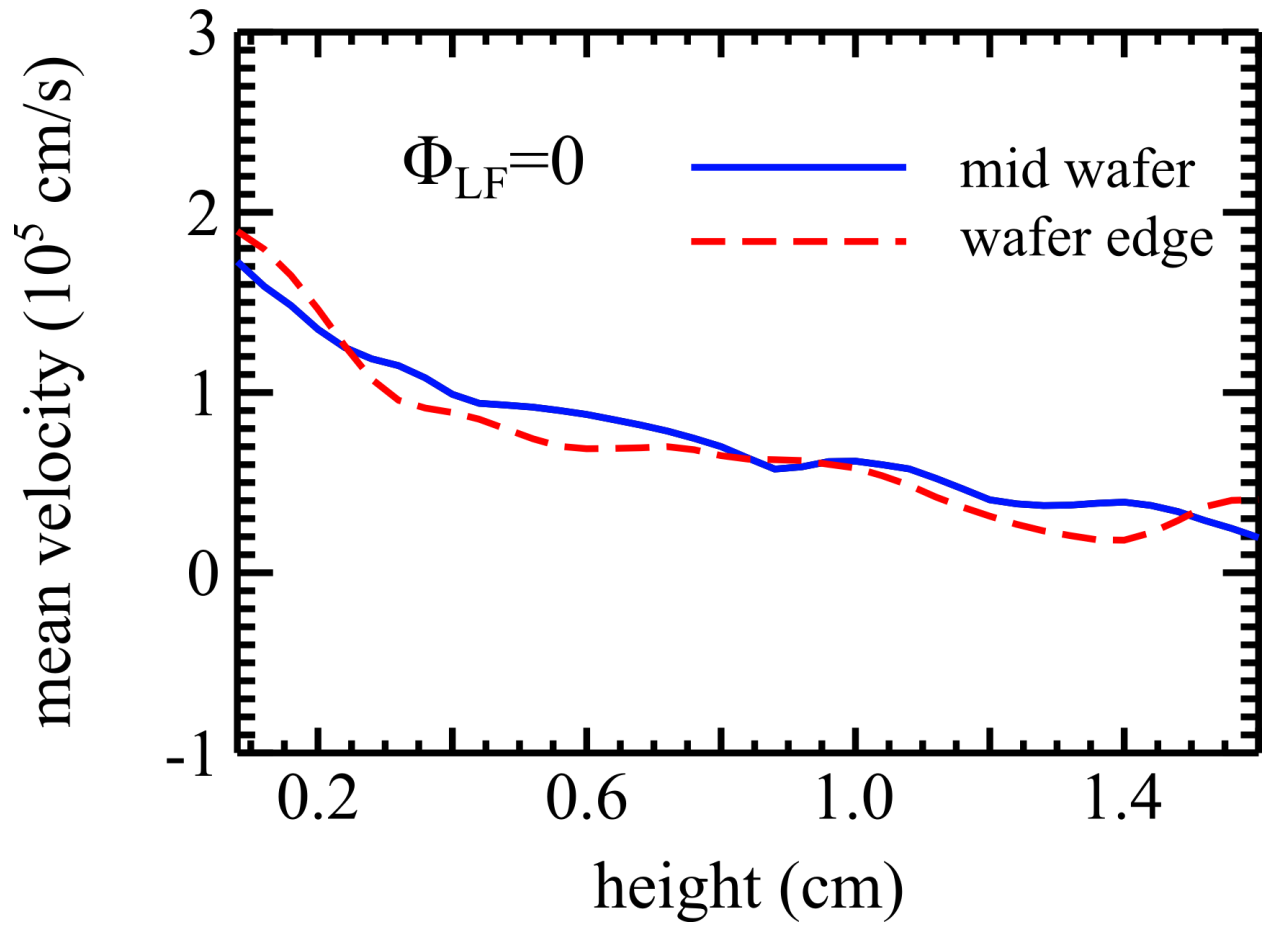


Figure 6.14. A comparison of the mean velocities at the edge of the wafer to velocities at mid wafer as a function of height above the surface of the wafer for the least negative bias phase. As expected, the velocities are much lower than the velocities measured in the most negatively biased phase.

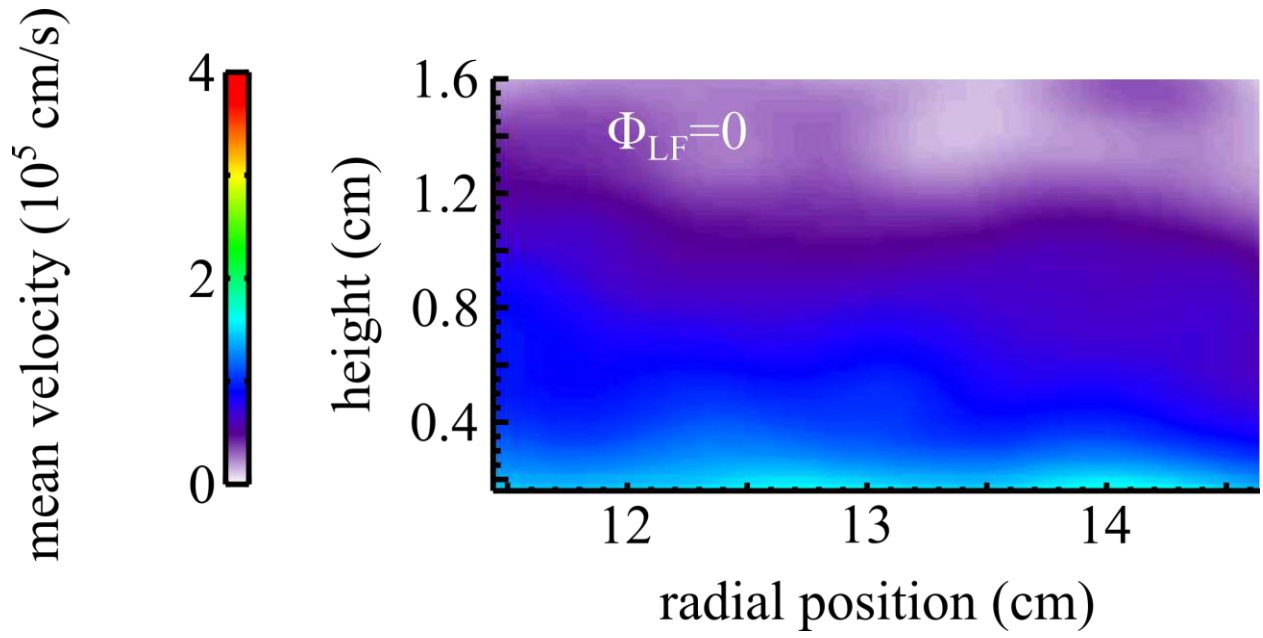


Figure 6.15. The spatial variation of the mean velocities for the lowest bias phase. The velocities were substantially smaller than those measured in the $\Phi_{LF} = \pi$ case and exhibited relatively little radial variation.

ions for the two phases, the ratio of velocities near the surface of the wafer would be $(2350/450)^{1/2} = 2.3$, which compares favorably to the measurements.

Calculated fluxes ($\Gamma_i(r, z, t) = \int v_z f(r, z, v_z, t) dv_z$) are shown for the two phases in Figs. 6.16 and 6.17 as a function of radial position and height above the wafer. In the expanded sheath case, the flux increases as the ions move from the plasma bulk towards the presheath. As the ions approach the sheath, the flux reaches a maximum and remains relatively constant through the sheath and to the surface of the wafer. Fluxes observed in the collapsed sheath case are much lower, as expected. The flux is relatively constant in the presheath and decreases as the ion traverse the sheath towards the wafer, in contrast to the $\Phi_{LF} = \pi$ phase. In both cases the flux was seen to be relatively radially uniform, which would be desired for processing plasmas.

Summary

IEDs in a dual frequency sheath were measured as a function of height, radial position, and phase above a biased silicon wafer for the first time using planar laser-induced fluorescence. IEDs were found to be multi-peaked, in contrast with the single-peaked distributions observed in the single frequency bias case. These multiple peaks are well-approximated by a fit of multiple Maxwellian distributions. While the density was found to be much less radially uniform in the dual frequency case, the ion flux was substantially more radially uniform. This uniformity in the ion flux would be highly desirable in industrial etching applications. However, this flux uniformity is a trade off with the undesirable multi-peaked structure observed in the ion energy distribution functions.

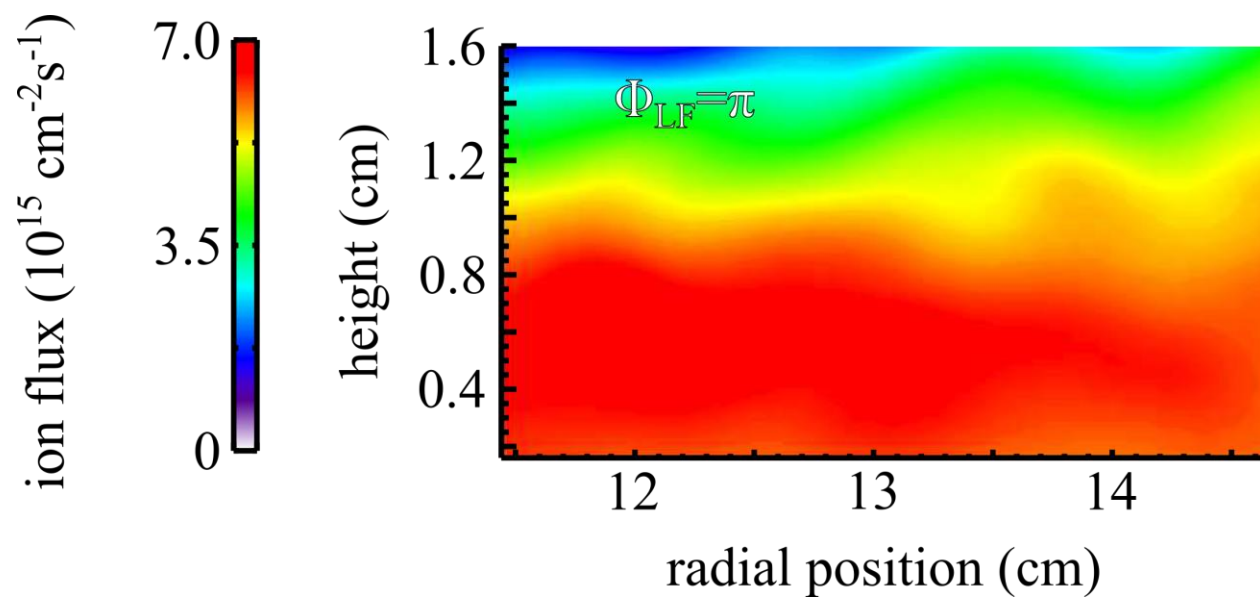


Figure 6.16. The spatial variation of the ion flux directed to the surface of the wafer for the most negative bias. The flux was found to be relatively radially uniform.

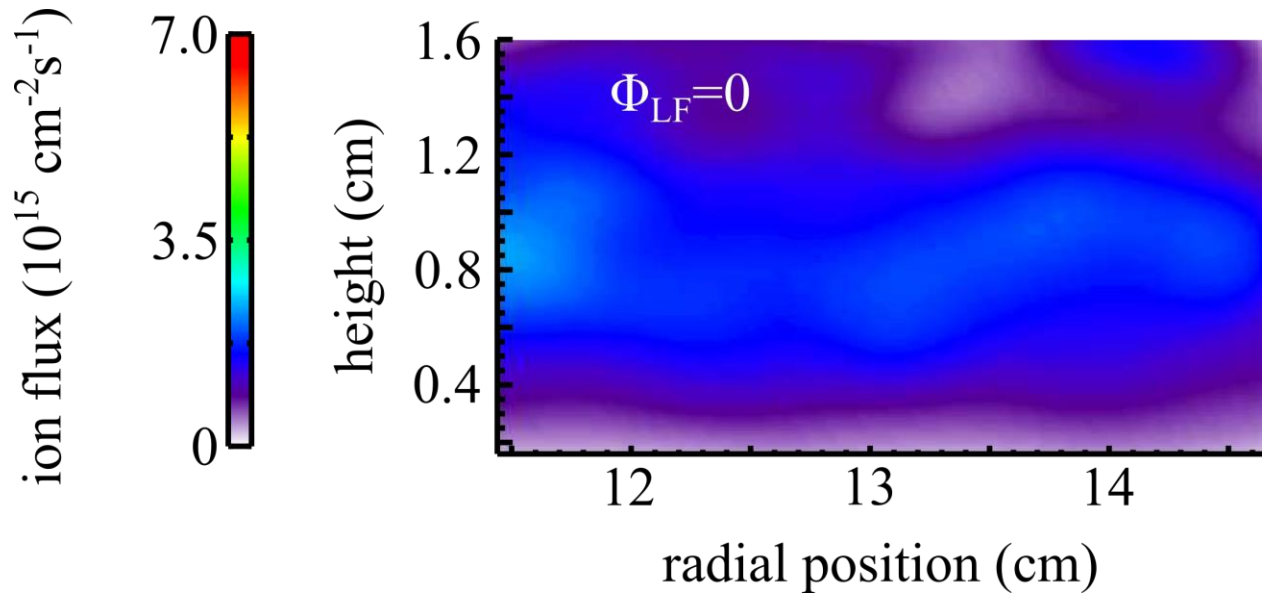


Figure 6.17. The spatial variation of the ion flux directed to the surface of the wafer for the low bias phase. The flux for this phase was also relatively radially uniform and decreased through the sheath, close to the surface of the wafer. The observed fluxes were expectedly much lower than those measured in the $\Phi_{LF} = \pi$ phase.

Chapter 7

Concluding Remarks

Experimental Results

Laser-induced fluorescence has been applied to measuring the perpendicular and parallel IVDs in the sheath above a single radio frequency biased silicon wafer in a plasma etching reactor. The time-averaged energy distribution functions in transit through the sheath are generally not as sharply peaked as those arriving on the substrate which have been measured in several experiments [21-28] or predicted by theory [10,15]. These trends are consistent with previous measurements in this device [35]. Furthermore, the energy separations ΔE_i , were less than values predicted by Panagopoulos [15]: For $\omega_{ion}/\omega_{rf} = 0.5$ and a peak-to-peak sheath potential of 650 V, the predicted ΔE_i , is 575 ± 70 eV . Measured values at a height of 1.2 mm at several radial positions were approximately 150 eV. Once again, this discrepancy has been seen previously in this machine and is most likely a result of the measurement height; it is not unreasonable to expect the ions to accelerate substantially and the peak separation to increase over the remaining portion of the sheath, where the electric field is largest.

Illumination from a planar laser sheet allows simultaneous measurement of velocity distribution functions at multiple radial positions along the surface of the wafer. These measurements showed little variation in sheath thickness and maximum energy attained at the edge of the wafer as compared to values measured towards the middle of the wafer. Transverse velocity distribution function measurements show a lack of transversely moving high energy ions, which

reflect the small radial electric fields ($\frac{\Delta E_r}{\Delta E_z} \sim 10^{-3}$ near the wafer surface). Transverse drift of ions however, do still contribute to net mean flows and heat flux. The contribution is most pronounced towards the edge of the wafer and the less negatively biased phases. This may help explain a relatively inferior etch quality for these regions of the wafer described in other tools as the angle of impact of ions at the edge of the wafer were twice the angles observed closer to the middle of the wafer. This increased angle of impact (and hence increased horizontal etch) would negatively impact the resulting feature size of the etched silicon.

Single frequency results showed good qualitative agreement between a model designed specifically for this etch tool and the experiment, though there is also a systematic difference. To obtain the same range of energies of IEDs and the same behavior of the IEDs as a function of phase within the spatial window that is accessible to the experiments, the amplitude of the rf voltage in the computer model must be larger than that in the experiment. These effects are on the order of 10-20%. It may be that ions are actually being accelerated less immediately adjacent to the wafer and more further from the wafer. Basic sheath theory would predict a different trend in which the electric field increases nearly linearly as one approaches the wafer. However this basic theory was developed for cathode-fall like conditions with a fixed voltage on a metal electrode, and does not account for the details of surface charging and discharging as occurs on a mildly conducting wafer having a significant capacitive component to the current. For example, a larger negative charge on or near the wafer would reduce the electric field near the wafer and reduce the voltage drop across the sheath.

Planar laser-induced fluorescence has also been used to measure the ion velocity distribution functions above a dual radio frequency biased silicon wafer in the same industrial plasma etch tool. Measurements were phase locked to the high voltage 2 MHz low frequency bias

while the 19 MHz high frequency bias was time-averaged. Multi-peaked IEDs were observed in the sheath for the most strongly biased phase. While the exact locations of the peaks varied with radius across the surface of the wafer, the overall structure was similar. These results and number of peaks are consistent with other experiments and simulations [40,53]. For a disparate low bias phase, the measured IEDs exhibited few peaks. One peak roughly corresponded to the time-average of the high frequency bias with the exact position again depending on the radial position.

Densities, velocities, and ion fluxes were calculated from the measured IVDs. The radial dependence of the ion density differed substantially between the two phases investigated. For the strongly biased low frequency case, the density was highly dependent on the radial position with densities decreasing substantially towards the wafer edge. This decrease in ion density was not observed in the disparate low bias phase where the density was relatively radially uniform and similar to the density profile above an unbiased wafer. These trends are consistent with other experiments and simulations [53]. Velocity profiles exhibited less radial variation, though mean velocities at the edge of the wafer were observed to be slightly larger. A comparison of the maximum velocity measured in the two phases were consistent with expectations given the peak-to-peak voltage of the applied biases. Ion fluxes showed no strong radial dependence, a characteristic which would be desired in an industrial setting. This is in stark contrast to the single frequency case where measured fluxes were extremely radially non-uniform. Uniformity in the flux would provide a more uniform etch radially across the wafer which would in turn result in a larger usable area of etched silicon. It appears that for this dual frequency case, the desired uniformity in the flux is a trade off with the undesirable multi-peaked structure observed in the ion energy distribution functions.

Results from this study have provided insight into the ion dynamics within both a single and dual radio frequency sheath in an industrial etch tool. This study has shown that the addition of a second radio frequency bias can improve the radial uniformity of mean ion velocities and ion fluxes, traits that are highly desirable in industrial applications. Such results are important to both the improvement of existing processing techniques and the validation of simulations and models. Comparison of the experimental results with results from computer simulations can help improve the underlying models which can then in turn be used to help guide further progress in processing techniques.

Future Work

The laser-induced fluorescence diagnostic used in this experiment has been shown to be a powerful tool for the investigation of ion dynamics within a radio frequency sheath. In conjunction with this diagnostic, the existing experimental setup can be used to measure ion dynamics in various plasma conditions and help further validate current models and simulations.

The dual frequency experiment can be extended to measure IEDs in several phases of the phase-locked low frequency bias, such as with the single frequency experiment presented in this dissertation. Such measurements would allow for time-resolved simulations to be rigorously compared with dual frequency experimental results. In addition, the existing optical setup for planar LIF parallel to the surface of the wafer are still in place to allow for measurement of radial velocity distribution functions. Such measurements would give the ion angular energy distribution function, a critical factor in anisotropy and quality of the etch.

Independent control of both the ion energy and ion flux remains an important problem in the industrial application of plasma etching. To this end, measurements of the ion distribution function in a dual frequency sheath with several low and high frequency input parameters would prove useful. In particular, the existing experimental setup could be used with a combination of several low frequency input powers and fixed high frequency power and vice versa. Such measurements could provide insight to the degree of coupling between the ion energies and flux that occurs between the two different biases. The driving frequencies could also be varied to investigate this coupling, though this would be more difficult as the driving circuit for each bias would need to be changed for each configuration.

There has also been increased interest in the use of pulsed plasmas for the use of plasma etching [2, 10, 20]. While the ICP source was used in continuous wave operation for the LIF experiment presented, the experiment can be repeated under pulsed operation with no additional modifications needed to the existing setup. The laser timings can be adjusted so that LIF measurements can be taken at various times in the plasma afterglow. Various pulsing configurations of the dual frequency biases could also be investigated. It should be noted it could be more difficult to take LIF measurements during pulsed ICP operation. When pulsing the ICP source, it is necessary to have a higher operating pressure in order to sustain the plasma. This higher operating pressure could lead to neutral quenching and decrease the population of metastable ion states in the plasma which would result in a lower LIF signal. In order to mitigate this problem, a high duty cycle could be used in conjunction with a higher pulsing frequency. Reducing the plasma off time generally reduces the fill pressure necessary to sustain the plasma.

While control of the ion energy distribution function in the context of plasma etching has made impressive progress, optimization of etching processes in industry still rely to a degree on

trial and error techniques. Simulations and modeling have helped guide progress, but experimental validation is still required to ensure the underlying assumptions of the models are correct. Further experimental investigation into ion sheath dynamics is thus critical to the progress of the fabrication of integrated circuits for electronics.

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