

PLASMA PHYSICS

VIII. PROCESSING PLASMAS

Introduction

Plasmas are used to manufacture semiconductors, to modify the surfaces of materials, to treat emissions and wastes before they enter the environment, etc.

The plasma is a source of ions.

Industry wants

- plasma devices that are simple and compact
- that enable processing at high rates with high efficiencies
- processing to be uniform over large areas

In order to produce the best plasma for the process in question, we can control

- size and shape of plasma device, gas mixture, p , s , V , i , B , ω

which determine

- ion and electron densities and temperatures, ion fluxes and energies.

Besides the plasma physics, there atomic and molecular processes within the volume of the gas and on the surface to be understood as well.

Applications

Deposition by sputtering

target is source of coating material

DC sputtering: metals, the target is the cathode

RF sputtering: non-conducting materials

ion-beam sputtering:

reactive sputtering: e.g., TiN coatings for wear resistance, Ti target and N₂ gas

substrate may be biased so ion bombardment modifies the growing film

Deposition by Plasma-assisted CVD

CVD (chemical vapour deposition)

- is a thermal process - the reaction between gas and hot surface.

- requires high temperatures

Plasma-assisted (or plasma-enhanced) CVD

- Electron bombardment of atoms and molecules in the plasma volume results in excitation, ionization and dissociation thereby producing a variety of chemically reactive species with vastly different properties from their parent gas.

- requires lower temperatures

e.g., TiN for wear resistance. A gas mixture of TiCl_4 , N_2 and H_2 . thermal CVD 900-1100 °C (above the softening temperature for steel), plasma CVD 500 °C

e.g., Si_3N_4 for passivation layer in semiconductor manufacture. A gas mixture of SiH_4 , N_2 , NH_3 . thermal CVD 900 °C, plasma CVD 300 °C.

e.g., diamond thin films. A diamond thin film is exceptionally hard, low electrical conductivity, high thermal conductivity. Our experiment uses a 2.45 GHz magnetron source, no magnetic field. The process uses a 99% H_2 , 1% CH_4 gas mixture at a pressure of 10's of torr. The film is grown on a silicon wafer which is subsequently etched away. The individual diamonds are nm to μm in size depending on the detail of the deposition process.

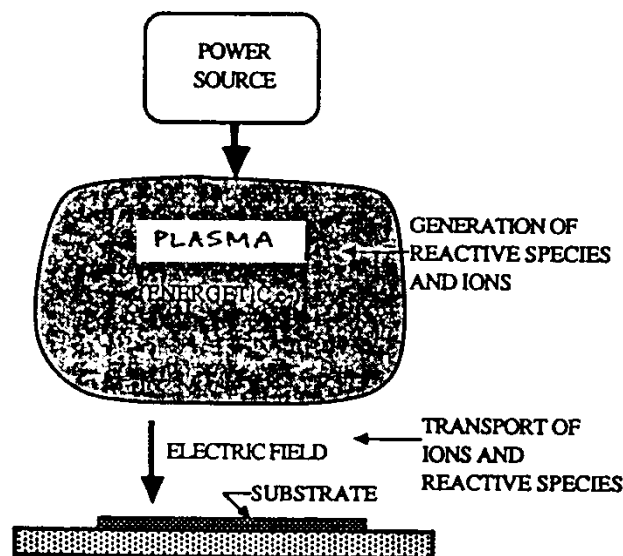
Etching

sputter etching

reactive ion etching

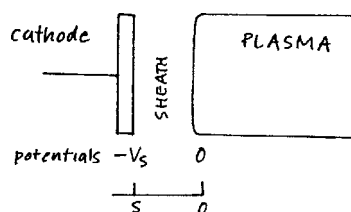
e.g., in semiconductor manufacture, reactive F radicals react with Si to form volatile species that can be pumped out.

A generic plasma reactor for deposition and etching



DC discharges

Cathode sheath



At the cathode, ions accelerated across the sheath strike the cathode and cause (i) secondary emission of electrons (essential to the maintenance of the discharge - see Chapter I) and (ii) sputtering of material from the cathode. This material coats the substrate.

$T_e \gg T_i$ in the plasma.

However we will suppose the electron density in the sheath is small enough to ignore and the ions have a small velocity $u_s = \sqrt{\frac{kT_e}{m_i}}$ as they enter the sheath. Small means that the kinetic energy of the ions as they enter the sheath is much less than the kinetic energy they gain as they are accelerated across the sheath towards the cathode.

If *low pressure*, there are no ion collisions.

The equation of continuity is

$$n(x)v(x) = n_s u_s \quad (1).$$

The equation of conservation of energy is

$$\frac{1}{2} m_i v(x)^2 + e\phi(x) = 0 \quad (2).$$

Eliminate $v(x)$ from (1) and (2) and obtain an expression for $n(x)$. Substitute this into Poisson's equation

$$\frac{d^2 \phi(x)}{dx^2} = -\frac{en(x)}{\epsilon_0}$$

and solve.

Find that the potential across the sheath follows the the Child-Langmuir law

$$\phi(x) \propto x^{\frac{4}{3}},$$

and the sheath thickness

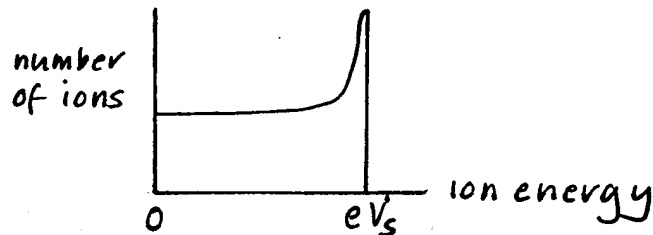
$$s \approx \left(\frac{e\phi_s}{kT_e} \right)^{\frac{3}{4}} \lambda_D,$$

so the thickness of this sheath could be hundreds of λ_D 's.

If *high pressure*, there are ion-neutral charge exchange collisions and both ions and neutrals strike the cathode.

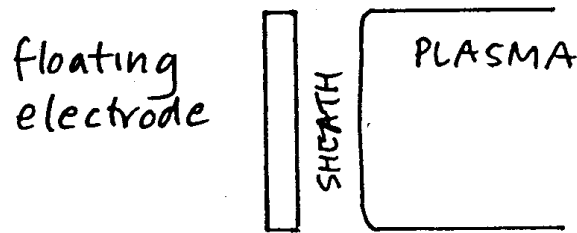
Instead of conservation of energy use $v = \mu E = -\mu \frac{d\phi}{dx}$ where μ is the mobility.

The ion energy distribution looks like:



The low energy continuum is a result of ion collisions.

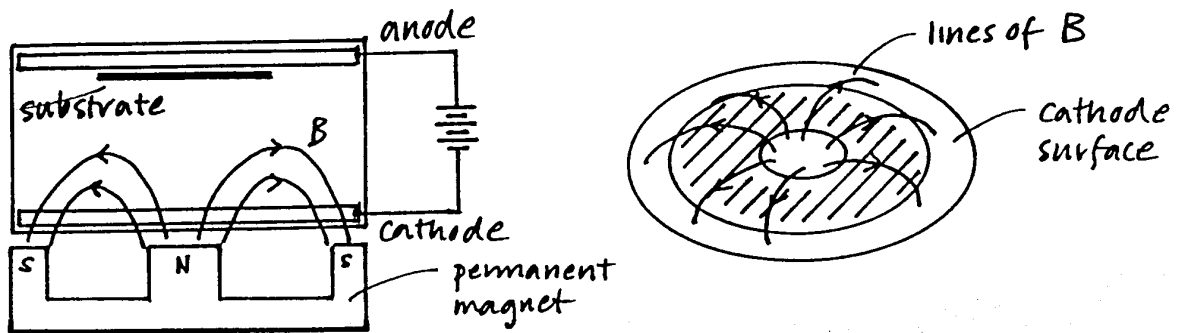
Sheath near a floating electrode or wall.



There are both rapidly-moving electrons and slowly-moving ions in the sheath. The key equation expresses the fact that the net current (due to both ions and electrons) to the floating electrode is zero (See Chapter VII, Exercise 1).

The sheath thickness is $\approx \lambda_D$ and the p.d. across it is $V_F - V_S \approx \frac{kT_e}{e}$ which is insufficient to accelerate the ions for sputtering.

Magnetron



The figure shows the planar magnetron.

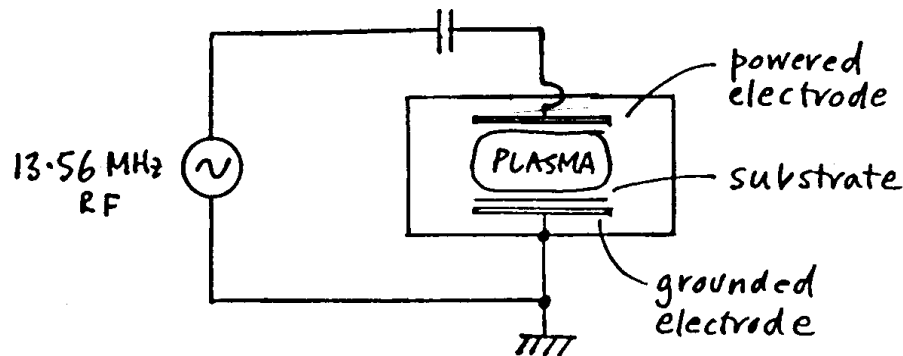
(The figures do not show gas inlets, vacuum pumping ports or matching networks.)

The magnetron is used for sputter coating and metallization. It is capable of high current densities - and fast processing.

The magnetic field (typically 0.02 T) confines the secondary electrons so a bright plasma ring sits above the cathode. Ions however can reach the cathode and bombard it.

RF discharges

Capacitively-coupled RF discharge also called RF diode



Under the applied RF voltage the plasma-sheath boundary at each electrode oscillates up and down. The bulk of the plasma remains uniform.

This is the most common plasma source for materials processing. Low pressure discharges can provide high ion energies for etching and high pressures discharges can provide low ion energies for deposition.

The main plasma heating mechanism are:

Ohmic heating. $P = I^2 R$. In this case the RF current is capacitively-coupled across the sheaths.

Stochastic heating. The sheath edges are oscillating up and down. Electrons striking the sheath edge have their velocities changed and over 1 period, there is a net gain in energy. The word stochastic refers to the probabilistic nature of the electron collisions with the sheath.

Advantages:

- simple construction,
- no magnetic field required

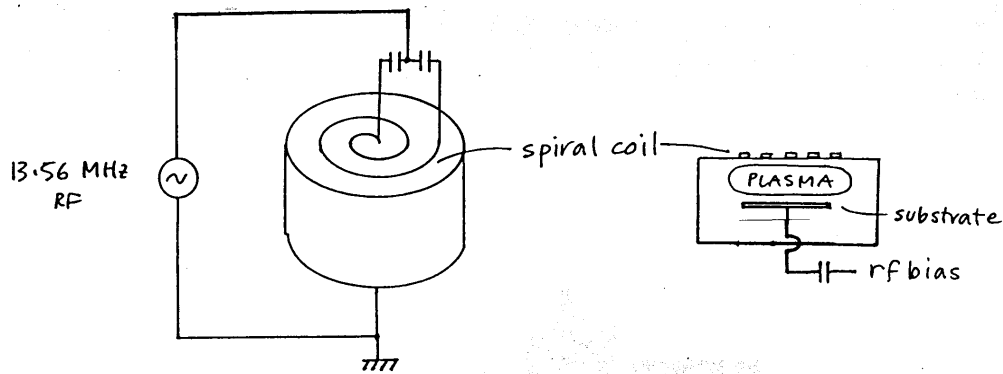
Disadvantages:

Low ion flux and high ion energy (typically 100's of eV), these cannot be varied independently. If damage to the substrate is likely, processing must be carried out slowly.

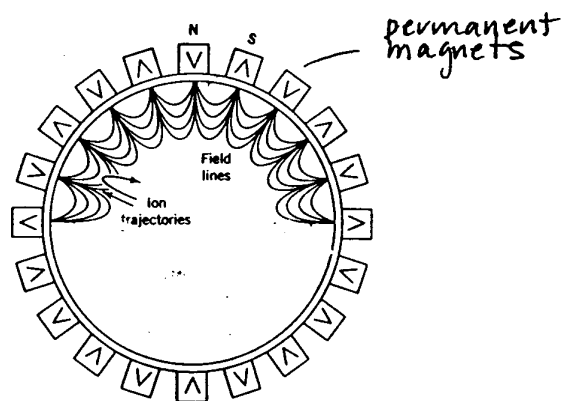
Voltage drop at sheath is sensitive to geometry (The total area of the grounded surfaces is much greater than the area of the powered electrode. The sheath at the powered electrode therefore has a smaller capacitance and hence a larger voltage drop.)

Inductively-coupled RF discharge

The spiral coil is the primary, the plasma is the secondary.



A multipole magnetic field can be used to enhance the confinement of the plasma.



Advantages:

Ion energy can be controlled independently by applying capacitively-coupled rf to bias the substrate.

The ion energies are much less, 10's of eV and have a much milder action on the substrate.

Disadvantages:

diameter/height is large making cooling and pumping difficult
non-uniform density profile (ring-shaped)

RF or microwave heated discharges

Here is an outline of how we might calculate the power absorbed by the plasma.

Start with the electron momentum equation

$$\rho_e \frac{\partial \mathbf{v}_e}{\partial t} + \rho_e \mathbf{v}_e \cdot \nabla \mathbf{v}_e = -n_e e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - \rho_e \nu \mathbf{v}_e$$

In the last term we have assumed that velocities \mathbf{v}_i and \mathbf{v}_n are $\ll \mathbf{v}_e$.

This time, consider oscillations, not waves, so $\mathbf{E} = \mathbf{E}^1 e^{-j\omega t} \hat{\mathbf{x}}$, write $n = n^0 + n^1 e^{-j\omega t}$ and $\mathbf{v}_e = \mathbf{v}_e^1 e^{-j\omega t}$ and consider only the first-order terms.

(i) No magnetic field.

$$v_{ex}^1 = \frac{-e}{m_e} \frac{1}{-j\omega + \nu} E^1.$$

Power absorbed per unit volume

$$\mathbf{p} = \mathbf{j} \cdot \mathbf{E}.$$

Now $j_x = -n^0 e v_{ex}^1$.

Some care is required here. To calculate the power you must take the real part of j_x and multiply it by the real part of E . This gives the instantaneous power. The time-averaged power absorbed (over one cycle) is

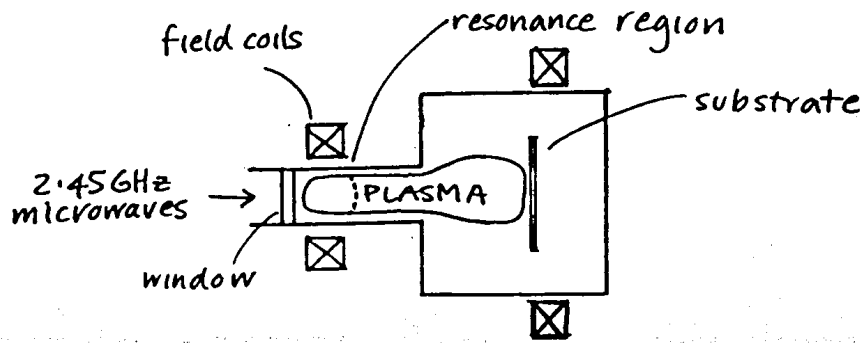
$$\langle p \rangle = \frac{1}{2} \frac{n^0 e^2}{m_e} \frac{E^{12}}{\nu} \frac{\nu^2}{\nu^2 + \omega^2}$$

Note that if there are no collisions, there is no power absorbed.

(ii) magnetic field

$$\langle p \rangle = \frac{1}{2} \frac{n^0 e^2}{m_e} \frac{E^{12}}{\nu} \left(\frac{1}{2} \frac{\nu^2}{\nu^2 + (\omega - \omega_{ce})^2} + \frac{1}{2} \frac{\nu^2}{\nu^2 + (\omega + \omega_{ce})^2} \right)$$

ECR discharge (electron cyclotron resonance)

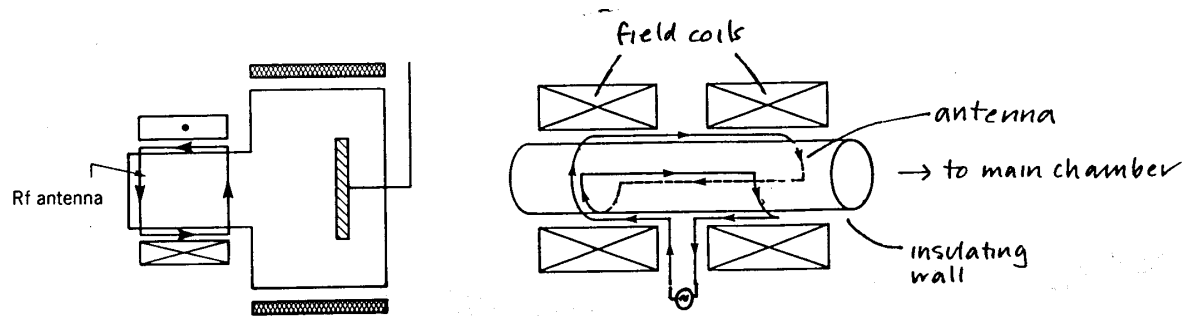


Note that in case (ii) above the power absorbed is large if the frequency is near the electron cyclotron resonance frequency. ECR is an improvement over the non-resonant case.

The ECR discharge uses inexpensive 2.45 GHz magnetron microwave sources that can deliver 0.3 to 6 kW. The microwaves are launched as RHCP waves into the high-field region and are absorbed in the resonance region where $\omega = \omega_{ce}$. When $f_{ce} = 2.45$ GHz, the resonance magnetic field $B = 0.0875$ T. The plasma created in the resonance region flows into the main chamber.

You do. Why does the ECR discharge use RHCP waves travelling from the high field region? Refer to the CMA diagram in Chapter V.

Helicon plasma



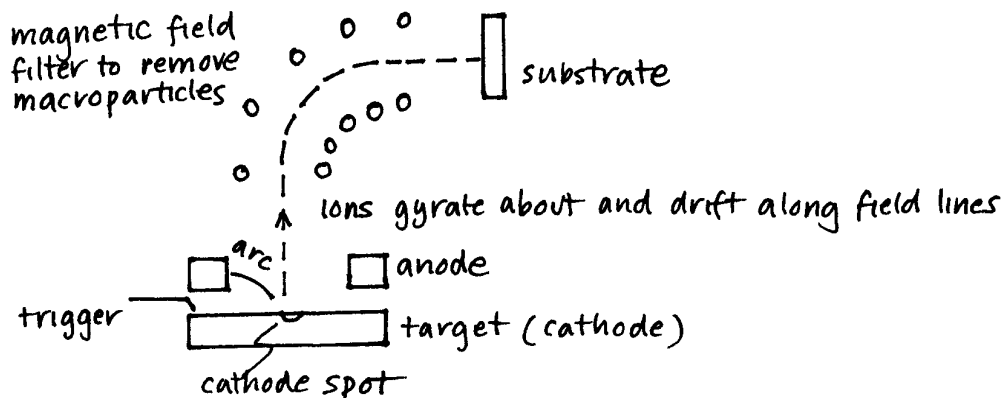
RF driven antenna excites a helicon wave (see Chapter VI) and a resonant wave-particle interaction transfers energy to the plasma. The plasma flows into the main chamber. This results in a high density plasma.

Vacuum arc

plasma is fully ionized

high deposition rate, low substrate temperature

greatest drawback is the formation of macroparticles. Use magnetic field filter.



PI³ Plasma immersion ion implantation

Ions from the plasma are accelerated by means of a series of negative high-voltage pulses.

The beam injected into the surface changes the atomic composition and the structure near the surface.

semiconductor manufacture; now routine

metallurgy; an emerging technology in for creation of new surface alloys - not restricted to planar surfaces.