UPORABA PLAZME V ELEKTRONIKI
APPLICATION OF PLASMA IN ELECTRONICS

PLASMA PROCESSES

PART I: PLASMA BASICS, PLASMA GENERATION

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Applications of plasma processes are becoming increasingly popular in many industrial and research communities. Electronics, microelectronics, automotive, aircraft, and food industry are among the most frequent plasma users. This is not surprising if we consider e.g. the field of cleaning applications. There, plasma cleaning or plasma combined with some suitable wet precleaning technique can totally replace CFC and some other toxic cleaning agents.

The first article describes basic plasma physics and plasma generation while the second focuses mainly on application of plasma in R&D and industrial processes.

Technics Plasma GmbH in Kirchheim, Germany is among the pioneers and leaders in plasma technology and its application in academic and industrial environments. We will focus mainly on their systems and give an overview of successful applications of their machines and processes in different environments.

1.0 INTRODUCTION

A plasma is a gas containing charged and neutral species, including some or all of the following: electrons, positive ions, negative ions, neutral atoms in ground and excited states, neutral molecules in ground and excited states, radicals and photons. On average a plasma is electrically neutral, because any charge imbalance would result in electric fields that would tend to move the charges in such a way as to eliminate the imbalance.

An important parameter of a plasma is the degree of ionization, which is the fraction of the original neutral species (atoms and/or molecules) which have been ionized. In weakly ionized plasmas the degree of ionization is much smaller than unity and the presence of large population of neutral species governs its behaviour. Most of the plasmas that we will be dealing with are weakly ionized.

To form and sustain a plasma some energy source is necessary to produce the required ionization. In steady state, the rate of ionization must balance the losses of ions and electrons from the plasma volume by recombination and diffusion or convection to the boundary of the plasma and the surrounding walls.

Plasmas are usually initiated and sustained by electric fields which are produced either by direct current (DC) or alternating current (AC) power supplies. Typical AC frequencies of excitation are 100 kHz, at the low end of the spectrum, 13.56 MHz in the radio frequency (RF) portion of the spectrum, and 2.45 GHz in the microwave region. These plasmas are also referred to as electric discharges, gaseous discharges, or glow discharges (the latter because they emit light).

In figure 1, a generic plasma reactor for thin film etching and deposition is depicted. A power source supplies energy to the main plasma discharge where reactive species and ions are generated. These species are transported to the substrate for etching or deposition. In many configurations, depending also on the excitation freguency, there is an electric field in the vicinity of the substrate which accelerates the ions.

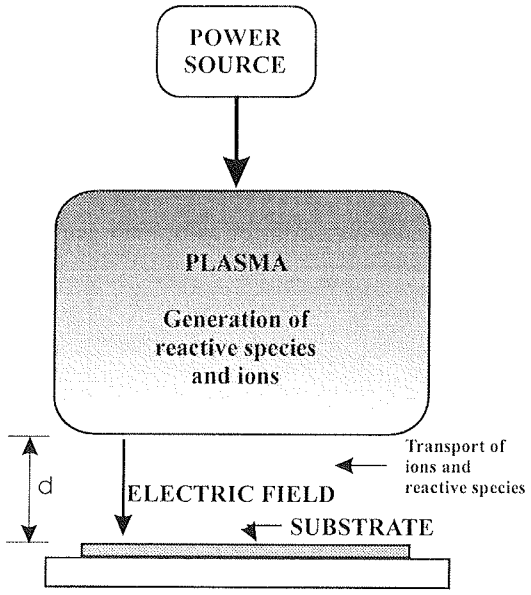


Figure 1: Generic plasma reactor

As we shall see later, electrons play the most important role in plasmas. It is useful to characterize plasma in terms of electron densities and electron energies. In a number of cases electrons have Maxwellian energy distribution if they are in thermodynamic equilibrium:

$$f(\varepsilon) = \frac{2\varepsilon^{1/2}}{\pi^{1/2}(kT)^{3/2}} \exp\left(-\frac{\varepsilon}{kT}\right) \quad (1)$$

$f(\varepsilon)$ is the electron energy distribution function (EEDF) and T the electron temperature

Average electron energy is related to the temperature and is calculated as

$$\int \varepsilon f(\varepsilon) d\varepsilon = \langle \varepsilon \rangle = \frac{3}{2} kT \quad (2)$$

Electron energies are usually expressed in eV. 1 eV is equivalent to the temperature of approximately 11600 K while energy of 0.025 eV corresponds to the electron average temperature of 300 K.

In figure 2, typical values of electron densities and temperatures are shown for a variety of plasmas. They range from the very rarified and cold interstellar plasmas up to the dense and hot plasmas used for controlled fusion. The plasmas of interest here are the process plasmas, which have electron densities in the range of 10^9 to 10^{12} cm^{-3} and average electron energies between 1 and 10 eV. The degree of ionization for these plasmas varies from about 10^{-6} up to 0.1. At the lower end of the density, energy, and ionization scale are the discharges that are formed between planar electrodes, while the upper end of this scale applies to discharges sustained at a frequency that corresponds to some natural frequency for the plasma (such as electron cyclotron resonance (ECR) plasmas).

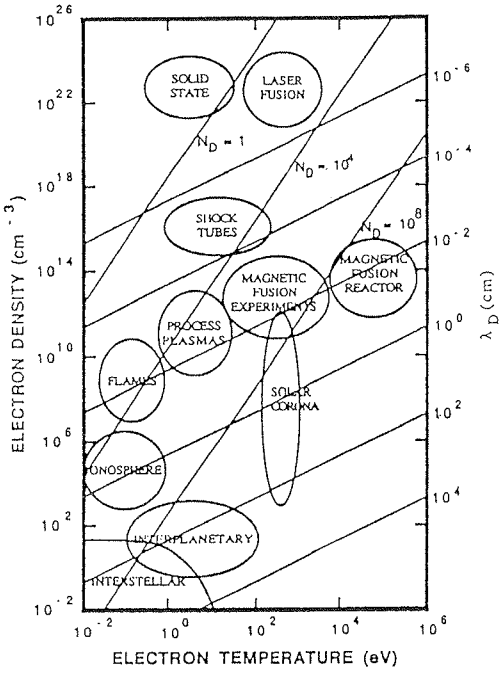


Figure 2: Electron density and temperature ranges for a variety of natural and man made plasmas.

The extensive use of plasmas for the deposition and etching of thin films derives from two salient features. Firstly, plasmas are capable of efficiently generating chemically active species.This is initiated by the bombardment of molecules and atoms by the plasma electrons, which have sufficient energy to break chemical bonds. The products of the electron bombardment processes which include radicals and ions, can undergo further reactions often at high rates, to form additional chemically reactive species. Radicals are very important for processes to be performed in plasmas. A radical is an atom, or electrically neutral molecule which is in a state of incomplete chemical bonding with highly increased reactivity. Some typical examples of radicals include F, Cl, O, H and CF_x,where x= 1,2 or 3. In general, radicals are thought to exist in plasmas in much higher concentration than ions, because they are generated at a faster rate, and they exist longer than ions in the plasma. The radicals, in fact, are responsible for most of the actual chemical etching phenomena that occur at the surface of the material being treated.

The second feature that makes plasma discharges so useful is their ability to generate ions and to accelerate these ions to energies of 50-1000 eV in the vicinity of the deposition or etching substrate.Energetic ions are useful for sputtering, as well as play sinergetic role in the deposition or etching of thin films.

To summarize, the gas in a plasma chamber when there is a plasma generated, generally consists of the following species, in order of decreasing concentration, and estimated concentration ranges:

- (etch) neutral gas molecules: 70-98 % of the total species in the chamber
- product molecules: 2-20 %
- radicals: 0.1-20 %
- charged species including positive ions, electrons and negative ions: 0.001-10 %

2.0 COLLISION PROCESSES

Collision processes among different types of particles are responsible for forming and sustaining plasma. Through collisions the particle kinetic energy is used up to create radicals, ions, excited atoms/molecules and photons.

2.1 ELASTIC AND INELASTIC COLLISIONS

Collision processes can be broadly divided into elastic and inelastic types according to whether the internal energies of the colliding bodies are maintained. Single particles usually have two types of energy: kinetic due to their motion and equal to 1/2 mv^2 for translational motion and internal or potential energy which may be in the form of electronic excitation and/or ionization, etc. (and in the case of molecules also in the form of vibrational as well as rotational internal energies).

An elastic collision is one in which there is an interchange of kinetic energy only. An inelastic collision has no such restriction, and internal energies can also change.

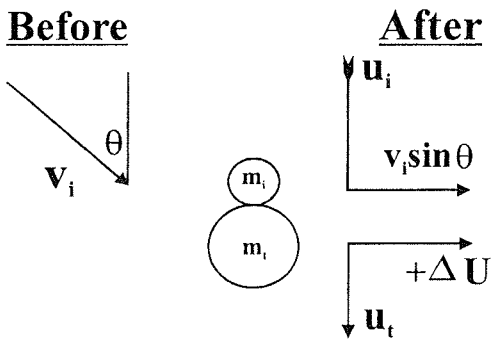


Figure 3: Collision between two particles

Refering to the figure 3, we can write the following GENERAL equation for energy transfer from incoming particle to the target particle:

$$\frac{1/2\, m_t u_t^2}{1/2 m_i v_i^2} = \frac{m_t u_t^2}{m_i}\left(\frac{2m_t u_t}{\frac{m_t}{m_i}(m_t + m_i)u_t^2 + 2\Delta U}\right)^2 \qquad (3)$$

and inelastic energy transfer function, which measures the portion of kinetic energy of the incoming particle transferred to the internal energy of the target atom (ΔU) is defined as

$$\frac{\Delta U}{1/2 m_i v_i^2} = \frac{m_t}{m_t + m_i}\cos^2\theta \qquad (4)$$

m_i, m_t: masses of incoming and target particles

v_i, u_t: velocities of incoming and target particles

ΔU: gained internal energy by target particle

Putting ΔU = 0 brings us to the elastic collision case where maximum energy transfer for head on collision is given by the equation:

$$\frac{1/2 m_t u_t^2}{1/2 m_i v_i^2} = \frac{4 m_i m_t}{(m_i + m_t)^2} \qquad (5)$$

We see that light impact particles (like electrons, $m_i << m_t$) can transfer only very small portion of kinetic energy to the kinetic energy of heavy ion, atom or a gas molecule. However in this case electron's momentum changes very much. On the other side elastic collisions of heavy ions, atoms or gas molecules among themselves always lead to overall equalization of kinetic energies, since having $m_i \approx m_t$, elastic energy transfer function is equal to 1!

In case of inelastic collision the situation is quiet different. Equation (4) predicts that a light particle striking much heavier particle ($m_i \approx m_t$) can transfer almost all of its kinetic energy into particle's internal energy and inelastic energy transfer function tends to 1!

2.2 THE MAIN COLLISION PROCESSES

As already mentioned a glow discharge contains many different particles. In principle we should consider collisions between all possible pair permutations, but fortunately some collisions are more important than others. Collisions involving electrons are dominant in determining the macroscopic behaviour of the glow discharge that is why we will describe them in more detail.

Electron - atom elastic collisions

The simplest collisions are elastic so that kinetic energy is conserved. But since the electron and any atom (molecule) have such different masses, we know that the transfer of energy is negligible, so electron just changes direction without significantly changing its speed, figure 4. If an electron is moving in an electric field, elastic collisions generally have the effect of restricting its velocity in the direction of the field. In both cases, the colliding atom is virtually unaffected.

As an example cross section for elastic scattering of electron in argon at 15 eV is about $2.5 \cdot 10^{-15}$ cm^2. So at 10 mtorr (0.013 mbar) when there are $3.54 \cdot 10^{14}$ atoms/cm^3 , the probability of elastic collision of a 15 eV electron is about 0.9/cm.

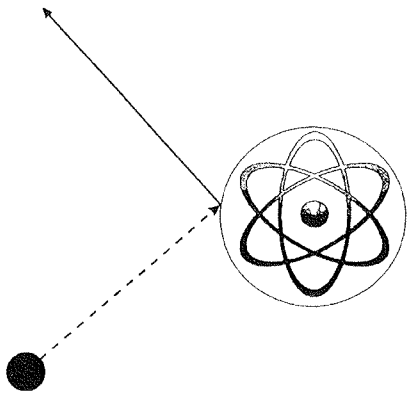


Figure 4: electron - atom elastic collision: no energy transfer - only electron momentum changes

Ionization

All other types of electron collisions are inelastic. The most important of these in sustaining the glow discharge is *electron impact ionization*, figure 5 in which the primary electron removes an electron from the atom, producing a positive ion and two electrons, for example

$$e + Ar \rightarrow 2e + Ar^+ \qquad (6)$$

The two electrons produced by the ionization collision can then be accelerated by an electric field until they, too, can produce ionization. **It is by this multiplication process that a glow discharge is maintained.**

There is minimum energy requirement for this ionization process to occur, equal to the energy to remove the most weakly bound electron from the atom, and this is

known as the ionization potential. For xenon this has a value of 12.08 eV, and for argon 15.8 eV. However, it is not only by electron impact that ionization is produced. In principle, ionization could be due to any suitable energy input, and the possibilities in the discharge must therefore include thermal and photon activation. Thermal activation means energy received by impact with neutral ground state atoms or with the atoms of the walls. For our "cold" plasmas, the temperature does not greatly exceed ambient so thermal activation is very unlikely.

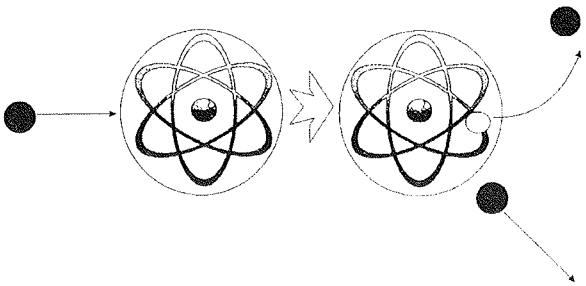


Figure 5: electron - atom inelastic collision causing ionization

Photoionization can be significant, however. Argon photoionization cross section rises to maximum of $2.6 \cdot 10^{-16}$ cm^2 and then falls down with energy. But at higher energies this does not necessarily mean that there is very little ionization since after photoionization the free electron receives excess photon energy in the form of kinetic energy and is capable of further ionization by itself; as well the hole left in the atom electron shell after ionization will be filled with another electron transition from a higher level and the accompanying photon emission usually causes more ionization - and hence the ejection of more electrons - on its way out of the atom (the Auger effect is an example). Similar arguments can be used to explain photoelectron emission from chamber walls and all internal surfaces, including electrodes. As a result one would expect a large proportion of photon energy to lead ultimately to ionization.

Excitation

In the ionization process, a bound electron in an atom is ejected from that atom. A less dramatic transfer of energy to the bound electron would enable the electron to jump to a higher energy level within the atom with a corresponding quantum absorption of energy. This process is known as an *excitation*, and as with ionization, can result from electron impact excitation, photoexcitation, or thermal excitation, although the latter is rare in our "cold" plasmas, figure 6.

The excited state is conventionally represented by an asterisk superscript, e.g. Ar*. As with ionization, there is minimum energy for excitation to occur. The value of the excitation potential for argon is 11.56 eV, somewhat less than the ionization potential, as would be expected since excitation raises an electron to a higher (less bound) shell, and ionization completely removes the electron from the atom. In an exciting collision the primary electron loses kinetic energy equal to the excitation potential and will also be deflected.

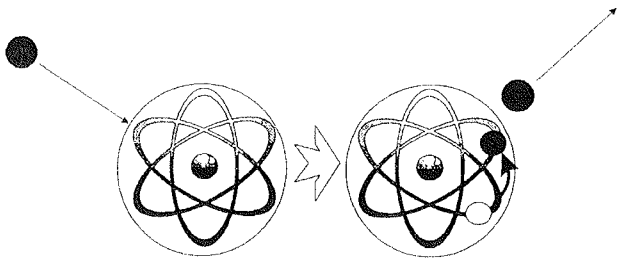


Figure 6: inelastic collision process that results in excitation of an atom

Atomic hydrogen excitation potential threshold is 10.2 eV, while molecular hydrogen excitation potential threshold is much lower - below 0.5 eV - due to the possibilities of vibrational and rotational excitations as discussed earlier.

Relaxation

One of the immediately self-evident features of the glow discharge is that it glows! This glow is due to the relaxation or de-excitation of electronically excited atoms and molecules - the inverse of the excitation process just discussed.

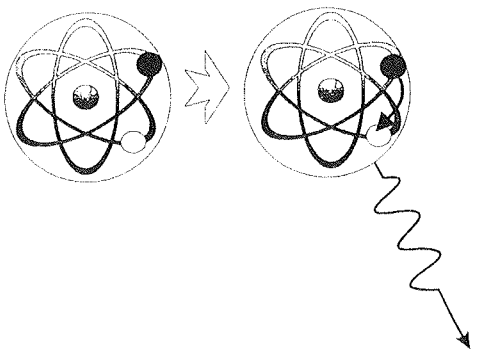


Figure 7: Relaxation (or de-excitation)

These excited states are rather unstable and the electron configuration soon returns to its original (ground) state in one or several transitions, with lifetimes varying enormously from nanoseconds to seconds, figure 7.

Each transition is accompanied by the emission of a photon of very specific energy, equal to the difference ΔE in energy between the relevant quantum levels. Our eyes are sensitive only to wavelengths between about 4100 Å (violet) and 7200 Å (red), corresponding to

electron transitions of 3.0 eV and 1.7 eV respectively, but with suitable detection equipment, photons from deep UV (atomic transitions) to far infra red (molecular vibrational and rotational transitions) can be detected.

As an example, in table 2, we present a list of light wavelengths emitted by excited reactants or products in plasmas typically used for etching and cleaning. Atoms and molecules emit a series of spectral lines which are unique to each species and thus can be used for end point detection purposes or plasma characterization.

Table 2: Species and emission wavelengths when etching different films

FILM	SPECIES	WAVELENGTH (nm)
Resist	CO	297.7, 483.5, 519.8
	OH	308.9
	H	656.3
Silicon, Polysilicon	F	704
	SiF	777
Silicon Nitride	F	704
	CN	387
	N	674
Aluminum	AlCl	261.4
	Al	396

Dissociation

The process of dissociation is the breaking apart of a molecule. An oxygen molecule can be dissociated into two oxygen atoms, but an atomic gas such as argon cannot be dissociated at all.

As with the other inelastic processes we have been studying, dissociation can in principle be accomplished with any energy in excess of the dissociation threshold, i.e. the relevant bond strength in the molecule. In glow discharges, electron impact dissociation is common:

$$e + O_2 \rightarrow e + O + O \qquad (7)$$

A normal result of dissociation is an enhancement of chemical activity since the products are usually more reactive than the parent molecule.

Dissociation may or may not be accompanied with ionization:

$$e + CF_4 \rightarrow e + CF_3 + F \text{ (dissociation)} \qquad (8)$$

$$e + CF_4 \rightarrow 2e + CF_3^+ + F \text{ (dissociative ionization)} \qquad (9)$$

There are different probabilities and hence different cross sections, for each of these processes.

Electron attachment

There is a possibility that an electron colliding with an atom may join on to the atom to form a negative ion. This process is known as electron attachment. The noble gases, including argon, already have filled outer electron shells and so have little or no propensity to form negative ions. Halogen atoms, however, have an unfilled state in their outer electron shells; they have high electron affinities and so readily form negative ions.

2.3 ION - NEUTRAL COLLISIONS

Charge transfer

The probability of a collision leading to the exchange of charge, generically known as charge transfer, is usually greater for atomic ions moving in parent atoms (symmetrical resonant charge transfer), e.g.

$$A + A^+ \rightarrow A^+ + A \qquad (10)$$

or similarly for molecular ions moving in parent molecular gases, than in charge exchange between unlike systems, e.g.:

$$B^+ + C \rightarrow B + C^+ \qquad (11)$$

which is known as assymetric charge transfer and tends to be less efficient.

Ionization by ion impact

Just as ionization can be produced by photon bombardment, so it can also be produced by fast ion or fast atom bombardment, provided the incident particles have enough energy.

3.0 PLASMA GENERATION

In the introduction we have briefly mentioned that plasma is usually produced by DC or AC electric field from which charged particles absorb energy in the form of kinetic energy. Then by inelastic collision processes they transform it into internal energy of neutral atoms or molecules finally producing plasma consisting of different neutral, excited, charged particles, radicals and photons.

The energetic electrons are responsible for most of the ionization, which produces additional electrons and ions to sustain the discharge against the various loss processes.

Since charged particle - electric, or magnetic field interaction is so important, we will describe it in more detail having always in mind their influence on macroscopic plasma behaviour.

Interaction of electrons with a static electric field

In a static electric field an electron experiences the following force which causes change of its momentum:

$$\vec{F} = -e\vec{E} = \frac{d}{dt}(m\vec{u}) \qquad (12)$$

For example, in argon at 30 mtorr (0.04 mbar) there are 10^{15} cm^{-3} atoms, and average mean free path is about $\lambda \approx 1$ cm. If we assume only elastic electron-neutral collisions (cross section is about 10^{-15} cm^2) electron gains in the average $eE\lambda\cos\theta$ energy between two collisions (θ is the angle between electron trajectory and electric field). We have already seen that after making elastic collision with heavy neutral, electron looses only $2 \cdot 10^{-4}$ fraction of its initial energy while its momentum change is large, as shown in the figure 8. Thus, the elastic collisions effectively transform the directed energy which electrons acquire from the electric field into random energy. This begins to establish the electron energy distribution function, and the electrons "heat up".

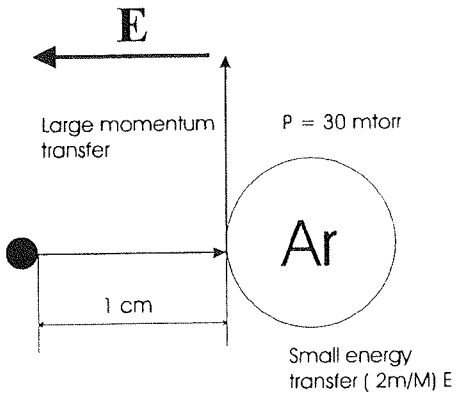


Figure 8: Elastic collision between electron and Ar atom

To be more precise, we can rewrite equation (12) to include the effect of collisions in the form of Langevin equation as:

$$(d / dt)(mu) = -eE - mu\, \nu_e \qquad (13)$$

where u is average drift (directed) velocity due to the electric field, and ve is the electron - neutral collision frequency. Steady state solution is:

$$u = \mu E \qquad (14)$$

where μ is electron mobility defined as $\mu = e/(m\nu_e)$.

Electron current density is:

$$J = enu = \sigma E = ne^2/(m\nu_e)E \qquad (15)$$

and finally we can calculate the rate at which the external power source inputs energy into electrons as

$$P_{in} = JE = \sigma E^2 = ne^2E^2/(m\nu_e) \qquad (16)$$

The rate at which the energy is lost due to collisions is:

$$P_{OUT} = n\delta W \nu_e + n\Sigma W_i \nu_i \qquad (17)$$

where the first term is energy lost due to elastic collisions and the second term is the sum over all inelastic processes, with energy loss Wi and collision frequency ν_i.

For the simplicity let us assume that only elastic collisions dominate. In this case if we equate $P_{in} = P_{OUT}$, we get expression for W, energy gained per electron:

$$W = \frac{E^2e^2}{4m\nu_e^2}\frac{M}{m} \qquad (18)$$

As an example, let us consider He at 0.5 torr (0.66 mbar) in a typical electric field of 1V/cm (100 V/m). Then, the equation (18) predicts an electron energy of approximately 5eV. The energy lost per collision is only 0.00125 eV, which in steady state is just equal to the energy which an electron gains from the electric field between collisions. Since such a small fraction of the electron's energy is lost in a collision, the electron must heat up to 5 eV to provide the energy balance. The small energy transfer results in negligible heating of the neutrals, which therefore usually remain at the room temperature.

The inclusion of inelastic processes will modify the energy balance because, in those processes, an electron can lose a large fraction of its energy. This will result in a lower electron energy than predicted by equation (18). However, the cross sections for inelastic processes are usually smaller than for elastic processes, so that the electrons will still have a higher temparture than the neutrals.

Interaction of electrons with a time dependent electric field

We will now consider the particle motion that results from using an AC power source at frequency ω, with no magnetic field present. It is convenient to write the electric field as a complex quantity:

$$\vec{E} = \vec{E}_0 \exp(i\omega t) \qquad (19)$$

Due to changing electric field the motion of the particles will be oscillatory, as will be the particle drift velocity. Solving the Langevin equation for such a case gives the following particle mobility:

$$\mu = \frac{e}{m(\nu_e + i\omega)} \qquad (20)$$

and

$$\sigma = \frac{ne^2}{m(\nu_e + i\omega)} \qquad (21)$$

Power input to the electrons is now

$$P_{IN} = Re(JE) = \frac{ne^2 E_0^2}{m\nu_e\left(1+(\omega/\nu_e)^2\right)} \qquad (22)$$

Let us examine some special cases. If $\omega = 0$, we recover the DC case. If there were no collisions ($\nu_e = 0$), we find that Pin averages to zero. The reason for that is that the drift velocity and electric field would be 90° out of phase, and thus no power could be transferred. As in the DC case, the collisions transform the directed energy that the electrons gain from the oscillating electric field to the random energy that represents electron heating.

If $\omega >> \nu_e$, then the mobility and conductivity are similar to the DC case with ν replaced by ω^2/ν_e. The power input would therefore decrease with increasing frequency.

Although it is not obvious from our derivations here, a more detailed calculation would reveal the fact that the maximum power input occurs when $\omega = \nu_e$. This can be seen qualitatively by the following argument. If the AC power frequency is much lower than the collision frequency, then the particle makes numerous collisions during each AC cycle which prevents the particles from reaching maximum energy during the AC oscillations. On the other hand, if $\omega >> \nu_e$, then the particles undergo many oscillations between collisions, but this does not increase their energy. When $\omega = \nu_e$, the electrons make approximately one collision for every cycle of the AC power, and that represents the optimum for transforming energy from the electric field to the electron energy distribution.

We are particularly interested in microwave spectrum of AC power input. Its specifics can be understood by examining the process in a simple example gas such as helium. The effective electron - neutral collision frequency at 300 K for helium is given by:

$$\nu_e = 2.3 \cdot 10^9 \cdot P, \quad P = \text{pressure in torr} \qquad (23)$$

For optimum power absorption we need $\omega = \nu$ condition and consequently we can see that good microwave energy coupling depends on the discharge pressure. For a 2.45 GHz excitation frequency maximum power absorption in helium occurs at approximately 7 torr (9.2 mbar) and discharge pressures of 5-10 torr (6.6-13 mbar) provide efficient coupling of microwave energy into a helium discharge. Generalizing this result to other gases with different elastic cross sections and accounting for the influence of the discharge walls, the optimum pressure range for efficient discharge breakdown and maintenance with 2.45 GHz microwave energy usually occurs between 0.5-10 torr (0.6-13 mbar). In practice, an optimum pressure range is found between 0.1 mbar and about 10 mbar.

Interaction of electrons with a time dependent electric field in the presence of a static magnetic field

We know that the total force exerted on a charged particle in an electric and magnetic field is:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \qquad (24)$$

However, having present only a static magnetic field charged particles will oscillate around the direction of magnetic field. Their gyration frequency and radius are determined by:

$$\omega_c = \frac{eB}{m}, \quad \rho_c = \frac{mv_\perp}{qB} \qquad (25)$$

Obviously, lighter particles will oscillate with higher frequency having shorter radius of oscillation.

If we introduce a perpendicular AC electric field of freguency ω which is resonant with ω_c, then we will be able to accelerate electrons synchronously. This effect we call ECR - Electron Cyclotron Resonance - AC energy is coupled to natural resonance plasma frequency.

As electron's perpendicular energy increases, the gyration radius will increase, but the cyclotron frequency will remain constant, and therefore the particles will remain in phase with the applied field, figure 9. As in all the previous cases if we want to heat the electrons, we will need collisions to transform this directed energy to random thermal energy. However one big difference here is that the electron energy is increasing with each cycle, so that there is no need to have the collision frequency equal to the applied frequency. This facilitates the operation at lower pressures. However, if the collision frequency becomes of the order of ω_c or larger, then the electrons will not be able to undergo the complete cyclotron orbit. If the resonance is sufficiently broad, then there is little advantage to have a magnetic field at all.

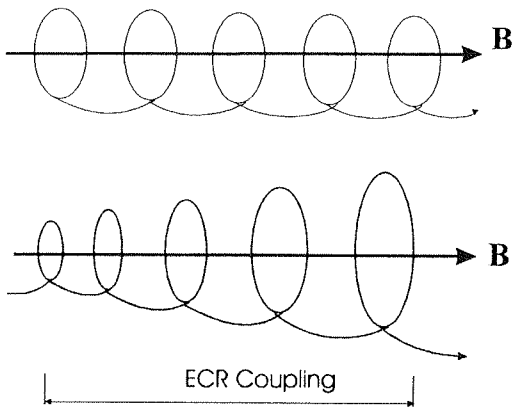


Figure 9: Electron motion in a static magnetic field
a) zero electric field
b) alternating electric field with $\omega = \omega_c$ and $E \perp B$

However, rewriting equation (22) taking into account ECR resonance, we obtain:

$$P_{IN} = Re(JE) = \frac{ne^2E_0^2\nu_e}{2m}\left(\frac{1}{\nu_e^2+(\omega-\omega_c)^2}+\frac{1}{\nu_e^2+(\omega+\omega_c)^2}\right) \quad (26)$$

ECR effect actually becomes very important at very low pressures (≤100 mtorr (0.13 mbar)). That is when the mean free path of electron-neutral and electron-ion collisions becomes very long ($\nu_e << \omega_c$). In such a case, using only MW radiation for plasma excitation, we need high electric fields to sustain the discharge at low pressures. This can be seen from equation (22) which becomes proportional to

$$P_{IN} = Re(JE) = \frac{ne^2E_0^2}{m\nu_e}\left(\frac{\nu_e}{\omega}\right)^2 \quad (27)$$

However, the presence of an ECR static magnetic field simplifies discharge maintenance below pressures of 20 mtorr (0.025 mbar). This can easily be observed by studying equation (26). When $\nu_e << \omega_c$, and at the $\omega = \omega_c$ resonant frequency, electron velocity perpendicular to the static magnetic field increases, resulting in an outward, spiralling motion along a magnetic field line. The electron gains energy proportional to the square of time and in a typical discharge the radius of the electron orbit is limited by an elastic or inelastic collision, a collision with the walls or the electron moving out of the ECR region.

However, at higher pressures, when pressure is such that $\nu e \rightarrow \omega = \omega_c$, magnetic field has little influence on heating the electron gas. Thus it is clear that ECR is a coupling technique for low pressure discharges where the electrons can orbit many times between elastic and inelastic collisions.

In practice, MW energy at 2.45 GHz is usually applied to generate plasma. From equation (25) by putting ω_c = 2.45 GHz and m = m_e we can calculate B, needed magnetic field strength to create ECR at the stated frequency. This value is 875 Gauss.

4.0 WHY MICROWAVE PLASMA?

In figure 10 we show a comparison of Electron Energy Distribution Function (EEDF) for plasmas generated with frequencies below and above 100 MHz. For electron energies above 15 eV, when gas atoms ionization begins, as well as for energies below 7 eV, when dissociation of most commonly used gases takes place, the number of electrons generated with microwave (MW) frequencies is larger than the number of electrons generated with RF. This helps to explain why the degree of ionization, as well as the degree of dissociation are higher in the case of MW plasma generation. This means higher plasma densities per unit volume and faster creation of reactive chemical radicals. But, the electron density per unit volume is mainly determined by the limits of wave propagation leading to a so called cut-off electron density which is strongly different for RF and MW frequencies.

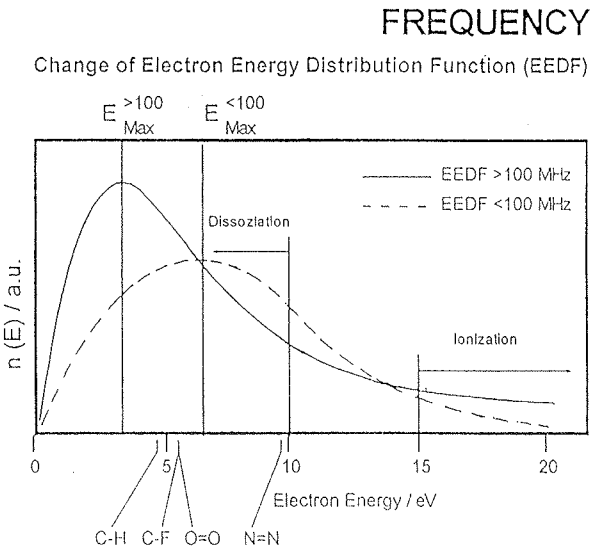
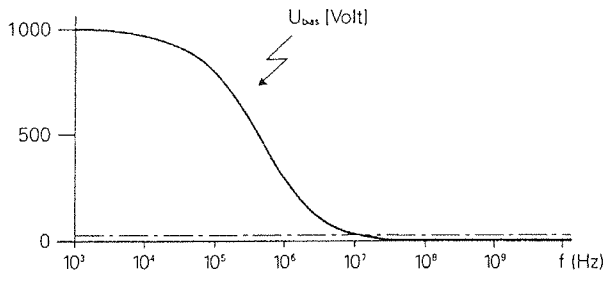


Figure 10: EEDF as a function of plasma excitation frequency

Another beautiful feature of the MW plasma can be seen in the figure 11, where substrate "floating potential", or selfbias, is shown as a function of frequency. In the region of MW frequencies, there is no, or very little selfbias which means "gentle" processing due to lower ion energies which assure minimum damage to sensitive substrates.



Prof. S. Vepřek, International Sommer School on Plasma Chemistry, Technical University Munich, 1992

Figure 11: Substrate selfbias potential as a function of plasma excitation frequency

We have already seen in section 3 that MW and MW/ECR plasmas are effectively generated at quiet low pressures. That is when electrons gain enough kinetic energy due to motion in AC electric field before making collisions with neutrals. ECR effect further pumps en-

ergy into electrons and keeps them longer within plasma volume preventing their recombination with reactor walls. This is not demonstrated only in the EEDF but also in electron temperature, which increases with decreasing pressure, as seen in the figure 12.

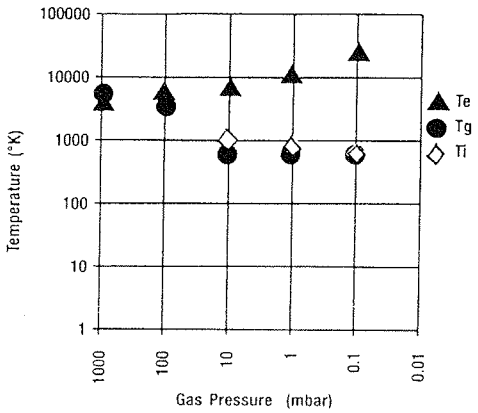


Figure 12: Electron (T_e), ion (T_i) and gas atom (T_g) temperatures versus total pressure

As well, MW plasma processors are compact, simple, reliable systems which require nearly no maintenace. MW radiation which is produced by commercially available magnetrons is coupled to the plasma via special applicators which are mounted on the wall of the vacuum chamber. So, there is no need for special electrodes for RF coupling, as well as none, or very little impedance matching is required. However, special MW/ECR sources have more components than their MW counterparts due to the presence of magnetic coils and - in some cases - collimation optics.

In table 2 we summarize and compare plasma characteristics generated at different frequencies.

	DC=	RF 13.56 MHz	MW 2.45 GHz	MW/ECR 2.45 GHz
Operating pressure, mbar	10^{-2}-10^{-3}	2-10^{-1}	2-10^{-1}	10^{-1}-10^{-4}
Ion density, cm^{-3}	10^{9}	10^{9}-10^{10}	10^{10}-10^{11}	10^{10}-10^{11}
Degree of ionization	10^{-7}	10^{-5}	10^{-4}-10^{-3}	10^{-2}-10^{-1}
Electron temperature, K		$5{\cdot}10^{4}$		$10{\cdot}10^{4}$
Level of dissociation	low	low	high	high
Self bias or plasma potential,V	>100	>100	<20	<20

5.0 MW PLASMA GENERATION

Microwave discharges are often required to operate with different gases, variable gas mixtures and flow rates over a wide range of operating pressures. Thus the MW discharge system should be able to efficiently produce a stable, repeatable and controllable discharge for many experimental conditions including discharge start up and adjustment for final processing operation. As well, application of such systems in industrial environments require certain level of automatic control without the need of a highly trained microwave engineer.

A generic MW plasma processing system together with its equivalent circuit is depicted in figure 13. It consists of several components such as:

- a power source, usually a constant frequency but variable power MW oscillator
- transmission line, often a waveguide or coaxial cable
- a MW applicator
- the MW plasma load

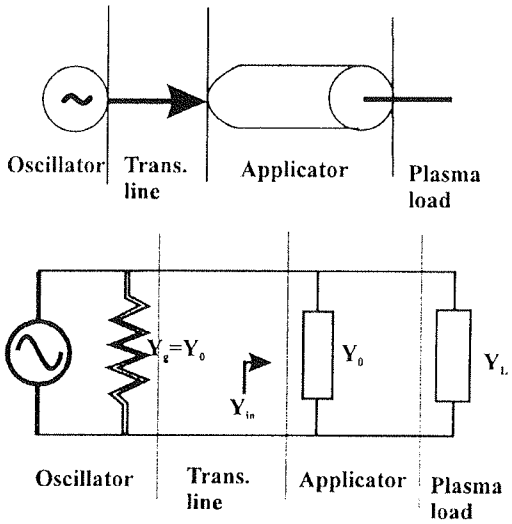


Figure 13: MW processing system and its equivalent circuit

An efficient plasma processing system is designed for maximum power transfer between the MW oscillator and the plasma - loaded applicator. This happens when the output admittance of the MW oscillator Y_g and the input admittance of the plasma loaded applicator Yin are equal to the transmission line characteristic admittance Y_0.

A major difficulty in the design of a MW or MW/ECR system is the variable, nonlinear often reactive discharge load. However, careful design of the applicator and the chamber can lead to the overall system construction which is robust enough to successfully transmit MW energy to varying plasma loads. Nevertheless, minor tuning is still required and is often performed via simple tuning stubs at the initial start up of the machine or after overhaul maintenance.

A typical industrial MW plasma barrel system is depicted in figure 14. It consists of:

- a plasma chamber where the substrates are placed during the process
- a roughing pump which is needed to evacuate the chamber
- several gas inlets distributed around the plasma chamber
- MW source/applicator usually on the wall of the chamber

Plasma is generated in the volume in the vicinity of the quartz or ceramic window and its species diffuse throughout the chamber volume and react with the substrates and chamber walls. Large reactor designs use several plasma sources to obtain high plasma densities and good uniformity within the chamber. Typically, two gas channels are sufficient (normally for O_2 and CF_4 gases) but several additional gas channels can be added for more exotic processes if required (air, He, Ar and their mixtures).

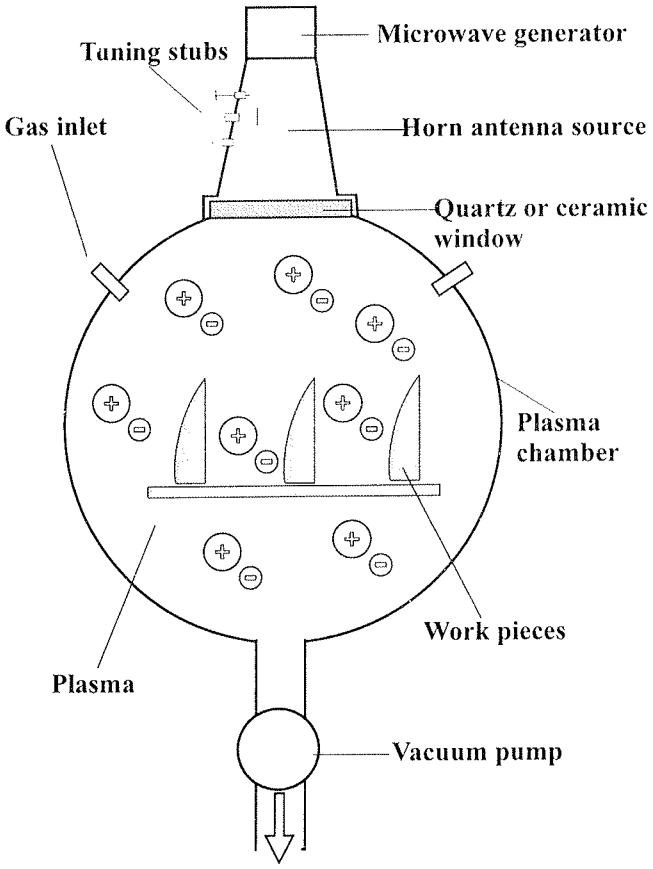


Figure 14: MW plasma barrel system

A schematic diagram of an ECR microwave plasma source is depicted in figure 15. As in normal MW plasma source designs, MW power of 2.45 GHz is transmitted to the plasma via a waveguide and through a quartz or alumina window. However, due to added magnetic coils there is a magnetic field parallel to the MW propagation vector introduced. In the plasma dome a resonant field of 875 Gauss is formed needed to trigger the ECR effect.

ECR source depicted in figure 15 operates in so called PLASMA STREAM mode since the majority of ionized species are extracted through the slit from plasma zone using only existing magnetic field gradient while non-charged particles freely diffuse through the slit into the chamber.

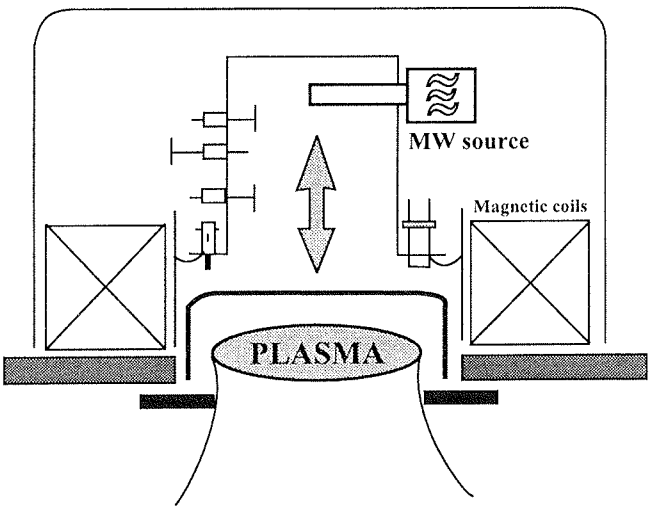


Figure 15: ECR plasma stream source

Slightly different mode of operation is achieved if biased extraction electrodes are added directly below the plasma dome. By varying the extraction voltage, beam of ions with controlled kinetic energy can be produced and directed to the substrate where suitable reactions take place. As well, current density varies with applied extraction voltage. This is so called ION BEAM mode of ECR source operation which is usually used for Reactive (RIBE) and Non-reactive (IBE) Ion Beam Etching of different thin films and substrates.

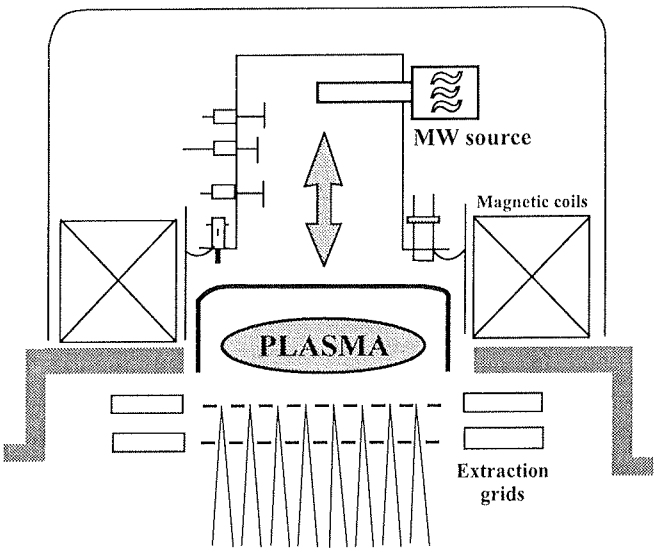


Figure 16: ECR ion beam source

Operating characteristics of a typical Technics Plasma ECR Ion Beam source (Model PLASMODULE ECR-160) are as follows:

- Extraction grids: two grids made of graphite (Mo if wanted)
- Extraction voltage: variable, 0 - 2000 V
- Ion current density: 1 - 2 mA/cm^2
- Ion beam area: 160 mm^2
- Ion beam uniformity: ±5% within 120 Φmm
- Beam divergence: 5°
- Working pressure: 10^{-4} to 10^{-5} mbar

6.0 LITERATURE

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/2/ B.Chapman, GLOW DISCHARGE PROCESSES, John Wiley&Sons 1980, ISBN 0-471-07828-X

/3/ S.M.Rossnagel, J.J.Cuomo, W.D.Westwood editors, HANDBOOK OF PLASMA PROCESSING TECHNOLOGY, Noyes Publications 1990, ISBN 0-8155-1220-1

/4/ Technics Plasma GmbH, Application Reports

COMMENT: For more information about Technics Plasma systems and their applications, please call:

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PREDSTAVLJAMO PODJETJE Z NASLOVNICE
REPESENT OF COMPANY FROM FRONT PAGE

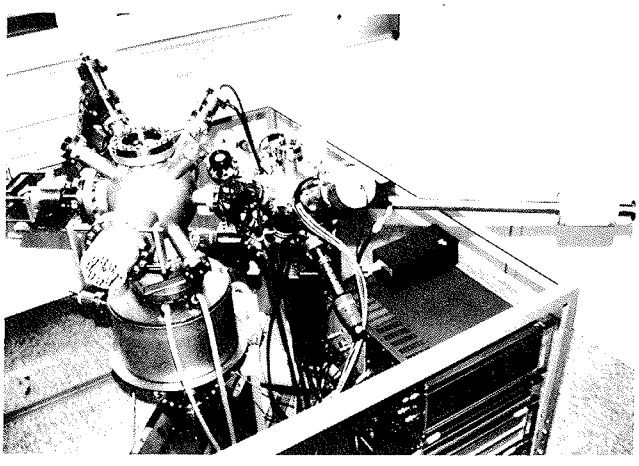
INŠTITUT ZA ELEKTRONIKO IN VAKUUMSKO TEHNIKO - IEVT

IEVT deluje kot samostojna raziskovalno-razvojna organizacija že od leta 1954. Ker so osnovo takratne elektronike predstavljale elektronske cevi, te pa so bile povezane z vakuumsko tehniko, so glavne dejavnosti potekale prav na teh dveh področjih. Poznejši razvoj podjetja je potekal skladno z razvojem tehnike v svetu ter potrebami in možnostmi v takratni Jugoslaviji. To so bili časi zaprtega tržišča, lačnega zlasti tehnično zahtevnih izdelkov. Temu je IEVT znal prisluhniti in kaj hitro je poleg programsko izredno razvejane raziskovalno - razvojne dejavnosti zrasla tudi maloserijska proizvodnja kot zadnja faza razvoja. Nekateri od programov so se s programsko in kadrovsko izdvojitvijo prenesli tudi v štiri nova podjetja, ki jih je osnoval IEVT.

Aktivnosti IEVT-ja danes so naslednje: raziskave, aplikativni razvoji izdelkov in tehnologij, maloserijska proizvodnja in storitve na področjih:

- vakuumski sistemi in komponente
- oprema za medicino
- hermetično zaprti stikalni elementi
- posebna svetila
- elektronska oprema in sklopi

Skoraj vsa omenjena področja so tesno povezana z vakuumsko tehniko, ki je izrazito interdisciplinarno področje, saj se v njem prepletajo fizika, strojništvo, elektronika, elektrotehnika, kemija in metalurgija. Danes je vakuumska tehnika nepogrešljiva v mikroelektroniki in



Slika 1: Visokovakuumski črpalni sistem z manipulatorjem, izdelek IEVT