Department of Nuclear Engineering,
University of California at Berkeley,
Introduction to Controlled Fusion:

Weakly Ionized Plasmas

Jón Tómas Guðmundsson
tumi@hi.is

December 2., 2004

Overview

- Introduction to plasmas
- Applications of plasmas
- Plasma parameters
- Plasmas and Discharges
- Electron density and electron temperature
- Ion bombardment energy
- Sputtering
- Magnetron Sputtering Discharge
- Summary
Introduction to plasmas

- Plasma is weakly- or fully ionized gas that consist of electrons, ions, neutral atoms and neutral molecules
- Fully ionized plasma consists of only electrons and ions but weakly ionized plasma has neutral particles as well
- Most of the universe is made of plasma
  - The interior of stars and their atmosphere, the gaseous nebula and most of the interstellar hydrogen are plasmas
  - We know plasma from the fluorescent tube, neon signs, and the Aurora Borealis

---

Introduction to plasmas

- In the early 20th century gas conductivity and gas breakdown, electron emission and electron impact excitation of atoms was investigated in discharges
- In the later half of the 20th century application of plasmas include, light sources, lasers and materials processing
- Today plasmas play a fundamental role in integrated circuits fabrication
Applications of plasmas

- Molecular discharges and their mixtures play a key role in etching and deposition of thin films in integrated circuit fabrication
- Oxygen plasma is used to remove the photoresist and to grow thin oxide films
- Silicon is etched in plasmas that include fluorine or chlorine
- The use of plasmas is the only known method to etch the small features that are the backbone of modern electronics

Applications of plasmas

- In order to get a nuclear fusion the repulsive force between particles has to be overcome
- Since kinetic energy is equivalent to heat, nuclear fusion is more likely of the particles (the fuel) are at high temperature - millions of degrees Kelvin - at this temperature the fuel is fully ionized
- To retain this high temperature the gas mixture can not touch a surface or walls or any other material
- There are mainly two methods that have been applied to create this high temperature gas:
  - The fuel is confined in a magnetic bottle with a magnetic field
  - Powerful laser pulses are shot at a solid fuel
Plasma processing of materials

- integrated circuits fabrication
  - etching
  - deposition of thin films
- deposition of unique materials
- magnetic materials
- hard, protective, and wear resistant coatings
- optical coatings
- decorative coatings
- low friction films

Plasma processing of materials

- The main application of plasma processing of materials is in the electronics industry (integrated circuits) (Graves, 1994)
- Plasmas are used to etch semiconductors, metals og dielectrics
- Plasmas are used to deposit thin, semiconducting films, metallic films and dielectrics
- The plasma chemistry is complicated, since it includes both neutral and charged particles
- The electron energy distribution plays a key role in determining the plasma chemistry
- Exposure of a surface to ions and reactive atoms gives much higher etch rate than only ions or only reactive atoms
Plasma processing of materials

- As the feature sizes of integrated circuits shrink (now < 90 nm) the processing technology has to be improved
- This lead to the move from wet etching to dry etching

(a)  

(b)  

- The etching profiles (a) wet or chemical etching and (b) dry or plasma etching

Plasma parameters
Plasma parameters

- The plasma is described by the following parameters
  - Electron density \( n_e \) and ion density \( n_i \)
  - Electron temperature \( T_e \)
  - Plasmas, which are quasineutral \( (n_i \approx n_e) \), are joined to wall surfaces across a positively charged layers, called sheaths, of thickness \( s \)
  - A potential is formed between the bulk plasma and the wall, the plasma potential, \( V_{pl} \)

Plasma parameters

- Given the control parameters
  - Neutral gas pressure \( p \)
  - Applied power \( P_{abs} \) or voltage \( V_{rf} \)
  - Driving frequency \( \omega \)
  - Discharge size \( R \) and \( L \)

we are interested in
  - Ion and atom flux to the surface \( \Gamma_i, \Gamma_n \)
  - Ion energy distribution (IED) \( f(\xi_i) \)
  - Electron energy distribution (EED) \( f(\xi_e) \)
  - Sheath thickness \( s \)
A global (volume averaged) model

- The plasma chemistry can be complicated
  - Argon discharge consists of
    e, Ar, Ar⁺, Ar∗, ...
  - Oxygen discharge consists of
    e, O, O₂, O₂⁺, O⁺, O⁻, O₂⁻, O₂⁺, O⁺, ....
  - SF₆ discharge consists of
    e, SF₆, SF₆⁺, SF₄⁺, SF₃⁺, F⁺, F⁻, F⁺, F₂, F, ....

A global (volume averaged) model

- The global model is based on:
  - Energy balance
  - Particle balance for all particles

- For argon discharge:
  Power balance
  - Absorbed power = Power loss
  - \( P_{\text{abs}} = en_o u_B A_{\text{eff}} \varepsilon_T \)
  Particle balance
  - Particles lost to the surface = Ionization in the bulk
  - \( n_o u_B A_{\text{eff}} = k_i z n_g n_o \pi R^2 L \)
A global (volume averaged) model

- The total energy lost per ion lost from the system:
  \[ \mathcal{E}_T = \mathcal{E}_c + \mathcal{E}_e + \mathcal{E}_i \]

  where
  - \( \mathcal{E}_c \) is the collisional energy loss per electron-ion pair created
    \[ \mathcal{E}_c = \mathcal{E}_{iz} + \sum_i \mathcal{E}_{ex,i} \frac{k_{ex,i}}{k_{iz}} + \frac{k_{el}}{k_{iz}} \frac{3m_e}{m_i} T_e \]
  - \( \mathcal{E}_e \) is the mean kinetic energy lost per electron lost. If the electrons have Maxwellian energy distribution \( \mathcal{E}_e = 2T_e \)
  - \( \mathcal{E}_i \) is the mean kinetic energy lost per ion and is mainly due to acceleration across the sheath

A global (volume averaged) model

- The collisional energy loss per electron-ion pair created versus the electron temperature for argon, atomic oxygen and molecular oxygen
A global (volume averaged) model

- Rate coefficients for electron impact collisions are calculated for electron impact collisions from collisional cross sections assuming Maxwellian electron energy distribution

\[ k = \left( \frac{2e}{m_e} \right)^{1/2} \int_0^\infty \mathcal{E}^{1/2} \sigma(\mathcal{E}) f(\mathcal{E}) \, d\mathcal{E} \]

and the Bohm velocity

\[ u_B = \left( \frac{eT_e}{m_i} \right)^{1/2} \]

A global (volume averaged) model

- Effective area

\[ A_{\text{eff}} = 2\pi R (Rh_R + Lh_L) \]

where \( h_R = \frac{n_{sR}}{n_o} \) and \( h_L = \frac{n_{sL}}{n_o} \)
A global (volume averaged) model

- Gives estimates of the plasma parameters with limited calculations or computing power \( (n_e, T_e, V_{pl}, n_i) \)
- Tool to investigate which reactions are important in gas mixtures
- It is a volume averaged model, no spatial variation
- The electron energy distribution function is given

Plasmas and Discharges

Capacitive discharge

- In the early days dry etching was performed in a capacitive discharge with ions and reactive neutral particles (atoms and molecules)
- The ion density is determined by the rf voltage that is applied (parallel plate capacitor). The ion density and the ion bombarding energy cannot be controlled independently
Plasmas and Discharges

Electron cyclotron resonance (ECR) and Inductively coupled discharge

- To increase throughput and achieve better control of the production new discharges have been developed (Lieberman and Gottscho, 1994; Gudmundsson, 1999b)
- The inductively coupled discharge and the ECR discharge have 1 – 2 orders of magnitude higher ion density than the capacitively coupled discharge
- The ion energy is an order of magnitude lower
- These discharges allow for independent control of ion density and ion energy
  - Ion density is controlled by the power applied to the inductive coil (or microwave power)
  - The ion energy is controlled by rf bias that is applied to the substrate holder
Plasmas and Discharges

<table>
<thead>
<tr>
<th>Pressure [m Torr]</th>
<th>Capacitively coupled</th>
<th>High density</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 – 1000</td>
<td>0.5 – 50</td>
<td></td>
</tr>
<tr>
<td>Power [W]</td>
<td>50 – 2000</td>
<td>100 – 5000</td>
</tr>
<tr>
<td>Driving frequency [MHz]</td>
<td>0.05 – 13.56</td>
<td>0 – 2450</td>
</tr>
<tr>
<td>Electron density [cm$^{-3}$]</td>
<td>$10^9$ – $10^{10}$</td>
<td>$10^{10}$ – $10^{12}$</td>
</tr>
<tr>
<td>Electron temperature [eV]</td>
<td>1 – 5</td>
<td>2 – 7</td>
</tr>
<tr>
<td>Ion energy [eV]</td>
<td>200 – 1000</td>
<td>&lt; 100</td>
</tr>
</tbody>
</table>

Langmuir probe

- $I - V$ characteristic gives
  - electron density $n_e$
  - electron temperature $T_{ef}$
  - dc plasma potential $V_{pl}$
  - electron energy distribution function (EEDF)
Electrons-Capacitively coupled discharge

- The electron energy probability function (EEPF) in the bulk of an argon discharge measured with a Langmuir probe at 30 and 300 mTorr pressure (Godyak et al., 1993)
- At low pressure the electron energy probability function can be described by a sum of two Maxwellian distributions that becomes more Druyvesteyn like as the pressure is increased

Electrons-Inductively coupled discharge

- The electron energy probability function (EEPF) in the bulk of an oxygen discharge at 720 W measured with a Langmuir probe at 2.5, 10, 20 og 35 mTorr pressure (Gudmundsson et al., 2000)
- The electron energy distribution is Maxwellian at low pressure but deviates from Maxwellian as the pressure is increased
Electrons-Inductively coupled discharge

- The plasma parameters along the radii of an inductively coupled oxygen discharge at 720 W (Gudmundsson et al., 2000)
  - (a) electron density $n_e$
  - (b) effective electron temperature $T_{\text{eff}}$
  - (c) dc plasma potential

Ions-Capacitively coupled discharge

- The ion energy distribution in a capacitively coupled oxygen discharge at 1000 W and 2mTorr. The peaks indicated by 1 are due to $O_2^+$ ions and peaks indicated by 2 are due to $O^+$ ions (Kuypers and Hopman, 1988)
Ions-Inductively coupled discharge

- The ion energy distribution from an inductively coupled oxygen discharge at 675 W and 3, 7 and 20 mTorr pressure (Gudmundsson, 1999a).

Ions-Inductively coupled discharge

- The mean energy of O\(^+\) and O\(_2^+\) ions in an oxygen discharge at 565 W versus the gas pressure in a planar inductively coupled discharge
- Ion energy

\[ \mathcal{E}_i = \frac{T_e}{2} + V_{pl} + V_{rf} \sin(\omega t) \]
dc Sputtering

- Sputtering was discovered in 1852
- An ion sputters an atom and/or releases electrons from a target
- This can be done by accelerating ions from a plasma which is created between electrodes when a dc voltage of 1000 – 3000 V is applied

dc Sputtering

- Disadvantages of dc sputtering
  - Slow film growth
  - Low ionization
  - Heating of the substrate
- It is beneficial to have the sputtering discharge work at
  - higher current density
  - lower operating voltage
  - lower gas pressure
  than is possible in a dc sputtering discharge
Planar Magnetron Sputtering Discharge

- The planar magnetron was developed to enhance the sputtering and increase the deposition rate
- A typical planar magnetron discharge consist of a planar cathode (sputtering source or target) parallel to an anode surface
- In a magnetron sputtering discharge the anode is of secondary importance

Planar Magnetron Sputtering Discharge

- A magnet is placed at the back of the cathode target with the pole pieces at the center and perimeter
- It generates magnetic field lines that enter and leave through the cathode plate
- The magnetic field confines the energetic electrons near the cathode, where they undergo numerous ionizing collisions before being lost to a grounded surface
Planar Magnetron Sputtering Discharge

- Ions, not confined by the magnetic field, are accelerated toward the cathode and strike it at high energy
- The impact of the ions on the cathode (target) results in sputtering of metal atoms and secondary electron emission from the cathode surface
- Energy gained in the cathode sheath by secondary electrons emitted from the cathode goes into the ionization necessary to maintain the discharge

(After Field et al. (2002))

- The discharge forms as a high-density, bright, circular plasma that sits just below the cathode
Planar Magnetron Sputtering Discharge

- A typical dc planar magnetron operates at a pressure of 1 – 10 mTorr with a magnetic field strength of 0.01 – 0.05 T and at cathode potentials 300 – 700 V
- The magnetic field can be created by permanent magnets, electromagnets or combination of both

Reactive Magnetron Discharge

- Conventional dc magnetron sputtering is ideal for depositing thin metallic films
- Compounds such as oxides and nitrides must be deposited with reactive sputtering in which a metal target is sputtered inside a discharge of reactive gas
Reactive Magnetron Sputtering Discharge

- The reactive process has required the development of more sophisticated sputtering systems such as
  - rf magnetron sputtering discharge
  - pulsed rf magnetron sputtering discharge
  - asymmetric bipolar magnetron sputtering discharge

Summary

- Weakly ionized plasmas and its applications was reviewed
- The use of Langmuirprobe was discussed
- The ion energy distribution of processing discharges was discussed
- Sputtering and magnetron sputtering discharge was reviewed
References


