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

# Weakly Ionized Plasmas

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# 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
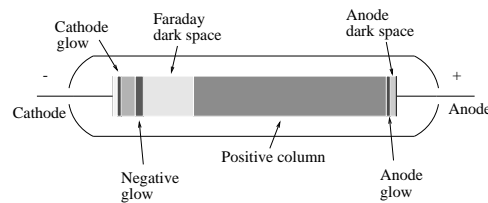


- In the early 20th century gas conductivity and gas breakdown, electron emission and electron impact excitation of atoms was investigated in dischages

- 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 temperture 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 temperture 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
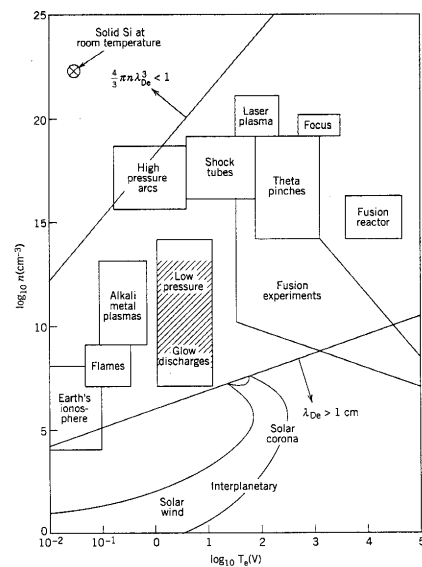
# Plasma processing of materials

- 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
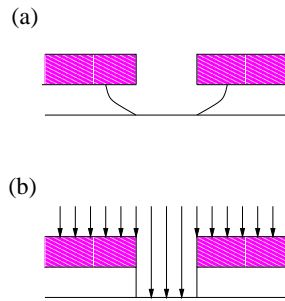


- The etching profiles (a) wet or chemical etching and (b) dry or plasma etching
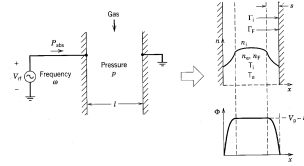
# Plasma parameters

# Plasma parameters

- The plasma is described by the following parameters
  - Electron density $n_\mathrm{e}$ and ion density $n_\mathrm{i}$
  - Electron temperature $T_\mathrm{e}$
  - Plasmas, which are quasineutral ($n_\mathrm{i} \approx n_\mathrm{e}$), 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, $V_\mathrm{pl}$

# Plasma parameters

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

  we are intersted in
  - Ion and atom flux to the surface $\Gamma_\mathrm{i}, \Gamma_n$
  - Ion energy distribution (IED) $f(\mathcal{E}_\mathrm{i})$
  - Electron energy distribution (EED) $f(\mathcal{E}_\mathrm{e})$
  - 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, O$_2$, O$_2^+$, O$^+$, O$_2^-$, O$^-$, O$_2^*$, O$^*$, .....
  - SF$_6$ discharge consists of
    e, SF$_6$, SF$_5^+$, SF$_4^+$, SF$_3^+$, F$^+$, F$^-$, F$^*$, F$_2$, 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
  - $P_{\mathrm{abs}} = e n_o u_{\mathrm{B}} A_{\mathrm{eff}} \mathcal{E}_T$

  Particle balance
  - Particles lost to the surface = Ionization in the bulk
  - $n_o u_{\mathrm{B}} A_{\mathrm{eff}} = k_{iz} n_g n_o \pi R^2 L$

# A global (volume averaged) model

- The total energy lost per ion lost from the system:

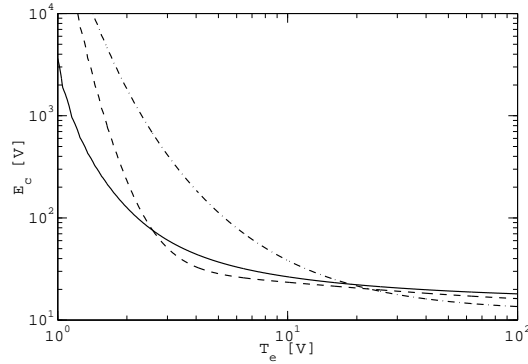$$\mathcal{E}_T = \mathcal{E}_c + \mathcal{E}_e + \mathcal{E}_i$$

  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
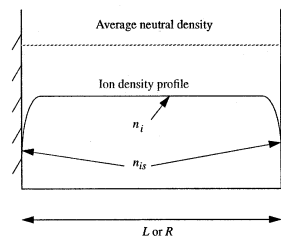
# A global (volume averaged) model

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

$$k = \left(\frac{2e}{m_\mathrm{e}}\right)^{1/2} \int_0^\infty \mathcal{E}^{1/2} \sigma(\mathcal{E}) f(\mathcal{E}) d\mathcal{E}$$

and the Bohm velocity

$$u_\mathrm{B} = \left(\frac{eT_\mathrm{e}}{m_\mathrm{i}}\right)^{1/2}$$

# A global (volume averaged) model



- Effective area

$$A_\mathrm{eff} = 2\pi R \left(R h_\mathrm{R} + L h_\mathrm{L}\right)$$

where $h_\mathrm{R} = n_\mathrm{sR}/n_o$ and $h_\mathrm{L} = n_\mathrm{sL}/n_o$

# A global (volume averaged) model

- Gives estimates of the plasma paramters with limited calculations or computing power $(n_e, T_e, V_{pl}, n_i)$

- Tool to investigate which reactions are improtant in gas mixtures

- It is a volume averaged model, no spatial variation

- The electron energy distribution function is given
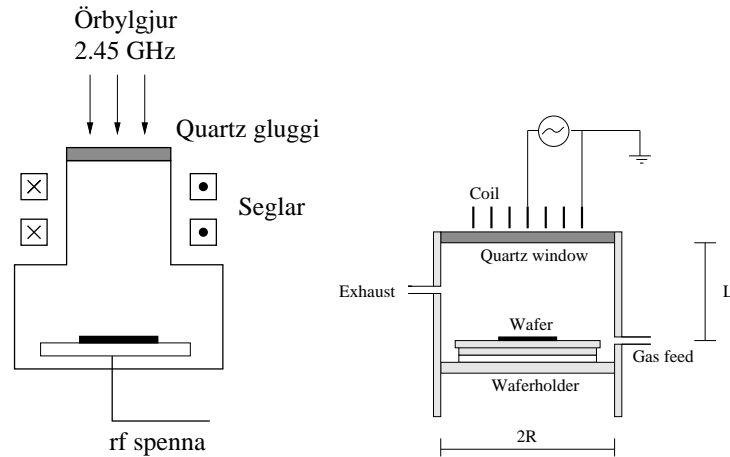
# Plasmas and Discharges

**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
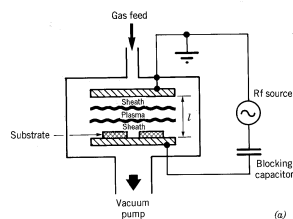
# Plasmas and Discharges

**Electron cylclotron resonance (ECR) and Inductively coupled discharge**

Örbylgjur
2.45 GHz

Quartz gluggi

Seglar

Coil

Quartz window

Exhaust

Wafer

Gas feed

L

Waferholder

rf spenna

2R

# Plasmas and Discharges

- To increase throughput and achive 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

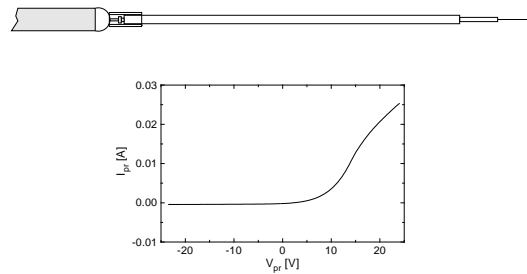# Plasmas and Discharges
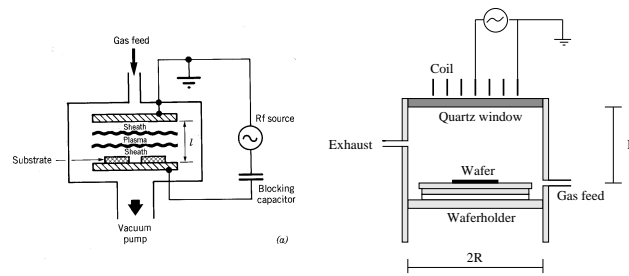


| | Capacitively coupled | High density |
|---|---|---|
| Pressure [mTorr] | $10 - 1000$ | $0.5 - 50$ |
| Power [W] | $50 - 2000$ | $100 - 5000$ |
| Driving frequency [Mhz] | $0.05 - 13.56$ | $0 - 2450$ |
| Electron density [cm$^{-3}$] | $10^9 - 10^{10}$ | $10^{10} - 10^{12}$ |
| Electron temperature [eV] | $1 - 5$ | $2 - 7$ |
| Ion energy [V] | $200 - 1000$ | $< 100$ |

# Langmuir probe



- $I - V$ characteristic gives
    - electron density $n_{\mathrm{e}}$
    - electron temperature $T_{\mathrm{eff}}$
    - dc plasma potential $V_{\mathrm{pl}}$
    - electron energy distribution funtion (EEDF)

# Electrons-Capacitively coupled discharge
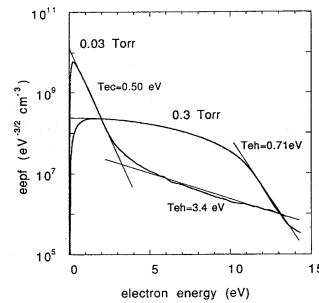


- The electron energy probability function (EEPF) in the bulk of an argon discharge measured with a Langmuir probe at 30 and 300 mTorr pressure (Godyak et al., 1993)

- 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
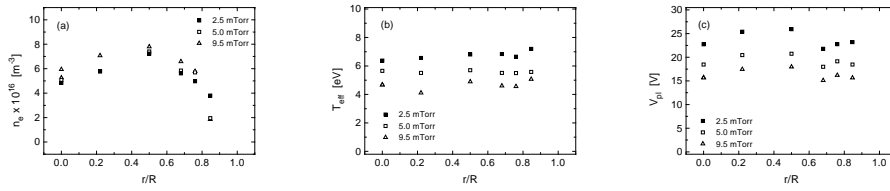
# Electrons-Inductively coupled discharge
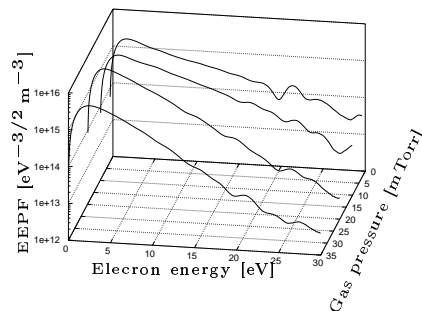


- The electron energy probability function (EEPF) in the bulk of an oxygen discharge at 720 W measured with a Langmuir probe at 2.5, 10, 20 og 35 mTorr pressure (Gudmundsson et al., 2000)

- The electron energy distribution is Maxwellian at low pressure but deviates from Maxwellian as the pressure is increased
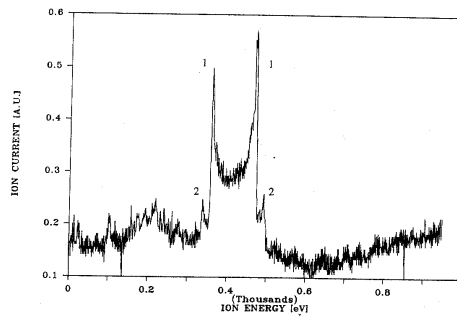
# Electrons-Inductively coupled discharge



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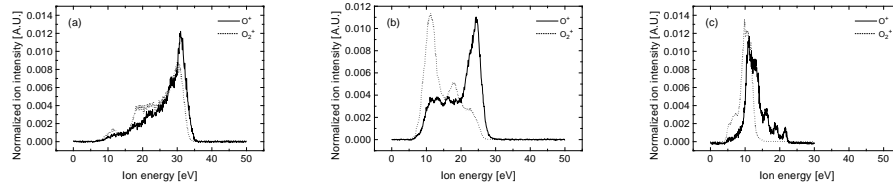  - (b) effective electron temperature $T_{eff}$
  - (c) dc plasma potential

# 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)
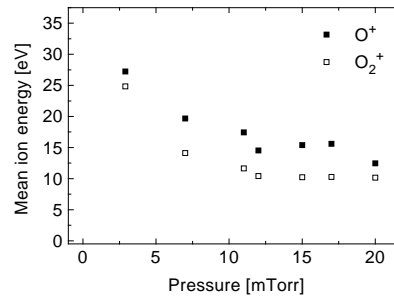
# Ions-Inductively coupled discharge



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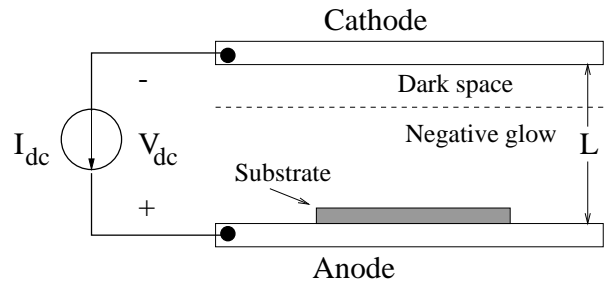
# Ions-Inductively coupled discharge



- 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

$$\mathcal{E}_\mathrm{i} = \frac{T_\mathrm{e}}{2} + V_\mathrm{pl} + V_\mathrm{rf}\sin(\omega t)$$

# 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
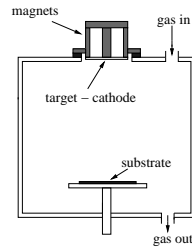
# dc Sputtering

- 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
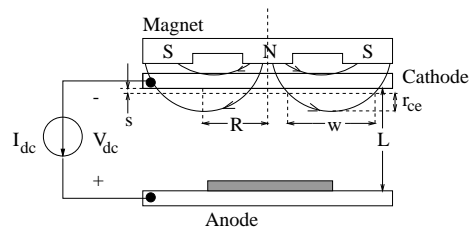


- A magnet is placed at the back of the cathode target with the pole pieces at the center and perimeter

- 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
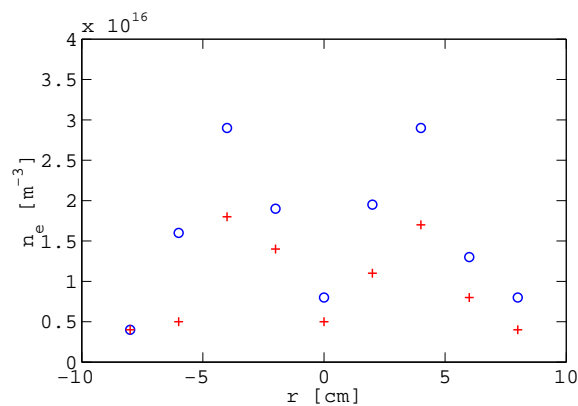
# Planar Magnetron Sputtering Discharge
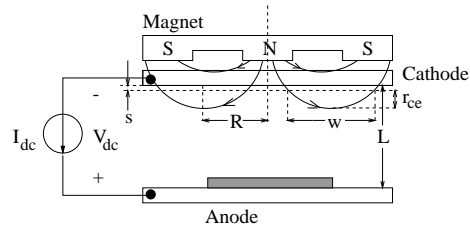


- Ions, not confined by the magnetic field, are accelerated toward the cathode and strike it at high energy

- 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
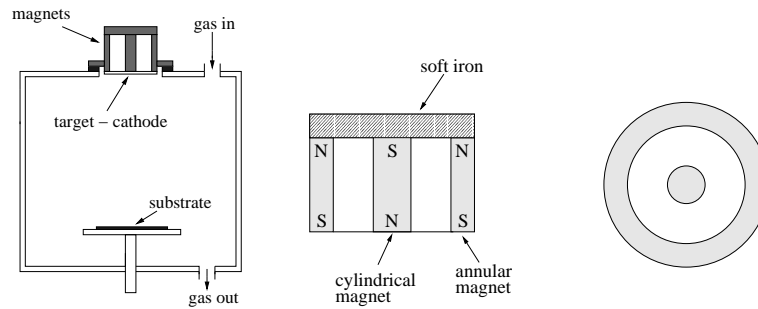
# Planar Magnetron Sputtering Discharge



(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
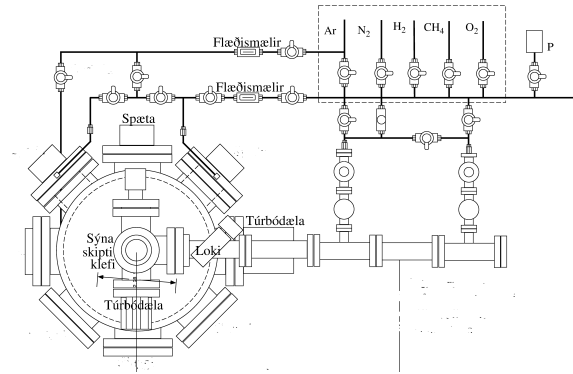
# Reactive Magnetron Discharge
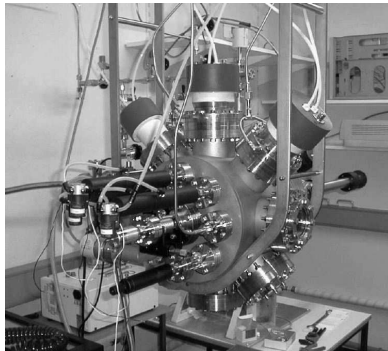


- Conventional dc magnetron sputtering is ideal for depositing thin metallic films

- 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

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