Plasma Diagnostics

What is Plasma Diagnostic?

Plasma diagnostics are experimental methods based on various electrical and spectroscopic techniques that allow the measurement of internal plasma parameters.

Plasma diagnostic tools are an essential element towards the proper understanding and development of technological plasmas. Knowledge of the particle densities and energies in the bulk and at boundaries, the electrical potentials and the spatial and temporal evolution of these parameters allow technologists to operate plasmas in the most efficient way and allow the intrinsic plasma processes to be tailored to suit a particular application. There are many different diagnostic tools that can be used, depending on the type of plasma under investigation and the specific information that is required.

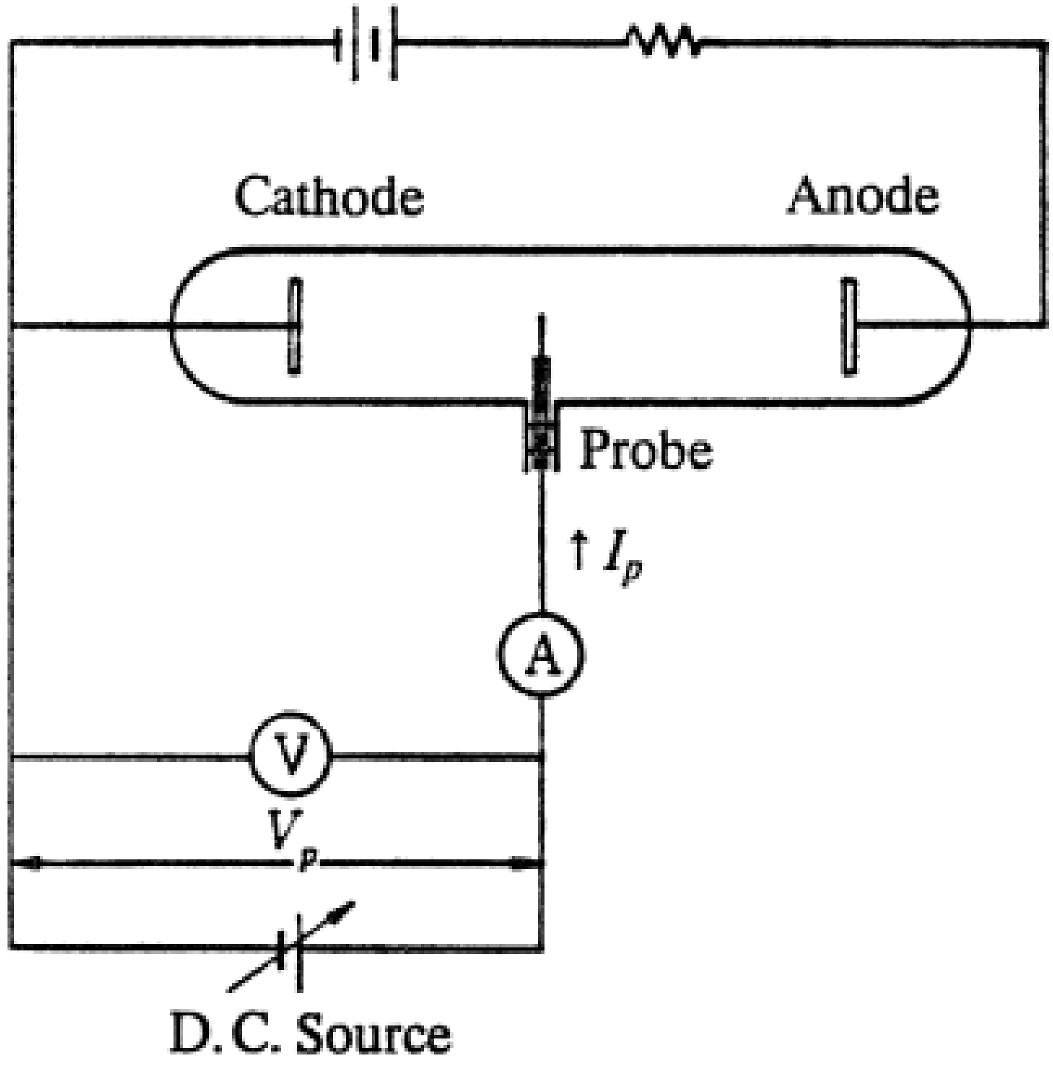
Few Plasma Diagnostic Techniques:

1. Langmuir Probe – directly inserted in the plasma.
2. Optical Emission Spectroscopy (OES) – indirect method. Not in direct contact with plasma.
3. Interferometry
4. Mass Spectroscopy
5. Plasma Imaging

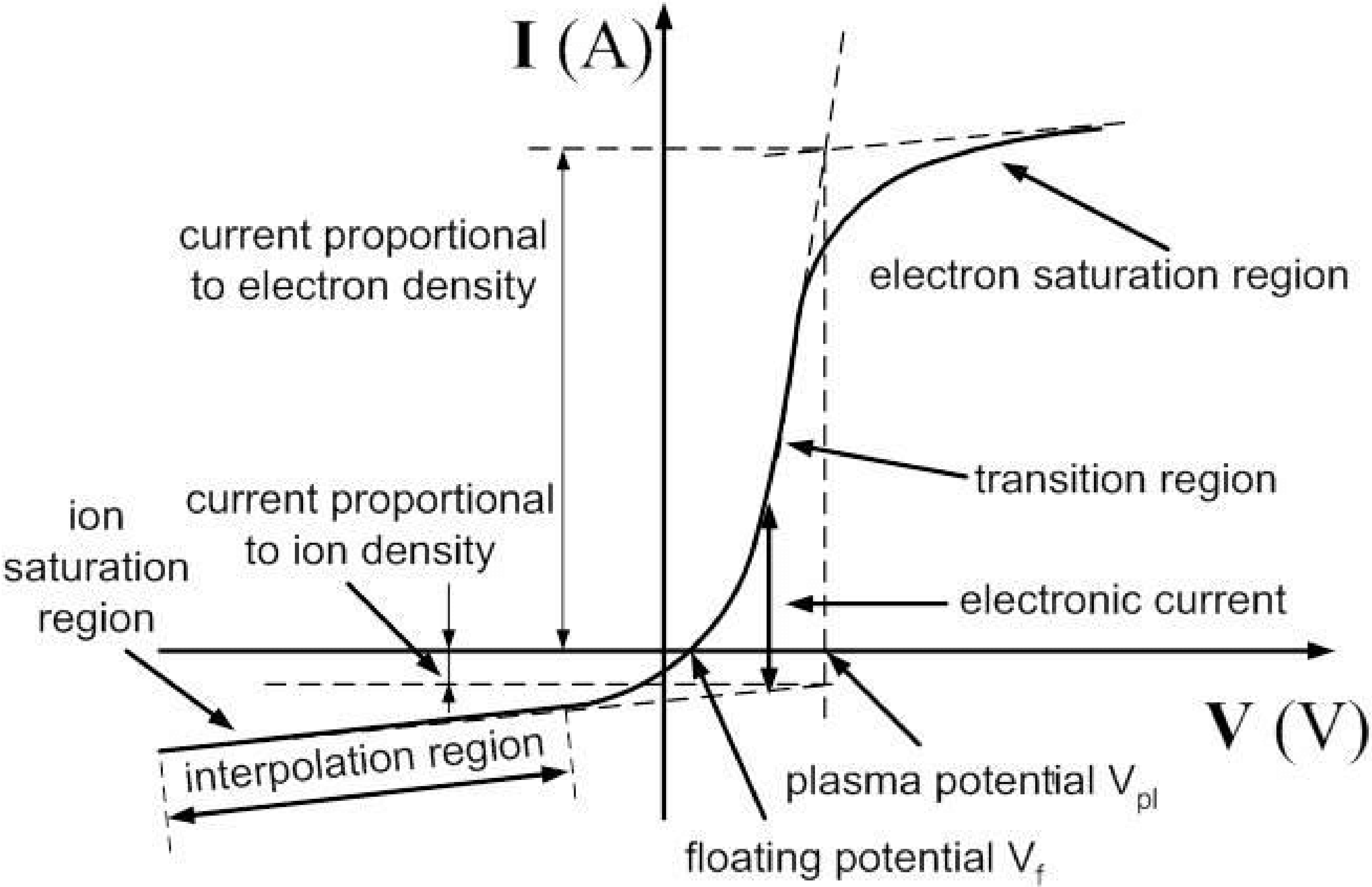
Langmuir Probe method

The most basic probe used for measuring the properties of plasma is an electrostatic probe. This technique was developed by Langmuir in 1924. It is simply a small metallic electrode in the form of wire inserted into the plasma. A variable biasing voltage is applied on this electrode, which may be positive or negative with respect to the plasma. The current collected by the probe with respect to the applied voltage provides various information about the plasma condition. It has been observed that under certain conditions, such as in the presence of strong magnetic field as well as in the turbulent plasma conditions these measurements become difficult. However in spite of all difficulties, it can provide information about the local parameters (plasma density and temperature) in comparison to the other plasma diagnostics in the cold plasma.

Basic Langmuir Probe set up



Langmuir Probe Current – Voltage characteristic curve



Calculation of Electron Temperature and Electron Density:

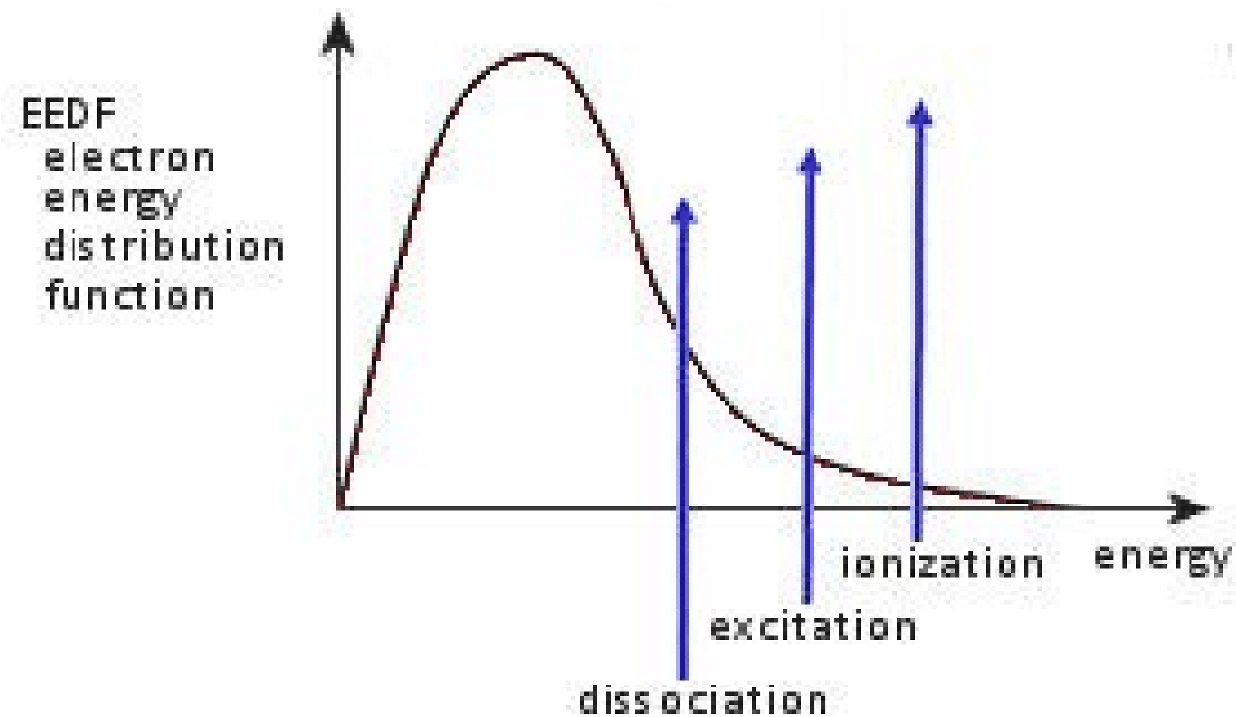
Electron density (n_e) and the average electron temperature (Te) from the current (I)- voltage (V) characteristics of the Langmuir probe using the relations

$$n_e = \left(\frac{2\pi m_e}{kT_e}\right)^{1/2} \frac{I_{sat}}{Ae} \qquad T_e = \frac{dV}{d(\ln I_e)}$$

where I_e is the electron current, I_{sat} is the electron current at plasma potential, me is the electron mass, e is the electron charge and A is the exposed area of the probe tip

Electron Energy Distribution Function (EEDF) can also be analyzed from Langmuir Probe method

The electron energy distribution function (EEDF) is essential in plasma processing because it is needed to compute reaction rates for electron collision reactions.



If the plasma is in thermodynamic equilibrium, the EEDF has a Maxwellian shape. In most plasmas, for technical purposes, deviations from the Maxwellian form occur.

Optical Emission

$$X + e^- \xrightarrow{k_e} X_u^* + e^-$$

$$X_u^* \xrightarrow{k_{em}} X_\ell^*$$

$$\frac{dn_{X*}}{dt} = k_{ex} n_X n_e - k_{em} n_{X*} = 0$$

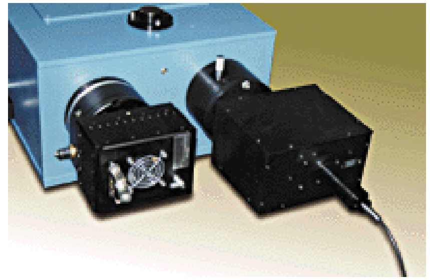
$$n_{X*} = \frac{k_{ex} n_X n_e}{k_{em}}$$

$$I = S(\lambda) k_{em} n_{X*} = S(\lambda) k_{ex} n_X n_e$$

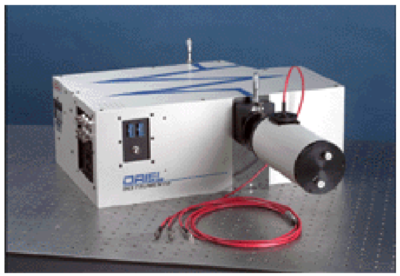
$$k_{ex} = \sqrt{\frac{2}{m_e}} \int_0^\infty \sigma_{ex}(\varepsilon) \sqrt{\varepsilon} f(\varepsilon) d\varepsilon$$

- Emission intensity depends on n_x, n_e and T_e
- Emission intensity is not a measure of X concentration

Optical Emission Spectroscopy



Imaging Spectrographs with CCDs

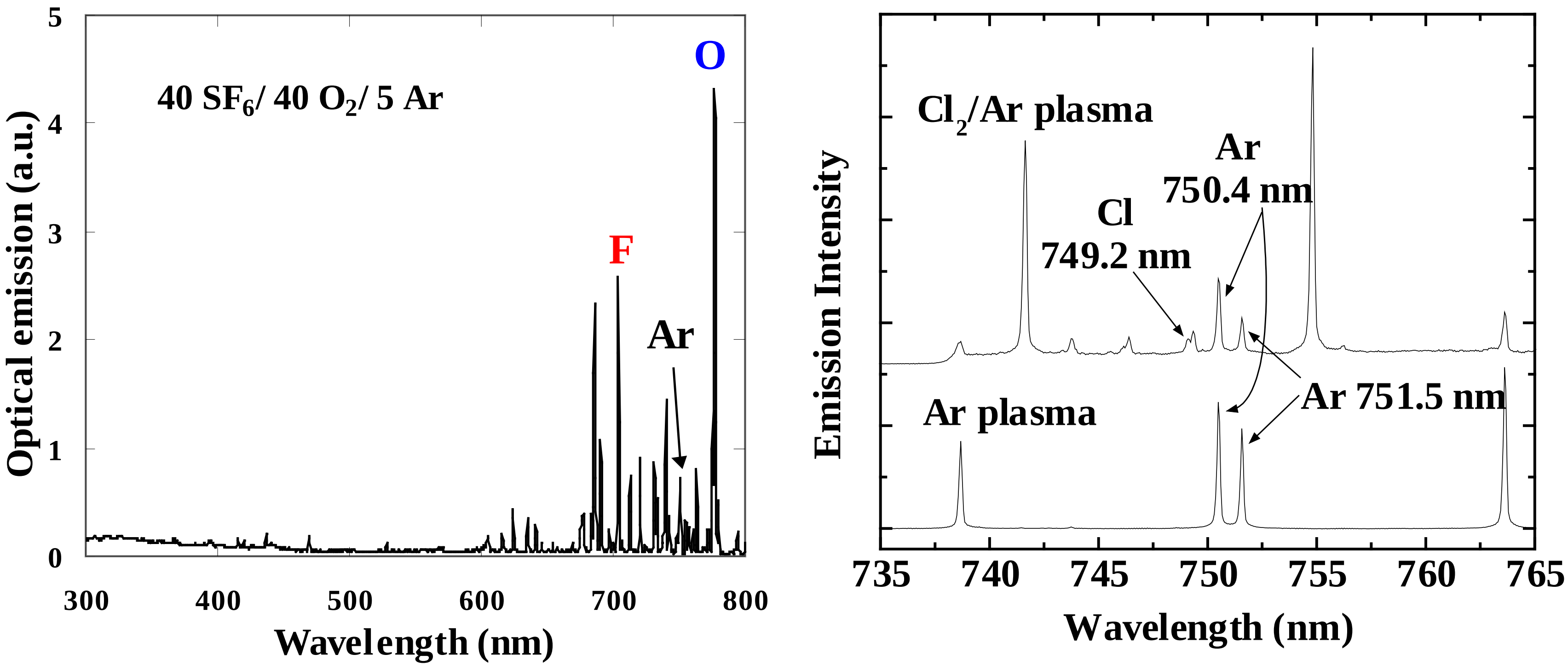


Monochromator & PMT

Integrated spectrographs and data acquisition

Photodiode and narrow pass filter

Optical Emission Spectra



OES for end point detection and control in Plasma deposition

The endpoint detection (EPD) is the most important technique in plasma etching process. In semiconductor manufacturing, spectrometers are used for measuring the emission spectrum from a plasma chamber in real time and for diagnosis of manufacturing processes and analysis of materials such as optical emission spectrometer (OES) and end point detection (EPD). With the help of some analyzing software, the optical emission spectrometer systems can be eventually set up as end point detection systems.

Inductively coupled plasma optical emission spectroscopy (ICP-OES)

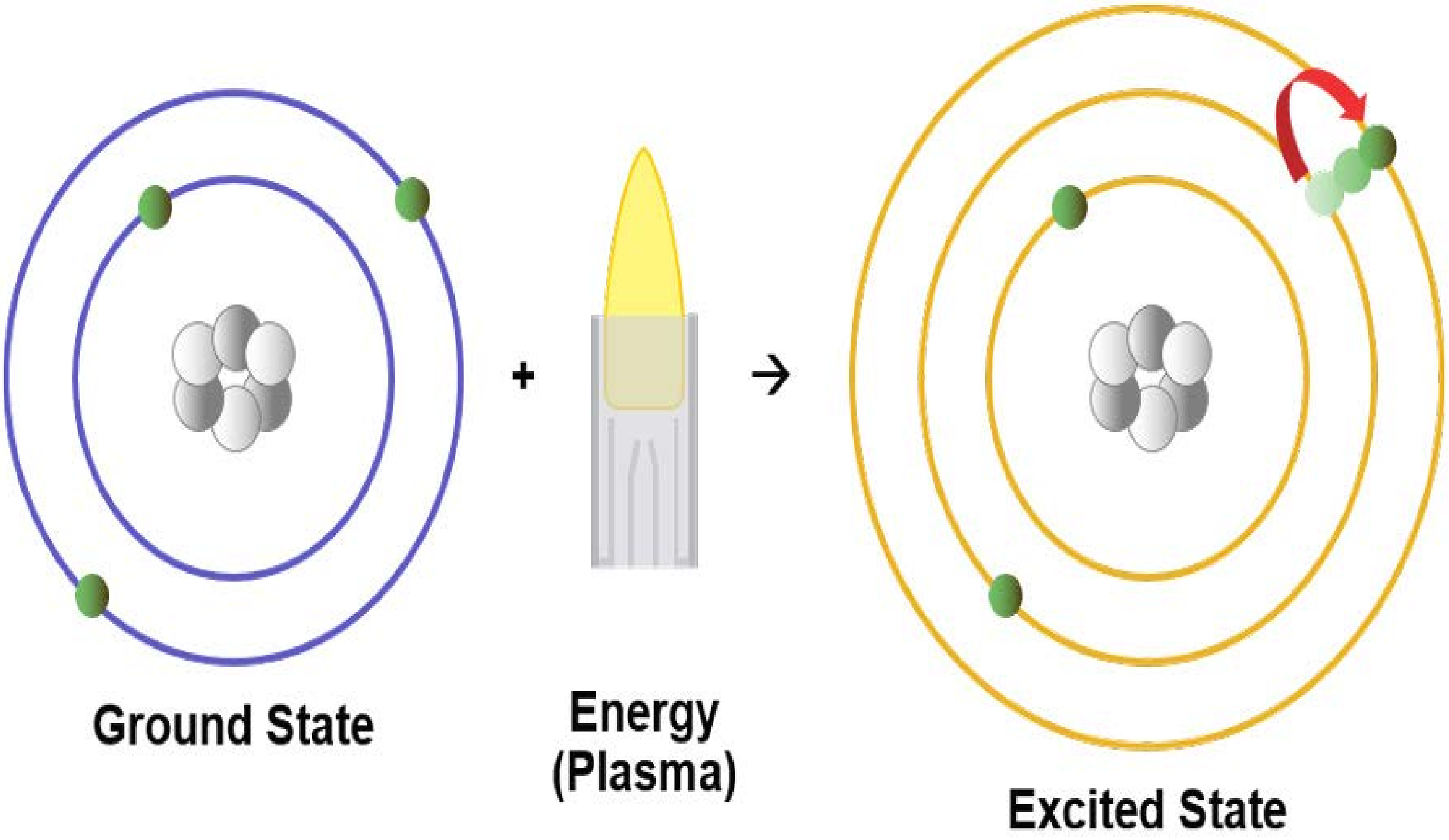
ICP-OES is the technique of choice for many different applications, including those in the environmental, metallurgical, geological, petrochemical, pharmaceutical, materials, and food safety arenas.

ICP-OES is an analytical technique used to determine how much of certain elements are in a sample. The ICP-OES principle uses the fact that atoms and ions can absorb energy to move electrons from the ground state to an excited state. In ICP-OES, the source of that energy is heat from an argon plasma that operates at 10,000 kelvin.

The ICP-OES principle relies on those excited atoms releasing light at specific wavelengths as they transition to a lower energy level.

How ICP-OES works?

Plasma of a gas (let’s say Argon) which contains a significant number of argon ions. The plasma is formed by seeding the argon gas passing through a plasma torch with electrons. The electrons are accelerated and collide with argon atoms releasing more electrons and forming argon ions. Elements, in the form of atoms, are introduced into the plasma. A proportion of theses atoms will be become ionized within the plasma. When an atom or ion is excited within the plasma, its electrons jump from a lower to higher energy level as shown in the figure below. Upon relaxation of these electrons to their initial 'ground' state, energy is emitted in the form of photons. The emitted photons possess wavelengths that are characteristic of their respective elements.



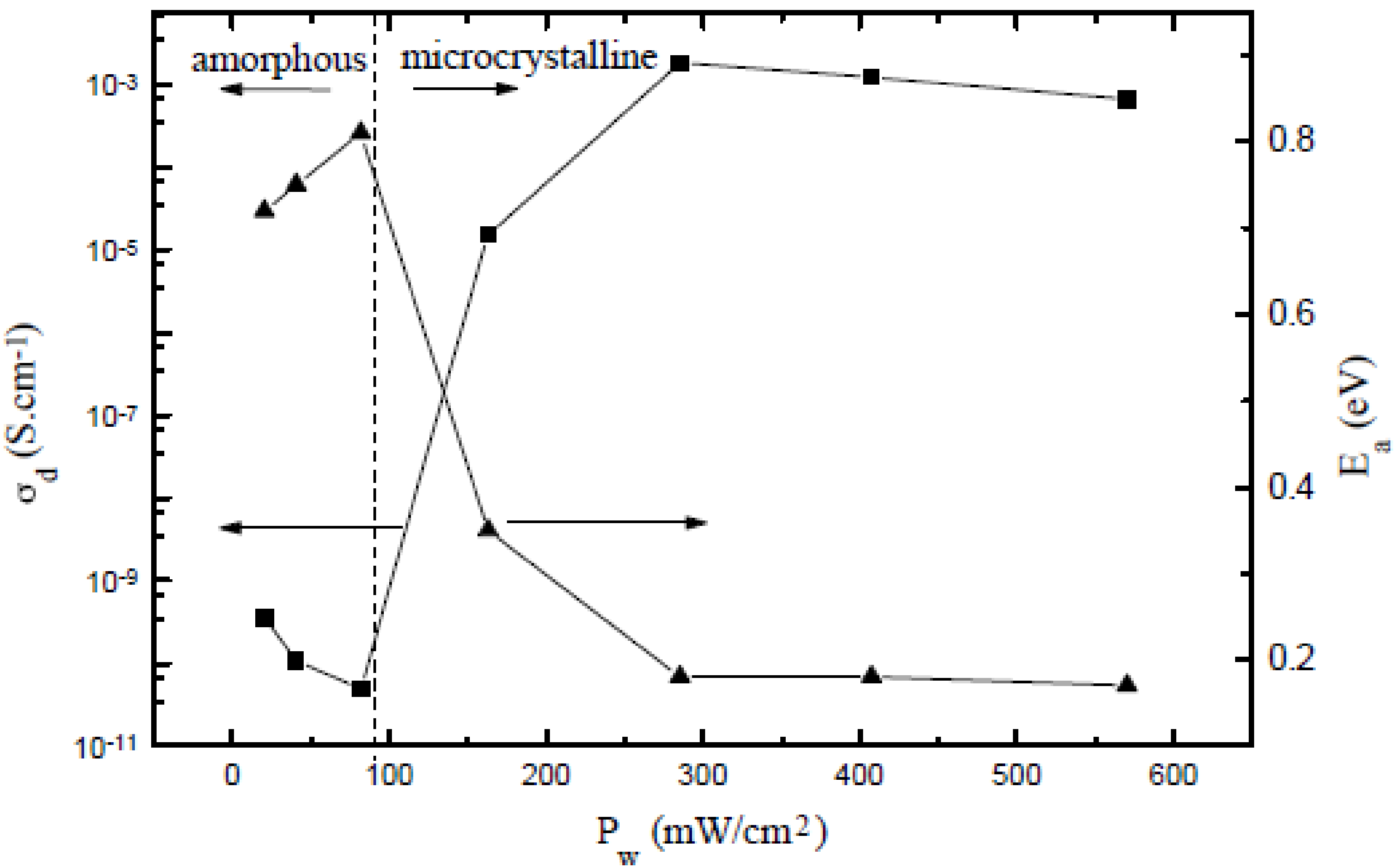
Excitation of an atom by a plasma

Use of Plasma diagnostics in Material Processing

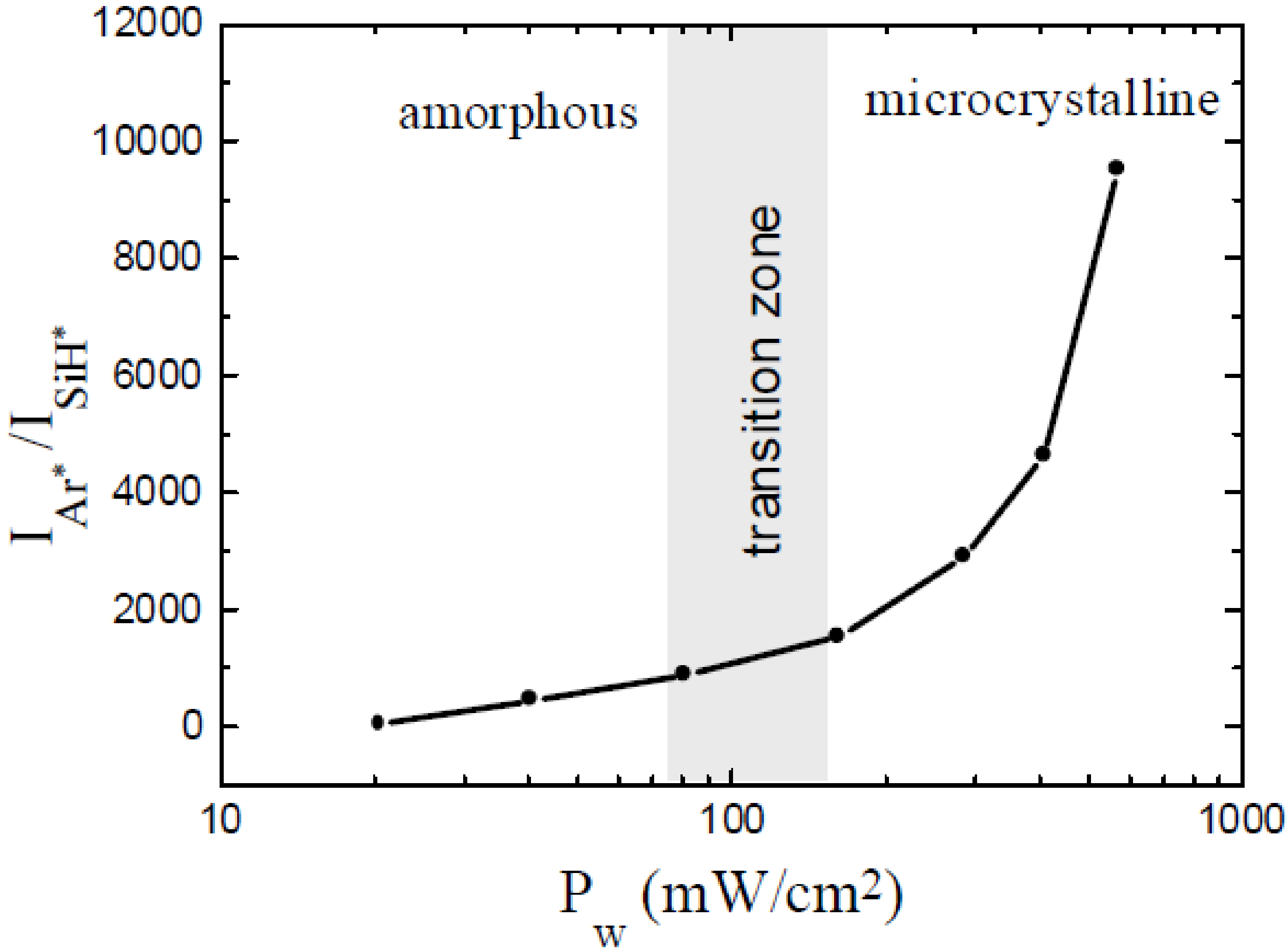
- Different plasma parameters can be estimated by varying the plasma processing conditions – i.e. by varying the process parameters like RF power, chamber pressure, gas flow ratio, substrate temperature etc.
- Materials developed in a particular process condition can be characterized to check different their structural, optical, electronic properties.
- Normally characterization of materials are time consuming and need lots of instrumentation facility. Whereas Plasma diagnostic is less time consuming.
- Material properties are optimized to get the best device performance.
- We can compare plasma properties with material properties and can correlate. After that we can only develop material at this particular plasma condition.

Discussion on a result of Optical Emission Spectroscopy to correlate with materials properties

In this plasma diagnostics we have used OES and measured emission lines for different species. Here we have considered two emission lines due to excited Argon (Ar^*) and radical SiH^*. We have measured the intensity of emission lines due to excited Argon and SiH with the variation of Radio Frequency power density. Then we compare with the material property.



amorphous
microcrystalline
10-3
10-5
10-7
10-9
10-11
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
σd (S.cm-1)
Ea (eV)
Pw (mW/cm2)



The ratio of the intensity of the Ar* (I_{Ar*}=) to that of SiH* (I_{SiH*}) with rf power density