Ion Energy Distributions in Pulsed Plasmas with Synchronous DC Bias: Effect of Noble Gas

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Outline

• Motivation
• Experimental Apparatus
• Results and Discussion
  • Ion energy distribution (IED) control
  • Effect of noble gas (Ar, Kr, Xe)
• Summary and Conclusions
Motivation: control of IED

- Wide range of ion energies results in surface roughness and damage
  \[ E_i < E_{\text{chemical sputtering}} \]
  \[ E_i > E_{\text{physical sputtering}} \]
- Nearly monoenergetic ion bombardment results in higher level of control
  - Low surface damage
  - Accurate thickness control
  - High selectivity

• Control of IED:
  - Accurate control of ion energy peak position
  - Narrow width of ion energy distribution

• Energy

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Experimental apparatus

- Ion energy analyzer at Z= 170mm
- Differentially pumped ion energy analyzer (IEA)
- Movable Langmuir probe (LP)

Ion energy can be manipulated by applying DC bias to Boundary Electrode.
Control of $V_p$ using DC boundary voltage

- Continuous DC bias on the boundary electrode in cw plasma

- The DC bias on the boundary electrode is superimposed to the plasma potential.

- With positive DC bias, $V_p$ is shifted by corresponding boundary bias voltage.

- Negative DC bias barely changed $V_p$ since ion flux to the wall is limited.
IEDs in CW plasma with *continuous* DC boundary voltage

- Ion energy peaks indicate plasma potential because the IEA entrance is ground ($V_p=V_{sh}$).
- $V_p$ is in excellent agreement with Langmuir probe measurement at the same location.
- Positive DC bias on boundary electrode shifts plasma potential.
- IEDs from continuous wave plasma are *broad*.

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Timing scheme for pulsed plasma with synchronous DC boundary voltage in afterglow

- **rf power**
- **10kHz Modulation**
  - 20µs ON
  - 80µs OFF

- Positive DC bias (+24V)
Control of $V_p$ using DC boundary voltage

- Time-resolved LP measurements in pulsed plasma

**Continuous bias**

- +10V continuous bias on BE
- No bias on BE

**Synchronous bias**

- +23V synchronous BE bias during 70-97μs

Synchronous DC bias on the boundary electrode can shift plasma potential only during biasing window.
IEDs of pulsed plasma with synchronous DC boundary voltage

- Low energy broad peaks are due to active glow; High energy sharp peaks are due to DC bias in the afterglow.
- Separation of the peaks can be tuned by DC bias value and pressure.
- Narrow IED can be achieved in the afterglow.
- Full width at half maximum (FWHM) of the IED ranges from 1.7 to 2.4 eV and scales with $T_e$.

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Broadening of IED

- Qualitative IEDs resulting from synchronous DC bias during part of afterglow.

- The IED shifts to lower energies and becomes sharper with time.
- The measured IED in the afterglow is a time-averaged distribution.
- Width of IED correlates with $T_e$ and variation of $V_p$ during bias window.
$T_e$ and $V_p$ change during bias

- Time-resolved Langmuir probe measurements

The smaller the electron temperature and the variation of plasma potential during the biasing window, the sharper the ion energy distribution.
• Early afterglow biasing ($V_p$ changes considerably and $T_e$ is high) vs. late afterglow biasing ($V_p$ and $T_e$ have decayed to low values).

• IED width is smaller with late afterglow biasing.
Outline

• Motivation ✓

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• Results and Discussion ✓
  • Ion energy distribution (IED) control ✓
  • Effect of noble gases (Ar, Kr, Xe)

• Summary
• At the edge of the plasma, the plasma density is nearly constant, even over a long afterglow duration of 80 µs.

• Transport of electrons from the higher density central region of the plasma to the edge region, is balancing the loss of plasma due to diffusion.

• Maintaining a nearly constant ion (and electron) density during the afterglow may be useful in processes employing pulsed plasmas.
Temporal evolution of $T_e$ and $V_p$ for different noble gases

- $T_e$ and $\Delta V_p$ are in the order of Ar $<$ Kr $<$ Xe
- $T_e$ and $V_p$ decay slower in Xe plasma (slower diffusion cooling).
- Experimental data of $T_e$ are consistent with predictions from global model.
IEDs for different carrier gases

- IED shows the same order of $T_e$ and $\Delta V_p$ during bias window:
  \[ \text{Ar} < \text{Kr} < \text{Xe} \]

- FWHM of the narrow peak is 1.6, 2.4, and 3.0 eV for Ar, Kr and Xe

- The area under the IED peak resulting from afterglow biasing is proportional to the ion flux
IEDs for different Cl₂ additions

40 sccm Ar (14mTorr)

- 0% Cl₂
- 1% Cl₂
- 2% Cl₂
- 3% Cl₂
- 4% Cl₂
- 5% Cl₂

- Similar IEDs were found with trace amount of Cl₂ addition (<5%)

- Peak ion energy was lower by a few eV, possibly due to lower V_p and T_e from Cl₂ plasma.

- Such control of IED can be applied to plasma etching with high precision.
Summary and Conclusions

1. Nearly monoenergetic IEDs can be achieved using synchronous DC bias in the afterglow of a pulsed plasma.
2. The peak values and the FWHM of the IED can be controlled by varying DC bias and the time window it is applied, operating pressure, and carrier gas.
3. FWHM depends on the electron temperature and plasma potential variation during the time of biasing.
4. Maintaining a nearly constant ion (and electron) density during the afterglow may be useful in processes employing pulsed plasmas.
5. By adding small amounts of chlorine to an argon plasma the IEDs are shifted to slightly smaller energies.
Questions?
Backup slides
Time-resolved $T_e$ in pulsed plasma

- At higher pressure, $T_e$ is lower during active glow, but higher during afterglow.
- $T_e$ decays to low values in 15 – 20 ms after plasma is turned off.
- Duty cycle has no effect on the $T_e$ decay.
$V_p$ variation during bias window

$V_{p_i} + V_{dc}$

$kT_{e_i}$

$kT_{e_f}$

$V_{p_f} + V_{dc}$

$V_{p_i} + V_{dc}$

Energy (eV)
Time scheme for different mod. frequency

10kHz

\[ \Delta t_{\text{bias}} = 50 \mu s \]

7.5kHz

\[ \Delta t_{\text{bias}} = 50 \mu s \]

5kHz

\[ \Delta t_{\text{bias}} = 50 \mu s \]
IED with different mod. frequency

- Decreasing area of high energy peaks is due to lower $T_e$ and ion density
- Overall, pulsed Ar plasma shows best FWHM in the afterglow
Etching process monitoring

- 20% pulsed 1% Cl₂, 5% TRG, 94% Ar plasma, 10kHz
- 100W, 70-97µs synchronous boundary electrode bias

**Si removal by synchronous biasing in the afterglow.**

**Si removal during activeglow.**

- **Boundary electrode bias voltage (V)**
  - Afterglow etching threshold was found ~16V
  - Activeglow p-type Si etching with sub-threshold ion energy
  - The sub-threshold etch rate is significant, compared to ion-assisted etching, for process such as atomic layer etching.